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Alexis Rebecca Werner Olsho

An Investigation of Introductory Student Understanding of Special Relativity in the Context of the Relativity of Simultaneity

Alexis Rebecca Werner Olsho

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Reading Committee:

Peter S. Shaffer, Chair

Paula Heron

Leslie Rosenberg

Program Authorized to Offer Degree:
Department of Physics

University of Washington

Abstract

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Alexis Rebecca Werner Olsho

Chair of the Supervisory Committee:
Professor Peter S. Shaffer
Department of Physics

This dissertation describes the results of an investigation into introductory student understanding of special relativity in the context of the relativity of simultaneity. The research probes the extent to which students are able to use concepts from both Galilean and special relativity to determine, for multiple reference frames, the time sequence of events that have a spacelike separation. To this end, three parallel investigations were conducted. The first probed student ability to apply the formalism of a reference frame to determine both the time and location of events, for multiple reference frames. The second probed student understanding of relevant consequences of the invariance of the speed of light. Finally, we examined student understanding of concepts related to causality, which can be seen as the basis of a qualitative understanding of the relativity of simultaneity. These investigations identified a number of significant conceptual and reasoning difficulties in this population of students. Modification and assessment of curricular materials intended to address the identified difficulties is also described.

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DEDICATION

To my other “Big Project” over the last seven years: Jason, Daisy, and Willa

Chapter 1

INTRODUCTION

This dissertation describes an investigation of student understanding of key ideas in Galilean and special relativity. This research has taken place in the introductory calculus-based physics sequence at the University of Washington. In particular, this dissertation documents how the results of the research have led to the modification of existing curricular materials meant to improve student understanding of basic concepts in special relativity. The modified curriculum seeks to help students develop facility with the concepts of events, reference frames, Einstein's postulates of special relativity, and causality as used to understand the relativity of simultaneity. Assessment of the effectiveness of the curriculum is performed by comparison of pretest and post-test results.

The Physics Education Group at the University of Washington is involved in numerous investigations of student understanding of topics in physics and physical science [1]. Prior research by members of the group has identified a variety of student difficulties with concepts in Galilean and special relativity. These prior investigations led to the development of curricula intended for use by students of varying levels of expertise. A major goal of the research described in this dissertation was to assess the effectiveness of these existing curricula for students in introductory, calculus-based physics courses, as well as to modify the curricula to address the difficulties of this new population.

This introduction is organized into six sections. §1.1 defines the scope of the investigation, and includes a brief background of the physics required. In §1.2, we describe motivation for the research described in this dissertation. A description of the research performed by the Physics Education Group and the resulting curricula are described in §1.3. In §1.4, we describe the context in which the investigation in this dissertation was done, including a brief description of the student population involved. §1.5 presents the methods employed in

this investigation, including a description of the statistical methods used. Finally, in §1.6 we preview the organization of the remainder of this dissertation.

1.1 *Scope of investigation*

The research and curriculum modifications described in this dissertation span a range of topics in Galilean and special relativity. We focus broadly on student understanding of the relativity of simultaneity, the idea that spatially separated events that occur simultaneously in one reference frame do not occur simultaneously in other reference frames. The relativity of simultaneity provides a context for research into student understanding of a number of more fundamental concepts: reference frames and measurement, the invariance of the speed of light, and events and causality. The relativity of simultaneity is a particularly rich context in special relativity that can be understood without complex (or any) mathematics, using only ideas from Galilean relativity and Albert Einstein's two postulates of special relativity. Moreover, the relativity of simultaneity can serve as a basis for understanding other foundational results from special relativity, such as length contraction and time dilation.

Below is a discussion of the basic concepts of special relativity that are needed to understand the relativity of simultaneity. Additionally, we describe Einstein's train paradox, an illustrative example of the relativity of simultaneity and the basis for some of the curricular materials used in this research. Resolution of Einstein's train paradox is provided by way of three methods.

1.1.1 *Basic concepts of special relativity*

Understanding of the relativity of simultaneity requires understanding of some basic concepts of Galilean and special relativity. These include: (a) events, reference frames, and intelligent observers; (b) temporal separation of events, Einstein's postulates of special relativity, and simultaneity; and (c) causality and the principle of coincidence. These ideas are summarized here.

The discussion is consistent with that in many introductory physics textbooks; in particular, those used in the introductory physics courses during the period of this investigation [2]. The order of presentation of these concepts below is the same as in the curricular materials

which were the focus of our investigation.

1.1.1-a *Events, reference frames, and intelligent observers*

The construct of a *reference frame* is central to Galilean and special relativity. A reference frame can be defined in many ways, but for the purposes of this dissertation, a reference frame is defined as a three-dimensional grid of meter sticks and synchronized clocks that can be used to determine the time and position (that is, the *spacetime coordinate*) of any event. An event is anything that can be associated with a single spacetime coordinate. All relative motion described in this dissertation is one-dimensional; therefore, the spacetime coordinate of a given event can be described with a single x -coordinate and single t -coordinate, (x, t) . The spatial coordinate of an event in a given reference frame S can be described as the coordinate label at the location of the event on the grid of meter sticks; the time coordinate is the reading of the clock at the location of the event at the instant that the event occurs.

We assume that all observers in special relativity are *intelligent observers* who can use a reference frame to determine correctly the spacetime coordinate of any event using a reference frame. An intelligent observer always uses the grid of meter sticks and synchronized clocks that is at rest with respect to him or her. This specification implies that observers at rest with respect to each other use the same reference frame; observers at rest with respect to each other are said to share or be in the same reference frame.

1.1.1-b *Temporal separation of events, Einstein's postulates of special relativity, and simultaneity*

The *temporal separation* between two events (1 and 2) in a given reference frame S is defined as $\delta t_{12}^{(S)} = t_2^{(S)} - t_1^{(S)}$, where the time coordinate of each event has been determined by the method described above. Two events are said to be *simultaneous* when the temporal separation of the two events is equal to zero. That is, two events are simultaneous when the readings on the clocks of a given reference frame at the locations of the events are identical at the moment the two events occur. This makes clear the importance of synchronization of

the clocks of a given reference frame. In addition, because the time coordinates of events are determined using the clocks of a particular reference frame, in special relativity (in which time is *not* absolute), the temporal separation of events is necessarily dependent on the reference frame in which they are measured. In Galilean relativity, however, time is absolute; both the time of a given event, and the temporal separation of two given events are the same in every reference frame.

Einstein's two postulates of special relativity are the basis for the departure of the predictions of special relativity from those of Galilean relativity. Einstein's first postulate is the *Principle of Relativity*: the laws of physics are the same in all inertial frames of reference. The first postulate is an extension of *Galilean invariance*, which states that the laws of (Newtonian) mechanics are invariant under Galilean transformation. Einstein extended this invariance to all laws of physics, most notably to the laws of electromagnetism. Einstein's second postulate describes the invariance of the speed of light: as measured in an inertial reference frame, the speed of light in vacuum is finite and equal to c , independent of the motion of the emitting body. An important consequence of the second postulate is that the origin of a spherical wavefront of light is stationary in all inertial reference frames. Awareness of this consequence is of particular importance for the results described below.

The two postulates, when added to Galilean relativity, have some surprising consequences. A key result is the relativity of simultaneity: two events with non-zero spatial separation that are simultaneous in one reference frame are not simultaneous in any other reference frame. This result is responsible for many of the “paradoxes” of special relativity; these paradoxes are easily resolved when one accepts that simultaneity is not absolute.

1.1.1-c Causality and the principle of coincidence

The concept of *causality* is not unique to special relativity. The idea that events or processes are causally related is a cornerstone of science. Special relativity does rely, though, on the idea that causality is independent of reference frame. This is a special case of the first postulate of special relativity.

Most generally, two events that are possibly causally related in one reference frame must be possibly causally related in every reference frame. The speed of light describes the maximum propagation speed of any signal; therefore, a possible causal relationship between events is limited by the spatial and temporal separations of those events and the speed of light. A more specific case of this can be stated as follows: if there exists a reference frame in which two events occur at the same spatial coordinate, the time sequence of those events is preserved across all frames. This is necessary to uphold causality, as such events are inevitably possibly causally related.

Even more specific is the *principle of coincidence*: if two events share a single spacetime coordinate in one reference frame, they must share a spacetime coordinate in all reference frames. Again, this can be seen as necessary to uphold causality, as seen in the following argument. Consider that an event is anything that can be associated with a single spacetime coordinate. If two events (1 and 2) share the same spacetime coordinate, $(x_1^{(S)}, t_1^{(S)}) = (x_2^{(S)}, t_2^{(S)}) = (x^{(S)}, t^{(S)})$, we might define a third event (3) as “events 1 and 2 occur at spacetime coordinate $(x_3^{(S)}, t_3^{(S)}) = (x^{(S)}, t^{(S)})$ ”. All events that occur in one frame must occur in all frames (again, to uphold possible causal relationships between events), so event 3 occurs in all frames, though the particular spacetime coordinate may differ.

1.1.2 Einstein’s train paradox

Einstein’s train paradox is the classic example of the relativity of simultaneity. To understand the resolution of the paradox, students must be familiar with most of the concepts discussed in the prior section. In Einstein’s train paradox, a train moves at constant speed on a long, straight track. The train passes an observer standing near the track; at the instant that the observer is exactly half-way between the ends of the train, lightning strikes both ends of the train simultaneously. A short time later, the observer receives the light from the two lightning strikes simultaneously, since the observer is equidistant from the locations of the lightning strikes and given that the light propagates at the same speed from both strikes. Einstein’s insight was that in the reference frame of the train, and in fact any reference frame other

than the reference frame of the ground, the lightning strikes are not simultaneous. There are a number of ways to see that the lightning strikes are not simultaneous in other reference frames; three methods for determining the order of the lightning strikes in reference frames other than the reference frame of the ground are described below: mathematically using the Lorentz transformation for time; qualitatively; and through the construction of spacetime diagrams.

1.1.2-a Lorentz transformations

One can determine the time coordinates of the events corresponding to the two lightning strikes using the Lorentz transformations for time.

Consider two reference frames: the reference frame of the ground, and the train's reference frame. Suppose that the origins of these two reference frames are coincident at the rear of the train at the instant that the rear lightning strikes. Then $t_r^{(G)} = t_r^{(T)} = 0$ and $x_r^{(G)} = x_r^{(T)} = 0$.

In the reference frame of the ground, the front lightning strike has spacetime coordinate $(x_f^{(G)}, t_f^{(G)}) = (0, L)$, where L is the length of the train as measured in the ground frame. The Lorentz transformation for time tells us that $t_f^{(T)} = \gamma(t_f^{(G)} - \frac{v}{c^2}x_f^{(G)}) = \gamma(0 - \frac{v}{c^2}L) < 0$, where v is the relative speed of the ground and train reference frames. Because $t_r^{(T)} = 0$ and $t_f^{(T)} < 0$, we conclude that in the reference frame of the train, the front lightning strike occurred before the rear lightning strike.

1.1.2-b Qualitative arguments

The order of the lightning strikes can be determined using entirely qualitative arguments. Consider the observer at rest with respect to the ground near the train tracks. As stated, this observer is halfway between the ends of the train when the lightning strikes the ends of the train simultaneously. The instant that the lightning strikes the ends of the train simultaneously in the ground reference frame is shown in Figure 1.1

In the reference frame of the ground, the origins of the wavefronts of light from the

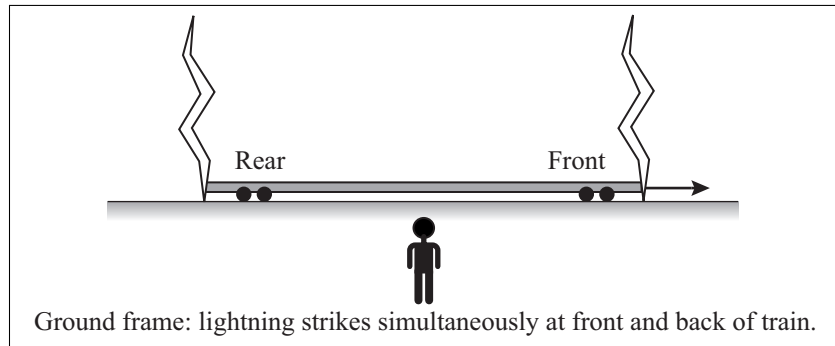


Figure 1.1: The instant that the lightning strikes the ends of the train simultaneously in the reference frame of the ground

lightning strikes are stationary with respect to the ground, located where the ends of the train were when the lightning struck. Because the observer is halfway between those points, the wavefronts are emitted simultaneously, and the speed of wavefronts is the same in all directions in the ground reference frame, the observer will receive the light from the lightning strikes simultaneously. This instant in the ground reference frame is shown in Figure 1.2

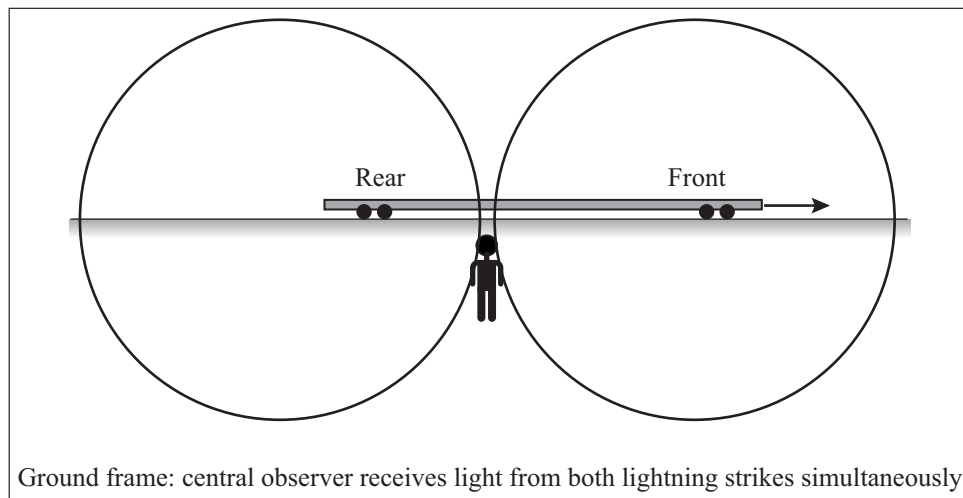


Figure 1.2: The instant that observer receives the wavefronts from the lightning strikes simultaneously in the reference frame of the ground

By the principle of coincidence, we know that the observer must receive wavefronts from

the lightning strikes simultaneously in the reference frame of the train. However, in the train reference frame, the wavefronts of light from the lightning strikes are located not at stationary points on the track, but at the ends of the train. The instant in the train reference frame that the observer receives the light from the lightning strikes is shown in Figure 1.3. Note that the wavefront from the front lightning strike has a larger radius than that from the rear lightning strike.

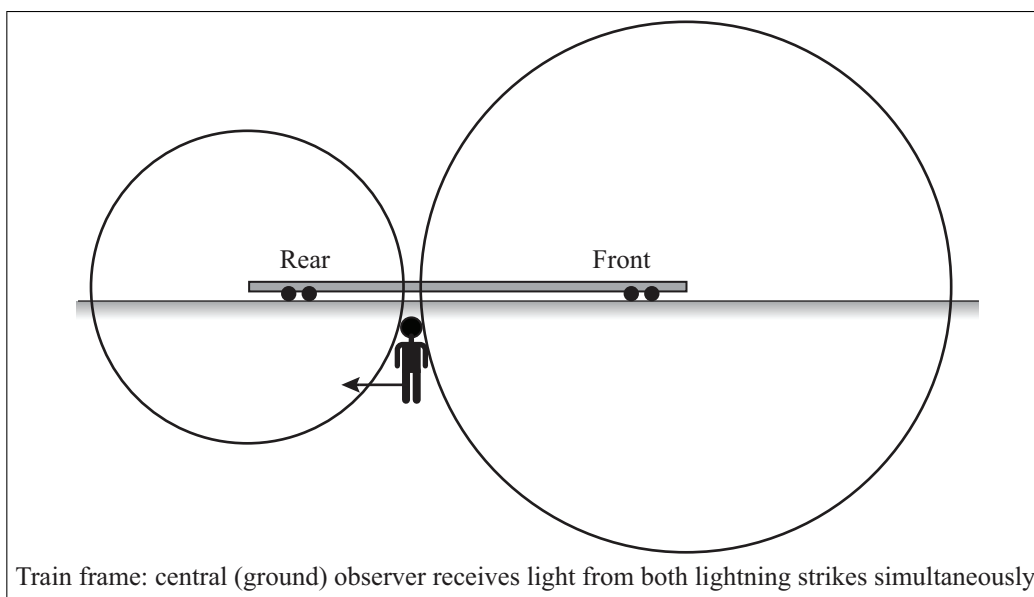


Figure 1.3: The instant that observer receives the wavefronts from the lightning strikes simultaneously in the reference frame of the train

The speed of light is the same in the train reference frame as it is in the ground reference frame, and is not different for the light from the front and rear lightning strikes. Therefore, in order for the wavefront from the front lightning strike to have a larger radius, the front lightning strike must have occurred before the rear lightning strike in the reference frame of the train.

This chain of reasoning, which is based on understanding of time and position measurements in multiple reference frames, the invariance of the speed of light, and causality and the principle of coincidence, is the basis for understanding the relativity of simultaneity as

described in this dissertation.

1.1.2-c Spacetime diagrams

Spacetime diagrams are presented as a third method for determining the order of the lightning strikes in the reference frame of the train, but it should be noted that proper construction of spacetime diagrams for multiple reference frames requires understanding of much of the qualitative argument described above. In particular, it relies on understanding of the principle of coincidence and the invariance of the speed of light. Additionally, knowledge of conventions of spacetime diagrams is necessary.

The correct spacetime diagrams for the train and ground reference frames are shown in Figure 1.4. Note that the speed of the train in the reference frame of the ground is equal to the speed of the observer in the reference frame of the train, though they move in opposite directions. The observer sees the light from both lightning strikes simultaneously in both reference frames (event E_S), and is closer to the rear of the train when he does so. The speed of light is the same in both reference frames, apparent by the angle of the “world lines” of the light signals being equal to 45° in all cases.

As described in the setup of the train paradox, the events corresponding the front and rear lightning bolts striking (E_R and E_F) occur simultaneously in the ground reference frame; these two events also occur simultaneously with the event corresponding to the observer passing the center of the train (E_P). By following the conventions and rules stated in the paragraph above, we see that the time coordinate of E_P in the reference frame of the train is earlier than that of E_R , and later than that of E_F .

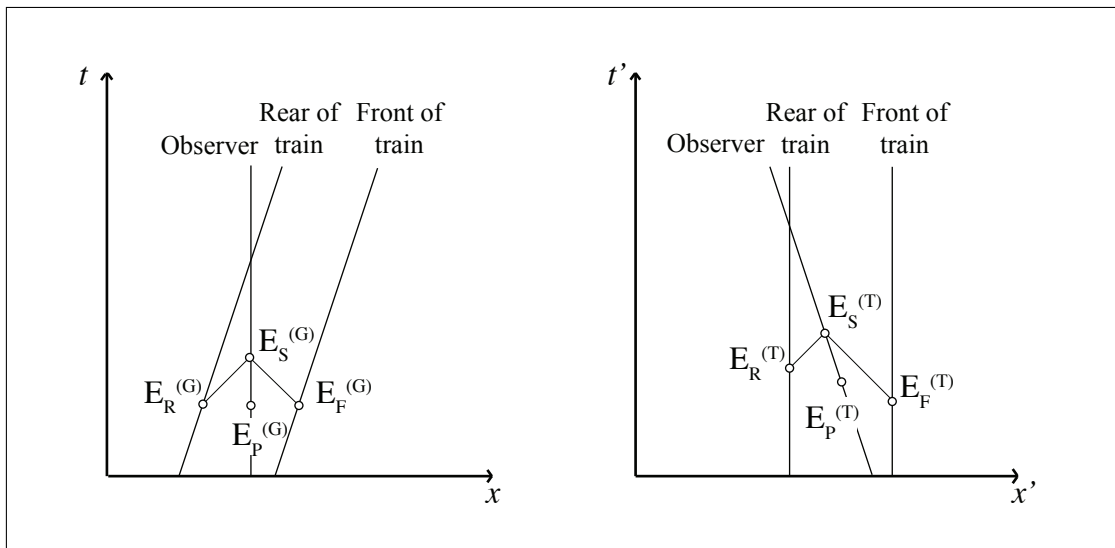


Figure 1.4: Spacetime diagrams for the reference frame of the ground (left) and train (right) showing the sequence of events in Einstein's train paradox.

1.2 Motivation for research

In this section, we present two different motivations for conducting systematic research on student understanding of topics in Galilean and special relativity.

First, we note that the emergence of special theory of relativity as a scientific model required a revolutionary shift in scientific thought. For students to understand special relativity, they must also undergo a radical shift in thinking to accommodate results that seem contradictory and counterintuitive. Special relativity has a basis in postulates that are nominally easy to understand, but have consequences that are hard for many students (and others) to accept fully [3–5]. Investigation into if and how students accomplish a shift in understanding may illustrate how students learn and amend their scientific models when necessary.

Second, and more specific to this investigation, coverage of special relativity was added to the non-honors, calculus-based, introductory physics sequence at the University of Washington in the Autumn of 2009. Prior research indicated that students have difficulty with many concepts related to special relativity, sometimes stemming from an incomplete understanding of Galilean relativity [6, 7]. Prior research by members of the Physics Education Group resulted in a series of “tutorials” in special relativity, aimed at helping students gain conceptual understanding this challenging topic [8, 9]. We sought to discover whether these existing materials were effective with this new population, and if not, how we might improve them to be more so.

1.2.1 Special relativity as a context for scientific accommodation

Einstein’s special theory of relativity is sometimes seen as “a prototype of a scientific revolution” [4].

Surprising experimental results regarding the speed of light (e.g., from the Michelson-Morley interferometry experiment) led to the development of the Electron Theory by Lorentz and Poincaré. The Lorentz transformation equations were published and accepted by the

scientific community in the context of the Electron Theory. The Lorentz transformation equations allowed for the *measured* invariance of the speed of light, regardless of the observer's reference frame, without changing the absolute concepts of space and time. The length contraction predicted by the Lorentz transformation for distance was believed to be a physical effect due to motion relative to the ether, and still required acceptance of an absolute frame of reference (i.e., one in which the ether was at rest).

The publication of Einstein's two postulates of special relativity did not immediately lead to acceptance of the special theory of relativity. The surprising result of the relativity of simultaneity, in particular, was troubling to many in the scientific community. Although Lorentz himself admitted that the predictions of his Electron Theory were inconsistent with emerging results of quantum theory, leaving special relativity as the only theory explaining relativistic effects without contradicting quantum phenomena, special relativity was not accepted in its entirety until after the publication of the general theory of relativity.

Given the scientific community's sluggish acceptance of special relativity, it is not surprising that students may also have trouble accommodating the theory's more surprising results. Students often believe relativistic effects (such as length contraction, and the relativity of simultaneity) to be *apparent* effects, due to what an observer might *perceive* rather than what is physically "true" or "real" [5]. Understanding of the relativity of simultaneity, length contraction, and time dilation requires an acceptance of the idea that time and space are not absolute. Investigations of student understanding of special relativity have different metrics with which to measure student "acceptance" of special relativity as a useful theory, and assimilation of its postulates and results into their existing models (see Chapter 3). As described above, this investigation focuses on student understanding of the relativity of simultaneity through a qualitative line of reasoning, rather than one based on calculation. We believe student ability to use such qualitative arguments is more indicative of acceptance and assimilation of special relativity than ability to calculate a result using the Lorentz transformations. Therefore, discovering a way to teach the relativity of simultaneity effectively might illustrate ways we might teach other difficult topics that require a significant shift in

student thinking.

1.2.2 Addition of special relativity to introductory instruction

Prior to Autumn 2009, special relativity was not being taught to students in the (non-honors), calculus-based, introductory physics sequence at the University of Washington. Earlier research into the student understanding of special relativity at the University of Washington focused on learning by students with various levels of expertise, and indicated that students of all levels had difficulty with ideas related to Galilean and special relativity. (see Chapter 3 for a description of this research.) This research resulted in the development of curricular materials (“tutorials”) intended to address these difficulties [7–9]. Although the research included students at the introductory levels, the resulting tutorials were used only with a select group in an “honors” introductory physics sequence. It was not known whether these tutorials would be effective for students in the non-honors introductory sequence.

Our initial investigation indicated that this new population of students had many of the same problems with this as those identified previously at the University of Washington. Additionally, we found that while implementation of the existing tutorials in the introductory sequence led to improved student performance on certain tasks, key outstanding difficulties remained. This motivated the investigation discussed in this dissertation and led to modifications of the special relativity tutorials as well as continued investigation into student understanding of special relativity in the context of the relativity of simultaneity. Understanding the relativity of simultaneity qualitatively requires the synthesis of key ideas of Galilean and special relativity; therefore, an investigation of student understanding of the relativity of simultaneity allows us to study both the breadth and the depth of student understanding of special relativity.

1.3 Research and curriculum development by the Physics Education Group

1.3.1 Motivation

The Physics Education Group, and physics education research more generally, investigates the teaching and learning of physics. There is a great deal of research indicating that traditional lecture instruction often fails to develop conceptual understanding of physics in students. The Physics Education Group uses an iterative cycle of research, curriculum development, and instruction to develop teaching methods and curricular material to improve conceptual understanding. Two core curricula have been developed by the Physics Education Group: *Physics by Inquiry* and *Tutorials in Introductory Physics* [10, 11].

1.3.2 Physics Education Group curricula

1.3.2-a Physics by Inquiry

Physics by Inquiry is a laboratory-based, self-contained curriculum designed for use primarily by pre- and in-service teachers. It is intended to teach physics and physical science as a process of inquiry; modules of the curriculum lead students through the construction of scientific models using simple experiments and exercises focused on observation. Students “start from scratch” and base their models on experiments they perform and inferences drawn from their observations. Each module focuses on an individual subject or area of physics or physical science; examples include *Properties of Matter*, *Electric Circuits*, and *Kinematics*. *Physics by Inquiry* is also structured to teach students about the process of science.

Physics by Inquiry is intended to be used by groups of two or three students working collaboratively in a small-class setting. Student groups are expected to participate in “checkouts”—extended conversations in which their understanding of the material is assessed by an instructor—before proceeding. During checkouts, instructors also engage students in semi-Socratic dialogues meant to extend their understanding of the material.

1.3.2-b *Tutorials in Introductory Physics*

Unlike *Physics by Inquiry*, *Tutorials in Introductory Physics* is a *supplementary* curriculum, intended for use alongside traditional instruction in introductory physics. Each tutorial worksheet focuses on development of conceptual understanding of a topic in introductory physics (e.g., *Acceleration in one-dimension*, *Electric potential difference*, or *Wave properties of light*). A tutorial for a given subject is usually administered after relevant lecture coverage of the same material. Therefore, the tutorials assume familiarity with some concepts and definitions. For some topics, a sequence of tutorials is used over two or more weeks; special relativity is one such topic.

Each tutorial is designed to take approximately 50 minutes to complete, and is intended to be completed during the tutorial class session. Students are expected to work collaboratively in groups of three to five. As with the *Physics by Inquiry* curriculum, instruction by teaching assistants is expected to be semi-Socratic, leading students to discover answers for themselves. Students are also expected to engage in peer instruction, helping and relying on other students in the group to learn the material.

Every tutorial has an associated homework worksheet. Students are generally expected to complete the associated homework within a week of the in-class tutorial session. A given homework may extend the models presented in the tutorial, test the ideas presented in the tutorial in new contexts, or occasionally introduce new material related to the in-class tutorial. Graders use a rubric to grade tutorial homework; the rubrics require the homework to be graded not just for the “correct” answer, but also for the explanation provided by the student.

A sequence of three tutorials was developed to address student difficulties with special relativity, with a focus on the relativity of simultaneity. Due to quarterly instructional time constraints, we were limited to use of two of the three tutorials. This dissertation describes modification of the sequence of these two tutorials in special relativity, and their associated homework: *Events and reference frames* and *Simultaneity*.

Basic instructional strategies Although the tutorials cover a wide range of topics in introductory physics, some common instructional strategies are used throughout. Many of the tutorials focus on the construction and application of models to various phenomena. Others help students feel comfortable using conventional representations of systems or processes.

Of particular importance is the *elicit-confront-resolve* strategy; this strategy is used multiple times in the sequence of special relativity tutorials. A question or exercise is designed to *elicit* a common, incorrect idea or assumption. Next, students are *confronted* with this incorrect idea and how it contradicts the correct physics or model. Finally, students are guided to *resolve* the inconsistencies of their incorrect idea with the correct one.

1.4 Context of investigation

All research described in this dissertation was done in the regular (non-honors), calculus-based, introductory Physics sequence. The introductory physics sequence is a year-long course, consisting of three, one-quarter classes: Physics 121 (Mechanics), 122 (Electricity and magnetism), and 123 (Waves, optics, and modern physics). The entire sequence is often referred to as the Physics 12x sequence. Each course in the Physics 12x sequence consists of three components: lecture, laboratory, and tutorial.

The majority of students ($\sim 70\%$) enrolled in the Physics 12x sequence are pre-engineering majors. Most students are sophomores when they complete the three-quarter sequence.

Coverage of special relativity, for the majority of this investigation, was included in the “modern physics” portion near the end of Physics 123. In 2016, adoption of a new textbook led to the restructuring of the Physics 12x sequence.¹ As a result, coverage of special relativity was moved to Physics 122 as part of the introduction to magnetism. As of Spring 2017, special relativity has minimal lecture coverage in any quarter of Physics 12x, and the special relativity tutorials are no longer being used in the non-honors introductory sequence. All of the data described in this dissertation were collected from students enrolled in Physics 123.

Course identification notation Throughout this dissertation, student responses are summarized using tables. These tables often abbreviate course sections. For example, the abbreviation **123A112** should be read as **123A-11-2**, which is short for Physics **123**, section **A**, year **2011**, and quarter number **2** (i.e., spring). Winter is considered quarter 1, spring is quarter 2, summer is quarter 3, and autumn is quarter 4 (which is the beginning of the academic year at the University of Washington). This code and the indices at the back of this dissertation can be used to view the questions and curricula administered to each

¹From 2009-2016, the course textbook was *Physics for Scientists and Engineers* by Paul Tipler and Gene Mosca [2]; *Principles & Practice of Physics* by Eric Mazur [12] was adopted as the course textbook beginning during the 2016-17 academic year.

section.

1.5 Research methods

The Physics Education Group at the University of Washington focuses largely on student conceptual understanding of topics in physics and physical science. Because of this, questions and tasks probing student understanding tend to be qualitative rather than quantitative. Although the Physics Education Group has a number of research methods by which conceptual understanding can be assessed, our systematic investigation of student understanding of special relativity was limited to use of written questions. Occasionally, informal observations and interviews in the classroom provided additional guidance not yielded by analysis of student responses on written questions.

This section also contains a description of the statistical methods employed for data analysis throughout this dissertation.

1.5.1 Written questions

To assess the effectiveness of the special relativity tutorials, we use written questions administered before and after tutorial instruction. Questions and tasks administered before tutorial instruction are referred to as *pretests*; questions intended to test student understanding of material presented in the tutorials are called *post-tests*.

1.5.1-a Pretests

Pretests are administered before tutorial instruction on a subject. Generally, pretests for a particular subject are administered after all relevant lecture material on the same subject has been presented. All of the pretest questions described in this dissertation were given after relevant lecture instruction.

The pretest questions described in this dissertation were presented to students via Catalyst, an online survey tool produced by the University of Washington. The Catalyst system allows for both multiple-choice and free-response questions. Typically, we have used multiple-choice questions on the online pretests, and asked for students to explain their answers in a

follow-up free-response question. Questions are largely qualitative, and multiple-choice distractors are often chosen to be representative of what we expect or have found to be common student errors. For ease of understanding, the pretest questions are presented in the text of the dissertation in a free-response form, with the “multiple-choice” answers indicated in the question statement. Complete versions of the pretests in the form presented to students are included in the appendices.

The pretests have several purposes: to test student understanding of material after lecture instruction; to identify particular areas of student difficulty with the material; and to provide students a “preview” of the material to be presented in the in-class tutorial that week.

Pretests have a time-limit of 15-20 minutes to limit student ability to work collaboratively with other students, or to look up material in a textbook, in lecture notes, or online. Students are given course credit for completing the pretests, but pretests are not graded for correctness.

1.5.1-b Post-tests

All of the post-test questions described in this dissertation were administered as part of course midterm or final examinations. Post-tests are administered after all relevant material (lecture and tutorial) has been presented. Because of the timing of instruction in special relativity in the Physics 12x sequence, the majority of post-test questions described in this dissertation were presented on the final course examination for Physics 123.

Multiple-choice post-tests Final course examinations in the Physics 12x sequence usually consist entirely of multiple-choice questions. Therefore, most of the post-test questions used in this investigation were multiple-choice. Because our focus is on conceptual understanding rather than quantitative ability, very few questions *requiring* calculations were used as part of this investigation.² To assess student reasoning, we attempted to write multiple-choice questions and distractors that would reveal student thinking. Looking at patterns of

²Because questions were multiple choice, we can't know what methods students used to answer them; however, in most cases, we attempted to design questions that could be answered without any calculations.

multiple-choice responses (i.e., the sequences of answers students chose on multiple, related questions) gave additional insight into student reasoning.

Free-response post-tests On a few occasions, we were able to run free-response post-test questions. As with pretest and multiple-choice post-test questions, the questions were usually qualitative in nature. All free-response post-test questions asked for students to explain their reasoning. In these cases, we were able to analyze the written explanations accompanying student answers to determine how students were thinking about and approaching the questions. Often, we probe student understanding of multiple concepts relating to special relativity in a single exam context. Questions relevant to particular areas of research are included in the appropriate chapters of this dissertation but may omit questions that are less relevant. Complete exam questions can be found in the appendices.

1.5.2 Informal observations

Because tutorials are structured so that students interact with each other and teaching assistants, we are regularly able to make informal observations of student conversations. These conversations are not systematic, but the observations allow us insight into student thinking that might guide curriculum development and instruction. In particular, informal observations may reveal particular lines of student reasoning or student difficulties not apparent through analysis of written responses. Moreover, informal observations allow us to observe student interpretation of statements or exercises in the tutorial material in the classroom.

1.5.3 Statistical analysis of student performance

This section describes how student performance is translated into quantitative data, and how different data are compared in order to determine the effectiveness of curricula.

Results from tasks presented to students are usually described as a percentage of students answering a question in a particular way (correctly, or in way that is consistent with a particular line of reasoning, etc.). Additionally, percentages are rounded to the nearest 5%

for all percentages greater than 5%; this is, in part, for reasons that will be described below. However, we also wish to remove some precision in order to see overall patterns in student performance and reasoning.

Comparison of student performance on similar tasks on pretests and post-tests (that is, before and after tutorial instruction) are rarely performed on a single set of students; in general, we compare performance for one group of students on the pretest to a different group on the post-test. This requires that we know or estimate the variation in student performance on a given task, in order to determine whether a difference in pre- and post-test performance is due to chance or instruction. For tasks used several times, a standard deviation in student performance can be calculated directly; however, it is not uncommon for us to use a particular task only once or twice. We must therefore estimate the variation in student performance on some tasks, which we do based on findings from a review of historical variations in student performance on 20 different pretest questions (spanning 15 years) designed by Physics Education Group members [13]. This review found that the standard deviation in performance for a majority these questions was between 5 and 10 percentage points. This suggests that differences in pretest and post-test performance greater than 20 percentage points is not due to normal variation but rather to the effect of tutorial instruction.

1.6 Organization of dissertation

Basic organization of the dissertation is as follows: Part I (Background and preliminary research) and Part II (In-depth investigation).

1.6.1 Part I

Part I consists of two chapters, and describes prior research of student understanding of special relativity as well as our own preliminary investigation. The first, Chapter 2, briefly describes prior research done by researchers both at the University of Washington and elsewhere. Chapter 3 describes our initial investigation of understanding of special relativity by students at the introductory level at the University of Washington, as well as an assessment of the effectiveness of existing curricular materials in addressing suspected student difficulties.

1.6.2 Part II

In Part II, we describe our systematic, in-depth investigation of student understanding of the relativity of simultaneity. In Chapter 4, we describe our research into the student understanding of reference frames as used to measure the time and location of events, including identification of student difficulties and modification and assessment of curricular materials. In Chapter 5, we describe the identification of student difficulties regarding the invariance of the speed of light as used in qualitative reasoning about the relativity of simultaneity. In Chapter 6, we describe the identification of student difficulties with events and causality, as well as the resulting modifications to the special relativity tutorials to address these difficulties.

Part I

PRIOR AND PRELIMINARY RESEARCH

Chapter 2

PRIOR RESEARCH

This chapter describes prior research into student understanding of topics in Galilean and special relativity relevant to the investigation described in this dissertation. Investigations by researchers at the University of Washington and elsewhere are briefly described.

2.1 Introduction

The prior research described in this chapter is presented in two sections. §2.2 outlines the investigations of researchers in the Physics Education Group at the University of Washington, particularly those investigations leading to the development and modification of tutorials in Galilean and special relativity. More detailed descriptions of the research and findings of Physics Education Group members is described as necessary in the relevant chapters of this dissertation. In §2.3 we briefly describe research into student understanding of topics in Galilean and special relativity by investigators not at the University of Washington.

2.2 *Prior research at the University of Washington*

This section describes research performed by members of the Physics Education Group at the University of Washington. Section 2.2.1 describes research into student understanding of special relativity. Investigations of student understanding of topics in Galilean relativity are described in section 2.2.2.

2.2.1 *Prior research of student understanding of special relativity at the University of Washington*

The investigation of introductory student understanding of special relativity in the context of the relativity of simultaneity described in this dissertation grew directly out of research performed by Rachel Scherr, a former graduate student in the Physics Education Group at the University of Washington. Scherr investigated student understanding of time, simultaneity, and reference frames in special relativity and identified a number of difficulties in a range of student populations, from students enrolled in a physics course for non-science majors to physics graduate students [8]. Much of her investigation focused on student understanding of measurement of the time and location of events and the formalism of reference frame [5, 6].

Scherr found that many students fail to apply the formalism of a reference frame to determine the time and position of an event, and tend to treat reference frames as location- or observer-dependent. In particular, Scherr identified difficulties of students related to the reception of a signal from an event: many students associated the time of an event in an observer's reference frame with the time that the observer received the signal from the event. Others treated an observer's reference frame as dependent only the sensory experiences of that observer. Scherr's research also indicated that many students treat simultaneity as absolute, sometimes reducing the relativity of simultaneity to an "apparent" effect of special relativity. Many students treated the relativity of simultaneity as an artifact of signal travel time, dependent on the location of observation and independent of relative motion. Scherr also identified some student difficulties related to understanding of causality

and the invariance of the speed of light.

Based on her research, Scherr developed a series of tutorials to address the identified student difficulties and to improve student learning. The tutorial *Events and reference frames* was intended to give students the necessary background in Galilean relativity to understand special relativity. It was also intended to improve student understanding of reference frames and motivate the use of a reference frame to measure the time and location of any event. The *Measurement* tutorial built on the ideas introduced in the tutorial *Events and reference frames* to help students recognize how the time and location of events could be used to measure the length of an object. Finally, the *Simultaneity* tutorial helped students work through a variation of Einstein’s train paradox in order to illustrate that spatially separated events that are simultaneous in one reference frame are not simultaneous in another. Notably, the *Simultaneity* tutorial developed by Scherr depended on student understanding of some consequences of the invariance of the speed of light, and concepts related to causality.

Caleb Teel extended Sherr’s work by investigating understanding of events and causality in “advanced introductory” students enrolled in the honors introductory sequence or a sophomore-level course in modern physics [9]. Teel’s work, like Scherr’s, used the relativity of simultaneity as a context, but focused primarily on student understanding of two causality-related ideas: the principle of causality, which states that the time-sequence of events occurring at a single location in some reference frame must be preserved across all reference frames; and the frame-independence of events (i.e., an event that occurs in one reference frame must occur in all reference frames). Teel found that students had difficulty with both of these causality-related concepts both before and after tutorial instruction. Results of Teel’s research motivated some changes to the *Simultaneity* tutorial to address student difficulties with causality.

2.2.2 Prior research of student understanding of Galilean relativity at the University of Washington

Tara O'Brien Pride investigated student understanding of introductory mechanics, including collisions and student ability to use the center-of-mass frame [14]. This allowed her to probe student understanding of changes in reference frame. Additionally, O'Brien Pride investigated student ability to describe correct measurement procedures, in the context of both Galilean and special relativity. She also performed a preliminary investigation of student understanding of simultaneity in special relativity.

Andrew Boudreaux conducted a thorough review of student understanding of kinematics and dynamics in the context of Galilean relativity [7]. Boudreaux found that students had particular difficulty making measurements of quantities such as displacement, velocity, and momentum in reference frames other than the laboratory or ground frame. He also found that student difficulties with concepts such as acceleration and relative motion had a basis in difficulties with more basic concepts, such as displacement. His findings also indicated that difficulties with measurements in frames moving with respect to the laboratory frame could be traced to difficulties with concepts in laboratory frame kinematics.

2.3 Prior research outside of the University of Washington

This describes prior work from researchers that were not members of the Physics Education Group at the University of Washington. Investigations of student understanding of topics in special relativity are described in section 2.3.1. Section 2.3.2 describes research on understanding of topics in Galilean relativity.

2.3.1 Prior research of student understanding of special relativity outside of the University of Washington

2.3.1-a Approaches to teaching special relativity

Arriaseq and Greca explored a method of teaching special relativity to high school students in Argentina that contextualized the subject both epistemologically and historically [15, 16]. In a 1998 study, Villani described the “problem of the learning of Special Relativity” by high school and college students, drawing parallels between the conceptual shifts necessary by students with the conceptual shifts made by the scientific community over the course of the gradual acceptance of the theory of special relativity [3]. Villani uses this parallel to motivate possible teaching strategies.

A number of researchers have explored the use of computers and technology in teaching special relativity. Belloni developed a series of special relativity “Physlets” to help students visualize the representation of a reference frame as a grid of meter sticks and synchronized clocks [17]. Similarly, Savage developed “Real Time Relativity,” a virtual reality program that allows students to see visual, space, and time effects [18] when relative motion is at relativistic speeds. Implementation of Real Time Relativity has been described by different researchers [19–21]. Similarly, researchers in Norway developed the online “ReleQuant” program, a series of animations, simulations, and exercises to develop conceptual understanding of modern physics—including special relativity—in Norwegian high school seniors.

2.3.1-b Research on the identification of student difficulties with special relativity

A number of researchers have investigated student understanding of specific and basic concepts in special relativity, although relatively few have focused on introductory-level undergraduates as a student population.

Several researchers have identified common student beliefs about reference frames consistent with the difficulties identified by Scherr at the University of Washington. These difficulties, and others, were identified in preservice teachers [22, 23], advanced introductory students [24], and high school students [25].

Villani and Pacca used the answers to two questions involving the speed of light given to physics graduate students to probe student thinking [26]. Student answers indicated a belief in a “preferred” reference frame, with a basis in misunderstandings of Galilean relativity. Hewson performed a series of three interviews about special relativity with a single graduate tutor to determine how deeply held beliefs (such as a belief in absolute simultaneity) change over the course of instruction in special relativity, and how these “metaphysical beliefs” affect learning of material that challenges them [27]. Pietrocola studied undergraduate students’ use of the principle of relativity in the interpretation of a large number of physical phenomena, finding that students rarely applied it completely [28].

In a paper published in 1982, Posner, Strike, Hewson, & Gertzog described the use of special relativity as a context for describing the accommodation of a novel scientific conception [4].

2.3.2 Prior research of student understanding of Galilean relativity outside of the University of Washington

Student difficulties with reference frames similar to the difficulties described by Rachel Scherr have been found in undergraduate students in the context of Galilean relativity [29]. Researchers also identified difficulties understanding inertial *vs.* non-inertial observers, and distance, time, and energy laws [30, 31]. Saltiel and Malgrange described student reason-

ing about elementary kinematics in 11-year-olds and 4th-year university students and found reasoning from both populations to be similar [32].

Chapter 3

IMPLEMENTATION OF EXISTING TUTORIALS IN special relativity WITH INTRODUCTORY STUDENTS

This chapter presents our preliminary research into introductory student understanding of topics in special relativity. We describe the implementation of these unmodified tutorials with a new population of students. Prior work by researchers at the University of Washington, including the development of tutorials in special relativity, is discussed. All new data were collected from pretests and post-tests administered to students enrolled in Physics 123 (the waves, optics, and modern physics portion of the introductory, calculus-based course at the University of Washington) during the 2009-2010 academic year.

3.1 Introduction

In Autumn Quarter of 2009, coverage of special relativity was added to Physics 123, the third quarter of the non-honors, calculus-based, introductory physics sequence at the University of Washington. Prior research at the University of Washington and elsewhere had indicated that students at all levels have difficulty with topics in special relativity (see Chapter 2). The decision was made by a department committee for the introductory sequence to include one week of special relativity coverage in the course. As part of this change, two tutorials were included in the course, using tutorials developed at University of Washington for students in more advanced courses. Only two tutorials were used as limited time was available in a 10-week course.

Data were collected during the first quarter in which the tutorials were implemented to determine whether introductory students had difficulties similar to those of more advanced students and (if so), whether the existing tutorials were effective in addressing those difficulties.

This remainder of this chapter is divided into three parts. §3.2 discusses prior work by members of the Physics Education Group at the University of Washington leading to the development of tutorials in special relativity; additionally, the versions of the special relativity tutorials used during the initial implementation with non-honors introductory students in Autumn 2009 are described. §3.3 describes the initial implementation of the special relativity tutorials with this new population of students, including an assessment of student understanding of topics in special relativity before and after the use of the tutorials. In §3.4, we present our conclusions from the preliminary research described in this chapter.

3.2 Prior research and curriculum development by the Physics Education Group

As discussed in chapter 2, research done by Rachel Scherr and others at the University of Washington led to the development a series of tutorials covering topics in special relativity. These were designed to be used with students in a range of courses: the *honors* calculus-based introductory sequence; a sophomore-level modern physics course; a junior-level course in electricity and magnetism; and a junior-level elective course in special and general relativity. Five tutorials in special relativity were developed in total: *Events and reference frames*, *Measurement, Simultaneity, Synchronization and causality*, and *Electric and magnetic fields in multiple frames of reference*.

Scherr found that students had particular difficulty with understanding the concept of time in special relativity in the context of the relativity of simultaneity. The difficulties were especially evident in student understanding of events and reference frames. Scherr identified two common, central, incorrect beliefs that seemed to be the source of student problems; these beliefs were explored by Scherr using questions that will be described in detail below. The first is the belief that the order of events in an observer’s reference frame is determined by the order in which that observer receives the signals from those events (the “signal-reception error”). The second is the belief that simultaneity is absolute, regardless of reference frame [8].¹ These incorrect ideas guided the development of two of the tutorials listed above: *Events and reference frames* and *Simultaneity*.

It was expected that introductory students would have difficulties similar to those of more advanced students. Therefore, these two tutorials were chosen for implementation in Autumn Quarter 2009 with students enrolled in Physics 123, the third quarter of the non-honors, calculus-based, introductory physics sequence.

¹Although these two errors may seem to be at odds with each other, careful reading of student explanations reveals that the former is actually predicated on the latter. This will be discussed further in this chapter.

3.2.0-a Research task

In her preliminary investigation, Scherr probed student understanding of the relativity of simultaneity in general, and reference frames in particular, using variations of the Seismologist question, shown below. The question was often accompanied by a figure.

Mt. Rainier and Mt. Hood, which are 300 km apart in their rest frame, suddenly erupt at the same time in the frame of a seismologist at rest in a laboratory midway between the volcanoes.

The seismologist's assistant is at rest in a lab near Rainier when it erupts. A fast spacecraft, flying directly from Rainier toward Hood at $v = 0.8c$ relative to the ground, is above Rainier when it erupts.

1. Does Rainier erupt *before*, *after*, or *at the same time as* Hood:
 - (a) in the frame of the seismologist's assistant? Explain.
 - (b) in the frame of the spacecraft? Explain.

This question is physically identical to Einstein's train paradox, discussed in the introduction of this dissertation. To answer part (a), students need only recognize that the seismologist and the seismologist's assistant are at rest with respect to each other. Thus, they share the same reference frame (a system of meter sticks and synchronized clocks at rest relative to them), and they agree on the time (and therefore, the relative order) of all events. Therefore, in the seismologist's assistant's frame, the eruptions are simultaneous. To answer part (b), students could recognize that the seismologist receives the light signals from the two eruptions simultaneously, and at a single location (*i.e.*, the reception events share a single spacetime coordinate) in the ground frame. This means that the seismologist receives the signals simultaneously in all reference frames, including that of the spacecraft (this reasoning uses the causality argument described in section 1.1.1-c in the introduction of this dissertation). In the spacecraft frame, the seismologist is moving toward the location of

the event “Rainier erupts” and away from the location of the event “Hood erupts.” Because of this, and because of the seismologist’s simultaneous reception of signals in the spacecraft frame, Hood must have erupted first in the spacecraft frame.

Scherr found that fewer than 25% of students in any of the populations she studied answered correctly, regardless of reasoning. The errors they made fell into two major categories.

3.2.0-b Description of student errors

Reasoning behind the signal-reception error Scherr observed the signal-reception error among a large fraction of students in all of the populations she surveyed, although she found that the percentage of students making the signal-reception error varied by population (from 40% to 75%) even after traditional instruction.

Scherr noticed two basic lines of reasoning that were consistent with the reception time error. The first line of reasoning was a tendency to associate the time of an event with the time at which an observer receives the signal from that event. On the Seismologist question above, for example, students using this reasoning would answer both parts (a) and (b) the same way: that because both the seismologist’s assistant and the spacecraft would see (i.e., receive the light from) the Rainier eruption first (being closer to Rainier than to Hood), Rainier erupted first in both frames. Note that this answer depends on an assumption that the eruptions are simultaneous in both the frame of the assistant and the frame of the spacecraft. Correct determination of the order of signal reception relies not only on the signal propagation time, but also on the timing of the two events.

Related to this was the second incorrect line of reasoning that Scherr identified. Some students had a tendency to regard an observer as dependent only on his or her personal sensory experiences. Like students using the first line of reasoning described above, these students would also conclude that Rainier erupted first in both the frame of the seismologist’s assistant and the frame of the spacecraft. These students, though, seemed to place undue emphasis on an observer’s experience, with some even claiming that an event doesn’t happen in an observer’s frame until that observer observes that event.

Students using reception time reasoning fail to correctly apply the formalism of a reference frame to make measurements of the timing of events. Applying the formalism of a reference frame would involve considering the time reading of the clocks *at the locations of the events associated with the eruptions of the mountains*, rather than the times at which a particular observer received the signals from those events. (Note that simply applying the formalism of a reference frame would not be sufficient to determine the timing of events in the spacecraft frame; one would also need to use the causality-based argument described in the introduction and above.) These students also tend to regard the relativity of simultaneity as an apparent effect, or an artifact of signal travel time. Such students fundamentally misunderstand what is meant by “reference frame,” interpreting it as a description of what an observer experiences.

Reasoning behind the absolute simultaneity error As noted above, the reception-time error is often predicated on absolute simultaneity, as correct determination of signal reception order relies in part on the timing of the events producing the signals. To probe the tendency of students to treat simultaneity as absolute, Scherr asked a variation of the Seismologist question above, in which students were told “observers are intelligent observers, *i.e.*, they correct for signal travel time in order to determine the time of events in their reference frame. Each observer has clocks that are synchronized with those of all the other observers in his or her reference frame.”

This version was administered as an interview task to advanced undergraduate and graduate students ($N = 7$), and as part of a qualifying exam to graduate students ($N = 23$). Only 2 of the 23 graduate students taking the qualifying exam (and none of the students in the interview task) answered explicitly that the eruptions would be simultaneous in the reference frame of the spacecraft. In the interview task, 55% of students answered that Rainier would erupt first, which is consistent with the signal-reception error described above. On the qualifying exam, 60% of students made this error. Even though the students did not explicitly state that the eruptions were simultaneous in all frames, analysis of the written ex-

planations and interview statements of these students indicate that most held the belief that simultaneity is absolute, and therefore that the relativity of simultaneity is just an apparent effect based on observer location. Some students regarded the Lorentz transformations for time as a way to correct for signal propagation time.

3.2.1 Descriptions of the tutorials *Events and reference frames* and *Simultaneity*

The tutorials *Events and reference frames* and *Simultaneity* and their associated homework were developed by Scherr and other members of the Physics Education Group, and later modified by others at the University of Washington, to address the difficulties described above. The tutorial *Events and reference frames* is preparatory in nature, in that it is intended to help students develop the construct of a reference frame as a method by which observers can measure the time and location of any event. In the subsequent tutorial *Simultaneity*, students work through a variation of Einstein’s train paradox, which motivates the idea that simultaneity is not absolute. The versions of these two tutorials first used in this current investigation were implemented in the non-honors, calculus-based, introductory sequence in Autumn Quarter 2009. They are described below and can be found in their entirety in Appendix A.

3.2.1-a Description of the *Events and reference frames* tutorial and homework

Five key exercises and the homework for the first tutorial *Events and reference frames* are discussed below

Exercise 1 The first exercise in *Events and reference frames*, shown in Figure 3.1, was designed to help students devise method(s) to correctly determine the time of an event. It is also intended to help students distinguish between the time that a signal is emitted and the time it is received by an observer. In the exercise, observer Alan would like to know the time that a distant beeper emits a beep, but is unable to travel to it. Alan has a large number of

meter sticks, synchronized clocks, and assistants who are free to move. Students are asked to describe two methods by which Alan can determine the time that the beep is emitted.


In the first method, Alan can use his knowledge of the speed of sound in air. The intended method is for Alan to note the time at which he hears the beep and to use this time, the distance between him and the beeper (measured by the assistants), and the speed of sound to determine when the beep was emitted. This exercise also helps focus student attention on the fact that signal propagation time is finite.

In the second method, students are told that Alan cannot use the speed of sound in air. The intended method uses the idea that for an assistant standing at the location of the beeper, the time at which the beep is emitted is the same as the time at which the beep is heard. An assistant standing at the beeper can note the time at which the beeper beeped, and share this time with Alan. This further develops the ideas from the first method, and also motivates the formalism of a reference frame as a system of measuring devices (including synchronized clocks) and assistants that can be used to determine the time (and location) of an event.

Exercise 2 The concept of a reference frame is further developed in the next exercise, shown in Figure 3.2, in which a group of reporters wishes to record the time and location of the confession of a “fugitive from justice.” Students are asked to describe an arrangement of observers and equipment (including synchronized clocks) with which the reporter may record the position and time of the confession. An observer’s *reference frame* is then defined as “an arrangement of assistants and equipment with which the observer may record the position and time of anything that occurs.” Students are asked to interpret the claim that the reporter’s arrangement of observers and equipment is the reporter’s reference frame. They are also asked whether all of the reporters would attribute the same time and location to the confessions, and to explain how their answer is a consequence of the definition of a reference frame. This exercise is meant to help students recognize that anyone using the same arrangement of measuring equipment will determine the same time and location for

A physics student named Alan stands far away from a beeper as shown at right. The beeper is about to emit a beep, and Alan wants to determine the exact time at which it does so. However, he is unable to travel to it.

Alan



Beeper




Diagram not to scale

Alan is equipped with accurate meter sticks and clocks. A number of other students are willing to help him, if necessary.

1. Describe a set of measurements by which Alan can determine the time at which the beep is emitted using his knowledge of the speed of sound in air.

2. Describe a method by which Alan can determine the time at which the beep is emitted *without* knowing or measuring the speed of sound. (*Hint: Alan's assistants are free to stand at any location.*)

Figure 3.1: Exercise from the version of the tutorial *Events and reference frames* used in Autumn 2009 that develops a procedure for measurement of the time of an event.

any given event; observers in the same reference frame therefore necessarily agree on the time and location of all events.

Exercise 3 After “reference frame” is defined, students are asked to apply the definition to determine the order of events described. In the exercise shown in Figure 3.3, a horn is placed between Alan and the beeper; the horn emits one honk, and the beeper emits one beep. Students are asked to describe a method to determine the time separation between these two events given that Alan hears the two sounds at the same instant, without knowing or measuring the speed of sound.

Finally, the term “intelligent observer” is defined as someone who “is equipped with measuring devices (such as meter sticks, clocks, and assistants) and is able to use them to make correct and accurate determinations of where and when something occurs.” Students are told that all observers in special relativity are assumed to be intelligent observers.

A fugitive from justice is at large in Seattle. The identity and whereabouts of the fugitive are unknown. A group of reporters believe that the fugitive will soon confess to the crime, and want to record as exactly as possible the time and place of the confession. Their funding for this project is excellent.

1. Describe an arrangement of observers and equipment with which the reporters can record the position and time of the confession.

An observer's *reference frame* is an arrangement of assistants and equipment with which the observer may record the position and time of anything that occurs.

2. Justify the claim that the reporters' arrangement of observers and equipment is a reference frame.
3. Would all the reporters attribute the same time and location to the confession? Explain how this result is a consequence of the definition of a reference frame.


Figure 3.2: Exercise from the version of the tutorial *Events and reference frames* used in Autumn 2009 that develops the formalism of a reference frame.

Exercises 4 & 5 In the next section of the tutorial, the term *event* is defined as something “associated with a single location in space and a single instant in time.” Students are also introduced to *event diagrams* as a way to describe a sequence of events in a given reference frame, similar to a spacetime diagram.² In the final section of the tutorial, students develop a method by which clocks in a reference frame can be synchronized using light signals.

Although neither of these sections is designed to develop the idea of a reference frame explicitly, both encourage students to use the formalism of a reference frame. The exercises in these last two sections also help to remind students that the emission and reception of signals are distinct events, and that signal propagation time is finite, even when the signal is light.

²Like a spacetime diagram, an event diagram shows the time and location of “events of interest.” In an event diagram, simple pictures are drawn showing the locations of relevant objects and observers at each instant. Successive instants are shown one below the other, with each instant shown exactly once and the location of each event of interest indicated in the appropriate picture.

A horn is now placed between Alan and the beeper. The beeper beeps once and the horn honks once. Alan hears both sounds at the same instant.



1. Describe a method by which Alan can measure the time separation between the emission of the beep and the emission of the honk *in his reference frame without* knowing or measuring the speed of sound.

2. In Alan's reference frame, is the beep emitted *before*, *after*, or *at the same instant* as the honk is emitted? Explain.

An *intelligent observer* is equipped with measuring devices (such as meter sticks, clocks, and assistants) and is able to use them to make correct and accurate determinations of where and when something occurs. All observers in the study of relativity are intelligent observers.

Figure 3.3: Exercise from the version of the tutorial *Events and reference frames* used in Autumn 2009 that encourages the use of the formalism of a reference frame.

Homework The *Events and reference frames* homework discusses inertial *vs.* non-inertial reference frames using Newton's second law of motion, and gives students practice drawing event diagrams featuring relative motion.

3.2.1-b Description of the *Simultaneity* tutorial and homework

The *Simultaneity* tutorial consists of two parts, I and II.

Part I

The *Simultaneity* tutorial begins with an exercise designed to help students understand a key consequence of the invariance of the speed of light: for events that involve the emission of light in all directions, the location of the center of the wavefront of the emitted light is the same as the event location at all times, and that this result does not depend on the reference frame. (This exercise is discussed in greater detail in Chapters 4 and 5.) Understanding of this idea is necessary for understanding of the relativity of simultaneity.

Part II

The remainder of the *Simultaneity* tutorial is a series of exercises designed to elicit and resolve student difficulties with the relativity of simultaneity, using a variation of Einstein's train paradox.

Exercise 1 In the first exercise, shown in Figure 3.4, students are told that sparks R and F jump between the rear and front of a train and the train tracks. Each spark leaves a char mark on both the end of the train from which it jumped, and the track. Events R and F are defined as “spark R jumps” and “spark F jumps,” respectively. An observer Alan stands on the ground equidistant from the char marks on the track, and students are told that the wavefronts from the two sparks reach him simultaneously.

The first part of exercise 1 involves observers in the ground frame. Students are asked to determine the order of events R and F in Alan's frame. By using the fact that Alan is equidistant from the char marks on the track, and that he received the light from the two sparks at the same instant (as well as the fact that the speed of light is the same in all directions in the ground frame), students can conclude that the sparks must have jumped at the same instant in the ground frame. This exercise helps students “anchor” the locations of events R and F in the ground frame at the char marks on the track, as well as reminds them that the emission and reception of the light signals are distinct events and that signal travel time is finite.

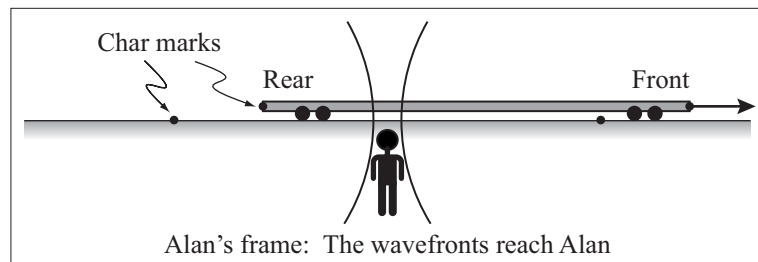
The next question asks about the event order for another observer (Abigail) standing on the ground, closer to the location of event F than event R. Students can answer by recognizing that Alan and Abigail are in the same reference frame, and therefore agree on the time of all events. This exercise encourages students to use the formalism of a reference frame, as well as the definition of an intelligent observer. Note that students are not given enough information to determine the order of events (e.g., quantitative values for the distances between Abigail and the char marks on the track, and the times at which she receives the two signals); they must rely solely on the information given about Alan's position and signal reception.

A spark jumps between the front end of a train and the track (spark F), and another spark jumps between the rear end of the train and the track (spark R). When each spark jumps, it emits a flash of light (wavefronts F and R). Each spark also leaves a char mark on both the train and the track. Let event F be “spark F jumps” and event R be “spark R jumps.”

Alan is standing on the ground equidistant from the char marks on the track. The wavefronts reach him simultaneously.

Alan’s frame

The diagram at right represents Alan’s frame at the instant the wavefronts reach him.

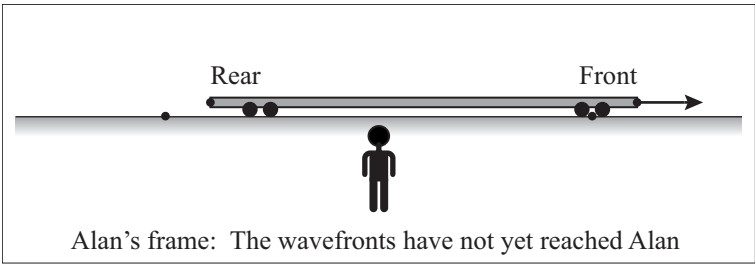


1. In Alan’s frame, does spark F jump *before*, *after*, or *at the same instant as* spark R? Explain.
2. Abigail (not shown) stands at rest relative to the track, near the front char mark on the track.

In Abigail’s frame, does spark F jump *before*, *after*, or *at the same instant as* spark R? Explain.

Figure 3.4: Exercise from the tutorial *Simultaneity* in which students analyze a variant of Einstein’s train paradox in the ground frame.

3. The diagram at right represents an instant a short time after the spark jumps between the front of the train and the track in Alan's frame (before he receives either wavefront).



Alan's frame: The wavefronts have not yet reached Alan

Complete the diagram by drawing the wavefronts at this instant. Explain.

4. In Alan's frame, where are the centers of wavefronts F and R? Explain.

5. Beth stands at rest relative to the train, exactly halfway between the front and rear of the train. Let event P be "Alan and Beth pass each other." Recall that event F is "spark F jumps" and event R is "spark R jumps."

- In Alan's frame, does event F happen *before*, *after*, or *at the same instant as* event P? Explain.
- In Alan's frame, does wavefront F reach Beth *before*, *after*, or *at the same instant as* wavefront R? Explain.

Figure 3.5: Exercise from the tutorial *Simultaneity* in which students analyze a variant of Einstein's train paradox in the ground frame.

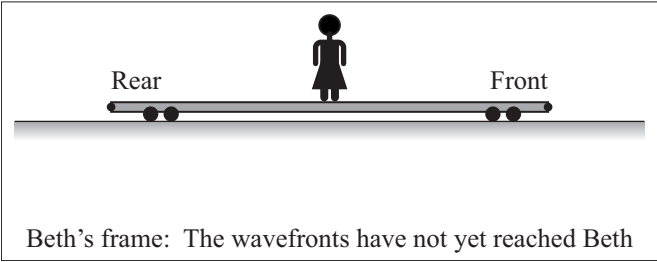
In the third part of exercise 1, students still analyze the ground frame, but are asked a series of questions designed to lay a foundation for later questions about Alan's reasoning for the order of reception of signals by Beth, an observer in the rest frame of the train. (See Figure 3.5.)

Questions 3 and 4 in this exercise have students analyze the wavefronts and the centers of the wavefronts in the ground frame. In question 3, students are asked to draw the wavefronts from sparks R and F after they have been emitted but before they have reached Alan; this helps students recognize that the two wavefronts are always equidistant from Alan. Finally, students are asked to identify the centers of the wavefronts from sparks R and F, which they should realize are at the char marks on the track. These two questions also lay the groundwork for the subsequent questions involving Beth, an observer in the train frame.

Next, students are told that Beth stands at rest relative to the train, exactly halfway

Beth's frame

1. Complete the diagram at right by drawing wavefronts F and R, in Beth's frame, before either wavefront reaches her.
2. In Beth's frame, does event F happen *before*, *after*, or *at the same instant as* event R? Explain.
3. In Beth's frame, where are the centers of wavefronts F and R? Explain.
4. In Beth's frame, does wavefront F reach Beth *before*, *after*, or *at the same instant as* wavefront R? Explain.



Beth's frame: The wavefronts have not yet reached Beth

Figure 3.6: Exercise from the tutorial *Simultaneity* in which students analyze a variant of Einstein's train paradox in the train frame.

between the ends of the train. Event P is defined as “Alan and Beth pass each other.” The first part of question 5 asks about the relative timing of events F and P. To answer, students can recognize that because Alan is equidistant from the locations of F and R in the ground frame, and the ends of the train are at the locations of F and R at the instant the events occur, Alan must be at the center of the train (Beth's location) when event F occurs. Therefore, events F and P must occur at the same instant. In the last part of the exercise, students are asked to determine the order in which Alan would say that Beth would receive the wavefronts from the sparks. In Alan's frame, Beth moves toward wavefront F and away from wavefront R; therefore, she receives wavefront F first.

Part III

The next section of the tutorial *Simultaneity* asks students to analyze the same sequence of events in the train frame. (See Figure 3.6.)

Students are first asked to draw the wavefronts F and R at an instant before either wavefront reaches Beth, who is on the train at its center. To answer correctly, students should recognize that the events corresponding to her reception of the two signals have

a possible causal relationship (i.e., there is a reference frame (the train's) in which the two events occur at the same location, so the events must have the same time order in all frames). Because we know that Beth received wavefront F before wavefront R in the ground frame (see question 5), wavefront F must be closer to her than wavefront R at any time after both sparks have jumped and before she receives either wavefront.

Next, students are asked about the time order of events R and F in the train frame. Because Beth receives wavefront F before wavefront R, and she is equidistant from the event locations in the train frame (the ends of the train), spark F must have jumped first in the train frame. For the last two questions, students are asked about the locations of the centers of the wavefronts in the train frame, and the order in which the wavefronts reach Beth in the train frame. The answers to these last two questions should be used to answer the first two; putting them after the first two questions forces students to be explicit in their reasoning and checks for consistency in reasoning.

Commentary on student progression through part III of the *Simultaneity* tutorial In developing the tutorial, Scherr found that students rarely use the above reasoning to answer these questions regarding event order in Beth's frame correctly. She found student-held belief in absolute simultaneity (and failure to recognize possible causal relationships between events) persists even after traditional instruction in the relativity of simultaneity. Part III of the *Simultaneity* tutorial used in this investigation was written to *elicit* these incorrect ideas. A majority of students will correctly determine that the events occurred at the ends of the train in Beth's frame, but make the assumption that events R and F occur simultaneously in the train frame. They thus decide that Beth receives the wavefronts from the two sparks simultaneously in her frame. The remaining exercises in the *Simultaneity* tutorial assumes that students have made this error and try to help them see (and resolve) a contradiction.

Relating Alan's and Beth's frames

A device consisting of two firecrackers attached to light sensors lies on the floor of the train at Beth's feet. If both wavefronts hit the device at the same instant, both firecrackers explode. If wavefront F hits the device first, only firecracker 1 explodes. If wavefront R hits the device first, only firecracker 2 explodes.

1. Which firecracker(s) explode in each of the following frames? Explain.
 - Alan's frame
 - Beth's frame

Figure 3.7: Exercise from the tutorial *Simultaneity* using causality to relate the frames of Beth and Alan.

Part IV³

In the next section of the tutorial, students are told that a device attached to two firecrackers sits at Beth's feet on the train (see figure 3.7). If the wavefront from spark F hits the device first, only firecracker 1 will explode; if the wavefront from spark R hits the device first, only firecracker 2 will explode. If both wavefronts hit the device at the same instant, both firecrackers explode. Students are asked to determine which firecracker(s) explode in Alan's frame, and which explode in Beth's frame, based on their analyses performed in the earlier exercises.

A surprising result is that a majority of students incorrectly answer that only firecracker 1 explodes in Alan's frame, while both firecrackers explode in Beth's frame.

To help students begin to resolve this paradox, a "student dialogue" is used.⁴ (See figure 3.8.) In the dialogue, student 1 proposes that firecracker 2 both explodes and does not

³This section, in which students are asked to relate Alan's and Beth's reference frames, differs significantly from the version developed by Scherr, though both rely heavily on the idea of causality. In Scherr's original tutorial, a cassette player sits at Beth's feet; the behavior of the tape player depends on the order in which wavefronts F and R reach it. The version of the tutorial described below was written prior to Autumn 2009 (and prior to this research) by researchers in the Physics Education Group at University of Washington, in response to interactions with students during tutorial sessions.

⁴The student dialogue was not in Scherr's original tutorial. It was added in response to interactions with students regarding causality and preferred reference frames; difficulties with the ideas expressed in the student dialogue will be discussed in later chapters.

2. Consider the following dialogue between two students:

Student 1: "Special relativity is strange; firecracker 2 explodes and does not explode, depending on which reference frame you are in."

Student 2: "I don't believe a firecracker can both explode and not explode. We must have made a mistake. What if the train stops and Alan gets on? Would he see firecracker 2 whole like he expected?"

Student 1: "No, firecracker 2 is in Beth's frame, and, in Beth's frame, it explodes. When Alan gets on the train, he would see that firecracker 2 actually did explode. But, until he got on the train, he would think that firecracker 2 did not explode."

With which student do you agree, if either? Explain.

Figure 3.8: Student dialogue from the tutorial *Simultaneity* that elicits student misconceptions about causality.

explode, depending on which reference frame is considered. [Note: this is a violation of causality (i.e., that an event that occurs in one reference frame must occur in all reference frames).] Student 2 suggests that perhaps a mistake was made during the analysis in Alan's or Beth's frame, not believing that a firecracker can both explode and not explode. Student 1 then responds that the analysis performed in Beth's frame must be the correct one, because the firecrackers are in Beth's frame, suggesting that there is a preferred frame of reference for these events.

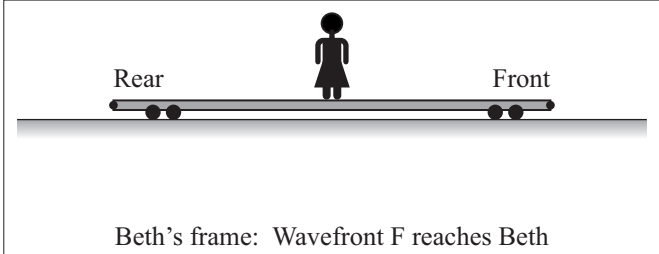
The instructional sequence used in this section of the tutorial relies on an expectation that students will intuitively want to uphold causality. The intent of the student dialogue is that students will agree with student 2, and recognize that they made a mistake in their analysis of one of the frames (although they might not yet know what that mistake was).

The final exercise of this section of the *Simultaneity* tutorial, shown in Figure 3.9, relies on student acceptance of causality as a guiding principle in the analysis of Beth's frame. They should argue that because only firecracker 1 explodes in Alan's frame (the frame in which sufficient information was provided to correctly determine the order of events F and R), only firecracker 1 can explode in Beth's frame. This means she must receive wavefront

Suppose that Alan's conclusion that firecracker 1 explodes and firecracker 2 does not explode is also true in Beth's frame.

a. If only firecracker 1 explodes, then, in Beth's frame, does wavefront F reach Beth *before, after, or at the same instant as* wavefront R? Explain.

Based on your answer above, complete the diagram at right by drawing wavefronts F and R in Beth's frame at the instant when wavefront F reaches Beth. Explain.



b. Based on your diagram, in Beth's frame, does event F (the front spark jumps) happen *before, after, or at the same instant as* event R (the rear spark jumps)? Explain.

Figure 3.9: Exercise from the tutorial *Simultaneity* that highlights the use of causality as a guiding principle in understanding the relativity of simultaneity.

F first in her own frame. Based on this fact, and the location of the centers of wavefronts F and R at the ends of the train in her frame, students should conclude that the front spark jumped first in Beth's frame.

A final student dialogue in the tutorial is used (see Figure 3.10), to try to make explicit the choice that arises in Einstein's train paradox—between causality and absolute simultaneity.

Commentary on parts IV and V of the *Simultaneity* tutorial The ideas presented in the student dialogues in parts IV and V of the *Simultaneity* tutorial can be quite challenging for students. In our experience, the tutorial itself does not provide significant guidance. Generally, students require intervention from an instructor to resolve the apparent paradox presented by the student dialogue in part IV. Without instructor intervention at that point, many students do not understand the implications of the final exercise of the tutorial. Discussion with an instructor is also often necessary after the final exercise. Many students do not understand the implications of the choices presented by student 1, and therefore may

Consider the following student dialogue about event F (the spark at the front of the train jumps) and event R (the spark at the rear of the train jumps):

Student 1: "Event F happens before event R for Beth and at the same time as event R for Alan. It depends on which reference frame you are in."

Student 2: "I don't believe that things can happen simultaneously in one frame and at different times in another frame. We must have made a mistake somewhere."

Student 1: "Well, we have two choices. Either (1) events F and R happen at the same time or at different times, depending on your reference frame, or (2) the event corresponding to the firecracker exploding happens or does not happen, depending on your reference frame."

With which of the two choices presented by student 1 do you agree? Explain.

Figure 3.10: Final student dialogue from the tutorial *Simultaneity*.

not see why it is preferable to give up absolute simultaneity and not causality.

***Simultaneity* homework** The homework associated with the *Simultaneity* tutorial used in Autumn 2009 treats the relativity of simultaneity in an alternative fashion from the tutorial, deriving it as a consequence of length contraction. Students first consider the train paradox that they saw in the tutorial, and then a variation of the pole-barn paradox (featuring a tunnel and train).

3.3 Assessment of impact of the tutorials on student understanding

To assess impact of the special relativity tutorials used in Autumn Quarter of 2009, we administered research tasks after lecture instruction but before the tutorials (pretests) and after all instruction on a course exam. Students enrolled in Physics 123 had three lectures covering topics in special relativity. The first two covered Lorentz transformations, the relativity of simultaneity, and addition of velocities. The third covered momentum and energy in special relativity.

Student understanding of reference frames and the relativity of simultaneity after lecture instruction was measured using pretests for the tutorials *Events and reference frames* and *Simultaneity*. (See section 3.3.1.) The first pretest (for *Events and reference frames*) came after the first lecture, which covered an introduction to special relativity, including a discussion of Galilean relativity and transformation of coordinates, the postulates of special relativity, the Lorentz transformations, and time dilation and length contraction. The *Simultaneity* pretest was run after all three special relativity lectures (including lecture coverage of the relativity of simultaneity). A post-test was given after the students had worked through the tutorials (see 3.3.3).

3.3.1 Pretest for the *Events and reference frames* tutorial: *Sparks* question

The pretest for the tutorial *Events and reference frames* used in Autumn 2009 was designed to probe incorrect student ideas about reference frames after standard instruction. In particular, we wanted to confirm that students enrolled in the non-honors, calculus-based, introductory sequence had the same types of incorrect ideas as nominally more advanced students, and to determine the prevalence of such errors. The *Sparks* question discussed below served as a context for the *Events and reference frames* pretest.

Two physics students, Alan and Beth, are shown in the diagram. Alan and Beth have each measured their exact relative distances from points X and Y .

Two sparks, X -spark and Y -spark, occur at the points marked X and Y . When each spark occurs, it emits a flash of light.

Let event 1 be “the X -spark jumps.”

Let event 2 be “the Y -spark jumps.”

Alan, who is equidistant from points X and Y , receives the wavefronts from each spark at the same instant.

1. In Alan’s reference frame, is the time coordinate of Event 1 earlier than, later than, or exactly the same as the time coordinate of Event 2? Explain.
2. Does Beth receive the wavefront from the X -spark *before*, *after*, or *at exactly the same time* as the wavefront from the Y -spark? Explain.
3. In Beth’s reference frame, is the time coordinate of Event 1 earlier, later, or exactly the same as the time coordinate of Event 2? Explain.

Diagram not to scale

Figure 3.11: Reference frame pretest question for the *Events and reference frames* tutorial.

3.3.1-a Description of the Events and reference frames pretest

The first question in the *Sparks* context, shown in Figure 3.11, involves two observers, Alan and Beth, who have measured their distances from points X and Y . Sparks occur at points X and Y , and each spark emits a flash of light. Students are told that Alan is equidistant from points X and Y and receives the wavefronts from the two sparks at the same instant.

Students are then asked to determine (1) the order of the events associated with the sparks jumping in Alan’s frame, (2) the order in which Beth receives the wavefronts from the sparks, and (3) the order of the events in Beth’s frame. (1): For Alan’s frame, we can determine that the sparks jumped at the same time: Alan is equidistant from the locations where the sparks jumped, and he receives the signals simultaneously. Because we know that the speed of light is the same in all directions, the sparks jump simultaneously in Alan’s frame. (2)

and (3): For Beth's frame, we can determine that the sparks also jumped simultaneously, as Beth and Alan are at rest with respect to each other, so share the same reference frame. Therefore, Alan and Beth agree on the timing of all events. This means that the signal from the X-spark reaches Beth first, as she is closer to point X than point Y, and the wavefronts travel at the same speed.

Students making the signal-reception error are likely to answer that the X-spark occurs at the same time as the Y-spark in Alan's frame (which is correct), and that the X-spark occurs before the Y-spark in Beth's frame.

3.3.1-b Results from the Events and reference frames pretest in Autumn 2009

For the first question, regarding the order of events in Alan's frame, more than 95% of students answered correctly that the events corresponding to the sparks occurring have the same time coordinate in Alan's frame.⁵ However, as noted above, students making the signal-reception error would also determine that the events have the same time coordinate in Alan's frame, as the problem states that Alan receives the wavefronts from the two sparks at the same instant. A correct and *complete* explanation would consist of three components: Alan is equidistant from the sources of the wavefronts; the signal propagation speed is the same for both wavefronts; and the wavefronts reach him at the same instant.

Very few students (10%) used correct and complete or mostly complete reasoning on this question. An overwhelming majority of students had components of correct reasoning: 45% used reasoning with a primary focus on the time at which Alan received the wavefronts from the two sparks, as in the student statement below:

| “[H]e sees both lights go on at the same time, therefore to him they have
the same time coordinates” |

Another 45% of students used reasoning based primarily on Alan's distance from the two events:

⁵Explanations provided by the small number of students that answered incorrectly indicate a misunderstanding of the context rather than a specific misunderstanding of the physics.

Table 3.1: Autumn 2009 *Events and reference frames* pretest results: student reasoning about order of events in Alan’s frame. The correct answer is highlighted.

Order of event’s in Alan’s frame	($N = 142$) ^a
Same time	> 95%
Reasoning	
Correct and complete or mostly complete	10%
Consistent with Signal reception error	45%
Distance-based reasoning	45%
Other incorrect/absent	10%

^a Section 123A094.

| “[B]ecause the flash locations are equal distance from him”. |

Explanations of the former type are consistent with the “classic” signal-reception error, while the latter type are referred to as “distance-based reasoning” in Table 3.1, which summarizes the results from question 1. However, analysis of explanations for questions 2 and 3, discussed in depth below, indicates that students using “distance-based reasoning” may also be making the signal-reception error. The students using this type of reasoning seem to believe that an observer’s perception of events is what defines that observer’s reference frame. Because the problem statement says that Alan receives the two wavefronts at the same instant, and these students may see the term “Alan’s reference frame” as synonymous with “Alan’s perception,” the provided explanations focus on *why* Alan receives the signals at the same instant. As one student wrote, “Since he is equidistant, the sparks hit him at exactly the same time.”

Results from the second two *Events and reference frames* pretest questions are shown in Tables 3.2, and 3.3.

As noted in Table 3.2, almost all of the students who answered question 2 (regarding the order in which Beth receives the wavefronts from the two sparks) incorrectly either misunderstood the context (for example, misinterpreting Beth’s position relative to the event locations) or assumed that the time difference would be small enough to be considered

Table 3.2: Autumn 2009 *Events and reference frames* pretest results: order of signal reception for Beth. The correct answer is highlighted.

Order of reception in Beth's frame ($N = 142$) ^a	
Same time	5% ^b
X-spark wavefront first	90%
Y-spark wavefront first	< 5% ^b

^a Section 123A094.

^b Based on provided explanations, most of the < 10% of students answering incorrectly misunderstood the context, or assumed that the difference in reception time for the two wavefronts was small enough to be negligible.

Table 3.3: Autumn 2009 *Events and reference frames* pretest results for event order in Beth's frame. The correct answer is highlighted.

Event order in Beth's frame ($N = 130$) ^b	
Same time	20%
X-spark wavefront first	75%
Y-spark wavefront first	< 5%

^a Section 123A094. ^b Includes on students who answered question 2 correctly.

negligible. For this reason, Table 3.3 shows only results for question 3 from students who answered question 2 correctly. Fewer than a quarter of these students answered correctly that the events would be simultaneous in Beth’s reference frame. The majority of students answering correctly used reasoning that was consistent with a belief in absolute simultaneity; that is, many of these students stated that the events are simultaneous without including an explanation why they must be so in Beth’s frame. The following responses are representative of the reasoning of such students:

“It takes the wavefront from the y-spark longer to get to her but point y is proportionally further from her so it should seem to her that events 1 and 2 happened at the same time.”

“If both events happen at the same time the time coordinates should be the same regardless of Beth’s distance from X and Y.”

Only two students used correct and complete reasoning. Their explanations are included below.

“...Beth’s inertial reference frame is the same as Alan’s inertial reference frame, since neither appear to be moving from each other’s perspectives (this is not explicitly stated, but I think it’s safe to assume this).”

“Neither Beth nor Alan are moving, so their reference frames are not moving relative to each other, so they are in the same reference frame. This means that $t=t'$, the time coordinates in the two reference frames are the same.”

Three-quarters of the students in Table 3.2 answered question 3 in a way that is consistent with the signal-reception error; almost all of them (more than 95%) used reasoning that indicated a belief that the order of events in an observer’s reference frame is determined by the order in which the signals from those events is received by that observer.

Table 3.4: Autumn 2009 *Events and reference frames* pretest results for students making the SRE: reasoning about the order of events in Alan’s frame The correct answer is highlighted.

Reasoning	($N = 105$) ^a
Correct	10%
Distance-based reasoning	45%
Explicit signal-reception error	45%
Other	< 5%

^aSection 123A094.

“Beth receives the wavefront from event 1 first so it appears to happen first.”

“The time coordinate of event 1 is earlier than the time coordinate of event 2 because she is closer to x then to y so she will observe the event 1 before event 2.”

“Since x is closer it seems to her that 1 occurred before 2”

“She is closer to event 1 than event two. Therefore t is smaller according to the Lorentz transformation for event 1.”

Overall, almost 75% of the students answered questions 1,2, and 3 in a way that is consistent with the signal-reception error.⁶ As seen above, the explanations for the order of events in Beth’s frame from almost all of these students were based on the signal-reception error. Table 3.4 summarizes reasoning about the order of events in Alan’s frame for this subset of students.

A small number of these students used seemingly correct reasoning for Alan’s frame, and incorrect, signal-reception based reasoning for Beth’s frame. The following quotes are from

⁶That is, these students answer that the events occur simultaneously in Alan’s frame, that Beth receives the wavefront from the X-spark before that from the Y-spark, and that in Beth’s frame, the time coordinate for the X-spark is earlier than that of the Y-spark.

a single student; the first was his provided explanation for question 1 (order of events in Alan’s frame), and the second was the explanation provided for question 3 (order of events in Beth’s frame).

“The wavefronts reach Alan at exactly the same time and he is the same distance away from both sources, so they occur at the same time.”

“Beth receives the wavefront from event 1 first so it appears to happen first.”

It is clear that this student is not correctly applying the formalism of a reference frame in all situations in which it would be appropriate to do so.

Results shown in the table above also support the idea that distance-based reasoning is a subset of the signal-reception error. For students who believe that an observer’s reference frame is the same as that observer’s perception of events, the prompt to explain is not interpreted as “Explain how you determined the order of events in Alan’s frame” but rather “Explain why Alan received the wavefronts at the same instant.” These explanations, therefore, rely on an assumption of absolute simultaneity, and use distance to determine the order in which the wavefront reach Alan’s position. The following student explanation exemplifies this line of thinking:

“If he is equidistant from each and they both happen at the same time, then the waves will reach him at the same time (same distance to Alan / same speed = same time).”

3.3.1-c Conclusions from the Events and reference frames pretest

Results from the *Events and reference frames* pretest suggest that a large proportion of students in the calculus-based introductory sequence does not use the correct definition of reference frame even in simple, non-relativistic contexts. The signal-reception error was seen consistently in a large percentage of these students. In addition, some students seem to apply

the formalism of a reference frame correctly in some contexts but not others.

3.3.2 Pretest for the *Simultaneity* tutorial: *Two Towers* question

The pretest for the tutorial *Simultaneity* was designed to elicit student ideas (correct and incorrect) about the relativity of simultaneity, as well as about reference frames specifically. In this sense, the *Simultaneity* pretest serves as both a pretest (for the *Simultaneity* tutorial) and as a post-test (for the *Events and reference frames* tutorial). As was the case for the *Events and reference frames* pretest, we intended to determine whether this new population of students had the same type of difficulties as the more advanced students for whom the original special relativity tutorials were developed.

3.3.2-a Description of the Autumn 2009 *Simultaneity* pretest

The relevant portion of the *Simultaneity* pretest is shown in Figure 3.12. This pretest was run after all relevant lecture instruction, including a discussion of the relativity of simultaneity using Einstein's train paradox.

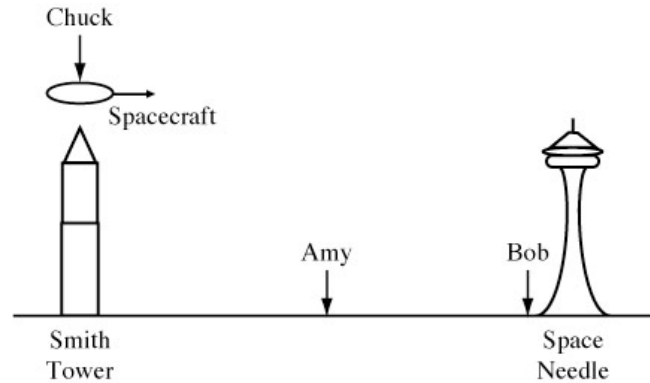
The context for the pretest for the *Simultaneity* tutorial is the *Two Towers* question, which is physically equivalent to the Seismologist question used by Rachel Scherr. An observer, Amy, stands exactly halfway between two buildings, Smith Tower and the Space Needle. A second observer, Bob, stands at the foot of the Space Needle. A spacecraft with a third observer (Chuck), flies from Smith Tower toward the Space Needle at relativistic speed. Amy sees flashes of light from the tops of the two buildings simultaneously; the spacecraft is directly above Smith Tower when the light above Smith Tower flashes.

Students are asked about the order of the flashes of light in the reference frames of Amy, Bob, and Chuck, as well as the order in which Bob and Chuck see the flashes from the two buildings. As with the *Events and reference frames* pretest, and the Seismologist question, we can determine the order of the events corresponding to the flashes of light in Amy's frame by recognizing that Amy is located equidistant from the event locations in her frame, and receives the signals from the events simultaneously. Because the signal propagation speed is

Amy is at rest midway between Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

Amy sees flashes of light above Smith Tower and the Space Needle at exactly the same time.

Chuck is in the center of a spacecraft moving from Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above Smith Tower when the light above Smith Tower flashes.



Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

1. In Amy's reference frame, does the flash above Smith Tower occur *before*, *after*, or *at the same time* as the flash above the Space Needle? Explain.
2. Does Bob *see* the flash above Smith Tower *before*, *after*, or *at the same time* as he sees the flash above the Space Needle? Explain.
3. In Bob's reference frame, does the flash above Smith Tower occur *before*, *after*, or *at the same time* as the flash above the Space Needle? Explain.
4. Does Chuck *see* the flash above Smith Tower *before*, *after*, or *at the same time* as he sees the flash above the Space Needle? Explain.
5. In Chuck's reference frame, does the flash above Smith Tower occur *before*, *after*, or *at the same time* as the flash above the Space Needle? Explain.

Figure 3.12: Reference frame and relativity of simultaneity pretest question for the *Simultaneity* tutorial.

the same for both light wavefronts, the flashes must have occurred at the same instant in her reference frame. This reasoning is identical to the correct reasoning for Alan's reference frame in the Autumn 2009 *Events and reference frames Two Towers* pretest (section 3.3.1-a).

For Bob's reference frame, we need only realize that Bob is at rest with respect to Amy, and therefore shares the same reference frame as her; therefore, Amy and Bob agree on the timing of events, and the events were simultaneous in Bob's reference frame as well. Because the events are simultaneous in his frame, but he is closer to the Space Needle, Bob must see the flash above the Space Needle before he sees the flash above Smith Tower. This reasoning is identical to the correct reasoning for Beth's frame in the Autumn 2009 *Events and reference frames Two Towers* pretest.

In Chuck's frame, we treat Amy as moving toward the location of the Smith Tower flash and away from the location of the Space Needle flash. Because the speed of light is the same in all reference frames, the centers of the wavefronts from the flashes of light are at the event locations in all frames. Amy saw the flashes from the two buildings simultaneously and at a single location in her frame, so she must have seen them simultaneously and at a single location in Chuck's frame; at the instant she sees the flashes, she is closer to the center of the wavefront from the Smith Tower flash than the center of the wavefront from the Space Needle flash. Therefore, the light above the Space Needle must have flashed first in Chuck's reference frame. Although the Space Needle light flashes first in Chuck's frame, he sees the light from Smith Tower first, as he is directly over Smith Tower when its light flashes.

3.3.2-b Results from the *Simultaneity* pretest in Autumn 2009

Question 1 Performance on question 1 about the order of events in the reference frame of the centrally-located observer (Amy) was almost identical to the analogous question on the *Events and reference frames* pretest, with more than 95% of students answering correctly. Table 3.5 shows the reasoning used by students answering this question correctly.

At first glance, student performance (including explanation) on event order in the frame of the centrally-located observer did not seem significantly better on the *Simultaneity* pretest

Table 3.5: Autumn 2009 *Simultaneity* pretest results: student reasoning about order of events in Amy’s frame. The correct answer is highlighted.

Event order (Amy’s frame)	($N = 143$) ^a
Same time	> 95%
Reasoning	
Correct: “definition”	5%
Correct: other	10%
Signal-reception error	30%
Distance-based reasoning	50%
Other incorrect/absent	< 5%

^a Section 123A094.

than the *Events and reference frames* pretest. On the *Simultaneity* pretest, 15% of students providing correct explanations, compared to 10% on the *Events and reference frames* pretest. Analysis of the explanations, however, showed that students were providing a new type of correct explanation, not seen at all in student responses on the *Events and reference frames* pretest; 5% of students invoked a “definition” of simultaneity. The following quotes are representative of this type of reasoning:

“This is the definition of simultaneity. When an observer is half way between two events, and the light from both events get to the observer at the exact same time.”

“According to the definition of simultaneity, two events are simultaneous if it is observed at the same time in the midway between the two locations.”

This definition was presented during lecture instruction as a quote from the textbook: “Two events in a reference frame are simultaneous if light signals from the events reach an observer halfway between the events at the same time.” This definition is very similar to the “distance-based reasoning” seen on the analogous question on the *Events and reference frames* pretest; as seen in Table 3.5, there was a slight increase in distance-based reasoning. Based on other results discussed below, it seems likely that many of the student providing

distance-based reasoning on the *Simultaneity* pretest were providing an incomplete version of the definition above, rather than making the signal-reception error as students did on the *Events and reference frames* pretest. The percentage of students making the “classic” version of the signal-reception error also decreased.

Another result of note is the percentage of students making reference to Amy’s velocity relative to the buildings; approximately 10% of students used Amy’s velocity as part of their explanation. The majority of students referencing Amy’s relative motion used distance-based reasoning, although two students who reasoned correctly about the order of events in Amy’s frame also mentioned that she was stationary with respect to the buildings.⁷

Questions 2 and 3 There was also improvement on the *Simultaneity* pretest over the *Events and reference frames* pretest on questions about the non-centrally-located observer (Bob). About 90% recognized that Bob sees the Space Needle flash before the flash from Smith Tower, and half of the students who answered correctly about the order in which Bob receives the signal went on to correctly conclude that the flashes occurred at the same instant in Bob’s frame. Results from questions 2 and 3 are shown in Tables 3.6 and 3.7. As on the pretest for *Events and reference frames*, the majority of students answering incorrectly on question 2 did so because of a misunderstanding of the context (e.g., some of these students believed that Bob was equidistant, or closer to Smith Tower than to the Space Needle). For this reason, results for question 3 include only those students who answered question 2 correctly.

Student performance on question 3 was significantly better on the *Simultaneity* pretest than on the analogous *Events and reference frames* pretest question (question 3), with about half of the students in Table 3.7 answering correctly that the events corresponding to the flashes above the two buildings were simultaneous in Bob’s frame. Students answering cor-

⁷As noted above, it is unknown whether students who used distance-based reasoning on this question were making the signal-reception error (as described in the results for the *Events and reference frames* pretest) or if they were reasoning incompletely based on the “definition” of simultaneity provided in lecture and in the textbook.

Table 3.6: Autumn 2009 *Simultaneity* pretest results: order of signal reception for Bob. The correct answer is highlighted.

Order of reception in Bob's frame ($N = 143$) ^a	
Same time	5% ^b
Space Needle flash first	90%
Smith Tower flash first	< 5% ^b

^a Section 123A094.

^b As on the *Events and reference frames* pretest, based on provided explanations, most of the < 10% of students answering incorrectly misunderstood the context, or assumed that the difference in reception time for the two wavefronts was small enough to be negligible.

Table 3.7: Autumn 2009 *Events and reference frames* pretest results for students that answered question 2 correctly: event order in Bob's frame The correct answer is highlighted.

Event order in Bob's frame ($N = 126$) ^a	
Same time	50%
Space Needle flash first	45%
Smith Tower flash first	< 5%

^a Section 123A094.

rectly were also more likely to have used correct reasoning, with 20% of students noting explicitly that Amy and Bob share the same reference frame and would make the same conclusions about the timing of events. As on the *Events and reference frames* pretest, many students provided explanations consistent with a belief in absolute simultaneity, stating that the events were simultaneous in Bob's frame without stating how they determined that to be the case. Unlike responses on the *Events and reference frames* pretest, however, many of these students invoked the idea of an "intelligent observer." [Recall that the *Events and reference frames* tutorial defined "intelligent observer" as someone "that is equipped with measuring devices (such as meter sticks, clocks, and assistants) and is able to use them to make correct and accurate determinations of where and when something occurs."] Although the observer Bob was intended to be an intelligent observer as defined in the tutorial, students were not given any relevant distances that could be used to determine the order of events in Bob's frame; it is not clear from these students' responses how they knew that Bob would in fact measure the time coordinates of the events corresponding to the flashes above the buildings to be identical. As will be discussed below, responses to question 5 indicate that students misunderstand the term "intelligent observer" and use it incorrectly.

As on question 1, on question 3 students were also more likely to mention relative motion in their explanations, with more than 5% mentioning that Bob was at rest with respect to *the buildings*.

Reasoning supporting a correct answer for question 3 correctly is tabulated in Table 3.8. Only results from students who also answered question 2 correctly are included.

As seen in Table 3.7, 45% of students who answered question 2 correctly (Bob sees the flash above the Space Needle before he sees the flash above Smith Tower) answered question 3 in the same way (i.e., that the flash above the Space Needle happens before the flash above Smith Tower in Bob's reference frame). Almost all of these students made the classic signal-reception error, assuming that the order in which Bob received the wavefronts from the events determined the order of the events in his frame. A few students (fewer than 10%) used distance-based reasoning.

Table 3.8: Autumn 2009 *Events and reference frames* pretest reasoning for students that answered questions 2 and 3 correctly: event order in Bob’s frame.

	($N = 126$) ^a
Correct	35%
Relative motion to buildings	10%
Intelligent observer/Absolute simultaneity	50%
Incorrect (other)	5%

^aSection 123A094.

Table 3.9: Autumn 2009 *Events and reference frames* pretest results for students that answered question 4 correctly: event order in Chuck’s frame. The correct answer is highlighted.

Event order in Chuck’s frame	($N = 102$) ^a
Same time	20%
Space Needle flash first	20%
Smith Tower flash first	60%

^aSection 123A094.

Questions 4 and 5 For question 4, 75% of students answered correctly that Chuck would see the light from the flash above Smith Tower before the light from the flash above the Space Needle. About 10% of students answered that Chuck would see the Space Needle flash before the Smith Tower flash; another 10% answered that not enough information was provided to answer the question. Reasoning provided by students in these latter two groups was not easily categorizable, though it is clear that these students did not recognize that the time coordinate of the light flashing above Smith Tower would be the same as the time coordinate of the instant that Chuck saw the light from that flash. For question 5, regarding the order of the events in Chuck’s frame, we consider only students who answered question 4 correctly.

Results for question 5 (about the event order in the reference frame of Chuck, moving relativistically with respect to the ground) are shown below in Table 3.9. Half of the students answering question 5 correctly seemed to rely on a memorized rule that relies on the relative

motion of the frame and the event locations:

“after he accounts for the differences in distances for the light to get to him, Chuck will conclude that the Space Needle flash happened first (because Chuck is moving toward the Space Needle and away from Smith Tower).” Others referenced relativistic effects such as time dilation and length contraction, without specifying how those effects were relevant.

Only one student used reasoning that was mostly correct, not based on a seemingly memorized rule:

“The two flashes reach Amy at the same time regardless of reference frame, and in Chuck’s reference frame she starts out equidistant from the two sources but is moving towards S Smith Tower, so the flash has longer to go from the Space Needle and it must have been generated earlier.”

Although this student seems to be linking the event locations in the spaceship to the two towers, the overall reasoning is correct.

All of the students who answered that the flashes occurred at the same time in Chuck’s frame assumed absolute simultaneity:

“After adjusting for his relative distance and speed, Chuck could calculate that the flashes did indeed occur simultaneously.”

“Chuck is an intelligent observer and should know his velocity and its effects to be able to conclude the light flashes were simultaneous events.”

“Even though Chuck sees the flash from the Smith Tower first, he would calculate that the flash from the Smith Tower occurs at the same time as the flash above the Space Needle through the theory of Relativity.”

A majority of students answered incorrectly that the flash above the Smith Tower occurred first in Chuck’s frame. About three-quarters of these students used signal-reception reasoning; some focused on the order of signal reception, while others focused on Chuck’s

distance from the two buildings. The other quarter of these students seem to understand that the events are not simultaneous in Chuck’s frame, but do not seem to have a good understanding of how to determine which event occurred first:

“Since he is moving at very fast speeds relativity applies.”

“In his reference frame he is moving in a direction that is towards the needle, and away from Smith. So with the flashes occurring as they do for him, the Smith flash occurs first.”

3.3.2-c Conclusions from the *Simultaneity* pretest

Student performance on the questions on the *Simultaneity* pretest requiring them to use the construct of a reference frames is better than analogous questions from the *Events and reference frames* pretest. However, many students still are still prone to making the signal-reception error even after all relevant lecture instruction as well as working through the *Events and reference frames* tutorial. Although about a third of the students seem to recognize that events that are simultaneous and spatially separated in one frame are not simultaneous in another reference frame, a majority of students still seem to believe in absolute simultaneity. Many of these students explicitly claim that the events are simultaneous in all frames, while others treat the relativity of simultaneity as an apparent effect. Students in the latter group tend to make the signal-reception error. This is further evidence of the importance of understanding and using the formalism of reference frames when discussing the relativity of simultaneity with this population of students.

3.3.3 Autumn 2009 post-test: *Relativistic Plane context*

The effectiveness of the *Events and reference frames* and *Simultaneity* tutorials was assessed using a series of multiple choice questions on the Autumn 2009 Physics 123 course final exam. The questions were based on the material from the *Events and reference frames* and *Simultaneity* tutorials, and featured a context not yet seen by the students.

The post-test was run after all lecture coverage of special relativity, as well as the full sequence of the two special relativity tutorials, *Events and reference frames* and *Simultaneity*, and their associated homework. The *Simultaneity* tutorial homework was not required. It was neither handed in nor graded, but was provided to students. Students were encouraged to complete the homework in order to study for the final exam.

The final consisted of 31 multiple-choice questions. Four were based on the material from the tutorials *Events and reference frames* and *Simultaneity*. Only the first three questions are discussed below, as they are the most relevant to student understanding of reference frames and the relativity of simultaneity. The fourth question was related to causality in special relativity, and will be discussed in Chapter 6. Because the questions were entirely multiple-choice, we cannot definitively determine student reasoning, but distractors were included that are consistent with the same types of incorrect reasoning as seen on the *Events and reference frames* and *Simultaneity* pretests.

3.3.3-a The Relativistic Plane context

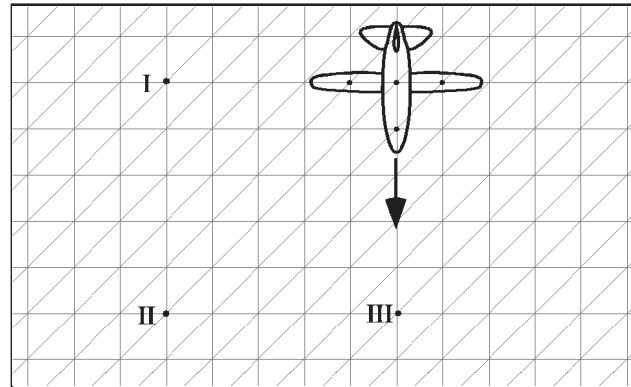
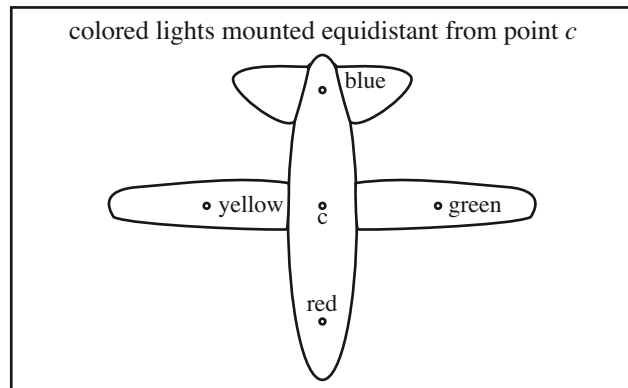
All of the questions were in the *Relativistic Plane* context, shown in Figure 3.13.

In the relativistic plane context, four lights on an airplane are programmed to flash simultaneously in the frame of the airplane. The plane flies at relativistic speed with respect to the ground. Observers I, II, and III are at rest with respect to the ground. The first three questions involve the order in the ground frame of the flashes of the various lights. It is worth noting that the figures accompanying the text do not specify a time. Many students seemed to interpret the lower figure as showing the instant that the lights flash simultaneously in the ground frame (despite the fact that the lights do not flash simultaneously in the ground frame).

Question 1 involves the timing of the flashing of the red and blue lights (at the front and back of the plane, respectively) for observer III, directly in front of the plane. This question was intended to test student understanding of the relativity of simultaneity. To answer this

Four powerful strobe lights of different colors are mounted equidistant from point c on a relativistic airplane. When the plane was at rest in the factory, the lights were programmed for an emergency distress signal consisting of simultaneous flashes of all four lights at regular intervals.

The plane now flies due south at a relativistic speed and the pilot (at rest in the plane) begins testing the emergency distress signal. Three ground-based observers are shown. In what follows, ignore any color changes due to the Doppler effect.



1. Which of the following statements concerning the timing of the first flash of the red and blue lights in the reference frame of observer III is true?

- A. The red and blue lights flash simultaneously in observer III's reference frame.
- B. The red light flashes before the blue light in observer III's reference frame.
- C. The blue light flashes before the red light in observer III's reference frame.
- D. Relativity does not allow us to determine the order of flashes in observer III's reference frame.
- E. The order of flashes can be determined, but more information is needed.

2. In the reference frame(s) of which observer(s), if any, does the flash of the red light occur at the same time as the flash of the blue light?

- A. Observers I, II, and III.
- B. Observer I only.
- C. Observer II only.
- D. Observer III only.
- E. None of the observers.

3. In the reference frame(s) of which observer(s), if any, does the flash of the yellow light occur at the same time as the flash of the green light?

- A. Observers I, II, and III.
- B. Observer I only.
- C. Observer II only.
- D. Observer III only.
- E. None of the observers.

Figure 3.13: *Relativistic Plane* context for Autumn 2009 post-test

question, students can use the fact that in the plane frame (and therefore, in all frames), the light from the red and blue flashes must reach point c on the plane simultaneously. In the ground frame, point c moves toward the location of the red flash and away from the location of the blue flash; thus, point c is closer to the location of the red flash at the instant both wavefronts from the flashes reach it. We can conclude from this that the blue light must have flashed first in the frame of observer III (option C on the multiple-choice question).

Question 2 was intended to test student understanding of reference frame. Students are asked to determine for which of the observers' frames, if any, the red and blue flashes are simultaneous. There are two lines of reasoning that students might use to answer this correctly. The first is that students can recognize that observers I, II, and III all share the same reference frame, and therefore agree on the time of all events. Because we know from question 1 that the events are not simultaneous for observer III, they must not be simultaneous for observers I or II, either. Alternatively, students could rely on the fact that events that are simultaneous but with a non-zero spatial separation in one frame are not simultaneous in any other frames. Both lines of reasoning lead to the conclusion that the events corresponding to the flashes of the red and blue lights are not simultaneous in the frames of observers I, II, and III (option E).

Question 3 was intended to probe student ability to reason about a pair of events that are simultaneous in both the reference frame of the airplane as well as the ground frame. Students are asked to determine the order of the events corresponding to the flashing of the green and yellow lights (on the wings of the plane). To answer, we again consider that light from the green and yellow reaches point c in the middle of the plane simultaneously in the frame of the plane. Therefore, point c receives the wavefronts from those two flashes simultaneously in all frames. In the ground frame, point c does not move toward either the green or the yellow light; thus, point c is equidistant from the event locations when the signals are received in the ground frame. Because the signals travel the same distance and at the same speed, and reach point c at the same instant, they must flash simultaneously in

Table 3.10: Post-test results on question 1 of the *Relativistic Plane* context administered Autumn 2009. The correct answer is highlighted.

Order of events in ref. frame of obs. III	($N = 190$) ^a
A (Same time)—consistent with absolute simultaneity	10%
B (Red flash first)—consistent with signal-reception error	75%
C (Blue flash first)	15%
D (Cannot be determined)	0%
E (Not enough information)	< 1%

^aSection 123A094.

the frame of all three observers.

3.3.3-b Post-test results

Question 1 Student performance on question 1 is summarized in Table 3.10. Only 15% of the students were able to correctly determine the order of events for observer III. Three-quarters of the students gave answer C, that the blue light flashed before the red light in the reference frame of observer III; this answer is consistent with the signal-reception error. The answer consistent with a belief in absolute simultaneity (answer A) was chosen by 10% of students.

Question 2 Student performance on question 2 is shown in Table 3.11. Answer A (that the flashes are simultaneous in the frames of all three observers) is consistent with the idea that all observers who share a reference frame agree on the time of events. It is also consistent with absolute simultaneity. It is not possible to determine what type of reasoning students choosing this answer used. Almost all of the students who answered A for question 1 (consistent with a belief in absolute simultaneity) also answered A for question 2, and vice versa. This pattern of answers is consistent with a belief in absolute simultaneity and an understanding that observers at rest with respect to each other share the same reference frame, but it is also consistent with a belief in absolute simultaneity and a belief that each

Table 3.11: Autumn 2009 post-test results on question 2 of the *Relativistic Plane* context. The correct answer is highlighted.

Ref. frames with simultaneous red & blue flashes	($N = 190$) ^a
A (Observers I,II, & III)	10%
B (Observer I only)	65%
C (Observer II only)	~ 1%
D (Observer III only)	~ 1%
E (None of the observers)	25%

^aSection 123A094.

observer is in his or her own reference frame, regardless of relative velocity.

On question 2, answer B (that the red and blue lights flash simultaneously in the frame observer I only) is consistent with students making the signal-reception error. This indicates a fundamental misunderstanding of the formalism of a reference frame. Almost all of the students answering B on question 2 also answered B on question 1. The simplest interpretation of this result is that these students strongly believe that the order of events in a given observer's reference frame is determined by the order in which that observer receives the signals from those events.

Interestingly, 10% of all students answered B (incorrect) on question 1 and E (correct) on question 2. Again, it is not possible to determine the reasoning used by students, but this pattern suggests that these students recognize that observers I, II, and III share a reference frame and they agree on the timing of events. It is also possible that they continue to make the signal-reception error on both questions but incorrectly determined the order in which observer I would receive the signals from the flashes, assuming that the flashes were in fact simultaneous in the ground frame as well as the frame of the airplane. Finally, about 10% of the students answered questions 1 and 2 correctly; it seems likely that these students answered correctly for the correct reasons.

Question 3 Student performance on question 3 is shown in Table 3.12. Only 5% of students answered all three questions correctly. Given the difficulty of these questions, it seems

likely that these students have a functional understanding of reference frames, as well as the relativity of simultaneity.

Student answers for question 3 alone, as well as patterns of answers across all three questions can provide additional insights into student thinking.

- Just over 20% of students chose an answer consistent with an understanding that all observers at rest with respect to each other are in the same reference frame and agree on the time of events (answers A or E). Almost all of those students chose A. While choice A is correct, it is also consistent with a belief in absolute simultaneity. Indeed, almost half of students answering A on question 3 also answered A on questions 1 and 2, consistent with a belief in absolute simultaneity.

Most of the remaining students answered A on question 2 but B (red flash first in observer III's frame) or C (blue flash first in observer III's frame) on question 1. This suggests that these students recognize that simultaneity is relative (although they may continue to have difficulty determining the correct time sequence of events), and also that they recognize that observers at rest with respect to each other agree on the times of events.

- Over 75% of students chose answer D on question 3, consistent with the signal-reception error. Almost 80% of students answering D on question 3 also chose answers consistent with the signal-reception error on questions 1 and 2.

Common answer sequences (with possible interpretations) for the three questions are shown in Table 3.13.

Table 3.12: Post-test results on question 3 of the *Relativistic Plane* context in Autumn 2009. The correct answer is highlighted.

Ref. frames with simultaneous yellow & green flashes ($N = 190$) ^a	
A (Observers I,II, & III)	20%
B (Observer I only)	< 5%
C (Observer II only)	0%
D (Observer III only)	75%
E (None of the observers)	~ 1%

^aSection 123A094.

Table 3.13: Post-test results: most common answer sequences on questions 1, 2, and 3 in Autumn 2009. The correct answer is highlighted.

Answer sequence	($N = 190$) ^a
CEA (correct)	5%
BEA (mostly correct, incorrect event sequence)	< 5%
BED (possible signal-reception error)	5%
AAA (absolute simultaneity)	10%
BBD (signal-reception error)	60%

^aSection 123A094.

3.4 Conclusions based on preliminary research

Based on the results from the *Events and reference frames* and *Simultaneity* pretests, it would seem that students enrolled in the non-honors, introductory, calculus-based Physics sequence at the University of Washington have some of the same difficulties as the nominally more advanced students (e.g., students enrolled in upper division courses in electricity and magnetism, and special relativity) studied by Rachel Scherr and others at the University of Washington. In particular, we found that the students in our study had serious difficulty with the formalism of a reference frame. Many of the students made the signal-reception error, predicated on absolute simultaneity. These students largely seemed to believe that the term “reference frame” is synonymous with “point of view.” In the view of these students, the order in which events occur in a particular observer’s reference frame is the order in which signals from those events reach that observer.

This lack of understanding of the formalism of a reference frame makes understanding of the relativity of simultaneity nearly impossible. Students may correctly decide that the order of events that are simultaneous in the ground frame is different for an observer in motion with respect to the ground, but may do so based on that observer’s location, rather than his or her motion. Consistent with what Scherr found in more advanced populations, this reduces the relativity of simultaneity to an *apparent* effect of special relativity in the minds of many students.

Results from the *Relativistic Plane* post-test suggest that the existing tutorials were not effective in addressing these difficulties in this population. In particular, very few people ($\sim 5\%$) were able to answer all three questions correctly. We also saw that while the percentage of students making the signal-reception error varied over the pre- and post-tests, post-test scores were not significantly better than the first (*Events and reference frames*) pretest scores.

Table 3.14 shows the longitudinal prevalence of the two most common errors: (1) the signal-reception error, and (2) the explicit belief in absolute simultaneity during the entire period of the course (before the *Events and reference frames* tutorial, after that tutorial

Table 3.14: Prevalence of common errors throughout the instructional sequence Autumn 2009.

	Signal Reception Error	Absolute simultaneity
<i>Events and reference frames</i> pretest (N = 142) ^a	70%	25%
<i>Simultaneity</i> pretest (N = 143) ^a	30%	20%
Course post-test (N = 190) ^a	60%	10%

^a Section 123A094.

but before the *Simultaneity* tutorial, and after all lecture and tutorial instruction on the post-test).

The prevalence of the signal-reception error even after all instruction suggests that the tutorials used in Autumn 2009 were not particularly effective in addressing the difficulties students in this population have regarding event time and reference frames. Without an understanding of reference frames, and the use of a reference frame to measure the time and location of any event, understanding of the relativity of simultaneity is impossible. For this reason, we determined that changes to the *Events and reference frames* tutorial and homework, in particular, were necessary to improve understanding of the relativity of simultaneity.

Part II

**IDENTIFYING AND ADDRESSING STUDENT
DIFFICULTIES WITH THE RELATIVITY OF
SIMULTANEITY**

Chapter 4

STUDENT UNDERSTANDING OF REFERENCE FRAMES

This chapter presents our research into introductory student understanding of reference frames. Modification and assessment of curricular materials (tutorials) to improve student understanding of time measurements in Galilean and special relativity are described. We also discuss how we have used the idea of *event location* as an alternative test of student understanding of reference frames and the effect of the tutorials on student ability to apply this idea in multiple frames of reference. All data were collected from pretests and post-tests administered to students enrolled in the last quarter of the introductory physics course (Physics 123) at the University of Washington between the years 2010 and 2016.

4.1 Introduction

As described in Chapter 1, an understanding of the formalism of a reference frame and its use in determining the time and location of events is necessary for qualitative understanding of the relativity of simultaneity. The version of the tutorial *Events and reference frames* used in Autumn Quarter 2009 described in Chapter 3 was designed by Rachel Scherr and others in the Physics Education Group at the University of Washington to help students develop such an understanding. However, our preliminary research, also described in Chapter 3, indicated that the *Events and reference frames* tutorial was not effective in addressing the difficulties of students enrolled in the regular, calculus-based, introductory Physics sequence. (As mentioned in Chapter 3, the materials were originally developed for use with other, often more advanced populations of students.)

In particular, we found that student ability to apply the formalism of a reference frame to make correct determinations of the times of given events was not improved by implementation of the existing special relativity tutorials. On the (multiple-choice) post-test, almost two-thirds of students chose answers consistent with the “signal-reception error.” These students seemed to be associating the order of events in an observer’s frame with the order in which that observer received the signals from those events. This reflects a fundamentally incorrect definition of the term “reference frame.”

To address student difficulties with these ideas, we performed several iterations of modification and assessment of the *Events and reference frames* curriculum, described below in §4.2. These modifications led to improvement in student performance on some types of questions on post-tests, and seemed to decrease the percentage of students making the signal-reception error significantly. Lower performance on questions in more complex contexts, however, particularly those involving relative motion, indicated that student understanding of reference frames was still insufficient for qualitative understanding of the relativity of simultaneity. We developed questions involving event location, in addition to event time, to probe student understanding of reference frames further. The investigation of student understanding of event location is described in §4.3. §4.4 summarizes the results and discusses directions for

future work.

In the following section we present a definition for *reference frame* and discuss consequences of the definition that can be used to probe student understanding.

All of Galilean and special relativity relies upon the idea of a reference frame. The term *reference frame* is variously defined, but for the purposes of this dissertation, we will define it as follows (which is similar to the definition found in many textbooks):

Reference Frame. *A reference frame is a three-dimensional grid of meter sticks and synchronized clocks, used by an observer at rest with respect to that grid to measure the time and location (spacetime coordinate) of any event.*¹

This formalism suggests a method by which the spacetime coordinate of any event might be measured. The time coordinate of an event is recorded by the clock at the location of that event, while the location of the event is defined as the location of the clock that recorded it. To measure the spacetime coordinate of an event, an observer reads the time from the recording clock, and notes the clock's position.

This definition of reference frame—and the procedure by which an observer uses it to measure the spacetime coordinate of an event—has several consequences. In particular:

1. All observers at rest with respect to each other are in the same reference frame, and agree on the spacetime coordinates of all events
2. Observers with non-zero relative velocity with respect to each other are in different reference frames, and do not (in general) agree on the spacetime coordinates of events
3. The spacetime coordinate of a given event does not change with time in any reference frame

The first consequence can be derived from the statement that a particular grid of meter sticks and clocks is used by an observer at rest with respect to that grid. If multiple observers

¹An *event* is defined as anything that can be associated with a single location in space and a single instant in time.

use the same reference frame, they must all be at rest with respect to that grid, and are therefore also at rest with respect to each other. Such observers would necessarily measure the same spacetime coordinate for a given event, as they are using the same system of clocks to do so. This is true in both Galilean and special relativity.

The second consequence is similarly obtained; in this case, we recognize that observers with a non-zero relative velocity with respect to each other do not use the same grid of meter sticks and clocks, and therefore may measure different spacetime coordinates. It is worth noting that in Galilean relativity, spacetime coordinates for a given event differ only in the spatial coordinate. In special relativity, both the time and spatial coordinates generally differ in different frames.

The third consequence results (again) from the fact that an observer uses the grid of clocks at rest with respect to him or herself, and the procedure by which the spacetime coordinate of a given event is measured. The clock at the location of the event records the time of the event at the instant the event occurs, while the clock's location marks the location of the event. An observer in that frame can read the spacetime coordinate of that event from that clock at any point after the event occurs, and will obtain the same result no matter when the measurement is made, as neither the recorded time nor the position of the clock change with time. Like consequence 1, consequence 3 holds in both Galilean and special relativity.

Evidence of student understanding and use of these three consequences in the context in the relativity of simultaneity is not necessarily evidence of complete understanding of reference frames, or use of the formalism of a reference frame when determining the spacetime coordinate of an event. However, evidence of lack of understanding of these consequences does indicate a lack of understanding of reference frame. The prior and preliminary research described in Chapter 3 was primarily an investigation of student understanding of consequences 1 and 2, for the time coordinates of events. The prevalence of the signal-reception error, in particular, indicates that students did not understand consequence 1. We began our in-depth investigation and curriculum modification project as a continuation of this line of

research, focusing on improving student understanding of consequence 1 for the time coordinate of events. As described in §4.2, below, post-test results suggest that we were successful in improving student understanding of this idea.

We have found that consequence 3, especially when applied to the *spatial* coordinates of events, is highly non-intuitive for students [8]. For this reason, it is more likely that an understanding of consequence 3 reflects an understanding of the use of the formalism of a reference frame. After modifications to the *Events and reference frames* tutorial and homework seemed to improve student performance on questions involving consequence 1, we began to probe student understanding of consequence 3, as described in §4.3. Persistent student difficulty with questions involving consequence 3 suggested that improvements in student understanding of consequence was not indicative of an improvement in student understanding of the formalism of a reference frame.

4.2 Student understanding of event time

In this section, we present an in-depth investigation of student understanding of the application of the formalism of a reference frame to measure event time. Also described are a series of modifications to the tutorial *Events and reference frames* as well as its associated homework.

4.2.1 Introduction

As discussed in §4.1, complete understanding of a definition of reference frame would result in an ability to determine if two observers shared the same reference frame; it should also result in the knowledge that two observers in the same reference frame would measure the same spacetime coordinate for a given event. These two ideas are equivalent to “consequence 1.”

In Autumn 2009, we conducted preliminary research into student understanding of (primarily) consequence 1. Our findings, described in Chapter 3, suggest that many students were unaware of this consequence of the definition of reference frame; from this, we concluded that these students did not have a good understanding of what is meant by an observer’s reference frame, nor how to use a reference frame in order to determine the time of an event. Because of the importance of understanding the construct of a reference frame in the context of the relativity of simultaneity, further research into student understanding of reference frames was a clear starting point, and motivated modifications to the *Events and reference frames* tutorial and homework.

In section 4.2.2, we discuss prior research. Section 4.2.3 is a comprehensive description of our investigation of student understanding of event time and reference frames prior to tutorial instruction, via tutorial pretests. Section 4.2.4 details modifications and assessments of the *Events and reference frames* tutorial and homework.

4.2.2 *Prior research*

Rachel Scherr’s investigation of student understanding of event time and reference frames in the context of the relativity of simultaneity is described in detail in Chapter 3. Scherr found that a majority of students across populations believe that a reference frame is determined by location rather than relative velocity; this is evident in the belief of many students that the time order of events in an observer’s reference frame is determined by the order in which that observer receives the signals from those events.[8] (The error that results from this belief is called the “signal-reception belief” or the “signal-reception error” in this current investigation.)

This belief (and error) has also been documented in other populations. C. de Hosson, I. Kermen, and E. Parizot found that a majority of the pre-service middle and high school physics and chemistry teachers they studied were unable to correctly determine when observers shared the same reference frame [23]. About a quarter of the subjects studied by de Hosson et al. made an error that could be characterized as the signal-reception error. de Hosson et al. also found that these subjects had great difficulty using the Lorentz transformations correctly. G. Selçuk found similar results in preservice teachers [22]. Other researchers have found similar difficulties with reference frames in the context of Galilean relativity [29].


4.2.3 *Investigation of student understanding of reference frames and event time*

The *Noisy Bird* context shown in Figure 4.1 has served as a basis for almost all of the pretests for the *Events and reference frames* tutorial from Winter 2010 until Autumn 2016. In the *Noisy Bird* pretest, Alan, Beth, and a bird stand a large distance apart, with Alan exactly equidistant between Beth and the bird. Alan wears a watch with an alarm set to go off at 12:00 PM; Beth hears the alarm from Alan’s watch at exactly the same instant that she hears the bird tweet. Students are asked to determine the order of the events “Alan’s alarm sounds” and “the bird tweets” in Beth’s reference frame. They are also asked to determine


the order in which Alan hears the sounds of the alarm and the bird, as well as the order of the events in Alan’s reference frame.

Alan and Beth are in the middle of a clearing in the forest. Beth is exactly midway between Alan and a noisy bird, which sits on the ground, as shown at right. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Beth hears the bird tweet and the alarm from Alan’s watch at *exactly the same time*.


Alan



Beth



Bird



(Drawing not to scale)

1. In Beth’s reference frame, does the bird tweet *before*, *after*, or *at exactly the same time as* Alan’s alarm sounds? Explain.
2. Does Alan *hear* the bird tweet *before*, *after*, or *at exactly the same time as* he hears his watch alarm? Explain.
3. In Alan’s reference frame, does the bird tweet *before*, *after*, or *at exactly the same time as* his watch alarm sounds? Explain.

Figure 4.1: *Noisy Bird* pretest for the *Events and reference frames* tutorial

Physically, this context is very similar to the *Seismologist* question (for the ground frame observers), as well as the *Sparks* and *Two Towers* contexts used in the *Events and reference frames* and *Simultaneity* pretests, respectively, in Autumn 2009 (see Chapter 3), except that the *Noisy Bird* context involves events that produce sound rather than light. The wording used in the *Noisy Bird* question is also slightly different than that used in the *Sparks* context. In the *Sparks* context, recall that students were asked to determine the order of the “time coordinates” of two defined events in the reference frames of two different observers at rest with respect to each other. In the *Noisy Bird* context, the events of interest are not explicitly defined as events; instead, students are asked directly whether the bird tweets before, after, or at exactly the same time as Alan’s alarm sounds. The language used in the *Noisy Bird* context is much more colloquial; we believe that it does not rely as heavily on student understanding of the terms “event” or “(space)time coordinate.” We did not have significant evidence that the time-coordinate wording was misunderstood by students,

Table 4.1: Student performance on the basic version of *Noisy Bird* pretest (versions U2a, U2a1, U2g, and U2gi). The correct answer is highlighted.

$N = 2246^a$	
Correct	20%
Signal-reception error	70%
Other incorrect	10%

^a Sections

123A101102122124131132134
 123A144161162164,
 123B131161164, and
 123C122132162

but we wanted to test whether changing the wording would have an effect on the prevalence of the signal-reception error.

The basic version of the *Noisy Bird* context, described above and shown in 4.1, was used on four pretest versions² over eleven quarters. Complete copies of all of the pretests discussed in this chapter can be found in Appendix B. Performance on these pretests was very consistent, with approximately 70% of students making the signal-reception error each quarter. Student reasoning was very similar to the reasoning seen on the pretest used in Autumn 2009. Table 4.1 shows student performance on the *Noisy Bird* question over these eleven quarters. Data are pooled, due to the similarity in student performance across quarters. For this pretest, and others described in §4.2, we focus on student performance on questions regarding the non-centrally located observer (in this case, Alan), unless otherwise specified.


In other quarters, we made variations to the wording shown above to probe different aspects of student understanding. These changes, and their effects on student performance on the *Events and reference frames* pretest, are described in the sections labeled *a, b, c,* and *d* below. Table 4.5 summarizes the results from the basic version and variations thereof.

²Versions U2a, U2a1, U2g, and U2gi

4.2.3-a *Restless Bird context*

The *Restless Bird* context is identical to the noisy bird context, except that the events involved involve light, rather than sound. In the *Restless Bird* context, Beth stands equidistant between a restless bird and Alan, who makes a spark with a flint and steel at exactly 12 noon. Students are told that Beth sees the bird flap its wings, and the spark from Alan's flint at exactly the same time. As in the *Noisy Bird* context, students are asked to determine the order of the events in both Beth's and Alan's reference frames, as well as the order in which Alan sees the events. The *Restless Bird* version of the *Events and reference frames* pretest is shown in Figure 4.2.

Alan and Beth are in the middle of a clearing in the forest. Beth is exactly midway between Alan and a restless bird, which sits on the ground, as shown at right. Alan creates a spark with a flint and spark at exactly 12 noon.



(Drawing not to scale)

Bird

Beth sees the bird flap its wings and the spark from Alan's flint at *exactly the same time*.

1. In Beth's reference frame, does the bird flap its wings *before*, *after*, or *at exactly the same time* as the flint sparks? Explain.
2. Does Alan *see* the bird flap its wings *before*, *after*, or *at exactly the same time* as he sees the flint spark? Explain.
3. In Alan's reference frame, does the bird flap its wings *before*, *after*, or *at exactly the same time* as the flint sparks? Explain.

Figure 4.2: *Restless Bird* pretest for the *Events and reference frames* tutorial

This version of the question was written to test whether students had more or less difficulty with the ideas of events and reference frames with events that involve the emission of light rather than sound. The signal propagation speeds are different in the *Noisy Bird* and *Restless Bird* contexts, but there is no difference in the reasoning needed to answer questions in the two versions.

Table 4.2: Student performance on the basic version of *Restless Bird* pretest (version U2b). The correct answer is highlighted.

	All students $N = 731^a$	Students ans. Q2 correctly $N = 532$
Correct	15%	25%
Signal-reception error	60%	70%
Other incorrect	15%	5%

^a Sections 123A114121, 123B101, 123C102112

The major difference in student performance on this version of the pretest seems to be due to student belief that the speed of light is effectively infinite. A relatively large proportion of students (20%) answered that Alan would also see the bird flap its wings at the same time that he saw the spark from the flint; this is more than double the proportion of students who answered similarly for the *Noisy Bird* (sound) version. In the given context, the belief that Alan—the non-centrally located observer—would not notice a difference in the times at which the signals reach him is reasonable. However, this was not the intent of the question, and a majority of students (75%) answered that Alan would see the flint spark before he saw the bird flap its wings, as was intended.

If we consider all student responses, including those from students who treated the speed of light as effectively infinite, a slightly smaller percentage of students (60%) made the signal-reception error. However, if we limit our analysis to only those students who answered consistently with the intent of the question, we find that the results in the *Restless Bird* context are identical to those from the *Noisy Bird* context, with 70% of students answering in a way consistent with the signal-reception error. There were no major differences in student reasoning between the two versions.

4.2.3-b *Noisy Bird* (with distances) context

In another two versions of the *Noisy Bird* context, students were told the distances between Alan, Beth, and the bird. In version U2d, the distances as well as the speed of sound in air

were mentioned in the problem setup, though the figure used was identical to that in the basic *Noisy Bird* question. The distances and signal propagation speed were included for a second page of questions that asked students to determine the time coordinates of various events associated with the context; student performance on those questions will be discussed in section 4.2.3-d, below. Otherwise, version U2d of the *Noisy Bird* question was identical to the basic version described above. The wording used in version U2d is shown in Figure 4.3.

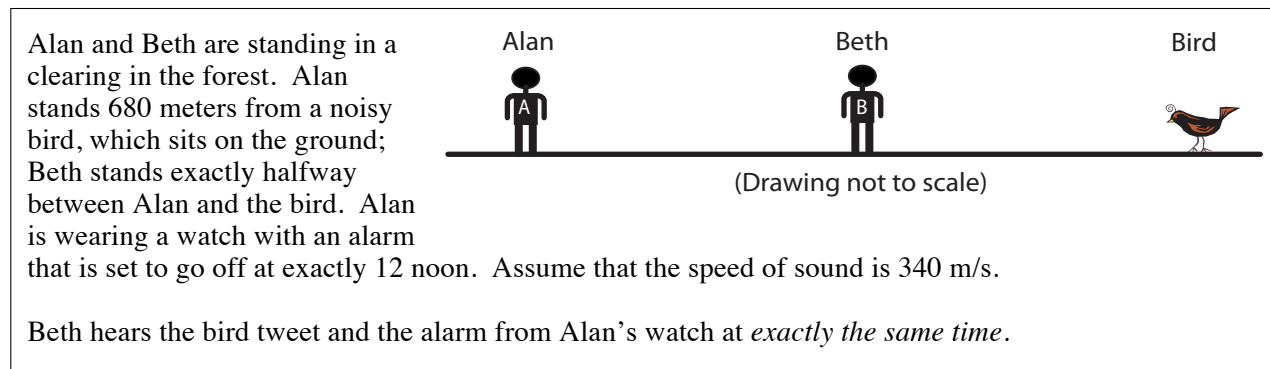


Figure 4.3: Version U2d pretest for the *Events and reference frames* tutorial

This one difference (distances mentioned in the problem setup) had no significant effect on student performance, with approximately 70% of students making the signal-reception error. In version U2f, however, the distances were mentioned in the context setup as well as listed in the figure, as shown in Figure 4.4. Including the distance on the figure was correlated with a decrease in the proportion of students making the signal-reception error, with 50% of students answering that the order of the events in Alan's frame is determined by the order in which Alan's perceives them. The prevalence of the signal-reception error is significantly different on the two pretests; although we can't calculate a standard deviation for the average class performance on the *Noisy Bird* with distances question from a single measurement, recall that we can assume a standard deviation of 10% or less based on work done at the University of Washington by Paula Heron (see 1.5.3). Comparisons of the averages of the percentage of students making the signal-reception error on two questions

suggests that the prevalence of the signal-reception error is significantly different on the two versions. Our results suggest that including the distances on the figure improves student performance on the pretest significantly.

Approximately 30% of students correctly determined that the events were simultaneous in Alan's frame on this version of the pretest, although there was not an increase in correct reasoning. There was, however, a greater proportion of students who explicitly mentioned signal propagation time. It is possible that including numeric distances in the figure accompanying the *Noisy Bird* question cued students to consider signal propagation time, leading students to recognize the difference between the emission and reception of a signal and decreasing the proportion of students making the signal-reception error. This suggests that students may have an easier time interpreting the meaning of "reference frame" when they consider signal propagation time. However, the increase in correct answers without an increase in correct and complete reasoning may be due to an increase in a belief in absolute simultaneity. This cannot be determined for this pretest because the *Noisy Bird* context lacks any relative motion, and does not require relativistic corrections to time.

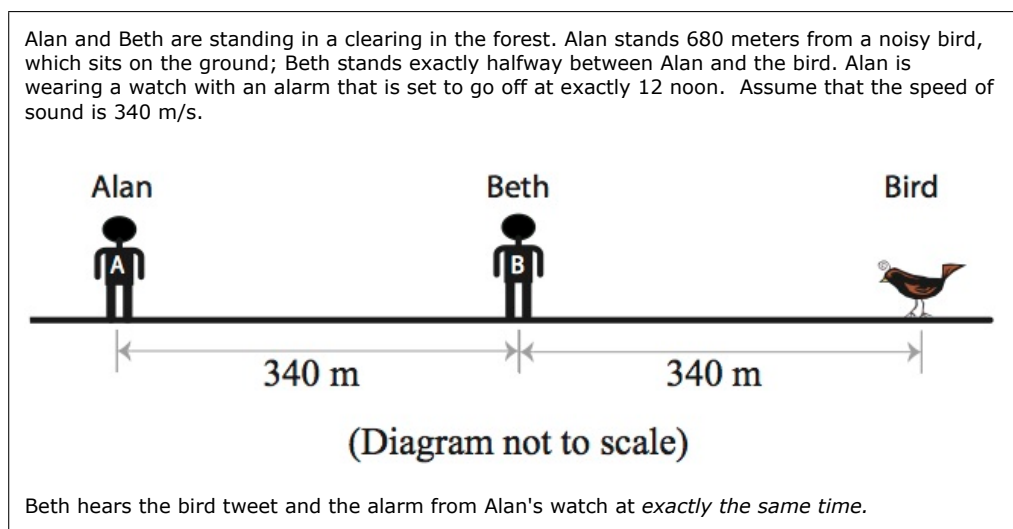


Figure 4.4: Version U2f pretest for the *Events and reference frames* tutorial

Results from these two versions of the *Noisy Bird* pretest are tabulated in Table 4.3.

Table 4.3: Student performance on the *Noisy Bird* (with distances) pretest (versions U2d and U2f). The correct answer is highlighted.

	Version U2d $N = 525^a$	Version U2f $N = 133^b$
Correct	20%	30%
Signal-reception error	70%	50%
Other incorrect	10%	20%

^aSections 123A141142, 123B141, and 123C142 ^bSection 123A154

4.2.3-c *Noisy Bird* (ground frame) context

In pretest version U2e, we changed the way we referred to the relevant reference frame. In all of the other pretests described in this section, we use the convention of describing a reference frame by as being associated with a particular observer (e.g., Alan’s reference frame). In the *Noisy Bird* (ground frame) pretest, we use the term “ground frame.” The problem setup is identical to that in version U2f, with distances mentioned in the text and shown on the diagram. Questions 1,2, and 3 are replaced with a single question: “In the ground frame, does the bird tweet before, after, or at exactly the same time as Alan’s alarm sounds? Explain.” Students were also given the distractor “the answer to this question depends on the location of the observer determining the timing of events.” This distractor describes a belief consistent with the signal-reception error.

Performance on this version of the task was significantly better than any of the other pretest versions described in this chapter. Only 10% of students chose the signal-reception error distractor. However, careful analysis of student reasoning for some of the other answer choices suggest that some students chose a single observer (Beth or Alan) as representative of the ground frame, and considered only that observer’s order of signal reception. An additional 10% of student made statements consistent with the signal-reception error in their explanations. The prevalence of the signal-reception error on this version of the pretest was about a third of that on the basic version of the pretest described above.

Table 4.4: Student performance on the *Noisy Bird* (ground frame) pretest (version U2e). The correct answer is highlighted.

Version U2e $N = 466^a$	
Correct	75%
Signal-reception error	20%
Other incorrect	5%

^aSections 123A151152, 123B151, and 123C152

Commentary on observer *vs.* ground frame reasoning We used the alternative “ground frame” wording in this version due to a concern that referring to the reference frame of an observer (e.g., “Alan’s reference frame”) was misleading to students. The term “ground frame” may suggest an extended frame to students, whereas “Alan’s reference frame” may seem limited to Alan’s location. Because the idea that a reference frame is location-dependent—rather than dependent on relative velocity—is consistent with the signal-reception error, we believed that using the term “ground frame” would result in a smaller percentage of students making that error.

Our results above suggest using ground-frame wording does decrease the prevalence of the signal-reception error on the *Events and reference frames* pretest. Despite this improvement in pretest performance, we decided to continue to use observer-frame wording in the tutorials. As described in Chapter 1, the *elicit-confront-resolve* strategy is used throughout *Tutorials in Introductory Physics*, including the *Events and reference frames* and *Simultaneity* tutorials; eliciting student’s incorrect ideas allows us to address them more directly. This is especially important in this case because many textbooks use the observer’s-frame wording. Moreover, describing a reference frame other than the ground or laboratory frame in terms of an extended object can be cumbersome. One might describe a frame S' , in which a spaceship is at rest, that moves with speed $0.8c$ relative to the Earth, but it is easier to describe such a frame as the reference frame of the spaceship. This is also consistent with how the term “reference frame” is used in many texts.

As described in section 4.2.4 below, the *elicit-confront-resolve* strategy can be effective

Table 4.5: Percentage of students making the signal-reception error on each of the *Noisy Bird* pretest variations described in section 4.2.3

Pretest version	Signal Reception Error
<i>Noisy Bird</i> (basic) $N = 2246^a$ (U2a, U2a1, U2g, U2gi)	70%
<i>Restless Bird</i> $N = 532^b$ (U2b)	70%
<i>Noisy Bird</i> (distances, text only) $N = 525^c$ (U2d)	70%
<i>Noisy Bird</i> (distances, text and figure) $N = 133^d$ (U2f)	50%
<i>Noisy Bird</i> (ground frame) $N = 466^e$ (U2e)	15%

^a Sections 123A101102122124131132134144161162164, 123B131161164, and 123C122132162 ^b Sections 123A114121, 123B101, 123C102112

^c Sections 123A141142, 123B141, and 123C142 ^d Section 123A154

^e Sections 123A151152, 123B151, and 123C152

in this case. After modifications to the *Events and reference frames* tutorial and homework, student performance on post-test questions using observer's-frame wording showed a significant decrease in the prevalence of the signal-reception error. We conclude that students can learn that a reference frame is not location-dependent even when observer-frame wording is used.

Table 4.5 presents the percentage of students who answered in a way consistent with the signal-reception error on each of the pretest variations described in this section.

4.2.3-d Other relevant pretest results

Each of the pretests described above included questions other than those in the *Noisy Bird* (or variation) context. The results from some of these other questions are relevant to the curriculum modification and research described in section 4.2.4. Two of these extra questions are described below.

Questions on student understanding of synchronized clocks and the signal-reception error On *Events and reference frames* pretest U2a1, which included the basic version of the *Noisy Bird* context, the *Clocks* question was used to probe student understanding of what is meant by “synchronized clocks.” It was also intended to probe the robustness of signal-reception reasoning.

Suppose that Alan and Beth both wear watches equipped with alarms, but stand a large distance apart. Each watch is set so that its alarm will sound when it reads 1:00 PM. Alan then noted that he hears the two alarms at exactly the same time.

Are the watches synchronized in Alan’s frame? Explain.

To answer this question correctly, one should recognize that because Alan is at the same location as his own watch, the time at which he hears the alarm is the same as the time that the alarm sounds. In addition, Beth’s watch is a large distance away from Alan, and it will take some time for the sound from the alarm to travel from Beth to Alan. If Alan hears the two alarms at the same time, Beth’s alarm must have sounded first. Finally, one must recognize that watches or clocks that are synchronized have the same reading at every instant; if the two clocks were side-by-side, they would look identical at all times. If the two watches were synchronized, the alarms would have sounded at exactly the same time, but due to the finite signal propagation speed, Alan would hear his own alarm first. Because Alan hears both alarms at the same instant, we can conclude that the two watches are not synchronized in Alan’s frame.

We hypothesized that students making the signal-reception error would answer the *Clocks* question incorrectly, determining that because Alan heard the alarms at the same instant that the clocks were synchronized. This would be consistent with student reasoning in the *Noisy Bird* context that in Alan’s reference frame, his alarm sounded before the bird tweeted because Alan heard the alarm first. It is worth noting, though, that the reasoning required for the *Clocks* question is somewhat different than that required for the *Noisy Bird*

Table 4.6: Student performance on the *Noisy Bird* and *Clocks* questions (version U2a1).

Version U2a1	$N = 1325^a$	
	Signal Reception Error (<i>Clocks</i>)	Correct (<i>Clocks</i>)
Signal Reception Error (<i>Noisy Bird</i>)	40%	30%
Correct (<i>Noisy Bird</i>)	< 5%	10%

^a Sections 123A122122124131132134, 123B131, and 123C122132

question. In the *Noisy Bird* question, correct and complete reasoning requires using the fact that Beth, the centrally-located observer, hears the noises at the same instant, and recognition that Alan and Beth are in the same reference frame, and therefore agree on the timing of all events. In answering the *Clocks* question correctly, students must rely on the fact that Alan receives the sounds from the two alarms at the same instant but is not centrally-located to determine that the sounds were not emitted at the same instant (and that non-simultaneous alarms indicates that the clocks are not synchronized).

We found that 50% of the students asked this question recognized that the alarms were not synchronized in Alan's reference frame, while 50% determined that the clocks were synchronized in Alan's frame. Virtually all of the students who answered that the clocks were synchronized in Alan's frame used reasoning consistent with the signal-reception error. Despite the improvement in student performance on the *Clocks* question compared to the *Noisy Bird* question, the signal-reception error was still common.

Of the 70% of students who made the signal-reception error in the *Noisy Bird* context, only slightly more than half also made the signal-reception error on the *Clocks* task. Table 4.6 summarizes student performance on the *Noisy Bird* and *Clocks* questions.

As shown in Table 4.6, almost all students who answered the *Noisy Bird* question correctly also answered the *Clocks* question correctly. These students seem to have a consistent and

correct understanding of what is meant by the term reference frame. Approximately 40% of students made the signal-reception error on both questions. Although these students answered both questions incorrectly, they seem to have a consistent belief that perception determines event order in an observer's reference frame.

Another 30% of students made the signal-reception error on the *Noisy Bird* question but answered the *Clocks* question correctly. We were particularly interested in the reasoning used by this subset of students, as something in the *Clocks* question seemed to trigger an understanding that Alan's reception of the two signals simultaneously did not imply that the events corresponding to the emission of the signals occurred simultaneously in his frame. These students seemed to have an understanding of what is meant by "synchronized clocks." Many students seemed to reason based on what Alan would observe if the two clocks *were* synchronized:

"In Alan's frame, if the two watches are synchronized, then he would hear his alarm first."

"The two clocks are not synchronized in Alan's frame because if the two clocks were synchronized then he would hear his own alarm before he hears the other alarm."

This might indicate that student understanding of what is meant by "synchronized clocks" improves student understanding of what is meant by "reference frame," which would suggest that a definition of reference frame based on synchronized clocks could improve student understanding. It may also be that the *Clocks* task was simply easier for students than the *Noisy Bird* question: determining whether two signals were emitted at the same time given that a non-centrally-located observer received them at the same time is more straightforward than determining the order of events for an observer that does not receive the signals simultaneously.

Questions using a “student dialogue” to probe directly student understanding of the meaning of reference frame On the second page of *Events and reference frames* pretests U2g and U2gi,³ students saw one of two versions of a student dialogue regarding the *Noisy Bird* context. (Students saw the *Noisy Bird* questions on the first page of the pretest.) In the student dialogue, one student proposes that the definition of “reference frame” is consistent with the signal-reception error, i.e., that the order of events in an observer’s reference frame is determined by the order in which that observer receives the signals from the two events. The other student proposes a method for measuring the time of events that includes correcting for signal propagation time. The difference between the two versions on each pretest was the order in which the students in the dialogue presented their arguments.

The two versions of the student dialogue are shown below in Figures 4.5 and 4.6.

Consider the following student dialogue regarding Alan's reference frame.

Student 1: Alan hears the alarm from his watch before he hears the bird tweet, so in his reference frame, the alarm goes off first. That's what reference frame means.

Student 2: I disagree. Alan needs to account for the time it takes for each sound to get to him in order to figure out what happened first in his reference frame.

With which of the students do you agree, if either? Explain.

Figure 4.5: Version 1 of student dialogue on *Events and reference frames* pretests U2g and U2gi

This question allows us to probe student interpretation of the term “reference frame” directly. We wrote the two versions (in which the statements by the two students are reversed) in order to ensure that students weren’t unduly influenced by statement order, or whether the correct definition was presented as a direct statement or a rebuttal to the incorrect definition.

Performance on the two versions was identical, with 55% of students on both versions choosing the statement that describes the signal-reception error, and 45% choosing the cor-

³The U2g and U2gi pretests are identical in terms of content. Each pretest had two versions; the only difference between the U2g and U2gi pretests is how students were divided between the two versions.

Consider the following student dialogue regarding Alan's reference frame.

Student 1: Alan hears the alarm from his watch before he hears the bird tweet, but he doesn't know whether the alarm goes off before or after the bird tweets in his reference frame. He would need to account for the time it takes for each sound to get to him in order to figure out what happened first.

Student 2: I disagree. Alan hears the alarm from his watch before he hears the bird tweet, so in his reference frame, the alarm goes off first. That's what reference frame means.

With which of the students do you agree, if either? Explain.

Figure 4.6: Version 2 of student dialogue on *Events and reference frames* pretests U2g and U2gi

Table 4.7: Student performance on the *Noisy Bird* and student dialogue questions (versions U2g and U2gi).

Versions U2g and U2gi	$N = 733^a$	
	Signal Reception Error (student dialogue)	Correct (student dialogue)
Signal Reception Error (<i>Noisy Bird</i>)	40%	30%
Correct (<i>Noisy Bird</i>)	< 5%	15%

^aSections 123A161162164, 123B161164 and 123C162

rect statement. Student belief that signal-reception order determines event order in an observer's frame persists for a majority of students even when they are presented with a statement that describes a correct procedure for determining the order of events in a reference frame.

As with the *Clocks* question described above, some students who made the signal-reception error on the *Noisy Bird* question answered chose the correct statement from the student dialogue. Student performance on the *Noisy Bird* and student dialogue questions is shown in Table 4.7.

Description of the initial version of *Events and reference frames* The full versions of the unmodified *Events and reference frames* tutorial and homework can be found in Appendix A.

As described in Chapter 3, the original *Events and reference frames* tutorial consisted of three sections: I. Reference frames; II. Events; and III. Synchronized clocks. In the first section, exercises motivate the formalism of a reference frame as an arrangement of observers and equipment that can be used to determine the time and location of anything that happens. The first section also introduces event diagrams. The second section defines the term “event” as anything associated with a single location in space and a single instant in time. The third section relies on student intuition about the meaning of “synchronized” and has students develop a method for the synchronization of clocks using light pulses. It also includes an exercise designed to help students recognize that light has a finite speed, and that the propagation time of light signals must be considered when determining the time of an event.

The homework associated with the *Events and reference frames* tutorial used during the first two quarters with the introductory students had two sections. The first section introduced the idea of an inertial reference frame, and had a series of exercises designed to help students understand how the physics of a non-inertial reference would differ from that of an inertial reference frame, using Newton’s Second Law as an example. In the second section, students were asked to consider two reference frames with relative motion, and to draw an event diagram in the ground reference frame. Follow up questions asked students to determine the distance between events using the event diagram just drawn.

4.2.4 Initial changes to the *Events and reference frames tutorial homework*

Our initial revisions were to the homework only.⁴ We felt that the first section, regarding inertial *vs.* non-inertial reference frames, was an extension of the material in the tutorial that was not necessary for student understanding of the relativity of simultaneity. The first section was replaced with a series of exercises designed to motivate the “observer’s frame” wording used in the tutorial, as well as introducing relative motion as the factor that distinguishes one reference frame from another.

The new first section of the *Events and reference frames* homework features two observers, Anton and Barry, moving with different constant velocities relative to the ground. A third observer, Carl, stands at rest on the ground. A series of questions about this context are intended to help students think what it means for two observers to be at rest with respect to each other. Students are also told that an observer’s rest frame is often the most useful reference frame for that observer to use; students are told that there are a number of names for such a frame, including the “observer’s reference frame.” That statement connects the observer’s frame wording used in the *Events and reference frames* tutorial to the idea that relative velocity, rather than position, determines an observer’s reference frame. The two questions following the statement defining an observer’s reference frame are intended to help students understand that an observer is at rest in his or her own reference frame, and that two observers moving with the same velocity are in the same reference frame.

The revised first section for the *Events and reference frames* tutorial homework is shown in Figure 4.7.

The second section of the original *Events and reference frames* homework was replaced by a series of exercises designed to help students recognize that event time does not always correspond to the time at which the signal from that event is received by an observer. In this section, observer’s Anton and Barry stand on the ground, at rest, separated by a distance of

⁴Changes to the *Simultaneity* tutorial homework were made concurrently. The focus of the modified *Simultaneity* homework was on causality as a basis for understanding the relativity of simultaneity. It seems unlikely, therefore, that modifications to the *Simultaneity* homework had a large effect on the questions presented in this chapter.

1. *Relative velocity and rest frames*

Anton is walking at a constant speed, 1.5 m/s due north. Barry is jogging due south with a constant speed, 3 m/s. Carl stands at rest.

- a. What is Anton's speed relative to Carl? What is Anton's speed relative to Barry? Explain.
- b. Could Carl change his speed such that he is at rest relative to Anton? Could Anton change his speed such that he would be at rest relative to Carl? Explain.
- c. Suppose that you are told that Carl and Anton are at rest relative to each other. What, if anything, can you say about the distance between them? (*Hint: Consider both the value itself and the manner in which this value changes over time.*)
- d. Suppose that Barry reduced his speed to 1.5 m/s, but continued moving in the same direction (due south). Would Barry and Anton be at rest with respect to each other? Why or why not?

Is a common speed the only factor that determines whether two bodies are at rest with respect to each other?

Often, the most useful reference frame for an observer to use is one in which the observer is at rest. It is common to refer to such a frame as the *rest frame of the observer*, the *observer's rest frame*, the *observer's reference frame*, or simply *the observer's frame*.

- e. Is it possible for an individual to have a non-zero velocity in his or her own reference frame? If so, explain how. If not, explain why not.
- f. Is it possible for two people *in the same rest frame* to be moving with different velocities? Why or why not? Explain.

Figure 4.7: Series of exercises that replaced the first section of the original *Events and reference frames* homework

150 meters. A dog, Clover, sits between them but is not equidistant from them, and barks once. The first two exercises ask students to think about when Anton and Barry each hear the bark, and to calculate the amount of time it takes for the sound of the bark to travel from Clover to each of the observers. Students are reminded of the definition of *intelligent observer* and are then asked a series of questions about whether Anton and Barry agree on the time at which Clover barked, and whether Anton and Barry can be considered to be in the same reference frame. Students are asked to generalize their results and state that all observers in the same reference frame agree on the time coordinate of any given event.

The revised first section for the *Events and reference frames* tutorial homework is shown in Figure 4.8.

2. *Signal reception and event time*

Anton and Barry are standing at rest 150 meters apart. A dog, Clover, sits between them, 50 meters from Anton and 100 meters from Barry. At exactly 12 noon, Clover barks. Assume the speed of sound is 340 m/s.

- Who hears the bark first, Anton or Barry? Explain.
- How long after Clover barks does Anton hear the bark? How long after Clover barks does Barry hear the bark? Show your work.

Assume that Anton and Barry are intelligent observers. (Recall that an *intelligent observer* is someone who can make correct and accurate determinations of where and when something occurs.)

- Suppose that Anton and Barry independently determine the time at which the bark occurred. Is the time determined by Anton *earlier than*, *later than*, or *at the same time as* that determined by Barry? Explain.
- Suppose that Anton were standing 150 meters away from Clover the dog. Would your answers to parts a and b change? Why or why not?
- Based on the ideas developed in question 1 of this homework, are Anton and Barry in the same reference frame? Explain.
- Generalizing these results, what, if anything, can you say about the time that a given event must occur for all people in a given reference frame?

Figure 4.8: Series of exercises that replaced the second section of the original *Events and reference frames* homework

A new third section was added to give students instruction in drawing event diagrams for multiple reference frames, and in drawing event diagrams for reference frames other than those of observers at rest with respect to the ground. The first part of this section is shown in Figure 4.9. To draw a correct and complete reference frame for a frame other than the ground frame, students should rely on their understanding that an observer (or dog) is always at rest in his or her own reference frame; in addition, they must learn how to show relative motion (or lack thereof) in an event diagram.

After students draw the event diagrams, they are asked to describe how event diagrams for

3. *Event diagrams in different reference frames*

Clover the dog is running to the right. She passes Anton at $t = 10$ seconds; she passes Barry at $t = 20$ seconds. Both Barry and Anton carry flashlights, which they flash on and off when Clover runs by.

Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes.

Event 2: Barry's flashlight flashes.

Below is an event diagram in Barry's reference frame. In the spaces provided, draw the event diagrams for Anton's reference frame and Clover's reference frame. Indicate the location and the time of each event of interest, and use arrows to indicate the directions of any motions in that frame.

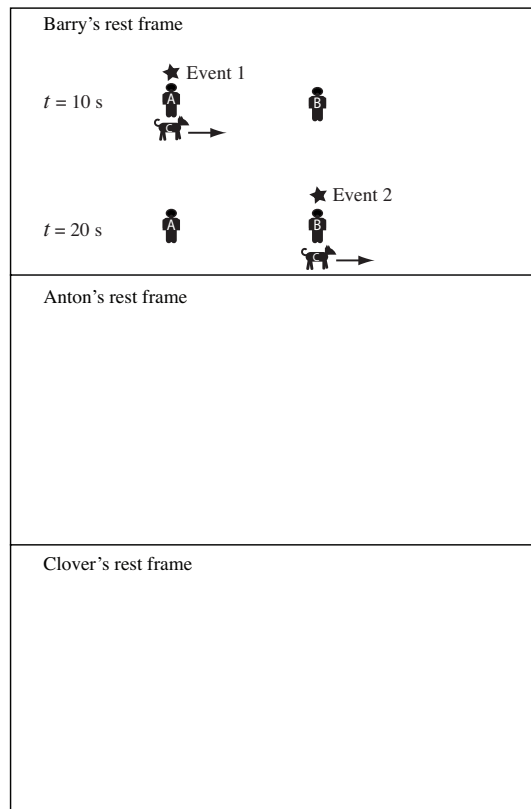


Figure 4.9: *Event diagram* exercise of the new third section of the *Events and reference frames* homework.

observers at rest with respect to each other compare, and how event diagrams for observers with non-zero relative motion with respect to each other compare. The intent is for students to recognize that observers at rest with respect to each other (i.e., in the same reference frame) will draw identical event diagrams for a given set of events; event diagrams for observers in

different reference frames will differ in some ways (e.g., the locations and distances between events) and not in others (e.g., the presence of all of the events).

The final part of section 3 of the revised *Events and reference frames* tutorial homework is shown in Figure 4.10.

- a. How, if at all, do the event diagrams for Anton’s and Barry’s reference frames differ?
- b. How, if at all, do the event diagrams for Anton’s and Clover’s reference frames differ?
- c. Suppose a second dog, Chip, chases Clover, moving with exactly the same velocity. How, if at all, would the event diagrams for Clover’s and Chip’s reference frames differ? Explain.
- d. Generalizing these results, what, if anything, must be true about the event diagrams drawn by two observers in the same reference frame?

Figure 4.10: Final exercises of the revised *Events and reference frames* homework

This version of the homework both introduces some new ideas and reviews some concepts from the *Events and reference frames* tutorial. New material includes instructing students on how to determine when two observers share the same reference frame, and how to draw event diagrams for multiple frames of reference. Ideas from the *Events and reference frames* tutorial that are reviewed and reenforced in the homework include the idea that observers must account for signal propagation time when determining the time of an distant event, and that observers in the same reference frame agree on the time of events.

4.2.5 Assessment of the initial revisions to the Events and reference frames homework

For several quarters the changes made to the *Events and reference frames* homework described above were the only significant changes to the special relativity tutorial curriculum meant to address student difficulty with reference frames. We ran a series of tasks on post-tests to assess the effectiveness of these changes. These tasks are (a) the *Relativistic Plane* multiple-choice post-test; (b) the *Bug and Shuttle* free-response post-test; (c) the *Light Boxes* multiple-choice post-test; and (d) the *Moving Volcanoes* multiple-choice post-test.

4.2.5-a *Relativistic Plane post-test*

The *Relativistic Plane* context was used two times over the period when the only change to the special relativity tutorial curriculum was a revision of the *Events and reference frames* homework. The *Relativistic Plane* question was run in Winter 2011 and Spring 2011. Repeated use of this question allowed us to make a direct comparison of student performance before and after the modifications to the *Events and reference frames* homework. Data from Winter 2011 and Spring 2011 are pooled, as student performance was not significantly different by most measures.⁵ Students seeing the *Relativistic Plane* question in Autumn 2009 will be referred to as the “pre-modification group.” Winter and Spring 2011 students will be called the “post-modification group.”

The context and questions are reproduced in Figure 4.11.

Because an identical set of questions was used, we can perform the same analysis and do a direct comparison of student performance. Recall that the correct answers for questions 1, 2, and 3 are C, E, and A, respectively.⁶ Reminders of possible meanings of student responses are noted in the appropriate table.

For question 1, 15% of post-modification students answered correctly (choice C). This result is the same as that from the pre-modification group. This question does not test understanding of reference frames directly. However, the distractors for this question were chosen such that common misconceptions are represented: answer A is consistent with a belief in absolute simultaneity, while option B is consistent with the signal-reception error. The percentage of post-modification students choosing A increased to 25% (up from 10%) while the percentage of students choosing B decreased to 60%.

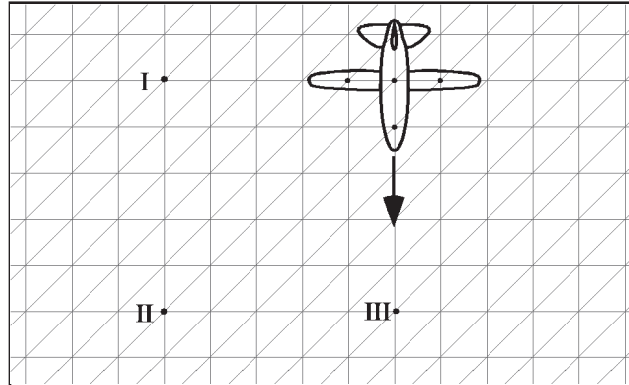
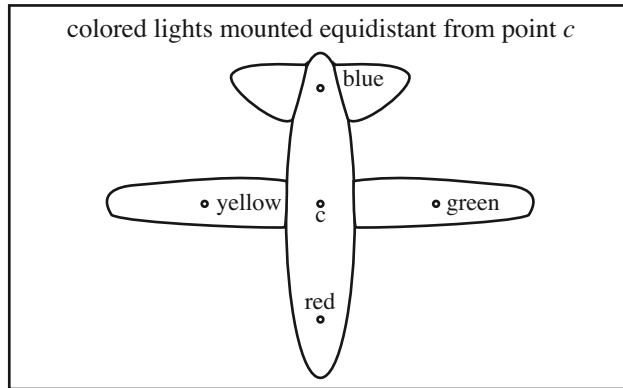
Question 2 is meant as a direct test of student understanding of reference frame. Students

⁵For multiple-choice questions 1 and 3, a chi-square test resulted in p-values of 0.57 and 0.53, respectively, suggesting no significant difference between the two populations. In addition, for both populations, 80% of students chose one of the five most popular answer sequences; a chi-square test for the percentage of students choosing each answer sequence resulted in a p-value of 0.24, again suggesting no significant differences. Only results for question 2 were statistically significantly different for the two classes ($p = 0.028$). Given the similarity in the other results, we felt comfortable pooling the results for all analyses.

⁶For in-depth reasoning and descriptions of these questions, see section 3.3.3-a.

Four powerful strobe lights of different colors are mounted equidistant from point c on a relativistic airplane. When the plane was at rest in the factory, the lights were programmed for an emergency distress signal consisting of simultaneous flashes of all four lights at regular intervals.

The plane now flies due south at a relativistic speed and the pilot (at rest in the plane) begins testing the emergency distress signal. Three ground-based observers are shown. In what follows, ignore any color changes due to the Doppler effect.



1. Which of the following statements concerning the timing of the first flash of the red and blue lights in the reference frame of observer III is true?

- A. The red and blue lights flash simultaneously in observer III's reference frame.
- B. The red light flashes before the blue light in observer III's reference frame.
- C. The blue light flashes before the red light in observer III's reference frame.
- D. Relativity does not allow us to determine the order of flashes in observer III's reference frame.
- E. The order of flashes can be determined, but more information is needed.

2. In the reference frame(s) of which observer(s), if any, does the flash of the red light occur at the same time as the flash of the blue light?

- A. Observers I, II, and III.
- B. Observer I only.
- C. Observer II only.
- D. Observer III only.
- E. None of the observers.

3. In the reference frame(s) of which observer(s), if any, does the flash of the yellow light occur at the same time as the flash of the green light?

- A. Observers I, II, and III.
- B. Observer I only.
- C. Observer II only.
- D. Observer III only.
- E. None of the observers.

Figure 4.11: 'Relativistic Plane' context

Table 4.8: A comparison of Autumn 2009 and Winter 2011 post-test results on question 1 of the *Relativistic Plane* context. Bolded post-modification numbers indicate statistically significant differences. The correct answer is highlighted.

Order of events in ref. frame of obs. III	Post-mod ($N = 290$) ^a	Pre-mod($N = 190$) ^b
A (Same time) ^c	25%	10%
B (Red flash first)	60%	75%
C (Blue flash first)	15%	15%
D (Cannot be determined)	0%	0%
E (Not enough information)	< 1%	< 1%

^a Section 123A111112. ^b Section 123A094.

^c Recall that answer A is most consistent with a belief in absolute simultaneity; answer B is most consistent with the signal-reception error.

Table 4.9: A comparison of Autumn 2009 and Winter 2011 post-test results on question 2 of the *Relativistic Plane* context. The correct answer is highlighted.

Ref. frames with sim. yellow & green flashes	Post-mod ($N = 290$) ^a	Pre-mod($N = 190$) ^b
A (Observers I,II, & III)^c	20%	10%
B (Observer I only)	45%	65%
C (Observer II only)	1%	1%
D (Observer III only)	5%	1
E (None of the observers)	30%	25%

^a Section 123A111112. ^b Section 123A094.

^c Recall that answer A is consistent with a belief in absolute simultaneity, as well as a correct understanding of reference frames; choice B is consistent with the signal-reception error.

choosing options A or E might have an understanding that all three observers are in the same reference frame and agree on the timing of events; option A is more consistent with a belief in absolute simultaneity. Choice B is consistent with the signal-reception error. As on question 1, the percentage of students answering correctly did not change significantly, while the proportion of students indicating a belief in absolute simultaneity or making the signal-reception error increased and decreased, respectively.

Like question 2, question 3 is a more direct test of student understanding of reference frame. Student performance on question 3 improved significantly, with about a third of

Table 4.10: A comparison of Autumn 2009 and Winter 2011 post-test results on question 3 of the *Relativistic Plane* context. Bolded post-modification numbers indicate statistically significant differences. The correct answer is highlighted.

Ref. frames with sim. red & blue flashes	Post-mod ($N = 290$) ^a	Pre-mod($N = 190$) ^b
A (Observers I,II, & III) ^c	35%	20%
B (Observer I only)	5%	5%
C (Observer II only)	0%	0%
D (Observer III only)	60%	75%
E (None of the observers)	< 5%	< 5%

^a Section 123A111112.

^b Section 123A094. ^c Recall that answer A is correct, but it is also consistent with a belief in absolute simultaneity. Answer D is consistent with the signal-reception error.

students answering correctly. However, given the results from questions 1 and 2, this improvement is likely due to an increase in the number of students with a belief in absolute simultaneity. This claim is strengthened by the analysis of the sequence of student responses, below. As in the previous two questions, there was a significant decrease in the number of students making the signal-reception error.

As described in Chapter 3, sequences of individual student responses are illustrative. As in Autumn 2009, the five most popular sequences of responses were: CEA, BEA, BED, AAA, and BBD. Recall that answer sequence CEA is correct, and suggests a good understanding of reference frames and the relativity of simultaneity. Sequence BEA is almost correct. These students seem to understand that observers at rest with respect to each other are in the same reference frame, and agree on the timing of events, but may have trouble determining the sequence of events in some reference frames. Sequence BBD is consistent with the signal-reception error; BED is mostly consistent with the signal-reception error, or may represent another, unknown error (or a random choice). Answer sequence AAA is consistent with a belief in absolute simultaneity.

As suggested by the results of the individual questions, overall student understanding of the relativity of simultaneity was not significantly improved. We do observe a shift in

Table 4.11: Autumn 2009 post-test results: common answer sequences on questions 1, 2, and 3. The correct answer is highlighted.

Answer sequence	Post-mod ($N = 290$) ^a	Pre-mod($N = 190$) ^b
CEA (correct)	10%	5%
BEA (mostly correct, incorrect event sequence)	5%	5%
BED (possible signal-reception)	5%	5%
AAA (absolute simultaneity)	20%	10%
BBD (signal-reception error)	40%	60%

^a Section 123A111112 ^b Section 123A094.

(incorrect) student reasoning, with the percentage of students answering in a way consistent with a belief in absolute simultaneity increasing, and the number of students answering in a way consistent with the signal-reception error decreasing.

Although the changes to the *Events and reference frames* tutorial homework were made with the intent of improving student understanding of the formalism of a reference frame, the main focus was on addressing the signal-reception error. This suggests that the modifications to the homework had a positive effect on post-test performance. Despite this improvement, nearly half of students made the signal-reception error even after modifications.

4.2.5-b Bug and Shuttle post-test

In Spring 2010, we were able to run a post-test question on the third midterm exam in Physics 123A. Unlike the majority of research performed during the course of this investigation, the question was free-response, and tested the material from *Events and reference frames* but *not Simultaneity*. The post-test question is shown below.

Amy is watching a distant launch of the space shuttle Endeavor through a powerful telescope. Just as Amy sees Endeavor begin to lift off from the launch pad, she also sees a small bug land on the eyepiece of the telescope.

In Amy's reference frame, does the bug land on the telescope *before*, *after*, or *at exactly the same time as* the space shuttle Endeavor begins to lift off? Explain.

To answer correctly, we recognize that the signals from two events (“the space shuttle Endeavor begins to launch” and “the bug lands on the telescope”) reach Amy at the same instant. The event corresponding to the launch of the Endeavor is much farther away from Amy than the event corresponding to the bug landing on the telescope, and because the signal propagation speed is the same for both events, the launch must have started first if the signals reach Amy at the same instant. Therefore, the bug lands on the telescope *after* the space shuttle Endeavor begins lift off in Amy’s reference frame.

Although this question requires understanding of what is meant by reference frame, and a recognition of how event timing can be determined using reception of signals and relative distances from the events, the reasoning required is more like the reasoning required for the *Noisy Bird* and *Clocks* question described in section 4.2.3-d. As in the *Noisy Bird* and *Clocks* question, students are told that an observer receives the signals from two events simultaneously, but that the observer is not equidistant from the two events. The wording of the question, however, is more like that of the basic *Noisy Bird* question, as students are asked to determine whether one of the events occurred before, after, or at the same time as the other event.

Post-test results from Spring 2010 are shown in Table 4.12. Only 20% of students made the signal-reception error, explicitly defining Amy’s reference frame as what Amy sees. Another 10% of students answered “before.” A majority of those students seemed to interpret the question differently than what was intended. Explanations suggested that these students believed that the events were simultaneous, and that they were being asked to determine which event Amy saw first. The remaining 70% of students answered correctly, with a majority of those using correct and complete or mostly complete reasoning. A large proportion of students answering correctly cited Amy as an “intelligent observer” that would be able to correctly calculate the timing of the events.

Table 4.12: Student performance on free-response post-test question for *Events and reference frames*. The correct answer is highlighted.

	$N = 172^a$
After	70%
Same time (consistent with signal-reception error)	20%
Before	10%

^a Section 123A102

4.2.5-c *Light Boxes post-test*

In Autumn 2010, we ran a series of questions on the final course exam of Physics 123 A. The context of the *Light Boxes* questions is shown in Figure 4.12. We asked five questions total in the *Light Boxes* context; two of them are discussed here as relevant to research into student understanding of reference frames.

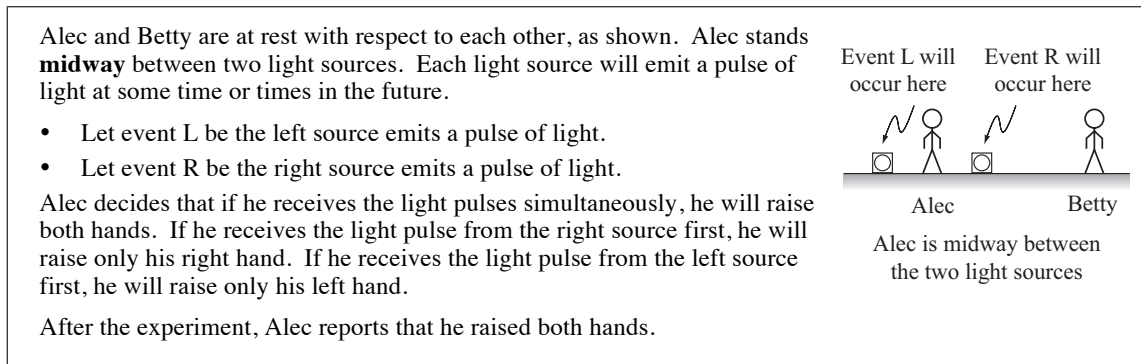


Figure 4.12: Context for the Autumn 2010 post-test on reference frames

In the *Light Boxes* context, Alec and Betty are at rest with respect to each other, and Alec is exactly halfway between two light sources (L and R) that are also at rest with respect to him. Betty stands closer to light source R. The light sources are set to emit pulses of light, but it is not known when they will do so. Alec decides he will raise both hands if he receives light from the two sources simultaneously; otherwise, he will raise only one hand, corresponding to the light source from which he receives the signal first. After the flashes,

Table 4.13: Student performance on first multiple-choice post-test question for *Events and reference frames* in Autumn 2010. The correct answer is highlighted.

Order of events in Betty's frame	$N = 178^a$
Event L at same instant as event R	65%
Event L after event R (consistent with signal-reception error)	35%
Event L before event R	< 5%

^a Section 123A104

Alec reports that he raises both hands.

In the first question, students are asked to determine the timing of events L and R (the events corresponding to the emission of the light pulses from sources L and R, respectively) in Betty's frame.

To answer, we note that Alec raises both hands, indicating that he received the light from both sources simultaneously. Alec is equidistant from the two sources, and the speed of signal propagation is the same for both light pulses, so the sources must have emitted the pulses of light at the same instant. Alec and Betty are at rest with respect to each other, and as such agree on the time of all events; therefore, in Betty's frame, event L occurs at the same instant as event R.

We expect students making the signal-reception error to answer that event L occurs after event R. These students are likely to determine that the events “actually” happen simultaneously, using the fact that the centrally-located observer observes the events simultaneously, and then determine that Betty would see the light from source R before that of source L. The signal-reception error would then lead these students to conclude that event L occurs after event R in Betty's frame.

Almost two-thirds of students answered that events L and R occurred simultaneously in Betty's frame. Although this is the correct answer, it is not possible to know how students reasoned using results from this question alone; this answer choice is also consistent with a belief in absolute simultaneity. Student performance on this question is tabulated in Table 4.13.

For another question in the *Light Boxes* context, students are told that Alec, Betty, and the light sources repeat the experiment on a spaceship that travels at a speed close to the speed of light with respect to a nearby space station. An observer, Carl, stands at rest on the space station. Again, Alec reports that he raises both hands. Students are asked about the order of events L and R in Carl's reference frame.

The revised context for this question is shown in Figure 4.13.

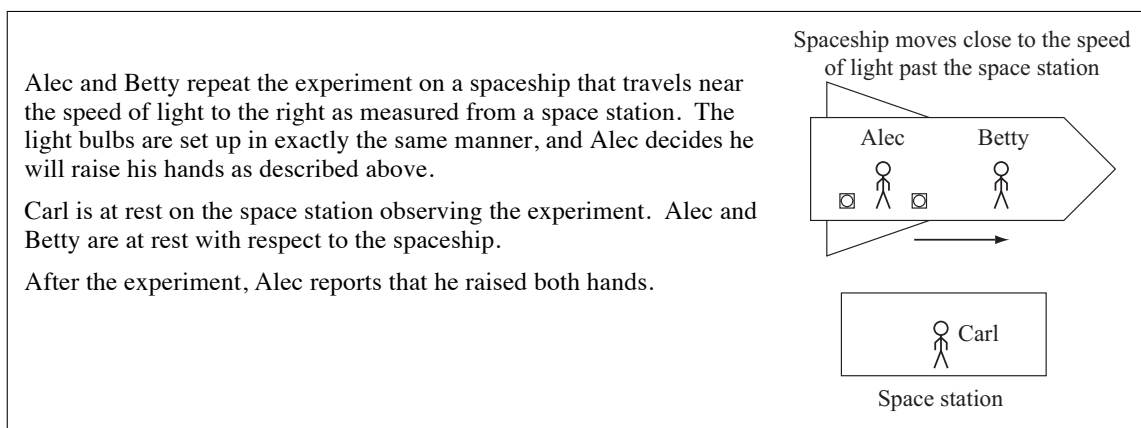


Figure 4.13: Context for the Autumn 2010 post-test on reference frames

To answer, we recognize that Alec receives the light from the two events simultaneously in all reference frames. In Carl's reference frame, Alec moves toward the center of the wavefront of the light from event R, and away from the center of the wavefront of the light from event L. This means that the wavefront from event L has a larger radius at the instant that Alec receives the two wavefronts simultaneously. Because the speed of light is the same in all reference frames, regardless of the motion of the source, this means that event L occurs before event R in Carl's reference frame.

This question tests student understanding of the relativity of simultaneity, and student ability to determine the order of events in multiple frames of reference. Students that answer that events L and R occur at the same instant in Carl's reference frame are likely to have a belief in absolute simultaneity; assuming students' model of reference frame is consistent across questions, we can use results from this question to determine the percentage of students

Table 4.14: Student performance on fifth multiple-choice post-test question for *Events and reference frames* in Autumn 2010. The correct answer is highlighted.

Order of events in Carl's frame	$N = 178^a$
Event L at same instant as event R	25%
Event L after event R	35%
Event L before event R	25%
At least one of the events doesn't occur	< 5%
Not simultaneous, but not enough information to determine	15%

^a Section 123A104

who answered the first question, above, using incorrect reasoning.

Table 4.14 shows the results from *Light Boxes* question regarding the order of events in Carl's reference frame. Almost a quarter of students answered that the events would be simultaneous, indicating a belief in absolute simultaneity. Approximately a quarter of students answered correctly. Note that there is no particular time associated with the figure accompanying the question; Carl's location at the instant the events occur simultaneously in the reference frame of the spaceship is unknown. Therefore, no answer choice is particularly representative of the signal-reception error.

As with the *Relativistic Plane* post-test, we can determine more precisely how students were reasoning by looking at patterns of responses. In particular, students who answer that the events occur simultaneously in the reference frames of Betty and Carl are more likely to believe in absolute simultaneity. Approximately a quarter of students answered both questions correctly. Less than 10% of students answered that the events occurred at the same instant in both frames; however, this suggests that only 55% of students answered the first question correctly with correct reasoning.

4.2.5-d Moving Volcanoes post-test

The *Moving Volcanoes* question, a variation of the *Seismologist* question used by Rachel Scherr in the research described in Chapter 3, was used in Spring 2011. The context and the

question relevant to this research are shown in Figure 4.14.

Holly is at rest exactly midway between Mt. Rainier and Mt. Hood. Adelaide is at rest near the foot of Mt. Rainier.

Jasper is in the center of a spacecraft moving from Mt. Rainier toward Mt. Hood at speed $v = 0.8c$ relative to the ground. Floyd is in the center of a spacecraft that is also moving from Rainier toward Hood at speed $v = 0.8c$ relative to the ground.

In Floyd's frame, he receives light from *both eruptions* at the instant shown. At this instant, he is located exactly halfway between the mountains. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). Treat all observers as intelligent observers.

In Jasper's frame, the order of the two events (Mt. Rainier erupts and Mt. Hood erupts)

- Is the same as in Mt. Rainier's frame.
- Is the same as in Holly's frame.
- Is the same as in Floyd's frame.
- More than one of the above choices is correct.
- None of the above choices is correct.

Figure 4.14: Context and question from *Events and reference frames* post-test in Spring 2011. Answer C is correct.

For this question, we are told that observers Holly and Adelaide are at rest with respect to the ground; observers Jasper and Floyd are in spacecrafts that move with relativistic speed with respect to the ground. Two volcanoes, Mt. Rainier and Mt. Hood, each erupt. Floyd is exactly halfway between the mountains and exactly over Holly when he receives the light from the two eruptions simultaneously. Jasper is located over Mt. Rainier at the same instant. The question asks students to determine whether the timing of the eruptions in Jasper's frame is the same as the timing of the events in another reference frame.

Unlike many of the questions used in this research, the figure accompanying the *Moving Volcanoes* question does not portray an instant in the ground frame; rather, it shows an instant in the reference frame of an observer in a spacecraft that moves with relativistic speed with respect to the ground. In addition, the figure does not show the instant that the

Table 4.15: Student performance on multiple choice post-test question for *Events and reference frames* in Spring 2011. The correct answer is highlighted.

Order of events in Jasper's frame	($N = 173$) ^a
A (Same as Mt. Rainier's)	15%
B (Same as Holly's)	5%
C (Same as Floyd's)	60%
D (More than one of above)	15%
E (None of above)	5%

^a Section 123C112.

spatially-separated events occur simultaneously in some reference frame, but the instant at which an observer receives the light from two events. These differences very likely make the context more difficult for students.

To answer, we recognize that Jasper will agree on the timing of events with any other observer that is at rest with respect to him. Only Floyd is at rest with respect to Jasper, so the correct answer must be C. The distractors were chosen to represent common student misconceptions, but may not align perfectly with particular errors or beliefs, given the differences in this context and question from others.

Choice A was intended to be the most consistent with the signal-reception error, as at the instant shown Jasper and Mt. Rainier share the same position. Note that although Jasper does in fact receive the light from the eruption of Mt. Rainier before that from the eruption of Mt. Hood, he would not be at the location of Mt. Rainier at the instant it erupts. Thus, students making the signal-reception error might not believe that Mt. Rainier and Jasper share the same reference frame. For careful (but still incorrect) students making the signal-reception error, therefore, answer E is more correct.

Choice D is consistent with a belief in absolute simultaneity.

Student performance is shown in Table 4.15

4.2.5-e Summary of results

As stated earlier, the changes to the *Events and reference frames* homework were largely intended to address the signal-reception error. The percentage of students making the signal-reception error after modification of the homework generally decreased, often significantly. However, challenging questions, such as the *Relativistic Plane* context, suggest that a large percentage of students still use signal-reception reasoning when asked to determine the order of events in a given observer's reference frame. In addition, the number of students who answered in a way consistent with a belief in absolute simultaneity *increased* in many quarters. This latter results is not surprising, given that the *Events and reference frames* tutorial and homework are intended to give students necessary background in Galilean relativity; with non-relativistic relative speeds, simultaneity is indeed absolute.

To try to decrease further the percentage of students making the signal-reception error, as well as to try to improve student understanding of reference frames in general, we began making modifications to the *Events and reference frames* tutorial.

4.2.6 Modifications to the tutorial *Events and reference frames*

The full version of the unmodified *Events and reference frames* tutorial can be found in Appendix A. A description of the full unmodified *Events and reference frames* tutorial can be found in Chapter 3.

Recall that the original *Events and reference frames* tutorial consisted of three sections: I. Reference frames; II. Events; and III. Synchronized clocks. The goal of the tutorial modification was to introduce reference frames in a way that would address the signal-reception error, as well as help students apply the formalism of a reference frame when considering the order of events in multiple frames of reference. We wanted to motivate a reference frame more strongly as a tool to be used to determine the time and location of any event. For this reason, we reorganized the sections of the tutorial: I. Synchronized Clocks; II. Events; and III. Reference Frames. This allowed to specify what is meant by synchronized clocks (as well

as a given clock time), and to define the term event before introducing reference frames.

The Synchronized Clocks section was unchanged from the original version, except for its location in the tutorial. The Events section was modified slightly, because of its new location; and the part of the Events section that introduced event diagrams was moved to the Reference Frames section.

In addition to the reordering of the material, two significant changes were made to the section Reference Frames: the removal of the “fugitive from justice” exercise, and new definitions for *reference frame* and *intelligent observer*. The original definitions for reference frame and intelligent observer are shown below:

An observer’s *reference frame* is an arrangement of assistants and equipment with which the observer may record the position and time of anything that occurs.

An *intelligent observer* is equipped with measuring devices (such as meter sticks, clocks, and assistants and is able to use them to make correct and accurate determinations of where and when something occurs. All observers in special relativity are intelligent observers.

Although these definitions are consistent with the definition presented in §4.1, there is no mention of relative motion; thus there is no way to determine correctly when two observers share the same reference frame, or will agree on the time and location of events. In addition, based on interactions during class, we found that some students were failing to see the two definitions as connected. With this in mind, we wrote the following statement for the *Events and reference frames* tutorial to replace the original definitions:

In special relativity, Alan and his assistants are considered intelligent observers in the same reference frame. A *reference frame* can be thought of as an imaginary grid of meter sticks and synchronized, recording clocks. The time and location of an event are recorded by the clock nearest to that event. An *intelligent observer* is a person that measures the time and location of an event by collecting and reporting data from the recording clocks. An intelligent observer uses the grid of meter sticks and clocks that is at rest relative to that observer.

These definitions not only allow us to determine when two observers share the same reference frame, but they also specify how a reference frame is used to measure the spacetime coordinate of a given event.

To address the signal-reception error, an exercise featuring a student dialogue, shown in Figure 4.15 was included right after the definitions of reference frame and intelligent observer. The intent was for students to recognize the inconsistency between the definitions and the student statements.

Student 1: The beeper and horn go off at the same time in Alan's reference frame since he hears them at the same time. Each of the student-assistants to the left of the horn would agree with him. The student-assistants to the right of the beeper would say the beeper goes off first in their reference frames, since they would hear the beeper first.

Student 2: That's right. Each person's reference frame is different. Only the observer at the horn knows when it really honked and only the observer at the beeper knows exactly when it beeped.

Do you agree with students 1 and 2? Why or why not?

Figure 4.15: Student dialogue in the tutorial *Events and reference frames* intended to address the signal-reception error.

The revisions of the definitions of reference frame and intelligent observer, and the inclusion of the student dialogue to address the signal-reception error were the most significant changes to the *Events and reference frames* tutorial. Although modifications were made to

the *Events and reference frames* tutorial homework as well, the changes focused on improving student understanding of causality and events in special relativity, rather than reference frames specifically. These changes are discussed in Chapter 6 of this dissertation.

4.2.7 Assessment of initial modifications to the *Events and reference frames* tutorial

The version of the *Events and reference frames* tutorial described in the section above (4.2.6) was used for two quarters. Three post-test questions assessing the effectiveness of the modifications are described in this section.

4.2.7-a *Marathoners in Space* post-test

The *Marathoners in Space* context is shown in Figure 4.16.

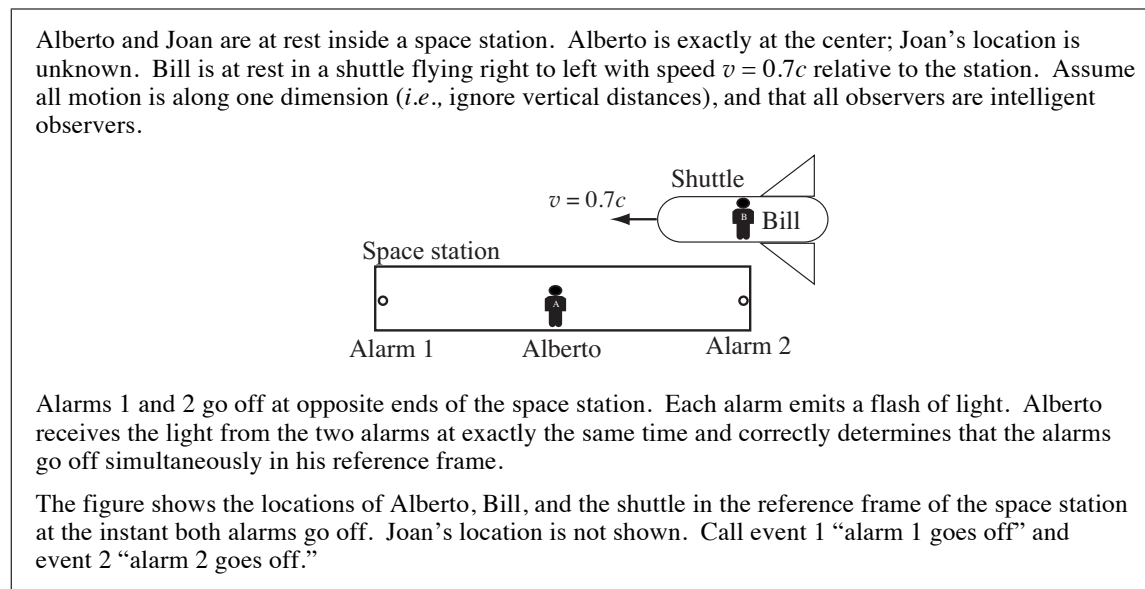


Figure 4.16: *Marathoners in Space* context used on post-test for *Events and reference frames*.

The *Marathoners in Space* context describes observers Alberto and Joan (named after well-known marathon runners Alberto Salazar and Joan Benoit Samuelson) as being at rest inside a space station. Alberto's position is specified as at the center of the space station, but

Joan's location is stated to be unknown. Bill [Rodgers] is in a space shuttle that moves at relativistic speed from right to left relative to the space station. Alarms 1 and 2, located at either end of the space station, go off simultaneously in Alberto's reference frame, emitting flashes of light.

Two multiple choice questions were written to probe student understanding of reference frames. The first is regarding the order of events 1 and 2 (the events associated with the alarms 1 and 2 emitting flashes of light) in Joan's reference frame. This question was intended as a direct test of student understand that relative velocity, not position, is what specifies an observer's reference frame, and that all observers at rest with respect to each other agree on the timing of all events. Similar to other related questions, because Joan and Alberto are at rest with respect to each other, they share the same reference frame, and thus agree that events 1 and 2 happened simultaneously.

The second question asks about the order of the events in Bill's reference frame. As with questions described in section 4.2.5, this does not test student understanding of reference frames directly, but allows us to infer student reasoning under the assumption that students' understanding of the term "reference frame" is consistent across questions. Therefore, students who answer that the events are simultaneous in both Joan's and Bill's frames likely believe in absolute simultaneity, and likely did not use correct reasoning in coming to the correct answer for Joan's frame.

The wording used in the two multiple-choice questions about Joan's and Bill's reference frames is shown in Figure 4.17.

Student performance on the question about the order of events in Joan's reference frame is shown in Table 4.16. Over 80% of students answered correctly that events 1 and 2 would occur at the same instant in Joan's reference frame. Only 15% of students answered that more information was needed to answer. This answer is consistent with signal-reception reasoning, as students making the signal-reception error would believe that Joan's exact location is needed to determine the order of events in her reference frame.

On the question about Bill's reference frame, just under 90% of students answered that

Would Joan (at rest with respect to the space station) measure that:

- A. Event 1 occurs *before* event 2.
- B. Event 1 occurs *after* event 2.
- C. Event 1 occurs *at the same time* that event 2 occurs.
- D. More information is needed to answer.

Would Bill (moving to the left at speed $v = 0.7c$ relative to the space station) measure that:

- A. Event 1 occurs *before* event 2.
- B. Event 1 occurs *after* event 2.
- C. Event 1 occurs *at the same time* that event 2 occurs.
- D. More information is needed to answer.

Figure 4.17: Multiple-choice questions used in *Marathoners in Space* context to probe student understanding of reference frames

events 1 and 2 would not be simultaneous; answers were split almost equally between the two non-simultaneous options (A and B). Almost all of the remaining students answered that the events were simultaneous. All but one student that answered that the events would be simultaneous in Bill's reference frame also answered that the events would be simultaneous in Joan's reference frame, suggesting a belief in absolute simultaneity. It seems reasonable to conclude that the percentage of students answering the question about the order of events in Joan's reference frame correctly with correct reasoning is closer to 70%.

Table 4.16: Student performance on multiple choice post-test question for *Events and reference frames* in Autumn 2012: order of events in Joan's reference frame. The correct answer is highlighted.

Order of events in Joan's reference frame	($N = 219$) ^a
A (Event 1 before event 2)	< 2%
B (Event 1 after event 2)	< 2%
C (Events 1 and 2 simultaneous)	80%
D (More information needed to answer)	16%

^aSection 123A124.

Performance on this post-test task (particularly on the question about the order of events in Joan's reference frame) was significantly better than performance on analogous questions from post-test tasks run before the modifications to the *Events and reference frames* tutorial. This suggests that the changes to the tutorials were effective in changing student thinking about the meaning of the term reference frame. Approximately 70% of students answered the two questions (regarding the order of events in Joan's and Bill's reference frames) in a way that is consistent with the idea that it is relative motion, rather than a particular observer's position and the order in which that observer receives the signals from events, that determines the order of events in a given reference frame.

4.2.7-b Conclusions

Performance on simple questions regarding the order of events for an observer of unknown location, at rest with respect to an observer that correctly concludes that two spatially-separated events are simultaneous seemed to be improved by modifications to the *Events and reference frames* tutorial. In particular, reformulation of the definition of reference frame seems to have been effective in addressing student tendency to make the signal-reception error when trying to determine the order of events in an observer's reference frame.

However, we see a small but statistically significant increase in the proportion of students answering in a way consistent with a belief in absolute simultaneity. Although a belief in absolute simultaneity is not necessarily inconsistent with understanding of the formalism of a reference frame in Galilean relativity, it does suggest that students do not recognize what might be different in different reference frames. Moreover, students with a belief in absolute simultaneity may not recognize the importance of relative motion in making measurements of the time and location of events.

4.2.8 *Additional changes to the Events and reference frames tutorial and homework*

We made one more round of modifications to the *Events and reference frames* tutorial and homework to attempt to address student difficulties with reference frames, informed by the post-test results described above.

4.2.8-a *Changes to the Events and reference frames tutorial*

As described in section 4.2.6, on the first round of changes to the *Events and reference frames* tutorial, the most significant change was to the definitions of *reference frame* and *intelligent observer*. Changes to the definitions seemed to have the result of improved student performance on certain types of post-test questions, but we were concerned that improvements were the result of memorization of the definitions without a significant increase in understanding. Although the exercises leading up to the modified definitions in the *Events and reference frames* tutorial were intended to build toward the idea of the formalism of a reference frame, we were also concerned that students were not seeing the connection between the exercises and the statements in the definition. Finally, although the new definitions mention relative motion, we believed that students might not understand the connect between motion and reference frame.

To motivate student understanding of the paragraph containing the definitions of reference frame and intelligent observer, we replaced the student dialogue with questions that ask students to use the information in the paragraph to answer them. First, we ask students to determine the relative velocity of observers in the same reference frame. Because students are told that an intelligent observer uses the grid of meter sticks and clocks at rest relative to that observer, they can conclude that two intelligent observers in the same reference frame (i.e., using the same grid of meter sticks and clocks) must be at rest with respect to the same grid, and therefore at rest with respect to each other. Second, we ask students whether intelligent observers in the same reference frame always measure the same time and location

for any given event. As for the first question, students can conclude that observers in the same reference frame are using the same grid of meter sticks and clocks to measure the time and location of any given event, so will determine the same spacetime coordinate for that event.

We believed that these questions would help students not only to understand the definition of reference frame, but also help them understand the method by which an intelligent observer measures the spacetime coordinate of a given event. The definitions and new followup questions are shown in Figure 4.18.

In special relativity, a *reference frame* can be thought of as an imaginary grid of meter sticks and synchronized clocks. An *intelligent observer* is a person who measures the time and location of an event using the grid of meter sticks and clocks that is at rest relative to that observer. In the exercises above, Alan and his assistants can be thought of as intelligent observers in the same reference frame.

Answer the following questions based on the descriptions of intelligent observer and reference frame in the paragraph above.

- What is the relative velocity of intelligent observers in the same reference frame? Explain.
- Would intelligent observers in the same reference frame always measure the same time and location for any given event? Explain.

Figure 4.18: Definitions of *reference frame* and *intelligent observer* with modified followup exercises in the *Events and reference frames* tutorial.

4.2.8-b Changes to the *Events and reference frames* homework

On the second round of changes to the *Events and reference frames* homework, the first exercise was replaced to make the homework more consistent with the new definitions of reference frame and intelligent observer in the *Events and reference frames* tutorial. Rather than having students determine the time of events based on signal propagation speed and

time of signal reception, the new exercise focuses on the formalism of the grid of meter sticks and clocks to make measurements. The new homework exercise is shown in Figure 4.19.

Anton is seated on a train that moves with constant velocity relative to the ground. Barry stands at rest on the ground. Both are intelligent observers. Imagine that there is a grid of meter sticks and clocks at rest with respect to the train, and another grid of meter sticks and clocks at rest with respect to the ground. A small beeper is somewhere on the train, and is about to emit a beep. Define event 1 as “the beeper beeps.”

The time and location of event 1 are recorded by the closest recording clock on the train to be $(t_1^{(\text{train})}, x_1^{(\text{train})})$. The time and location of event 1 are recorded by the closest recording clock on the ground to be $(t_1^{(\text{ground})}, x_1^{(\text{ground})})$.

- Would Anton measure the time and location of event 1 as $(t_1^{(\text{train})}, x_1^{(\text{train})})$, $(t_1^{(\text{ground})}, x_1^{(\text{ground})})$, or as some other time and location? Explain.
- Would Barry measure the time and location of event 1 as $(t_1^{(\text{train})}, x_1^{(\text{train})})$, $(t_1^{(\text{ground})}, x_1^{(\text{ground})})$, or as some other time and location? Explain.
- Recall that in the tutorial *Events and reference frames*, an intelligent observer is defined as a person who measures the time and location of events by using a grid of meter sticks and synchronized clocks that is at rest with respect to him or her.

Check that your answers to parts a and b, above, are consistent with this definition of intelligent observer.

Figure 4.19: New exercise for the *Events and reference frames* tutorial homework relying on modified definition of reference frame

In addition, minor changes were made to the exercises in the *Events and reference frames* homework requiring students to draw event diagrams for multiple reference frames. A new notation for times was used, consistent with the notation used in the first exercise described above. Although the motion described in the tutorial homework is non-relativistic, the new notation—which specifies the frame in which the time is being measured—does not assume that motion is non-relativistic, and suggests that measurements of time *are* frame-dependent. Also, the exercise was designed to show students that some measurements (e.g., the spatial distance between events) might be different in different reference frames. Though this idea is not extended to time measurements in the exercise, we wanted students to work through an example in which measurements were frame-dependent. The modified event diagram exercise from the *Events and reference frames* homework is shown in Figure 4.20.

Now suppose that Anton and Barry stand at opposite ends of a train that moves with a constant speed relative to the ground. The train is 50 meters long. Clover the dog stands near the train track, at rest relative to the ground. As measured in Anton's reference frame, Clover and Anton pass each other at $t = t_1^{(\text{Anton})}$ and Clover and Barry pass each other at $t = t_2^{(\text{Anton})}$.

Both Anton and Barry carry flashlights, which they each flash when passing Clover. Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes.

Event 2: Barry's flashlight flashes.

Below is an event diagram for Anton's reference frame. In the spaces provided, draw the event diagrams for Barry's reference frame and for Clover's reference frame. Indicate the location and time of each event of interest. Use arrows to indicate the directions of any motions in that frame. Recall that an observer (or dog) has zero velocity in his or her own frame.

Anton's reference frame

$t = t_1^{(\text{Anton})}$

$t = t_2^{(\text{Anton})}$

Barry's reference frame

$t = t_1^{(\text{Barry})}$

$t = t_2^{(\text{Barry})}$

Clover's reference frame

$t = t_1^{(\text{Clover})}$

$t = t_2^{(\text{Clover})}$

Figure 4.20: New exercise for the *Events and reference frames* tutorial homework relying on modified definition of reference frame

4.2.9 Assessment of additional changes to the *Events and reference frames* tutorial and homework

As for earlier revisions, we were able to assess the effectiveness of the special relativity tutorial curriculum by running multiple-choice questions on the final exams of Physics 123 courses. All of the questions used are based on very physically similar contexts, with the

differences between the questions being largely aesthetic. Because of the similarity between questions and results, the results from similar (but non-identical) questions can be combined for analysis. Two sets of results are described below: results from the Mountain Firecracker context, which is similar to the *Seismologist* context written by Rachel Scherr and described in Chapter 3; and results from the *Marathoners in Space* context, described above in section 4.2.7-a, have been combined with results from similar contexts. All the exam question contexts used can be found in Appendix B.

4.2.9-a Mountain Firecrackers post-test results

The *Mountain Firecrackers* context is almost identical to the *Seismologist* context written by Rachel Scherr. Firecrackers 1 and 2 sit on top of mountains 1 and 2, respectively. An observer Amy stands at rest exactly halfway between the two mountains. She receives the light from the explosions of the firecrackers simultaneously and correctly determines that events 1 and 2 (the events associated with the explosions of firecrackers 1 and 2) occurred simultaneously in her frame. Another observer, Bob, stands at rest on the ground in an unknown location. A third observer is at rest in a shuttle that flies with relativistic speed from left to right relative to the ground, and is at the location of mountain 1 at the instant the firecrackers explode in Amy's reference frame.

As in the *Seismologist* context, and the *Marathoners in Space* context, students are asked to determine the order of events 1 and 2 in the reference frames of the observers in the shuttle and on the ground. The *Mountain Firecrackers* context and the relevant multiple-choice questions are shown in Figure 4.21.

Performance on the question about the order of events in Bob's frame (at rest on the ground) is shown in Table 4.17. Almost 75% of students answered correctly that the events would be simultaneous in Bob's frame, while 20% of students chose answer D, consistent with the signal-reception error.

For the question regarding the order of events in the shuttle observer's reference frame, 15% of students answered that the events would be simultaneous. This suggests that 15%

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob's location is not known. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances), and that all observers are intelligent observers.

Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light. Amy receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows the locations of Amy and the shuttle in the reference frame of the ground at the instant both firecrackers explode. Bob's location is not shown. Call event 1 "firecracker 1 explodes" and event 2 "firecracker 2 explodes."

Would Bob (at rest with respect to the ground) measure that:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

Would an observer in the shuttle frame (moving to the right at speed $v = 0.7c$ relative to the ground) measure that?

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

Figure 4.21: Mountain Firecracker context and questions to probe student understanding of reference frames

of students believe that simultaneity is absolute. Almost all students answering that the events would be simultaneous in the shuttle frame also answered that the events would be simultaneous in the ground frame, implying that only 60% of students answered the question about the order of events in the ground-based observer's frame correctly with correct reasoning. Moreover, almost half of students (45%) chose the answer consistent with the signal-reception error for the shuttle frame, while only 35% of students chose the correct answer. While this indicates that over 80% of students recognize that the events are not simultaneous in the reference frame of the shuttle, it also suggests that students have difficulty determining the order of events in multiple reference frames. Students may resort to guessing,

Table 4.17: Student performance on multiple choice post-test question for *Events and reference frames* in Winter 2013: order of events in Bob’s reference frame. The correct answer is highlighted.

Order of events in Bob’s reference frame	($N = 522$) ^a
A (Event 1 before event 2)	< 2%
B (Event 1 after event 2)	0%
C (Events 1 and 2 simultaneous)	75%
D (More information needed to answer)	25%

^a Sections 123A131, 123B141, and 123C132

Table 4.18: *Events and reference frames Mountain Firecrackers* post-test results for multiple-choice question: order of events in shuttle reference frame. The correct answer is highlighted.

Order of events in Shuttle reference frame	($N = 522$) ^a
Event 1 before event 2 (consistent with signal-reception error)	45%
Event 1 after event 2 (correct)	35%
Events 1 and 2 simultaneous (consistent with absolute simultaneity)	15%
More information needed to answer	5%

^a Sections 123A131, 123B141, and 123C132

or may fall back on signal-reception reasoning when faced with a more difficult question. Student performance on the question about the order of events in the shuttle reference frame is shown in Table 4.18.

4.2.9-b *Marathoners in Space post-test repeat*

We reran the *Marathoners in Space* question (see section 4.2.7-a on three occasions after the final revisions of the *Events and reference frames* tutorial and homework. Results from those post-tests are shown in Tables 4.19 and 4.20.

Approximately 20% of students answered that the events would be simultaneous in both frames, suggesting that only slightly more than half of students were able to answer the question about the order of events in Joan’s reference frame correctly with correct reasoning. As with the *Mountain Firecrackers* questions, the answer choice consistent with signal-reception

Table 4.19: Student performance on multiple choice *Marathoners in Space* post-test question for *Events and reference frames* order of events in Joan's reference frame. The correct answer is highlighted.

Order of events in Joan's reference frame	($N = 508$) ^a
Event 1 before event 2	1%
Event 1 after event 2	1%
Events 1 and 2 simultaneous	71%
More information needed to answer (consistent with signal-reception error)	27%

^a Sections 123A132134141.

Table 4.20: Student performance on multiple choice *Marathoners in Space* post-test question for *Events and reference frames* order of events in Bill's reference frame. The correct answer is highlighted.

Order of events in Bill's reference frame	($N = 508$) ^a
Event 1 before event 2 (correct)	30%
Event 1 after event 2 (consistent with signal-reception error)	45%
Events 1 and 2 simultaneous (consistent with absolute simultaneity)	20%
D (More information needed to answer)	10%

^a Sections 123A132134141.

reasoning for the shuttle frame was slightly more popular than the correct answer.

4.2.10 Conclusions

After modifications to the *Events and reference frames* tutorial and homework, we observed an improvement on certain types of post-test questions. In particular, we saw a decrease in the percentage of students making the signal-reception error on questions similar to the *Noisy Bird* question used on the *Events and reference frames* pretest. Between 70% and 80% of students, on average, were able to answer correctly questions about the order of events for an observer in a given reference frame, when that observer was at rest with respect to another observer for whom the events were simultaneous. This can be compared to post-test results from before any modifications to the *Events and reference frames* tutorial or homework, when we found only that only 15-20% of students recognized that the events would be simultaneous. After modifications to the *Events and reference frames* homework only, between 60% and 70% of students were answering correctly on questions of this type. The percentage of students answering in a way that is consistent with the the signal-reception error dropped to approximately 20% for the post-test on those questions, compared to 60% before any modifications.

However, additional analysis indicated about a fifth of students maintain a belief in absolute simultaneity, up from 10% before any modifications were made. Although absolute simultaneity holds in Galilean relativity, continued belief in absolute simultaneity even in contexts when relative velocities are close to the speed of light indicates a lack of understanding about the ways in which one reference frame may differ from another. Moreover, even students who seem to recognize that events that are simultaneous in one frame may not be simultaneous in another have difficulty determining the correct sequence of events in multiple reference frames, with many students choosing the answer consistent with the signal-reception error for the “moving” reference frame. This suggests that although the *Events and reference frames* tutorial has improved student ability to determine event order for observers that are at rest with respect to each other, they may be returning to signal-

reception reasoning for more difficult questions, or falling back on memorized (but incorrect) results.

The *Events and reference frames* tutorial contains no relative motion, and the homework for *Events and reference frames* involves only non-relativistic motion. It is therefore unsurprising that the *Events and reference frames* materials do not address students' incorrect belief in absolute simultaneity. Moreover, the *Events and reference frames* tutorial was not designed to address student difficulty with the relativity of simultaneity; that is the function of the *Simultaneity* tutorial and homework. Rather, the *Events and reference frames* tutorial and homework are preparatory in nature, and are meant to improve student understanding of events and reference frames. Many exercises in the *Events and reference frames* tutorial and homework were motivated by the prevalence of the signal-reception error in particular. The significant decrease in this error after tutorial instruction suggests that the *Events and reference frames* tutorial and homework were successful in this regard.

In the next section, we describe our investigation of student understanding of event location, which allows us to probe student understanding of the formalism of a reference frame.

4.3 Student understanding of event location

Complete understanding of the relativity of simultaneity requires not just knowledge of what is meant by “reference frame” but also use of the formalism of a reference frame (among other concepts that will be described in later chapters); that is, it is not enough to recognize that two observers at rest with respect to each other share the same reference frame. One must also be comfortable applying the formalism of a reference frame to measure the time and location of an event. In this section, an investigation of student understanding of the formalism of reference frame using event *location*, rather than event time, is described.

4.3.1 Introduction

As discussed in §4.2, there was an improvement in student performance on post-test questions involving event time for observers in the same reference frame. This suggested that modifications to the special relativity tutorials had improved student understanding of reference frames. In particular, correct student responses on multiple-choice post-tests were consistent with student understanding that observers at rest with respect to each other share the same reference frame and agree on the time coordinates of all events. Because the questions were multiple choice, however, it was not clear whether students were applying the formalism of a reference frame in determining the times of events. It is possible that students were relying on a memorized statement regarding observers in the same reference frames; this idea is explicitly discussed in the *Events and reference frames* tutorial. Use of a memorized statement may allow students to answer simple questions regarding reference frames, but may not help them on questions regarding the relativity of simultaneity. To understand the relativity of simultaneity, a deeper understanding of reference frame is needed. As shown in §4.2, student performance on questions involving the time of events in a reference frame with a non-zero velocity relative to the ground may indicate that students revert to reception-time reasoning in more complex contexts.

The disparity in student performance on questions about ground vs. “moving” frames

was indicative of a lack of understanding of reference frame beyond what could be probed by multiple choice questions about event time. It was clear from post-test results that the disparity existed, but we could not be sure how, if at all, student reasoning was changing over the course of instruction. Because of the difficulty of asking free-response questions on the final course exam, it was necessary to try to probe student understanding of reference frames from a different angle. To probe further the extent to which the tutorials improved student understanding of reference frame, we designed questions that involve event location.

Recall that there are three key consequences of the definition of reference frame that result from the procedure used to measure the spacetime coordinates of events:

1. All observers at rest with respect to each other are in the same reference frame, and agree on the spacetime coordinates of all events.
2. Observers with non-zero relative velocity with respect to each other are in different reference frames, and do not (in general) agree on the spacetime coordinates of events.
3. The spacetime coordinate of a given event does not change with time in any reference frame

The first and (to a lesser extent) the second consequences were the focus of §4.2, for the time coordinates of events.

Understanding of the third consequence, in particular, requires the use of the formalism of a reference frame to measure the location of an event (i.e., the spatial coordinate of an event). Recall the definition of a reference frame as a three-dimensional grid of meter sticks and synchronized clocks at rest with respect to some observer. For that observer (and all other observers at rest with respect to that observer), the location of an event can be determined by the location of the clock that recorded the time of that event (i.e., the clock at the location of the event). The observer can “measure” the location of an event by querying the clocks of that observer’s reference frame.

Correct application of this formalism leads to the determination that event location does not change with time, since the clocks of an observer's reference frame do not move with respect to that observer. Additionally, we see that an event location cannot be linked to the location of an object at all times unless that object is at rest with respect to the observer. Finally, use of the formalism of reference frame to measure the location of an event makes it clear that the time at which the event location "measurement" is made does not affect the event location; we will determine the same location for a given event whether the measurement is made a short or long time after the event occurs.

Because the third consequence is strongly linked to the formalism of reference frame, it was the focus of our investigation into student understanding of event location. In addition, although all three consequences hold for both the time and spatial coordinates of events, use of the third consequence for event location is necessary for qualitative understanding of the relativity of simultaneity.

Section 4.3.2 describes prior research on student understanding of event location. Section 4.3.3 describes our ongoing investigation of student understanding of event location. Section 4.3.4 presents our conclusions and possible directions for future work.

4.3.2 Prior research on student understanding of event location

Research by Rachel Scherr found that students had a tendency to associate the location of an event with the location of an object [8]. Even advanced students had difficulty using the formalism of a reference frame to make length measurements of objects moving with respect to the measurer; only one of nine graduate students interviewed did so spontaneously.⁷

Scherr interviewed 30 graduate and advanced undergraduate students using the *Seismologist* question; an excerpt of the question is included below:

⁷A reference frame may be used to make length measurements by recognizing that the distance between simultaneous events located at the ends of an object is equal to the length of that object. This requires understanding of how to make measurements of locations of events.

Two volcanoes, Mt. Rainier and Mt. Hood, are 300 km apart in their rest frame. Each erupts suddenly in a burst of light. A seismologist at rest in a laboratory midway between the volcanoes receives the light signals from the volcanoes at the same time.

Define Event 1 to be “Mt. Rainier erupts,” and Event 2 to be “Mt. Hood erupts.”

A fast spacecraft flies past Mt. Rainier toward Mt. Hood with velocity $v = 0.8c$ relative to the ground ($\gamma = 5/3$). At the instant Mt. Rainier erupts, the spacecraft is directly above it and so the spacecraft pilot receives the light from Mt. Rainier instantaneously.

During the interviews, Scherr asked students to generate an event diagram for the spacecraft frame for the situation described in the problem statement, including marking the locations of Events 1 and 2. A correct event diagram with the locations of the events marked is shown in Figure 4.22. Note that the location of event 1 can be correctly described as “at the spaceship.” This is because, considering the reference frame of the ship, the clock that records the time and location of event 1 shares the location of the volcano and the location of the spaceship at the instant that the event occurs. Because the spaceship is at rest (and the volcano is not) in the spaceship’s reference frame, the event location can be said to be at the spaceship at all times.

Scherr found that several students marked the locations of the events at the tops of the volcanoes not only at the times of the events, but also at times before and after the events occurred in the spacecraft frames. Scherr noted that this indicates not only difficulty with generating correct event diagrams but also a belief that the location of an event changes with time in some reference frames. Although Scherr noted this tendency, she did not undertake any in-depth investigation into this difficulty.

Research by Andrew Boudreaux similarly found that students did not spontaneously apply the formalism of a reference frame when asked to determine the positions of events in

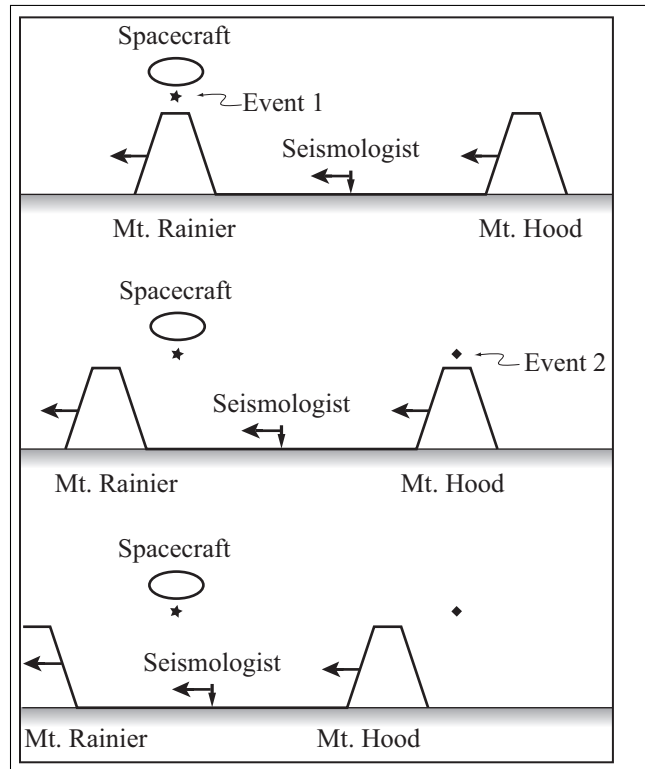


Figure 4.22: A correct event diagram showing the locations of events 1 and 2 for the spacecraft frame for the *Seismologist* task. The location of event 1 is marked by a small star; the location of event 2 is marked by a small diamond.

frames moving relative to the “laboratory” or ground frame [7]. During his research investigating student understanding of displacement in multiple frames of reference, Boudreaux noted that many students used an incorrect procedure for measuring position. To probe these difficulties, he developed an interview question in which students were asked to determine the distance between events in a frame moving relative to the ground frame.

A ship moves with uniform motion from left to right alongside a dock. An explosion occurs at the right end of the dock; two seconds later, another explosion occurs at the left end of the dock. The speed of the ship relative to the dock is 3 m/s, and the length of the dock is 12 m. Observers are stationed at a series of portholes evenly spaced along the side of the ship facing the dock.

Students were then asked to determine the distance between the locations at which the explosions occur, both relative to the ship and relative to the dock.

In the ship's reference frame, one could use the portholes of the ship as a reference frame, noting the locations of the events by drawing an event diagram and determining which portholes were adjacent to the two explosions when they occurred. The distance between those two portholes of the ship is then equal to the distance between the events in the ship frame.

Like Scherr's, Boudreaux's investigation was more qualitative than quantitative for this topic. Boudreaux interviewed 8 introductory students, and found that only two of them were able to answer the question correctly with little to no guidance. Boudreaux found that many of the remaining students did not have a correct procedure to find the distance between the locations at which the explosions occur. Others seemed to have particular difficulty with the analysis in the ship frame, which Boudreaux interpreted as student difficulty with frames of reference other than the ground or laboratory frame. Some students claimed that the distance between the events in the ship frame would be equal to the length of the dock. This can be interpreted in a number of ways. Students may be linking the event locations to physical objects (in this case, the ends of the dock where the events nominally occur). It's also possible that students fail to recognize that the distance between events that do not share a time coordinate will be different in different frames; these students may default to procedures performed in the more familiar ground (dock) frame.

4.3.3 Ongoing research on student understanding of event location

To probe student understanding that the spatial coordinate of a given event does not change with time in any reference frame, we focused on two key ideas: that the spatial coordinate of an event does not depend on the time at which the measurement is made; and that the spatial coordinate (“event location”) of an event is stationary in all frames. Since we were interested in the impact of the tutorials on student understanding, we designed pretests and post-tests to probe student understanding of these concepts. Below (4.3.3-a), there is first a discussion of the pretests used to probe student understanding, then a discussion of the parts of the *Simultaneity* tutorial that address these ideas (4.3.3-b). Section 4.3.3-c presents an assessment of the effectiveness of the tutorials in addressing student difficulties with this concept.

4.3.3-a *Simultaneity pretests*

The following *Beth and Box* context was used on a pretest for the tutorial *Simultaneity*. There were two questions; the first question involved sound, while the second question involved light.⁸ Each question had two versions. All students ($N = 718$) saw both questions (one involving sound, and one involving light), with approximately half ($N = 375$) seeing version 1, and the other half ($N = 343$) seeing version 2.

Both versions of question 1 (*Beth and Box (sound)*) will be discussed first. The two versions are shown below.

Question 1. Beth moves with half the speed of sound toward a beeper that sits on the ground; the beeper emits a beep just as she passes it.

- Version 1 (marker object): At a later time in Beth’s frame, the beeper is 400 meters to her left; in Beth’s frame, which of the following best

⁸The purpose of running versions with different types of signals (i.e., light and sound) was to probe student understanding of the invariance of the speed of light, and how the propagation of light differs from that of sound. The investigation of student understanding of these ideas is described in Chapter 5.

describes the location of the event “the beeper beeps:” *at Beth, at the beeper, or at a location between Beth and the beeper?*

- Version 2 (coordinate): Beth correctly determines the x' -coordinate of the event “the beeper beeps” to be $x' = 0$ m. At a later time, the beeper is 400 meters to the left of Beth. In Beth’s frame, at that later time, which of the following represents the location of the event “the beeper beeps:” $x' = 0$ m, $x' = 400$ m, or $x' = -400$ m?

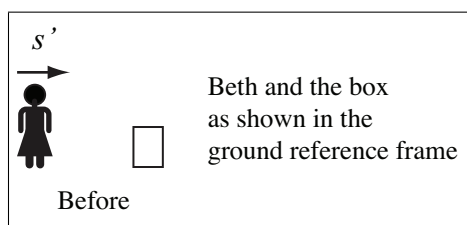


Figure 4.23: Figure accompanying *Beth and Box* pretest question

Students who saw version 1 of question 1 were asked to explain their reasoning. Students who saw version 2 were not asked to explain their reasoning. Version 2 was written with the intent of triggering the idea of a spacetime coordinate. It was expected that student performance on version 2 would be better than that on version 1, and that explanations of the correct answer would not be particularly illustrative on student understanding. This is also the reason that the distractor “-400 m” was used instead of a distractor that was more parallel to “at a location between Beth and the beeper.”

Results from question 1

Question 1, version 1, on the pretest above was intended to test how strongly students associate an event with the object “responsible for” that event in a frame that has nonzero velocity relative to that object. Version 2 of question 1 was a variation of this, and checked to see if providing a formal spatial coordinate for an event triggered student understanding that event location does not change with time. Results are tabulated below in Table 4.21.

Table 4.21: Comparison of performance on two versions of *Simultaneity* pretest *Beth and Box (sound)* context. The correct answer is highlighted.

Event location (Version 1) (objects)	$N = 375^a$	Event location (Version 2) (coordinate)	$N = 343^b$
At Beth	30%	$x' = 0$ m	30%
At the beeper	50%	$x' = 400$ m	50%
In between	20%	$x' = -400$ m	20%

^a Sections 123A1511521541 and 123B151
123C152

^b Sections 123A151154, 123B151, and

As seen in Table 4.21, 50% of students answered in a way that is consistent with linking the event to the beeper, regardless of whether a spatial coordinate was provided. This idea was explicit in student responses in the “marker object” version, as multiple students justified their answer by stating simply “the beeper beeps at the beeper.” Although students who saw version 2 were not asked to explain (for reasons stated above), the similarity in percentages of students answering correctly on the two versions suggests that students are thinking about them similarly. Because the distractors for the two versions are significantly different (though the percentages are the same), we will not attempt to draw parallels between students choosing the incorrect answers on the two versions.

A handful of students correctly noted that the center of the wavefront of the beep would be located at the beeper; however, these students also seem to believe that the location of the center of the wavefront is the same as the location of the event. This would be true for a flash of light, as the speed of light is the same in every reference frame. The speed of sound is not the same in every frame, so the origin of the wavefronts is the same as the event location only in frames at rest with respect to the medium of the sound wave (e.g., the air). Student understanding of the second postulate of special relativity regarding the speed of light will be discussed in Chapter 5.

“The sound wave is still spreading from the central point centered on the beeper. The sound was not emitted in a reference frame at rest with respect to [Beth’s frame], it was emitted in the reference frame of the ground and [Beth’s frame] is moving relative to the ground, so the sound wave is still centered on the beeper which is at rest wrt the ground.”

Most students answering “at the beeper” indicated that the location of the event must be at the beeper because that’s where the event occurred. For frames that move with nonzero velocity relative to the beeper, this is correct only at the instant at which the event occurred. It is not correct at later instants.

“The beep occurred at the beeper in the reference frame of Beth so it stays with the beeper.”

“The beeps are coming from the beeper, hence they move with the beeper relative to [Beth’s frame]”

“Since the beeper is the one that made the sound, the location of the event will still be at the beeper regardless of the reference frame from which it is viewed”

About half of the students who answered correctly used correct or partly correct and complete reasoning. The following student response is representative of students who used correct and complete or mostly complete reasoning.

“Beth is stationary in [Beth’s frame] and the beeper beeps when they pass each other, so the event happened where Beth is still currently at.”

Although no students explicitly mentioned how a reference frame is used to measure the location of an event, responses such as the above are consistent with the procedure described in the *Events and reference frame* tutorial. These students seem to recognize that the location of the event is the same as the location of the beeper at the instant of the event, and that in Beth’s frame, that location does not change with time. Many of these students seemed

to use the fact that the beeper beeped as it passed Beth as a way to hold the location of the event fixed in Beth's frame. It is not clear whether these students would have performed differently if the beeper had beeped at a different instant/location: for example, one second before the beeper reached Beth in her frame.

Responses from the remaining half of students answering that the location of the event was at Beth were varied. For the most part, there was no unifying theme to these responses. A few students did link the location of the event to Beth's location using the (incorrect) belief that in Beth's reference frame, the time and location of the event are determined by the time and location of Beth at the instant she receives the wavefront from the beep.

Students who answered "at a location somewhere between Beth and the beeper" often provided explanations that were not illustrative of their thinking. Some students seemed to choose a third reference frame in which Beth and the beeper move in opposite directions ("Beth is moving to the right and the beeper moved to the left") or one in which the event location was fixed but the locations of both Beth and the beeper changed with time ("that location didn't change position but beth [sic] and beeper did"). A few students linked the event location to Beth's location at the instant at which she heard the beep; these students did not recognize that Beth's location does not change with time in her own frame, or that because the beeper beeps as Beth passes it, the time that Beth hears the beep is the same time at which the beep is emitted. The number of students making use of either of these lines of reasoning was relatively small (less than 5% of all students in both cases).

Question 2 involved light rather than sound, and also had two versions, described below.

Question 2. Suppose instead that Beth moves with half the speed of light relative to the ground toward a box that sits on the ground.

- Version 1 (strobe): The box is a strobe light that emits a flash of light just as Beth passes it. The flash of light moves outward in all directions. Consider the event "the strobe light flashes."
- Version 2 (spark): A spark jumps between Beth and the box at the

instant she passes it. The spark emits a flash of light that moves outward in all directions. Consider the event “the spark jumps.”

Both versions: For (a) Beth’s frame, and (b) the ground frame, indicate whether the location of the event is *stationary*, *moves with half the speed of light to the right*, or *moves with half the speed of light to the left*.

The strobe version of question 2 was intended to probe student understanding that event location is stationary in all frames; that is, for a given event, the location of the event does not change with time in any frame. As seen above, students have a tendency to link an event with the object responsible for that event; in the strobe version, students were asked about the motion of the event location to probe whether they would believe the location of the event has the same motion (in a given reference frame) as the box that produced the flash of light.

Version 2, involving a spark jumping “between” frames, was intended to see whether student understanding was changed when an event can not be strongly linked to an object in a single frame. Results are tabulated below. For both versions, only 10% of students answered correctly (“stationary”) for both frames.

For the strobe version of question 2, more than half of students answered that the event location moves to the left; this answer is consistent with the location of the event being at the box at all times. Similar to the sound version (question 1), students seem to link event location to the object that produces that event. In the box frame, 80% of students had the event location stationary (also consistent with “at the box”). We also find, however, that nearly a third of students answered that the event location moves to the right in Beth’s frame. This is consistent with Boudreaux’s findings that students have difficulty with analyses of relative motion in frames other than the ground frame.

Results from the spark context indicate that students also have difficulty with analyses in all frames when an event is not easily linked to a single frame. Only two-thirds of students were able to answer correctly for the box frame; in Beth’s frame, answers were distributed more even among all of the answer choices than they were in the strobe flash context.

Table 4.22: Comparison of student performance on two versions of *Beth and Box (light)* pretest question

Event location (flash)	$N = 375^a$	Event location (spark)	$N = 343^b$
Beth's frame			
Stationary	15%	20%	
Moves right	30%	40%	
Moves left	55%	25%	
None of these	-	15%	
Box frame			
Stationary	80%	65%	
Moves right	10%	15%	
Moves left	10%	10%	
None of these	-	10%	

^a Sections 123A1511521541 and 123B151

^b Sections 123A151154, 123B151, and 123C152

Together, these results suggest students do not have as deep as understanding reference frames as they should have after instruction, even after completing the *Events and reference frames* tutorial. We cannot tell from these data whether the *Events and reference frames* homework helps student with these ideas. Because of the timing of the instructional sequence, it is likely that many of the students completing the *Simultaneity* pretest have not yet completed the *Events and reference frames* homework. There are, however, parts of the *Simultaneity* tutorial that require students to use these ideas, as described below.

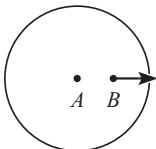
4.3.3-b Exercises addressing the idea of event location in the tutorial *Simultaneity*

At the beginning of the *Simultaneity* tutorial, students work through the exercise shown below.

This exercise helps guide students to recognize that the location of the event corresponding to the spark jumping between Alan and Beth depends on the reference frame. In Beth's frame, the spark occurs at Beth, so the event location is at Beth at all times. Likewise in

Two students, Alan and Beth, move past each other. At the instant that they pass, a spark jumps between them. The spark emits a flash of light that moves outward in all directions.

The first diagram at right represents the wavefront of the flash of light in Alan's frame, a short time after the spark jumps.



Alan's frame: The wavefront a short time after the spark

Alan's frame: The wavefront at a later time

1. Explain how this picture is consistent with the fact that Alan observes the speed of light to be the same in all directions.
2. In the second diagram above, sketch the wavefront at a later time in Alan's frame. Include both Alan's and Beth's positions in your sketch.
3. Is there a time at which the distance between Alan and Beth is greater than the distance between Alan and the wavefront? Explain.

In the spaces at right, sketch Alan, Beth, and the wavefront in Beth's frame. Draw diagrams for a short time after the spark jumps and at a later time.

Are your sketches consistent with the fact that Beth observes the speed of light to be the same in all directions? If not, modify your diagrams so they are consistent with this observation.

Beth's frame: The wavefront a short time after the spark

Beth's frame: The wavefront at a later time

Figure 4.24: Exercise from the tutorial *Simultaneity*

Alan's frame, the event location is at Alan at all times. In both frames, the speed of light is the same in all directions, so Beth is at the center of the wavefronts in her frame, while Alan is at the center of the wavefronts in his frame. (Note that this exercise also requires students to recognize that the wavefronts from the flash of light are located in the same place as the events in both frames. Thus, students must also understand that the speed of light is the same in all frames. Student difficulty with this idea will be discussed in the following chapter.)

The rest of the *Simultaneity* worksheet focuses on a version of Einstein's train paradox. Small sparks (rather than the lightning in Einstein's version) jump between the ends of the

train and the track. These sparks leave char marks on both the ends of the train as well as the track, as shown in the figure 4.25 below. Students are asked to locate the centers of the wavefronts in both frames. The char marks on the train and the tracks are intended to help students “anchor” the events to particular points in both frames. As in the previous exercise, this requires students to recognize that the centers of the wavefronts (used synonymously with “event location” for events involving a flash of light) are at rest in both frames.

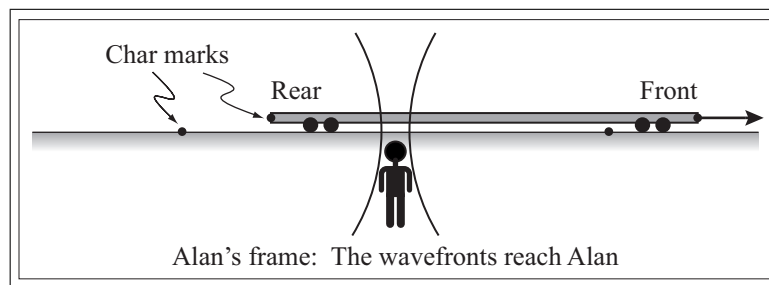


Figure 4.25: Figure from *Simultaneity* showing resulting char marks after sparks jump between train and track

4.3.3-c Preliminary assessment of tutorial sequence on student understanding of event location

As a preliminary investigation into the effectiveness of the two-tutorial sequence on addressing student difficulties with event location, we developed the two free-response exam questions shown below. Free-response post-test version 1 (*Spaceships*) corresponds somewhat to pretest question 1 (version 2), while post-test version 2 (*Strobe Train*) corresponds to pretest question 1 (version 1).

Version 1 (*Spaceships*):

In the frame of spaceship A, observers A and B pass each other (“event P”) just as the strobe light at observer A’s feet emits a flash of light (“event S”). See Figure 4.26.

In the frame of spaceship B at a later time t_1 , observers A and B are separated by a distance of 30 km. In the frame of spaceship B, what is the distance between the location of event S and the location of observer B at time t_1 ?

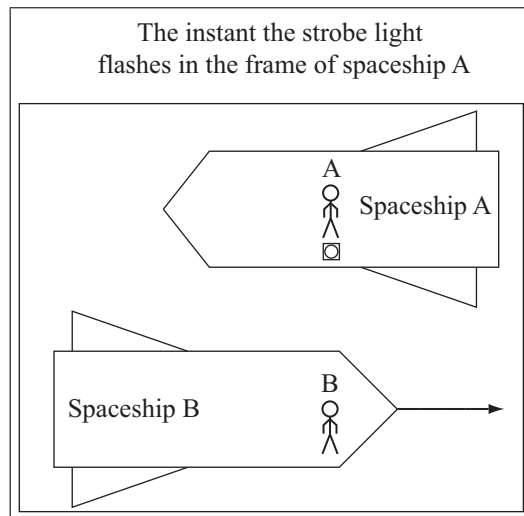


Figure 4.26: Figure from the *Spaceships* post-test question

Version 2 (*Strobe Train*): A train moves to the right (relative to the ground) at relativistic speed. See Figure 4.27. Strobe lights 1 and 2, at the center of the train, emit flashes of light simultaneously in the train frame. Call event 1 “strobe light 1 flashes” and event 2 “strobe light 2 flashes.” Observer B stands on the ground near the train tracks. In the ground frame, event 1 (strobe light 1 flashes) occurs just as strobe light 1 passes observer B.

At a later time t_1 in the ground frame, is the location of event 1 *at the strobe*, *at the location of observer B*, or *somewhere between the strobe and observer B*? Explain.

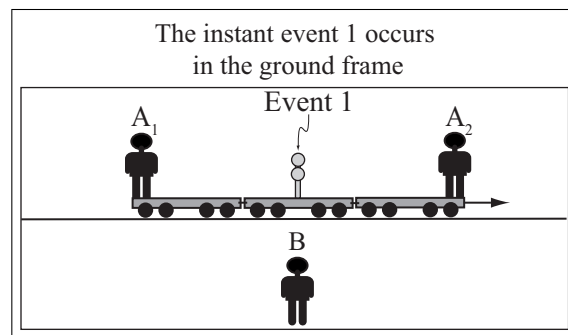


Figure 4.27: Figure from the *Strobe Train* post-test question

Results: Version 1 (*Spaceships*) The question in version 1 can be answered by determining the location of event S in the frame of spaceship B, and recognizing that event location does not change over time in any reference frame. At the instant that event S occurs in the frame of spaceship B, the strobe light is directly above observer B. Therefore, the location of event S in the frame of spaceship B is best described as at the location of observer B. Because event location does not change over time, the distance between event S and observer B is zero at all times.

Student performance on version 1 can be found in Table 4.23.

Table 4.23: *Spaceships* event-location task post-test results. The correct answer is highlighted.

Distance between events	$N = 147^a$
0 km	50%
15 km	10%
30 km	35%
Other	5%

^a Section 123B151

Student performance on this post-test was significantly better than that on the corresponding pretest, on which only 30% of the students to whom the question was administered answered correctly. In addition, almost all of the students answering correctly used correct, or mostly correct reasoning. A typical student explanation that we treated as correct is provided below. Note that the student references the definition of event and correctly describes the location of the event in the reference frame of spaceship B, as well as the event location's motion.

“Zero. Event S is associated with a specific time and place which was where the strobe went off (right at spaceship B). In the reference frame of spaceship B, only spaceship A is moving at a speed relative to B and the location of the event S has not moved relative to spaceship B.”

As seen in the table above, 30 kilometers was the second-most common response. Most of these students indicated that event S happened “at the strobe light” or at observer A. These students reasoned that the distance between the events would be the same as the distance between the two observers. The student quote below is typical of such responses.

“It will still be 30 km as event S was the strobe flash. Since the strobe is on spaceship A and A & B are 30 km away. So at t_1 , B and the strobe light is 30 km away.”

Finally, 15% of the students answered 15 kilometers or another distance. All students who answered something other than 0, 15, or 30 kilometers chose distances between 0 and

30 kilometers. Students answering 15 kilometers often seemed to link event S not to the reference frame of spaceship A, but rather to a perceived “rest frame” in which the two ships move at equal speeds but opposite directions. This may be due to the fact that the ships in the problem statement were said to be “moving past each other.” A few students seem to interpret the statement that the spaceships were “moving at relativistic speed” as “close to the speed of light” which led them to conclude that the spaceships had approximately equal speeds in opposite directions. It’s not clear from the brief explanations why students have this idea. The student response below was typical of students answering 15 kilometers.

“The distance between the location of event S and the location of observer B at t_1 is 15 km assuming that A and B move at the same speed.”

Results, version 2 As for version 1, version 2 can be answered by realizing that event 1 occurs at observer B’s location. The location of the event does not change over time, so the location of event 1 in the ground frame is best described as “at the location of observer B” at all times.

Student performance on version 2 is shown in Table 4.24.

Performance on version 2 ($N = 194$) was significantly better than that on version 1, with over 80% of students answering correctly that the location of the event 1 in the ground frame is best described as at the location of observer B. Almost all of the students answering correctly used correct or mostly correct reasoning; all but 6 students used at least partially

Table 4.24: Strobe train event-location post-test question results. The correct answer is highlighted.

Location of event 1	$N = 194^a$
Observer B	80%
Strobe	5%
Somewhere between	10%

^a Section 123A151

correct reasoning. Only slightly over 5% of students answered that the event location was at the strobe light, with all of those students using reasoning that indicated a belief that the event should be at the strobe light in all frames because the strobe was the source of the flash. As in section A, 10% of students answered that the event location was somewhere between the strobe and observer B. There was no common line of reasoning employed by this group of students; most explanations indicated a significant lack of understanding of both Galilean and special relativity. It is hard to explain these responses in this context, as it is difficult to identify a “stationary” reference frame other than the ground frame.

The difference in performance on these two questions might be attributed to a number of factors. In version 2, there is an identifiable rest frame. Moreover, students had seen a context with a train in both the tutorial *Simultaneity* and the associated homework, which might have made it easier for students to understand. Also, the wording in version 1 was more open-ended than that in version 2, in which students were given three choices for the event location. The wording in version 1 prompted some students to try to calculate a distance using a Lorentz transformation. All of these might suggest that version 2 was easier for students.

Versions 1 and 2 were also given to classes with two different instructors (though past research indicates that performance on tutorial-based questions is not significantly affected by lecture instructor).

Finally, in version 2, some students had difficulty with causality-related ideas, which will be discussed in-depth in a later chapter. In order for students to recognize that event S is located at observer B in B’s frame, they must understand that event S occurs at the moment that observers A and B pass each other. About 20% of the students did not recognize that event S happens at the same time that observer B passes observer A in the reference frame of observer B. About half of these students answered the question regarding event location incorrectly but with correct or mostly correct reasoning. These students did not recognize that observer B passed the strobe light as it flashed in observer B’s frame, and determined that there was a non-zero distance between the location of event S and observer B’s location

at time $t = t_1$.

Results from both versions suggest that the tutorial *Simultaneity* likely improves student understanding of event location, though some difficulties remain. In addition, the responses on the exam do not indicate that improved performance on questions relating to event location is due to a more complete understanding of what is meant by “reference frame;” rather, students may be using a memorized result, having seen similar contexts in tutorial and tutorial homework.

Additional results We also had the opportunity to run variations of the pretest questions described above as multiple choice post-test questions. The students who saw these questions as post-test questions did not see them on the *Simultaneity* (or any other) pretest. There were two versions: *Willa* and *Daisy*.

The *Willa and the Box (sound)* question is shown in Figure 4.28.

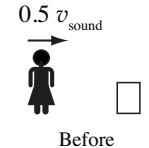
A small box sits on the ground on a calm, windless day. Willa moves to the right at half the speed of sound relative to the ground, as shown in the figure at right.

The box beeps four times as Willa approaches and passes it. The second beep is emitted at the instant that Willa passes the box. The beep produces a sound wave that moves outward in all directions. Call “the box beeps for the second time” event B_2 . Willa passes the box at spacetime coordinate $(x, t) = (0 \text{ m}, 0 \text{ s})$ in her frame.

Four seconds after Willa passes the box, the box emits the fourth beep. Call “the box beeps for the fourth time” event B_4 . What is $\delta x_{24}^{(\text{Willa})}$, the distance between events B_2 and B_4 in Willa’s reference frame?

A. $\delta x_{24}^{(\text{Willa})} = 0 \text{ m}$
 B. $\delta x_{24}^{(\text{Willa})} = 343 \text{ m}$
 C. $\delta x_{24}^{(\text{Willa})} = 686 \text{ m}$
 D. $\delta x_{24}^{(\text{Willa})} = 1372 \text{ m}$
 E. None of these

$0.5 v_{\text{sound}}$



Willa and the box in the reference frame of the box

Before

Figure 4.28: *Willa and the Box (sound)* event location post-test question

For the *Willa* version, we can determine the correct answer by recognizing that in Willa’s frame, event B_2 occurs at her location; event B_4 occurs at the location of the beeper in Willa’s frame four seconds later. Therefore, the distance between the events is equal to the distance between Willa and the beeper in Willa’s frame at the instant event B_4 occurs.

Table 4.25: Post-test results for multiple-choice *Willa and the Box (sound)* question. The correct answer is highlighted.

$\delta x_{24}^{(\text{Willa})}$	Version 1 ($N = 170$) ^a
0 m	10%
343 m	10%
686 m	60%
1372 m	15%
None of these	5%

^a Section 123A164

Because the beeper moves to the left at a speed of half the speed of sound ($v_{\text{sound}} = 343 \text{ m/s}$) in Willa's frame, the distance between the events is 686 meters. Student performance on this post-test question is shown in Table 4.25.

Performance on this version was relatively good, with more than half of students answering correctly. Surprisingly, only 10% of students answered that the distance between the events was 0 meters; this answer would be consistent with students linking the event location to the box. The most popular incorrect answer was 1372 meters, for unknown reasons. It is possible that students took the relative speed of Willa and the box to be the speed of sound, rather than half the speed of sound, which would lead them to answer double the correct answer. Because the post-test questions were multiple choice, we could not determine how students reasoned about the question.

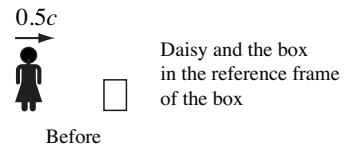
The *Daisy and the box (light)* question is shown in Figure 4.29.

The context involving light requires no calculation, only recognition that the location associated with any event does not change with time in any reference frame; therefore, in any reference frame, the event location is stationary. As in version 1, for events associated with an object (e.g., the box) that has nonzero relative velocity in the reference frame of interest, the location of the event and the location object are only the same at the instant that the event occurs.

Student performance is shown in Table 4.26.

A small box sits on the ground. Daisy moves to the right at half the speed of light relative to the ground, as shown in the figure at right.

The box emits four flashes of light as Daisy approaches and passes it. The second flash is emitted at the instant that Daisy passes the box. The flash produces a light wave that moves outward in all directions. Call “the box flashes for the second time” event F_2 . Daisy passes the box at spacetime coordinate $(x', t') = (0 \text{ m}, 0 \text{ s})$ in her frame.



In Daisy’s reference frame, which of the below correctly describes the motion of the location of the event F_2 ?

- A. Stationary
- B. Moves with half the speed of light to the right
- C. Moves with half the speed of light to the left
- D. None of above

Figure 4.29: *Daisy and the box (light)* event location post-test question

Table 4.26: *Daisy and the box (light)* multiple-choice post-test results. The correct method is highlighted.

Motion of event location	Version 2 ($N = 150$) ^a
Stationary	45%
Moves with half the speed of light to the right	5%
Moves with half the speed of light to the left	45%
None of the above	5%

^a Section 123B171.

Only 45% of students answered correctly that the location of the event was stationary in Daisy’s frame. Additionally, 45% of students chose “moves with half the speed of light to the left” which is consistent with the event location being at the box at all times.

Because no explanations were required for either post-test multiple choice question, we cannot be sure why performance on the *Willa* version was better than that on the *Daisy* version. The two versions of the question were written with the intent that students would use similar reasoning. One possible explanation is that students tend to perform better on quantitative questions, despite not having a deeper understanding of the material. Students could calculate the correct answer simply by multiplying the relative velocity by the time

interval between the beeps; although this answer is easy to calculate, understanding why that gives the correct answer in this case is much more difficult.

4.3.4 Summary

Although student performance on post-test questions involving event location is better than performance on similar pretest questions, these results suggest that the special relativity tutorials do not adequately address student difficulties. Students have particular difficulty when asked specifically about the motion of the event location in “moving” frames, especially when an event is easily linked to an object. Student ability to use event location to calculate the distance between events seems to be better, though only marginally so; student performance on this type of question may not indicate a deeper understanding of reference frame.

4.4 Conclusions and future work

Modifications made to the *Events and reference frames* tutorial and homework seem to have been effective in addressing some specific student difficulties with reference frames. In particular, we saw a marked decrease in the percentage of students making the signal-reception error after targeted modifications to the *Events and reference frames* curriculum. Approximately 70% of students answered pretest tasks in a way that was consistent with signal reception reasoning, while only about 20% of students answered consistently with signal reception reasoning on similar post-test tasks after administration of the most recent versions of the *Events and reference frames* tutorial and homework. Before modifications to the curriculum, approximately 60% of students answered consistently with signal-reception reasoning on post-test tasks. This suggests that the more recent versions of the *Events and reference frames* tutorial and homework are moderately successful in addressing the signal-reception error with this population of introductory physics students.

Results from post-test tasks also suggest that administration of the most recent versions of the *Events and reference frames* tutorial and homework is associated with an increase in the number of students answering in a way that is consistent with an explicit belief in absolute simultaneity. However, a belief in absolute simultaneity is consistent with understanding of reference frames in Galilean relativity; therefore, an increase in this particular error should not be seen as a failing of the *Events and reference frames* curriculum, as it suggests that students have gained a more sophisticated view of reference frames in every-day (non-relativistic) contexts.

However, further research into student understanding of event location suggests that the *Events and reference frames* curriculum is not as effective at improving student understanding of the formalism of a reference frame. That is, although students seem to understand that observers at rest with respect to one another share the same reference frame and will agree on the time and location of events, they are often not able to use the formalism of a reference frame to correctly determine the location of an event in multiple reference frames. In particular, student tendency to link the location of an event to an object that is asso-

ciated with that event frequently prevents students from recognizing that event location is stationary in all reference frames, even after the tutorials.

The research presented in this chapter suggests that specific, targeted exercises regarding the correct procedure for the measurement of the time and location of a given event (i.e., using the formalism of a reference frame) and the consequences of that procedure (e.g., the fact that event location does not change with time in any reference frame) in the *Events and reference frames* tutorial and homework (or in a new tutorial) may be appropriate.

Chapter 5

STUDENT UNDERSTANDING OF THE IMPLICATIONS OF THE INVARIANCE OF THE SPEED OF LIGHT

This chapter presents our research into introductory student understanding of Einstein's second postulate of special relativity, regarding the invariance of the speed of light. Portions of the *Simultaneity* tutorial that cover the use of Einstein's second postulate in the understanding of the relativity of simultaneity are described. Assessment of student functional understanding of the invariance of the speed of light via comparisons of pretest and post-test performance is discussed. All data were collected from pretests (after lecture instruction in special relativity but before the *Simultaneity* tutorial) and post-tests (after all relevant instruction) administered to students in the last quarter of the introductory physics course (Physics 123) at the University of Washington between the years 2010 and 2016.

5.1 Introduction

As described in Chapter 1, an understanding of the implications of the invariance of the speed of light is critical for a qualitative understanding of the relativity of simultaneity; in fact, the relativity of simultaneity is arguably the most fundamental (and historically troubling) result of Einstein's two postulates of special relativity. Einstein's postulate regarding the speed of light is taught in lecture coverage of special relativity, and is also readily in textbooks. We have found (informally) that students are able to state with confidence that the speed of light is the same in all reference frames. However, results from pre- and post-tests suggest that students do not understand the implications of the invariance of c , and that this lack of understanding can lead to a breakdown in the chain of reasoning needed to understand the relativity of simultaneity.

Although the *Simultaneity* tutorial contains exercises requiring student use of the invariance of the speed of light, there has been little investigation into student understanding of this idea by researchers (both in the Physics Education Group at the University of Washington and elsewhere). The purpose of our investigation into student understanding of the speed of light was to determine whether student difficulties exist after introduction to Einstein's postulates in lecture and textbook coverage, and if so, whether these difficulties are addressed by the existing exercises in the *Simultaneity* tutorial. No modifications to the *Simultaneity* tutorial were made as we found the investigation to be challenging on its own.

The remainder of this chapter of the dissertation consists of three parts. §5.2) gives two formulations of Einstein's second postulate regarding the invariance of the speed of light, and discusses the consequences of the second postulate when applied to Einstein's train paradox. It also describes the results of prior research on related ideas. §5.3 begins by describing key parts of the tutorial *Simultaneity* that are related to the speed of light and informal observations of student understanding of this topic. This is followed by a discussion of post-tests (administered after tutorial instruction) to probe the ability of students to apply the invariance of the speed of light and then the development of additional pre- and post-test tasks that grew out of this research. Finally, §5.4 is a summary of the results.

5.2 Background and prior research

5.2.1 Background

There are two commonly stated formulations of Einstein's second postulate of special relativity regarding the speed of light, shown below:

Einstein's second postulate (version 1)

The speed of light in vacuum has the same value c in all inertial frames of reference.

Einstein's second postulate (version 2)

The speed of light is equal to c and is independent of the motion of the source.

Although these two statements are physically equivalent, we focus on the second, which is somewhat more applicable to the understanding of the relativity of simultaneity as needed by students in working through the *Simultaneity* tutorial. The discussion below illustrates the use of the second statement in a modified version of the train paradox (which is slightly different from that used in the tutorials).

5.2.2 Description of the modified train paradox

In this version of the train paradox, pressure-sensitive firecrackers are placed on the train tracks a distance L apart, where L is the length of the train as measured in the reference frame of the tracks. The front firecracker (firecracker F) is set to go off when the front of the train hits it; the rear firecracker (firecracker R) is set to go off when the rear of the train hits it. An observer in the ground frame stands equidistant between the two firecrackers.

Analysis in the ground frame In the reference frame of the ground, firecracker R and F explode simultaneously, at the same instant when the center of the train passes the observer. In the ground reference frame, each firecracker emits a spherical wavefront of light, centered at the locations of the firecrackers on the ground. This is consistent with the speed of light being equal to c in all directions in the ground frame.

Analysis in the train frame The analysis in the train frame is somewhat different. One key aspect is recognizing that the wavefronts in the train frame cannot be centered at the firecrackers, which are moving in the reference frame of the train. If that were the case, then an observer on the train would *not* measure the speed of light to be equal to c in all directions. The invariance of the speed of light requires the centers of the wavefronts to be stationary in the reference frame of the train, and for the centers to be located at the ends of the train (which are the locations of the events associated with the explosions of the firecrackers in the train frame). [Note that it follows that for the wavefronts to simultaneously reach the ground frame observer, who in the train frame is moving toward the rear of the train, then firecracker R must explode after firecracker F.]

The statement above—that the centers of the wavefronts from the explosions of the firecrackers are at rest in the train frame—can be generalized as a sort of corollary to Einstein’s second postulate. Consider an event E_L that results in the emission of a flash of light. The resulting wavefront of light is spherical and centered at the location (i.e., the spatial coordinate) of E_L in every reference frame. Note that functional knowledge of this “corollary” requires student understanding of event location; §4.3 presents our investigation into student understanding of that idea.

5.2.3 Prior research on student beliefs about the speed of light and relative motion

Relatively little research regarding student understanding of the speed of light that is relevant to the difficulties described in this chapter has been done. Villani and Pacca, in an investigation of physics graduate students, found that understanding of the invariance of the speed of light is limited by student difficulties with Galilean relativity. Their research indicated that students often held a belief in a preferred reference frame; in particular, students tend to treat motion as absolute with respect to some preferred frame. This tendency understandably impacts student understanding of the invariance of the speed of light.

At the University of Washington Andrew Boudreaux performed a comprehensive investi-

gation of student understanding of topics in Galilean relativity, including relative motion and transformation of velocities in one-dimension. Boudreaux found that only about two-thirds of introductory physics students were able to determine the magnitude of an object's velocity when transformation of velocity was required. In the context of this present investigation, this result suggests that a third (or more) of students may have difficulty understanding why having a wavefront with a center that changes location with time in a given frame is not consistent with the invariance of the speed of light.

Results from both of these prior studies are consistent the findings described in sections 5.3.2 and 5.3.3.

In §5.3, we describe our preliminary investigation of student understanding of the invariance of the speed of light, focusing on student use of the above corollary.

5.3 Student understanding of the invariance of the speed of light

We begin our discussion of student understanding of the invariance of the speed of light by describing the parts of the *Simultaneity* tutorial in which students are expected to use the invariance of the speed of light (section 5.3.1). We also discuss the informal observations made in the classroom that led us to believe that students had greater difficulty with this idea than was expected. In section 5.3.2, we present post-tests designed to test student understanding of the invariance of the speed of light after completion of the tutorial, and discuss the results. In section 5.3.3, we present pretest tasks designed on the basis of the results described in section 5.3.2, meant to probe student ideas about the propagation of light, and how it differs from the propagation of other types of signals such as sound.

5.3.1 Use of the invariance of the speed of light in the tutorial *Simultaneity* and informal investigation of student understanding

The *Simultaneity* tutorial does not include any explicit instruction in Einstein’s postulates of special relativity, but it makes use of the invariance of the speed of light in several exercises. In particular, students are expected to use the “corollary” to the second postulate described in §5.1 above.

Part I of the *Simultaneity* tutorial The tutorial begins with a relatively abstract context and exercises that requires students to apply the invariance of the speed of light. Students are told that two observers, Alan and Beth, move past each other. Just as they pass, a spark jumps between them. The spark emits a flash of light that moves outward in all directions.

Students are provided a diagram that shows the locations of Alan, Beth, and the wavefront of light from the flash in Alan’s reference frame a short time after the spark has jumped. The wavefront is shown as a circle centered at Alan’s location. Students are first asked (1) to explain how this diagram is consistent with the fact that Alan observes the speed of light to be the same in all directions; then, students are asked (2) to complete a second diagram

showing the locations of Alan, Beth, and the wavefront a short time later. The first exercise is shown in Figure 5.1. A spark that jumps between Alan and Beth is used, rather than a device that lies in one reference frame or the other.

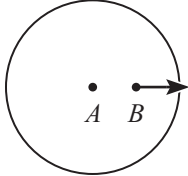
Two students, Alan and Beth, move past each other. At the instant that they pass, a spark jumps between them. The spark emits a flash of light that moves outward in all directions.

The first diagram at right represents the wavefront of the flash of light in Alan's frame, a short time after the spark jumps.

Explain how this picture is consistent with the fact that Alan observes the speed of light to be the same in all directions.

In the second diagram above, sketch the wavefront at a later time in Alan's frame. Include both Alan's and Beth's positions in your sketch.

Is there a time at which the distance between Alan and Beth is greater than the distance between Alan and the wavefront? Explain.



Alan's frame: The wavefront a short time after the spark

Alan's frame: The wavefront at a later time

Figure 5.1: Exercise from the tutorial *Simultaneity* requiring use of the fact that the speed of light is invariant and isotropic

Diagram from Alan's reference frame To complete the diagram for (1) correctly, students must recognize that because the speed of light is the same in all directions in Alan's reference frame, the wavefront must always be circular, and centered at his location. Moreover, they must recognize that Alan doesn't move in his own reference frame; therefore, Alan (and the center of the wavefront) should be drawn in the same location in the second sketch that they were in the first. Finally, students should recognize that at the instant shown in the first diagram, Beth is located halfway between Alan and the wavefront; because Beth and the wavefront left Alan's location at the same time, and Beth has moved half as far, we can determine that Beth is moving at half the speed of light in Alan's reference frame. Therefore, she should be halfway between Alan and the wavefront at all times.

The correct diagrams for Alan's reference frame are shown in Figure 5.2.

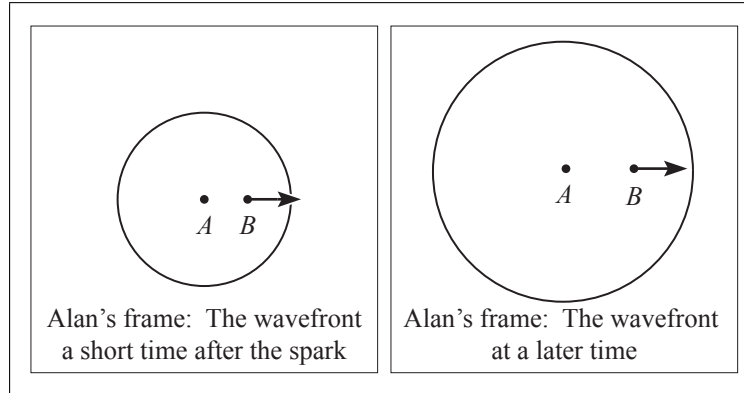


Figure 5.2: Correctly completed diagrams from the first exercise from the *Simultaneity* tutorial

Diagram for Beth's reference frame The second exercise (2) asks students to complete the analogous diagrams (for a short time after the spark has jumped, and then a later time) for Beth's reference frame. Students are asked to ensure that their sketches are consistent with the fact that Beth also observes the speed of light to be the same in all directions. The second exercise is shown in Figure 5.3.

In the spaces at right, sketch Alan, Beth, and the wavefront in Beth's frame. Draw diagrams for a short time after the spark jumps and at a later time.

Are your sketches consistent with the fact that Beth observes the speed of light to be the same in all directions? If not, modify your diagrams so they are consistent with this observation.

Beth's frame: The wavefront
a short time after the spark

Beth's frame: The wavefront
at a later time

Figure 5.3: Second exercise from the tutorial *Simultaneity* requiring use of the fact that the speed of light is invariant and isotropic

To complete the diagrams correctly, we recognize that in order for Beth to observe the speed of light to be the same in all directions, the wavefront must be stationary in her reference frame, and spherical. Because in Beth's reference frame the spark jumped at Beth's location, she will be stationary and at the center of the wavefront. Finally, in Beth's reference frame Alan moves to the left at the same speed that Beth moved in Alan's reference frame (i.e., half the speed of light), so Alan will be located halfway between Beth and the wavefront at all times in Beth's reference frame.

The correct diagrams for Beth's reference frame are shown in Figure 5.4.

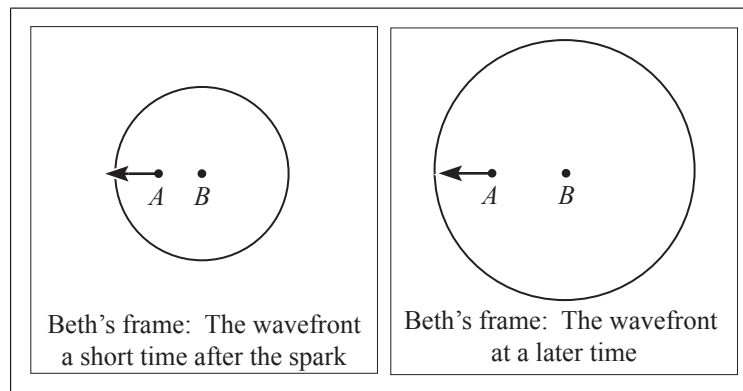


Figure 5.4: Correctly completed diagrams from the second exercise in the tutorial *Simultaneity* requiring use of the fact that the speed of light is invariant and isotropic

Reflections on part I of the *Simultaneity* tutorial Informal observations of students in tutorial sessions indicate that many students complete these exercises easily; in fact, it is common for students to work through these exercises with little or no apparent reflection on their significance. Although some students struggle to see why the wavefronts must be centered at Alan in Alan's reference frame, and at Beth in Beth's reference frame, experience suggests that a majority of students assume this to be the case without understanding why. When asked to explain how they knew to draw the diagrams as they did (correctly), many students comment on the shape of the wavefronts, but not the location of the centers. We hypothesize that students recognize that the circular shape of the wavefronts is consistent

with the isotropy of the speed of light, but not that the location of the center of the wavefronts is necessary to preserve the invariance of the speed of light.

Part II of the *Simultaneity* tutorial As described earlier in the dissertation, the remainder of the *Simultaneity* tutorial consists of exercises that lead students through a variation of Einstein’s train paradox. In this variation, sparks jump between the ends of the train and the track; notably, the sparks leave small char marks on both the train and the track at the locations where the sparks jumped. These char marks are intended to serve as “markers,” anchoring the locations of the events corresponding to the sparks jumping in each reference frame. Students are meant to associate the char marks on the tracks with the locations of the events in the reference frame of the ground, and the char marks on the train with the locations of the events in the train reference frame.

Analysis in Alan’s reference frame Students first consider the reference frame of Alan, at rest with respect to the ground. In one part of this section, students determine the order in which observer Beth (standing at rest on the train at its center) receives the wavefronts from the sparks in Alan’s reference frame. As part of this exercise, students are asked about the locations of the centers of the wavefronts in Alan’s reference frame. Because Alan must measure the speed of light to be the same in all directions, the centers of the wavefronts must be at rest with respect to him, and located at the same spatial coordinate of the events associated with the sparks jumping. Therefore, the wavefronts are centered at the char marks on the track.

An excerpt from this exercise is shown in Figure 5.5.

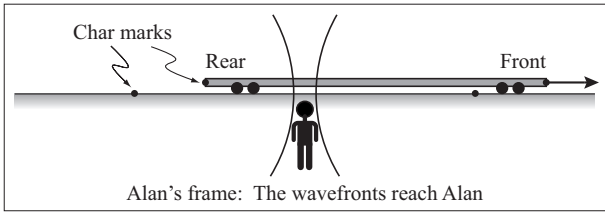
The final direct application of the invariance of the speed of light in the *Simultaneity* tutorial is in an exercise analyzing the train paradox in Beth’s reference frame. As in Alan’s reference frame, students are asked to determine the locations of the centers of the wavefronts from the front and rear sparks. In this case, the wavefronts must be centered at the ends of the train. If the wavefronts were centered at the char marks on the track, Beth would be moving toward the center of the wavefront from the front spark, and away from the center of

A spark jumps between the front end of a train and the track (spark F), and another spark jumps between the rear end of the train and the track (spark R). When each spark jumps, it emits a flash of light (wavefronts F and R). Each spark also leaves a char mark on both the train and the track. Let event F be “spark F jumps” and event R be “spark R jumps.”

Alan is standing on the ground equidistant from the char marks on the track. The wavefronts reach him simultaneously.

Alan’s frame

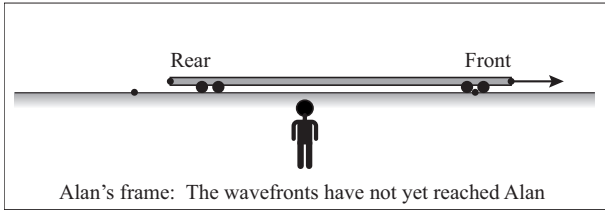
The diagram at right represents Alan’s frame at the instant the wavefronts reach him.



1. In Alan’s frame, does spark F jump *before*, *after*, or *at the same instant as* spark R? Explain.

2. Abigail (not shown) stands at rest relative to the track, near the front char mark on the track. In Abigail’s frame, does spark F jump *before*, *after*, or *at the same instant as* spark R? Explain.

3. The diagram at right represents an instant a short time after the spark jumps between the front of the train and the track in Alan’s frame (before he receives either wavefront).



Complete the diagram by drawing the wavefronts at this instant. Explain.

4. In Alan’s frame, where are the centers of wavefronts F and R? Explain.

Figure 5.5: Third exercise from the tutorial *Simultaneity* requiring use of the fact that the speed of light is invariant and isotropic

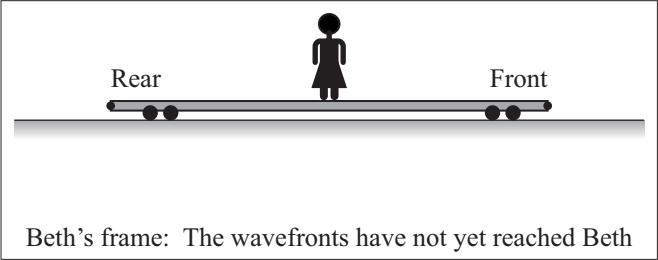
the wavefront from the rear spark. This would mean that she would see the wavefront from the front spark moving toward her at a speed greater than c ; likewise, the wavefront from the rear spark would be moving toward her at a speed less than c . Because both wavefronts must approach her at a speed equal to c , the centers of the wavefronts must be stationary in her Beth’s reference frame, and located at the spatial coordinates associated with the sparks jumping.

An excerpt from this exercise is shown in Figure 5.6.

Observations from the classroom suggest that almost all students complete the third

Beth's frame

1. Complete the diagram at right by drawing wavefronts F and R, in Beth's frame, before either wavefront reaches her.
2. In Beth's frame, does event F happen *before*, *after*, or *at the same instant as* event R? Explain.
3. In Beth's frame, where are the centers of wavefronts F and R? Explain.
4. In Beth's frame, does wavefront F reach Beth *before*, *after*, or *at the same instant as* wavefront R? Explain.



Beth's frame: The wavefronts have not yet reached Beth

Figure 5.6: Fourth exercise from the tutorial *Simultaneity* requiring use of the fact that the speed of light is invariant and isotropic

exercise (locating the centers of the wavefronts from the sparks in Alan's reference frame) very easily and without reflection on the reason for their answer. The fourth exercise gives students significantly more difficulty. Many students have not considered that the centers of the wavefronts could be anywhere but the char marks on the track. Follow-up conversations with these students indicate that students are not considering the invariance of the speed of light when answering these questions.

These observations are consistent with our observations that students in tutorial (after lecture instruction) are often able to state Einstein's second postulate of special relativity, but frequently fail to see the implications of it. This indicates that students have memorized the statement but do not truly understand it; nor do students seem have a functional understanding of the differences in propagation of light, sound, and particles.

5.3.2 Assessing the tutorial *Simultaneity* through post-tests

As described above, qualitative understanding of the relativity of simultaneity and the invariance of the speed of light requires use of the fact that for events that involve the emission

of a flash of light, the center of the wavefronts of the light is co-located with the spatial coordinate of the event. (In other words, both the event location and the center of the wavefronts of light for each observer is at a fixed position, unmoving with respect to that observer.) This particular aspect of the invariance of the speed of light is used multiple times in the *Simultaneity* tutorial, but is (in our experience) rarely discussed during traditional instruction in special relativity. We were unsure whether the *Simultaneity* tutorial was sufficient in addressing the difficulties our students faced during the tutorial session; therefore, we began our investigation of student understanding of the invariance of the speed of light with post-testing, after all relevant instruction.

To this end, we designed post-tests with four questions similar to the contexts used in the first two exercises of the *Simultaneity* tutorial (in which a spherical wavefront is emitted at the location of an observer or observers) as well as the second two relevant exercises (in which spherical wavefronts are emitted some distance away from an observer or observers) were designed. Both types of post-test questions are described below. Note that due to the constraints of the course, the *Simultaneity* tutorial was always used after the last midterm and before the final course examination. Thus, these questions always appeared on the final course exam, which usually consists entirely of multiple-choice questions.

5.3.2-a *Beth and Strobe post-test*

The *Beth and Strobe* post-test is a multiple-choice question using a context similar to that in the first exercises in the *Simultaneity* tutorial, in which a flash of light is emitted as an observer passes. In this case, an observer Beth passes a strobe that is fixed on the ground. She passes it just as it emits a flash of light. Students are shown a figure that shows the locations of Beth, the strobe, and the locations of the wavefronts of the flash of light shortly after the flash has occurred in the reference frame of an observer Andy who is at rest with respect to the ground. In Andy's reference frame, the wavefronts are centered at the strobe. Students are asked to determine the location of the center of wavefronts in Beth's reference frame. The relevant excerpt of the *Beth and Strobe* context is shown in Figure 5.7.

Andy, at rest with respect to the ground, places a strobe midway between two light detectors, F and R, which are a few meters apart. (A strobe is a device that emits a short pulse of light in all directions.) He then stands near detector F. Beth moves relativistically along the line connecting the detectors and strobe.

At the instant that Beth passes the strobe in Andy's frame, it emits a flash of light. The circle at right represents the wavefront of the flash of light in Andy's frame a short time after the strobe goes off.

- Let **event F** be detector F detects a flash of light from the strobe.
- Let **event R** be detector R detects a flash of light from the strobe.

In Beth's frame, which of the following best describes the location of the center of the wavefront after the strobe goes off?

- Only at Andy's location
- Only at Beth's location
- Only at the strobe's location
- Both at Beth's and the strobe's location (these are equivalent)

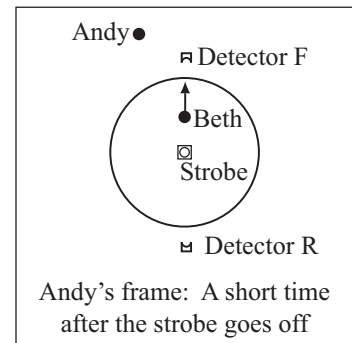


Figure 5.7: *Beth and Strobe* post-test excerpt testing student understanding of the invariance of the speed of light

The correct reasoning for this question is very similar to the reasoning for the first two speed-of-light exercises in the *Simultaneity* tutorial. In this case, because the strobe flashes just as Beth passes it, the location of the event “the strobe flashes” in Beth’s reference frame is best described as at Beth’s location. In order for the speed of light to be equal to c in Beth’s reference frame, this must also be the location of the center of the wavefronts in her frame. Therefore, the correct answer is B. We note that this question is likely to be slightly more difficult for students than the context in the tutorial in which a spark jumps between two observers; as described in Chapter 4, students have greater difficulty determining the correct location of events when the event is more strongly associated with a single frame. In this case, we suspected that many students would associate the strobe flash with the reference frame of the strobe. In the *Simultaneity* tutorial context, the event associated with the spark jumping is less easily associated with a single frame, as the spark jumps between

Table 5.1: Multiple-choice post-test results for *Beth and Strobe* multiple choice question involving the invariance of the speed of light. The correct answer is highlighted.

Location of center of wavefronts in Beth's reference frame ($N = 165$) ^a	
A (Andy's location)	5%
B (Beth's location)	60%
C (Strobe's location)	20%
D (Both Beth's and Strobe's location)	15%

^aSection 123B111.

observers in different reference frames. Therefore, we expect students who have difficulty determining event location, as well as students that do not understand the consequences of the invariance of the speed of light to answer that the wavefronts are centered at the strobes location even in Beth's reference frame.

Student performance on the *Beth and Strobe* question is shown in Table 5.1. Almost two-thirds of the students ($N = 165$) answered correctly that the wavefront would be centered at Beth in Beth's reference frame (answer B). About 20% of students answered that the wavefront would be centered at the strobe (answer C), while a surprising 15% of students answered that the wavefront would be centered at both Beth and the strobe (answer D). There are several possible reasons for this latter result. One possibility is that students did not understand that the question was asking specifically about Beth's reference frame; in that case, choice D would be a correct answer, as the wavefront would be centered at Beth's location or the strobes location, depending on the frame.¹ Another possibility is that students recognize (correctly) that Beth's location is equivalent to the strobe's location at the instant the strobe flashes, but fail to recognize that these locations are not equivalent at any other time. Because the question was multiple choice, we cannot be sure of student reasoning on this question.

Similarly, we cannot be sure why performance on this question was relatively good (60%

¹There are other reference frames in which neither of these locations would be correct, but the context does not explicitly include any of these other reference frames.

correct). It is possible that this context was similar enough to the context in the *Simultaneity* tutorial that students were able to transfer their reasoning to the new context easily. It is also possible that this particular type of question, in which the observer herself serves as the marker of the event location, is less difficult for students in general, despite the fact that the event “the strobe light flashes” is easily linked to the reference frame of the strobe.

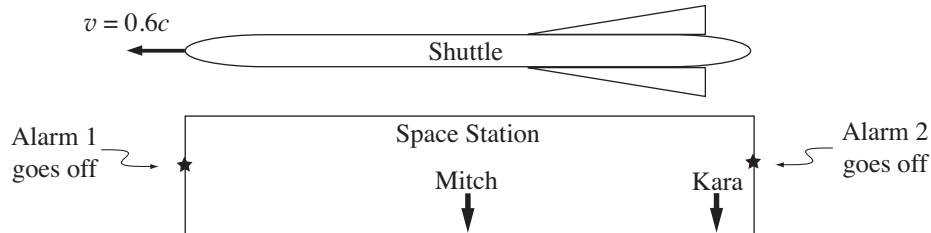
5.3.2-b *Mountain Firecrackers vs. Long Shuttle context*

In Spring Quarter 2012, we ran two questions using two different contexts in the two sections (A and C) of Physics 123. We had observed that students performed relatively well on the speed-of-light question in Winter 2011, but we wanted to examine other aspects of their understanding. Conversations with students during tutorial sessions gave us insight into student use of the ends of the train (particularly with the char marks) to locate the centers of the wavefronts from the sparks in the reference frame of the train. We therefore hypothesized that students would perform better on a post-test in which they had an object to use to locate the centers of the wavefronts in the “moving” frame. To test this, we ran two versions, one with a shuttle that was long enough to mark both event locations, and one with a shorter shuttle. We also wanted to see if student would do worse than on the *Beth and Strobe* question if the observer in the “moving” frame was not at the event location.

Long Shuttle context In Physics 123A, we ran the *Long Shuttle* context. In the *Long Shuttle* task, a long shuttle flies past a space station at relativistic speed. In the reference frame of the space station, the length of the shuttle happens to be equal to the proper length of the space station. Alarms 1 and 2 are located at the ends of the space station, each of which emits a flash of light when triggered. The alarms are triggered simultaneously in the reference frame of the space station. In the frame of the space station, the front of the shuttle is at the location of alarm 1 when it goes off. An excerpt of the *Long Shuttle* is shown in Figure 5.8.

The question had several parts, one of which was designed to test student understanding

Mitch and Kara are at rest inside a space station. Mitch is exactly at the center; Kara is at the right end. A shuttle is flying from right to left with speed $v = 0.6c$ relative to the station. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Alarms 1 and 2 go off at opposite ends of the space station. Each alarm emits a flash of light (circular wavefronts 1 and 2, respectively). Mitch, an intelligent observer in the reference frame of the space station, receives the light from the two alarms at the same instant and correctly determines that the alarms go off simultaneously in his frame.

The figure shows Mitch, Kara, and the shuttle in the reference frame of the space station at the instant both alarms go off.

In the shuttle frame, the center of wavefront 1:

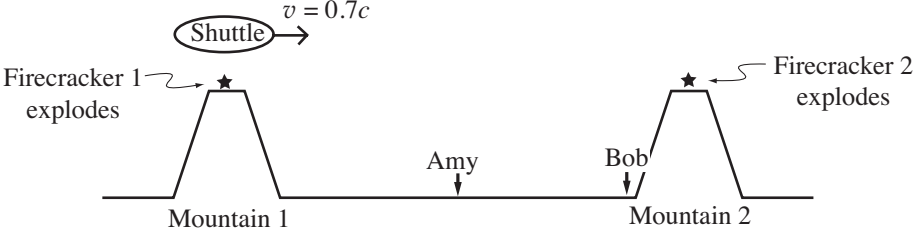
- A. moves to the right
- B. moves to the left
- C. is stationary
- D. More information is needed to answer

Figure 5.8: *Long Shuttle* post-test excerpt testing student understanding of the invariance of the speed of light

of the invariance of the speed of light. In this part, students are asked whether the center of wavefront 1 (the wavefront from alarm 1) moves to the right (answer A), moves to the left (answer B), or is stationary (answer C) in the reference frame of the shuttle. Because the center of the wavefront of a light wave must be stationary in every frame, the correct answer must be answer C. We would expect that students who link the location of the event to the alarm, or students who don't understand that the speed of light does not depend on the motion of the source would choose answer A (moves to the right). Students who choose answer B might have difficulty determining the direction of relative motion in multiple reference frames.

Mountain Firecrackers context In Physics 123C, we used the *Marathoners in Space* context, described in Chapter 4, section 4.2.9-a. The question asked was identical to the question asked in the *Long Shuttle* question. The relevant section of the *Mountain Firecrackers* question is shown in Figure 5.9.

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob is near mountain 2. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light (circular wavefronts 1 and 2, respectively). Amy, an intelligent observer in the reference frame of the ground, receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows Amy, Bob, and the shuttle in the reference frame of the ground at the instant both firecrackers explode.

In the shuttle frame, the center of wavefront 2:

- moves to the right
- moves to the left
- is stationary
- More information is needed to answer.

Figure 5.9: Mountain Firecracker post-test excerpt testing student understanding of the invariance of the speed of light

Note that in this case, the short shuttle is at the location of firecracker 1 when it explodes, and is moving toward firecracker 2. The location of the center of wavefront 2 is located some distance beyond the front of the shuttle, and “floats” there. There is nothing in the reference frame of the shuttle to which the location of the wavefront is easily linked. We expected that performance on this version would be lower than that on the *Long Shuttle* question. Table

Table 5.2: Multiple-choice post-test results for *Beth and Strobe* multiple choice question involving the invariance of the speed of light. The correct answer is highlighted.

Motion of center of wavefront in shuttle reference frame	($N = 151$) ^a	($N = 193$) ^b
A (moves in direction of “source”)	60%	65%
B (moves opposite of direction of “source”)	10%	5%
C (stationary)	30%	25%
D (Not enough information to answer)	0%	0%

^a Section 123A122. ^b Section 123C122.

5.2 compares student performance on the two questions.²

Commentary on *Long Shuttle* and *Mountain Firecracker* questions Although performance was slightly better on the Long Shuttle version, it was not markedly so. In both versions, students seem to have particular difficulty with the idea that the location of the center of a wavefront of light does not change with time (that is, it is stationary) in any reference frame, whether or not an object exists to help locate it. Approximately two-thirds of students in both classes answered that the center of the wavefronts would move in the direction of the object responsible for the emission of the wavefront. Fewer than a third of students in both sections answered correctly.

Note that student performance on both the *Long Shuttle* and *Mountain Firecracker* questions than on the question described in section 5.3.2-a, in which the observer was at the location of the event associated with the emission of light when it occurred.

5.3.2-c New wording on multiple post-test contexts

The difference in performance on the questions described in section 5.3.2-b compared to the *Beth and Strobe* question (5.3.2-a) may have been due to differences in the location of the observer or to wording used in the *Long Shuttle* and *Mountain Firecrackers* contexts. was

²Note that the direction of the shuttle is opposite in the two contexts; for ease of presentation of the data, I have changed the answers to be consistent with both questions.

confusing, or that students were not understanding what was being asked. To check this, we reworded the questions and answer choices as follows:

[The observer in the shuttle frame] correctly determines the location of event 1 in the shuttle frame to be x_1 . In the shuttle frame, the center of the wavefront of the light from event 1 is:

- A. spherical and centered at location x_1 (which is stationary in the shuttle frame)
- B. spherical and centered at alarm 1 (which moves to the right in the shuttle frame)
- C. non-spherical and centered at location x_1 (which is stationary in the shuttle frame)
- D. spherical and centered at alarm 1 (which moves to the right in the shuttle frame)

This wording (with only slight variations to account for the direction of the relative motion and changes in the object associated with the event in the natural “rest frame” of the question) was used in multiple contexts over several quarters. The results from each quarter were similar enough that the data are pooled, and the results from all contexts are tabulated together. The contexts in which this question and wording were used are: the *Marathoners in Space* and *Mountain Firecrackers* contexts, both described in Chapter 4; and the *Long Shuttle* context, described above. Results from these contexts are shown in Table 5.3. In the table, the term “source” refers to the object that emits the light (e.g., a firecracker or alarm).

With this wording, post-test performance was somewhat better, although not at the level of student performance on the *Beth and Strobe* task. The majority of students (80%) recognize that the wavefront should be spherical in shape, consistent with the exercises in the *Simultaneity* tutorial; however, only half of students recognize that the center of the wavefront must also be stationary. Students choosing answer B do not seem to recognize that a spherical wavefront with a center that changes location with time is not consistent with the idea that the speed of light is the same in all directions in all frame, nor the invariance

Table 5.3: Multiple-choice post-test results for multiple contexts involving the invariance of the speed of light. The correct answer is highlighted.

Motion of center of wavefront in shuttle reference frame ($N = 1085$) ^a	
A (spherical and at event location)	50%
B (spherical and at source)	30%
C (non-spherical and at event location)	10%
D (non-spherical and at source)	10%

^a Sections 123A124131132, 123B131141, and 123C132.

of the speed of light.

5.3.2-d Preliminary conclusions

Based on the post-test results described above, the *Simultaneity* tutorial is not sufficient in addressing student difficulties regarding the invariance of the speed of light. Although a majority of students are able to answer questions in which an observer marks the location of the center of a wavefront (e.g., the *Beth and Strobe* task), performance on more difficult tasks suggests that students are using a memorized result, rather than answering based on true understanding. We also found that using a long spaceship, the ends of which could serve as markers of event location in the spaceship frame (as in the *Long Shuttle* context) did not improve student performance on post-tests. It is still unclear whether including a physical mark left by an event (such as the char marks left by the sparks in the *Simultaneity* tutorial) would prove more effective for students. However, it seems that the context featuring a long ship did not prompt students to imagine similar marks any more than the contexts involving a shorter ship.

Finally, our results suggest that at least half of students do not recognize how a non-stationary center of wavefronts is inconsistent with the invariance of the speed of light. It is possible that failure to see this inconsistency is related to difficulties with Galilean relativity, including transformation of velocities.

5.3.3 Further investigation of student understanding of the invariance of the speed of light

Based on the results from the previous section, the focus of our investigation shifted to a more in-depth probe of student difficulties with the invariance of the speed of light. We developed both pre- and post-tests for this part of the research, which had a focus on student understanding of the differences in propagation of light and sound wavefronts.

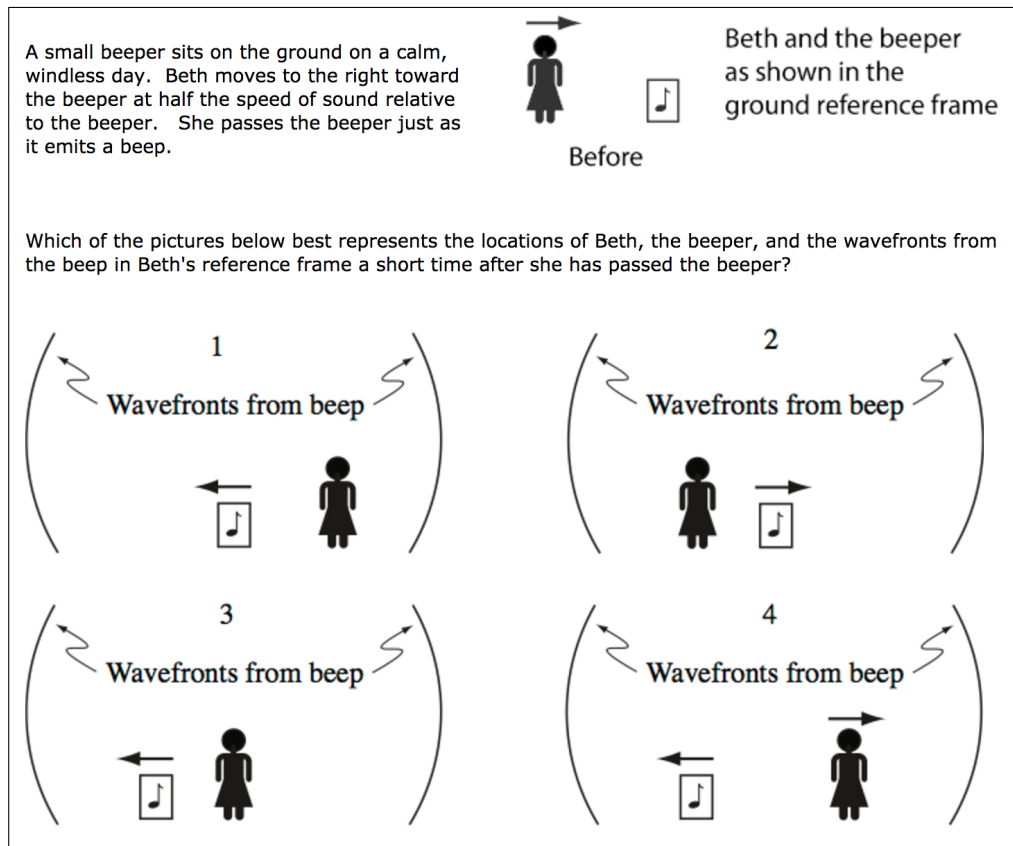
5.3.3-a Speed of light pretest tasks: *Beth and Box*

We began by comparing results from two pretest questions in which the only difference was the type of signal emitted by a box as an observer passed it. The *Beth and Box* pretest context was introduced in Chapter 4 because of questions relating to event location. This pretest context also included questions relating to student understanding of the difference between the propagation of light and sound. We describe both the original version and a modified version.

Original version of *Beth and Box* question In the *Beth and Box* (sound) context, Beth approaches a small box that sits on the ground on a calm, windless day. Beth moves at half the speed of sound relative to the ground. The box emits a beep just as Beth passes it. Students are shown four pictures that show the locations of Beth, the box, and the wavefronts of the beep and are asked to identify which picture correctly depicts a short time after the beep is emitted in Beth's frame. The *Beth and Box* (sound) task is shown in Figure 5.10.³

Other students were given a similar task, *Beth and Box* (light). In this context, shown in Figure, Beth approaches a small box that sits on the ground but she moves at half the speed of *light* relative to the ground. The box emits a flash of light just as Beth passes it. Students

³The manner in which Beth's reference frame is specified was varied in the multiple times the context was used; this variation did not have an effect of the results, so only a single example of the wording is shown here. Additionally, sometimes the box was described as a beeper, while other times it was just a box. Again, this change in wording had no effect on the results so only a single version is shown here.

Figure 5.10: *Beth and Box* (sound) pretest context

are shown the same four pictures and asked to identify the picture that most correctly shows the locations of Beth, the box, and the wavefronts from the flash of light in Beth's reference frame a short time after she has passed the box.

Although these two questions are very similar, they require slightly different reasoning and have different answers. To answer the sound version, students must recognize that although the speed of sound does not depend on the motion of the source, an observer's measurement of the speed of sound does depend on that observer's velocity relative to the medium in which the sound wave propagates. In this case, the sound wave propagates through air that is still relative to the ground; the source of the sound (the box) is also at rest relative to the medium. Therefore, the center of the wavefront is located at the box. In Beth's reference frame, the box moves to the left, so picture 1 must be the correct answer.

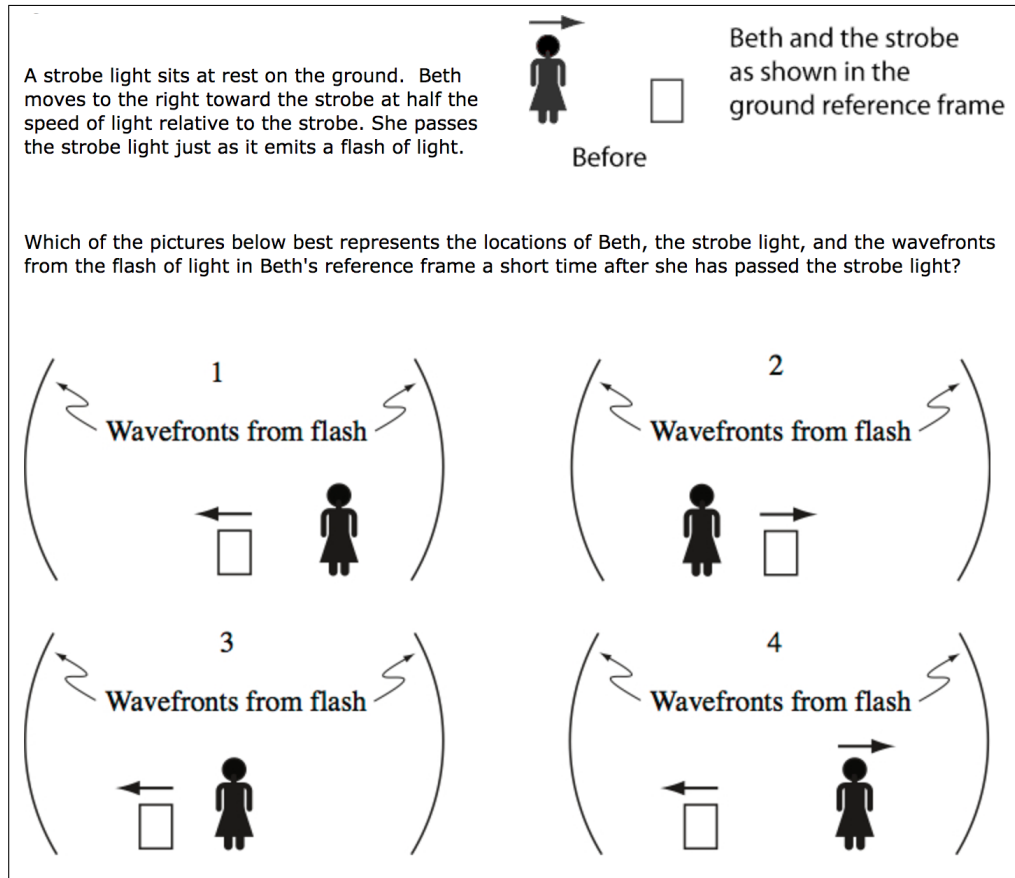


Figure 5.11: *Beth and Box* (light) pretest context

For the light context, we recognize that the speed of light must be the same in all directions in Beth's reference frame as well as in the reference frame of the box, and the event associated with the flash being emitted is located at Beth in her reference frame. Therefore, Beth should be at the center of the wavefronts in her reference frame; the correct answer is picture 3.

Picture 2 has the location of the box correct, but the motion is opposite what it should be in Beth's reference frame. Likewise, Beth is on the wrong side of the box. In picture 4, the location of the center of the wavefronts is halfway between Beth and the box. This picture would be correct for the sound context if Beth and the box had a relative velocity of half the speed of sound, but also a relative speed of a quarter of the speed of sound relative to

Table 5.4: Comparison of student performance on *Beth and Box* sound and light pretest tasks. The correct answers are highlighted.

Answer	Sound context ($N = 143$) ^a	Light context ($N = 794$) ^b
Picture 1	35%	35%
Picture 2	5%	5%
Picture 3	25%	45%
Picture 4	25%	15%
None of these	10%	< 5%

^a Section 123B132.

^b Sections 123A132134141142144, 123B141, and 123C142.

the ground in opposite directions. This picture cannot be correct for Beth's reference frame in any case, as Beth should have zero relative velocity in her own reference frame.

These questions were designed to test student understanding of the difference between the propagation of sound and light. We expect that many students understand that light does not propagate as a particle does; that is, we believe that many students know that the speed of a laser beam that is emitted from a spaceship moving at close to the speed of light is not greater than c . This question instead probes student understanding of the fact that, although light is a wave, its speed is not the same relative to a medium but rather is absolutely invariant as measured in any inertial reference frame.

Results from original version of *Beth and Box* question These two versions were given to different groups of students; for the results reported, no student saw both the light and sound contexts. The students were divided between the contexts based on the section of Physics 123 in which they were enrolled. However, due to an error in programming the pretests, the sound context was only run in one section for one quarter. Results for both contexts are shown in Table 5.4.

Although the percentage of students answer the light version appears somewhat greater than that of the sound version, performance in both contexts is relatively poor. The results from these versions of the *Beth and Box* pretest are not particularly illustrative. To get

Table 5.5: Student performance on *Beth and Box* sound and light pretest tasks. The correct answers are highlighted.

Picture choice ($N = 632$) ^a	Sound	Light
Picture 1	45%	30%
Picture 2	5%	5%
Picture 3	35%	40%
Picture 4	15%	20%
None of these	5%	5%
Same picture for both	60%	
Picture 1 for both	25%	
Picture 3 for both	25%	
Correct on both	15%	

^a Sections 123A151152154, 123B151, and 123C152.

greater insight into student reasoning about the difference between light and sound propagation, we designed a pretest task in which students saw both the sound and light contexts.

Modified *Beth and Box* question As described in section 4.3.3-a, the light question on the pretest had two versions. In the first version, the box emits a flash of light as described above. In the second version, a spark jumps between Beth and the box at the instant she passes it, and the spark emits a spherical wavefront of light. This difference was, in part, an attempt to look for differences in student performance on the light version when the source of the light wasn't at rest in a particular reference frame. There was a difference in student performance between the two versions on questions involving event location specifically as described in section 4.3 but there was no significant difference on questions involving the location of the center of the wavefronts of light. Therefore, results from the two versions are combined in the following analyses.

Results from modified *Beth and Box* question Performance on both questions was approximately the same, with 45% of students choosing the correct picture (picture 1) for the

sound context, and 40% choosing the correct picture (picture 3) for the light context. The most popular incorrect answer for both questions was the correct picture for the other context (i.e., picture 3 for the sound context, and picture 1 for the light context). Sixty percent of students chose the same picture for both contexts, with 50% of all students choosing either picture 1 or picture 3 for both; the remaining 10% chose picture 4 for both.

After choosing a picture for the light context, students were asked to explain why the picture should be the same in both cases (if they chose the same picture for both) or why the pictures should be different (if they chose different pictures for both). Interestingly, explanations by students choosing picture 1 for both were indistinguishable from explanations from students choosing picture 3 for both. The majority of explanations focused only on the relative speeds of Beth and the wavefronts in the reference frame of the ground. Students choosing picture 4 for both contexts had similar reasoning, though explanations from these students tended to be less complete. The following quotes are representative of explanations for students choosing the same picture for both contexts.

“They should be the same because in the first she is half the speed of sound and a sound is emitted. In the second she is half the speed of light and a light is emitted.” (Picture 1 for both)

“It is the same exact setup but in the first one the relative speed between Beth and object is $1/2$ speed of sound when sound is emitted. In second light, which is faster is emitted instead of sound but the relative speed between object and Beth is now half the speed of LIGHT. So the difference in diagrams is non existent. The relative speeds of the objects in the system do not change (Beth compared to radially emitted sound or light).” (Picture 3 for both)

“The relative positions will be the same since Beth is moving half the speed of the wave in either case.” (Picture 4 for both)

Based on the explanations alone, there is little evidence how students chose one picture over another; it seems likely that many guessed without understanding the difference between

the two figures. These students did not seem to consider that light and sound behave differently. Perhaps unsurprisingly, students who chose either picture for both contexts did not mention the invariance of the speed of light in their explanations. Although this pretest was administered after lecture instruction on special relativity, including coverage of Einstein's postulates, it seems clear that students are not considering the consequences of the invariance of the speed of light in this context.

Only 15% of students answered both questions correctly. The majority of students answering correctly used at least partially correct reasoning, suggesting that they understood that their answers to the two contexts were necessarily different due to the invariance of the speed of sound. If we remove this 15% of students from the population, we see that approximately equal proportions of students chose picture 1 or 3 in both the light and sound contexts. This result lends weight to the hypothesis suggested above that students chose a picture based on ideas other than the invariance of the speed of light.

5.3.3-b *Speed of light post-test tasks: Observer and Box*

To test whether the special relativity tutorials affect student ability to think about the location of the center of wavefronts in sound and light contexts, we gave a post-test in Physics 123 that was similar to those on the *Beth and Box* pretests. The students receiving the post-test did not see these questions on the pretest for the *Simultaneity* tutorial. One section of Physics 123 saw the sound context (Willa and Box); the other saw the light context (Daisy and Box). The two contexts are shown in Figures 5.12 and 5.13.

A comparison of student performance on the two questions is shown in Table 5.6.

Although we saw a significant increase in the percentage of students answering correctly in both contexts, we did not see a decrease in the percentage of students choosing the picture for the opposite context; that is, for the light task, 30% of students chose the picture that would have been correct in the sound context, and for the sound task, 40% of students chose the picture that would have been correct in the light task.

If we assume that students who chose the incorrect answer did so for the same reasons

A small box sits on the ground on a calm, windless day. Willa moves to the right at half the speed of sound relative to the ground, as shown in the figure at right.

The box beeps four times as Willa approaches and passes it. The second beep is emitted at the instant that Willa passes the box. The beep produces a sound wave that moves outward in all directions. Call “the box beeps for the second time” event B_2 . Willa passes the box at spacetime coordinate $(x, t) = (0 \text{ m}, 0 \text{ s})$ in her frame.

Which picture below shows the location of Willa, the location and velocity of the box, and the locations of the wavefronts from the second beep in Willa’s reference frame a short time after Willa has passed the box?

0.5 v_{sound}

Willa and the box in the reference frame of the box

Before

1
Wavefronts from beep 2

2
Wavefronts from beep 2

3
Wavefronts from beep 2

4
Wavefronts from beep 2

A. Picture 1
B. Picture 2
C. Picture 3
D. Picture 4
E. None of these

Figure 5.12: Willa and Box (sound) post-test task

as students who saw the paired version of these questions on the pretest described in section 5.3.3-a above (i.e., for reasons other than understanding of the invariance of the speed of light, or lack of invariance of the speed of sound), we might hypothesize that approximately equal percentages of students picked picture 1 or 3 in either context for incorrect reasons. That is, because in the Willa and Box (sound) context we see 40% of students (incorrectly) chose picture 3, we might assume that approximately 40% of students chose the correct picture (picture 1) with incorrect reasoning. Similarly, we might guess that only 30% of students answered the Daisy and Box (light) task correctly with correct reasoning. Making these

A small box sits on the ground. Daisy moves to the right at half the speed of light relative to the ground, as shown in the figure at right.

The box emits four flashes of light as Daisy approaches and passes it. The second flash is emitted at the instant that Daisy passes the box. The flash produces a light wave that moves outward in all directions. Call “the box flashes for the second time” event F_2 . Daisy passes the box at spacetime coordinate $(x', t') = (0 \text{ m}, 0 \text{ s})$ in her frame.

Which picture below shows the location of Daisy, the location and velocity of the box, and the locations of the wavefronts from the second flash in Daisy’s reference frame a short time after Daisy has passed the box?

1
Wavefronts from flash 2

2
Wavefronts from flash 2

3
Wavefronts from flash 2

4
Wavefronts from flash 2

A. Picture 1
B. Picture 2
C. Picture 3
D. Picture 4
E. None of these

Figure 5.13: Daisy and Box (light) post-test context

assumptions would lead us to the possible conclusion that the *Simultaneity* tutorial improved student reasoning about the invariance of the speed of light, but did not improve student understanding of the speed of sound. Apparent improvement in the sound context may have been due instead to an improved understanding of pictures from a particular reference frame or ability to think about relative motion. Given the focus on the propagation of wavefronts of light rather than sound in the *Simultaneity* tutorial, this imbalanced improvement in the two contexts may not be surprising.

Table 5.6: Comparison of student performance on Willa and Box (sound) and Daisy and Box (light) post-test tasks. The correct answers are highlighted.

Answer	Willa and Box (sound) ($N = 170$) ^a	Daisy and Box (light) ($N = 150$) ^b
Picture 1	55%	30%
Picture 2	< 2%	< 2%
Picture 3	40%	60%
Picture 4	< 2%	5%
None of these	0%	0%

^a Section 123A164. ^b Section 123B164.

5.3.3-c Related post-test results: Asteroids task

To test student understanding of the invariance of the speed of light more directly than in the post-tests described in section 5.3.3-b, we ran the *Asteroids* question as part of a post-test. In the *Asteroids* problem, a space station is halfway between asteroids A and B, with all three objects at rest with respect to each other. A probe moves with relativistic speed past the three objects; when the probe passes the space station, both the probe and the space station emit a light signal that moves out in all directions. Students were asked whether the light signal from the probe reached asteroid A before, after, or at exactly the same time as the light signal from the space station.

The relevant portion of the *Asteroids* context is shown in Figure 5.14.

Because the probe and the space station each emit a light signal at the instant that they share a location, and the speed of light does not depend on the motion of the source, the two signals should reach asteroid A at the same instant. Students that believe that the speed of light depends on the speed of the source are likely to answer that asteroid A receives the signal from the space station before the signal from the probe (choice A), as the probe is moving away from asteroid A.

Only 40% of students answered correctly that asteroid A would receive the signals from the space station and probe simultaneously. This question was designed to probe, in particular, the second formulation of Einstein's postulate regarding the speed of light. These

A space station is halfway between asteroid A and asteroid B. All three objects are at rest with respect to one another. A probe moves with constant relativistic speed v along a line that passes very close to all three objects.

The picture at right represents the reference frame of the space station at the instant the probe passes the space station. At that instant in the space station frame, the probe and space station each emit light signals that move outward in all directions.

In the reference frame of the probe, in what order does asteroid A receive the signals from the space station and the probe?

A. Asteroid A receives the signal from the space station *before* the signal from the probe.
 B. Asteroid A receives the signal from the space station *after* the signal from the probe.
 C. Asteroid A receives the signal from the space station *at exactly* the signal from the probe.
 D. Not enough information is provided to answer this question.

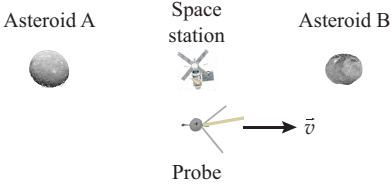


Figure 5.14: *Asteroids* post-test task testing student understanding of the invariance of the speed of light.

Table 5.7: Multiple-choice post-test results for the *Asteroids* task. The correct answer is highlighted.

Order in which Asteroid receives signals	($N = 191$) ^a
A (space station before probe)	50%
B (space station after probe)	10%
C (same instant)	40%
D (not enough information)	0%

^a Section 123B161.

results suggests that students do not recognize that the speed of light does not depend on the motion of the source. As mentioned previously, we find (informally) that a majority of students are able to state that the speed of light is the same in all reference frames. However, it is possible that students have not heard the second formulation or do not recognize its equivalence to the first. The most popular incorrect answer (that the signal from the space station arrives before the signal from the probe) indicates that students believe that the speed of the light from the probe in the frame of the space station is less than that of the space station.

Although results from this question suggest that most students do not recognize that the

speed of light is the same in all reference frames, it is possible that other student difficulties are preventing students from recognizing that the two signals are arriving at asteroid A at the same instant. In particular, research that will be discussed in Chapter 6 indicates that many students don't understand the principle of coincidence: if two (or more) events share a single spacetime coordinate in one reference frame, the events must share a single spacetime coordinate in all reference frames. In the *Asteroids* task, recognition of this fact is necessary to answer correctly: students must realize that the events corresponding to the emission of the signals from the probe and space station happen simultaneously in the reference frame of the probe as well as the reference frame of the space station. It is possible that these students are misunderstanding or overgeneralizing the relativity of simultaneity to mean that no events that are simultaneous in one reference frame are also simultaneous in any other reference frame.

5.4 Conclusions and future work

The investigation described in this chapter suggests that students do not have sufficient understanding of the invariance of the speed of light after traditional instruction to understand that the motion of the center of a wavefront of light must be stationary in all frames; moreover, a majority of students do not understand that the behavior of light is different from that of sound in this respect. Use of the *Simultaneity* tutorial is associated with small improvements in student performance in contexts involving light; however, it is not known whether students recognize the differences in propagation of light and sound after tutorial instruction. This suggests that further post-testing probing this aspect of student understanding is necessary.

The evidence of student difficulties recognizing the differences in propagation of light and sound from pretests for the *Simultaneity* tutorial indicates that student understanding of topics in Galilean relativity, particularly understanding of relative motion and addition of velocities, is not as deep as we want. Many students seem to lack the understanding that for light, a non-stationary center of wavefronts would contradict the invariance of the speed of light. This idea seems to be particularly difficult for students when there is not an observer at the location of the center of the wavefront of light.

As we will discuss in Chapter 6, a lack of understanding of the consequences of the invariance of the speed of light is associated with a lack of understanding of concepts related to causality. The *Simultaneity* tutorial and the associated homework encourage students to use causality as a basis for determining the order of spatially separated events in frames other than the ground frame. However, we find that incorrect student assumptions about event location and the location of the center of wavefronts from a flash of light (stemming from difficulties with reference frames and the invariance of the speed of light) are leading students to fail to uphold causal relationships in all reference frames. This indicates that students are not using the key concepts identified in this dissertation (reference frames, the invariance of the speed of light, and causality) as necessary for conceptual understanding of the relativity of simultaneity to determine the order of events in reference frames other than

the ground frame.

The results from this chapter suggest that changes to the special relativity tutorials (including modifications to the existing tutorials as well as development of new curricula) are necessary to improve student understanding of the invariance of the speed of light, and the consequences of that invariance.

Chapter 6

STUDENT UNDERSTANDING OF EVENTS AND CAUSALITY IN SPECIAL RELATIVITY

This chapter presents our investigation into introductory student understanding of events and causality. We describe tutorial exercises developed to address student difficulties with the idea that coincident events must share a single spacetime coordinate in all reference frames. Persistent student difficulties with the principle of coincidence and events associated with the reception of signals, as well as student understanding of the frame-independence of events are discussed. All data were collected from pretests and post-tests administered to students enrolled in the last quarter of the introductory physics course (Physics 123) at the University of Washington between the years 2010 and 2016.

6.1 Introduction

The concept of causality (the idea that one event or process causes another) is not unique to special relativity; the principle of causality underlies all scientific understanding of how the universe works. However, the principle of causality played an important role in the development of the special theory of relativity in general, and in Einstein’s train paradox in particular. It is necessary to give up absolute simultaneity in order to preserve causality. Accepting that simultaneity is relative resolves the “paradox,” as described in qualitative discussions of Einstein’s train paradox in this dissertation. (See, for example, Chapter 1.)

As with Einstein’s second postulate of special relativity, there are a number of ways that the principle of causality can be stated. Most simply, the principle of causality states that if event A causes event B, then all observers would measure that event A happens first. Even more simply stated: the cause must precede the effect. However, because the time coordinates of events may not be the same as measured by observers in different reference frames, we may more carefully state the principle of causality as this:

The principle of causality

If there exists a reference frame in which two given events occur at the same spatial coordinate, the time sequence of those events must be preserved across all reference frames.

A specific and important case of this is the *principle of coincidence*:

The principle of coincidence

If two (or more) events occur at a single spacetime coordinate in one reference frame, those events occur at a single spacetime coordinate in all reference frames.

Both of these principles rely on the frame-independence of events (i.e., the fact that an event that occurs in one reference frame must occur in all reference frames). Although this idea may seem so fundamental that it does not need to be stated, some of the research described in this chapter indicates that student belief in absolute simultaneity is so persistent

that it often leads to a willingness to give up not only the principle of causality but also the frame-independence of events. Other results suggest that student may fail to recognize the necessity of upholding causal relationships between events in all reference frames, or that any measurements made in any reference frame will lead to a correct determination of what occurs.

The principle of causality is rarely taught in the above form during lecture instruction in special relativity, nor is it an idea that can be easily seen through the application of formulas, although it is consistent with the idea of time dilation. The formula for time dilation, $\Delta t' = \gamma \Delta t$, is used to compare differences in the interval of time between two events. The proper time, Δt , is the time interval measured by a clock *at the position of the two events*; it is related to the time interval $\Delta t'$ measured by a clock in a different reference frame by the Lorentz factor γ . The quantity γ is greater than zero, and therefore Δt and $\Delta t'$ always have the same sign. This implies that the events have the same time sequence in every frame. Moreover, when $\Delta t = 0$, it follows that $\Delta t' = 0$ for all other reference frames—consistent with the principle of coincidence. However, we find (informally) that many introductory students do not understand the consequences of time dilation and are unable to use the formula for time dilation to support these causality-related ideas.

Organization of Chapter 6 In §6.2, we discuss the use of causality-related concepts in qualitative analyses of the relativity of simultaneity, as well as prior research on student understanding of causality in special relativity. In §6.3, we describe the exercises in the special relativity tutorials that rely on the principle of causality, as well as exercises designed to address student difficulties with the principle of coincidence. We also comment on student difficulties with these ideas that have been observed during tutorial sessions, and student ability to apply the principle of causality appropriately and spontaneously. We also describe some initial attempts to help students by making changes to the tutorials and associated homework. It quickly became clear however the modifications were not effective and a more detailed understanding of student reasoning was necessary. In §6.4, we describe pre-

and post-test tasks used to identify and explore student difficulties with causality-related ideas. Additionally, we describe student difficulties related to the identification of events, and the effect those difficulties have on student understanding of causality. Finally in §6.5, we summarize our findings, discuss the effectiveness of the tutorials, and suggest areas for future research and curriculum development.

6.2 Causality and the relativity of simultaneity

As described in Chapter 1, application of the principle of causality is necessary for qualitative understanding of the relativity of simultaneity in Einstein's train paradox. Recall that in the train paradox, a train moves at constant speed along a long, straight track. Both ends of the train are struck by lightning simultaneously in the reference frame of the ground. An observer stands near the track and is passed by the middle of the train just as the lightning strikes. Being halfway between lightning strikes that occur simultaneously in his reference frame, the observer receives the wavefronts from the lightning strikes simultaneously.

This simultaneous reception of the two wavefronts qualifies as two coincident events; therefore, the principle of coincidence states that the observer must receive the wavefronts from the lightning strikes simultaneously in all reference frames, including the reference frame of the train. However, in the train reference frame, the ground observer is closer to the center of the wavefront from the rear lightning strike at the instant he receives the two wavefronts, and further from the center of the wavefront from the front lightning strike. (Recall that the centers of the wavefronts for the train frame are fixed at the ends. Because the speed of light is the same in all reference frames, this implies that the front lightning strike must have occurred first in the reference frame of the train.)

6.2.1 Causality as related to the tutorial *Simultaneity*

Although the train paradox can be understood using the principle of coincidence, as outlined above, it may also be understood by using the principle of causality. As described in Chapter 3, students work through a variation of Einstein's train paradox in the tutorial *Simultaneity*, in which sparks (rather than lightning bolts) jump between the ends of the train and the track. In the tutorial, an observer Beth stands at the middle of the train, and passes an observer Alan just as the sparks jump simultaneously in Alan's reference frame. In Alan's reference frame, Beth is moving toward the center of the wavefront from the front spark, and thus receives the wavefront from the front spark before she receives the wavefront from

the rear spark. By the principle of causality, because Beth is at a single location in her own reference frame, and therefore receives the two wavefronts at a single location, we know that the time sequence of the events associated with her reception of the signals must be preserved across frames. We can conclude, then, that Beth receives the front wavefront first in all reference frames, including her own. Because in her reference frame, Beth is equidistant from and stationary with respect to the centers of the wavefronts of the light from the sparks, but receives the light from the front spark first, the front spark must have jumped first in Beth's reference frame (i.e., the reference frame of the train). Thus both methods of solution yield identical results.

6.2.2 Prior research

Rachel Scherr, in her investigation of student understanding of concepts in special relativity, identified several student difficulties with events and causality [5, 6, 8]. Scherr found that many students were willing to give up the frame-independence of events in order to preserve absolute simultaneity. Scherr also found that students rarely used the principle of causality spontaneously when determining the order of events in multiple frames.

Caleb Teel, in his Master's Thesis, describes findings similar to Scherr's [9]. In an in-depth investigation into sophomore-level student understanding of events, Teel found that many students believe that events are frame dependent after traditional instruction in special relativity. In addition, Teel also found that many sophomore-level students have difficulty with the principles of causality and coincidence. Teel's research led to minor modifications of Scherr's original *Simultaneity* tutorial to address student difficulties with frame independence and student tendency to view the results of one reference frame as more correct than the results of other reference frames.

6.3 Causality-related exercises in the special relativity tutorials

In this sections we describe the exercises in the special relativity tutorials that involve the concept of causality. First, we describe the sections of the tutorial *Simultaneity* in which students are expected to use the principle of causality. Then, we present new and modified exercises in the *Events and reference frames* tutorial and homework (which precede the *Simultaneity* tutorial) which attempt to address student difficulties with the principle of coincidence. Finally, we discuss new exercises in the *Simultaneity* homework in which students are expected to use the principle of coincidence in order to determine the order of spatially separated events in multiple frames of reference.

6.3.1 Sections of *Simultaneity* relying on the use of the principle of causality

As described above, students work through a modified version of Einstein’s train paradox in the *Simultaneity* tutorial. Students are told that observer Alan, at rest with respect to the ground, simultaneously receives the wavefronts of light from sparks that jump between the ends of a train and the track. The front spark is called “spark F” while the rear spark is called “spark R.” Students are able to determine that the sparks jump simultaneously in Alan’s reference frame using his simultaneously reception of the wavefronts, and the fact that Alan is equidistant from the char marks left on the track by the sparks.¹

Students are then told that Beth is an observer on the train, standing at its center. They are first asked to analyze the situation using Alan’s reference frame. Because Alan is equidistant from the ends of the train when the sparks jump in his reference frame, and Beth stands at the center of the train, students are able to determine that Alan and Beth pass each other at the instant that the sparks jump in Alan’s reference frame. Using this fact, and the fact that Beth is moving toward the center of the wavefront from the front spark and away from the center of the wavefront from the rear spark, students determine

¹Sparks that jump between the track and the train, rather than sparks that are emitted by devices that are at rest in one of the frames are used because of a known student tendency to link an event with a particular reference frame—in particular, the rest frame of the object seen as “responsible” for the event. See reference [8] and §4.3 of this dissertation.

that Beth receives the wavefront from the front spark before the wavefront from the rear spark in Alan's reference frame. These exercises are shown in Figure 6.1.

Beth stands at rest relative to the train, exactly halfway between the front and rear of the train. Let event P be "Alan and Beth pass each other." Recall that event F is "spark F jumps" and event R is "spark R jumps."

- a. In Alan's frame, does event F happen *before*, *after*, or *at the same instant as* event P? Explain.
- b. In Alan's frame, does wavefront F reach Beth *before*, *after*, or *at the same instant as* wavefront R? Explain.

Figure 6.1: Exercise from the tutorial *Simultaneity* in which students determine the order in which Beth receives wavefronts from sparks F and R in Alan's reference frame

Next, students work through an exercise to determine the order that the sparks jump in Beth's reference frame. To answer correctly, students must apply the principle of causality and recognize that Beth receives the wavefront from spark F before she receives the wavefront from spark R in her own reference frame, just as she did in Alan's reference frame. This exercise is shown in Figure 6.2.

Beth's frame

1. Complete the diagram at right by drawing wavefronts F and R, in Beth's frame, before either wavefront reaches her.
2. In Beth's frame, does event F happen *before*, *after*, or *at the same instant as* event R? Explain.
3. In Beth's frame, where are the centers of wavefronts F and R? Explain.
4. In Beth's frame, does wavefront F reach Beth *before*, *after*, or *at the same instant as* wavefront R? Explain.

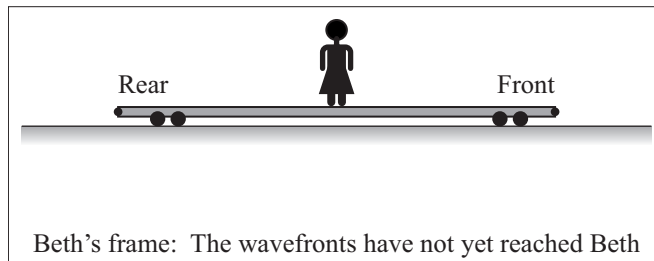


Figure 6.2: Exercise from the tutorial *Simultaneity* in which students determine the order in which Beth receives wavefronts from sparks F and R in Beth's reference frame

Commentary on the use of the principle of causality by students during the *Simultaneity* tutorial As discussed in Chapter 3, very few students correctly answer the latter questions described above (those regarding the analysis in the train frame). The assumption of absolute simultaneity is so persistent among students that a majority start by drawing the wavefronts centered at the ends of train and equidistant from Beth. From this, students determine that Beth receives the wavefronts simultaneously in her reference frame, and therefore that the sparks jumped simultaneously in her reference frame. Informal observations of students suggest that some students believe that this “discrepancy” (Beth receiving the wavefronts simultaneously in her own reference frame but not in Alan’s reference frame) is what is meant by “the relativity of simultaneity.” Because students are generally not taught the principle of causality during traditional instruction on special relativity, very few recognize that they are violating it. Thus, on their own, few students recognize the need to resolve the conflict.

Subsequent exercises in the *Simultaneity* tutorial continue under the assumption that most students have answered the questions about Beth’s reference frame incorrectly and would recognize a conflict to be resolved. However, these exercises often reveal an incorrect student belief that analyses of the firecrackers performed in reference frames other than Beth’s are invalid; students seem to believe that Beth’s reference frame is the only valid reference frame because the firecrackers are at rest with respect to her. Although this belief is not directly related to causality, it does effect student understanding of causality; it will be discussed more fully in section 6.4.2-c below.

6.3.2 Exercises in Events and reference frames designed to address student difficulties with principle of coincidence

As discussed above, we expect students to use the principle of coincidence while working through the *Simultaneity* tutorial in order to understand the relativity of simultaneity qualitatively. Since we found, in practice, that this was not happening, we modified several of the existing exercises in the preceding *Events and reference frames* tutorial and homework

to include these ideas.

6.3.2-a *Treating two events as a single event*

The principle of coincidence can be understood as a special case of the principle of causality. Alternatively, it can be understood as a special case of the frame independence of events, if we treat two (or more) coincident events as a single event (because they share a single spacetime coordinate). Although prior research indicated that students have difficulty with both the principle of causality and the frame independence of events, we believed that students might have a stronger intuitive understanding of the idea that “events that happen in one reference frame happen in all reference frames.” Therefore, we wrote exercises in the *Events and reference frames* tutorial and homework meant to enforce this intuitive belief.

Events and reference frames tutorial In the tutorial *Events and reference frames*, events are defined as something that can be associated with a single instant in time and a single location in space (i.e., a single spacetime coordinate). After defining event as such, students are asked to identify whether the items on a list are objects, events, locations, instants, or something else. The relevant exercise is shown in Figure 6.3. One of the items in the list (“Beth’s watch reads 50 s and Beth’s laser emits a pulse in Alan’s direction”) is a pair of coincident events. (Beth is treated as a single point in space.) Because coincident events share a single spacetime coordinate, their coincidence can be considered a single event with the same spacetime coordinate as each of the individual events. In this sense, coincident events can be treated as a single event.

Later in the tutorial, students draw an event diagram for a simple situation. Alan stands a distance away from a beeper, which can emit a beep. In between Alan and the beeper sits a horn. Alan hears the beep from the beeper and a honk from the horn at exactly the same time. A completed event diagram showing these events is shown in Figure 6.4.

After completing the event diagram, students are asked a series of question meant to help develop their understanding of the information included in an event diagram. One of the

In the study of relativity, we refer to material *objects*, *locations* in space, *instants* in time, and *events*. An *event* is associated with a single location in space and a single instant in time.

State whether each item below is an *object*, a *location*, an *instant*, an *event*, or *none of these*.

- Beth's laser
- Beth's laser emits a pulse in Alan's direction
- Beth's watch reads 50 s
- Beth's watch reads 50 s and Beth's laser emits a pulse in Alan's direction
- Alan receives the pulse of light from Beth's laser
- the exact time at which Beth's laser emits a pulse
- light travels from Beth to Alan
- Alan's laser and Beth's laser each emit a pulse of light at the same time

Figure 6.3: Exercise from the tutorial *Events and reference frames* in which students identify events, including a pair of coincident events (bullet point four).

exercises asks students to identify a coincident pair of events, and to justify why such a pair of events could be considered a single event. In particular, students are expected to recognize that Alan's reception of the sound wavefronts from the beep and the honk simultaneously is a pair coincident events (with the same x and t value). Additionally, students might recognize that the wavefront from the beep passes the horn just as it emits a honk; these events are also coincident. The relevant exercise is shown in Figure 6.5.

Events and reference frames homework In the *Events and reference frames* homework, the exercises focus on developing the idea of the principle of coincidence (rather than treating coincident events as a single event, as in the tutorial). First, students draw event diagrams for two frames in relative motion that include non-simultaneous, spatially separated events. Students are asked to determine the distance between the events in two different reference frames. They determine that observers in different frames do not agree on the

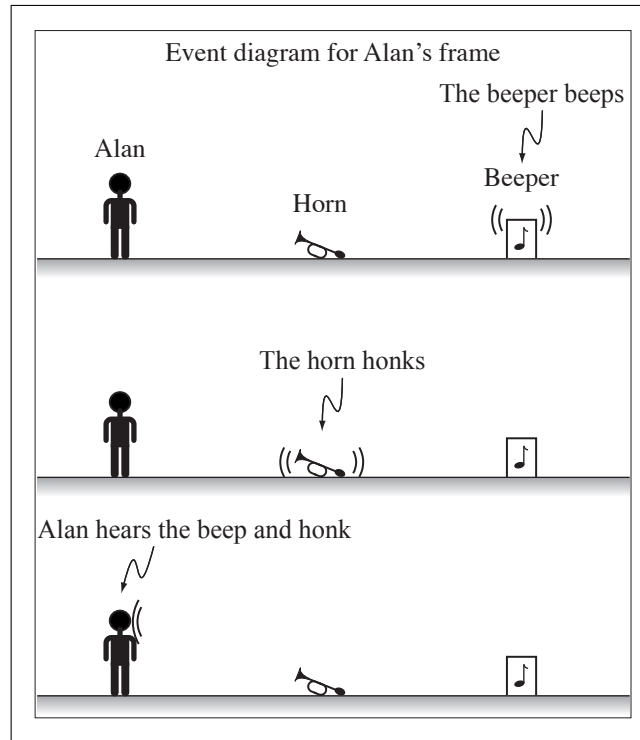


Figure 6.4: A completed event diagram showing the events “the beeper beeps,” “the horn honks,” and “Alan hears the beep and honk at the same instant.”

distance between the given events. (This result is a surprise to many students.²)

Next, students draw event diagrams that include a pair of coincident events in two reference frames. Again, students are asked to determine the distance between the events; in this case, they should determine that the spatial separation between the events is equal to zero, in both reference frames. A statement of the principle of coincidence is then given in the tutorial homework, as shown in Figure 6.6. After this statement, students are asked to justify why the coincident events could be treated as a single event in one of the observer’s reference frames, and whether the events could be treated as a single event in any reference frame. This series of exercises is meant to enforce the connection between the principle of

²Research identifying a failure of students to recognize that the distance between spatially-separated events depends on the reference can be found in Andrew Boudreaux’s dissertation on student understanding of topics in Galilean relativity [7].

Suppose that two events occur in the same location, and appear in the same picture of an event diagram. Explain why such an occurrence could be treated as a single event.

Identify such an event in the example above.

Figure 6.5: Exercise for *Events and reference frames* that asks students to justify the treatment of coincident events as a single event.

coincidence and the frame independence of events.

As you found above, observers in different rest frames may not measure the same distance between events. The exception is if, in a given rest frame, the two events occur not only at the same location but also at the same time. In that case all observers would agree, regardless of reference frame, that the location and time of the first event is exactly the same as the location and time of the second event.

3. Explain why it would be possible to treat events 1 and 3 as a single event in Anton's frame.
4. Would it be possible to treat events 1 and 3 as a single event in any frame? Explain.

Figure 6.6: Statement of the principle of coincidence from the *Events and reference frames* homework

6.3.3 Exercises in the *Simultaneity* homework that use the principle of coincidence in analysis of the relativity of simultaneity

The *Simultaneity* homework used in Autumn 2009 did not rely explicitly on the idea of causality. Instead, the first part of the unmodified *Simultaneity* homework had a series of exercises meant to help students understand the relativity of simultaneity as a consequence of length contraction. In the second part, students used event diagrams and the Lorentz transformation for time to show (again) that simultaneity is relative in the modified version

of Einstein's train paradox used in the *Simultaneity* tutorial. While the second part of the homework relied implicitly on the principle of coincidence (particularly to aid in the construction of event diagrams in the reference frame of the train), the homework was not designed to improve or reinforce student understanding of the use of causality in the context of the relativity of simultaneity.

We felt that the unmodified *Simultaneity* homework was too challenging for our population of introductory students. Although length contraction and the Lorentz transformations are taught during lecture instruction in special relativity in the introductory courses at the University of Washington, we suspect that a majority of students don't understand these ideas deeply enough for the exercises in the *Simultaneity* homework to improve student understanding of the relativity of simultaneity. Therefore, the *Simultaneity* homework was completely rewritten to help students use the principle of coincidence explicitly in determining the order of spatially separated events in multiple reference frames.

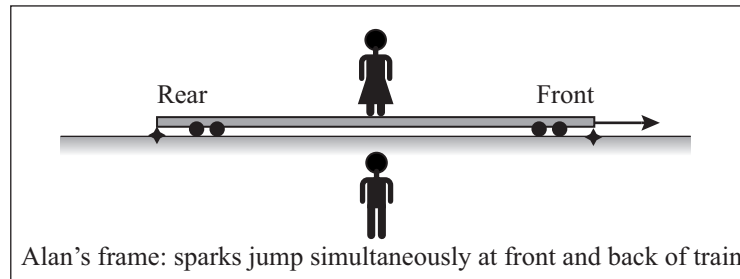
The first exercise in the modified homework includes significant scaffolding and hints for students, with the intent of teaching students the basic procedure by which the order of events can be determined. The second exercise is designed to give students practice applying this procedure with less guidance.

Modified *Simultaneity* homework: part I The modified version of the *Simultaneity* homework begins by revisiting the modified version of Einstein's train paradox that students saw in the *Simultaneity* tutorial. Students are reminded that the sparks jump between the ends of the train simultaneously in the reference frame of Alan (at rest with respect to the ground) but *not* in the reference frame of Beth (at rest with respect to the train). The context for the first exercise of the *Simultaneity* homework is shown in Figure 6.7.

Students first consider Alan's reception of the wavefronts from sparks R and F in Beth's reference frame. A hint is given that suggests to students that Alan's reception of the two signals in his own reference frame can be considered a single event, and asks whether all events occur in all reference frames. This exercise requires students to draw on the exercises

In the tutorial *Simultaneity*, you examined the relativity of simultaneity by considering sparks that jump at both ends of a train that is moving relative to an observer, Alan, while a second observer, Beth, stands at rest relative to the train.

Below is a figure showing the relative positions of the observers and the train at the moment that the two sparks jump in Alan's frame. As in tutorial, let event F be "spark F jumps" and let event R be "spark R jumps." (Recall that spark R is at the rear of the train and spark F is at the front of the train.)



We determined in tutorial that the sparks do *not* jump simultaneously in Beth's frame. The following questions can serve as a guide in determining the order of events F and R in Beth's frame.

Figure 6.7: The context for the first exercise of the modified *Simultaneity* homework.

that were added to the *Events and reference frames* tutorial and homework (see prior section) as well as on students' intuitive understanding of the frame-independence of events in order to determine that Alan must receive the two wavefronts simultaneously in all reference frames.

In the next two exercises, students are prompted to apply the principle of coincidence for a second time. They are asked to imagine that Alan is next to a particular window on the train when he receives the two wavefronts simultaneously in his reference frame. The exercise asks students to draw a picture for an event diagram for the instant that Alan receives the two wavefronts simultaneously in his reference frame. This is intended to help students recognize that Alan is next to a window that is closer to the rear of the train than to the front of the train at the instant he receives the wavefronts. The next exercise expects students to apply the principle of coincidence again to recognize that in Beth's reference frame Alan must be next to the same window (and is therefore closer to the rear of the

Alan's reception of signals in Beth's frame

1. In Beth's frame, does Alan receive the light from spark R *before, after, or at exactly the same time* as he receives the light from spark F? Explain. (*Hint: Alan's reception of the light from the two sparks can be considered a single event in Alan's reference frame. Do all events occur in all reference frames?*)

Figure 6.8: The first exercise in the modified *Simultaneity* homework: treating two coincident events as a single event.

train) when he receives the wavefronts. These exercises are shown in Figure 6.9

Finally, students are asked to use the fact that Alan is closer to the rear of the train, paired with the fact that the centers of the wavefronts from the sparks are located at the ends of the train in Beth's reference frame, to determine that the front spark must have jumped first in Beth's reference frame. The fourth exercise is shown in Figure 6.10.

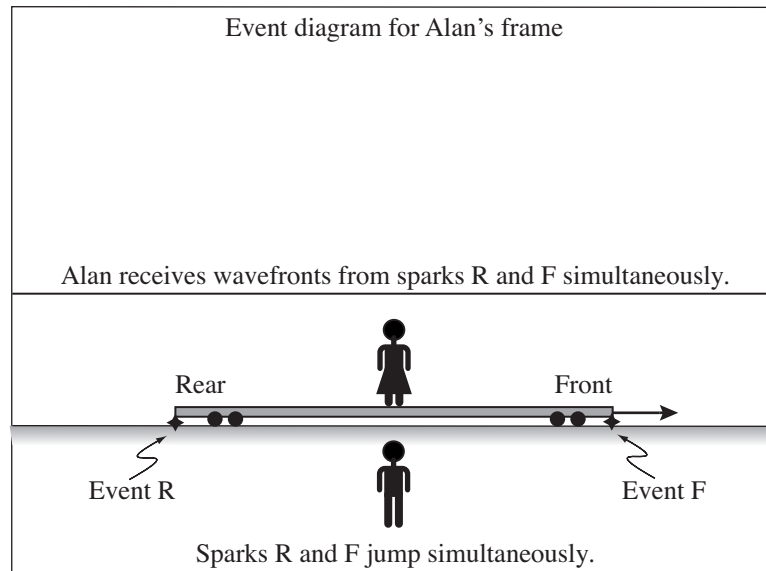
Modified *Simultaneity* homework: part II The second part of the modified *Simultaneity* homework is shown in Figure 6.11. As described above, students are expected to apply the same procedure as in the first part of the homework, with significantly less scaffolding. The second part involves an astronaut Bea, who is at rest at the center of a space station exactly equidistant from two alarms (1 and 2) that will each emit a flash of light (events 1 and 2). Students are told that alarms go off simultaneously in Bea's reference frame, and that a shuttle flying with relativistic speed from alarm 1 toward alarm 2 is directly over alarm 1 when the alarms go off in Bea's frame. Students are then asked to determine the order in which Bea receives the light from the alarm, and why it is unnecessary to specify a reference frame to answer that question. They are also asked to determine whether Bea is closer to the location of event 1 or event 2 in the reference frame of the shuttle. Finally students are asked to determine the order of events 1 and 2 in the reference frame of the shuttle, using their answers to the first two questions in part II.

To answer this second part, students should recognize that Astronaut Bea receives the signals from the alarms simultaneously in all frames because her reception of the signals is

Relating the location of events in Beth's and Alan's frames.

2. Suppose that Alan is next to a particular window on the train when he receives the wavefronts from the sparks in his frame. Draw the picture for instant that Alan receives the two wavefronts in the space below.

In Alan's frame, is the window closer to the front or the back of the train?



3. In Beth's frame, is Alan next to the same window when he receives the wavefronts from the sparks? Explain.

In Beth's frame, is Alan closer to the front or the back of the train when he receives the wavefronts from the sparks?

Figure 6.9: The second and third exercises in the modified *Simultaneity* homework: a second application of the principle of coincidence.

a pair of coincident events. In the reference frame of the shuttle, Bea is closer to the center of the wavefront from alarm 1 when she receives the signals simultaneously; therefore, the signal from alarm 2 had to travel farther to reach her. This means that alarm 2 must have gone off first in the reference frame of the shuttle.

Comments on student performance on the *Simultaneity* homework As noted earlier in this dissertation, the special relativity tutorials are usually run during the last two weeks of the third and final quarter of the Physics 12x sequence. For this reason,

Determining the order of events in Beth's frame.

4. Based on your responses to questions 1-3 above, determine which spark (R or F) jumped first in Beth's frame. Explain. (Hint: In Beth's frame, are the wavefronts from the sparks centered at the char marks on the train or the char marks on the tracks?)

Figure 6.10: The fourth exercise in the modified *Simultaneity* homework: determining the order of events in the reference frame of the train.


the homework for *Simultaneity* is very rarely turned in or graded, although students are encouraged to complete it as part of their preparation for the course final exam. We cannot say for certain, therefore, how well most students perform on either part of the *Simultaneity* homework. We can however comment on observations of a fraction of students who do try to complete the homework,

Informal interactions with students working on the homework indicate that while students are able to apply the principle of coincidence during intermediate steps when guided (i.e., on exercises 1-3 in the first part), many often do not do so spontaneously (e.g., on exercise 1 in the second part). Additionally, we have found that students often have difficulty applying the chain of reasoning expected in exercise 4 of the first part of the *Simultaneity* homework; this difficulty is even more pronounced on exercise 3 of the second part of the homework.

These informal observations suggested that the changes to the tutorials were not having a big impact on student understanding. Results from post-tests were consistent with this results. We therefore realized that we needed a more detailed understanding of student thinking. In the next section, we describe a more in-depth investigation to identify the particular difficulties of this population of students with concepts related to causality.

Events, signals, and the relativity of simultaneity

A space station has two alarms that emit a flash of light when triggered. Astronaut Bea is at rest with respect to the station, and is exactly halfway between the two alarms. A shuttle flies with speed $v = 0.6c$ from one end of the station to the other. The two alarms go off at exactly the same time in Bea's frame; the diagram above shows the instant the alarms go off in Bea's frame. Call event 1 "alarm 1 goes off" and event 2 "alarm 2 goes off."



Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). Treat all observers as intelligent observers.

1. Does Bea receive the signal from alarm 1 *before*, *after*, or *at exactly the same time* as she receives the signal from alarm 2? Why is it unnecessary to specify a reference frame in this instance? Explain.
2. In the shuttle's frame, is Bea closer to the location of event 1 or event 2 when she receives the light from the alarms? (Hint: Bea is *not* at rest relative to the origins of the flashes in the shuttle's frame.) Explain.
3. In the shuttle's frame, does alarm 1 go off *before*, *after*, or *at the same time* as alarm 2? (Hint: Consider your responses to parts 1 and 2, above.) Explain.

Figure 6.11: The second part of the modified *Simultaneity* homework: applying the principle of coincidence and the invariance of the speed of light to determine the order of spatially separated events.

6.4 Identification of student difficulties with events and causality

As described above, the application of the principles of causality and coincidence in the context of the relativity of simultaneity is difficult for the population of introductory students described in this dissertation. Moreover, we found very little improvement from pretest to post-test on research tasks given to these students, despite the relatively extensive targeted instruction described in §6.3. The results described in this section, therefore, are presented as part of an investigation into student difficulties with these ideas, rather than as an assessment of the tutorials. Although we found that we were able to improve student understanding of the principle of coincidence in some contexts (discussed below), the range of those contexts is limited.

In section 6.4.1, we discuss results from pretests and post-tests on student understanding of the principle of coincidence. We present data that suggest that students have greater difficulty with coincident events that are associated with the reception of signals than with coincident events that are associated with the emission of signals. Our research into student ability to see the frame-independence of events as a motivation for the principle of coincidence is described in section 6.4.2; the questions in that section probe the extent to which students understand that causal relationships must be upheld in all reference frames. Finally, in section 6.4.3, we examine the possibility that student difficulties with events as a limiting factor in their understanding of causality in special relativity.

6.4.1 Student understanding of the principle of coincidence

In this section, we describe our investigation into student understanding of the principle of coincidence; that is, student recognition of the idea that coincident events (two or more events that occur at a single spacetime coordinate) must be coincident in every reference frame. We present results from research tasks (from both pretests and post-tests) involving the simultaneous reception of light signals by an observer, as well as post-test tasks that involve the simultaneous emission of signals.

6.4.1-a Pretest results for coincident reception events: Two Towers context

In Einstein's train paradox, one qualitative argument that can be used to determine the order of events in the reference frame of the train relies on the principle of coincidence. Since the observer at rest with respect to the ground received the light from the two lightning strikes simultaneously in his reference frames, the events must be simultaneous in all reference frames. Student understanding of this fact is of particular importance. Much of our research into student understanding of the principle of coincidence has involved an investigation of student understanding that simultaneous reception of signals by an observer in one reference frame implies simultaneous reception of signals by that observer in all reference frames.

Our earliest investigations into the student understanding of the principle of coincidence with reception events were on pretests for the tutorial *Simultaneity* using the *Two Towers* context.

In the *Two Towers* context, also described in Chapter 3, observers Amy and Bob stand at rest on the ground between the Space Needle and Smith Tower. Amy is exactly equidistant between the two buildings, while Bob stands near the foot of the Space Needle. A third observer, Chuck, is in a spacecraft that flies with relativistic speed relative to the ground, from Smith Tower to the Space Needle.

Lights flash over both buildings, and Amy sees the light from the flashes simultaneously. Chuck, in the spacecraft, is directly over Smith Tower when the light flashes above it. The *Two Towers* context is shown in Figure 6.12.

The *Two Towers* consisted of two basic tasks: (1) a relativity of simultaneity task in which students were asked to determine the order of the flashes over the towers in Chuck's reference frame, and (2) a causality-related task in which students were questioned about Amy's reception of the light signals from the flashes in Chuck's reference frame. Because student performance on the two tasks was related, results from both will be presented here.

To determine the order of events in Chuck's reference frame, students could use a line of reasoning similar to that described in §6.2 for Einstein's train paradox, because the two contexts are physically equivalent. Amy's reception of signals can be considered coincident

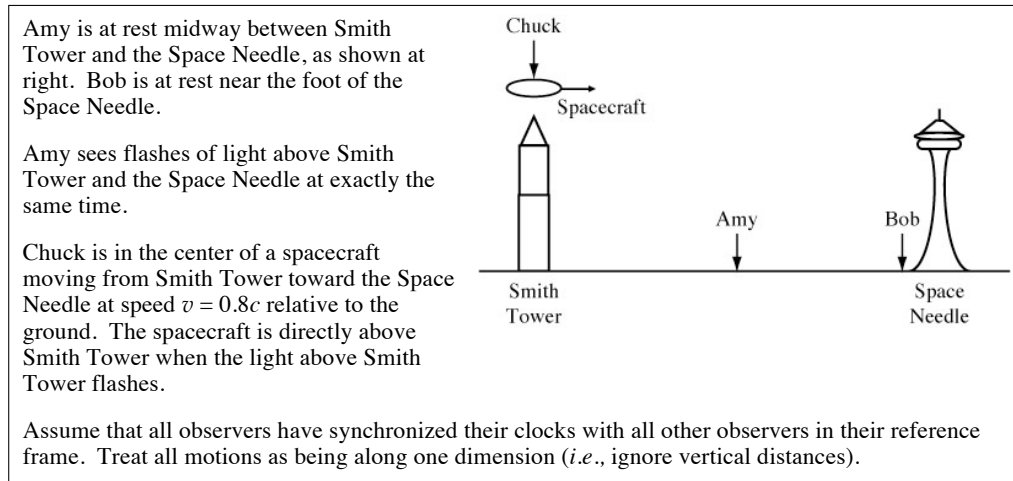


Figure 6.12: The *Two Towers* context used in multiple *Simultaneity* pretests.

events, which must be coincident in all reference frames. However, in Chuck's reference frame, Amy is closer to the center of the wavefront from the flash over Smith Tower than she is to the center of the wavefront from the flash over the Space Needle. This implies that the flash over the Space Needle must have occurred first in Chuck's reference frame.

On the *Two Towers* relativity of simultaneity task, a quarter of students answered that the flashes above the buildings were simultaneous in Chuck's reference frame, consistent with a belief in absolute simultaneity. Also, while the remaining three-quarters of students recognized that the flashes above the towers would not be simultaneous, only 25% answered correctly that the flash above the Space Needle would occur first in Chuck's reference frame. Very few students (about 5%) answered correctly and provided correct or mostly correct reasoning for this task. Student performance on the relativity of simultaneity task for Chuck's frame is summarized in Table 6.1.

To test student understanding of the principle of coincidence, the following task was given:

Table 6.1: Results for the relativity of simultaneity task on for Chuck’s frame on *Simultaneity* pretest in the *Two Towers* context. The correct answer is highlighted.

Order of flashes in Chuck’s frame	$N = 758^a$
Space Needle flash first	25%
Smith Tower flash first	50%
Simultaneous flashes	25%

^a Sections 123A111112114121, 123B111114121, and 123C112

Table 6.2: Results for the principle of coincidence task on *Simultaneity* pretest in the *Two Towers* context. The correct answer is highlighted.

Principle of coincidence task response	$N = 758^a$
I agree	35%
I disagree	55%
Not enough information	10%

^a Sections 123A122122124131132134, 123B131, and 123C122132

Consider the following two statements about the situation described above. Indicate whether you agree or disagree with each statement.

- In Bob’s reference frame, Amy sees both flashes of light at the same time.
- In Chuck’s reference frame, Amy sees both flashes of light at the same time.

Explain the reasoning you used to answer the question above.

Because Amy’s reception of each light signal can be considered an event, and the two reception events are coincident, we know that she must receive the light from the two flashes simultaneously in all reference frames. Here, we consider only results for the question about Chuck’s reference frame. Table 6.2 shows how students responded on this task.

Just over a third of students correctly recognized that Amy must see the flashes of light

Table 6.3: Student reasoning for the principle of coincidence task on *Simultaneity* pretest in the *Two Towers* context. The correct answer is highlighted.

$N = 758$	Amy sees flashes sim. in Chuck's frame	
I agree	35%	
	Correct reasoning	5%
	Absolute simultaneity reasoning	15%
	"Other" reasoning	15%
I disagree	55%	
	Non-simultaneous events reasoning	15%
	Relative motion reasoning	30%
	"Other" reasoning	10%
Not enough information	10%	

^a Sections 123A122122124131132134, 123B131, and 123C122132

from above the two buildings simultaneously in Chuck's reference frame; the other two-thirds of students either disagreed with the statement for Chuck's frame, or answered that there was not enough information to determine. Both incorrect answers are consistent with a lack of understanding or recognition that Amy's reception of light signals from the two flashes must be simultaneous in all reference frames.

Student reasoning on the principle of coincidence task in the *Two Towers* context is summarized in Table 6.3.

Only 5% of students answered correctly with correct reasoning. Some of these students provided explanations that were consistent with a statement of the principle of coincidence. Others used reasoning based on the idea that what Amy experiences (i.e., what she sees) must be the same in all reference frames. Examples that are representative of these types of explanations are provided below.

"The light reaches Amy at the same time regardless of the reference frame."

“I don’t think that the reference frame can change what [Amy] sees.”

About 15% of students answered correctly but reasoned incorrectly based on a belief that the flashes above the towers occurred simultaneously in Chuck’s reference frame. (This type of reasoning is called “absolute simultaneity” reasoning in Table 6.3.) Explanations from these students often included reference to an incorrect belief that the flashes occur simultaneously in all reference frames. It is important to note that this type of reasoning also requires that Amy be halfway between the locations of the events associated with the flashes of light. Very few students explicitly stated it in their explanation, research described in §4.3 indicates that many students link event location to objects seen as responsible for a given event. In this instance, the buildings would be such objects.

Typical student responses based on the flashes of light being simultaneous in all reference frames are shown below.

“In all of the observer[s’] reference frames both flashes of light occur at the same time. ”

“Even though they are all in different positions, each one knows that the flashes happened at the same time, using algebra.”

Reasoning based on the order of the flashes themselves was also seen in the explanations of students who answered incorrectly that Amy would *not* see the flashes of light simultaneously in Chuck’s reference frame. Like the students using “absolute simultaneity” reasoning described above, these students seem to believe that Amy is located halfway between the locations of the events associated with the flashes of light, and therefore receives the light in the same order that the light was emitted. About 15% of students answered that Amy would see the flashes at different times and used this type of reasoning, called “non-simultaneous events reasoning” in Table 6.3. A representative student explanation is shown below.

[Chuck's] reference frame doesn't have the flashes occurring simultaneously, so it would be impossible for Amy to see them simultaneously outside of her own reference frame.

A plurality of students (30%) answered that Amy would not see the flashes simultaneously in Chuck's reference frame and used reasoning based on Chuck's motion relative to Amy. These students seem to recognize that observers in different reference frames may not agree on measurements of events, but do not recognize that Amy's simultaneous reception of signals is independent of reference frame. Two student statements included in this category are shown below.

"Bob and Amy are in the same reference frames, so their perception of the timing of the events should be the same. Chuck is traveling near the speed of light so things should change."

"Because Bob and Amy are at rest and in the same reference frame. Chuck is moving relative to Amy so their reference frames are different."

6.4.1-b Post-test results for coincident reception events: multiple contexts

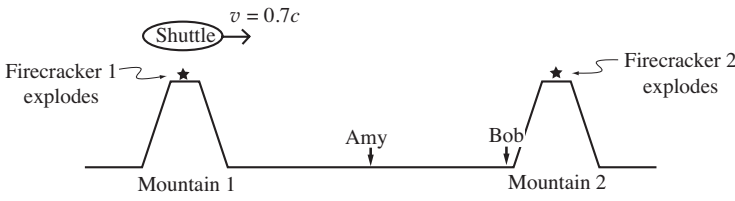
Questions testing student understanding of the principle of coincidence with reception events have been used in several post-test contexts. The context has not significantly affected student performance; therefore, results from multiple contexts have been pooled and will be presented together, below. A single, representative context (*Mountain Firecrackers*) will be discussed for clarity. All relevant post-test contexts can be seen in their entirety in Appendix C.

Recall that in the *Mountain Firecrackers* context, firecrackers 1 and 2 are on top of mountains 1 and 2, respectively. Observers Amy and Bob, at rest with respect to the ground, stand between the two mountains. Amy is equidistant from the two mountains, while Bob stands at the foot of mountain 2. A shuttle flies with relativistic speed from mountain 1 to mountain 2, and is directly over mountain 1 when firecracker 1 explodes. Amy sees the light

from the two firecracker explosions simultaneously.

To test student understanding of the principle of coincidence with events associated with the reception of signals, students were asked about the order in which observer Amy would receive the light wavefronts from the explosions in the shuttle frame. The *Mountain Firecrackers* context and the relevant principle of coincidence task are shown in Figure 6.13.

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob is near mountain 2. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light (circular wavefronts 1 and 2, respectively). Amy, an intelligent observer in the reference frame of the ground, receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows Amy, Bob, and the shuttle in the reference frame of the ground at the instant both firecrackers explode.

In the shuttle frame, which of the following correctly describes the order in which Amy receives wavefronts 1 and 2?

- Wavefront 1 reaches Amy *before* wavefront 2.
- Wavefront 1 reaches Amy *after* wavefront 2.
- Wavefront 1 reaches Amy *at the same time* as wavefront 2.
- More information is needed to answer.

Figure 6.13: A post-test task that is representative of the tasks used to test student understanding of the principle of coincidence (*Mountain Firecrackers* context)

It is worth noting that this post-test task is physically equivalent to the *Two Towers* post-test task used on the pretest for the *Simultaneity* tutorial. The results tabulated in Table 6.4 include data from students who saw the *Two Towers* context (with the principle of coincidence task described above) as well as students who saw other pretests with different (not causality-related) tasks. As mentioned above, the results across quarters were not significantly different; it seems unlikely that seeing a similar task on the pretest affected post-test results.

Table 6.4: Student performance on multiple choice post-test task testing understanding of the principle of coincidence for reception events. The correct answer is highlighted.

Ground observer's order of reception in "moving" reference frame	($N = 1414$) ^a
A (Signal 1 before signal 2)	40%
B (Signal 1 after signal 2)	15%
C (Simultaneous reception of signals 1 and 2)	45%
D (More information needed to answer)	5%

^a Sections 123A101112122141152152154162 and 123C122152162.

Student performance on this and similar post-test tasks is shown in Table 6.4. For ease of analysis, in contexts in which the direction of relative motion was reversed for the object (e.g., the shuttle) moving with respect to the ground, the percentages for answer choices A and B are switched.

Fewer than half of students recognize that simultaneous reception of signals by a single observer in one reference frame implies simultaneous reception of signals by that observer in all reference frames. Forty percent of students answered that, in the reference frame of the shuttle, the observer at rest with respect to the ground would receive signal 1 first. This is consistent with the signal reception error as well as a lack of understanding of other concepts required for qualitative understanding of the relativity of simultaneity. Analysis of the responses of these students on other post-test tasks suggests that between 70 and 85% of students choosing answer A (or the equivalent) use signal reception reasoning (see §4.2) when determining the order of events in the reference frames of other (non-centrally located) observers.

Although student performance on this post-test task seems to be better than that on the analogous pretest task, the low percentage of correct answers suggests that the principle of coincidence is difficult for students to apply unprompted in the context of reception events.

6.4.1-c Post-test results for coincident emission events

Three contexts that will be described in this section were used for post-test questions. The results from these post-tests suggest that students have significantly less difficulty with the principle of coincidence when the coincident events are associated with the emission rather than the reception of signals, though challenges remain. One of the contexts (The *Strobe Train* context) was used for both a multiple-choice and a free-response task. The *Alarmed Astronauts* context was used for a multiple-choice post-test task. The *Spaceships* task was given as a free-response post-test question. The coincident events in the *Spaceships* task are not both easily seen as emission events, but the task is included in this section for reasons that will be described below.

***Strobe Train* task** The *Strobe Train* context was described previously in §4.3 of this dissertation. In the *Strobe Train* context, students are told that a train moves with relativistic speed from left to right. Two students, F and R, stand at the front and rear of the train, respectively. Two strobes (1 and 2) are mounted at the center of the train and emit flashes of light simultaneously in the reference frame of the train. The emission events are defined as events 1 and 2. To test understanding of the principle of coincidence with events associated with the emission of signals, students are asked to determine the order of events 1 and 2 in the reference frame of the ground. The *Strobe Train* and the relevant principle of coincidence task are shown in Figure 6.14.³

Performance on the two versions (multiple-choice and free-response) of the *Strobe Train* task were similar and so the overall results are combined in the Table 6.5 and the discussion below. Additionally, it seems reasonable to assume that the reasoning used by students on the free-response version of the task indicates the types of reasoning used by students on the multiple-choice version.

³In the free-response version of this question, the observers were named “observer A₁” and “observer A₂” and there was no statement comparing the reception times for the two observers of the light from event 1. The question statement was “In the ground frame, does event 1 occur *before*, *after*, or *at exactly the same time as* event 2? Explain.”

A train moves with relativistic speed from left to right.

- Student R stands at rest on the train at the rear of the train.
- Student F stands at rest on the train at the front of the train.

Strobe lights 1 and 2, at the center of the train, emit flashes of light simultaneously in the reference frame of the train. Call event 1 “strobe light 1 flashes” and event 2 “strobe light 2 flashes.” Students R and F receive the light from event 1 simultaneously. The instant that the strobe lights flash in the train frame is shown in the figure above.

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

In the ground frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in the ground frame cannot be determined with the information provided.

The instant strobe lights 1 and 2 flash in the train frame

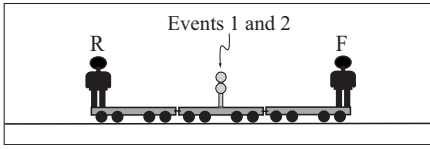


Figure 6.14: Multiple-choice version of a post-test task (the *Strobe Train* task) used to test student understanding of the principle of coincidence for events associated with emission of signals.

Over 90% of students given the *Strobe Train* context were able to answer correctly that events 1 and 2 occurred simultaneously in the reference frame of the ground. Incorrect responses were split evenly between the distractors, and were few enough that overall patterns cannot be detected. On the free-response version, most of the students answering correctly did so with correct reasoning, with 80% of students answering correctly with correct and complete or mostly complete reasoning. Almost half of all students stated that events 1 and 2 could be treated as a single event, and therefore had to occur simultaneously in all

Table 6.5: Student performance on *Strobe Train* multiple choice post-test task testing understanding of the principle of coincidence for reception events. The correct answer is highlighted.

Order of events in the ground frame	($N = 388$) ^a
A (Event 1 before event 2)	< 3%
B (Event 1 after event 2)	< 3%
C (Events 1 and 2 simultaneous)	90%
D (More information needed to answer)	< 3%

^a Sections 123A162 and 123B151.

Table 6.6: Student reasoning on free-response principle of coincidence *Strobe Train* task. The correct answer is highlighted.

Order of events in the ground frame	($N = 194$) ^a
Events 1 and 2 simultaneous	90%
Reasoning (percentage of total)	
Coincident events treated as single event	50%
Principle of coincidence	35%
Reception of signals by ground frame observer	10%
Absolute simultaneity	2%

^a Section 123B151.

reference frames. Over a third of students stated a version of the principle of coincidence in their response. Fewer than 2% of students (3 out of 194) used reasoning based on absolute simultaneity.

One line of reasoning seen in fewer than 10% of students was based on the reception of signals by someone in the ground frame. Students using this reasoning often stated that events 1 and 2 must be simultaneous in the reference frame of the ground because an observer in that reference frame would receive the signals simultaneously. While this statement is correct, it cannot be seen as complete reasoning for this task, as it assumes that the events occur simultaneously in the ground reference frame without justification that they must do so. This lack of reasoning is similar to the signal reception reasoning used by students for spatially separated events. Table 6.6 shows popularity of student reasoning in support of the correct answer for the free-response version of the *Strobe Train* task.

***Alarmed Astronauts* task** In the *Alarmed Astronauts* task, we examine student ability to apply the principle of coincidence when different types of signals (i.e., light and sound) are emitted from a single spacetime coordinate. The *Alarmed Astronauts* task is shown in Figure 6.15. In this task, students are told that an alarm in a space station goes off just as a shuttle (moving at relativistic speed) passes overhead. The alarm emits both a single flash of light and a single audible beep, events L and S, respectively. These two events are

coincident in the reference frame of the space station, and therefore must be coincident in the reference frame of the shuttle as well.

Two observers, A_1 and A_2 , are standing at the ends of a very large space station. An alarm at the center of the space station emits a single flash of light and a single audible beep simultaneously in the frame of observers A_1 and A_2 .

Call “the alarm emits a flash of light” event L and “the alarm emits an audible beep” event S. The instant that events L and S occur in the frame of observers A_1 and A_2 is shown in the figure.

Observer B stands at the front of a shuttle that moves to the left at relativistic speed. **In observer B’s frame**, event S occurs just as observer B passes the alarm.

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

In observer B’s frame:

- Event L occurs before event S.
- Event L occurs after event S.
- Event L occurs at exactly the same time as event S.
- Not enough information is provided to answer this question.

Figure 6.15: *Alarmed Astronauts* multiple-choice post-test task used to test student understanding of the principle of coincidence for events associated with emission of different types of signals.

Student performance on this task suggests it is significantly more difficult than the *Strobe Train* task, with 65% of students answering correctly. The most popular incorrect answer was that event L occurs before event S in the reference frame of the shuttle, with 25% of student choosing that response. This response is consistent with the signal reception error, as the shuttle would receive the light signal before the sound signal. The prevalence of this response on the *Alarmed Astronauts* question suggests that some of the students answering the *Strobe Train* question correctly did so based on the signal reception error rather than using correct reasoning, especially those students who focused on the simultaneous reception of the light signals by an observer in the reference frame of the ground.

Student performance on the *Alarmed Astronauts* task is shown in Table 6.7.

Spaceships task The *Spaceships* task was included in a free-response post-test. This context was discussed previously in §4.3. The context and the task relevant to our investigation of are shown in Figure 6.16. In the *Spaceships* context, observer A stands at the middle of

Table 6.7: Student performance on *Alarmed Astronauts* multiple choice post-test task testing understanding of the principle of coincidence for emission events of different types. The correct answer is highlighted.

Order of events in the shuttle frame	($N = 170$) ^a
A (Event L before event S)	25%
B (Event L after event S)	5%
C (Events L and S simultaneous)	65%
D (More information needed to answer)	0%

^a Sections 123A164.

spaceship A. A strobe light sits at the feet of observer A. Observer B stands at the front of spaceship B, which moves with relativistic speed past spaceship A. The strobe light at observer A's feet flashes once just as observer A and B pass each other. Event S (the strobe light flashes) and event P (observers A and B pass each other) are coincident events and must be simultaneous in all reference frames.

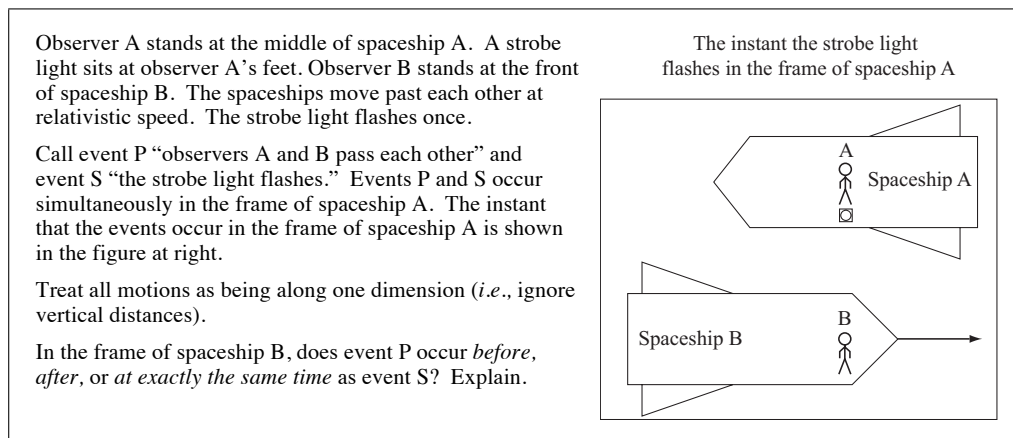


Figure 6.16: *Spaceships* free-response post-test task used to test student understanding of the principle of coincidence for non-reception events.

Unlike the other tasks described in this category, this task features only one event that is clearly associated with the emission of a signal (the flashing of the strobe). However, informal observations during tutorial sessions suggests that an event such as "two observers

Table 6.8: Student performance on multiple choice post-test task testing understanding of the principle of coincidence for emission events of different types. The correct answer is highlighted.

Order of events in the frame of spaceship B	($N = 170$) ^a
Event P before event S	15%
Event P after event S	5%
Events P and S simultaneous	80%

^a Sections 123A151.

pass each other” is categorized by students as more similar to an emission event than to a reception event. We believe that students often rely on the colloquial meaning of the term event (i.e., “something that happens”) rather than the definition presented in the *Events and reference frames* tutorial or in a course textbook. The flashing of a strobe light or two observers passing are more easily seen as events than the reception of a signal by an observer for many students. Therefore, the results from *Spaceships* task are included in this section rather than presented separately.

Student performance on the *Spaceships* task falls between that of the *Alarmed Astronauts* and *Strobe Train* tasks. Eighty percent of students were able to determine that events P and S occurred simultaneously in the reference frame of spaceship B, with 70% of total students using correct reasoning. Almost all of the 20% of students answering incorrectly based their incorrect response on the order in which observer B would receive the signals from the two events; however, unlike this error on the *Strobe Train* task, on the *Spaceships* task it seemed to stem from difficulty recognizing that the two events occurred at the same location. This is consistent with the results presented in §4.3, which suggested that students have greater difficulty with events that are strongly linked with a particular reference frame (such as a spark jumping between observers in different reference frames, or two observers passing each other). Results from the free-response *Spaceships* task are shown in Table 6.8.

Student reasoning in support of a correct response on the *Spaceships* task was also different than that for the *Strobe Train* task; in particular, students were less likely to treat events P and S as a single event in the Spaceship task than the events corresponding to the

Table 6.9: Student reasoning on free-response principle of coincidence *Spaceships* task. The correct answer is highlighted.

Order of events in the frame of spaceship B ($N = 147$) ^a	
Events P and S simultaneous	80%
Reasoning (percentage of total)	
Coincident events treated as single event	25%
Principle of coincidence	45%
Absolute simultaneity	5%
Other	5%

^a Section 123B151.

strobes flashing in the *Strobe Train* task. Only 25% of students used this type of reasoning for the *Spaceships* task. The reasons for this disparity are not clear, but we believe that there are several possibilities. One possible reason is that the events described in the *Spaceships* context (a strobe flash and two observers passing each other) are less similar than those in the *Strobe Train* context (two strobes flashing). Additionally, the strobes flashing in the *Strobe Train* context were physically closer together (with less spatial separation in the vertical direction), and were labeled together in the figure on the post-test. Almost half of all students (more than half of students answering correctly) stated the principle of coincidence in some form. Student reasoning for students answering correctly is shown in Table 6.9.

6.4.2 Student understanding of the relationship between the principle of coincidence and the frame independence of events

The tasks described in the previous section (6.4.1) to a large extent probed student thinking about the ideas of the frame-independence of events and the principle of coincidence separately. However, the two ideas are related, and we saw that some students are able to see the connection between them after relevant instruction. This was especially apparent in the data presented in which we saw many students treat two coincident events as a single event that must occur in all frames.

Exercises in the *Simultaneity* tutorial and homework rely on intuitive understanding of the frame-independence of events (e.g., the explosion(s) of firecracker(s)) to motivate the principle of coincidence. We therefore decided to examine student ability to relate the two concepts. In the sections below, we present data that speak to student ability to use the frame-independence of events to motivate the principle of coincidence. The data are drawn from three questions administered to students: (a) the *Strobe Spaceship* multiple choice post-test task; (b) the *Firecracker 1* pretest task; and (c) the *Firecracker 2* pretest task.

6.4.2-a *Strobe Spaceship* post-test

In the *Strobe Spaceship* post-test task, we examine whether telling students that an event occurs in one reference frame affects their ability to determine that two related events must be coincident in another reference frame.

Students are told that observer Alec stands equidistant between two strobe lights in a spaceship. Alec decides that he will raise both hands if he receives the light from the two strobe lights simultaneously; if he receives the light from the left or right strobe light first, he will raise only his left or right hand, respectively. The lights flash, and Alec reports afterward that he raised both hands. Students are then asked to determine the order in which Alec received the light from the two strobes in the reference frame of Carl, at rest with respect to a space station that has non-zero relative velocity with respect to the spaceship in which Alec travels. Figure 6.17 shows the context and relevant multiple-choice question.

To answer correctly, students should first recognize that Alec raising both hands indicates that he received the signals from the two lights simultaneously. Then there are two ways that students could determine that Alec receives the signals simultaneously in Carl's reference frame as well: they could recognize that Alec's simultaneous reception of signals constitutes a pair of coincident events that must be coincident in all reference frames by the principle of coincidence; or they could recognize that if Alec raised both hands in his own reference frame, he must do so in Carl's as well, by the frame-independence of events. This would indicate, therefore, that Alec received the signals simultaneously in Carl's reference frame as

Alec and Betty are at rest with respect to each other, as shown. Alec stands **midway** between two light sources. Each light source will emit a pulse of light at some time or times in the future.

- Let event L be the left source emits a pulse of light.
- Let event R be the right source emits a pulse of light.

Alec decides that if he receives the light pulses simultaneously, he will raise both hands. If he receives the light pulse from the right source first, he will raise only his right hand. If he receives the light pulse from the left source first, he will raise only his left hand.

Alec and Betty repeat the experiment on a spaceship that travels near the speed of light to the right as measured from a space station. The light bulbs are set up in exactly the same manner, and Alec decides he will raise his hands as described above.

Carl is at rest on the space station observing the experiment. Alec and Betty are at rest with respect to the spaceship.

After the experiment, Alec reports that he raised both hands.

In Carl's reference frame, which of the following best describes when Alec receives the two light signals?

- Alec receives light from the left source first.
- Alec receives light from the right source first.
- Alec receives light from both sources simultaneously.
- Alec does not receive light from at least one of the sources.
- Alec receives light from one of the sources before the other, but there is not enough information to tell which.

The diagram consists of two parts. The top part shows a horizontal line representing the space station. On the left, a light source is labeled 'Event L will occur here'. On the right, a light source is labeled 'Event R will occur here'. In the center, two figures are labeled 'Alec' and 'Betty'. Below them, text says 'Alec is midway between the two light sources'. The bottom part shows a spaceship moving to the right, indicated by an arrow. Inside the spaceship, Alec and Betty are shown with light sources. Below the spaceship, a figure labeled 'Carl' is shown on the 'Space station'.

Figure 6.17: Free-response post-test task used to test effect of student understanding of the frame-independence of events on understanding of the principle of coincidence.

well.

Results from this task suggest that student performance was not improved by the explicit presence of a single event to signal the occurrence of the coincident events. Performance on this question was similar to performance on questions that didn't include such an event, with 35% of students answering correctly that Alec would receive the two signals simultaneously. (Recall that approximately 45% of students answered similar questions with reception events without an additional event such as an observer raising his hands; student performance on such questions is summarized in Table 6.4.) Half of all students seeing the *Strobe Spaceship* task answered that Alec would receive the light from the right strobe first, consistent with the signal reception error. Student performance on the *Strobe Spaceship* task is summarized in Table 6.10.

Table 6.10: Student performance on multiple choice post-test task testing understanding use of frame-independence of events to motivate the principle of coincidence. The correct answer is highlighted.

Alec's order of reception in Carl's reference frame	($N = 170$) ^a
A (L received before R)	5%
B (L received after R)	50%
C (Simultaneous reception of R and L)	35%
D (Alec doesn't receive L and/or R)	< 2%
E (Not simultaneous, but not enough information)	5%

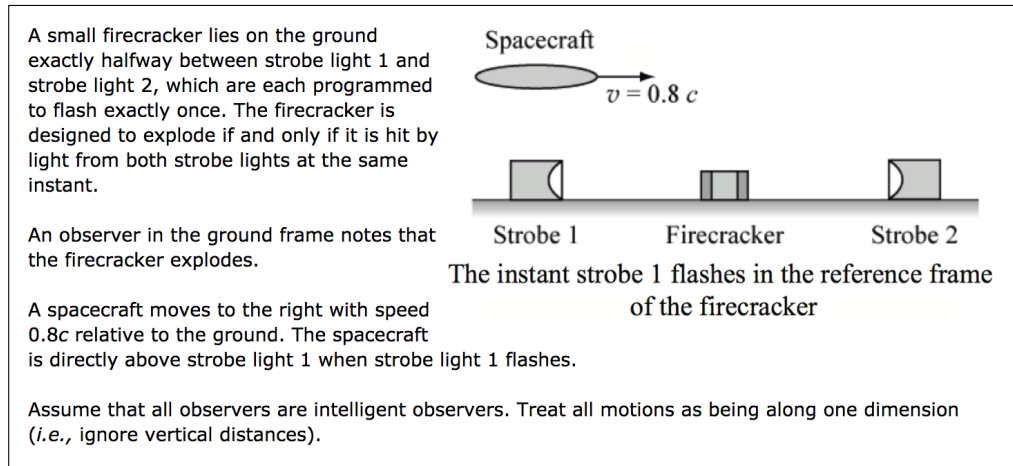
^aSections 123A104.

6.4.2-b *Firecracker 1 pretest task*

We were interested in testing more explicitly student ability to connect the ideas of the frame-independence of events and the principle of coincidence. In the *Firecracker 1* task, we asked a series of four questions about the *Firecracker* context shown in Figure 6.18. For the *Firecracker* context, students are told that a firecracker sits on the ground, equidistant between two strobe lights, strobe 1 and strobe 2. Each strobe light is programmed to flash exactly once. The firecracker is programmed to explode only if light from the two strobes hit it simultaneously. Additionally, a spacecraft flies from strobe 1 to strobe 2 at relativistic speed. An observer in the reference frame of the ground notes that the firecracker explodes.

Version A We created two versions of this pretest, in which we asked the same four questions, but in different orders. In version A, the four questions were given to students in the following order:

1. In the reference frame of the firecracker, does strobe 1 flash *before*, *after*, or *at exactly the same time as* strobe 2?
2. In the reference frame of the spacecraft, does strobe 1 flash *before*, *after*, or *at exactly the same time as* strobe 2?

Figure 6.18: *Firecracker* pretest context

3. In the reference frame of the spacecraft, does the wavefront from the flash from strobe 1 reach the firecracker *before*, *after*, or *at exactly the same time as* as the wavefront from the flash from strobe 2?
4. In the reference frame of the spacecraft, does the firecracker explode?

For each question, students were asked to explain their reasoning. To answer question 1, students could use the fact that the firecracker explodes in the reference frame of the ground, and must therefore receive the wavefronts from the flashes from the two strobes simultaneously. Using this fact, and reasoning similar to the reasoning used in the train paradox, for question 2 students could then determine that in the reference frame of the spacecraft, strobe 1 must flash after strobe 2. For question 3, students could apply the principle of coincidence to determine that, because the events associated with the firecracker receiving the wavefronts from the strobes are coincident events, they must also be coincident in the reference frame of the spaceship. Finally, for question 4, students could use their response to question 3, or recognize that events are frame-independent to determine that the firecracker exploded in the reference frame of the spacecraft.

One of the purposes of Version A was to determine whether student awareness of the

relativity of simultaneity (i.e., the fact that the strobes do not flash simultaneously in the reference frame of the spacecraft) affects their ability to determine whether the signals from strobes reach the firecracker simultaneously in the reference frame of the spacecraft. However, other results suggest that students have difficulty determining the order of spatially separated events in “moving” reference frames (such as that of the spacecraft). Therefore, we did not expect most students to be able to answer question 2 correctly. We were also interested in determining whether students would use their response to question 3 to answer question 4: were students who answered that the wavefronts reach the firecracker at different times in the reference frame of the spacecraft more likely to determine that the firecracker did not explode in the reference frame of the spacecraft? And conversely, if students answered that the signals reached the firecracker simultaneously in the reference frame of the spacecraft, would they be more likely to determine that the firecracker exploded in that frame, as well?

Version B In version B, the four questions were presented in the following order:

1. In the reference frame of the firecracker, does strobe 1 flash *before*, *after*, or *at exactly the same time as* strobe 2?
2. In the reference frame of the spacecraft, does the firecracker explode?
3. In the reference frame of the spacecraft, does the wavefront from the flash from strobe 1 reach the firecracker *before*, *after*, or *at exactly the same time as* as the wavefront from the flash from strobe 2?
4. In the reference frame of the spacecraft, does strobe 1 flash *before*, *after*, or *at exactly the same time as* strobe 2?

These four questions can be answered using the same reasoning as in version A; however, we were interested in whether students would use the following chain of reasoning for questions 2, 3, and 4:

2. Events are frame independent, so the firecracker explodes in all frames if it exploded in the reference frame of the ground.
3. Because the firecracker exploded in the reference frame of the spacecraft (as determined in question 2), the wavefronts must have reached it at the same instant in that frame as well.
4. Because the firecracker is closer to the center of the wavefront from strobe 1 at the instant that it receives the wavefronts from the two strobes simultaneously, the wavefront from strobe 2 must be further from its origin in the reference frame of the spacecraft, indicating that strobe 2 must have flashed before strobe 1.

That is, we were interested in learning whether students' possible, intuitive belief in the frame independence of events would help them answer questions 3 and 4 correctly.

Results from Versions A and B Because we were interested in how question order affected student performance and reasoning, the tables below summarize results from both versions of the pretest when possible.

Performance on the question regarding the occurrence of the explosion of the firecracker in the reference frame of the spacecraft (question 4 in version A and question 2 on version B) are almost the same on the two versions. Sixty percent of students given version A of the *Firecracker 1* task answered correctly that the firecracker would explode in the spacecraft reference frame, while 70% of students given version B answered correctly. Although the performance of students on version B was slightly better, as we might have predicted given the question order, the difference was not significant.

Similarly, question order did not seem to affect student performance on the question regarding the order of signal reception by the firecracker in the spacecraft reference frame (question 3 on both versions) or on the question about the order of the strobe flashes in the reference frame of the spacecraft (question 2 on version A and question 4 on version B). Results from these three questions are summarized in Table 6.11.

Table 6.11: Overall results for the *Firecracker* task for the spacecraft frame for both versions of the pretest.

Percentage of students answering correctly for questions about the spacecraft frame		
	Version A ($N = 301$) ^a	Version B ($N = 304$) ^b
Firecracker explosion	60%	70%
Signal reception	35%	40%
Order of strobe flashes	25%	25%

^a Sections 123A151152154 and 123B154. ^b Sections 123A151154, 123B154, and 123C152.

Although the percentages of students answering correctly were not significantly different for the two versions, we did find a difference in student reasoning, particularly for the question about the reception of the signals at the firecracker. In both versions, about half of the students who answered correctly that the firecracker must explode in the reference frame of the spacecraft also answered correctly that the wavefronts from the strobe flashes must reach the firecracker simultaneously in the reference frame of the spacecraft. However, on version B (in which the question about the explosion of the firecracker preceded the question about the firecracker's signal reception) students were much more likely to reference the firecracker's explosion in their explanation about the firecracker's signal reception. In version A, only 5% of students (total) used the explosion of the firecracker to justify why the signals must have reached the firecracker simultaneously; in version B, 30% of students did so.

There was no significant difference in student reasoning for the question regarding the order of strobe flashes in the reference frame of the spacecraft for the two versions of the *Firecracker 1* task.

6.4.2-c *Firecracker 2 pretest task*

The *Firecracker 1* pretest described above (6.4.2-b) was intended to probe whether students could be prompted to recognize the necessity of the principle of coincidence based on a belief in the frame-independence of events. While we did not see a difference in student performance

Table 6.12: Overall results for the *Firecracker 2* task for the spacecraft frame. The correct answers are highlighted.

$N = 860^a$	Firecracker explodes	60%
Order of signal reception	Same time	30%
	Different times	30%
	Firecracker does not explode	40%
Order of signal reception	Same time	5%
	Different times	35%

^a Sections 123A161162164171, 123B161164171, and 123C162.

on two versions of the *Firecracker 1* pretest, on which question order was varied, we did see an increase in explanations that recognized the connection between the two causality-related ideas.

To probe student understanding of the relationship between the frame-independence of events and the principle of coincidence, we ran another version of the *Firecracker* context. For the *Firecracker 2* context, students were told explicitly that the two strobes flash simultaneously in the ground frame, and that the firecracker explodes. For the causality-related portion of the *Firecracker* task, students were asked first whether, in the reference frame of the spacecraft, the firecracker would explode. Second, they were asked about the order in which the wavefronts of light from the strobe flashes would reach the firecracker in the frame of the spacecraft. Finally, students were shown their responses from the first two questions, and asked to explain how their answers were consistent with their understanding of special relativity. Figure 6.19 shows the task context and the first two questions; Figure 6.20 shows an example of the question students might have seen for the third portion of the task, for one possible set of answers. For the actual pretest task, students were shown each question on a separate page, and were not allowed to “backtrack” to change their answers.

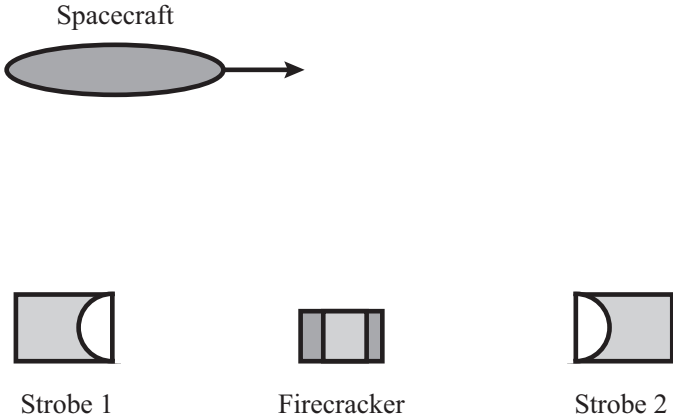
Results of the first two questions are summarized in Table 6.12.

Below, we describe the reasoning used on the third question (regarding the reasoning for the previous two questions) for four subsets of students. Two of the subsets describe student

A firecracker lies on the ground exactly halfway between strobe 1 and strobe 2. The firecracker is designed to explode if it is hit by light from both strobes at the same instant; it will not explode if light from the two strobes hits it at different instants.

In the firecracker frame, strobes 1 and 2 flash at exactly the same instant, and the firecracker explodes.

A spacecraft moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe 1 at the instant it flashes.



Spacecraft

Strobe 1 Firecracker Strobe 2

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (i.e., ignore vertical distances).

1. In the reference frame of the spacecraft, does the firecracker explode, or not explode?
2. In the reference frame of the spacecraft, does the light from strobe 1 reach the firecracker *before*, *after*, or *at exactly the same time* as the light from strobe 2?

Figure 6.19: Context and first two questions for the *Firecracker 2* pretest task testing student understanding of the relationship between the frame independence of events and the principle of coincidence.

responses from students who answered the two previous questions “consistently.” First we describe students who answered both questions correctly (the firecracker explodes, and the signals reach the firecracker simultaneously) and then students who answered both questions incorrectly. The other two subsets consist of students who answered the two questions inconsistently. First, we describe students who answered that the firecracker would not explode, but the signals would arrive at the firecracker at the same instant. Finally, we describe students who answered that the firecracker would explode but the signals reach the firecracker at different instants.

Consistent answers: firecracker explodes; signals arrive at same time Almost a third of the students (30%) answered both questions correctly, determining that the firecracker explodes and that the light wavefronts from the two strobes hit the firecracker simul-

3. Consider again the scenario described on the previous page. Recall that the firecracker explodes **in the reference frame of the firecracker**.

Consider your responses to the previous two questions:

- The firecracker explodes
- The light from strobe 1 reaches the firecracker before the light from strobe 2

Explain how these two answers are consistent with your understanding of special relativity.

Figure 6.20: Portion of the *Firecracker 2* pretest task asking students to relate the frame-independence of events and the principle of coincidence.

taneously in the reference frame of the spacecraft. However, only about 5% of all students used correct reasoning; these students often noted the relationship between the explosion of the firecracker and its reception of the wavefronts of the light from the two strobes. Below are explanations from students relying on this idea.

“The firecracker must explode still regardless of reference frame so the light from each [strobe] must still hit the firecracker at the same time for this to happen. However distance appears different in the craft’s ref frame.”

“Special relativity and theories of reference frames state that events that happen at the same time and at the same [place] (i.e. the light from the two hitting the firecracker) look the same from any reference frame. Therefore the firecracker would explode because the light would hit the firecracker at the same time. The emission of light would appear to be at different times.”

Others noted that the firecracker’s reception of the two signals can be considered a single event that occurs in all reference frames, as in the student explanations below:

“Seems impossible for it not to explode. Also, since the two strobes hit the same place at the same time in the firecracker reference frame, it seems like it’s an event, so must be at one place and time in Spacecraft frame too.”

“Any events that occur at both the same place and the same time in ANY reference frame will always occur at the same place and time in all other reference frames. The two lights reach the firecracker at the same time in the firecracker’s reference frame, so they must in the spacecraft’s frame as well.”

Many of the students answering both questions correctly but with incorrect reasoning relied on absolute simultaneity, a misunderstanding of the invariance of the speed of light, or both. These students were likely to state that the firecracker is equidistant from the strobes in both reference frames (which is correct) but then determine that the time taken to reach the firecracker from the two strobes would be the same in each reference frame (which is incorrect). These students may be relying on absolute simultaneity as well as an incorrect belief that the centers of the light wavefronts are centered at the strobes in both reference frames.

Consistent answers: firecracker does not explode; signals arrive at different times

Thirty-five percent of students answered both questions incorrectly, claiming that the firecracker would not explode and the signals from the strobes reach the firecracker at different times. These students were likely to state that the firecracker would explode in the reference frame of the spacecraft only if the signals reached it simultaneously in that reference frame as well. Although they answered both questions incorrectly, students in this subset were the most likely to connect the order of reception of the light wavefronts to the event corresponding to the explosion of the firecracker, with over half of them (20% of total students to whom this task was administered) making the connection. Many of the students answering both questions incorrectly relied on a misunderstanding of the relativity of simultaneity, stating that events that are simultaneous in one reference frame cannot be simultaneous in any other reference frame.

For students answering both questions incorrectly, there was no significant difference in student explanations regarding causality-related concepts from students who answered that the light from strobe 1 would reach the firecracker before the light from strobe 2, or the

opposite. Students answering that the light from strobe 1 would reach before that from strobe 2 were more likely to make the signal reception error, described in detail in Chapters 3 and 4.

Inconsistent answers: firecracker does not explode; signals arrive at different instants A few students (5%) answered the light from the two strobes would reach the firecracker simultaneously, but that the firecracker would not explode. Of these students, about half recognized that their answers were not consistent and stated that they should have answered the first question (regarding the explosion of the firecracker in the reference frame of the spacecraft) differently. Only one student referenced the fact that events that are coincident in one frame are coincident in all frames; based on this student's explanation and responses to other questions, it seems that the reasoning is based on absolute simultaneity rather than an understanding of the principle of coincidence:

“Light travels at the same speed in all reference frames so my initial answer is incorrect in that the firecrackers does not explode. If in the reference frame of the firecracker, the light hits at the same time, then it must be true for the spacecraft reference frame as well.”

Inconsistent answers: firecracker explodes; signals arrive at different times About 30% of the students answered that the firecracker would explode but that the signals from the strobes would reach the firecracker at different times. Three common lines of reasoning were identified for these students.

The first was based on a recognition that the strobes would flash at different times in the reference frame of the spacecraft and an incorrect assumption that the centers of the wavefronts from the flashes of light were located at the strobes in that reference frame. None of the 10% of total students using this reasoning mentioned the explosion of the firecracker in their responses. This might indicate that many of them do not consider the explosion of the firecracker as related to the firecracker's order of signal reception in the reference frame of the spacecraft.

Another 10% of students used reasoning that violates the principle of relativity, treating the reference frame of the firecracker as a preferred frame. Reasoning by these students was sometimes based on a belief that the order of signal reception by the firecracker was important only in the reference frame of the firecracker, as in the student statement below:

“The firecracker exploding will only happen if the lights hit it at the same moment in the firecracker’s reference frame, so regardless of the fact [that] from the space craft the lights hit at different times the firecracker will explode.”

Other students seemed to express the belief that the firecracker functioned differently in different reference frame, requiring simultaneous reception of signals to explode only in the rest frame of the firecracker and not in other frames:

“The event of the explosion is a single event that all inertial observers can agree [on], I.E. it [has] the same position and time, therefore invariant. But because of the velocity transformation, the two lights [don’t] hit the strobe at the same time, I.E. simultaneity is inconsistent, but the workings of the firecracker operate in the reference frame of the firecracker.”

Almost all of the students whose responses were in this category (i.e., responses that treat the reference frame of the firecracker as a preferred frame) expressed a belief that the firecracker had to explode in all frames, but also that the signals would *actually* reach the firecracker at different instants.

The final 10% of students used reasoning that indicated a belief that some reference frames are more valid than others for analyzing this context. Many of these student used reasoning based on the idea that an observer in the reference frame of the spacecraft would *perceive* the signals reaching the firecracker at different instants, but that the observer would be incorrect. The following student response illustrates this type of reasoning.

“The firecracker would explode. If [it’s] measuring whether the flashes hit it at the same instant and neither one of the strobes are moving relative to it then that can all be considered the normal frame. The spaceship will see the oncoming flash hit the firecracker first then the one [it’s] moving with. Problem here is that because the two different times from the perspective of the space ship, the firecracker shouldn’t explode.”

This student seems to be saying that an observer in the reference frame of the spacecraft would see the signals reach the firecracker at different instants and would determine that the firecracker should not explode, but is incorrect. However, the reference frame of the firecracker is the “normal” frame, and in that reference frame the signals arrive simultaneously and the firecracker explodes, which determines what really happens:

Similarly, students sometimes expressed a belief that only the rest frame of the firecracker could be used to determine what events happen (or not):

“In [the firecracker’s] stationary frame both lights hit it at the same time so this is the reality of the situation. However, the moving spacecraft observes a different reality. ”

Unlike students treating the rest frame of the firecracker as a preferred reference frame, these students often express a belief that an observer in another reference frame may see or observe something that is not consistent with what actually happens. Unsurprisingly, this type of response was more prevalent in students who answered that strobe 1 would flash before strobe 2 in the reference frame of the spacecraft for another question on the same pretest. This is consistent with the signal reception error.

We don’t regard the tendency of students to consider the spacecraft reference frame an invalid frame in which to do analyses as a difficulty with causality, although it leads to similar responses. Rather, we believe that the difficulty is one with student understanding of reference frames.

Commentary on exercises in the *Simultaneity* tutorial addressing student belief in “invalid” frames The tendency of students to treat certain reference frames as valid or

invalid is not unexpected, and is elicited explicitly by the *Simultaneity* tutorial, as described below.

Recall that in the *Simultaneity* tutorial (see page 45), students work through a modified version of Einstein's train paradox, in which sparks jump between a train and the track that it moves along. Students determine that in the reference frame of Alan (an observer at rest with respect to the track) the sparks jump at either end of the train simultaneously. As discussed in section 3.2.1-b, the tutorial then allows students to determine (incorrectly) that the two sparks also jump simultaneously in the reference frame of Beth, an observer at rest with respect to the train. This error would lead students to believe that Beth receives the wavefronts from the two sparks simultaneously in her own reference frame, but would receive that wavefront from the front spark first in the reference frame of Alan.

To demonstrate how this difference between the two reference frames would lead to a violation of causality, students are then asked to imagine that a small device attached to two firecrackers sits at Beth's feet. The device is programmed such that if the wavefronts from the two sparks hit it simultaneously, both firecrackers would explode. If one of the wavefronts from the spark hits it before the other, only one of the firecrackers explodes. Students are asked to determine which of the firecracker(s) explode in the two reference frames. This exercise is shown in Figure 6.21.

Relating Alan's and Beth's frames

A device consisting of two firecrackers attached to light sensors lies on the floor of the train at Beth's feet. If both wavefronts hit the device at the same instant, both firecrackers explode. If wavefront F hits the device first, only firecracker 1 explodes. If wavefront R hits the device first, only firecracker 2 explodes.

1. Which firecracker(s) explode in each of the following frames? Explain.
 - Alan's frame
 - Beth's frame

Figure 6.21: Exercise from the tutorial *Simultaneity* designed to help students recognize a violation of the principle of causality.

The majority of students have concluded that Beth receives wavefront F first in Alan's reference frame, but both wavefronts simultaneously in her own reference frames. Therefore, most students answer that only firecracker 1 explodes in Alan's reference frame, while both firecrackers explode in Beth's reference frame. In our experience, many students recognize the impossibility of their answers at this point, but do not know how to proceed. The next exercise consists of a student dialogue aimed at resolving this "paradox." In the student dialogue, shown in Figure 6.22, the first student suggests that the apparent frame-dependence of the event associated with the explosion of firecracker 2 is just a "strange" results of special relativity. The second student responds that it doesn't seem possible for a firecracker to both explode and not explode, depending on the reference frame, and that they must have made a mistake at some point. The first student replies that both firecrackers actually do explode, and that what Alan would have perceived (firecracker 1 exploding, and firecracker 2 remaining whole) is incorrect. The first student implies that Beth's reference frame is the only one in which an observer could really know what firecracker-related events occurred, as that is the rest frame of the firecrackers.

2. Consider the following dialogue between two students:

Student 1: "Special relativity is strange; firecracker 2 explodes and does not explode, depending on which reference frame you are in."

Student 2: "I don't believe a firecracker can both explode and not explode. We must have made a mistake. What if the train stops and Alan gets on? Would he see firecracker 2 whole like he expected?"

Student 1: "No, firecracker 2 is in Beth's frame, and, in Beth's frame, it explodes. When Alan gets on the train, he would see that firecracker 2 actually did explode. But, until he got on the train, he would think that firecracker 2 did not explode."

With which student do you agree, if either? Explain.

Figure 6.22: Student dialogue from the tutorial *Simultaneity* designed elicit the "invalid frame" belief in response to a violation of the frame-independence of events

Student 1's response is remarkably similar to the responses seen in the *Firecracker 2*

pretest task described in this section. (It was written before the *Firecracker 2* task was written but was developed on the basis of informal discussions with students working through earlier versions of the tutorial.) Student 1's response, and the responses of students described above, suggest a belief in the frame-independence of events. They also suggest a belief that events associated with objects (such as the explosion of a firecracker) can only be reliably observed by observers at rest with respect to those objects.

6.4.3 Student difficulty identifying reception as an event

An understanding of concepts that underlie causality (such as the frame-independence of events, and the principle of coincidence) is necessary to work (qualitatively) through situations that are physically equivalent to Einstein's train paradox. Students seem to have a number of persistent beliefs about events, reference frames, and the invariance of the speed of light that interfere with their ability to recognize and uphold causality in all reference frames. Some of these ideas have been discussed, as relevant, in the sections above. In this section, we describe student difficulties with events in more detail, as well as the role those difficulties seem to play on student understanding of causality in the context of the relativity of simultaneity.

In particular, we focus on a tendency of students to disregard observer reception of signal as an event. Comparison of student performance on tasks such as the *Strobe Train* task (in which two coincident events could be associated with the emission of light signals) to performance on tasks such as the *Mountain Firecrackers* task (in which the two coincident events were associated with the reception of signals) led us to believe that students have more difficulty recognizing and upholding the principle of coincidence with reception events than with emission events. We suspected that students may have more difficulty recognizing that reception of a signal can be considered an event

To determine whether students have trouble classifying the reception of a signal as an event, we used results from a free-response pretest, as well as results from multiple-choice tasks used on course final exams. We also use data from *Events and reference frames* pretests,

to determine whether the tutorials improve student understanding of signal reception as an event.

***Events and reference frames* pretest results** Each pretest for the tutorial *Events and reference frames* contains a task asking students to determine whether or not a given item is an event as defined in the *Events and reference frames* tutorial (something that can be associated with a single instant in time and a single location in space). A representative example of such an exercise is shown in Figure 6.23.

Indicate whether each of the items listed below is an event as defined in the context of special relativity.

- A cannon
- A cannon fires
- A soldier hears the cannon fire
- Two distant cannons fire at the same time.

Figure 6.23: Representative example of exercise to test student understanding of the term “event” before tutorial instruction.

We focus here on comparison of student responses for the second and third bullet points: “A cannon fires,” and “A soldier hears a cannon fire.” Both of these can be considered events, as both can be associated with a single location in space, and a single location in time (i.e., a single spacetime coordinate). Results from this and similar pretest tasks are shown in Table 6.13.

Almost all students (95%) recognize that a cannon firing can be considered an event, whereas only a majority of students (75%) recognize that a soldier hearing the cannon fire could be considered an event as well. More than two-thirds of students answered correctly for both items. So although most students are able to answer both questions correctly, students have an easier time considering a cannon firing an event than someone hearing the noise associated with a cannon firing.

Table 6.13: Student performance on pretest task for tutorial *Events and reference frames* to test student understanding of the term “event.” The correct answers are highlighted.

$(N = 2273)^a$	Event	Not an event
A cannon fires	95%	5%
A soldier hears the cannon fire	75%	25%
	70% correct on both	

^aSections 123A101102122124131132134144161162164, 123B131161164, and 123C122132162

Free-response post-test results A free-response question was used on a midterm exam for Physics 123 to test student understanding of reception of a signal as an event. The question statement is shown in Figure 6.24.

Indicate whether each of the items listed below is an event as defined in the tutorial *Events and Reference Frames*. For each case, explain briefly.

- A person sees a flash of lightning
- Two flashes of lightning strike at the same time on opposite sides of a city

Figure 6.24: Post-test task for the tutorial *Events and reference frames* that tests student understanding of the reception of a signal as an event

We focus here on only the first bullet point, regarding an observer seeing a flash of lightning; 70% of students ($N = 188$) answered correctly that a person seeing a flash of lightning could be considered an event. This is slightly worse (but not significantly different) than performance on the analogous pretest task. Although students see an exercise very similar to that on the pretest in the tutorial *Events and reference frames* (in which they are asked to determine whether given items can be considered events), the *Events and reference frames* tutorial does not seem to improve student performance on this type of task.

Because this was a free-response question, we were able to analyze student responses to determine their reasoning. The most common type of explanation provided in support of an

incorrect answer is exemplified by the student response below:

| *The lightning striking is the event, not someone seeing it.* |

This suggests that the *Events and reference frames* tutorial is successful in teaching students that there is a difference between the emission and the reception of a signal (which are sometimes confused by students making the signal reception error). However, it also seems that some students take from this an incorrect result, and do not regard reception as an event at all.

Multiple-choice post-test results We see very similar results from a multiple-choice post-test task, shown in Figure 6.25. In the context for this task (not shown) an observer is standing equidistant from and at rest with respect to two lights, one blue and one red. For this question, 25% of students chose answer C (the light flashing is an event, but the observer seeing the flash is not an event), where as 95% of students chose an answer (A or C) that indicates an understanding that the flashing of a light can be considered an event.

Consider whether each of the items listed below is an event as defined in the tutorial *Events and reference frames*.

- (i) The red light flashes
 - (ii) Observer W sees the red flash
- A. Both (i) and (ii) are events
 - B. Neither (i) nor (ii) is an event
 - C. (i) is an event but (ii) is not an event
 - D. (ii) is an event but (i) is not an event

Figure 6.25: Post-test task for the tutorial *Events and reference frames* that tests student understanding of the reception of a signal as an event

Together, these results suggest that students have a more difficult time defining reception of a signal as an event, compared to emission of a signal. This may be, in part, why student

performance on post-test tasks involving coincident emission events was better than that one post-test tasks with reception events.

6.5 Conclusions and future work

The results presented in this chapter suggest that concepts related to causality are difficult for introductory physics students. Despite targeted instruction in the *Events and reference frames* tutorial and homework, and the *Simultaneity* homework, these difficulties are persistent and widespread. Using research tasks on pretests and post-tests, we have identified particular difficulties with causality which may inform modification or development of the tutorial curriculum in special relativity to improve student learning.

Informal interactions with students during the *Simultaneity* tutorial revealed that students do not spontaneously apply the principle of causality when trying to determine the time sequence of events at a single location. Moreover, students seem not to recognize the importance of the principle of causality, even when confronted with the incorrect idea that an event could happen in one reference frame but not another.

Results from pretests and post-tests also suggest that students do not recognize that two or more *reception* events that are coincident (i.e., that share a single spacetime coordinate) in one reference frame must be coincident in every reference frame. Consistent with our observations of students from tutorial, these data also indicate that an intuitive belief in the frame-independence of events is not enough to motivate acceptance and use of the principle of coincidence. Students do not spontaneously use the principle of coincidence when analyzing contexts involving the relativity of simultaneity. Students fail to use the principle of coincidence as a basis for reasoning about the ordering of events in multiple reference frames even when questions are presented to them in an order that might suggest its application, as described in section 6.4.2-b.

Results from free-response post-tests tasks such as the *Strobe Train* task suggest that students have less difficulty with recognizing the results of the principle of coincidence with events associated with the emission of signals than events associated with the reception of signals. Results from tasks testing student ability to identify events indicate that some of the difficulty that students have applying the principle of coincidence with reception events may be due to difficulties related to the identification of a reception of signal(s) as an event.

However, the difference in student performance on principle of coincidence tasks for reception and emission events is larger than one might expect if this were the only contributing difficulty. We believe that some of the difficulties identified in the *Firecracker* tasks (namely, student difficulties with event location and consequences of the invariance of the speed of light) also contribute to poorer performance on tasks involving reception of signals. Student tendency to link the location of an emission event (and therefore, the location of the center of the wavefront from that event) to the object emitting the signal is very strong. This seems to lead many students to conclude that an observer that is centrally-located between event locations in one reference frame is centrally-located in all reference frames; this would imply that the observer would receive the signals in the same order in which they were emitted.

Student responses on the *Firecracker* pretests tasks indicate that many students do not recognize that causal relationships between events must be maintained in every reference frame (see 6.4.2-c). Although these students seem to recognize that an event such as the explosion of a firecracker is frame-independent (that is, the firecracker must explode in every reference frame if it explodes in the ground frame), they do not recognize that the simultaneous reception of light wavefronts by the firecracker is also an event (and is therefore also frame independent). A number of students use reasoning that indicates that the order of signal reception by the firecracker is only important in the rest frame of the firecracker. Some of these students stated explicitly that the function of the firecracker is different in different reference frames. Others made errors based on a lack of understanding of event location or consequences of the invariance of the speed of light, but seemed not to recognize the inconsistency of claiming that firecracker would explode and that the wavefronts of light from the strobes would reach the firecracker at different instants.

Results from the *Firecracker 2* pretest also help us identify a related error in which students seem to claim that observers in some reference frames would not be able to make correct observations of what actually happened. Some students seem to believe that while the signals from the strobe flashes would reach the firecracker simultaneously and that the firecracker would explode, only observers in the rest frame of the firecracker would be able

to come to this conclusion based solely on observation. Some students claim that observers in other reference frames might see the signals reach the firecracker at different instants, and come to the conclusion that the firecracker would not explode, but that those observers would do so incorrectly.

The results presented in this chapter imply that few students use causality as a guiding principle when reasoning about the relativity of simultaneity. This, in turn, suggests that a majority of students do not understand what is “paradoxical” about Einstein’s train paradox. Students seem not to recognize that giving up absolute simultaneity is required in order to uphold causality. Implications for instruction and curriculum development based on these findings will be discussed in Chapter 7.

Chapter 7

SUMMARY AND CONCLUSIONS

The unusual results of special relativity (such as length contraction, time dilation, and the relativity of simultaneity) follow as consequences of the addition of Einstein's two postulates to the framework of Galilean relativity. The research presented in this dissertation suggests that introductory student difficulties with special relativity are the result of a lack of understanding of both Galilean relativity and Einstein's postulates. In addition, we find that many students have a tendency to disregard causality as a guiding principle. Because all of these ideas are necessary to develop a conceptual understanding of the relativity of simultaneity, we conclude that most students leave a traditional introductory course without a functional understanding of what is arguably the key result of special relativity.

This dissertation documents our investigation of student understanding of special relativity in the context of the relativity of simultaneity. Also illustrated is the iterative process of research, modification of curriculum, and instruction leading to the development of curricular materials designed to improve the learning of introductory students in this topic. Below is a brief summary of difficulties identified in this population of students, as well as implications for instruction and curriculum development, and directions for future work.

7.1 Summary of specific difficulties

We have identified a number of student difficulties with Galilean relativity leading to difficulties with topics in special relativity. Most prominent among these was the signal-reception error, associated with a misinterpretation by students of what is meant by “reference frame.” Students making this error tend to associate the time of an event in a given observer’s reference frame with the time that the signal from that event was received by that observer. Students using this type of reasoning fail to recognize that relative motion, rather than position, determines an observer’s reference frame. In addition, students making this error (often unknowingly) assume that simultaneity is absolute, and attribute the apparent differences between measurements in different reference frames to differences in signal propagation time. This error was previously identified by Rachel Scherr and Caleb Teel in a range of student populations [8, 9]. Our findings are consistent with theirs.

We also found that many students do not recognize that simultaneity is relative for spatially-separated events. Student tendency to believe in absolute simultaneity was seen implicitly in students making the signal-reception error, as described above, as well as more explicitly. Moreover, the vast majority of students were observed to assume absolute simultaneity while working through relevant sections of the *Simultaneity* tutorial. Although observations from tutorial sessions are difficult to quantify, we estimate that up to 95% of students make this error in the tutorial classroom, even after lecture instruction in the relativity of simultaneity.

Many students lack the ability to use the formalism of a reference frame to determine the time and location of an event. In particular, we find that many students identify the location of an event as at an object associated with that event. For example, many students identify the location of the event “a beeper beeps” as “at the beeper.” Although this correctly identifies the location of the event at the instant that the event occurs, it does not correctly label the location of the event at all times after the event occurs—except for in the rest frame of the beeper. Students often fail to recognize that event location must be stationary in all reference frames, or equivalently, the location of an event should not change with time

in any reference frame.

Related to this is a student difficulty with recognizing that a consequence of the invariance of the speed of light is that, for events associated with the emission of a light signal, the center of the wavefronts of the light is stationary in all reference frames, and is co-located with the position of the event. As with event location, there is a tendency of students to associate the location of the center of the wavefronts from a flash of light at an object associated with the emission of the light.

Our research also indicates that students fail to recognize that a non-stationary center of wavefronts is inconsistent with the speed of light being the same in all reference frames. This may be related to difficulties with determining kinematical quantities in frames other than the ground or “laboratory” frame of reference. Investigations of introductory student understanding of the invariance of the speed of light also reveal that many students do not recognize a difference in the propagation of light and sound signals. Both of these difficulties are similar to difficulties identified by Andrew Boudreaux in the context of Galilean relativity [7].

Finally, we have identified a number of introductory student difficulties with concepts that underlie causality. Overall, we find that many introductory students fail to use causality as a guiding principle when considering events in different reference frames, and that they often consider a failure to uphold causality to be one of special relativity’s non-intuitive effects. Students seem to have particular difficulty recognizing that *reception* events that are coincident (e.g., the simultaneous reception of signals by a single observer) in one reference frame must also be coincident in all reference frames. We also found that a surprising number (up to 40%) of students believe that events can be dependent on reference frame—that is, that an event may happen in one reference frame but not another

Investigation into a combination of these ideas (the principle of coincidence and the frame-independence of events) led to the identification of a difficulty related to the recognition that causal relationships between events must be maintained in all reference frames. We identified two lines of reasoning among students that seem to recognize that events are

frame independent, but seemingly do not recognize that an event must have the same cause in every frame. The first was an apparent belief in a preferred frame. Similar to student difficulties related to event location and the motion of the center of wavefronts from a flash of light, students tend to associate a given event with a particular object, and choose the rest frame of that object as the preferred frame. Some students seem to believe that the causal relationship between events must be upheld in the identified preferred frame only.

The second line of reasoning seemed to stem from a belief that only observers at rest with respect to the object linked to the event could determine what “really” happened on the basis of their observations and measurements. Explanations from students with this belief indicated that observations or measurements made by observers in motion relative to the relevant object would not result in an accurate description of events.

Overall, very few students seem to be able to synthesize key ideas such as reference frames, the invariance of the speed of light, and causality in order to determine the order of spatially-separated events in multiple reference frames. Rather than using causality as a basis for their understanding, incorrect student beliefs result in violations of causality, and therefore, the principle of relativity.

7.2 Implications for instruction and the development of curriculum

Our investigation of introductory student understanding of special relativity in the context of the relativity of simultaneity led to a number of modifications of the existing special relativity tutorial materials. Based on our findings that student difficulties with topics in Galilean relativity underlay their difficulties with special relativity, we focused our efforts primarily on the *Events and reference frames* tutorial and homework, which attempts to give students necessary background in the formalism of a reference frame.

Modifications to the *Events and reference frames* tutorial included a reformulation of the definition of reference frame, as well as change in the sequence of the introduction of topics. This was done, in part, to motivate the idea of a reference frame as tool to be used to measure the time and location of any event. The *Events and reference frames* homework was entirely rewritten to include relative motion. Exercises intended to help students identify quantities that might be different in different reference frames were included, as well as a series of exercises introducing the principle of coincidence.

The *Simultaneity* homework was also entirely rewritten, with exercises designed to help students use causality generally (and the principle of coincidence particularly) as a guiding principle to determine the order of spatially-separated events in reference frames in which the events are not simultaneous.

7.3 Assessment of student learning

Over the course of our investigation, we have tested a number of variations of the special relativity tutorial curriculum with introductory students at the University of Washington. We have found the sequence of tutorials *Events and reference frames* and *Simultaneity* to be effective at improving student learning in some areas, and less so in others. The *Events and reference frames* tutorial and homework seem to address a key student difficulty (the signal-reception error) effectively, but do not seem to improve student understanding of the formalism of a reference frame to the extent that we want. The *Simultaneity* tutorial and homework are not especially effective in helping students determine the order of spatially-separated events in multiple-reference frames, nor do they seem to help students use causality as a guiding principle.

To address the more persistent difficulties of introductory students, it may be necessary to increase the number and scope of special relativity tutorials used with introductory students. Based on the results of the investigation described in this dissertation, we propose a possible sequence of special relativity tutorials, as follows.

1. *Events and reference frames*

- Defines events and reference frames in the context of Galilean relativity
- Introduces “event diagrams” as a tool for analysis of events
- Develops the consequences of using the formalism of a reference frame for the measurement of the time and location of events
- Introduces the principle of coincidence

2. *Relativity and Einstein’s postulates*

- Builds on framework of Galilean relativity introduced in *Events and reference frames* tutorial and homework

- Develops the consequences of the invariance of the speed of light with exercises showing the differences in propagation of light and sound
- Uses the principle of relativity to motivate the necessity of maintaining causal relationships across all reference frames

3. *Simultaneity*

- Builds on framework developed in prior tutorials
- Steps students through Einstein's train paradox using causality and the invariance of the speed of light as a basis
- Helps students develop a qualitative procedure for determining the order of spatially-separated events in multiple reference frames

7.4 Questions for further research

Our investigation of introductory student understanding of special relativity led to the discovery that student difficulties with necessary concepts were far more complex than we initially anticipated. Our initial belief was that if we improved student understanding of Galilean relativity through modifications of the *Events and reference frames* curriculum, student performance on tasks involving relativistic speeds would also improve. Although we were able to improve student understanding of events and reference frames, we found that introductory student performance on tasks related to the relativity of simultaneity did not improve significantly. We now believe that student understanding of the invariance of the speed of light and concepts related to causality must also be addressed if we want student performance on relativity of simultaneity tasks to improve as well. We hope to modify the existing curriculum as well as develop a new tutorial, and to assess the effects of those new materials.

This dissertation describes the process of identification of specific difficulties, curriculum development, and instruction to improve introductory student learning of special relativity. We believe we have gained insight into how students learn this topic, as well as how students attempt to accommodate special relativity's surprising and often non-intuitive results into their understanding of Galilean relativity.

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Part III

**APPENDICES: UNABBREVIATED QUESTIONS AND
CURRICULAR MATERIAL**

All of the curricular material relevant to this research is included.

Unabbreviated versions of all of the pretest and post-test questions administered as part of this research is also provided. Note that pretests and post-tests may appear multiple times, as multiple research tasks were often included on a single pre- or post-test.

Appendix A (beginning on the following page) is devoted to the tutorials *Events and reference frames* and *Simultaneity* used in our preliminary research in Autumn 2009, as well as the pretests and post-tests used in that quarter as described in Chapter 3.

Appendix B (beginning on page 301) provides the material related to our investigation into student understanding of reference frames, described in Chapter 4.

Appendix C (beginning on page 369) provides the material related to our investigation into student understanding of the invariance of the speed of light, described in Chapter 5.

Appendix D (beginning on page 393) provides the material related to our investigation into student understanding of concepts related to causality, described in Chapter 6.

Appendix A

**QUESTIONS AND CURRICULAR MATERIAL DESCRIBED
IN CHAPTER 3**

In this portion of the Appendix we provide the pretest, in-class worksheets, homework, and post-test used in the preliminary investigation conducted in Autumn 2009, described in Chapter 3.

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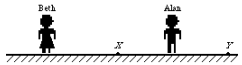
A.1 Pretests used in Autumn 2009

In this section we provide the online pretests related to the tutorials *Events and reference frames* and *Simultaneity* used in Autumn 2009.

8/17/2017 Catalyst WebQ

Print view of '(ERF)U1a_Default'
[Print this page](#)

A. Two physics students, Alan and Beth, are shown in the diagram. Alan and Beth have each measured their exact relative distances from points X and Y.



Two sparks, X-spark and Y-spark, occur at the points marked X and Y. When each spark occurs, it emits a flash of light.

Let Event 1 be The X-spark occurs.
 Let Event 2 be The Y-spark occurs.

Alan, who is equidistant from points X and Y, receives the wavefront from each spark at the same instant.

Question 1.
 In Alans reference frame, is the time coordinate of Event 1 *earlier than*, *later than*, or *exactly the same as* the time coordinate of Event 2?

Select one...
 unanswered
 In Alans frame, the time coordinate of Event 1 is earlier than the time coordinate of Event 2
 In Alans frame, the time coordinate of Event 1 is later than the time coordinate of Event 2
 In Alans frame, the time coordinate of Event 1 is the same as the time coordinate of Event 2

Question 2.
 Explain.

Question 3.
 Does Beth receive the wavefront from the X-spark *before*, *after*, or *at exactly the same time as* the wavefront from the Y-spark?

Select one...
 unanswered
 Beth receives the wavefront from the X-spark before the wavefront from the Y-spark
 Beth receives the wavefront from the X-spark after the wavefront from the Y-spark
 Beth receives the wavefront from the X-spark at the same time as the wavefront from the Y-spark

Question 4.
 Explain.

Question 5.
 In Beths reference frame, is the time coordinate of Event 1 *earlier*, *later*, or *exactly the same as* the time coordinate of Event 2?

Select one...
 unanswered
 In Beths frame, the time coordinate of Event 1 is earlier than the time coordinate of Event 2

<https://catalyst.uw.edu/webq/build/tipwo/84827> 1/2

Figure A.1: Catalyst *Events and reference frames* pretest version U1A administered in Autumn 2009 to PHYS 123A. (Two pages.)

8/17/2017

Catalyst WebQ

- In Beths frame, the time coordinate of Event 1 is later than the time coordinate of Event 2
- In Beths frame, the time coordinate of Event 1 is the same as the time coordinate of Event 2

Question 6.

Explain.

B. Determine whether or not each of the items below is an event as defined in your physics class.

Question 7.**Rows**

a cannon
the cannon fires
a soldier hears the cannon fire
two distant cannons fire at the same time

- is an event
- is not an event

Question 8.

Explain your reasoning for each case above.

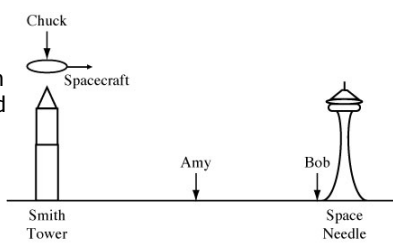
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University of Washington, Winter 2005

Questions or comments?
Contact us or email catalysthelp@uw.edu

8/18/2017 Catalyst WebQ

Print view of '(SIM)U2a'
[Print this page](#)

Amy is at rest midway between Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.



Chuck is in the center of a spacecraft moving from Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above Smith Tower when the light above Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 In Amy's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Bob's reference frame, the flash above Smith Tower occurs:

<https://catalyst.uw.edu/webq/build/tipwo/90179> 1/2

Figure A.2: Catalyst *Simultaneity* pretest version U2A administered in Autumn 2009 to PHYS 123A. (Two pages.)

8/18/2017

Catalyst WebQ

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Consider the following statement:

In the above situation, all three observers (Amy, Bob, and Chuck) agree that Amy sees both flashes simultaneously.

Do you agree or disagree with this statement?

- I agree with this statement.
- I disagree with this statement.

Question 12.

Explain the reasoning you used to answer the question above.

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University of Washington, 2012

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A.2 Special relativity tutorials and tutorial homework used in Autumn 2009

In this section we provide the in-class tutorial worksheets used in Autumn 2009.

EVENTS AND REFERENCE FRAMES

I. Reference frames

A physics student named Alan stands far away from a beeper as shown at right. The beeper is about to emit a beep, and Alan wants to determine the exact time at which it does so. However, he is unable to travel to it.




Diagram not to scale

ST
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A. Alan is equipped with accurate meter sticks and clocks. A number of other students are willing to help him, if necessary.

1. Describe a set of measurements by which Alan can determine the time at which the beep is emitted using his knowledge of the speed of sound in air.

2. Describe a method by which Alan can determine the time at which the beep is emitted *without* knowing or measuring the speed of sound. (*Hint:* Alan's assistants are free to stand at any location.)

B. A fugitive from justice is at large in Seattle. The identity and whereabouts of the fugitive are unknown. A group of reporters believe that the fugitive will soon confess to the crime, and want to record as exactly as possible the time and place of the confession. Their funding for this project is excellent.

1. Describe an arrangement of observers and equipment with which the reporters can record the position and time of the confession.

An observer's *reference frame* is an arrangement of assistants and equipment with which the observer may record the position and time of anything that occurs.

2. Justify the claim that the reporters' arrangement of observers and equipment is a reference frame.

3. Would all the reporters attribute the same time and location to the confession? Explain how this result is a consequence of the definition of a reference frame.

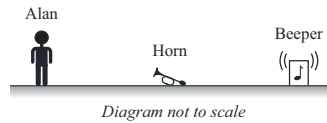
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Figure A.3: *Events and reference frames* in-class tutorial worksheet administered in Autumn 2009 to PHYS 123A. (Four pages.)

ST 298 *Events and reference frames*

C. A horn is now placed between Alan and the beeper. The beeper beeps once and the horn honks once. Alan hears both sounds at the same instant.



1. Describe a method by which Alan can measure the time separation between the emission of the beep and the emission of the honk *in his reference frame without* knowing or measuring the speed of sound.

2. In Alan's reference frame, is the beep emitted *before, after, or at the same instant* as the honk is emitted? Explain.

An *intelligent observer* is equipped with measuring devices (such as meter sticks, clocks, and assistants) and is able to use them to make correct and accurate determinations of where and when something occurs. All observers in the study of relativity are intelligent observers.

II. Events

A. In the study of relativity, we refer to material *objects, locations* in space, *instants* in time, and *events*. An *event* is associated with a single location in space and a single instant in time.

State whether each of the items below is an *object, a location, an instant, an event, or none of these*.

- the beeper of section I

- the beeper emits a beep

- Alan hears the beep

- the exact time at which the beeper beeps


- a sound wave travels from the beeper to Alan

- two beepers beep at the same time

B. For the situation in part C of section I:

1. Sketch a picture that shows Alan, the beeper, the horn, and any other objects of interest at the instant the beeper beeps. Label the position of the event "the beeper beeps" on the picture.
2. Below the first picture, sketch a picture that shows the objects of interest at the instant the horn honks. Label the position of the event "the horn honks" on this picture.
3. Repeat question 2 for any remaining events of interest. On each picture, indicate the locations of all the relevant objects and label the events of interest.

Event diagram for Alan's frame



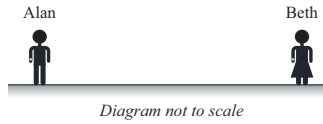
C. A diagram such as the one you drew above is called an *event diagram*. An event diagram has the following characteristics:

- The objects of interest are shown at the instants of the events of interest.
 - Successive instants are shown one below the other.
 - The location of each event of interest is indicated in the appropriate picture.
1. Does the (entire) first picture in your event diagram represent an *object*, a *location*, an *instant*, an *event*, or *none of these*?
 2. Is it possible for a single event to appear in more than one picture in an event diagram? Explain why or why not.
 3. Describe the circumstances under which more than one event would appear in a single picture in an event diagram.
 4. How do event diagrams drawn by two observers in the same reference frame compare? Explain.

ST 300 *Events and reference frames*

III. Synchronization of clocks

Alan and Beth are exactly 10^8 light-seconds apart relative to the floor. (One light-second is the distance that light travels in one second.) Each of them wears a watch. Both watches are extremely accurate, run at the same rate, and measure time in seconds. However, the reading on Beth's watch is not the same as the reading on Alan's watch.



- A. Determine the amount of time that it will take a light signal to travel from Alan to Beth.
- B. Beth and Alan decide in advance that, at the instant Alan's watch reads 50 s, he will use a laser pointer to emit a pulse of light in Beth's direction.
- What time will Alan's watch read at the instant Beth first receives the light from the laser pointer?
- C. Describe a method by which Beth could synchronize her watch with Alan's (*i.e.*, make her watch have the same reading as Alan's at every instant).
- D. Another physics student, Caroline, is at rest with respect to Alan and Beth but is very far away from them. Caroline looks at the reading on Alan's watch with a powerful telescope, and finds that, at every instant, the reading she sees on Alan's watch through the telescope is identical to the reading on her watch.
- Is Caroline's watch synchronized with Alan's? Explain why or why not.

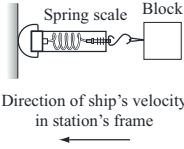
EVENTS AND REFERENCE FRAMES

Name _____

ST
HW-205

1. *Inertial reference frames*

A spaceship in deep space travels in a straight line past a space station that is at rest relative to the fixed stars. In the frame of the station, the spaceship is speeding up. Inside the spaceship, a block is attached to the end of a spring scale that is attached to a wall. It is observed that the reading on the spring scale does not change.



Top view

Spring scale Block

Direction of ship's velocity
in station's frame

a. Alan is standing in the space station (*i.e.*, at rest relative to the station).

- i. Determine the direction of the acceleration of the block (if any) in Alan's reference frame. State explicitly if the acceleration is zero. Explain.
- ii. In the space at right, sketch a free-body diagram for the block in Alan's reference frame. Include only *real forces* (forces exerted on one object by another object).

Show that all the forces on your diagram are real by indicating (on the diagram) the object that exerts each force and the object on which each force is exerted.
- iii. Compare the direction of the net force on the block to the direction of the acceleration of the block in Alan's reference frame.

b. Beth is in the spaceship, at rest relative to the spaceship.

- i. Determine the direction of the acceleration of the block (if any) in Beth's reference frame. Explain.
- ii. In the space at right, draw a free-body diagram for the block in Beth's reference frame. Include only real forces. Indicate the object that exerts each force and the object on which each force is exerted.

Determine the direction of the net force on the block in Beth's reference frame.

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Figure A.4: *Events and reference frames*— tutorial homework worksheet administered in Autumn 2009 to PHYS 123A. (Three pages.)

ST Events and reference frames
HW-206

- c. How does the magnitude of the net force on the block in Beth's frame compare to its magnitude in Alan's reference frame? Discuss the physical evidence for your answer.

Describe the *set* of reference frames in which the net force on the block would have the same magnitude as in Alan's reference frame.

- d. Alan measures the acceleration of the block and determines that the acceleration of the block is equal to the ratio of the net force on the block to the mass of the block; that is, the net force is related to the motion of the block in accordance with Newton's second law.

State whether, in Beth's reference frame, Newton's second law correctly relates the net force on the block to the acceleration of the block. Explain.

- e. In some reference frames, the observed net force on an object is in the same direction as the acceleration of the object; in other reference frames, the net force and the acceleration are not related in the same way.

In an *inertial* reference frame, the acceleration of an object is zero *if and only if* the net force on the object is also zero. (Similarly, in an inertial reference frame, if the acceleration of an object is nonzero, the net force on the object must also be nonzero.)

Is it possible that Alan's reference frame is an inertial reference frame? Explain.

Is it possible that Beth's reference frame is an inertial reference frame? Explain.

- f. Two students discuss the situation described above.

Student 1: "You can tell that Beth's reference frame is not an inertial reference frame by observing that Beth is accelerating relative to Alan."

Student 2: "That seems right. But Alan is also accelerating relative to Beth; doesn't that mean his reference frame is noninertial and hers is not? This is totally contradictory."

Resolve the contradiction posed by student 2.

Events and reference frames

Name _____

ST
HW-207

2. Event diagrams

A train moves with a constant speed of 6 m/s from left to right along a long, straight stretch of train track. The train is 12 meters long.

Alan stands at rest relative to the track. His assistant, Andy, is also at rest relative to the track and stands 12 meters to the right of Alan.

Events 1, 2, and 3 are defined as follows.

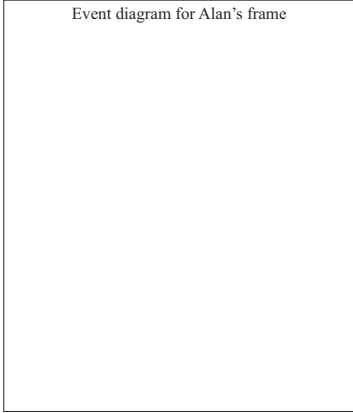
Event 1: The front of the train is next to Alan

Event 2: The front of the train is next to Andy

Event 3: The rear of the train is next to Alan

- a. Sketch an event diagram for Alan's frame for the situation described. Indicate the location and the time of each event of interest.

Event diagram for Alan's frame



- b. On your event diagram, draw and label a line that indicates the distance between the locations of events 1 and 2. Give an interpretation of the length of this line.
- c. On your event diagram, draw and label a line that indicates the distance between the locations of events 2 and 3. Give an interpretation of the length of this line.
- d. Suppose that you drew an event diagram for Andy's frame. How, if at all, would it be different from the one for Alan's frame? Explain.

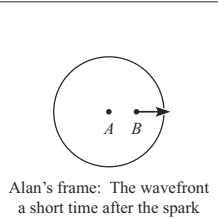
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SIMULTANEITY

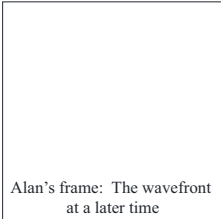
I. Spherical wavefronts

Two students, Alan and Beth, move past each other. At the instant that they pass, a spark jumps between them. The spark emits a flash of light that moves outward in all directions.

A. The first diagram at right represents the wavefront of the flash of light in Alan's frame, a short time after the spark jumps.



Alan's frame: The wavefront a short time after the spark



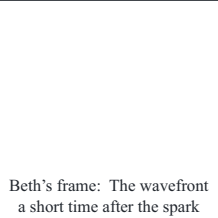
Alan's frame: The wavefront at a later time

1. Explain how this picture is consistent with the fact that Alan observes the speed of light to be the same in all directions.

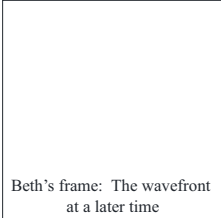
2. In the second diagram above, sketch the wavefront at a later time in Alan's frame. Include both Alan's and Beth's positions in your sketch.

3. Is there a time at which the distance between Alan and Beth is greater than the distance between Alan and the wavefront? Explain.

B. In the spaces at right, sketch Alan, Beth, and the wavefront in Beth's frame. Draw diagrams for a short time after the spark jumps and at a later time.



Beth's frame: The wavefront a short time after the spark



Beth's frame: The wavefront at a later time

Are your sketches consistent with the fact that Beth observes the speed of light to be the same in all directions? If not, modify your diagrams so they are consistent with this observation.

⇒ Discuss your answers with a tutorial instructor.

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Figure A.5: *Simultaneity*— in-class tutorial worksheet administered in Autumn 2009 to PHYS 123A. (Five pages.)

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Simultaneity

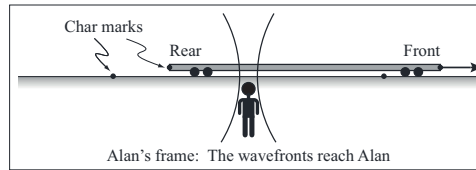
II. Relativity of simultaneity

A spark jumps between the front end of a train and the track (spark F), and another spark jumps between the rear end of the train and the track (spark R). When each spark jumps, it emits a flash of light (wavefronts F and R). Each spark also leaves a char mark on both the train and the track. Let event F be “spark F jumps” and event R be “spark R jumps.”

Alan is standing on the ground equidistant from the char marks on the track. The wavefronts reach him simultaneously.

A. Alan's frame

The diagram at right represents Alan's frame at the instant the wavefronts reach him.

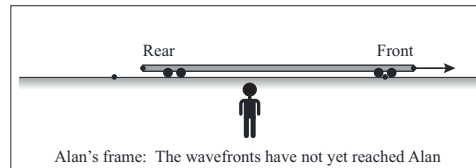


1. In Alan's frame, does spark F jump *before*, *after*, or *at the same instant* as spark R? Explain.

2. Abigail (not shown) stands at rest relative to the track, near the front char mark on the track.

In Abigail's frame, does spark F jump *before*, *after*, or *at the same instant* as spark R? Explain.

3. The diagram at right represents an instant a short time after the spark jumps between the front of the train and the track in Alan's frame (before he receives either wavefront).



Complete the diagram by drawing the wavefronts at this instant. Explain.

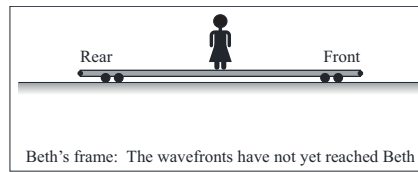
4. In Alan's frame, where are the centers of wavefronts F and R? Explain.

-
5. Beth stands at rest relative to the train, exactly halfway between the front and rear of the train. Let event P be “Alan and Beth pass each other.” Recall that event F is “spark F jumps” and event R is “spark R jumps.”
 - a. In Alan’s frame, does event F happen *before*, *after*, or *at the same instant* as event P? Explain.
 - b. In Alan’s frame, does wavefront F reach Beth *before*, *after*, or *at the same instant* as wavefront R? Explain.

⇨ Discuss your reasoning with an instructor before continuing.

B. Beth’s frame

1. Complete the diagram at right by drawing wavefronts F and R, in Beth’s frame, before either wavefront reaches her.
2. In Beth’s frame, does event F happen *before*, *after*, or *at the same instant* as event R? Explain.



3. In Beth’s frame, where are the centers of wavefronts F and R? Explain.
4. In Beth’s frame, does wavefront F reach Beth *before*, *after*, or *at the same instant* as wavefront R? Explain.

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C. Relating Alan's and Beth's frames

A device consisting of two firecrackers attached to light sensors lies on the floor of the train at Beth's feet. If both wavefronts hit the device at the same instant, both firecrackers explode. If wavefront F hits the device first, only firecracker 1 explodes. If wavefront R hits the device first, only firecracker 2 explodes.

1. Which firecracker(s) explode in each of the following frames? Explain.

- Alan's frame

- Beth's frame

2. Consider the following dialogue between two students:

Student 1: "Special relativity is strange; firecracker 2 explodes and does not explode, depending on which reference frame you are in."

Student 2: "I don't believe a firecracker can both explode and not explode. We must have made a mistake. What if the train stops and Alan gets on? Would he see firecracker 2 whole like he expected?"

Student 1: "No, firecracker 2 is in Beth's frame, and, in Beth's frame, it explodes. When Alan gets on the train, he would see that firecracker 2 actually did explode. But, until he got on the train, he would think that firecracker 2 did not explode."

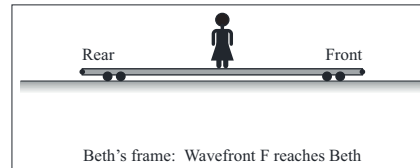
With which student do you agree, if either? Explain.

⇒ Discuss your reasoning with a tutorial instructor before continuing.

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3. Suppose that Alan's conclusion that firecracker 1 explodes and firecracker 2 does not explode is also true in Beth's frame.
- a. If only firecracker 1 explodes, then, in Beth's frame, does wavefront F reach Beth *before, after, or at the same instant as* wavefront R? Explain.

Based on your answer above, complete the diagram at right by drawing wavefronts F and R in Beth's frame at the instant when wavefront F reaches Beth. Explain.



- b. Based on your diagram, in Beth's frame, does event F (the front spark jumps) happen *before, after, or at the same instant as* event R (the rear spark jumps)? Explain.

Is your answer above consistent with your answer to part B.2? If not, resolve any inconsistencies. The following dialogue may help you in resolving any conflicts.

Consider the following student dialogue about event F (the spark at the front of the train jumps) and event R (the spark at the rear of the train jumps):

Student 1: "Event F happens before event R for Beth and at the same time as event R for Alan. It depends on which reference frame you are in."

Student 2: "I don't believe that things can happen simultaneously in one frame and at different times in another frame. We must have made a mistake somewhere."

Student 1: "Well, we have two choices. Either (1) events F and R happen at the same time or at different times, depending on your reference frame, or (2) the event corresponding to the firecracker exploding happens or does not happen, depending on your reference frame."

With which of the two choices presented by student 1 do you agree? Explain.

- ⇔ Discuss your reasoning with a tutorial instructor.

SIMULTANEITY

Name _____ ST
HW-213

1. *Length contraction*

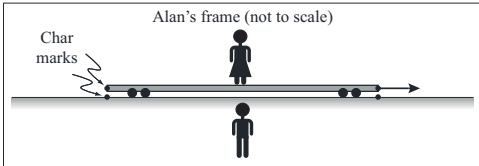
In the tutorial *Simultaneity*, Alan stands at rest near a long, straight stretch of train track. Beth is at rest at the exact middle of the train, which moves with relativistic speed relative to Alan. Sparks jump between the front of the train and the track (spark F) and between the rear of the train and the track (spark R), leaving char marks on the train and on the track.

A straight stick lies on the ground parallel to the train track. One end of the stick is at the front char mark on the ground, and the other end of the stick is at the rear char mark on the ground.

Recall from the tutorial that, in Alan's frame, sparks F and R jump at the same instant. The diagram at right shows the train in Alan's frame at this instant.

a. Is the length of the stick in Alan's frame, $d^{(A)}$, greater than, less than, or equal to the length of the train in Alan's frame, $L^{(A)}$? Explain.

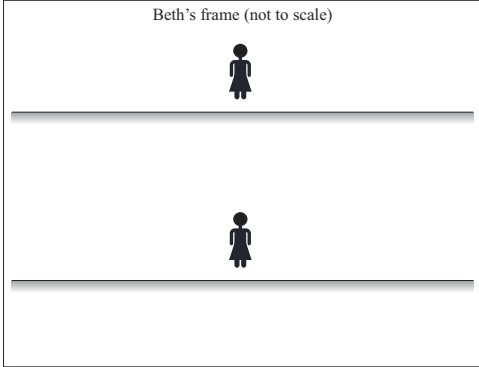
Alan's frame (not to scale)



b. Recall from the tutorial that, in Beth's frame, spark F jumps before spark R. The diagram at right shows Beth and the track in Beth's frame at the instant of each spark. The top figure represents the instant of spark F, and the bottom figure represents the instant of spark R.

Complete the diagram by adding the train, Alan, the stick, and any char marks on the track that exist at each instant. Check that your diagram is consistent with the fact that Alan is equidistant from the char marks on the track.

Beth's frame (not to scale)



c. In Beth's frame, does Alan pass Beth *before*, *after*, or *at the same instant* as spark F jumps? Explain.

d. Is the length of the stick in Beth's frame, $d^{(B)}$, greater than, less than, or equal to the length of the train in Beth's frame, $L^{(B)}$? Explain.

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Figure A.6: *Simultaneity* tutorial homework worksheet administered in Autumn 2009 to PHYS 123A. (Four pages.)

ST *Simultaneity*
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- e. Consider the following dialogue between two students.

Student 1: "In Beth's frame, the stick is shorter than the train, because the length of the stick is the contracted length of the train. So if the train is 10 m long in Beth's frame, the stick might be 8 m long, meaning the length of the train in Alan's frame is 8 m."

Student 2: "If the train's length contracts when it's moving, the stick's length should contract when it's moving too. If the length of the stick in Alan's frame is 8 m, its length in Beth's frame should be less than 8 m."

With which student do you agree? Explain.

- f. Suppose the length of the train in Beth's frame is 10 m ($L^{(B)} = 10$ m).

- i. Which of the following quantities might correspond to the length of the stick in Beth's frame? Circle one and explain.

• $d^{(B)} = 6.4$ m • $d^{(B)} = 8$ m • $d^{(B)} = 10$ m • $d^{(B)} = 12.5$ m

- ii. Which of the following quantities might correspond to the length of the stick in Alan's frame? Circle one and explain.

• $d^{(A)} = 6.4$ m • $d^{(A)} = 8$ m • $d^{(A)} = 10$ m • $d^{(A)} = 12.5$ m

- iii. Which of the following quantities might correspond to the length of the train in Alan's frame? Circle one and explain.

• $L^{(A)} = 6.4$ m • $L^{(A)} = 8$ m • $L^{(A)} = 10$ m • $L^{(A)} = 12.5$ m

- g. Check that your responses to part f are consistent with your response to the student dialogue in part e.

The phenomenon that the measured length of an object is greater in the frame in which it is at rest than it is in a frame in which it is in motion is known as *length contraction*.

Simultaneity

Name _____

ST
HW-2152. *Simultaneity, event diagrams, and Lorentz transformations*

In the tutorial *Simultaneity*, Alan stands at rest near a long, straight stretch of train track. Beth is at rest at the exact middle of the train, which moves with relativistic speed relative to Alan. Sparks jump between the front of the train and the track (spark F) and between the rear of the train and the track (spark R), leaving char marks on the train and on the track.

- a. Draw event diagrams for Alan's frame and Beth's frame to represent the events:

Event 1: Spark F jumps

Event 2: Alan and Beth pass each other

Event 3: Spark R jumps

In your diagrams include Alan, Beth, the train, the wavefronts, and the two pairs of char marks.

Event diagram for Alan's frame

Event diagram for Beth's frame

- b. Suppose that, in Alan's frame, the velocity and length of the train are v_o and $L^{(A)}$ respectively, and event 2 occurs at $t_2^{(A)} = 0 = x_2^{(A)}$.

- i. Use your event diagram for Alan's frame to determine the locations and times of events 1–3 in Alan's frame. Explain.

Event 1	$t_1^{(A)} =$	$x_1^{(A)} =$
Event 2	$t_2^{(A)} = 0$	$x_2^{(A)} = 0$
Event 3	$t_3^{(A)} =$	$x_3^{(A)} =$

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- ii. Use the Lorentz transformations to determine the locations and times of events 1–3 in Beth’s frame. Show your work.

Event 1	$t_1^{(B)} =$	$x_1^{(B)} =$
Event 2	$t_2^{(B)} =$	$x_2^{(B)} =$
Event 3	$t_3^{(B)} =$	$x_3^{(B)} =$

- iii. Explain how the time order of events 1–3 in Beth’s frame that you determined in part B.ii is consistent with your event diagram for Beth’s frame (part a).

- iv. Alex, at rest on the track, is located many train lengths to the right of Alan. Suppose that event 4 is “Alex sneezes.” Suppose further that event 4 is simultaneous with event 1 in Alan’s frame.

In Beth’s frame, does event 4 occur *before*, *after*, or *at exactly the same time as* event 1? Explain your reasoning.

- c. Events P and Q are simultaneous in frame F. Furthermore, $x_p^{(F)} < x_Q^{(F)}$. Generalize from your responses above to answer the following questions. (Consider only motion in one dimension.)

- Suppose that a frame moves with positive velocity relative to frame F. What is the time order of events P and Q in that frame? Explain.
- Suppose that a frame moves with negative velocity relative to frame F. What is the time order of events P and Q in that frame? Explain.
- Suppose instead that events P and Q are simultaneous in frame F but $x_p^{(F)} = x_Q^{(F)}$. What is the time order of events P and Q in any other frame? Explain.

Appendix B

**QUESTIONS AND CURRICULAR MATERIALS DESCRIBED
IN CHAPTER 4**

In this portion of the Appendix we provide the pretests and post-tests containing research tasks used during our investigation into student understanding of reference frames, described in Chapter 4.

Contents of appendix

B.1	Pretests	302
B.2	Exam questions described in Chapter 4	326
B.3	Curricular materials described in Chapter 4	335

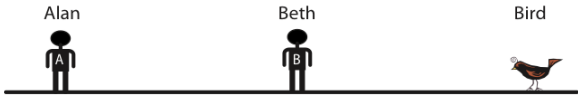
B.1 Pretests described in Chapter 4

In this section, complete pretests with portions described in Chapter 4: *Student understanding of reference frames* are included.

8/17/2017 Catalyst WebQ

Print view of '(ERF)U2a'
[Print this page](#)

Alan and Beth are standing in a clearing in the forest. Alan stands a very large distance from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon.



(Drawing not to scale)

Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Question 1.
 In Beth's reference frame, the bird tweets:

- Before Alan's alarm sounds.
- After Alan's alarm sounds.
- At the same time as Alan's alarm sounds.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Alan *hears* the bird's tweet:

- Before he hears his alarm sound.
- After he hears his alarm sound.
- At the same time as he hears his alarm sound.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Alan's reference frame, the bird tweets:

- Before his alarm sounds.
- After his alarm sounds.
- At the same time as his alarm sounds.
- There is not enough information provided to answer this question.

Question 6.
 Explain the reasoning you used to answer the question above.

Question 7.

<https://catalyst.uw.edu/webq/build/tipwo/96427> 1/2

Figure B.1: Catalyst *Events and reference frames* pretest version U2A (*Noisy Bird* context). (Two pages.)

8/17/2017

Catalyst WebQ

Indicate whether or not each of the items listed below is an event in the context of special relativity.

Rows

a cannon
the cannon fires
a soldier hears the cannon fire
two distant cannons fire at the same time

- is an event.
 is not an event.

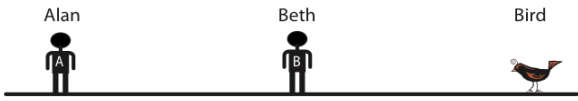
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Print view of '(ERF)U2a1-(Clocks)'
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Alan and Beth are standing in a clearing in the forest. Alan stands a very large distance from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon.



(Drawing not to scale)

Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Question 1.
In Beth's reference frame, the bird tweets:

- Before Alan's alarm sounds.
- After Alan's alarm sounds.
- At the same time as Alan's alarm sounds.
- There is not enough information provided to answer this question.

Question 2.
Explain the reasoning you used to answer the question above.

Question 3.
Alan *hears* the bird's tweet:

- Before he hears his alarm sound.
- After he hears his alarm sound.
- At the same time as he hears his alarm sound.
- There is not enough information provided to answer this question.

Question 4.
Explain the reasoning you used to answer the question above.

Question 5.
In Alan's reference frame, the bird tweets:

- Before his alarm sounds.
- After his alarm sounds.
- At the same time as his alarm sounds.
- There is not enough information provided to answer this question.

Question 6.
Explain the reasoning you used to answer the question above.

Question 7.
Suppose that Alan and Beth both wear watches equipped with alarms, but stand a large distance apart. Each watch is set so that its alarm will sound when it reads 1:00 PM. Alan then notes that

<https://catalyst.uw.edu/webq/build/tipwo/167930> 1/2

Figure B.2: Catalyst *Events and reference frames* pretest version U2A1 (*Noisy Bird* context). (Two pages.)

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he hears the two alarms at exactly the same time.

Are the watches synchronized in Alan's frame?

- Yes, the two clocks are synchronized in Alan's frame.
 No, the two clocks are not synchronized in Alan's frame.
 There is not enough information given to determine whether or not the two clocks are synchronized.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

Indicate whether or not each of the items listed below is an event in the context of special relativity.

Rows

a cannon

the cannon fires

a soldier hears the cannon fire

two distant cannons fire at the same time

- is an event.
 is not an event.

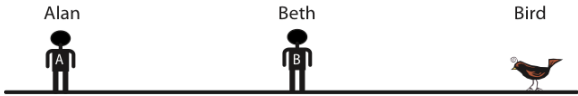
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Print view of '(ERF)U2b'
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Beth the botanist and Alan the archeologist are in the middle of a clearing in the forest. Beth is exactly midway between Alan and a restless bird, which sits on the ground, as shown below. Alan creates a spark with a flint and steel at exactly 12 noon.



(Drawing not to scale)

Beth sees the bird flap its wings and the spark from Alan's flint at *exactly the same time*.

Question 1.
 In Beth's reference frame, the bird flaps its wings:

- Before the flint sparks.
- After the flint sparks.
- At the same time as the flint sparks.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Alan sees the bird flap its wings:

- Before he sees the flint spark.
- After he sees the flint spark.
- At the same time as he sees the flint spark.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Alan's reference frame, the bird flaps its wings:

- Before the flint sparks.
- After the flint sparks.
- At the same time that the flint sparks.
- There is not enough information provided to answer this question.

Question 6.
 Explain the reasoning you used to answer the question above.

Question 7.
 Indicate whether or not each of the items listed below is an event as defined in your physics class.

<https://catalyst.uw.edu/webq/build/tipwo/96505> 1/2

Figure B.3: Catalyst *Events and reference frames* pretest version U2B (*Restless Bird* context). (Two pages.)

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Rows

- a strobe light
 - the strobe light flashes
 - a person sees the strobe flash
 - two distant strobe lights flash at the same time
- is an event.
 is not an event.

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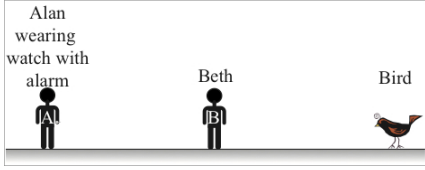
Print view of '(ERF)U2d_EventDiagrams'
[Print this page](#)

Question 1.
 Indicate whether or not each of the items listed below is an event in the context of special relativity.

Rows
 a cannon
 the cannon fires
 a soldier hears the cannon fire
 two cannons at opposite ends of a town fire at the same time

is an event.
 is not an event.

Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Question 2.
 In Beth's reference frame, the bird tweets:

Before Alan's alarm sounds.
 After Alan's alarm sounds.
 At the same time as Alan's alarm sounds.
 There is not enough information provided to answer this question.

Question 3.
 Explain the reasoning you used to answer the question above.

Question 4.
 Alan *hears* the bird's tweet:

Before he hears his alarm sound.
 After he hears his alarm sound.
 At the same time as he hears his alarm sound.
 There is not enough information provided to answer this question.

Question 5.
 Explain the reasoning you used to answer the question above.

<https://catalyst.uw.edu/webq/build/tipwo/225728> 1/3

Figure B.4: Catalyst *Events and reference frames* pretest version U2D (*Noisy Bird* (with distances) context). (Three pages.)

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Question 6.

In Alan's reference frame, the bird tweets:

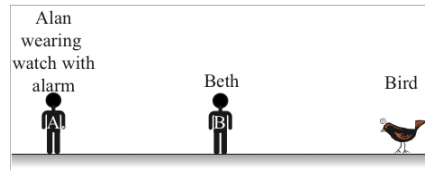
- Before his alarm sounds.
 After his alarm sounds.
 At the same time as his alarm sounds.
 There is not enough information provided to answer this question.

Question 7.

Explain the reasoning you used to answer the question above.

The scenario from the previous page is reproduced below for your convenience.

Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Consider the following five events from the scenario described above: Alan's alarm sounds when his watch reads exactly 12:00:00; the bird tweets; Beth hears the alarm; Beth hears the tweet; Alan hears the tweet.

Question 8.

Suppose that Beth were to record the times of the five events. (Recall that in a given reference frame, each event is associated with a particular time and location.) In the table below, indicate the times that Beth would record for each of these five events. (Note: you may not need to use all of the times provided.)

Rows

12:00:00
12:00:01
12:00:02
12:00:03
12:00:04

- Alarm sounds
 Bird tweets
 Beth hears alarm
 Beth hears tweet
 Alan hears tweet

Question 9.

Suppose that Alan were to record the times of the five events. (Recall that in a given reference frame, each event is associated with a particular time and location.) In the table below, indicate the times that Alan would record for each of these five events. (Note: you may not need to use all of the times provided.)

<https://catalyst.uw.edu/webq/build/tipwo/225728>

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Rows

12:00:00
12:00:01
12:00:02
12:00:03
12:00:04

- Alarm sounds
- Bird tweets
- Beth hears alarm
- Beth hears tweet
- Alan hears tweet

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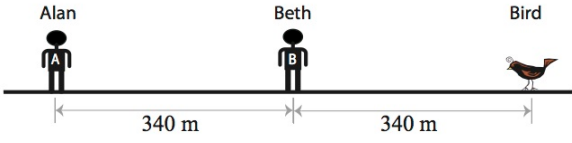
Question 1.
Indicate whether or not each of the items listed below is could be associated with a single instant in time and a single location in space.

Rows

a cannon
the cannon fires
a soldier hears the cannon fire
two cannons at opposite ends of a town fire at the same time
a soldier hears the booms from the two cannons at the same time

Yes
 No

Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



(Diagram not to scale)

Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Question 2.
In the ground frame, the bird tweets:

Before Alan's alarm sounds.
 After Alan's alarm sounds.
 At the same time as Alan's alarm sounds.
 The answer to this question depends on the location of the observer determining the timing of the events.

Question 3.
Explain the reasoning you used to answer the question above.

The scenario from the previous page is reproduced below for your convenience.

Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth

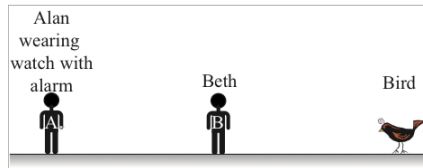
<https://catalyst.uw.edu/webq/build/tipwo/259612> 1/3

Figure B.5: Catalyst *Events and reference frames* pretest version U2E (*Noisy Bird* (ground frame) context). (Three pages.)

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stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Consider the following five events from the scenario described above:
 Alan's alarm sounds when his watch reads exactly 12:00:00
 The bird tweets

Beth hears the alarm
 Beth hears the tweet

Alan hears the tweet.

Recall that in a given reference frame, each event is associated with a particular time and location. In the questions below, indicate the times for the five events in the ground frame.

Question 4.

The alarm sounds.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

Question 5.

The bird tweets.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

Question 6.

Beth hears the alarm.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

Question 7.

Beth hears the tweet.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04

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It is impossible to determine the time of this event with the information given

Question 8.

Alan hears the tweet.

12:00:00

12:00:01

12:00:02

12:00:03

12:00:04

It is impossible to determine the time of this event with the information given

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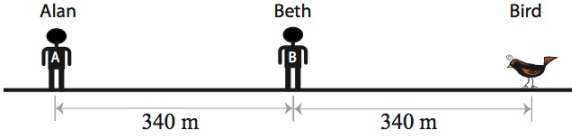
Question 1.
Indicate whether or not each of the items listed below is could be associated with a single instant in time and a single location in space.

Rows

a cannon
the cannon fires
a soldier hears the cannon fire
two cannons at opposite ends of a town fire at the same time
a soldier hears the booms from the two cannons at the same time

Yes
 No

Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



(Diagram not to scale)

Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Question 2.
In Beth's frame, the bird tweets:

Before Alan's alarm sounds.
 After Alan's alarm sounds.
 At the same time as Alan's alarm sounds.
 The answer to this question depends on the location of the observer determining the timing of the events.

Question 3.
In Alan's frame, Alan hears the bird tweet:

Before he hears his alarm sound
 After he hears his alarm sound
 At the same time as he hears the alarm sound
 There is not enough information provided to answer this question

Question 4.
In Alan's frame, the bird tweets:

Before his alarm sounds
 After his alarm sounds
 At the same time as his alarm sounds
 There is not enough information provided to answer this question

Question 5.

<https://catalyst.uw.edu/webq/build/tipwo/287367> 1/3

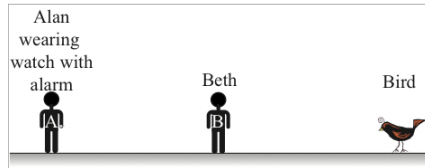
Figure B.6: Catalyst *Events and reference frames* pretest version U2F (*Noisy Bird* (distances, text and figure) context). (Three pages.)

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Explain the reasoning you used to answer the question above.

The scenario from the previous page is reproduced below for your convenience. Alan and Beth are standing in a clearing in the forest. Alan stands 680 meters from a noisy bird, which sits on the ground; Beth stands exactly halfway between Alan and the bird. Alan is wearing a watch with an alarm that is set to go off at exactly 12 noon. Assume that the speed of sound is 340 m/s.



Beth hears the bird tweet and the alarm from Alan's watch at *exactly the same time*.

Consider the following five events from the scenario described above:

Alan's alarm sounds when his watch reads exactly 12:00:00
 The bird tweets
 Beth hears the alarm
 Beth hears the tweet

Alan hears the tweet.

Recall that in a given reference frame, each event is associated with a particular time and location. In the questions below, indicate the times for the five events in Alan's reference frame.

Question 6.

The alarm sounds.

- 12:00:00
 12:00:01
 12:00:02
 12:00:03
 12:00:04
 It is impossible to determine the time of this event with the information given

Question 7.

The bird tweets.

- 12:00:00
 12:00:01
 12:00:02
 12:00:03
 12:00:04
 It is impossible to determine the time of this event with the information given

Question 8.

Beth hears the alarm.

- 12:00:00
 12:00:01
 12:00:02

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- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

Question 9.
Beth hears the tweet.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

Question 10.
Alan hears the tweet.

- 12:00:00
- 12:00:01
- 12:00:02
- 12:00:03
- 12:00:04
- It is impossible to determine the time of this event with the information given

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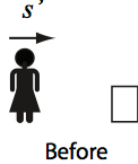
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(SIM)U2g(S&L)

Question 2.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.



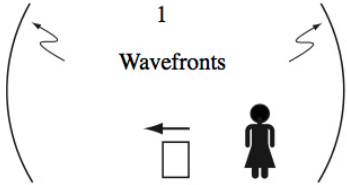
Beth and the beeper as shown in the ground reference frame

Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for frame s' for an instant shortly after Beth has passed the beeper.

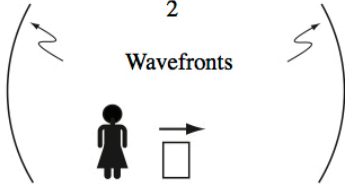
1

Wavefronts



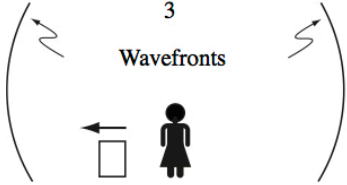
2

Wavefronts



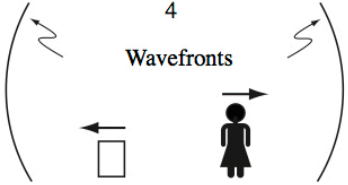
3

Wavefronts



4

Wavefronts



Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

Question 3.

At a later time in frame s' , the beeper has moved 400 meters to the left.

In frame s' , which of the following best describes the location of the event "the beeper beeps" at that later time?

https://catalyst.uw.edu/webq/preview 1/3

Figure B.7: Catalyst *Simultaneity* pretest version U2G (*Beth and Box* context [Version 1]). (Four pages.)

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- At Beth
- At the beeper
- At a location somewhere between Beth and the beeper

Time remaining: 0:19:57

Question 4.

Explain the reasoning you used to answer the question above.

Question 5.

Suppose instead that Beth moves toward a strobe light, in a frame s'' that moves to the right at half the speed of **light** relative to the ground.

The strobe flashes just as Beth passes it. The flash of light moves outward in all directions.



Beth and the strobe as shown in the ground reference frame

Before

From the diagrams in question 1 above, choose the diagram for frame s'' for an instant shortly after Beth has passed the strobe light.

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 6.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 7.

Consider the event "the strobe light flashes." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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8/22/2017

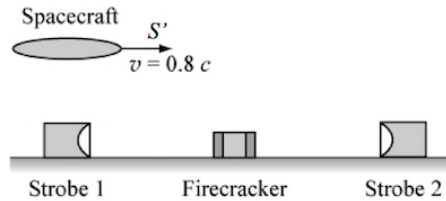
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(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 8.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

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Question 9.

Explain the reasoning you used to answer

Time remaining: 0:19:51

Question 10.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

Question 11.

Explain the reasoning you used to answer the question above.

Question 12.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
- After wavefront from the flash from strobe 2.
- At the same time as the wavefront from the flash from strobe 2.
- It's not possible to determine with the information given.

Question 13.In frame S' , the firecracker:

- Explodes.
- Does not explode.
- There is not enough information provided to answer.

Question 14.

Explain the reasoning you used to answer the question above.

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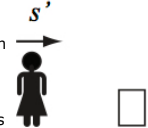
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(SIM)U2g(S&L)

Question 15.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.



Beth and the beeper as shown in the ground reference frame

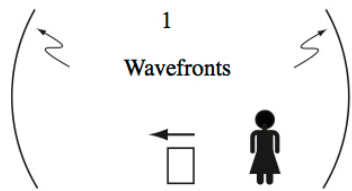
Before

Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for **frame s'** for an instant shortly **after** Beth has passed the beeper.

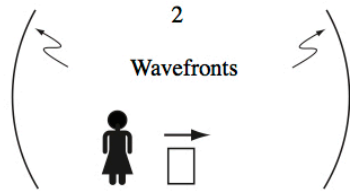
1

Wavefronts



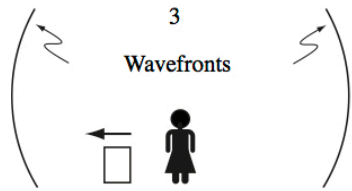
2

Wavefronts



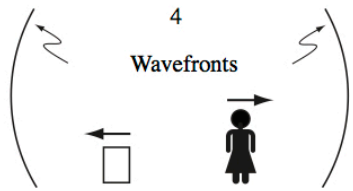
3

Wavefronts



4

Wavefronts



Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

Question 16.

Beth correctly determines the x' -coordinate of the event "the beeper beeps" to be $x'=0$ m.

At a later time, the beeper is 400 meters to the left of Beth. In frame s' , which of the following represents the location of the event "the beeper beeps?"

<https://catalyst.uw.edu/webq/preview> 1/2

Figure B.8: Catalyst *Simultaneity* pretest version U2gC (*Beth and Box* context [Version 2]). (Four pages.)

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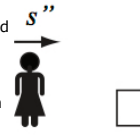
- $x' = 0$ m
- $x' = 400$ m
- $x' = -400$ m
- There is not enough information provided to answer this question.

Time remaining: 0:19:57

Question 17.

Suppose instead that Beth is in frame s'' that moves to the right at half the speed of light relative to the ground.

A spark jumps between Beth and the beeper at the instant she passes it. The spark emits a flash of light that moves outward in all directions.



Beth and the beeper as shown in the ground reference frame

From the diagrams in question 1 above, choose the diagram for frame s'' , for an instant shortly after Beth has passed the beeper.

Before

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 18.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 19.

Consider the event "the spark jumps." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

[<< Previous](#) [Next >>](#)

Questions or Comments?

Contact Tutorial Coordinator at tipwo@u.washington.edu



8/22/2017

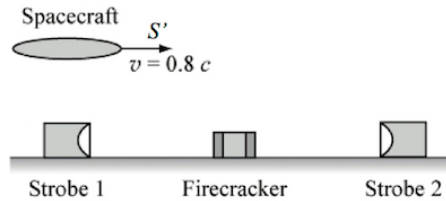
Catalyst WebQ - Preview

Time remaining: 0:19:57

This is only a preview of the survey. Responses will not be saved. [Close](#)

(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



Ground frame at the instant strobe 1 flashes

An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 20.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

8/22/2017

Catalyst WebQ - Preview

Question 21.

Explain the reasoning you used to answer

Time remaining: 0:19:57

Question 22.In frame S' , the firecracker:

- Explodes.
 Does not explode.
 There is not enough information provided to answer.

Question 23.

Explain the reasoning you used to answer the question above.

Question 24.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
 After wavefront from the flash from strobe 2.
 At the same time as the wavefront from the flash from strobe 2.
 It's not possible to determine with the information given.

Question 25.

Explain the reasoning you used to answer the question above.

Question 26.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
 After strobe light 2 flashes.
 At the same time as strobe light 2 flashes.
 The answer to this question depends on the location of the observer

Question 27.

Explain the reasoning you used to answer the question above.

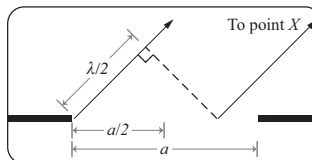
B.2 Exam questions described in Chapter 4

In this section, complete exam questions with portions described in Chapter 4: *Student understanding of reference frames* are included.

Name _____ Student ID _____ Score _____
last first

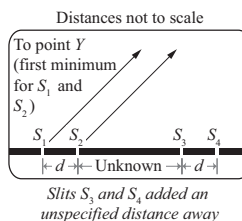
III. [20 points total] This problem consists of three unrelated parts, A, B, and C.

A. [5 pts] Monochromatic light is incident on a slit of width a . The rays on the diagram at right show the path from two particular points in the slit to point X on a very distant screen. The difference in distance, ΔD , from the two points to point X is $\lambda/2$.



Is point X a point of zero intensity (*i.e.*, a minimum)? Explain.

B. Coherent monochromatic light is incident on two *very narrow* slits S_1 and S_2 that are a distance d apart. The rays on the diagram show the path from S_1 and S_2 to point Y , the first minimum (due solely to S_1 and S_2) to the right of the central maximum on a distant screen.



Two additional slits, S_3 and S_4 , also a distance d apart, are then uncovered. The distance between S_2 and S_3 is unknown (see diagram). All slits are identical and can be treated as point sources.

i. [5 pts] Will point Y remain a point of zero intensity (*i.e.*, a minimum) for all four slits? If there is not enough information, state what additional information is needed. Explain.

ii. [5 pts] Does the first minimum on the screen for all four slits (*i.e.*, the minimum closest to the center of the screen) lie to the left of point Y , to the right of point Y , exactly at point Y , or are there no points of zero intensity? Explain.

C. [5 pts] Amy is watching the distant launch of the space shuttle Endeavor through a powerful telescope. Just as Amy sees Endeavor begin to lift off from the launch pad, she also sees a small bug lands on the eyepiece of the telescope.

In Amy's reference frame, does the bug land on the telescope *before*, *after*, or *at exactly the same time* as the space shuttle Endeavor begins to lift off? Explain.

Figure B.9: Written third midterm examination administered in Spring 2010 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

III. [25 points total] Tutorial Multiple Choice

Alec and Betty are at rest with respect to each other, as shown. Alec stands **midway** between two light sources. Each light source will emit a pulse of light at some time or times in the future.

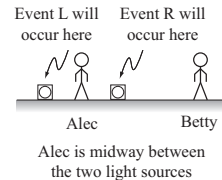
- Let event L be the left source emits a pulse of light.
- Let event R be the right source emits a pulse of light.

Alec decides that if he receives the light pulses simultaneously, he will raise both hands. If he receives the light pulse from the right source first, he will raise only his right hand. If he receives the light pulse from the left source first, he will raise only his left hand.

After the experiment, Alec reports that he raised both hands.

21. [5 pts] In Betty's reference frame, which of the following best describes events L and R?

- Event L occurs before event R.
- Event L occurs after event R.
- Event L occurs at the same instant as event R.
- At least one of the events does not occur.
- One of the events occurs before the other, but there is not enough information to tell which.



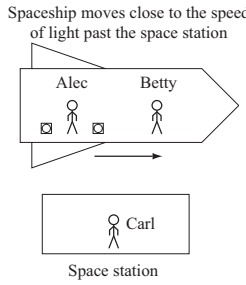
Alec and Betty repeat the experiment on a spaceship that travels near the speed of light to the right as measured from a space station. The light bulbs are set up in exactly the same manner, and Alec decides he will raise his hands as described above.

Carl is at rest on the space station observing the experiment. Alec and Betty are at rest with respect to the spaceship.

After the experiment, Alec reports that he raised both hands.

22. [5 pts] In Betty's reference frame, which of the following best describes events L and R?

- Event L occurs before event R.
- Event L occurs after event R.
- Event L occurs at the same instant as event R.
- At least one of the events does not occur.
- One of the events occurs before the other, but there is not enough information to tell which.



23. [5 pts] In Betty's reference frame, which of the following best describes when Alec receives the two light signals?

- Alec receives light from the left source first.
- Alec receives light from the right source first.
- Alec receives light from both sources simultaneously.
- Alec does not receive light from at least one of the sources.
- Alec receives light from one of the sources before the other, but there is not enough information to tell which.

Physics 123A, Autumn 2010 Final Exam, page 6 WO-UWA123A104T-EF(ERF.SIM)mc.doc

Figure B.10: Written multiple-choice final examination administered in Autumn 2010 to PHYS 123A.

Name _____ Student ID _____
last first

III. [20 points total] Four powerful strobe lights of different colors are mounted equidistant from point c on an airplane. When the plane was at rest in the factory, the lights were programmed for an emergency distress signal consisting of simultaneous flashes of all four lights at regular intervals.

The plane now flies due south at a relativistic speed and the pilot (at rest in the plane) begins testing the emergency distress signal. Three ground-based observers are shown. In what follows, ignore any color changes due to the Doppler effect.

colored lights mounted equidistant from point c

23. [5 pts] Which of the following statements concerning the timing of the first flash of the red and blue lights in the reference frame of observer III is true?

- The red and blue lights flash simultaneously in observer III's reference frame.
- The red light flashes before the blue light in observer III's reference frame.
- The blue light flashes before the red light in observer III's reference frame.
- Relativity does not allow us to determine the order of flashes in observer III's reference frame.
- The order of flashes can be determined, but more information is needed.

24. [5 pts] In the reference frame(s) of which observer(s), if any, does the flash of the red light occur at the same time as the flash of the blue light?

- Observers I, II, and III.
- Observer I only.
- Observer II only.
- Observer III only.
- None of these observers.

25. [5 pts] In the reference frame(s) of which observer(s), if any, does the flash of the yellow light occur at the same time as the flash of the green light?

- Observers I, II, and III.
- Observer I only.
- Observer II only.
- Observer III only.
- None of the observers.

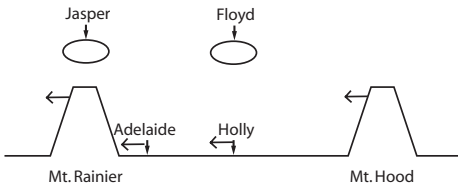
Physics 123A, Winter 2011 Final Exam WO-UWA123A111T-EF(ERF,SIM)mc.doc

Figure B.11: Written multiple-choice final examination administered in Winter 2011, Spring 2011, and Autumn 2011 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

VII. [20 points total] Holly is at rest exactly midway between Mt. Rainier and Mt. Hood. Adelaide is at rest near the foot of Mt. Rainier.

Jasper is in the center of a spacecraft moving from Mt. Rainier toward Mt. Hood at speed $v = 0.8c$ relative to the ground. Floyd is in the center of a spacecraft that is also moving from Rainier toward Hood at speed $v = 0.8c$ relative to the ground.



In Floyd's frame, he receives light from *both eruptions* at the instant shown. At this instant, he is located exactly halfway between the mountains. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). Treat all observers as intelligent observers.

27. [5 pts] In Floyd's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

28. [5 pts] In Jasper's frame, the order of the two events (Mt. Rainier erupts and Mt. Hood erupts)

- Is the same as in Mt. Rainier's frame.
- Is the same as in Holly's frame.
- Is the same as in Floyd's frame.
- More than one of the above choices is correct.
- None of the above choices is correct.

29. [5 pts] In Holly's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

30. [5 pts] In Holly's frame, Floyd receives the light from Mt. Rainier

- Before he receives the light from Mt. Hood.
- After he receives the light from Mt. Hood.
- At the same time as he receives the light from Mt. Hood.
- It is impossible to determine from the information given.

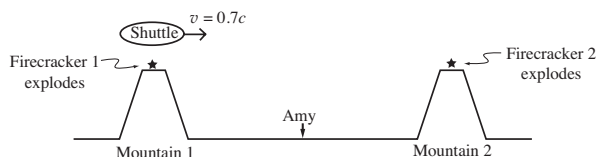
Physics 123C, Spring 2011 Final Exam EM-UWA123C112T-EF(ERF.SIM)mc.doc

Figure B.12: Written multiple-choice final examination administered in Spring 2011 to PHYS 123C.

Name _____ Student ID _____
last first

IV. [15 points total]

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob's location is not known. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances), and that all observers are intelligent observers.



Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light. Amy receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows the locations of Amy and the shuttle in the reference frame of the ground at the instant both firecrackers explode. Bob's location is not shown. Call event 1 "firecracker 1 explodes" and event 2 "firecracker 2 explodes."

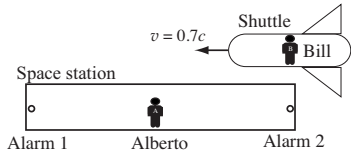
28. [5 pts] Would Bob (at rest with respect to the ground) measure that:
- Event 1 occurs *before* event 2.
 - Event 1 occurs *after* event 2.
 - Event 1 occurs *at the same time* that event 2 occurs.
 - More information is needed to answer.
29. [5 pts] The location of event 1 in the shuttle frame is correctly determined to be x_1 . In the shuttle frame, the center of the wavefront of the light from event 1 is:
- spherical and centered at location x_1 (which is stationary in the shuttle frame)
 - spherical and centered at firecracker 1 (which moves to the left in the shuttle frame)
 - non-spherical and centered at location x_1 (which is stationary in the shuttle frame)
 - non-spherical and centered at firecracker 1 (which moves to the left in the shuttle frame).
30. [5 pts] Would an observer in the shuttle frame (moving to the right at speed $v = 0.7c$ relative to the ground) measure that?
- Event 1 occurs *before* event 2.
 - Event 1 occurs *after* event 2.
 - Event 1 occurs *at the same time* that event 2 occurs.
 - More information is needed to answer.

Figure B.13: Written multiple-choice final examination administered in Winter 2013 for PHYS 123A, Winter 2014 for PHYS 123B, and Winter 2012 and Spring 2013 for PHYS 123C.

Name _____ Student ID _____
last first

III. [15 points total]

Alberto and Joan are at rest inside a space station. Alberto is exactly at the center; Joan's location is unknown. Bill is at rest in a shuttle flying to the left with speed $v = 0.7c$ relative to the station. Assume all motion is along one dimension (*i.e.*, ignore vertical distances), and that all observers are intelligent observers.



Alarms 1 and 2 go off at opposite ends of the space station. Each alarm emits a flash of light. Alberto receives the light from the two alarms at exactly the same time and correctly determines that the alarms go off simultaneously in his reference frame.

The figure shows the locations of Alberto, Bill, and the shuttle in the reference frame of the space station at the instant both alarms go off. Joan's location is not shown. Call event 1 "alarm 1 goes off" and event 2 "alarm 2 goes off."

29. [5 pts] Would Joan (at rest with respect to the space station) measure that:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

30. [5 pts] Bill correctly determines the location of event 1 in the shuttle frame to be x_1 . In the shuttle frame, the center of the wavefront of the light from event 1 is:

- spherical and centered at location x_1 (which is stationary in the shuttle frame)
- spherical and centered at alarm 1 (which moves to the right in the shuttle frame)
- non-spherical and centered at location x_1 (which is stationary in the shuttle frame)
- non-spherical and centered at alarm 1 (which moves to the right in the shuttle frame)

31. [5 pts] Would Bill (moving to the left at speed $v = 0.7c$ relative to the space station) measure that:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

Physics 123A, Spring 2013 Final Exam WO-UWA123A132T-EF(ERF,SIM)

Figure B.14: Written multiple-choice final examination administered in Winter 2013 for PHYS 123A, Winter 2014 for PHYS 123B, and Winter 2012 and Spring 2013 for PHYS 123C.

Name _____ Student ID _____
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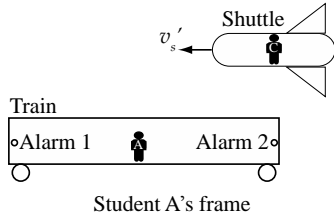
IV. Relativistic train [15 points total]

A train moves to the right with a speed $v_t = 0.5c$ with respect to the ground. A shuttle flies to the left with speed $v_s = 0.7c$ relative to the ground. Students A, B, and C are intelligent observers.

- Student A stands at rest in the middle of the train.
- Student B stands at rest at an unknown location on the train.
- Student C stands at rest in the middle of the shuttle.

Alarms 1 and 2 go off at opposite ends of the train. Call event 1 “alarm 1 goes off” and event 2 “alarm 2 goes off.” **Events 1 and 2 occur simultaneously in student A’s reference frame.**

The picture at right represents **student A’s reference frame** at the instant the alarms go off. Let v_s' represent the shuttle’s velocity in student A’s reference frame.



30. [5 pts] In student B’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

31. [5 pts] How does v_s , the speed of the shuttle as measured in the ground frame, compare to v_s' , the speed of the shuttle as measured in student A’s frame?

- $v_s > v_s'$
- $v_s < v_s'$
- $v_s = v_s'$
- More information is needed to answer.

32. [5 pts] In student C’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- More information is needed to answer.

Physics 123A, Fall 2013 Final Exam WO-UWA123A134T-EF(ERF,SIM)

Figure B.15: Written multiple-choice final examination administered in Autumn 2013 to PHYS 123A.

Name _____ Student ID _____
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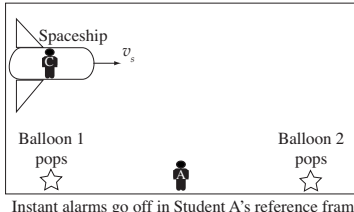
IV. [20 points total]

A spaceship flies in a straight line over a very large field.

- Student A stands at rest in the middle of the field.
- Student B stands at rest at an unknown location in the field.
- Student C stands at rest in the middle of the spaceship.

Balloons 1 and 2 pop at opposite ends of the field. Call event 1 “balloon 1 pops” and event 2 “balloon 2 pops.” **Events 1 and 2 are simultaneous in student A’s reference frame.**

The picture shows student A’s reference frame at the instant the balloons pop. Let v_s be the spaceship’s velocity in student A’s reference frame.



Instant alarms go off in Student A’s reference frame.

23. [5 pts] In student B’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in student B’s reference frame cannot be determined without knowing student B’s location.

24. [5 pts] In student C’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in student C’s reference frame cannot be determined without knowing student C’s velocity.

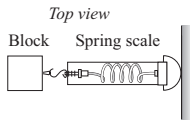
25. [5 pts] Student A **hears** the balloons pop simultaneously in her reference frame. In student C’s frame, student A hears balloon 1 pop:

- Before she hears balloon 2 pop.
- At the same time she hears balloon 2 pop.
- After she hears balloon 2 pop.
- The order cannot be determined without knowing student C’s velocity.

A different spaceship slows down relative to the field as it passes by in a straight line from left to right. Inside the spaceship, a block is attached to a spring scale that is fastened to a wall, as shown. The spring scale reading does not change.

26. [5 pts] In student A’s reference frame, the acceleration of the block is:

- To the right
- To the left
- Zero
- It is impossible to determine the direction of the acceleration of the block in student A’s reference frame.



Physics 123A, Winter 2014 Final Exam WO-UWA123A141T-EF(ERF,SIM)

Figure B.16: Written multiple-choice final examination administered in Autumn 2013 to PHYS 123A.

B.3 Curricular materials described in Chapter 4

In this section, complete tutorial and homework worksheets with portions described in Chapter 4: *Student understanding of reference frames* are included.

<p>EVENTS AND REFERENCE FRAMES</p> <hr style="border: 1px solid black;"/> <p>1. <i>Relative velocity and rest frames</i></p> <p>Anton is walking at a constant speed, 1.5 m/s due north. Barry is jogging due south with a constant speed, 3 m/s. Carl stands at rest.</p> <p>a. What is Anton's speed relative to Carl? What is Anton's speed relative to Barry? Explain.</p> <p>b. Could Carl change his speed such that he is at rest relative to Anton? Could Anton change his speed such that he would be at rest relative to Carl? Explain.</p> <p>c. Suppose that you are told that Carl and Anton are at rest relative to each other. What, if anything, can you say about the distance separating them?</p> <p>d. Suppose that Barry reduced his speed to 1.5 m/s, but continued moving in the same direction (due south). Would Barry and Anton be at rest with respect to each other? Why or why not?</p> <p style="text-align: center;">Is a common speed the only factor that determines whether two bodies are at rest with respect to each other?</p> <p style="text-align: center;">Often, the most useful reference frame for an observer to use is one in which the observer is at rest. It is common to refer to such a frame as the <i>rest frame of the observer</i>, the <i>observer's rest frame</i>, the <i>observer's reference frame</i>, or simply <i>the observer's frame</i>.</p> <p>e. Is it possible for an individual to have a non-zero velocity in his or her own reference frame? If so, explain how. If not, explain why not.</p>	<p>Name _____</p> <p style="text-align: right;">ST HW-1</p>
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Figure B.17: *Events and reference frames* tutorial homework worksheet administered starting in Spring 2010 to PHYS 123. (Four pages.)

ST Events and reference frames
HW-2

- f. Is it possible for two people in the same rest frame to be moving with different velocities? Why or why not? Explain.

2. Signal reception and event time

Anton and Barry are standing at rest 150 meters apart. A dog, Clover, sits between them, 50 meters from Anton and 100 meters from Barry. At exactly 12 noon, Clover barks. Assume the speed of sound is 340 m/s.

- a. Who hears the bark first, Anton or Barry? Explain.
- b. How long after Clover barks does Anton hear the bark? How long after Clover barks does Barry hear the bark? Show your work.

Assume that Anton and Barry are intelligent observers. (Recall that an *intelligent observer* is someone who can make correct and accurate determinations of where and when something occurs.)

- c. Suppose that Anton and Barry independently determine the time at which the bark occurred. Is the time determined by Anton *earlier than*, *later than*, or *at the same time as* that determined by Barry? Explain.
- d. Suppose that Anton were standing 150 meters away from Clover the dog. Would your answers to parts a and b change? Why or why not?
- e. Based on the ideas developed in question 1 of this homework, are Anton and Barry in the same reference frame? Explain.
- f. Generalizing these results, what, if anything, can you say about the time that a given event must occur for all people in a given reference frame?

Events and reference frames

Name _____ ST
HW-3

3. Event diagrams in different reference frames

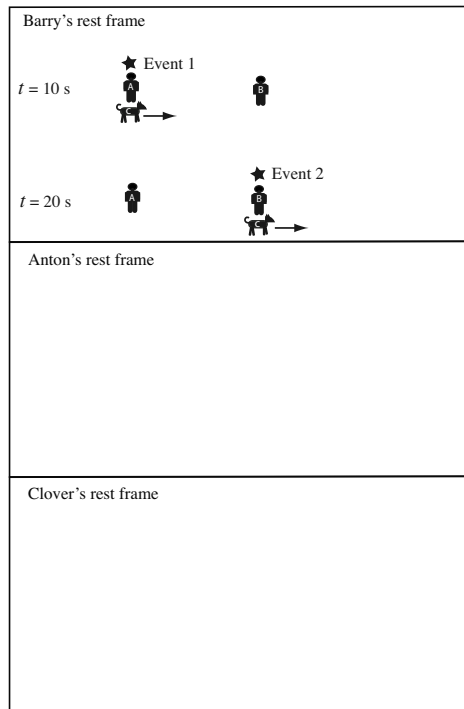
Clover the dog is running to the right. She passes Anton at $t = 10$ seconds; she passes Barry at $t = 20$ seconds. Both Barry and Anton carry flashlights, which they flash on and off when Clover runs by.

Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes, and

Event 2: Barry's flashlight flashes.

Below is an event diagram in Barry's reference frame. In the spaces provided, draw the event diagrams for Anton's reference frame and Clover's reference frame. Indicate the location and the time of each event of interest, and use arrows to indicate the directions of any motions in that frame.



EVENTS AND REFERENCE FRAMES	Name _____	ST HW-1
--	------------	------------

1. Anton and Barry are standing at rest 150 m apart; they have synchronized clocks. A dog, Clover, sits between them, 50 m from Anton and 100 m from Barry. At exactly 12 noon, Clover barks. Assume the speed of sound is 340 m/s.

a. How long after Clover barks does Anton hear the bark? How long after Clover barks does Barry hear the bark? Show your work.

Assume that Anton and Barry are intelligent observers. (Recall that an *intelligent observer* is someone who can make correct and accurate determinations of where and when something occurs.)

b. Suppose that Anton and Barry independently determine the time at which the bark occurred. Is the time determined by Anton *earlier than*, *later than*, or *at the same time as* that determined by Barry? Explain.

c. Suppose that Anton had been standing 150 m away from Clover the dog. Would your answer to part b be different in this case? Explain.

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University of Washington (Spring 2012)

Figure B.18: *Events and reference frames* tutorial homework worksheet administered starting in Spring 2012 to PHYS 123. (Five pages.)

ST *Events and Reference Frames*
 HW-2

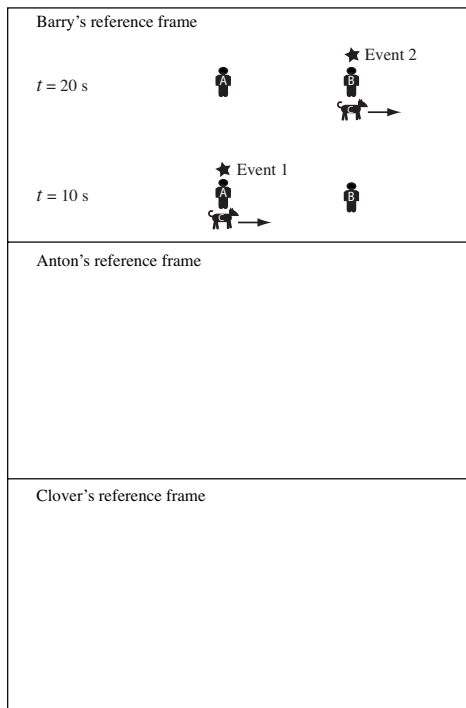
2. Clover the dog is running to the right at a constant speed. Anton and Barry stand at rest, 10 m apart. Clover passes Anton at $t = 10$ s; she passes Barry at $t = 20$ s. Both Barry and Anton carry flashlights, which they flash when Clover runs by.

Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes.

Event 2: Barry's flashlight flashes.

Below is an event diagram for Barry's reference frame. In the spaces provided, draw the event diagrams for Anton's reference frame and Clover's reference frame. Indicate the location and time of each event of interest. Use arrows to indicate the directions of any motions in that frame.



Events and Reference Frames

Name _____

ST
HW-3

-
- a. For each of the following reference frames, what is the distance between the location of event 1 and the location of event 2? In each case, explain how you can tell from the event diagram.
- Anton's reference frame

 - Barry's reference frame

 - Clover's reference frame
- b. Consider a third observer, Daisy. Describe Daisy's motion if the distance between event 1 and event 2 in Daisy's reference frame is:
- the same as in Anton's reference frame.

 - the same as in Barry's reference frame.

 - the same as in Clover's reference frame.
- c. What characterizes the motion of all observers who measure the same distance between events 1 and 2?

ST *Events and Reference Frames*
 HW-4

The results of the exercise above suggest an important result. All observers at rest with respect to one other measure the same distance between any two events; observers who are not at rest with respect to each other may not measure the same distance between events. Often, the most useful reference frame for an observer to use is one in which the observer is at rest. It is common to refer to such a frame as the *rest frame of the observer*, the *observer's rest frame*, the *observer's reference frame*, or simply the *observer's frame*.

3. Consider again the situation described in part 2, but suppose that Clover the dog barks as she passes Anton. Define events 1, 2, and 3 as follows:

- Event 1: Anton's flashlight flashes.
- Event 2: Barry's flashlight flashes.
- Event 3: Clover barks.

In the spaces below, draw the event diagrams for the reference frames of Anton and Clover.

<p style="text-align: center;">Anton's reference frame</p> <p style="text-align: center;">$t = 20$ s</p> <p style="text-align: center;">$t = 10$ s</p>
<p style="text-align: center;">Clover's reference frame</p> <p style="text-align: center;">$t = 20$ s</p> <p style="text-align: center;">$t = 10$ s</p>

*Events and Reference Frames*Name _____ ST
HW-5

-
- a. Consider events 1 and 3 in Anton's reference frame. For each question, justify your response using your event diagram for Anton's reference frame.
- What is the distance between the events 1 and 3?

 - Does event 1 happen *before*, *after* or *at exactly the same time* as event 3?
- b. Consider events 1 and 3 in Clover's reference frame. For each question, justify your response using your event diagram for Clover's reference frame.
- What is the distance between the events 1 and 3?

 - Does event 1 happen *before*, *after* or *at exactly the same time* as event 3?

As you found above, observers in different rest frames may not measure the same distance between events. The exception is if, in a given rest frame, the two events occur not only at the same location but also at the same time. In that case all observers would agree, regardless of reference frame, that the location and time of the first event is exactly the same as the location and time of the second event.

- Explain why it would be possible to treat events 1 and 3 as a single event in Anton's frame.

- Would it be possible to treat events 1 and 3 as a single event in any frame? Explain.

ST *Events and reference frames*
 HW-2

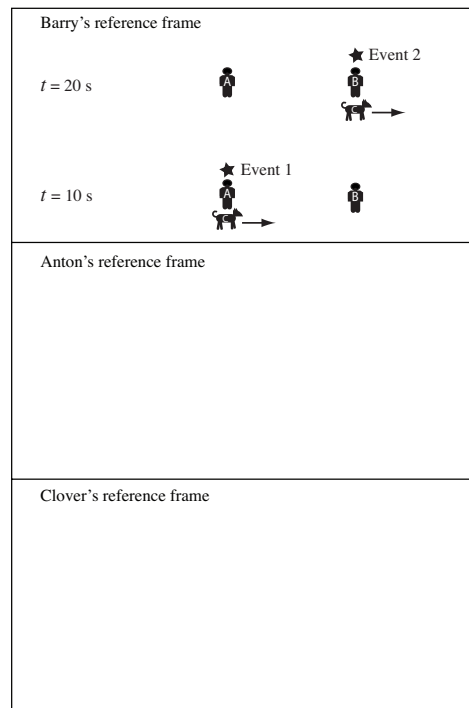
2. Now suppose that Anton and Barry stand at opposite ends of a train that moves with a constant speed relative to the ground. Clover the dog stands near the train track, at rest relative to the ground. Clover and Anton pass each other at $t = 10$ s; Clover and Barry pass each other at $t = 20$ s. Both Barry and Anton carry flashlights, which they flash when they pass Clover.

Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes.

Event 2: Barry's flashlight flashes.

- a. Below is an event diagram for Anton's reference frame. In the spaces provided, draw the event diagrams for Barry's reference frame and Clover's reference frame. Indicate the location and time of each event of interest. Use arrows to indicate the directions of any motions in that frame.



Events and reference frames

Name _____

ST
HW-3

-
- b. For each of the following reference frames, what is the distance between the location of event 1 and the location of event 2? In each case, explain how you can tell from the event diagram.
- Anton's reference frame

 - Barry's reference frame

 - Clover's reference frame
- c. Consider a third observer, Daisy. Describe Daisy's motion if the distance between event 1 and event 2 in Daisy's reference frame is:
- the same as in Anton's reference frame.

 - the same as in Barry's reference frame.

 - the same as in Clover's reference frame.
- d. Suppose two observers measure the same distance between two events. What, if anything, can you say about the relative motion of the two observers? (Consider only relative motion in one dimension.)

ST *Events and reference frames*
 HW-4

The results of the exercise above suggest an important result. Observers at rest with respect to each other (*i.e.*, observers in the same reference frame) will measure the same distance between events; observers who are not at rest with respect to each other may *not* measure the same distance between events.

- e. Are your answers to parts b and c above consistent with the idea that all observers at rest with respect to each other measure the same distance between events? If not, resolve any inconsistencies.
3. Consider again the situation described in part 2, but suppose that Clover the dog barks as she and Anton pass each other. Define events 1, 2, and 3 as follows:
- Event 1: Anton's flashlight flashes.
 - Event 2: Barry's flashlight flashes.
 - Event 3: Clover barks.

In the spaces below, draw the event diagrams for the reference frames of Anton and Clover.

<p style="text-align: center;">Anton's reference frame</p> <p style="text-align: center;">$t = 20$ s</p> <p style="text-align: center;">$t = 10$ s</p>
<p style="text-align: center;">Clover's reference frame</p> <p style="text-align: center;">$t = 20$ s</p> <p style="text-align: center;">$t = 10$ s</p>

Events and reference frames

Name _____

ST
HW-5

a. Consider events 1 and 3 in Anton's reference frame. For each question, justify your response using your event diagram for Anton's reference frame.

i. What is the distance between the events 1 and 3?

ii. Does event 1 happen *before*, *after* or *at exactly the same time as* event 3?

b. Consider events 1 and 3 in Clover's reference frame. For each question, justify your response using your event diagram for Clover's reference frame.

i. What is the distance between the events 1 and 3?

ii. Does event 1 happen *before*, *after* or *at exactly the same time as* event 3?

As you found above, observers in different rest frames may not measure the same distance between events. The exception is if, in a given rest frame, the two events occur not only at the same location but also at the same time. In that case all observers agree, regardless of reference frame, that the location and time of the first event is exactly the same as the location and time of the second event.

c. Explain why it would be possible to treat events 1 and 3 as a single event in Anton's frame.

d. Would it be possible to treat events 1 and 3 as a single event in any frame? Explain.

ST *Events and reference frames*
 HW-2

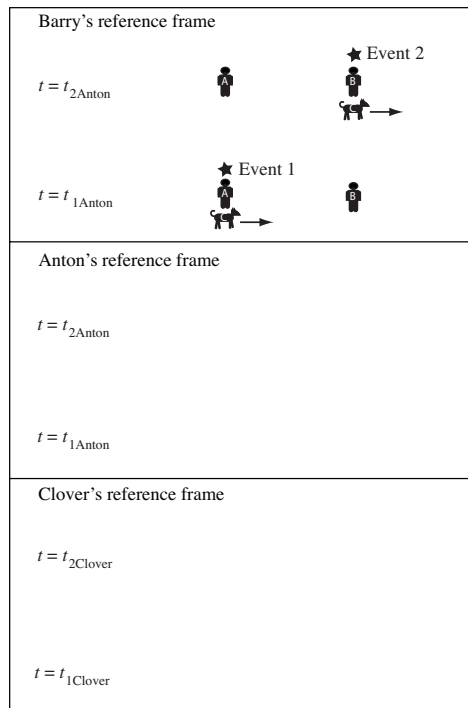
2. Now suppose that Anton and Barry stand at opposite ends of a train that moves with a constant speed relative to the ground. The train is 60 meters long. Clover the dog stands near the train track, at rest relative to the ground. As measured in Anton's reference frame, Clover and Anton pass each other at $t = t_{1Anton}$. Clover and Barry pass each other at $t = t_{2Anton}$. Both Barry and Anton carry flashlights, which they each flash when passing Clover.

Define events 1 and 2 as follows:

Event 1: Anton's flashlight flashes.

Event 2: Barry's flashlight flashes.

- a. Below is an event diagram for Barry's reference frame. In the spaces provided, draw the event diagrams for Anton's reference frame and for Clover's reference frame. Indicate the location and time of each event of interest. Use arrows to indicate the directions of any motions in that frame.



Events and reference frames

Name _____

ST
HW-3

-
- b. For each of the following reference frames, what is the distance between the location of event 1 and the location of event 2? In each case, explain how you can tell from the event diagram.
- Anton's reference frame

 - Barry's reference frame

 - Clover's reference frame
- c. Consider a third observer, Daisy. Determine the distance between the location of event 1 and the location of event 2 if Daisy:
- is at rest with respect to Anton.

 - is at rest with respect to Barry.

 - is at rest with respect to Clover.

The results of the exercise above suggest an important result. Observers at rest with respect to each other (*i.e.*, observers in the same reference frame) measure the same distance between events; observers who are not at rest with respect to each other might *not* measure the same distance between events.

- d. Are your answers to parts b and c above consistent with the idea that all observers at rest with respect to each other measure the same distance between events? If not, resolve any inconsistencies.

ST Events and reference frames
HW-4

3. Consider again the situation described in part 2, but suppose that Clover the dog barks as she and Anton pass each other. Define events 1, 2, and 3 as follows:

- Event 1: Anton's flashlight flashes.
Event 2: Barry's flashlight flashes.
Event 3: Clover barks.

In the spaces below, draw the event diagrams corresponding to the reference frames of Anton and Clover.

<p>Anton's reference frame</p> <p style="text-align: center;">$t = t_{2\text{Anton}}$</p> <p style="text-align: center;">$t = t_{1\text{Anton}}$</p>
<p>Clover's reference frame</p> <p style="text-align: center;">$t = t_{2\text{Clover}}$</p> <p style="text-align: center;">$t = t_{1\text{Clover}}$</p>

- a. Consider events 1 and 3 in Anton's reference frame. For each question, justify your response using your event diagram for Anton's reference frame.
- i. What is the distance between the events 1 and 3?

 - ii. Does event 1 happen *before*, *after* or *at exactly the same time* as event 3?

Events and reference frames

Name _____

ST
HW-5

b. Consider events 1 and 3 in Clover's reference frame. For each question, justify your response using your event diagram for Clover's reference frame.

i. What is the distance between the events 1 and 3?

ii. Does event 1 happen *before*, *after* or *at exactly the same time* as event 3?

As you found in question 2, observers in different reference frames may not measure the same distance between events. The exception is if, in a given reference frame, the two events occur not only at the same location but also at the same time, as in question 3. In that case all observers agree, regardless of reference frame, that the location and time of the first event is exactly the same as the location and time of the second event.

c. Explain why it would be possible to treat events 1 and 3 as a single event in Anton's frame.

d. Would it be possible to treat events 1 and 3 as a single event in any frame? Explain.

EVENTS AND REFERENCE FRAMES

I. Synchronization of clocks

Alan and Beth are exactly 10^8 light-seconds apart relative to the floor. (One light-second is the distance that light travels in one second.) Each of them wears a watch. Both watches are extremely accurate, run at the same rate, and measure time in seconds. However, Alan and Beth did not start their watches at the same time.

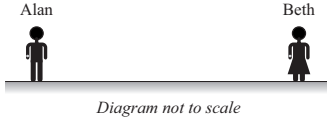


Diagram not to scale

ST
1

A. Determine the amount of time that it will take a light signal to travel from Beth to Alan.

B. Beth and Alan decide in advance that, at the instant Beth's watch reads 50 s, she will use a laser pointer to emit a pulse of light in Alan's direction.

What time will Beth's watch read at the instant Alan first receives the light from the laser pointer?

C. Describe a method by which Alan could use the laser pulse to synchronize his watch with Beth's (*i.e.*, make his watch have the same reading as Beth's at every instant).

D. Another physics student, Caroline, is at rest with respect to Alan and Beth but is very far away from them. Caroline looks at the reading on Alan's watch with a powerful telescope, and finds that, at every instant, the reading she sees on Alan's watch through the telescope is identical to the reading on her watch.

Is Caroline's watch synchronized with Alan's? Explain why or why not.

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Figure B.21: *Events and reference frames* in-class tutorial worksheet administered starting in Spring 2012 to PHYS 123. (Four pages.)

ST Events and reference frames
2

II. Reference Frames

A. A physics student named Alan stands far away from a beeper as shown at right. The beeper is about to emit a beep, and Alan wants to determine the exact time at which it does so. However, he is unable to travel to it.



Diagram not to scale

B. Alan is equipped with accurate meter sticks and synchronized clocks. A number of other students are willing to help, if necessary.

1. Describe a set of measurements by which Alan can determine the time at which the beep is emitted:
 - a. Using his knowledge of the speed of sound in air.
 - b. Without knowing or measuring the speed of sound. (*Hint: Alan's assistants are free to stand at any location.*)

C. Suppose now that there is a line of many beepers; one of the beepers is about to emit a beep, but neither Alan nor the other students know which beeper it is.

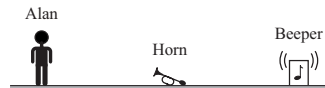
1. Describe an arrangement of students and equipment with which Alan can record the position of the active beeper and the time at which it beeps.

An *intelligent observer* is equipped with measuring devices (such as meter sticks, synchronized clocks, and assistants) and is able to use them to make correct and accurate determinations of where and when something occurs. An observer's *reference frame* is such an arrangement of assistants and equipment that is at rest with respect to that observer. Each of the assistants can be considered to be an intelligent observer in the same reference frame.

Events and reference frames ST
3

2. Would all the physics students attribute the same time and location to the beeper beeping? Explain.

- D. A horn is now placed between Alan and a single beeper. The beeper beeps once and the horn honks once. Alan hears both sounds at the same instant.



1. Describe a method by which Alan can measure the time separation between the emission of the beep and the emission of the honk in his reference frame *without* knowing or measuring the speed of sound.

2. In Alan's reference frame, is the beep emitted *before*, *after*, or *at the same instant* as the honk is emitted? Explain.

Consider the following student dialog:

Student 1: The beeper and horn go off at the same time in Alan's reference frame since he hears them at the same time. Each of the student-assistants to the left of the horn would agree with him. The student-assistants to the right of the beeper would say the beeper goes off first in their reference frames, since they would hear the beeper first.

Student 2: That's right. Each person's reference frame is different. Only the observer at the horn knows when it really honked and only the observer at the beeper knows exactly when it beeped.

Do you agree with students 1 and 2? Why or why not?

- ⇨ Check your answers with a tutorial instructor.

ST Events and reference frames
4

III. Events

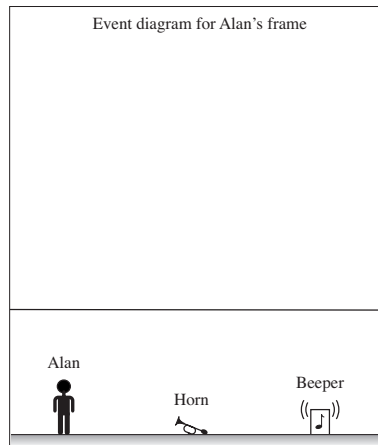
A. In the study of relativity, we refer to material *objects*, *locations* in space, *instants* in time, and *events*. An *event* is associated with a single location in space and a single instant in time.

State whether each of the items below is an *object*, a *location*, an *instant*, an *event*, or *none of these*.

- the beeper of section I
- the beeper emits a beep
- Alan hears the beep
- the exact time at which the beeper beeps
- a sound wave travels from the beeper to Alan
- two beepers beep at the same time

B. Consider again the situation in part D of section II. A picture that shows Alan, the beeper and the horn at the instant the beeper beeps has been provided at right, below. Complete the following:

1. Label the position of the event “the beeper beeps” on the picture.
2. Above the first picture, sketch a picture that shows the objects of interest at the instant the horn honks. Label the position of the event “the horn honks” on this picture.
3. Repeat question 2 for any remaining instants at which there is an event or events of interest. On each picture, indicate the locations of all the relevant objects and label the events of interest.



C. A diagram such as the one you drew above is called an *event diagram*. An event diagram has the following characteristics:

- The objects of interest are shown at the instants of the events of interest.
- Successive instants are shown one above the other; each instant is shown only once.
- The location of each event of interest is indicated in the appropriate picture.


EVENTS AND REFERENCE FRAMES

I. Synchronization of clocks

Alan and Beth are exactly 10^8 light-seconds apart relative to the floor. (One light-second is the distance that light travels in one second.) Each of them wears a watch. Both watches are extremely accurate, run at the same rate, and measure time in seconds. However, Alan and Beth did not start their watches at the same time.

ST
1

Alan



Beth




Diagram not to scale

A. Determine the amount of time that it will take a light signal to travel from Beth to Alan.

B. Beth and Alan decide in advance that, at the instant Beth's watch reads 50 s, she will use a laser pointer to emit a pulse of light in Alan's direction.

What time will Beth's watch read at the instant Alan first receives the light from the laser pointer?

C. Describe a method by which Alan could use the laser pulse to synchronize his watch with Beth's (*i.e.*, make his watch have the same reading as Beth's at every instant).

D. Another physics student, Caroline, is at rest with respect to Alan and Beth but is very far away from them. Caroline looks at the reading on Beth's watch with a powerful telescope and finds that, at every instant, the reading she sees on Beth's watch through the telescope is identical to the reading on her watch.

Is Caroline's watch synchronized with Beth's? Explain why or why not.

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University of Washington (Fall 2012)

Figure B.22: *Events and reference frames* in-class tutorial worksheet administered starting in Autumn 2012 to PHYS 123. (Five pages.)

ST Events and reference frames
2

II. Events

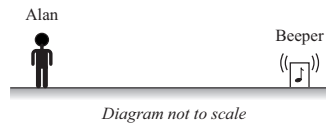
A. In the study of relativity, we refer to material *objects*, *locations* in space, *instants* in time, and *events*. An *event* is associated with a single location in space and a single instant in time.

State whether each of the items below is an *object*, a *location*, an *instant*, an *event*, or *none of these*.

- Beth's laser
- Beth flashes her laser in Alan's direction
- Alan sees the flash from Beth's laser
- the exact time at which Beth's laser flashes
- light travels from Beth to Alan
- Alan and Beth each flash a laser at the same time

III. Reference Frames

A. A physics student named Alan stands far away from a beeper as shown at right. The beeper is about to emit a beep, and Alan wants to determine the exact time at which it does so. However, he is unable to travel to it.

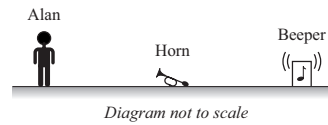


Alan is equipped with accurate meter sticks and synchronized clocks. A number of other physics students are willing to help, if necessary.

1. Describe a set of measurements by which Alan can determine the time at which the beep is emitted:
 - a. Using his knowledge of the speed of sound in air.
 - b. *Without* knowing or measuring the speed of sound. (*Hint*: Alan's assistants are free to stand at any location.)

Events and reference frames ST
3

B. A horn is now placed between Alan and a single beeper. The beeper beeps once and the horn honks once. Alan hears both sounds at the same instant.



1. Describe a method by which Alan can measure the time separation between the emission of the beep and the emission of the honk *without* knowing or measuring the speed of sound.

2. Using the method devised above, will Alan determine that the beep was emitted *before*, *after*, or *at the same instant* as the honk is emitted? Explain.

In special relativity, Alan and his assistants are considered intelligent observers in the same reference frame. A *reference frame* can be thought of as an imaginary grid of meter sticks and synchronized, recording clocks. The time and location of an event are recorded by the clock nearest to that event. An *intelligent observer* is a person that measures the time and location of an event by collecting and reporting data from the recording clocks. An intelligent observer uses the grid of meter sticks and clocks that is at rest relative to that observer.

Consider the following student dialog:

Student 1: The beeper and horn go off at the same time in Alan's reference frame since he hears them at the same time. Each of the student-assistants to the left of the horn would agree with him. The student-assistants to the right of the beeper would say the beeper goes off first in their reference frames, since they would hear the beeper first.

Student 2: That's right. Each person's reference frame is different. Only the observer at the horn knows when it really honked and only the observer at the beeper knows exactly when it beeped.

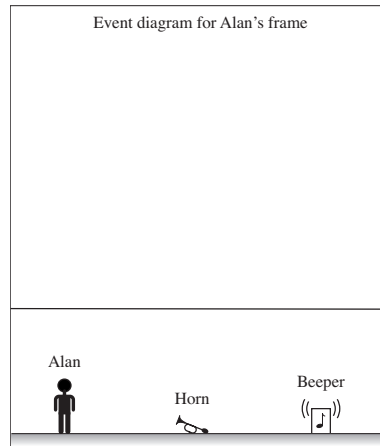
Do you agree with students 1 and 2? Why or why not?

↔ Check your answers with a tutorial instructor.

ST Events and reference frames
4

C. Consider again the situation in part B, above. A picture that shows Alan, the beeper and the horn at the instant the beeper beeps has been provided at right, below. Complete the following:

1. Label the position of the event “the beeper beeps” on the picture.
2. Above the first picture, sketch a picture that shows the objects of interest (Alan, the horn, the beeper, *etc.*) at the instant the horn honks. Label the position of the event “the horn honks” on this picture.
3. Repeat question 2 for any remaining instants at which there is an event or events of interest. On each picture, indicate the locations of all the relevant objects and label the events of interest.



D. A diagram such as the one you drew above is called an *event diagram*. An event diagram has the following characteristics:

- The objects of interest are shown at the instants of the events of interest.
 - Successive instants are shown one above the other; each instant is shown only once.
 - The location of each event of interest is indicated in the appropriate picture.
1. Does the entire first (lower) picture in your event diagram best correspond to *an object, a location, an instant, or an event*?
 2. Is it possible for a single event to appear in more than one picture in an event diagram? Explain why or why not.
 3. Describe the circumstances under which more than one event would appear in a single picture in an event diagram.

Events and reference frames ST
5

4. Suppose that two events occur at the same location but at different times. Describe how you could tell from an event diagram that the events occur at the same location.

5. Suppose that two events occur in the same location, and appear in the same picture of an event diagram. Explain why such an occurrence could be treated as a single event.

Is there any such event in the example above?

6. How do event diagrams drawn by two observers in the same reference frame compare? Explain.

↔ Check your answers with a tutorial instructor.

EVENTS AND REFERENCE FRAMES

I. Synchronization of clocks

Alan and Beth are exactly 10^8 light-seconds apart relative to the floor. (One light-second is the distance that light travels in one second.) Each of them wears a watch. Both watches are extremely accurate, run at the same rate, and measure time in seconds. However, Alan and Beth did not start their watches at the same time.

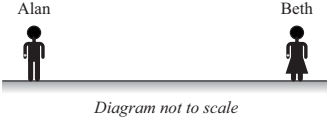


Diagram not to scale

ST
1

A. How long will it take a light signal to travel from Beth to Alan?

B. Beth and Alan decide in advance that, at the instant Beth's watch reads 50 s, she will use a laser pointer to emit a pulse of light in Alan's direction.

What time will Beth's watch read at the instant Alan first receives the light from the laser pointer?

C. Describe a method by which Alan could use the laser pulse to synchronize his watch with Beth's (*i.e.*, make his watch have the same reading as Beth's at every instant).

D. Another physics student, Caroline, is at rest with respect to Alan and Beth but is very far away from them. Caroline looks at the reading on Beth's watch with a powerful telescope and finds that, at every instant, the reading she sees on Beth's watch through the telescope is identical to the reading on her watch.

Is Caroline's watch synchronized with Beth's? Explain why or why not.

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University of Washington (Spring 2013)

Figure B.23: *Events and reference frames* in-class tutorial worksheet administered starting in Spring 2013 to PHYS 123. (Five pages.)

ST Events and reference frames
2

II. Events

A. In the study of relativity, we refer to material *objects*, *locations* in space, *instants* in time, and *events*. An *event* is associated with a single location in space and a single instant in time.

State whether each of the items below is an *object*, a *location*, an *instant*, an *event*, or *none of these*.

- Beth's laser
- Beth flashes her laser in Alan's direction
- Alan sees the flash from Beth's laser
- the exact time at which Beth's laser flashes
- light travels from Beth to Alan
- Alan and Beth each flash a laser at the same time

III. Reference Frames

A. A physics student named Alan stands far away from a beeper as shown at right. The beeper is about to emit a beep, and Alan wants to determine the exact time at which it does so. However, he is unable to travel to it.

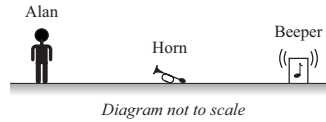


Diagram not to scale

Alan is equipped with accurate meter sticks and synchronized clocks. A number of other physics students are willing to help, if necessary.

1. Describe a set of measurements by which Alan can determine the time at which the beep is emitted:
 - a. Using his knowledge of the speed of sound in air.
 - b. *Without* knowing or measuring the speed of sound. (*Hint*: Alan's assistants are free to stand at any location.)

B. A horn is now placed between Alan and the beeper. The beeper beeps once and the horn honks once. Alan hears both sounds at the same instant.



1. Describe a method by which Alan can measure the time separation between the emission of the beep and the emission of the honk *without* knowing or measuring the speed of sound. (*Hint:* Alan's assistants are still willing to help.)

2. Using the method devised above, will Alan determine that the beep was emitted *before*, *after*, or *at the same instant* as the honk was emitted? Explain.

In special relativity, a *reference frame* can be thought of as an imaginary grid of meter sticks and synchronized, recording clocks. The clock at the location of an event records both the time and location of that event. An *intelligent observer* is a person that measures the time and location of an event by collecting and reporting data from the recording clocks; an intelligent observer uses the grid of meter sticks and clocks that is at rest relative to that observer. In the exercises above, Alan and his assistants can be thought of as intelligent observers in the same reference frame.

3. Answer the following questions based on the descriptions of intelligent observer and reference frame in the paragraph above.

What is the relative velocity of intelligent observers in the same reference frame? Explain.

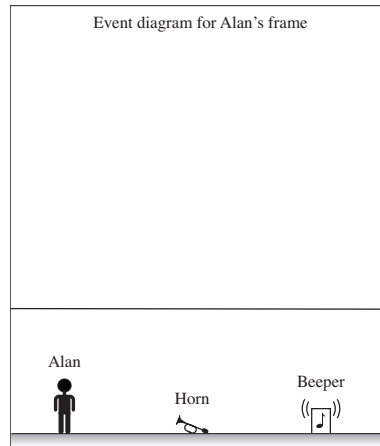
Would intelligent observers in the same reference frame always measure the same time and location for any given event? Explain.

↔ Check your answers with a tutorial instructor.

ST
4 *Events and reference frames*

C. Consider again the situation in part B. A picture that shows Alan, the beeper and the horn at the instant the beeper beeps has been provided at right, below. Complete the following:

1. Label the position of the event “the beeper beeps” on the picture.
2. Above the first picture, sketch a picture that shows the objects of interest (Alan, the horn, the beeper, *etc.*) at the instant the horn honks. Label the position of the event “the horn honks” on this picture.
3. Repeat question 2 for any remaining instants at which there is an event or events of interest. On each picture, indicate the locations of all the relevant objects and label the events of interest.



D. A diagram such as the one you drew above is called an *event diagram*. An event diagram has the following characteristics:

- The objects of interest are shown at the instants of the events of interest.
 - Successive instants are shown one above the other; each instant is shown only once.
 - The location of each event of interest is indicated in the appropriate picture.
1. Does the entire first (lower) picture in your event diagram best correspond to *an object, a location, an instant, or an event?*
 2. Is it possible for a single event to appear in more than one picture in an event diagram? Explain why or why not.
 3. Describe the circumstances under which more than one event would appear in a single picture in an event diagram.

Events and reference frames ST
5

4. Suppose that two events occur at the same location but at different times. Describe how you could tell from an event diagram that the events occur at the same location.

5. Suppose that two events occur in the same location, and appear in the same picture of an event diagram. Explain why such an occurrence could be treated as a single event.

Is there any such event in the example above?

6. How do event diagrams drawn by two intelligent observers in the same reference frame compare? Explain.

↔ Check your answers with a tutorial instructor.

Appendix C

**PRETEST AND POST-TEST QUESTIONS DESCRIBED IN
CHAPTER 5**

In this portion of the Appendix we provide the pretests and post-tests containing research tasks used during our investigation into student understanding of the invariance of the speed of light, described in Chapter 5.

Contents of appendix

C.1	Pretests	370
C.2	Exam questions described in Chapter 5	388

C.1 Pretests described in Chapter 5

In this section, complete pretests with portions described in Chapter 5: *Student understanding of the speed of light* are included.

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Print view of '(SIM)U2f(light)'
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Amy is at rest midway between the Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

The diagram shows a horizontal ground line. On the left is the Smith Tower, and on the right is the Space Needle. A spacecraft is moving from the Smith Tower towards the Space Needle. Chuck is in the center of the spacecraft. Amy is on the ground between the Smith Tower and the Space Needle. Bob is at the base of the Space Needle. Strobe lights are at the top of both towers.

Strobe lights are at the top of each tower. They are set to go off so that Amy sees the flashes at exactly the same time.

Chuck is in the center of a spacecraft moving from the Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above the Smith Tower when the light above the Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
Amy is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
Explain the reasoning you used to answer the question above.

Question 3.
Bob would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
Explain the reasoning you used to answer the question above.

Question 5.
<https://catalyst.uw.edu/webq/build/tipwo/203431> 1/3

Figure C.1: Catalyst *Simultaneity* pretest version U2F (light context). (Three pages.)

8/18/2017

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Bob is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

Chuck is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

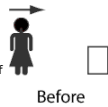
- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

A strobe light sits at rest on the ground. Beth moves to the right toward the strobe at half the speed of light relative to the strobe. She passes the strobe light just as it emits a flash of light.

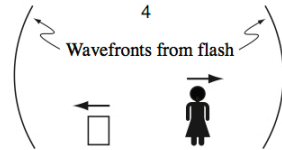
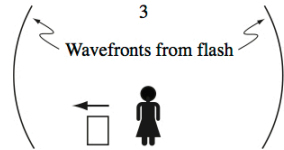
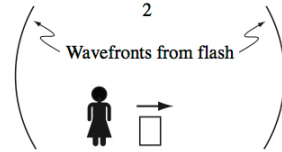
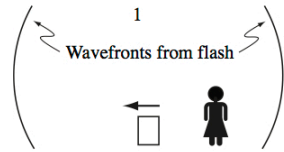


Beth and the strobe as shown in the ground reference frame

Which of the pictures below best represents the locations of Beth, the strobe light, and the wavefronts from the flash of light in Beth's reference frame a short time after she has passed the strobe light?

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- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these.

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Print view of '(SIM)U2f(sound)'
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Amy is at rest midway between the Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

Strobe lights are at the top of each tower. They are set to go off so that Amy sees the flashes at exactly the same time.

Chuck is in the center of a spacecraft moving from the Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above the Smith Tower when the light above the Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame, and that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 In Amy's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

<https://catalyst.uw.edu/webq/build/tipwo/203114> 1/3

Figure C.2: Catalyst *Simultaneity* pretest version U2F (sound context). (Three pages.)

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Question 5.

In Bob's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

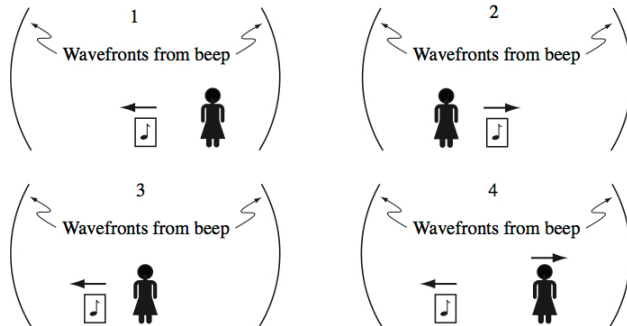
Question 11.

A small beeper sits on the ground on a calm, windless day. Beth moves to the right toward the beeper at half the speed of sound relative to the beeper. She passes the beeper just as it emits a beep.



Beth and the beeper as shown in the ground reference frame

Which of the pictures below best represents the locations of Beth, the beeper, and the wavefronts from the beep in Beth's reference frame a short time after she has passed the beeper?



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- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these.

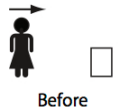
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Question 1.
 A small beeper sits on the ground on a calm, windless day. Beth moves to the right toward the beeper at half the speed of sound relative to the beeper.



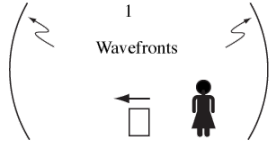
Beth and the beeper as shown in the ground reference frame

At the instant Beth passes the beeper it emits a beep.

Which picture below best shows the locations of Beth, the beeper, and the wavefronts in Beth's reference frame a short time after she has passed the beeper?

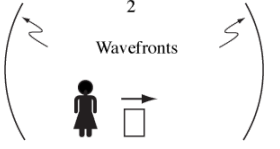
Choose the diagram for Beth's reference frame for an instant shortly after she has passed the beeper.

1



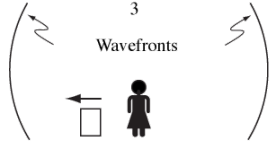
Wavefronts

2



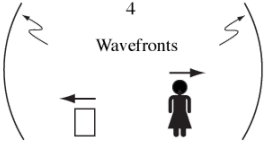
Wavefronts

3



Wavefronts

4

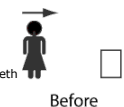


Wavefronts

Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these.

Question 2.
 Explain your reasoning for the previous question.

Question 3.
 Suppose instead that Beth moves to the right toward a strobe light at half the speed of light relative to the strobe.



Beth and the strobe as shown in the ground reference frame

The strobe emits a flash of light just as Beth passes it.

From the diagrams in question 1 above, choose the diagram for Beth's reference frame for an instant shortly after she has passed the strobe light.

Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

<https://catalyst.uw.edu/webq/build/tipwo/254245> 1/3

Figure C.3: Catalyst *Simultaneity* pretest version U2F (sound and light context). (Three pages.)

8/18/2017

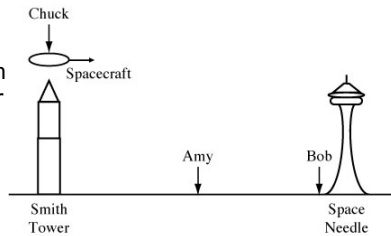
Catalyst WebQ

Question 4.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Amy is at rest midway between the Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.



Strobe lights are at the top of each tower. They are set to go off so that Amy sees the flashes at exactly the same time.

Chuck is in the center of a spacecraft moving from the Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above the Smith Tower when the light above the Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame, and that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 5.

In Amy's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Bob would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

<https://catalyst.uw.edu/webq/build/tipwo/254245>

2/3

8/18/2017

Catalyst WebQ

Explain the reasoning you used to answer the question above.

Question 9.

In Bob's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Chuck would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 12.

Explain the reasoning you used to answer the question above.

Question 13.

In Chuck's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 14.

Explain the reasoning you used to answer the question above.

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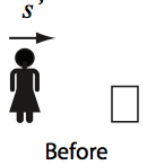
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(SIM)U2g(S&L)

Question 2.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.



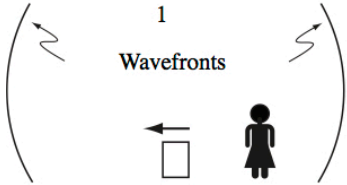
Beth and the beeper as shown in the ground reference frame

Before

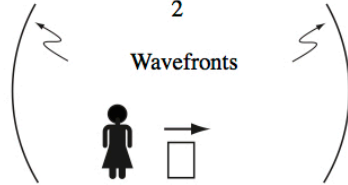
Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for frame s' for an instant shortly after Beth has passed the beeper.

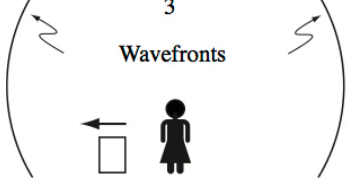
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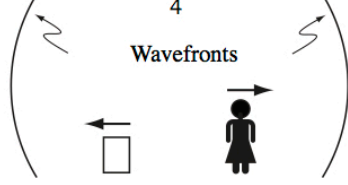
2



3



4



Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

Question 3.

At a later time in frame s' , the beeper has moved 400 meters to the left.

In frame s' , which of the following best describes the location of the event "the beeper beeps" at that later time?

<https://catalyst.uw.edu/webq/preview> 1/3

Figure C.4: Catalyst *Simultaneity* pretest version U2GA. (Four pages.)

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Catalyst WebQ - Preview

- At Beth
- At the beeper
- At a location somewhere between Beth and the beeper

Time remaining: 0:19:57

Question 4.

Explain the reasoning you used to answer the question above.

Question 5.

Suppose instead that Beth moves toward a strobe light, in a frame s'' that moves to the right at half the speed of **light** relative to the ground.

The strobe flashes just as Beth passes it. The flash of light moves outward in all directions.



Beth and the strobe as shown in the ground reference frame

Before

From the diagrams in question 1 above, choose the diagram for frame s' for an instant shortly after Beth has passed the strobe light.

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 6.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 7.

Consider the event "the strobe light flashes." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

[<< Previous](#) [Next >>](#)

8/22/2017

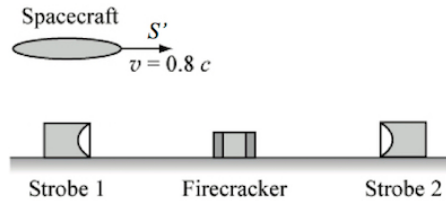
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(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



Ground frame at the instant strobe 1 flashes

An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 8.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

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Question 9.

Explain the reasoning you used to answer

Time remaining: 0:19:51

Question 10.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

Question 11.

Explain the reasoning you used to answer the question above.

Question 12.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
- After wavefront from the flash from strobe 2.
- At the same time as the wavefront from the flash from strobe 2.
- It's not possible to determine with the information given.

Question 13.In frame S' , the firecracker:

- Explodes.
- Does not explode.
- There is not enough information provided to answer.

Question 14.

Explain the reasoning you used to answer the question above.

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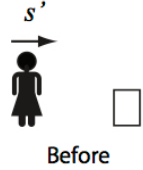
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(SIM)U2g(S&L)

Question 15.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.

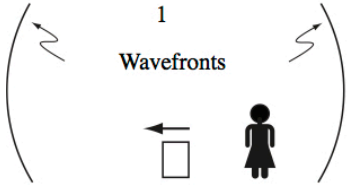


Beth and the beeper as shown in the ground reference frame

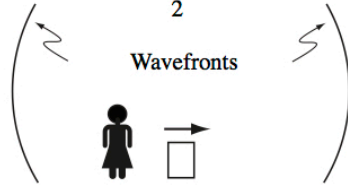
Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for frame s' for an instant shortly after Beth has passed the beeper.

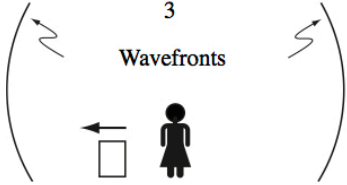
1



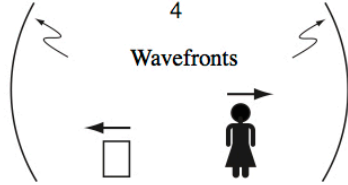
2



3



4



Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

Question 16.

Beth correctly determines the x' -coordinate of the event "the beeper beeps" to be $x'=0$ m.

At a later time, the beeper is 400 meters to the left of Beth. In frame s' , which of the following represents the location of the event "the beeper beeps?"

<https://catalyst.uw.edu/webq/preview> 1/2

Figure C.5: Catalyst *Simultaneity* pretest version U2GC. (Four pages.)

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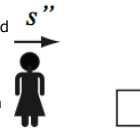
- $x' = 0$ m
- $x' = 400$ m
- $x' = -400$ m
- There is not enough information provided to answer this question.

Time remaining: 0:19:57

Question 17.

Suppose instead that Beth is in frame s'' that moves to the right at half the speed of light relative to the ground.

A spark jumps between Beth and the beeper at the instant she passes it. The spark emits a flash of light that moves outward in all directions.



Beth and the beeper as shown in the ground reference frame

From the diagrams in question 1 above, choose the diagram for frame s'' , for an instant shortly after Beth has passed the beeper.

Before

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 18.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 19.

Consider the event "the spark jumps." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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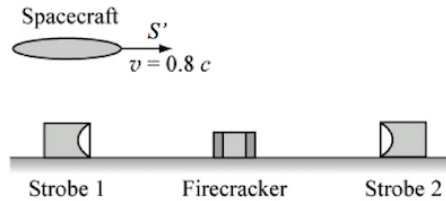
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(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



Ground frame at the instant strobe 1 flashes

An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 20.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

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Question 21.

Explain the reasoning you used to answer

Time remaining: 0:19:57

Question 22.In frame S' , the firecracker:

- Explodes.
 Does not explode.
 There is not enough information provided to answer.

Question 23.

Explain the reasoning you used to answer the question above.

Question 24.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
 After wavefront from the flash from strobe 2.
 At the same time as the wavefront from the flash from strobe 2.
 It's not possible to determine with the information given.

Question 25.

Explain the reasoning you used to answer the question above.

Question 26.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
 After strobe light 2 flashes.
 At the same time as strobe light 2 flashes.
 The answer to this question depends on the location of the observer

Question 27.

Explain the reasoning you used to answer the question above.

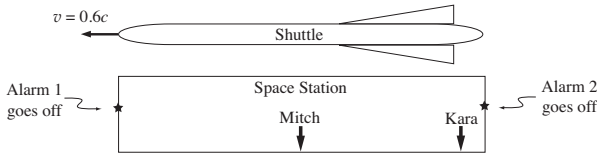
C.2 Exam questions described in Chapter 5

In this section, complete exam questions with portions described in Chapter 5: *Student understanding of the speed of light* are included.

Name _____ Student ID _____
last first

II. Relativity (continued)

Mitch and Kara are at rest inside a space station. Mitch is exactly at the center; Kara is at the right end. A shuttle is flying from right to left with speed $v = 0.6c$ relative to the station. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Alarms 1 and 2 go off at opposite ends of the space station. Each alarm emits a flash of light (circular wavefronts 1 and 2, respectively). Mitch, an intelligent observer in the reference frame of the space station, receives the light from the two alarms at the same instant and correctly determines that the alarms go off simultaneously in his frame.

The figure shows Mitch, Kara, and the shuttle in the reference frame of the space station at the instant both alarms go off.

11. [5 pts] Would intelligent observer Kara (in the reference frame of the space station) determine that:

- Alarm 1 goes off *before* alarm 2 goes off.
- Alarm 1 goes off *after* alarm 2 goes off.
- Alarm 1 goes off *at the same time* as alarm 2 goes off.
- More information is needed to answer.

12. [5 pts] In the shuttle frame, which of the following correctly describes the order in which Mitch receives wavefronts 1 and 2?

- Wavefront 1 reaches Mitch *before* wavefront 2.
- Wavefront 1 reaches Mitch *after* wavefront 2.
- Wavefront 1 reaches Mitch *at the same time* as wavefront 2.
- More information is needed to answer.

13. [5 pts] In the shuttle frame, the center of wavefront 1:

- moves to the right
- moves to the left
- is stationary
- More information is needed to answer

14. [5 pts] For the shuttle frame, which of the following correctly describes the order in which the alarms go off?

- Alarm 1 goes off *before* alarm 2 goes off.
- Alarm 1 goes off *after* alarm 2 goes off.
- Alarm 1 goes off *at the same time* as alarm 2 goes off.
- More information is needed to answer.

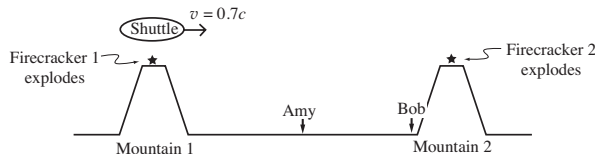
Physics 123A, Spring 2012 Final Exam WO-UWA123A122T-EF(ERF,SIM)

Figure C.7: Written multiple-choice final examination administered in Spring 2012 to PHYS 123A.

Name _____ Student ID _____
last first

II. Relativity (continued)

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob is near mountain 2. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light (circular wavefronts 1 and 2, respectively). Amy, an intelligent observer in the reference frame of the ground, receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows Amy, Bob, and the shuttle in the reference frame of the ground at the instant both firecrackers explode.

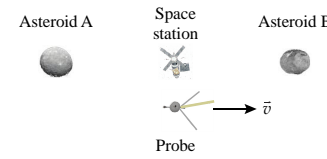
11. [5 pts] Would intelligent observer Bob (in the reference frame of the ground) determine that:
 - A. Firecracker 1 explodes *before* firecracker 2 explodes.
 - B. Firecracker 1 explodes *after* firecracker 2 explodes.
 - C. Firecracker 1 explodes *at the same time* as firecracker 2 explodes.
 - D. More information is needed to answer.
12. [5 pts] In the shuttle frame, which of the following correctly describes the order in which Amy receives wavefronts 1 and 2?
 - A. Wavefront 1 reaches Amy *before* wavefront 2.
 - B. Wavefront 1 reaches Amy *after* wavefront 2.
 - C. Wavefront 1 reaches Amy *at the same time* as wavefront 2.
 - D. More information is needed to answer.
13. [5 pts] In the shuttle frame, the center of wavefront 2:
 - A. moves to the right
 - B. moves to the left
 - C. is stationary
 - D. More information is needed to answer.
14. [5 pts] For the shuttle frame, which of the following correctly describes the order in which the firecrackers explode?
 - A. Firecracker 1 explodes *before* firecracker 2 explodes.
 - B. Firecracker 1 explodes *after* firecracker 2 explodes.
 - C. Firecracker 1 explodes *at the same time* as firecracker 2 explodes.
 - D. More information is needed to answer.

Figure C.8: Written multiple-choice final examination administered in Spring 2012 to PHYS 123C.

Name _____ Student ID _____ Score _____
last first

IV. [15 points total] For questions 28-30, a space station is halfway between asteroid A and asteroid B. All three objects are at rest with respect to one another. A probe moves with constant relativistic speed v along a line that passes very close to all three objects.

The picture at right represents the reference frame of the space station at the instant the probe passes the space station. At that instant in the space station frame, the probe and space station each emit light signals that move outward in all directions.



28. [5 pts] **In the reference frame of the probe**, in what order does asteroid A receive the signals from the space station and the probe?

- Asteroid A receives the signal from the space station *before* the signal from the probe.
- Asteroid A receives the signal from the space station *after* the signal from the probe.
- Asteroid A receives the signal from the space station *at exactly* the signal from the probe.
- Not enough information is provided to answer this question.

29. [5 pts] **In the reference frame of the probe**, which of the following statements best describes the order in which asteroids A and B receive the signal from the space station?

- Asteroid A receives the signal from the space station *before* asteroid B receives the signal from the space station.
- Asteroid A receives the signal from the space station *after* asteroid B receives the signal from the space station.
- Asteroid A receives the signal from the space station *at exactly the same time as* asteroid B receives the signal from the space station.
- Not enough information is provided to answer this question.

30. [5 pts] **In the reference frame of the space station**, which of the following statements best describes the order in which asteroids A and B receive the signal from the probe?

- Asteroid A receives the signal from the probe *before* asteroid B receives the signal from the probe.
- Asteroid A receives the signal from the probe *after* asteroid B receives the signal from the probe.
- Asteroid A receives the signal from the probe *at exactly the same time as* asteroid B receives the signal from the probe.
- Not enough information is provided to answer this question.

Physics 123B, Winter 2016 Final Exam WO-UWA123B161T-EF(ERF,SIM)

Figure C.9: Written multiple-choice final examination administered in Spring 2016 to PHYS 123B.

Appendix D

**PRETEST AND POST-TEST QUESTIONS DESCRIBED IN
CHAPTER 6**

In this portion of the Appendix we provide the pretests and post-tests containing research tasks used during our investigation into student understanding of causality, described in Chapter 6.

Contents of appendix

D.1	Pretests	394
D.2	Exam questions described in Chapter 6	418

D.1 Pretests described in Chapter 6

In this section, complete pretests with portions described in Chapter 6: *Student understanding of causality* are included.

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Print view of '(SIM)U2a'
[Print this page](#)

Amy is at rest midway between Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

Amy sees flashes of light above Smith Tower and the Space Needle at exactly the same time.

Chuck is in the center of a spacecraft moving from Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above Smith Tower when the light above Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 In Amy's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Bob's reference frame, the flash above Smith Tower occurs:

<https://catalyst.uw.edu/webq/build/tipwo/90179> 1/2

Figure D.1: Catalyst *Simultaneity* pretest version U2A. (Two pages.)

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- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Consider the following statement:

In the above situation, all three observers (Amy, Bob, and Chuck) agree that Amy sees both flashes simultaneously.

Do you agree or disagree with this statement?

- I agree with this statement.
- I disagree with this statement.

Question 12.

Explain the reasoning you used to answer the question above.

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Print view of '(SIM)U2b'
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Amy is at rest midway between Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

Amy sees flashes of light above Smith Tower and the Space Needle at exactly the same time.

Chuck is in the center of a spacecraft moving from Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above Smith Tower when the light above Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 In Amy's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Bob's reference frame, the flash above Smith Tower occurs:

<https://catalyst.uw.edu/webq/build/tipwo/97318> 1/2

Figure D.2: Catalyst *Simultaneity* pretest version U2B. (Two pages.)

8/18/2017

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- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Consider the following two statements about the situation described above. Indicate whether you agree or disagree with each statement.

Rows

In Bob's reference frame, Amy sees both flashes of light at the same time.

In Chuck's reference frame, Amy sees both flashes of light at the same time.

- I agree.
- I disagree.
- Not enough information

Question 12.

Explain the reasoning you used to answer the question above.

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Print view of '(SIM)U2d'
[Print this page](#)

Amy is at rest midway between Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.

Amy sees flashes of light above Smith Tower and the Space Needle at exactly the same time.

Chuck is in the center of a spacecraft moving from Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above Smith Tower when the light above Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 In Amy's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
 In Bob's reference frame, the flash above Smith Tower occurs:

<https://catalyst.uw.edu/webq/build/tipwo/126268> 1/3

Figure D.3: Catalyst *Simultaneity* pretest version U2D. (Two pages.)

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- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck sees the flash above Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Consider the following two statements about the situation described above. Indicate whether you agree or disagree with each statement.

Rows

In Bob's reference frame, Amy sees both flashes of light at the same time.

In Chuck's reference frame, Amy sees both flashes of light at the same time.

- I agree.
- I disagree.
- Not enough information

Question 12.

Explain the reasoning you used to answer the question above.

Question 13.

Which people/objects are in the same reference frame as Smith Tower? Check all that apply.

- Amy
- Bob
- Chuck
- Space Needle
- None of these

Question 14.

Explain the reasoning you used to answer the question above.

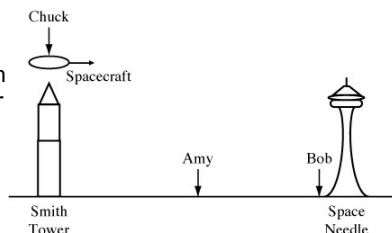
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Print view of '(SIM)U2di'[Print this page](#)

Amy is at rest midway between the Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.



Amy sees flashes of light above the Smith Tower and the Space Needle at exactly the same time.

Chuck is in the center of a spacecraft moving from the Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above the Smith Tower when the light above the Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.

In Amy's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.

Explain the reasoning you used to answer the question above.

Question 3.

Bob sees the flash above the Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.

Explain the reasoning you used to answer the question above.

Question 5.

In Bob's reference frame, the flash above the Smith Tower occurs:

<https://catalyst.uw.edu/webq/build/tipwo/169075>

1/3

Figure D.4: Catalyst *Simultaneity* pretest version U2DI. (Two pages.)

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- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck sees the flash above the Smith Tower:

- Before he sees the flash above the Space Needle.
- After he sees the flash above the Space Needle.
- At the same time as he sees the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

In Chuck's reference frame, the flash above the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Consider the following two statements about the situation described above. Indicate whether you agree or disagree with each statement.

Rows

In Bob's reference frame, Amy sees both flashes of light at the same time.

In Chuck's reference frame, Amy sees both flashes of light at the same time.

- I agree.
- I disagree.
- Not enough information

Question 12.

Explain the reasoning you used to answer the question above.

Question 13.

Which people/objects are in the same reference frame as the Smith Tower? Check all that apply.

- Amy
- Bob
- Chuck
- Space Needle
- None of these

Question 14.

Explain the reasoning you used to answer the question above.

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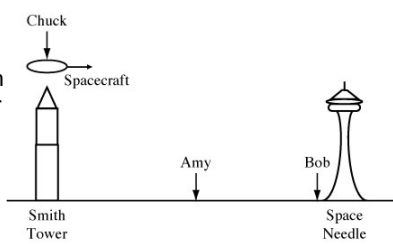
Question 15.

Have you done the homework for the Events and Reference Frames tutorial?

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Print view of '(SIM)U2e'
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Amy is at rest midway between the Smith Tower and the Space Needle, as shown at right. Bob is at rest near the foot of the Space Needle.



Chuck is in the center of a spacecraft moving from the Smith Tower toward the Space Needle at speed $v = 0.8c$ relative to the ground. The spacecraft is directly above the Smith Tower when the light above the Smith Tower flashes.

Assume that all observers have synchronized their clocks with all other observers in their reference frame. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 1.
 Amy is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 2.
 Explain the reasoning you used to answer the question above.

Question 3.
 Bob would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 4.
 Explain the reasoning you used to answer the question above.

Question 5.
<https://catalyst.uw.edu/webq/build/tipwo/168926>

1/3

Figure D.5: Catalyst *Simultaneity* pretest version U2E. (Three pages.)

8/18/2017

Catalyst WebQ

Bob is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 6.

Explain the reasoning you used to answer the question above.

Question 7.

Chuck would see the flash above the Smith Tower:

- Before he would see the flash above the Space Needle.
- After he would see the flash above the Space Needle.
- At the same time as he would see the flash above the Space Needle.
- There is not enough information provided to answer this question.

Question 8.

Explain the reasoning you used to answer the question above.

Question 9.

Chuck is an intelligent observer, and would determine that the flash over the Smith Tower occurs:

- Before the flash above the Space Needle occurs.
- After the flash above the Space Needle occurs.
- At the same time as the flash above the Space Needle occurs.
- There is not enough information provided to answer this question.

Question 10.

Explain the reasoning you used to answer the question above.

Question 11.

Suppose that there is a small firecracker at Amy's feet; the firecracker is designed to explode if wavefronts from the flashes over the Smith Tower and the Space Needle hit it at exactly the same time. If the wavefronts from the two towers hit the firecracker at different times, it does not explode.

Indicate whether each of the intelligent observers (Amy, Bob, and Chuck) would predict that the firecracker explodes.

Rows

Amy predicts

Bob predicts

Chuck predicts

- Firecracker at Amy's feet explodes
- Firecracker at Amy's feet does not explode
- Not enough information

Question 12.

Explain the reasoning you used to answer the question above.

Question 13.

Which people/objects are in the same reference frame as the Smith Tower? Check all that apply.

- Amy
- Bob
- Chuck
- Space Needle
- None of these

Question 14.

Explain the reasoning you used to answer the question above.

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Question 15.

Have you done the homework for the Events and Reference Frames tutorial?

- Yes, completely finished.
- Started, but not finished.
- No, have not started.

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(SIM)U2g(S&L)

Question 2.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

s'

Beth and the beeper as shown in the ground reference frame

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.

Before

Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for frame s' for an instant shortly after Beth has passed the beeper.

1

2

3

4

Picture 1
 Picture 2
 Picture 3
 Picture 4
 None of these

Question 3.

At a later time in frame s' , the beeper has moved 400 meters to the left.

In frame s' , which of the following best describes the location of the event "the beeper beeps" at that later time?

<https://catalyst.uw.edu/webq/preview> 1/3

Figure D.6: Catalyst *Simultaneity* pretest version U2GA. (Four pages.)

8/22/2017

Catalyst WebQ - Preview

- At Beth
- At the beeper
- At a location somewhere between Beth and the beeper

Time remaining: 0:19:57

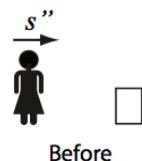
Question 4.

Explain the reasoning you used to answer the question above.

Question 5.

Suppose instead that Beth moves toward a strobe light, in a frame s'' that moves to the right at half the speed of **light** relative to the ground.

The strobe flashes just as Beth passes it. The flash of light moves outward in all directions.



Beth and the strobe as shown in the ground reference frame

From the diagrams in question 1 above, choose the diagram for frame s' for an instant shortly after Beth has passed the strobe light.

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 6.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 7.

Consider the event "the strobe light flashes." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

[<< Previous](#) [Next >>](#)

8/22/2017

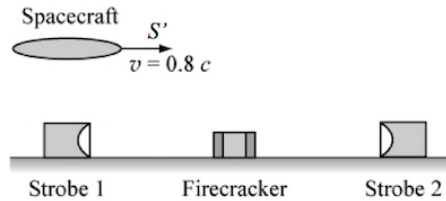
Catalyst WebQ - Preview

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(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 8.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

8/22/2017

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Question 9.

Explain the reasoning you used to answer

Time remaining: 0:19:51

Question 10.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

Question 11.

Explain the reasoning you used to answer the question above.

Question 12.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
- After wavefront from the flash from strobe 2.
- At the same time as the wavefront from the flash from strobe 2.
- It's not possible to determine with the information given.

Question 13.In frame S' , the firecracker:

- Explodes.
- Does not explode.
- There is not enough information provided to answer.

Question 14.

Explain the reasoning you used to answer the question above.

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(SIM)U2g(S&L)

Question 15.

A small beeper sits on the ground on a calm, windless day. Beth is in reference frame s' , which moves to the right at half the speed of **sound** relative to the ground.

Before

Beth and the beeper as shown in the ground reference frame

The beeper beeps at the instant that Beth passes it. The beep emits a sound wave that moves outward in all directions.

Which picture below best shows the locations of Beth, the beeper, and the wavefronts in reference frame s' a short time after Beth has passed the beeper?

Choose the diagram for frame s' for an instant shortly after Beth has passed the beeper.

1

Wavefronts

2

Wavefronts

3

Wavefronts

4

Wavefronts

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 16.

Beth correctly determines the x' -coordinate of the event "the beeper beeps" to be $x'=0$ m.

At a later time, the beeper is 400 meters to the left of Beth. In frame s' , which of the following represents the location of the event "the beeper beeps?"

https://catalyst.uw.edu/webq/preview 1/2

Figure D.7: Catalyst *Simultaneity* pretest version U2GC. (Four pages.)

8/22/2017

Catalyst WebQ - Preview

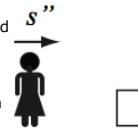
Time remaining: 0:19:57

- $x' = 0$ m
- $x' = 400$ m
- $x' = -400$ m
- There is not enough information provided to answer this question.

Question 17.

Suppose instead that Beth is in frame s'' that moves to the right at half the speed of light relative to the ground.

A spark jumps between Beth and the beeper at the instant she passes it. The spark emits a flash of light that moves outward in all directions.



Beth and the beeper as shown in the ground reference frame

From the diagrams in question 1 above, choose the diagram for frame s'' , for an instant shortly after Beth has passed the beeper.

Before

- Picture 1
- Picture 2
- Picture 3
- Picture 4
- None of these

Question 18.

If you chose the same picture for questions 3 and 1, explain why the picture should be the same for light as for sound.

If you chose a different picture for question 3 than for question 1, explain why the picture should be different for light and sound.

Question 19.

Consider the event "the spark jumps." For each of the frames listed below, indicate the motion of the location of the event.

	Stationary	Moves with half the speed of light to the right	Moves with half the speed of light to the left	None of these correctly describes the event location
Ground frame	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Frame s''	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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Questions or Comments?

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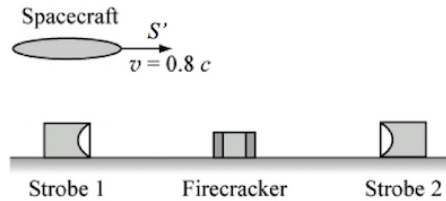
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Time remaining: 0:19:57

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(SIM)U2g(S&L)

A small firecracker lies on the ground exactly halfway between strobe light 1 and strobe light 2, which are each programmed to flash exactly once. The firecracker is designed to explode if and only if it is hit by light from both strobe lights at the same instant.



Ground frame at the instant strobe 1 flashes

An observer in the ground frame notes that the firecracker explodes.

A spacecraft is in reference frame S' that moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above strobe light 1 when strobe light 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Question 20.

In the ground frame, strobe light 1 flashes:

- Before strobe light 2 flashes.
- After strobe light 2 flashes.
- At the same time as strobe light 2 flashes.
- The answer to this question depends on the location of the observer

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Catalyst WebQ - Preview

Question 21.

Explain the reasoning you used to answer

Time remaining: 0:19:57

Question 22.In frame S' , the firecracker:

- Explodes.
 Does not explode.
 There is not enough information provided to answer.

Question 23.

Explain the reasoning you used to answer the question above.

Question 24.In frame S' , the wavefront from the flash from strobe 1 reaches the firecracker:

- Before the wavefront from the flash from strobe 2.
 After wavefront from the flash from strobe 2.
 At the same time as the wavefront from the flash from strobe 2.
 It's not possible to determine with the information given.

Question 25.

Explain the reasoning you used to answer the question above.

Question 26.In frame S' , strobe light 1 flashes:

- Before strobe light 2 flashes.
 After strobe light 2 flashes.
 At the same time as strobe light 2 flashes.
 The answer to this question depends on the location of the observer

Question 27.

Explain the reasoning you used to answer the question above.

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Time remaining: 0:14:56

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(SIM)U4a

A firecracker lies on the ground exactly halfway between flashlight 1 and flashlight 2. The firecracker is designed to explode if it is hit by light from both flashlights at the same instant; it will NOT explode if light from the two flashlights hits it at different instants.

In the firecracker frame, flashlights 1 and 2 flash at exactly the same instant, and the firecracker explodes.

A spacecraft moves to the right with speed $0.8c$ relative to the ground. The spacecraft is directly above flashlight 1 when flashlight 1 flashes.

Assume that all observers are intelligent observers. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Spacecraft

The instant strobe 1 flashes in the reference frame of the firecracker

Question 1.
In the reference frame of the spacecraft, the firecracker:

Required.

Explodes.

Does not explode.

[Next >>](#)

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<https://catalyst.uw.edu/webq/preview> 1/1

Figure D.8: One instance of Catalyst *Simultaneity* pretest version U2GA. Note that text on page 3 depends on answers from pages 1 and 2. (Four pages.)

8/22/2017

Catalyst WebQ - Preview

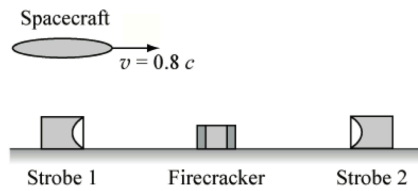
Time remaining: 0:14:55

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(SIM)U4a

Question 2.

Consider again the scenario described on the previous page. The figure is reproduced below for your convenience.



The instant strobe 1 flashes in the reference frame of the firecracker

In the reference frame of the spacecraft, the light from flashlight 1 reaches the firecracker:

Required.

- Before the light from flashlight 2.
- After the light from flashlight 2.
- At the same time as the light from flashlight 2.

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Catalyst WebQ - Preview

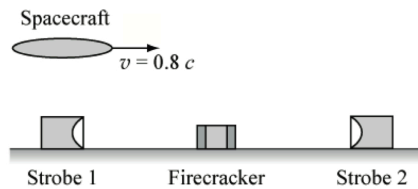
Time remaining: 0:14:55

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(SIM)U4a

Question 3.

Consider again the scenario described on the previous page. The figure is reproduced below for your convenience. Recall that the firecracker explodes **in the reference frame of the firecracker**.



The instant strobe 1 flashes in the reference frame of the firecracker

Consider your responses to the previous two questions about the **spacecraft** frame:

- The firecracker explodes
- The light from flashlight 1 reaches the firecracker before the light from flashlight 2.

Explain how these two answers are consistent with your understanding of special relativity.

[Next >>](#)

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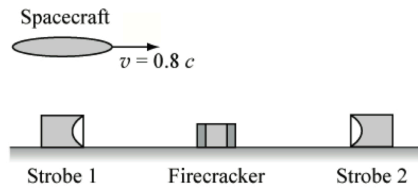
Time remaining: 0:14:58

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(SIM)U4a

Question 10.

Consider again the scenario described on the previous pages. The figure is reproduced below for your convenience. Recall that the flashlights flash simultaneously **in the reference frame of the firecracker**.



The instant strobe 1 flashes in the reference frame of the firecracker

In the reference frame of the spacecraft, flashlight 1 flashes:

- Before flashlight 2 flashes.
- After flashlight 2 flashes.
- At the same time as flashlight 2 flashes.

Question 11.

Explain your answer to the previous question.

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D.2 Exam questions described in Chapter 6

In this section, complete exam questions with portions described in Chapter 6: *Student understanding of causality* are included.

Name _____ Student ID _____ Score _____
last first

III. [20 points total] Ann is at rest exactly midway between Mt. Rainier and Mt. Hood. Ben is at rest near the foot of Mt. Rainier. Mt. Rainier and Mt. Hood erupt at exactly the same time in *Ann's* frame.

Adam is in the center of a spacecraft moving from Mt. Rainier toward Mt. Hood at speed $v = 0.8c$ relative to the ground. Betsy is in the center of a spacecraft that is also moving from Rainier toward Hood at speed $v = 0.8c$ relative to the ground.

The diagram above shows the instant in *Ann's* frame when both volcanoes erupt. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). Treat all observers as intelligent observers.

23. [5 pts] In Ben's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

24. [5 pts] In Adam's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

25. [5 pts] In Betsy's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

26. [5 pts] In Betsy's frame, Ann receives the light from Mt. Rainier

- Before she receives the light from Mt. Hood.
- After she receives the light from Mt. Hood.
- At the same time as she receives the light from Mt. Hood.
- It is impossible to determine from the information given.

Physics 123A, Winter 2010 Final Exam EM-UWA123A101T-EF(ERF.SIM)mc.doc

Figure D.9: Written multiple-choice final examination administered in Spring 2010 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

III. [25 points total] Tutorial Multiple Choice

Alec and Betty are at rest with respect to each other, as shown. Alec stands **midway** between two light sources. Each light source will emit a pulse of light at some time or times in the future.

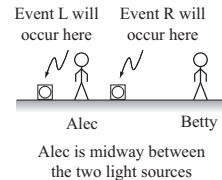
- Let event L be the left source emits a pulse of light.
- Let event R be the right source emits a pulse of light.

Alec decides that if he receives the light pulses simultaneously, he will raise both hands. If he receives the light pulse from the right source first, he will raise only his right hand. If he receives the light pulse from the left source first, he will raise only his left hand.

After the experiment, Alec reports that he raised both hands.

21. [5 pts] In Betty's reference frame, which of the following best describes events L and R?

- Event L occurs before event R.
- Event L occurs after event R.
- Event L occurs at the same instant as event R.
- At least one of the events does not occur.
- One of the events occurs before the other, but there is not enough information to tell which.



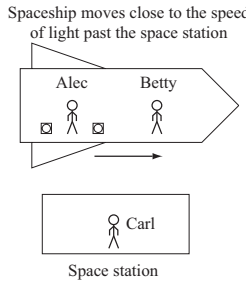
Alec and Betty repeat the experiment on a spaceship that travels near the speed of light to the right as measured from a space station. The light bulbs are set up in exactly the same manner, and Alec decides he will raise his hands as described above.

Carl is at rest on the space station observing the experiment. Alec and Betty are at rest with respect to the spaceship.

After the experiment, Alec reports that he raised both hands.

22. [5 pts] In Betty's reference frame, which of the following best describes events L and R?

- Event L occurs before event R.
- Event L occurs after event R.
- Event L occurs at the same instant as event R.
- At least one of the events does not occur.
- One of the events occurs before the other, but there is not enough information to tell which.



23. [5 pts] In Betty's reference frame, which of the following best describes when Alec receives the two light signals?

- Alec receives light from the left source first.
- Alec receives light from the right source first.
- Alec receives light from both sources simultaneously.
- Alec does not receive light from at least one of the sources.
- Alec receives light from one of the sources before the other, but there is not enough information to tell which.

Physics 123A, Autumn 2010 Final Exam, page 6 WO-UWA123A104T-EF(ERF.SIM)mc.doc

Figure D.10: Written multiple-choice final examination administered in Autumn 2010 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

VII. [20 points total] Holly is at rest exactly midway between Mt. Rainier and Mt. Hood. Adelaide is at rest near the foot of Mt. Rainier.

Jasper is in the center of a spacecraft moving from Mt. Rainier toward Mt. Hood at speed $v = 0.8c$ relative to the ground. Floyd is in the center of a spacecraft that is also moving from Rainier toward Hood at speed $v = 0.8c$ relative to the ground.

In Floyd's frame, he receives light from *both eruptions* at the instant shown. At this instant, he is located exactly halfway between the mountains. Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). Treat all observers as intelligent observers.

27. [5 pts] In Floyd's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

28. [5 pts] In Jasper's frame, the order of the two events (Mt. Rainier erupts and Mt. Hood erupts)

- Is the same as in Mt. Rainier's frame.
- Is the same as in Holly's frame.
- Is the same as in Floyd's frame.
- More than one of the above choices is correct.
- None of the above choices is correct.

29. [5 pts] In Holly's frame, Mt. Rainier erupts

- Before Mt. Hood erupts.
- After Mt. Hood erupts.
- At the same time as Mt. Hood erupts.
- It is impossible to determine from the information given.

30. [5 pts] In Holly's frame, Floyd receives the light from Mt. Rainier

- Before he receives the light from Mt. Hood.
- After he receives the light from Mt. Hood.
- At the same time as he receives the light from Mt. Hood.
- It is impossible to determine from the information given.

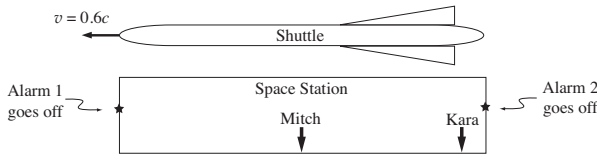
Physics 123C, Spring 2011 Final Exam EM-UWA123C112T-EF(ERF.SIM)mc.doc

Figure D.11: Written multiple-choice final examination administered in Spring 2011 to PHYS 123C.

Name _____ Student ID _____
last first

II. Relativity (continued)

Mitch and Kara are at rest inside a space station. Mitch is exactly at the center; Kara is at the right end. A shuttle is flying from right to left with speed $v = 0.6c$ relative to the station. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Alarms 1 and 2 go off at opposite ends of the space station. Each alarm emits a flash of light (circular wavefronts 1 and 2, respectively). Mitch, an intelligent observer in the reference frame of the space station, receives the light from the two alarms at the same instant and correctly determines that the alarms go off simultaneously in his frame.

The figure shows Mitch, Kara, and the shuttle in the reference frame of the space station at the instant both alarms go off.

11. [5 pts] Would intelligent observer Kara (in the reference frame of the space station) determine that:

- Alarm 1 goes off *before* alarm 2 goes off.
- Alarm 1 goes off *after* alarm 2 goes off.
- Alarm 1 goes off *at the same time* as alarm 2 goes off.
- More information is needed to answer.

12. [5 pts] In the shuttle frame, which of the following correctly describes the order in which Mitch receives wavefronts 1 and 2?

- Wavefront 1 reaches Mitch *before* wavefront 2.
- Wavefront 1 reaches Mitch *after* wavefront 2.
- Wavefront 1 reaches Mitch *at the same time* as wavefront 2.
- More information is needed to answer.

13. [5 pts] In the shuttle frame, the center of wavefront 1:

- moves to the right
- moves to the left
- is stationary
- More information is needed to answer

14. [5 pts] For the shuttle frame, which of the following correctly describes the order in which the alarms go off?

- Alarm 1 goes off *before* alarm 2 goes off.
- Alarm 1 goes off *after* alarm 2 goes off.
- Alarm 1 goes off *at the same time* as alarm 2 goes off.
- More information is needed to answer.

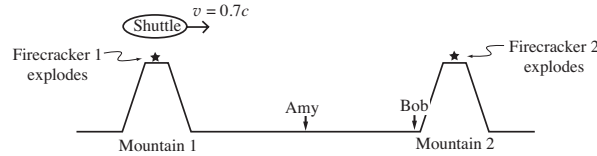
Physics 123A, Spring 2012 Final Exam WO-UWA123A122T-EF(ERF,SIM)

Figure D.12: Written multiple-choice final examination administered in Spring 2012 to PHYS 123A.

Name _____ Student ID _____
last first

II. Relativity (continued)

Amy and Bob are at rest on the ground. Amy is exactly halfway between mountain 1 and mountain 2; Bob is near mountain 2. A shuttle is flying from left to right, with speed $v = 0.7c$ relative to the ground. Assume all motion is along one dimension (*i.e.*, ignore vertical distances).



Firecrackers 1 and 2 explode at the tops of mountains 1 and 2. Each emits a flash of light (circular wavefronts 1 and 2, respectively). Amy, an intelligent observer in the reference frame of the ground, receives the light from the two explosions at the same instant and correctly determines that the explosions are simultaneous in her frame.

The figure shows Amy, Bob, and the shuttle in the reference frame of the ground at the instant both firecrackers explode.

11. [5 pts] Would intelligent observer Bob (in the reference frame of the ground) determine that:
 - A. Firecracker 1 explodes *before* firecracker 2 explodes.
 - B. Firecracker 1 explodes *after* firecracker 2 explodes.
 - C. Firecracker 1 explodes *at the same time* as firecracker 2 explodes.
 - D. More information is needed to answer.
12. [5 pts] In the shuttle frame, which of the following correctly describes the order in which Amy receives wavefronts 1 and 2?
 - A. Wavefront 1 reaches Amy *before* wavefront 2.
 - B. Wavefront 1 reaches Amy *after* wavefront 2.
 - C. Wavefront 1 reaches Amy *at the same time* as wavefront 2.
 - D. More information is needed to answer.
13. [5 pts] In the shuttle frame, the center of wavefront 2:
 - A. moves to the right
 - B. moves to the left
 - C. is stationary
 - D. More information is needed to answer.
14. [5 pts] For the shuttle frame, which of the following correctly describes the order in which the firecrackers explode?
 - A. Firecracker 1 explodes *before* firecracker 2 explodes.
 - B. Firecracker 1 explodes *after* firecracker 2 explodes.
 - C. Firecracker 1 explodes *at the same time* as firecracker 2 explodes.
 - D. More information is needed to answer.

Figure D.13: Written multiple-choice final examination administered in Spring 2012 to PHYS 123C.

Name _____ Student ID _____
last first

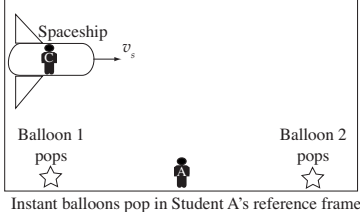
IV. [30 points total]

A spaceship flies in a straight line over a very large field.

- Student A stands in the middle of the field.
- Student B stands at an unknown location in the field.
- Student C stands in the middle of the spaceship.

Balloons 1 and 2 pop at opposite ends of the field. Call event 1 “balloon 1 pops” and event 2 “balloon 2 pops.” **Events 1 and 2 are simultaneous in student A’s reference frame.**

The picture shows student A’s reference frame at the instant the balloons pop. Let v_s be the spaceship’s velocity in student A’s reference frame. Students A, B, and C are intelligent observers.



Instant balloons pop in Student A’s reference frame

23. [5 pts] In student B’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in student B’s reference frame cannot be determined without knowing student B’s location.

24. [5 pts] In student C’s reference frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2.
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in student C’s reference frame cannot be determined without knowing student C’s velocity.

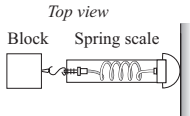
25. [5 pts] Student A **hears** the balloons pop simultaneously in her reference frame. In student C’s frame, student A hears balloon 1 pop:

- Before she hears balloon 2 pop.
- At the same time she hears balloon 2 pop.
- After she hears balloon 2 pop.
- The order cannot be determined without knowing student C’s velocity.

A different spaceship slows down relative to the field as it passes by in a straight line from left to right. Inside the spaceship, a block is attached to a spring scale that is fastened to a wall, as shown. The spring scale reading does not change.

26. [5 pts] In student A’s reference frame, the acceleration of the block is:

- To the right
- To the left
- Zero
- It is impossible to determine the direction of the acceleration of the block in student A’s reference frame.



Physics 123A, Winter 2014 Final Exam WO-UWA123A141T-EF(ERF,SIM,MSI)

Figure D.14: Written multiple-choice final examination administered in Winter 2014 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

IV. [15 points total] Observer A stands at the middle of spaceship A. A strobe light sits at observer A's feet. Observer B stands at the front of spaceship B. The spaceships move past each other at relativistic speed. The strobe light flashes once.

Call event P "observers A and B pass each other" and event S "the strobe light flashes." Events P and S occur simultaneously in the frame of spaceship A. The instant that the events occur in the frame of spaceship A is shown in the figure at right.

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

A. [5 pts] In the frame of spaceship B, does event P occur *before*, *after*, or *at exactly the same time* as event S? Explain.

B. [5 pts] In the frame of spaceship B, does the light from the strobe flash reach the front of spaceship A *before*, *after*, or *at exactly the same time* as the light from the strobe flash reaches the rear of spaceship A? Explain.

C. [5 pts] In the frame of spaceship B at a later time t_1 , observers A and B are separated by a distance of 30 km. In the frame of spaceship B, what is the distance between the location of event S and the location of observer B at time t_1 ? Explain.

The instant the strobe light flashes in the frame of spaceship A

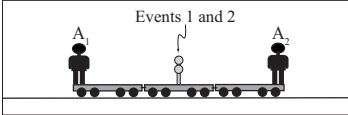
Physics 123A, Winter 2015 Final Exam WO-UWA123A15IT-EF(ERF,SIM).docx

Figure D.15: Written free-response final examination administered in Winter 2015 to PHYS 123A.

Name _____ Student ID _____ Score _____
last first

IV. [15 points total] Two observers, A_1 and A_2 , are standing at the ends of a train moving to the right (relative to the ground) at relativistic speed. Strobe lights 1 and 2, at the center of the train, emit flashes of light simultaneously in the train frame. Call event 1 "strobe light 1 flashes" and event 2 "strobe light 2 flashes." The instant that the strobe lights flash in the train frame is shown in the figure at right.

The instant strobe lights 1 and 2 flash in the train frame



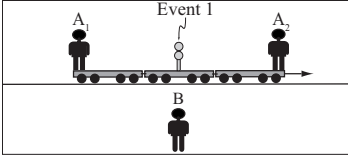
Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

A. [5 pts] In the ground frame, does event 1 occur *before*, *after*, or *at exactly the same time* as event 2? Explain.

B. [5 pts] In the ground frame, does the light from the strobe lights reach observer A_1 *before*, *after*, or *at exactly the same time* as the light from the strobe lights reaches observer A_2 ? Explain.

C. [5 pts] Observer B stands on the ground near the train tracks. In the ground frame, event 1 (strobe light 1 flashes) occurs just as strobe light 1 passes observer B.

The instant event 1 occurs in the ground frame



At a later time t_1 , the train has moved 500 m to the right, relative to the ground. At t_1 in the ground frame, is the location of event 1 *at the strobe*, *at the location of observer B*, or *somewhere between the strobe and observer B*? Explain.

Physics 123B, Winter 2015 Final Exam WO-UWA123B15IT-EF(ERF.SIM).docx

Figure D.16: Written free-response final examination administered in Winter 2015 to PHYS 123B.

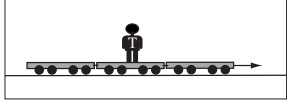
Name _____ UW Net ID _____ Score _____
last first

III. A train moves to the right at relativistic speed relative to the ground. Observer T stands at the middle of the train. Fireflies (not shown) fly in random directions near the track. (A firefly is an insect that can emit flashes of light.)

Call event F “a firefly at the front of the train flashes” and event R “a firefly at the rear of the train flashes.” Observer T receives the light from events F and R simultaneously in the reference frame of the train.

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

Reference frame of the ground
 at an arbitrary time (fireflies not shown)



12. [5 pts] **In the reference frame of the train**, event F occurs

- Before event R
- After event R
- At exactly the same time as event R
- The order of the events is different for different observers in the reference frame of the train

13. [5 pts] **In the reference frame of the ground**, observer T receives the light from the event F

- Before the light from event R
- After the light from event R
- At exactly the same time as the light from event R
- The order of light reception in the reference frame of the ground cannot be determined for an observer in the reference frame in the train because the fireflies are in neither the reference frame of the train nor the reference frame of the ground

14. [5 pts] **In the reference frame of the ground**, event F occurs

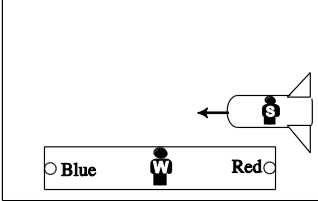
- Before event R
- After event R
- At the same time as event R
- This cannot be determined in the ground frame with the information given

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Figure D.18: Written multiple-choice final examination administered in Spring 2015 to PHYS 123C.

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IV. Two colored lights are placed at the ends of a warehouse.
 Observer W stands at the middle of the warehouse and *sees the light from the red and blue flashes simultaneously* in the reference frame of the warehouse.
 Observer S stands in the center of a spaceship that moves from right to left at relativistic speeds relative to the ground. Observer S is directly over the red light when it flashes.
 Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). **Ignore any color changes due to the Doppler effect.**



**Reference frame of the warehouse
 at the instant the red light flashes**

25. [5 pts] Consider whether each of the items listed below is an event as defined in the tutorial *Events and reference frames*.

- (i) The red light flashes
- (ii) Observer W sees the red flash

A. Both (i) and (ii) are events
 B. Neither (i) nor (ii) is an event
 C. (i) is an event but (ii) is not an event
 D. (ii) is an event but (i) is not an event

26. [5 pts] **In the reference frame of the spaceship**, observer W sees the red flash

- A. Before the blue flash
- B. After the blue flash
- C. At exactly the same time as the blue flash
- D. The order of light reception for an observer in the reference frame of the warehouse cannot be determined in the reference frame of the spaceship because the lights are in the reference frame of the warehouse

27. [5 pts] **In the reference frame of the spaceship**, the red light flashes

- A. Before the blue light flashes
- B. After the blue light flashes
- C. At the same time that the blue light flashes
- D. The lights flash at different times in the reference frame of the ground, but not enough information has been provided to determine the order

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Figure D.19: Written multiple-choice final examination administered in Autumn 2015 to PHYS 123A.

Name _____ Student ID _____
last first

III. Special Relativity, continued (tutorial)

A train moves with relativistic speed from left to right.

- Student R stands at rest on the train at the rear of the train.
- Student F stands at rest on the train at the front of the train.

Strobe lights 1 and 2, at the center of the train, emit flashes of light simultaneously in the reference frame of the train. Call event 1 “strobe light 1 flashes” and event 2 “strobe light 2 flashes.” Students R and F receive the light from event 1 simultaneously. The instant that the strobe lights flash in the train frame is shown in the figure above.

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances).

15. [5 pts] Consider whether each of the items below can be considered **a single event** as defined in the tutorial *Events and reference frames*.

- Events 1 and 2 occur simultaneously in the train frame.
- Student R receives the light from event 1.

- Both (i) and (ii) are events
- Neither (i) nor (ii) is an event
- (i) is an event but (ii) is not an event
- (ii) is an event but (i) is not an event

16. [5 pts] In the ground frame:

- Event 1 occurs *before* event 2.
- Event 1 occurs *after* event 2
- Event 1 occurs *at the same time* that event 2 occurs.
- The order of events in the ground frame cannot be determined with the information provided.

17. [5 pts] In the ground frame:

- Student R receives the light from event 1 *before* student F receives the light from event 1.
- Student R receives the light from event 1 *after* student F receives the light from event 1.
- Student R receives the light from event 1 *at the same time as* student F receives the light from event 1.
- The order of reception of the light signals by students R and F cannot be determined in the ground frame.

The instant strobe lights 1 and 2 flash in the train frame

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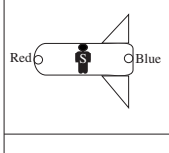
Figure D.20: Written multiple-choice final examination administered in Spring 2016 to PHYS 123A.

Name _____ Student ID _____
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III. Special Relativity, continued (tutorial)

[15 points total] Two colored lights are placed on a spaceship, one at each end.

The spaceship moves to the left at relativistic speed relative to the ground. The two lights flash simultaneously in the reference frame of the spaceship. Observer S stands at the middle of the spaceship and receives the light from the flashes simultaneously in the frame of the spaceship.



Reference frame of the spaceship at the instant observer S receives the red and blue flashes

Treat all motions as being along one dimension (*i.e.*, ignore vertical distances). **Ignore any color changes due to the Doppler effect.**

12. [5 pts] Consider whether each of the items below can be treated as **a single event** as defined in the tutorial *Events and reference frames*.

- (i) The red and blue lights flash simultaneously in the reference frame of the spaceship
- (ii) Observer S receives the light from the flashes simultaneously in the spaceship frame

A. Both (i) and (ii) are events
 B. Neither (i) nor (ii) is an event
 C. (i) is an event but (ii) is not an event
 D. (ii) is an event but (i) is not an event

13. [5 pts] **In the reference frame of the ground**, observer S receives the red flash

- A. before the blue flash
- B. after the blue flash
- C. at exactly the same time as the blue flash
- D. The order of light reception in the reference frame of the ground cannot be determined for an observer in the spaceship because the lights are in reference frame of the spaceship

14. [5 pts] **In the reference frame of the ground**, the red light flashes

- A. before the blue light flashes
- B. after the blue light flashes
- C. at the same time that the blue light flashes
- D. The lights flash at different times in the reference frame of the ground, but not enough information has been provided to determine the order

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Figure D.21: Written multiple-choice final examination administered in Spring 2016 to PHYS 123C.

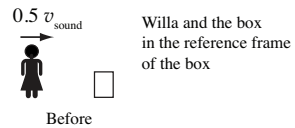
Name _____ Student ID _____
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III. Tutorial, continued

A small box sits on the ground on a calm, windless day. Willa moves to the right at half the speed of sound relative to the ground, as shown in the figure at right.

The box beeps four times as Willa approaches and passes it. The second beep is emitted at the instant that Willa passes the box. The beep produces a sound wave that moves outward in all directions. Call “the box beeps for the second time” event B_2 . Willa passes the box at spacetime coordinate $(x, t) = (0 \text{ m}, 0 \text{ s})$ in her frame.

27. [7 pts] Which picture below shows the location of Willa, the location and velocity of the box, and the locations of the wavefronts from the second beep in Willa’s reference frame a short time after Willa has passed the box?



0.5 v_{sound}
 Willa and the box in the reference frame of the box

Before

1
 Wavefronts from beep 2

2
 Wavefronts from beep 2

3
 Wavefronts from beep 2

4
 Wavefronts from beep 2

A. Picture 1
 B. Picture 2
 C. Picture 3
 D. Picture 4
 E. None of these

28. [7 pts] Four seconds after Willa passes the box, the box emits the fourth beep. Call “the box beeps for the fourth time” event B_4 . What is $\delta x_{24}^{(\text{Willa})}$, the distance between events B_2 and B_4 in Willa’s reference frame?

A. $\delta x_{24}^{(\text{Willa})} = 0 \text{ m}$
 B. $\delta x_{24}^{(\text{Willa})} = 343 \text{ m}$
 C. $\delta x_{24}^{(\text{Willa})} = 686 \text{ m}$
 D. $\delta x_{24}^{(\text{Willa})} = 1372 \text{ m}$
 E. None of these

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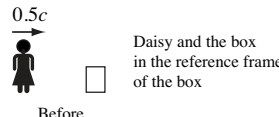
Figure D.22: Written multiple-choice final examination administered in Autumn 2016 to PHYS 123A.

Name _____ Student ID _____
last first

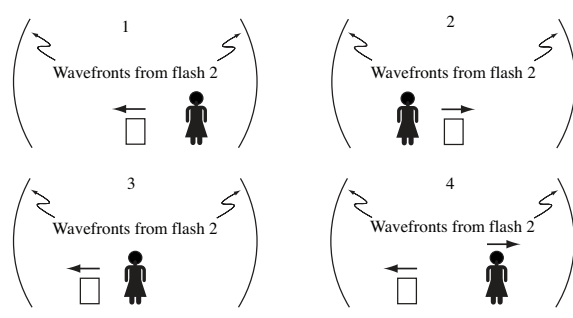
III. Tutorial, continued

A small box sits on the ground. Daisy moves to the right at half the speed of light relative to the ground, as shown in the figure at right.

The box emits four flashes of light as Daisy approaches and passes it. The second flash is emitted at the instant that Daisy passes the box. The flash produces a light wave that moves outward in all directions. Call “the box flashes for the second time” event F_2 . Daisy passes the box at spacetime coordinate $(x', t') = (0 \text{ m}, 0 \text{ s})$ in her frame.



27. [7 pts] Which picture below shows the location of Daisy, the location and velocity of the box, and the locations of the wavefronts from the second flash in Daisy’s reference frame a short time after Daisy has passed the box?



A. Picture 1
 B. Picture 2
 C. Picture 3
 D. Picture 4
 E. None of these

28. [7 pts] In Daisy’s reference frame, which of the below correctly describes the motion of the location of the event F_2 ?

A. Stationary
 B. Moves with half the speed of light to the right
 C. Moves with half the speed of light to the left
 D. None of above

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Figure D.23: Written multiple-choice final examination administered in Autumn 2016 to PHYS 123B.

VITA

Alexis Olsho grew up (mostly) in Seattle, Washington. She received her first Bachelor's degree in applied mathematics from Oberlin College in 2001. In 2003, she enrolled in a Specialty Desserts and Breads program at Seattle Central Community College to learn to bake on a large scale. Two years of working graveyard shift in a bakery was enough to convince her to go back to school as a postbac in physics at the University of Washington, with the eventual goal of a Ph.D. She received her Bachelor's degree in physics in 2010. Three days after marrying her husband Jason in 2010, she began the University of Washington's Ph.D. program in physics. She gave birth to her older daughter, Daisy, in 2013. Her younger daughter, Willa, was born 3 years later in 2016. In 2017 she earned a Doctor of Philosophy in physics.