

**Discovering the Parameters of Sound Creation:  
Physics Informed String Pedagogy**

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## **Abstract**

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For more than a century physicists have worked to understand how the bowed string functions. In the past decade studies have become increasingly detailed through computer modeling and mechanical bowing machines. The goal of the present study is to synthesize the physical realities of sound creation to generate models for teaching and learning stringed instruments. Through understanding the main factors of bow-bridge distance, velocity, and force and exploring the outer reaches of acceptable playing conditions, the string player may utilize the widest set of sounds to achieve their technical and artistic goals.

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## Introduction

The timbre and mechanism of stringed instruments has long puzzled both scientists and musicians. Even among present day scholars the intricacies of bowed string physics are debated. Of course, understanding the physics behind sound creation is not a prerequisite for teaching or performing at a high level—most of the great violinists don't cognitively know the details of how sound is created on the violin. However, it is clear that these performers inherently understand the sound, sensation, and control of the physical realities that allow for the creation of their musical ideas.

My goal is to highlight the practical physics occurring when producing a sound on a bowed string instrument. Although the bow/string interaction is by no means the only consideration for a violinist, the bow's ability to create vibrations on the string and control volume and harmonic content is at the very core of the unique sound of the violin. In terms of scope, I will primarily focus on this fundamental interaction—what directly controls the creation of sound and how we may utilize this knowledge in both performance and teaching. The mechanics of the violin's resonance, the reason for the tone of great instruments and bows, and the myriad intricacies of the left hand will not be discussed. Rather, I hope to present the details behind how the player controls sound through the bow/string interaction and discuss methods for gaining both a mental and kinesthetic understanding of these facts.

## Chapter 1: The Physics of the Bowed String

The bowed string is unique in both the mechanism of vibration and the resulting sound. On an instrument such as the piano, harp, or guitar, the energy and overall volume of sound dissipates rapidly after the initial strike or pluck. However, everything changes with the bowed string: sustaining, altering, and even increasing the string's vibration over time is possible. Due to microscopic variables and endless variations of resulting timbre, bowed string instruments are often shrouded in mystery. Fortunately, research for more than a century has shown that sound and timbre are controlled on the violin by only a few primary factors. Managing these factors and leveraging their potential is paramount for the string player.

The mechanism behind the violin's timbre is a distinctive string vibration. German scientist Hermann Von Helmholtz was the first to view and describe this unique vibration, which has since become known as the Helmholtz motion.<sup>1</sup> After executing an ingenious experiment using a vibrating microscope in 1877, Helmholtz discovered that the bowed string did not vibrate as a plucked string, but rather as a kink or corner rotating around the string. It has since been shown that nearly all sounds produced on a bowed string are a result of the shape, amplitude, and periodicity of the Helmholtz motion. Not only can the string player create a sustained sound through this motion, but she may also variegate the harmonic spectrum through sharpening or softening the rotating corner's shape. Everything from initial attacks, modification of volume and timbre, and non-traditional

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<sup>1</sup> Neville Fletcher and Thomas Rossing, *The Physics of Musical Instruments*, 2nd ed. (New York: Springer, 1998), 46.

sounds, such as *sul ponticello* (bowed near the bridge) are created via changing the Helmholtz motion.

Although the plucked string has two corners moving in opposite directions, the bowed string only has only one corner, once the vibration pattern has been established.<sup>2</sup> Much like pulling the string aside with a finger, when the bow moves across the string it carries the string in the direction of its travel, dividing the string into two straight lines. This is possible through friction created by the adhesive and abrasive properties of the rosin and bow hair, the bow's weight, and any applied force. Eventually, the bow drags the string laterally to a point where the restoring force of the string overcomes the static friction and the string is released from the bow. Much like a spring recoiling, the string moves rapidly in the opposite direction of the bow (see Figure 1.1). When this occurs the corner created by the two straight lines is released from the contact point of the bow and begins its journey around the string, first traveling towards the bridge.<sup>3</sup> In actuality, two corners are released, one moving towards the bridge and one towards the nut; however, the corner that moves towards the bridge first is the only corner that will be sustained.<sup>4</sup>

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<sup>2</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 42.

<sup>3</sup> Lothar Cremer, *The Physics of the Violin* (Cambridge, Mass.: MIT Press, 1984), 43.

<sup>4</sup> John C. Schelleng, "The Physics of the Bowed String." *Scientific American* 230, no. 1 (1974): 89.

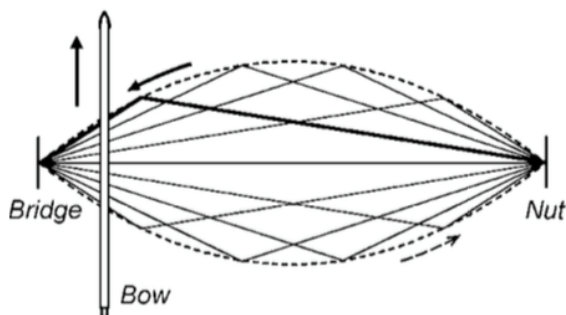


Figure 1.1: The Helmholtz Motion<sup>5</sup>

Once the corner is reflected off the bridge, the static friction of the bow catches the rebounding string, pulling the string once again in the direction of the bow. Meanwhile, the corner continues traveling around the string and is reflected back by the nut. If all of the physical parameters are within the correct margins, the corner returns to the point of contact just in time for the bow to release the string again (see Figure 1.2).<sup>6</sup> In the steady state Helmholtz motion the returning corner assists in knocking the string loose of the static friction of the bow, releasing the corner for another cycle.<sup>7</sup> Since the sustained corner always travels towards the bridge after the slip, the direction of rotation of the Helmholtz depends on the direction of the bow: clockwise for the down-bow, and counter-clockwise for the up-bow.<sup>8</sup> Unlike Figures 1.1 and 1.2, in real playing conditions, the rotating corner is

<sup>5</sup> Knut Guettler, "Looking at starting transients and tone coloring of the bowed string," *Journal of ITC Sangeet Research Academy*, Vol. 18, 61.

<sup>6</sup> Ian D. Johnston, *Measured Tones: The Interplay of Physics and Music*, 2nd ed. (Bristol; Philadelphia: Institute of Physics Pub., 2002), 120.

<sup>7</sup> John S. Rigden, *Physics and the Sound of Music*, 2nd ed. (New York: J. Wiley, 1985), 129.

<sup>8</sup> John C. Schelleng, "The Physics of the Bowed String," *Scientific American* 230, no. 1 (1974): 71.

not a true right angle; instead, the corner is rounded to various extents due to energy loss to the bridge and string stiffness.<sup>9</sup>

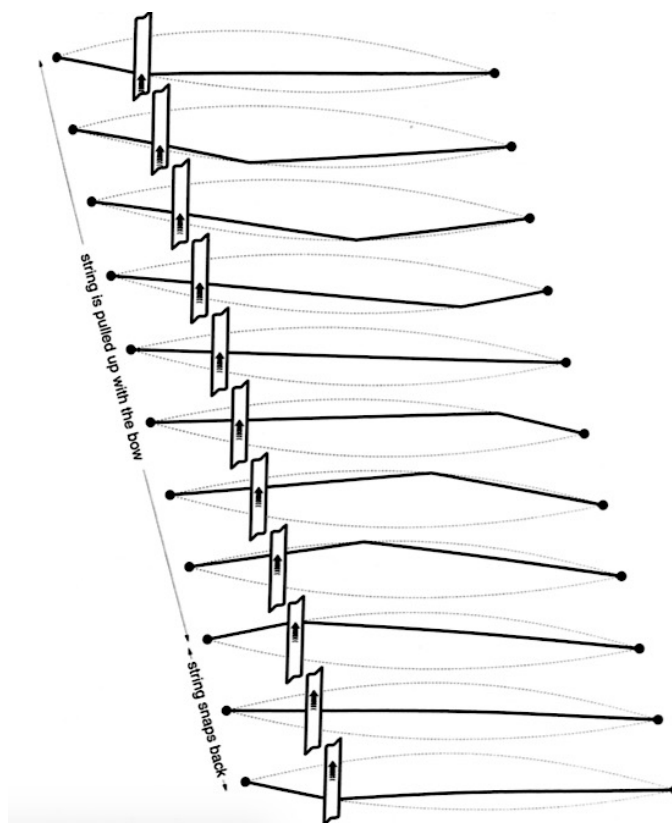


Figure 1.2: Rotating corner<sup>10</sup>

Frictional has central importance for sustaining the Helmholtz protocol. In particular, the stick/slip mechanism is understood through the relationship between static and dynamic (or sliding) friction. Static friction occurs between two stationary objects and dynamic friction describes the friction between two moving objects. Static friction has larger coefficients compared to dynamic friction.<sup>11</sup> A common example of frictional force is experienced when moving furniture. In order to slide a couch, one must overcome the static friction due to the gravitational force holding the couch against the floor. The initial

<sup>9</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 280.

<sup>10</sup> Johnston, *Measured Tones*, 121.

<sup>11</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 49.

applied force needed to start the couch sliding is greater than the force needed to keep the couch in motion.<sup>12</sup> Another example of the slip/stick mechanism is the resulting squeal from slamming on the brakes in a car. The tires, which are no longer rotating, alternate rapidly between sticking to the pavement and slipping, the latter of which causes the squealing sound.

Likewise, the vibration of the bowed string is sustained by this alternation between the bow hair sticking and slipping on the string. Due to static friction the bow carries the string in the direction of the bow's movement. Eventually the restoring force of the string is greater than the friction created by the bow and the string slips under the bow. Since the sliding friction coefficient is less than that of static friction, the string moves contrary to the bow's motion at a much greater velocity. After the corner has been reflected off the bridge, as it reaches the point of contact the bow once again sticks to the string with static friction, carrying the string in the direction of the bow.

The lateral velocity of the string being pulled forward by the bow is relatively slow, however, when the string slips underneath the bow and rebounds in the opposite direction it moves up to 19 times faster.<sup>13</sup> The farther the string is carried away from its normal straight line the greater the restoring force and larger the amplitude of the string, supplying more energy to the bridge.<sup>14</sup> Although minimal, in order to keep a constant tone

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<sup>12</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 49.

<sup>13</sup> John C. Schelleng, "The Bowed String and the Player," *The Journal of the Acoustical Society of America* 53 (1973): 28, doi: 10.1121/1.1913322.

<sup>14</sup> Johnston, *Measured Tones*, 120.

the energy input into the string must be at least enough to replace the energy lost to the bridge.<sup>15</sup>

The successful Helmholtz motion is periodic and the frequency is determined by the lowest mode of the string.<sup>16</sup> For example, when playing an A 440Hz, the corner makes 440 cycles per second. The string also vibrates at each of the regular harmonic series—in fact the bowed string excites all of strings' modes simultaneously.<sup>17</sup> The tone of the violin may sound stable, but the unique and rich timbre is created by constant fluctuations in the harmonic spectrum.<sup>18</sup> With more upper partials or stronger upper partials, the tone is more brilliant and rich. Conversely, sounds with fewer or weaker partials sound more dull, flat or cold. Although the timbre is partially constrained by the instrument, the player also has significant control over the timbre.

At the basic level, the Helmholtz motion must be sustained in order to create a stable sound on a stringed instrument. Beyond this, the relative sharpness or rounding of the rotating corner determines the tone color and harmonic spectrum.<sup>19</sup> There are three main parameters that must be considered in order to sustain the Helmholtz motion—the distance the bow is placed relative to the bridge (hereafter called the bow-bridge distance), force, and velocity. These parameters are inextricably linked and interrelated for the creation and sustaining of the Helmholtz corner. When any two parameters are given, the

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<sup>15</sup> James Beament, *The Violin Explained: Components, Mechanism, and Sound* (Oxford; New York: Oxford University Press, 2000), 16.

<sup>16</sup> Anders Askenfelt, "Measurement of the bow motion and bow force in violin playing," *Journal of the Acoustical Society of America* 80 No. 4 (1986), 1007.

<sup>17</sup> Bernard Richardson, "The physics of the violin," in *The Cambridge Companion to the Violin*, ed. Robin Stowell (Cambridge University Press, 1992), 34.

<sup>18</sup> Tol Halmrast et al. "Gesture and Timbre," in *Musical Gestures: Sound, Movement, and Meaning* ed. Rolf Inge Godoy and Marc Leman (New York; London: Routledge, 2010), 185.

<sup>19</sup> Guettler, "Starting Transients," 61.

third must fall into a particular range otherwise the periodic motion will fail. For example, for each bow-bridge and velocity combination, there is a minimum and maximum bow force limit that will create a steady Helmholtz motion. Outside of these limits of force the resulting sound will be filled with crunches, squeaks, and irregular overtones. Fortunately, the Helmholtz motion is effectively self-stabilizing—it is the string player’s role to allow for the correct range of conditions so that the motion stabilizes.<sup>20</sup>

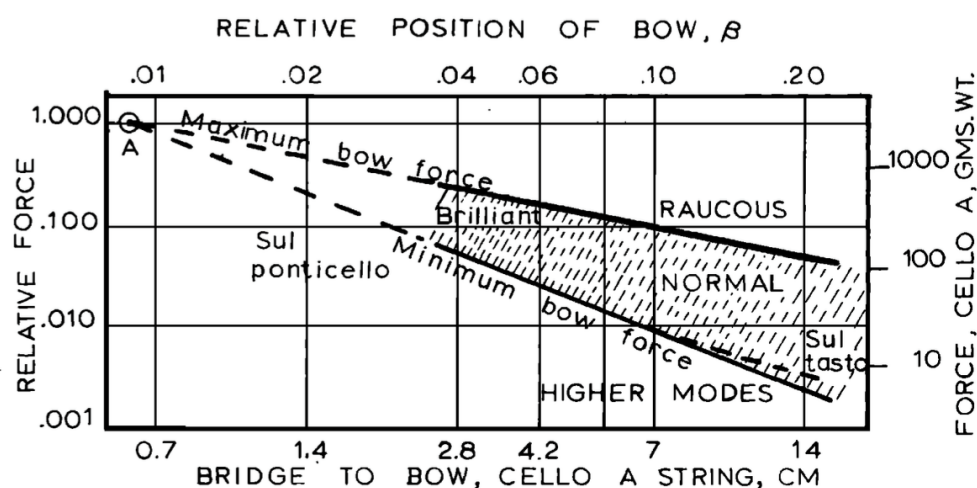


Figure 1.3: Schelleng Diagram<sup>21</sup>

### Schelleng Diagram

In 1973 John Schelleng published a detailed article noting empirical data defining the maximum and minimum limits for the main bowing parameters.<sup>22</sup> In the article he included an important graph that has become known as the Schelleng Diagram (see Figure 1.3). Using a mechanical bowing machine with a given speed of 20cm/s, he determined the

<sup>20</sup> Beament, *Violin Explained*, 16.

<sup>21</sup> Schelleng, "String and the Player," 31.

<sup>22</sup> Ibid.

minimum and maximum bow force limits for sounding points between  $1/100^{\text{th}}$  and  $1/5^{\text{th}}$  the relative distance of the string. As is clear from the diagram, the closer to the bridge the bow is placed, the narrower the distance between upper and lower bow force limits. When the bow is farther away from the bridge there is a greater margin of error for creating an acceptable tone, the tradeoff being that maximum bow force is lessened, diminishing the potential for harmonic richness. Although Schelleng's diagram is based off data from a cello D string, the relative force and bow-bridge distance values for the violin and viola are similar. The actual force coefficients on the violin are lower by a factor of 2.5.<sup>23</sup>

### **A closer look at the main parameters**

#### **I. Bow-Bridge distance**

The first crucial parameter for sound creation on the bowed string is the bow-bridge distance. The bow-bridge distance may influence both the amplitude of the vibrations and the relative sharpness of the rotating corner.<sup>24</sup> Theoretically the bow might be placed anywhere on the string in order to make a sound, but in normal playing conditions the bow generally makes contact with the string between  $1/50^{\text{th}}$  the string length and  $1/5^{\text{th}}$  the string length from the bridge.<sup>25</sup> By changing the bow-bridge distance the volume may change considerably. With a constant speed and force, moving the bow from a point 6mm from the bridge to 66mm from the bridge can make a dynamic change of 20 decibels.<sup>26</sup> By

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<sup>23</sup> Schelleng, "String and the Player," 32.

<sup>24</sup> Murray Campbell et al., *Musical Instruments: History, Technology, and Performance of Instruments of Western Music* (Oxford; New York: Oxford University Press, 2004), 235.

<sup>25</sup> Anders Askenfelt, "Measurement of the Bowing Parameters in Violin Playing. II: Bow-bridge Distance, Dynamic Range, and Limits of Bow Force," *Journal of the Acoustical Society of America* 86, no. 2 (1989): 504, doi: 10.1121/1.398230.

<sup>26</sup> Askenfelt, "Measurement in Violin Playing," 504.

comparison, the average difference measured between *pianissimo* and *fortissimo* on the violin is about 15dB and generally there is a maximum span of 31dB.<sup>27</sup> Simply by manipulating the sounding point, the performer may cover the majority of the dynamic range.

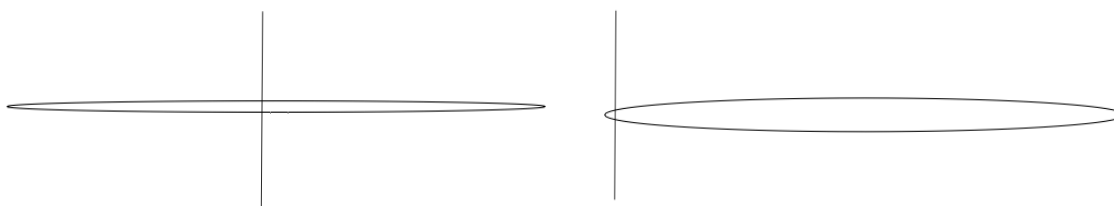


Figure 1.4: Amplitude of vibration and bow position

Due to the constraints of the lateral velocity of the bow and string, as well as the pitch of the note, the string is carried the same distance by the bow.<sup>28</sup> As illustrated in Figure 1.4, when the bow is placed at the midpoint of the string between the bridge and the nut, the amplitude may only be the total distance the bow can carry the string. As the bow is moved closer to the end of the string, the resulting vibration may be much larger than the distance the bow can actually carry the string. In addition to the amplitude of the vibration, bow-bridge distance also influences harmonic content. When the bow is placed at a position closer to the bridge, the angle of the corner is more pronounced, resulting in stronger and more abundant upper harmonics.<sup>29</sup>

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<sup>27</sup> Askenfelt, "Measurement in Violin Playing," 507.

<sup>28</sup> Ibid.

<sup>29</sup> Askenfelt, "Bow Force," 1007.

## II. Velocity

The second main parameter is velocity. The speed of the bow is largely responsible for the overall size of the amplitude. In fact, the excursion of the string is directly proportional to bow velocity.<sup>30</sup> With a given force and bow-bridge distance, increasing the velocity will cause a larger vibration, raising the volume by up to 23dB.<sup>31</sup> Although higher velocity increases the amplitude of the string, the resulting sound has fewer harmonics and a duller timbre.<sup>32</sup> The diminished harmonic content is due to longer slip intervals between the bow and string.<sup>33</sup> Conversely, when the velocity is reduced, the harmonic content will increase. As an example, slowing the bow speed from 10 to 3 centimeters per second increases harmonics 16-65 by an average of 5.2 decibels.<sup>34</sup> These spectral changes are evident simply by lowering bow speed, not through increased force. This effect was also seen when slowing the speed from 30-10 cm/s, but the difference in the upper partials was limited to an average of .2 dB.

Recently, Schoonderwaldt et al. used a sophisticated computer controlled bowing machine to examine Schelleng's work and also add a variable bow speed of 5, 10, 15, 20 cm/s on the violin.<sup>35</sup> Generally, Schelleng's predictions were consistent with their findings; however, the variance of velocity and differing strings made noticeable differences. The study clearly shows that lowering the bow speed creates a higher relative bow force.

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<sup>30</sup> Askenfelt, "Bow Force," 1007.

<sup>31</sup> Askenfelt, "Measurement in Violin Playing," 515.

<sup>32</sup> Knut Guettler, Erwin Schoonderwaldt, and Anders Askenfelt, "Bow Speed or Bowing Position—Which One Influences Spectrum the Most?" (paper presented at Stockholm Music Acoustics Conference, Stockholm, Sweden, August 6-9, 2003,) 2, <http://www.knutsacoustics.com/files/Bow-speed-or-bowing-position-SMAC03.pdf>.

<sup>33</sup> Guettler, "Closer Look," 13.

<sup>34</sup> Guettler, "Starting Transients," 4.

<sup>35</sup> Schoonderwaldt et al., "Empirical Investigation," 610.

However, with a higher velocity, the acceptable playing region is increased—primarily as a result of the upper force limit being raised since the the lower force limit stayed virtually constant.<sup>36</sup>

### III. Force

The final main parameter central to sustaining the Helmholtz motion is force. The relative sharpness of the rotating Helmholtz corner and the resulting harmonic content is largely controlled by force. This force comes from a variety of sources including applied force from the musician, gravitational force from the bow's weight and leverage, and normal force. When an additional downward force is applied to the bow, the bow hair and string are brought into closer contact, resulting in greater frictional force. With position and speed given, the force generally may not exceed ten times the minimum force.<sup>37</sup> Theoretically, there is a point very near to the bridge where the maximum and the minimum bow force are the same; however, the required invariable force for that bow-bridge distance is impossible in real playing conditions. As the bow is moved farther from the bridge the minimum and maximum force diverge, allowing for a greater range of acceptable force. For instance, at around 1/100<sup>th</sup> the cello string length from the bridge, the range of force is very narrow and requires a force of over 1000 grams of weight. But at a distance of 1/5<sup>th</sup> string length from the bridge, the range of force is from about 100 grams to 5 grams.<sup>38</sup>

If the force is too great for a particular speed and sounding point, the sound will become coarse. The bow holds the string too long for the regular release of the corner,

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<sup>36</sup> Schoonderwaldt et al., "Empirical Investigation," 610.

<sup>37</sup> Schelleng, "Physics of the Bowed," 74.

<sup>38</sup> Schelleng, "String and the Player," 31.

resulting in irregular slips and extra noise components.<sup>39</sup> With insufficient force, the bow will not carry the string far enough to start the Helmholtz and the string may slip two or three times per cycle, starting multiple unsustainable corners.<sup>40</sup> This causes a marked difference in the tone, often described as surface sound. If the second slip happens exactly at the midway point of the Helmholtz phase it may produce a sound an octave higher.<sup>41</sup> When force below minimum is used, an audible sound may still occur, but the second harmonic (or higher) will be emphasized over the fundamental.<sup>42</sup>

Increasing the force influences the spectral content greatly since the corner is sharpened each time it is pulled forward by the bow—the farther the string is pulled, the sharper the corner, particularly increasing upper partials 5-17.<sup>43</sup> The higher spectral content may only provide about two decibels to the overall volume, but the ear perceives the brighter sounding tones as louder, creating the impression of a larger dynamic difference.<sup>44</sup> String stiffness and loss of energy to the bridge rounds the Helmholtz corner every cycle, but the bow re-sharpens this corner each time it passes.

Although relative values remain similar for all stringed instruments, each string may have slightly different force values.<sup>45</sup> Compared to the D string on the violin, the upper and lower bow force limits for the E string are both lower: the upper limit is 19% lower and the

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<sup>39</sup> Schoonderwaldt et al., “An Empirical Investigation of Bow-Force Limits in the Schelleng Diagram,” *Acta Acustica United with Acustica* Vol. 94 (2008), 604. doi: 10.3813/AAA.918070.

<sup>40</sup> Richardson, “Physics of the Violin,” 35.

<sup>41</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 278.

<sup>42</sup> *Ibid.*, 280.

<sup>43</sup> Knut Guettler, “A closer look at the string player's bowing gestures,” *Catgut Acoustical Society Journal* Vol. 4 No. 7(II), 13, [http://knutsacoustics.com/files/guettler\\_gestures0317.pdf](http://knutsacoustics.com/files/guettler_gestures0317.pdf).

<sup>44</sup> Tol Halmrast et al., “Gesture and Timbre,” 198.

<sup>45</sup> Schoonderwaldt et al., “An Empirical Investigation,” 613.

lower limit is 64% lower.<sup>46</sup> This is due to the torsional difference between the gut or synthetic core of the D and the solid steel E string. In addition, the upper bow force limit is proportional to the velocity of the bow, even though the lower limit is virtually unaffected by bow velocity.<sup>47</sup> Thus, choice of force when near the lower force limits has little to do with the velocity of the bow. As might be expected, the delineated lines from the Schelleng diagram have grey areas, where the transition from a periodic Helmholtz motion to irregular motion is difficult to distinguish.<sup>48</sup>

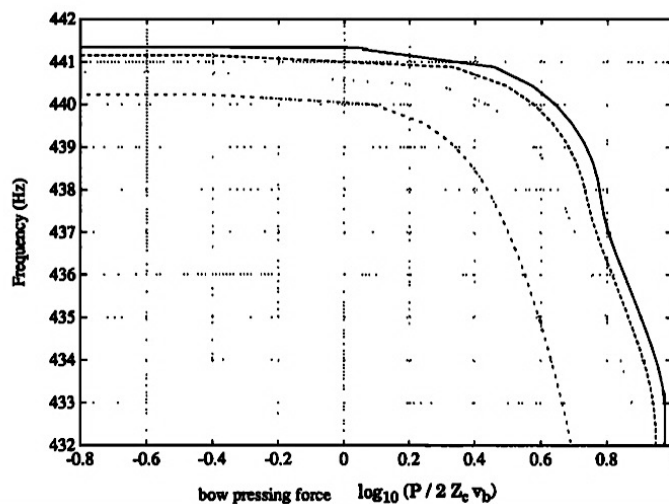


Figure 1.5: Pitch flattening<sup>49</sup>

With excessive force there may also be flattening of the pitch due to an extra “jump” at the release of the stick-slip causing a slight delay in the Helmholtz period.<sup>50</sup> For pitch flattening, the excess force does not cause a raucous sound due to the irregular release of

<sup>46</sup> Schoonderwaldt et al., “Empirical Investigation,” 613.

<sup>47</sup> Ibid., 614.

<sup>48</sup> Schoonderwaldt et al., “Empirical Investigation,” 621.

<sup>49</sup> Askenfelt, “Bow Force,” 1007.

<sup>50</sup> Xavier Boutillon, “Analytical Investigation of the Flattening Effect: The Reactive Power Balance Rule,” *Journal of the Acoustical Society of America* 90, no. 2 (1991): 755, doi: 10.1121/1.401945.

corners, but it generates too much energy, some of which must be absorbed by the string, resulting in a flattened pitch.<sup>51</sup> With pitch flattening an A440 Hz may drop as much as 7 cents to 433 Hz (see Figure 1.5).<sup>52</sup> This effect is particularly noticeable at low velocities, higher positions, and on thicker strings such as the G string.<sup>53</sup> It is interesting to note that pitch may rise as harmonic content gets richer—one study noted a rise from 440Hz to 441.3Hz when an “A” had increased upper harmonics.<sup>54</sup>

Unfortunately, it is impossible to completely isolate each parameter since they are all interdependent. For instance, the amplitude of the vibration is inversely proportional to the distance the bow is placed from the bridge (closer to farther).<sup>55</sup> The farther away from the bridge the bow moves, the greater the range for acceptable force and to some extent velocity. As the bow is brought near to the bridge, the variance of acceptable force is greatly limited—the force values must be increased and be more exacting. Ultimately, the return for the more risky set of parameters is a greater number of harmonics and brilliance of sound.

## **Secondary Parameters**

### **I. Bow position**

Beyond the basic task of sustaining a periodic Helmholtz motion, bow position, or the part of the bow in which the player chooses to play, has significant physical ramifications. Due to constantly changing force values when playing from the frog to the

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<sup>51</sup> Boutillon, “Analytical Investigation,” 756.

<sup>52</sup> Ibid., 759.

<sup>53</sup> M. McIntyre and J. Woodhouse, “On the Fundamentals of Bowed-String Dynamics,” *Acustica* 43, no. 2 (1979): 94.

<sup>54</sup> Boutillon, “Analytical Investigation,” 759.

<sup>55</sup> Askenfelt, “Bow Force,” 1007.

tip, the string player must continuously compensate to maintain a stable tone. At the frog, more than 20 inches of the bow extend from the string and this mass acts as a lever. The string and the thumb are the axis upon which the bow pivots. When at the frog, the string and thumb are quite close and act as a single axis. As the bow is moved towards the tip, the string supports more of the weight of the bow, which is divided between the player's right hand and the string, lowering the leverage provided by the bow's extended mass. When playing on the G string and the bow is nearly horizontal, this change represents over 300 grams of force difference between a bow position at the tip and at the frog.<sup>56</sup>

Due to these realities, the string player will generally choose to begin a loud or accented note on a down-bow. If a soft start is desired, generally he will start at the tip where the inherent force of the bow is significantly less than at the frog. When unaccounted for the inevitable change in force potential over the course of a bow stroke will greatly alter the form of the Helmholtz, even leading to the breakdown of the regular motion. The bulk of this change happens in the first third of the bow, nearest the frog.<sup>57</sup> In a study of advanced violinists in real playing conditions, it is possible to see increased force on the string at the frog compared to the tip, indicating that the extra force at the lower third of the bow had not been fully considered.<sup>58</sup>

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<sup>56</sup> Askenfelt, "Measurement in Violin Playing," 508.

<sup>57</sup> Ibid.

<sup>58</sup> Askenfelt, "Measurement in Violin Playing," 507.

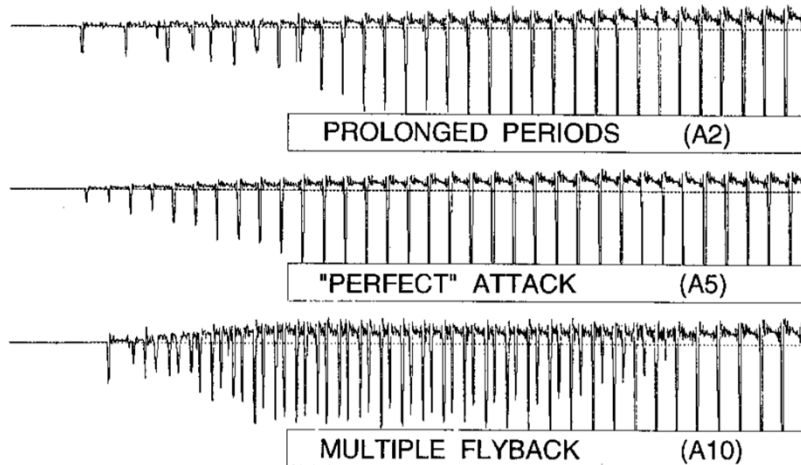


Figure 1.6: Pre-Helmholtz transient<sup>59</sup>

## II. Acceleration

Another secondary parameter involved with altering sound is acceleration.<sup>60</sup> The start of every note includes a short period before a regular Helmholtz motion is achieved, which Askenfelt refers to as the pre-Helmholtz transient.<sup>61</sup> In order to create a clean beginning to a note, perfectly timed acceleration must occur. There are three possible outcomes during the transition period: a prolonged period, multiple flybacks, or a clean start (see Figure 1.6). The prolonged period occurs when the bow is unable to escape the excessive force compared to the rate of acceleration, resulting in a “crunchy” sound.

Multiple flybacks occur when the bow has too much acceleration for the chosen force and is

<sup>59</sup> Guettler and Askenfelt, “Acceptance Limits,” 2904.

<sup>60</sup> Erwin Schoonderwaldt and Matthias Demoucron, “Extraction of Bowing Parameters from Violin Performance Combining Motion Capture and Sensors,” *Journal Of The Acoustical Society Of America* 126, no. 5 (2009): 2695, *Academic Search Complete*, EBSCOhost (accessed March 10, 2016).

<sup>61</sup> Knut Guettler and Anders Askenfelt, “Acceptance Limits for the Duration of Pre-Helmholtz Transients in Bowed String Attacks,” *Journal of the Acoustical Society of America* 101, no. 5 I (1997): 2903, doi: 10.1121/1.418520.

unable to drag the string far enough to start a regular motion, causing a loose sound with aperiodic starts.<sup>62</sup>

Defined by prolonged starts and multiple flybacks, Askenfelt found a range of acceptable accelerations for any given force. The beginning of each note has pre-Helmholtz transient, but in order for the listener to approve of the clear start on the violin, the pre-Helmholtz transient must be between 30-50 milliseconds when prolonged or around 90 ms when closer to multiple flybacks.<sup>63</sup> Thus, with a stronger consonant at the start of a stroke, the player has a much shorter time frame in which to establish the regular Helmholtz motion, if the goal is a clean start. The acceleration may be more extreme when playing higher frequencies, but must be tempered for the lower strings that have increased mass.<sup>64</sup> Achieving the control necessary for a clean start is extremely demanding and studies have shown that more than half the strokes of advanced students and professionals fail to meet acceptable time limits for establishing periodic Helmholtz motion.<sup>65</sup> In real playing conditions all types of attacks are acceptable and even desirable, but, in relationship to establishing the Helmholtz motion, a steady acceleration is crucial.

### **III. Tilting Bow Hair**

Another factor that influences spectral content is tilting the hair of the bow. Generally, tilting the hair excites the upper partials—above the 20<sup>th</sup> partial there is actually a gain of 3-6 decibels. The increase in upper partials due to bow tilt is particularly evident

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<sup>62</sup> Guettler, "Acceptance," 2904.

<sup>63</sup> *Ibid.*, 2905.

<sup>64</sup> Guettler, "Closer Look," 14.

<sup>65</sup> Guettler, "Acceptance," 2903.

with a faster velocity and higher force values.<sup>66</sup> For the very high partials, tilting the bow produces results almost as great as bow force, although this change does not extend of the lower harmonics and fundamental.<sup>67</sup>

There are many theories to explain this increase in harmonic content. Schoonderwaldt, et al. suggest that with less bow hair on the string each individual hair has a greater friction coefficient, contributing to a sharper corner.<sup>68</sup> Guettler has also posited that due to the width of the ribbon, playing with all the hair on the string creates a discrepancy in the lateral velocity of the string, increasing extra noise in the sound.<sup>69</sup> When the bow is tilted, this extra noise may be diminished. Overall, the total effect of tilting the bow is small, but on the thinner strings it may be noticeable.<sup>70</sup>

#### IV. **Parallel bow, bow angle, and finger pads**

Maintaining a bow motion parallel to the bridge is influential to the harmonic content of a sound. Frequent, extraneous slips occur when the bow is askew, interfering with the periodic Helmholtz motion.<sup>71</sup> Furthermore, as will be further examined in Chapter 2, a crooked bow greatly limits a player's ability to control the point of contact. The timbre of the sound may also be affected by angling the bow too far off the outer strings, e.g. the G

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<sup>66</sup> Erwin Schoonderwaldt, Knut Guettler, and Anders Askenfelt, "Effect of the Width of the Bow Hair on the Violin String Spectrum," (paper presented at Stockholm Music Acoustics Conference, Stockholm, Sweden, August 6-9, 2003), 3, <http://www.speech.kth.se/prod/publications/files/961.pdf>.

<sup>67</sup> Ibid., 4.

<sup>68</sup> Schoonderwaldt, Guettler, and Askenfelt, "Effect of the Width," 1.

<sup>69</sup> Guettler, "Closer Look," 14.

<sup>70</sup> Ibid.

<sup>71</sup> Halmrast et al., "Gesture and Timbre," 195.

or E string on the violin.<sup>72</sup> When the bow is tilted extremely towards the c-bouts, the vibration of the string fails to move parallel to the top of the bridge, affecting the string's influence on the bridge. A final factor proven to change timbre on a stringed instrument is the left hand fingers. When the Helmholtz is reflected off the hard surface of the nut, little energy is lost, creating higher harmonic content and a very bright sound.<sup>73</sup> When the finger is placed on the string the pad absorbs some of the string's vibration, diminishing the strength of the upper partials.

Although quantitative evidence illuminates the main factors that control sound on the bowed string instrument, these numbers are always in flux during real playing conditions. Each string, position, and player will have a slightly different set of outcomes. Even resonances of each particular instrument, including very fine ones, influence acceptable limits for each parameter.<sup>74</sup> However, the study and understanding of these factors illuminates important considerations for both performing and teaching. Physics has proven that there are specific results for the manipulation of each parameter; understanding these possibilities is vital for controlling and maximizing the violin's sound potential.

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<sup>72</sup> Beament, *Violin Explained*, 38.

<sup>73</sup> Guettler, "Closer Look," 16.

<sup>74</sup> Schelleng, "String and the Player," 31.

## Chapter 2: Exploring the Parameters

The violin is a wonder of imagination, craftsmanship, and physics. From a small wooden resonating box, four strings, and a stick strung with horsehair, an astonishing array of sound is produced. The great performers on stringed instruments may elicit the most jarring and strident sounds only to follow it with tones sublimely pure and sweet. Unsurprisingly, learning to fully utilize the violin to create such variation is bewildering. Hundreds of books and articles address ways of making any given sound, but keeping track of every idea can be overwhelming when learning and teaching. As described in the previous chapter, there are primarily three main parameters which effect sound: bow-bridge distance, velocity, and force. Through an examination of the actual physical parameters of the violin and exercises to facilitate mental and kinetic understanding of each parameter, any string player can master these ingredients to gain greater control of their sound. All sounds produced on an instrument can be musical expressions—whether it be beautiful or coarse, the greatest artistry is possible when a musician can create any sound she desires at any given time.

At the fundamental level, sound is created when friction from drawing the bow across the strings excites the slip-stick mechanism, resulting in a rotating corner as described by Helmholtz. The energy from the string's vibration is then amplified through the body of the instrument. Fortunately, there is very little that a string player actually needs to do in order to make a sound. To illustrate this, place your instrument on a secure surface, hold the bow lightly by the screw and draw it across the strings. It may not be the best tone, but it is important to realize that the instrument is designed to create sound with very little work.

The parameters of bow-bridge distance, velocity and force are familiar to most string players, but the recognition of their centrality to all sound creation is often marginalized. There are two main results achieved through manipulating these parameters: overall string amplitude and harmonic content of the sound.<sup>75</sup> For ease of understanding, the physicist's titles of bow-bridge distance and velocity will subsequently be replaced by point of contact and speed. The point of contact effects both harmonic content and amplitude, the speed of the bow primarily controls volume, and force is largely responsible for sharpening the rotating corner thus effecting harmonic content. Of course, speed can also affect harmonic content since a faster bow without increased force will soften the corner, leading to fewer partials. Force may also make a few decibel difference depending on the point of contact, or cause a sound that is perceived as louder because of the strength of the partials. Ultimately, control of sound is governed only by how wide or narrow the string vibrates and the sharpness of the rotation corner.

### **Sound Formula**

The physics of the bow/string interaction is described by a plethora of complex formulas. Although not scientifically quantifiable, it is possible to make a simplistic formula for the creation of any sound on the violin. This sound formula is:

$PC + (SDF) = \text{Desired Sound}$ .<sup>76</sup> The point of contact plus a combination of speed, distance, and force facilitates the creation of virtually any desired sound. As an aid in teaching and learning the central three parameters, distance is also added to the formula. Distance is merely speed multiplied by time, but it is crucial for describing and learning to fully utilize

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<sup>75</sup> Halmrast et al., "Gesture and Timbre," 187.

<sup>76</sup> Ronald Patterson, interview by the author, Seattle, WA, April 7, 2015.

speed and the changing gravitational force of the bow. Although “PC+(SDF) = Desired Sound” may sound abstruse, it may be compared to a recipe. For example, when making simple brownies there are a few main ingredients: sugar, cocoa, eggs, milk, and flour. By varying the ratios of these basic ingredients, the entire outcome of the brownie will be changed. With different combinations the chef may produce a range of brownies—dense and fudge-like or light and fluffy, and from bitter to sweet. If one ingredient is drastically changed without changing the amounts of the other ingredients, you will get a very different brownie. The point being that with only a few ingredients it is possible to make many variations of brownie. Likewise, the string player only has a few ingredients; in various combinations these ingredients are responsible for generating nearly any possible sound.

### **Instruments**

There are many types of instruments: surgical instruments, financial instruments, flight instruments, and of course, musical instruments. In all of these examples, instrument is just another way of describing a tool. Tools are designed to help accomplish a specific task—usually in a more efficient or powerful way. For example, a seasoned construction worker generally swings a hammer with little brute force. Rather, the hammer is wielded in such a way that the mechanical advantage of the tool magnifies the effort. Another example is found in tennis. Any tennis player knows the feeling (and sound) of hitting the ball on the “sweet spot” of the racket. When connecting with the ball at the ideal part of the racket, the ball is returned with maximum response for any given amount of effort. Tennis players

who frequently connect with the ball towards the margins of the racket magnify the odds of fatigue, inconsistency, and injury.

The violin and bow are much like a hammer or a tennis racket—they are tools to help accomplish a given goal. When a violinist uses the instrument to its full potential and mechanical advantage he is much more likely to achieve his desired sound and artistic goals. Violin students often learn to create a given sound through inefficient means, which is disruptive for future growth, artistic expression, and physical wellbeing. Cognitive and physical understanding of the factors responsible for sound creation enables string players to utilize their instrument's potential efficiently.

Full size bows are all basically the same length, but many string players are unable to comfortably use their entire bow. It is common to see string players neglecting the final three inches of hair at both ends of the bow; the total of these lost inches account for nearly 20% of the bow. A tennis player who is unable to use 20% of the racket's potential is at a significant disadvantage to their opponent who uses the entire racket. Likewise, in order to reach the full potential of sound, learning to utilize the entire bow is crucial. Of course using the whole bow all the time doesn't always make musical sense, but training should focus on using the whole bow, which provides the greatest opportunity to maximize the production of sound.

### **Practical Considerations**

The following suggestions and exercises provide ways to isolate and gain understanding for each of the main parameters. Rather than having many specific directions such as “keep the elbow at such and such height” or “always keep your right

thumb in *X* angle,” the focus is towards helping gain intellectual, kinesthetic, and aural awareness of the ingredients used for the creation of any sound. It is therefore possible to utilize these ideas with many technical schools. Once the ingredients are understood, the possibilities for sound creation are nearly infinite.

When working on these exercises avoid looking directly at the fingers and bow, rather monitor the progress using a mirror. Looking directly at the bow teaches the eyes to control the bow. Unfortunately, if control is based only on visual cues, as soon as the eyes are required to look at the music or conductor, the bow will go awry. Eventually, the goal is to have control of every inch of the bow without relying on visual cues.

Also, whether teaching or learning, it is important to be aware of the semantics used when describing actions on the violin. A commonly used and detrimental phrase among violinist is “bow hold” or “bow grip” for referring to the right hand’s placement on the bow. Unfortunately, these terms often lead to exerting excessive pressure on the bow, resulting in less control of the bow and potential pain in the right hand or arm. Furthermore, although a central sound creation parameter, the term force is easily misunderstood. It is vital that students interpret force more as the feeling of friction rather than arm weight or pressure. Not only are these phrases potentially confusing, but they may also lead to tension and poor tone.

### **Parallel Motion of the Bow**

To fully utilize the main parameters, the string player must learn to move the bow parallel to the bridge from the frog to the tip. The successful maintenance of the Helmholtz motion is dependent upon the ability to control the point of contact. The following initial

exercises are useful for all of the parameters, but assist principally with establishing a bow stroke parallel to the bridge and controlling the point of contact. Many pedagogues have described similar exercises for establishing the parallel motion of the bow, particularly Galamian, Fischer, and Patterson.

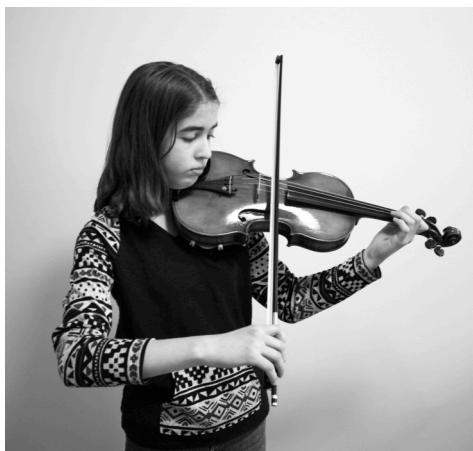


Figure 2.1: Square position<sup>77</sup>

First, using sticky notes or rubber tape, mark off the four quarters of the bow (a little over 6 inches per quarter on a full size bow). In order to facilitate the parallel travel of the bow, when learning or teaching, start by working with only half the bow at a time. This creates two separate segments of movement to master. If the bow is placed in the middle, depending on the length of the arm, it will make a square (see Figure 2.1).<sup>78</sup> When playing from the middle to the tip, the motion is described as extension of the forearm or opening/closing the inner elbow, much like the hinge of a door. Place the right index finger in the inner elbow and feel the arm swing open and closed from the joint. When the forearm extends outward, the right hand will naturally move towards the right side of the

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<sup>77</sup> The term square position was used by Galamian and has been widely employed by pedagogues.

<sup>78</sup> Ivan Galamian, *Principles of Violin Playing & Teaching*, 2<sup>nd</sup> Ed. (Englewood Cliffs, N.H.: Prentice-Hall, 1985), 52.

body. To compensate for this lateral motion the elbow must drift slightly towards the midpoint of the body when nearing the tip.

It is also important to feel the transfer of energy in the right hand when moving from the middle to the tip. When in the middle of the bow, four fingers are equally balanced on top of the bow; as the bow is moved towards the tip, the weight transfers towards the index finger or “front” of the hand. To discover the role of each finger at the tip, use the following exercise.

- 1) With a bow position at the tip, repeatedly alternate placing the bow on the string and removing the bow from the string.
- 2) Next, take the pinky, third and second fingers off the bow and try again to remove the bow from the string.

At this point, it is nearly impossible to lift the bow off the string with only the thumb and index finger. If the pinky is placed back on the bow it is once again possible to remove the bow from the string, demonstrating the pinky’s primary role at the tip: taking the bow off of the string. When the pinky is held tightly from the middle to the tip, the distal range of motion is reduced and competing pressures between the fingers will result in unnecessary tension. For producing sound at the tip, the only digit that is directly necessary, aside from the thumb, is the first finger. All the fingers may stay on the bow or the pinky may come off when approaching the tip, but it is crucial that there is no active engagement of the pinky.

When playing on an individual string, the bow may move a relatively large distance vertically before connecting with adjacent strings. When learning the basic bow stroke, playing on two strings at once will train both the vertical and horizontal motions of the bow. Since chapter one illustrates the importance of not tipping too far off the E or G

string towards the C-bouts, it is advantageous to train the three planes that are employed when playing on two strings at once: on the violin G/D, D/A, A/E. By tipping slightly from each plane it is possible to play each string by itself. Many violinists go radically past these planes on the G and E string (one of the telltale signs is rosin on the C-bout). However, not only is this unnecessary motion, it also causes the string to vibrate more vertically, creating buzzing and diminished sound quality.<sup>79</sup>

### **Exercise 1 (a): Upper half of the bow and the forearm**

- 1) Place the bow on the middle marker with a point of contact midway between the bridge and fingerboard. Rest the bow on both the A and D string.
- 2) Tap each finger of the right hand on the bow to make sure none of the digits are gripping or unmovable. Think about evenly balancing the fingers on the bow in relationship to the thumb.
- 3) Using a mirror to monitor the movement, play both the A and D to the third quarter marker. Concentrate on extending the forearm and opening and closing the inner elbow like the hinge of a door.
- 4) While keeping a consistent point of contact, move the bow between the tip and the third marker. It is important to go all the way to the tip and to stop right at the third quarter marker. As you move in the top quarter, pay attention to the balance of the bow shifting towards the index finger or the “front” part of your hand. Whether your pinky actually leaves the bow at the tip is not important;

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<sup>79</sup> Beament, *Violin Explained*, 37.

however, if it stays on the bow, any pressure is counterproductive, as previously illustrated.

- 5) Next, practice moving the entire upper half of the bow. With a metronome set to 72bpm, move a quarter bow for each click. There will be two clicks per direction of the bow—practice with a slight stop at each quarter and also without stops. The primary consideration at this point is the motion of the arm and a consistent point of contact.

If playing to the tip is impossible for students using a bow that is too long for their size, it may be necessary to mark off a false tip. However, it is very common for violinists of any size to think it is impossible to play to the tip due to arm length when it is rather a failure to disengage the pinky in the upper part of the bow. To play to the tip unhindered by “back of hand” tension, try the below exercise.

### **Exercise 1 (b): Releasing the pinky**

- 1) Begin with the bow in the middle of the string and tap the fingers to ensure the right hand is supple.
- 2) Moving only in the upper half of the bow, move from the middle to the tip removing first your pinky, then third finger, then second finger from the bow. When done rhythmically this will correspond with the four quarters of the upper half of the bow.
- 3) At the fourth quarter, only have the first finger will remain on the bow. As you return to the middle gently and sequentially place the second finger, third finger, and pinky back onto the bow.

- 4) After many repetitions of this exercise, slowly begin to leave the fingers on the bow when traveling from the middle to the tip, but imagine relaxing each finger in the same order. Generally, if the fingers have released, it will now be possible to draw a straight bow all the way to the tip.

Many violinists play comfortably in the upper half of the bow but struggle to consistently reach the frog. The basic movement in the lower half of the bow is created by moving your lateral or “outside” elbow. To feel this motion, without holding your violin or bow, begin with your right arm in square position. The basic motion of the lower half of the bow is replicated by touching your left ear with your right hand without turning your head. Make sure that the elbow follows the gentle upward motion of the right hand rather than moving parallel to the floor or up towards the ceiling. Also, be aware that raising the right shoulder does not help your elbow to move, but rather limits the range of motion. Galamian stressed that raising the right shoulder was, “the evil source of frustrations and disturbances in the bow arm and, for the sake of a healthy bowing development, should be eliminated as soon as possible.”<sup>80</sup>

### **Exercise 2 (a): Lower half of the bow**

- 1) Start with the bow in the middle, placed on the A and D string midway between the bridge and the fingerboard and tap the right hand fingers.

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<sup>80</sup> Galamian, *Teaching and Playing*, 51.

- 2) With your attention towards your outer elbow, move from the middle to the first quarter marker. As you go back and forth, make sure you are stopping at each marker. It can be helpful to also tap your fingers at either end of the stroke.
- 3) Move on to the lowest quarter of the bow. Use your elbow to push the bow all the way to the furl. Hitting the furl is fine when first starting; it is easier to shorten a bow stroke than to lengthen it later.
- 4) Notice the energy needed by the pinky, which is now supporting nearly the entire weight of the bow. Begin the down-bow from the elbow by initiating the action towards the direction from which it came without dropping the elbow towards the floor or raising it towards the ceiling.

As previously noted, when approaching the tip the energy transfers to the front of the hand. Likewise, when nearing the frog, the energy transfers to the “back” of the hand and the pinky. The next exercise helps to sense this transfer of energy to the back of the hand.

### **Exercise 2 (b): Engaging the pinky**

- 1) Begin in the middle of the bow and tap your fingers. Then play an up-bow traveling towards the frog until you connect with the ferrule. Once at the frog the pinky should feel the majority of the bow’s weight.
- 2) Remove the first finger and play in the lowest quarter near the frog. There is sufficient force provided by the weight of the bow to make a full sound—dependent on point of contact and speed, in some cases too much force.

- 3) Now play back to the middle of the bow without replacing the first finger. When nearing the midpoint the bow will no longer have sufficient force and the sound will become weak and dull.
- 4) Repeat steps 1-3 but slowly take the first finger off when getting close to the frog and slowly replace it on the down-bow to achieve an even sound from the middle to the frog.
- 5) Finally, play from the middle to the frog while keeping the first finger on the bow, but remain aware of the energy transfer to the pinky when approaching the frog.

Once these basic movements are comfortable, the next exercise efficiently integrates these motions into the violinist's bow stroke. The first eight notes of Kreutzer's Second Etude provide an effective mix of string crossings, simple left hand patterns, and repetition.<sup>81</sup> Now that the basic motion is more familiar, imagine that the right hand is merely riding on the bow as it moves back and forth without direct input. Allow the bow to shift in the hand as needed so that the motion of the arm, not the fingers, controls the point of contact.

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<sup>81</sup> Rudolf Kreutzer, "2: *Allegro Moderato*" in *Forty-Two Studies or Caprices for the Violin* (New York: New York, G. Schirmer, 1923).

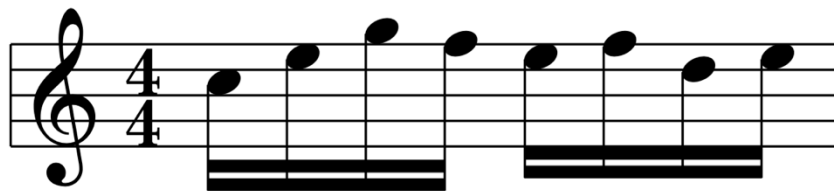


Figure 2.2: Kreutzer No. 2<sup>82</sup>

### Exercise 2: Kreutzer 2

- 1) Begin with the metronome at 70bpm. Practice the eight-note exercise (see Figure 2.2) in each quarter of the bow, repeating the note pattern indefinitely. Concentrate on the basic motion of the forearm and the inner elbow opening and closing for the upper quarters and outer the elbow pushing/pulling for the lower half.
- 2) Next, with the same eight notes, play two quarters in the same direction (down/down, up/up), thus using half of the bow every two notes. Once you are comfortable with both the top half and bottom half of the bow, practice using the middle two quarters while making stops at each marker on the bow.
- 3) Finally, practice with the bowing pattern, down/down, up/down, up/up, down/up. This makes the pattern more difficult but reinforces the same speed, distance, and point of contact.

Once the violinist can use the entire bow while staying parallel to the bridge at a given sounding point, it becomes possible to more closely examine each of the main parameters from the sound formula. Even though the main ingredients from the sound formula are interconnected, understanding each parameter individually is important for

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<sup>82</sup> Kreutzer, *Studies*, 4.

creating the greatest variation of sound. By learning to control the bow arm's basic motion from the previous exercises, it possible to look more deeply into each ingredient.

### **Point of Contact**

The first ingredient in the sound recipe is the point of contact (PC). The point of contact is where the bow is drawn across the string, generally somewhere between the bridge and the fingerboard. Point of contact leads the sound creation formula due to its potential to modify both the dynamics of the sound and the harmonic content.

Furthermore, without the ability to control the sounding point, the sound effecting capabilities of the other parameters are greatly hampered. Composers occasionally dictate a point of contact through markings such as *sul tasto*, or *sul ponticello*, but most often it is left to the performer to decide where to place the bow.<sup>83</sup> Even though there is rich harmonic potential with points of contact near to the bridge, many players never learn how close they actually may play near the bridge. Gaining awareness and control of the point of contact is central to the ability to create any desired sound.

#### **Exercise 3: Dropping into the point of contact.**

- 1) Play an open D *sul ponticello* with relatively strong force. Set a metronome at around 80 bpm, moving at a speed of 4 clicks per bow.
- 2) Very slowly move your bow away from the bridge until a clear, rich tone is heard. It will almost feel like the bow has fallen into a notch on the string. Once this point has been found, do not continue farther towards the fingerboard.

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<sup>83</sup> *Sul Tasto* directs the player to bow over the fingerboard and *sul ponticello* indicates a position close to the bridge.

- 3) Return past the margin of pure, rich tone towards the bridge and repeat steps 1 and 2, pivoting across the clear/raucous margin until the sensation becomes comfortable.
- 4) Finally, experiment with steps 1 and 2 on different strings and different positions, noting how the position of the notch will change slightly for each note and string. For example, play an A440 on the D string. Then play an A an octave higher, but still on the D string—notice again how the position of the margin line changes.

### **Speed**

The speed of the bow is primarily responsible for the amplitude of the vibration. Simply by watching the string while increasing bow speed, the violinist may observe speed's effect on the size of the vibration envelope. This is particularly evident when a sounding point near the bridge is chosen. Many string players unconsciously have widely varying bow speeds within a single stroke. Unfortunately, these unsteady speeds will result in variation of the volume unless the other parameters are constantly compensating for these changes.

In addition to affecting the amplitude of the vibration, bow speed may vary the frictional force of the bow and affect the harmonic content. Figure 2.3 illustrates this change; particularly with lower speeds, the friction becomes much greater. Eventually, once the speed becomes too slow for any given sounding point and force value, the friction will become too great for the string and the regular Helmholtz motion will break down,

resulting in crunches or pitch flattening. Thus, for any given bow force and point of contact, increasing the speed will lower the partials present in the sound.<sup>84</sup>

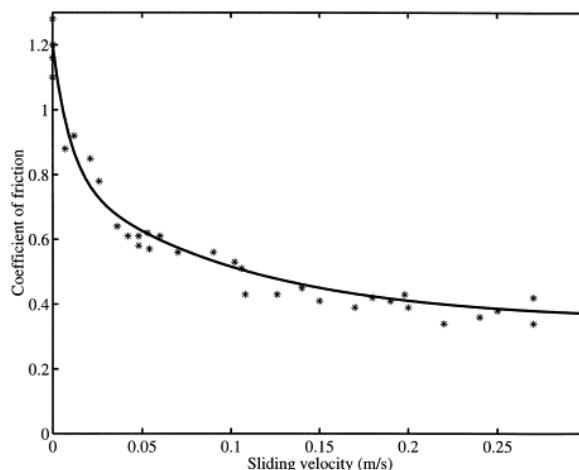


Figure 2.3: Speed and friction<sup>85</sup>

When a faster speed is chosen the bow has diminished frictional force, leading to sliding or skipping on the string and attenuated harmonic content.<sup>86</sup> The violinist might make a crescendo with velocity alone, but the resulting louder sound will have diminished harmonic content unless bow force is increased.<sup>87</sup> When the bow is drawn slowly at a point close to the bridge the corner achieves maximum sharpness, creating a brilliant sound. In order to establish this maximum sharpness, there must also be a fast acceleration at the start of the stroke.<sup>88</sup> If a softer or less direct sound is desired, the bow should accelerate gradually but reach a faster speed, thus keeping the rotating corner more rounded.

<sup>84</sup> Guettler, "Starting Transients," 65.

<sup>85</sup> J.H. Smith and Jim Woodhouse, "The Tribology of Rosin," *Journal of the Mechanics and Physics of Solids* 48, no. 8 (2000): 1640, Figure 4.

<sup>86</sup> R. Pitteroff, and Jim Woodhouse, "Mechanics of the Contact Area between a Violin Bow and a String. Part II: Simulating the Bowed String," *Acustica* 84, no. 4 (1998): 752.

<sup>87</sup> Askenfelt, "Measurement of Violin Playing," 511.

<sup>88</sup> Halmrast et al., *Gesture and Timbre*, 198.

## **Distance**

The distance traveled on the bow is a crucial sub-parameter for sound creation. Primarily, distance is included in the sound formula for ease of teaching and learning. Although the outer limits for bow speed are about 1.5 inches per second to about 118 inches per second with the average range being 8 inches/second to 40 inches/second, these numbers are impractical for teaching and learning speed.<sup>89</sup> Bow speed is enigmatic and difficult to describe, but distance is very simple. Distance is a result of speed multiplied by time. Quarter markers on the bow provide visual and physical cues and serve as guides to learn speed. Utilizing a fixed distance and rhythm will ensure a given speed. Distance also encompasses the part of the bow in which the player may choose to play. As seen in chapter one, when playing the entire length of the bow, inherent gravitational force values change dramatically. Being aware of the part of the bow is crucial for efficiently and effectively managing bow force.

In addition to the below exercises, exercises 1 and 2 are excellent ways to learn to control speed and distance; the speed of the bow is trained effectively since the metronome regulates the time and the markers delineate distance.

### **Exercise 4: Speed and Distance**

- 1) Begin with a very slow bow speed (60 bpm playing 8 clicks per bow) and a full clear tone. Watch in the mirror to confirm that the bow is dividing evenly and arriving every two clicks at a quarter marker.
- 2) Once this speed and sound are comfortable, without changing the friction, double the bow speed by playing four clicks per bow, still dividing the bow

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<sup>89</sup> Askenfelt, "Measurement in Violin Playing," 513.

evenly. Continue to halves and eventually reach a whole bow per click. If the force has remained constant, the sound will now sound glassy and dull, perhaps generating a harmonic.

- 3) With the bow still moving at 60bpm per full bow, slowly increase the force until the sound becomes full and rich. Now practice slowing the bow without changing the force—first slow to half bows per click, then quarters, then to eighth divisions. The force that was once appropriate for the fast bow speed will soon be too strong, resulting in a choked sound.
- 4) Now practice steps two and three with appropriate force changes to ensure a pure tone with the bow speed variations.
- 5) Finally, begin to change the distance per click within the same direction of the bow. Moving the bow in the same direction, play two quarters per click and then one half for the last click—return the up-bow with the same division. Practice with various combinations of quarters, halves, three quarters, and full bows per click. Work to keep an even tone without accents for faster speeds and a full tone for the slower speeds.

The opening phrase from the second movement of the Bruch G minor Violin Concerto is also an effective way to work on speed and distance.<sup>90</sup> In order to achieve a sweet and sustained sound without notes disappearing or jumping out of the texture, the bow must be divided evenly. Begin by determining how many sixteenth notes fit in each down-bow and up-bow. Using the whole bow for every stroke ensures an even distance,

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<sup>90</sup> Max Bruch, *Violin Concerto in G Minor, Op. 26*, (New York: E.F. Kalmus, 1900), 5.

while also dictating that the speed will be constantly changing dependent on the number of notes that must fit into each bow—sometimes there are six sixteenths, sometimes eight, and sometimes two. Since speed is a primary factor in volume, this will also demonstrate that it is possible to create a compelling musical phrase structure without excessive use of force.

### **Force**

Force is perhaps the most difficult ingredient to describe and teach since learning about force is largely about understanding the sensation of friction. Although force has been used in the sound formula for scientific accuracy, it may be described for pedagogical purposes as friction. The other parameters also affect friction, but force is best understood by the sensation of friction. Terms such as “arm weight” or “pressure” often lead to excessive tension and the false conclusion that the string player must push down towards the floor to create more sound. Force generated from excessive pressing results in a costive sound. The role of friction is rather to pull or push the string horizontally, setting up the condition to sustain the Helmholtz motion. In fact, the French words for down-bow and up-bow are *pousse* (push) and *tire* (drawn or pulled), which describe the motion of the bow in more accurate language. There is little upward motion or downward force, rather the bow is drawn across the strings much like pushing and pulling a sandpaper block—there is little need for excessive downward pressure, rather than frictional properties of the sandpaper grip the wood as the block is moved back and forth. A byproduct of all friction is

heat; the bow's friction on the string is no exception as a *fortissimo* tremolo may heat the string by nearly 25-30 degrees!<sup>91</sup>

Mental imagery to sense friction includes the resistance felt when mopping the floor, or even something as subtle as the way the bristles on a paintbrush react to the wall. When painting there is very little force towards the wall, but the bristles are still pulled and pushed to the side. It is also helpful to think of the top of the right hand as an escalator. If the top of the hand remains parallel to the floor as the hand ascends and descends, the balance transfer in the hand happens naturally and torque is organically created at the tip. Patterson also suggests imagining providing a flat surface so that a little man could stand on top of your hand.<sup>92</sup> When playing in the middle of the bow this is quite intuitive, but when approaching the tip the pinky and third finger will have less contact in order to keep a flat hand. One may also replace the imaginary little man with an actual quarter or a rubber mute.

It is important to grasp how the bow's natural weight changes over the course of any bow stroke. A violin bow held vertically generally weighs around 60 grams, plus or minus a few grams. However, when the bow is turned parallel to the floor, the weight differential in the hand is 3N or around the equivalent of 300 grams of frictional force.<sup>93</sup> Due to these natural forces changing over the length of the bow, equal energy input from the right hand will result in an unequal sound. Furthermore, when playing on each string, the bow produces differing gravitational force. The greatest leverage potential is found on the G string since the bow is nearly parallel to the ground; when playing on the E string

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<sup>91</sup> Fletcher and Rossing, *Physics of Musical Instruments*, 284.

<sup>92</sup> Ronald Patterson, Interview.

there is much less inherent force as the bow is generally tilted more towards perpendicular.

It is imperative that the string player accounts for these large changes in friction producing potential of the bow and learn to harness the bow's mechanical advantage. Students often produce a raucous tone at the frog since the increased weight of the bow is ignored. In order to produce a consistent sound when playing the length of the bow, the front of the hand (towards the index finger) is utilized to create more friction near the tip of the bow. When at the frog, the back of the hand (towards the pinky) will support much of the weight of the outstretched bow and the mechanical advantage may often generate the entirety of the necessary force.



Figure 2.4: Changing weight of the bow

### Exercise 5: Sensing bow friction

- 1) Hold the bow perpendicular to the ground with a normal right hand placement (see Figure 2.4). Slowly rotate the arm so that the hair is towards the floor. The weight of the bow will shift from being evenly balanced in the hand to being supported by the pinky and the back of the hand. This is similar to what the hand should feel like at the frog when utilizing the mechanical advantage of the bow.

- Return to perpendicular, then rotate the arm so that the hair is facing up. The index finger (or the front of the hand) will now have the bulk of the support. In a simplistic way, this shift in the hand mimics the change that occurs when playing from the frog to the tip. At the frog, the first finger is not needed and the pinky is supporting the bow. As the player gets farther out in the bow, the weight will shift towards the front of the hand where, if the top of the hand remains parallel to the floor, the natural torque will compensate for the diminishing bow force.
- 2) Another way to learn to feel friction is through the sensation of slight resistance in the arm. With the bow on the string at the tip, imagine that the bow is much longer than its normal length—long enough to touch the wall, which is made out of a malleable substance.<sup>94</sup> On the up-bow, the bow is pushed into the wall, and on the down-bow it is pulled out of the wall. This mental image helps the violinist to sense that there is no need to push towards the floor in order, but rather the bow is pulled and pushed across the strings.
- 3) Bend over so that the top of the violin is facing the ground and the bow hair is facing the ceiling. The first finger will have most of the support since gravity is pulling the bow away from the string. Play a warm *forte* on various strings listening for a clear sound. While still playing, slowly stand up keeping that same

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<sup>94</sup> Although there are myriad substances that might work for the imaginary wall, in my experience, suggesting the wall is made of cheese invariably and inexplicably makes a substantial difference in the sound.

feeling in the first finger and you will notice a richer sound and a sensation of stickiness on string.

The bow hand fingers are always moving and adjusting to the different ingredients required for any sound, including variable amounts of force. When practicing these exercises be aware that the acceptance limits for force will be different on each string.<sup>95</sup> Since the acceptable force on the upper strings is less than the lower strings, playing a four-note chord requires differing force values. If the force remains the same during a chord, the upper strings will have a raucous tone and may suffer from pitch flattening. Although it is perhaps the most difficult ingredient to master, learning to understand and feel the friction of the bow frees the string player to more closely control tone color and harmonic content.

### **Exploring margins**

As noted previously in chapter 1, Schelleng created a diagram illustrating his findings about bow force and bow position (see Figure 1.3).<sup>96</sup> The acceptable range of the parameters is shaped like a triangle and provides useful visuals for discovering the roles of the main parameters. Just like it is crucial to learn to use the entire bow even though the entire bow will not always be needed, learning to use this entire range gives string players greater control and diversity of sound.

In the Schelleng diagram, the x axis describes the point of contact and the y axis represents force (see Figure 1.1). Since every instrument, string, and position on the instrument will have a slightly different acceptable area, the diagram's actual values of 0-

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<sup>95</sup> Schoonderwaldt et al., "Empirical Investigation," 613.

<sup>96</sup> Schelleng, "Bowed String," 31.

1000 grams or .02 cm to 14 cm from the bridge are immaterial. What matters is the diagram's representation of relative change. Even though Schelleng's findings were based upon a cello D string, the proportional range on the violin string is very similar.<sup>97</sup> Although the diagram may appear esoteric, it is possible to learn to follow the margins delineated by Schelleng.

### **Exercise 6: Force Margin**

- 1) In order to keep a given speed, set a metronome at a comfortable four clicks per bow at 100bpm. Using the entire bow, make sure that each quarter is being divided accurately, so that an even speed is achieved. Begin by playing a *pianissimo* open D well over the fingerboard with as little force as possible.
- 2) Once a steady tone has been established, while keeping the same speed and force, slowly start to move the bow closer to the bridge. In a rather short distance, the friction from the bow will no longer be sufficient to generate a clear tone. When this happens stop at that point of contact and practice crossing this margin—from fuzzy to clear and back, without changing the force.
- 3) Then increase the force slightly as you move towards the bridge so that the tone now stays clear where it was previously unclear. Once you have established a new clear tone, continue to move closer to the bridge. Repeated step 2 each time the sound is no longer clear.

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<sup>97</sup> Erwin Schoonderwaldt, Knut Guettler, and Anders Askenfelt, "Schelleng in Retrospect—A Systematic Study of Bow Force Limits for Bowed Violin Strings," (presented at International Symposium on Musical Acoustics, Barcelona, Spain, September 9-12, 2007).

- 4) As you approach the bridge the friction needed will become significantly more. The goal is to play as close to the bridge as possible with a clear sound. Once you find the place very close to the bridge, but with a clear tone, you have reached the top of the triangle (or as near as feasible in actual playing conditions).
- 5) Keeping the same force you just achieved, slowly move the bow away from the bridge. The sound will soon become raucous and there may be pitch flattening. You have now discovered the upper limit of force for that particular sounding point, well before you have reached the fingerboard.
- 6) After traversing the margin between clear and unclear a few times, move the bow towards the fingerboard again but also lower your force level slightly until the tone becomes clear. Continue to slowly move closer to the fingerboard, repeatedly crossing the margins. Eventually, you will reach the fingerboard. Although the range of possible force values is larger when over the fingerboard, in actual playing condition it becomes limited due to the bow coming into contact with adjacent strings.
- 7) Once you have returned to the fingerboard with a clear tone, you have surrounded the margins of the Schelleng diagram.

The playable triangle will change slightly on each string and theoretically each note—practice on each open string and notes in mid and high positions. Eventually, it is possible to traverse the margins of these triangles quickly, ensuring that the string player has the widest range of possibilities at her disposal.

In 2004 Guettler published an updated Schelleng Diagram that also models the effects of speed on the Schelleng diagram when friction and point of contact are fixed.<sup>98</sup> By lowering the speed, it is possible to move from a position near to the minimum force limit to a position near to the maximum force limit. Slowing the bow effectively increases the friction, resulting in a sharper Helmholtz corner and a more harmonically rich sound. In Figure 2.5 speed is represented by an arrow coming through three Schelleng diagrams. The farthest diagram's speed is 20cm/s, the middle is 5cm/s, and the closest is 1.25cm/s. As the speed gets slower, the arrow's position in the acceptable triangle moves closer to the maximum bow force limit.

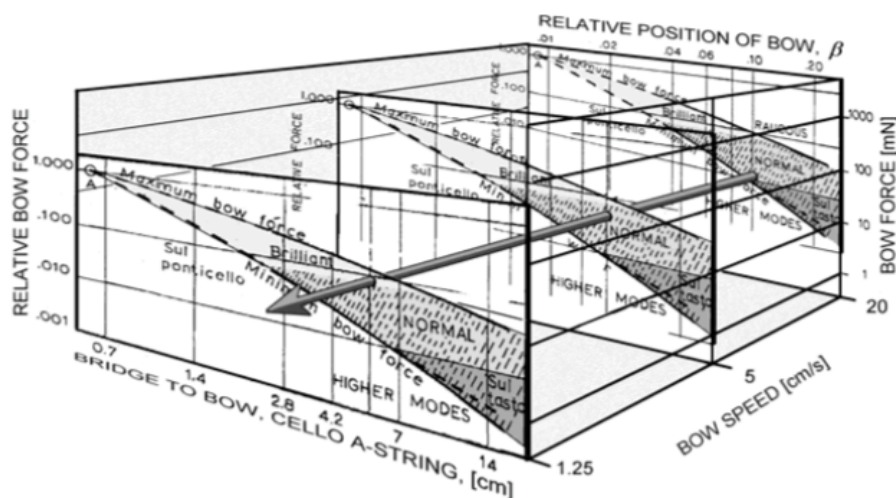


Figure 2.5: Schelleng Diagram including bow speed<sup>99</sup>

### Exercise 7: Speed Margin

- 1) Start with a contact point more towards the fingerboard with a comfortable *forte* and a fast bow speed—180bpm with four clicks per bow is roughly equivalent to 20 cm/s.

<sup>98</sup> Guettler, "Starting Transients," 61.

<sup>99</sup> Guettler, "Starting Transients," 61.

- 2) Without changing the point of contact and force, slowly begin to lower your bow speed. Gradually the bow will transmit more resistance to the hand and the sound will get more brilliant.
- 3) Keep slowing the bow until the sound becomes raucous and pitch flattening may occur. Now that the margin of that particular speed and point of contact has been reached, lighten the force in your right hand until the sound becomes clear again. Continue to get slower, noticing the necessary lessening of force.
- 4) Try to reach an extremely slow speed—at 1.25 cm per second it would take nearly 52 seconds to play the length of the bow! Once the bow is extremely slow and yet the sound is still clear, begin to slowly increase the speed, but do not increase the force. Quite quickly the sound will become unclear and may even turn into a harmonic. After crossing the clear/unclear margin several times, increase the force slightly to achieve a pure tone. Gradually increase the speed of the bow until you have returned to a fast bow speed with a clear tone.
- 5) Repeat the exercise using various points of contact, different strings, and different positions. Also, reverse the above exercise by keeping maximum force from the fingerboard to the bridge and minimum force from the bridge to the fingerboard.

## Conclusion

There are hundreds of formulas used by physicists to explain nearly every aspect of sound creation on a stringed instrument. The physics of how the bow interacts with the string is incredibly complex, but understanding the basic mechanics can help both the beginner and advanced player better utilize their instrument and have greater control of their sound. Specific coefficients and equations given by science have a limited application for the performing or teaching musician; however, the principles and general truths they illuminate regarding sound creation are beneficial for every string player.

The principle factors for modifying and creating sound are inexorably linked—it is impossible to completely isolate each factor. However, by highlighting each primary factor for sound creation and exploring their various roles for creating any given sound, a deeper understanding is possible. A chef who understands the taste and role of each ingredient has the greatest freedom to create anything she can imagine. Likewise, the string player who comprehends the role and potential of the main parameters of sound creation may utilize endless variations of ingredients to reach her artist goals. These exercises and considerations are not an end but a beginning point from which to explore, create, and utilize the full potential of the bowed stringed to create any desired sound.

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