Organoselenium-Catalyzed Oxidative Transformations of Alkenes

John R. Tabor

A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2020

Reading Committee:

Forrest E. Michael, Chair

Gojko Lalic

Michael H. Gelb

Program Authorized to Offer Degree:

Department of Chemistry

University of Washington

Abstract

Organoselenium-Catalyzed Oxidative Transformations of Alkenes

John R. Tabor

Chair of the Supervisory Committee:

Associate Professor Forrest E. Michael

Department of Chemistry

The field of homogeneous catalysis is dominated by transition metals. There exists a vast array of methods available for the conversion of a huge variety of starting materials into an equally diverse collection of useful products through the use of the many transition metal elements as catalysts, and the state of the art of organic synthesis has benefited immensely from this research. However, this is not without disadvantages such as the cost, air/moisture sensitivity and toxicity of these transition metal reagents. The development of an alternative catalyst class that can achieve the same useful transformations that transition metals can, but without the disadvantages listed above, is highly desirable. This dissertation presents work aimed at that goal, with a focus on the development of a new class of organoselenium catalysts and the exploration of their ability to catalyze oxidative transformations of alkenes.

Initial exploration established the relative reactivity of a variety of main group elements in an oxidative diacyloxylation reaction of alkenes. These main group elements can adopt hypervalent configurations, which give them attributes similar to transition metals that are key in enabling catalytic redox reactivity. This early work revealed that organoselenium reagents were uniquely effective in catalyzing oxidation reactions of alkenes, while other chalcogens (S, Te) and pnictogens (P, As, Sb, Bi) gave no desired reactivity.

The growth of the field of organoselenium catalysis has been stunted due to the nearly universal dependence on diphenyl diselenide as a catalyst, which is not easily derivatized and whose derivatives are very restricted in functional diversity. With the aim of providing a better handle with which to tune reactivity, a new class of phosphine selenide catalysts was developed, encompassing much more steric and electronic diversity than has previously been allowed. These catalysts were used to develop a regioselective metal-free aza-Heck reaction of terminal alkenes with improved yields, regioselectivities and stereoselectivities. Deuterium labelling experiments and kinetic isotope effect studies enabled the proposal of a catalytic cycle, in which a key step is a syn-elimination through a selenium-fluorine bond to yield the products and regenerate the catalyst.

Informed by these mechanistic studies, a selenophosphoramide-catalyzed 1,2-diamination and oxyamination of alkenes and esters/carbonates, respectively, was developed. This transformation was made possible by diversion from the typical syn-elimination pathway by introduction of a fluoride scavenger, allowing an atypical substitution to occur instead. Careful tuning of the catalyst revealed that selenophosphoramides were the optimum catalysts, giving the highest yields of the desired products. The transformation was successful for a wide array of terminal- and trans-1,2-disubstituted alkenes, giving the products in high yields with exclusive selectivity for trans-diamines and tolerating a variety of functional groups. Additionally,

substrates bearing appropriate internal nucleophiles, such as esters and carbonates, were induced to undergo intramolecular substitution reactions, giving rearrangement and cyclization product in good yields.

Table of Contents

List of Figures

List of Tables

List of Schemes

List of Abbreviations

3A MS:	3 Angstrom molecular sieves
Ac:	Acetyl
Ar:	Aryl
Bu:	Butyl
Bz:	Benzoyl
COD:	1,5-cyclooctadiene
Cy:	Cyclohexyl
DCE:	1,2-dichloroethane
DCM:	Dichloromethane
dr:	Diastereomeric ratio
ESI MIS:	Electrospray ionization mass spectrometry
Et:	Ethyl
equiv:	Equivalents
FTIR:	Fourier transform infrared spectroscopy
GCMS:	Gas chromatography mass spectrometry
HMDS:	Hexamethyldisilazane
HPLC:	High Performance Liquid Chromatography
hrs:	Hours
Hz:	Hertz
IMe:	1,3-dimethylimidazolium

IPr:	1,3-Bis(2,6-diisopropylphenyl)imidazolium
KIE:	Kinetic isotope effect
L:	Ligand
M:	Metal
mCPBA:	*meta*-Chloroperoxybenzoic acid
Me:	Methyl
MHz:	Megahertz
mmol:	millimol
mp:	Melting point
NFBS:	N-fluorobenzenesulfonimide
NHC:	N-heterocyclic carbene
NMMO:	4-methylmorpholine N-oxide
NMR:	Nuclear Magnetic Resonance

Abbreviations for NMR splitting:

s:	singlet
d:	doublet
dd:	doublet of doublets
ddd:	doublet of doublet of doublets
ddt:	doublet of doublet of triplets
dq:	doublet of quartets
dt:	doublet of triplets
dtd:	doublet of triplet of doublets
t:	triplet

tdd:	triplet of doublet of doublets
tt:	triplet of triplets
q:	quartet
quin:	quintet
m:	multiplet
br:	broad
Np:	Naphthyl
Ns:	4-nitrobenzenesulfonyl
Nu, HNu:	Nucleophile
Ph:	Phenyl
Phen:	Phenanthroline
Phth:	Phthalimide
PMP:	*p*-methoxyphenyl
ppm:	parts per million
Py:	Pyridine
rt:	Room temperature
SM:	Starting material
TBDMS:	tert-butyldimethylsilyl
TBDPS:	tert-butyldiphenylsilyl
^{t}Bu:	tert-butyl
Tces:	Trichloroethoxysulfonyl
TEMPO:	2,2,6,6-Tetramethyl-1-piperidinyloxy
Tf:	Trifluoromethylsulfonyl

TFA:	Trifluoromethylcarboxylic acid
TFA-:	Trifluoromethyl carbonyl-
TFAA:	Trifluoroacetic Anhydride
Tfes:	Trifluoroethoxysulfonyl
TfOH:	Trifluoromethanesulfonic acid
THF:	Tetrahydrofuran
TIPS:	Triisopropylsilyl
TLC:	Thin layer chromatography
TMS:	Tetramethylsilane
TMS-:	Trimethylsilyl
TMSOTf:	Trimethylsilyl trifluoromethanesulfonate
TMSOTf:	Trimethylsilyl trifluoromethanesulfonate
Tol, p-Tol:	4-methyl(phenyl)
Ts:	*p*-Toluenesulfonyl
wt:	Weight

ACKNOWLEDGEMENTS

The writing of this dissertation and completion of my graduate studies would not have been possible without the help and support of many people. I will do my best to thank some of them here, but there will certainly be people who are not listed that I owe at least some of this success to.

I would like to offer my very great appreciation to Professor Forrest E. Michael for his guidance throughout my assistantship in graduate school, and for all of the time and effort he put into my development as a chemist. His sharp memory, innate intelligence and genuine dedication to the study of synthetic organic chemistry made him an invaluable resource for project ideas, diverse but thorough knowledge of the literature, inspiration and direction. Forrest's casual and "hands-off" management style allowed me the freedom to explore ideas on my own and greatly improved my self-sufficiency as an experimental scientist. He was a very patient yet articulate teacher with stringent personal standards for what it means to understand a given topic, and I had many long and enlightening discussions about organic chemistry with him.

I would also like to thank Professor Gojko Lalic who served on my committee, who co-supervised joint group meetings, and with whom I took introductory physical organic chemistry in my first year at the University of Washington. He was another great source of knowledge and learning for me.

My graduate school experience would have been twice as tough had I not had the company of my lab mate and very close friend, Derek Obenschain. Joining in the same year, we went through the entire six-year experience of graduate school side by side through the highs and the lows. He is a naturally gifted scientific thinker and an immaculate research planner and was invaluable for

project discussions and inspiration for just how much bench work can be accomplished in a single day. In addition to his natural talents at chemistry, Derek is also naturally hilarious, and he never failed to put a smile on my face, especially when I needed it the most.

I would like to thank the other members of the Michael Lab, past and present, who made my time at UW easier and more enjoyable: Andrew Holtzen, Valerie Lesniak, Wei Pin Teh, Alex Dohoda, Parker Maloney, Janna Berman, Tianyi Zheng, Jessie Spillane and Zach Stein. I also would like to thank all of the members of the Lalic lab who I interacted with in my time at UW, especially Hester Dang and Mycah Euhling who were great role models. I want to give my thanks to other professors and faculty including who keep the department alive and well, including Dr. Michael Gelb, Dr. Christine Luscombe, Dr. Martin Sadilek, Loren Kruse, Loch Hickock, Kim Quigley and Diana Knight.

Of course, I would not be where I am today without the love and support of my family, and I could never thank them enough. Though we were separated by a great distance, I felt that there was never any separation at all in spirit, and I knew they'd always be a phone call away if I needed it.

Lastly, but probably most importantly, I must thank my wonderful wife, Liz Tabor. Before we were married when I was first accepted into UW she dropped everything including her home, family and friends without a moment's hesitation and made a move across the country, from Texas to Seattle, with me. For six years she has selflessly taken care of me in too many ways to count, always being willing to pick up the slack that I left behind when I was bogged down with research. She kept me grounded and balanced, especially when things were tough, by caring about all of the little things that make up life outside of work. I owe her more than I'll ever be able to repay, and I will remain forever grateful for her love, support and sacrifices during this period of our lives.

DEDICATION

To my wife, Liz,

my brother, Danny, my sisters, Katie and Jojo, and my mom and dad

For your love and support.

Chapter 1 – Exploration of Main Group Element Redox Ability in Bis(trifluoroacetoxylation) of Alkenes

Section 1: Introduction

Within synthetic organic chemistry, transition metals have grown to dominate the field of homogeneous catalysis.[1] There exists a vast array of methods utilizing each of the many different transition metal elements to achieve an impressive variety of chemical transformations. These transformations are used to access an incredible diversity of organic products ranging widely in structural and electronic composition. Given the sheer amount of literature in this area and the widely applicable utility of these methods, it must be acknowledged that the state of the art of synthetic organic chemistry has benefited immensely from the developments in this field. However, this is not without certain disadvantages. One the biggest drawbacks to the use of transition metals in catalysis is the fact that many of them are very expensive due to their low natural abundance.[2] Additionally, many of these transition-metal complexes are air and moisture sensitive, causing an operational hurdle in their employment and often requiring the use of a glovebox and/or other air-free techniques. Another concern with the use of these reagents, especially with regards to industrial or commercial application, is that many of the transition metals, and complexes formed from them, are toxic.[3]

Many research groups, including our own, are working to provide alternatives to traditional transition metal-based catalysts. A new class of catalysts than can achieve the same useful transformations that transition metals can, but without the disadvantages listed above, is highly desirable. Amongst the countless areas that utilize transition metal catalysis are oxidative transformations of alkenes.[4] Our lab has long had a central focus on oxidative alkene

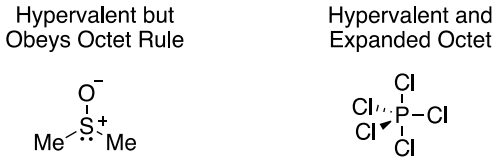
functionalization reactions, and indeed has developed several transition-metal catalyzed transformations thereof.[5] Given our interest in alkene functionalization reactions and the disadvantages associated with the use of transition metal catalysts, we sought to explore the possibility of developing methodology based on alternative catalyst sources. With this goal in mind, we looked towards the possibility of using main group elements to take the place of transition metals as catalysts in alkene functionalization reactions.

Compounds derived from main group elements are much cheaper and more abundant, easier to handle, and in some cases less toxic than their transition metal counterparts. The main characteristic of transition metals that allows them to perform so much interesting and desirable chemistry is the presence of d-orbitals. Main group elements are a promising substitute for transition metals because they can adopt hypervalent structures, giving them behavior that is similar to transition metals under certain reaction conditions. The two most important properties that transition metals and hypervalent main group species have in common is their ability to exist in multiple oxidation states and to change coordination number, characteristics that are enabled specifically by d-orbitals in transition metals and by hypervalency in main-group elements. The ability to easily move between two oxidation states is desirable because it enables catalytic cycles that operate on the basis of redox couples. An example of this can be seen in the incredibly useful palladium-catalyzed cross coupling reactions, which move through a Pd(0)/Pd(II) redox couple.[6] Additionally, the ability to change coordination number is important because it allows for certain elementary mechanistic steps like oxidative addition and reductive elimination, which require an increase and decrease in coordination number, respectively. Indeed, these two important characteristics of transition metals are inextricably woven together, for an elementary mechanistic step like oxidative addition is not possible without increasing both coordination number and

oxidations state. Before continuing, it is important to establish what is meant by the term 'hypervalent'.

The idea of "hypervalency" was created in order to rationalize the existence of compounds for which traditional models did not adequately explain the bonding situation. The currently accepted definition of hypervalency, introduced originally by Jeremy Musher, is as follows: 'we classify as "hypervalent" molecules and ions all those molecules and ions formed by elements in Groups V–VIII of the periodic table in any of their valences other than their lowest stable chemical valence of 3, 2, 1, and 0 respectively'.[7b] This definition relies solely on oxidation state to determine hypervalency, and any atom with an abnormal oxidation state is considered hypervalent. However, there are many compounds that are hypervalent in both the above sense and in an additional way – namely, through octet expansion. The structure of these compounds cannot be described without the allowance of "octet expansion", where the central atom necessarily has more than 8 valence electrons. For example, take dimethyl sulfoxide and phosphorus pentachloride (Figure 1.1).

Figure 1.1. Hypervalency in Dimethyl Sulfoxide vs. Phosphorus Pentachloride

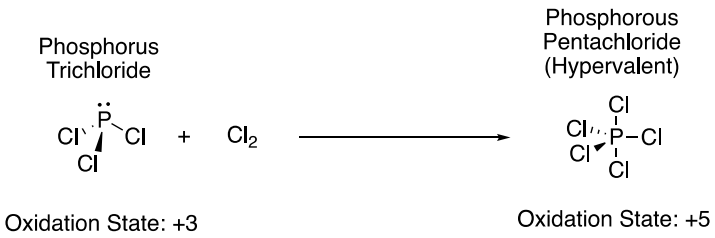


Using Musher's definition, both compounds are hypervalent (i.e. exist in an oxidation state that is abnormal for that particular element). However, dimethyl sulfoxide does not have an expanded octet while the phosphorus pentachloride does.

The nature of the chemical bonds to the central atom in hypervalent compounds has been studied both experimentally and theoretically and has been explained in two main ways: using 3-center-4-electron bonds[7c], or by involvement of d-orbitals in bonding. The concept of hypervalency and the theoretical explanation of the electronic/bonding configurations in these

compounds have been hotly debated for decades, with the latter case gaining more support in recent years. However, we are concerned less with precisely how to describe these species and choose to use the expanded octet model for its simplicity and compatibility with arrow pushing mechanisms. What we are more interested in, and excited about, is the fact that these compounds participate in very interesting chemistry by virtue of their "hypervalent" character (or whatever other term one would prefer to use), which greatly expands their versatility and reactivity. In a manner that is analogous to transition metals' unique reactivity due to the presence of d-orbitals, hypervalent compounds can participate in mechanistic steps that aren't possible for molecules with simpler bonding configurations. This increase in reactivity will be discussed in more detail in the sections below, but a quick example is presented in Scheme 1.1.

Scheme 1.1. Increased Oxidation State and Coordination Number in Hypervalent Compounds



Phosphorous trichloride (PCl_3) has a normal bonding valency and an oxidation state of +3. This high oxidation state causes PCl_3 to be quite a strong electrophile. Phosphorus pentachloride (PCl_5) is synthesized by further oxidizing the already electron poor PCl_3 with chlorine gas, to reach an oxidation state of +5. As a result, PCl_5 is even more reactive and an even stronger electrophile that PCl_3. This enhanced reactivity of PCl_5 is enabled by its ability to exist as a hypervalent structure. Analogous to what was discussed above with transition metals, we observe that ability to shuttle between oxidation states and occupy multiple coordination numbers are the characteristics that enable hypervalency and provide this enhanced reactivity. As is the case with the above example, many hypervalent intermediates are accessed via oxidation of a parent species. The oxidized,

highly reactive hypervalent species can then be used to oxidize a desired substrate, returning the hypervalent intermediate to a lower oxidation state and normal valency. Given the strong parallels with transition metals, we were interested in this redox activity of hypervalent main group species and the potential to manipulate it to achieve desired catalytic reactivity.

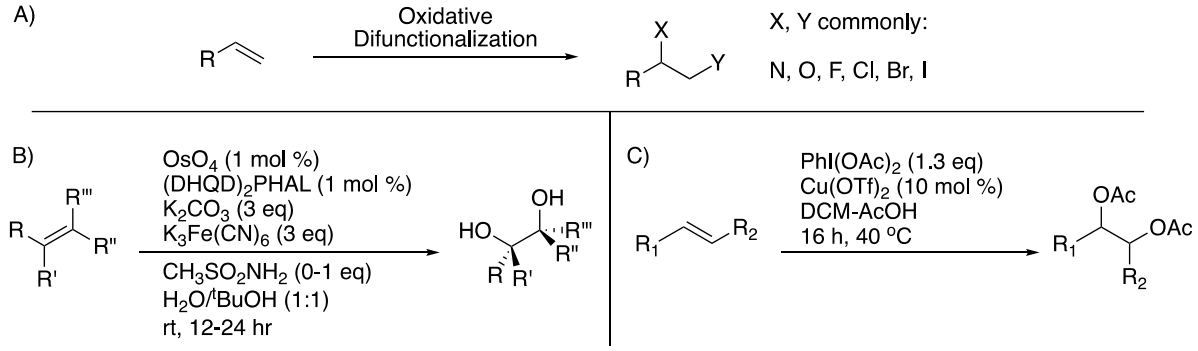
Several of the chalcogens (sulfur, selenium and tellurium) and pnictogens (phosphorus, arsenic, antimony and bismuth) are known to adopt hypervalent structures and exhibit redox activity.[8] The most commonly utilized member of the redox active hypervalent main group elements is hypervalent iodine. Hypervalent iodine reagents have characteristics similar to transition metals in their reactivity via certain elementary mechanistic steps such as ligand exchange and oxidative addition, and in their ability to oxidize alkenes.[9] However, a major drawback of hypervalent iodine-promoted chemistry is that most reactions are stoichiometric in iodine reagent. This is due to the fact that the low valent organo-iodine that results as a byproduct of alkene oxidation is difficult to re-oxidize back to the active hypervalent species under useful reaction conditions. Typically, the use of a strong oxidant that is incompatible with many substrates or functional groups is required to re-oxidize the iodine. For example, mCPBA, a very reactive peroxyacid, is the most common terminal oxidant in hypervalent iodine-catalyzed transformations (Figure 1.2).[9c]

Figure 1.2. Hypervalent Iodine-Catalyzed Intramolecular Aminofluorination of Alkenes

Due to this limitation the number of methods that are catalytic in iodine is currently low, yet the utility of this field is improving. We wondered whether other main group elements might be easier to re-oxidize in-situ and allow for these alkene oxidative functionalizations to be made catalytic.

One very important category of oxidative alkene transformations is oxidative difunctionalization, which can be used to access a wide variety of vicinally-functionalized products.[4c] Oxidative difunctionalization involves the addition of two electronegative groups (relative to carbon) across a carbon-carbon double bond, as seen in Scheme 1.2a. As is suggested in the name, these transformations require a terminal oxidant. Transition metal-catalyzed alkene oxidative difunctionalizations are popular and versatile. An example is the famous osmium catalyzed Sharpless dihydroxylation (Scheme 1.2b).[10]

Scheme 1.2. Sharpless Dihydroxylation and Iodine-(III)-Promoted Diacetoxylation



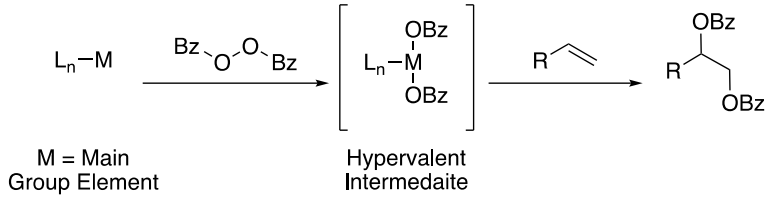
Related stoichiometric diacetoxylations can be achieved with hypervalent iodine (Scheme 1.2c).[11] It is important to note that iodine-(III) reagents can be used as the active species that reacts directly with the alkene (as seen in Figure 1.2), or as a general oxidant that reacts with a precatalyst to generate an active catalytic species (Scheme 1.2c). The former function of iodine is what we hoped to achieve with hypervalent main group catalysts. To begin our exploration into hypervalent main group redox chemistry, we decided to use this known iodine-(III) promoted diacetoxylation reaction of alkenes as a benchmark and starting point. We intended to explore the relative redox activity of main group elements, using this reaction as the tool to do so. The goal was to identify which hypervalent main group elements were empirically the most useful, and then use this knowledge as a basis for discovery of new reactivity.

Section 2: Results and Discussion

1.2.1 Main Group Element Redox Activity Exploration

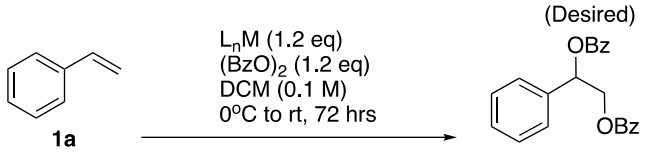
Regarding the mechanism (in a broad sense), we hoped that the benzoyl peroxide would oxidize the main group reagent, L_nM, to a hypervalent intermediate, which would subsequently transfer the benzoyl groups to the alkene resulting in a net oxidative diaddition (Figure 1.3).

Figure 1.3. Desired Dibenzoyloxylation Reaction Mechanism and Outcome



We began our exploration into this desired reactivity by screening a variety of reagents based on the main group elements mentioned above in the presence of benzoyl peroxide and styrene **1a**.

Table 1.1. Main Group Element Redox Activity Exploration



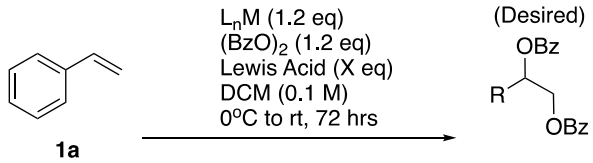
Entry	L_nM	Result
1	Ph_3P	SM + Ph_3P=O
2	Ph_3As	SM + Ph_3As=O
3	Ph_3Sb	SM + Ph_3Sb=O
4	Ph_2Se	SM + Ph_2Se=O
5	Ph_2Te	SM + Ph_2Te=O

As seen in Table 1.1, there was no desired dibenzoyloxylation under any of the conditions attempted. In all cases, the oxide of the main group species, L_nM=O, was observed. The reactions

of diphenyl selenide and diphenyl telluride were very exothermic, hinting that these elements are most easily oxidized amongst those species tried (entries 4, 5).

In a related hypervalent iodine promoted diacetoxylation of alkenes, Chai and coworkers discovered that a Brønsted or Lewis Acid catalyst improved the success of the reaction.[11] Similarly, a Brønsted or Lewis Acid might facilitate our desired reaction by activation of the hypervalent intermediate. The previous reactions were rerun in presence of $Cu(OTf)_2$, BF_3OEt_2 or TFA, but no difference in result was observed (Table 1.2, entries 1-9).

Table 1.2. Screen of Brønsted and Lewis Acids



1a

Entry	L_nM	Lewis Acid	SM Recovered
1	Ph_3P	BF_3OEt_2 (1.2 eq)	SM + Ph_3P=O
2	Ph_3As	BF_3OEt_2 (1.2 eq)	SM + Ph_3As=O
3	Ph_3Sb	BF_3OEt_2 (1.2 eq)	SM + Ph_3Sb=O
4	Ph_2Se	BF_3OEt_2 (40 mol %)	SM + Ph_2Se=O
5	Ph_2Se	$Cu(OTf)_2$ (20 %)	SM + Ph_2Se=O
6	Ph_2Se	TFA (30 %)	SM + Ph_2Se=O
7	Ph_2Te	BF_3OEt_2 (40 mol %)	SM + Ph_2Te=O
8	Ph_2Te	$Cu(OTf)_2$ (20 %)	SM + Ph_2Te=O
9	Ph_2Te	TFA (30 %)	SM + Ph_2Te=O
10[a]	$Ph_3Bi(OAc)_2$	None	SM
11[a]	$Ph_3Bi(OAc)_2$	40%	SM
12[a]	$Ph_3Bi(OAc)_2$	$Cu(OTf)_2$ (20 %)	SM
13[a]	$Ph_3Bi(OAc)_2$	TFA (30 %)	SM

[a]$Ph_3Bi(OAc)_2$ in place of $(BzO)_2$

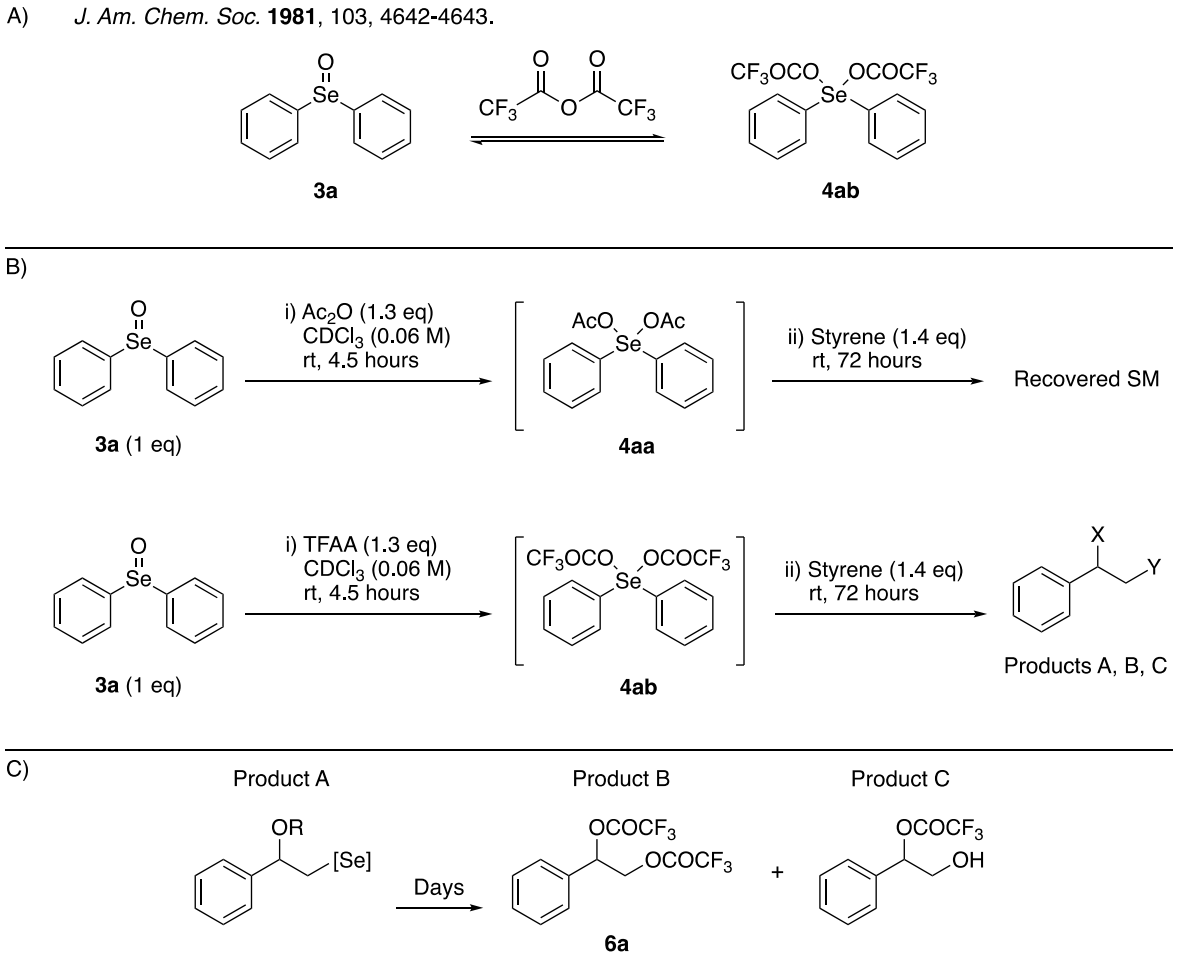
Commercially available pre-oxidized triphenylbismuth diacetate in place of benzoyl peroxide was also tested, both with and without Brønsted/Lewis Acid additive, but similarly gave no desired

product (entries 10-13). In these reactions, evidence of the bismuth oxide could not be confirmed by ^{1}H NMR spectroscopy but each reaction yielded an insoluble white residue, which could perhaps be the bismuth oxide.

1.2.2 NMR Studies

At this point we decided to look more closely at the reaction to see at which point it was failing. It has been demonstrated that the oxides of main group elements react with acetic- and trifluoroacetic anhydride to give hypervalent diacetoxy- and bis(trifluoroacetoxy) species (Scheme 1.3a).[12]

Scheme 1.3. Literature Precedent and NMR Experiments

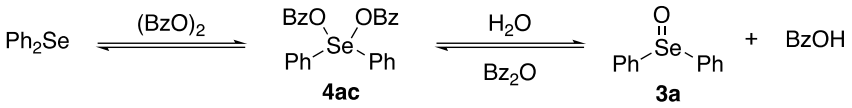


We decided to independently synthesize the hypervalent intermediates by this alternative method in order to test their reactivity. We tracked the reaction of several main group oxides with several acyl anhydrides by ^{1}H NMR over time (Scheme 1.3b). We observed that diphenyl selenoxide **3a**, in the presence of acetic anhydride and trifluoroacetic anhydride, was fully converted over the course of several hours, giving diacetoxyselenurane **4aa** and bis(trifluoroacetoxyselenurane) **4ab**, respectively. After these intermediates were formed, styrene was introduced to each of the reactions. Diacetoxyselenurane **4aa** showed no reactivity after multiple days in the presence of styrene, while bis(trifluoroacetoxy) **4ab** showed formation of an initial diaddition product (Product A) by 24 hours. The mixture was monitored over time, revealing that Product A slowly converted into two new products over several days (Products B and C). The identity of Product B was confirmed to be the desired bis(trifluoroacetate) product **6a** by comparison of the ^{1}H NMR spectrum with that of an authentic sample. Products A and C remain unknown, but we hypothesize that Product A is an organoselenium intermediate, which gives way to the desired bis(trifluoroacetate) **6a** and a mixed OH/TFA diaddition product (Scheme 1.3c). This is purely speculative and has not been confirmed by any spectroscopic means. This was the first proof that the hypervalent diacyloxyselenurane intermediates are able to *intermolecularly* oxidize alkenes.[13a] Additionally, it revealed that diacetoxy reagent **4aa** is not reactive enough to oxidize the alkene, while the bis(trifluoroacetoxy) **4ab** reagent is. These NMR tracking experiments were repeated with both diphenyl sulfoxide and diphenyl telluroxide. Diphenyl telluroxide gave the hypervalent intermediates, which showed no reactivity in presence of the alkene. Diphenyl sulfoxide did not form any detectable amount of the desired intermediates. These observations will be further discussed in Section 1.2.4.

1.2.3 Optimization

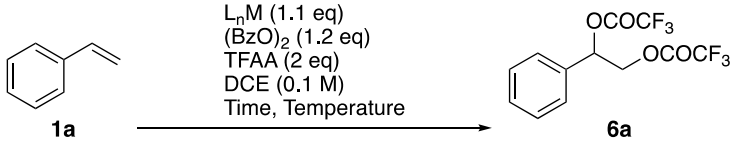
Given this demonstration that diacyloxyselenuranes can indeed perform intermolecular oxidation of alkenes, we wondered why our previous attempts at this reaction had been failing. We suspected that perhaps the presence of water was shutting down the reaction. As mentioned above, there is an equilibrium between the selenoxide and the selenurane, as shown in the equilibrium of **3a** and **4ac** in Figure 1.4 below.

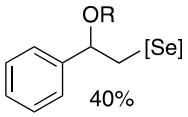
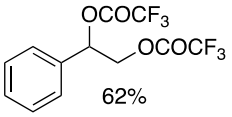
Figure 1.4. Equilibrium Between Selenoxide and Selenurane



Water favors the formation of diphenyl selenoxide **3a** plus benzoic acid. We had observed evidence of both **3a** and byproduct benzoic acid by ^{1}H NMR spectroscopy. The commercial source of benzoyl peroxide we had been using contained 25 weight % water. Another important consideration was our observation that trifluoroacetic anhydride was necessary to obtain a reactive enough intermediate for the reaction to proceed. To address both of these issues we chose to run the reaction with dry benzoyl peroxide in the presence of TFAA. Under these conditions, the reaction gave 40% of diaddition Product A (Table 1.3, entry 1 vs. 2).

Table 1.3. Optimization of Olefin Dibenzoyloxylation



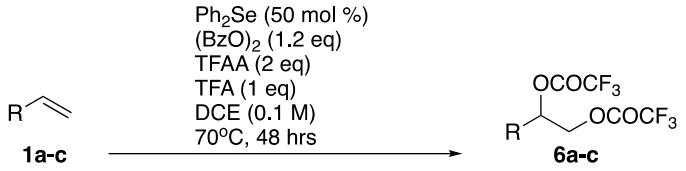
Entry	Catalyst	Temperature	Time	Result[c]
1[a]	Ph_2Se	rt	48 hrs	Ph_2Se=O + SM
2[b]	Ph_2Se	rt	19 hrs	Product A  40%
3[b]	Ph_2Se	70°C	40 hrs	 62%
4[b]	Ph_2S	70°C	40 hrs	NR
5[b]	Ph_2Te	70°C	40 hrs	NR

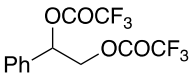
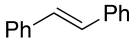
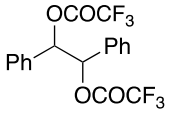
[a]$(BzO)_2$ (25 wt % H_2O). [b]Dry $(BzO)_2$ [c]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

Heating the same reaction to 70 ^oC for 40 hours caused conversion of Product A into desired bis(trifluoroacetate) **6a** in 62% yield (entry 3). Under the same conditions, diphenyl sulfide and diphenyl telluride gave no desired product (entries 4 and 5).

Reaction optimization (additives, equivalents, solvents, concentration) was performed in attempt to improve the yield of the reaction under catalytic conditions (50 mol % diphenyl selenide). The only positive change revealed was that the introduction of trifluoroacetic acid improved the reaction, giving 73% yield of the desired bis(trifluoroacetate) **6a** (Table 1.4, entry 1).

Table 1.4. Alkene Screen for Olefin Dibenzoyloxylation



Entry	Alkene	Result
1	 **1a**	 **6a** 73%
2	 **1b**	Variety of minor products
3	 **1c**	 **6c** 52%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

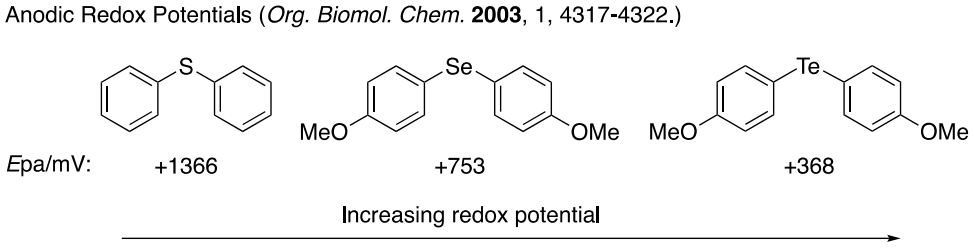
A control reaction without diphenyl selenide gave no detectable amount of product and starting material was recovered. A simple terminal olefin **1b** gave a variety of minor products while stilbene **1c** gave 52% yield of the desired bis(trifluoroacetoxylation) product **6c** (entries 2 and 3). These results suggest that the reaction might require an activated olefin for success.

1.2.4 Rationalization of Empirical Redox Trends

It was becoming clear from our studies and literature precedent that amongst the main group elements considered (S, Se, Te, P, As, Sb, Bi), selenium gave optimal reactivity under the current conditions. When considering the catalytic redox activity of the chalcogens, selenium appears to occupy a “sweet spot” between sulfur and tellurium. We have identified 5 trends we

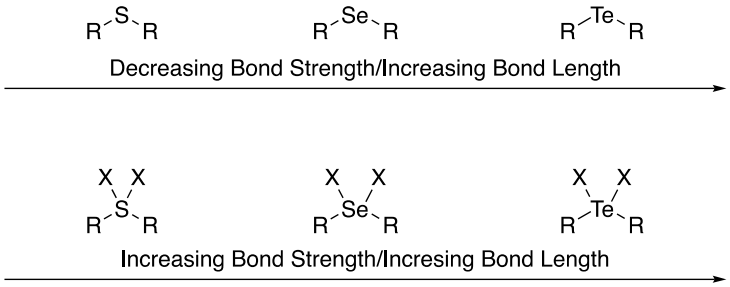
believe are important in explaining this superior reactivity. 1) Oxidation Potential – Amongst the chalcogens selected (S, Se, Te), organotellurides have the lowest anodic oxidation potential (are the easiest to oxidize) while organosulfides have the highest anodic oxidation potential (are the most difficult to oxidize), with organoselenides sitting in between the two (Figure 1.5).[14]

Figure 1.5. Anodic Oxidation Potential of Several Chalcogens



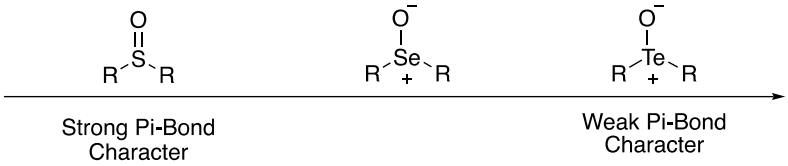
2) Polarizability – This trend is one of several that correlate with atomic mass. Polarizability increases as atomic mass increases, which in turn leads to higher reactivity, both electrophilically and nucleophilically. This can explain the trend in anodic oxidation potential mentioned above; selenium is more polarizable/nucleophilic than sulfur and will therefore be more reactive towards an electrophilic oxidant (i.e. easier to oxidize) and have a lower anodic oxidation potential.[15] This trend also suggests that hypervalent selenuranes and telluranes are stronger electrophiles than sulfuranes. 3) Bond Lengths/Strength – Bond strengths typically decrease when moving down a column of the periodic table. A rare example to the contrary is seen in hypervalent species, where higher bond strengths are observed for heavier elements. Bond lengths for both normal valent and hypervalent species increase when moving down the periodic table. (Note: Shorter bonds don't always indicate stronger bonds.[16])

Figure 1.6. Bond Length & Strength Trends Amongst Several Chalcogens



In hypervalent species, these longer bonds reduce destabilizing steric interactions between the increased number of substituents on the chalcogen. 4) Ability to Form Pi Bonds – The ability to form pi-bonds decreases as one moves down the periodic table. Selenium and tellurium have drastically reduced abilities to form pi bonds. Consider, for example, the chalcogen oxide species, $L_nM{=}O$ (Figure 1.7).

Figure 1.7. Pi Bond Character Amongst Several Chalcogen Oxides

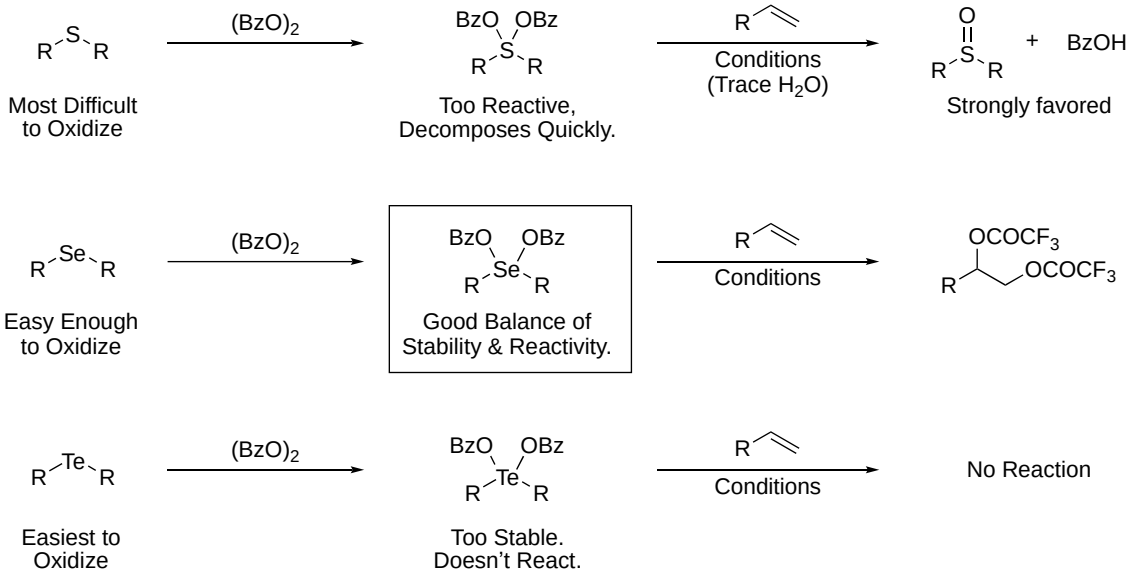


Sulfoxides can participate in back-bonding via donation of the oxygen lone pair electrons to acceptor orbitals on sulfur. As a result, sulfoxides have much more pi bond character than selenoxides or telluroxides, and sulfoxides are incredibly stable and often form irreversibly. 5) Stability of Hypervalent Chalcogen Species – The previous two trends can be combined to explain the observation that heavier elements can better tolerate hypervalent structures. Telluranes and selenuranes are much more stable than sulfuranes and are thus formed much more readily. On the contrary, sulfuranes are high in energy and quickly decompose, commonly to sulfoxide species, even at very low temperatures. This trend in ease of formation of hypervalent species is true both for formation of sulfuranes, selenuranes and telluranes via oxidation from a

normal valency sulfide, selenide or telluride, and for their formation from addition of an acyl anhydride to sulfoxides, selenoxides, and telluroxides.

Considering these five trends together, we speculate that organoselenides are easy enough to oxidize under catalytically relevant conditions, and that the hypervalent selenuranes are stable enough to exist for kinetically useful periods of time while simultaneously being reactive enough to participate in redox chemistry with alkenes. On the other hand, sulfuranes are often too unstable and telluranes are too stable to be useful (Scheme 1.4).

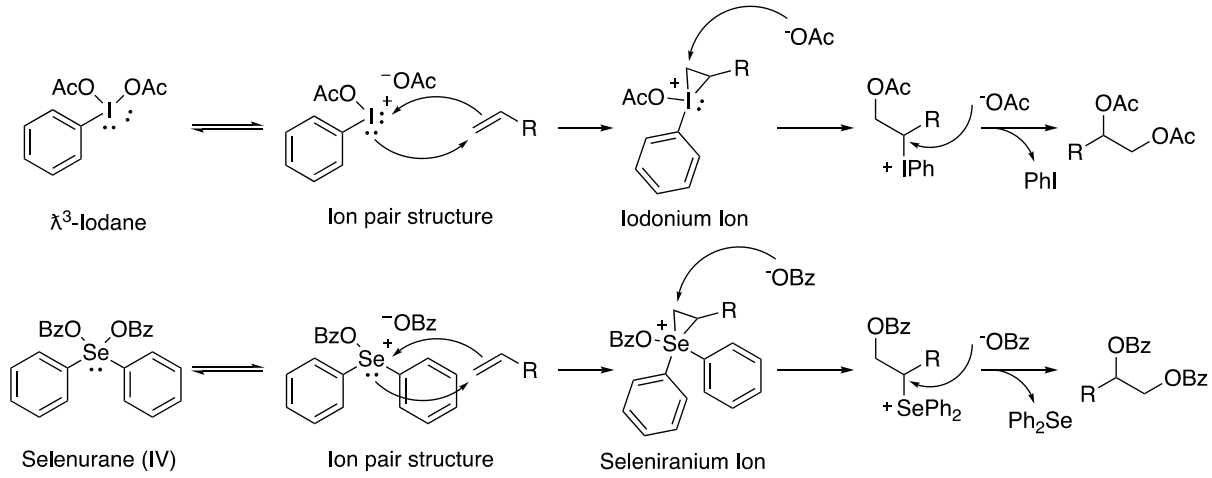
Scheme 1.4. Conversion of Trends to Explain Empirical Redox Ability in Olefin Diadditions



1.2.5 Analogy Between Hypervalent Selenium and Hypervalent Iodine

An analogy can be drawn between hypervalent selenium and iodine-(III) reagents and their success in promoting oxidative transformations of alkenes (Figure 1.8)

Figure 1.8. Analogy Between Hypervalent Iodine and Hypervalent Selenium



Hypervalent iodine-(III) reagents, or λ3-iodanes, are isoelectronic to selenium (IV) reagents, or selenuranes. Both λ3-iodanes and selenuranes can exist in equilibrium with a reactive ion-pair structure in which one of the ligands has dissociated.[13b,17] These ion pair intermediates are electrophilic and react with alkenes to generate iodonium ions and seleniranium ions.[9] From here, a nucleophile can open the iodonium or seleniranium to give a covalent C-I or C-Se bond, respectively, which can be displaced by a second nucleophile to give an oxidative difunctionalization product.

Section 3: Conclusions

In an effort to move away from transition metal-based catalysts, key stoichiometric transformations of alkenes were explored with a range of main group elements. With the goal of observing empirical trends in relative redox abilities, a variety of main group elements were tested in a diacyloxylation reaction of alkenes. Of all of the chalcogens (S, Se, Te) and pnictogens (P, As, Sb, Bi) tested, only selenium and tellurium gave any observable hypervalent intermediates, and further only the hypervalent selenuranes gave an observable reaction with styrene. It was discovered that a water-free environment is a necessary condition for obtaining the hypervalent

selenuranes, as the presence of water favors the selenoxide, which does not show reactivity towards the alkene. This equilibrium between the selenurane and the selenoxide can be pushed towards the selenurane by using acyl anhydrides. Diacetoxyselenurane showed no reaction towards the alkene while bis(trifluoroacetoxy)selenurane did, suggesting that the ability to form a more reactive ion pair structure via dissociation of a good leaving group is important. ^{1}H NMR studies show that under the reaction conditions there is formation of an initial product believed to be a covalently bound selenium intermediate, which slowly converts into the desired bis(trifluoroacetate) and an unknown product C, which we speculate is a mixed OH/TFA incorporation product. A brief optimization revealed that the presence of trifluoroacetic acid improved the yield of the initial Product A, and heating to 70 ^{o}C caused quicker and cleaner conversion into the desired bis(trifluoroacetoxylation) product. A screen of several alkenes suggests that the reaction might require an activated alkene for success. With these initial observations in hand, we sought to explore other organoselenium catalyzed oxidative functionalizations of alkenes, particularly those giving C-N bond formation.

Section 4: Experimental

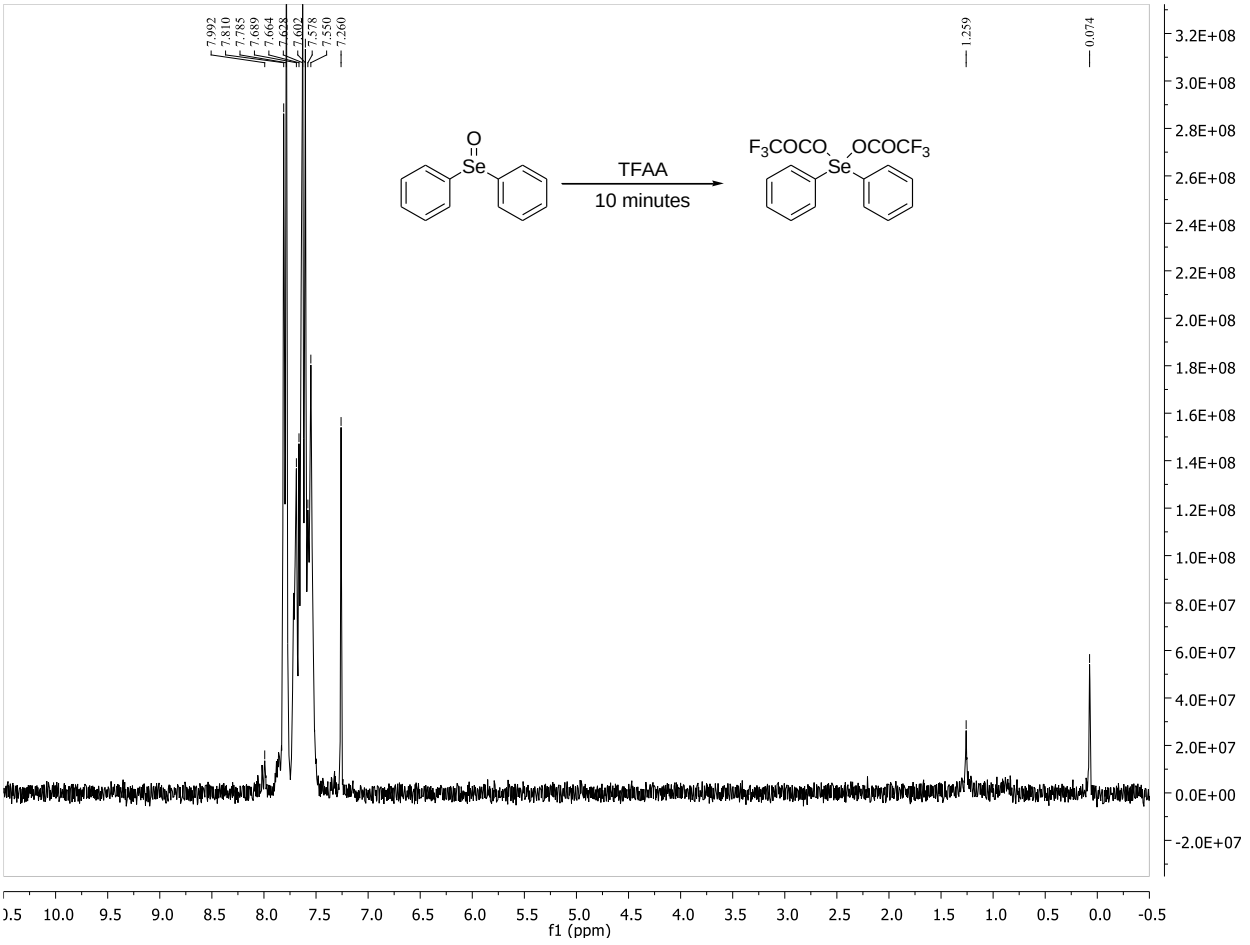
General Procedures. All reactions were performed under a nitrogen atmosphere using flame-dried glassware unless otherwise noted. Infrared spectra were measured on a Perkin Elmer Spectrum RX I spectrometer. Mass spectra were collected on a Hewlett Packard 5971A Gas Chromatograph - Mass Spectrometer or Bruker Esquire 1100 Liquid Chromatograph - Ion Trap Mass Spectrometer. Column chromatography was performed using silica gel (Whatman, 60 Å, 230-400 mesh). NMR spectra were recorded on a Bruker AV-300, AV-301, DRX-499 or AV-500 spectrometer. ^{1}H NMR chemical shifts (δ) are reported in parts per million (ppm) and are

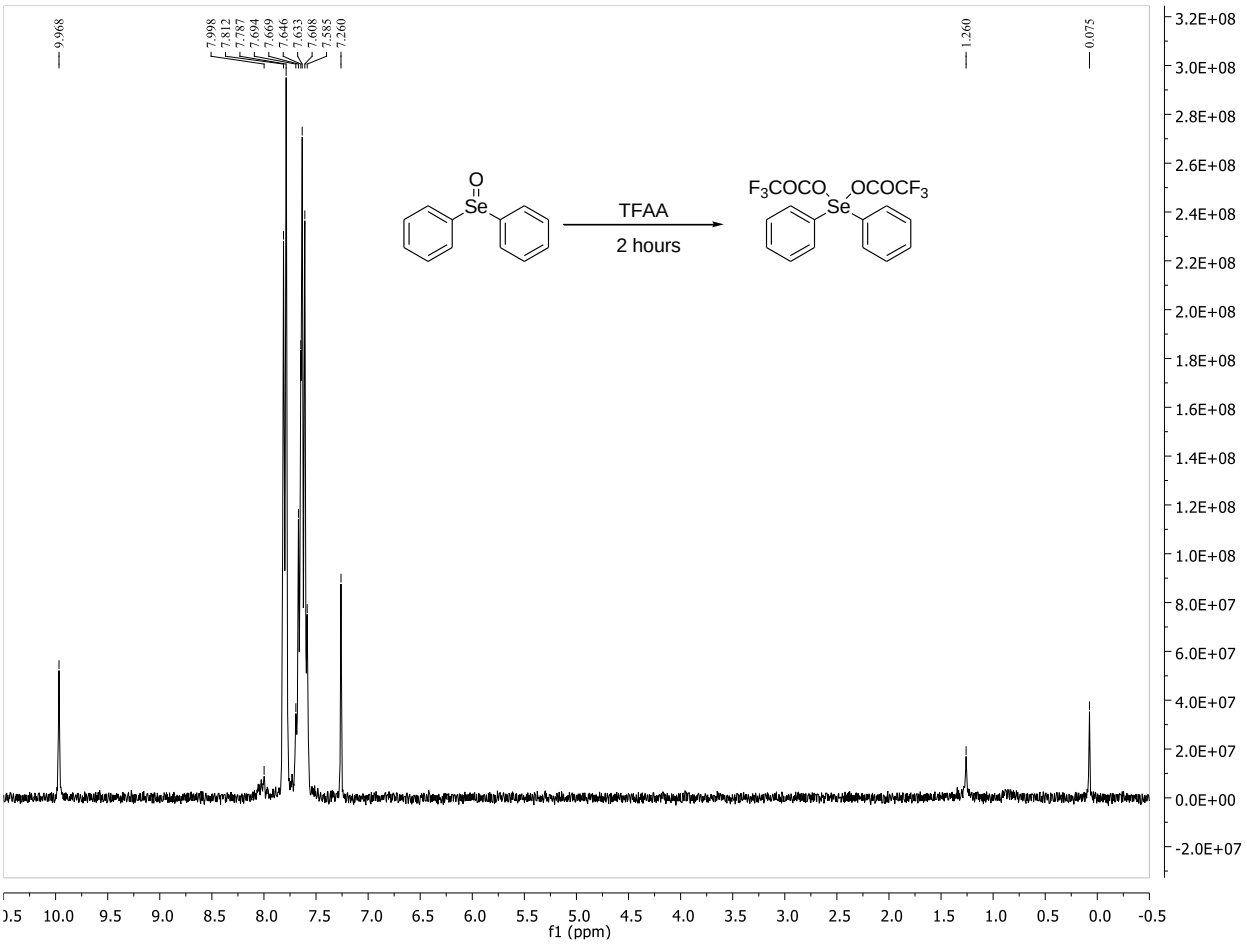
referenced relative to TMS (0.00 ppm) or residual $CHCl_3$ (7.26 ppm). ^{13}C NMR chemical shifts (δ) are reported in parts per million (ppm) relative to the carbon resonance of $CDCl_3$ (77.16 ppm). Melting points were taken on a MEL-TEMP melting point apparatus and are uncorrected.

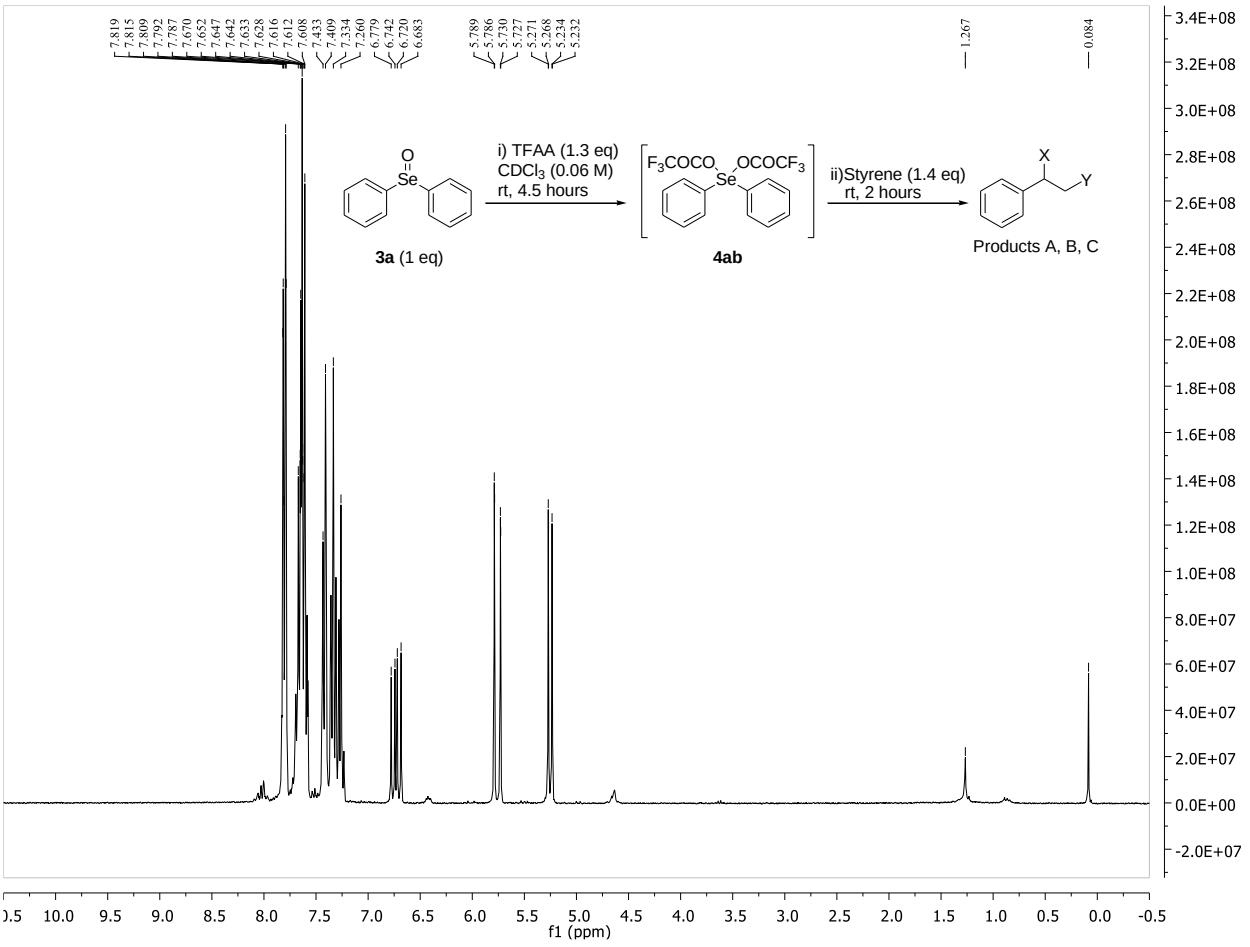
Materials. All commercial reagents were used as received, unless otherwise noted. All solvents were degassed and dried on solvent columns of neutral alumina. Deuterated solvents were purchased from Cambridge Isotope Laboratories Inc., stored over 4 Å molecular sieves, and were used without further purification. Diphenyl selenide and diphenyl telluride[18], diphenyl sulfoxide, diphenyl selenoxide and diphenyl telluroxide[19], and 1-phenyl-1,2-bis(trifluoroacetoxy)ethane[20] were prepared according to previously published procedures and their respective spectroscopic signatures (^1H NMR) were found to be consistent with values reported therein.

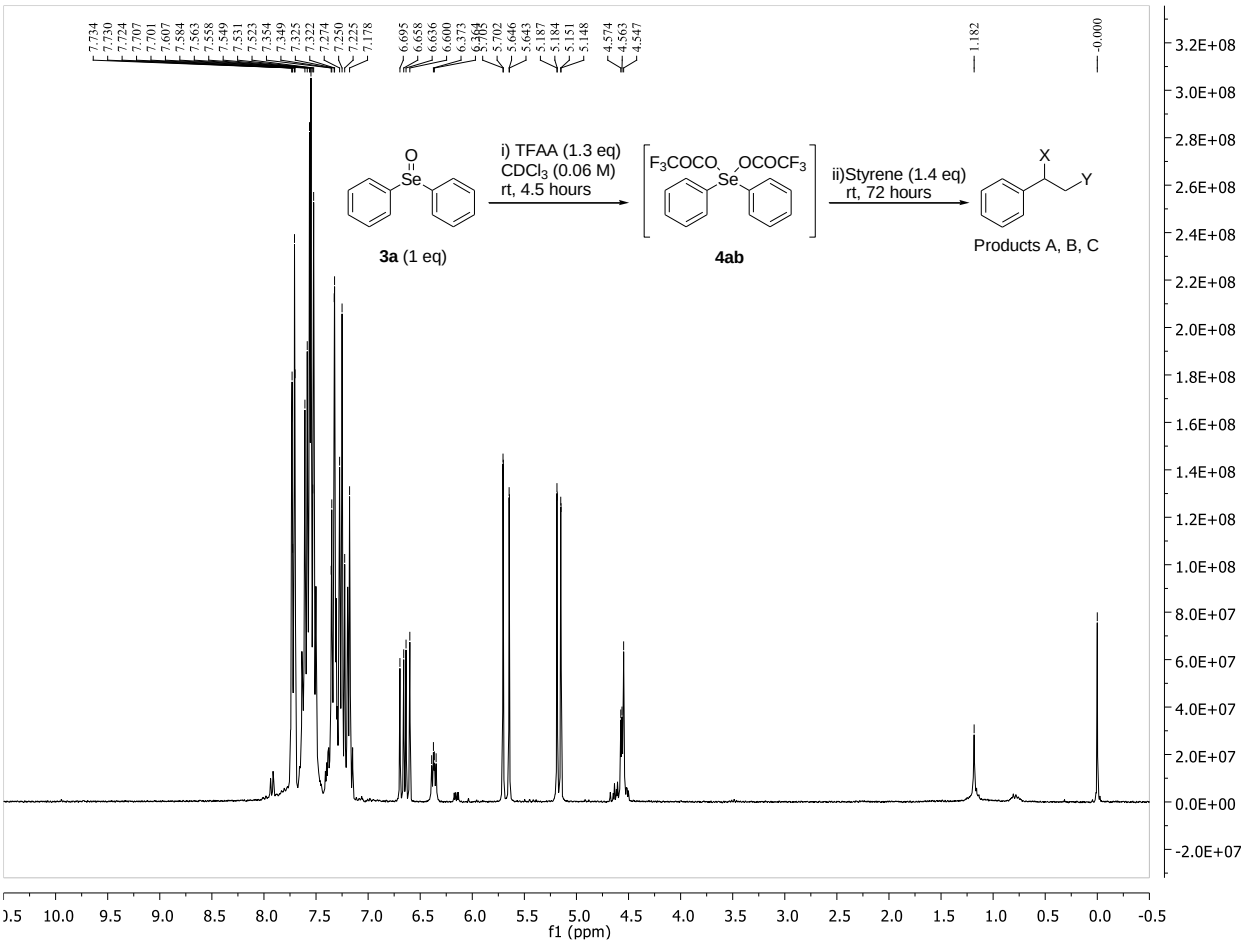
General Procedure A for the synthesis of 1,2-bis-trifluoroacetate products. To a flame-dried 1-dram vial was added a stir bar and benzoyl peroxide (58.1 mg, 1.2 eq). The vial was flushed with nitrogen. Next, DCE (2 mL, 0.1 M), diphenyl diselenide (12.5 mg, 20 mol %), TFAA (56.5 uL, 2 eq), TFA (15.3 uL, 1 eq) and styrene (22.9 uL, 1 eq) were added sequentially. The vial was capped and stirred at 70 degrees C and was monitored by TLC for conversion. Upon completion, the reaction was diluted with ether and washed with thiosulfate, sodium bicarb then water. The mixture was concentrated in vacuo and a crude NMR was taken.

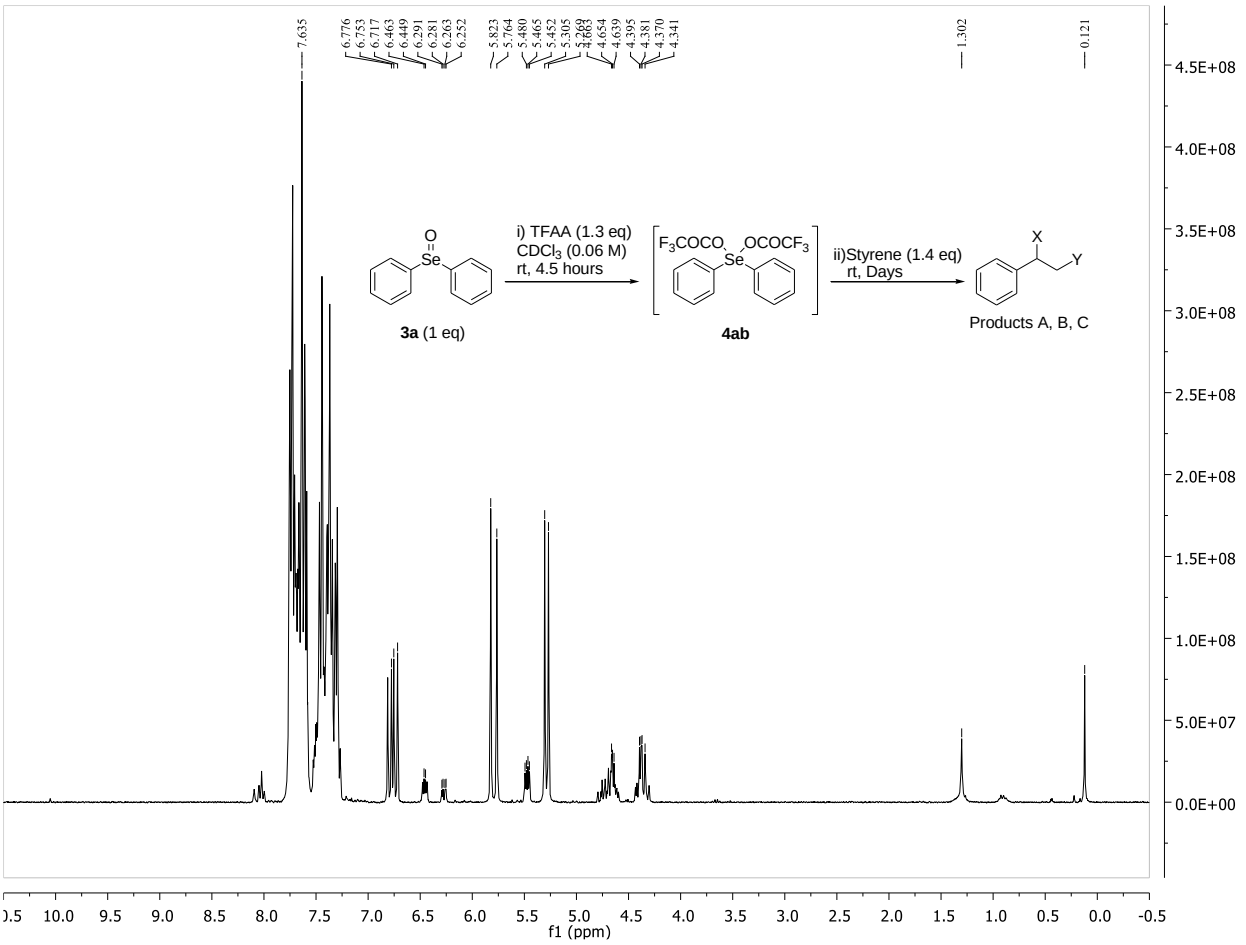
NMR Studies


7.992
7.810
7.785
7.689
7.664
7.628
7.602
7.578
7.550
7.260
1.259
0.074
O
Se
TFAA
10 minutes
F3COCO
OCOCF3
Se
3.2E+08
3.0E+08
2.8E+08
2.6E+08
2.4E+08
2.2E+08
2.0E+08
1.8E+08
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
-2.0E+07
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)

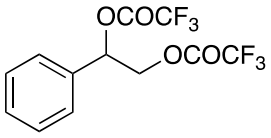

9.968
7.998
7.812
7.787
7.694
7.669
7.646
7.633
7.608
7.585
7.260
1.260
0.075
O
Se
TFAA
2 hours
F3COCO
OCOCF3
Se
3.2E+08
3.0E+08
2.8E+08
2.6E+08
2.4E+08
2.2E+08
2.0E+08
1.8E+08
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
-2.0E+07
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)


7.819
7.815
7.809
7.792
7.787
7.670
7.652
7.647
7.642
7.633
7.628
7.616
7.612
7.608
7.433
7.409
7.334
7.260
6.779
6.742
6.720
6.683
5.789
5.786
5.730
5.727
5.271
5.268
5.234
5.232
1.267
0.084
O
Se
i) TFAA (1.3 eq)
CDCl3 (0.06 M)
rt, 4.5 hours
F3COCO
Se
OCOCF3
ii)Styrene (1.4 eq)
rt, 2 hours
X
Y
3a (1 eq)
4ab
Products A, B, C
3.4E+08
3.2E+08
3.0E+08
2.8E+08
2.6E+08
2.4E+08
2.2E+08
2.0E+08
1.8E+08
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
-2.0E+07
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)

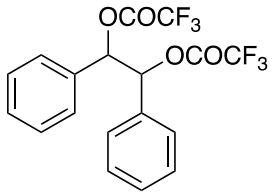

7.734
7.730
7.724
7.707
7.701
7.607
7.584
7.563
7.558
7.549
7.531
7.523
7.354
7.349
7.325
7.322
7.274
7.250
7.225
7.178
6.695
6.658
6.636
6.600
6.373
6.364
5.705
5.702
5.646
5.643
5.187
5.184
5.151
5.148
4.574
4.563
4.547
1.182
-0.000
O
Se
3a (1 eq)
i) TFAA (1.3 eq)
CDCl3 (0.06 M)
rt, 4.5 hours
F3COCO
OCOCF3
Se
4ab
ii)Styrene (1.4 eq)
rt, 72 hours
X
Y
Products A, B, C
3.2E+08
3.0E+08
2.8E+08
2.6E+08
2.4E+08
2.2E+08
2.0E+08
1.8E+08
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
-2.0E+07
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
f1 (ppm)



Characterization of Products



1-phenyl-1,2-bis(trifluoroacetoxy)ethane (6a). Synthesized according to General Procedure A. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.54 – 7.35 (m, 5H), 6.23 (dd, J = 8.8, 3.1 Hz, 1H), 4.72 (dd, J = 12.2, 8.9 Hz, 1H), 4.61 (dd, J = 12.2, 3.2 Hz, 1H).



1,2-diphenyl-1,2-bis(trifluoroacetoxy)ethane (6c). Synthesized according to General Procedure A and identified by diagnostic peaks listed here: **$_1$H NMR (300 MHz, CDCl$_3$):** δ 6.22 (d, J = 7.1 Hz, 2H).

Notes to Chapter 1.

1) Zhou, Q. L. *Angew. Chem. Int. Ed.* **2016**, 55, 5352-5353.
2) Ludwig, J. R.; Schindler, C. S. *Chem*, **2017**, 2, 331-316.
3) Ghosh, R.; Lindstedt, E.; Jalalian, N.; Olofsson, B. *ChemistryOpen*, **2014**, 3, 54-57.
4) For examples of transition metal-catalyzed oxidations, see: a) Punniyamurthy, T.; Velusamy, S.; Iqbal, J. Chem. Rev. 2005, 105, 2329−2363. b) Togni, A., Grutzmacher, H., Eds. Catalytic Heterofunctionalization; Wiley-VCH: Weinheim, 2001. c) Lin, J.; Hu, Ming.; Li, J. H. *Chem. Rec*. **2019**, 19, 440–451.
5) Selected examples: (a) Michael, F. E.; Sibbald, P. A.; Cochran, B. M. *Org. Lett.* **2008**, 10, 793-796. (b) Cochran, B. M.; Michael, F. E. *Org. Lett.* **2008**, 10, 5093-5042. (c) Rosewall, C. F.; Sibbald, P. A.; Liskin, D. V.; Michael, F. E. *J. Am. Chem. Soc.* **2009**, 131, 9488-9489. (d) Sibbald, P. A.; Rosewall, C. F.; Swartz, R. D.; Michael, F. E. *J. Am. Chem. Soc.* **2009**, 131, 15945-15951. (e) Sibbald, P. A.; Michael, F. E. *Org. Lett.* **2009**, 11, 1147-1149. (f) Lovick, H. M.; Michael, F. E. *J. Am. Chem. Soc.* **2010**, 132, 1249-1251.
6) Biffis, A.; Centomo, P.; Zotto, A. D.; Zecca, M. *Chem. Rev.* **2018**, 118, 2249-2295.
7) (a) W. B. Jensen, *J. Chem. Educ*., **2006**, 83, 1751–1752. (b) Durrant, M. C. *Chem. Sci.* **2015**, 6, 6614-6623. (c) R. E. Rundle, *J. Chem. Phys*. **1949**, 17, 671-675.
8) (a) Knight, F. R.; Fuller, A. L.; Buhl, M.; Slawin, A. M. Z.; Woollins, J. D. *Inorg. Chem*. **2010**, 49, 7577-7596. (b) Rat, C. I.; Silvestru, C.; Breunig, H. J. *Coord. Chem. Rev*. **2013**, 257, 818-879. (c) *Chemistry of Hypervalent Compounds*; Akiba, K. y., Ed.; WileyVCH: New York, 1999.

9) Hypervalent iodine review: (a) Yoshimura, A.; Zhdankin, V. V.*Chem. Rev*. **2016**, 116, 3328−3435. (b) Lee, J. H.; Choi, S.; Hong, K. B. *Molecules*, **2019**, 24, 2634-2657. (c) Selected example: Kitamura, Tsugio.; Miyake, A.; Muta, K.; Oyamada, J. *J. Org. Chem.* **2017**, 82, 11721-11726.

10) Choudary, B. M.; Chodari, N. S.; Jyothi, K.; Kantam, M. L. *J. Am. Chem. Soc.*, **2002**, *124*, 5341-5349.

11) Seayad, J.; Seayad, A. M.; Chai, C. L. L. *Org. Lett.* **2010**, 12, 1412-1415.

12) (a) Marino, J. P.; Larsen, R. D. *J. Am. Chem. Soc.* **1981**, 103, 4642-4643. (b) Foster, D. G. *Recl. Trav. Chim. Pays-Bas*, **1935**, 54, 447.

13) (a) The intramolecular transfer of benzoyloxy groups from a dibenzoyloxyselenurane to a pendant alkene is known: Okamoto, Y.; Homsany, R. Yano, T. Tet. Lett. **1972**, 25, 2529-2531. (b) Ion pair intermediate: Okamoto, Y.; Chellappa, K. L.; Homsany, R. *J. Org. Chem*. **1973**, 88, 3172-3175.

14) Giles, G. I.; Fry, F. H.; Tasker, K. M.; Holme, A. L.; Peers, C.; Green, K. N.; Klotz, L. O.; Sies, H.; Jacob, C. *Org. Biomol. Chem*. **2003**, 1, 4317–4322.

15) Reich, H. J.; Hondal, R. J. *ACS Chem. Biol*. **2016**, 11, 821−841

16) Kaupp, M.; Metz, B.; Stoll, H. *Angew. Chem. Int. Ed*. **2000**, 39, 4607-4609.

17) Lee, J. H.; Choi, S.; Hong, K. B. *Molecules* **2019**, *24*, 2634-2657.

18) Wang, L.; Wang, M.; Huang, F. *Synlett*. **2005**, 13, 2007–2010

19) Nicolaou, K. C.; Koumbis, A. E.; Snyder, S. A.; Simonsen, K. B. *Angew. Chem. Int. Ed*. **2000**, 39, 2529-2533.

20) Tellitu, I.; Dominguez, E. *Tetrahedron*. **2008**, 64, 2465-2470.

Chapter 2 – Phosphine Selenide-Catalyzed Regioselective Aza-Heck Reaction of Terminal Alkenes[1]

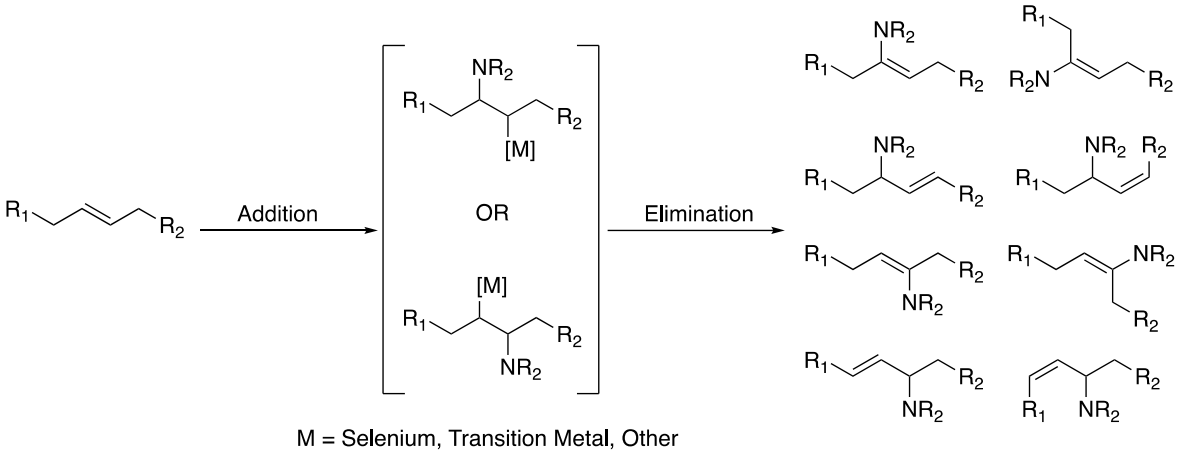
Section 1: Introduction

As mentioned in Chapter 1, our goal was to develop a new class of catalysts that could serve to replace transition metals in oxidative alkene functionalization reactions. Through our initial exploration we discovered that organoselenium reagents are successful in catalyzing redox chemistry with alkenes. Aside from the obvious success in terms of achieving desired reactivity, selenium has other advantages when compared to transition metals. Selenium is significantly cheaper than most of the transition metals, is readily available in bulk quantities, and many selenium-based catalysts are air- and moisture-stable. There has been exploration into the use of selenium catalysts to achieve different types of transformations, however, the depth of this research is significantly less than that undertaken with more traditional transition metal catalysts such as palladium or nickel. This contrast is even more notable when taking into consideration selenium catalysts' ability to achieve many of the highly desirable transformations that typically require transition metals. Consequently, the continued exploration of selenium-based catalysis is an important endeavor.

It has been demonstrated that organoselenium reagents can catalyze oxidative transformations of alkenes resulting in a variety of vinyl- or allyl-functionalized products.[2,3] Given the ubiquitous presence of carbon-nitrogen bonds in agrochemicals, pharmaceuticals, biologically relevant compounds, and other highly desirable products[4], we sought to utilize this mode of reactivity to achieve a direct, oxidative C-N bond formation starting from alkenes. We imagined that one of the biggest obstacles to achieving such a transformation would be exercising control of the regioselectivity and stereoselectivity. Regardless of the class of catalysis (selenium, transition

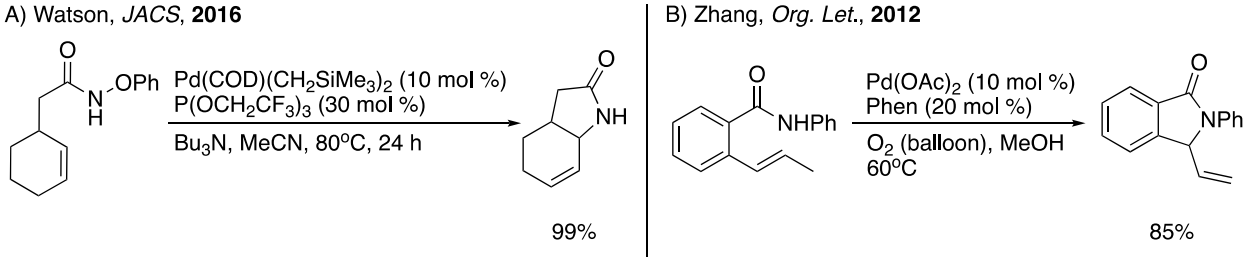
metal, other), these aza-Heck/aza-Wacker transformations proceeding through an addition-elimination sequence suffer from the same universal selectivity obstacles. To illustrate this, consider the following typical mechanism for an addition-elimination sequence (Scheme 2.1).

Scheme 2.1. Regio- and Stereochemical Possibilities in Addition-Elimination Reactions



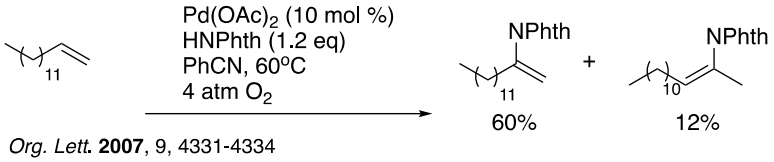
The addition of a metal (or selenium) and a nitrogen across a C=C bond can yield two possible regioisomeric intermediates, each of which can eliminate in two different directions. Furthermore, each elimination can produce an *E*- or *Z*-isomer of the product. The net result is that there are as many as eight potential regio- and stereoisomeric products from which the selectivity of a single one in absence of the others is desired. Using palladium catalysis, this obstacle has been circumvented by the use of highly engineered substrates in which the nucleophile and alkene are tethered to one another, resulting in an intramolecular reaction (Scheme 2.2).[5,6]

Scheme 2.2. Intramolecular Pd-Catalyzed Aza-Heck Reactions of Alkenes



While providing high selectivity for a single isomer, the intramolecularity of these reactions severely limits the generality of the substrate scope, resulting in limited product diversity. When the reaction is performed intermolecularly on simple, unactivated olefins the regio- and stereoselectivities often suffer (Scheme 2.3).[7,8]

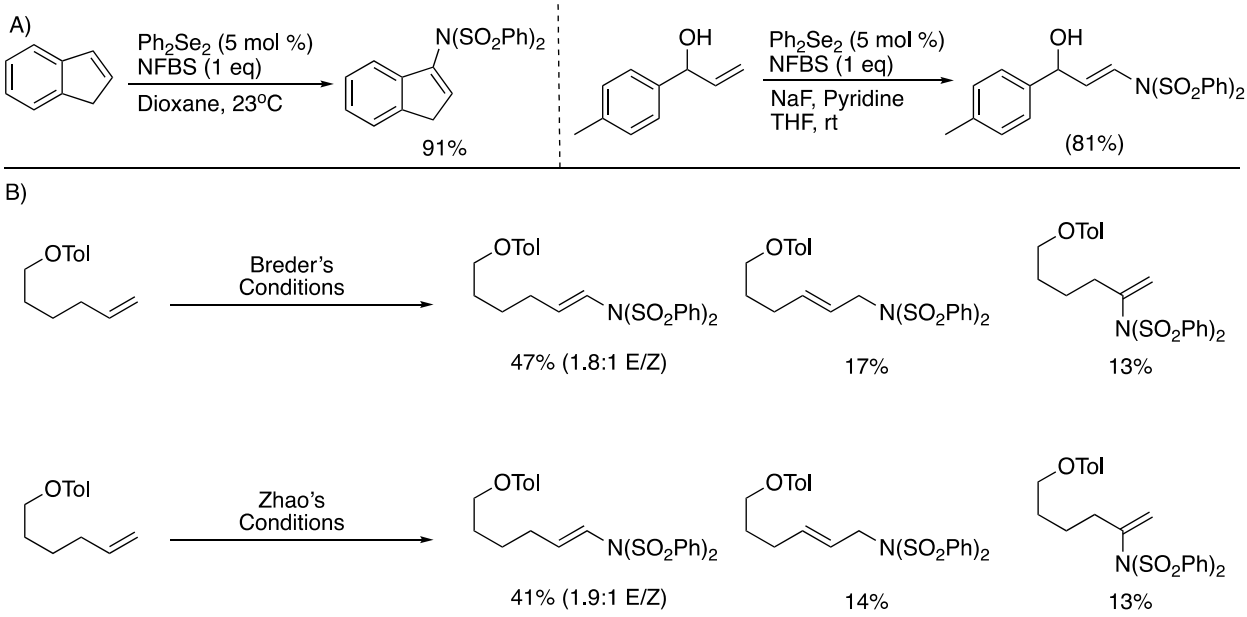
Scheme 2.3. Intermolecular Palladium-Catalyzed Aza-Heck Reaction of Alkenes



Org. Lett. **2007**, 9, 4331-4334

Breder[9] and Zhao[10] have achieved high regioselectivities in aza-Heck reactions of styrenes and allylic alcohols, respectively, using diphenyl diselenide as a catalyst (Scheme 2.4a).

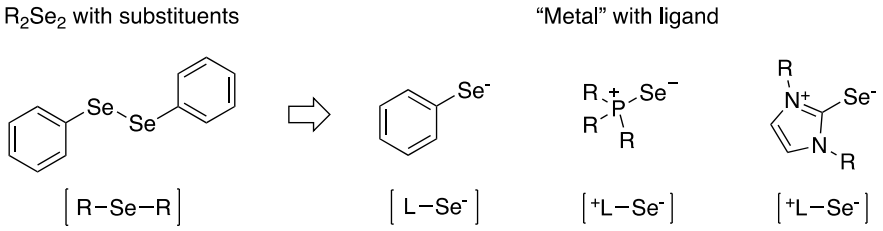
Scheme 2.4. Diphenyl Diselenide Catalyzed Aza-Heck Reactions of Alkenes



However, their conditions gave poor regioselectivity when applied to a simple, terminal olefin, resulting in mixtures of four regio- and stereoisomers (Scheme 2.4b). While the combined yields of these examples suggest that organoselenium catalysis holds promise as a potential solution to current problems in synthetic chemistry, the further development of this field is hindered by the

difficulty of synthesizing a diverse set of difunctionalized diselenide catalysts. The vast majority of chemistry in this field is conducted with commercially available diphenyl diselenide. Difunctionalized diselenides are synthesized under strongly basic conditions, prohibiting the incorporation of sensitive functional groups.[11] Additionally, only alkyl or aryl groups are tolerated as substituents on selenium, drastically limiting the diversity of this catalyst class. Our approach to improving the utility of selenium catalysis was made possible by viewing these catalysts from a different perspective. We hypothesized that the selectivity of reactions catalyzed by selenium compounds could be improved by conceiving of the phenyl group (of diphenyl diselenide) as a ligand for selenium rather than a substituent. By conceptualizing these reagents more like a metal with ligands, rather than a diselenide with substituents, we were able to imagine a much broader variety of catalysts encompassing more steric and electronic diversity (Figure 2.1). This new diversity stands in stark contrast to the lack of steric and electronic variety accessible with dialkyl- or diaryl diselenides.

Figure 2.1. Conceptual Framework for New Selenium Catalyst Design



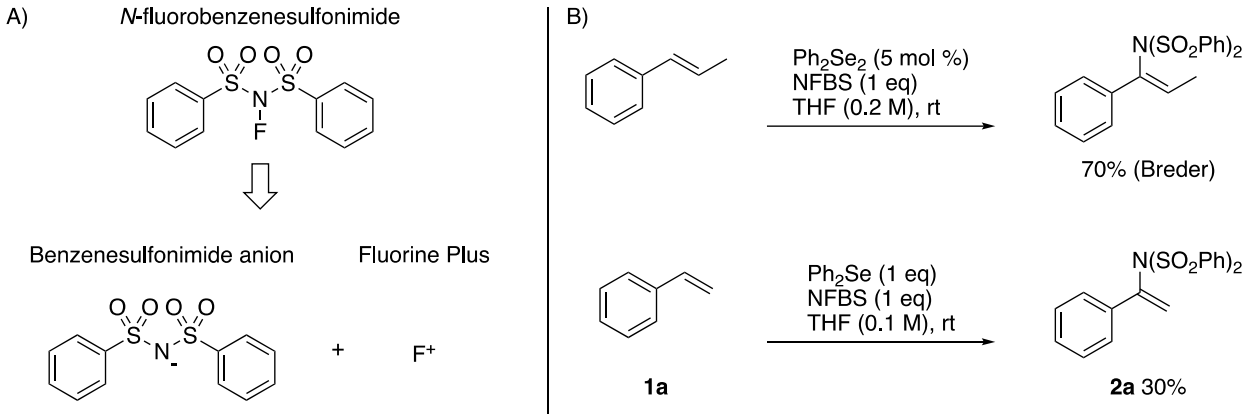
With this new conceptual model, the design and subsequent synthesis of a new selenium-based catalyst library was possible. We hoped to use this new catalyst library to improve the yield, selectivity and substrate scope of this reaction, and further, to discover new selenium-catalyzed transformations.

Section 2: Results and Discussion

2.2.1 Catalyst Exploration – Diaryl Selenides

Although it has been suggested that the Se-Se bond is necessary for catalytic activity[9], we wondered if other classes of catalysts, such as monoselenides, could be successfully employed in the reaction. With this goal in mind, we sought to directly compare diphenyl diselenide with the analogous monoselenide catalyst, diphenyl selenide. The oxidant chosen for these reactions was *N*-fluorobenzenesulfonimide (NFBS), which is a source of "F^+" equivalent along with an equivalent of anionic benzenesulfonimide (Scheme 2.5a). Reaction of styrene **1a** with stoichiometric diphenyl selenide in the presence of NFBS gave 30% yield of the desired vinyl amination product **2a** (Scheme 2.5b).

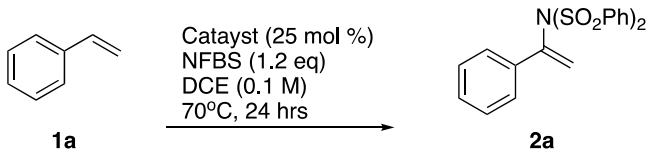
Scheme 2.5. Comparison of Diphenyl Diselenide with Diphenyl Selenide



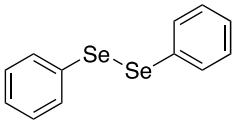
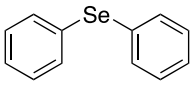
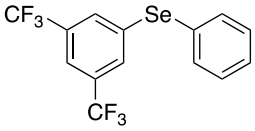
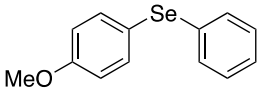
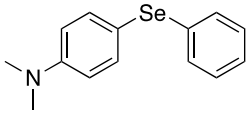
Even under stoichiometric conditions, diphenyl selenide was much less effective than catalytic diphenyl diselenide. In the hopes of improving the yield obtained using diphenyl selenide as a catalyst, reaction optimization was performed. Screens of solvents, elevated temperatures (up to 70 ^oC), acid additives (BzOH, $HN(SO_2Ph)_2$, TFA) and the introduction of molecular sieves (4Å) provided no improvement to the yield. We next turned to the possibility of improving the yield by

tuning the catalyst. A variety of functionalized diaryl selenides were synthesized and screened in order to probe the electronic effects of the catalyst on the yield (Table 2.1).

Table 2.1. Diaryl Selenide Catalyst Screen



1a **2a**

Entry	Catalyst	Yield **2a**
1		80%
2		13%
3		17%
4		37%
5		45%

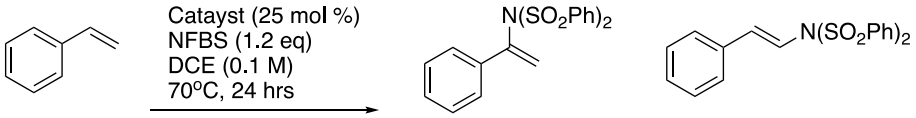
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

Electron donating substituents on the phenyl ring provided an increase in yield (entries 4, 5 vs. 2), but the diaryl selenides were still far inferior than the commonly used diphenyl diselenide (entry 1). At this point we sought to continue to explore other classes of mono-selenide catalysts such as imidazolium derived N-heterocyclic carbene (NHC)-selenides and phosphine selenides.

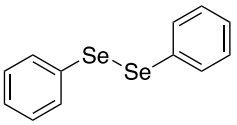
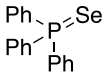
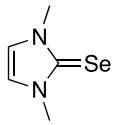
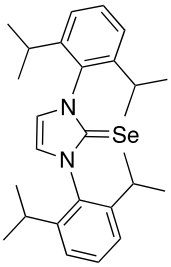
2.2.2 Catalyst Exploration – NHC-Selenides and Phosphine Selenides

As seen in Table 2.2, NHC-selenides and phosphine selenides were much more effective than diaryl selenides, giving yields comparable to those of diphenyl diselenide.

Table 2.2. Catalyst Screen – Ph_2Se_2, Phosphine Selenides, NHC-Selenides



1a **2a** **4a**

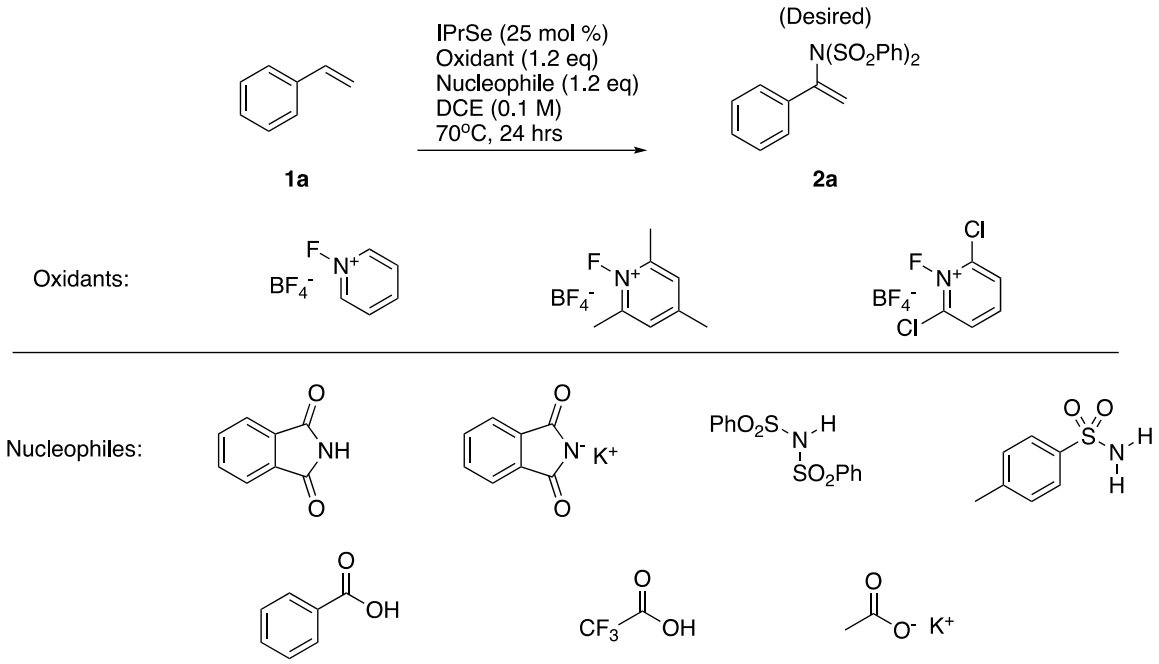
Entry	Catalyst	Yield **2a**	Yield **2b**
1		80%	-
2		65%	-
3		72%	5%
4		86%	-

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

These results were exciting because these catalyst classes can be synthetically diversified much easier than both diaryl diselenides and diaryl selenides, and thorough tuning of the catalyst design can be rapidly and easily achieved. All of the phosphine selenides can be made in a single step by stirring phosphine ligand with selenium powder, assuming the phosphine is commercially available. Given that IPrSe (entry 4) gave the most desirable reactivity, we sought to examine if we could use this catalyst in combination with other N-F oxidants, such as N-fluoropyridinium salts, in the presence of exogenous nucleophiles to incorporate different groups at the vinyl position. It was hoped that oxidants with non-nucleophilic nitrogen leaving groups, such as N-fluoropyridiniums, might allow for an exogenous nucleophile to participate. Several N-

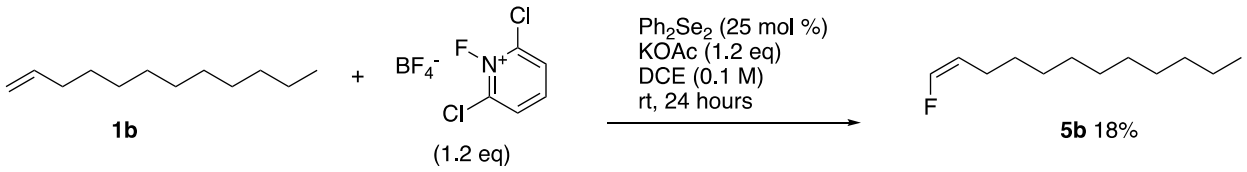
fluoropyridinum oxidants were screened, each in combination with a variety of nucleophiles, but no desired vinyl amination products were obtained. (Scheme 2.6).

Scheme 2.6. Oxidant/Nucleophile Screen



Diphenyl diselenide was also screened as a catalyst with these nucleophile/oxidant combinations but, again, no products were observed aside from an interesting product formed under the conditions shown in Figure 2.2 below. The product appears to be vinyl fluorination product **5b**, however the identity of this product was not confirmed by any means other than ^{1}H NMR spectroscopy.

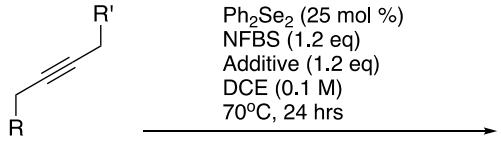
Figure 2.2. Vinyl Fluorination Product

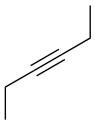
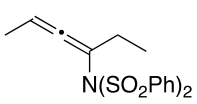
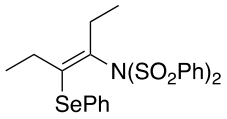
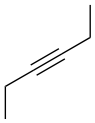
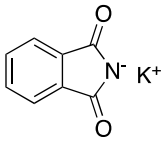
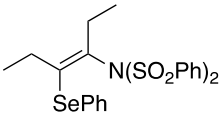
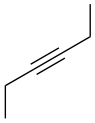
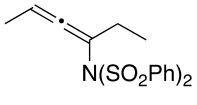
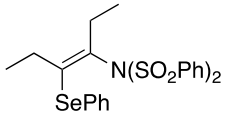
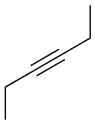
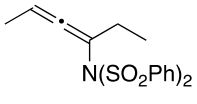
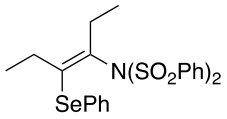
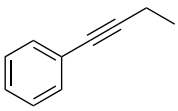
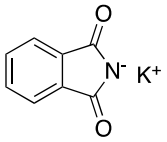
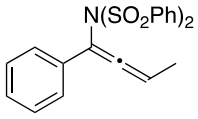
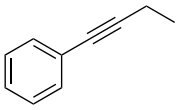
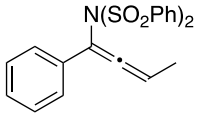


2.2.3 Alkyne Exploration with Current Conditions

(NOTE: None of the products in Section 2.2.3 were characterized by any means other than ^{1}H NMR, unless otherwise noted.) Given the fact that we were observing desirable reactivity with alkenes, we were interested to see what alkynes would do under the same conditions. A screen of several alkynes with diphenyl diselenide as a catalyst and NFBS as oxidant in the presence of a variety of nucleophiles/bases gave unexpected results (Table 2.3).

Table 2.3. Initial Alkyne Screen Under Current Conditions



Entry	Alkyne	Additive	Result
1		-	 16% +  48%
2			 23%
3		$HN(SO_2Ph)_2$	 14% +  40%
4		KOAc	 38% +  50%
5			 26%
6		$HN(SO_2Ph)_2$	 24%

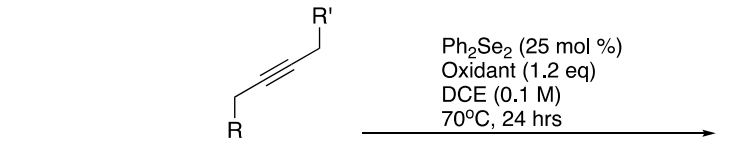
[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

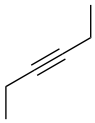
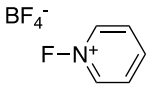
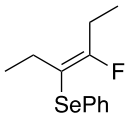
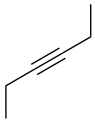
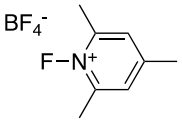
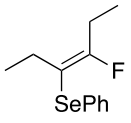
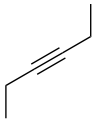
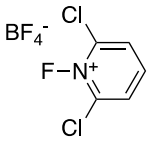
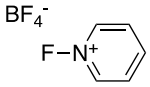
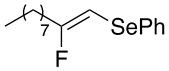
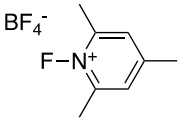
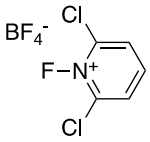
It was observed that 3-hexyne gave a mixture of two products which we suspect are an N-substituted allene product and a diaddition product containing a covalent carbon selenium bond (entry 1). Potassium acetate appeared to increase the reactivity, giving higher conversion to the

allene (entry 4). The analogous allene product was also obtained with 1-phenyl-1-butyne (entries 4, 5).

A screen of N-fluoropyridinium oxidants with several alkynes gave different reactivity.

Table 2.4. Alkynes with N-Fluoropyridinium Oxidants



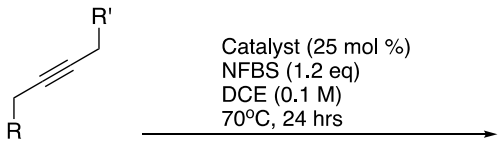
Entry	Alkyne	Oxidant	Result
			 25%
			 10%
			Minor products
			 15%
			Minor products
			Minor products

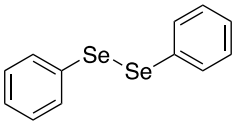
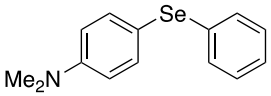
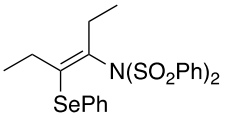
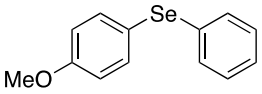
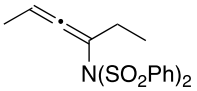
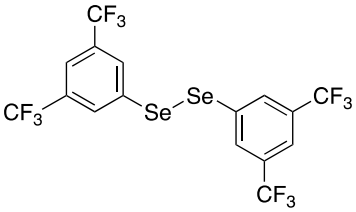
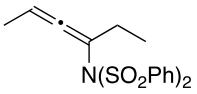
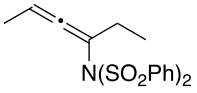
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

Both alkynes gave diaddition products that we suspect are from incorporation of selenium and fluorine across the triple bond, as shown in Table 2.4. This reactivity is somewhat similar to that observed under related conditions with alkenes (Figure 2.2).

A variety of catalysts were screened with 3-hexyne in the hopes of improving the yield of the allene product (Table 2.5).

Table 2.5. Catalyst Screen with Alkynes

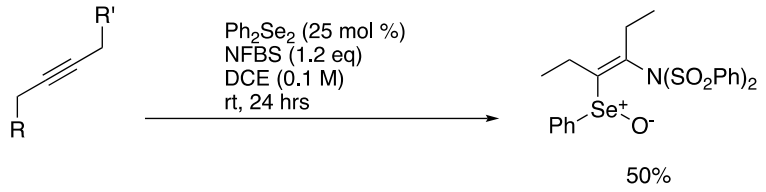


Entry	Catalyst	Result[a]	Entry	Catalyst	Result[a]
1		-	5		 12%
2		-	6	IPrSe	 33%
3		-	7	IMeSe	 24%
4	$(PhO)_3P=Se$	-	8	$Ph_3P=Se$	 20%

[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

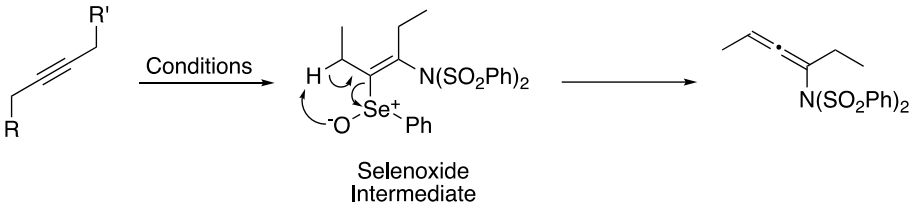
It was discovered that the yield of the allene was improved using IPrSe as the catalyst, giving 33% yield of the desired product (entry 6). A repeat of the same screen at room temperature showed very poor reactivity, with only several catalysts giving any products. One of the few catalysts that reacted at room temperature was diphenyl diselenide, which gave the selenoxide of the previously observed diaddition product. (Figure 2.3).

Figure 2.3. Selenoxide Formation with Diphenyl Diselenide



This product was isolated by column chromatography and the corresponding m+1 peak was observed by GCMS. With regards to the mechanism of these reactions, we hypothesize that the initial product is a selenium/$N(SO_2Ph)_2$ diaddition across the alkyne which gives the selenoxide intermediate seen in Figure 2.3. This product is the only product observed at lower temperatures. Then with heating and time this product eliminates, perhaps via a selenoxide syn-elimination, to give the observed allene product (Figure 2.4)

Figure 2.4. Proposed Mechanism for Allene Formation

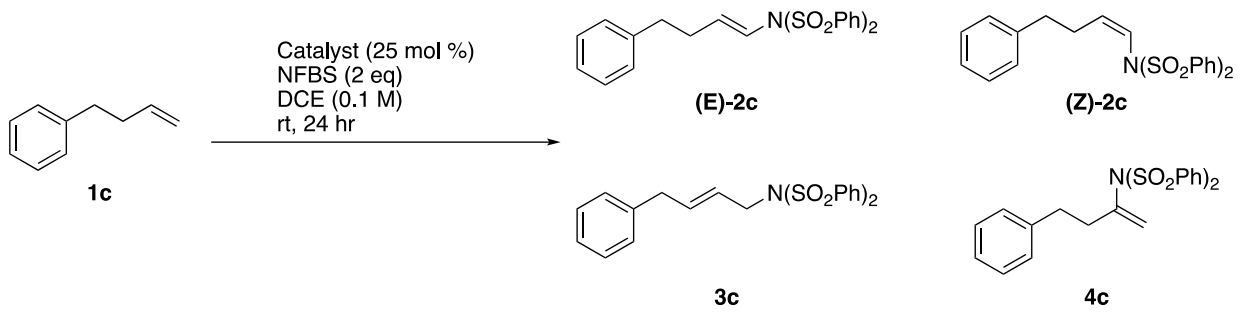


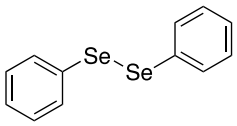
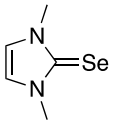
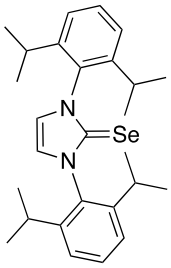
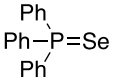
Additional optimization including screens looking at catalysts, solvents, concentration, bases or equivalents did not provide much improvement to the yield. At this point we moved back to exploring vinyl amination of alkenes.

2.2.4 Reaction Optimization – Vinyl Amination

One of our original goals for this aza-Heck reaction was to achieve a much more general substrate scope than that of prior methods. Consistent with this goal, we sought to move away from screening with an activated alkene, like styrene, to a simple, unactivated terminal olefin. 4-phenyl-1-butene **(1c)** was selected for this purpose and was screened with our most effective catalysts in the presence of NFBS (Table 2.6).

Table 2.6. Catalyst Screen with 4-phenyl-1-butene

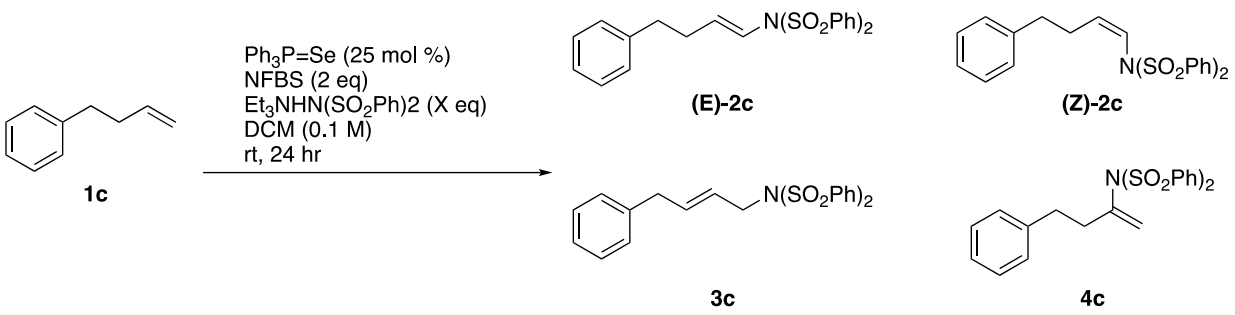


Entry	Catalyst	Yield **(E)-2c**	Yield **(Z)-2c**	Yield **3c**	Yield **4c**
1		23%	17%	-	15%
2		tr	-	tr	-
3		30%	-	7%	-
4		58%	-	7%	-

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

As mentioned previously, with unactivated olefins, diphenyl diselenide gives poor regio- and stereoselectivity, resulting in a mixture of isomeric products (entry 1). It was observed that NHC-selenides (entries 2, 3) and phosphine selenides improved the selectivity and reactivity, with triphenylphosphine selenide giving the optimum performance (entry 4). It was subsequently observed that the introduction of two equivalents of exogenous benzenesulfonimide nucleophile improved the reactivity, providing higher combined yield of amination products, albeit with less selectivity (Table 2.7).

Table 2.7. Effect of Exogenous Triethylammonium Benzenesulfonimide

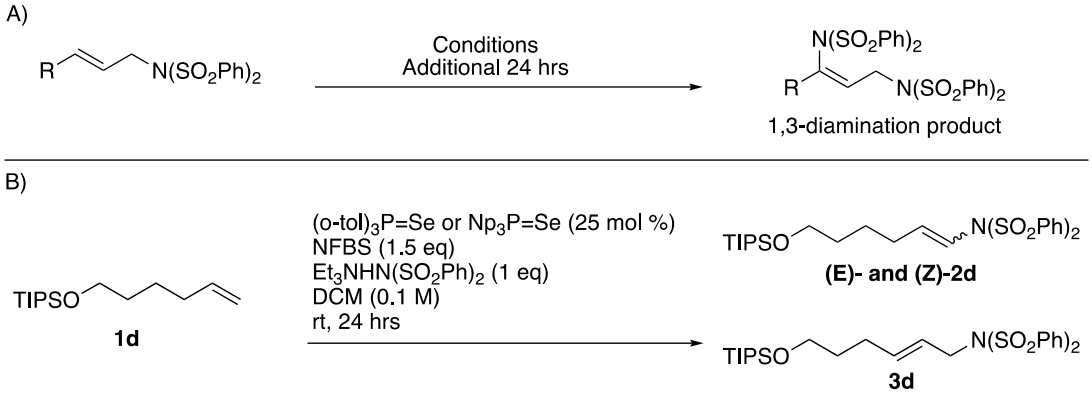


Entry	$Et_3NHN(SO_2Ph)_2$	Yield **(E)-2c**	Yield **(Z)-2c**	Yield **3c**	Yield **4c**
1	-	58%	-	7%	-
2	2 equiv	63%	10%	15%	4%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

At this point my colleague, Tianyi Zheng, joined the project and performed optimization and catalyst exploration, culminating in the conditions shown below (Table 2.8b, entry 1). Bulky triaryl phosphine selenides were the highest performing catalysts, with tri-naphthylphosphine selenide and tri-ortho-tolylphosphine selenide performing similarly. It was also discovered that running the reaction for 48 hours caused conversion of all of the allylic isomer byproduct to a 1,3-diamination product, which was separable by column chromatography (Table 2.8a), further improving the isolated purity of the desired isomer.

Table 2.8. 1,3-Diamination Product and Catalyst Loading Screen

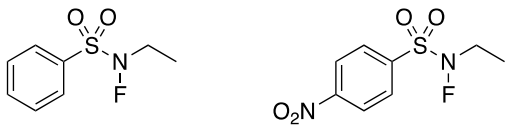


Entry	Catalyst	Catalyst Loading	Yield **(E)- and (Z)-2d**	Yield **3d**	SM %
1	$Np_3P=Se$	25 mol %	73%	10%	-
2	$Np_3P=Se$	10 mol %	72%	10%	-
3	$Np_3P=Se$	5 mol %	56%	10%	23%
4	$Np_3P=Se$	2.5 mol %	40%	6%	42%
5	$(o\text{-}tol)_3P=Se$	10 mol %	69%	9%	-
6	$(o\text{-}tol)_3P=Se$	5 mol %	58%	9%	13%
7	$(o\text{-}tol)_3P=Se$	2.5 mol %	18%	6%	41%

[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

It was observed that the catalyst loading could be reduced to 10 mol % without any effect on the yield, but loadings below that number proved detrimental (entries 2 vs. 3 and 5 vs. 6). In the hopes of incorporating a more synthetically relevant nitrogen source, several N-alkyl-N-fluoro-benzenesulfonamides were used as oxidants under otherwise standard conditions, but gave no reactivity and starting material was recovered (Figure 2.5).

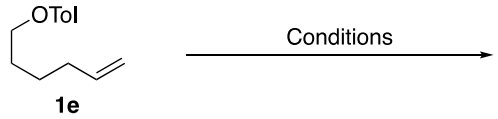
Figure 2.5. N-alkyl-N-fluorobenzenesulfonamides



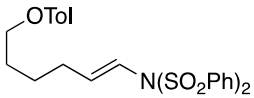
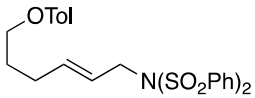
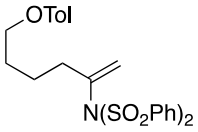
As mentioned previously, the goal of this project was to improve the yield, selectivity and substrate generality of the aza-Heck reaction by utilizing new classes of selenium catalysts to

manipulate reactivity. As shown in Table 2.9, our new catalyst and conditions have achieved this goal, providing high yield and regioselectivity of the desired product with improved stereoselectivity (entries 1, 2 vs. 3).

Table 2.9. Improvements in Yield and Selectivity with Optimized Conditions



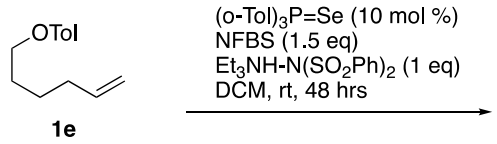
1e

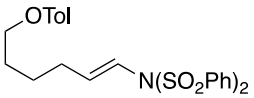
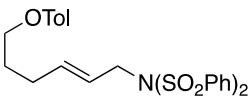
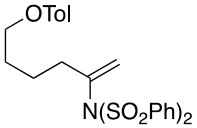
Entry	Conditions	 **2e** (%) (E/Z)	 **3e** (%)	 **4e** (%)
1	Breder	47 (1.8:1)	17	13
2	Zhao	41 (1.9:1)	14	13
3[a]	This work	74 (5.7:1)	tr	4

Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

With the optimized conditions in hand, control reactions were performed (Table 2.10). In absence of catalyst (entry 2) and oxidant (entry 3) there was no reaction and starting material was recovered. Catalytic selenium powder gave a similar result (entry 5). However, when catalytic selenium powder and phosphine ligand were allowed to pre-stir in solvent for 30 minutes before adding the other reagents, the reaction proceeded as normal with no significant loss of yield or selectivity, suggesting the catalyst is formed in-situ (entry 4).

Table 2.10. Control Reactions



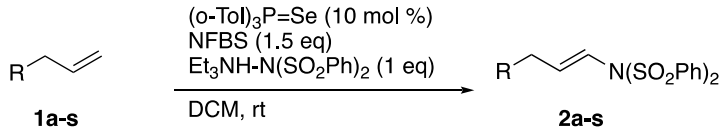
Entry	Deviation from standard	 Yield **2e** (E/Z)	 Yield **3e** %	 Yield **4e**	Starting Material
1	None	74 (5.7:1)	12	4	-
2	Omit Catalyst	-	-	-	100%
3	Omit Oxidant	-	-	-	55%
4	$(o\text{-Tol})_3P$ (10 mol %) + Se (15 mol %)	70 (4.8:1)	14	5	-
5	Se (10 mol %)	0	0	0	100%

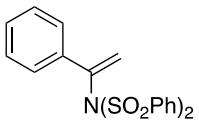
[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

2.2.5 Substrate Scope

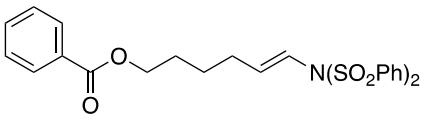
The optimized conditions were applied to a variety of terminal alkenes (Scheme 2.7). Yields and selectivities were generally high. The reaction tolerated many functional groups including esters, ethers, electron-rich aromatics, silyl ethers, sulfonamides, and nitriles. Additionally, aliphatic and aromatic halides were successful as substrates (**2i, 2j** and **2q**). The reaction was also performed on 4 mmol scale under an ambient atmosphere with no significant loss of yield or selectivity (**2e**), providing a significant operational improvement over transition metal chemistry, which often requires air free conditions. 1,1-disubstituted alkenes gave mixtures of vinyl- and allylamine products while 1,2-disubstituted- trisubstituted- and tetra-substituted alkenes gave poor yields.

Scheme 2.7. Substrate Scope of Phosphine Selenide Catalyzed Aza-Heck Reaction

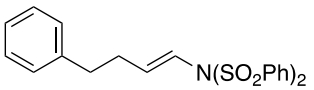




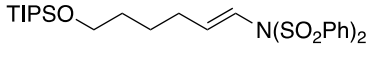
2a 97%



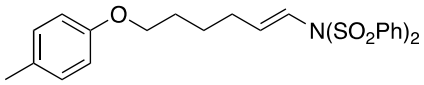
2b 70% (7.6:1 *E/Z*)



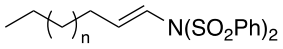
2c 71%, (5.5:1 *E/Z*)



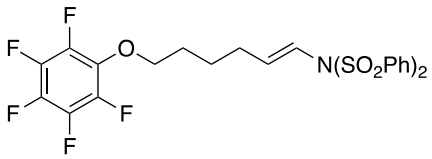
2d 73%, (6.2:1 *E/Z*)



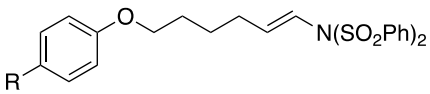
2e 78% (5.9:1 *E/Z*)
4 mmol scale: 76%, 11:1 *E:Z*



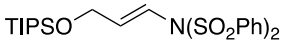
2f n = 1, 71%, (5.7:1 *E/Z*)
2g n = 11, 65%, (9.1:1 *E/Z*)



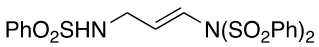
2h 71%, (7.7:1 *E/Z*)



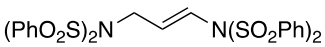
2i R = Cl, 76%, (8.3:1 *E/Z*)
2j R = I, 81%, (6.6:1 *E/Z*)
2k R = CF_3, 68%, (6.4:1 *E/Z*)
2l R = NO_2, 62%, (8.4:1 *E/Z*)
2m R = CN, 73%, (7.4:1 *E/Z*)



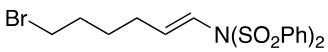
2n 77%, (15:1 *E/Z*)



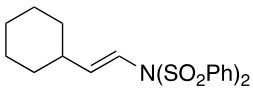
2o 84%, (8.3:1 *E/Z*)



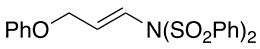
2p 87%, (12:1 *E/Z*)



2q 75%, (6.2:1 *E/Z*)



2r 76%, (17:1 *E/Z*)



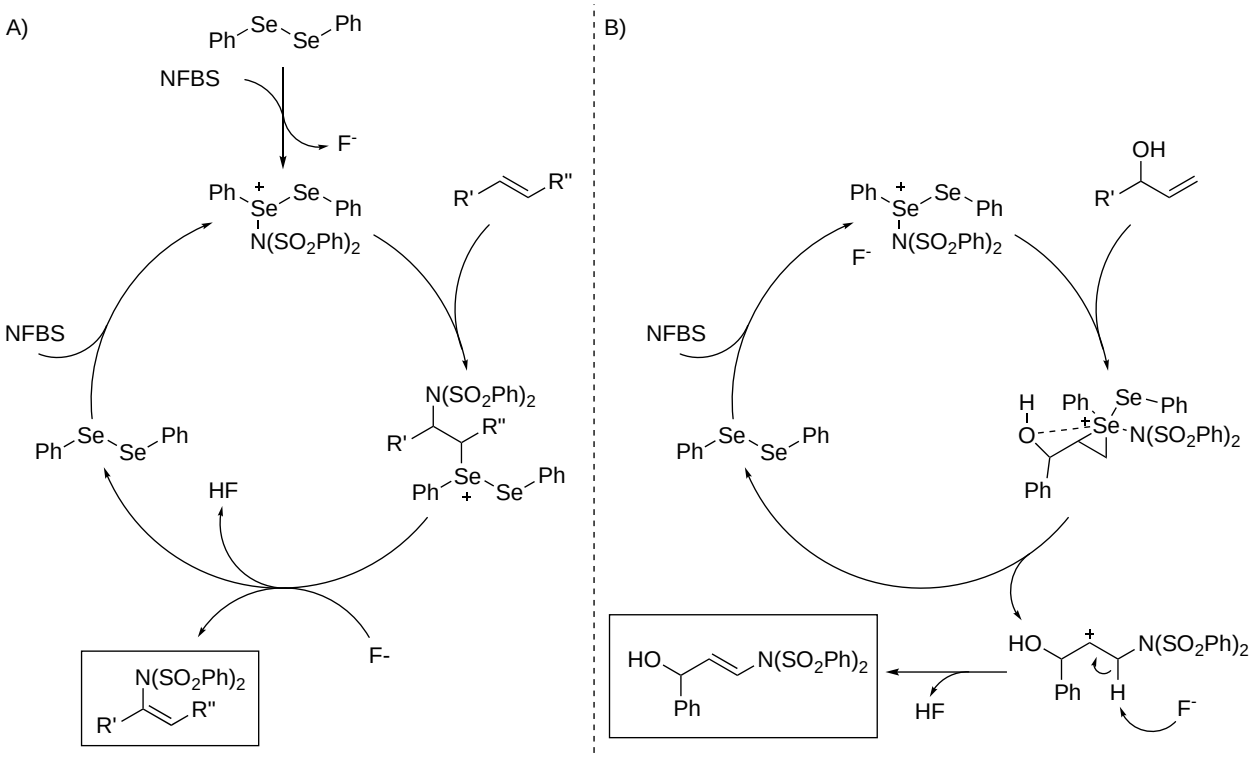
2s 80%, (7.6:1 *E/Z*)

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

2.2.6 Mechanistic Studies

While authors have suggested plausible mechanistic cycles for this reaction[9,10], there had not yet been any investigation into the details of the mechanism. Shown below are possible catalytic cycles presented by Breder and Zhao.

Scheme 2.8. Plausible Mechanistic Cycles for Selenium-Catalyzed Vinyl Amination of Olefins



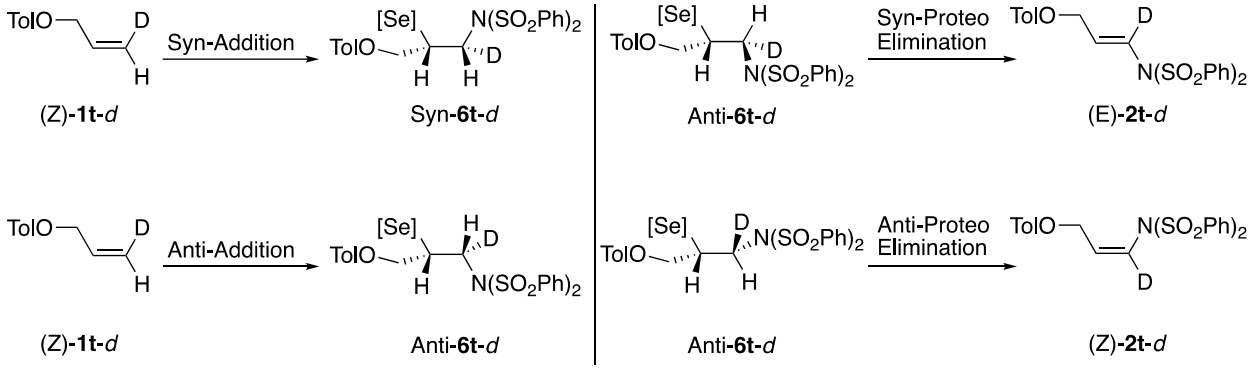
Breder, *ACIE*, **2013**, 52, 8952-8956.

Zhao, *Org. Lett.* **2015**, 17, 1834-1837.

Both examples suggest that the Se-Se bond remains intact for the entirety of the catalytic cycle and is crucial to the completion of the cycle. As we were achieving success with monoselenide catalysts where a Se-Se is not present, we questioned the validity of this assertion. Additionally, both cycles propose an *inter*molecular elimination by a fluoride anion to give the final product, producing HF as a byproduct. We wondered whether the elimination might actually occur *intra*molecularly, in a manner that is isoelectronic to the well-known selenoxide syn-elimination. We were also curious to learn the stereochemistry of the addition and elimination steps (syn vs. anti), as well as which step was the rate determining step and which step was the product determining step. With these questions in mind, we sought to perform mechanistic studies to learn about the reaction in more detail.

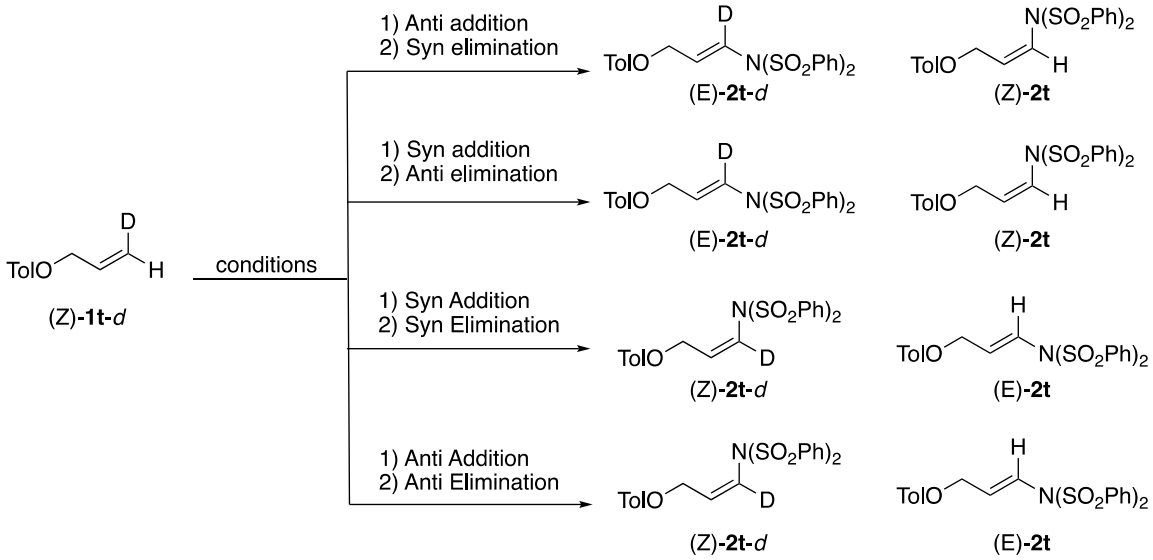
Looking very broadly at the overall mechanism, we hypothesized that our reaction was proceeding through an addition of selenium and nitrogen across the C=C bond of the alkene, followed by elimination of the intermediate organoselenium species to give the final product, in a manner similar to those presented above. Addition and elimination can each proceed with syn- or anti-stereochemistry, giving a handful of different possible stereochemical outcomes of the reaction. For example, consider deuterated substrate (Z)-**1t**-*d* (Scheme 2.9).

Scheme 2.9. Possible Stereochemistry of Addition and Elimination Steps



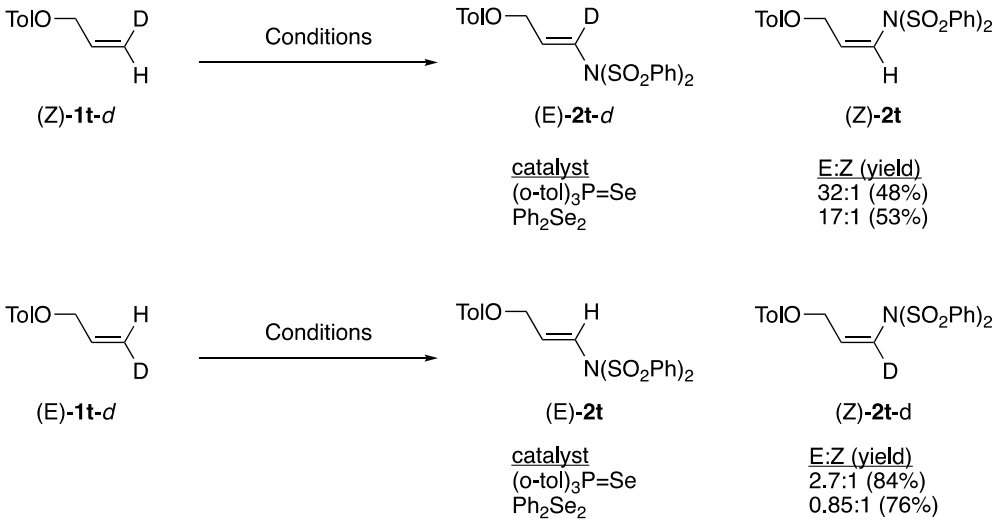
Addition of selenium and nitrogen across the C=C bond in (Z)-**1t**-*d* can occur with either syn- or anti- stereochemistry, producing intermediates Syn-**6t**-*d* and Anti-**6t**-*d*, respectively. Arbitrarily choosing Anti-**6t**-*d* to continue this analysis, this intermediate can undergo syn or anti elimination of a proton to produce (E)-**2t**-*d* and (Z)-**2t**-*d*. This intermediate could also undergo syn or anti elimination of deuterium to give a different set of products (not shown). As seen above, both the stereochemical permutations of the addition and elimination steps as well as the possibility of eliminating either a proton or deuterium will have an effect on the structure and stereochemistry of the products. Carrying through this same line of analysis with all possible permutations of syn and anti-addition/elimination gives an array of all potential products, as shown in Scheme 2.10.

Scheme 2.10. Potential Products of Vinyl Amination of Alkenes



Cis- and trans-deutero substrates (Z)-**1t**-*d* and (E)-**1t**-*d* were synthesized and subjected to the optimized conditions, as well as conditions using diphenyl diselenide as a catalyst. (Figure 2.6).

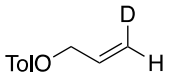
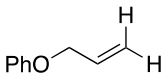
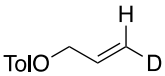
Figure 2.6. Deuterium Labelling Experiment

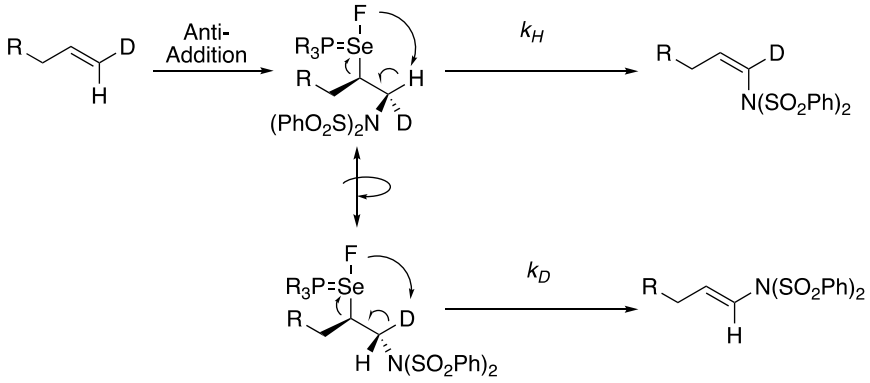


Both substrates, under all conditions, gave only those products coming from either the anti-addition/syn-elimination or syn-addition/anti-elimination sequences, and the other stereochemical permutations could be ruled out. These results are consistent with literature precedent, which has demonstrated that seleniranium ions are opened with nucleophiles to give a net anti-addition.[12] We

also suspected that our elimination was happening through a process that was isoelectronic to the selenoxides syn-elimination, which has been shown to proceed with syn stereochemistry. To summarize, the observed stereochemistry of the products is consistent with an anti-addition followed by a syn-elimination. Additionally, the product *E:Z* ratios show that the stereoselectivity of the reaction was strongly influenced by the geometry of the starting alkene. The Z-deutero alkene gave higher *E:Z* ratios, while the E-deutero alkene gave much lower *E:Z* ratios. These ratios can be compared to that of closely related non-deuterated substrate **1s** (7.6:1) to observe that the *E:Z* ratios increase by a factor of 3-4 when using the Z-deutero substrate and decrease by roughly the same amount when using the E-deutero substrate (Scheme 2.11).

Scheme 2.11. *E:Z* Ratios of Labelled Stereoisomers vs. Unlabeled Substrate

Substrate	 (Z)-**1t**-*d*	 **1s**	 (E)-**1t**-*d*
Product E/Z Ratio	32:1	7.6:1	2.7:1

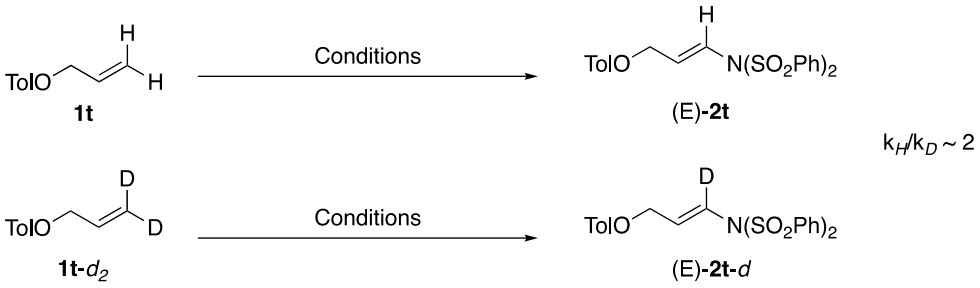


We propose that the reaction proceeds through a syn-elimination from the selenium-fluorine bond, a process that is isoelectronic to the well-known selenoxide syn-elimination. During this intramolecular elimination, the kinetic preference of eliminating a proton rather than a deuterium is reflected in the *E:Z* ratios of the products (see figure above). This difference in *E:Z* by a factor

of 3-4 can be explained as the intramolecular KIE of the elimination step, which is relatively consistent with known syn-selenoxide KIE values (~5).[12,13]

We sought to find out whether or not a C-H bond was formed/broken in the rate determining step (in other words, whether or not elimination was the rate determining step). Consumption of unlabeled substrate **1t** and labelled **1t**-*d*$_2$ were monitored over time in separate reaction vessels (Scheme 2.12).

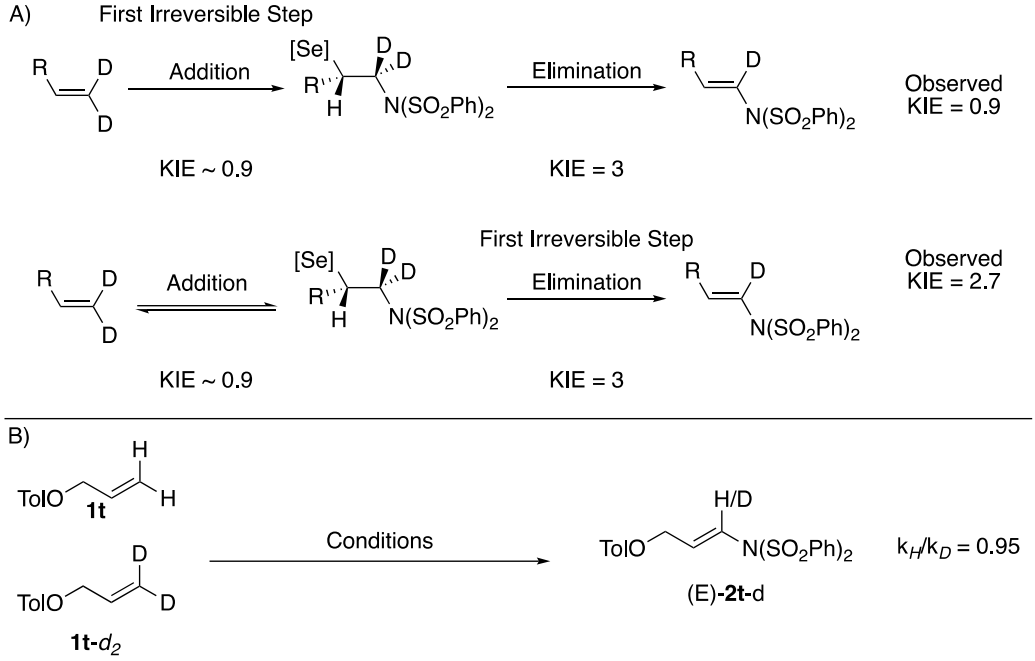
Scheme 2.12. Independent Rate Measurement Experiment



It was observed that the deuterated **1t**-*d*$_2$ was consumed much more slowly than the unlabeled **1t**, indicating a primary KIE ($k_H/k_D \sim 2$). This primary KIE of the overall reaction indicates that there is a C-H bond formed/broken in the rate determining step. Based on our proposed mechanism, the only point at which a C-H bond is formed or broken is during the elimination step, in which a C-H bond is broken. Thus, the data suggests that elimination is the rate determining step (see experimental section for data).

In order to probe which step was the product determining step, a competition experiment was performed, in which unlabeled compound **1t** and deuterated **1t**-*d*$_2$ were subjected to the reaction conditions in the same reaction vessel (Scheme 2.13).

Scheme 2.13. Possible and Actual Intermolecular Competition Outcomes

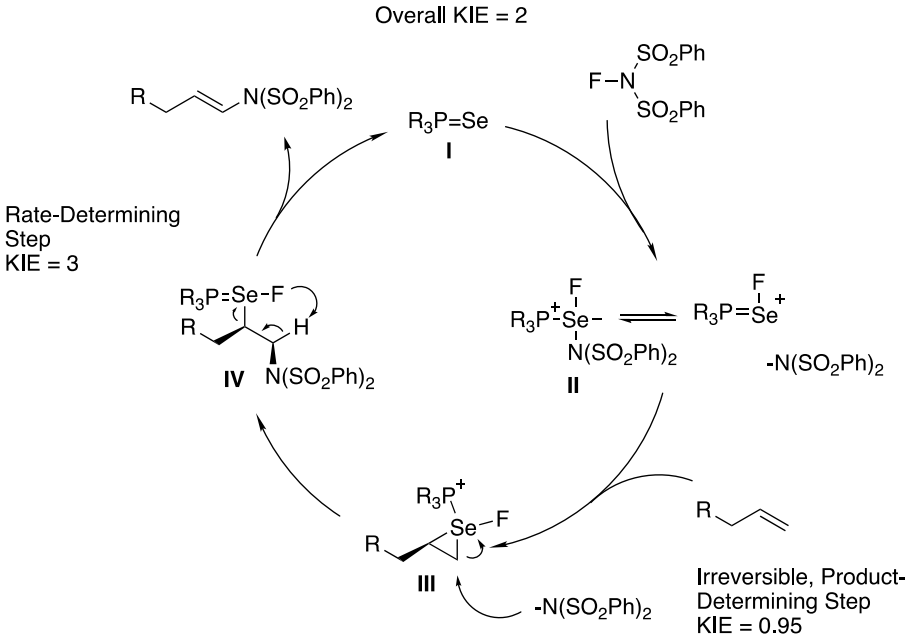


There are two potential scenarios for this experiment, each giving a different outcome (Scheme 2.13a). Scenario 1: Addition is the first irreversible product-determining step. In this scenario, the product distribution is set as soon as the addition happens, and none of the subsequent steps will have any effect on the KIE (which is determined by product distribution). Thus, the observed KIE would reflect the KIE of the addition step. Scenario 2: The elimination is the first irreversible product-determining step. In this scenario, since the product distribution is not set until the elimination happens, the elimination and all preceding steps can play a role in determining the KIE. Thus, the observed KIE would be a product of both the addition step and the elimination step. We took known KIE values for similar alkene addition reactions in combination with our experimentally determined KIE of the elimination step (see Scheme 2.12, above) to calculate expected values for these two potential outcomes. When we conducted this competition experiment, we observed a small inverse KIE (k_H/k_D ~ 0.95), which is typical for alkene addition

reactions[14], suggesting that the addition is the irreversible product determining step (Scheme 2.13b).

Based upon the above results and literature precedent, we propose the following mechanism. (Figure 2.7).

Figure 2.7. Mechanistic Proposal for Phosphine Selenide-Catalyzed Aza-Heck Reaction



Oxidative addition of NFBS to phosphine selenide **I** gives hypervalent selenium species **II**. Related species have been isolated and crystal structures have been obtained.[15] We propose that species **II** is in equilibrium with an ion-pair structure in which one of the benzenesulfonimide anions is dissociated.[16] This ion pair structure can react with an alkene to generate seleniranium ion **III** via an irreversible product-determining step. The anionic benzenesulfonimide can act as a nucleophile to open the seleniranium ion, giving 1,2-selenofunctionalized intermediate **IV**, which can the undergo the rate determining syn-elimination to give the final product and regenerate the catalyst.

Section 3: Conclusion

An organoselenium-catalyzed regioselective aza-Heck reaction of terminal alkenes was developed. Key to the success of the transformation was the utilization of a new class of phosphine selenide catalysts which improved regio- and stereoselectivity from that achieved with diphenyl diselenide, which is typically used in related chemistry. Extended reaction times allowed for the conversion of the allylic isomeric byproduct to a 1,3-diamination product that could be separated from the mixture, further improving the purity of the desired isomer. The reaction worked well on a variety of terminal olefins, generally giving good yields and regioselectivities. Deuterium labelling experiments support a mechanism proceeding through an anti-addition of selenium and nitrogen across the C=C bond of the alkene, followed by syn-elimination from a selenium-fluorine bond to yield the final product. Substitution of deuterium at different positions of the starting alkene caused a different effect on the product *E:Z* ratios, reflecting an intramolecular KIE of ~3, which is relatively consistent with known selenoxide syn-elimination values. Independent rate measurement experiments gave a k_H/k_D = 2, supporting that this syn-elimination is the rate determining step. A competition experiment gave a k_H/k_D = 0.95, suggesting that an irreversible addition is the product-determining step. All attempts to derivatize the products were unsuccessful.

Section 4: Experimental

General Procedures. All reactions were performed under a nitrogen atmosphere using flame-dried glassware unless otherwise noted. Infrared spectra were measured on a Perkin Elmer Spectrum RX I spectrometer. Mass spectra were collected on a Hewlett Packard 5971A Gas Chromatograph - Mass Spectrometer or Bruker Esquire 1100 Liquid Chromatograph - Ion Trap Mass Spectrometer. Column chromatography was performed using silica gel (Whatman, 60 Å,

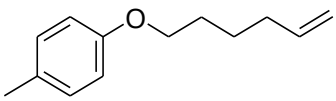
230-400 mesh). NMR spectra were recorded on a Bruker AV-300, AV-301, DRX-499 or AV-500 spectrometer. ^{1}H NMR chemical shifts (δ) are reported in parts per million (ppm) and are referenced relative to TMS (0.00 ppm) or residual $CHCl_3$ (7.26 ppm). ^{13}C NMR chemical shifts (δ) are reported in parts per million (ppm) relative to the carbon resonance of $CDCl_3$ (77.16 ppm). Melting points were taken on a MEL-TEMP melting point apparatus and are uncorrected.

Materials. All commercial reagents were used as received, unless otherwise noted. All solvents were degassed and dried on solvent columns of neutral alumina. Deuterated solvents were purchased from Cambridge Isotope Laboratories, Inc., stored over 4 Å molecular sieves, and were used without further purification. Vinyl cyclohexane, allyl phenyl ether, allyl tolyl ether, styrene, 1-hexene and 1-hexadecene were purified by distillation from calcium hydride and stored over 4 Å molecular sieves.[17] See Chapter 1 experimental section for the synthesis of diphenyl selenide. N-allylbenzenesulfonamide[18], Nallylbenzenesulfonimide[19], (hex-5-enyloxy)triisopropylsilane[20], hex-5-en-1-yl benzoate[21], triethylammonium benzenesulfonimide[22], (4-methoxphenyl)phenyl selane, (3,5-bis-trifuloromethylphenyl)phenyl selane and (4-dimethylaminophenyl)phenyl selane[29], N-fluoro-N-ethylbenzenesulfonamide and N-fluoro-N-ethyl-(para-nitrobenzene)sulfonamide[30], triphenyl phosphine selenide and tri-(ortho)tolyl phosphine selenide[23], 1,3-dimethyl-1H-imidazole-2(3H)-selenone[31], triphenylphosphoroselenoate[32], 1,3-bis[2,6-bis(1-methylethyl)phenyl]-1,3-dihydro-2H-imidazole-2-selone (IPrSe)[33], and tri-1-napthalenylphosphine selenide[34] were prepared according to previously published procedures and their respective spectroscopic signatures (^{1}H NMR) were found to be consistent with values reported therein.

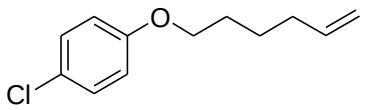
Synthesis of Starting Materials

General Procedure A. In a flamed dried 250 mL two-neck round bottom flask, 6-bromo-1-hexene (10 mmol, 1.0 equiv) was added dropwise to a solution of p-substituted phenol (12 mmol, 1.2 equiv) and K_2CO_3 (30 mmol, 3.0 equiv) in acetonitrile (80 mL). The reaction mixture was heated at reflux for 12 hours. After the reaction was complete, it was cooled to room temperature, white solids were filtered off, and the solvent was removed under reduced pressure. The crude product was purified by silica gel flash chromatography to afford the corresponding alkene.

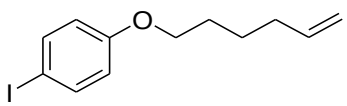
Characterization of Starting Materials



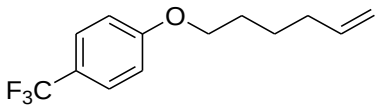
1-(hex-5-enyloxy)-4-methylbenzene (1e).[24] Synthesized according to General Procedure A to afford the product as a colorless oil (1.7 g, 90% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). **IR (thin film)**: 2940, 2865, 1641, 1615, 1586, 1512, 1474, 1390, 1291, 1244, 1176, 1110, 1037, 995, 910, 818, 511 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.07 (d, J = 8.4 Hz, 2H), 6.79 (d, J = 8.5 Hz, 2H), 5.83 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 5.11 – 4.88 (m, 2H), 3.94 (t, J = 6.5 Hz, 2H), 2.28 (s, 3H), 2.13 (q, J = 7.1 Hz, 2H), 1.87 – 1.71 (m, 2H), 1.67 – 1.47 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 157.10, 138.74, 129.99, 129.83, 114.83, 114.48, 67.94, 33.61, 28.93, 25.50, 20.60. **GC-MS (m/z):** 190 (1, M^+), 108 (3.2, C_7H_7OH), 55(100, $C_4H_7^+$).



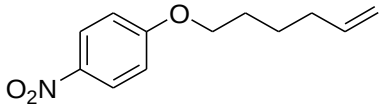
1-chloro-4-(hex-5-enyloxy)benzene (1i).[24] Synthesized according to General Procedure A to afford the product as colorless oil (1.85 g, 88% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). **IR (thin film)**: 2940, 1597, 1493, 1473, 1287, 1244, 1170, 1092, 1006, 913, 823, 668 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.57 (d, J = 8.8 Hz, 2H), 6.93 (d, J = 8.8 Hz, 2H), 5.82 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 5.18 – 4.89 (m, 2H), 4.01 (t, J = 6.4 Hz, 2H), 2.13 (q, J = 7.1 Hz, 2H), 1.96 – 1.71 (m, 2H), 1.66 – 1.48 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 157.84, 138.59, 129.40, 125.46, 115.88, 114.95, 68.21, 33.54, 28.77, 25.42. **GC-MS (m/z):** 210/212 (15/5, M^+), 128/130 (100/33, C_6H_4ClOH).



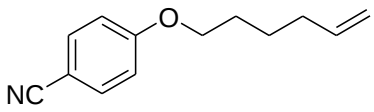
1-(hex-5-enyloxy)-4-iodobenzene (1j).[25] Synthesized according to General Procedure A to afford the product as a white solid (2.6 g, 86% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). IR(thin film): 2937, 1586, 1487, 1283, 1244, 1174, 819 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.54 (d, J = 8.8 Hz, 2H), 6.67 (d, J = 8.8 Hz, 2H), 5.90 – 5.73 (m, 1H) , 5.16 – 4.88 (m, 2H), 3.92 (t, J = 6.4 Hz, 2H), 2.12 (q, J = 7.2 Hz, 2H), 1.90 – 1.67 (m, 2H), 1.64 – 1.45 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 159.10, 138.57, 138.29, 117.05, 114.96, 82.59, 68.01, 33.53, 28.71, 25.40. **GC-MS (m/z):** 302 (26, M^+), 220 (100, C_6H_4IOH)



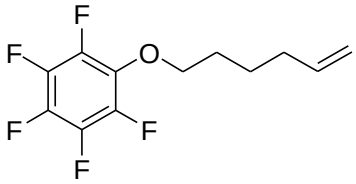
1-(hex-5-enyloxy)-4-(trifluoromethyl)benzene (1k).[25] Synthesized according to General Procedure A to afford the product as colorless oil (2.13 g, 87% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). **IR (thin film)**: 2941, 1617, 1567, 1520, 1331, 1258, 1161, 1110, 1068, 913, 836 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.53 (d, J = 8.6 Hz, 2H), 6.94 (d, J = 8.6 Hz, 2H), 5.83 (ddt, J = 16.9, 10.2, 6.7 Hz, 1H), 5.12 – 4.90 (m, 2H), 4.00 (t, J = 6.4 Hz, 2H), 2.14 (q, J = 7.1 Hz, 2H), 1.92 – 1.72 (m, 2H), 1.69 – 1.46 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 161.74, 138.51, 126.98, 124.69 (q, J = 271.0 Hz), 122.78 (q, J = 32.6 Hz), 114.98, 114.55, 68.12, 33.53, 28.67, 25.39. **GC-MS (m/z):** 244 (13, M^+), 162 (81, $C_6H_4CF_3OH$), 55(100, $C_4H_7^+$).



1-(hex-5-enyloxy)-4-nitrobenzene (1l).[26] Synthesized according to General Procedure A to afford the product as dark orange oil (1.77 g, 80% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). **IR (thin film)**: 2940, 1640, 1593, 1510, 1340, 1260, 1172, 1110, 994, 913, 844, 751, 690, 655 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 8.20 (d, J = 9.2 Hz, 2H), 6.94 (d, J = 9.1 Hz, 2H), 5.96 – 5.68 (m, 1H) , 5.14 – 4.88 (m, 2H), 4.06 (t, J = 6.4 Hz, 2H), 2.14 (q, J = 7.2 Hz, 2H), 1.97 – 1.76 (m, 2H), 1.68 – 1.46 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 164.30, 141.42, 138.33, 125.99, 115.09, 114.49, 68.76, 33.40, 28.48, 25.25. **GC-MS (m/z):** 221 (10, M^+), 139 (10, $C_6H_4NO_2OH$), 55(100, $C_4H_7^+$).

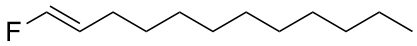


4-(hex-5-enyloxy)benzonitrile (1m).[25] Synthesized according to General Procedure A to afford the product as orange oil (1.83 g, 91% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). IR(thin film): 2940, 2224, 1606, 1508, 1302, 1258, 1171, 913, 834, 748 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.57 (d, J = 8.9 Hz, 2H), 6.93 (d, J = 8.9 Hz, 2H), 5.82 (ddt, J = 16.9, 10.2, 6.7 Hz, 1H), 5.11 – 4.93 (m, 2H), 4.01 (t, J = 6.4 Hz, 2H), 2.13 (q, J = 7.2 Hz, 2H), 1.91 – 1.76 (m, 2H), 1.65 – 1.48 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 162.52, 138.39, 134.10, 119.45, 115.30, 115.10, 103.84, 68.31, 33.45, 28.53, 25.31. **GC-MS (m/z):** 201 (21, M^+), 119 (53, C_6H_4CNOH), 55(100, $C_4H_7^+$).

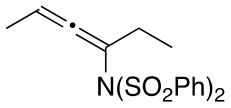


1,2,3,4,5-pentafluoro-6-(hex-5-enyloxy)benzene (1h). Synthesized according to General Procedure A to afford the product as a colorless oil (2.26 g, 85% yield). Purified by column chromatography (EtOAc/Hexanes = 1/50). IR(thin film): 3081, 2947, 1643, 1514, 1469, 1388, 1314, 1162, 1032, 997, 914 cm^{-1}. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 5.81 (ddt, J = 16.9, 10.0, 6.6 Hz, 1H), 5.11 – 4.89 (m, 2H), 4.16 (t, J = 6.4 Hz, 2H), 2.12 (q, J = 7.1 Hz, 2H), 1.91 – 1.68 (m, 2H), 1.71 – 1.43 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 142.07 (ddd, J = 248.1, 10.9, 3.8 Hz), 138.50 (d, J = 255.9 Hz), 138.37, 138.61 – 136.14 (m), 133.98 (t, J = 11.2 Hz), 114.95, 75.78, 33.42, 29.41, 24.98. **GC-MS (m/z):** 266 (1, M^+), 184 (13, C_6F_5OH), 55(100, $C_4H_7^+$).

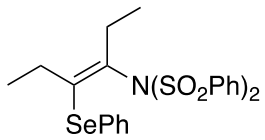
Characterization of Products from Test Reactions of Alkynes



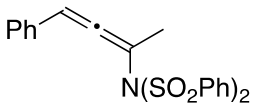
1-fluoro-1-dodecene. Identified by diagnostic peaks listed here: **^{1}H NMR (300 MHz, $CDCl_3$):** δ 6.67 (dd, J = 21.0, 7.9 Hz, 1H), 5.07 – 4.96 (m, 1H).



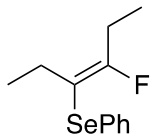
***N*-(hexa-3,4-dien-3-yl)-*N*-benzenesulfonimide.** Identified by diagnostic peaks listed here: **^{1}H NMR (300 MHz, $CDCl_3$):** δ 5.25 – 5.03 (m, 1H), 2.35 – 2.23 (m, 2H), 1.43 (d, J = 7.2 Hz, 3H), 1.20 (t, J = 7.6 Hz, 3H).



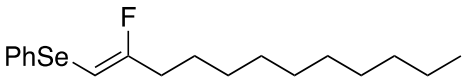
(*Z*)-*N*-(4-(phenylselanyl)hex-3-en-3-yl)-*N*-benzenesulfonimide. Identified by diagnostic peaks listed here: **^{1}H NMR (300 MHz, $CDCl_3$):** δ 2.68 (q, J = 7.5 Hz, 2H), 1.55 (q, J = 7.3 Hz, 2H), 0.96 (t, J = 7.3 Hz, 3H), 0.73 (t, J = 7.3 Hz, 3H).



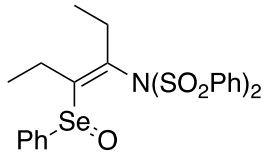
***N*-(4-phenylbuta-2,3-dien-2-yl)-*N*-benzenesulfonimide.** Identified by diagnostic peaks listed here: **^{1}H NMR (300 MHz, $CDCl_3$):** δ 5.55 (q, J = 7.4 Hz, 1H), 1.63 (d, J = 7.4 Hz, 3H).



(*Z*)-(4-fluorohex-3-en-3-yl)(phenyl)selane. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.36 (dd, J = 8.1, 1.5 Hz, 2H), 7.30 – 7.14 (m, 3H), 2.67 (dq, J = 22.8, 7.5 Hz, 2H), 2.40 – 2.30 (m, 2H), 1.10 (t, J = 7.5 Hz, 3H), 1.03 (t, J = 7.4 Hz, 3H).



(*Z*)-(2-fluorodecy-1-enyl)(phenyl)selane. Identified by diagnostic peaks listed here: **^{1}H NMR (300 MHz, $CDCl_3$):** δ 6.00 (d, J = 18.9 Hz, 1H), 2.54 (dt, J = 22.8, 7.4 Hz, 2H).



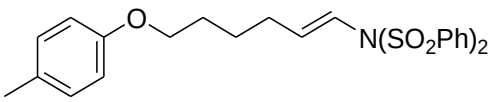
Selenoxide Product. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.08 (d, J = 7.8 Hz, 2H), 7.87 – 7.76 (m, 2H), 7.76 – 7.65 (m, 3H), 7.65 – 7.47 (m, 6H), 7.34 (t, J = 7.9 Hz, 2H), 2.93 (dq, J = 15.2, 7.5 Hz, 1H), 2.75 (dq, J = 15.3, 7.5 Hz, 1H), 1.85 – 1.59 (m, 2H), 1.36 – 1.22 (m, 3H), 0.75 (t, J = 7.4 Hz, 3H).

General Procedure for Synthesis of Aza-Heck Products

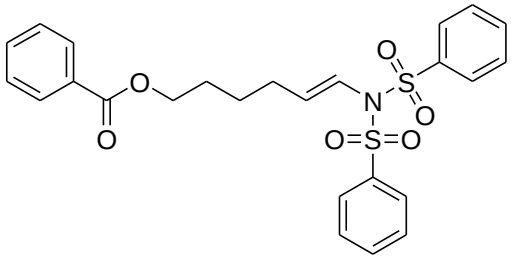
General Procedure B. To an oven-dried 1-dram vial was added phosphine selenide (0.01 equiv), DCM (2 mL), alkene (0.2 mmol, 1.0 equiv), triethylammonium benzenesulfonimide (79.4 mg, 0.2 mmol, 1.0 equiv) and NFBS (94.6 mg, 0.3 mmol, 1.5 equiv), in that order. The vial was then

flushed with nitrogen and capped with a Telfon-lined screw cap and the reaction was stirred at room temperature for 24 or 48 hours. To the reaction mixture was added deionized water (2 mL) and dimethyl sulfide (66 µL, 4.5 equiv). After stirring for an additional 20 minutes, the reaction mixture was diluted with diethyl ether (15 mL) and washed with citric acid (1 M), saturated $NaHCO_3$, and brine. The organic layer was dried over sodium sulfate, filtered and concentrated in vacuo. An NMR was taken with 1,3-dinitrobenzene as internal standard to obtain NMR yield. The crude product was purified by column chromatography to afford the corresponding product.

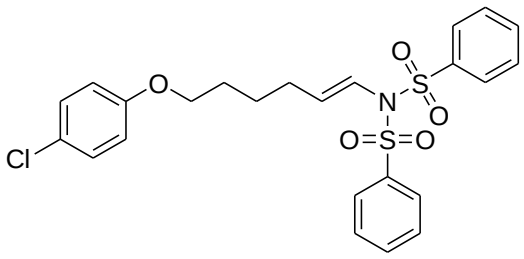
Characterization of Aza-Heck Products



(E)-N-(6-(p-tolyloxy)hex-1-enyl)benzenesulfonimide (2e). Synthesized according to general procedure B to afford the product as a pale, white solid (77 mg, 78% yield, *E:Z* = 8.7:1). Purified by column chromatography (EtOAc/Hexanes = 1/9). **Mp:** 92.8-94.6 ^{o}C. **IR (thin film)**: 3066, 2944, 2867, 1614, 1585, 1512, 1477, 1449, 1378, 1360, 1312, 1292, 1243, 1172, 1122, 1087, 1026, 1000, 961, 916, 818, 754, 740, 722, 686, 608, 577, 551, 513 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.98 (d, *J* = 7.3 Hz, 4H), 7.65 (t, *J* = 7.3 Hz, 2H), 7.54 (t, *J* = 7.5 Hz, 4H), 7.10 (d, *J* = 8.1 Hz, 2H), 6.81 (d, *J* = 8.3 Hz, 2H), 6.01 – 5.76 (m, 2H), 3.93 (t, *J* = 6.1 Hz, 2H), 2.30 (s, 3H), 2.25 – 2.14 (q, *J* = 13.6, 6.9 Hz, 2H), 1.84 – 1.69 (m, 2H), 1.65 – 1.50 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 156.92, 142.49, 139.64, 133.96, 129.98, 129.13, 128.78, 128.21, 120.67, 114.39, 67.52, 29.74, 28.62, 25.16, 20.55. **HRMS(ESI):** ($M+H^+$) calculated 486.1403, found 486.1392

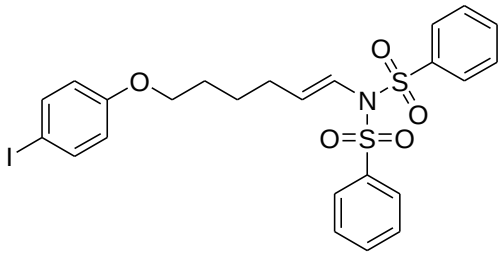


(E)-6-(N-phenylsulfonimido)hex-5-enyl benzoate (2b). Synthesized according to general procedure B to afford the product as a white solid (69.9 mg, 70% yield, *E:Z* = 7.6:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 60-63 ^{o}C. **IR (thin film)**: 3074, 2937, 2860, 1716, 1448, 1378, 1275, 1171, 1114, 1086, 1026, 957, 914, 754, 720, 686, 576, 550 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 8.04 (d, *J* = 7.2 Hz, 2H), 7.96 (d, *J* = 7.5 Hz, 4H), 7.64 (t, *J* = 7.4 Hz, 2H), 7.58 – 7.49 (m, 5H), 7.45 (t, *J* = 7.5 Hz, 2H), 5.98 – 5.73 (m, 2H), 4.32 (t, *J* = 6.4 Hz, 2H), 2.20 (q, *J* = 7.1 Hz, 2H), 1.82 – 1.71 (m, 2H), 1.62 – 1.48 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 166.71, 142.16, 139.70, 134.00, 133.08, 130.45, 129.66, 129.16, 128.52, 128.26, 120.89, 64.59, 29.67, 28.13, 25.14. **HRMS(ESI):** (M+H^{+}) calculated 500.1196, found 500.1185

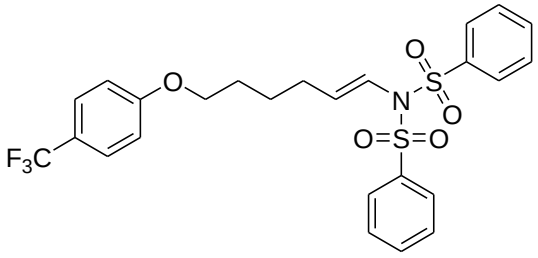


(E)-N-(6-(4-chlorophenoxy)hex-1-enyl)benzenesulfonimide (2i). Synthesized according to general procedure B to afford the product as a white solid (76.9 mg, 76% yield, *E:Z* = 8.3:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 86-87 ^{o}C. **IR (thin film)**: 2944, 1596, 1492, 1448, 1378, 1358, 1288, 1244, 1171, 1086, 915, 826, 753, 722, 686, 576, 550 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.96 (d, *J* = 7.2 Hz, 4H), 7.65 (t, *J* = 7.4 Hz, 2H), 7.53 (t, *J* = 7.6

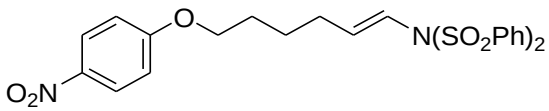
Hz, 4H), 7.22 (d, *J* = 9.0 Hz, 2H), 6.81 (d, *J* = 9.0 Hz, 2H), 6.05 – 5.63 (m, 2H), 3.91 (t, *J* = 6.2 Hz, 2H), 2.27 – 2.12 (q, *J* = 7.1 Hz, 2H), 1.82 – 1.69 (m, 2H), 1.64 – 1.49 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 157.72, 142.31, 139.73, 134.01, 129.46, 129.17, 128.28, 125.63, 120.85, 115.86, 67.89, 29.77, 28.55, 25.15. **HRMS(ESI):** ($M+NH_4^+$) calculated 523.1123, found 523.1107



(E)-N-(6-(4-iodophenoxy)hex-1-enyl)benzenesulfonimide (2j). Synthesized according to general procedure B to afford the product as a white solid (96.8 mg, 81% yield, *E:Z* = 6.6:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 107.8-108.2 ^{o}C. S6 **IR (thin film)**: 2941, 1586, 1486, 1448, 1378, 1358, 1284, 1243, 1171, 1085, 915, 821, 753, 722, 686, 576, 550 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.96 (d, *J* = 7.3 Hz, 4H), 7.64 (t, *J* = 7.4 Hz, 2H), 7.58 – 7.44 (m, 6H), 6.66 (d, *J* = 8.8 Hz, 2H), 5.99 – 5.65 (m, 2H), 3.90 (t, *J* = 6.2 Hz, 2H), 2.18 (q, *J* = 7.0 Hz, 2H), 1.82 – 1.67 (m, 2H), 1.62 – 1.45 (m, 2H).**^{13}C NMR (126 MHz, $CDCl_3$)** δ 158.95, 142.29, 139.68, 138.32, 133.99, 129.15, 128.24, 120.81, 117.00, 82.73, 67.66, 29.73, 28.47, 25.10. **HRMS(ESI):** ($M+NH4^+$) calculated 615.0479, found 615.0461

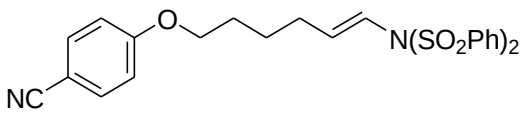


(E)-N-(6-(4-(trifluoromethyl)phenoxy)hex-1-enyl)benzenesulfonimide (2k). Synthesized according to general procedure B to afford the product as colorless oil (73.4 mg, 68% yield, *E:Z* = 6.4:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **IR (thin film)**: 2942, 1616, 1519, 1449, 1379, 1330, 1258, 1172, 1112, 1086, 1068, 916, 837, 754, 722, 686, 638, 576, 551cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, *J* = 7.6 Hz, 4H), 7.65 (t, *J* = 7.3 Hz, 2H), 7.59 – 7.43 (m, 6H), 6.94 (d, *J* = 8.5 Hz, 2H), 6.03 – 5.70 (m, 2H), 3.99 (t, *J* = 6.2 Hz, 2H), 2.20 (d, *J* = 7.0 Hz, 2H), 1.85 – 1.74 (m, 2H), 1.67 – 1.53 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 161.56, 142.19, 139.75, 134.01, 129.16, 128.28, 127.03, 124.60 (q, *J* = 270.8 Hz), 122.94 (q, *J* = 32.8 Hz), 120.92, 114.55, 67.83, 29.74, 28.45, 25.12. **HRMS(ESI):** (M+NH$_4$$^+$) calculated 557.1386, found 557.1372

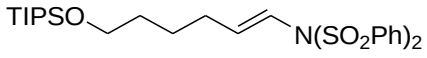


(E)-N-(6-(4-nitrophenoxy)hex-1-enyl)benzenesulfonimide (2l). Synthesized according to general procedure B to afford the product as an off-white solid (64.1 mg, 62% yield, *E:Z* = 8.4:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 93-96.3 ^{o}C. **IR (thin film)**: 3066, 2942, 1607, 1593, 1511, 1448, 1378, 1341, 1297, 1263, 1172, 1111, 1085, 1024, 961, 914, 846, 753, 722, 686 , 656, 608, 576, 551 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 8.18 (d, *J* = 9.2 Hz, 2H), 7.96 (d, *J* = 7.5 Hz, 4H), 7.65 (t, *J* = 7.4 Hz, 2H), 7.54 (t, *J* = 7.7 Hz, 4H), 6.93 (d, *J* = 9.2 Hz, 2H), 5.98 – 5.76 (m, 2H), 4.04 (t, *J* = 6.2 Hz, 2H), 2.21 (q, *J* = 13.8, 7.0 Hz, 2H), 1.89 – 1.75 (m, 2H), 1.66 – 1.52 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 164.12, 142.01, 139.69, 134.02, 129.15,

128.36, 128.24, 126.04, 120.98, 114.51, 68.47, 29.68, 28.31, 25.01. **HRMS(ESI):** ($M+H^+$) calculated 517.1098, found 517.1085

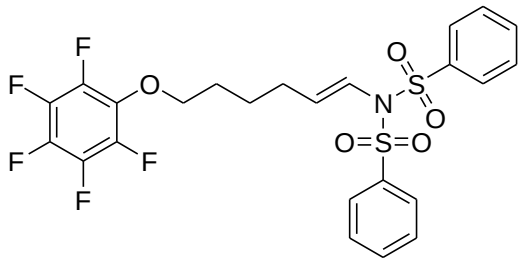


(E)-N-(6-(4-cyanophenoxy)hex-1-enyl)benzenesulfonimide (2m). Synthesized according to general procedure B to afford the product as a white solid (72.8 mg, 73% yield, *E:Z* = 7.4:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 112.5- 115.3 ^{o}C. **IR (thin film)**: 3068, 2945, 2872, 2225, 1606, 1574, 1509, 1477, 1448, 1378, 1303, 1260, 1172, 1116, 1086, 1024, 961, 914, 836, 722, 686, 607, 576, 550 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.96 (d, *J* = 7.4 Hz, 4H), 7.65 (t, *J* = 7.4 Hz, 2H), 7.60 – 7.46 (m, 6H), 6.92 (d, *J* = 8.8 Hz, 2H), 5.98 – 5.75 (m, 2H), 3.99 (t, *J* = 6.2 Hz, 2H), 2.20 (q, *J* = 13.8, 7.0 Hz, 2H), 1.86 – 1.73 (m, 2H), 1.65 – 1.51 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 162.35, 142.05, 139.68, 134.10, 134.01, 129.14, 128.23, 120.94, 119.32, 115.27, 103.99, 67.99, 29.68, 28.31, 25.02. **HRMS(ESI):** ($M+H^+$) calculated 497.1199, found 497.1192

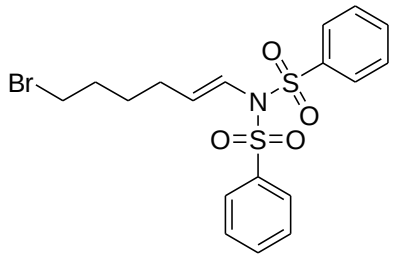


(E)-N-(6-(triisopropylsilyloxy)hex-1-enyl)benzenesulfonimide (2d). Synthesized according to general procedure B to afford the product as a yellow oil (80 mg, 73% yield, *E:Z* = 6.2:1). Purified by column chromatography (EtOAc/Hexanes = 1/19). **IR (thin film)**: 2942, 2865, 1451, 1381, 1173, 1091, 916, 722, 686, 577, 551 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, *J* = 7.8 Hz, 4H), 7.64 (t, *J* = 7.2 Hz, 2H), 7.54 (t, *J* = 7.6 Hz, 4H), 5.94 – 5.68 (m, 2H), 3.68 (t, *J* = 5.8 Hz, 2H), 2.14 (q, *J* = 12.9, 6.5 Hz, 2H), 1.60 – 1.41 (m, 2H), 1.15-0.97 (m, 23H). **^{13}C NMR (126 MHz,**

CDCl$_3$) δ 142.87, 139.67, 133.82, 129.01, 128.16, 120.29, 62.93, 32.24, 29.84, 24.93, 18.06, 12.01. **HRMS(ESI):** ($M+H^+$) calculated 552.2268, found 552.2275

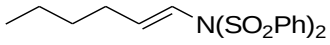


(E)-N-(6-(perfluorophenoxy)hex-1-enyl)benzenesulfonimide (2h). Synthesized according to general procedure B to afford the product as colorless oil (79.7 mg, 71% yield, *E:Z* = 7.7:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **IR (thin film)**:1514, 1449, 1379, 1172, 1086, 1028, 996, 915, 754, 722, 686, 577, 551 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, *J* = 7.3 Hz, 4H), 7.66 (t, *J* = 7.4 Hz, 2H), 7.55 (t, *J* = 7.6 Hz, 4H), 6.00 – 5.72 (m, 1H), 4.14 (t, *J* = 6.1 Hz, 2H), 2.20 (q, *J* = 7.0 Hz, 2H), 1.83 – 1.69 (m, 2H), 1.66 – 1.50 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 143.33 – 140.67 (m), 142.09, 139.71, 139.38 – 136.96 (m), 138.81 – 135.98 (m), 134.42 – 133.74 (m, 2C), 129.16, 128.26, 120.99, 75.40, 29.61, 29.14, 24.67. **HRMS(ESI):** ($M+H^+$) calculated 562.0776, found 562.0803

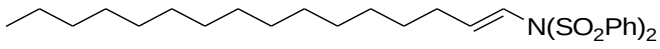


(E)-N-(6-bromohex-1-enyl) benzenesulfonimide (2q). Synthesized according to general procedure B to afford the product as a white solid (77.9 mg, 85% yield, *E:Z* :Allyl = 6.2:1:1).

Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 70-73 ^{o}C. **IR (thin film)**: 2939, 1448, 1378, 1171, 1086, 916, 723, 686, 577, 550 cm^{-1}. **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, J = 7.3 Hz, 4H), 7.66 (t, J = 7.4 Hz, 2H), 7.56 (t, J = 7.6 Hz, 4H), 5.97 – 5.72 (m, 2H), 3.40 (t, J = 6.6 Hz, 2H), 2.16 (q, J = 7.0 Hz, 2H), 1.91 – 1.77 (m, 2H), 1.65 – 1.46 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 141.93, 139.69, 134.04, 129.20, 128.27, 120.99, 33.36, 31.92, 29.19, 27.05. **HRMS(ESI):** (M+NH$_4^+$) calculated 475.0355, found 475.0346

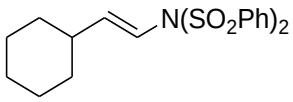


(E)-N-(hex-1-enyl)benzenesulfonimide (2f). Synthesized according to general procedure B to afford the product as a yellow oil (53.5 mg, 71% yield, *E:Z* = 5.7:1). Purified by column chromatography (EtOAc/Hexanes = 1/19). **IR (thin film)**: 2932, 2864, 1450, 1380, 1173, 1088, 953, 914, 751, 723, 686, 576, 551 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, J = 7.7 Hz, 4H), 7.65 (t, J = 7.4 Hz, 2H), 7.54 (t, J = 7.6 Hz, 4H), 6.01 – 5.59 (m, 2H), 2.11 (q, J = 12.9, 6.6 Hz, 1H), 1.43 – 1.16 (m, 4H), 0.89 (t, J = 7.0 Hz, 3H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 143.20, 139.78, 133.94, 129.12, 128.27, 120.25, 30.63, 29.76, 22.10, 13.87. **HRMS(ESI):** (M+H$^+$) calculated 380.0985, found 380.0988

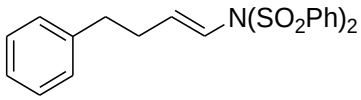


(E)-N-(hexadec-1-enyl)benzenesulfonimide (2g). Synthesized according to general procedure B to afford the product as a white solid (67.6 mg, 65% yield, *E:Z* = 9.1:1). Purified by column chromatography (EtOAc/Hexanes = 1/19). **Mp:** 47.2-50.5 ^{o}C. **IR (thin film)**: 2926, 2854, 1450, 1381, 1173, 1088, 915, 722, 687, 576, 551 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.97 (d, J = 7.8 Hz, 4H), 7.65 (t, J = 7.3 Hz, 2H), 7.54 (t, J = 7.6 Hz, 4H), 5.98 – 5.69 (m, 2H), 2.11 (q, J = 12.8,

6.5 Hz, 1H), 1.41 – 1.16 (m, 24H), 0.88 (t, *J* = 6.0 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 143.22, 139.80, 133.92, 129.11, 128.28, 120.23, 36.23, 32.05, 30.10, 29.81, 29.81, 29.78, 29.71, 29.48, 29.07, 28.56, 27.70, 26.97, 22.81, 14.24. **HRMS(ESI):** ($M+H^+$) calculated 520.2550, found 520.2539

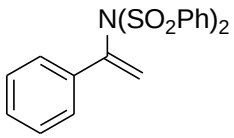


(E)-N-(2-cyclohexylvinyl)benzenesulfonimide (2r). Synthesized according to general procedure B to afford the product as a white solid (61.2 mg, 76% yield, *E:Z* = 17.1:1). **Mp:** 104.8-106.4 ^{o}C. Purified by column chromatography (EtOAc/Hexanes = 1/19). **IR (thin film)**: 3067, 2927, 2853, 1585, 1480, 1449, 1380, 1360, 1313, 1292, 1171, 1130, 1086, 1025, 1000, 958, 916, 794, 754, 741, 722 , 686, 635, 619, 578, 550 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.96 (d, *J* = 7.6 Hz, 4H), 7.65 (t, *J* = 7.3 Hz, 2H), 7.54 (t, *J* = 7.6 Hz, 4H), 5.73 (dt, *J* = 13.4, 10.4 Hz, 2H), 2.14-2.05 (m, 1H), 1.79 – 1.58 (m, 4H), 1.39 – 0.97 (m, 6H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 148.15, 139.61, 133.82, 128.98, 128.20, 118.67, 38.93, 32.00, 25.83, 25.55. **HRMS(ESI):** ($M+H^+$) calculated 406.1141, found 406.1142

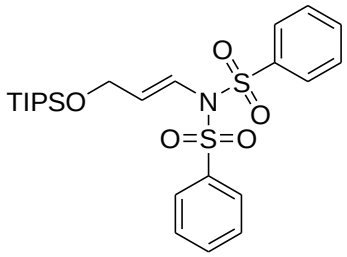


(E)-N-(4-phenylbut-1-enyl)-N-benzenesulfonimide (2c). Synthesized according to general procedure B to afford the product as a colorless oil (71.8 mg, 84% yield, *E:Z* :Allyl = 5.5:1:0.9). Purified by column chromatography (EtOAc/Hexanes = 1/19). **IR (thin film)**: 3061, 3030, 2926, 2854, 1592, 1498, 1450, 1379, 1171, 1119, 1083, 1026, 912, 782, 741, 684, 575, 549. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.87 (d, *J* = 7.4 Hz, 4H), 7.62 (t, *J* = 6.9 Hz, 2H), 7.49 (t, *J* = 7.6 Hz, 4H),

7.34 – 7.13 (m, 5H), 5.99 – 5.75 (m, 2H), 2.72 (t, *J* = 7.4 Hz, 2H), 2.46 (q, *J* = 12.2, 6.9 Hz, 2H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 141.58, 140.59, 139.67, 133.91, 129.10, 128.60, 128.33, 128.18, 126.28, 120.98, 34.74, 31.63. **HRMS(ESI):** (M+Na$^+$) calculated 450.0804, found 450.0796

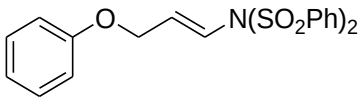


N-(1-phenylvinyl)benzenesulfonimide (2a). Synthesized according to general procedure B to afford the product as an off-white solid (77.5 mg, 97% yield). Purified by column chromatography (EtOAc/Hexanes = 1/6). **Mp:** 148-149 ^{o}C. **IR (thin film)**: 3061, 1623, 1576, 1488, 1449, 1379, 1263, 1170, 1086, 1019, 932, 756, 722, 686, 593, 545 cm^{-1} . **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.95 (d, *J* = 7.6 Hz, 4H), 7.62 (t, *J* = 7.4 Hz, 2H), 7.48 (t, *J* = 7.8 Hz, 4H), 7.39 (d, *J* = 7.1 Hz, 2H), 7.32 – 7.12 (m, 3H), 5.90 (s, 1H), 5.05 (s, 1H). **^{13}C NMR (126 MHz, CDCl$_3$)** δ 142.12, 139.43, 135.40, 134.10, 129.18, 129.18, 128.90, 128.40, 127.19, 120.30. **HRMS(ESI):** (M+H$^+$) calculated 400.0672, found 400.0665

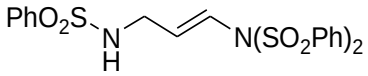


(E)-N-(3-(triisopropylsilyloxy)prop-1-enyl)benzenesulfonimide (2n). Synthesized according to general procedure B to afford the product as a white solid (78.5 mg, 77% yield, *E:Z* = 15.4:1). Purified by column chromatography (EtOAc/Hexanes = 1/4). **Mp:** 43-45 ^{o}C. **IR (thin film)**: 2943, 2866, 1448, 1383, 1351, 1171, 1126, 1086, 883, 811, 754, 722, 685, 624, 579, 550 cm^{-1} . **^{1}H NMR**

(300 MHz, $CDCl_3$): δ 7.97 (d, J = 7.5 Hz, 4H), 7.65 (t, J = 7.4 Hz, 2H), 7.53 (t, J = 7.6 Hz, 4H), 6.18 (dt, J = 13.2, 1.9 Hz, 1H), 5.96 (dt, J = 13.2, 4.0 Hz, 1H), 4.35 (dd, J = 3.9, 2.0 Hz, 2H), 1.18 – 1.01 (m, 21H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 139.73, 139.66, 133.98, 129.16, 128.32, 120.71, 61.56, 18.09, 12.07. **HRMS(ESI):** ($M+H^+$) calculated 510.1799, found 510.1808

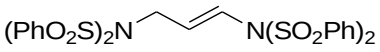


(E)-N-(3-phenoxyprop-1-enyl)benzenesulfonimide (2s). Synthesized according to general procedure B to afford the product as a white solid (61.6 mg, 71% yield, pure E). Purified by column chromatography (EtOAc/Hexanes = 1/19). **Mp:** 90.1-91.9 ^{o}C. **IR (thin film)**: 3066, 1599, 1587, 1496, 1448, 1379, 1241, 1171, 1136, 1085, 1032, 913, 753, 722, 685, 574, 548 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.93 (d, J = 7.6 Hz, 4H), 7.65 (t, J = 7.4 Hz, 2H), 7.51 (t, J = 7.7 Hz, 4H), 7.32 (t, J = 8.0 Hz, 2H), 7.01 (t, J = 7.4 Hz, 1H), 6.91 (d, J = 7.9 Hz, 2H), 6.30 (d, J = 13.5 Hz, 1H), 6.08 (dt, J = 13.5, 5.0 Hz, 1H), 4.64 (dd, J = 5.0, 1.5 Hz, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 158.01, 139.45, 134.52, 134.11, 129.69, 129.20, 128.26, 123.33, 121.48, 115.01, 65.39. **HRMS(ESI):** ($M+H^+$) calculated 430.0777, found 430.0783



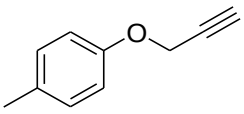
(E)-N-(3-(phenylsulfonamido)prop-1-enyl)benzenesulfonimide (2o). Synthesized according to general procedure B to afford the product as a white solid (82.8 mg, 84% yield, $E:Z$ = 8.3:1). **Mp:** 121.6-124.5 ^{o}C. Purified by column chromatography (EtOAc/Hexanes = 1/3). **IR (thin film)**: 3300, 3067, 1480, 1448, 1379, 1332, 1170, 1086, 914, 754, 740, 722, 686, 579, 549 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.92 – 7.82 (m, 6H), 7.67 – 7.58 (m, 3H), 7.58 – 7.44 (m, 6H), 6.11

(d, *J* = 13.5 Hz, 1H), 5.83 (dt, *J* = 13.4, 6.7 Hz, 1H), 5.17 (t, *J* = 6.2 Hz, 1H), 3.64 (t, *J* = 6.2 Hz, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 139.64, 139.26, 134.22, 134.03, 133.04, 129.40, 129.26, 128.24, 127.15, 123.71, 42.63. **HRMS(ESI):** ($M+H^+$) calculated 493.0556, found 493.0560



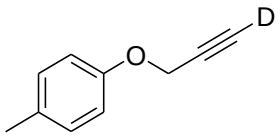
(E)-N-(3-phenylsulfonimido)prop-1-enyl)benzenesulfonamide) (2p). Synthesized according to general procedure B to afford the product as a white, bubbly solid (109.4 mg, 87% yield, *E:Z* = 12.4:1). Purified by column chromatography (100%DCM). **Mp:** 42.3-47 S9 ^{o}C. **IR (thin film)**: 3072, 1449, 1377, 1171, 1087, 911, 816, 728, 686, 579, 549 cm^{-1} . **^{1}H NMR (300 MHz, $CDCl_3$):** δ 8.06 (d, *J* = 7.5 Hz, 4H), 7.92 (d, *J* = 7.6 Hz, 4H), 7.65 (t, *J* = 6.9 Hz, 4H), 7.6-7.48 (m, 8H), 6.28 (d, *J* = 13.6 Hz, 1H), 6.02 (dt, *J* = 13.6, 6.8 Hz, 1H), 4.36 (d, *J* = 6.8 Hz, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)** δ 139.39, 139.28, 134.22, 134.19, 131.60, 129.33, 129.27, 128.44, 128.27, 125.95, 47.51. **HRMS(ESI):** ($M+H^+$) calculated 633.0488, found 633.0491

Experimental Procedures for Mechanistic Studies

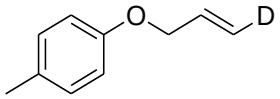


1-methyl-4-(prop-2-ynyloxy)benzene.[27] Synthesized according to general procedure A. The crude product was dissolved in ether and washed with 2 M NaOH (aq). The organic layer was dried over sodium sulfate, filtered, and concentrated under reduced pressure. The product was used for the next step without further purification. (2.3 g, 85% yield). **^{1}H NMR (300 MHz, $CDCl_3$):** δ

7.10 (d, *J* = 8.3 Hz, 2H), 6.88 (d, *J* = 8.6 Hz, 2H), 4.66 (d, *J* = 2.4 Hz, 2H), 2.50 (t, *J* = 2.4 Hz, 1H), 2.29 (s, 3H).

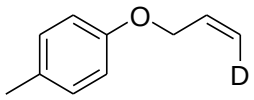


1-methyl-4-(3-deuterio-2-propynyloxy)benzene. 1-methyl-4-(prop-2-ynyloxy)benzene was dissolved in dry THF under nitrogen at - 78 ^{o}C followed by addition of 2.5 M nBuLi in THF (2 equiv). After being stirred for additional 2 hours, the reaction mixture was cooled down to -78 ^{o}C, quenched with D2O (excess), diluted with ether, and washed with water. After extraction, the organic layer was dried over sodium sulfate, filtered and concentrated in vacuo. The crude product was purified through column chromatography (EtOAc/Hexanes = 1/50) to afford a colorless oil (2.03 g, 89% yield). **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.10 (d, *J* = 8.3 Hz, 2H), 6.88 (d, *J* = 8.5 Hz, 2H), 4.66 (s, 2H), 2.29 (s, 3H).

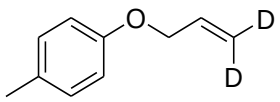


(E)-1-(3-deuterio-prop-2-enyloxy)-4-methylbenzene ((E)-1t-d). To Cp_2ZrCl_2 (1.5 equiv) in THF was added $LiAlH_4$ (0.4 equiv) powder. The reaction mixture was stirred at room temperature for 3 hours and 1-methyl-4-(prop-2-ynyloxy)benzene (1.0 eq) was added. The reaction mixture was stirred for additional 5 hours, quenched with D_2O, and was allowed to stir overnight. The reaction mixture was diluted with ether and was washed with 1 M HCl(aq), saturated $NaHCO_3$ (aq), and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated under reduced pressure. The crude was purified through column chromatography (EtOAc/Hexanes =

1/50) to afford a pale-yellow oil (727.2 mg, 50% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.08 (d, J = 8.2 Hz, 2H), 6.82 (d, J = 8.4 Hz, 2H), 6.05 (dt, J = 16.9, 4.8 Hz, 1H), 5.39 (d, J = 17.2 Hz, 1H), 4.64 – 4.33 (m, 2H), 2.29 (s, 3H).



(Z)-1-(3-deuterio-prop-2-enyloxy)-4-methylbenzene ((Z)-1t-d). To Cp_2ZrCl_2 (1.5 equiv) in THF was added $LiAlH_4$ (0.4 equiv) powder. The reaction mixture was stirred at room temperature for 3 hours and 1-methyl-4-(3-deuterio-2-propynyloxy)benzene (1.0 eq) was added. The reaction mixture was stirred for additional 5 hours, quenched with deionized water, and was allowed to stir overnight. The reaction mixture was diluted with ether and was washed with 1 M HCl (aq), saturated $NaHCO_3$ (aq), and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated under reduced pressure. The crude was purified through column chromatography (EtOAc/Hexanes = 1/50) to afford a pale-yellow oil (600 mg, 40% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.08 (d, J = 8.2 Hz, 2H), 6.82 (d, J = 8.4 Hz, 2H), 6.05 (d, J = 5.2 Hz, 1H), 5.26 (d, J = 10.6 Hz, 1H), 4.51 (d, J = 4.0 Hz, 2H), 2.28 (s, 3H).



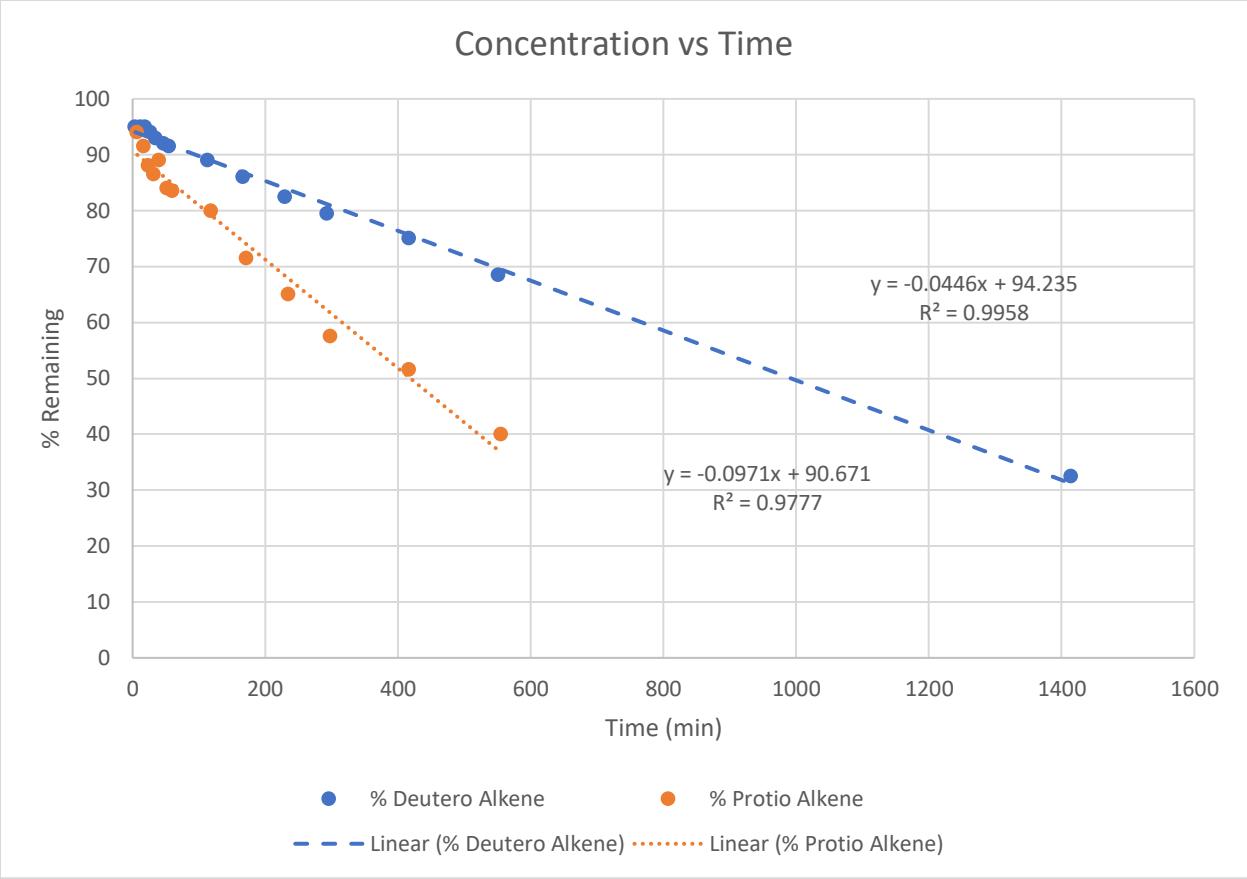
1-(3,3-di-deuterio-prop-2-enyloxy)-4-methylbenzene (1t-d_2).[28] To Cp_2ZrCl_2 (1.5 equiv) in THF was added $LiAlH_4$ (0.4 equiv) powder. The reaction mixture was stirred at room temperature for 3 hours and 1-methyl-4-(3-deuterio-2-propynyloxy)benzene (1.0 equiv) was added. The reaction mixture was stirred for additional 5 hours, quenched with D_2O, and was allowed to stir overnight. The reaction mixture was diluted with ether and was washed with 1 M HCl (aq), saturated $NaHCO_3$

(aq), and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated under reduced pressure. The crude was purified through column chromatography (EtOAc/Hexanes = 1/50) to give a yellow oil (1.54 g, 74% yield). **$_1$H NMR (300 MHz, $CDCl_3$):** δ 7.08 (d, J = 8.4 Hz, 2H), 6.82 (d, J = 8.5 Hz, 2H), 6.13 – 5.90 (m, 1H), 4.51 (d, J = 5.3 Hz, 2H), 2.29 (s, 3H).

Both (E)-1t-d and (Z)-1t-d were subjected to the conditions described in General Procedure B and Breder's conditions, respectively. Crude NMRs were taken and analyzed for mechanistic studies.

A competition experiment was run in which a mixture of 1:1 molar ratio of 1t and 1t-d_2 was subjected to the reaction conditions described in General Procedure B and Breder's Conditions, respectively. Crude NMRs were taken and analyze for mechanistic studies.

Both 1t and 1t-d_2 were independently subjected to the reaction conditions described in General Procedure B in an NMR tube with $CDCl_3$ as solvent. Spectra were taken at various time points and the results are shown in the graph below.


Concentration vs Time
% Remaining
Time (min)
y = -0.0446x + 94.235
R² = 0.9958
y = -0.0971x + 90.671
R² = 0.9777
% Deutero Alkene
% Protio Alkene
Linear (% Deutero Alkene)
Linear (% Protio Alkene)

Notes to Chapter 2

1) Portions of this chapter have been published as Zheng, T.; Tabor, J. R.; Stein, Z. L. Michael, F. E. *Org. Lett.* **2018**, 20, 6975-6978**.**
2) Selenium catalysis review: Singh, F. V.; Wirth, T. *Catal. Sci. Technol*. **2019**, 9, 1073–1091.
3) For select examples of selenium catalysis, see: (a) Hori, T.; Sharpless, K. B. *J. Org. Chem*. **1979**, 44, 4204–4208; (b) Tiecco, M.; Testaferri, L.; Tingoli, M.; Bagnoli, L.; Santi, S. *J. Am. Chem. Soc.* **1993**, 637–639; (c) Wirth, T.; Hauptli, S.; Leuenberger, M. *Tetrahedron: Asymmetry*, **1998**, 9, 547– 550; (d) Tunge, J. A.; Mellegaard, S. R. *Org. Lett.* **2004**, 6, 1205–1207; (e) Trenner, J.; Depken, C.; Weber, T.; Breder, A. *Angew. Chem., Int. Ed.* **2013**, 52, 8952–8956; (f) Denmark, S. E.; Hartmann, E.; Kornfilt, D. J. P.; Wang, H. *Nat. Chem*. **2014**, 6, 1056–1064; (g) Deng, Z.; Wei, J.; Liao, L.; Huang, H.; Zhao, X. *Org. Lett*. **2015**, 17, 1834–1837.
4) Hili, R.; Yudin, A. K. *Nature Chemical Biology*, **2006**, 2, 284–287.
5) Shuler, S. A.; Guoyin, Y.; Krause, S. B.; Vesper, C. M.; Watson, D. A.; *J. Am. Chem. Soc.* **2016**, 138, 13830−13833.
6) Yang, G.; Zhang, W.; *Org. Lett*. **2012**, 14, 268-271.
7) Rogers, M. M.; Kotov, V.; Chatwichien, J.; Stahl, S. S.; *Org. Lett*. **2007**, 9, 4331−4334.
8) Liu, G.; Yin, G.; Wu, L.; *Angew. Chem., Int. Ed*. **2008**, 47, 4733−4736.
9) Trenner, J.; Depken, C.; Weber, T.; Breder, A. *Angew. Chem., Int. Ed.* **2013**, 52, 8952−8956.
10) Deng, Z.; Wei, J.; Liao, L.; Huang, H.; Zhao, X. *Org. Lett*. **2015**, 17, 1834−1837.
11) *Org. Synth.* **1979**, *59*, 141

12) (a) It is well established that seleniranium ions are opened with nucleophiles to give a net anti-addition. For an example, see: Cresswell, A. J.; Eey, S. T. C.; Denmark, S. E. *Nat. Chem.* **2015**, 7, 146-152. (b) It is also known that selenoxide species participate in syn-elimination, see: Young, M. W.; Lauer, R. F.; Sharpless, K. B. *Tet. Lett.* **1973**, 22, 1979-1982. We propose a similar elimination in our mechanism.

13) Kwart, L. D.; Horgan, A. G.; Kwart, H. *J. Am. Chem. Soc*. **1981**, 103, 1232−1234.

14) (a) Denney, D. B.; Tunkel, N. *Chem. Ind*. **1959**, 1383. (b) Merrigan, S. R.; Singleton, D. A. *Org. Lett*. **1999**, 1, 327−329.

15) (a) Aragoni, M. C.; Arca, M.; Demartin, F.; Devillanova, F. A.; Garau, A.; Grimaldi, P.; Isaia, F.; Lelj, F.; Lippolis, V.; Verani, G. *Eur. J. Inorg. Chem*. **2004**, 2363−2368. (b) Godfrey, S. M.; Jackson, S. L.; McAuliffe, C. A.; Pritchard, R. G. *J. Chem. Soc., Dalton Trans*. **1998**, 4201−4204.

16) Ion pair intermediate: Okamoto, Y.; Chellappa, K. L.; Homsany, R. *J. Org. Chem*. **1973**, 88, 3172-3175.

17) W. L. F. Armarego, C. L. L. Chai. Purification of Laboratory Chemicals, 5th Ed.; Elsevier: Burlington, MA, 2003.

18) J. Wang, F. Li, W. Pei, M. Yang, Y. Wu, D. Ma, F. Zhang, J. Wang, *Tetrahedron Lett*. **2018**, 59, 1902-1905.

19) X. Dong, R. Sang, Q. Wang, X. Y. Tang, M. Shi. *Chem. Eur. J*. **2013**, 19, 16910 – 16915.

20) W. B. Reid, J. J. Spillane, S. B. Krause, D. A. Watson. *J. Am. Chem. Soc*. **2016**, 138, 5539-5542.

21) S. Mizuta, S. Verhoog, K. M. Engle, T. Khotavivattana, M. O'Duill, K. Wheelhouse, G. Rassias, M. Medebielle, V. Gouverneur. *J. Am. Chem. Soc*. **2013**, 135, 2505-2508.

22) P. A. Sibbald, F. E. Michael. *Org. Lett*. **2009**, 11, 1147-1149.

23) D. W. Allen, I. W. Nowell, B. F. Taylor. *J. Chem. Soc., Dalton Trans*. **1985**, 0, 2505-2508.

24) L. Zhu, L. Wang, B. Li, B. Fu, C. Zhang, W. Li. *Chem. Commun*. **2016**, 52, 6371-6374

25) K. Zhang, J. B. Liu, F. L. Qing. *Chem. Commun*. **2014**, 50, 14157-14160.

26) K. Garg, C. Majumder, S. K. Gupta, D. K. Aswal, S. K. Nayak, S. Chattopadhyay. *Chem. Sci.* **2016**, 7, 1548-1557.

27) C. Efe, I. N. Lykakis, M. Stratakis. *Chem. Commun*. **2011**, 47, 803-805.

28) U. K. Pomeranz, H. Schmid, H. J. Hanse. *Helvetica Chimica Acta*. **1977**, 60, 768-797

29) Kumar, A; Bhakuni, B. S.; Prasad, C. D.; Kumar, S. Kumar, S. *Tetrahedron*. **2013**, 69 5383-5392

30) Wang, D.; Wu, L.; Wang, F.; Wan, X.; Chen, P.; Lin, Z.; Liu, G. *J. Am. Chem. Soc.* **2017**, 139, 6811-6814.

31) Tian, F.; Chen, Y.; Wu, L.; Li, P.; Lu, S. *J. Chem. Res.* **2014**, 38, 375-377.

32) Grandclaudon, C.; Ruamps, M.; Duboc, R.; Michelet, V.; Toullec, P. Y. *Synlett*, **2018**, 29, 1181-1186.

33) Nelson, D. J.; Collado, A.; Manzini, S.; Meiries, S.; Slawin, A. M. Z.; Cordes, D. B.; Nolan, S. P. *Organometallics*, **2014**, 33, 2048-2058.

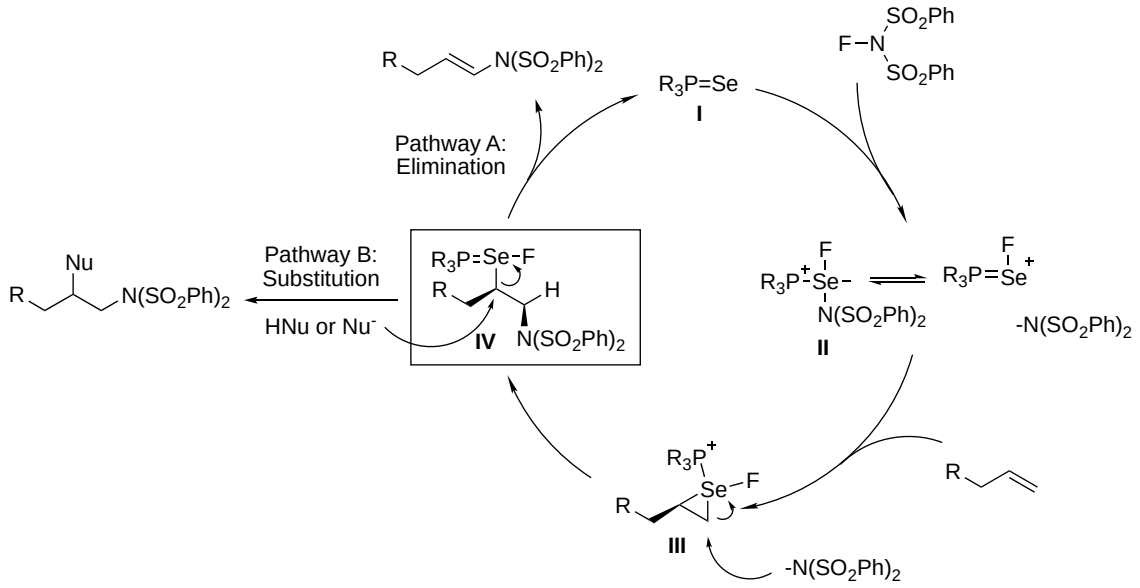
34) Tiedemann, M. A.; Mandell, C. L.; Chan, B. C.; Nataro, C. *Inorganica Chimica Acta*, **2014**, 422, 193-201.

Chapter 3 – Selenophosphoramide Catalyzed 1,2-Diamination and Oxyamination of Alkenes[1]

Section 1: Introduction

Given our success with synthesizing a new class of sterically and electronically diverse catalysts and employing them in an existing transformation[2] to improve yields and selectivities, we wondered whether we could use these catalysts to achieve an entirely new transformation. A key step in our proposed mechanism (Figure 3.1, Pathway A) is the syn elimination from the selenium-fluorine bond from intermediate IV.

Figure 3.1. Catalytic Cycle and Elimination vs. Substitution from Intermediate IV



We imagined that if, instead of undergoing syn elimination, intermediate IV were intercepted with a nucleophile then the result would be a net 1,2-difunctionalization of the alkene (Figure 3.1, Pathway B). However, as we and many other authors have discovered, achieving an intermolecular substitution in favor of the relatively quicker intramolecular elimination is very difficult. As a result, the vast majority of organoselenium-promoted transformations end in this elimination step,

giving vinyl- or allyl-functionalized products[2-5], while a selenium-catalyzed 1,2-difunctionalization is nearly unheard of. To our knowledge, only Denmark's syn-dichlorination- and diamination of alkenes are the only known difunctionalizations of alkenes proceeding through a seleniranium ion.[6]

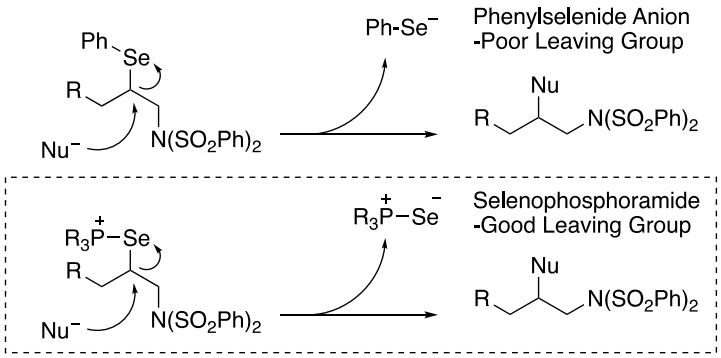
We sought to utilize this new reaction pathway to install two amine nucleophiles across the C=C bond, giving a net 1,2-diamination of the olefin. Vicinal diamines constitute a very desirable product class and find widespread use in many different areas, including as biologically active compounds, drug molecules or ligands.[7,8] While several protocols exist for synthesizing 1,2-diamines from alkenes, most suffer from a limited and/or highly engineered substrate scope.[8,9] There are comparatively few general and broadly applicable fully intermolecular 1,2-diamination methods.[10]

Section 2: Results and Discussion

3.2.1 TMSOTf as a Fluoride Scavenger

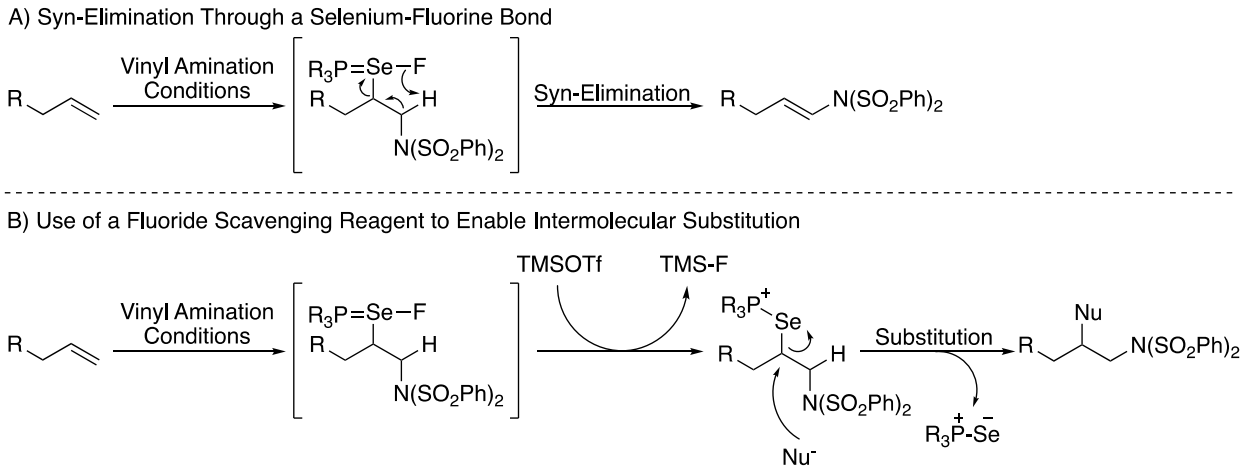
We expected that our newly developed phosphine selenide catalysts might increase the possibility of favoring substitution over elimination (see Figure 3.1 above), particularly when considering the leaving group that results from this mechanistic step (Figure 3.2).

Figure 3.2. Substitution of Phenylselenide vs. Phosphine Selenide



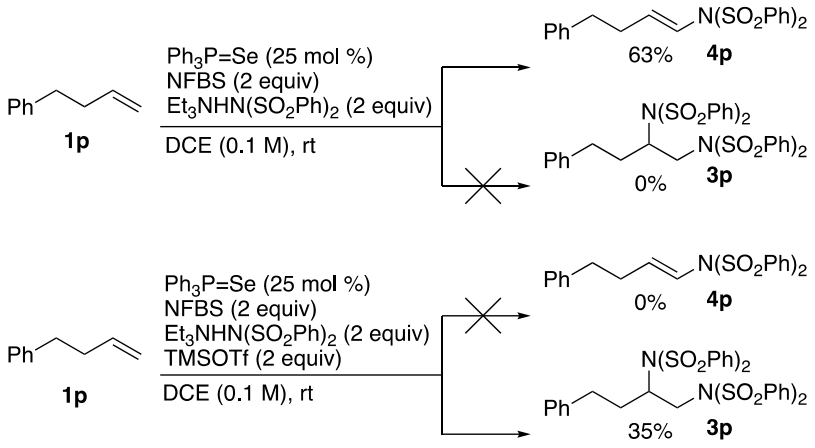
As seen in the figure above, when using diphenyl diselenide as a catalyst the leaving group is the relatively unstable phenylselenide anion with a net -1 charge. On the other hand, when using a phosphine selenide as a catalyst the leaving group is net neutral, and thus more stable and more willing to participate as a leaving group. As a result, phosphine selenides should increase the efficacy of the desired intermolecular substitution. However, in addition to encouraging the substitution step, it was also necessary to inhibit the highly favorable intramolecular syn-elimination pathway. Our previous work suggested that the syn-elimination proceeds through a selenium-fluorine bond (Scheme 3.1a).[2]

Scheme 3.1. Elimination vs. Substitution Pathways



We hypothesized that the introduction of a fluoride scavenging agent might shut down the elimination pathway by sequestering fluorine, allowing for substitution to take place (Scheme 3.1b). We began our studies by testing this hypothesis. 4-Phenyl-1-butene was subjected to our previous vinyl amination conditions and, as expected, only vinyl amination product was observed. (Scheme 3.2).

Scheme 3.2. Effect of TMSOTf on Elimination vs. Substitution



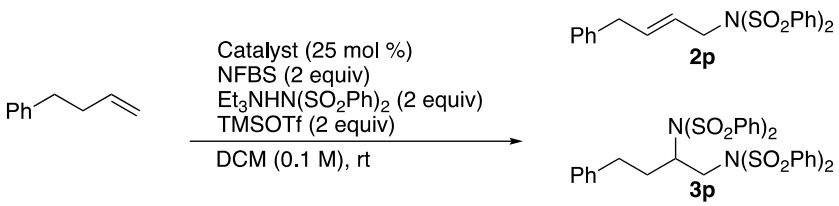
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

However, the introduction of two equivalents of trimethylsilyl trifluoromethanesulfonate (TMSOTf) suppressed the elimination completely, giving 35% yield of the desired diamination product.

3.2.2 Reaction Optimization

A catalyst screen revealed that selenophosphoramide catalysts (phosphine selenides with three nitrogen substituents on phosphorus) were effective catalysts, with tris(diethylamino)phosphine selenide providing better performance triphenylphosphine selenide, giving 50% yield of the desired diamination **3p** and 17% of an allylic amination byproduct **2p** (Table 3.1, entry 4 vs. 3).

Table 3.1. Catalyst Screen for 1,2-diamination

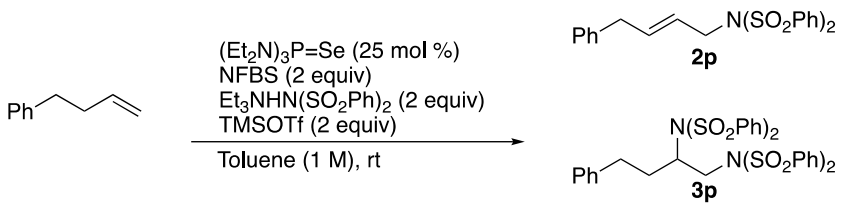


Entry	Catalyst	Yield **2p**	Yield **3p**
1	IPrSe	15%	19%
2	Ph_2Se_2	10%	20%
3	$Ph_3P{=}Se$	-	35%
4	$(Et_2N)_3P{=}Se$	17%	50%

[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

A screen of several sources of benzenesulfonimide nucleophile was performed. (Table 3.2). All anionic benzenesulfonimides had similar reactivity, and tetrabutylammonium benzenesulfonimide was chosen for subsequent screening due to its increased solubility. A solvent screen showed that ether, ethyl acetate, dichloromethane and toluene were all comparable solvents, giving similar yields.

Table 3.2. Source of Benzenesulfonimide Nucleophile



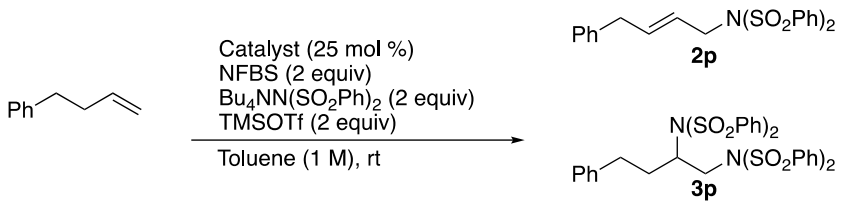
Entry	Nucleophile	Yield **2p**	Yield **3p**	SM
1	$HN(SO_2Ph)_2$	-	-	5%
2	$Ph_4PN(SO_2Ph)_2$	9%	53%	-
3	$Et_3NHN(SO_2Ph)_2$	-	55%	-
4	$Bu_4NN(SO_2Ph)_2$	9%	56%	-

[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

3.2.3 Catalyst Exploration and Additive Screen

As mentioned previously, the fundamental idea supporting the goal of discovering new organoselenium catalyzed transformations was the synthesis and application of a new library of sterically and electronically diverse catalysts. In order to enact this approach, a catalyst library was synthesized and all of the catalysts were screened under the conditions. We began our exploration by looking at NHC-selenides as well as a few sulfur analogues (Table 3.3).

Table 3.3. Catalyst Screen – Phosphine Sulfides and NHC-Selenides

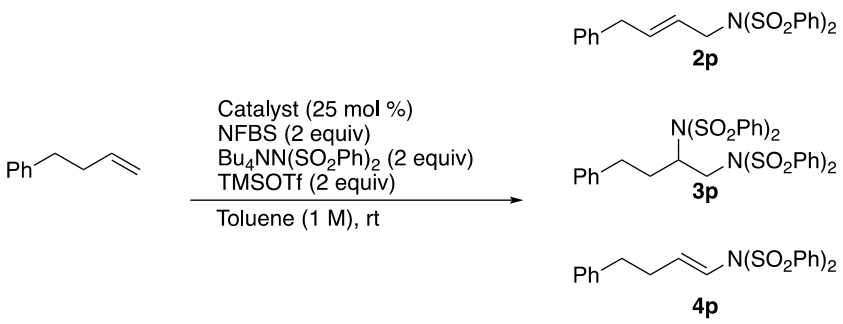


Entry	Catalyst	Yield **2p**	Yield **3p**	SM
1	$(Et_2N)_3P{=}S$	-	-	-
2	$Ph_3P{=}S$	-	-	53%
3	IMeSe	-	-	-
4	IPrSe	4%	3%	-

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

As NHC-selenides showed reasonable reactivity in our previous aza-Heck chemistry[2], we sought to explore their use in the related diamination conditions. However, phosphine sulfides (entries 1,2) and NHC-selenides (entries 3,4) were very poor catalysts, giving little to no reactivity. We next sought to explore phosphine selenides with carbon, nitrogen and oxygen substituents on phosphorus.

Table 3.4. Catalyst Screen – Phosphine Selenides with Carbon Substituents

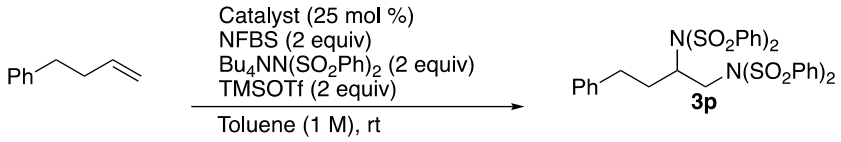


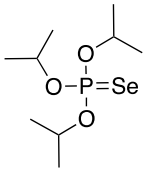
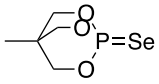
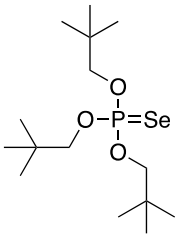
Entry	Catalyst	Yield **2p**	Yield **3p**	Yield **4p**
1	$Cy_3P{=}Se$	10%	22%	16%
2	$Ph_3P{=}Se$	-	33%	10%
3	$^tBu_3P{=}Se$	13%	44%	-
4	$(o\text{-tol})_3P{=}Se$	-	53%	-

[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

As seen in Table 3.4, amongst phosphine selenides with carbon substituents, sterically hindered phosphines were observed to enhance the reactivity (entry 3 vs. 1 and 4 vs. 2). Additionally, it appeared that phosphines with aryl substituents were higher performing than alkyl (entry 4 vs. 3, 1).

Table 3.5. Catalyst Screen – Phosphine Selenides with Oxygen Substituents



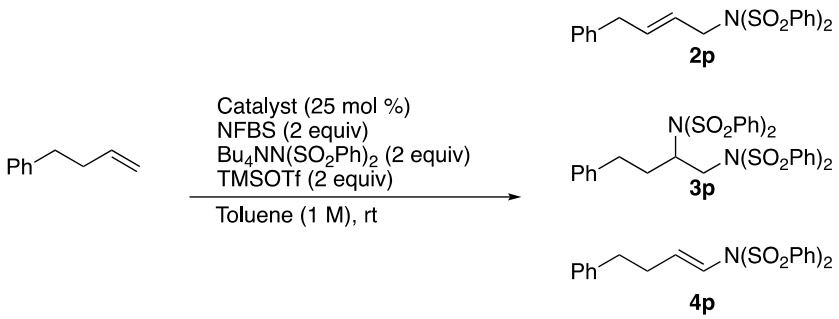
Entry	Catalyst	Yield **3p**
1		39%
2	$(MeO)_3P{=}Se$	41%
3	$(PhO)_3P{=}Se$	42%
4	$(^tBuO)_3P{=}Se$	44%
5		44%
6		46%

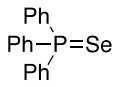
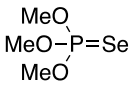
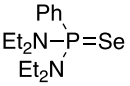
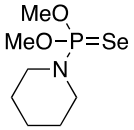
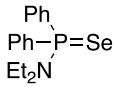
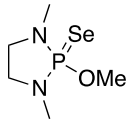
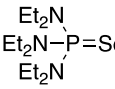
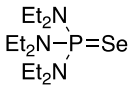
[a]Yields determined by ^1H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

As seen in Table 3.5, amongst selenophosphates with oxygen substituents there was no clear trend or significant difference in reactivity, and all catalysts gave similar yields of the desired product. Interestingly, these catalysts gave cleaner reaction mixtures, and no detectable amounts of elimination products were formed. It seemed that phosphine selenides with oxygen substituents gave, in general, higher yields than those with carbon substituents (Table 3.5 vs. 3.4). When comparing the yields given from these two catalyst classes with tris(diethylamino)phosphine selenide (Table 3.1, entry 4) it became clear that catalysts with electron donating ligands gave the highest yields, with a reactivity trend of: carbon (least reactive) < oxygen < nitrogen (most

reactive). Carbon, with its absence of non-bonding electrons, is the least electron donating of the three elements. Between oxygen and nitrogen, which both have non-bonding electrons that can resonance donate to the phosphorus, nitrogen is the more donating of the two because of its lower electronegativity.

Table 3.6. Phosphine Selenide Substituent Comparison



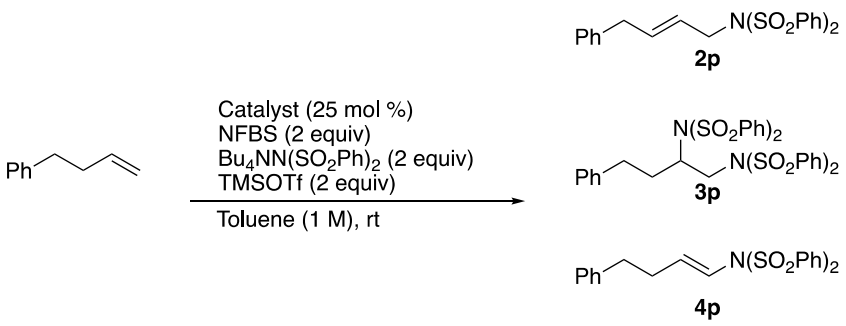
Entry	Catalyst	Yield **2p**	Yield **3p**	Yield **4p**	Entry	Catalyst	Yield **2p**	Yield **3p**	Yield **4p**
1		-	33%	10%	5		-	41%	-
2		10%	43%	-	6		-	49%	-
3		-	36%	-	7		-	50%	-
4		5%	55%	-	8		5%	55%	-

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

To further elucidate this trend, we systematically evaluated the change from carbon to oxygen to nitrogen substituents by making catalysts with mixed substituents (Table 3.6, entries 2, 3, 6, 7). Entries 1-4 illustrate the increase in yield as substituents on phosphine are switched from carbon to nitrogen and entries 5-8 show the same increase by switching from oxygen to nitrogen

Before a full exploration of selenophosphoramide catalysts was undertaken, a screen of additives with the best catalyst was performed (Table 3.7).

Table 3.7. Additive Screen



Entry	Deviation from standard	Yield **2p**	Yield **3p**	Yield **4p**
1	None	5%	55%	-
2	H_2O (1 eq)	12%	-	56%
3	3A MS (100 mg/mL)	11%	30%	16%
4	TEMPO (20 mol %)	8%	48%	-
5	NMMO (1 eq)	6%	42%	5%
6	Pyridine N-oxide (1 eq)	-	36%	-
7[b]	BF_3OEt_2 (2 eq)	11%	25%	22%
8[b]	BF_3OEt_2 (4 eq)	tr	48%	tr
9	TFA (2 eq)	5%	-	25%
10[b]	TFA (2 eq)	6%	-	30%
11	TfOH (2 eq)	-	-	-
12[b]	TfOH (2 eq)	-	-	10%

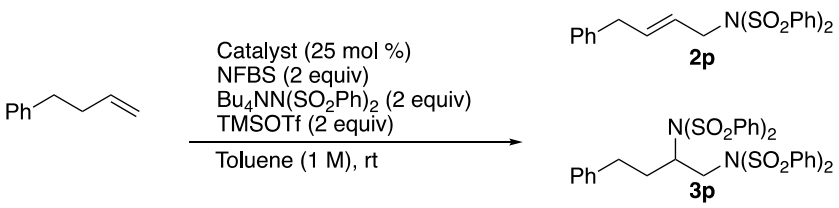
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard. [b]Bronsted/Lewis Acid used in place of TMSOTf

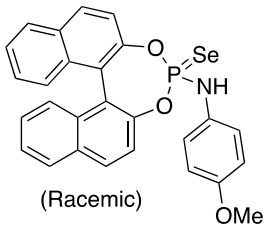
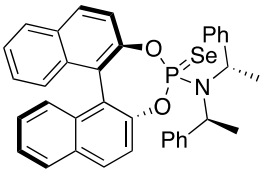
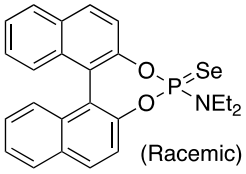
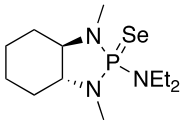
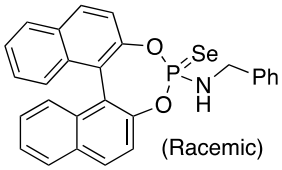
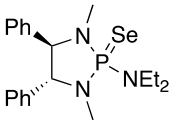
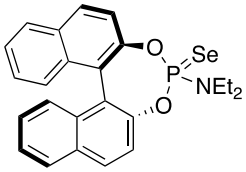
It was observed that small amounts of water completely shut down the substitution reaction (entry 2). Water is known to decompose TMSOTf, and we hoped that the complete removal of water from the reaction mixture might give an increase in yield. Unfortunately, addition of 3Å MS did

not provide any improvement (entry 3). Addition of catalytic amounts of TEMPO was not found to have a significant effect on the reaction (entry 4), suggesting that a radical pathway is not involved. Denmark observed a rate enhancement and improvement of reactivity by the addition of electron donating Lewis bases in his selenium-catalyzed syn-dichlorination reaction.[6a] However, addition of NMMO or pyridine N-oxide provided no improvement to the yield of the desired product (entries 5, 6). It was observed that BF_3OEt_2 could be used as a Lewis acid/fluoride scavenger in place of TMSOTf, but it was less effective (entry 7) and 4 equivalents were required to obtain similar yields (entry 8). Brønsted acids (TFA, TfOH) in place of Lewis Acids shut down the desired reactivity (entries 9-12).

In the hopes of achieving enantioselectivity, several chiral catalysts were synthesized and subjected to the standard conditions (Table 3.8).

Table 3.8. Chiral Catalyst Screen



Entry	Catalyst	Yield **2p**	Yield **3p**	%ee	Entry	Catalyst	Yield **2p**	Yield **3p**	%ee
1	 (Racemic)	23%	32%	0	5		-	46%	0
2	 (Racemic)	-	36%	0	6		9%	30%	0
3	 (Racemic)	-	40%	0	7		-	49%	0
4		10%	56%	0					

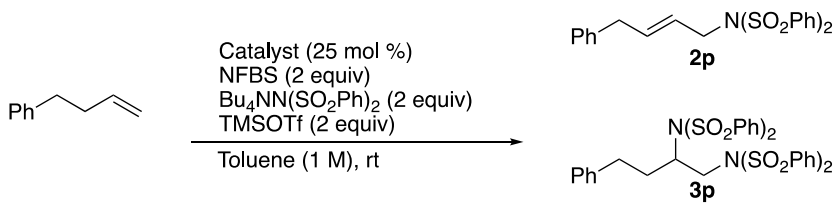
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

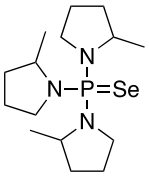
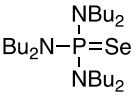
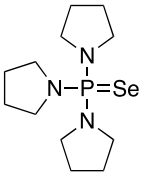
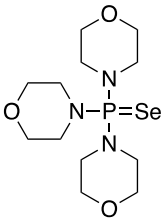
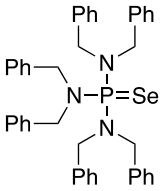
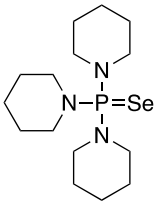
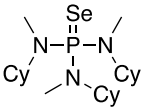
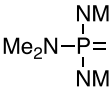
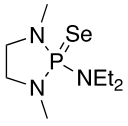
Initially, several racemic phosphoramidite selenides were synthesized in order to observe whether or not they were effective catalysts (entries 1-3). As expected, based on the trends in catalyst previously observed (Table 3.6 above), these catalysts generally gave lower yields than the selenophosphoramides did. Several chiral variants were tested, however none of them gave any enantioselectivity (entries 4-7). Despite the lack of success with these few attempts,

enantioselectivity in this transformation is very desirable and will potentially be the subject of future efforts in the Michael lab.

Given the highest performance of selenophosphoramide catalysts, a wide variety of selenophosphoramides were synthesized and subjected to the reaction conditions with the aim of increasing the yield.

Table 3.9. Initial Selenophosphoramide Catalyst Screen



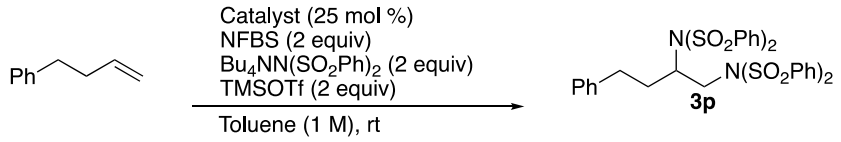
Entry	Catalyst	Yield **2p**	Yield **3p**	Entry	Catalyst	Yield **2p**	Yield **3p**
1		13%	20%	6		5%	50%
2		6%	36%	7	$(Et_2N)_3P{=}Se$	5%	55%
3		-	40%	8		-	58%
4		-	45%	9		-	62%
5		-	47%	10		-	62%

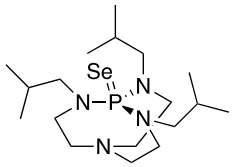
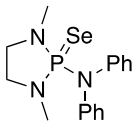
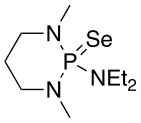
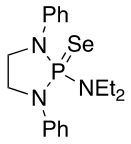
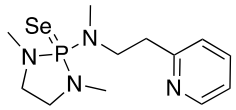
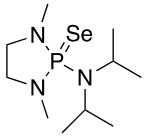
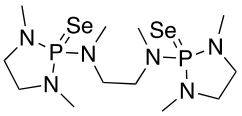
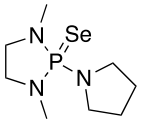
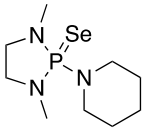
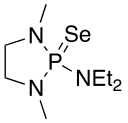
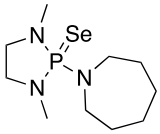
[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

Table 3.9 shows a screen of various selenophosphoramides. Within this class of catalysts, there were no obvious steric or electronic trends observed. However, this screen confirms, when compared to the results in Table 3.6, that electron donating ligands are preferred. The selenophosphoramide catalyst with a bidentate substituent derived from N,N'-

dimethylethylenediamine and a monodentate substituent derived from diethylamine, was the highest performing (entry 10). Given the effectiveness of this scaffold, several variants manipulating both the bidentate portion and the monodentate portion were synthesized (Table 3.10).

Table 3.10. N,N'-dimethylethylenediamine-derived Catalysts



Entry	Catalyst	Yield **3p**	Entry	Catalyst	Yield **3p**
1		31%	7		57%
2		47%	8		59%
3		49%	9		60%
4[b]		55%	10		61%
5		57%	11		62%
6		57%			

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard. [b]10 mol % catalyst

While many were comparable in yield to (entries 5-10), none were better. In the hopes of further increasing the electron donating ability of the substituents, catalysts with an additional

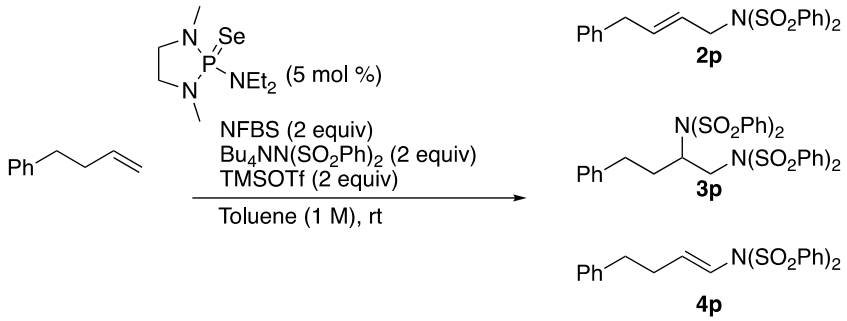
coordinating ligand were synthesized (entries 1, 3), but unfortunately provided no increase in yield. A catalyst with two P=Se groups was tested (entry 4), but again provided no improvement.

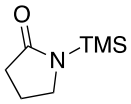
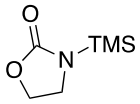
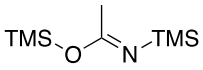
It was observed that the catalyst loading could be reduced to 5 mol % with only a negligible effect on the yield.

3.2.4 Continued Optimization

A screen of Lewis acids revealed that most gave no desired product (Table 3.11). Surprisingly, even silyl triflates other than TMSOTf gave poor reactivity (entries 5, 6).

Table 3.11. Lewis Acids

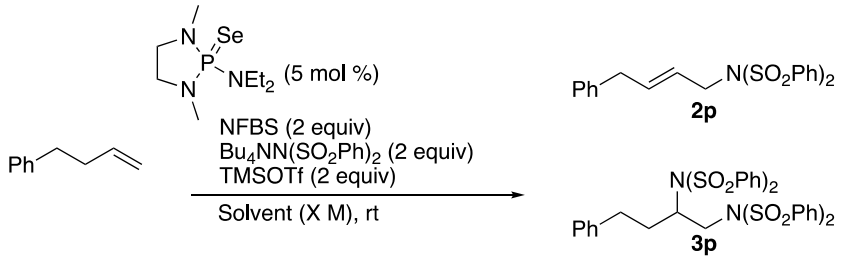


Entry	Lewis Acid	Yield **2p**	Yield **3p**	Yield **4p**	SM
1	TMSCl	-	-	-	20%
2	TMSBr	-	-	-	-
3		-	-	-	60%
4		-	-	-	10%
5	TBDMSOTf	-	8%	12%	-
6	TIPSOTf	-	-	10%	-
7	AgOTf	-	-	-	53%
8	$HN(TMS)_2$	-	-	-	65%
9	TMS-TMS	20%	-	-	25%
10		-	-	-	68%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

A solvent screen revealed DCM and toluene were comparable solvents, and a concentration screen led DCM (0.1 M) to be selected for continued exploration (Table 3.12, entry 7).

Table 3.12. Solvent and Concentration Screen



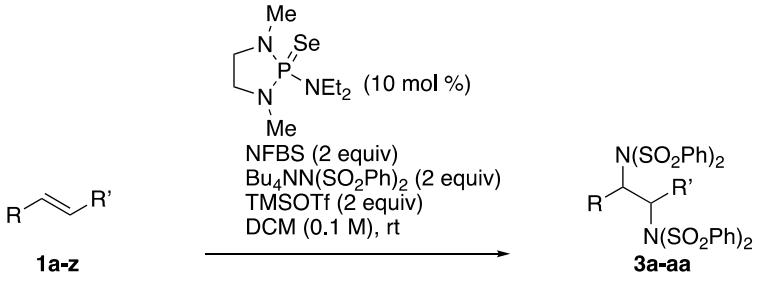
Entry	Solvent	Concentration	Yield **2p**	Yield **3p**
1	Toluene	1 M	-	59%
2	Toluene	0.4 M	15%	62%
3	Toluene	0.2 M	10%	58%
4	Toluene	0.1 M	5%	58%
5	DCM	1 M	57%	13%
6	DCM	0.4 M	18%	63%
7	DCM	0.2 M	10%	63%
8	DCM	0.1 M	14%	63%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

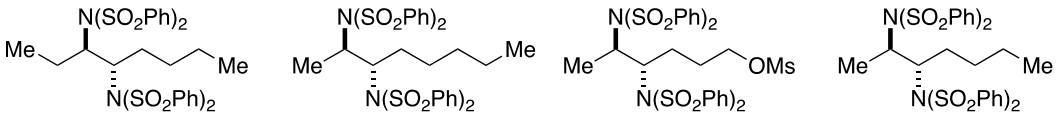
3.2.5 Olefin 1,2-Diamination – Substrate Scope and Deprotection

A variety of alkenes were subjected to the optimized conditions (Table 3.13). Both terminal- and 1,2-disubstituted olefins gave diamination products in good to excellent yields (Tables 3.13 and 3.14).

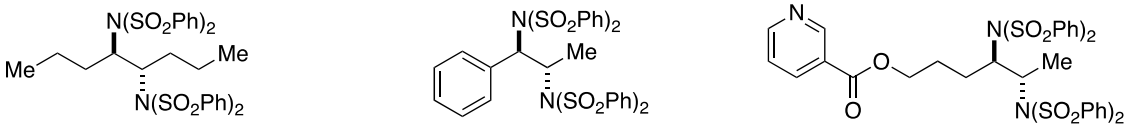
Table 3.13. Substrate Scope – Trans-1,2-Disubstituted Olefins



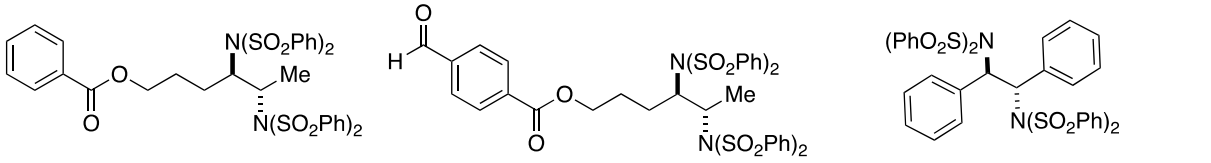
(Trans-1,2-disubstituted olefins)



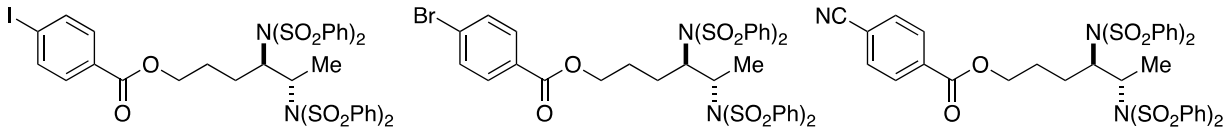
3a 88% **3b** 83% **3c** 88% **3d** 88%



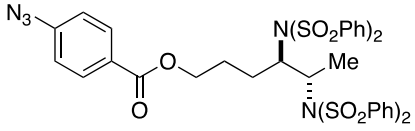
3e 74% **3f** 85% **3g** 40%



3h 90% **3i** 96% **3j** 75%



3k 93% **3l** 83% **3n** 87%

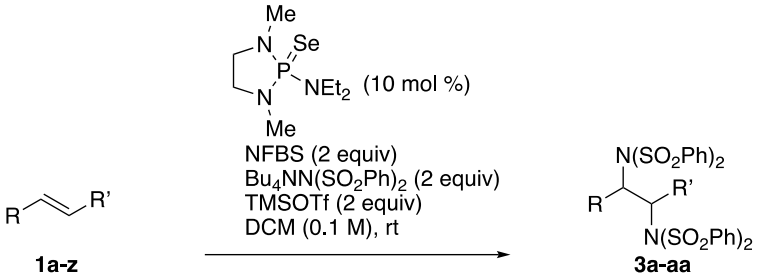


3m 84%

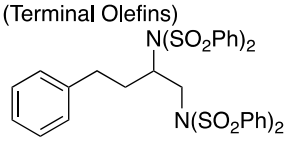
Isolated Yields.

The reaction is tolerant of silyl ethers, alkyl halides (including allyl), aryl halides, electron-rich and electron-poor aromatics, esters, nitriles, azides, sulfonates, and aldehydes. Internal olefins performed particularly well, giving yields from 74–96% (Table 3.13). Aryl iodide **3k** and heteroarene **3g** were noteworthy, as these substrates are not compatible with typical metal-catalyzed protocols (Table 3.13). All products derived from internal alkenes were formed with high diastereoselectivity, giving anti-1,2-diamines with no detectable amounts of the syn diastereomers.[11] (Z)-1,2-disubstituted-olefins gave diamine products, but in poor diastereoselectivity. Tri- and tetrasubstituted olefins gave poor yields under these conditions.

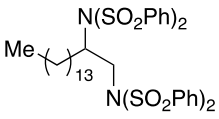
Table 3.14. Substrate Scope – Terminal Olefins



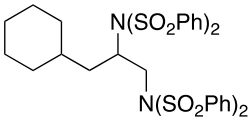
(Terminal Olefins)



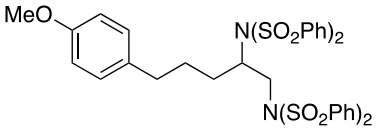
3p 56%



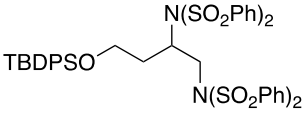
3q 51%



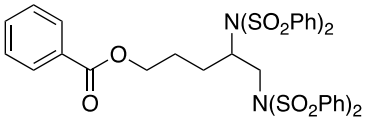
3r 54%



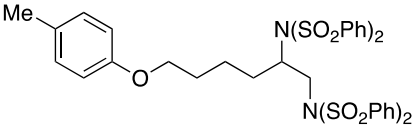
3s 48%



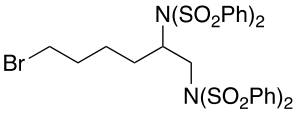
3u 60%



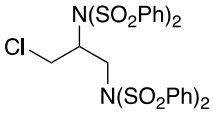
3v 64%



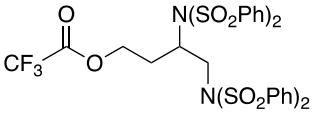
3w 65%



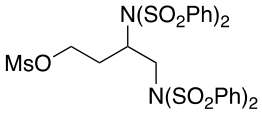
3x 75%



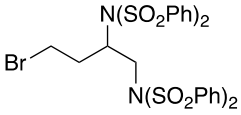
3z 43%



3aa 69%



3t 76%

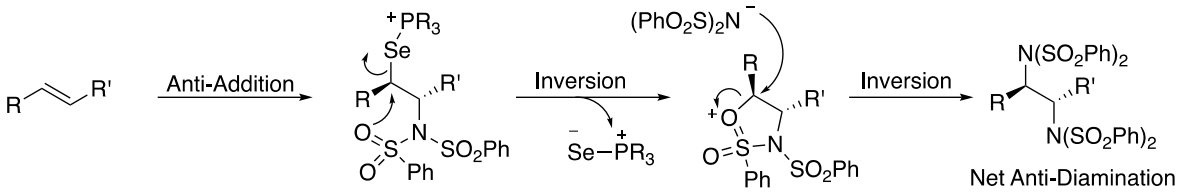


3y 70%

Isolated Yields.

An examination of the products reveals that the diamination occurs with trans stereoselectivity, whereas our proposed mechanism suggests that a syn-addition of the nucleophiles should occur. In order to account for this observed stereochemistry, we propose the following mechanism (Scheme 3.3).

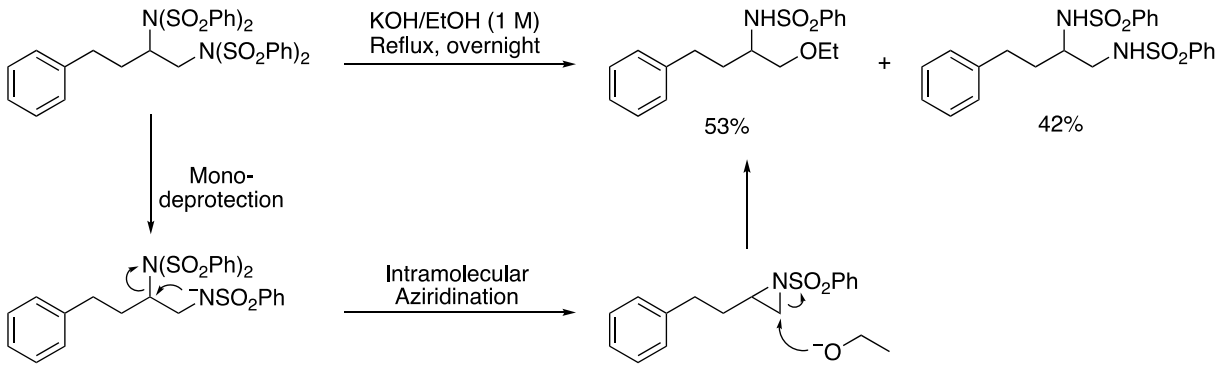
Scheme 3.3. Mechanism to Give Anti-Diaddition



Anti-addition of selenium and nitrogen across the C=C bond is followed by an intramolecular attack from the sulfonimide oxygen, giving a 5-membered ring intermediate and causing a first inversion. A benzenesulfonimide anion can open this ring causing a second inversion, giving the observed anti stereochemistry. A similar stereochemistry and explanation have been disclosed by Muniz in related work.[10a]

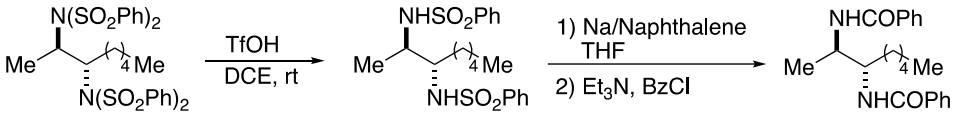
In order to demonstrate the synthetic utility of the products, we sought to perform a deprotection of the benzenesulfonimide groups. There exist a variety of different procedures for deprotecting sulfonamides[10a,10e,12], including several different protocols for acidic cleavage with heated hydrochloric or sulfuric acid. Unfortunately, our products were insoluble in the acidic aqueous media and these methods gave no reaction. There are also basic hydrolysis protocols using potassium hydroxide in methanol or ethanol. These conditions gave mixtures of desired product and ethoxide substitution (Scheme 3.4).

Scheme 3.4. Attempts at Basic Hydrolysis of Sulfonimide Products



We suspect that once the first sulfonimide is deprotected, the resulting anionic sulfonamide does an intramolecular attack on the adjacent sulfonimide, forming an aziridine intermediate, which then undergoes attack from ethoxide anion. We found success in deprotection of the bis(sulfonimide) with triflic acid at room temperature to give the bis(sulfonamide) **8** (Table 3.15). Bis(sulfonamide) **8** was deprotected with sodium/naphthalene to give the free diamine, which was converted to benzamide **9** for ease of isolation.

Table 3.15. Deprotection of Bis-Sulfonimide Products

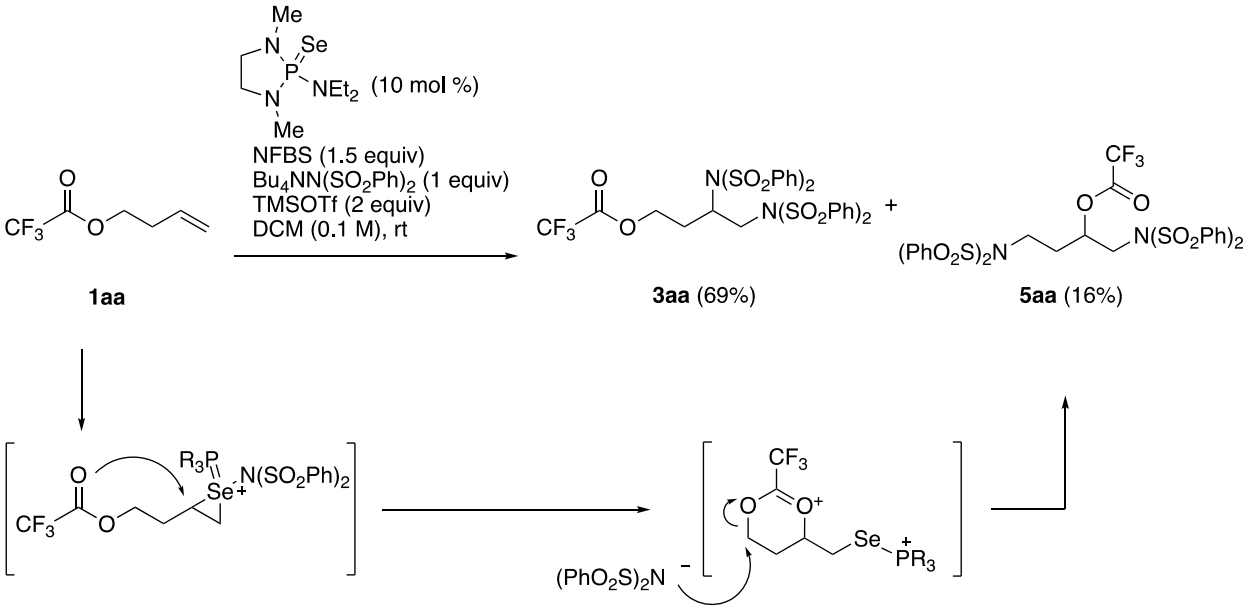


3b **8** 86% **9** 61%

3.2.6 Ester and Carbonate Rearrangement – Optimization and Substrate Scope

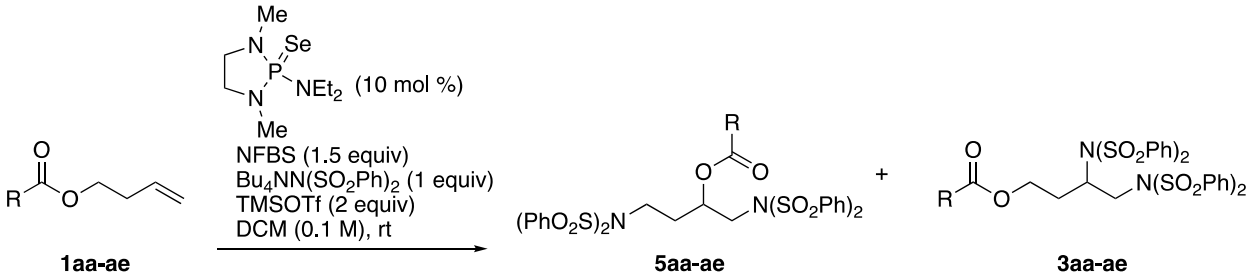
While performing the substrate scope, it was discovered that homoallyl trifluoroacetate **1aa** gave the normal 1,2-diamination product **3aa** along with an unexpected rearrangement product **5aa** (Scheme 3.5). The following mechanism is proposed in order to account for this product.

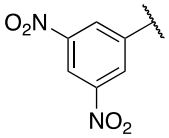
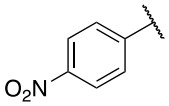
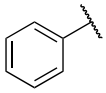
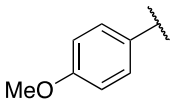
Scheme 3.5. Ester Rearrangement Mechanism



The olefin reacts with hypervalent selenium to give a seleniranium ion. Instead of nucleophilic attack from an exogenous nucleophile, as typically happens, we propose an intramolecular attack from the oxygen of the carbonyl group in the ester to give a cyclic intermediate. Nucleophilic attack from a benzenesulfonimide anion now occurs, but at a different position, to generate the product. We hypothesized that a reduction in the amount of exogenous benzenesulfonimide nucleophile added would lead to less competition with the intramolecular attack from the carbonyl oxygen shown in Scheme 3.5 above. In order to test this hypothesis, a screen of a variety of equivalents of benzenesulfonimide nucleophile was performed. It was discovered that lowering the equivalents of tetrabutylammonium benzenesulfonimide provided an increase in the ratio of rearrangement to diaddition, probably due to less competition from exogenous nucleophile during the carbonyl attack. In light of this result, we hypothesized that we could selectively generate either one of the isomeric products by changing the nucleophilicity of the ester oxygen. A series of electronically varied homoallyl esters **1aa-ae** were synthesized and screened under the reaction conditions (Table 3.16).

Table 3.16. Electronic Properties of Ester Affect Rearrangement vs. Diaddition

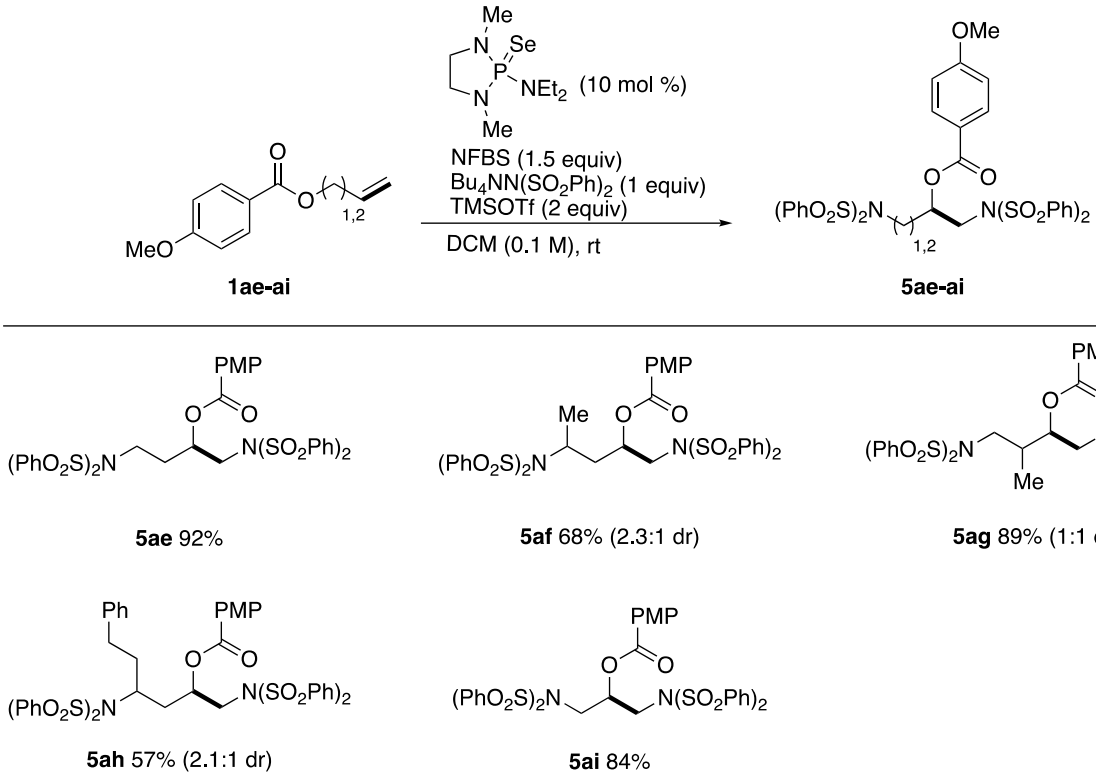


Entry	Starting Material	R =	Diaddition (**3**)	Rearrangement (**5**)
1	**1aa**		69%	16%
2	**1ab**		45%	25%
3	**1ac**		40%	50%
4	**1ad**		15%	66%
5	**1ae**		-	100%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard

We observed a very clear trend wherein electron-rich esters strongly favored rearrangement (entry 5), while electron-poor esters tended to favor diaddition (entry 1). This is consistent with our proposed mechanism, in which an electron-rich ester would be more likely to act as a nucleophile, participating in the intramolecular cyclization before intermolecular nucleophilic attack can happen. Since the *p*-methoxybenzoate ester gave exclusively rearrangement product, several other substrates bearing this ester were subjected to the reaction conditions.

Scheme 3.6. Substrate Scope – Ester Rearrangement



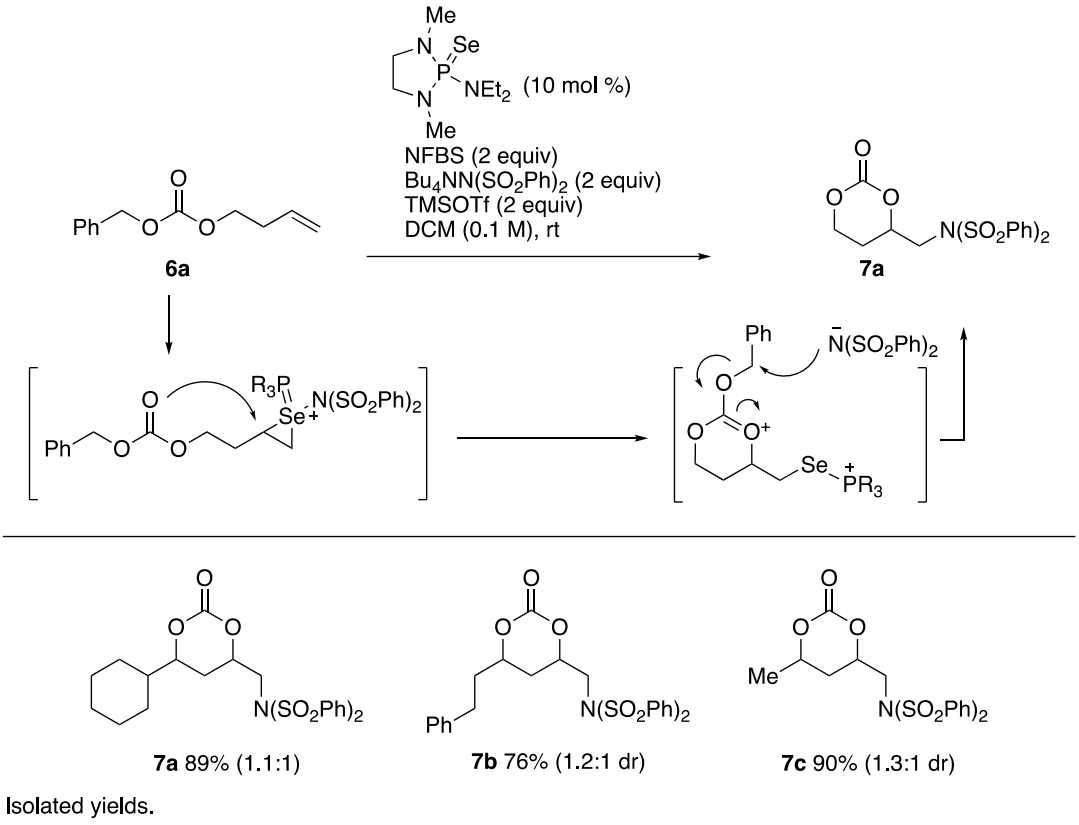
Isolated yields.

As shown in Scheme 3.6, several allyl- and homoallyl esters gave rearrangement products in moderate to high yields. Diastereoselectivities were low and there was no obvious trend between diastereoselectivity and sterics of the substituents on the carbon backbone. We found that in addition to the electronic properties of the ester, the chain length of the alkene also played a role. Allyl and homoallyl esters readily participated in the rearrangement, whereas longer chains gave little to no rearrangement (Table 3.14, compound **3v**). These reactions are interesting because they afford 1,3-diamino-2-alcohols and 1,4-diamino-2-alcohols, both common structural units in HIV-protease inhibitors.[13]

Since intramolecular substitution with ester groups proceeded readily to give rearrangement products **5**, we envisioned that appropriately chosen carbonates could give cyclic

products via a similar intramolecular attack, followed by dealkylation of the carbonate substituent (Scheme 3.7).

Scheme 3.7. Carbonate Rearrangement

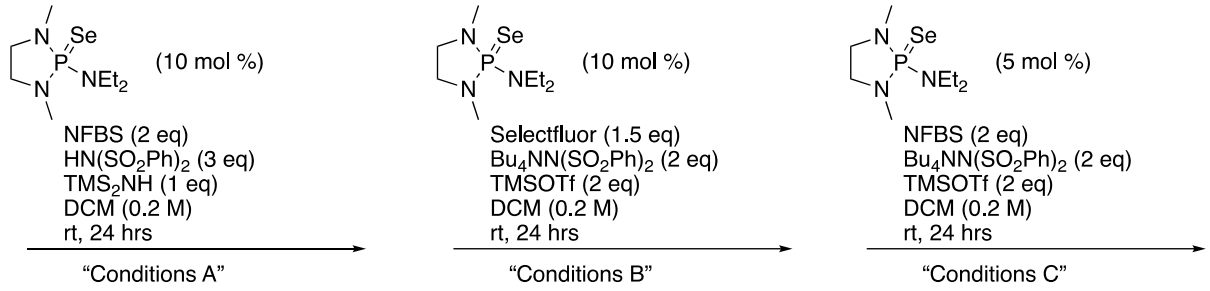


Indeed, a brief screen of carbonates (Me, t-Bu, Bn) revealed that benzyl carbonates were optimal for this purpose, giving the desired cyclic carbonates in high yields.

3.2.7 Optimization/Exploration – Incorporation of Other Nucleophiles

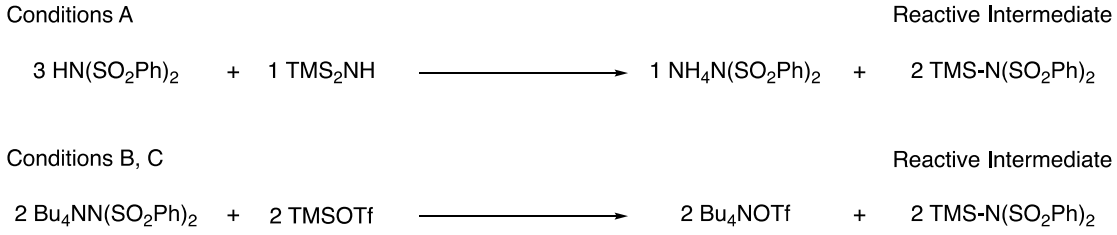
During this project, two other sets of conditions that were able to form the product in reasonable yield were developed. The optimization for both of these conditions was extensive, including for each solvent screen, concentration screen, temperature screen, equivalents screen, catalyst screen and catalyst loading screen. The resulting final conditions are shown in Figure 3.3.

Figure 3.3. Sets of Conditions for 1,2-Diamination



While the standard conditions ("Conditions C") gave the highest yields for nearly all substrates, the two additional sets of conditions ("A" and "B") were developed with the goal of installing other nucleophiles in the products, in place of benzenesulfonimide. With Conditions A it is be possible to use HNu in their neutral form. These HNu can react with hexamethyldisilazane (HMDS, TMS_2NH) to produce TMS-Nu, species that we suspect are involved under all three sets of conditions shown above (Scheme 3.8). In other words, HNu/HMDS and Bu_4NNu/TMSOTf are two ways of arriving at the same reactive intermediates. As such, we might expect similar results from these three sets of conditions.

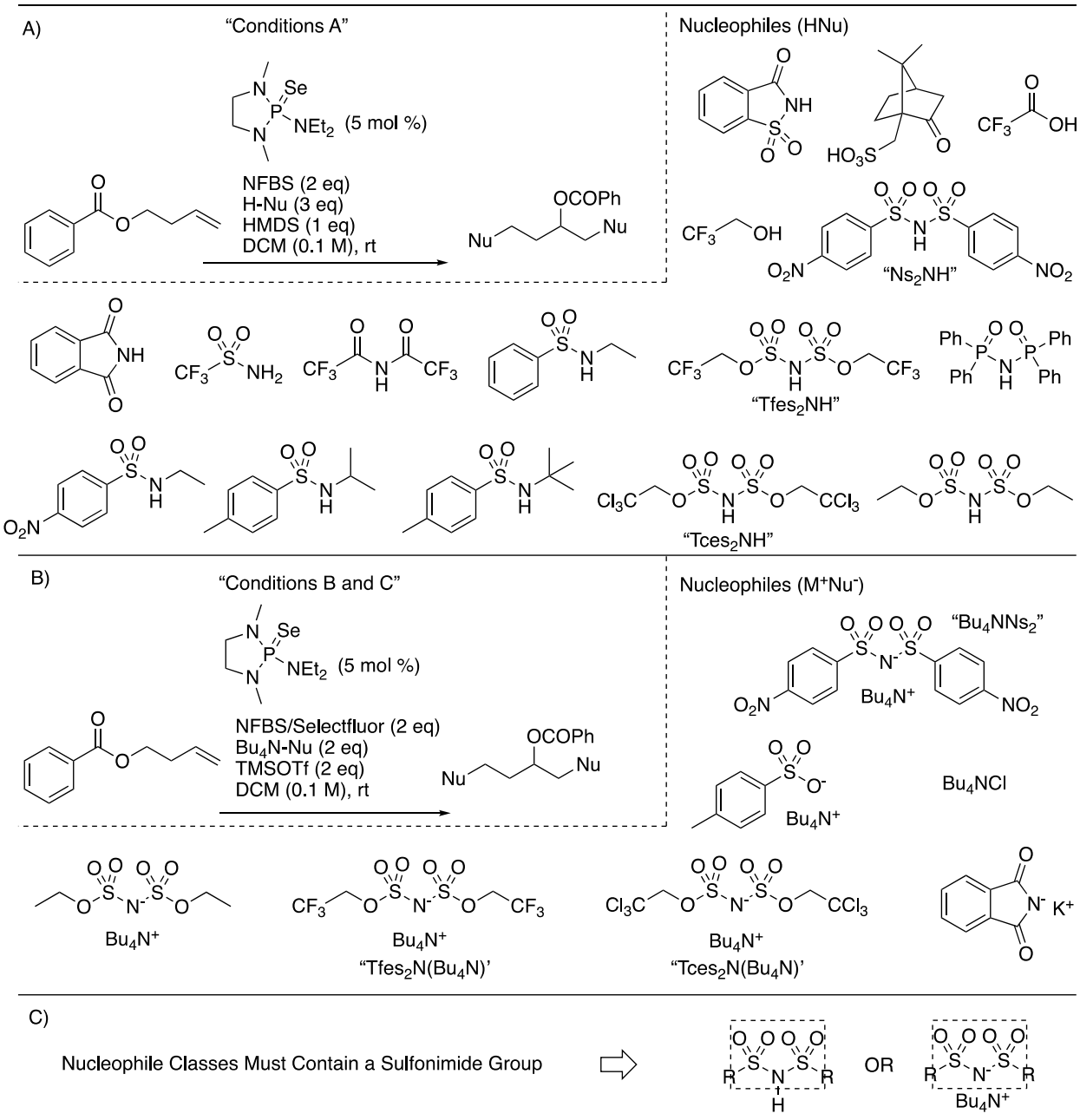
Scheme 3.8. Generation of Nucleophilic Intermediate via Conditions A, B and C



When considering a broad variety of nucleophiles, these neutral HNu are often more desirable than anionic salt versions, which are sometimes difficult to synthesize and to ensure their dryness. Conditions B were optimized to use Selectfluor as the oxidant. Selectfluor doesn't contain a competing nucleophilic leaving group like NFBS does, so there is more potential for other

nucleophiles to be used. A variety of different nucleophiles were screened under the three sets of conditions with homoallyl benzoate as the substrate, as seen in Figure 3.4a.

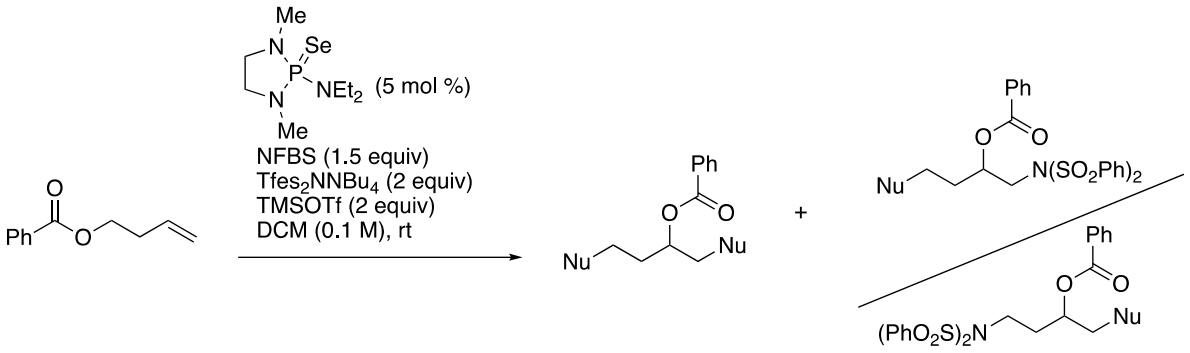
Figure 3.4. Nucleophile Screen Under 3 Sets of Conditions

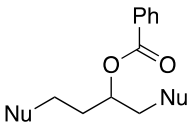
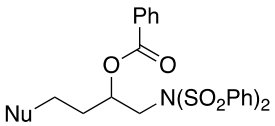
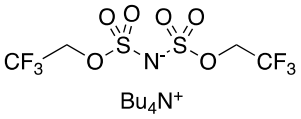
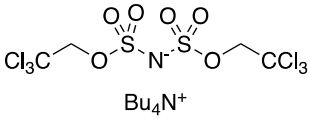
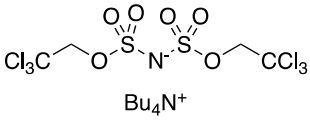
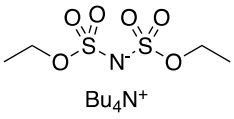


Only nucleophiles containing a sulfonimide group (Figure 3.4c) gave any amount of product or reactivity, an all other nucleophiles gave only recovered starting material. Nucleophiles containing a sulfonimide group were further explored.

Despite containing a sulfonimide group, tetrabutylammonium nosylimide (Bu_4NNs_2) was highly insoluble and gave no reactivity and nearly quantitative SM under all solvents screened (Conditions C). Tetrabutylammonium salts of several bis(alkoxysulfonyl) amines were synthesized, including $Tfes_2N^-$, $Tces_2N^-$, and $(EtOSO_2)_2N^-$. Since we saw that the presence of water was detrimental to this reaction by causing decomposition of the fluoride scavenging reagent/Lewis (Table 3.7, entry 2), we propose that the fact that these nucleophiles were very hygroscopic was causing poor yields. $Tfes_2N(Bu_4N)$ and $(EtOSO_2)_2N(Bu_4N)$ were more hygroscopic than $Tces_2N(Bu_4N)$, and consequently gave lower yields (Table 3.17, entries 1,4 vs. 2).

Table 3.17. Nucleophile Screen



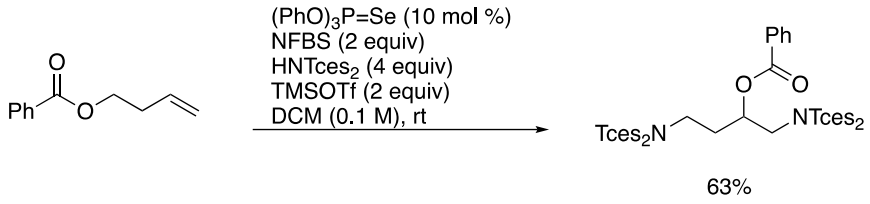
Entry	Nucleophile		 (both regioisomers)	SM
1	 Bu_4N^+	33%	47%	-
2	 Bu_4N^+	40%[b]	35%	-
3	 Bu_4N^+	45%	32%	
4	 Bu_4N^+	19%[c]	-	47%

[a]Yields determined by ^{1}H NMR Spectroscopy using 1,3-dinitrobenzene as internal standard. [b]$(PhO)_3P{=}Se$ as catalyst.
[c]Yield represents total of all 3 products

All three nucleophiles gave side-products from mixed incorporation of benzenesulfonimide (from NFBS) and the new nucleophile. Given these results, $Tces_2N(Bu_4N)$ was chosen for further optimization. A catalyst screen revealed that $(PhO)_3P{=}Se$ gave the highest yields, though still giving mixed products (entry 3). This competition between nucleophiles under Conditions C had no obvious solution, so we switched to Conditions A using $Tces_2NH$ as the nucleophile to see if it suffered from the same complication. A catalyst and equivalents screen gave new optimized

conditions. Gratifyingly, the rearrangement product was isolated in 63% yield with no mixed side product (Figure 3.5).

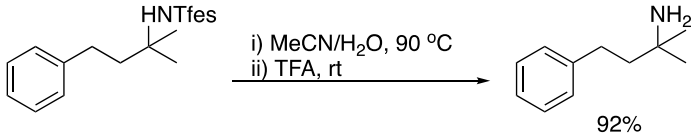
Figure 3.5. Isolated Yield of Di-Tces2N Incorporation



Additional optimization was performed, but the results were not improved. Unfortunately, when applied to other substrates these conditions gave mixtures of Tces2N/Tces2N and mixed Tces2N/(PhO2S)2N incorporation. Switching to Selectfluor in order to remove competition from benenesulfonimide gave inferior results, with much lower yields. At this point the goal was abandoned. However, this preliminary data suggests that incorporation of other nucleophiles is possible, and perhaps alternate conditions can be found to enable their incorporation. We suspect that these nucleophiles might be preferable to benzenesulfonimide for their potentially milder deprotection (Figure 3.6).[12e]

Figure 3.6. Deprotection of TfesNH Group

Adv. Synth. Catal. **2015**, 357, 4063-4068.



Section 3: Conclusion

A selenophosphoramide-catalyzed 1,2-diamination and oxyamination of alkenes was developed. Informed by previous mechanistic studies, this transformation was made possible by diversion from the typical syn-elimination pathway by introduction of a fluoride scavenger, allowing an atypical substitution to occur instead. In addition to suppressing the undesirable

elimination pathway, we were able to facilitate the desired substitution through careful tuning of the catalyst. It was observed that electron donating ligands were the highest performing, and selenophosphoramide catalysts were optimal. The transformation was successful for a wide array of terminal- and trans-1,2-disubstituted alkenes, giving products in high yields with exclusive selectivity for trans-products and tolerating a variety of functional groups. Additionally, substrates bearing appropriate internal nucleophiles, such as esters and carbonates, could be induced to undergo intramolecular substitution reactions, giving rearrangement and cyclization products. The bis-sulfonimide products were successfully deprotected to give the free diamines. Preliminary results suggest the potential for incorporating other nucleophiles such as bis(alkoxysulfonyl) amines in the transformation, however, competition from the benzenesulfonimide anion in NFBS is an obstacle.

Section 4: Experimental

General Procedures. All reactions were performed under a nitrogen atmosphere using flame-dried glassware unless otherwise indicated. Infrared spectra were acquired using a Perkin Elmer Spectrum RX I Spectrometer. Mass spectra were acquired using a Bruker Esquire 1100 Liquid Chromatograph-Ion Trap Mass Spectrometer or a Hewlett Packard 5971A Gas Chromatograph - Mass Spectrometer. Column chromatography was performed using silica gel (Whatman, 60 Å, 230-400 mesh). NMR spectra were recorded on a Bruker AV-300, AV-301, DRX-499 or AV-500 Spectrometer. ^{1}H NMR chemical shifts (δ) are reported in parts per million (ppm) and are referenced relative to TMS (0.0 ppm), residual $CHCl_3$ (7.26 ppm), DCM (5.32 ppm) or acetone (2.05 ppm). ^{13}C NMR chemical shifts (δ) are reported in parts per million (ppm) relative

to the carbon resonance of $CDCl_3$ (77.16 ppm), CD_2Cl_2 (53.84 ppm) or acetone-d_6 (29.84 ppm). Melting points were taken on a MEL-TEMP melting point apparatus and are uncorrected.

Materials. All commercial reagents were used as received, unless otherwise noted. All solvents were degassed and dried on solvent columns of neutral alumina. Deuterated solvents were purchased from Cambridge Isotope Laboratories, Inc., stored over 4Å molecular sieves, and were used without further purification. 2-methyl-3-buten-1-ol, 4-phenyl-1-butene, beta-methylstyrene, 6-bromo-1-hexene, 1-hexadecene, allylcyclohexane, 4-octene, 3-octene, 2-octene, 2-heptene, allyl chloride, trans-stilbene, 4-bromo-1-butene and *N*-fluorobenzenesulfonimide were purchased from commercial sources and used without further purification. Trimethylsilyl trifluoromethanesulfonate was purified by vacuum distillation and stored under an atmosphere of nitrogen. See Chapter 2 experimental for the synthesis of triphenyl phosphine selenide, tri-(ortho)tolyl phosphine selenide, 1,3-dimethyl-1H-imidazole-2(3H)-selenone, triphenylphosphoroselenoate and trimethylphosphoroselenoate, 1,3-bis[2,6-bis(1-methylethyl)phenyl]-1,3-dihydro-2H-imidazole-2-selone (IPrSe), tri-1-napthalenylphosphine selenide, triphenylphosphine sulfide, triphenylphosphine selenide, tricyclohexylphosphine selenide, tri-tertbutylphosphine selenide, triethylammonium benzenesulfonimide and all new N-alkyl-sulfonamides and N-alkyl-N-fluoro-sulfonamides. 4-[(Tert-butyldiphenylsilyl)oxy]-1-butene[14], 5-(4-methoxyphenyl)-1-pentene[15], 6-(4-methylphenyl)-1-hexene[2], trans-4-hexenyl benzoate[16], 4-pentenyl benzoate[17], allyl p-methoxybenzoate[18], homoallyl p-methoxybenzoate[19], (2-methyl-3-butenyl)-p-methoxybenzoate[20], 3-butenyl-trifluoroacetate[21], hex-4-enyl methanesulfonate[22], triethylammonium benzenesulfonimide[12a], tri-tert-butylphosphoro selenoate[24], nosylimide and tetrabutylammonium nosylimide[25] were prepared according to

previously published procedures and their respective spectroscopic signatures (^{1}H NMR) were found to be consistent with values reported therein.

Synthesis of Starting Materials

General Procedure A: To a flame-dried flask under nitrogen atmosphere, DMAP (776 mg, 12.7 mmol) and triethylamine (3.2 mL, 22.86 mmol) were added to a solution of alcohol (12.7 mmol) in DCM (63.5 mL, 0.2 M). Next, *p*-methoxybenzoyl chloride (2.4 mL, 17.8 mmol) was slowly added to at 0 °C. The reaction was stirred at room temperature overnight. The resulting mixture was quenched with water (50 mL) and washed with DCM (3×50 mL). The combined organic layers were washed with 1 M HCl (100 mL), $NaHCO_3$ (sat. aq., 100 mL) and brine (100 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The products were purified by flash chromatography.

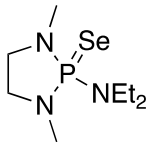
General Procedure B: *n*-Butyllithium (12 mL, 2 M in hexanes, 24 mmol) was added dropwise to a solution of alcohol (20 mmol) in THF (20 mL, 1 M) at 0 ^oC. The reaction mixture was stirred for 2 hours. The reaction was then quenched by pouring onto ice. The aqueous layer was extracted with ether (3x50 mL). The ether layers were combined and washed with brine, then dried over magnesium sulfate. The products were purified by flash chromatography on silica gel.

General Procedure C: Carboxylic acid (10 mmol), 4-hexen-1-ol (1.1 mL, 10 mmol), DMAP (122 mg, 1 mmol) and DCC (2 g, 10 mmol) were dissolved in anhydrous DCM (25 mL, 0.4 M), and the

mixture was stirred at room temperature for 24 h. The suspension was filtered, and the filtrate was concentrated in vacuo. The products were purified by silica gel chromatography.

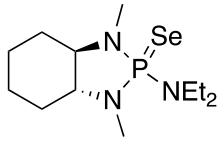
Characterization of Starting Materials, Catalysts and Reagents

General Procedure D for the synthesis of phosphine selenides with one monodentate and one bidentate ligand (example below for synthesis of 4f):

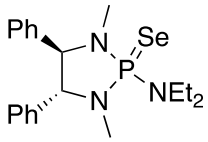


1,3-dimethyl-2-(pentan-3-yl)-1,3,2-diazaphospholidine selenide (4f). To a flame-dried round-bottomed flask under an atmosphere of nitrogen was added ether (200 mL, 0.15 M) followed by phosphorus trichloride (2.6 mL, 30 mmol). This mixture was cooled to -78 ^{o}C and *N*,*N*'-dimethylethylenediamine (3.2 mL, 30 mmol) then triethylamine (15 mL, 108 mmol) were added dropwise. The reaction was allowed to warm to room temperature with stirring for 1 hour. The reaction was cooled again to -78 ^{o}C and diethylamine (3.1 mL, 30 mmol) was added dropwise. Again, the reaction was allowed to warm to room temperature with stirring overnight. The mixture was filtered over a pad of celite and the filtrate was concentrated in vacuo to give 1,3-dimethyl-2-(pentan-3-yl)-1,3,2-diazaphospholidine as a yellow oil. The crude triaminophosphine was added to a round bottom flask along with selenium powder (2.8 g, 36 mmol) and DCM (60 mL, 0.5 M). This mixture was stirred under nitrogen at room temperature overnight. The mixture was then filtered through a pad of silica gel with ethyl acetate and the filtrate was concentrated in vacuo to give a beige solid. The solid was recrystallized from ethyl acetate to yield the final product as large colorless crystals. (6.1 g, 76% yield). **Mp:** 59.2-60.7 ^{o}C. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.33 – 3.10 (m, 6H), 3.10 – 2.88 (m, 2H), 2.47 (d, *J* = 12.8 Hz, 6H), 1.06 (t, *J* = 7.0 Hz, 6H). **^{13}C NMR**

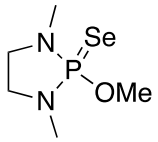
(126 MHz, $CDCl_3$): δ 47.70 (d, *J* = 8.8 Hz), 39.64 (d, *J* = 5.0), 32.11 (d, *J* = 7.6 Hz), 14.65 (d, *J* = 1.3 Hz). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 75.49 (J_{Se-P} = 791 Hz). **IR (thin film):** 2966.7, 2927.0, 2868.5, 2807.9, 1460.4, 1375.8, 1233.1, 1205.0, 1171.7, 1022.1, 939.7, 786.5, 736.3, 674.0, 525.8 cm^{-1}. **(ESI, positive mode):** 291.9 [M+Na]. **HRMS** (ESI): Calculated for $C_8H_{21}N_3PSe^+$ $[M+H]^+$: 270.0633, Found: 270.0631.



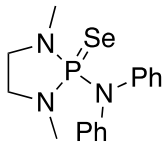
(3aR,7aR)-*N*,*N*-diethyl-1,3-dimethyl-hexahydro-1*H*-benzo[*d*][1,3,2]diazaphosphol-2(3*H*)-amine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** *δ* 3.41 – 3.21 (m, 2H), 3.20 – 3.01 (m, 2H), 2.91 – 2.70 (m, 1H), 2.55 – 2.49 (m, 1H), 2.48 (3, *J* = 12.2 Hz, 4H), 2.35 (d, *J* = 15.8 Hz, 3H), 2.07 – 1.89 (m, 2H), 1.89 – 1.67 (m, 2H), 1.42 – 1.12 (m, 4H), 1.07 (t, *J* = 7.0 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** *δ* 78.51 (s) (J_{Se-P} = 790 Hz).



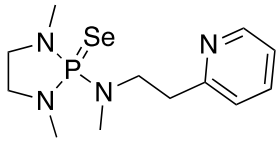
(4R,5R)-*N*,*N*-diethyl-1,3-dimethyl-4,5-dipheny-1,3,2-diazaphospholidin-2-amine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** *δ* 7.43 – 7.20 (m, 6H), 7.20 – 7.09 (m, 2H), 7.08 – 6.97 (m, 2H), 4.19 (d, *J* = 8.6 Hz, 1H), 3.80 (d, *J* = 8.6 Hz, 1H), 3.68 – 3.42 (m, 2H), 3.42 – 3.14 (m, 2H), 2.32 (d, *J* = 10.6 Hz, 2H), 2.25 (d, *J* = 14.7 Hz, 1H), 1.22 (t, *J* = 7.0 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** *δ* 76.46 (J_{Se-P} not determined).



2-methoxy-1,3-dimethyl-1,3,2-diazaphospholidine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.57 (d, J = 14.5 Hz, 3H), 3.31 (dt, J = 8.3, 6.1 Hz, 2H), 3.12 (ddd, J = 10.7, 7.2, 5.0 Hz, 2H), 2.68 (d, J = 12.6 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 81.40 ($J_{Se\text{-}P}$ not determined).

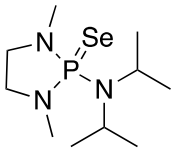


1,3-dimethyl-*N*,*N*-diphenyl-1,3,2-diazaphospholidin-2-amine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.41 – 7.26 (m, 8H), 7.26 – 7.14 (m, 2H), 3.09 – 2.87 (m, 4H), 2.77 (d, J = 12.3 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 68.51 ($J_{Se\text{-}P}$ = 823 Hz).

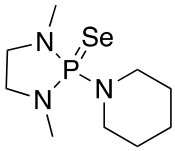


***N*-1,3-trimethyl-*N*-(2-(pyridine-2-yl)ethyl)-1,3,2-diazaphospholidin-2-amin selenide.** Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 8.51 (d, J = 4.1 Hz, 1H), 7.60 (td, J = 7.7, 1.8 Hz, 1H), 7.27 (d, J = 5.6 Hz, 1H), 7.11 (dd, J = 6.9, 5.4 Hz, 1H), 3.68 – 3.51 (m, 2H), 3.30 –

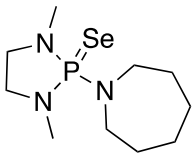
3.14 (m, 2H), 3.06 – 2.93 (m, 4H), 2.74 (d, J = 10.9 Hz, 3H), 2.43 (d, J = 12.7 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 75.92 ($J_{Se\text{-}P}$ = 794 Hz).



***N,N*-diisopropyl-1,3-dimethyl-1,3,2-diazaphospholidin-2-amine selenide.** Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 4.08 – 3.78 (m, 2H), 3.29 – 3.08 (m, 2H), 3.04 – 2.86 (m, 2H), 2.48 (d, J = 12.9 Hz, 6H), 1.27 (d, J = 6.9 Hz, 12H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 68.99 ($J_{Se\text{-}P}$ not determined).

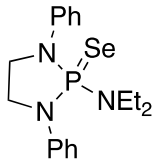


1,3-dimethyl-2-(piperidin-1-yl)-1,3,2-diazaphospholidine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.35 – 3.15 (m, 6H), 3.11 – 2.94 (m, 2H), 2.51 (d, J = 12.8 Hz, 6H), 1.67 – 1.53 (m, 2H), 1.53 – 1.38 (m, 4H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 74.14 ($J_{Se\text{-}P}$ = 789 Hz).

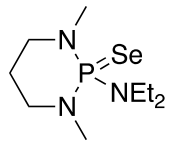


2-(azepan-1-yl)-1,3-dimethyl-1,3,2-diazaphospholidine selenide. Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H**

NMR (300 MHz, $CDCl_3$): δ 3.40 – 3.14 (m, 6H), 3.07 – 2.93 (m, 2H), 2.50 (d, J = 12.7 Hz, 6H), 1.73 – 1.47 (m, 8H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 75.19 ($J_{Se\text{-}P}$ = 831 Hz).

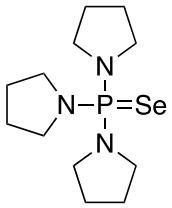


***N,N*-diethyl-1,3-diphenyl-1,3,2-diazaphospholidin-2-amine selenide.** Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 7.39 – 7.23 (m, 8H), 7.03 (t, J = 7.1 Hz, 2H), 3.92 – 3.70 (m, 4H), 3.34 (dt, J = 14.2, 7.9 Hz, 4H), 0.99 (t, J = 7.1 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 58.90 ($J_{Se\text{-}P}$ = 842 Hz).

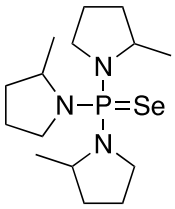


***N.N*-diethyl-1,3-dimethyl-1,3,2-diazaphosphepan-2-amine selenide.** Prepared according to General Procedure D and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.34 (dq, J = 14.1, 7.1 Hz, 4H), 2.91 (tdd, J = 12.6, 5.7, 2.8 Hz, 2H), 2.76 (ddd, 1H), 2.66 (ddd, J = 12.3, 4.2, 2.7 Hz, 1H), 2.27 (d, J = 15.6 Hz, 6H), 2.13 – 1.86 (m, 1H), 1.61 (ddd, J = 13.5, 4.1, 2.7 Hz, 1H), 1.09 (t, J = 7.1 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 83.70 ($J_{Se\text{-}P}$ = 770 Hz).

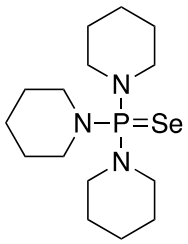
General Procedure E for the synthesis of phosphine selenides/sulfides with three monodentate oxygen and/or nitrogen ligands (example below for synthesis of Tris(1-pyrrolidinyl)phosphine selenide):



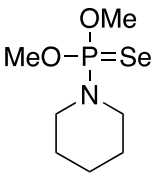
Tris(1-pyrrolidinyl)phosphine selenide. To a flame-dried, 50 mL round bottom flask was added ether (13.4 mL, 0.67 M) then pyrrolidine (4.5 mL, 6 eq). The round bottom flask was cooled to -78 degrees Celcius. Once cool, phosphorus trichloride (0.79 mL, 1 eq) was added dropwise followed by triethylamine (4.6 mL, 3.6 eq). The reaction was allowed to warm to room temperature and stirred overnight. Upon completion, the reaction was filtered through a fitted funnel and rinsed with ether. The filtrate was concentrated in vacuo and the crude product was used in the next step without purification. To a flame dried round bottom flask charged with stir bar was added selenium powder (2.5 eq) and ether (0.5 M). The mixture was cooled to 0 degrees Celcius then tris((pyrrolidino)phosphine (1 eq) was added. The reaction was stirred at rt while monitoring by TLC. Upon completion the reaction was filtered through a fritted glass funnel and concentrated in vacuo. The crude product was purified by column chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.31 – 3.05 (m, 12H), 1.97 – 1.73 (m, 12H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 61.51 ($J_{Se\text{-}P}$ = 760 Hz).



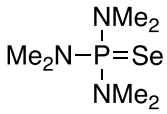
tris(2-methylcyclopentyl)phosphine selenide. Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, CDCl3):** δ 4.46 – 3.99 (m, 3H), 3.40 – 3.10 (m, 3H), 2.99 – 2.70 (m, 3H), 1.81 – 1.36 (m, 12H), 1.28 – 1.11 (m, 9H). **^{31}P NMR (121 MHz, CDCl3):** δ 70.57 ($J_{Se\text{-}P}$ not determined).



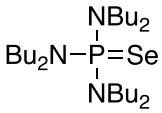
Tris(1-piperidinyl)phosphine selenide. Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.24 – 2.79 (m, 4H), 1.75 – 1.34 (m, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 75.35 ($J_{Se\text{-}P}$ not determined).



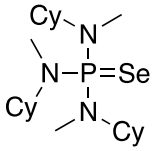
***O,O*-dimethyl piperidin-1-ylphosphonoselenoate.** Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.66 (s, 3H), 3.61 (s, 3H), 3.31 – 3.16 (m, 4H), 1.67 – 1.43 (m, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 82.47 ($J_{Se\text{-}P}$ = 887 Hz).



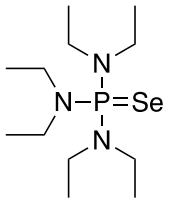
Tris(dimethylamino)phosphine selenide. Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 2.66 (d, J = 11.6 Hz, 18H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 81.83 ($J_{Se\text{-}P}$ = 784 Hz).



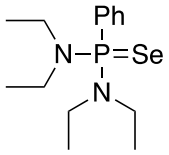
Tris(dibutylamino)phosphine selenide. Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.12 – 2.84 (m, 12H), 1.53 (tt, J = 8.1, 6.4 Hz, 13H), 1.36 – 1.17 (m, 12H), 0.93 (t, J = 7.3 Hz, 18H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 77.81 ($J_{Se\text{-}P}$ = 770 Hz).



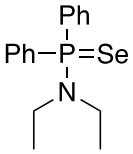
***N,N",N'"*-tricyclohexyl-*N,N",N'"*-trimethylselenophosphoramide.** Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.71 (qt, J = 11.6, 3.5 Hz, 3H), 2.49 (d, J = 10.9 Hz, 9H), 1.87 – 1.55 (m, 15H), 1.53 – 1.21 (m, 12H), 1.17 – 0.78 (m, 3H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 76.88 ($J_{Se\text{-}P}$ not determined).



Tris(diethylamino)phosphine selenide. Prepared according to General Procedure E and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.16 (dq, J = 14.2, 7.1 Hz, 12H), 1.13 (t, J = 7.1 Hz, 18H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 76.11 ($J_{Se\text{-}P}$ = 768 Hz).

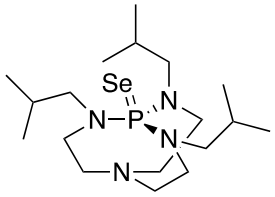


Bis(diethylamino)phenylphosphine selenide. Prepared according to modified General Procedure E (use dichlorophenylphosphine instead of phosphorous trichloride) and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 8.10 – 7.85 (m, 2H), 7.52 – 7.31 (m, 3H), 3.34 – 2.95 (m, 8H), 1.04 (t, J = 7.1 Hz, 12H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 77.05 ($J_{Se\text{-}P}$ = 760 Hz).

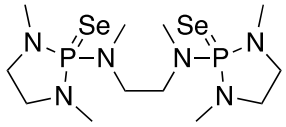


(Diethylamino)diphenylphosphine selenide. Prepared according to modified General Procedure E (use chlorodiphenylphosphine instead of phosphorous trichloride) and purified by silica gel chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 8.18 – 7.87 (m,

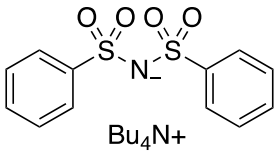
4H), 7.62 – 7.32 (m, 6H), 3.31 – 2.79 (m, 4H), 1.10 (t, J = 7.1 Hz, 6H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 66.41 ($J_{Se\text{-}P}$ = 745 Hz).



2,8,9-triisopropyl-2,5,8,9-tetraza-1-phosphabicyclo[3.3.3]undecane selenide. Trisaminophosphine ligand synthesized according to literature precedent.[26] The phosphine ligand was selenized according to literature precedent.[27] **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.83 – 2.39 (m, 12H), 2.80 (t, J = 5.0 Hz, 6H), 2.40 – 2.14 (m, 3H), 0.97 (18, J = 6.7 Hz, 17H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 76.88 ($J_{Se\text{-}P}$ = 767 Hz).

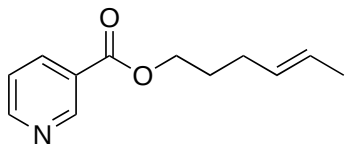


***N*$_1$,*N*$_1$-bis(1,3-dimethyl-1,3,2-diazaphospholidin-2-yl)-*N*$_1$,*N*$_2$-dimethylethane-1,2-diamine bis-selenide.** Phosphine ligand synthesized according to literature precedent.[28] To a 50 mL RBF was added selenium powder (1.5 g, 2.2 eq), DCM (18 mL, 0.5 M) and bis-aminophosphine ligand (2.9 g, 1 eq). The reaction was stirred at room temperature overnight, then was filtered through a pad of silica with ethyl acetate and purified by column chromatography followed by recrystallization. **^{1}H NMR (300 MHz, $CDCl_3$):** δ 3.14 (dq, J = 12.1, 7.1 Hz, 12H), 1.17 – 1.09 (m, 12H). **^{31}P NMR (121 MHz, $CDCl_3$):** δ 42.67 ($J_{Se\text{-}P}$ = 1,958 Hz).

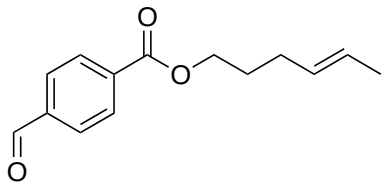


Tetrabutylammonium benzenesulfonimide. To a flame dried 1000 mL RBF was added sodium hydride mineral oil dispersion (8.8 g, 220 mmol) and benzenesulfonamide (15.7 g, 100 mmol). THF (400 mL, 0.25 M) was added and the flask was allowed to stir at room temperature for 3 hours, then benzenesulfonyl chloride (15.3 mL, 120 mmol) was added. The cloudy mixture was allowed to stir overnight. Solvent was removed in vacuo to give a white solid. Saturated sodium bicarbonate was added and the slurry was filtered with a fritted funnel (to remove any unreactive amide). The filtrate was reacidified with 6 M HCl (until pH = 2), and the product was extracted 3x with ether. The combined ether layers were washed with brine, dried over magnesium sulfate, and concentrated in vacuo to give a white solid. A minimal amount of 1 M NaOH solution was added slowly to the solid until the solid was dissolved and the pH reached 7-8. (If necessary, the mixture can be filtered to remove undissolved particles.) Next, tetrabutylammonium chloride (27.8 g, 100 mmol) dissolved in a minimum amount of deionized water was pipetted into the mixture and a white solid started to precipitate. The solid continued to precipitate overnight in the fridge. The solid was collected in a fritted funnel, washed with water and dried on the high vac. The resulting solid was recrystallized twice from a minimum amount of ethyl acetate to give large, almost transparent crystals. The crystals were crushed and dried under vacuum at 40 ^{o}C overnight. (36 g, 67% yield). **Mp:** 110-113.2 ^{o}C. **^{1}H NMR (300 MHz, CDCl$_3$):** δ 7.71 (d, *J* = 7.6 Hz, 4H), 7.32 – 7.22 (m, 2H), 7.18 (t, *J* = 7.4 Hz, 4H), 3.35 – 3.13 (m, 8H), 1.72 – 1.51 (m, 8H), 1.51 – 1.30 (m, 8H), 0.98 (t, *J* = 7.2 Hz, 12H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 145.60, 129.94, 127.71, 126.77, 58.63, 23.99, 19.68, 13.75. **IR (thin film):** 2960.8, 2874.4, 1478.6, 1444.6, 1381.1, 1279.8, 1155.0, 1132.9, 1086.9, 1054.5, 1023.7, 882.6, 791.1, 751.7, 719.5, 690.8, 593.1, 572.6, 554.0 cm^{-1}. **(ESI,**

negative mode): 295.9 [-N(SO_2Ph_2)$_2$]. **HRMS** (ESI): Calculated for $C_{16}H_{36}N^+$ [Bu_4N]$^+$: 242.2842, Found: 242.2841. Calculated for $C_{12}H_{10}NO_4S_2^-$ [N(SO_2Ph)$_2$]$^-$: 296.0046, Found: 296.001.

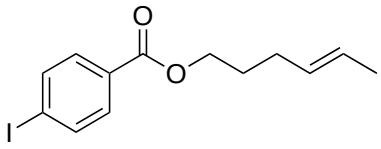


(*E*)-hex-4-enyl nicotinate (1g). Prepared according to General Procedure C and purified by silica gel chromatography (10% ethyl acetate/ 90% hexanes) to yield the product as a clear, yellow oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 9.23 (s, 1H), 8.86 – 8.66 (m, 1H), 8.39 – 8.19 (m, 1H), 7.51 – 7.33 (m, 1H), 5.60 – 5.36 (m, 2H), 4.36 (td, *J* = 6.6, 1.5 Hz, 2H), 2.15 (m, 2H), 1.92 – 1.78 (m, 2H), 1.65 (d, *J* = 5.8 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.42, 153.47, 151.05, 137.12, 129.87, 126.45, 126.22, 123.37, 65.07, 29.06, 28.56, 18.01. **IR (thin film):** 3021, 2958, 2937, 2918, 2854, 1725, 1591, 1450, 1419, 1388, 1327, 1284, 1237, 1193, 1113, 1025, 967, 741, 703 cm^{-1}. **(ESI, positive mode):** 206.0 [M+1]. **HRMS** (ESI): Calculated for $C_{12}H_{16}NO_2^+$ [M+H]$^+$: 206.1176, Found: 206.1174.

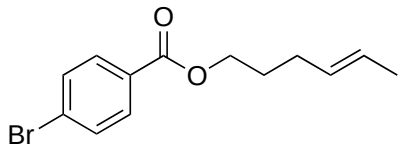


(*E*)-hex-4-enyl 4-formylbenzoate (1i). Prepared according to General Procedure C and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 10.11 (s, 1H), 8.25 – 8.11 (m, 2H), 8.01 – 7.90 (m, 2H), 5.63 – 5.33 (m, 2H), 4.36 (t, *J* = 6.6 Hz, 2H), 2.15 (dd, *J* = 13.2, 6.8 Hz, 2H), 1.96 – 1.80 (m, 2H), 1.65 (d, *J* = 5.8 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 191.78, 165.72, 139.24, 135.60, 130.29,

129.91, 129.63, 126.21, 65.27, 29.10, 28.58, 18.03. **IR (thin film):** 2958, 2937, 2853, 2733, 1722, 1705, 1699, 1695, 1684, 1386, 1275, 1202, 1117, 1106, 1016, 967, 855, 818, 759, 689 cm^{-1}. **GC-MS (m/z):** 233.1 (1, M+1), 133.0 (671, $C_8H_5O_2^+$), 83.10 (74.04, C_6H11^+), 67.10 (1,250, $C_5H_7^+$). **HRMS** (ESI): Calculated for $C_{14}H_{17}O_3^+$ $[M+H]^+$: 233.1172, Found: 233.1169.

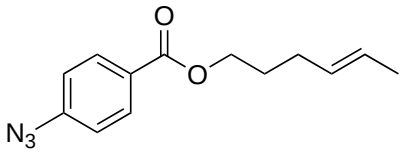


(*E*)-hex-4-enyl 4-iodobenzoate (1k). Prepared according to Genera Procedure C and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.79 (dd, *J* = 8.4, 1.7 Hz, 2H), 7.74 (dd, *J* = 8.3, 1.6 Hz, 2H), 5.60 – 5.31 (m, 2H), 4.30 (td, *J* = 6.6, 1.2 Hz, 2H), 2.13 (m, 2H), 1.93 – 1.72 (m, 2H), 1.65 (d, *J* = 5.6 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 166.23, 137.81, 131.13, 130.09, 129.98, 126.11, 100.69, 64.88, 29.09, 28.60, 18.03. **IR (thin film):** 3020, 2955, 2935, 2851, 1719, 1587, 1482, 1465, 1456, 1448, 1437, 1393, 1306, 1269, 1176, 1115, 1103, 1083, 1008, 966, 845, 753 cm^{-1}. **(ESI, positive mode):** 353.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{13}H_{16}IO_2^+$ $[M+H]^+$: 331.0189, Found: 331.0188.

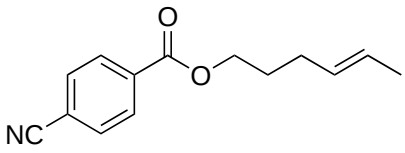


(*E*)-hex-4-enyl 4-bromobenzoate (1l). Prepared according to General Procedure C and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.90 (dd, *J* = 6.8, 1.8 Hz, 2H), 7.57 (dd, *J* = 8.4, 1.5 Hz, 2H), 5.58

– 5.31 (m, 2H), 4.31 (t, *J* = 6.6 Hz, 2H), 2.13 (m, 2H), 1.88 – 1.74 (m, 2H), 1.65 (d, *J* = 5.5 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 166.02, 131.81, 131.22, 129.99, 129.53, 128.05, 126.13, 64.91, 29.11, 28.61, 18.04. **IR (thin film):** 3020, 2957, 2936, 2853, 1718, 1591, 1398, 1271, 1173, 1116, 1103, 1069, 1012, 966, 847, 756 cm^{-1}. **(ESI, positive mode):** 305.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{13}H_{16}^{79}BrO_2^+$ $[M+H]^+$: 283.0328, Found: 283.0325.

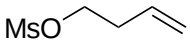


(*E*)-hex-4-enyl 4-azidobenzoate (1m). Prepared according to General Procedure C and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear, yellow oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.03 (dd, *J* = 6.8, 1.9 Hz, 2H), 7.11 – 6.93 (m, 2H), 5.58 – 5.35 (m, 2H), 4.31 (t, *J* = 6.6 Hz, 2H), 2.14 (m, 2H), 1.90 – 1.76 (m, 2H), 1.65 (d, *J* = 4.7 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.93, 144.76, 131.49, 130.04, 127.19, 126.07, 118.92, 64.71, 29.12, 28.66, 18.03. **IR (thin film):** 3020, 2937, 2853, 2413, 2258, 2123, 1719, 1603, 1504, 1274, 1173, 1131, 1109, 1015, 967, 850, 766, 690 cm^{-1}. **(ESI, positive mode):** 268.0 [M+Na].

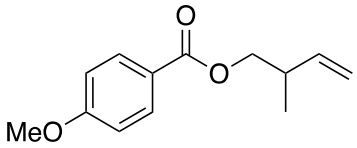


(*E*)-hex-4-enyl 4-cyanobenzoate (1n). Prepared according to General Procedure C and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.21 – 8.05 (m, 2H), 7.82 – 7.64 (m, 2H), 5.61 – 5.25 (m, 2H), 4.36 (td, *J* = 6.6, 1.2 Hz, 2H), 2.14 (dd, *J* = 13.5, 6.9 Hz, 2H), 1.84 (quin, *J* = 6.6 Hz, 2H), 1.65 (d,

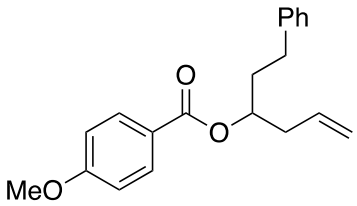
J = 5.8 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.06, 134.40, 132.31, 130.17, 129.80, 126.25, 118.11, 116.42, 65.44, 29.04, 28.51, 18.00. **IR (thin film):** 3098, 3052, 2958, 2937, 2918, 2854, 2231, 1719, 1450, 1405, 1388, 1310, 1275, 1177, 1119, 1108, 1019, 967, 862, 768, 692, 546 cm^{-1}. **(ESI, positive mode):** 252.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{14}H_{16}NO_2^+$ $[M+H]^+$: 230.1176, Found: 230.1172.



but-3-enyl methanesulfonate (1t). To a flame dried 100 mL round bottom flask was added 3-buten-1-ol (1.72 mL, 20 mmol) and DCM (20 mL, 1 M). The reaction was cooled to 0 ^{o}C and triethylamine (4.18 mL, 30 mmol) then methanesulfonyl chloride (2.32 mL, 30 mmol) were added dropwise. The reaction was stirred at 0 ^{o}C for 1 hour then at room temperature overnight. Saturated ammonium chloride (20 mL) was added and the mixture was extracted with ether (2x50 mL). The combined ether layers were dried over magnesium sulfate and concentrated in vacuo to give a yellow oil. The crude product was purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.89 – 5.69 (m, 1H), 5.23 – 5.10 (m, 2H), 4.27 (td, *J* = 6.7, 1.5 Hz, 2H), 3.01 (s, 3H), 2.60 – 2.40 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$)**: δ 132.53, 118.59, 68.97, 37.60, 33.52. **IR (thin film):** 3081, 3028, 2984, 2942, 1643, 1353, 1174, 976, 954, 910, 835, 805, 528 cm^{-1}. **(ESI, positive mode):** 172.8 [M+Na]. **HRMS** (ESI): Calculated for $C_5H_{11}O_3S^+$ $[M+H]^+$: 151.0423, Found: 151.0418.

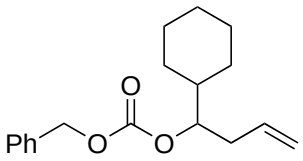


2-methyl-but-3-en-1-yl 4-methoxybenzoate (1ag). Prepared according to General Procedure A and purified by column chromatography (5% EtOAc in hexane) to give the product as a colorless oil (2.3 g, 69%). **^{1}H NMR (500 MHz, CDCl$_3$):** δ 7.99 (d, *J* = 8.9 Hz, 2H), 6.92 (d, *J* = 8.9 Hz, 2H), 5.83 (ddd, *J* = 17.3, 10.4, 7.0 Hz, 1H), 5.13 (dd, *J* = 17.3, 1.3 Hz, 1H), 5.07 (dd, *J* = 10.4 Hz, 0.9 Hz, 1H), 4.32 – 4.00 (m, 2H), 3.86 (s, 3H), 2.74 – 2.58 (m, 1H), 1.12 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 166.41, 163.46, 140.30, 131.70, 122.99, 115.11, 113.73, 68.61, 55.55, 37.30, 16.62. **IR (thin film):** 3079, 2966, 2839, 1714, 1607, 1511, 1316, 1276, 1257, 1168, 1114, 1102, 1031, 847, 770, 697, 613 cm^{-1}. **(ESI, positive mode):** 242.9 [M+Na]. **HRMS** (ESI): Calculated for $C_{13}H_{17}O_3^+$ [M+H]$^+$: 221.1172, Found: 221.1169.

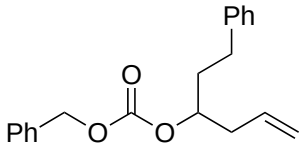


1-phenylhex-5-en-3-yl 4-methoxybenzoate (1ah). Prepared according to General Procedure A and purified by column chromatography (5 % EtOAc, 95% Hexane) to give the product as a colorless oil (2.3 g, 58%). **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.00 (d, *J* = 8.8 Hz, 2H), 7.28 – 7.23 (m, 2H), 7.17 (m, 3H), 6.92 (dd, *J* = 8.9, 2.0 Hz, 2H), 5.88 – 5.76 (m, 1H), 5.19 (m, 1H), 5.10 (d, *J* = 17.1 Hz, 1H), 5.06 (d, *J* = 10.2 Hz, 1H), 3.86 (s, 3H), 2.83 – 2.61 (m, 2H), 2.47 (t, *J* = 6.5 Hz, 2H), 2.13 – 1.88 (m, 2H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 166.07, 163.46, 141.75, 133.66, 131.72, 128.55, 128.48, 126.04, 123.16, 118.06, 113.73, 73.26, 55.57, 38.91, 35.60, 31.92. **IR (thin film):** 3078, 3025, 3004, 2952, 2839, 1707, 1606, 1511, 1316, 1274, 1256, 1167, 1114, 1102, 1031, 1009,

919, 848, 770, 698, 613 cm^{-1}. **MS (ESI, positive mode):** 310.9 [M+1], 333.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{20}H_{23}O_3^+$ $[M+H]^+$: 331.1642, Found: 311.1642.

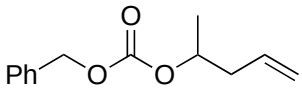


benzyl 1-cyclohexylbut-3-enyl carbonate (6a). Prepared according to general procedure B and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.42 – 7.28 (m, 5H), 5.87 – 5.68 (m, 1H), 5.16 (d, *J* = 12.2 Hz, 1H), 5.12 (d, *J* = 12.2 Hz, 1H), 5.07 (d, *J* = 17.1 Hz, 1H), 5.03 (d, *J* = 10.2 Hz, 1H), 4.61 (m, 1H), 2.44 – 2.26 (m, 2H), 1.82 – 1.60 (m, 5H), 1.60 – 1.47 (m, 1H), 1.27 – 1.09 (m, 3H), 1.09 – 0.95 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 155.36, 135.69, 133.84, 128.66, 128.49, 128.26, 117.87, 81.90, 69.47, 40.94, 35.96, 28.96, 28.04, 26.40, 26.16, 26.04. **IR (thin film):** 3067, 3034, 2929, 2853, 1741, 1643, 1498, 1451, 1385, 1352, 1332, 1258, 1185, 1099, 1081, 1029, 973, 915, 859, 787, 753, 738, 697 cm^{-1}. **(ESI, positive mode):** 311.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{18}H_{25}O_3^+$ $[M+H]^+$: 289.1798, Found: 289.1796.



benzyl 1-phenylhex-5-en-3-yl carbonate (6b). Prepared according to General Procedure B and purified by column chromatography (5% EtOAc in hexane) to give the product as a clear oil (851 mg, 14% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.41 – 7.30 (m, 5H), 7.26 (t, *J* = 8.0 Hz, 2H), 7.21 – 7.09 (m, 3H), 5.84 – 5.67 (m, 1H), 5.16 (s, 2H), 5.12 – 5.00 (m, 2H), 4.86 – 4.68 (m, 1H),

2.75 – 2.66 (m, 1H), 2.66 – 2.56 (m, 1H), 2.40 (t, *J* = 6.4 Hz, 2H), 2.00 – 1.81 (m, 2H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 155.04, 141.43, 135.55, 133.11, 128.72, 128.61, 128.57, 128.48, 128.38, 126.13, 118.41, 77.51, 69.60, 38.76, 35.41, 31.69. **IR (thin film):** 3064, 3028, 2953, 2861, 1740, 1735, 1496, 1454, 1385, 1261, 1029, 994, 916, 859, 789, 750, 698 cm^{-1}. **(ESI, positive mode):** 333.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{20}H_{22}O_3Na^+$ [M+Na]$^+$: 333.1461, Found: 333.1460.



benzyl pent-4-en-2-yl carbonate (6c). Prepared according to General Procedure B and purified by silica gel chromatography (5% ethyl acetate/ 95% hexanes) to yield the product as a clear oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.41 – 7.29 (m, 5H), 5.86 – 5.62 (m, 1H), 5.14 (s, 2H), 5.13 – 5.05 (m, 2H), 4.91 – 4.74 (m, 1H), 2.46 – 2.36 (m, 1H), 2.36 – 2.22 (m, 1H), 1.28 (d, *J* = 6.3 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 154.83, 135.54, 133.34, 128.70, 128.58, 128.41, 118.25, 74.69, 69.49, 40.35, 19.55. **IR (thin film):** 3068, 3034, 2980, 2935, 1743, 1456, 1382, 1350, 1262, 1128, 1051, 994, 913, 791, 753, 697 cm^{-1}. **(ESI, positive mode):** 242.9 [M+Na]. **HRMS** (ESI): Calculated for $C_{13}H_{17}O_3^+$ [M+H]$^+$: 221.1172, Found: 221.1169.

General Procedure for Selenophosphoramide-Catalyzed 1,2-Diamination of Olefins

Standard Conditions A

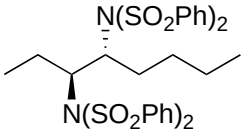
A flame-dried 1-dram vial was allowed to cool under positive pressure of nitrogen. To the vial was added phosphine selenide catalyst (5.4 mg, 0.02 mmol) and tetrabutylammonium benzenesulfonimide (215.5 mg, 0.4 mmol). Next, DCM (2 mL, 0.1 M), alkene (0.2 mmol), TMSOTf (72.4 uL, 0.4 mmol) and NFBS (126.1 mg, 0.4 mmol) were added in that order. The vial

was flushed with nitrogen, capped with a Teflon-lined cap and allowed to stir at room temperature for 24 hours. After 24 hours, dimethyl sulfide (60 uL) and water (0.5 mL) were added and the vial was capped and shaken. The mixture was diluted with DCM (2 mL) followed by ether (30 mL). The organic layer was washed 1 M citric acid (30 mL), saturated sodium bicarbonate (30 mL) and brine (30 mL), dried over magnesium sulfate, filtered and concentrated in vacuo.

Standard Conditions B

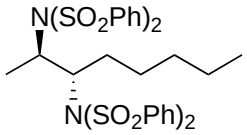
A flame-dried 1-dram vial was allowed to cool under positive pressure of nitrogen. To the vial was added phosphine selenide catalyst (5.4 mg, 0.02 mmol) and tetrabutylammonium benzenesulfonimide (107.8 mg, 0.2 mmol). Next, DCM (2 mL, 0.1 M), alkene (0.2 mmol), TMSOTf (72.4 uL, 0.4 mmol) and NFBS (94.6 mg, 0.3 mmol) were added in that order. The vial was flushed with nitrogen, capped with a Teflon-lined cap and allowed to stir at room temperature for 24 hours. After 24 hours, dimethyl sulfide (60 uL) and water (0.5 mL) were added and the vial was capped and shaken. The mixture was diluted with DCM (2 mL) followed by ether (30 mL). The organic layer was washed 1 M citric acid (30 mL), saturated sodium bicarbonate (30 mL) and brine (30 mL), dried over magnesium sulfate, filtered and concentrated in vacuo.

Characterization of Products

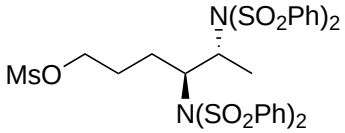


***N,N'*-(octane-3,4-diyl)bis(benzenesulfonimide) (3a).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield

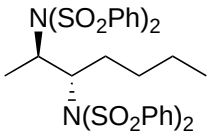
the product as an off-white solid (122.5 mg, 88% yield). **Mp:** 174.1-177.6 °C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.24 – 7.92 (m, 8H), 7.67 – 7.59 (m, 4H), 7.59 – 7.46 (m, 8H), 5.14 – 4.59 (m, 2H), 1.74 – 1.61 (m, 1H), 1.57 – 1.46 (m, 1H), 1.46 – 1.34 (m, 1H), 1.34 – 1.23 (m, 1H), 0.66 – 0.45 (m, 4H), 0.42 (t, *J* = 7.0 Hz, 3H), 0.35 (t, *J* = 7.4 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.27, 141.09, 139.18, 139.13, 134.27, 133.98, 129.74, 129.68, 129.29, 129.17, 128.91, 128.85, 128.83, 67.86, 67.36, 30.86, 28.40, 23.68, 22.38, 13.81, 10.85. **IR (thin film):** 3103, 3067, 2958, 2931, 2872, 1584, 1448, 1366, 1170, 1082, 993, 910, 845, 753, 730, 719, 686, 654, 592, 583, 555 cm^{-1}. **MS (ESI, positive mode):** 727.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{32}H_{36}N_2O_8S_4Na^+$ $[M+Na]^+$: 727.1247, Found: 727.1253.



***N,N'*-(octane-2,3-diyl)bis(benzenesulfonimide) (3b).** Prepared according to Standard Conditions A and purified by silica gel chromatography (15% ethyl acetate/ 85% hexanes) to yield the product as a tan solid (114.7 mg, 83% yield). **Mp:** 176.8-177.9 °C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.19 (d, *J* = 8.8 Hz, 2H), 8.17 (d, *J* = 8.1 Hz, 2H), 8.08 (d, *J* = 7.5 Hz, 2H), 8.00 (d, *J* = 7.4 Hz, 2H), 7.69 – 7.47 (m, 12H), 5.11 (td, *J* = 11.2, 3.4 Hz, 1H), 4.90 (dq, *J* = 10.3, 7.0 Hz, 1H), 1.77 – 1.55 (m, 2H), 1.09 – 0.83 (m, 4H), 0.83 – 0.69 (m, 8H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.46, 141.08, 139.05, 138.52, 134.28, 133.99, 133.94, 129.77, 129.31, 129.23, 129.00, 128.92, 128.88, 128.82, 128.67, 65.60, 62.68, 31.68, 30.25, 26.23, 22.52, 16.94, 14.16. **IR (thin film):** 3164, 3101, 3067, 2955, 2929, 2871, 1583, 1448, 1367, 1170, 1083, 911, 861, 753, 732, 721, 686, 652, 586, 555 cm^{-1}. **MS (ESI, positive mode):** 727.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{32}H_{36}N_2O_8S_4Na^+$ $[M+Na]^+$: 727.1247, Found: 727.1255.



4,5-bis(benzenesulfonimido)hexyl methanesulfonate (3c). Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as an off-white solid (142.7 mg, 88% yield). **Mp:** 145-147 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.16 (d, *J* = 7.7 Hz, 4H), 8.03 (d, *J* = 8.2 Hz, 2H), 7.93 (d, *J* = 8.2 Hz, 2H), 7.74 – 7.57 (m, 8H), 7.53 (t, *J* = 7.7 Hz, 4H), 5.13 (td, *J* = 10.4, 3.8 Hz, 1H), 4.97 – 4.87 (m, 1H), 3.86 (t, *J* = 5.8 Hz, 2H), 2.89 (s, 3H), 1.94 – 1.72 (m, 2H), 1.61 – 1.42 (m, 1H), 1.38 – 1.16 (m, 1H), 0.73 (d, *J* = 6.9 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.16, 140.75, 138.60, 138.05, 134.57, 134.39, 134.22, 129.70, 129.44, 129.21, 129.19, 129.14, 129.03, 128.84, 128.62, 69.49, 64.72, 62.18, 37.45, 26.47, 26.28, 16.54. **IR (thin film):** 3069, 2926, 2854, 1583, 1449, 1367, 1169, 1083, 961, 912, 860, 732, 722, 686, 651, 587, 555 cm^{-1}. **MS (ESI, positive mode):** 788.0 [M+NH_4], 793.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{31}H_{34}N_2O_{11}S_5Na^+$ [M+Na]$^+$: 793.0658, Found: 793.0665.



***N,N'*-(heptane-2,3-diyl)bis(benzenesulfonimide) (3d).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a white solid (110.3 mg, 88% yield). **Mp:** 190.2-199.1 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.18 (m, 4H), 8.08 (dd, *J* = 8.4, 1.0 Hz, 2H), 8.00 (dd, *J* = 8.4, 1.0 Hz, 2H), 7.70 – 7.45 (m, 12H), 5.11 (td, *J* = 11.1, 3.5 Hz, 1H), 4.90 (dq, *J* = 10.3, 7.0 Hz, 1H), 1.80 – 1.49 (m, 2H), 1.06 – 0.77 (m, 4H), 0.75 (d, *J* = 7.0 Hz, 3H), 0.61 (t, *J* = 7.2 Hz, 3H). **^{13}C NMR (126 MHz,**

$CDCl_3$): δ 141.46, 141.06, 139.05, 138.52, 134.29, 134.01, 133.95, 129.78, 129.32, 129.24, 129.01, 128.92, 128.89, 128.81, 128.67, 65.57, 62.69, 29.97, 28.59, 22.53, 16.91, 13.97. **IR (thin film):** 3067, 3029, 2956, 2871, 1583, 1448, 1367, 1170, 1083, 1045, 859, 753, 731, 720, 686, 652, 585, 554 cm^{-1}. **MS (ESI, positive mode):** 713.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{31}H_{34}N_2O_8S_4Na^+$ $[M+Na]^+$: 713.1090, Found: 713.1096.

In order to determine the relative stereochemistry of the products derived from internal olefins, the above product (**3d**) was compared to the analogous diaddition products, **8d** (trans) and **8k'** (cis), from Muniz's paper.[10a] These products contain p-toluenesulfonimide groups instead of benzenesulfonimide groups, but are in all other ways identical to **3d**. The alkene resonances of **3d** for both ^1H and ^{13}C NMR are consistent with a trans-1,2-diamination product.

3d: **^1H NMR (500 MHz, $CDCl_3$):** δ 5.11 (td, *J* = 11.1, 3.5 Hz, 1H), 4.90 (dq, *J* = 10.3, 7.0 Hz, 1H).

^{13}C NMR (126 MHz, $CDCl_3$): δ 65.57, 62.69.

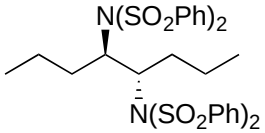
8d: **^1H NMR (500 MHz, $CDCl_3$):** δ 5.0 – 5.1 (m, 1H), 4.85 (dq, *J* = 10.3, 7.0 Hz, 1H).

^{13}C NMR (125 MHz, $CDCl_3$): δ 65.4, 62.5.

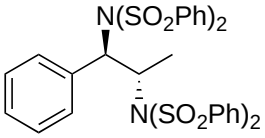
8k': **^1H NMR (500 MHz, $CDCl_3$):** δ 5.2 – 5.3 (m, 2H).

^{13}C NMR (125 MHz, $CDCl_3$): δ 69.5, 64.8.

The stereochemistry for all other products derived from trans-1,2-olefins was assigned on the same basis.

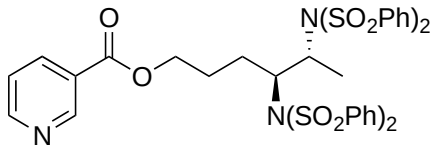


***N,N'*-(octane-4,5-diyl)bis(benzenesulfonimide) (3e).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 70% hexanes) to yield the product as a tan solid (100.8 mg, 74% yield). **Mp:** 204.5-206.4 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.15 (d, *J* = 7.5 Hz, 2H), 8.13 (d, *J* = 8.3 Hz, 2H), 7.68 – 7.61 (m, 4H), 7.55 (t, *J* = 7.7 Hz, 8H), 5.03 – 4.93 (m, 2H), 1.46 – 1.31 (m, 2H), 1.29 – 1.16 (m, 2H), 0.82 – 0.57 (m, 4H), 0.29 (t, *J* = 7.3 Hz, 6H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.18, 139.16, 134.28, 133.97, 129.72, 129.14, 128.94, 128.80, 66.93, 32.78, 19.60, 13.65. **IR (thin film):** 2963, 2872, 1449, 1366, 1169, 1082, 1058, 1020, 972, 913, 884, 843, 730, 719, 685, 667, 653, 594, 572, 553 cm^{-1}. **MS (ESI, positive mode):** 727.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{32}H_{36}N_2O_8S_4Na^+$ $[M+Na]^+$: 727.1247, Found: 727.1254.

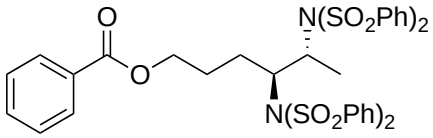


***N,N'*-(1-phenylpropane-1,2-diyl)bis(benzenesulfonimide) (3f).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as an off-white solid (114.8 mg, 85% yield). **Mp:** 173.5-181.5 ^{o}C. **^{1}H NMR (500 MHz, Acetone):** δ 8.23 – 8.17 (m, 2H), 8.05 – 8.02 (m, 2H), 7.85 – 7.76 (m, 4H), 7.74 – 7.66 (m, 4H), 7.60 – 7.50 (m, 4H), 7.42 (t, *J* = 7.4 Hz, 1H), 7.38 – 7.28 (m, 6H), 7.22 – 7.16 (m, 2H), 6.48 (d, *J* = 10.9 Hz, 1H), 6.00 (dq, *J* = 11.0, 6.9 Hz, 1H), 0.86 (d, *J* = 6.9 Hz, 3H). **^{13}C NMR (126 MHz, Acetone):** δ 206.11, 142.29, 142.27, 139.96, 139.66, 135.77, 135.61, 135.26, 134.56, 134.38, 132.04, 130.39, 130.32, 130.15, 130.04, 129.74, 129.62, 129.21, 128.72, 128.34, 66.61, 60.35,

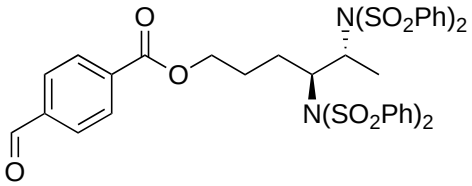
29.99, 29.84, 29.69, 17.63. **IR (thin film):** 2918, 2849, 1448, 1371, 1352, 1168, 1082, 846, 752, 733, 721, 684, 578, 554 cm^{-1}. **MS (ESI, positive mode):** 733.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{33}H_{30}N_2O_8S_4Na^+$ $[M+Na]^+$: 733.0777, Found: 733.0776.



4,5-bis(benzenesulfonimido)hexyl nicotinate (3g). Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as an off-white solid (63.1 mg, 40% yield). **Mp:** 191.2-196.1 ^oC. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 9.15 (s, 1H), 8.79 (s, 1H), 8.24 – 8.12 (m, 4H), 8.05 (d, *J* = 8.1 Hz, 2H), 7.99 (d, *J* = 7.5 Hz, 2H), 7.67 (t, *J* = 7.4 Hz, 1H), 7.64 – 7.42 (m, 12H), 7.40 – 7.32 (m, 1H), 5.16 (t, *J* = 10.9 Hz, 1H), 5.06 – 4.79 (m, 1H), 4.13 – 3.92 (m, 1H), 3.92 – 3.71 (m, 1H), 2.01 – 1.88 (m, 1H), 1.88 – 1.75 (m, 1H), 1.61 – 1.45 (m, 1H), 1.33 – 1.14 (m, 1H), 0.82 (d, *J* = 6.9 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.06, 153.44, 150.97, 141.32, 141.00, 138.74, 138.37, 137.26, 134.47, 134.36, 134.28, 133.99, 129.71, 129.28, 129.15, 129.02, 128.91, 128.65, 123.51, 65.18, 64.56, 62.37, 26.78, 25.75, 16.95. **IR (thin film):** 3067, 2953, 2894, 1723, 1591, 1448, 1367, 1285, 1169, 1083, 912, 859, 730, 721, 686, 651, 586, 554 cm^{-1}. **MS (ESI, positive mode):** 798.2 [M+H], 800.1 $[M+NH_4]$. **HRMS** (ESI): Calculated for $C_{36}H_{36}N_3O_{10}S_4^+$ $[M+H]^+$: 798.1278, Found: 798.1282.

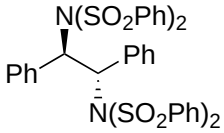


4,5-bis(benzenesulfonimido)hexyl benzoate (3h). Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a tan solid (142.7 mg, 90% yield). **Mp:** 188.5-191.2 ^{o}C. **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.21 – 8.15 (m, 4H), 8.09 – 8.05 (m, 2H), 8.01 (dd, *J* = 8.4, 1.1 Hz, 2H), 7.95 – 7.91 (m, 2H), 7.68 – 7.37 (m, 15H), 5.17 (td, *J* = 11.7, 3.1 Hz, 1H), 4.95 (dq, *J* = 10.4, 7.0 Hz, 1H), 4.02 – 3.88 (m, 1H), 3.83 – 3.66 (m, 1H), 2.00 – 1.88 (m, 1H), 1.85 – 1.73 (m, 1H), 1.58 – 1.45 (m, 1H), 1.32 – 1.16 (m, 1H), 0.84 (d, *J* = 7.0 Hz, 3H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 166.42, 141.36, 140.95, 138.72, 138.33, 134.45, 134.35, 134.24, 133.94, 133.00, 130.28, 129.72, 129.70, 129.27, 129.12, 129.02, 128.99, 128.98, 128.91, 128.54, 128.49, 65.24, 64.15, 62.42, 26.91, 25.88, 16.95. **IR (thin film):** 3165, 3067, 2954, 2892, 1718, 1449, 1367, 1276, 1170, 1083, 912, 860, 753, 731, 721, 686, 651, 586, 554 cm^{-1}. **MS (ESI, positive mode):** 814.2 [M+NH$_4$], 819.3 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{36}N_2O_{10}S_4Na^+$ [M+Na]$^+$: 819.1145, Found: 819.1150.

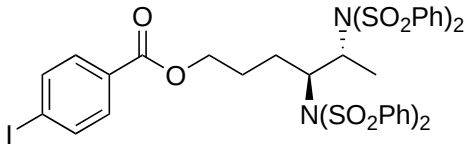


4,5-bis(benzenesulfonimido)hexyl 4-formylbenzoate (3i). Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as an off-white solid (159.1 mg, 96% yield). **Mp:** 206-201.2 ^{o}C. **^{1}H NMR (500 MHz, CD$_2$Cl$_2$):** δ 10.10 (s, 1H), 8.16 (d, *J* = 8.2 Hz, 2H), 8.13 (d, *J* = 8.2 Hz, 2H), 8.10 (d, *J* = 8.0 Hz, 2H), 8.04 (d, *J* = 8.1 Hz, 2H), 7.93 (d, *J* = 9.2 Hz, 2H), 7.92 (d, *J* = 8.7 Hz, 2H), 7.74 – 7.50 (m,

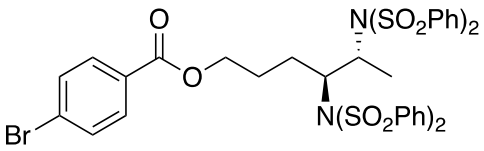
10H), 7.47 (t, *J* = 7.6 Hz, 2H), 5.17 (t, *J* = 10.9 Hz, 1H), 5.04 – 4.86 (m, 1H), 4.11 – 3.97 (m, 1H), 3.87 – 3.76 (m, 1H), 2.03 – 1.91 (m, 1H), 1.86 – 1.73 (m, 1H), 1.63 – 1.48 (m, 1H), 1.34 – 1.17 (m, 1H), 0.84 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 191.83, 165.42, 141.34, 141.00, 139.22, 138.72, 138.33, 135.24, 134.49, 134.37, 134.28, 133.92, 130.36, 129.71, 129.65, 129.29, 129.15, 129.01, 128.90, 128.66, 65.20, 64.68, 62.42, 26.83, 25.78, 16.87. **IR (thin film):** 3067, 2951, 2853, 2738, 1722, 1705, 1610, 1577, 1449, 1367, 1313, 1277, 1202, 1170, 1118, 1083, 1044, 955, 858, 755, 730, 721, 686, 651, 586, 554 cm^{-1}. **MS (ESI, positive mode):** 847.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{38}H_{37}N_2O_{11}S_4^+$ $[M+H]^+$: 825.1275, Found: 825.1281.



***N*,*N*'-(1,2-diphenylethane-1,2-diyl)bis(benzenesulfonimide) (3j).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a yellow solid (116 mg, 75% yield). **Mp:** 159.5-161.8 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.77 (s, 4H), 7.49 (d, *J* = 7.5 Hz, 4H), 7.40 – 7.30 (m, 4H), 7.21 (s, 2H), 7.14 – 7.06 (m, 14H), 7.01 (t, *J* = 7.4 Hz, 4H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.30, 138.69, 135.06, 133.36, 133.07, 128.92, 128.54, 128.51, 128.43, 128.10, 66.60. **IR (thin film):** 3100, 3065, 3034, 1584, 1500, 1448, 1370, 1337, 1166, 1081, 985, 910, 843, 751, 734, 721, 703, 684, 605, 582, 552 cm^{-1}. **MS (ESI, positive mode):** 795.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{38}H_{32}N_2O_8S_4Na^+$ $[M+Na]^+$: 795.0934, Found: 795.0939.

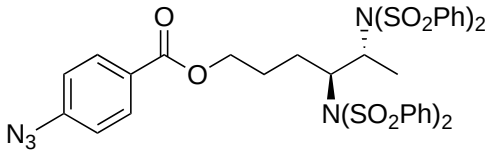


4,5-bis(benzenesulfonimido)hexyl 4-iodobenzoate (3k). Prepared according to Standard Conditions A and purified by silica gel chromatography (100% DCM) to yield the product as a white solid (182.2 mg, 93% yield). **Mp:** 219.5-226.3 ^{o}C. **^{1}H NMR (500 MHz, CD_2Cl_2):** δ 8.14 (d, *J* = 8.1 Hz, 2H), 8.11 (d, *J* = 8.2 Hz, 2H), 8.08 (d, *J* = 8.3 Hz, 2H), 7.97 (d, *J* = 8.1 Hz, 2H), 7.86 (d, *J* = 8.3 Hz, 2H), 7.78 – 7.56 (m, 12H), 7.53 (t, *J* = 7.8 Hz, 2H), 5.19 (t, *J* = 11.0 Hz, 1H), 4.99 (m, 1H), 4.10 – 3.95 (m, 1H), 3.87 – 3.71 (m, 1H), 2.06 – 1.88 (m, 1H), 1.88 – 1.69 (m, 1H), 1.68 – 1.43 (m, 1H), 1.40 – 1.18 (m, 1H), 0.88 (d, *J* = 7.0 Hz, 3H). **^{13}C NMR (126 MHz, CD_2Cl_2):** δ 166.19, 141.68, 141.38, 139.18, 138.70, 138.35, 135.06, 134.97, 134.83, 134.53, 131.58, 130.45, 130.06, 129.81, 129.52, 129.27, 129.07, 101.05, 65.79, 64.76, 62.76, 27.25, 26.31, 17.23. **IR (thin film):** 3066, 2955, 1719, 1586, 1448, 1367,1280, 1270, 1169, 1083, 860, 753, 685, 585, 554 cm^{-1}. **MS (ESI, positive mode):** 944.9 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{35}IN_2O_{10}S_4Na^+$ $[M+Na]^+$: 945.0111, Found: 945.0121.

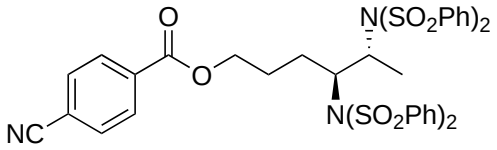


4,5-bis(benzenesulfonimido)hexyl 4-bromobenzoate (3l). Prepared according to Standard Conditions A and purified by silica gel chromatography (100% DCM) to yield the product as a white solid (145.5 mg, 83% yield). **Mp:** 212.9-217.6 ^{o}C. **^{1}H NMR (500 MHz, CD_2Cl_2):** δ 8.18 – 8.07 (m, 4H), 8.02 (d, *J* = 7.2 Hz, 2H), 7.91 (d, *J* = 7.5 Hz, 2H), 7.80 (d, *J* = 8.6 Hz, 2H), 7.72 – 7.50 (m, 12H), 7.47 (t, *J* = 7.9 Hz, 2H), 5.18 – 5.07 (m, 1H), 5.00 – 4.85 (m, 1H), 3.98 (dt, *J* =

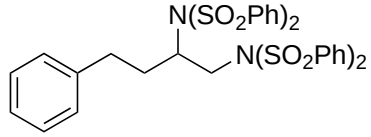
10.9, 5.5 Hz, 1H), 3.75 (ddd, *J* = 10.9, 8.4, 5.4 Hz, 1H), 1.98 – 1.87 (m, 1H), 1.81 – 1.68 (m, 1H), 1.59 – 1.43 (m, 1H), 1.32 – 1.08 (m, 1H), 0.82 (d, *J* = 7.0 Hz, 3H). **^{13}C NMR (126 MHz, CD_2Cl_2):** δ 165.95, 141.68, 141.38, 139.18, 138.70, 135.06, 134.97, 134.83, 134.53, 132.30, 131.70, 130.06, 129.90, 129.81, 129.53, 129.26, 129.08, 128.39, 65.80, 64.78, 62.76, 27.25, 26.31, 17.23. **IR (thin film):** 3068, 2956, 1716, 1590, 1449, 1367, 1273, 1169, 1083, 860, 754, 721, 685, 586, 555 cm^{-1}. **MS (ESI, positive mode):** 897.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{3579}BrN_2O_{10}S_4Na$ $[M+Na]^+$: 897.0250, Found: 897.0257.



4,5-bis(benzenesulfonimido)hexyl 4-azidobenzoate (3m). Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as a yellow solid (143 mg, 84% yield). **Mp:** 191.8-194 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.19 (d, *J* = 6.5 Hz, 2H), 8.17 (d, *J* = 7.1 Hz, 2H), 8.06 (d, *J* = 7.6 Hz, 2H), 8.00 (d, *J* = 7.6 Hz, 2H), 7.92 (d, *J* = 8.5 Hz, 2H), 7.70 – 7.39 (m, 12H), 7.03 (d, *J* = 8.5 Hz, 2H), 5.16 (t, *J* = 10.9 Hz, 1H), 5.01 – 4.83 (m, 1H), 4.03 – 3.88 (m, 1H), 3.84 – 3.62 (m, 1H), 1.97 (t, *J* = 13.6 Hz, 1H), 1.88 – 1.70 (m, 1H), 1.62 – 1.38 (m, 1H), 1.35 – 1.14 (m, 1H), 0.83 (d, *J* = 6.9 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.59, 144.79, 141.37, 140.97, 138.72, 138.32, 134.45, 134.35, 134.24, 133.91, 131.56, 129.69, 129.27, 129.12, 128.99, 128.90, 128.60, 126.82, 118.96, 65.25, 64.17, 62.40, 26.87, 25.83, 16.90. **IR (thin film):** 3067, 2953, 2124, 1715, 1603, 1448, 1382, 1367, 1275, 1169, 1083, 858, 731, 721, 686, 586, 555 cm^{-1}. **MS (ESI, positive mode):** 838.0 [M+H]. **HRMS** (ESI): Calculated for $C_{37}H_{36}N_5O_{10}S$ $[M+H]^+$: 838.1340, Found: 838.1348.

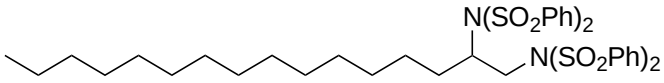


4,5-bis(benzenesulfonimido)hexyl 4-cyanobenzoate (3n). Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as an off-white solid (141.7 mg, 87% yield). **Mp:** 219.6-223.5 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.28 – 8.10 (m, 4H), 8.10 – 7.90 (m, 6H), 7.79 – 7.38 (m, 14H), 5.23 – 5.09 (m, 1H), 4.94 (dq, *J* = 10.3, 7.0 Hz, 1H), 4.10 (dt, *J* = 10.7, 5.4 Hz, 1H), 3.85 – 3.72 (m, 1H), 2.20 – 2.01 (m, 1H), 1.95 – 1.78 (m, 1H), 1.69 – 1.49 (m, 1H), 1.37 – 1.11 (m, 1H), 0.79 (d, *J* = 7.0 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 164.84, 141.33, 141.04, 138.73, 138.30, 134.51, 134.40, 134.31, 134.10, 133.90, 132.36, 130.28, 129.73, 129.32, 129.17, 129.06, 129.03, 129.01, 128.88, 128.73, 118.16, 116.40, 65.17, 64.81, 62.47, 26.80, 25.79, 16.78. **IR (thin film):** 3067, 2957, 2230, 1724, 1449, 1367, 1277, 1169, 1083, 860, 686, 586, 555 cm^{-1}. **MS (ESI, positive mode):** 844.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{38}H_{35}N_3O_{10}S_4Na^+$ [M+Na]$^+$: 844.1097, Found: 844.1102.

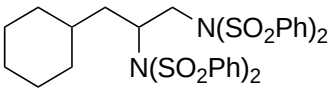


***N,N*'-(4-phenylbutane-1,2-diyl)bis(benzenesulfonimide) (3p).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as an off-white solid (79.8 mg, 56% yield). **Mp:** 189.5-199.2 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.18 (dd, *J* = 11.8, 7.9 Hz, 4H), 8.05 (d, *J* = 7.7 Hz, 4H), 7.69 – 7.46 (m, 12H), 7.14 (t, *J* = 7.3 Hz, 3H), 6.60 (d, *J* = 6.5 Hz, 2H), 4.99 – 4.85 (m, 1H), 4.77 (dd, *J* = 14.4, 11.5 Hz, 1H), 3.74 (dd, *J* = 14.5, 3.8 Hz, 1H), 2.18 – 1.98 (m, 2H), 1.95 – 1.84 (m, 1H), 1.78 (dt, *J* = 19.0, 4.8 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 141.09, 140.55, 139.72, 139.35, 134.30, 134.27, 134.10,

129.34, 129.30, 129.19, 129.05, 128.97, 128.63, 128.26, 128.18, 126.02, 62.15, 51.47, 32.41, 30.27. **IR (thin film):** 3065, 3028, 2942, 1448, 1379, 1358, 1170, 1084, 911, 895, 860, 795, 753, 735, 720, 686, 651, 281, 554 cm^{-1}. **MS (ESI, positive mode):** 747.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{34}H_{32}N_2O_8S_4Na^+$ $[M+Na]^+$: 747.0934, Found: 747.0939.

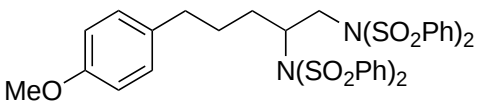


***N,N'*-(hexadecane-1,2-diyl)bis(benzenesulfonimide) (3q).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a tan oil (82.4 mg, 51% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.16 (d, *J* = 7.4 Hz, 4H), 8.06 (d, *J* = 7.4 Hz, 4H), 7.68 – 7.59 (m, 4H), 7.54 (td, *J* = 7.9, 5.0 Hz, 8H), 4.78 (tt, *J* = 11.3, 3.3 Hz, 1H), 4.70 (dd, *J* = 14.0, 11.5 Hz, 1H), 3.71 (dd, *J* = 14.1, 3.5 Hz, 1H), 1.85 – 1.69 (m, 1H), 1.47 – 1.36 (m, 1H), 1.36 – 1.19 (m, 15H), 1.19 – 1.11 (m, 2H), 1.08 – 0.97 (m, 2H), 0.89 (t, *J* = 6.9 Hz, 3H), 0.85 – 0.73 (m, 2H), 0.73 – 0.57 (m, 2H), 0.57 – 0.42 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.95, 139.98, 139.48, 134.21, 134.09, 133.98, 129.30, 129.19, 128.96, 128.94, 128.88, 128.58, 127.92, 62.11, 51.64, 32.05, 29.84, 29.83, 29.80, 29.78, 29.69, 29.57, 29.50, 29.45, 29.17, 28.67, 26.36, 22.82, 14.25. **IR (thin film):** 3067, 2924, 2856, 1448, 1379, 1359, 1170, 1084, 753, 731, 720, 686, 585, 555 cm^{-1}. **MS (ESI, positive mode):** 834.4 $[M+NH_4]$, 839.3 [M+Na]. **HRMS** (ESI): Calculated for $C_{40}H_{52}N_2O_8S_4Na^+$ $[M+Na]^+$: 839.2499, Found: 839.2505.



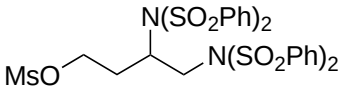
***N,N'*-(3-cyclohexylpropane-1,2-diyl)bis(benzenesulfonimide) (3r).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80%

hexanes) to yield the product as white solid (79.4 mg, 54% yield). **Mp:** 210.8-213.8 ^{o}C. **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.20 (d, *J* = 7.4 Hz, 2H), 8.19 (d, *J* = 7.4 Hz, 2H), 8.03 (d, *J* = 7.5 Hz, 4H), 7.72 – 7.60 (m, 4H), 7.60 – 7.47 (m, 8H), 4.99 – 4.84 (m, 1H), 4.64 (dd, *J* = 14.7, 11.1 Hz, 1H), 3.77 (dd, *J* = 14.7, 3.6 Hz, 1H), 1.75 (t, *J* = 12.8 Hz, 1H), 1.55 (d, *J* = 12.0 Hz, 1H), 1.49 – 1.36 (m, 3H), 1.36 – 1.19 (m, 1H), 0.97 – 0.78 (m, 3H), 0.78 – 0.58 (m, 2H), 0.58 – 0.44 (m, 1H), 0.16 (dd, *J* = 21.0, 10.0 Hz, 1H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 141.17, 140.37, 139.43, 134.22, 134.02, 133.96, 129.28, 129.19, 129.01, 128.98, 128.91, 128.72, 59.63, 52.09, 35.84, 33.66, 33.51, 31.73, 26.36, 26.22, 25.78. **IR (thin film):** 3067, 2924, 2851, 1448, 1378, 1170, 1084, 911, 883, 867, 825, 796, 753, 732, 720, 686, 652, 586, 553 cm^{-1}. **MS (ESI, positive mode):** 739.3 [M+Na]. **HRMS** (ESI): Calculated for $C_{33}H_{36}N_2O_8S_4Na^+$ [M+Na]$^+$: 739.1247, Found: 739.1251.

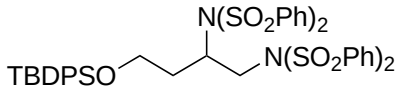


***N*,*N*'-(5-(4-methoxyphenyl)pentane-1,2-diyl)bis(benzenesulfonimide) (3s).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a yellow resin (75.8 mg, 48% yield). **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.15 (d, *J* = 7.4 Hz, 2H), 8.14 (d, *J* = 6.2 Hz, 2H), 8.04 (d, *J* = 7.4 Hz, 4H), 7.67 – 7.46 (m, 12H), 6.75 (d, *J* = 2.2 Hz, 4H), 4.79 (tt, *J* = 11.2, 3.3 Hz, 1H), 4.71 (dd, *J* = 14.0, 11.4 Hz, 1H), 3.78 (s, 3H), 3.72 (dd, *J* = 14.0, 3.5 Hz, 1H), 2.10 – 2.00 (m, 1H), 1.98 – 1.85 (m, 2H), 1.59 – 1.48 (m, 1H), 1.01 – 0.88 (m, 1H), 0.88 – 0.73 (m, 1H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 157.81, 140.95, 139.85, 139.42, 134.25, 134.15, 134.08, 133.86, 129.32, 129.21, 129.05, 128.98, 128.85, 128.55, 113.73, 61.79, 55.40, 51.60, 34.52, 28.60, 28.55. **IR (thin film):** 3067, 3006, 2935, 2860, 1512, 1448, 1378, 1358, 1246, 1170, 1084, 908, 753, 731, 720, 686, 585, 554 cm^{-1}. **MS (ESI, positive**

mode): 786.2 [M+NH_4], 791.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{36}H_{36}N_2O_9S_4Na^+$ $[M+Na]^+$: 791.1196, Found: 791.1202.

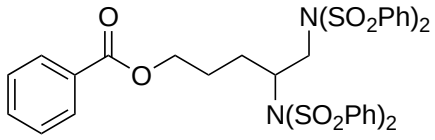


3,4-bis(benzenesulfonimido)butyl methanesulfonate (3t). Prepared according to Standard Conditions A and purified by silica gel chromatography (100% DCM) to yield the product as a white solid (114.6 mg, 76% yield). **Mp:** 175.8-184.7 ^oC. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.14 – 8.07 (m, 4H), 8.01 (d, *J* = 7.4 Hz, 4H), 7.75 – 7.63 (m, 4H), 7.60 (t, *J* = 7.7 Hz, 6H), 7.55 (t, *J* = 7.9 Hz, 2H), 5.06 (tt, *J* = 11.5, 3.6 Hz, 1H), 4.62 (dd, *J* = 14.7, 11.3 Hz, 1H), 3.90 (dt, *J* = 10.0, 5.1 Hz, 1H), 3.65 (dd, *J* = 14.6, 4.0 Hz, 1H), 3.58 (td, *J* = 9.6, 4.5 Hz, 1H), 2.91 (s, 3H), 2.47 (ddt, *J* = 16.0, 11.6, 4.5 Hz, 1H), 2.33 – 2.21 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.38, 139.12, 138.69, 134.62, 134.59, 129.52, 129.44, 129.38, 128.95, 128.82, 128.75, 66.27, 58.13, 50.21, 37.20, 28.51. **IR (thin film):** 3067, 3032, 2939, 1583, 1449, 1376, 1359, 1083, 950, 909, 859, 754, 732, 720, 686, 650, 586, 554 cm^{-1}. **MS (ESI, positive mode):** 760.2 [M+NH_4], 765.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{29}H_{30}N_2O_{11}S_5Na^+$ $[M+Na]^+$: 765.0345, Found: 765.0348.

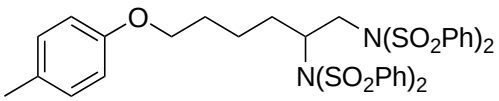


***N,N*'-(4-(*tert*-butyldiphenylsilyloxy)butane-1,2-diyl)bis(benzenesulfonimide) (3u).** Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as a yellow resin (109 mg, 60% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.09 (d, *J* = 7.5 Hz, 2H), 8.02 (m, 6H), 7.59 – 7.49 (m, 6H), 7.47 – 7.31 (m, 16H), 5.00 (tt, *J* = 11.5, 3.8 Hz, 1H), 4.69 (dd, *J* = 14.7, 11.2 Hz, 1H), 3.69 (dd, *J* = 14.7, 4.2 Hz, 1H), 3.24

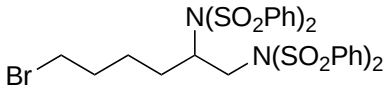
(td, *J* = 10.1, 4.0 Hz, 1H), 2.89 (dd, *J* = 17.9, 7.7 Hz, 1H), 2.32 (dddd, *J* = 15.5, 11.7, 7.6, 4.1 Hz, 1H), 2.02 (dtd, *J* = 11.6, 8.0, 3.5 Hz, 1H), 0.96 (s, 9H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.87, 139.33, 138.86, 135.60, 135.57, 134.27, 134.13, 133.99, 133.94, 133.59, 129.70, 129.23, 129.14, 129.01, 128.87, 128.83, 128.81, 127.84, 127.78, 60.44, 59.02, 50.55, 31.93, 26.98, 19.30. **IR (thin film):** 3070, 2957, 2930, 2857, 1584, 1448, 1378, 1360, 1171, 1111, 1084, 909, 856, 785, 753, 731, 720, 704, 686, 650, 585, 555 cm^{-1}. **MS (ESI, positive mode):** 925.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{44}H_{46}N_2O_9S_4SiNa^+$ $[M+X]^+$: 925.1748, Found: 925.1757.



4,5-bis(benzenesulfonimido)pentyl benzoate (3v). Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a clear oil (99.8 mg, 64% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.20 – 8.13 (m, 4H), 8.03 (d, *J* = 7.9 Hz, 4H), 7.93 (d, *J* = 7.9 Hz, 2H), 7.63 (t, *J* = 7.4 Hz, 2H), 7.61 – 7.50 (m, 7H), 7.50 – 7.38 (m, 6H), 4.83 (t, *J* = 11.4 Hz, 1H), 4.79 – 4.70 (m, 1H), 3.85 (dt, *J* = 11.3, 5.8 Hz, 1H), 3.76 – 3.68 (m, 2H), 2.03 – 1.89 (m, 1H), 1.78 – 1.67 (m, 1H), 1.21 – 1.11 (m, 1H), 1.11 – 0.99 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 166.28, 140.80, 139.59, 139.33, 134.30, 134.27, 134.24, 133.05, 130.30, 129.70, 129.29, 129.10, 128.92, 128.84, 128.52, 128.49, 128.28, 63.74, 61.65, 51.44, 25.67, 25.35. **IR (thin film):** 3166, 3067, 3007, 2959, 2894, 1717, 1602, 1584, 1449, 1379, 1 358, 1314m 1275, 1170, 1084, 908, 754, 732, 686, 651, 584, 555 cm^{-1}. **MS (ESI, positive mode):** 805.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{36}H_{34}N_2O_{10}S_4Na^+$ $[M+Na]^+$: 805.0988, Found: 805.0944.

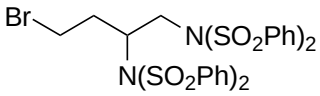


***N,N'*-(6-(*p*-tolyloxy)hexane-1,2-diyl)bis(benzenesulfonimide) (3w).** Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as a tan solid (101.5 mg, 65% yield). **Mp:** 68.4-74.2 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.16 (d, *J* = 8.8 Hz, 2H), 8.14 (d, *J* = 7.8 Hz, 2H), 8.05 (d, *J* = 7.4 Hz, 4H), 7.65 – 7.55 (m, 4H), 7.55 – 7.46 (m, 6H), 7.08 (d, *J* = 8.3 Hz, 2H), 6.69 (d, *J* = 8.5 Hz, 2H), 4.83 – 4.76 (m, 1H), 4.76 – 4.67 (m, 1H), 3.72 (dd, *J* = 13.7, 3.2 Hz, 1H), 3.56 – 3.40 (m, 2H), 2.30 (s, 3H), 1.98 – 1.76 (m, 1H), 1.58 – 1.42 (m, 1H), 1.32 – 1.21 (m, 1H), 1.21 – 1.09 (m, 1H), 0.88 – 0.75 (m, 1H), 0.73 – 0.59 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 156.87, 140.87, 139.72, 139.37, 134.28, 134.18, 134.09, 129.94, 129.79, 129.32, 129.22, 129.02, 128.97, 128.92, 128.86, 128.54, 114.41, 67.45, 61.89, 51.51, 28.76, 28.49, 22.97, 20.59. **IR (thin film):** 3066, 3032, 3006, 2925, 2869, 1612, 1584, 1511, 1488, 1378, 1358, 1243, 1170, 1084, 1043, 999, 910, 890, 851, 793, 753, 720, 686, 651, 585, 555 cm^{-1}. **MS (ESI, positive mode):** 800.3 [M+NH_4], 805.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{38}N_2O_9S_4Na$ [M+Na]$^{+}$: 805.1352, Found: 805.1360.

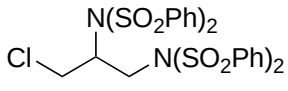


***N,N'*-(6-bromohexane-1,2-diyl)bis(benzenesulfonimide) (3x).** Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as an off-white solid (111.4 mg, 75% yield). **Mp:** 63.4-71.2 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.15 (d, *J* = 9.3 Hz, 2H), 8.14 (d, *J* = 8.4 Hz, 2H), 8.04 (d, *J* = 7.9 Hz, 4H), 7.66 (dt, *J* = 10.3, 7.3 Hz, 4H), 7.55 (dd, *J* = 14.2, 7.3 Hz, 6H), 4.76 (tt, *J* = 11.0, 3.0 Hz, 1H), 4.73 – 4.66 (m, 1H), 3.72 (dd, *J* = 13.9, 3.2 Hz, 1H), 3.04 – 2.87 (m, 2H), 1.84 (dtd, *J* = 15.4, 11.4, 4.2 Hz,

1H), 1.50 – 1.40 (m, 1H), 1.40 – 1.30 (m, 1H), 1.30 – 1.18 (m, 1H), 0.86 – 0.74 (m, 1H), 0.72 – 0.59 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.96, 139.66, 139.37, 134.34, 134.25, 134.14, 129.36, 129.28, 129.08, 128.92, 128.87, 128.57, 61.72, 51.47, 32.93, 32.29, 27.96, 25.01. **IR (thin film):** 3067, 2959, 1584, 1448, 1378, 1358, 1171, 1084, 907, 754, 731, 720, 686, 584, 554 cm^{-1}. **MS (ESI, positive mode):** 777.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{30}H_{31}BrN_2O_8S_4Na^+$ $[M+Na]^+$: 777.0039, Found: 777.0043.

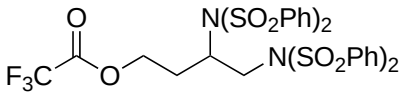


***N,N*'-(4-bromobutane-1,2-diyl)bis(benzenesulfonimide) (3y).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as an off-white resin (114.7 mg, 70% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.17 – 8.11 (m, 4H), 8.02 (dd, *J* = 7.5, 1.0 Hz, 4H), 7.72 – 7.63 (m, 4H), 7.63 – 7.51 (m, 8H), 4.82 (t, *J* = 11.3 Hz, 1H), 4.68 (dd, *J* = 14.6, 11.3 Hz, 1H), 3.62 (dd, *J* = 14.6, 4.0 Hz, 1H), 2.73 (td, *J* = 10.1, 4.4 Hz, 1H), 2.63 (m, 1H), 2.59 – 2.43 (m, 1H), 2.16 – 2.00 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.44, 139.36, 139.01, 134.50, 134.45, 129.44, 129.42, 129.37, 128.91, 128.85, 128.70, 60.53, 50.77, 32.62, 27.79. **IR (thin film):** 3067, 2927, 1448, 1378, 1171, 1084, 753, 731, 720, 685, 583, 554 cm^{-1}. **MS (ESI, positive mode):** 749.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{28}H_{27}{}^{79}BrN_2O_8S_4Na^+$ $[M+Na]^+$: 748.9726, Found: 748.9733.

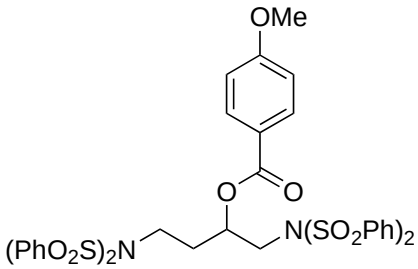


***N,N*'-(3-chloropropane-1,2-diyl)bis(benzenesulfonimide) (3z).** Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield

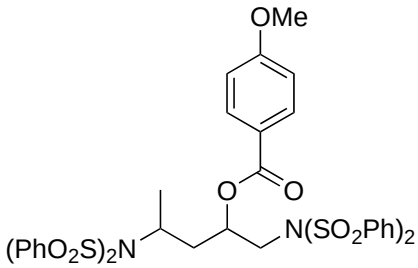
the product as an off-white solid (57.5 mg, 43% yield). **Mp:** 196.8-204.9 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.17 (d, *J* = 7.9 Hz, 2H), 7.99 (d, *J* = 7.9 Hz, 6H), 7.69 (t, *J* = 7.5 Hz, 3H), 7.64 (t, *J* = 7.5 Hz, 1H), 7.61 – 7.54 (m, 6H), 7.51 (t, *J* = 7.8 Hz, 2H), 4.99 (tt, *J* = 11.0, 4.1 Hz, 1H), 4.62 (dd, *J* = 14.9, 11.4 Hz, 1H), 4.05 (dd, *J* = 12.6, 11.1 Hz, 1H), 3.89 (dd, *J* = 14.9, 4.4 Hz, 1H), 3.67 (dd, *J* = 12.7, 3.9 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.17, 138.65, 138.53, 134.61, 134.49, 134.34, 129.51, 129.40, 129.21, 129.15, 129.14, 128.99, 128.93, 128.67, 62.38, 49.56, 41.39. **IR (thin film):** 3067, 2927, 1449, 1378, 1360, 1170, 1084, 753, 732, 720, 685, 583, 554 cm^{-1}. **MS (ESI, positive mode):** 691.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{27}H_5ClN_2O_8S_4Na$ $[M+Na]^+$: 691.0074, Found: 691.0079.



3,4-bis(benzenesulfonimido)butyl 2,2,2-trifluoroacetate (3aa). Prepared according to Standard Conditions A and purified by silica gel chromatography (20% ethyl acetate/ 80% hexanes) to yield the product as a yellow resin (103.6 mg, 68% yield). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.12 (d, *J* = 7.8 Hz, 2H), 8.08 (d, *J* = 7.7 Hz, 2H), 7.99 (d, *J* = 7.7 Hz, 4H), 7.72 – 7.62 (m, 4H), 7.62 – 7.47 (m, 8H), 4.92 (tt, *J* = 11.6, 3.8 Hz, 1H), 4.67 (dd, *J* = 14.7, 11.2 Hz, 1H), 3.91 – 3.75 (m, 2H), 3.59 (dd, *J* = 14.7, 4.3 Hz, 2H), 2.51 – 2.34 (m, 1H), 2.14 (dtd, *J* = 11.5, 8.1, 3.4 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 156.92 (q, *J* = 42.4 Hz), 140.39, 138.84, 138.68, 134.54, 134.34, 129.45, 129.37, 129.30, 129.10, 128.88, 128.77, 128.70, 114.50 (q, *J* = 285.8 Hz) ,77.36, 64.20, 60.47, 58.15, 50.01, 27.49, 21.14, 14.29. **IR (thin film):** 3167, 3069, 2960, 1789, 1449, 1377, 1361, 1221, 1170, 1083, 911, 879, 818, 780, 753, 733, 721, 686, 651, 584, 554 cm^{-1}. **MS (ESI, positive mode):** 783.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{30}H_7F_3N_2O_{10}S_4Na^+$ $[M+Na]^+$: 783.0393, Found: 783.0396.

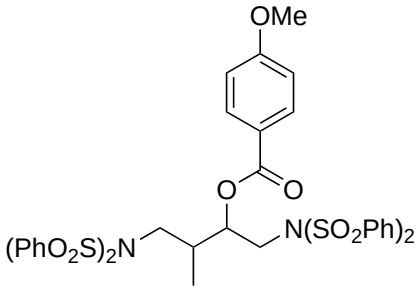


1,4-bis(benzenesulfonimido)butan-2-yl 4-methoxybenzoate (5ae). Prepared according to Standard Conditions B and purified by silica gel chromatography (25% ethyl acetate/ 75% hexanes) to yield the product as a white solid (147.1 mg, 92% yield). **Mp:** 115.7-120.9 ^{o}C. **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.03 – 7.96 (m, 6H), 7.92 (dd, *J* = 8.4, 1.1 Hz, 4H), 7.64 – 7.54 (m, 4H), 7.47 (m, 8H), 6.96 – 6.87 (m, 2H), 5.36 – 5.18 (m, 1H), 4.12 (dd, *J* = 15.4, 7.5 Hz, 1H), 3.91 – 3.83 (m, 1H), 3.85 (s, 3H), 3.75 (m, 2H), 2.26 – 2.16 (m, 1H), 2.16 – 2.05 (m, 1H). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 165.51, 163.80, 139.53, 139.29, 134.13, 134.04, 132.08, 129.27, 129.23, 128.40, 128.23, 121.84, 113.79, 69.79, 55.58, 50.51, 45.39, 32.97. **IR (thin film):** 3067, 3007, 2960, 2934, 2841, 1712, 1606, 1512, 1448, 1374, 1355, 1259, 1170, 1085, 1026, 912, 842, 753, 736, 720, 686, 582, 551 cm^{-1}. **MS (ESI, positive mode):** 816.5 [M+NH$_4$], 821.5 [M+Na]. **HRMS** (ESI): Calculated for $C_{36}H_{34}N_2O_{11}S_4Na^+$ [M+Na]$^+$: 821.0938, Found: 821.0944.



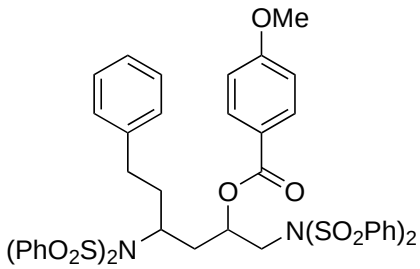
1,4-bis(benzenesulfonimido)pentan-2-yl 4-methoxybenzoate (5af). Prepared according to Standard Conditions B and purified by silica gel chromatography (25% ethyl acetate/ 75% hexanes) to yield the product as a yellow resin (110.8 mg, 68% yield, 2.3:1 dr). **^{1}H NMR (500**

MHz, $CDCl_3$): δ 8.09 – 7.84 (m, 22H, Major+Minor), 7.66 – 7.37 (m, 22H, Major+Minor), 6.95 (d, *J* = 9.0 Hz, 2H, Major), 6.90 (d, *J* = 8.9 Hz, 2H, Minor), 5.29 – 5.09 (m, 2H, Major+Minor), 4.39 – 4.28 (m, 1H, Minor), 4.28 – 4.18 (m, 1H, Major), 4.07 (dd, *J* = 15.4, 7.0 Hz, 1H, Major), 4.02 (dd, *J* = 15.9, 7.8 Hz, 1H, Minor), 3.92 (dd, *J* = 15.3, 5.0 Hz, 1H, Major), 3.87 (s, 3H, Major), 3.85 (s, 3H, Minor), 3.79 (dd, *J* = 15.9, 3.1 Hz, 1H, Minor), 2.71 – 2.61 (m, 1H, Major), 2.52 – 2.41 (m, 1H, Minor), 2.24 – 2.14 (m, 1H, Minor), 2.13 – 2.03 (m, 1H, Major), 1.42 (d, *J* = 6.8 Hz, 3H, Minor), 1.23 (d, *J* = 6.8 Hz, 3H, Major). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.76, 165.37, 163.90, 163.70, 139.39, 139.25, 134.14, 134.08, 132.20, 132.03, 129.26, 129.17, 128.47, 128.43, 122.10, 121.75, 113.81, 113.73, 71.63, 69.01, 56.64, 56.16, 55.60, 55.56, 50.91, 50.70, 39.86, 38.70, 29.78, 20.03, 18.42. **IR (thin film):** 3068, 3006, 2935, 2842, 1711, 1606, 1512, 1448, 1370, 1259, 1169, 1085, 1030, 910, 753, 733, 721, 686, 583, 551 cm^{-1}. **MS (ESI, positive mode):** 835.0 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{36}N_2O_{11}S_4Na^+$ [M+X]$^+$: 835.1094, Found: 835.1085.



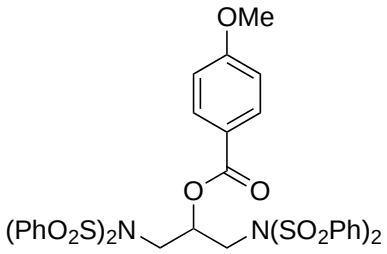
3-methyl-1,4-bis(benzenesulfonimido)butan-2-yl 4-methoxybenzoate (5ag). Prepared according to Standard Conditions B and purified by silica gel chromatography (25% ethyl acetate/ 75% hexanes) to yield the product as a yellow resin (144.1 mg, 89% yield, 1:1 dr). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.05 – 7.96 (m, 14H, A+B), 7.95 (dd, *J* = 8.4, 0.9 Hz, 4H, A+B), 7.89 (dd, *J* = 8.4, 0.9 Hz, 4H, A+B), 7.65 – 7.53 (m, 8H, A+B), 7.53 – 7.39 (m, 14H, A+B), 6.92 (dd, *J* = 8.8, 1.2 Hz, 4H, A+B), 5.40 (m, 2H, A+B), 4.22 (dd, *J* = 15.7, 9.1 Hz, 1H, A), 4.10 (dd, *J* = 15.4, 7.9

Hz, 1H, B), 3.93 (dd, *J* = 15.4, 4.7 Hz, 1H, B), 3.89 – 3.82 (m, 8H, A+B), 3.77 (dd, *J* = 14.6, 4.2 Hz, 2H, A+B), 3.65 (dd, *J* = 14.8, 10.4 Hz, 1H, B), 2.61 – 2.46 (m, 2H, A+B), 1.03 (d, *J* = 7.0 Hz, 3H, A), 0.96 (d, *J* = 7.0 Hz, 3H, B). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.42, 165.26, 163.74, 163.71, 139.44, 139.31, 139.27, 134.10, 134.01, 132.18, 132.10, 129.22, 129.20, 129.14, 128.47, 128.41, 128.31, 122.00, 113.77, 113.72, 77.36, 74.00, 72.74, 60.47, 55.57, 51.74, 50.41, 49.80, 48.78, 36.29, 35.18, 29.78, 21.14, 14.30, 13.86, 11.65. **IR (thin film):** 3067, 2971, 2935, 2842, 1712, 1605, 1512, 1448, 1374, 1355, 1259, 1169, 1085, 1031, 912, 794, 782, 753, 738, 720, 686, 583, 551 cm^{-1}. **MS (ESI, positive mode):** 835.3 [M+Na]. **HRMS** (ESI): Calculated for $C_{37}H_{36}N_2O_{11}S_4Na^+$ $[M+Na]^+$: 835.1094, Found: 835.1100.

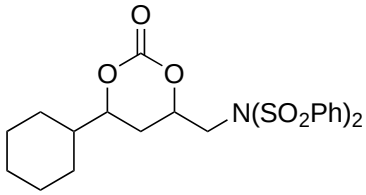


6-phenyl-1,4-bis(benzenesulfonimido)hexan-2-yl 4-methoxybenzoate (5ah). Prepared according to Standard Conditions B and purified by silica gel chromatography (25% ethyl acetate/ 75% hexanes) to yield the product as an off-white resin (102.6 mg, 57% yield, 2.1:1 dr). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.21 – 7.90 (m, 20H, Major+Minor), 7.80 (d, *J* = 7.8 Hz, 2H, Major), 7.69 – 7.31 (m, 22H, Major+Minor), 7.29 – 7.21 (m, 2H, Minor), 7.21 – 7.06 (m, 4H, Major+Minor), 6.97 (d, *J* = 8.0 Hz, 4H, Major), 6.91 (d, *J* = 7.8 Hz, 2H, Minor), 6.75 (d, *J* = 7.0 Hz, 2H, Minor), 5.36 – 5.29 (m, 1H, Minor), 5.29 – 5.18 (m, 1H, Major), 4.36 – 4.25 (m, 1H, Minor), 4.24 – 4.14 (m, 1H, Major), 4.07 (dd, *J* = 15.7, 6.7 Hz, 1H, Major), 3.99 – 3.91 (m, 1H, Minor), 3.91 – 3.83 (m, 7H, Major+Minor), 3.78 – 3.68 (m, 1H, Minor), 2.64 – 2.52 (m, 1H, Major), 2.43 – 2.32 (m,

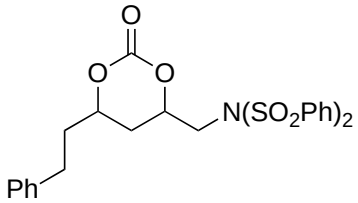
1H, Minor), 2.32 – 2.11 (m, 2H, Major+Minor), 2.11 – 1.97 (m, 4H, Major+Minor), 1.94 – 1.76 (m, 4H, Major+Minor). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.79, 165.55, 163.93, 163.74, 141.50, 141.29, 140.86, 139.49, 139.13, 138.83, 134.16, 134.10, 133.80, 132.27, 132.09, 131.77, 129.47, 129.28, 129.21, 129.17, 129.05, 128.85, 128.61, 128.58, 128.51, 128.44, 128.38, 128.35, 128.33, 128.29, 126.04, 122.15, 121.81, 113.86, 113.78, 77.36, 71.59, 68.88, 61.46, 61.25, 60.48, 55.61, 55.59, 51.04, 50.59, 38.64, 36.28, 34.37, 33.57, 32.86, 21.15, 14.30. **IR (thin film):** 3064, 3026, 2935, 2843, 2360, 2340, 1710, 1605, 1448, 1373, 1355, 1259, 1169, 1084, 1026, 910, 753, 732, 720, 686, 582, 551 cm^{-1}. **MS (ESI, positive mode):** 920.2 $[M+NH_4]$, 925.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{44}H_{42}N_2O_{11}S_4Na^+$ $[M+Na]^+$: 925.1564, Found: 925.1561.



1,3-bis(benzenesulfonimido)propan-2-yl 4-methoxybenzoate (5ai). Prepared according to Standard Conditions B and purified by silica gel chromatography (25% ethyl acetate/ 75% hexanes) to yield the product as a white solid (128.8 mg, 82% yield). **Mp:** 153.7-159.1 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.01 – 7.93 (m, 10H), 7.57 (t, *J* = 7.5 Hz, 4H), 7.45 (t, *J* = 7.9 Hz, 8H), 6.86 (d, *J* = 9.0 Hz, 2H), 5.58 (tt, *J* = 7.3, 4.7 Hz, 1H), 4.21 (dd, *J* = 15.8, 7.3 Hz, 2H), 4.10 (dd, *J* = 15.8, 4.6 Hz, 2H), 3.82 (s, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 165.34, 163.66, 139.08, 134.13, 132.23, 129.20, 128.55, 121.81, 113.65, 69.71, 55.52, 48.96. **IR (thin film):** 3067, 3007, 2936, 2841, 1718, 1605, 1448, 1374, 1259, 1170, 1085, 784, 753, 736, 721, 685, 583, 551 cm^{-1}. **MS (ESI, positive mode):** 802.2 $[M+NH_4]$, 807.4 [M+Na]. **HRMS** (ESI): Calculated for $C_{35}H_{32}N_2O_{11}S_4Na^+$ $[M+Na]^+$: 807.0781, Found: 807.0784.

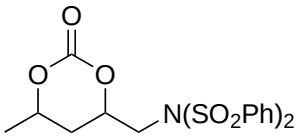


***N*-((6-cyclohexyl-2-oxo-1,3-dioxan-4-yl)methyl)-benzenesulfonimide (7a).** Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as a tan solid (89 mg, 89% yield, 1.16:1 dr). **Mp:** 68.9-72.5 ^{o}C. **^{1}H NMR (500 MHz, CDCl$_3$):** δ 8.06 (d, *J* = 7.8 Hz, 4H, minor), 8.02 (d, *J* = 7.9 Hz, 4H, major), 7.68 (d, *J* = 6.5 Hz, 2H, minor), 7.67 (d *J* = 6.0 Hz, 2H, minor), 7.56 (t, *J* = 7.8 Hz, 8H, major+minor), 4.82 (quin, *J* = 5.9 Hz, 1H, major), 4.78 – 4.66 (m, 1H, ,minor), 4.23 (q, *J* = 6.5 Hz, 1H, major), 4.11 (m, 3H, major+minor), 3.82 – 3.67 (m, 2H, major+minor), 2.09 – 1.91 (m, 4H, major+minor), 1.91 – 1.46 (m, 10H, major+minor), 1.35 – 1.09 (m, 8H, major+minor), 1.09 – 0.91 (m, 4H, major+minor). **^{13}C NMR (126 MHz, CDCl$_3$):** δ 148.36, 148.26, 138.94, 138.86, 134.44, 134.38, 129.32, 129.28, 128.81, 128.72, 82.75, 80.09, 77.36, 77.12, 74.85, 51.62, 50.56, 42.06, 41.54, 28.30, 27.99, 27.84, 27.75, 26.18, 26.11, 25.74, 25.63, 25.55. **IR (thin film):** 3067, 2930, 2854, 2360, 2341, 1749, 1448, 1375, 1169, 735, 721, 686, 582, 550 cm^{-1}. **MS (ESI, positive mode):** 511.3 [M+NH$_4$], 516.2 [M+Na]. **HRMS** (ESI): Calculated for $C_{23}H_{31}N_2O_7S_2^+$ [M+NH$_4$]$^+$: 511.1567, Found: 511.1570.



***N*-((2-oxo-6-phenethyl-1,3-dioxan-4-yl)methyl)-benzenesulfonimide (7b).** Prepared according to Standard Conditions A and purified by silica gel chromatography (25% ethyl acetate/ 75%

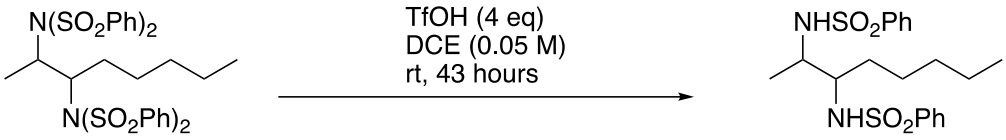
hexanes) to yield the product as a yellow resin (77.9 mg, 76% yield, 1.25:1 dr). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.10 – 7.91 (m, 8H, major+minor), 7.74 – 7.60 (m, 4H, major+minor), 7.55 (t, *J* = 7.6 Hz, 8H, major+minor), 7.38 – 7.14 (m, 10H, major+minor), 4.83 (quin, *J* = 6.1 Hz, 1H, major), 4.78 – 4.69 (m, 1H, minor), 4.54 – 4.44 (m, 1H, major), 4.34 – 4.23 (m, 1H, minor), 4.09 (dd, *J* = 15.8, 6.7 Hz, 2H, major+minor), 3.70 (dt, *J* = 15.6, 6.6 Hz, 2H, major+minor), 2.88 – 2.64 (m, 4H, major+minor), 2.10 – 1.74 (m, 6H, major+minor), 1.70 – 1.54 (m, 2H, major+minor). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 148.04, 147.96, 140.29, 138.73, 134.50, 134.44, 129.35, 129.28, 128.84, 128.73, 128.55, 126.43, 77.46, 77.36, 75.42, 74.55, 51.48, 50.52, 36.86, 36.44, 30.96, 30.61, 30.50, 28.39. **IR (thin film):** 3064, 3027, 2926, 2852, 1749, 1448, 1375, 1355, 1203, 1169, 1130, 1084, 754, 738, 721, 686, 582, 551 cm^{-1}. **MS (ESI, positive mode):** 538.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{25}H_{25}NO_7S_2Na^+$ [M+Na]$^+$: 538.0965, Found: 538.0964.



***N*-((6-methyl-2-oxo-1,3-dioxan-4-yl)methyl)-benzenesulfonimide (7c).** Prepared according to Standard Conditions A and purified by silica gel chromatography (30% ethyl acetate/ 70% hexanes) to yield the product as an off-white solid (77.3 mg, 90% yield, 1.3:1 dr). **Mp:** 58-62.4 ^{o}C. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.04 (d, *J* = 7.4 Hz, 8H, major+minor), 7.67 (t, *J* = 6.7 Hz, 4H, major+minor), 7.56 (t, *J* = 6.1 Hz, 8H, major+minor), 4.90 – 4.82 (m, 1H, major), 4.82 – 4.74 (m, 1H, minor), 4.73 – 4.63 (m, 1H, major), 4.53 – 4.43 (m, 1H, minor), 4.12 (td, *J* = 16.3, 6.8 Hz, 2H, major+minor), 3.73 (td, *J* = 15.6, 5.4 Hz, 2H, major+minor), 2.19 – 2.01 (m, 2H, major+minor), 1.95 – 1.83 (m, 1H, major), 1.59 (m, 1H, minor), 1.36 (d, *J* = 6.2 Hz, 6H, major+minor). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 148.07, 147.96, 138.73, 138.68, 134.48, 134.43,

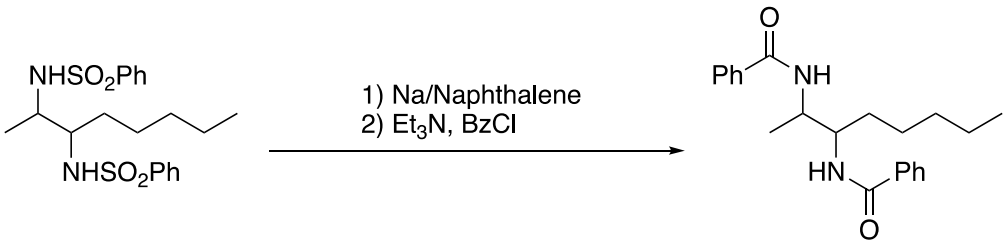
129.32, 129.26, 128.82, 128.72, 77.26, 75.12, 74.36, 72.79, 51.48, 50.63, 32.18, 29.61, 21.19, 20.64. **IR (thin film):** 3067, 2983, 2935, 1750, 1449, 1373, 1355, 1247, 1203, 1170, 1128, 1084, 913, 822, 755, 736, 721, 686, 583, 551 cm^{-1}. **MS (ESI, positive mode):** 488.1 [M+Na]. **HRMS** (ESI): Calculated for $C_{18}H_9NO_7S_2Na$ $[M+Na]^+$: 448.0495, Found: 448.0492.

I. Deprotection of Products



A flame dried round bottom flask equipped with a stir bar and a rubber septum was charged with bis-benzenesulfonimide substrate (956 mg, 1.36 mmol), DCE (34 mL, 0.04 M), and triflic acid (480 uL, 5.43 mmol) at 0 °C under nitrogen. The mixture was stirred at room temperature for 43 hours and then quenched with 15 drops of neat ethylenediamine and subsequently diluted with 1.0 M NaOH aq. solution. The resulting biphasic mixture was extracted with DCM (3x). The combined organic extracts were dried over Na2SO4, filtered, and then concentrated in vacuo. The product was purified via silica gel flash column chromatography (30% pentane/ 70% ether) to yield the product as a yellow resin (496 mg, 86% yield).^{12d} **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.86 (d, *J* = 7.4 Hz, 2H), 7.80 (d, *J* = 7.4 Hz, 2H), 7.64 – 7.56 (m, 2H), 7.56 – 7.44 (m, 4H), 5.40 (d, *J* = 9.0 Hz, 1H), 4.96 (d, *J* = 8.9 Hz, 1H), 3.34 – 3.19 (m, 1H), 3.00 – 2.87 (m, 1H), 1.24 – 1.15 (m, 1H), 1.12 – 1.05 (m, 1H), 1.05 – 0.96 (m, 2H), 0.94 (d, *J* = 6.8 Hz, 3H), 0.93 – 0.74 (m, 4H), 0.72 (t, *J* = 7.3 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 140.84, 140.09, 133.00, 132.74, 129.25, 129.24, 127.38, 127.30, 57.84, 52.33, 31.56, 31.08, 25.25, 22.33, 16.59, 13.93. **IR (thin film):** 3278, 3066, 2955,

2931, 2860, 1586, 1448, 1385, 1325, 1263, 1162, 1092, 1024, 905, 801, 756, 721, 690, 597, 559, 457 cm-1. **MS (ESI, positive mode):** 425.1 [M+1], 447.1 [M+Na].



An oven dried, two-neck flask was charged with naphthalene (621 mg, 4.85 mmol) in THF (12.13 mL, 0.08 M) and cut-up Na (112 mg, 4.85 mmol) was gradually added. The solution quickly turned dark green, and was stirred at room temperature for 4h. The bis-benzenesulfonamide (412 mg, 0.97 mmol) in THF (12.13 mL, 0.08 M) was then added to the above solution via syringe at 0 oC, and the mixture was stirred overnight at room temperature. Water (0.7 mL) was added to quench reaction and the mixture was diluted with EtOAc. The organic layer was dried over $MgSO_4$ and filtered. The organic solution was concentrated and then diluted in DCM (25 mL) and triethylamine (811 uL, 5.82 mmol) and benzoyl chloride (676 uL, 5.82 mmol) were added. The reaction was allowed to stir for 3 hours then water was added. The mixture was extracted DCM (3x). The combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuo. The resulting solid was purified by silica gel flash column chromatography (70% hexane /30% EtOAc) to yield the product as a white solid (209.2 mg, 61% yield).[10e] **Mp:** 228.9-230.8 oC. **1H NMR (500 MHz, $CDCl_3$):** δ 7.98 (d, *J* = 6.1 Hz, 1H), 7.90 (d, *J* = 7.2 Hz, 2H), 7.85 (d, *J* = 7.4 Hz, 2H), 7.53 (M, 2H), 7.49 – 7.43 (m, 4H), 6.51 (d, *J* = 7.5 Hz, 1H), 4.28 (dd, *J* = 11.9, 5.7 Hz, 2H), 1.75 – 1.62 (m, 1H), 1.62 – 1.51 (m, 1H), 1.51 – 1.39 (m, 2H), 1.38 – 1.29 (m, 4H), 1.26 (d, *J* = 6.6 Hz, 3H), 0.88 (t, *J* = 6.7 Hz, 3H). **13C NMR (126 MHz, $CDCl_3$):** δ 169.24, 167.15, 134.58, 132.03, 131.47, 128.92, 128.69, 127.28, 127.19, 55.12, 51.27, 32.45, 31.74, 26.39, 22.64, 15.25,

14.12. **IR (thin film):** 3287, 2954, 2924, 2856, 2360, 1630, 1622, 1532, 1479, 1449, 1336, 1155, 696 cm^{-1}. **MS (ESI, positive mode):** 375.2 [M+Na].

Notes to Chapter 3.

1) Portions of this chapter have been published as Tabor, J. R.; Obenschain, D. C.; Michael, F. E. *Chem. Sci*. **2020**, 11, 1677–1682.
2) Zheng, T.; Tabor, J. R.; Stein, Z. L. Michael, F. E. *Org. Lett.* **2018**, 20. 6975-6978.
3) T. Wirth, in Organoselenium Chemistry: Synthesis and Reactions, Wiley-VCH, Weinheim, 2012.
4) Selenium catalysis review: F. V. Singh and T. Wirth. *Catal. Sci. Technol*. **2019**, 9, 1073–1091.
5) For select examples of selenium catalysis, see: (a) T. Hori and K. B. Sharpless, *J. Org. Chem.*, **1979**, 44, 4204–4208; (b) M. Tiecco, L. Testaferri, M. Tingoli, L. Bagnoli and S. Santi, *J. Am. Chem. Soc*., **1993**, 637–639; (c) T. Wirth, S. Hauptli and M. Leuenberger, *Tetrahedron: Asymmetry*, **1998**, 9, 547– 550; (d) J. A. Tunge and S. R. Mellegaard, *Org. Lett.*, **2004**, 6, 1205–1207; (e) J. Trenner, C. Depken, T. Weber and A. Breder, *Angew. Chem., Int. Ed*., **2013**, 52, 8952–8956; (f) S. E. Denmark, E. Hartmann, D. J. P. Kornfilt and H. Wang, *Nat. Chem.*, **2014**, 6, 1056–1064; (g) Z. Deng, J. Wei, L. Liao, H. Huang and X. Zhao, *Org. Lett*., **2015**, 17, 1834–1837.
6) (a) A. J. Cresswell, S. T.-C. Eey and S. E. Denmark, *Nat. Chem*., **2015**, 7, 146–152; (b) While our diamination paper was under review, a syn-diamination of styrenes using a urea as bidentate nitrogen source was reported: Z. Tao, B. B. Gilbert and S. E. Denmark, *J. Am. Chem. Soc.*, **2019**, 141, 19161–19170.

7) (a) A. Viso, R. Fernandez, A. Garcia and A. Flores, *Chem. Rev*., **2005**, 105, 3167–3196. (b) D. Lucet, T. L. Gall and C. Mioskowski, *Angew. Chem., Int. Ed.*, **1998**, 37, 2580–2627; *Angew. Chem*., **1998**, 110, 2724– 2772;

8) Review: F. Cardona and A. Goti, *Nat. Chem*., **2009**, 1, 269– 275.

9) Select examples: (a) T. P. Zabawa, D. Kasi and S. R. Chemler, *J. Am. Chem. Soc.*, **2005**, 127, 11250–11251; (b) Y. Zhu, R. G. Cornwall, H. Du, B. Zhao and Y. Shi, *Chem. Res*., **2014**, 47, 3665–3678; (c) E. L. Ingalls, P. A. Sibbald, W. Kaminsky and F. E. Michael, *J. Am. Chem. Soc*., **2013**, 135, 8854–8856; (d) J. Streuff, C. H. Hovelmann, A. Nunez and K. Muniz, *Angew. Chem., Int. Ed.*, **2007**, 46, 7125–7127.

10) Fully intermolecular diamination of alkenes: (a) J. A. Souto, Y. Gonzalez, A. Iglesias, D. Zian, A. Lishchynskyi and K. Muniz, *Chem. Asian J.*, **2012**, 7, 1103–1111; (b) C. Martinez and K. Muniz, *Angew. Chem., Int. Ed*., **2012**, 51, 7031–7034; (c) M. W. Danneman, K. B. Hong and J. N. Johnston, *Org. Lett*., **2015**, 17, 2558–2561; (d) K. Muniz, L. Barreiro, R. M. Romero and C. Martinez, *J. Am. Chem. Soc*., **2017**, 139, 4354–4357; (e) S.-S. Weng, K.-Y. Hsieh, Z.-J. Zeng and J.-W. Zhang, *Tetrahedron Lett*., **2017**, 58, 670–673; (f) N. Fu, G. S. Sauer, A. Saha, A. Loo and S. Lin, *Science*, **2017**, 357, 575–579; (g) B. Zhao, W. Yuan, H. Du and Y. Shi, *Org. Lett*., **2007**, 9, 4943–4945.

11) Stereochemistry assigned by analogy to ref. 10a. See experimental for details.

12) (a) P. A. Sibbald and F. E. Michael, *Org. Lett.*, **2009**, 11, 1147– 1149; (b) A. Iglesias, R. Alvarez, R. L. Angel and K. Muniz, *Angew. Chem., Int. Ed*., **2012**, 51, 2225–2228; (c) Y. Okamura, D. Sato, A. Yoshimura, V. V. Zhdankin and A. Saito, *Adv. Synth. Catal*., **2017**, 359, 3243–3247; (d) T. Javorskis and E. Orentas, *J. Org. Chem*., **2017**, 82, 13423– 13439; (e) Fei, J.; Wang, Z.; Cai, Z.; Sun, H.; Cheng, X. *Adv. Synth. Catal.* **2015**, 357, 4063-4068.

13) 1,3-diamino-2-alcohols and 1,4-diamino-2-alcohols: N. T. Ngoc Tam, G. Magueur, M. Ourevitch, B. Crousse, J. P. Begue and D. Bonnet-Delpon, *J. Org. Chem.*, **2005**, 70, 699–702.

14) Chen, X. M.; Ning, X. S.; Kang, Y. B. *Org. Lett*. **2016**, 18, 5368−5371.

15) Ano, T.; Honma, H.; Ebisawa, K.; Hiroya, K.; Shigehisa, H. *Org. Lett*. **2016**, 18, 3622−3625.

16) Pyne, S. G.; Ung, A. T.; Sastraruji, T. *Tetrahedron.* **2012**, 68, 598-602.

17) Hu, K. F.; Ning, X. S.; Qu, J. P.; Kang, Y. B. *J. Org. Chem*. **2018**, 83, 11327−11332.

18) Ma, X.; Dang, H.; Rose, J. A.; Rablen, P.; Herzon, S. B. *J. Am. Chem. Soc*. **2017**, 139, 5998−6007.

19) Guo, W.; Lu, L. Q.; Wang, Y.; Wang, Y. N.; Chen, J. R.; Xiao, W. J. *Angew. Chem. Int. Ed.* **2015**, 54, 2265 –2269.

20) Suzawa, H.; Sugimura, T.; Okuyama, T.; Fujita, M. *Tet. Lett.* **2008**, 49, 3326–3329.

21) Yu, Z.; Eno, M. S.; Annis, A. H.; Morken, J. P. *Org. Lett*. **2015**, 17, 3264−3267.

22) Clive, D. L. J.; Hisaindee, S. *J. Org. Chem*. **2000**, 65, 4923-4929.

23) Allen, D. W.; Nowell, I. W.; Taylor, B. F. *J. Chem. Soc., Dalton Trans.* **1985**, 2505-2508.

24) Mark, V.; Wazer, J. R. V. *J Org. Chem.* **1964**, 29, 1006-1008.

25) Kutt, A.; Rodima, T.; Saame, J.; Raamat, E.; Maemets, V.; Kaljurand, I.; Koppel, I. A.; Garlyauskayte, R. Yu.; Yagupolskii, Y. L.; Yagupolskii, L. M.; Bernhardt, E.; Willner, H.; Leito, I. *J. Org. Chem.* **2011**, 76, 391-395.

26) Kisanga, P. B.; Verkade, J. G. *Tetrahedron*, **2001**, 57, 467-475.

27) Laramay, M. A. H.; Verkade, J. G. *J. Am. Chem. Soc.* **1990**, 112, 9421-9422.

28) Powell, J.; Lough, A.; Raso, M. *J. Chem. Soc. Dalton Trans.* **1994**, 1, 1571-1576.

Bibliography

Akiba, K. y., Chemistry of Hypervalent Compounds; Ed.; WileyVCH: New York, 1999.

Allen, D. W.; Nowell, I. W.; Taylor, B. F. J. Chem. Soc., Dalton Trans. 1985, 2505-2508.

Ano, T.; Honma, H.; Ebisawa, K.; Hiroya, K.; Shigehisa, H. Org. Lett. 2016, 18, 3622−3625.

Aragoni, M. C.; Arca, M.; Demartin, F.; Devillanova, F. A.; Garau, A.; Grimaldi, P.; Isaia, F.; Lelj, F.; Lippolis, V.; Verani, G. Eur. J. Inorg. Chem. 2004, 2363−2368.

Armarego, W. L. F.; Chai, C. L. L.; Purification of Laboratory Chemicals, 5th Ed.; Elsevier: Burlington, MA, 2003.

Biffis, A.; Centomo, P.; Zotto, A. D.; Zecca, M. Chem. Rev. 2018, 118, 2249-2295.

Cardona, F.; Goti, A.; Nat. Chem., 2009, 1, 269– 275.

Chen, X. M.; Ning, X. S.; Kang, Y. B. Org. Lett. 2016, 18, 5368−5371.

Choudary, B. M.; Chodari, N. S.; Jyothi, K.; Kantam, M. L. J. Am. Chem. Soc., 2002, 124, 5341-5349.

Clive, D. L. J.; Hisaindee, S. J. Org. Chem. 2000, 65, 4923-4929.

Cochran, B. M.; Michael, F. E. Org. Lett. 2008, 10, 5093-5042.

Cresswell, A. J.; Eey, S. T. C.; Denmark, S. E. Nat. Chem. 2015, 7, 146-152.

Danneman, M. W.; Hong, K. B.; Johnston, J. N.; Org. Lett., 2015, 17, 2558–2561.

Deng, Z.; Wei, J.; Liao, L.; Huang, H.; Zhao, X. Org. Lett. 2015, 17, 1834–1837.

Denmark, S. E.; Hartmann, E.; Kornfilt, D. J. P.; Wang, H. Nat. Chem. 2014, 6, 1056–1064.

Denney, D. B.; Tunkel, N. Chem. Ind. 1959, 1383.

Dong, X.; Sang, R.; Wang, Q.; Tang, X. Y.; Shi. M.; Chem. Eur. J. 2013, 19, 16910 – 16915.

Durrant, M. C. Chem. Sci. 2015, 6, 6614-6623.

Efe, C.; Lykakis, I. N.; Stratakis, M.; Chem. Commun. 2011, 47, 803-805.

Fei, J.; Wang, Z.; Cai, Z.; Sun, H.; Cheng, X. Adv. Synth. Catal. 2015, 357, 4063-4068.

Foster, D. G. Recl. Trav. Chim. Pays-Bas, 1935, 54, 447.

Fu, N.; Sauer, G. S.; Saha, A.; Loo, A.; Lin, S.; Science, 2017, 357, 575–579.

Garg, K.; Majumder, C.; Gupta, S. K.; Aswal, D. K.; Nayak, S. K.; Chattopadhyay, S.; Chem. Sci. 2016, 7, 1548-1557.

Ghosh, R.; Lindstedt, E.; Jalalian, N.; Olofsson, B. ChemistryOpen, 2014, 3, 54-57.

Giles, G. I.; Fry, F. H.; Tasker, K. M.; Holme, A. L.; Peers, C.; Green, K. N.; Klotz, L. O.; Sies, H.; Jacob, C. Org. Biomol. Chem. 2003, 1, 4317–4322.

Godfrey, S. M.; Jackson, S. L.; McAuliffe, C. A.; Pritchard, R. G. J. Chem. Soc., Dalton Trans. 1998, 4201−4204.

Grandclaudon, C.; Ruamps, M.; Duboc, R.; Michelet, V.; Toullec, P. Y. Synlett, 2018, 29, 1181-1186.

Guo, W.; Lu, L. Q.; Wang, Y.; Wang, Y. N.; Chen, J. R.; Xiao, W. J. Angew. Chem. Int. Ed. 2015, 54, 2265 –2269.

Hili, R.; Yudin, A. K. Nature Chemical Biology, 2006, 2, 284–287.

Hori, T.; Sharpless, K. B. J. Org. Chem. 1979, 44, 4204–4208.

Hu, K. F.; Ning, X. S.; Qu, J. P.; Kang, Y. B. J. Org. Chem. 2018, 83, 11327−11332.

Iglesias, A.; Alvarez R.; Angel, R. L.; Muniz, K Angew. Chem., Int. Ed., 2012, 51, 2225–2228.

Ingalls, E. L.; Sibbald, P. A.; Kaminsky, W.; Michael, F. E.; J. Am. Chem. Soc., 2013, 135, 8854–8856.

Javorskis, T.; Orentas, E.; J. Org. Chem., 2017, 82, 13423– 13439.

Jensen, W. B.; J. Chem. Educ., 2006, 83, 1751–1752.

Kaupp, M.; Metz, B.; Stoll, H. Angew. Chem. Int. Ed. 2000, 39, 4607-4609.

Kisanga, P. B.; Verkade, J. G. Tetrahedron, 2001, 57, 467-475.

Knight, F. R.; Fuller, A. L.; Buhl, M.; Slawin, A. M. Z.; Woollins, J. D. Inorg. Chem. 2010, 49, 7577-7596.

Kumar, A; Bhakuni, B. S.; Prasad, C. D.; Kumar, S. Kumar, S. Tetrahedron. 2013, 69 5383-5392

Kutt, A.; Rodima, T.; Saame, J.; Raamat, E.; Maemets, V.; Kaljurand, I.; Koppel, I. A.; Garlyauskayte, R. Yu.; Yagupolskii, Y. L.; Yagupolskii, L. M.; Bernhardt, E.; Willner, H.; Leito, I. J. Org. Chem. 2011, 76, 391-395.

Kwart, L. D.; Horgan, A. G.; Kwart, H. J. Am. Chem. Soc. 1981, 103, 1232−1234.

Laramay, M. A. H.; Verkade, J. G. J. Am. Chem. Soc. 1990, 112, 9421-9422.

Lee, J. H.; Choi, S.; Hong, K. B. Molecules 2019, 24, 2634-2657.

Lin, J.; Hu, Ming.; Li, J. H. Chem. Rec. 2019, 19, 440–451.

Liu, G.; Yin, G.; Wu, L.; Angew. Chem., Int. Ed. 2008, 47, 4733−4736.

Lovick, H. M.; Michael, F. E. J. Am. Chem. Soc. 2010, 132, 1249-1251.

Lucet, D.; Gall, T. L.; Mioskowski, C.; Angew. Chem., Int. Ed., 1998, 37, 2580–2627; Angew. Chem., 1998, 110, 2724– 2772;

Ludwig, J. R.; Schindler, C. S. Chem, 2017, 2, 331-316.

Ma, X.; Dang, H.; Rose, J. A.; Rablen, P.; Herzon, S. B. J. Am. Chem. Soc. 2017, 139, 5998−6007.

Marino, J. P.; Larsen, R. D. J. Am. Chem. Soc. 1981, 103, 4642-4643.

Mark, V.; Wazer, J. R. V. J Org. Chem. 1964, 29, 1006-1008.

Martinez, C.; Muniz, K.; Angew. Chem., Int. Ed., 2012, 51, 7031–7034.

Merrigan, S. R.; Singleton, D. A. Org. Lett. 1999, 1, 327−329.

Michael, F. E.; Sibbald, P. A.; Cochran, B. M. Org. Lett. 2008, 10, 793-796.

Mizuta, S.; Verhoog, S.; Engle, K. M.; Khotavivattana, T.; O'Duill, M.; Wheelhouse, K.; Rassias, G.; Medebielle, M.; Gouverneur, V.; J. Am. Chem. Soc. 2013, 135, 2505-2508.

Muniz, K.; Barreiro, L.; Romero, R. M.; Martinez, C.; J. Am. Chem. Soc., 2017, 139, 4354–4357.

Nelson, D. J.; Collado, A.; Manzini, S.; Meiries, S.; Slawin, A. M. Z.; Cordes, D. B.; Nolan, S. P. Organometallics, 2014, 33, 2048-2058.

Ngoc Tam, N. T.;, Magueur, G.; Ourevitch, M.; Crousse, B.; Begue, J. P.; Bonnet-Delpon, D.; J. Org. Chem., 2005, 70, 699–702.

Nicolaou, K. C.; Koumbis, A. E.; Snyder, S. A.; Simonsen, K. B. Angew. Chem. Int. Ed. 2000, 39, 2529-2533.

Okamoto, Y.; Chellappa, K. L.; Homsany, R. J. Org. Chem. 1973, 88, 3172-3175.

Okamoto, Y.; Homsany, R. Yano, T. Tet. Lett. 1972, 25, 2529-2531.

Okamura, Y.; Sato, D.; Yoshimura, A.; Zhdankin, V. V.; Saito, A.; Adv. Synth. Catal., 2017, 359, 3243–3247.

Org. Synth. 1979, 59, 141

Pomeranz, U. K.; Schmid, H.; Hanse, H. J.; Helvetica Chimica Acta. 1977, 60, 768-797

Powell, J.; Lough, A.; Raso, M. J. Chem. Soc. Dalton Trans. 1994, 1, 1571-1576.

Punniyamurthy, T.; Velusamy, S.; Iqbal, J. Chem. Rev. 2005, 105, 2329−2363.

Pyne, S. G.; Ung, A. T.; Sastraruji, T. Tetrahedron. 2012, 68, 598-602.

Rat, C. I.; Silvestru, C.; Breunig, H. J. Coord. Chem. Rev. 2013, 257, 818-879.

Reich, H. J.; Hondal, R. J. ACS Chem. Biol. 2016, 11, 821−841

Reid, W. B.; Spillane, J. J.; Krause, S. B.; Watson, D. A.; J. Am. Chem. Soc. 2016, 138, 5539-5542.

Rogers, M. M.; Kotov, V.; Chatwichien, J.; Stahl, S. S.; Org. Lett. 2007, 9, 4331−4334.

Rosewall, C. F.; Sibbald, P. A.; Liskin, D. V.; Michael, F. E. J. Am. Chem. Soc. 2009, 131, 9488-9489.

Seayad, J.; Seayad, A. M.; Chai, C. L. L. Org. Lett. 2010, 12, 1412-1415.

Shuler, S. A.; Guoyin, Y.; Krause, S. B.; Vesper, C. M.; Watson, D. A.; J. Am. Chem. Soc. 2016, 138, 13830−13833.

Sibbald, P. A.; Michael, F. E. Org. Lett. 2009, 11, 1147-1149.

Sibbald, P. A.; Rosewall, C. F.; Swartz, R. D.; Michael, F. E. J. Am. Chem. Soc. 2009, 131, 15945-15951.

Singh, F. V.; Wirth, T. Catal. Sci. Technol. 2019, 9, 1073–1091.

Souto, J. A.; Gonzalez, Y.; Iglesias, A.; Zian, D.; Lishchynskyi, A.; Muniz, K.; Chem. Asian J., 2012, 7, 1103–1111.

Streuff, J.; Hovelmann, C. H.; Nunez, A.; Muniz, K.; Angew. Chem., Int. Ed., 2007, 46, 7125–7127.

Suzawa, H.; Sugimura, T.; Okuyama, T.; Fujita, M. Tet. Lett. 2008, 49, 3326–3329.

Tabor, J. R.; Obenschain, D. C.; Michael, F. E. Chem. Sci. 2020, 11, 1677–1682.

Tao, Z.; Gilbert, B. B.; Denmark, S. E.; J. Am. Chem. Soc., 2019, 141, 19161–19170.

Tellitu, I.; Dominguez, E. Tetrahedron. 2008, 64, 2465-2470.

Tian, F.; Chen, Y.; Wu, L.; Li, P.; Lu, S. J. Chem. Res. 2014, 38, 375-377.

Tiecco, M.; Testaferri, L.; Tingoli, M.; Bagnoli, L.; Santi, S. J. Am. Chem. Soc. 1993, 637–639.

Tiedemann, M. A.; Mandell, C. L.; Chan, B. C.; Nataro, C. Inorganica Chimica Acta, 2014, 422, 193-201.

Togni, A., Grutzmacher, H., Eds. Catalytic Heterofunctionalization; Wiley-VCH: Weinheim, 2001.

Trenner, J.; Depken, C.; Weber, T.; Breder, A. Angew. Chem., Int. Ed. 2013, 52, 8952–8956.

Tsugio.; Miyake, A.; Muta, K.; Oyamada, J. J. Org. Chem. 2017, 82, 11721-11726.

Tunge, J. A.; Mellegaard, S. R. ; Org. Lett., 2004, 6, 1205–1207.

Viso, A.; Fernandez, R.; Garcia, A.; Flores, A.; Chem. Rev., 2005, 105, 3167–3196.

Wang, D.; Wu, L.; Wang, F.; Wan, X.; Chen, P.; Lin, Z.; Liu, G. J. Am. Chem. Soc. 2017, 139, 6811-6814.

Wang, J.; Li, F.; Pei, W.; Yang, M.; Wu, Y.; Ma, D.; Zhang, F.; Wang, J.; Tetrahedron Lett. 2018, 59, 1902-1905.

Wang, L.; Wang, M.; Huang, F. Synlett. 2005, 13, 2007–2010

Weng, S.-S.; Hsieh, K.-Y.; Zeng, Z.-J.; Zhang, J.-W.; Tetrahedron Lett., 2017, 58, 670–673.

Wirth, T. in Organoselenium Chemistry: Synthesis and Reactions, Wiley-VCH, Weinheim, 2012.

Wirth, T.; Hauptli, S.; Leuenberger, M. Tetrahedron: Asymmetry, 1998, 9, 547– 550.

Yang, G.; Zhang, W.; Org. Lett. 2012, 14, 268-271.

Yoshimura, A.; Zhdankin, V. V.Chem. Rev. 2016, 116, 3328−3435.

Young, M. W.; Lauer, R. F.; Sharpless, K. B. Tet. Lett. 1973, 22, 1979-1982.

Yu, Z.; Eno, M. S.; Annis, A. H.; Morken, J. P. Org. Lett. 2015, 17, 3264−3267.

Zabawa, T. P.; Kasi, D.; Chemler, S. R.; J. Am. Chem. Soc., 2005, 127, 11250–11251.

Zhang, K.; Liu, J. B.; Qing, F. L.; Chem. Commun. 2014, 50, 14157-14160.

Zhao, B.; Yuan, W.; Du, H.; Shi, Y.; Org. Lett., 2007, 9, 4943–4945.

Zheng, T.; Tabor, J. R.; Stein, Z. L. Michael, F. E. Org. Lett. 2018, 20, 6975-6978.

Zhou, Q. L. Angew. Chem. Int. Ed. 2016, 55, 5352-5353.

Zhu, L.; Wang, L.; Li, B.; Fu, B.; Zhang, C.; W. Li. Chem. Commun. 2016, 52, 6371-6374

Zhu, Y.; Cornwall, R. G.; Du, H.; Zhao, B.; Shi, Y.; Chem. Res., 2014, 47, 3665–3678.

Vita

John R. Tabor was born and raised in Houston, TX. He earned his Bachelor of Science from The University of Texas at Austin, majoring in chemistry in 2010. Immediately after graduating from UT, he attended graduate school at the University of Washington where he worked in Dr. Forrest Michael's synthetic chemistry laboratory. In 2020 he earned a Doctor of Philosophy degree in Chemistry from the University of Washington.