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Tell all the Truth but tell it Slant: The Essential Role of Metaphor in Constructing Physics

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The Essential Role of Metaphor in Constructing Physics

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—Emily Dickinson

If Science is the pursuit of truth, what does it mean to tell that truth slant? What if success only lies in the circuit around reality? Perhaps we are all children in this universe and we must learn the truth slowly, must grab at it in pieces, must learn how to build an elephant from just its ear. Perhaps every one of us is blind but in different ways and our strength is when we gather together.

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I. Introduction

I call myself the Cross Country Physicist Poet. I am a long-distance cross country runner and I am double majoring in Physics and English. I do physics and I write poetry and the line between those two is most days nonexistent.

I reach up and grab moonlight, and definite integrals, and Lorentz transformations, and mountains and rivers of words, and I spin them together in a cosmic rinse cycle all in the name of reducing life to something that can be studied. The space inside my head is small. I bump elbows with Emily Dickinson, Maxwell's equations, and the strange gray matter where literature and physics have mixed. This space does not look quite like anyone else's and I have learned to embrace that. I get to see the world with both math and metaphor. It turns out the two are not really separate.

I came to physics through a book. When I was 16 I read *A Wrinkle in Time* by Madeline L'Engle and I decided that I wanted to become an astronomer. The idea of a world beyond our own simultaneously enthralled and terrified me. It was like I was 7 years old again and reading books about our solar system. The pictures of all the planets scared me, but I could not stop looking at them. Perhaps I wanted to escape this world. Perhaps I wanted to be able to hold the universe in my hands. Perhaps I did not yet understand that neither is possible. What is possible is holding curiosity in my hands and every day choosing to enter more fully into this world. Imagination, curiosity, and conversation are all possible. They are also all necessary.

So I write poetry. It is how I piece together the world and myself. I write about hands, cars on fire, mysterious pronouns, dropping a brain, galaxies colliding, light's finite speed, temperature, micro-states, the cosmic microwave background, and the mountains. I am an astronomer and a poet. I am someone who uses scientific laws, math, and rational thought to describe the universe. I am also someone who compares galaxy collisions to human relationships in order to make sense of both cosmological and human extreme phenomena. I sometimes write poetry while sitting in physics classes. Sometimes it is to keep myself awake. But most times it is because there is something about listening to a lecture on partition functions and micro-states that sparks the poetry-writing part of my brain. So, in between working problems and scribbling down derivations and conceptual questions, I write. In fact, other than the space of intense emotional need, it is one of the only spaces in which I write. The world is ripe for imagination, and the act of intensely learning about very real aspects of the world within the language of reason and math makes my head spin with metaphor. Perhaps it is because whenever we talk about anything in the sciences, we inevitably are talking in metaphors. We naturally, in fact we have to, talk about things we cannot touch in terms of things that we can.

I am a poet. Of course I work in metaphor. I am an astronomer. Of course I work in metaphor. Math teaches us that if $a = b$ and $c = b$ then $a = c$. If poets work in metaphor and scientists work in metaphor, then how can they be diametrically opposed? How can they even be partially opposed? We all use language to try to understand and describe the world around us. For the scientists, that language is first math, and then the familiar realm of words in an attempt to transfer the math to something that we can better understand. When I was in an introductory astrophysics class I learned that when galaxies collide, their stars do not also collide. To wrap my head around this I wrote a poem about it. When I learned that stars can form from a cloud of gas that collapses when a sound wave passes through it, I wrote a poem. I am always writing in an attempt to make sense of what I am learning. I turn physical phenomena into metaphor to help me better understand the world in which I live. I also turn words into metaphor to help me understand the physics I learn in the classroom. It is a double edged sword.

Double majoring in physics and English automatically makes me the weird one in almost every room. Except, perhaps, in a room of academics. They each seem to have their own flavor of weird. Whenever I tell someone my combination of majors, they take a moment to process what I said because whatever their stock reply was, it does not work with me. Finally they say something along the lines of "wow that sounds hard but it probably balances you out. You must be really smart!" I never know what to say so I fumble a reply about how it is fun and keeps me busy. What I mean is that I am not smarter than anyone else. This particular major combo is not that hard. It is a lot of time, but it is not fundamentally harder than what anyone else is doing. I am not particularly weird. I am just particularly stubborn.

Everyone can do English. Everyone can do physics. There is some level of talent involved but determination, curiosity and desire are far more important. Doing the two of them together requires a certain level of stubborn focus but not a certain level of genius. In fact, I think doing them together makes me better at each. Half of the battle with science is communication. You have to convince yourself, your colleagues, and your funding agency that what you want to do is worthwhile. You have to figure out how to turn your results into a plot or a figure that explains the science and then you have to be able to explain that result in words that people can understand. Words. The favorite tool of the English majors. They are the ones who force us to learn about metaphor in middle school and they are the ones who continue to teach us to recognize the ways metaphor operates in our everyday life. They are the ones who can teach us to better wield our metaphors so that we can do even better science.

I am an astronomer. I am a physicist. I am a poet. I am a woman. I am a runner. I see the world through the lens of Emily Dickinson, the Heisenberg uncertainty principle, William Faulkner, and the cosmic microwave background. It all mixes in my head and I do not believe trying to separate it is worthwhile or useful. My particular biases and neural matter allow me to approach a problem differently than anyone else. This is good and useful. I should not have to shut off half of my brain in order to enter into an astronomy career. I should not have to pretend like I do not write poems about my research. Because I do and it will not stop just because I enter graduate school or get a fellowship or am offered a faculty job. In fact, I think that scribbling poems will let me see questions from new perspectives and will be a part of what makes me a successful scientist.

Science is messy. Academia is messy. English is messy. Poetry is messy. Running marathons is messy. Humans are messy and we all bring a kaleidoscope of experience and interests to whatever we do. A physicist is someone who does physics. Full stop. As long as their results are believable and supported they are doing physics. Whatever else they do is not what makes them a physicist. It is what makes them human.

I believe in interdisciplinary scholarship. That is a large part of why I chose to major in English and Physics. It is a way to create an interdisciplinary conversation inside my own head. I believe in the importance of starting those conversations in the real world. I believe that the way into those conversations is by way of metaphor. Most of our world is constructed from metaphor and it is in harnessing our words that we can begin to move forward in discovery. To do this we need wisdom from the humanities and the sciences. In this thesis I look at metaphor in physics as a way to argue for interdisciplinary conversation and collaboration across the science/humanities divide. This includes synthesis of research on metaphor and its implications for physics, being a physicist, communicating as a physicist, and educating in physics.

II. All is Metaphor: Conceptual Metaphor in Physics

Black holes might be the best metaphor we have and maybe that is why I want to study them.

…

You cannot speak without tripping over a metaphor. Metaphor is not merely the icing on the cake in the hands of poets; rather, metaphor makes up the foundation of our cognition. George Lakoff claims that "the essence of metaphor is understanding and experiencing one kind of thing in terms of another" (Lakoff 5). Most of us can agree that metaphor shapes our understanding. However, Lakoff takes it further and claims that metaphorical understanding shapes our experience, and in fact is inseparable from our experience.

But what is metaphor? Firstly, metaphor is not analogy. An analogy says that something is like something else in order to make an explanatory point. A cliche example is "life is like a race." This analogy tells us that life is like a race. It implies that there is a finish line, and that it will take hard work to reach the finish, but if you keep moving forward you will get there eventually. This analogy likens certain aspects of a race to certain aspects of life in order to better explain the experience of moving through life. On the other hand, a metaphor says that something is something else. When we say "life is a race" we are no longer examining certain aspects of life and racing. We are taking the experience of life and mapping it onto the experience of a race, letting all the overlap explain the abstract experience of life.

The metaphor “life is a race” has become so common that it is a cliche and we do not consciously think of it as a metaphor that helps us to better understand the experience of life. Rather, it has wormed its way so deeply into our consciousness that we say things like “I just need to get past this hurdle and then things will settle down,” perhaps in regards to a work deadline. This statement is connected to the “life is a race metaphor.” Hurdles are literally objects one encounters in a track race, and more broadly are any difficulty encountered in a journey, such as a race. We think of life as a physical space to move through, with a specific path, rules, and finish line. We think of life as a race and that affects how we describe the process of living.

In other words, we have mapped the domain of life onto the domain of races. Zoltan Kövecses in the chapter of the book, *Routledge Handbook of Metaphor,* titled, “Conceptual metaphor theory,” states that “a conceptual metaphor is a systematic set of correspondences between two domains of experience” (Kövecses 2017). This definition makes clear that metaphor is not merely a stylistic technique for writers of prose and poetry. Rather, metaphor is cognitive process by which we furnish cognitive correspondences between different events, objects, and experiences.

Lakoff takes this to its logical conclusion and claims that if metaphor is primarily a result of our cognitive processing, then our language is necessarily metaphorically structured. “The concept is metaphorically structured, the activity is metaphorically structured, and consequently, the language is metaphorically structured” (Lakoff 5). In other words, we have so few absolutely direct experiences that we must conceptualize things in terms of others in order to determine and make meaning of our experiences. Even phrases of speech that seem natural are metaphorical in nature.

We often think of metaphors as clever or creative turns of speech that liken two unlike things in order to make a point. Or we think of them as a mode of style in casual or creative writing. Which they are. Metaphors are usually thought of in terms of literary disciplines or as weapons in the hands of poets. They are indeed linguistic expressions that are used to stretch language in new ways. But they are also more than that. They are one of the foundational building blocks with with we conceptualize and understand our world. "Metaphors as linguistic expressions are possible precisely because there are metaphors in a person's conceptual system" (Lakoff 6). A metaphor is likening one thing to another, saying that one thing is something else. When you say "life is a rollercoaster" you are not saying that life is like a rollercoaster and then explaining the ways in which they are similar. No, you are saying that life is fundamentally a rollercoaster, and that shapes our understanding of the concept of life. This is an example of a non-fundamental metaphor. It does not live underneath our consciousness and as such it affects the way we move through life.

Conceptual metaphors, on the other hand, do live underneath our consciousness. They are subtle and often go unnoticed. For instance, Lakoff uses the fact that we have a concept of argument and we have a conceptual metaphor "argument is war." This metaphor comes out in a variety of phrases including, "your claims are indefensible," "He shot down my argument," and "his criticisms were right on target" (Lakoff 4). It is clear that we have this general conceptualization of argument as a battle to be won, or more specifically, a war. This necessarily structures how we view arguments. Our response to a conversation that devolves into argument will be one of anticipation, fear, and adrenaline—much like the response of a soldier on a battlefield. We actually see argument as a type of war: it is something we can win, the other person is our opponent, we can gain and lose ground, and we attack the other person's viewpoint. Imagine if we thought of arguing without the Argument is War metaphor and instead think about it as a collaborative dance between two people. The participants would be performers interested in creating a collaborative piece of art. An argument would inspire feelings of excitement, preparedness, and a sense of listening and responding to the other argument "performer." Not the adrenaline and dread that comes from the Argument as War metaphor. In fact, our culture, which is so used to experiencing and understanding arguments as wars, would view a culture as arguing like a dance to be doing something entirely foreign. Our metaphor of Argument is War shapes our collective understanding and action in subtle ways from the moment we are born.

If something as benign and fundamental to the human experience as arguing is necessarily conceptualized and understood in metaphor, is there anything that is not? We can think of metaphors as having experiential bases—or in other words, a base in something that is physically and universally experienced. Think of the way we think of happiness. When someone is happy their spirits are high. They feel upbeat. When someone is sad, they are down. They have sunk into depression. In other words, the state of happiness is up. The idea of "up" as the state of happiness is an example of an orientation metaphor. Orientation metaphors, such as up down, in out, forward back, are fundamental metaphors because they are based on physical experiences. The up down metaphor was born because humans are oriented in an up down matter. Happy people tend to stand erect and sad people tend to slump or lie down, and so the happy is up metaphor was born. Thus we can say that metaphors do depend on reality, and in fact are deeply informed by our universal experiential reality. Lakoff claims that "no metaphor can ever be comprehended or even adequately represented independently of its experiential base" (Lakoff

19). In order for a metaphor to make any sense, one of the things being compared must be able to be directly experienced. Or there must be layers of metaphor that are rooted in a experiential basis. Otherwise we are just blowing smoke.

If our language is fundamentally metaphorical in nature, and our conceptual understanding of anything other than our physical orientation and presence in the world is through metaphor, then science is necessarily metaphorically understood. This is especially true in physics, the most mathematical and abstract of the sciences. Whether we want to admit it or not, our understanding of physics is necessarily based on metaphors. Because of this, the metaphors that we unconsciously use when describing and understanding physics, shape our perception of the phenomena, and thus our process of research and conclusions that we draw from that research. In fact, it is shifts in metaphor that can be most powerful in reframing physics study and allow researchers to reach beyond current understanding. In addition, the metaphors used in describing and communicating physics affect how the public perceives the universe and their place in it. Which in turn affects future physicists and thus these patterns get engrained. One example of this is the shift from a geocentric to a heliocentric model. We can think of both models as a sort of container metaphor. The universe is a container, and that container is oriented around some center and has some depth and some surface. With the geocentric model, the earth is the center and everything else lives on the surface. The heliocentric model however, puts the sun at the center and the earth on the surface. In both cases the fundamental metaphor remains the sense: the universe is a container. We see this metaphor when we say that we are a “part” of the universe. Or when we talk about traveling “through” the universe. The universe contains the galaxies, the intergalactic medium, and all the dark matter. We understand the universe as a container which means we necessarily understand it as the thing which holds all else, as something with an inside, and an outside and within which can exist other containers and systems. Our view from within this container is thus highly dependent on how our earth is oriented in and on the container.

The use of metaphor in science is widespread and necessary. Especially in the realm of modern science and its increasing abstractness, metaphor is used to help scientists and non-scientists alike understand things such as light, energy, and the expansion of the universe. We use metaphors in our science classrooms, in our conversations with other scientists, in our conversations with non-scientists, and in our papers on our scientific research. They are inescapable.

We must make the distinction between analogy and metaphor clear when talking about science, in order to deconstruct our idea that the role of metaphor in science is only a pedagogical one, whereas metaphor really is an essential tool for conceptualizing science. For example, when we tell General Physics students that quantum energy levels are like stairs in that you can only stand on the first or second stair, not the one-and-a-half stair, that is an analogy. This comparison between stairs and energy levels is in order to explain something about the nature of quantum energy levels that could not be explained without a comparison to something tangible. On the other hand, a metaphor says that something is something else. When we say that the the possible energy states of electrons in an atom are energy levels, this is a metaphor. Specifically it is a substance metaphor. In using the word "levels" we say that the atomic electron energy states are physical "levels." In other words, we use metaphorical language to allow us to think about the atom which lives in wave space in terms of our three dimensions. Both analogy and metaphor are necessary for scientific discussion and education, but the one that is more unconscious and thus perhaps worth exploring and explicitly focusing on, is metaphor.

One place where we see the use of metaphor in physics to teach, understand, and conceptualize an abstract reality is in the study of energy. Benedikt W. Harrer in his article, “On the origin of energy: Metaphors and manifestations as resources for conceptualizing and measuring the invisible, imponderable,” examines the development of the conceptual and mathematical understanding of energy, and how metaphors deeply informed and allowed that understanding to unfold. “In particular, the use of substance metaphors has permeated the history of the developing energy concept. Planck, for example, pointed out that drawing analogical parallels between energy and matter was helpful in establishing acceptance of the energy concept among scientists of the 19th century. He also strongly suggested that a substance-like conception of energy, in addition to adding clarity to the abstract concept, would inspire progress in the development of energy theory that goes beyond mere quantitative considerations. Such a theory of energy, Planck argued, would allow scientists to not only know the number that represents a quantity of energy but also enable them to identify the existence of energy within a system and trace it across system boundaries” (Harrer 2017). Harrer claims that the use of substance metaphors—metaphoric language that directly compares energy to matter—were critical to the development of the theory of energy. The concept of energy was born out of early 19th century physicists attempting to explain the interconnections between forces, motion, and heat. The scientists knew that objects in motion had some property which they called vis viva—the “living force.” They quantified this property as “mass times velocity squared” after much debate. This vis viva property seemed to be conserved in most cases, but there were time it was not which befuddled the physicists. At first they called the vis viva property a force, just as they called Newtonian forces. This created much ambiguity as the physicists tried to debate and conceptualize this mysterious property. Experimentation to determine the general law of energy conservation was proposed in 1840 by Joule, Colding, Mayer, and Helmholtz. A few years later, Hermann von Helmholtz derived a version of our modern energy conservation law through a philosophical argument that assumed that a) perpetual motion is impossible and b) all effects in nature are caused by central Newtonian forces. Following these two assumptions, Hemholtz concluded that the quantitative properties of forces (i.e. what we now call energy) are conserved. He still did not understand the nature of this strange force, though he gave it a name, “Arbeitskraft,” which literally translates to “work force.” This name tried to get at the essence of the mysterious energy force, by describing its ability to perform mechanical work, as understood in physics. Half a century later, still no scientist had pinned down a definition of energy. We knew it existed. Our experiments indicated that it was conserved. But we could not touch it, and thus we could not explain it. Enter, metaphor.

In attempting to define the mysterious “work force” that we know as energy, physicists had to spin narratives about reality. The experiments indicated that there was another layer to the world of Newtonian forces that we understood. There was this other layer that interacted with and was informed by the forces, but was not directly accessible like they were. They needed language with which to fish for the answers, language to begin to discuss, and thus define, this thing. We had the math, we knew how to quantify energy, we just needed a way to qualitatively describe it.

The series of energy metaphors began with its first name: "work force." Notice that this name is not an analogy, but a metaphor, and specifically a substance metaphor. A substance metaphor is one that represents an abstraction as material and is a common metaphor in physics. The name "work force" states that energy is a force that does work. Not that it is like a force that does work. It links energy with the world of matter. Work is something done to material objects. Therefore energy is now linked with material objects, because it can interact with them. It also says that energy is a force. We now know that this is faulty, but calling energy a force, putting any words on it, no matter how faulty, opened a way into the conversation.

Substance metaphors are rampant when it comes to conceptualizing and explaining energy. Planck claimed that using substance metaphors to explain energy would not only allow scientists to understand the concept of energy, but also allow the theory of energy to evolve beyond only quantitative considerations. For example, we talk about energy being "deposited." Harrer claims that "A Google Scholar search for scientific articles published since 2011 in physics journals that contain the phrase "deposited energy" yields about 1800 results" (Harrer 2017). The word choice "deposited" can only apply to something physical. Specifically, in this context, it refers to something that can be transferred, which must be something that can occupy different spaces and also be localized. In other words, something of a physical nature. Scientists recognize energy as an abstract numerical concept. But they also recognize it as something physical, as evidenced by their description of energy as "deposited." In fact, they have to use a substance metaphor to describe their work in order to convey a narrative beyond the numerical data and results. By saying that the energy is deposited, the scientists give their readers something to hang on to, some context in which to put their results. It invokes comparisons—

some helpful, some not—to the workings of the material world with which we directly interact. Through these comparisons, both the helpful and the unhelpful, the understanding of energy expands beyond what it could if energy was strictly thought about as a numerical abstraction.

Alan Lightman, the first person to receive a joint appointment at MIT in science and the humanities, is perhaps the figure to most explicitly demonstrate the interaction of science and the humanities. He has worked as a professor at Harvard and MIT, as a postdoctoral fellow at Cornell, and as a research scientist at the Harvard-Smithsonian Center for Astrophysics. He has also written a novels, book of poetry, and many articles about science and its interaction with other disciplines and ways of being. His writing is as acclaimed as his scientific work. Lightman wrote an article addressing physicists' use of metaphor published in Science in 2002. The article is titled "Magic on the Mind: Physicists' Use of Metaphor." Lightman begins the article with a story about when he was in a cosmology class and the professor was trying to conceptually explain the expansion of the universe. The students could work the math to describe the universe expansion, but they could not conceptually understand it. That is, until the professor told the students to think about blowing up a balloon and how each point on the balloon expands away from every other point. Lightman uses this example to point out the necessity of metaphor in both explaining and conceptualizing science. He claims that "metaphor is critical to science. Metaphor in science serves not just as a pedagogical device, like the cosmos balloon, but also as an aid to scientific discovery" (Lightman 2002). In other words, we do not just need metaphors to help students understand physics concepts, but also to aid scientists in their research. The process of describing something in a new way, using new words, opens up new possibilities for that thing and the way in exists in and interacts with the world. When the expansion of the universe becomes like an inflating balloon, suddenly the students have a space of understanding within which they can explore and ask questions of their own.

Someone who is relatively literate in the field of physics can see that there are deliberate metaphors used to describe various phenomena. As previously mentioned, a common one is “quantum energy levels are like stairs. You cannot be halfway between stair one and stair two.” This metaphor is deliberately used to illustrate something about the nature of quantized energy. The fact that metaphors are uses deliberately leads us to the conclusion that they are also used non-deliberately. While deliberate metaphors are useful for teaching and initial conceptual understanding, non-deliberate metaphors (or as we have referred to them before, conceptual metaphors) are markers of growing expertise in physics understanding. Gerard Steen, in his article “When is Metaphor Deliberate?” explores the question posed in the article title. Deliberate metaphor is “defined by the property that it leaves the addressee no option but to consciously set up a cross-domain mapping” (Steen 2008). In other words, and deliberate metaphor forces the addressee to associate the metaphor with the situation, object, or concept in question. In the example of the quantum energy levels as stairs metaphor, the addressee cannot help but connect stairs to energy levels. This makes it a direct metaphor. An example of an indirect metaphor on the other hand is the concept metaphor of “a mathematical function is a machine.” This metaphor is demonstrated in a phrase such as “when I plug in the numbers I get (fill in the blank with some value).” This metaphor is not necessarily deliberate. Plugging numbers into a function is common language surrounding mathematical metaphors.

But if direct metaphor is what we think of when we think of metaphor in physics, it begs the question: how often is it used and is it used deliberately? Is direct metaphor where we should spend our energy as scientists? Steen claims that “direct metaphor does not occur very frequently...We estimate that direct metaphors accounts for at most one percent of all metaphors in discourse” (Steen 2008). Direct metaphor is obviously very useful in teaching physics. How else are we going to be able to explain things such as energy or gravity? But the metaphor that does the real heft in our language, scientific and other, is indirect metaphor. While direct metaphor leaves the addressee with no choice other than to recognize it as a metaphor, indirect metaphor is much more subtle. It manifests in how we talk about breaking up with a partner as going separate ways (Love is a Journey metaphor) or plugging in values and getting something out of a mathematical function (a Function is a Machine metaphor). In other words, our language functions as a result of indirect metaphor. It allows us to take abstract concepts such as love and conceptualize them in terms of a more accessible spatial concept, such as a journey. It follows that our scientific language also rests heavily on indirect metaphor. We use direct metaphors in the ways described above: in teaching and in describing novel ideas or concepts. However we also use indirect metaphor. We must. We are talking about things we cannot directly touch and so we conceptualize them in terms of things more easily touched.

The question then becomes one of the difference between deliberate and non-deliberate metaphor. Steen phrases this question as “In particular, most metaphor seems to be conventional and automatic and unconscious, but some metaphor clearly is not, so that the question arises: When is metaphor deliberate?” (Steen 2008). It is rather easy to identify direct metaphor and it is reasonable to assume that “one part of the answer to this question is that metaphor is deliberate when it is direct” (Steen 2008). The construction of a simile assumes some deliberateness on the part of the constructor. A physicist explaining conversion between potential and kinetic energy by comparing it to rolling down a hill cannot be mistaken as using anything but a metaphor. They also cannot argue that they have used this metaphor deliberately. On the other hand, a physicist talking about transfer of energy, as all physicists do, is also using a metaphor (Energy is a Substance). However, most people would not recognize this as a metaphor, making it an indirect metaphor. In addition, the person using the Energy is a Substance metaphor most likely does not recognize it as a metaphor, making it a non-deliberate metaphor.

Indirect metaphor can be deliberate however. Steen argues that for a metaphor to be deliberate it "requires some feature which alerts the addressee that it is intended to be realized as a metaphor" (Steen 2008). In terms of scientific communication, this is in one sense useful and in one sense not. In terms of science education, it is important to deliberately use metaphor, both direct

and indirect. Otherwise it is easy for students to get caught up in the metaphor and not understand the underlying concept. Students need to understand that metaphor is used in science, that it is necessary, but that just because we we can use metaphor does not mean that we should get caught up in the metaphor. On the other hand indirect metaphor is useful because it does not necessarily need to indicate that it is a metaphor. Talking about energy as if it is a substance is necessary because otherwise we only have equations with which to speak. But we must recognize that it is a metaphor and that we could have used a wide assortment of metaphors to talk about energy, it just so happens that we historically use substance metaphors. We need metaphors in order to re-think questions in physics. In order to change the metaphors we use we need to recognize those we are already using. But it quickly becomes contrived when we feel as if we have to make every metaphor obvious and recognizable. Physics is the discipline of understanding the untouchable. I cannot touch gravity but I know it pulls me towards the Earth. It interacts with the physical world and so we talk about it as if it is something physical. Students need to understand that gravity is both physical and non-physical, that it pulls us towards the earth and also warps the fabric of spacetime. They need to understand that space is not actually a fabric, but that fabric is our chosen metaphor. They need to understand that they are trying to understand an inherently quantum superposition of a substantive and non-substantive world. Metaphor is inescapable, and we need to educate our scientists to recognize them, accept them, and use them both in direct and indirect ways. Perhaps the criterion for deliberate metaphor should be not that it is recognizable as a metaphor for the addressee, but for the user, and that the user is able to communicate why they chose that specific metaphor and understand its limitations and possibilities.

Another place that metaphor rears its head in physics is in the use of non-propositional instead of propositional reasoning. Propositional reasoning is reasoning that relies on propositions such as "and," "if," "or," and "not." In physics, propositional reasoning is used when relying on equations or defined physics laws and principles rather than intuitive or imaginative reasoning. In other words, propositional reasoning tends to be formal reasoning. Non-propositional reasoning is often marked by conceptual metaphors, particularly ones that insert the reasoner into the situation, rather than keep them separate. It has been found that novice physics students (such as undergraduates) tend to use propositional reasoning at higher rates than do more advanced students such as Ph.D. students. There must then be some shift that occurs as students advance that allows them to move away from strictly formulaic reasoning into a more organic, creative reasoning process. This is most likely linked to the changing use of metaphor as students progress from undergraduate to graduate. In their article, “Varying Use of Conceptual Metaphors across Levels of Expertise in Thermodynamics” Fredrik Jeppsson, Jesper Haglund and Tamer G. Aminc explore this differing use of conceptual metaphor and non-propositional reasoning in undergraduate and graduate students solving standard Thermodynamic problems. They claim that “abstract scientific understanding and reasoning are grounded in more concrete, bodily-based knowledge structures and non- propositional modes of reasoning, including analogical reasoning, imagistic simulation and application of physical intuition” (Jeppsson, Haglund & Aminc 2015). In other words, the ability to understand abstract scientific principles is connected to the use of metaphorical conceptualization that links the abstract world to the concrete world. Advanced understanding comes when one can link abstract principles to the concrete, observed world. Being overly reliant on abstract physics principles is a form of “‘the Icarus effect’, metaphorical disconnection from earthly matters. From this perspective, developing expertise in physics entails fathoming a broader range of semantic gravity, connecting general laws to particular circumstances” (Jeppsson, Haglund & Aminc 2015). After all, physics is the study of our physical universe. Becoming a physicist, in other words, is a matter of learning to recognize that which is not seemingly physical (electrons, dark matter, muons, energy, etc.) as actually physical. The way to do this is through metaphor.

The power of metaphor is that it allows the user to enter into the abstract space of concept and connect it to the less abstract physical world. It allows a skilled scientist to both identify with and disconnect from the studied physical phenomena. “A particularly prominent aspect of the use of conceptual metaphors by the [Ph.D students] was the degree of engagement between the problem solvers, on the one hand, and the physical situation and quantitative reasoning, on the other” (Jeppsson, Haglund & Aminc 2015). In other words, what differentiated the Ph.D. students from the undergraduates is that they were able to insert themselves into the problem, by using the conceptual metaphor, A Problem Solver is the System. When the Ph.D. students talk about energy flow in a system as if they themselves are flowing they are using the conceptual metaphor. This “use of conceptual metaphors transformed what might have been expected to be highly formal reasoning to a process of reasoning that contained many elaborate concrete, imagistic scenarios in which the problem solver him-/herself is construed as a component” (Jeppsson, Haglund & Aminc 2015). In other words, physicists are not highly formal reasoners. They are rational, but also creative, thoughtful, but imaginative, and most of all are able to combine many modes of thought in order to reach a conclusion.

The act of being a physicist is inherently metaphorical. Professors when solving unfamiliar physics problems often search first for conservation laws or other principles but they also use “different kinds of visualizations and analogies to map the unfamiliar problem to a more familiar domain” (Jeppsson & Haglund & Aminc 2015). This is the business of physics. Mapping the unfamiliar to the familiar using metaphor. Whether we recognize the metaphor or not, it exists, and it is the means through which we understand our world. If we need a conceptual metaphor to understand the universal human experience of love (Love is a Journey) then how much more do we need metaphors of all kinds to understand the abstract untouchable realm of physics? Metaphor is the means through which professors are able to blend physics principles with visualization and analogy.

This discussion of metaphor raises the question: why must all abstract things be conceptualized in terms of physical things? Well, simply because abstract thought is hard.

Humans tend to need pictures to think about things they cannot see. We build pictures in our head based on pictures we have already seen. When trying to explain the ocean to a child who has never seen it before, you might describe it as a really big lake. Or assuming they also have not seen a lake, as a very large puddle. In other words, we use the known to build pictures of the unknown. And when there is not a clear known building block of the unknown, we use metaphor as our bridge.

The next question is one of embodiment. Why is it that, for example, our metaphorical conceptualization of energy as a substance focuses it on its physicality as a fluid? Why do we not emphasize all possible physical manifestations of energy? Because by our nature we focus on different aspects of our experiential world, a phenomena that Zoltán Kövecses calls "differential experiential focus" (see Kövecses, 2005). Kövecses claims that "embodiment consists of several components and that any of these can be singled out and emphasized by different cultures (or, as a matter of fact, individuals within cultures)" (Kövecses 2008). In other words, embodiment is not a singular universal experience. Rather, there are universal physical phenomena from which that individuals single out specific experiences that inform their physical metaphors. Embodiment is thus a "complex set of factors to which speakers can apply different experiential foci" (Kövecses 2008). Embodiment metaphors differ slightly between cultures and even between individuals not because it is a faulty, inconsistent system, but because the experiential world is vast and so we naturally focus on a small part of the whole. This is not problematic for cross-cultural or interpersonal communication because the individual metaphors all stem from the larger, universal physical experience. Physiological symptoms of anger include increased body temperature and increased blood pressure. For various individual reasons I might single out the increased body temperature aspect of anger and that will inform the conceptual metaphors I use in regards to anger. I will say that I feel heated when I feel angry. Another person might focus on the increased blood pressure aspect of anger and will say that they feel about to burst when they are angry. Neither of us are right or wrong, and further, we are both able to understand the other because the metaphors are based in a universal reality. The fact that we can use such seemingly different conceptualizations of anger and understand each other is important because it indicates that various metaphors can be used in science in order to get a bigger picture without sacrificing communicability. Think of the familiar, quantized energy levels are like stairs, metaphor. After some examination this is both a direct and an indirect metaphor. The “like” clearly indicated that it is meant to be used as a metaphor, but it also is indicative of a larger metaphor, “energy levels are points in space with varying altitudes.” This becomes apparent when we think of how we talk about energy levels. Electrons can “fall” back to the “ground” level. They can “jump up” levels. If they have enough energy they can even “escape” the atom and the energy levels all together. Electrons do not “walk” from one energy value to another. They do not operate on a plane in our minds. Rather, they operate along a vertical cliff. This stems from a conceptual metaphor we use when talking about energy in general: that of kinetic energy as skiing down the mountain and potential energy as riding the lift back up the mountain. In other words, energy as moving up and down is not a new conceptualization. However, we also think of energy as flowing from one system to another. Most generally we think of energy as a substance that moves. The fact that our specific conceptual metaphor shifts based on the context is not problematic. They are all based on our foundational “energy is a substance” metaphor and just focus on different aspects of that metaphor.

What then, if we tried to exhaust our experience of substances in an effort to fully understand energy? What if we speak about it as blocks, as crumbles, as a phase changing substance, as moving on its own and being moved? What if we teach our students to do the same. Teach them the equations, the conservation laws, then let them rewrite them with all the substance metaphors we can imagine. What then? Have we created creative scientists or physics terrorists armed with metaphors that will sabotage the integrity of the discipline? This question seems ridiculous but it is the one we ask ourselves every time we approach young physicists-in-training.

Alan Lightman admits that metaphor is necessary in science. Not only for teaching but for discovery and understanding. “Metaphor is critical to science. Metaphor in science serves not just as a pedagogical device...but also as an aid to scientific discovery. In doing science, it is almost impossible not to reason by physical analogy, not to form mental pictures, not to imagine balls bounding and pendulums swinging. Metaphor is part of the process of science” (Lightman 2002). We must imagine a physical equivalent for the untouchable reality of physics in order to understand, discover and create new experiments. Metaphor is a necessary tool in the hands of scientists.

However, Lightman switches tracks at the end of his article and recommends great caution when using metaphor in science. He claims that scientific metaphors must carry more weight than their relatives in literature, art, or history because they must create reality from scratch rather than color what is already there .“When we use metaphors in ordinary human affairs, we usually have a good sense of the principle object to begin with...But when we say that a photon scattered off an electron, what concrete experience do we have with electrons or photons?" (Lightman 2002). We cannot directly see an electron interact with a photon. So we say that the photon scatters and immediately I think of confetti scattered on a table top, of children scattering when a bully walks towards them, of scattering grass seed on the ground. None of these capture the full reality and we would be amiss if we said that photons are children and the electron is the bully. But we are not amiss in allowing ourselves to imagine the reality as any of these situations. We are not amiss in using any of these images in our classrooms, the formulation of our science experiments, or the interpretation of our data. As long as it is consistent with the math, current accepted physics, and our data, then it is appropriate. So what if it is wrong. We are human and we do not understand everything. Our mistakes will set up the next group of scientists to get one step closer to the actual reality. Lightman disagrees and says, "although aware that the ether was based only on mechanical analogy, Maxwell believed it existed...If a giant of science like Maxwell was seduced by his own metaphor. what can happen to the rest of us?...Metaphors in science should be handled with caution, and with a clear knowledge of the sensory limits of the world" (Lightman 2002). But what Lightman neglects is that our current understanding of electromagnetic waves claims that E&M waves propagate through the electromagnetic field. What is this field if not some sort of substance metaphor for whatever the reality is? What was the ether if not some sort of substance metaphor for whatever the reality is? The difference is that Maxwell believed in the actual existence of a physical substance called the ether, while we now understand that there is not such a physical substance. However, we still use his substance metaphor when we talk about "waves" propagating "though" a field. We conceptualize the field as physical and where would we be without Maxwell's ether? We should not condemn Maxwell for the use of metaphor. Rather we should ask of ourselves and the scientists that we train the ability to think in all kinds of metaphors. Lets not hide metaphor from the young, or the weak, or anyone. Rather, let us teach our scientists that everything they know they know because of a metaphor. Teach them that, to borrow Lightman's words, "we must breathe, even in thin air" (Lightman 2002). Give them the oxygen tank of metaphor as they dive deeper into the intoxicating, lonely, untouchable and unseeable world of physics. Let them have words and images when they have nothing else. Teach them to treat their metaphors like they treat their data, with great respect and ruled by the iron fist of experimentation. But most of all, teach them to use metaphor.

III. What Makes a Physicist?: Physics Identity

I sat at a table with the staff scientist for the James Clerk Maxwell telescope, drinking wine and she gave us more drink tickets so that "we don't think the radio astronomers have more fun." We showed her our posters and tried to explain reverberation mapping, and lamented about the rude old male scientists who try to ruin our days. We are people, all of us, Ph.D. or not, responsible for a large telescope or just undergraduates trying to get into graduate school.

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We live in a Western Society where we believe that we can do anything and be anything. This is not quite the reality however, as many of us have realized. Certain contexts require certain types of people and thought. Physics is very much one of these exclusionary contexts. If they have not already, physics students quickly realize that physicists are expected to be rational thinkers, mathematically gifted, quick learners and calculators, and able to think abstractly and non-linearly. How does a student construct their identity as a physicist in a discipline that explicitly outlines what kind of identity they are allowed to inhabit? The short answer is that they do not. They are handed an identity and expected to fit inside it, adjust to it, or leave. Here we define “identity” as the set of characteristics and traits typical of successful people in specific settings. Research on physics identity has shown the importance of physics identity in student retention among undergraduate physics majors, specifically when women and other minority groups are involved. But identity research primarily focuses on how students are able to assimilate into the accepted ways of being a physicist, while ignoring the broader question of why only certain types of people are allowed to be physicists in the first place. We need to examine the field itself, rather than merely the people who make up that field. In other words, what kind of scientists does the field allow? How does our physics education system produce the types of scientist the field allows? What kind of culture does this system perpetuate?

As one might imagine, identity of any sort is a complex, multifaceted subject. Geoff Potvin and Zahra Hazari, in their article titled “The Development and Measurement of Identity across the Physical Sciences,” have created a model of student physics identity containing three factors: “recognition, interest, and performance/competence beliefs” (Potvin & Hazari 2013). They define recognition as a combination of both being recognized by others as as a physicist as well as self-recognition as a physicist. Interest is the student’s interest in science and in physics specifically. Performance is belief in one’s ability to perform in the physics classroom and the field at large. Competence is belief in one’s ability to understand physics concepts. Potvin and Hazari found that performance/competence beliefs vary in different contexts. Specifically they found that “students’ performance/competence beliefs fell into one of three contextual categories: academic/classroom, interpersonal/conversational, and laboratory/experimental contexts” (Potvin

& Hazari 2013). In other words, a student feels varying levels of belief in their competence and performance in different physics situations. For example, a student might struggle to feel competent in the classroom but excels when explaining concepts to their peers in a study group. Or (in my case) a student might feel proud of their performance in the classroom but struggle to believe in themselves in laboratory classes. Theses different types of performance/competence beliefs carry through to a student's physics identity and desire to continue in the field, perhaps more than any other factor. They also influence a student's interest in science and their self-recognition as a physicist, the two other pillars of physics identity. I struggle with using laboratory equipment and I still do not understand how to use an oscilloscope though I have had to use one in three laboratory courses. It is in these laboratory classes that I feel the most like a non-physicist because I do not believe in my ability to perform at the given tasks.

I once spoke with a freshman trying to decide if she wanted to continue down the path of being a physics major. She came into college wanting to be an engineer and planned on studying physics to set herself up for further education in engineering. However, all her friends were humanities majors and kept pressuring her to change to a humanities major. In addition, Intro Physics was proving to be much harder than she had anticipated. In high school she was used to putting in the work and getting good grades. In Intro Physics however, she put in the work and still struggled to get good grades on the exams. So she began to question her life plan and ultimately decided to leave physics. This story is illustrative of the role of physics identity for a few reasons. First, the freshman lost all belief in her performance/competency due to difficult tests. This is not an uncommon experience in introductory physics classes. College physics requires a more abstract mode of thinking than do high school science classes, including high school physics. Intro college physics courses also cover a lot of material in the short span of a semester. They are also usually taken in the first few semesters of college, so while the student is trying to learn physics, often for the first time, they are also trying to adjust to the demands of college life. All of these things combine to make it difficult to excel in introductory physics classes. But many students struggle in introductory physics and still continue in the field. Performance/competency beliefs must not be the only factor, or at least are affected by other factors. When a student is surrounded by people who confirm their identity as a physicist they tend to stick with their physics studies. This freshman was surrounded by peers who did not understand their desire to study physics and actively pushed them to study the humanities instead. In other words, the freshman was not recognized by their peers as a physicist which made it harder for them to recognize herself as a physicist. She also was already interested in studying the humanities and did not see a way to be successful in both fields, because of course a real physicist would not also want to study Peace and Justice. Because she was already doubting her ability to succeed in physics and questioning how she could be a physicist who loves something that seems to be the opposite of physics, she left the field to pursue a program of study in the humanities. Was this correct choice? Perhaps. Could she have existed in the field as someone who struggles to succeed in class and occupies half of her brain with a second major in the humanities? Perhaps, if she was encouraged enough by her professors and peers. But she still would have been swimming upstream, and that is not an easy feat unless you have someone in front of you parting the current. Even then it is still hard.

The example of this freshman points out that not only is physics identity comprised of these three categories, but that they all influence each other. I came into college wanting to be an astrophysicist but not sure if that was the correct path. If my introductory physics class had not held my interest, and if I had not excelled in that class while many of my peers floundered, would I still have recognized myself as a physicist? Perhaps more importantly, would my professor have still recognized me as a physicist? I am not sure. If I got 18% on my first physics exam as did my intro physics professor, rather than the class leading 98%, would I still be here today? Maybe, maybe not. If I did not have successful research experiences under my belt where I felt satisfied with my performances, would I still be applying to astronomy graduate programs even though my parents keep encouraging me to apply to english graduate programs instead? I do not know. I only know that many factors came together to make me into a confident physics student who is comfortable with calling herself an physicist/astronomer who also has a second major in English and tattoos paying homage to various poets rather than various physics principles.

Potvin and Hazari define identity as being recognized as a certain kind of person. In response to this however, they raise the question: “recognized by whom?” (Potvin & Hazari 2013). Who is the one recognizing these young physicists? It should be foremost the students themselves. But oftentimes before these students can recognize themselves as physicists, they must be recognized by someone from the field whom they respect. In other words, they must be recognized by the field itself. This raises a deeper question: “what kind of person does the field of physics deems acceptable to be a physicist?” This is the question we must first address when asking questions of student physics identity. What type of student are we unconsciously excluding from the field? For a long time it was women, and while that is still true to some extent, the percentage of women in the field has slowly grown. But the field is still rather homogenous. It is true that physics requires a certain type of curiosity and determination. But those are both cultivatable skills. We see many determined and curious students leaving the field due to other circumstances. The freshman I mentioned earlier was an honors student. This indicates that she is a determined and curious student. That was not enough however. Her performance did not allow her to identify as a physicist and thus led to her leaving the field. Perhaps this points to an unrealistic performance standard put forward by the field. Perhaps we want geniuses rather than the students willing to work endless hours to perform as well as their more "gifted in physics" peers. Perhaps we want students who like me, manage to get high scores on intro physics exams while the other students, all with approximately equal intellect and determination, flounder. We prioritize the students to whom the physics kind of thinking comes easily. What would happen if we encouraged anyone with interest and determination to pursue physics, and then did not try to push them away when they inevitably hit patches of struggle? Perhaps we would have a more diverse field, and ultimately produce an even better research community.

These questions of physics identity depend on questions about the culture of physics. My experience as a college student studying physics has been largely positive. My professors have worked hard to create inclusive classrooms and to give every student equal chances of success in the class and in the major. When students struggle, professors are available to work with them through problems and every encounter I have had or witnessed others have with my professors has been encouraging. This is not to say that the classes are easy. I have taken some very difficult physics classes, but each student in that class is equally supported regardless of their "natural physics talent." If the student is putting in work, the professors also work to make sure they succeed. In talking with physics students at other institutions, and in my interactions with faculty from other institutions, I get the sense that this encouraging environment is fairly commonplace nowadays. Of course there are always outliers and toxic or exclusionary classrooms still exist. However, there seems to have been a cultural shift in the physics classroom from elitism to diversity and inclusion. Yet there is still an internalized sense of the old elitist physics culture among students. The story I told about the freshman who struggled in intro physics and ultimately decided to leave the major illustrates this. I know the professor for that intro physics course. He is endlessly supportive of his students. I know that any conversations that the student had with him were full of him encouraging her to stick with the major, telling her that she is able to do physics, and that test scores are not indicative of the fullness of physics aptitude. However, the student had so internalized this idea that if they do not score well on tests they are not able to be a physicist. This indicates that there is an elitist culture of physics that is so deeply entrenched in our psyche that even well meaning professors have not yet been able to weed it out. In other words, this outdated notion that only a very specific kind of person can be a physicist is not coming from the top of the field, but rather is a bottom up phenomenon that starts in the broader society. In order to question what types of people are allowed to do physics, we need to question this underlying culture.

Barbara L. Whitten, in her 1996 article titled, “What Physics Is Fundamental Physics? Feminist Implications of Physicists' Debate over the Superconducting Supercollider,” examines the culture of physics and its self-created identity of being the fundamental field. In the beginning of the article, Whitten points out that “Physicists ask questions about many things: the universe; galaxies and stars; bridges, spaceships and other machines; the structure of crystals, atoms, nuclei, and quarks. But some of these questions are regarded as more important—physicists say more "fundamental"—than others, and the branches of physics that pursue these questions are more elite and competitive than others" (Whitten 1996). Whitten raises this point in light of the discussion around building the superconductor supercollider (SSC) and the argument in its favor that it would study "fundamental physics." Whitten points out however, that this idea of fundamental physics, and the hierarchy among physics subfield that it necessitates, is not inherent to the field, but rather is a manmade construct built and upheld by physicists. This idea of a hierarchy among subfields translates into a hierarchy among scientists, and further a universal hierarchy atop of which perches physics. As the focus of the physics gets smaller and more unreachable, it attains a new level of elitism, actively creating an exclusionary community. This implies that there are levels of importance granted to various physics questions, based not on their practicality or some other objective factor, but on their assigned value of fundamentality. If we exist within a field that defines important questions by how fundamental they are, where fundamental is a mostly arbitrary distinction, then we must realize that the rest of the field has been infiltrated by these subjective hierarchies. If certain questions are more valid than others, then it follows that certain ways of asking questions, thinking about the questions, and going about answering the questions are more valid than others. It also follows that certain types of people are more valid than others. These are not distinct issues. The issue of what questions are given the most weight is connected to the issue of what types of people are able to answer the questions that carry much weight.

The culture of physics often feels like one of few voices. There seem to be a few loud voices that define the field for everyone else, including the general public. One example of this is the Nobel Prize in physics. Whitten points out that “at any given time, the study of the particles that are "fundamental" is regarded as the most important subfield by the physics community. This is seen most clearly in the awarding of Nobel prizes” (Whitten 1996). Nobel Prizes are a public projection of how the field wants to be seen. It puts the “most significant” achievements in physics at the forefront of the public perception of physics and it creates spokespersons, willing or not, for the field. Whitten points out that the repeated awarding of the Prize to whatever physics is at the time deemed the most “fundamental" further serves to cement the idea that fundamental is equal to most important. But this is allowing a small, self-selected, rarely changing committee to give meaning and importance to the many questions being explored in physics. There has been a lot of pushback in recent years against the ways that the Prize favors white men, but there has not been much discussion about the inherent eliteness in a field that allows a small subset of people to determine the most important people, questions, and discoveries in the field. This is not a democratic system. It is a system of values determined by a small group of people. It is hierarchal system propagated by the bureaucracy of academia. This type of system cannot possibly be objective.

Amy Bug in her article titled, “Has Feminism Changed Physics” makes this very point about physics and objectivity: “That a broader community could be generative of more good ideas is not troubling to a physicist. That it could be more objective is” (Bug 2003). She points out that a broader and more inclusive community of physicists can help to generate more and better ideas regarding research. This is not necessarily controversial. The controversial idea is that a broader group of physicists and a more inclusive physics culture could be more objective than the field we have now. This idea is troubling because it implies that the field is not currently truly objective. The field of physics prides itself on being fundamental and objective and has thus created a currency for itself of “truth” which depends on objectivity. The idea that the field can become more objective undermines everything that has been achieved in the field so far, because it devalues the currency, destabilizing the field, and supposedly creating chaos.

Physics is exclusionary, based on hierarchy, concerned with the “fundamental” questions and thus the “important” questions. It also prides itself on being objective and is unable to believe that it is possible to become more objective. It is resistant to change. It is elite, in that it only allows a small group of the population to participate in the field. It is a skeptical field, wary of any new method or way of thinking that threatens to ruin the supposed objectivity of the field. Yet it is a wonderful field, doing wonderful things. It has produced Newtonian mechanics, quantum mechanics, the image of the black hole, Hubble telescope images, smart phones, satellites, and general relativity. In other words, the field has worked as is for so long, and done so much good, so why now is there the sudden push for change? As questions of diversity and inclusion have come forward, physics has been accused, and rightly so, of being predominantly white and male, and more abstractly, genius. Of course we want to invite people into the field who do not fit that mold. But the change is slow going. The field has created a culture for itself of being inflexible and that necessarily translates to difficulty in changing the field.

An example of the ways that undergraduate education perpetuate this inflexible physics culture is found in Anders Johansson’s 2016 paper titled, “Shut up and calculate’’: the available discursive positions in quantum physics courses.” This paper explores the question of physics identity, what it means to become a physicist. and whats types of thought are privileged in physics, through the specific lens of the identity required and taught in a quantum physics class.

One of the traits that he claims is expected in physicists is "a kind of ''authentic intelligence'' or ''smartness''" (Johansson 2016). In other words, physicists are expected to be naturally gifted in the intelligence required in physics. This disadvantages the students who need time to reflect on material learned in class, rather than being able to immediately spit out answers or ask thoughtful questions in class.

Johansson looks at the physics method that he calls "shut up and calculate." He examined several quantum physics classes in two Swedish universities in order to determine the ways in which scientists are trained, what types of scientists are created in the process, and the culture that it perpetuates. He finds that the emphasis on calculating in quantum physics classes necessarily limits the possibilities of positioning oneself as a "good quantum physics student." Quantum physics is a much hyped class. I remember when I took undergraduate quantum, I was very excited to explore this "strange" realm of physics where all the Newtonian mechanics I had spend years learning seemed to fall apart. Much of the modern large names of physics were fundamental in formulating quantum physics. In a sense, I suppose I figured that I would become more of a physicist by entering into this quantum discourse that radically shifted the field and the way that we view the universe. In other words, I anticipated that my quantum course would usher me into the before closed off world of physics. I assume that the other students in my class had their own preconceived notions and expectations for the course as quantum physics is foregrounded in popular science writing, the medium that often brings students to the field in the first place. But what popular science writing has in common with my dreams about my quantum class is this: the idea of an intellectual journey. I imagined the class would feel like I was alongside Schrödinger, discovering and formulating the quantum world for the first time.

However, as I learned to work with the Schrödinger equation and solve the standard undergraduate problem of particle in a box, I quickly realized that I was not going to discover: I was going to calculate what had already been discovered, and not only that, but I was going to calculate the most simplified problems because that was all I could calculate at an undergraduate level. As you can imagine, this was slightly disappointing.

My experience with quantum being new forms of math, rather than a fundamentally new way of understanding the universe is not isolated. Johansson claims that “the novelty of quantum physics is expressed primarily as new ways to calculate, not new ways of modeling or understanding reality” (Johansson 2016). This is understandable. Quantum mechanics does require a specific mathematical skill set that must be cultivated in order to teach students about the field. Anyone can recognize the necessary value of learning to work with the tools before using them to create something new. However, the dominant focus on calculation in quantum physics sends a message to students about what type of student is able to continue onto the journey of scientific discovery. The emphasis on calculation also serve to limit the modes of approach.

Like many physics classes, a quantum class tries to cram a lot of information into a semester. After all, the instructor has to get through what took years to understand in a 16 week semester. This causes issues as it does not provide an opportunity for students to think of and ask the questions they need to understand. Johansson points out that, “the focus on getting through the material meant that there was not much time for questions or reflection from the students, who were put in a kind of pedagogical double-bind as they were simultaneously urged to ask questions” (Johansson 2016). A good physics student is expected to ask questions. Not asking questions is a sign of confusion, boredom, or lack of interest. In addition, there is an emphasis on asking good, enlightening questions that imply that the student has some understanding of the class material. This “may put students in a position where only ‘‘smart’’ questions can be asked, that is, if asking questions would imply ‘‘getting it’’” (Johansson 2016). In other words, part of being a physics student is being able to quickly absorb information and ask intelligent questions. The students who need more time to reflect and absorb the information before coming back with questions are short-changed and seen as not as competent of physics students as their quicker peers.

It is important to point out that it is not necessarily the professors who impose the idea that competent students are the ones who can ask good questions in class. This is often a mindset that students perpetuate among themselves. As a student, if I cannot formulate a question it often means I am very lost. I start to feel like I don’t belong or I am not as smart as the kids who ask lots of questions and seem able to process and talk in class. I know that this is not true, that I will probably do better on the exams than they will, and that I simply need more time to reflect than they do. The point is that the specific expectations of what makes a physicist are not traceable. Rather, they are a product of the physics culture and are self-perpetuated by that exclusive, closed culture. This also indicates that even with better, more conceptually oriented, more explorative classes, there still is a systemic culture that defines the priorities of the discipline and allows only certain modes of thought.

Johansson talks about a moment in class where students were watching a TA solve problems on the blackboard, a common teaching practice in physics classes. They were then told that they were going to solve some problems on their own and then hand them in at the end of the class. This is also standard in physics classes. Johansson points out that this indicates that "being a good student meant both listening carefully and applying what you had heard to your own problem solving" (Johansson 2016). In other words, being a good student is a passive act. It is absorbing and then using the absorbed material to come up with a pre-determined answer. This does not match the creative discovery process that was required to formulate quantum physics in the first place. A world of physicists who have learned only to absorb and then "shut-up and calculate" is not going to produce new discoveries or knowledge. The shut-up and calculate approach will stagnate the field if left to its own devices. However, this is not the world we see. There are many physicists who are doing good work and moving the field forward. Something must happen in between undergraduate and graduate education that shifts students from people who sit down, shut up, and calculate, to people who are curious and exploratory, who realize that the world is described by much more than just undergraduate calculations.

Johansson clearly points out the problems of a physics education system where the emphasis is on calculations, "a kind of teaching that focuses too much on calculation risks reproducing a culture of physics where the only thing that matters is getting results, a ''shut up and calculate''- culture" (Johansson 2016). It is easy to imagine the implications of physicists focused on only getting results. This leads to unethical research, toxic work environments, and the exclusion of anyone who cannot publish results fast enough. It eliminates slow, careful thought, creative, winding paths, and the carefulness that good research requires. In other words, it removes the person from the research, and makes them only a cog in the machine of producing results. This is obviously detrimental to the field. However, that is not the current state of the field. For the most part, physicists are doing good work, creative work. For the most part they are trying to be more inclusive and make it easier for certain demographics to work in the field. But the foundation of calculation that most every physics education is built upon, necessarily shapes the way students approach the field for the rest of their careers. The question the becomes one of how we can train smart, innovative, creative researchers when so much of their education has been focused on repeating and calculating.

The universe belongs to no one. In fact, in our modern, western society, it might be one of the few things that is not owned and exploited by some group. It often feels like we have forgotten that however, and have drawn boundaries around the universe, assigning portions to certain people to study and not allowing anyone else in. The realm of people has been allowed to the humanities: to literature, history, and the study of languages. The realm of the impersonal living world has been given to biologists. The world of atoms has been given to the chemists, and the entire non-human world has been given to physicists. The physicists have free reign over the entire universe and over everything that humans cannot touch. Perhaps this is why we as a field are so terrible at the human interactions and why we can only allow certain types of people to practice in this field. There is a joke that goes, "how can you tell an extroverted physicist from an introverted one? When they talk to you they look at your shoes rather than their own." This is sadly an accurate, though not necessarily literal, depiction of the field. I have met some physicists who are very comfortable with human interaction. I have also met some who would rather hide in their office using their computer to discover the secrets of the universe than talk to another person. But as a field we have a problem with looking beyond our own shoes, and when we are able to, we can only look at the shoes of other people. The problem with this is that everyone's feet look the same, especially when physicists only have one type of shoe that they are allowed to wear. The field is a professional Nike sponsored track team and its members are only allowed to wear Nike shoes and Nike products. When the members seem unworthy to wear the Nike logo, we try to usher them out of the field. We measure people by how quickly they can produce good results in high quantities. When, for whatever reason, a physicist does not follow the trajectory of intense production early and often, we start to question if they are able to do science. There is no allowance for any human element outside of the science. As Johansson 2016 implied, the human is only a cog in the machine of science. Chanda Prescod-Weinstein, in her blog post titled "Let Physics Be the Dream It Used To Be: Or, how to make physics fun" draws on her experience as a person who is black, queer, and from a working class background trying to find a place in physics. In short, Prescod-Weinstein didn't and still does not fit into the dominant physics culture and in her words this has "sucked a lot of the fun out of physics for me" (Prescod-Weinstein) and points out that this is a systemic issue and argues that "this is in fact a real issue that doesn't magically go away with admissions and diversity initiatives that fail to address underlying cultural, structural issues" (Prescod-Weinstein). It is not only a matter of inviting people into the field who do not fit the majority picture of what a physicist is (white, male, straight, and a sort of elusive "genius"). It is also a matter of making these people feel welcome, not just like they were admitted to fill a certain diversity quota, but that they belong in the room as much as any one else in that room. Prescod-Wienstein declares that "I don't know how to deal with a community full of people who don't understand that what they are demanding of us is that we assimilate to their sensibility of what's "true" and "fair" in science" (Prescod-Weinstein). It is not inclusive to invite people into the field and then demand that they become a certain kind of person in order to remain in the field. What is inclusive is allowing all different expressions of people to practice physics. The universe is not a gentlemen's club. There is not an oppressive price of membership other than the determination necessary to make it through an undergraduate degree and then possibly a Ph.D. program.

Prescod-Weinstein also points out that the sole measure of success in physics is productivity in research. This is true even at the undergraduate level. In one sense this is reasonable because a successful physicist needs to be able to conduct independent research and research experience is an indicator of future success in research. But it should not be the only metric, because as Prescod Weinstein points out, this criterion ends up excluding a group of people otherwise very qualified to continue in the field: "I don't know how to deal with a community that has a job application process that is frankly fairly dehumanizing for most participants, especially those of us who for a host of reasons couldn't be on "the perfect trajectory"" (Prescod-Weinstein). Not everyone can spend every free hour in the library studying the material in their physics classes. Perhaps they need to work in order to put themselves through school. Perhaps they simply cannot spend every free hour studying because their mental health will not allow it. Perhaps success in undergraduate physics should not be at the expense of one's bodily and mental health. There have been many semesters where I was the TA for multiple labs, taking 18 credits, playing a collegiate sport, taking multiple physics classes, and as a result sleeping 3-5 hours a night and wondering why I spent a good portion of every day crying. A less stubborn person than I would have broken down a lot sooner than I did. Not everyone can spend their summers doing research because they need to be at home to take care of family, or need to be doing something more lucrative during the summer in order to attend school the following fall. Should these people be excluded from the graduate applicant pool simply because their time was more constrained than other people's? While, yes, we want qualified applicants to attend our graduate programs, we maybe we need to rethink what we define as qualified in order to include people whose applications look different for whatever reason.

Perhaps the most important metric when evaluating students' ability to continue in the field is their creativity. Will they be able to come up with creative solutions to their research problems? When they begin teaching will they be able to creatively adjust as they go? Students who have to find their way through an undergraduate physics degree without the luxury of multiple free hours a day to study have to be creative at least to some extent. Maybe we should prioritize these students or at least weight their applications as heavily as the students who have spent their summers doing research and have high grades in all their classes. But the field does not behave as if it prioritizes creativity: "does it matter that by forcing us into a box, the community is teaching us not to improvise, even though creativity is maybe the second most important quality for us to have as scientists (after persistence)?" (Prescod-Weinstein). When there is only one way to be a person in the field, we end up excluding any creativity from the field. It is no wonder that undergraduates have such a distorted view of the field. They see a cookie cutter physics, fumble their way into graduate school on the merits of their good grades, and then find out that the field is messy and that they need to be creative problem solvers in order to succeed. But we don't teach creativity. We are still teaching a gentlemen's club physics with updated content and with the snazzy new methods of active learning and flipped classrooms. We still teach students that they are trying to participate in a field that values genius and the commitment to endless work. No wonder so many chemists say that they wanted to be physicists, they just did not think that they were "smart" enough.

One way to start to redefine who the field allows to become a physicist is to more explicitly encourage interdisciplinary curiosity and discussion among physics students. Tyler D. Scott et al. wrote an article titled, "Interdisciplinary Affinity: Definitions and Connections to Physics Identity " that explores the idea of physics identity as affected by interdisciplinary thinking. They claim that physics has a special connection with interdisciplinary affinity because "a link between interdisciplinary affinity and mathematics identity is weaker" (Scott et al. 2014). In other words, even though mathematics is the language of physics, the field of mathematics is not as interested in interdisciplinary thought as is physics. Interdisciplinary affinity is "students' interest and desire to integrate information and perspectives from multiple disciplines as well as self-perceptions of their competence to do so" (Scott et al. 2014). In other words, a student has high interdisciplinary affinity if they are able to connect the things they learn in their various classes and feel confident in their ability to do so. Scott et al. looked at correlations between interdisciplinary affinity and physics identity, but split physics identity into two components: recognition and interest. They found that interdisciplinary affinity more highly correlates with with physics interest than with physics recognition, though a higher interdisciplinary affinity is a significant positive predictor of both physics recognition and interest.

If interdisciplinary affinity is highly correlated with physics interest we have a possible way forward in combatting the high weight given to performance/competency beliefs in the formation of student physics identity. We can foster interdisciplinary interest in students and in doing so foster their interest in physics and help bolster their identity as physicists. Think of the freshman who left the field because she did not feel that she could succeed and also be interested in the humanities. If we had been better able to affirm her varied interests and show how they can support her physics studies, she might have stuck with the physics major. Most students are like her in that they are not singularly interested in physics. They might also be interest in other science disciplines, art, music, athletics, or literature. They might be writers or poets or singers. They might love pure math or are fascinated with the human brain. In other words, humans are a compilation of many interests and influences and it is unhealthy to expect them to singularly focus on only one interest. Physics is a unique discipline in that it requires many aspects of thought that can be found in other disciplines. It is highly rational but also highly creative. It is abstract as well as grounded. Thinking like a physicist requires thinking with metaphors, which is a mode of thinking mappable to many other disciplines. The question is how to make students aware that physics allows them to think about many things other than physics.

Perhaps we should introduce interdisciplinary conversations and methods into our physics classrooms. Perhaps poetry and literature and art should be used in teaching physics. Perhaps we should simply encourage our students to pursue interests other that physics, and to think about how their experiences in those other interests map onto their interests in physics. This will serve to open the field up to new voices, therefore allowing them to begin to make the field more inclusive and ultimately more successful. It will also serve to encourage students to have a healthy interest in physics which will ultimately lead to more students staying the field. This will also make the field more diverse as the type of person allowed to practice physics becomes broader. Anyone can be interested in physics and also want it to connect to the world beyond just physics. It follows from this that then anyone can practice physics. To return to an earlier metaphor, the Nike sponsored track team of physics might begin to allow their athletes to practice in New Balance shoes, and eventually race in Adidas singlets. In other words, a physics that allows for interdisciplinary affinity as a former of physics identity starts to combat the monolithic nature of the field and make it more democratic, more inclusive, and ultimately as more voices speaking different languages enter the field, more objective. And isn't this the dream of every physicist?

IV. Storytelling in Physics

When I was doing observational astronomy at the University of Wyoming over the summer before my senior year, we observed a supermassive black hole in the galaxy, Markarian 6, or Mrk 6 for short. Another student referred to the black hole as "Mark 6" until told by our advisor that this was the wrong name and no one would know what she meant. But the black hole had become like a friend to us, its familiar spectrum a reason to celebrate every night we observed it. Galaxies deserve nicknames too. It is part of how we tell their stories.

…

We are all storytellers. In casual conversation we tell stories to describe our days or things that have happened to us. We also tell stories in more formal arguments and discussions. Perhaps not a story that is recognizable at first glance, but formal arguments consist of a narrative with characters who have conflicts implicitly implied. Perhaps our discussions and arguments are both a form of telling and of acting out story as we are both writers and characters. Science is also not exempt from storytelling. If stories are one of our primary modes of communication, it follows that scientific communication is also heavily dependent on storytelling. In a sense this is a metaphor: communication and argument are storytelling. We see this metaphor in how we talk about both communication and argument and how we position ourselves within those two. A story has characters, setting, plot, conflict, and resolution. The conflict in communication is apparent—one person wants to convince the other of a particular position. The characters in a communication story are the people talking. The characters can also include people who are adjacent to the issue at hand. The setting is the intellectual backdrop. In a scientific argument the setting is often the subfield at hand, and the characters are the scientists who have made the current research and argument possible. The plot is the process of the research: of setting it up, performing the research, all the pitfalls and adjustments, and the process of analysis. Finally, the resolution is the discussion of the results and conclusions and/or suggestions for continuation of the work.

If we are all storytellers then we are also all deeply dependent on metaphor. Story and metaphor are inseparable. The act of storytelling is one of depicting to another person an event at which they were not present. Thus it inherently involves abstraction and needs metaphor to communicate the abstraction.. In his article titled ""Everybody goes down": Metaphors, Stories, and Simulations in Conversations," L. David Ritchie explores the often disputed connection between metaphor and story. Ritchie claims that "it has also been shown that metaphors often imply stories, and that stories are often metaphorical" (Ritchie 2010). If metaphors imply stories then they are natural markers of a story and in fact can create layers within a story. On the other hand, if stories are often metaphorical then they must act as a way of understanding and experiencing the world beyond our direct sensual experience. We can then think of stories as extended metaphors that also rely on metaphors to convey meaning. Because stories are necessary to convey knowledge and to understand ourselves and the world around us, we must include metaphor in that conversation.

Not only does metaphor help us tell stories, it paints pictures of the things that are impossible to describe with language. Ritchie claims that "metaphors can be processed either by way of semantic or propositional connections, as when they are treated as semantic units, or by way of perceptual simulations, when the context justifies greater processing effort" (Ritchie 2010). In other words, metaphor provides a shortcut through particularly difficult concepts. Metaphors do heavy lifting in discourse in two ways—as semantic units carrying meaning, and as storytelling units that also carry meaning. The more difficult the concept in question, the more like a story the metaphor is going to become. In addition, for more difficult concepts, metaphors also invoke our ability to understand the concept with our senses, through what Ritchie calls "perceptual simulation." This is the ability of metaphor to invoke human senses towards the goal of describing that which cannot be easily described. We may not have a good sense of, say, love. But when we use metaphor to say that love is a journey, then we start to remember the physical sensations of a journey and connect them to the idea of love. A journey is tiring, and feels uncomfortable at times. You might think of journeying by foot and experiencing different types of weather. Or of journeying by car and the vibration and bumps that happen during a car ride. You might think of the snacks you typically eat on a journey. These examples all invoke the senses and through the metaphor, love is a journey, connect the sensual experience of a journey to the difficult to understand concept of love.

The key point here is that "metaphors often imply stories, and deep processing of metaphors is likely to include simulation of these implied stories" (Ritchie 2010). In other words, because metaphors each contain a small story, when we are required to deeply process that metaphor, we must rely on the simulation of that story. Another way of thinking about this is that metaphors are layered and cyclical. As you get further into the concept and thus into its linked metaphor, you encounter the metaphor's story and in doing so return to the metaphor itself.

Because metaphor is inseparable from storytelling, it follows that we have another reason why metaphor is also inseparable from science and its particular mode of storytelling. However, we do not conventionally think of academic writing as storytelling. In fact, that would be taboo. We think of scientific writing as opposed to anything literary. In his article titled, “The story of us: On the nexus between metaphor and story in writing scientific articles,” Mikael Holmgren Caicedo points out that, “the style of academic writing is oftentimes opposed to the literary one by way of dichotomies such as science and art, fact and fiction, discovery and invention, and truth and lie that reinforce its rhetorical purpose and apparently separate it from poetics and rhetoric” (Caicedo 2011). Here, Caicedo is saying that we set up this arbitrary distinction between scientific writing and other, more literary forms of writing. Scientific writing is concerned with ration and “truth” It is relies upon objectivity, because that is what we have decided is the measure of truth. However, Caicedo pushes back against this assumption that science equals truth and other methods of exploration and communication inherently involves falsehoods. Because it is indeed an assumption. We do not have a reason for why we believe that science is the only way to a form of truth. In addition, we have decided that objectivity is the measure of truth, and thus we place all our emphasis on objectivity in scientific research, teaching, and writing. Why, however, is objectivity the criterion for truth? And why is there an inability to recognize that absolute objectivity is impossible, even when science is at stake? I believe that scientists do admit, albeit only to themselves, that they are inherently not objective. So we submit our scientific writing to a rigorous review process in the name of integrity and objectivity, and we publish papers that are the closest to truth that we can make them. But we do this all while ignoring that at the root of scientific inquiry, is a story that we are trying to uncover, and to tell. A scientific paper is a story, which means that it also has a viewpoint, and even if we try to make our narrator completely omniscient and objective, we are still human and thus we include our human viewpoints for better or for worse. In fact, we should embrace the storytelling aspect of science, and try to tell the story with all the tools of storytelling at our disposal.

Caicedo says this succinctly: "Academic texts are thus often, for better or for worse, understood as bearers of reliable and trustworthy knowledge. They do so, however, following a style whose form serves a function and solves a problem: to decide what statements that should and are allowed to be asserted in function of what we believe about nature, science and the scientific community and its literature" (Caicedo 2011). Here Caicedo argues that scientific communities encourage and require scientific writing that follows a convention that reinforces the community that creates it. In other words, it is a cyclical process. Much like Christian music, an often bad art form because it is a commentary on itself and thus is not subject to growth or evolution, the science community is a closed loop than only comments on itself. Caicedo nicely says that the structure of scientific writing follows a form that reinforces what the scientific community has decided are statements that should be allowed to assert as a function of what the scientific community has decided to believe about reality and science's role in explaining that reality. This is clearly problematic in any realm other than science. We subject literature, art, music, social work, and even medicine to outside commentary that ends up strengthening the work. Science however is on a different plane, a plane of "truth" that sets it apart from any other discipline, and thus makes it not subject to outside commentary. In fact, it actively discourages outside commentary because engaging with scientific conversation requires a high level of scientific education. This excludes any non-scientific discipline from having a say in scientific discourse and writing.

Caicedo offers a way out of the exclusivity of scientific discourse, in the form of story telling. He argues that scientific writing is already a form of story telling, and it is an easy jump to more intentionally tell the story in order to make science more inclusive and also admit the inherent bias in scientific research and the challenge the idea that objectivity is the only measure of "truth." Caicedo says that "the APA publication manual presents a standard for authors to follow that dictates the style of scholarly texts aimed for publishing in scientific journals, the acceptable way to tell a story, if you will" (Caicedo 2011). In other words, Caicedo points out that scientific writing has a manual, the APA handbook, that details how to tell a scientific story. However, it does not claim that it does so.

The APA instructs its adherents to avoid style, as it distracts from the substance of their scientific ideas, but also says to use scientific style as outlined in the manual in order to eliminate unnecessary considerations that do not serve the science at hand. Caicedo points out that this is problematic because in doing so, APA is doing exactly what it tells scientists to not, and that is conflating one thing with another, namely scientific style with style in general. Caicedo says in response to the APA manual, "oddly enough, in a rhetorical move, the likes of which it tells its readers to avoid, style is addressed in the manual as if there was only one. In such a move, the generic term style is conflated with scientific style and the even more specific APA style according to which a writer should refrain from using 'devices that attract attention to words, sounds or other embellishments instead of to ideas' (American Psychological Association 2010, 70) because they are inappropriate to scientific writing" (Caicedo 2011). In other words, the APA handbook says that scientific style is the only means to writing scientific articles, and that it does not involve any stylistic elements that are integral to almost every other form of writing, and are widely recognized as valuable and necessary communication devices. Caicedo also points out that in the APA's handbook instruction to avoid stylistic devices, they themselves use metaphor to condemn the use of metaphor and other stylistic devices. "aside from the obvious metaphors – alliteration, rhyming and poetic expressions can be heavy and expression strained or forced – that are used in the manual, the question that emerges is how an author would go about writing if he or she were to avoid language?" (Caicedo 2011). This question that Caicedo poses is one worth considering. Our language involves and requires metaphor and other stylistic devices. We know this from Lakoff. Why then, do we exclude these elements from our scientific language, unless we want to eliminate the possibility of outside influence or commentary on science? By excluding stylistic elements from our scientific language, we create a language in which most people are unable to speak, which effectively excludes non-scientists from the conversation. It also ignores metaphor's huge contribution to scientific dialogue and process. Caicedo quotes Thurén who lists examples of science's dependence on metaphor and other stylistic devices. One example is that of a black hole, which Thurén points out is neither really black nor a hole. This is necessarily a metaphor in that is says that this singularity is a physical hole that is black. This metaphorical name also gives the public a way into the conversation and gives us all a picture of something that is not able to be pictured. Caiedo points out that "all language is metaphorical even if many times the metaphors have settled down to the point of being called dead. In consequence, the scientific writer cannot but write metaphors" (Caicedo 2011). Perhaps our metaphors are so entrenched in our language that they have become the reality and are dead metaphors. Scientists still use these, and are constantly creating new metaphors to explain physical phenomena. Caicedo claims that all language is metaphor, and so if a scientist wants to write or speak at all, they will necessarily rely on metaphors. It is therefore silly for the APA handbook to instruct scientists to avoid metaphor. It is harmful to the field. Let us not avoid metaphor, but rather embrace its role in our discourse and think of ways to better use that tool and to place it in the hands of students.

However, we should be careful to emphasize that metaphor does not necessarily play the same role in scientific writing as it does in other forms of writing. Caideo argues that "metaphor and plot in a scientific article do not make things appear greater and nobler as in tragedy or lesser and baser as in comedy, but truer and steadier. Metaphor, at the level of the scientific article, is thus the bringing together into a statement of identity of a discourse that attempts to articulate itself. It is a transition from the unnarratable to the narratable" (Caicedo 2011). Metaphor in scientific writing serves to bolster and better flesh out arguments. It allows us to narrate that which cannot by itself be narrated, by letting us bring in outside elements in order to comment on the data. The role of metaphor in science is not as a detractor from the truth, but a supporter of the truth by better communicating the findings. When a scientist effectively communicates their findings, other scientists are able to structure their work accordingly. Science is a conversation, which implies that it is a storytelling, and also that it needs good methods of communication.

Metaphor is essential in spoken and written communication, therefore it makes sense that the "truthfulness" of scientific research should be directly correlated with its effective communication, and thus with its careful and illustrative use of metaphors. Caicedo also points out that metaphor in science serves to build a sort of scientific identity within a community that attempts to define and articulate itself. Science does not subject itself to outside commentary or criticism. Metaphor however, because it is prevalent and necessary in every field of study, provides some of this outside perspective, even as scientists claim that it is unnecessary in their scientific communication. Metaphor inherently brings with it a sense of the disciplines outside the sciences that have embraced its use, and thus inflects the identity making of scientific disciplines with a non-scientific perspective, and in so doing, breaking down walls between disciplines.

So what if scientific writing uses metaphors and is a form of storytelling? How do we then move forward? Caicedo suggests that, "the problem thus paves the road ahead by soliciting and making a solution possible. It destabilizes the equilibrium only to make possible the transition and stabilize it anew into a different equilibrium. It does so by demarcating the conceptual borders of the narratable" (Caicedo 2011). In other words, Caicedo suggests that the problem that scientists are concerned with, whatever that may be in specific subfields, is the way forward. Scientists have to face new claims, new ideas, and sometimes seemingly incongruent results, and they have to make sense of them. The problem a scientist sets out to answer necessarily frames the story of their research, and thus the story they tell in the article they write about their research. The problem is the entrance into the conversation, therefore it could also be the way out of it. Caicedo claims that a scientific problem destabilizes the equilibrium of the field. If that is the case, then the field is in a continually destabilized state. Science always has unanswered questions and problems to be solved. For example, physics has the question of how to merge general relativity and quantum mechanics. At this point however, that question is so woven into the field that it is no longer a destabilizing element. It has been woven into the identity of the field. If we allowed the question of the nature of the field and its interaction with metaphor to arise and be addressed, it would destabilize the field, allowing a new equilibrium to emerge where perhaps science interacts with other fields through the lens of metaphor, thus strengthening the discipline by allowing it to be subject to outside commentary.

An example, albeit old, of a paper that tells an explicit story is Sir Dyson and Prof. Eddington's 1920 paper titled, "A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations Made at the Total Eclipse of May 29, 1919" These observations were made in order to test Einstein's theory of General Relativity by determining the deflection of starlight in the sun's gravitational field. It is an important paper because it was the first experimental test of Einstein's theories and had the potential to either catapult the world into Einsteinian thinking, or to keep us squarely in the realm of Newton. But as you read the paper it feels quite different from current papers. The first sentence of the paper begins "The purpose of the expeditions was to determine…" (Dyson & Eddington 1920). From the very beginning this project is framed as an "expedition." In other words, a journey or a quest, both of which imply a cast of characters, a plot, and a destination. In modern astronomy papers, we call these "expeditions," "campaigns." Which in some ways implies the same sense of a quest as "expeditions," but is also widely accepted and thus just sounds normal to our modern ears. Expedition throws us for a moment.

The second striking difference between Dyson & Eddington 1920 and modern papers is the absence of citations in Dyson & Eddington. Rather than citing sources using a system like we use today, anyone who specifically helped or made the expedition possible is mentioned by name. This feels very different than modern papers because it adds a layer of humanness to the science. Hearing the names of the people who made the project possible makes it feel almost like you are reading a story rather than a scientific paper. Or at least, the line starts to blur. The citation system in modern papers removes the human from the citation, making it only a last name and a year. The important thing is the work, not the person who did the work. This makes modern papers faster to read and easier to focus on the science rather than the cast of characters involved. However, it also makes the papers seem more divorced from the scientists who did the work. On one hand the modern standard is good because it makes it easier to read more papers. On the other hand, because it removed the humans from the paper, it makes science seem as if it happens in a vacuum. It has the potential to confuse young scientists about the process of science. Modern papers make the process feel sterile and rigid rather than the messy human expedition that research typically reflects.

In Dyson & Eddington there are also details about weather and transportation that would be considered extraneous in modern papers. As weather is an integral part of observational astronomy, it makes sense why they included weather information. Also, as they had one specific date and one specific time at which they could make the observations of the solar eclipse, weather and cloud coverage become even more important. In modern papers however, while weather still has final say over whether or not you observe, details on weather are not often mentioned. The only instance might be if you need to explain gaps in your data that are caused by periods of bad weather. Dyson & Eddington also include details about the transportation of their observing equipment to the observing sites. Details about the trials of changing instruments or building new telescopes are not often mentioned in modern observational astronomy papers. The specific telescope and instrument used are mentioned, but not the process of building the telescope or instrument. An example of this is the Event Horizon Telescope that produced the first image of the event horizon of a black hole in 2019. To make their observations they had to install special equipment at all of the telescopes they used. However, the papers they produced do not detail the trials and tribulations of installing that equipment. It mentions that things were installed, but the description ends there. In Dyson & Eddington the extra weather and equipment details serve to further make the paper feel like a story and less like an impersonal report. It gives us a sense of a tangible setting and paints a clearer picture of the winding process of scientific research for the physics student.

In addition to the extra weather and equipment details, Dyson & Eddington also use vocabulary that would today be considered "flowery" and would not make it into the final paper. My favorite example of this is the phrase "wintry weather of February" (Dyson & Eddington 1920). This phrase is explaining that because of the cold weather in February, the telescope mirrors needed to be silvered in order to keep them at the proper temperature. Obviously, there must be a way to rephrase this more economically and without the descriptive adverb. But the adverb is there, and it serves its purpose. We understand immediately that the issue in question here is temperature. We could make the sentence shorter without the "wintry" but in the process we might lose a marker of meaning that quickly focuses the readers attention on the important concept, rather than making them parse through the whole sentence before realizing to what they need to pay attention.

Dyson & Eddington raises the question of why do our papers look the way they do now. What happened to remove the “wintrys” and the detailed description of various climates and the perils of transporting equipment by trains? I do not have an answer. I am sure some of it has to do with saving space and removing biases from scientific writing. In addition I fully support the modern citation system as it makes papers far easier to read than having to wade through the names of everyone who contributed to the project. However, what if we allowed for a bit of creativity and more blatant storytelling in our modern papers? What if there were allowed to be some seemingly superfluous adverbs that actually pointed the reader towards the important concept in the sentence or paragraph. What if scientific writing ceased to be a performance of such dryness and became instead the story it refuses to acknowledge. Any scientist knows that research is not a smooth process. There are multiple adjustments along the way and often a catastrophe or two. The data is rarely as clear as you expected and there are always more questions to ask. But you must publish sometime or you will ceaselessly continue to refine, test, and edit in pursuit of perfection. A scientific paper is like a piece of art in that way: never finished, only abandoned. Sometimes papers make this clear. They always admit to further research that is necessary to better answer the question. But they try to whitewash the messy process of research and the messy people doing the research and the messy biases that they cannot help bringing to the research. Science pretending to be clean is perhaps the biggest lie we tell young scientists in training. The world is not clean. Research is not clean. Science is not the hallowed way of approaching the world. Science is messy and oftentimes we are all fumbling in the dark trying to figure out with what exactly we are fumbling. A physics Ph.D. does not make you into a polished scientist in a sparkling white lab coat. Rather, it teaches you how to exist within the messy world of science and how to figure out your own way through the fumbling. So maybe we should teach our young scientist that science is a story, they get to be a storyteller, and metaphor is their currency. Teach them the rules of science writing and then teach them to use the rules to frame their lab reports as stories. Teach them to think about the metaphors they're using and how they serve the story they are telling. In other words, teach them to reclaim the practice of science and to make all the parts of it fun. This will allow other facets of life to begin to comment on and help articulate the scientific disciplines. It will also allow our young scientists to make the fumbling a journey, and perhaps find a way through that no one else ever dreamed was possible.

V. The Physics/Poetry Study

A black hole that is millions of time the mass of the sun looks like a fuzzy grey blob through a telescope. This too is magical.

...

When I was a sophomore, one of Regis's physics professors, Dr. Stephen Ray, asked me to have a meeting with him because I was going to be his TA the following semester and we had never actually met. He wanted to get to know me better, he said. So I met him in his office one afternoon and he suggested that we take a walk. We walked laps around Regis and he asked me about my story, why I was majoring in physics, and when he learned of my double major he asked about that too. So, I told him about how I felt like a poet and physicist, how the two mixed so naturally in my head, and how it did not always feel like it was right. I talked about how all I really wanted to do was end up as a physics professor and have a class where students and I explored the intersection of poetry and physics and what they can tell us about how we ought to live. I talked about how I wanted to teach and share my love of the stars with students. I talked about how I was trying to figure out a way to graduate early, because I did not feel at home at Regis and I wanted to leave as soon as possible. And Dr. Ray made me realize that I actually wanted to finish the English major. He made me realize that I can be a physicist and poet and in the real world, as well as the safe space of my head. And later that evening, when I was back in my dorm room struggling through Classical Mechanics homework due the next day, I received an email inviting me into the first stages of this thesis. Dr. Ray wrote “As I continued to think about our conversation, I do not see a reason why we couldn’t try out a research project about how literature can enhance a students physics experience or conceptual understanding while you are at Regis. Something along the line of picking a book to read throughout the semester and finding a way to quantify the results.” And with that, the Physics/Poetry project began.

The goal of the project has always been to determine if reading literature concurrently with taking an introductory physics class helps students to better adjust to the “physics way of thinking.” We define the “physics way of thinking” as the abstract, non-linear, multimodal way of thinking necessary for success in physics classes. The details of the project have changed since I was a sophomore. We have settled on having Introductory Physics I with trig students read four poems over the first four weeks of the semester and answer three discussion questions per poem. The students also take the Colorado Learning Attitudes about Science Survey (CLASS) at the beginning and end of the semester in order to see if their way of “thinking like a physicist” improves after reading the poems. The CLASS is a survey developed by the Physics

Education Research group at University of Colorado at Boulder and designed to examine and measure student beliefs about physics and learning physics (Adams et al. 2006)

I have been the TA for intro physics and astronomy labs every semester since my sophomore year. In that time I have gotten to work with many intro physics students, the majority of whom will not continue in physics and will probably try their best to forget the experience as soon as they take whatever entrance exams are required for their graduate school of choice. These students are bright, curious and oftentimes by the end of the class are sick of physics, but at least know how to exist successfully in a physics class. I firmly believe that even if they forget every bit of material they learned in their intro physics class, the critical thinking skills and way of thinking they learn will serve them for the rest of their lives. Physics classes are hard, especially for non-physics science majors, because it requires a way of thinking unlike their other classes. To succeed in their non-physics science classes these students are accustomed to memorizing and recalling information. To varying degrees, they are used to clear rules for how to classify information and solve a problem. They bring this mindset with them to their introductory physics courses, and many students have difficulty switching to the specific type of thinking that success in physics courses requires. The "physics way of thinking" requires non-linear thinking, synthesizing multiple pieces of information, and use of multiple representations. (Kohl 2008, Reddish et al. 1998, Docktor & Heller 2009). To reap the benefits of the physics way of thinking (superior analytical and problem-solving skills) students have to be able to enter into the physics way of thinking and hold onto it after the class ends. But this is hard and many students have a difficult time with it. As a result, there are many students who go through an introductory physics course without really understanding the material or gaining the analytical and problem-solving skills that learning physics fosters. If students could become comfortable with non-linear thinking, synthesizing multiple pieces of information, and use of multiple representations through a more familiar medium than physics, they might have an easier time adjusting to their introductory physics course and as a result, their gains in analytical and problem-solving skills will increase. Enter poetry.

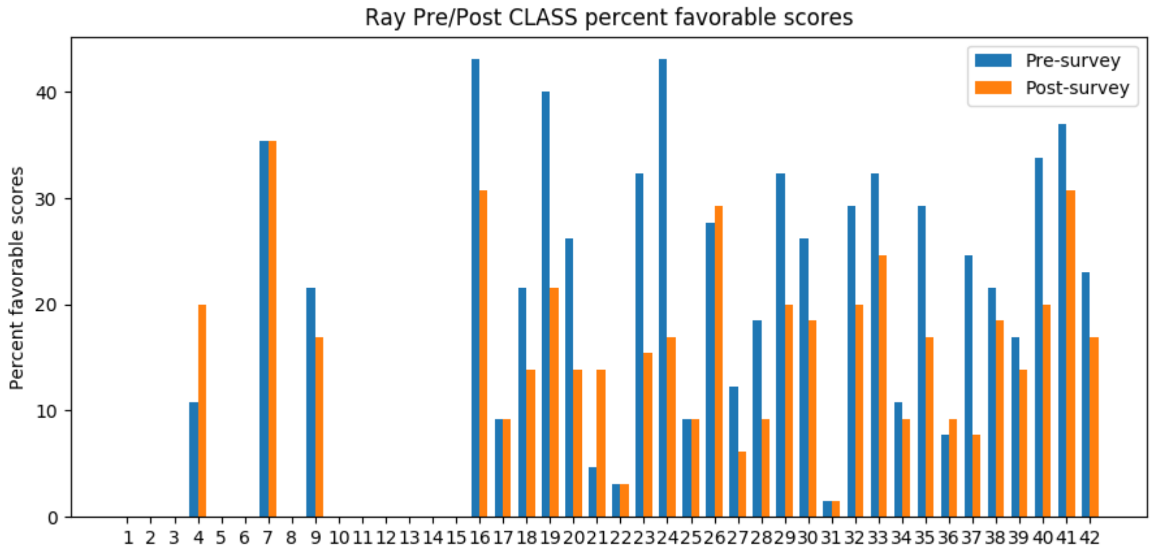
I chose the four poems from a variety of poets, time periods, and styles. Each poem was selected for its ability to elicit the non-linear thinking, synthesis of multiple concepts and pieces of information, and use of multiple of representations necessary for success in a physics class. I also tried to keep the poems relatively short so that they did not intimidate the students. I chose “The Emperor of Ice Cream” by Wallace Stevens, "Hyla Brook” by Robert Frost, “Ode to Broken Things” by Pablo Neruda, and “A still—Volcano—Life” by Emily Dickinson. The students read the poems in that order. One of my favorite parts of this project was spending afternoons reading poems trying to find the right ones. Poetry is the Titanic and I am constantly getting lost in it, convinced that I can postpone the sinking by building a net of words not my own.

Why poetry? My first answer is, why not? My second answer is because it is possible that poetry can help students adjust to “the physics way of thinking.” There have been studies examining the effect of the arts on scientific creativity and success (Root-Bernstein et al. 2008, Gurnon et al. 2013) as well as studies examining the similarities between scientific and artistic creativity (Neumann 2007). Reading and analyzing poetry engages non-linear thinking, synthesis of multiple themes and pieces of information, and it especially engages the use of multiple representations through, among other things, metaphor. Because of this, having students read and analyze poetry as they take Introductory Physics could help them to more quickly adjust to the physics way of thinking. As a result, students could experience greater gains in their problem-solving skills and analytical skills than they would have without the poetry. In other words, poetry could be an antidote to the problem of students struggling to adjust to their physics classes.

So, with IRB approval, we introduced poetry into the physics classroom. Between Texas State University (Dr. Rays current institution) and Regis, I had 79 full participants in the Physics/Poetry study over two years. Those students read the poems, answered the discussion questions, took the CLASS, and learned physics.

Below are our initial results, for each classroom in which we conducted the study. We have not yet performed statistics on the data, so we are not able to present a conclusive result. What we see here suggests that there is not a conclusive favorable shift, though there seems like there might be a favorable shift for specific questions. We define a favorable shift as students answering more of the questions correct in the post survey than the pre survey.
However, there are enough issues in this data set that it would have been hard to conclusively determine a significant favorable shift. But now we have a better idea of how to do the study differently in the future in order to be able to conclusively determine the effects of poetry on student's adjustment to physics.

(The plots on the next page show student answers in the different classrooms for each question on the CLASS, divided into the pre-survey and the post-survey.)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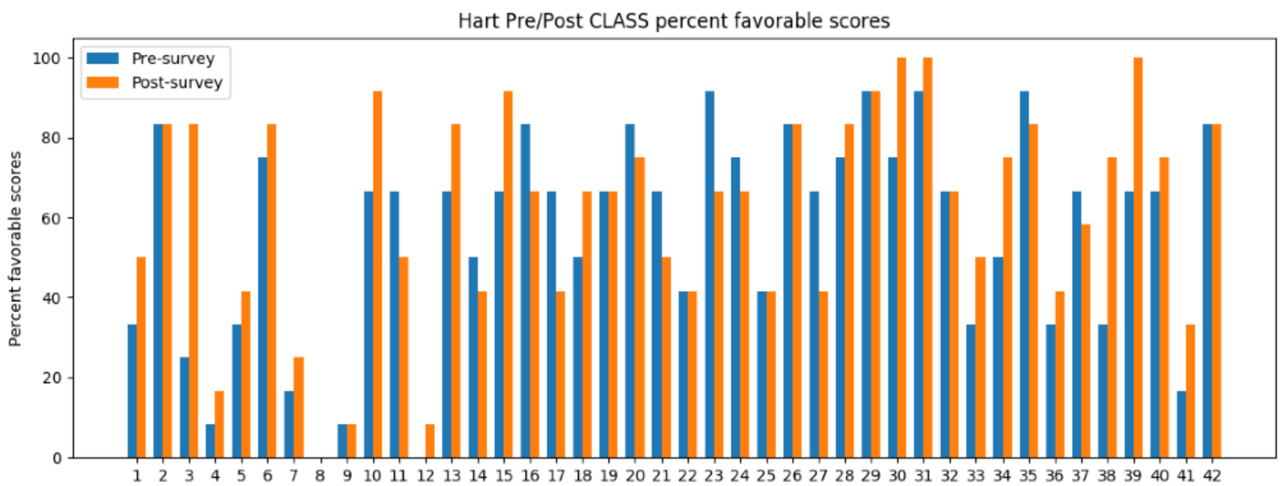
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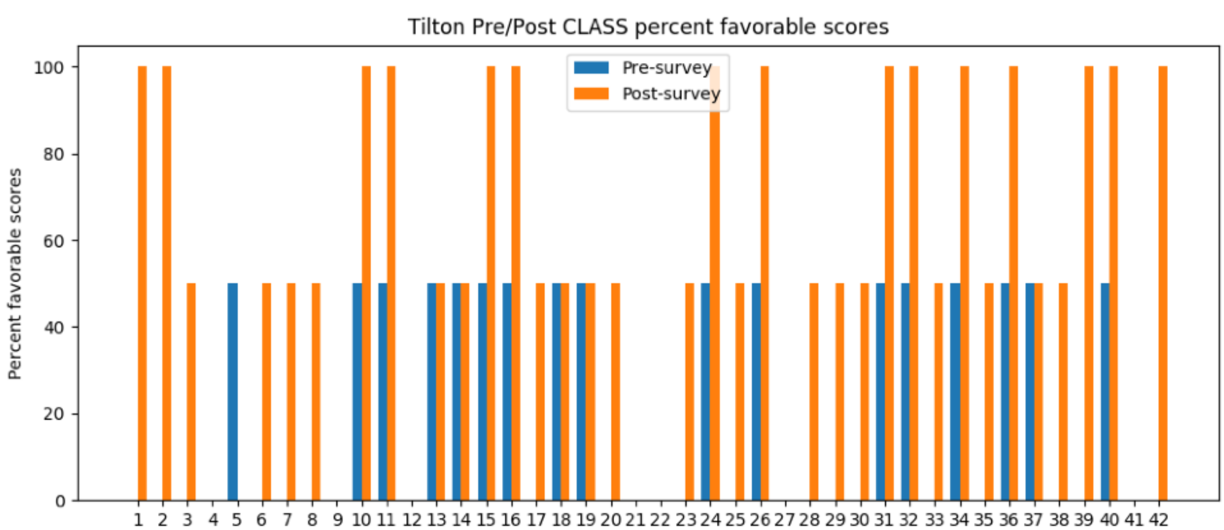
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Dr. Ray's Introductory Physics I with trig classes at Texas State University comprised our largest number of students who participated in the study. 65 Texas State students participated in the study in the fall of 2019, reading the poems, answering the discussion questions. and taking the CLASS at the beginning of the study and at the end of the semester. However, when I started to go through the CLASS data, I realized that none of the students answered every question on the survey. Most of the students answered a little more than half of the questions. This makes it nearly impossible to determine if there is a favorable shift in the overall class population, because the number of participants changes for each question. We will have to examine the data question by question and determine if there were enough participants for that specific question to show a significant favorable shift.

At Regis, we had two classrooms participate. Dr. Evan Tilton's and Dr. Quyen Hart's Introductory Physics I with trig classes participated in fall of 2018. These students consistently answered every question on the CLASS, but the number of students participating was small: 2 and 12 respectively. This few of participants make it difficult to determine if there is a favorable shift.

In other words, when we look at the raw data it seems as if certain CLASS questions show a favorable shift after the students undergo the poetry reading portion of the study. But without running statistics on the data it is not possible to determine if the favorable shift is conclusive. We also know that there are issues with our data set that will require special treatment before we can say if there is a significant favorable shift. In addition, even if we see a significant favorable shift in the data, it would be difficult to conclusively say that it is due to the poetry reading. In order to better tease out the exact effect of the poetry, we would need to conduct interviews with students. Most education research studies that use surveys such as the CLASS also use interviews to determine if the particular teaching method they are testing was successful.

Whether or not this study shows conclusively that poetry helps students to adjust to the physics way of thinking, it is still a useful exercise in what an interdisciplinary physics classroom might look like. Poetry is not often, if ever, used in physics classrooms. But why? It takes no more than two minutes to begin class by reading a poem. Asking students to write haikus about a physics concept on their homework sets is an easy way to give them an extra point and get them thinking in metaphors. The heart of physics is its ability to inspire wonder. The way to do this is through words. Let us give physics students metaphors. Read them poetry, ask them to read the poetry themselves, teach them to wield metaphor as one of their greatest tools in the physics classroom, and everywhere else as well.

VI. Conclusion

My little brothers like to tell me that physics is useless in order to get a reaction out of me. It works every time and I start pointing at all things surrounding them, the lights, the refrigerator, their phones, their bodies, and I exclaim: "it is all physics!" As if those are the magic words that God used to speak this universe into being, as if I recreate this world every time I recite Newton's laws, as if I myself, am sometimes one with the creator, and as if I am the only physicist to do so in the history of time. Spoiler alert: I am not.

…

To the Physicists:

The work you do is important. Not just because it allows us to create cool things or have electric lighting, but because your work is trying to understand this world and universe we all inhabit. The work you do is important because it reflects the questions you find most interesting. It is important because you have learned to speak a different language than the rest of us and you get the wonderful, humbling task of learning to translate it into language we can all understand. Sometimes this is with a picture. Sometimes it is with words. It is the attempt that matters.

The work you do matters because you are a person behind the work. You are the one asking the questions. This universe does not require your questions. But you ask them anyway. You ask them with all your interests, experiences, and biases standing behind you. And you try to answer them without any of that baggage. Do not, however, forget their role in the asking.

There are no questions without metaphor. There is no understanding without metaphor. There is not a way to position yourself within this world without metaphor. Every time you speak you rely on metaphor. Remember this too.

…

To the Physicists in Training:

Your job is to learn. Learn the accepted ways of approaching problems. Learn all the rules of physics that we know. Learn how to speak about science in front of people: scientists and non-scientists alike. Learn to teach children how to think like a scientist. They might never use it in a lab setting, but the process of developing and testing an idea will serve them well. Realize that you are not defined by your research or your classes. You are made up of so many experiences and desires. Carl Sagan said we are all stardust and he was right. You are literally made of elements formed in stars and you are figuratively made up of the same corners of this earth as everyone else. We are all compilations of matter and interactions and our strength is in our particular compilation. All of this is to say that you should nurture all your interests. By all means, be the best physics student you can be, but also be the best musician, poet, athlete, dancer, video-gamer, reader, speaker, and person that you can be. Be a full person. Scientists are not robots. Papers do not come from a sterilized mind, though they may seem to at times. They are written by humans with competing interests and desires and it is only in the presentation that all the human is stripped away.

…

To Everyone:

None of what I have written is confined to the discipline of Physics. We all use metaphor in every sentence we speak, and every space has some metaphors that it allows and some that it does not. Every space has some types of people that it allows and some that it does not. The fact that I often feel different than the other English majors in my classes shows that English also has a script dictating what kind of person makes a good English major. We see this in politics, in medicine, the arts, business, teaching, cooking, sports, and the list goes on. Think of those examples and picture what a person in that field looks like. We all probably have similar pictures. Perhaps the particulars are a little different, but in our heads doctors are smart and wear white coats. Business people wear suits. Politicians are intense. We say that anyone can do anything and yes, maybe that is true. But not everyone can do everything as themselves. Not really. Our collective archetypes of various kinds of people dictate what roles those people have to play. And if you do not happen to fit into the mold set for you by the field, then you spend your career justifying your presence in that space. Think of women entering into the workforce. A woman can do any job a man can do, but she cannot always do it as herself. Think of our stereotypical notion of nurses as female. A male nurse enters this space where the expectation is to be female and he has to justify his existence in that field as a masculine person.

Particular fields certainly are more open to including multiple types of people. The arts pride themselves on individual expression so there is more individuality embraced in that group. But this has its own problem. An aspiring artist might feel the need to become more unique or eccentric in order to successfully enter into the field. And that blocks their particular brand of creativity. Art needs the ordinary just as much as it needs the extraordinary.

Perhaps the way forward is collaboration. Let the physicists write poetry, tell their classrooms about their poetry, make haikus out of equations. Let the politicians cook and run and cry and love reality television. Let them read popular science. Let the artists dress like every other Millennial. Let the scientists learn to communicate their work to non-scientists. Let the public bask in the image of the black hole produced by the Event Horizon telescope, and let those astronomers figure out a way to explain long baseline interferometry so that we can all enter into the true wonder of the image. Let us embrace the psychologists and not dismiss their work as a soft science. Let us still remember that specialization is important and necessary. I will never make a career as a poet if I want to make a career as an astronomer. But I can talk to my poet friends about the questions I am currently pondering. I can listen to their perspective, listen to how they do work, wonder if their methods could work for me, try new things, and decide if they are worthwhile. I am a scientist after all—experimentation is what I do.

You can listen and not do. You can ponder and then reject. You can offer advice and they do not have to take it. The only requirement is listening. Let the poets tell the scientists if their way of proceeding makes sense. Let the scientists tell the poets if their writing processes are optimal. For now, neither party has to change, they only have to listen.

…

There is something on the other side— I don't know what,

but light bends around massive bodies like wrinkled sheets,

and we can see around the moon, the sun, blow it all out—

and all of your springtimes disheveled, and all of your winters,

one winter.

—Theodora Zastrocky

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