The Creation of “Entangled”: Employing the Filmic Narrative to Explain the Differences between Classical and Quantum Mechanics

by

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The principles of quantum mechanics have begun to supplant those of classical mechanics in scientists' attempts to understand the universe. Sharing this new quantum worldview with the public is imperative to promoting a common understanding of the underpinnings of the reality we function in and struggle to navigate. Where the complexity of the math involved in interpreting particle physics has estranged a larger community of thinkers, this project intends to cultivate this larger community by utilizing video entertainment, art and story instead of math to explain the basic principles of quantum mechanics, and the fundamental differences between quantum and classical mechanics. The fairy tale format has historically demonstrated its ability to provide the creative flexibility and educational structure necessary to capture the emotional investment of, and impart knowledge to, a diversely aged audience. However, to create a filmic narrative with the educational goal of explaining high

physics without math, three questions require attention. Firstly, how can a storyteller explain scientific phenomena that occur abstractly? This question leads to the next: How can the qualities of fiction film be exploited to beget an understanding of quantum mechanics without allowing the field's mathematical parameters to impair necessary developments in the narrative toward a powerful resolution relevant to a human audience? And finally, are slight discrepancies, such as in the over-simplification of complex probability equations, ethical in a fiction film advertising itself as scientifically accurate? Answering these three questions through scholastic investigation led me to the conception of the short film “Entangled,” which takes quantum mechanical principles and weaves them metaphorically into a fairytale animation with a cultural and historical familiarity.

Acknowledgements

I would like to express my heartfelt gratitude towards Professor Mossberg, for her abiding support and precious guidance in the creation of this atypical thesis project that strives to fuse two spheres society likes to think separate to its detriment – namely, science and art. Her understanding of the importance of narrative and imagination to the development of human civilization has steered this project in the best of directions. I would also like to deeply thank Professor Richard Taylor, for his detailed examination and input on how to appropriately translate the specifics of quantum mechanics into a metaphorical universe. Without his guidance who knows what technical pitfalls may have traumatized this fairytale. This film also could not have reached its potential without the meticulous insight of Dr. André Sirois, whose expertise in sound mixing made up for my lacking sound skillset that displayed itself very clearly in the first cut. Furthermore, I have the greatest of gratitude towards my many sponsors, cast and crew who helped make this exhausting animation a reality, and a work that I can share with the world via film festivals in 2016 and 2017. And finally, I cannot thank my parents enough, for literally being the best supporters a daughter could possibly ask for. So for all of the times something went wrong in this process and you were there to help get me on my feet again – whether it be with equipment, a contact, or just a piece of Sweet Life pie– my love for you spans every spatial and temporal dimension. I hope this project makes it far enough to make you proud. I love you.

You're an interesting species. An interesting mix. You're capable of such beautiful dreams, and such horrible nightmares. You feel so lost, so cut off, so alone, only you're not. See, in all our searching, the only thing we've found that makes the emptiness bearable, is each other.

The extraterrestrial in *Contact* (1997)

I credit this film with instigating my severe curiosity in science at age ten, at which age I came to realize that *Harry Potter* and physics were the same thing.

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List of Accompanying Materials

1. The temporary link to the short film “Entangled” while it is in the festival stage through 2017. After the festival stage it will most likely be locatable by its title on Vimeo.

https://drive.google.com/open?id=0B0gkIImkAKIiQnBDdDBFcWZaeGc

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Introduction

This project is an effort to synthesize the technical and theoretical skills I have attained through my studies of applied physics and film over the course of my undergraduate career. Struck by the success of the collaboration between renowned astrophysicist Kip Thorne, film director Christopher Nolan and screenwriter Jonathan Nolan in the production of *Interstellar* (2014), I endeavored to fuse physics and film in a similar manner. I produced the short animated film “Entangled” that utilizes the fairytale narrative format to explain the differences between classical mechanics and quantum mechanics, and the ramifications of each theory.

However, the development of such a project proved arduous as I came to face three dilemmas in the attempt to bridge the gap between hard science and filmic storytelling. The consequences of quantum mechanics may be macroscopic, but only subatomic and microscopic particles play by the theory’s rules. This quality of smallness may be the factor that has resulted in quantum mechanic’s restricted or inaccurate portrayal in past filmic narratives. Thus, the first question arose: How can a storyteller explain scientific phenomena that occur on an invisible scale? This question lead to the next: How can the qualities of fiction film be exploited to beget an understanding of quantum mechanics without allowing the scientific parameters to impair necessary developments in the narrative? This inquiry then necessitated the final question: As a fiction film advertising to be scientifically accurate, are slight discrepancies from fact ethical?

Before constructing a hard-science narrative that would simultaneously entertain and educate, I had to make three scholastic investigations that would address, if not answer, the mentioned three questions. The first of these investigations involved a review of the instructive methods employed by respected scientists and science writers to explain non-relativistic quantum theory to a lay audience; consulting the arguments of scholars and science popularizers concerning the necessary creative flexibility of educational fiction became the second point of scholastic research; the third and final task comprised of an analysis of the visual techniques, plot devices and degree of scientific rigor exercised by films considered hard-science fiction. I then built the narrative of my film on principles of quantum mechanics in a manner that incorporated my findings on how to make negotiations between science and art, ethics and entertainment. Ultimately, these investigations revealed that strong plot adherence to a set of scientifically-recognized technical rules chosen specifically for the story world generates a simultaneously educational and entertaining narrative.

A Note on Project Importance

Several arguments can defend the value of this project's endeavor. Firstly, the principles of quantum mechanics have begun to supplant those of classical mechanics in scientists' attempts to understand the universe. Sharing a new worldview with the public is imperative in promoting a common understanding of the underpinnings of the reality we function in and struggle to navigate. Visual entertainment has proven to be one of the most effective modes of communicating complex ideas to a lay audience. Moreover, quantum mechanics drives the operation of present electronic technology, and will allow for the future creation of machinery such as supercomputers and possibly even teleportation devices.[1] A film that explains the mechanics of quantum machinery currently integrating itself into the flow of human civilization will help encourage a public interest, understanding and curiosity in said mechanisms. The iPhone becomes more than a magic box.

Secondly, projects like this support the development of a scientifically literate public with voting power. When asked what a step might be towards a brighter future for the human race, Neil Degrasse Tyson, probably the most renowned science popularizer of the decade, responded that we need to "elect scientifically enlightened leaders. […] I want them to know what to do when we run out of energy. […] If we elect people just because we think we like their personality, then the civilization is doomed – doomed to return to the cave. That's not where I want to go."[2] Making science accessible through storytelling helps foster a society able to make informed decisions that have planetary impacts.

Thirdly, this project will add a missing, albeit small, piece to the library of hard science fiction in two ways. In my research so far I have not found a fiction film that strives to accurately or thoroughly incorporate quantum mechanics into its narrative. Thus the project by nature treads on new ground. But it is also worth mentioning that "hard SF is a largely Anglo-American and masculine production."[3] As a female filmmaker with technical training in physics, I hope to demonstrate the ability of

[1] *Fabric of the Cosmos*, performed by Brian Greene (2011; PBS), DVD.
[2] Rachel Carnes, "Look Up: Or look down – Neil deGrasse Tyson wants you to be scientifically literate," *Eugene Weekly. Com*, last modified June 2, 2016.
[3] David N. Samuelson, "Modes of Extrapolation: The Formulas of Hard Science Fiction," *Science Fiction Studies* 20 (1993), accessed July 26, 2016.

women to tackle complex science concepts in story form. If this production were successful, it would speak to the boons of integrating artistic and scientific disciplines perceived to be opposed, and the value in encouraging a diverse group of storytellers to engage with hard science.

Literature and Film Review

Producing an effective fiction film that explains the fundamental concepts of quantum mechanics necessitated the study of three bodies of work: educational media that strives to achieve the equivalent goal, scholastic literature analyzing hard-science fiction in opposition to soft-science fiction, and hard-science fiction films themselves. This chapter is divided into discussions according to these three research areas.

Educational Material

A large body of educational media aiming to demystify quantum mechanics for the layperson exists in the form of pop-science books, documentaries, TEDx talks, websites, and informational animations. Each creator chooses a different manner of representing the abstract phenomena. My understanding of how to strip the math-laden concepts down to visuals and thought puzzles has arisen from these works.

Theoretical physicist and science popularizer Brian Greene breaks down electron spin, wave-particle duality, the Many Worlds Interpretation and quantum entanglement in the NOVA documentary *Fabric of the Cosmos* (2011) successfully through classical analogies. For example, he relates the randomly generated spin of an electron to the motion of a spinning number wheel.[4] Note that factors such as the torque imparted on the spinning arrow by the spinner's hand, gravity, and the amount of friction between the arrow and the backboard would make the arrow's final destination classically predictable. Yet Greene ignores this analogy flaw, proceeding to utilize the general association of a spinning number wheel with randomness to allow the audience

[4] Electron spin is an intrinsic, random property of an electron. Two electrons are allowed per set of spatial quantum numbers, one with spin "up" (+1/2) and one with spin "down" (-1/2).

to connect a new, strange concept to a familiar idea. Greene also explains how the double-slit experiment evidences wave-particle duality by contrasting how a bowling ball and a water wave interact differently with a barrier with two openings.[5] Here the known properties of classical objects again help illustrate the more abstract and subatomic properties of particles. In a similar fashion, physicist Leo Kouwenhoven has related the superposition of states to the blending of colors in his Ted[x] presentation that breaks down his experimental work on quantum entanglement.[6,7,8] Thus both Kouwenhoven and Greene's explanatory tactics suggest that tying abstruse theoretical physics concepts to simple phenomena witnessed in daily life encourages a public comfort with science concepts that a lay audience might otherwise shy away from.

Taking advantage of the global Internet platform, both the popular YouTube science communicator Derek Muller and the French team "Physics Reimagined" strive to present quantum mechanics to an international web audience with exciting visuals and analogies dependent on the understanding of very little math. For example, Muller anthropomorphizes electrons to provide the abstract concept of electron spin with a fun

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[5] The double-slit experiment demonstrates the simultaneous wave-like and particle-like characteristics of light, or photons. In essence, a coherent light source is aimed at a plate with two parallel slits. The light travels through these slits and hits a screen behind the plate. If light were made of classical particles, then just two light bands would show directly behind the slits on the plate. But instead, the light creates an interference pattern of dark and light bands on the screen due to the wave-like nature of the light that splits into two waves that interfere after passing through the plate. Yet the light demonstrates a particle-like quality as well since the light is absorbed by the screen at discrete points. This experiment was first performed by Thomas Young in 1801.
[6] Superposition is the term used to describe the capacity of a quantum object to be in two or more quantum states simultaneously when the object's states are unmeasured.
[7] Quantum entanglement is a phenomenon whereby the corresponding states of two or more quantum objects can only be described together as a system. The details of this phenomena will be described in the "Science of 'Entangled'" section.
[8] Kouwenhoven, Leo, "'Spooky' Physics: Leo Kouwenhoven: TEDxDelft," YouTube video, last modified November 28, 2011.

and relatable visual in his YouTube Veritasium video "Quantum Entanglement and Spooky Action at a Distance."[9] Meanwhile, the Laboratoire de Physique des Solides team behind "Physics Reimagined" began the website quantummadesimple.com to share minimalistic animations and artistic, three-dimensionally modeled visualizations of phenomena such as state superposition. The contemporary and user-friendly website design only enhances the appeal of learning higher physics ideas.

Yet a discussion of educational tools that function to demystify quantum mechanics could not be complete without the acknowledgment of the first tool of its kind – the gedankenexperiment. "Gedanken" is the German word for "thought." Thus a gedankenexperiment is purely a "thought experiment." Because many of the concepts pertaining to this field are mathematically abstract and difficult if not impossible to test, theorists must sometimes teach and debate through thought puzzles rather than physical experiments. The founding fathers of quantum mechanics heavily utilized the gedankenexperiment to reason through strange mathematical findings.[10] These thought experiments are useful teaching instruments in their emphasis on logic rather than high math. Moreover, they require the development of a scenario and the process by which a quandary might be approached. In effect, they become culturally memorable because they tell a story. The popularity of such gedankenexperiments as Albert Einstein's twin paradox and Erwin Schrödinger's cat-in-a-box speaks to the value of teaching science

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[9] Veritasium, "Quantum Entanglement & Spooky Action at a Distance," YouTube video, last modified January 12, 2015.

[10] The founding fathers of quantum mechanics included men such as Max Planck, Niels Bohr, Werner Heisenberg, Louis de Broglie, Arthur Compton, Albert Einstein, Erwin Schrödinger, Max Born, and others.

through narrative.[11] Due to its influence on my final film, I will quickly walk through the historically infamous Schrödinger's cat experiment and its implications.

In 1935, the Austrian physicist Schrödinger shared his cat-in-the-box puzzle to delineate the absurd flaws in the Copenhagen Interpretation, or the standard interpretation of quantum phenomena that dominated the intellectual landscape from its inception in 1930 well into the 1980s.[12] The Copenhagen Interpretation, promoted most strongly by Danish physicist Niels Bohr, implies two difficult concepts: Firstly, that human observation is required for the manifestation of a singular, certain reality; and secondly, that Schrödinger's wavefunction collapses upon measurement.

Schrödinger's wavefunction essentially describes the probability of an electron (or any particle) having a particular property prior to measurement. Before looking, the electron of interest could be on the experiment screen, or it could be near Pluto (or anywhere for that matter). The quantum state prior to measurement is referred to as "superposition" due to a quantum particle's simultaneous existence in multiple, if not infinite states. Thus the probability wavefunction accounts for all possible quantum states of being. Bohr claims under the Copenhagen Interpretation that the human act of observation is necessary and responsible for the collapse of this wavefunction into a single spike - the manifestation of only a single reality. Yet this accepted interpretation ignores at least two astounding flaws in its design. It suggests that conscious beings are

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[11] Albert Einstein developed the twin paradox to demonstrate the time dilation effects of special relativity. In essence, if one twin remains on Earth while the other twin leaves on space journey travelling very fast (close to the speed of light), the space twin will return to Earth younger than the twin who remained on Earth. This phenomenon is the result of time dilation, whereby time moves more slowly for the twin on the fast-moving spaceship relative to the twin on Earth.

[12] John Gribbin, *Schrodinger's Kittens and the Search for Reality: Solving the Quantum Mysteries* (New York: Little, Brown and Company, 1995), 14.

necessary to make the world "real," and it fails to question why only one out of infinite realities realizes itself. Schrödinger attacked the first glitch with his cat conundrum as follows.

Imagine a closed box with a single electron inside of it. Without looking, the electron has an equal probability of being anywhere within the box so that its probability wave fills the box uniformly. Still without looking, place a partition in the box that divides the box in half. The electron's probability wave distribution is now equally split between the two halves of the box so that there is a fifty-fifty chance of its existence in either side of the box. If an observer were to look inside the box, the electron would immediately become "real" at a single location in one side of the box. Thus the Copenhagen Interpretation bizarrely dictates that, "the observer is responsible for the reality of the electron existing in one half of the box or the other."[13] However, the peculiarity of this claim only grows when the unopened, partitioned box is placed within a closed, windowless room with a cat, and an electron detector connected to an apparatus that will fill the room with poisonous gas if it detects an electron. No human is observing the closed room.

Now, imagine that one half of the box is opened so that if the electron were in the opened half of the box, it can now escape. In this case the detector will detect the electron, trigger the poisonous gas, and kill the cat. Upon detection the electron's probability wave should collapse and the cat's unfortunate fate should be 100% determined. However, according to the Copenhagen Interpretation, "because the electron detector is itself composed of microscopic entities of the quantum world

[13] Gribbin, *Schrodinger's Kittens*, 20.

(atoms, molecules, and so on) and the interaction with the electron takes place at this level, the detector is also subject to the quantum rules, including the probability rules."[14] In this light, a human observer would have to look inside the room to determine reality. The moment of observation would cause the electron to choose which half of the box it is in, then the detector to decide if it sees the electron or not, and ultimately the cat to choose whether it is dead or alive. Hence before a human has looked inside the room, the cat is simultaneously dead and alive in that it has not chosen a state of existence yet. This conception is rather absurd not only for its suggestion of a zombie-cat, but because it unfairly distinguishes the human from everything else within the universe. A human is also made up of the same microscopic entities as the electron detector, and is no more "conscious" than a cat in its ability to observe and analyze its environment.

In this way, the cat-in-the-box gedankenexperiment demonstrates the value of storytelling in scientific argumentation. Schrödinger developed and worked through a scenario to point out flaws in an unquestioned theory. His choice to replace partial differential equations with a simple setting, characters and plotline even allows for non-physicists to appreciate the trickiness of quantum mechanics. An average human might not be equipped with the tools to break down Schrödinger's equation, but an average human will probably remember a zombie-cat in a windowless room. This cat-in-a-box experiment also exhibits the necessity for creativity in furthering science – whether or not that requires thinking outside, or inside the box.

[14] Gribbin, Schrodinger's Kittens, 21.

When taken together, educational media that works to demystify quantum mechanics through simple visuals and thought puzzles has aided in generating a public understanding and interest in a fundamental physics field of study. However, the simplification of high math can come with a high price. Concepts broken down by physicists versed in the language of their field can then be reworked by non-physicists in a game of telephone until the original science becomes unrecognizable. Additionally, the philosophical quandaries that accompany quantum mechanics and require conjecture make the field susceptible to manipulation to fit a particular agenda.

The 2004 cult-classic film *What the Bleep Do We Know!?* (*WBDWK*) exemplifies these two dangers in presenting math-based subjects without math. Mixing narrative, documentary and animation, the filmmakers argue that a spiritual link exists between consciousness and quantum physics that allows for the creation of one's desired reality through positive thinking. The film's official website whatthebleep.com touts "a host of top scientists and mystics who serve as a modern day Greek chorus. Their wisdom and ideas are woven together as a tapestry of truth." Yet many "top scientists" have argued that *WBDWK* could not be farther from the "truth" in its deformation of quantum mechanics, instead finding the public's enrapture with the hit film its most frightening effect. Simon Singh (PhD in particle physics from Cambridge University) rants "I have spent my entire working life either doing science or conveying its meaning and beauty to the public. Consequently, I despise *What the Bleep Do We Know!?*, because it distorts science to fit its own agenda, it is full of half-truths and misleading analogies."[15] One of those misleading analogies is the simple but largely

[15] "The minds boggle," *The Guardian*, May 16, 2005.

erroneous relation placed between a basketball and a quantum particle. Clive Greated (Professor of Fluid Dynamics in the School of Physics at University of Edinburgh) points out that the scenes in which the boy, Reggie, wants Amanda to play basketball with him heavily suggest that an object as large as a basketball has quantum properties. Yet in reality, "quantum effects at large scales are extremely small and the motion of an object like a basketball is almost perfectly described by classical physics."[16] Other examples of contorted science abound in the film, such as Masaru Emoto's nonreplicable experiments on water molecule structures.[17]

The filmmakers deploy pseudoscience as an instrument to validate their metaphysical agenda. It should be noted that JZ Knight, the founder of the Ramtha Cult, sponsored the film. JZ acts as a "channeler" for "Ramtha," a dead warrior from Atlantis.[18] As Richard Dawkins (Charles Simonyi Professor of the Public Understanding of Science at Oxford) notes in his denouncement of the film, "Thirty-five thousand years in the grave have not dulled Ramtha's business sense: he charges $1,000 per counseling session. Poor JZ has her work cut out."[19] Ultimately, the film relies on flawed quantum mechanical conjecture to authenticate a brand of spiritual thinking and endorse the Ramtha Cult. *WBDWK* demonstrates the potential for math-less representations of this branch of physics to be easily distorted and serve a politicized purpose.

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[16] "The minds boggle." *The Guardian*.
[17] Masaru Emoto was a Japanese researcher who performed an experiment in which water in glasses was exposed to media with negative or positive connotations. He then examined the crystalline water structures, and claimed that exposure to negative or positive "energies" resulted in the structures' ugly or beautiful aesthetic quality. His experiment has not been repeatable, denying it any scientific basis.
[18] "The minds boggle." *The Guardian*.
[19] "The minds boggle." *The Guardian*.

In all, an exploration of educational media created to garner the public's basic understanding of quantum mechanics and its implications has exposed the program's delicate nature. However, it should be safe to say that media producers with technical training in said field who re-visualize high-math-based concepts for the sole purpose of fostering a stronger scientific community are the safer sources of education.

A difference exists between the types of creativity utilized in Schrödinger's cat experiment and *WBDWK* that needs to be acknowledged before attempting to create educational media that breaks down quantum mechanics. Schrödinger's imaginary scenario merely takes the rules set by the Copenhagen Interpretation and tests their limits by burdening them with interesting combinations of variables such as a cat, a door, and an electron. *WBDWK*, on the other hand, discards the physical rules, instead hopscotching through quantum concepts to support a non-scientific agenda under a scientific pretense. For example, the filmmakers make an unfounded jump from the Many Worlds Interpretation (MWI) and quantum uncertainty to the potential for a human to reach their ideal reality through positive thinking. MWI merely suggests that Schrödinger's wavefunction does not collapse upon the measurement of a particle's particular property; rather, every possible reality allowed for by the probability wave function manifests itself in a branching parallel universe. So far this claim has not been testable, and is only one of a number of leading alternative theories to the Copenhagen Interpretation. Yet its inability to be tested makes it an attractive piece of malleable science to weave into a metaphysical argument. The argumentative jump from MWI to the actualization of an ideal reality through the power of thought contains many, many intersecting problems not worth breaking down here. Based on a comparison of

WBDWK with Schrödinger's gedankenexperiment and the other quantum visualizations explored previously, a successful piece of educational media should allow creative analogies to arise from the rules set by the science. Establishing guidelines that ensure creative offshoots directly parallel the math is a necessary process if the goal is to teach scientific concepts with an acceptable degree of accuracy.

Scholastic Commentary on Hard (and Soft) Science Fiction

A different relationship and set of expectations exist between a science fiction author and her audience in comparison to those between a producer of educational science media and his audience. Where the latter teacher-student relationship dictates a high degree of trust in the presented material's factual basis, the former storyteller-audience relationship presumes a degree of factual elaboration. The extent of scientific embellishment an audience will tolerate depends where on the soft-to-hard sci-fi spectrum the work claims to be. Thus both *Star Wars* and *Star Trek* are celebrated works of sci-fi though they contrast highly in stringent attention to science known at the times of production.[20] Because my thesis objective is to teach through fiction, I tread on dangerous ground in terms of knowing when the needs of the narrative direction allow for disregarding scientific parameters. The next step then toward designing a filmic narrative that simultaneously teaches and entertains requires an exploration of the structural differences between soft and hard science fiction, and the merits and drawbacks of each subgenre. A historical perspective on the decisions writers have

[20] Berlin, Jeremy. "'Star Trek' Is Right About Almost Everything." *National Geographic*, June 16, 2016.

made in compromising science for story and vice versa should illuminate how to proceed with my own piece of fiction with specific educational goals.

Time has revealed the definition of hard science fiction to be loose and contingent on the critical atmosphere of a given time period (Westfahl);[21] however, the subgenre does work under a general set of constraints. David N. Samuelson (sci-fi critic and professor of English at California State University) posits that "Accurate but unobtrusive science may not define the subgenre, but neither does a rhetoric of hardness without scientific substance. In the best examples, the two interact positively, demanding reader sensitivity to both as indicators of quality."[22] The sci-fi historian Gary Westfahl raises the requirements, claiming that for a story to increase its chances to qualify as hard science fiction, it must "work out its scientific concepts completely" and not intermingle its scientific concepts with "large doses of gobbledygook and fuzzy science."[23] Westfahl points to the exclusion of Sir Fred Hoyle and Geoffrey Hoyle's works from the hard sci-fi category as an outcome of these enforced requirements; though the Hoyles' 1963 novel *Fifth Planet* heavily utilizes technical astronomy knowledge available at the time of writing, they choose to set the story in the distant future due to the "very nature of the plot" while admitting "it is hardly possible to foresee the shape of society a century or more ahead of one's own time."[24] In *Fifth Planet*, a planetary system consisting of five planets passes close to Earth. An Anglo-American expedition team vies with a rival Russian team to explore the fifth planet with

[21] Gary Westfahl, "'The Closely Reasoned Technological Story': The Critical History of Hard Science Fiction Author(s)," *Science Fiction Studies* 20.2 (1993): 168-172
[22] Samuelson, "Modes of Extrapolation."
[23] Westfahl, "'The Closely Reasoned Technological Story,' 166.
[24] Westfahl, "'The Closely Reasoned Technological Story,' 166.

traits suggestive of life support. Yet the mission goes awry when the team heads home and finds an unexpected passenger onboard. In the end, the combination of accurate astrophysics with conjectural world building prevents the story's solid classification as hard sci-fi in Westfahl's view.

Instead, *Fifth Planet* is considered "soft" - though not as squishy as a saga like *Star Wars*. Where the editors of *Cosmic Engineers and Hard Science Fiction* agree that hard science fiction allows the story to arise only from established science and "rigid postulation," they argue that soft science fiction lets human aspirations drive the creative elaboration on scientific possibilities for integration into the story.[25] The editors appear to present the former negatively in its coldness and fear to expand upon ideas, while rendering the latter positively in its humanness and willingness to brave the unknown. Yet understanding that soft and hard sci-fi meld together as a spectrum rather than act as a dichotomy provides an amount of wiggle room for an author to construct a scientifically informed story that still makes factual departures when required for one of several purposes explored in the following section. Ultimately a story such as *Fifth Planet* should not be undervalued as a piece of informed literature for its departures from the known, but celebrated for them instead. It exemplifies a story that could not have been written if the authors had not made a calculated compromise between the needs of the plot and the science.

Naturally, three of the most influential science popularizers have tackled this tricky question of how to balance science with story; they come to the similar consensus

[25] Gary Westfahl, *Cosmic Engineers: A Study of Hard Science Fiction* (Westport, Conn.: Greenwood Press, 1996).

that science should be used as a springboard, not a barrier. Tyson argues that, "good science fiction knows where science is, at any given moment, takes you there, and then goes beyond it. And if you're good, you can do that, and then the story is stronger for it. If you don't know much science, you really shouldn't be writing science fiction."[26] Tyson points out that a technical familiarity with a science subject provides an author with the tools to work with technical concepts, and then he or she can use creativity to logically expound upon those subjects. Carl Sagan asserted the societal importance of this well-reasoned speculation; he said he knew of many young people who would not be thunderstruck if humanity made contact with extraterrestrial life because they "have already accommodated to that future. I think it is no exaggeration to say that if we survive, science fiction will have made a vital contribution to the continuation and evolution of our civilization."[27] Thus science fiction acts as a form of societal premeditation. The process of working through closely reasoned what-if scenarios by constructing stories in which humans confront and interact with known and speculated forms of technology and natural phenomena can function as a form of cultural preparation.

Greene provides a final perspective on the calculated compromises between science and story. He asks for sci-fi writers to give themselves a license "to bend the rules at the edges in order to make the story work, but if the integrity of the core science that really matters for the story can be kept intact, I think that's a worthwhile goal to shoot for."[28] Based on the following case studies, a strict adherence to science would

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[26] Carnes, "Look Up."
[27] Carl Sagan. *Broca's Brain*. (New York: Ballantine Books, 1993), 172.
[28] "Theoretical Physicist Brian Greene Thinks You Might Be a Hologram," Wired, May 16, 2012.

prevent many important science-based films from success as visual entertainment, plausibility, and most importantly, the fulfillment of the basic narrative of human struggle fundamental to the tradition of storytelling.

The following five examples of films that come the closest to hard-science fiction (in the physics-based arena) but bend the rules at necessary points illustrate my claims.

(Almost) Hard Science Fiction Films

Contact (1997), *Primer* (2004), *Gravity* (2013), *Interstellar* (2014) and *The Martian* (2015) are five of the most popular hard sci-fi films that derive their stories from the regarded theories of leading theoretical physicists and proven physical phenomena. For the sake of brevity I will explore and compare the structures of *Interstellar* and *Primer*. Both break from established science when the plot needs to move in a specific direction, an image requires a higher entertainment value, or the creators just wish to explore unknown territory. Yet the favorable reception of these films as hard sci-fi hinges on their establishment and strict adherence to a set of technical rules unique to the story worlds that the writers have designed as plot parameters. The methods by which the filmmakers maintain a recognized degree of scientific authenticity while making factual departures for the aforementioned reasons serve as references for the shaping of my thesis film.

Interstellar constructs a story of human struggle out of the implications of general relativity. In the collaboration between astrophysicist Kip Thorne, screenwriter

Jonathan Nolan and director Christopher Nolan, both the filmmakers and the scientist made compromises to produce a product that visually and emotionally pleased the audience while not disrespecting fundamental laws of nature.[29] A simple example of this point of negotiation lies in the chosen depiction of the supermassive black hole Gargantua. Where Figure A displays a more accurate rendering of the black hole that accounts for the Doppler shift and the gravitational frequency shift, Figure B as used in the film erases these effects and adds lens flare to create a visually "flashier, 'less confusing'" image."[30]

[29] Note that the physics community is not universally accepting of the manner in which science is depicted in *Interstellar*, particularly with respects to the rather implausible ending. See Laurence Krauss bash the film in the YouTube clip "Lawrence Krauss 'Interstellar Was One Of The Worst Movies Ever Made'" December 10, 2014, and a discussion of Jonah Nolan's original ending in the Nerdist article by Kyle Hill, "Jonathan Nolan's Ending to Interstellar Made A Lot More Sense" March 19, 2015.
[30] Robbie Gonzalez, "The Truth Behind Interstellar's 'Scientifically Accurate' Black Hole," *io9: We Come from the Future*, February 17, 2015.

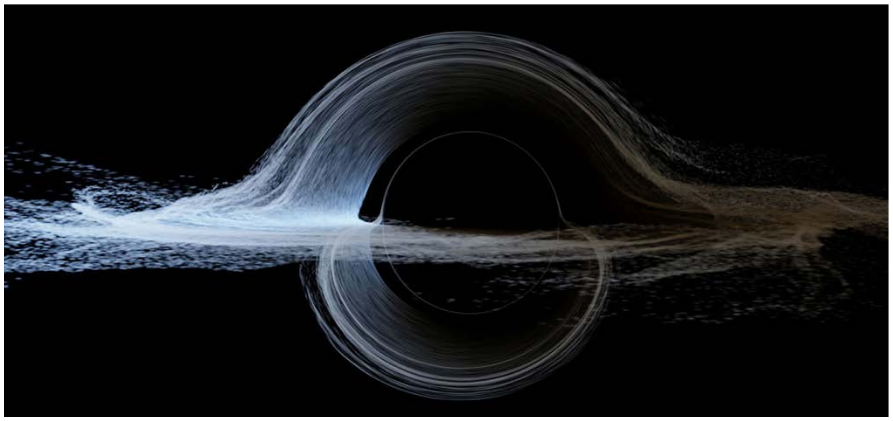

Figure A

A more scientifically accurate simulation of the black hole Gargantua by Double Negative as guided by Kip Thorne and the work of astrophysicist Jean-Pierre Luminet.[31]

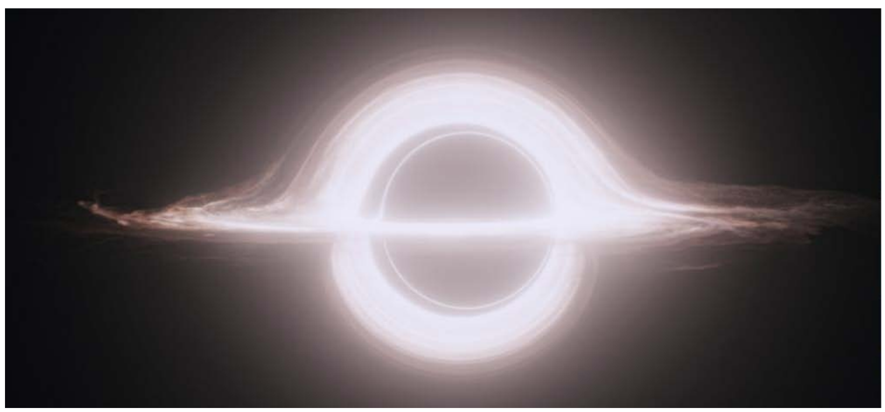

Figure B

The altered image of Gargantua by Double Negative used in the film disregards Doppler shift, the gravitational frequency shift and speed of the black hole's rotation, and adds lens flare to appease Christopher Nolan.[32]

Thorne and the Nolan brothers also negotiated over the portrayal of the wormhole to a similar end with the demands of compelling storytelling outweighing those of scientific theory.[33] As the tesseract involves an additional dimension

[31] Gonzalez, "The Truth Behind Interstellar's 'Scientifically Accurate' Black Hole."
[32] Gonzalez, "The Truth Behind Interstellar's 'Scientifically Accurate' Black Hole."
[33] Kip, Thorne. *The Science of Interstellar*, (New York: W.W. Norton & Company, 2014), 138-145.

unobservable by humans restricted to the perception of four dimensions, Thorne gave freer artistic reign to the visual effects studio Double Negative in their rendition of the mathematical construction.[34, 35] In the end the compromises made between art and science acted to strengthen a lay audience's interest and quick comprehension of complex subject matter, and allowed the story to come full circle through the ability of the protagonist to communicate with his daughter across space and time. The importance of this film lies in its delineation of the implications of general relativity through archetypal stories of survival and relationship dynamics.

Furthermore, the writers of *Interstellar* allow the final story to arise from a "rule set" that serves the dual purpose of outlining the story world's scientific parameters and generating suspense. Jonah Nolan tells Thorne that establishing a rule set in a sci-fi film is vital to answering the questions of "What do the laws of the era allow, and what do they forbid? If the rules are not clear, then many in the audience will expect some miraculous event to save the heroine, out of the blue, and the tension will fail to mount as it should."[36] Much more so than soft sci-fi, works that wish to own a hard sci-fi label must avoid the employment of deus ex machina by abiding to the rules they have set for themselves. Thorne notes that physicists are not confident about the mechanics of backward time travel, which are dictated by the laws of quantum gravity "which are terra almost incognita."[37] Thus, though the laws of physics allow for backward time travel, the lack of experimental proof and disagreement over a single descriptive

[34] A tesseract is a four-dimensional analog of a three-dimensional cube.
[35] Thorne. *The Science of Interstellar*, 252-261.
[36] Thorne. *The Science of Interstellar*, 262.
[37] Thorne. *The Science of Interstellar*, 263.

mathematical theory allow for the filmmakers to choose their time travel rules - within the realm of developed theory, that is. Chris Nolan chose two rules under Thorne's supervision that would dictate the mechanics of time travel in *Interstellar*:

> Rule 1: Physical objects and fields with three space dimensions, such as people and light rays, cannot travel backward in time from one location in our brane to another, nor can information that they carry.[38] The physical laws or the actual warping of spacetime prevent it. This is true whether the objects are forever lodged in our brane or journey through the bulk in a three-dimensional face of a tesseract, from one point in our brane to another. So, in particular, Cooper can never travel into his own past.
>
> Rule 2: Gravitational forces can carry messages into our brane's past.[39]

In this way, an amount of speculative leeway accompanies hard sci-fi films that tackle subjects that theoretical physicists currently struggle with such as time travel and quantum mechanics.

But the rules further serve to direct the creation of a compelling screenplay. As Thorne explains, Rule 1 produces tension in preventing the possibility that Cooper can return to his daughter Murph through backward time travel; Murph grows older on Earth while Cooper loiters in the proximity of a time-sucking black hole. Rule 2 serves to generate hope; if Cooper can find a way to utilize gravity to send his daughter the quantum data, then Murph might be able to save humanity.[40] It would seem then that the creation of a rule set for a hard sci-fi screenplay is an invaluable technique for fashioning both a scientifically informed story world and a gripping narrative.

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[38] A *n*-brane is an object with a *n*-dimensional spatial extent.
[39] Thorne. *The Science of Interstellar*, 263.
[40] Thorne. *The Science of Interstellar*, 263.

The scientific and narrative success of Shane Carruth's 2004 cult film *Primer* further validates the worth of devising a story-tailored rule set. Taking the Grand Jury Prize at the 2004 Sundance Film Festival, Carruth devised a plot around a rigorous mathematically developed time travel paradox involving the concept of recursion – or the feedback loop. Like *Interstellar*, *Primer* qualifies as hard sci-fi despite exploring experimentally unverified time travel territory since math might allow for backward time travel's actualization.

Yet it should be noted that Carruth only investigates the process and implications of human time travelling; he does not provide instructions on how to build a time machine. The characters build a time machine by accident; the filmmaker explains, "What they're trying to do at the beginning, degrading gravity using superconductors—that was technically researched. The point where it goes from saying we're doing such an efficient job degrading gravity that we're also blocking time—that's the leap."[41] But this "leap" seems much smaller than the unexplained development of the "flux capacitor" in *Back to the Future* (1985).[42] Most importantly, Carruth chooses to make this scientifically unqualified leap so that he can tell the rest of the mathematically supported story. This leap serves as a great example of a well-calculated compromise between science and story in hard sci-fi as it illustrates how science should not be a barrier but a springboard.

[41] Dennis Lim, "A *Primer* Primer," *The Village Voice*, October 5, 2004.
[42] The flux capacitor is an unexplained mechanism capable of causing a car to travel backwards and forwards in time in the *Back to the Future* film trilogy. It seems like the writers just threw together two physics words that could relate to time travel mechanics– "flux" meaning the magnitude and direction of the flow of a substance, and "capacitor" meaning a device that stores electrical charge.

Carruth called on his undergraduate studies of nonlinear dynamics and Richard Feynman's Feynman diagrams to construct a time travel rule set.[43] This rule set would not only heavily dictate the complex editing structure of the film that fans excitedly deconstruct as a puzzle, but guide the human drama through a technically stringent plot labyrinth. The filmmaker explains that "You have an equation y = x, and you take that answer and feed it right back in for x, and you chart this and sometimes you get fractals and sometimes you get orderly systems. The idea of recursion and whatever it leads to—that informed a lot of the story, the idea of creating a feedback loop."[44] This feedback loop produces several time travel rules that differ in form from those employed in *Interstellar*.[45] The time machine takes the shape of a human-sized box. A human turns on the box at time A, and a human gets into the box at a later time B. The human who gets into the box at time B waits in the box for a time period of time B minus time A, and gets out of the box at time A. So if the box is turned on at 8 AM, and someone gets into the box at 8 PM, then the person will sit in the box for 12 hours going back in time and space, and get out of the box at 8 AM. Thus someone now occupies the box from the moment the box is turned on. The diagram of the time travel system in *Primer* that fans like to use is shared as Figure C.

Figure C visualizes the following rule set. Firstly, only backward time travel is permitted. Secondly, each time travel machine may only be used once since a human

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[43] Lim, "A *Primer* Primer."

[44] Lim, "A *Primer* Primer."

[45] Chaunton, "Primer: Understanding the Most Complicated Sci Fi Movie Ever Made," *SparkNotes*, June 20, 2013.

occupies the box from the moment the box is turned on. Thirdly, "in order to avoid a paradox," Sparknotes blogger Chaunton observes, "you need to hide out during the entire time that the machine is on. That way the time traveler version of you can go around and do things during those hours when he comes out."[46] The mathematical worth of this filmic experiment lies in Carruth's severe adherence to this rule set. As with *Interstellar*, the rules also serve to generate suspense and other emotions that drive audience investment in the film; both the audience and the characters remain partially unsure of who is where at what time, which versions of characters are interacting in a certain scene, and how certain actions will impact a certain timeline. The nonlinear editing style of *Primer* only augments the audience's interest in the plot puzzle.

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[46] Chaunton, "Primer."

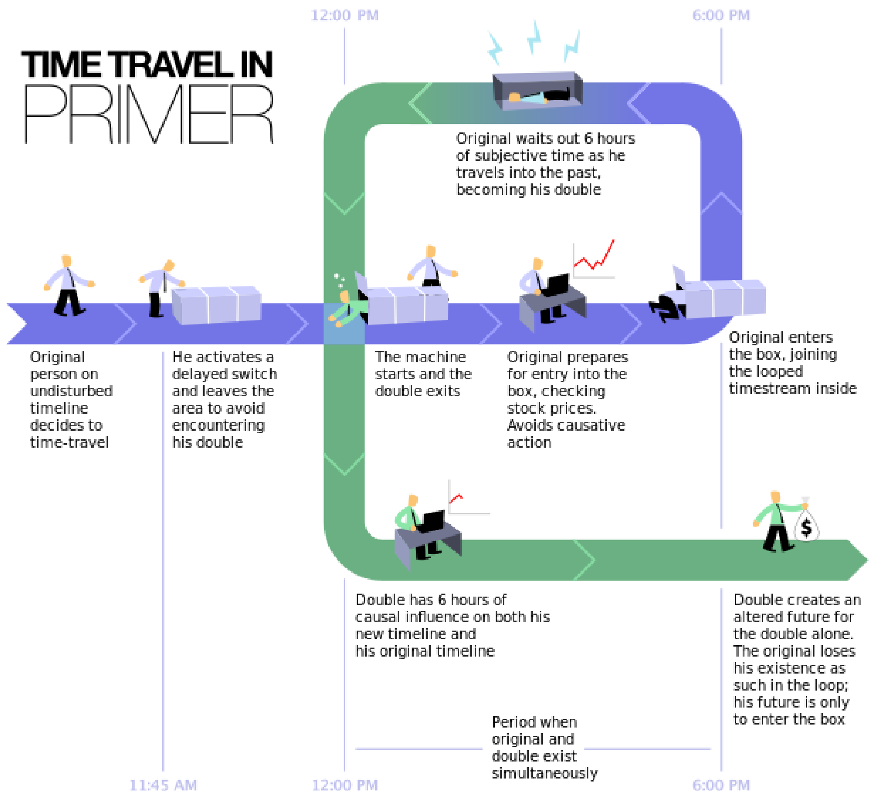

Figure C

"Time Travel in Primer" Visual depiction of time travel process in *Primer*[47]

As illustrated, both *Primer* and *Interstellar* stand as strong case studies of the value of establishing story-specific rule sets that help structure the plot around science, and generate plot tension strong enough to maintain audience interest. The choices the filmmakers make in compromising science for story prove well calculated in their pursuits of producing visually entertaining material, pushing the stories in necessary directions, and in exploring scientifically fresh territory. I looked to the structures of these films as I tried to capture their essence as scientifically informed stories that do not permit science to be an obstacle, but a guide in constructing my thesis film.

[47] CC BY-SA 3.0

The Film

In the idea phase of the filmmaking process, I generated a plethora of scenarios that built plots, characters and settings around the qualities of quantum particles and mechanics of quantum phenomena. I let the musical scores of *Interstellar* and *The Village* (2004) guide the flow of my thoughts. The end product of this brainstorming process ended up surprising me – and its unconventional design is hopefully one of the film's more intriguing qualities. Instead of utilizing a rather dull color palette and industrial production design typical of the hard sci-fi genre, I chose to metaphorically explain the basics of quantum mechanics through a grim fairytale. The fairytale format with an archetypal appeal possesses a simple structure that I could easily embed key features of quantum mechanics into for mass cultural consumption and appreciation. The decision to share science through fantasy was also a rather selfish decision, as I tend to gravitate toward colorful films and the dark fantasy subgenre. The end product might be somewhat of a gedankenexperiment as I took abstract technical concepts and applied them to objects with familiar properties; I then had to think through scenarios conditioned by the rules of quantum mechanics.

The following sections detail the science itself, the scientific metaphors made, and why I made some of the authorial decisions I made that might be controversial to certain viewers. Many directors (David Lynch, for one notorious example) hesitate to provide a detailed description of their thematic intentions as the dictation restricts the audience's ability to value its own interpretations. However, I felt it prudent to explain the choices I made here since I attempted to cram so much information into so short a film, and some analogies may have been lost in visual translation.

The Science of "Entangled"

The film will attempt to visually and narratively build off of the following simplified explanation of defining principles of classical and quantum mechanics and the cross-over point between the two theories. This explanation style reflects that of a gedankenexperiment in its emphasis on mental visualization and the process of thinking through simple scenarios. Allow me to be the teacher and you to be the student for this subsequent instructive walkthrough.

Humans perceive and interact with other constructions of matter on a macroscopic level. Experience permits humans to trust Isaac Newton's Laws of Motion when choosing how to manipulate macroscopic objects to create a desired physical state of their environment. In this way, humans function in a world governed by classical mechanics. Newton's laws allow for the prediction of a large object's position in space and time based on the object's initial state and the forces present. Throw a ball up and forward and shut your eyes. With your eyes still shut you can be confident about the ball's final position based on initial factors such as the ball's mass, the force vectors imparted by your arm, and present wind vectors. Thus humans operate under a philosophy of certainty in which each chosen action has a certain expected reaction regardless of an actual measurement of that reaction. Past events shape a single present environment with a limited number of probable directions for you to choose to steer the future. The classical world is one of certainty and informed choice.

Yet the foundations of reality are not so faithful. Phenomena on the atomic and subatomic levels reveal that certainty is the child of ultimate uncertainty, the finite of the infinite. To understand these concepts, erase all matter from the universe except for a single electron and your eyes. In this gedankenexperiment, your eyes merely symbolize an object capable of measurement, or of interaction, with the particle. Your open eyes measure the particle at a single position. Now if you shut and open your eyes, you will see the particle at a singular location dependent purely on chance. Note that only the act of measurement, or of interference, with the electron affected its final properties that manifested according to probability. Knowledge of the initial conditions did not permit certain prediction of the particle's final properties.

Quantum mechanics can account for atomic and subatomic particles' simultaneous identities as objects with mass and as probability wave packets. To explore the deeper implications of the particle-wave duality, return to the empty universe with a single electron and your eyes. This time when you shut your eyes, note that no force in the universe requires that the electron should be in one place more than another; that it should have a particular speed or any other particular property that an electron can have. The electron is as likely to be here as it is to be there, to have an up spin as it is to have a down spin.[48] In this manner, the unobserved electron IS

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[48] As noted by Professor Richard Taylor in our email correspondence, this statement might be somewhat misleading in that ONLY in this scenario in which no other objects or forces interact with the particle does the particle have an equal chance of being anywhere in the universe, or of having a certain property known to the particle. Professor Taylor provides a more detailed walkthrough of the superposition collapse process, writing:

> Let's say we are about to make a measurement. The current state C of the system can be written as a superposition of possible future states A, B, C, D, ..., that the system could collapse into upon measurement.
>
> Let's write this as C = *a*A + *b*B + *c*C + *d*D + …, where, say, a is the probability that the system will be knocked into state A. Thus, in the quantum world, the outcome of the measurement is a product of both the properties of the world (this is captured in the equations A, B, C, D) and the probabilistic nature of the act of measurement (i.e. on the assigned probabilities *a*, *b*, *c*, *d*, ...). Of course, if *a*, *b*, *c*, *d*, … are all equal then there is equal chance that the system will be knocked into any of the states.

everywhere and exhibiting all of its inherent properties simultaneously in a state called superposition. This state by its nature can never be observed, because the very act of observation, or just an interaction with the particle, collapses its extended probability wave into a single spike. Upon opening your eyes, you will see only one reality out of the infinite possible realities in which the electron displays certain and distinct properties. In this manner, the 10^{80} particles in the observable universe interfere with each other to cement each other's properties and build up the mirage of macroscopic certainty (Greene). Classical mechanics is then a product of quantum mechanics. Chaos harvests order.

Yet the question still remains: How can the probability wave (as described by the Schrödinger equation) collapse an infinite number of possible realities into a single actuality? One of the most well regarded theories explaining this phenomenon makes the unsettling yet untestable claim that the wave does not collapse. Instead, every possible reality is realized in a branching parallel universe according to the Many Worlds Interpretation (Bub). This requires that the observation of a particle with two possible spins – up or down, spawn one world in which the observer measures up, and another in which she measures down. Infinity is preserved and predestination might be pondered. As these parallel worlds are wholly inaccessible, the Many Worlds Interpretation opens up a distressing philosophical debate rather than an active avenue for physics research.

Yet one last spooky concept integral to quantum mechanics demands exploration: quantum entanglement. With your eyes shut, add another electron with the same wave function as the first electron to the empty universe. Because the electrons have the same wave function, they do not cause each other to actualize; the two electrons make up a composite system with a single wave function. Unfortunately, the last statement can only be described accurately through math, so just understand that particles can interact in a way that they remain in superposition and have resulting properties only determinable in relation to those of their system. When your eyes are closed, the two unobserved electrons both have the possibility to have a spin up or a spin down. In terms of the two-particle system, the system must have a total spin of zero as the spins up cancel the spins down (Holzgreve). Now the two electrons are said to be ‘entangled’ as their individual properties depend on the system’s total properties. When measured, one electron must have a spin up, and the other must have a spin down to satisfy the system’s total spin of zero.

The apparently supernatural aspect of entanglement as quantified in extensive experimentation lies within the instantaneous transfer of information between entangled particles. Place the two entangled electrons at opposite ends of the universe and look at only one of them. Upon measurement the electron immediately and randomly assumes either a spin up or a spin down. Without looking at the second electron, you can predict that it will have the opposite spin as the first measured electron. This pattern has been proven to occur one hundred percent of the time. Yet how can the randomly manifested property of the first measured electron inform the other electron’s property faster than the speed of light? How can a measurement on one particle affect a particle an arbitrary distance away? Theorists still struggle with this idea that conflicts with the demands of special relativity that requires anything moving forward in time to not travel faster than the speed of light.

In synthesis, where classical mechanics permits humans to make informed decisions when constructing their reality, quantum mechanics leaves an observed particle's fate to chance in a given world. My explanation style focuses on the confluence between Choice and Chance in these two physical law systems as my film's themes derive from the philosophical enigmas that arise from the juxtaposition of the two theories.

The Analogies in "Entangled"

The humans in this animation are to be treated as particles subject to quantum effects. So the electron-humans may be denoted as "humons." The large, dark, cavernous forest represents a vacuum, or empty space where few humons interact. Quantum effects display themselves strongest here as humons may be isolated for stretches of time from measurement by other humons. The isolation from measurement means that a new measurement, or interaction could result in a new manifestation of a certain property of a humon. Thus the forest is the quantum realm. Meanwhile, the citadel represents the classical realm. In civilization, the constant interaction between humons prevents humons from displaying quantum properties. The multitude of humons constantly measure one another. Their properties together become certain. A nice way of looking at this concept that I attempted to suggest in the animation is that the more people a person has to compare themselves to, the more certain their qualities become. In isolation, a person does not know if they are white, tall, smart, old, nice, evil, rich, or royalty. Yet when inaugurated into society, a person obtains these qualities through comparison, through interaction. In this way, the uncertain builds the certain, and the classical realm arises from the quantum realm.

The story centers around the strained relationship between twin sisters, Luella and Delwyn, who were born cursed with entangled faces. They share an ugly face and a beautiful face; one wears one face while the other must bear the other face. As they are entangled, the twins' interactions with each other do not cause a facial switch. Only a humon whose face is not entangled with theirs can trigger a facial switch between the twins. I have chosen as a rule for this analogy that humon sight, sound and touch are the forms of measurement, or of interaction that can incur a facial switch. Note that a measurement from the environment outside of the twin system might not trigger a switch as each face in superposition prior to measurement has a fifty percent chance of being ugly or beautiful. Due to the monstrous quality of the ugly face, the twins share their burden by living alone in the recesses of the forest to avoid societal reproach, and possible violence.

As noted repeatedly before, the narrative themes of this film derive themselves from the broad, contrasting implications of classical and quantum mechanics. The former allows humons to make informed choices that guide their actions to achieve certain reactions from their environment. The latter strips humons of their choice, leaving their fate to chance and rendering their actions somewhat pointless. Delwyn, the protagonist, grows bitter in her isolation from society and condemnation to the desolate forest. This bitterness displays itself in her mannerisms and words, and prompts uncertainty regarding her motives in the first act of the film. Whether or not she intended to hurt her sister Luella remains unclear. This uncertainty is purposeful in that Delwyn herself is in a state of emotional superposition. No event has occurred yet that has forced her to choose whether or not to act in her own self-interest.

The breaking point instead occurs at the climax of the film, where Delwyn must choose quickly between a glamourous life with the prince or a life sharing a burden with her sister alone in the forest. This point is a thematic form of measurement, or of metaphorically opening the door to see if the cat is dead or alive. If she leaves to the classical world, the rules of this film analogy dictate that Delwyn's face would remain beautiful since she would be in constant contact with other humons. Leaving would mean condemning Luella who would permanently bear the monstrous face. Yet note that Delwyn's decision is ultimately a choice she has calculated in her own self-interest. Though she did not choose her face at the moment she met the prince, she has the agency to choose between supporting her sister and the royal life. Thus therein lies the thematic conflux of choice versus chance in terms of contrasting the implications of classical and quantum mechanics. The fallout of Delwyn's choices are cruel from a storyteller's perspective – however I will let the audience decide what to make of the short film's ending.

Concluding Remarks

I put a tremendous amount of effort into the conception and production of this animation. I can only hope that the love I gave it shows in the final product. Though the project became more artsy and thematically-elusive than the original piece of instructive media I intended to create, I think that the ability to translate the science into metaphorical art only shows that I came to some richer understanding of the technical material I wanted to share. I acknowledge that the film takes multiple viewings to understand what is happening. Only larger audiences and time will tell which analogies read plainly and which ones are lost in translation. Viewers have usually wondered about the significance of the colorful lion-monster. I merely wanted to infer that colorful, wacky particles exist on the quantum level; their unknown and unpredictable qualities make them frightening, or monstrous, in a sense. In all, the subtlety and abstractness with which I embedded some of the concepts into the film makes the project somewhat more selfish than intended. Yet I have to wonder how many times a storyteller has ended up creating a story for herself rather than for the audience she promised it to. I would dare to guess it happens more often than not.

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