An exploration into the evidence and theories behind quantum mechanics, specific properties of quantum particles, and Marvel's scientific inaccuracies in relation to quantum mechanics. Consider the impact of Marvel and other inaccuracies on public opinion of quantum mechanics.

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Introduction:

Possibly the most famous and brilliant scientist of all time, Albert Einstein once declared that "God does not play dice with the universe." Not only does Einstein describe the complexity of a branch of science known as quantum mechanics, but his quote also provides an example of how personal interpretation can lead to misinformation and the negative effects that can occur. Many people interpret this quote as Einstein being religious and directly rejecting quantum mechanics, a branch of science concerned with the behavior of subatomic particles, however, Einstein is merely commenting on the unpredictable nature of the science. When Einstein mentioned God, he was not referring to the actual presence of God, rather he was using God as a metaphor. Mentioning dice, Einstein was citing the unpredictable randomness of quantum particles as opposed to fate.[1] This is a prime example of misinformation and the confusing nature of quantum mechanics, both of which are core themes for this essay.

Quantum mechanics, one of the most counterintuitive and confusing branches of science, attempts to describe and propose explanations for the behavior and properties of subatomic particles, such as protons, neutrons, electrons, and elementary particles (quarks, gluons, and leptons). Not only does quantum mechanics deal with fundamental particles, but it also examines the relationship between these particles and electromagnetic radiation (infrared, gamma, ultraviolet, x-rays, etc.), since radiation has an important impact on subatomic particles. The development of quantum mechanics can be traced back to the 18th century and the study of light, and the gradual acceptance that both matter and radiation share particle and wave properties. Early physicists believed that light consisted of particles known as corpuscles, however, experiments conducted during the 18th soon led physicists to accept light as being a wave.

[1] Dickerson, Kelley. "One of Einstein's Most Famous Quotes Is Often Completely Misinterpreted." *Business Insider Australia*, Pedestrian Group, 19 Nov. 2015, https://www.businessinsider.com.au/god-does-not-play-dice-quote-meaning-2015-11.

However, this theory was faulty as it could not explain the absorption and release of light. Max Plank proposed a solution for this; instead of light being emitted continuously, it is released in distinct ‘packets’ known as quanta. His subsequent formula and calculations matched exactly with what had been observed of light. Building upon Plank’s theory, Albert Einstein studied the photoelectric effect, which is where a surface, usually metal, will emit electrons upon being hit with electromagnetic radiation such as light. Using the information he gathered from his observations, Einstein used this effect to arrive at the conclusion that light consists of photons, which is the same thing as quantum, and that atoms can only completely absorb a complete photon or nothing at all. These photons, although particles, act similarly to a wave, and this wave-particle theory was later supported by subsequent experiments with other types of electromagnetic radiation, specifically X-rays. Experiments with crystals containing atoms in a three-dimensional lattice revealed the wavelike nature of X-rays while experiments with graphite and the resulting dispersion of the X-ray photons revealed the particle nature. Erwin Schrodinger, an Austrian physicist commonly known for his thought experiment ‘Schrodinger’s cat,’ developed the wave function, which mathematically describes the quantum state of a quantum system, that is, it calculates the probability of a particle being at a certain space as a function of position, spin, time, and momentum. Essentially the wave function predicts the probability of finding a particle in a given area. The main shortcoming of this equation is its inability to be solved precisely for atoms containing more than one electron, that is, any atom besides hydrogen. However, this issue was later solved by the introduction of approximation methods which provided fairly accurate solutions.[2]

[2] Squires, Gordon Leslie. “Quantum Mechanics.” *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 1 June 2021, https://www.britannica.com/science/quantum-mechanics-physics.

Now that the history and development of quantum mechanics are understood, an obvious question comes to mind; what are the practical applications of quantum mechanics? Besides the fact that understanding quantum mechanics and how quantum particles behave will further our understanding of how the universe works and lead to future inventions and discoveries we are unaware of, quantum mechanics has several useful applications. With the development of Schrodinger's wave function, scientists were able to update their structural model of the atom; clouds representing the probable position of electrons replaced explicit rotational pathways. This understanding lead to the development of transistors, which are used in computers, phones, cars, calculators, and pretty much everything electrical.[3] In terms of direct technological advancements, the principles of quantum mechanics led to the development of extremely accurate clocks; the NIST strontium clock will only lose or gain a second once every 5 billion years. Extremely accurate clocks are essentially for coordination, whether it be GPS piloting or the stock market. There are also experiments with developing entangled clocks, or clocks that use the quantum theory of entanglement (explained later) to create a network of synchronized timekeepers that can work cohesively regardless of location.[4] Not only can the theory of entanglement be utilized for integrated clock systems, but the principle can also be used to create uncrackable codes and increased security for coded messages. The essential principles of quantum mechanics and superposition can also be applied to computers and the encoding of information, allowing for ridiculously powerful supercomputers. The Japanese quantum computer, Jiuzhang, can complete a boson sampling in about 200 seconds, compared to the 600

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[3] Matson, John. "What Is Quantum Mechanics Good for?" *The Sciences*, Scientific American, 2 Nov. 2010, https://www.scientificamerican.com/article/everyday-quantum-physics/#:~:text=But%20it%20is%20also%20responsible,hence%20no%20Blu%2Dray%20players.

[4] Jenner, Nicola. "Five Practical Uses for 'Spooky' Quantum Mechanics." *Smithsonian.com*, Smithsonian Magazine, 1 Dec. 2014, https://www.smithsonianmag.com/science-nature/five-practical-uses-spooky-quantum-mechanics-180953494/.

million years it would have taken the world's fastest classical computer Fugaku.[5] A boson sampling is a method used to determine the speed of supercomputers, namely quantum computers since quantum computers can perform boson sampling at much faster speeds than conventional supercomputers. Considering these elements, the usefulness and practicality of quantum mechanics clearly demonstrate its value as a viable branch of science and reveals the importance of the branch being treated as serious science. However, the science is often discredited and labeled as mere theoretical science with no basis in fact as a result of misinformation and mislabeling.

Misinformation is a prevalent problem in our society, as the information age results in effortless access to massive amounts of information and leads to carelessness as people fail to fact-check the data they are being exposed to. Fake news has become the term referring to the spread of misinformation, and this affects quantum mechanics due to the mislabeling trend. Many industries such as the movie and writing industry use quantum mechanics as an explanation tool for scientific events they create that they are unable to explain with actual science. This gross labeling of anything scientifically unexplainable in fiction and science fiction results in a public discrediting of the field. This is detrimental to the subject since if the public tends to regard the area as ridiculous and irrational with no basis in actual science, it will be hard for quantum scientists to earn money and support for experiments and testing that could result in new discoveries. This essay will explore how the inaccurate portrayals of quantum mechanics in Hollywood movies affect society's perception of science, and explain several of the key concepts of quantum mechanics.

[5] Crane, Leah. *A Quantum Computer That Measures Light Has Achieved Quantum Supremacy*. New Scientist, 9 Dec. 2020, https://www.newscientist.com/article/2261906-a-quantum-computer-that-measures-light-has-achieved-quantum-supremacy/.

Fundamental Properties of Quantum Mechanics:

Wave-Particle Duality and the Wave Function - In order to understand the inaccurate portrayals of quantum mechanics, a solid grasp of the fundamental theories that constitute this branch is necessary. Wave-particle duality, one of the most important concepts in quantum mechanics, refers to the particle and wave-like nature of scientific objects, such as light. According to research and experiments, light travels in miniature packets called photons that act similarly to waves, thereby granting light properties of both. The duality of light is applicable to all microscopic particles and quantum entities in the known universe, including atoms and molecules. These properties, however, can only be witnessed on the microscopic level as macromolecules have exceptionally small wavelengths since the wavelength is directly proportional to velocity, and smaller particles will have greater velocity and consequently wavelength (assuming force is constant) when compared to larger particles. Describing the wave attributes of particles in mathematical terms, the wave function is another key component in quantum mechanics that reveals the field's probabilistic nature. The randomness inherent in quantum mechanics makes predictions of absolute certainty impossible, allowing only for probabilities of certain outcomes predicted by the wave function. For example, squaring the wave function gives the probability density of finding a particle in a certain location at a given time.[6]

[6] Orzel, Chad. "Six Things Everyone Should Know about Quantum Physics." *Forbes*, Forbes Magazine, 8 July 2015, https://www.forbes.com/sites/chadorzel/2015/07/08/six-things-everyone-should-know-about-quantum-physics/?sh=22aa0f367d46.

Entanglement and Superposition - Possibly the most mind-boggling and counterintuitive property of quantum mechanics, entanglement and superposition defy all sense of logical reasoning. In 1935, Einstein, along with Nathen Rosen and Boris Podolsky, wrote his EPR paper, which investigated entanglement and proposed a hypothetical solution. The EPR paper begins by describing a pair of entangled particles, particles originating from the same source that both have two distinct measurable properties. Both measurable properties contain two distinct results with an equal probability of occurring, and upon measurement, both particles demonstrate the same result. For example, if the results of one measurable property are 0 and 1, and the two particles are labeled as particle A and B, then measuring particle A and finding it to exhibit result 0 means that particle B will also display result 0 when examined. Making this characteristic particularly intriguing, the indeterminant states of the particles mean that either result is possible and only the act of measurement will cause a result to occur; the measurement determines the state. In other words, the act of measuring the particle's state forces the state into one of the possibilities. Essentially, the particle exists in multiple states at the same time until a measurement occurs, upon which the particle becomes forced into one of the states. This property is known as quantum superposition and seems to fly in the face of all basic logic and reason as one considers the insane implications that quantum particles can exist in multiple places at the same time since the position is a quantum state. However, there have been multiple experiments conducted that support this property (explored in the experiment section), and mathematically, the property works. For entangled particles, they are to be found in superposition, however, as soon as a singular particle is measured and forced into a state, the other particle is always forced into the same state, regardless of whether or not it was measured. Possibly the most incomprehensible characteristic is the fact distance is irrelevant to entangled particles; measuring the state of the first particle instantaneously forces the other entangled particle to also enter the same state even if the two particles are billions of light-years away from each other.[7] This property is known as quantum nonlocality, and in his paper, Einstein labeled it as "spooky action at a distance" and refused to accept the quantum mechanic interpretation that the particles are in superposition. Instead, he proposed the hidden variable theory, which declared that the state of both particles was predetermined by some sort of hidden variable that is unknown to us. John Bell, a physicist, soon discovered a method to test the EPR method, and physicists John Clauster in the 1970s and Alain Aspect in the 1980s was among the first of dozen physicists to test this prediction. Every single one of these experiments proved the quantum mechanics theory correct and the EPR proposal as false, since the EPR theory placed restrictions on the possible outcomes of entangled particles and the results failed to support these restrictions.

What This Tells Us About Reality: These fundamental properties of quantum mechanics are interesting and thought-provoking, but what do they tell us about reality? There are several different interpretations, including the formalist perception which focuses on the information given by the wave function. Rather than seeking to explain the implications, formalism accepts the information given by the wave function and uses its predictions of future dynamic properties for practical uses. The Copenhagen approach, however, attempts to look past the practical information and suggests that quantum states are not definite until observed. Our act of measurement determines the property, thus, particles exist in superposition until measurement.[8] An alternative theory, nicknamed the "Pilot Wave Theory" suggests that a separate wave exists

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[7] Voorhoede, De. "Superposition and Entanglement." *Quantum Inspire*, QuTech, https://www.quantum-inspire.com/kbase/superposition-and-entanglement/.

[8] Gleick, James. "What Does Quantum Physics Actually Tell Us about the World?" *Nonfiction*, The New York Times, 8 May 2018, https://www.nytimes.com/2018/05/08/books/review/adam-becker-what-is-real.html?action=click&module=RelatedCoverage&pgtype=Article®ion=Footer.

for each particle rather than a particle having wave/particle duality and being in superposition.[9] Similarly, the “hidden variable” theory suggests that some undetectable variable exists and quantum particles are not in superposition. Yet another theory, the “many-worlds interpretation,” proposes that for every quantum action, a new universe is created. Essentially, since quantum mechanics is probability-based, measuring a particle in a specific location means that an alternative universe was created for the other locations the particle was not found in. The theory most supported by evidence is the Copenhagen theory, as the other theories violate John Stewart Bell’s inequality theorem. All in all, the quantum wave function governs all small particles and can be used logistically regardless of the philosophical implications.

Experiments:

Double-Slit Experiment: One of the most famous experiments conducted in quantum mechanics, the double-slit experiment, demonstrates the property of quantum superposition and wave-particle duality. In the experiment, first developed by Thomas Young, individual particles of light (also works with electrons and neutrons) were shot through two slits in a barrier. The barrier was opaque, and behind the barrier was a detector. Classical theory expects the particles to form two bands directly across from the slits, however, this does not occur. Rather, alternating bands of dark and light form, an effect that occurs when two waves interact with each other. Despite the fact that particles are being sent, the resulting alternating bands suggest wave properties, thus validating the wave-particle duality theory. Additionally, the bands resulting only occur from waves interacting and interfering with one another, suggesting that each particle was

[9] Bennett, Jay. “The One Theory of Quantum Mechanics That Actually Kind of Makes Sense.” *Popular Mechanics*, Popular Mechanics, 15 Feb. 2018, https://www.popularmechanics.com/space/a24114/pilot-wave-quantum-mechanics-theory/.

going through both slits at the same time and interfering with themselves.[10] This violated classical physics, as the same particle can not be in two different locations at the same time and be interfering with itself. However, the evidence of the experiment left no alternative, throwing physicists' perceptions of reality askew. Mathematically, however, superposition works. If one uses a wave function for each slit, the combined wave functions accurately predict the probabilities of finding the particle at a location. More likely to be found at bands resulting from constructive interference between the waves (when the crests of each wave align with each other), the interaction between the quantum particle and the detector collapses the wave function, forcing the particle into one of the probable areas. Mathematically speaking, the results of the experiment works, but interpreting what it tells us about reality is a completely different ballgame.

Bell's Inequality Theorem: In 1964, John Stewart Bell came up with a thought experiment to determine whether the quantum theory of entanglement holds true using electron spin. Spin is a property of electrons and quantum particles, and it can be measured using north and south magnetic poles that create magnetic fields. Experimentation revealed that there are only two possible spin directions, up and down, and this holds no matter which axis the electron is being measured on. Additionally, if electrons have a known spin on a certain axis, their spin on all other axes is undefined. When electrons are entangled, measurements of the spin along the same axis will result in opposites 100% of the time. For example, if two electrons, electron A and B, are entangled and have spin-on axis x, y, and z, physicists measuring the spin of electron A on

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[10] Ananthaswamy, Anil. "What Does Quantum Theory Actually Tell Us about Reality?" *Scientific American Blog Network*, Scientific American, 3 Sept. 2018, https://blogs.scientificamerican.com/observations/what-does-quantum-theory-actually-tell-us-about-reality/.

axis x will find the exact opposite spin upon measuring the spin of electron B on axis x. To explain this phenomenon, physicists proposed the hidden variable theory, which suggested that there was some sort of hidden variable that determined the property (the spin) beforehand. Thus, we arrive at Bell's experiment. Bell proposed that if we assume the hidden variable theory was correct, and if we choose three axes, say x, y, and z again, then since there are only two options for the electron's spin (up and down) there are eight possible combinations for a spin on each axis ({up, up, up}, {up, up, down}, {up, down, down}, etc) for electron A and B. According to the hidden variable theory, the spins were already predetermined and thus the spins of the other entangled electron will be the exact opposite on all axes. However, only one axis can be measured at a time. Hence Bell's probability equation; if we take one combination of electron A, say down, up, up, then the other electron must be the opposite, which would be up, down, down. If physicists measured axis y of electron A, which was up, and then measured another axis on electron B, say axis z, which was down, they would have opposite results (up for A and down for B). This is ⅓ of the possible choices - there will always be at least one electron that has the opposite spin. Thus (with the exception of the combination of up, up, up and down, down, down), physicists would have to get opposite results at least 33% of the time. Similarly, they could get the same result at most 67% of the time - for each electron spinning in one direction, there can only be at most two other axes with the same. For example, take the same scenario - electron A has up-down. If axis x was measured, the result would be up. According to the hidden variable theory, electron B has to have the opposite spin of down on axis x, leaving only two axes unknown. Since axis x has been taken out of the picture, the maximum number of the same answers (up) can be two (if axis y was up and axis z was also up). We already determined that axis x can not be up. Therefore, physicists measuring electron spin can not possibly get the same spin direction more than 67% percent of the time. However, the equations and formulas of quantum mechanics declare that researchers will get the same result 75% percent of the time, which is higher than the 67% allowed by the hidden variable theory. Since the 1970s, countless experiments have confirmed the quantum mechanic's correlation as opposed to the hidden variable. Thus, the hidden variable theory and locality were disproved, and entanglement remains the current viable theory.[11]

Common Misconceptions Regarding Quantum Mechanics:

The Heisenberg Uncertainty Principle: The uncertainty principle refers to the probabilistic nature of quantum mechanics. As stated before, the wave function only gives probabilities of finding a particle in a certain state, not definite results. Many people attribute the lack of definite results to technological shortcomings, however, as technology grew more advanced and scientists began measuring with more accuracy, they were still unable to overcome the uncertainty principle. A property of quantum mechanics, scientists quickly realized technology was not the issue and that our concepts of 'position' and 'velocity' were not well defined in the quantum realm. Additionally, researchers found out that the better the measurement for the position, the worse the measurement for velocity; they were directly correlated.[12]

Quantum Mechanics Can Justify Anything: Possibly the worst misconception regarding quantum mechanics is that people think quantum mechanics can explain just about anything.

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[11] Brubaker, Ben. "How Bell's Theorem Proved 'Spooky Action at a Distance' Is ..." *Quanta Magazine*, Quanta Magazine, 20 July 2021, https://www.quantamagazine.org/how-bells-theorem-proved-spooky-action-at-a-distance-is-real-20210720/.

[12] Fernandez, Joseph John. "3 Common Misconceptions about Quantum Mechanics." *Medium*, Quantum1Net, 17 Apr. 2018, https://medium.com/quantum1net/3-common-misconceptions-about-quantum-mechanics-eb52db0b8855.

This occurs as a result of the weird behaviors and phenomena present in quantum mechanics such as superposition and entanglement. As crazy as they sound, these are theories that have experimental evidence and scientific backing. They were not just created by anyone, rather, they were heavily researched and thoroughly evaluated to ensure maximum accuracy. However, since these theories are naturally confusing and counterintuitive, many people fall under the impression that quantum mechanics can explain away anything weird. Almost everyone has had an experience where a sci-fi story or movie explains away some scientific impossibility with the words ‘quantum mechanics,’ however, most of these have absolutely nothing to do with quantum mechanics. Essentially, people assume that since superposition is true, many other weird sci-fi phenomena can be explained by quantum mechanics. As explored later, this gross misuse of quantum mechanics leads to discredibility for science as it turns into a sort of practical joke.

Examples of Quantum Mechanics Misinformation - Avengers Endgame: Extremely prevalent in the movie industry, quantum mechanics rarely receive accurate representation. One quantum mechanist scientist remarked that “The accuracy bar for invocations of quantum mechanics in the film is *unbelievably* low, even by the usual standards of science in film” and “in movies I’ve seen, ‘quantum’ just function as voodoo-words for whatever the writers want to have happen.” Marvel’s *Avenger: Endgame* demonstrates the gross misuse of the branch, as the character’s time travel back in time through the use of the quantum world. In the movie, Lang wonders, “What if there was a way that we could enter the quantum realm at a certain point in time but then exit the quantum realm at another point in time?” The statement suggests that some sort of time difference exists between the quantum realm and the real, and this has no evidence whatsoever. In fact, time was one of the few concepts that quantum mechanics did not impact at all, rather, relativity and gravity determined that time is inconsistent. This makes the suggestion that time acts differently in the quantum realm even more ridiculous, as relativity determined that high speeds and extreme gravity affect time, none of which are present in the quantum realm. Additionally, the fictional superhero Tony Stark mentions the Deutsch Proposition, which according to David Deutsch, the scientist referenced by Stark, did not exist in his papers.[13]

Effects of Misinformation:

What is Misinformation and What are the Effects: Misinformation, or incorrect information, is a dominant problem in today's society. When someone is misinformed, they are "holding inaccurate views and being uninformed about scientific facts and processes" (Scheufele and Krause, 2018). New media sources allow for easy access to information, which helps spread misinformation rapidly. The most important factor in causing misinformation in quantum mechanics is called "the misinformation effect," which is where misleading information can distort perceptions of factual knowledge. This means that, unless the movies industries portray quantum mechanics with close to 100% accuracy, people's perceptions of the science will be distorted. James Kakalios, the physicist who wrote *The Amazing Story of Quantum Mechanics*, described how quantum mechanics is "used too much as a justification for things that have nothing to do with quantum mechanics" (What Is Quantum Mechanics Good For). He goes saying how there is even an expression, "quantum woo," that refers to writers attempting to make unexplainable events more scientific by "affixing [them] to quantum mechanics." As this process continues, people tend to discredit the field and regard it with skepticism. When I talk to

[13] Lindbergh, Ben. "A Chat with a Quantum Physicist about the Time Travel in 'Endgame'." *The Ringer*, The Ringer, 3 May 2019, https://www.theringer.com/movies/2019/5/3/18527776/marvel-avengers-endgame-time-travel-david-deutsch-proposition-scott-aaronson.

friends about certain quantum mechanics concepts that are weird and counterintuitive, they are often skeptical and half-jokingly say "is that related to time travel," something often explained away by quantum mechanics' obscurity. Even though they aren't consciously thinking of movies' influence, not many people actually study quantum mechanics, so things they hear in movies and TV shows are their only exposure to and source of quantum mechanic knowledge. Since there is no consistency between movies misusing quantum mechanics, it becomes confusing, resulting in disbelief. People don't trust things that are confusing and don't make sense. Public opinion of a field is extremely important to the field.

Conclusion:

Why: Although the properties of quantum mechanics, such as superposition and entanglement may be counterintuitive and seem to be more trouble than they are worth, understanding these properties and the inherent nature of quantum mechanics can result in futuristic technologies that can drastically improve society. Misinformation, caused by inaccurate usage of quantum mechanics, results in negative public opinion, as people begin to regard the science as a joke. Marvel movies are especially damaging; they are incredibly popular. This hinders progress. The future of technology, which has already changed our world, is going to be heavily impacted by quantum mechanics. Quantum sensors, communication, and computing are some of the more important advancements that will occur, and these can have broad impacts, from self-driving cars to climate change.[14] As knowers, we can be skeptical of information we learn from the media. If we hear others discussing quantum mechanics inaccurately, we can correct them. Through small

[14]Itu. "The next Big Leap: How Quantum Physics Will Shape Technology." *ITU News*, 3 Dec. 2019, https://news.itu.int/the-next-big-leap-how-quantum-physics-will-shape-technology/.

and personal corrections, we can gradually eliminate misinformation, and help further the science and society.

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Scheufele, Dietram A., and Nicole M. Krause. “Science Audiences, Misinformation, and Fake News.” *PNAS*, National Academy of Sciences, 16 Apr. 2019, https://www.pnas.org/content/116/16/7662