the Nature of Science

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Neil Degrasse Tyson, an astrophysicist whom I greatly respect, said “The good thing about science is that it's true whether or not you believe in it.”. I have two objections. The first objection is that Tyson's statement does not argue for science. If someone were to say “The good thing about astrology is that it's true whether or not you believe in it.”, that statement would not make me more inclined to believe in astrology. A religious person might well say “The good thing about religion is that it's true whether or not you believe in it.”. Saying that something is true doesn't make it true, or add any evidence that it's true. Tyson's statement has the same content as “Yay for science!”, which clearly expresses his (and my) sentiment, but gives other people no reason to adopt the same sentiment.

My other objection to Tyson's statement, and the topic of this essay, is the word “true”. Science is not true. In my opinion (as a scientist), science is the single most important and successful method of understanding our world, but it is not true. Nor is it false. The words just don't apply. It's like asking whether basketball is true or false. Basketball may be many things, but it is neither true nor false. To make my point, I'll look at some astronomy, which is most appropriate for Neil Degrasse Tyson.

The Greek philosopher Aristotle (–383 to –321), and the Egyptian astronomer Ptolemy (100 to 170) described the universe as having the Earth motionless at its center, with the Sun orbiting around the Earth, and the other planets having a sort of spiral path, orbiting around the Sun as it orbits around the Earth. The Greek astronomer Aristarchus (–309 to –229), the Polish astronomer Copernicus (1473 to 1543), the Italian astronomer Galileo (1564 to 1642), and the German astronomer Kepler (1571 to 1630) described the universe as having a motionless Sun, with the Earth and other planets orbiting around the Sun. Many people today, including some scientists, say that Aristotle and Ptolemy were wrong; their description is false. They say that Aristarchus, Copernicus, Galileo, and Kepler were right; their description is true. An astronomer who is interested in the stars of the Milky Way Galaxy might say that Aristarchus, Copernicus, Galileo, and Kepler were wrong; the Sun is not motionless. They would say that the Sun orbits the center of the galaxy, with the Earth and other planets having a sort of spiral path, orbiting around the Sun as it orbits around the galaxy. We could even take a larger view in which the galaxies are in motion. Meanwhile, back here on Earth, a police officer who issues you a speeding ticket for going 120 km/h on a 100 km/h road will not be amused to be told that actually you were traveling at hundreds of thousands of kilometers per hour, along with the Earth and everything on it.

Aristotle and Ptolemy were not wrong; their description of the universe, in which the Earth is motionless, not even rotating about its own axis, in which the Sun rises in the east and sets in the west, is the appropriate description for our everyday purposes. The police officer meant that you were going 120 km/h relative to a motionless Earth. Even for describing the motions of the planets, Aristotle and Ptolemy were not wrong. All motion is relative to a frame of reference, which means an assumption about what is motionless. You can describe the motions of the planets very accurately as a spiral around the Sun as it orbits the motionless Earth. But it's complicated. The improvement made by Aristarchus and Copernicus was to simplify: a motionless Sun, with each planet moving in a circle around the Sun, is much simpler than spirals. Galileo and Kepler then made it more accurate, but a little less simple, by describing the planets' motions as ellipses. Modern astronomers have added accuracy, losing some simplicity, with precessing ellipses.

Science includes observing and measuring all that we can sense. It includes performing experiments to give us new events to observe and measure. But that's just the beginning. The next stage of science is to make a model, also known as a theory, of what we have observed and measured. The model can be physical, but most often it is mathematical. There are two qualities that we want the model to have: one is simplicity, and the other is accuracy. As the previous paragraph suggests, there is often a tradeoff between these two qualities. A perfectly accurate but extremely complex model is just a list of all observations ever made. That model is useless as an aid to understanding, and therefore useless for prediction. So we make a simpler model, even if we have to give up some accuracy. We might well have two models, one that's simpler and one that's more accurate. For example, Newton's theory that includes $F = m \times a$ (force equals mass times acceleration) is simpler than Einstein's relativistic theory that includes $E = m \times c^2$ (energy equals mass times the speed of light squared), but Einstein's theory is more accurate. We use Newton's theory for everyday experience where it is accurate enough, and move to Einstein's theory only for extreme masses and speeds.

All models are approximations to reality. Einstein's theories (special and general relativity) have had such strong experimental confirmation that many scientists regard them as true. This has a bizarre consequence. Einstein's theory of general relativity describes the motions of stars in our galaxy very well, but it does not describe the distribution and motions of distant galaxies well. It would describe them well if there were a lot more mass and energy in the universe than we observe. So, rather than admit that general relativity is not accurate at that scale, scientists propose that the universe is 95% dark matter and dark energy: mass and energy that we cannot observe but that is there so that Einstein's theory will be true – accurate at all scales. Something like this happened 120 years ago. The model of light then was waves, but waves have to wave something; they have to have a medium through which they travel. So how could light travel from the Sun to the Earth through empty space? Their answer was that space is filled with something they called “ether”. We don't observe ether, but it was needed for the model. Later, there was another model of light as particles called “photons”. In this model, photons can travel through empty space. We abandoned ether, but we didn't abandon the wave model because it is useful sometimes to talk about the wavelength and frequency of light. People who don't understand that science is models are bothered by the question how light can be both waves and particles; how can they both be true? An architect makes models of a building. One model may be made of balsa wood and paint, and it shows how the building will look, but in miniature. Another model is a blueprint on paper, showing all measurements. The models are not competing; they are complementary. No-one asks which model is true.

Another interesting consequence of the belief that science is true is the willingness to extrapolate to any degree. Looking at the red shift of light coming from distant galaxies, using a theory to calculate their speed and direction, and extrapolating the motions back 13.8 billion years, scientists say they have discovered that the universe began with a big bang from nothing. That's a very big extrapolation. It seems to me the bigger the extrapolation, the less trustworthy the result. Maybe the universe began with a big bang. Or maybe the models were used beyond the range in which they are reasonably accurate. Maybe some future theory of galactic motion, without dark matter and dark energy, will not extrapolate back to a big bang. And I have a suggestion. Planets rotate; stars rotate; solar systems rotate; galaxies rotate; galactic clusters rotate; maybe the entire universe rotates. Maybe the rotation of the universe can account for the expansion of the universe, without dark matter and dark energy.

There are scientists who waste their time exploring models of matter that are so complicated they require supercomputers. A real advance in science would be an equally accurate but simpler model of matter that does not require a supercomputer. Fortunately for us, Copernicus did not have a supercomputer to help him calculate planetary paths using Ptolemy's complicated Earth-centered model, so he found a model that is computationally simpler.

My impetus to write this essay began with three science videos by Derek Muller on his YouTube channel Veritasium, a word he invented because “veritas” means “truth” in Latin. He is a wonderful explainer, and I love his videos. In the first video, he explains that electricity is the flow of electrons through a wire. In the second, he says that he was wrong in the first video, and that actually, electricity is an electric field in and around a wire. In the third video, titled “How Electricity Actually Works”, he explains the electric-field view in detail, and shows an experiment that is explained by the electric-field view but not by the flow-of-electrons view. I highly recommend this video. I want to say that neither view is true, and neither view is false. Both are models, and both models have their uses. The flow-of-electrons view, which includes equations like $V = I \times R$ (voltage equals current times resistance), is simpler, and is used by circuit designers. The electric-field view, which includes Maxwell's partial differential equations, is much more complicated, and is used when circuit elements are close to each other making electrical interference between the elements significant, as in VLSI (very large scale integration) and touch-free charging. The electric-field view is so successful that many scientists regard electromagnetic fields as something real, or true. I am reminded that Newton's gravitational field theory was extremely successful, modeling our solar system so well that many scientists regarded gravitational fields as real. Then Einstein explained the same phenomena with a different theory: masses do not create gravitational fields; instead they affect the geometry of space. No matter how good electromagnetic field theory is, electromagnetic fields are part of the theory, or model, not reality. They are not true. The importance of the distinction is that a scientist who thinks their theory is true will distort reality with ether, or dark matter, or fields, to fit the theory, rather than accept that their theory has limitations. If they think their theory is true, they will not look for a better one, and they will not accept a better theory when someone else proposes one.

Sometimes a theory includes imaginary things that we have not observed, but that help to explain real things we have observed. At that point, the imaginary things are part of the theory, but as far as we know, not part of reality. Then later, the imaginary things are observed; it turns out they are part of reality. For example, up until the 1800s, atoms were just an idea that was immensely successful in explaining chemistry, but no-one had ever observed an atom. Now we have observed atoms, so atoms are part of reality. [Note added 2023-10-3. Three physicists have today been awarded a Nobel Prize for observing electrons.]

When we say we have observed atoms, it is worth asking what counts as observation. I see the world through a pair of glasses, and through my layers of neural abstractions from past experience. I mostly accept what I see as reality, but I retain some doubt, admitting that the signals I am receiving, or my neural abstractions, may be fooling me. Sometimes we see what we expect to see, rather than reality; this is what magicians rely on. Obviously we cannot see atoms with the naked eye; we use scanning tunneling microscopes. We observe through layers of hardware and software designed to show us something we expect to see: atoms. Perhaps we should retain some doubt?

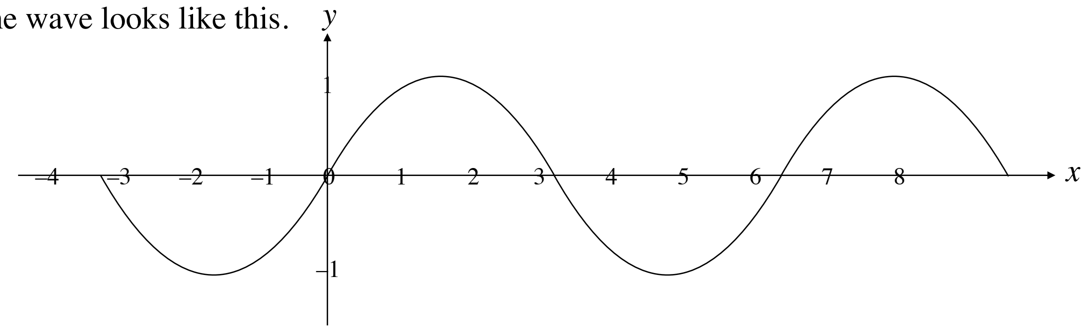
Some theories include things that cannot possibly be observed. Some people, mostly science fiction writers but also some scientists, talk about “many worlds”, and in this context, “world” means “universe”. Or they talk about worlds (universes) that exist in “other dimensions”. If the word “universe” means all that is, then there can't be anything else. So let's take “our universe” to mean all that we can sense, not just all that we have so far managed to sense, but all that we can, even in principle, ever sense. If we cannot sense them, then there cannot be evidence for “many worlds” or “other dimensions”. But there are models (theories) in which our world is one of many concurrently existing universes. And there are models in which our world is just a cross-section of a higher-dimensional world. These models are neither simpler nor more accurate than the models that don't involve many worlds and other dimensions, and that is the reason to dismiss them.

The many-worlds theory is an extension of quantum superposition, which is part of quantum theory. According to quantum theory, elementary particles can be in many states at once, a superposition of states, but any attempt to observe the particle collapses the superposition into one of the states. Therefore a superposition cannot be observed. The thought-experiment known as “Schrödinger's cat” imagines a cat and a flask of poison in a closed box. As a result of some elementary particle being put into a superposition of states, the cat is both killed and not killed. As long as you don't look in the box, the cat is both alive and dead. When you look, it becomes one of those states. I wonder: does it matter who looks in order for the superposed states to collapse to a single state? Can it be a cat? Can it be the alive cat in the box? The many-worlds people say that even when you look, the cat continues to be both alive in one world, and dead in another simultaneously existing world. I say they're all crazy. I say we are in desperate need of a new quantum theory that does not involve superposition. And it's obvious. When Schrödinger's equation is satisfied by several states, it doesn't mean the world is in all of those states; it means the world is in one of them, but we don't know which one. We find out which one when we look.

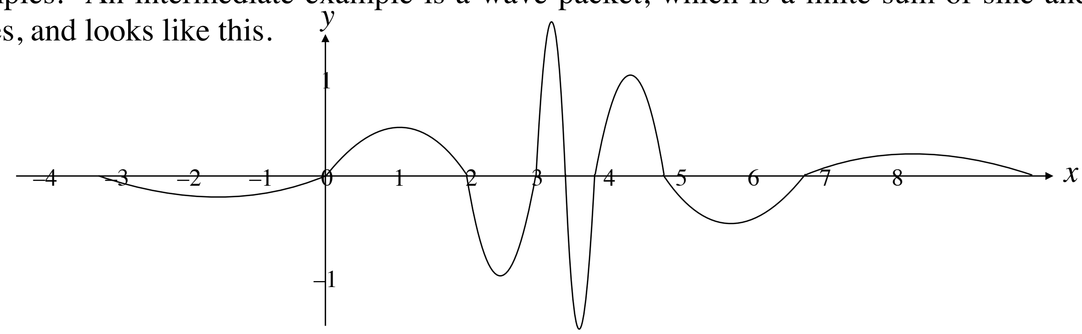
Schrödinger's equation is a differential equation. Differential equations were invented to describe continuous phenomena. Using differential equations to describe discrete quantum phenomena seems to me to be a mismatch, resulting in an incomplete description that we call superposition. Schrödinger used the mathematics he was familiar with, rather than inventing new mathematics to fit the quantum world.

Supporters of the current quantum theory can point to quantum computing, which makes use of the superpositions to speed up computation, and to teleportation. I have co-authored several such papers (here, here, and here), and still I say we need a new quantum theory without superposition.

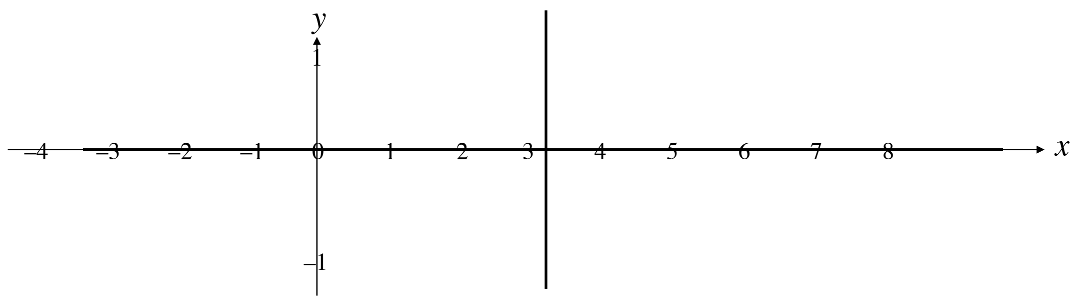
Another piece of quantum nonsense is the uncertainty principle. I will illustrate with an analogy. A sine wave looks like this.



If you are asked what is the wavelength of this wave, you can find it from its equation $y = sin\ x$. Or you can measure it with a ruler. No problem: it's $2\times\pi$. If you are asked what is its position along the *x*-axis, you would wonder what the question means. That's one extreme in a series of examples. An intermediate example is a wave packet, which is a finite sum of sine and cosine waves, and looks like this.



If you are asked what is the wavelength of this curve, you would be less clear about what is wanted, because the distance between axis crossings is not constant. But you could probably still come up with some sort of answer, with a margin of error. If you are asked what is its position along the *x*-axis, now you have some idea what is wanted, and can give an answer with a margin of error. At the other extreme we have an infinite sum of sine and cosine waves giving us the Dirac delta function; it is 0 everywhere along the *x*-axis except at $x=\pi$, where it has all values.



Now the position is clear. But the wavelength is meaningless. In all three cases, I am supposing that the curve is defined exactly, mathematically. Nothing is uncertain about the curves. The uncertainty is about the meaning of the words “position” and “wavelength”; they are not both simultaneously well-defined.

In quantum theory, Heisenberg's uncertainty principle says that there is a theoretical limit to our knowledge of the simultaneous position and wavelength of a particle. The more you know about the position, the less you know about the wavelength, and vice versa. Enemies of science have made great use of the supposed “fact” that our knowledge through science is forever limited. In science, position and wavelength (and all other observable quantities) are defined operationally. Follow procedure P, and the number you get is the position of the particle. Follow procedure W, and the number you get is the wavelength of the particle. Procedures P and W conflict with each other in the same way that “stand up” and “sit down” conflict with each other. The inability to do both completely at the same time is not a limitation on our knowledge. The limitation is on our definitions of position and wavelength: the better position is defined, the less well wavelength is defined, and vice versa. It makes no sense to say that a theory or experiment could demonstrate a limitation on our knowledge.

In summary, science is not a search for truth. Science is experiments that give us data, and the design of models (theories) to fit the data and aid our understanding of the world. These models are abstractions of reality, and approximations to reality. They are neither true nor false. They are designed for simplicity and accuracy; simpler is better, more accurate is better, but often there's a tradeoff. One theory (mathematical model) may work well in some situations and badly in others, while another theory is the reverse. Theories are judged by their usefulness, both by how accurately they describe and predict, and by how easily they describe and predict.

This essay may give comfort and confidence to people who, without learning or effort, propose alternative theories. But theories are not all equally good. They have to earn their respect by their usefulness in describing and predicting reality.

Perhaps Neil Degrasse Tyson should have said “The good thing about science is that it helps us understand our world, measure what has happened, predict what will happen, and invent wonderful and useful artifacts.”, leaving out the words “true” and “believe”. It would be prudent to remember that throughout history, what people believed to be true got overturned by later beliefs, and our current scientific beliefs may suffer the same fate.

Afterword

If you are a lazy reader who glances at this essay without understanding the points made, or a malevolent reader who wants to cause me trouble, you can easily take sentences of this essay out of context, and completely misrepresent me. For example:

> Hehner said “Science is not true.”. He's one of those anti-science nuts.

To be clear: I am very strongly pro-science.

> Hehner said “Aristotle and Ptolemy were not wrong”. He believes the Earth is motionless, and that the Sun revolves around the Earth.

To be clear: I do not believe that. I believe that the model in which the Earth is motionless, and the Sun revolves around the Earth, is useful for many everyday activities, but not so useful for studying our solar system or the universe.

> Hehner calls the uncertainty principle a “piece of quantum nonsense”. He doesn't understand the basics of quantum physics.

I wrote a thesis on quantum physics and earned a degree in physics, coming first in the faculty of science. It's quicker and easier to sling mud than to wash it off.

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