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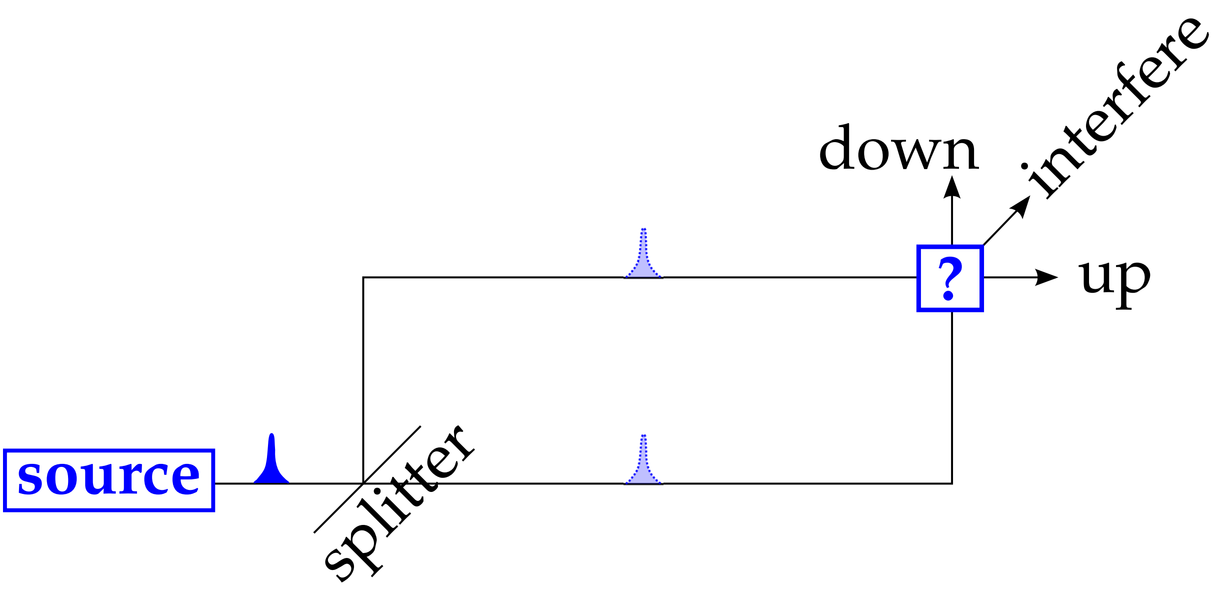
Visualizing Quantum Interference

Quantum interference is really, really, really well-supported by data, data, data. Visualizing quantum interference is a blank slate. This may be a root source of frustration with any world view based on quantum mechanics. More of our brains are devoted to visualization than any other process. Given a diet of equations and stories, the visual section of our brains in the back of the skull must sit idle. "Idleness is the devil's workshop."

In this blog, John Wheeler's delayed choice thought experiment will be explained. The idea briefly is to ask if a single photon goes down a specific path or if the solitary photon goes down two paths so it can interfere with itself. In 2006, the thought experiment was made real by Alain Aspect and his collaborators. The paper provides the simple equations I was able to use to make quaternion animations of the process. The reader will be able to see animations of quantum interference for the first time.

Here is a sketch of John Wheeler's nightmare:



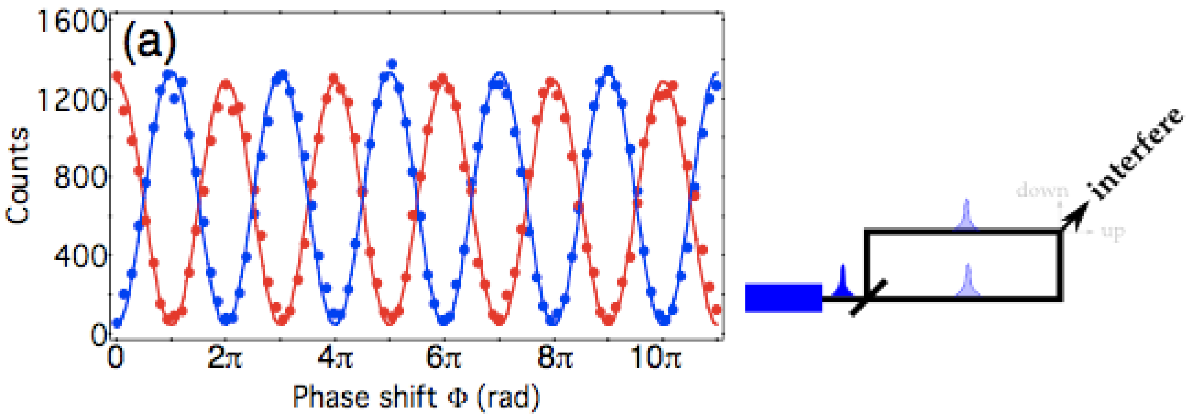
The intensity of the source is adjusted so that it emits one photon at a time. The photon comes to a beam splitter. The solitary photon can either stay down, or turn and go to the up path or perhaps the silent solitary one decides to go on both paths as part of a plan to create an interference pattern (photons are devilishly clever). At the detector box, the experimentalist makes a choice: see if the photon took the down path, or the up path, or both paths as would be needed to see an interference pattern. The decision about what type of measurement to do is delayed until after the photon has passed by the beam splitter (technically, a spacelike separation is required). Wheeler argued that the odd logic of quantum mechanics demands such schizophrenic behavior.

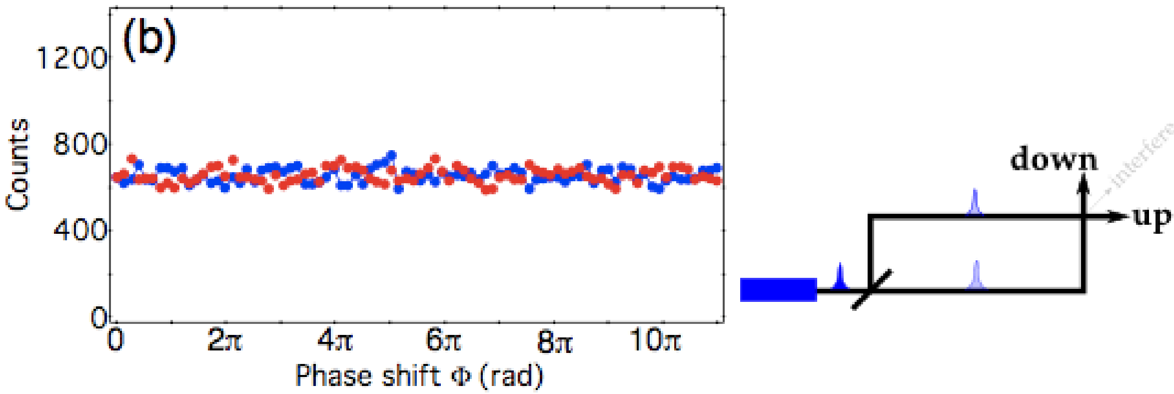
Wheeler's thought experiment was made real by Alain Aspect and his collaborators. The paper was fun to read and reread. I think the experimentalists got it right. Here is the entire abstract:

Side bar: The single photon red herring Intensity has never been an issue in quantum mechanics since the day Einstein explained the photo electric effect. People will nod along with the statement that intensity is not relevant to quantum processes. The consequence of the statement is that lowering the intensity to one photon a day does not change an effect except to slow the rate the experimentalist collects data. Water molecules hold hands using hydrogen bonds, so water waves are changed by intensity. Photons are isolationists, whether as solitary skaters in this experiment, or if sent as a swarm of a billion a second. The photons never hold hands or work together. Looking at a quantum effect one photon at a time is a red herring. People love their herrings and will defend their right to focus on the fish. I intend to swim on by.

> ABSTRACT: The quantum "mystery which cannot go away" (in Feynman's words) of wave-particle duality is illustrated in a striking way by Wheeler's delayed-choice Gedanken Experiment. In this experiment, the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: either the interferometer is closed (i.e. the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that Gedanken Experiment, where the light pulses are true single photons, allowing unambiguous which-way measurements, and the interferometer, which has two spatially separated paths, produces high visibility interference. The choice between measuring either the 'open' or 'closed' configuration is made by a quantum random number generator, and is space-like separated – in the relativistic sense – from the entering of the photon into the interferometer. Measurements in the closed configuration show interference with a visibility of 94%, while measurements in the open configuration allow us to determine the followed path with an error probability lower than 1%.

With the information provided so far, I don't think this story can make sense. People defend the idea that this story must be accepted as is, after all it is supported by the following data from the paper:





This situation reminds me of something I learned about illusion in the film "The Prestige". That was a great film by the way, one that has to be watched two or three times before you get it. An illusion has three parts:

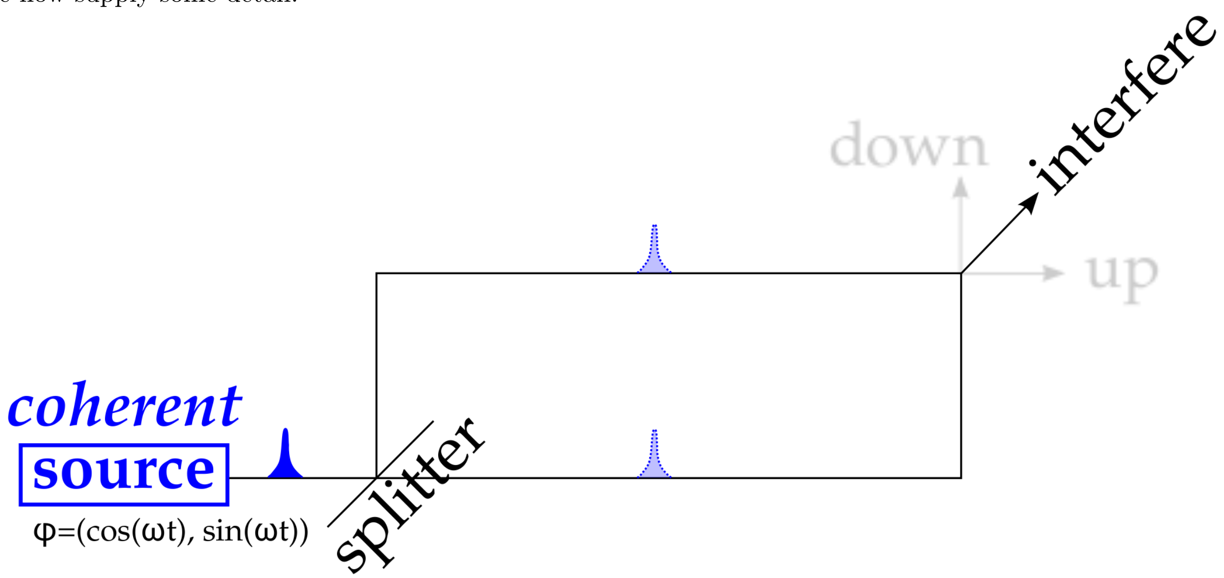
1. The Pledge

2. The Turn

3. The Prestige

The Pledge starts out the story with something ordinary. Members of the audience are invited on stage to prove to themselves the items are everyday, that knots are secure, that everything is as it seams. The Turn is when things disappear that should not be able to vanish. The audience is confused, nervous that something may have gone wrong. The work for the illusionist happens at the third step: the Prestige, when the missing thing is brought back, completely unharmed.

In quantum mechanics today, I feel we must live with the Turn. People who study and know some of the vital experiments in quantum oddness like the delayed choice experiment will tell you that is the way, accept that you cannot understand. A small circle of fringe folks will holler about their own approach, one which shows no understanding of the Pledge or Turn of quantum mechanics. A real illusionist would know exactly where the answer was placed. I put the answer in plain English, but surrounded it with words that would make the reader focus on a different subject. It was in the illustration, but let me now supply some detail:



I mentioned the source was coherent, but only in the context of intensity. The math of the source is treated as ordinary, even if it isn't.

The up/down path detector is another herring, albeit more tempting given the name of the thought experiment. No matter what the source is, we can detect if it went on one path or another after a beam splitter. That is not a mystery. What needs to be understood is the interference for a non-interacting particle of a coherent source.

The source is so not random. Write out the wave function that would account for both ports, the complete picture:

Take the norm in order to calculate the probabilities of being in port 1 or 2:

This is unity as it must be. Observers, sitting as they do at the spatial center of their own Universe (0, 0, 0), get probabilities of seeing an event from the source by taking the norm.

Let's use the quaternion animation software to look at the amplitude of the wave function as is, equation 1, even though no one can see it.

The animation has the symmetry U(1), a unit circle in the complex plane of Right-Left+time.

The animation reveals a problem with the visualization. When the phase shift is introduced, it will all be in the x direction. That shift will be darn near impossible to notice. To aid visualization, take the shift in x, and also create a corresponding shift in y. This spreads out what is happening along x.

Two walls collide. Is it possible to follow one value of the phase? Again we are not being physical because individual photons cannot be marked in red, but the software can do the job:

Why are there so many points in this animation? Because every point in spacetime can be mapped to this unit circle.

Label the two paths A and B. A is never shifted, B is shifted anywhere from phi = 0 to 10 pi. The data in figure 3 of the paper involves 4 calculations:

A* B - interference (3a) B* A - interference (3a)

A* A - no interference (3b) B* B - no interference (3b)

We can see the lack of ambiguity for the no interference case. The first two are going to be more complicated. For a fixed value of phi and omega = 1, vary t and plot:

This is what quantum interference can look like: the combination of three complex plane images: a straight line, a circle, and something sinusoidal. No wonder this is tricky! (one technical detail: for the way my software is designed, I had to swap the roles of x and y, as you can tell since the circle is now in the ty plane instead of the tx plane. A bigger and smoother version of this animation is available).

I am not going to market these images as trivial to understand as that would mock any earlier efforts to have a visual interpretation of quantum interference. Instead I can point out why these images are a challenge. Time is a scalar, space is a vector. In quantum mechanics, the scalar is not a dull, monotonically increasing function. Instead, time toys with space, but mapping it back into the same space, thus hiding its hand. I needed to take what was only happening between time and one dimension of space and use another dimension to get a better handle on what was happening.

"What does one plus equal?" That is good English, math gibberish. "Did the photon go on the up or the down path?" While the question is perfect English, its is a poorly formed question for quantum interference. Poorly formed questions can never be answered. "Was there a photon at this location and at this time?" is a well-formed question. If you know exactly when a photon is seen, then a second prior to being detected you can make a statement about where it was, no matter what detector was used. Say the beam splitter was 2 light seconds away from the detector. Then there is a 50-50 chance the photon was at the half-way point of the up or the down path. If the down detector saw the photon, then the photon was at the half-way point in the down path. Notice I said both time and space locations. The photon was not in some arbitrary place along the down path a light second before detection.

What can be said if the interference detector was used? If the interference saw the maximal constructive interference, then one light second before detection, the photon was a the half-way point between either up or down. If the interference was at the maximal destructive point, then there was definitely no photon at the halfway point in either branch. For interference value between these two extremes, it sets the odds on a photon being at the halfway point a light second before being detected.

The coherent source is exceptionally well organized. It is the exquisite organization of the source that one sees in the interference pattern. Let messengers from the neat source house of particles travel down two paths of different lengths, and the resulting pattern looks like interference. The emissaries have no need to interact with each other, the proverbial bump into each other.

From my perspective, the height of absurdity in theoretical physics today are those trying to work without time. No doubt they think the delayed choice experiment is on their side. The event of the beam splitting and the choosing the type of detector is spacelike separated (a feat that was technically a great challenge to accomplish). A physics illusionist would point out that spacelike separation is a calculation done on two events in spacetime.

The results look rational, the visual part of my brain is happy.

$$-\frac{GM_{\text{active}}m_{\text{gravitational}}}{R^2}(\hat{R}+\hat{V}) = m_{\text{inertial}}\frac{dV}{dt}\hat{R}+(V\frac{dm_{\text{inertial}}}{dt}+?Vc\frac{dm_{\text{inertial}}}{dR})\hat{V}$$

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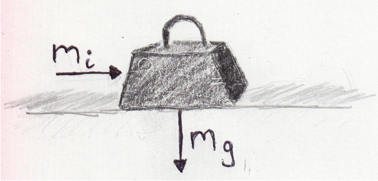


The Subheading

Snarky Puzzle

Snarky puzzle: Supersymmetry has superpartners to build super friends between particles that take different amounts of time to jog around a circle. Animate this:

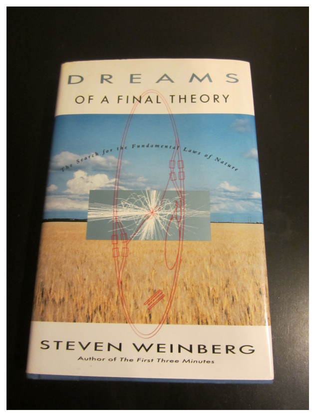
Notice how the tx takes 4 pi to get back to go, ty needs 2pi, and tz zips around in pi radians.If you like a three-way as much as I do (in theory at least), please discuss.

Steve Weinberg and I

I don't like Steven Weinberg.

Good, I have said it. I will provide a brief biographical sketch and a short list of his lengthy accomplishments. I read one of his science outreach books, "Dreams of a Final Theory: The Search for the Fundamental Law of Nature". I will pluck out three issues from the book to show why our scientific beliefs are divergent.

Steve-o went to the Bronx High School of Science. That school's reputation towers above all others in the nation, public or private. The school is a magnet pulling from the vast pool of scrappy New York City kids.



Stevie skipped through the elite tiers of higher ed: Cornell, the Neils Bohr Institute in Copenhagen, Princeton, Berkeley, Columbia, Harvard, a year visiting at MIT, and the University of Texas at Austin. The last stint was located close to the filled in hole in the ground known as the Superconducting Super Collider.

Steve is the third most creative physicist on the planet according to one study. He shared the 1979 Nobel Prize with his high school classmate, Sheldon "I-don't-care-what-SU(2)-looks-like" Glashow. The third scholar to share the prize was Mohammad Abdus Salam, who is Pakistani and grew up far away from the Bronx.

Sir Steven is exceedingly exceptional at mathematics. He finds math errors in other people's papers. If his skill had been spelling, he would correct the dictionary. His justified self-confidence is why I call him Alf, which stands for Arrogant F—. Someone might point out that the "l" in the acronym stands for nothing. It is there just to piss him off.

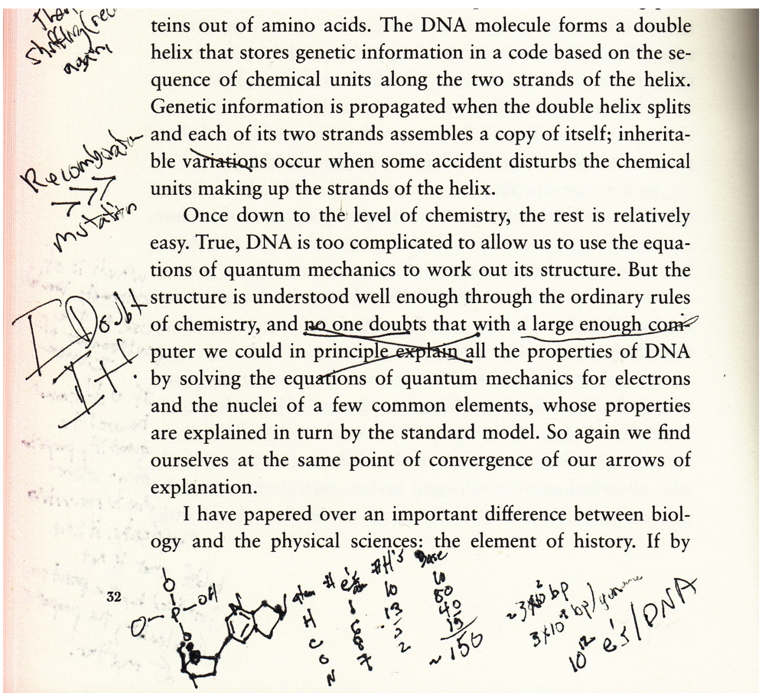
Alf is measurably smarter than I am. I know that, he knows that. Actually, he doesn't know that. The ultra-conservative fringe physicists like me is not on his radar. I am confident if he were to get to know me, he would not like me either. I am sloppy with technical jargon to a fault. Having not lived in the halls of elite institutions, I mispronounce names. I use math errors as an exploratory process. Pictures are central to my world view, a feature absent in much of his work.

Alf was a booster for the SSC. The book "Dreams of a Final Theory" was part of the failed promotion process for the collider. I read books with pen in hand to underline parts I like and to provide a way back to revisit those fun insights. This was the first and only book I felt I needed to read with a pen in hand so I could mark where I disagreed with the author. Every few pages there are notes scribbled in the margins. If he said it, I found a way to disagree.

I recall gripping my red pen and wondering why I was so angry at Alf? Science is a collection of theories well-supported by experimental data. We didn't have any issues with the theories or the scientific process. Where we differed is what I call scientific beliefs: these are the implications beyond the scope of the theory itself, beliefs that create views of meaning in the Universe. I now appreciate why scientists can totally not stand each other: it is less the science, and more the extension and implications of the work that leads to animated disagreements. That lesson was worth the red ink. I have chosen three margin notes for this blog.

DNA and Quantum Mechanics

When physicists start talking about DNA, it is time to defend my turf. Here were his comments about the double helix: Page 32:


teins out of amino acids. The DNA molecule forms a double helix that stores genetic information in a code based on the sequence of chemical units along the two strands of the helix. Genetic information is propagated when the double helix splits and each of its two strands assembles a copy of itself; inheritable variations occur when some accident disturbs the chemical units making up the strands of the helix.

Recombination >> mutation

Once down to the level of chemistry, the rest is relatively easy. True, DNA is too complicated to allow us to use the equations of quantum mechanics to work out its structure. But the structure is understood well enough through the ordinary rules of chemistry, and no one doubts that with a large enough computer we could in principle ~~explain~~ all the properties of DNA by solving the equations of quantum mechanics for electrons and the nuclei of a few common elements, whose properties are explained in turn by the standard model. So again we find ourselves at the same point of convergence of our arrows of explanation.

I Doubt It

I have papered over an important difference between biology and the physical sciences: the element of history. If by

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I will not go into my sex is more important than mutations riff which was the subject of another chapter. Just because I am sloppy in physics doesn't mean I am sloppy in biology. Actually, it does mean that because I use the same hardware. The base I wrote in the margin is in error. The ribose sugar connects to a nitrogen in the 5 member ring not the 6 member ring. The point of the imprecise sketch was to get an estimate for the number of electrons in one of our chromosomal sets of DNA. Accord to my margin note, it is on the order of 10^{12} electrons. There are the protons and neutrons to account for also.

Here is where Alf and I agree: There are laws of quantum mechanics that can be solved exactly for the hydrogen atom. Those same laws can be solved approximately for helium. As we go to more complex atoms and molecules, the calculations become more daunting. The agreement at this point is spot on.

Now we do a stretch, to a large enough computer. I think we both agree such a machine is not going to be built ever. This is where our beliefs differ. He imagines that the take home message is that the standard model is at the root of it all. My belief is that when a calculation becomes this all-consuming, Nature herself does not operate this way, that a new logic is born out of massive recursion. There will be a few, isolated simple systems where Schrödinger's equation will come into play, but in general, the standard model is irrelevant to a description of how DNA works.

Definitions of Beauty, Love, and Fear

Alf decides to dodge definitions of beauty, love, or fear. Page 134:

> mathematician Henri Poincaré admitted that "it may be very hard to define mathematical beauty, but that is just as true of beauty of all kinds."
>
> I will not try to define beauty, any more than I would try to define love or fear. You do not define these things; you know them when you feel them. Later, after the fact, you may sometimes be able to say a little to describe them, as I will try to do here.
>
> By the beauty of a physical theory, I certainly do not mean merely the mechanical beauty of its symbols on the printed page. The metaphysical poet Thomas Traherne took pains that his poems should make pretty patterns on the page, but this is no part of the business of physics. I should also distinguish the sort of beauty I am talking about here from the quality that mathematicians and physicists sometimes call elegance. An elegant proof or calculation is one that achieves a powerful result with a minimum of irrelevant complication. It is not important for the beauty of a theory that its equations should have elegant solutions. The equations of general relativity are notoriously

Without definitions science does not work

Love is the creation & reflection of being.

Fear is the destruction of self

Beauty is simplicity with purpose that creates complexity

That struck me as a cop out. Definitions are the starting point for science. It doesn't matter if the definition is universally accepted. It does matter that you have a precise one, to keep the discussion focused. Here are my three definitions.

Beauty is simplicity with purpose that creates complexity. I like the tension between simplicity and complexity that gets mitigated by purpose. Here is a clay sculpture I did called "Beth".

It is a simple nude. I remember looking at the skin on her back move against her ribs. I was disappointed that I was not going to be able to represent that aspect of her form, too complicated for clay. She was, and will remain for me, a beautiful representation of my species.

Love is the creation and reflection of being. That covers both making love, and the look between mother and child. It also excludes rocks loving water. Sure, the two interact, but no love is involved.

Fear is the destruction of self. Threats to self get me to run. When I got mugged, one question on my mind was about weapons - take my stuff, but I sure hope no one has a gun. Thank goodness no one in the tense interaction had exercised their second amendment rights to keep and bear arms as part of a well regulated militia (the NRA should point out regulation is part of the second amendment, no?). I had read articles on model mugging, a program that teaches women how to deal with such situations. One approach is to scream loudly. That was the technique I used: absolute, full volume shout out of the story of what was going on at the moment: "They took my bag, with my glucose meter and I am a diabetic..." When I saw the three run one way, I turned and went the other direction. It took a while to calm down, but the self was all there, and I even got the bag back. I guess my monologue created fear of being caught for them.

Rereading the passage from the book, I noticed his comments about general relativity:

> It is not important for the beauty of a theory that its equations should have elegant solutions. The equations of general relativity are notoriously difficult to solve except in the simplest situations, but this does not detract from the beauty of the theory itself.

Half of general relativity is beautiful, the pure geometry. The stress-energy tensor is clucky. The simplest, static solution is much uglier than it is usually marketed. The Minkowski metric for empty spacetime is simple with the purpose of preserving the spacetime interval. That does lead to something complicated: all the detailed observations of special relativity. Take the first baby step away from empty spacetime in isotropic coordinates, and here is what the Schwarzshild metric looks like:

$$d\tau^2 = (\frac{1 - \frac{GM}{2c^2R}}{1 + \frac{GM}{2c^2R}})^2 dt^2 - (1 + \frac{GM}{2c^2R})^4 (dR^2 + R^2(d\theta^2 + sin^2\theta \ d\phi^2))/c^2 \quad eq.\ 1$$

I always have to look this up in Misner, Thorne, and Wheeler, hidden in a question at the end of a chapter (p. 840, exercise 31.7). For me, this solution does detract from the beauty of general relativity. A final theory should have manifestly beautiful equations and solutions. Here is a claim I made about my unification equations in my second blog here:

> I will stand next to this strong statement: the derivation and field equations for the GEM unified standard model proposal are drop dead gorgeous. That claim already applies as is to the Maxwell equations, which are stunning. I am inviting a few more beauties to the party.

How about the solutions? One of them is comic. The solution to the first GEM field equation would have been known by Pierre Simon Laplace:

$$\frac{G\hbar}{c^3}\nabla^2\phi = 0$$

Most of this stuff was fresh for the Frenchman. Ben Franklin did his experiments in the mid 1700's. Henry Cavendish determine the value of G in 1798. http://en.wikipedia.org/wiki/Cavendish_experiment Planck's constant would have to wait. Still, Laplace could solve the equation that bears his name today. Take Newton's force for gravity written as a potential and subtract Gauss's law in potential form. Get the B as in Bingo.

Here are the other three GEM field equations:

$$\frac{G\hbar}{c^5}(\frac{dA_x}{dt} - c^2\frac{dA_x}{dy} - c^2\frac{dA_x}{dz}) = 0$$
$$\frac{G\hbar}{c^5}(\frac{dA_y}{dt} - c^2\frac{dA_y}{dx} - c^2\frac{dA_y}{dz}) = 0$$
$$\frac{G\hbar}{c^5}(\frac{dA_z}{dt} - c^2\frac{dA_z}{dy} - c^2\frac{dA_z}{dy}) = 0$$

Snarky puzzle: find the answers to these three equations. Look to for inspiration, sprinkling in minus signs were necessary. Bingo, bingo.

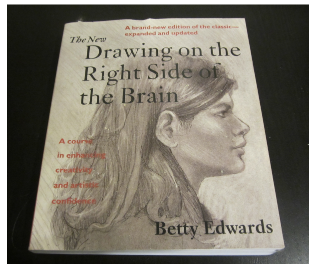
To my eye, the solutions are beautiful, nice variations on a 1/R potential. One up on general relativity. I don't get to say that everyday :-)

The Future of Quantum Mechanics

Alf is sure not much can change for quantum mechanics. Page 88-89 cial relativity. At least for the present I have given up on the problem; I simply do not know how to change quantum mechanics by a small amount without wrecking it altogether.

This theoretical failure to find a plausible alternative to quantum mechanics, even more than the precise experimental verification of linearity, suggests to me that quantum mechanics is the way it is because any small change in quantum mechanics
88 would lead to logical absurdities. If this is true, quantum me-
89 chanics may be a permanent part of physics. Indeed, quantum mechanics may survive not merely as an approximation to a deeper truth, in the way that Newton's theory of gravitation survives as an approximation to Einstein's general theory of relativity, but as a precisely valid feature of the final theory.

This guy is measurably more creative in physics than nearly everyone else. Does he have a blind side? My guess is that visually, he is a moron. There was not a single image in the book. It is common for people to get Ph.D.'s and not be able to draw. This is a horrible waste of mental resources. The back of the brain will not be able to do anything but think visually.



People can learn to think visually at any age. Please note I did not say draw. It is a common misconception that this is a hand thing. I highly recommend "Drawing on the Right Side of the Brain" by Betty Edwards This is how to engage the back of your brain to see what is there. While it may have been true that visual thinking was not important in Alf's time in quantum field theory, I think the future will demand a visualization of every equation in graduate level quantum field theory books. That would be a huge change - one could even share results with people not versed in the arcane arts of differential calculus (I do show my wife a few of the animations my work generates). The next generation of animated books would have to be computer based.

Much change to look forward to, unless you buy into Alf's view.

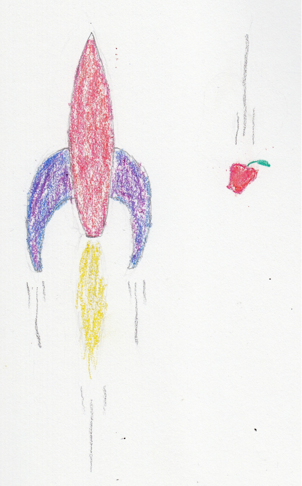
I do value my negative pseudo-relationship with Weinberg. The disagreements drove me to think, and thinking is good. Thanks Steven, all the best.

Justifying the Love for the Strong Equivalence Principle

The strong equivalence principle is a stately beauty queen of an idea. In the simplest of dresses, she refuses to dance with any theory except general relativity. The mundane reason for mass is beyond her concern. My call own effort at unifying the symmetries found in the standard model with gravity "GEM" for Gravity and EM, not to be confused with gravitomagnetism which sometimes goes by the same acronym. A duality between metric and 4-potential theory extends a hand between a metric explanation of gravity and Newton's scalar theory moving up to a 4-mansion. An obligatory cancellation in the GEM Lagrangian provides a field theory justification for the strong equivalence principle. If the Higgs boson is found, this house of cards collapses. If the Higgs is ruled out over the reasonable range of masses to 95% confidence, join the evolution.

Begin with Einstein's statement of the weak equivalence principle:

> A little reflection will show that the law of the equality of the inertial and gravitational mass is equivalent to the assertion that the acceleration imparted to a body by a gravitational field is independent of the nature of the body. For Newton's equation of motion in a gravitational field, written out in full, it is:
>
> It is only when there is numerical equality between the inertial and gravitational mass that the acceleration is independent of the nature of the body.



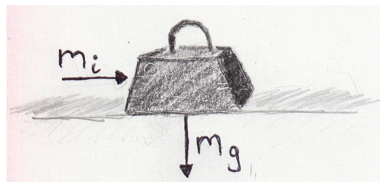
As an Accounting Jerk, I don't cut anyone slack, not even The Most Revered One. Newton's gravitational force law written out in full includes the rocket science term as an effect of gravity (perhaps Newton never wrote that one out either, which would be cool). I am not interested in a great approximation of the truth.

The systematic dismissal of the rocket science effect of gravity reminds me of the collapse of the housing market. Wall Street was given the keys to the money of mortgages. The quants, many trained as physicists, constructed models of how the markets would change, and how the changes in those changes would change. They understood it so well, they sold insurance whose market value was claimed to involve more money than the combination of the stock and mutual fund markets. They did forget to model what would happen if the value of real estate dropped, because of course that never happens.

Here is Newton's gravitational force law written out in full:

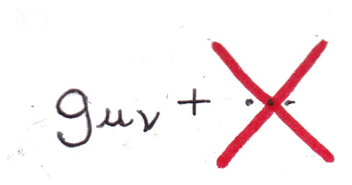
$$-\frac{GM_{\text{active}}m_{\text{gravitational}}}{R^2}(\hat{R}+\hat{V}) = m_{\text{inertial}}\frac{dV}{dt}\hat{R}+(V\frac{dm_{\text{inertial}}}{dt}+?Vc\frac{dm_{\text{inertial}}}{dR})\hat{V}$$

Gravity is broken in a variety of ways (enjoy the PHD Comics version if you haven't already). Research is concentrated on stuffing the ballot box, adding to the causes of gravity. I want to recount all the votes in the state, which worked in Minnesota but was blocked by the good brother in Florida.



The first tests of the weak equivalence principle were done by Galileo, rolling balls down inclined plane (caveat: I haven't had the time to check if he rolled balls made of different materials down the v-shaped planes. If he did do that sort of thing, wood versus glass say, then that would constitute the first equivalence test. Please comment if you know relevant details and I will edit the post). Everything obeys the same gravitational law. Proving this point requires the scientific method. People believe heavier things will fall the slightest bit faster than lighter things. That gut feeling is based on merging aerodynamic resistance with gravity to make a theory of falling. The weak equivalence principle is easy to get along with, just end up with a metric that is a solution that uses only a mass M in the theory. Do not junk up the equations with terms for bosons, fermions, or chirality.

Here is a statement of the strong equivalence principle:



> The strong equivalence principle suggests that gravity is entirely geometrical by nature (that is, the metric alone determines the effect of gravity) and does not have any extra fields associated with it. If an observer measures a patch of space to be flat, then the strong equivalence principle suggests that it is absolutely equivalent to any other patch of flat space elsewhere in the universe. Einstein's theory of general relativity (including the cosmological constant) is thought to be the only theory of gravity that satisfies the strong equivalence principle. A number of alternative theories, such as [scalar-tensor] Brans-Dicke theory, satisfy only the Einstein [weak] equivalence principle.

General relativity has the minimalist pole position: no rank 2 field theory can be simpler. The GEM work is trying to get into this exclusive club by working a floor below as a rank 1 field theory. I have shown how the exponential metric is a solution to the hypercomplex gravity field equations in an earlier blog. Rosen developed a theory that also has the same metric. Rosen's work introduces a flat back-ground metric. The extra field breaks the strong equivalence principle. It also provides a place to store energy and momentum, leading to a prediction of dipole gravity wave emissions. That prediction has not been confirmed in the analysis of gravity wave energy loss in binary pulsars, thus invalidating Rosen's efforts. The problem with dipole gravity waves is a common killer for alternatives to general relativity.

There is only one metric in the hypercomplex gravity work. Using the magic math of duality, I have shown a 4-potential solution to the gravitational Gauss's law field equation is identical to that using the exponential metric. The duality forms a bridge to Newton that gets light bending around the Sun half right. Partial duality is like being partially pregnant. Newton's theory must be expanded from a scalar theory to a 4-vector to be dual to a metric approach for light bending experiments. By working on a different rank than general relativity, GEM has a chance to play nicely with the strong equivalence principle.

$$g_{\mu\nu} \longleftrightarrow \nabla^{*} \boxtimes A$$

The Particles

There are two particles that may play a critical role with mass, but neither has been seen. The first is the graviton. The graviton is massless, so zips along at the speed of light. It cannot be spin 0 because light bends around the Sun. the simplest case that would mean like charges attract is spin 2.

The standard model as originally conceived had only *massless* particles. That is in violent disagreement with observation. The symmetries had to be preserved while bringing in mass. The gang of six had the same idea, a spin 0 field, later to be known as the Higgs boson. Nature may have a more complicated collection of particles up her sleeve, but so far, no cards have appeared (I may have to edit this statement at a later date). The first job of the Higgs is to provide mass to the particles involved with the weak force, the W+, W-, and the Z. Perhaps using a Yukawa potential, the Higgs could provide mass to a long list of fermions. If no Higgs is found, all bets are off.

Seeing into Lagrangians

A Lagrangian is every way energy can be traded inside of a box. Here is a list of things to look for in a Lagrangian dealing with mass: The home of gravitational mass. The home of inertial mass. The reason the equivalence principle is necessary. Why is there mass? Two Lagrangians will be looked at with this list in mind: general relativity and GEM.

EINSTEIN GUESSED at his field equations. Hilbert derived the field equations from the Lagrangian. Here is Hilbert's starting point:

$$\mathcal{L}_{GR} = R + \mathcal{L}_m$$

I could say this was elegant, but that is only a half truth. The Ricci scalar R is elegant. One could spend an academic career studying the Riemann curvature tensor, whose contraction of a contraction is the Ricci scalar. What happens after a vector loops around spacetime only to come back home? That is what the Riemann curvature tensor reveals.

The other term for matter fields is not so elegant. There is far more freedom to do as one pleases: simple (a cloud of non-interacting dust) or complicated (anything else). The Riemann curvature tensor is complex due to the intricate rules of its math machinery. The paucity of guidelines for the matter Lagrangian is a greater challenge. The mystery black box of general relativity is the matter term.

Let's pick apart this two letter Lagrangian. The gravitational mass goes into the Ricci scalar. In a vacuum, the curvature of spacetime all flows from the Ricci scalar. The inertial mass is somewhere in the matter Lagrangian. It is straightforward to justify the strong equivalence principle in the vacuum since the only player on the stage is the Ricci scalar. With the matter contribution, the story may get more complicated. To be honest, I don't have a deep enough training in general relativity to know if there are built in safeguards to the matter Lagrangian to assure consistency with the strong equivalence principle. I bet the only matter Lagrangians that get published are consistent, but how about pathological cases?

General relativity is *silent* as to why anything has mass. GR is not a player in the Higgs derby.

HERE IS THE GEM LAGRANGIAN:

$$\begin{aligned}\mathcal{L}_{\mathrm{GEM}} = \mathrm{scalar}(&\mathrm{J} \boxtimes \mathrm{A}^* - \mathrm{J} \times \mathrm{A} \\ &+ \frac{1}{2}(\nabla^* \boxtimes A)^* \boxtimes (A^* \boxtimes \nabla) \\ &- \frac{1}{2}(\nabla \times A) \times (A \times \nabla))\end{aligned}$$

The gravitational mass is in the terms with the hypercomplex products, indicated by the boxtimes symbol. The hypercomplex field strength depends on this gauge:

$$\mathrm{scalar}(\nabla^* \boxtimes \mathrm{A}) = \frac{\partial \phi}{\partial \mathrm{t}} - \nabla \cdot \mathrm{A}$$

The inertial mass hangs out with the quaternion products. The quaternion field strength has exactly the same gauge. The exact cancellation of the gauge terms in the hypercomplex and quaternion field strengths means that the most pathological choice of a potential or byzantine manifold to take derivatives will not break the equivalence principle, in both senses of the phrase.

Musing about Mass

So can we finally stand on a rock solid reason for mass? Sorry, but I have been trained to underplay a hand. The most important message for a general reader to take home is the GEM work provides an utterly different reason for mass that what is on the market today. The Higgs mechanism is a solution that plays nicely with all other work on the standard model. The GEM work plays great with Maxwell, the good symmetric twin, but flips the bird to GR and keeps the symmetries but drops the tensor products found in the standard standard model. Oops.

The ice is thin here, but I will give it a try. Most particles in the Universe have no mass. By most, I mean look at ten billion particles chosen at random, and only one will have mass. The Universe is not structured randomly: stuff with mass congregates in planets, stars, and galaxies. The massless do not have a story to tell. For them, a change in time is the same as a change in space.

Contrast that with particles with mass. They can tell a story. If the relativistic velocity between two particles is near unity, the story must be brief. For the particles still sitting on Earth, the shared stories have lasted at least 4 billion years.

I get this message every day with my gluten-free waffles and maple syrup. From a math wonk view, the gauge term is zero for the massless, and not zero for the massive. This is the edge of what I know.

Snarky Puzzle

Work with a pathological potential:

Calculate:

$$\nabla \times A$$
$$\nabla \times A - (\nabla \times A)^*$$
$$A \times \nabla$$
$$A \times \nabla - (A \times \nabla)^*$$
$$\nabla^* \boxtimes A$$
$$\nabla^* \boxtimes A - (\nabla^* \boxtimes A)^*$$
$$A^* \boxtimes \nabla$$
$$A^* \boxtimes \nabla - (A^* \boxtimes \nabla)^*$$

This is not as bad as it appears: do it one time, the rest are variations in the signs of different terms. Take the group U(1) pointed in the direction of (1, 2, 3, 4) and feed that group into these eight quaternion polynomials. There should be one obvious property of the ones where the gauge happens to be equal to zero.

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