Quantum Physics

Quantum Explanations

There's a widespread belief that quantum mechanics is *supposed* to be confusing. This is not a good frame of mind for either a teacher or a student.

And I find that legendarily "confusing" subjects often are not really all that complicated *as math*, particularly if you just want a very basic—but still mathematical—grasp on what goes on down there.

I am not a physicist, and physicists famously hate it when non-professional-physicists talk about quantum mechanics. But I do have some experience with explaining mathy things that are allegedly "hard to understand."

I wrote the Intuitive Explanation of Bayesian Reasoning because people were complaining that Bayes's Theorem was "counterintuitive"—in fact it was *famously* counterintuitive—and this did not seem right. The equation just did not seem complicated enough to deserve the fearsome reputation it had. So I tried explaining it *my way*, and I did not manage to reach my original target of elementary school students, but I get frequent grateful emails from formerly confused folks ranging from reporters to outside academic college professors.

Besides, as a Bayesian, I don't believe in phenomena that are *inherently* confusing. Confusion exists in our models of the world, not in the world itself. If a subject is widely known as *confusing*, not just *difficult*… you shouldn't leave it at that. It doesn't satisfice; it is not an okay place to be. Maybe you can fix the problem, maybe you can't; but you shouldn't be *happy* to leave students confused.

The first way in which my introduction is going to depart from the traditional, standard introduction to quantum mechanics, is that I am *not* going to tell you that quantum mechanics is supposed to be confusing.

I am not going to tell you that it's okay for you to not understand quantum mechanics, because no one understands quantum mechanics, as Richard Feynman once claimed. There was a historical time when this was true, but we no longer live in that era.

I am not going to tell you: "You don't understand quantum mechanics, you just get used to it." (As von Neumann is reputed to have said; back in the dark decades when, in fact, no one *did* understand quantum mechanics.)

Explanations are supposed to make you *less confused*. If you feel like you don't understand something, this indicates a *problem*—either with you, or your teacher—but at any rate a problem; and you should move to *resolve* the problem.

I am not going to tell you that quantum mechanics is *weird*, *bizarre*, *confusing*, or *alien*. Quantum mechanics is counterintuitive, but that is a problem with your intuitions, not a problem with quantum mechanics. Quantum mechanics has been around for billions of years before the Sun coalesced from interstellar hydrogen. Quantum mechanics was here before you were, and if you have a problem with that, *you* are the one who needs to change. Quantum mechanics sure won't. There are no *surprising facts*, only *models* that are *surprised by* facts; and if a model is surprised by the facts, it is no credit to that model.

It is always best to think of reality as perfectly normal. Since the beginning, not one unusual thing has ever happened.

The *goal* is to become completely at home in a quantum universe. Like a native. Because, in fact, that is where you live.

In the coming sequence on quantum mechanics, I am going to consistently speak as if quantum mechanics is *perfectly normal*; and when human intuitions depart from quantum mechanics, I am going to make fun of the *intuitions* for being weird and unusual. This may seem odd, but the point is to swing your mind around to a *native* quantum point of view.

Another thing: The traditional introduction to quantum mechanics closely follows the order in which quantum mechanics was discovered.

The traditional introduction starts by saying that matter sometimes behaves like little billiard balls bopping around, and sometimes behaves like crests and troughs moving through a pool of water. Then the traditional introduction gives some examples of matter acting like a little billiard ball, and some examples of it acting like an ocean wave.

Now, it happens to be a historical fact that, back when students of matter were working all this stuff out and had *no clue* about the true underlying math, those early scientists first thought that matter was like little billiard balls. And then that it was like waves in the ocean. And then that it was like billiard balls again. And then the early scientists got *really* confused, and stayed that way for several decades, until it was finally sorted out in the second half of the twentieth century.

Dragging a modern-day student through all this may be a *historically realistic* approach to the subject matter, but it also ensures the historically realistic outcome of *total bewilderment*. Talking to aspiring young physicists about "wave/particle duality" is like starting chemistry students on the Four Elements.

An electron is *not* a billiard ball, and it's *not* a crest and trough moving through a pool of water. An electron is a mathematically different sort of entity, *all the time and under all circumstances*, and it has to be accepted on its own terms.

The universe is not wavering between using particles and waves, unable to make up its mind. It's only human *intuitions* about quantum mechanics that swap back and forth. The intuitions we have for billiard balls, and the intuitions we have for crests and troughs in a pool of water, both look *sort of* like they're applicable to electrons, at different times and under different circumstances. But the truth is that both intuitions simply *aren't applicable*.

If you try to think of an electron as being like a billiard ball on some days, and like an ocean wave on other days, you will *confuse the living daylights* out of yourself.

Yet it's your eyes that are wobbling and unstable, not the world.

Furthermore:

The order in which humanity *discovered* things is not necessarily the best order in which to *teach* them. First, humanity noticed that there were other animals running around. Then we cut them open and found that they were full of organs. Then we examined the organs carefully and found they were made of tissues. Then we looked at the tissues under a microscope and discovered cells, which are made of proteins and some other chemically synthesized stuff. Which are made of molecules, which are made of atoms, which are made of protons and neutrons and electrons *which are way simpler than entire animals but were discovered tens of thousands of years later*.

Physics doesn't start by talking about biology. So why should it start by talking about very high-level complicated phenomena, like, say, the observed results of experiments?

The ordinary way of teaching quantum mechanics keeps stressing the experimental results. Now I do understand why that sounds nice from a rationalist perspective. Believe me, I understand.

But it seems to me that the upshot is dragging in big complicated mathematical tools that you need to analyze real-world situations, before the student understands what *fundamentally* goes on in the simplest cases.

It's like trying to teach programmers how to write concurrent multithreaded programs before they know how to add two variables together, because concurrent multithreaded programs are closer to everyday life. Being close to everyday life is not always a strong recommendation for what to teach first.

Maybe the monomaniacal focus on experimental observations made sense in the dark decades when *no one* understood what was fundamentally going on, and you *couldn't* start there, and all your models were just mysterious maths that gave good experimental predictions… you can still find this view of quantum physics presented in many books… but maybe today it's worth trying a different angle? The result of the standard approach is standard confusion.

The classical world is strictly implicit in the quantum world, but seeing from a classical perspective makes everything bigger and more complicated.

Everyday life is a higher level of organization, like molecules versus quarks—huge catalogue of molecules, six quarks. I think it is worth trying to teach from the perspective of the quantum world first, and talking about classical experimental results afterward.

I am not going to start with the normal classical world and then talk about a bizarre quantum backdrop hidden behind the scenes. The quantum world *is* the scene and it defines normality.

I am not going to talk as if the classical world is real life, and occasionally the classical world transmits a request for an experimental result to a quantum-physics server, and the quantum-physics server does some peculiar calculations and transmits back a classical experimental result. I am going to talk as if the quantum world is the really real and the classical world something far away. Not just because that makes it easier to be a native of a quantum universe, but because, at a core level, it's the truth.

Finally, I am going to take a strictly realist perspective on quantum mechanics—the quantum world is really out there, our equations describe the territory and not our maps of it, and the classical world only exists implicitly within the quantum one. I am not going to discuss non-realist views in the early stages of my introduction, except to say why you should not be confused by certain intuitions that non-realists draw upon for support. I am not going to apologize for this, and I would like to ask any non-realists on the subject of quantum mechanics to wait and hold their comments until called for in a later essay. Do me this favor, please. I think non-realism is one of the main things that confuses prospective students, and prevents them from being able to concretely visualize quantum phenomena. I *will* discuss the issues explicitly in a future essay.

But everyone should be aware that, even though I'm not going to discuss the issue at first, there is a sizable community of scientists who dispute the realist perspective on quantum mechanics. Myself, I don't think it's worth figuring both ways; I'm a pure realist, for reasons that will become apparent. But if you read my introduction, you are getting my view. It is not only my view. It is probably the majority view among theoretical physicists, if that counts for anything (though I will argue the matter separately from opinion polls). Still, it is not the only view that exists in the modern physics community. I do not feel obliged to present the other views *right away*, but I feel obliged to warn my readers that there *are* other views, which I will not be presenting during the initial stages of the introduction.

To sum up, my goal will be to teach you to think like a *native of a quantum universe*, not a *reluctant tourist*.

Embrace reality. Hug it tight.

Configurations and Amplitude

So the universe isn't made of little billiard balls, and it isn't made of crests and troughs in a pool of aether… Then what is the stuff that stuff is made of?

In Figure 1, we see, at *A*, a half-silvered mirror, and two photon detectors, Detector 1 and Detector 2.

Early scientists, when they ran experiments like this, became confused about what the results meant. They would send a photon toward the half-silvered mirror, and half the time they would see Detector 1 click, and the other half of the time they would see Detector 2 click.

The early scientists—you're going to laugh at this—thought that the silver mirror deflected the photon half the time, and let it through half the time.

Ha, ha! As if the half-silvered mirror did different things on different occasions! I want you to let go of this idea, because if you cling to what early scientists thought, you will become extremely confused. The half-silvered mirror obeys the same rule every time.

If you were going to write a computer program that *was* this experiment— not a computer program that *predicted* the result of the experiment, but a computer program that resembled the underlying reality—it might look sort of like this:

At the start of the program (the start of the experiment, the start of time) there's a certain mathematical entity, called a *configuration*. You can think of this configuration as corresponding to "there is one photon heading from the photon source toward the half-silvered mirror," or just "a photon heading toward *A*."

A configuration can store a single complex value—"complex" as in the complex numbers $(a + bi)$, with i defined as $\sqrt{-1}$. At the start of the program, there's already a complex number stored in the configuration "a photon heading toward *A*." The exact value doesn't matter so long as it's not zero. We'll let the configuration "a photon heading toward *A*" have a value of $(-1 + 0i)$.

All this is a fact within the territory, not a description of anyone's knowledge. A configuration isn't a proposition or a possible way the world could be. A configuration is a variable in the program—you can think of it as a kind of memory location whose index is "a photon heading toward *A*"—and it's out there in the territory.

As the complex numbers that get assigned to configurations are not positive real numbers between 0 and 1, there is no danger of confusing them with probabilities. "A photon heading toward *A*" has complex value -1, which is hard to see as a degree of belief. The complex numbers are values within the program, again out there in the territory. We'll call the complex numbers *amplitudes*.

There are two other configurations, which we'll call "a photon going from *A* to Detector 1" and "a photon going from *A* to Detector 2." These configurations don't have a complex value yet; it gets assigned as the program runs.

We are going to calculate the amplitudes of "a photon going from *A* toward 1" and "a photon going from A toward 2" using the value of "a photon going toward *A*," and the rule that describes the half-silvered mirror at *A*.

Roughly speaking, the half-silvered mirror rule is "multiply by 1 when the photon goes straight, and multiply by *i* when the photon turns at a right angle." This is the universal rule that relates the amplitude of the configuration of "a photon going in," to the amplitude that goes to the configurations of “a photon coming out straight” or “a photon being deflected.”[1]

So we pipe the amplitude of the configuration “a photon going toward *A*,” which is $(-1 + 0i)$, into the half-silvered mirror at *A*, and this transmits an amplitude of

$(-1 + 0i) \times i = (0 - i)$ to “a photon going from *A* toward 1,” and also transmits an

amplitude of $(-1 + 0i) \times 1 = (-1 + 0i)$ to “a photon going from *A* toward 2.”

In the Figure 1 experiment, these are all the configurations and all the transmitted amplitude we need to worry about, so we’re done. Or, if you want to think of “Detector 1 gets a photon” and “Detector 2 gets a photon” as separate configurations, they’d just inherit their values from “*A* to 1” and “*A* to 2” respectively. (Actually, the values inherited should be multiplied by another complex factor, corresponding to the distance from *A* to the detector; but we will ignore that for now, and suppose that all distances traveled in our experiments happen to correspond to a complex factor of 1.)

So the final program state is:

Configuration “a photon going toward A”*:* (−1+0i)

Configuration “a photon going from A toward 1”: (0−i)

Configuration “a photon going from A toward 2”: (−1+0i)

and optionally

Configuration “Detector 1 gets a photon”: (0−i)

Configuration “Detector 2 gets a photon”: (−1+0i).

This same result occurs—the same amplitudes stored in the same configurations—every time you run the program (every time you do the experiment).

Now, for *complicated* reasons that we aren’t going to go into here— considerations that belong on a higher level of organization than fundamental quantum mechanics, the same way that atoms are more complicated than quarks—there’s no *simple*measuring instrument that can directly tell us the exact amplitudes of each configuration. We can’t directly see the program state.

So how do physicists know what the amplitudes are?

We *do* have a magical measuring tool that can tell us the *squared modulus* of a configuration’s amplitude. If the original complex amplitude is $(a + bi)$, we can get the positive real number $(a^2 + b^2)$. Think of the Pythagorean theorem: if you imagine the complex number as a little arrow stretching out from the origin on a two-dimensional plane, then the magic tool tells us the squared length of the little arrow, but it doesn’t tell us the direction the arrow is pointing.

To be more precise, the magic tool actually just tells us the *ratios* of the squared lengths of the amplitudes in some configurations. We don’t know how long the arrows are in an absolute sense, just how long they are relative to each other. But this turns out to be enough information to let us reconstruct the laws of physics—the rules of the program. And so I can talk about amplitudes, not just ratios of squared moduli.

When we wave the magic tool over “Detector 1 gets a photon” and “Detector 2 gets a photon,” we discover that these configurations have the same squared modulus—the lengths of the arrows are the same. Thus speaks the magic tool. By doing more *complicated* experiments (to be seen shortly), we can tell that the original complex numbers had a ratio of i to 1.

And what is this magical measuring tool?

Well, from the perspective of everyday life—way, way, way above the quantum level and a lot more complicated—the magical measuring tool is that we send some photons toward the half-silvered mirror, one at a time, and count up how many photons arrive at Detector 1 versus Detector 2 over a few thousand trials. The ratio of these values is the ratio of the squared moduli of the amplitudes. But the reason for this is *not* something we are going to consider yet. Walk before you run. It is not possible to understand what happens *all the way up* at the level of everyday life, before you understand what goes on in much simpler cases.

For today’s purposes, we have a magical squared-modulus-ratio reader. And the magic tool tells us that the little two-dimensional arrow for the configuration “Detector 1 gets a photon” has the same squared length as for “Detector 2 gets a photon.” That’s all.

You may wonder, “Given that the magic tool works this way, what motivates us to use quantum theory, instead of thinking that the half-silvered mirror reflects the photon around half the time?”

Well, that’s just begging to be confused—putting yourself into a historically realistic frame of mind like that and using everyday intuitions. Did I say anything about a little billiard ball going one way or the other and possibly bouncing off a mirror? That’s not how reality works. *Reality* is about complex amplitudes flowing between configurations, and the laws of the flow are stable.

But if you insist on seeing a more complicated situation that billiard-ball ways of thinking can’t handle, here’s a more complicated experiment.

In Figure 2, *B* and *C* are full mirrors, and *A* and *D* are half-mirrors. The line from *D* to *E* is dashed for reasons that will become apparent, but amplitude is flowing from *D* to *E* under exactly the same laws.

Now let's apply the rules we learned before:

At the beginning of time "a photon heading toward *A*" has amplitude $(-1 + 0i)$.

We proceed to compute the amplitude for the configurations "a photon going from *A* to *B*" and "a photon going from *A* to *C*":

"a photon going from A *t*o B" = i × a photon heading toward A" = $(0 - i)$

Similarly,

"a photon going from A *t*o C" = 1 × a photon heading toward A" = $(-1 + 0i)$

The full mirrors behave (as one would expect) like half of a half-silvered mirror—a full mirror just bends things by right angles and multiplies them by i. (To state this slightly more precisely: For a full mirror, the amplitude that flows, from the configuration of a photon heading in, to the configuration of a photon heading out at a right angle, is multiplied by a factor of i.*)*

So:

"a photon going from B to D*"* = i × "a photon going from A to B*"* = $(1 + 0i)$,

"a photon going from C to D*"* = i × "a photon going from A to C*"* = $(0 - i)$

"B to D*"* and "C to D*"* are two different configurations—we don't simply write "a photon at D*"*—because the photons are arriving at two different angles in these two different configurations. And what D does to a photon depends on the angle at which the photon arrives.

Again, the rule (speaking loosely) is that when a half-silvered mirror bends light at a right angle, the amplitude that flows from the photon-going-in configuration to the photon-going-out configuration, is the amplitude of the photon-going-in configuration multiplied by *i*. And when two configurations are related by a half-silvered mirror letting light straight through, the amplitude that flows from the photon-going-in configuration is multiplied by 1.

So:

From the configuration "a photon going from B to D*,*" with original amplitude(1+0i)

Amplitude of $(1 + 0i) \times i = (0 + i)$ flows to "a photon going from D to E*.*"

Amplitude of $(1 + 0i) \times 1 = (1 + 0i)$ flows to "a photon going from *D* to *F*. "

From the configuration “a photon going from C to D,” with original amplitude(0−i)

Amplitude of $(0 - i) \times i = (1 + 0i)$ flows to “a photon going from D to F. ”

Amplitude of $(0 - i) \times 1 = (0 - i)$ flows to “a photon going from D to E.”

Therefore:

- The *total* amplitude flowing to configuration “a photon going from *D* to *E*” is $(0 + i) + (0 - i) = (0 + 0i) = 0$.
- The total amplitude flowing to configuration “a photon going from *D* to *F*” is $(1 + 0i) + (1 + 0i) = (2 + 0i)$.

(You may want to try working this out yourself on pen and paper if you lost track at any point.)

But the upshot, from that super-high-level “experimental” perspective that we think of as normal life, is that we see *no* photons detected at *E*. Every photon seems to end up at *F*. The ratio of squared moduli between “*D* to *E*” and “*D* to *F*” is 0 to 4. That’s why the line from *D* to *E* is dashed, in this figure.

This is not something it is possible to explain by thinking of half-silvered mirrors deflecting little incoming billiard balls half the time. You’ve *got* to think in terms of amplitude flows.

If half-silvered mirrors deflected a little billiard ball half the time, in this setup, the little ball would end up at Detector 1 around half the time and Detector 2 around half the time. Which it doesn’t. So don’t think that.

You may say, “But wait a minute! I can think of another hypothesis that accounts for this result. What if, when a half-silvered mirror reflects a photon, it does something to the photon that ensures it doesn’t get reflected next time? And when it lets a photon go through straight, it does something to the photon so it gets reflected next time.”

Now really, there’s no need to go making the rules so complicated. Occam’s Razor, remember. Just stick with simple, normal amplitude flows between configurations.

But if you want *another* experiment that disproves your *new* alternative hypothesis, it’s Figure 3.

Here, we've left the whole experimental setup the same, and just put a little blocking object between *B* and *D*. This ensures that the amplitude of "a photon going from *B* to *D*" is 0.

Once you eliminate the amplitude contributions from that configuration, you end up with totals of $(1 + 0i)$ in "a photon going from *D* to *F*, " and $(0 - i)$ in "a photon going from *D* to *E*."

The squared moduli of $(1 + 0i)$ and $(0 - i)$ are both 1, so the magic measuring tool should tell us that the ratio of squared moduli is 1. Way back up at the level where physicists exist, we should find that Detector 1 goes off half the time, and Detector 2 half the time.

The same thing happens if we put the block between *C* and *D*. The amplitudes are different, but the ratio of the squared moduli is still 1, so Detector 1 goes off half the time and Detector 2 goes off half the time.

This cannot *possibly* happen with a little billiard ball that either does or doesn't get reflected by the half-silvered mirrors.

Because complex numbers can have opposite directions, like 1 and −1, or *i* and −*i*, amplitude flows can cancel each other out. Amplitude flowing from configuration *X* into configuration *Y* can be canceled out by an equal and opposite amplitude flowing from configuration *Z* into configuration *Y*. In fact, that's exactly what happens in this experiment.

In probability theory, when something can either happen one way or another, *X* or ¬*X*, then $P(Z) = P(Z|X)P(X) + P(Z|\neg X)P(\neg X)$. And all probabilities are positive. So if you establish that the probability of *Z* happening given *X* is $\frac{1}{2}$, and the probability of *X* happening is $\frac{1}{3}$, then the total probability of *Z* happening is *at least* $\frac{1}{6}$ no matter *what* goes on in the case of ¬*X*. There's no such thing as negative probability, less-than-impossible credence, or $(0 + i)$ credibility, so *degrees of belief* can't cancel each other out like amplitudes do.

Not to mention that probability is in the mind to begin with; and we are talking *about* the territory, the program-that-is-reality, not talking *about* human cognition or states of partial knowledge.

By the same token, configurations are not *propositions*, not *statements*, not *ways the world could conceivably be*. Configurations are not semantic constructs. Adjectives like *probable* do not apply to them; they are not beliefs or sentences or possible worlds. They are not *true* or *false* but simply *real*.

In the experiment of Figure 2, do not be tempted to think anything like: "The photon goes to either *B* or *C*, but it *could* have gone the other way, and this possibility interferes with its ability to go to *E*…"

It makes no sense to think of something that "could have happened but didn't" exerting an effect on the world. We can *imagine* things that could have happened but didn't—like thinking, "Gosh, that car almost hit me"—and our imagination can have an effect on our future behavior. But the event of imagination is a real event, that actually happens, and *that* is what has the effect. It's your imagination of the unreal event—your very real imagination, implemented within a quite physical brain—that affects your behavior.

To think that the *actual event* of a car hitting you—this event which could have happened to you, but in fact didn't—is directly exerting a *causal* effect on your behavior, is mixing up the map with the territory.

What affects the world is real. (If things can affect the world without being "real," it's hard to see what the word "real" means.) Configurations and amplitude flows are causes, and they have visible effects; they are real. Configurations are not possible worlds and amplitudes are not degrees of belief, any more than your chair is a possible world or the sky is a degree of belief.

So what *is* a configuration, then?

Well, you'll be getting a clearer idea of that in later essays.

But to give you a quick idea of how the real picture differs from the simplified version we saw in this essay…

Our experimental setup only dealt with one moving particle, a single photon. Real configurations are about multiple particles. The next essay will deal with the case of more than one particle, and that should give you a much clearer idea of what a configuration is.

Each configuration we talked about *should* have described a joint position of all the particles in the mirrors and detectors, not just the position of one photon bopping around.

In fact, the *really real* configurations are over joint positions of all the particles in the universe, including the particles making up the experimenters. You can see why I'm saving the notion of *experimental results* for later essays.

In the real world, amplitude is a continuous distribution over a continuous *space* of configurations. This essay's "configurations" were blocky and digital, and so were our "amplitude flows." It was as if we were talking about a photon teleporting from one place to another.

If none of that made sense, don't worry. It will be cleared up in later essays. Just wanted to give you some idea of where this was heading.

---

1. [**Editor's Note:** Strictly speaking, a standard half-silvered mirror would yield a rule "multiply by −1 when the photon turns at a right angle," not "multiply by *i*." The basic scenario described by the author is not physically impossible, and its use does not affect the substantive argument. However, physics students may come away confused if they compare the discussion here to textbook discussions of Mach–Zehnder interferometers. We've left this idiosyncrasy in the text because it eliminates any need to specify which side of the mirror is half-silvered, simplifying the experiment.]

Joint Configurations

The key to understanding configurations, and hence the key to understanding quantum mechanics, is realizing on a truly gut level that configurations are about more than one particle.

Continuing from the previous essay, Figure 1 shows an altered version of the experiment where we send in *two* photons toward *D* at the same time, from the sources *B* and *C*.

The starting configuration then is:

"a photon going from B to D,

and a photon going from *C* to *D*."

Again, let's say the starting configuration has amplitude $(-1 + 0i)$.

And remember, the rule of the half-silvered mirror (at *D*) is that a right-angle deflection multiplies by *i*, and a straight line multiplies by 1.

So the amplitude flows from the starting configuration, separately considering the four cases of deflection/non-deflection of each photon, are:

1. The "*B* to *D*" photon is deflected and the "*C* to *D*" photon is deflected. This amplitude flows to the configuration "a photon going from *D* to *E*, and a photon going from *D* to *F*." The amplitude flowing is $(-1 + 0i) \times i \times i = (1 + 0i)$.
2. The "*B* to *D*" photon is deflected and the "*C* to *D*" photon goes straight. This amplitude flows to the configuration "two photons going from *D* to *E*." The amplitude flowing is $(-1 + 0i) \times i \times 1 = (0 - i)$.
3. The "*B* to *D*" photon goes straight and the "*C* to *D*" photon is deflected. This amplitude flows to the configuration "two photons going from *D* to *F*." The amplitude flowing is $(-1 + 0i) \times 1 \times i = (0 - i)$.
4. The "*B* to *D*" photon goes straight and the "*C* to *D*" photon goes straight. This amplitude flows to the configuration "a photon going from *D* to *F*, and a photon going from *D* to *E*." The amplitude flowing is $(-1 + 0i) \times 1 \times 1 = (-1 + 0i)$.

Now—and this is a *very important and fundamental idea in quantum mechanics*—the amplitudes in cases 1 and 4 are flowing to the *same* configuration. Whether the *B* photon and *C* photon both go straight, or both are deflected, the resulting configuration is *one photon going toward E and another photon going toward F*.

So we add up the two incoming amplitude flows from case 1 and case 4, and get a total amplitude of $(1 + 0i) + (-1 + 0i) = 0$.

When we wave our magic squared-modulus-ratio reader over the three final configurations, we'll find that "two photons at Detector 1" and "two photons at Detector 2" have the same squared modulus, but "a photon at Detector 1 and a photon at Detector 2" has squared modulus zero.

Way up at the level of experiment, we never find Detector 1 and Detector 2 both going off. We'll find Detector 1 going off twice, or Detector 2 going off twice, with equal frequency. (Assuming I've gotten the math and physics right. I didn't actually perform the experiment.)

The configuration's identity is *not*, "the *B* photon going toward *E* and the *C* photon going toward *F*. " Then the resultant configurations in case 1 and case 4 would not be equal. Case 1 would be, "*B* photon to *E*, *C* photon to *F*" and case 4 would be "*B*photon to *F*, *C* photon to *E*." These would be two distinguishable configurations, if configurations had photon-tracking structure.

So we would not add up the two amplitudes and cancel them out. We would keep the amplitudes in two separate configurations. The total amplitudes would have non-zero squared moduli. And when we ran the experiment, we would find (around half the time) that Detector 1 and Detector 2 each registered one photon. Which doesn't happen, if my calculations are correct.

Configurations don't keep track of where particles come from. A configuration's identity is just, "a photon here, a photon there; an electron here, an electron there." No matter how you get into that situation, so long as there are the same species of particles in the same places, it counts as the same configuration.

I say again that the question "What kind of information does the configuration's structure incorporate?" has *experimental consequences*. You can deduce, from experiment, the way that reality itself must be treating configurations.

In a classical universe, there would be no experimental consequences. If the photon were like a little billiard ball that either went one way or the other, and the configurations were our beliefs about possible states the system could be in, and instead of amplitudes we had probabilities, it would not make a difference whether we tracked the origin of photons or threw the information away.

In a classical universe, I could assign a 25% probability to both photons going to *E*, a 25% probability of both photons going to *F*, a 25% probability of the *B* photon going to *E* and the *C* photon going to *F*, and 25% probability of the *B* photon going to *F*and the *C* photon going to *E*. Or, since I *personally* don't care which of the two latter cases occurred, I could decide to collapse the two possibilities into one possibility and add up their probabilities, and just say, "a 50% probability that each detector gets one photon."

With probabilities, we can aggregate events as we like—draw our boundaries around sets of possible worlds as we please—and the numbers will still work out the same. The probability of two mutually exclusive events always equals the probability of the first event plus the probability of the second event.

But you can't arbitrarily collapse configurations together, or split them apart, in your model, and get the same experimental predictions. Our magical tool tells us the ratios of squared moduli. When you add two complex numbers, the squared modulus of the sum is not the sum of the squared moduli of the parts:

$$\mathrm{SquaredModulus}(C_1 + C_2) \neq \mathrm{SquaredModulus}(C_1) + \mathrm{SquaredModulus}(C_2))$$

E.g.

$$\mathrm{SquaredModulus}((2+i)+(1-i))$$

$$= \mathrm{SquaredModulus}(3+0i)$$

$$= 3^2 + 0^2$$

$$= 9$$

$$\mathrm{SquaredModulus}(2+i) + \mathrm{SquaredModulus}(1-i)$$

$$= (2^2 + 1^2) + (1^2 + (-1)^2)$$

$$= (4+1) + (1+1)$$

$$= 7$$

Or in the current experiment of discourse, we had flows of $(1 + 0i)$ and $(-1 + 0i)$ cancel out, adding up to 0, whose squared modulus is 0, where the squared modulus of the parts would have been 1 and 1.

If in place of Squared_Modulus, our magical tool was some linear function— any function where $F(X + Y) = F(X) + F(Y)$—then all the quantumness would instantly vanish and be replaced by a classical physics. (A *different* classical physics, not the same illusion of classicality we hallucinate from inside the higher levels of organization in our own quantum world.)

If amplitudes were just probabilities, they couldn't cancel out when flows collided. If configurations were just states of knowledge, you could reorganize them however you liked.

But the configurations are nailed in place, indivisible and unmergeable without changing the laws of physics.

And part of what is nailed is the way that configurations treat multiple particles. A configuration says, "a photon here, a photon there," not "*this* photon here, *that*photon there." "*This* photon here, *that* photon there" does not have a different identity from "*that* photon here, *this* photon there."

The result, visible in today's experiment, is that you can't factorize the physics of our universe to be about particles with individual identities.

Part of the reason why humans have trouble coming to grips with *perfectly normal*quantum physics, is that humans bizarrely keep trying to factor reality into a sum of individually real billiard balls.

Ha ha! Silly humans.

Distinct Configurations

The experiment in the previous essay carried two key lessons:

First, we saw that because amplitude flows can cancel out, and because our magic measure of squared modulus is not linear, the identity of configurations is nailed down—you can't reorganize configurations the way you can regroup possible worlds. Which configurations are the same, and which are distinct, has experimental consequences; it is an observable fact.

Second, we saw that configurations are about multiple particles. If there are two photons entering the apparatus, that doesn't mean there are two initial configurations. Instead the initial configuration's identity is "two photons coming in." (Ideally, each configuration we talk about would include every particle in the experiment—including the particles making up the mirrors and detectors. And in the real universe, every configuration is about *all* the particles… *everywhere*.)

What makes for distinct configurations is not distinct particles. Each configuration is about every particle. What makes configurations distinct is particles occupying different positions—at least one particle in a different state.

To take one important demonstration…

Figure 1 is the same experiment as Figure 2 in Configurations and Amplitude, with one important change: Between *A* and *C* has been placed a sensitive thingy, *S*. The key attribute of *S* is that if a photon goes past *S*, then *S* ends up in a slightly different state.

Let's say that the two possible states of *S* are *Yes* and *No*. The sensitive thingy *S* starts out in state *No*, and ends up in state *Yes* if a photon goes past.

Then the initial configuration is:

"photon heading toward A*;* and S in state *No,*" $(-1 + 0i)$

Next, the action of the half-silvered mirror at *A*. In the previous version of this experiment, without the sensitive thingy, the two resultant configurations were "*A* to *B*" with amplitude $-i$ and "*A* to *C*" with amplitude -1. Now, though, a new element has been introduced into the system, and all configurations are about all particles, and so every configuration mentions the new element. So the amplitude flows from the initial configuration are to:

"photon from A to B*;* and S in state N*o,*" $(0 - i)$

"photon from A to C*;* and S in state Y*es,*" $(-1 + 0i)$

Next, the action of the full mirrors at *B* and *C*:

"photon from B to D*;* and S in state *No,*" (1 + 0i*)* "photon from C to D*;* and S in state *Yes,*" (0 − i*)* .

And then the action of the half-mirror at *D*, on the amplitude flowing from both of the above configurations:

(1) "photon from D to E*;* and S in state *No,*" $(0 + i)$

(2) "photon from *D* to *F*; and *S* in state *No*," $(1 + 0i)$

(3) "photon from *D* to *E*; and *S* in state *Yes*," $(0 - i)$

(4) "photon from *D* to *F*; and *S* in state *Yes*," $(1 + 0i)$.

When we did this experiment without the sensitive thingy, the amplitude flows (1) and (3) of $(0 + i)$ and $(0 - i)$ to the "*D* to *E*" configuration canceled each other out. We were left with no amplitude for a photon going to Detector 1 (way up at the experimental level, we never observe a photon striking Detector 1).

But in this case, the two amplitude flows (1) and (3) are now to distinct configurations; at least one entity, *S*, is in a different state between (1) and (3). The amplitudes don't cancel out.

When we wave our magical squared-modulus-ratio detector over the four final configurations, we find that the squared moduli of all are equal: 25% probability each. Way up at the level of the real world, we find that the photon has an equal chance of striking Detector 1 and Detector 2.

All the above is true, even if we, the researchers, don't care about the state of *S*. Unlike possible worlds, configurations cannot be regrouped on a whim. The laws of *physics* say the two configurations are distinct; it's not a question of how we can most conveniently parse up the world.

All the above is true, even if we don't bother to look at the state of *S*. The configurations (1) and (3) are distinct in physics, even if we don't know the distinction.

All the above is true, even if we don't know *S* exists. The configurations (1) and (3) are distinct whether or not we have distinct *mental representations* for the two possibilities.

All the above is true, even if we're in space, and *S* transmits a new photon off toward the interstellar void in two distinct directions, depending on whether the photon of interest passed it or not. So that we couldn't *ever* find out whether *S* had been in *Yes* or *No*. The state of *S* would be embodied in the photon transmitted off to nowhere. The lost photon can be an implied invisible, and the state of *S* pragmatically undetectable; but the configurations are still distinct.

(The main reason it *wouldn't* work, is if *S* were nudged, but *S* had an original spread in configuration space that was larger than the nudge. Then you couldn't rely on the nudge to separate the amplitude distribution over configuration space into distinct lumps. In reality, all this takes place within a differentiable amplitude distribution over a continuous configuration space.)

Configurations are not belief states. Their distinctness is an objective fact with experimental consequences. The configurations are distinct even if no one knows the state of *S*; distinct even if no intelligent entity can ever find out. The configurations are distinct so long as at least *one particle* in the universe *anywhere* is in a different position. This is experimentally demonstrable.

Why am I emphasizing this? Because back in the dark ages when no one understood quantum physics…

Okay, so imagine that you've got no clue what's really going on, and you try the experiment in Figure 2, and no photons show up at Detector 1. Cool.

You also discover that when you put a block between *B* and *D*, or a block between *A* and *C*, photons show up at Detector 1 and Detector 2 in equal proportions. But only one at a time—Detector 1 or Detector 2 goes off, not both simultaneously.

So, yes, it *does* seem to you like you're dealing with a particle—the photon is only in one place at one time, every time *you* see it.

And yet there's some kind of… *mysterious phenomenon*… that prevents the photon from showing up in Detector 1. And this mysterious phenomenon depends on the photon being *able* to go both ways. Even though the photon only shows up in one detector or the other, which shows, *you would think*, that the photon is only in one place at a time.

Which makes the whole pattern of the experiments seem pretty bizarre! After all, the photon either goes from *A* to *C*, or from *A* to *B*; one or the other. (Or so you would think, if you were instinctively trying to break reality down into individually real particles.) But when you block off one course or the other, as in Figure 3, you start getting different experimental results!

It's like the photon wants to be *allowed* to go both ways, even though (you would think) it only goes one way or the other. And it can *tell* if you try to block it off, without actually going *there*—if it'd gone there, it would have run into the block, and not hit any detector at all.

It's as if mere *possibilities* could have causal effects, in defiance of what the word "real" is usually thought to *mean*…

But it's a bit early to jump to conclusions like *that*, when you don't have a complete picture of what goes on inside the experiment.

So it occurs to you to put a sensor between *A* and *C*, like in Figure 4, so you can tell which way the photon *really* goes on each occasion.

And the mysterious phenomenon goes away.

I mean, now how crazy is that? What kind of paranoia does that inspire in some poor scientist?

Okay, so in the twenty-first century we realize in order to “know” a photon’s history, the particles making up your brain [have to be correlated](https://www.lesswrong.com/lw/jl/what_is_evidence/) with the photon’s history. If having a tiny little sensitive thingy *S* that correlates to the photon’s history is enough to distinguish the final configurations and prevent the amplitude flows from canceling, then an entire sensor with a digital display, never mind a human brain, will put *septillions* of particles in different positions and prevent the amplitude flows from canceling.

But if you hadn’t worked that out yet…

Then you would ponder the sensor having banished the Mysterious Phenomenon, and think:

The photon doesn’t just want to be *physically* free to go either way. It’s not a little wave going along an unblocked pathway, because then just having a physically unblocked pathway would be enough.

No… I’m not allowed to know which way the photon went.

The mysterious phenomenon… *doesn’t want me looking at it too closely*… while it’s doing its mysterious thing.

It’s not *physical possibilities* that have an effect on reality… only *epistemic possibilities*. If I *know* which way the photon went, it’s no longer *plausible* that it went the other way… which cuts off the mysterious phenomenon as effectively as putting a block between *B* and *D*.

I have to *not observe* which way the photon went, in order for it to always end up at Detector 2. It has to be *reasonable* that the photon could have gone to either *B* or *C*. What I can *know* is the determining factor, regardless of which physical paths I leave open or closed.

STOP THE PRESSES! MIND IS FUNDAMENTAL AFTER ALL! CONSCIOUS AWARENESS DETERMINES OUR EXPERIMENTAL RESULTS!

You can *still read* this kind of stuff. In *physics textbooks*. Even now, when a majority of theoretical physicists know better. Stop the presses. Please, stop the presses.

Hindsight is 20/20; and so it’s easy to say that, in hindsight, there were certain clues that this interpretation was not correct.

Like, if you put the sensor between *A* and *C but don’t read it*, the mysterious phenomenon *still* goes away, and the photon still sometimes ends up at Detector 1. (Oh, but you *could* have read it, and possibilities are real now…)

But it doesn’t even have to be a *sensor*, a scientific instrument that you built. A single particle that gets nudged far enough will dispel the interference. A photon radiating off to where you'll never see it again can do the trick. Not much human involvement there. Not a whole lot of conscious awareness.

Maybe before you pull the dualist fire alarm on human brains being physically special, you should provide experimental proof that a rock can't play the same role in dispelling the Mysterious Phenomenon as a human researcher?

But that's hindsight, and it's easy to call the shots in hindsight. Do you *really* think you could've done better than John von Neumann, if you'd been alive at the time? The point of this kind of retrospective analysis is to ask what kind of fully general clues you could have followed, and whether there are any similar clues you're ignoring now on current mysteries.

Though it *is* a little embarrassing that even *after* the theory of amplitudes and configurations had been worked out—with the theory now giving the definite prediction that any nudged particle would do the trick—early scientists *still* didn't get it.

But you see… it had been established as Common Wisdom that configurations were possibilities, it was epistemic possibility that mattered, amplitudes were a very strange sort of partial information, and conscious observation made quantumness go away. And that it was best to avoid thinking too hard about the whole business, so long as your experimental predictions came out right.

Where Philosophy Meets Science

Looking back on early quantum physics—not for purposes of admonishing the major figures, or to claim that *we* could have done better if we'd been born into that era, but in order to try and learn a moral, and do better next time—looking back on the dark ages of quantum physics, I say, I would nominate as the "most basic" error…

… *not* that they tried to reverse course on the last three thousand years of science suggesting that mind was complex within physics rather than fundamental in physics. This is Science, and we do have revolutions here. Every now and then you've got to reverse a trend. The future is always absurd and never unlawful.

I would nominate, as the basic error not to repeat next time, that the early scientists forgot that they *themselves* were made out of particles.

I mean, I'm sure that most of them knew it in theory.

And yet they didn't notice that putting a sensor to detect a passing electron, or even *knowing* about the electron's history, was an example of "particles in different places." So they didn't notice that a quantum theory of distinct configurations already explained the experimental result, without any need to invoke consciousness.

In the ancestral environment, humans were often faced with the adaptively relevant task of predicting other humans. For which purpose you thought of your fellow humans as having thoughts, knowing things and feeling things, rather than thinking of them as being made up of particles. In fact, many hunter-gatherer tribes may not even have known that particles existed. It's much more *intuitive*—it *feels* simpler—to think about someone "knowing" something, than to think about their brain's particles occupying a different state. It's easier to phrase your explanations in terms of what *people know*; it feels more natural; it leaps more readily to mind.

Just as, once upon a time, it was easier to imagine Thor throwing lightning bolts, than to imagine Maxwell's Equations—even though Maxwell's Equations can be described by a computer program vastly smaller than the program for an intelligent agent like Thor.

So the ancient physicists found it natural to think, "I know where the photon was… what difference could *that* make?" Not, "My brain's particles' current state correlates to the photon's history… what difference could *that* make?"

And, similarly, because it felt easy and intuitive to model reality in terms of people knowing things, and the decomposition of knowing into brain states did not leap so readily to mind, it *seemed* like a simple theory to say that a configuration could have amplitude only "if you didn't know better."

To turn the dualistic quantum hypothesis into a *formal* theory—one that could be written out as a computer program, without human scientists deciding when an "observation" occurred—you would have to specify what it meant for an "observer" to "know" something, in terms your computer program could compute.

So is your theory of fundamental physics going to examine all the particles in a human brain, and decide when those particles "know" something, in order to compute the motions of particles? But then how do you compute the motion of the particles in the brain itself? Wouldn't there be a potential infinite recursion?

But so long as the terms of the theory were being processed by human scientists, they *just knew* when an "observation" had occurred. You said an "observation" occurred whenever it had to occur in order for the experimental predictions to come out right—a subtle form of constant tweaking.

(Remember, the basics of quantum theory were formulated before Alan Turing said anything about Turing machines, and *way* before the concept of computation was popularly known. The distinction between an effective formal theory, and one that required human interpretation, was not as clear then as now. Easy to pinpoint the problems in hindsight; you shouldn't learn the lesson that problems are usually this obvious in foresight.)

Looking back, it may *seem* like one meta-lesson to learn from history, is that philosophy really matters in science—it's not just some adjunct of a separate academic field.

After all, the early quantum scientists were doing all the right experiments. It was their interpretation that was off. And the problems of interpretation were not the result of their getting the statistics wrong.

Looking back, it seems like the errors they made were errors in the kind of thinking that we would describe as, well, "philosophical."

When we look back and ask, "How could the early quantum scientists have done better, even in principle?" it seems that the insights they needed were philosophical ones.

And yet it wasn't professional philosophers who swooped in and solved the problem and cleared up the mystery and made everything normal again. It was, well, physicists.

Arguably, Leibniz was at least as foresightful about quantum physics, as Democritus was once thought to have been foresightful about atoms. But that is hindsight. It's the result of looking at the solution, and thinking back, and saying, "Hey, Leibniz said something like that."

Even where one philosopher gets it right in advance, it's usually science that ends up *telling us* which philosopher is right—not the *prior consensus* of the philosophical community.

I think this has something fundamental to say about the nature of philosophy, and the interface between philosophy and science.

It was once said that every science begins as philosophy, but then grows up and leaves the philosophical womb, so that at any given time, "Philosophy" is what we haven't turned into science yet.

I suggest that when we look at the history of quantum physics and say, "The insights they needed were philosophical insights," what we are *really* seeing is that the insight they needed was of a form that is not yet taught in standardized academic classes, and not yet reduced to calculation.

Once upon a time, the notion of the scientific method—updating beliefs based on experimental evidence—was a philosophical notion. But it was not championed by professional philosophers. It was the real-world power of science that showed that scientific epistemology was good epistemology, not a prior consensus of philosophers.

Today, this philosophy of belief-updating is *beginning* to be reduced to calculation—statistics, Bayesian probability theory.

But back in Galileo's era, it was solely *vague verbal arguments* that said you should try to produce numerical predictions of experimental results, rather than consulting the Bible or Aristotle.

At the frontier of science, and especially at the frontier of scientific *chaos* and scientific *confusion*, you find problems of thinking that are not taught in academic courses, and that have not been reduced to calculation. And this will seem like a domain of philosophy; it will seem that you must do philosophical thinking in order to sort out the confusion. But when history looks back, I'm afraid, it is usually not a professional philosopher who wins all the marbles—because it takes intimate involvement with the scientific domain in order to do the philosophical thinking. Even if, afterward, it all seems knowable a priori; and even if, afterward, some philosopher out there actually *got* it a priori; even so, it takes intimate involvement to see it in practice, and experimental results to tell the world which philosopher won.

I suggest that, like ethics, philosophy really is important, but it is only practiced effectively from *within* a science. Trying to do the philosophy of a frontier science, as a separate academic profession, is as much a mistake as trying to have separate ethicists. You end up with ethicists who speak mainly to other ethicists, and philosophers who speak mainly to other philosophers.

This is not to say that there is no place for professional philosophers in the world. Some problems are so chaotic that there is no established place for them at all in the halls of science. But those "professional philosophers" would be very, very wise to learn every scrap of relevant-seeming science that they can possibly get their hands on. They should not be surprised at the prospect that experiment, and not debate, will finally settle the argument. They should not flinch from running their own experiments, if they can possibly think of any.

That, I think, is the lesson of history.

Can You Prove Two Particles Are Identical?

This post is part of the Quantum Physics Sequence.
Followup to: Where Philosophy Meets Science, Joint Configurations

Behold, I present you with two electrons. They have the same mass. They have the same charge. In every way that we've tested them *so far,* they *seem* to behave the same way.

But is there any way we can know that the two electrons are *really,* truly, entirely indistinguishable?

The one who is wise in philosophy but not in physics will snort dismissal, saying, "Of course not. You haven't found an experiment *yet* that distinguishes these two electrons. But who knows, you might find a new experiment tomorrow that does."

Just because your current model of reality files all observed electrons in the same mental bucket, doesn't mean that tomorrow's physics will do the same. That's mixing up the map with the territory. Right?

It took a while to discover atomic isotopes. Maybe someday we'll discover electron isotopes whose masses are different in the 20th decimal place. In fact, for all we know, the electron has a tiny little tag on it, too small for your current microscopes to see, reading 'This is electron #7,234,982,023,348...' So that you could in principle toss this one electron into a bathtub full of electrons, and then fish it out again later. Maybe there's some way to know in principle, maybe not—but for now, surely, this is one of those things that science just doesn't know.

That's what you would think, if you were wise in philosophy but not in physics.

But what kind of universe could you possibly live in, where a simple experiment can tell you whether it's possible *in principle* to tell two things apart?

Maybe aliens gave you a tiny little device with two tiny little boxes, and a tiny little light that goes on when you put two identical things into the boxes?

But how do you know that's what the device *really* does? Maybe the device was just built with measuring instruments that go to the 10th decimal place but not any further.

Imagine that we take this problem to an analytic philosopher named Bob, and Bob says:

> "Well, for one thing, you can't even get absolute proof that the two particles actually exist, as opposed to being some kind of hallucination created in you by the Dark Lords of the Matrix. We call it 'the problem of induction'."

Yes, we've heard of the problem of induction. Though the Sun has risen on billions of successive mornings, we can't know with absolute certainty that, tomorrow, the Sun will not transform into a giant chocolate cake. But for the Sun to transform to chocolate cake requires more than an unanticipated discovery in physics. It requires the observed universe to be a lie. Can any experiment give us an *equally strong level* of assurance that two particles are identical?

"Well, I Am Not A Physicist," says Bob, "but *obviously,* the answer is no."

Why?

"I already told you why: No matter how many experiments show that two particles are similar, tomorrow you might discover an experiment that distinguishes between them."

Oh, but Bob, now you're just taking your conclusion as a premise. What you said is exactly what we want to know. Is there some achievable state of evidence, some sequence of discoveries, from within which you can legitimately expect *never* to discover a future experiment that distinguishes between two particles?

"I don't believe my logic is circular. But, since you challenge me, I'll formalize the reasoning.

"Suppose there are particles {P1, P2, ...} and a suite of experimental tests {E1, E2, ...} Each of these experimental tests, according to our best current model of the world, has a causal dependency on aspects {A1, A2...} of the particles P, where an aspect might be something like 'mass' or 'electric charge'.

"Now these experimental tests can establish very reliably—to the limit of our belief that the universe is not outright lying to us—that the depended-on aspects of the particles are similar, up to some limit of measurable precision.

"But we can always imagine an additional aspect A0 that is not depended-on by any of our experimental measures. Perhaps even an epiphenomenal aspect. Some philosophers will argue over whether an epiphenomenal aspect can be truly real, but just because we can't legitimately know about something's existence doesn't mean it's not there. Alternatively, we can always imagine an experimental difference in any quantitative aspect, such as mass, that is too small to detect, but real.

"These extra properties or marginally different properties are conceivable, therefore logically possible. This shows you need additional information, *not* present in the experiments, to definitely conclude the particles are identical."

That's an interesting argument, Bob, but you say you haven't studied physics.

"No, not really."

Maybe you shouldn't be doing all this *philosophical analysis* before you've studied physics. Maybe you should beg off the question, and let a philosopher who's studied physics take over.

"Would you care to point out a particular flaw in my logic?"

Oh... not at the moment. We're just saying, You Are Not A Physicist. Maybe you shouldn't be so glib when it comes to saying what physicists can or can't know.

"They can't know two particles are perfectly identical. It is not possible to imagine an experiment that proves two particles are perfectly identical."

Impossible to imagine? You don't know that. You just know you haven't imagined such an experiment yet. But perhaps that simply demonstrates a limit on your imagination, rather than demonstrating a limit on physical possibility. Maybe if you knew a little more physics, you would be able to conceive of such an experiment?

> "I'm sorry, this isn't a question of physics, it's a question of epistemology. To believe that *all aspects* of two particles are *perfectly* identical, requires a different sort of assurance than any experimental test can *provide.* Experimental tests only *fail to establish a difference*; they do not *prove identity*. What particular physics experiments you can do, is a physics question, and I don't claim to know that. But what experiments can *justify believing* is an epistemological question, and I am a professional philosopher; I expect to understand that question better than any physicist who hasn't studied formal epistemology."

And of course, Bob is wrong.

Bob isn't being stupid. He'd be right in any classical universe. But we don't live in a classical universe.

Our ability to perform an experiment that tells us positively that two particles are entirely identical, goes right to the heart of what distinguishes the quantum from the classical; the core of what separates the way reality actually works, from anything any pre-20th-century human ever imagined about how reality might work.

If you have a particle P1 and a particle P2, and it's possible in the experiment for both P1 and P2 to end up in either of two possible locations L1 or L2, then the observed distribution of results will depend on whether "P1 at L1, P2 at L2" and "P1 at L2, P2 at L1" is the same configuration, or two distinct configurations. If they're the same configuration, we add up the amplitudes flowing in, then take the squared modulus. If they're different configurations, we keep the amplitudes separate, take the squared moduli separately, then add the resulting probabilities. As $(1 + 1)^2 \mathrel{!=} (1^2 + 1^2)$, it's not hard to distinguish the experimental results after a few trials.

(Yes, half-integer spin changes this picture slightly. Which I'm not going into in this series of blog posts. If all epistemological confusions are resolved, half-integer spin is a difficulty of mere mathematics, so the issue doesn't belong here. Half-integer spin doesn't change the experimental testability of particle equivalences, or alter the fact that particles have no individual identities.)

And the flaw in Bob's logic? It was a fundamental assumption that Bob couldn't even see, because he had no alternative concept for contrast. Bob talked about particles P1 and P2 as if they were individually real and independently real. This turns out to assume that which is to be proven. In our universe, the individually and fundamentally real entities are configurations of multiple particles, and the amplitude flows between them. Bob failed to imagine the sequence of experimental results which established to physicists that this was, in fact, how reality worked.

Bob failed to imagine the evidence which falsified his basic and invisibly assumed ontology—the discoveries that changed the whole nature of the game; from a world that was the sum of individual particles, to a world that was the sum of amplitude flows between multi-particle configurations.

And so Bob's careful philosophical reasoning ended up around as useful as Kant's conclusion that space, by its very nature, was flat. Turned out, Kant was just reproducing an invisible assumption built into how his parietal cortex was modeling space. Kant's imaginings were evidence only about his imagination—grist for cognitive science, not physics.

Be careful not to underestimate, through benefit of hindsight, how *surprising* it would seem, a priori, that you could perfectly identify two particles through experiment. Be careful not to underestimate how entirely and perfectly *reasonable* Bob's analysis would have seemed, if you didn't have quantum assumptions to contrast to classical ones.

Experiments tell us things about the nature of reality which you *just plain wouldn't expect* from *a priori* reasoning. Experiments falsify assumptions we can't even see. Experiments tell us how to do things that seem logically impossible. Experiments deliver surprises from blind spots we don't even know exist.

Bear this in mind, the next time you're wondering whether *mere empirical science* might have something *totally unexpected* to say about some impossible-seeming *philosophical* question.

Part of *The Quantum Physics Sequence*

Next post: "Classical Configuration Spaces"

Previous post: "Where Philosophy Meets Science"

Classical Configuration Spaces

Previously in series: Distinct Configurations

> Once upon a time, there was a student who went to a math lecture. When the lecture was over, he approached one of the other students, and said, "I couldn't follow that at all. The professor was talking about rotating 8-dimensional objects! How am I supposed to visualize something rotating in 8 dimensions?"
> "Easy," replied the other student, "you visualize it rotating in N dimensions, then let N go to 8."
> —old joke

Quantum configuration space isn't quite like classical configuration space. But in this case, considering that 8 dimensions is peanuts in quantum physics, even I concede that you ought to start with classical configuration space first.

(I apologize for the homemade diagrams, but this blog post already used up all available time...)

In classical physics, a configuration space is a way of visualizing the state of an entire system as a single point in a higher-dimensional space.

Conf1

Suppose that a system is composed of two particles, A and B, each on the same 1-dimensional line. (We'll call the two directions on the line, "forward" and "back".)

Then we can view the state of the complete system A+B as a single point in 2-dimensional space.

If you look at state 1, for example, it describes a state of the system where B is far forward and A is far back. We can view state 1 as being embodied either in two 1-dimensional positions (the representation on the right), or view it as one 2-dimensional position (the representation on the left).

To help grasp the idea of viewing a *system* as a point, this alternate graph shows A and B on the same line.

When A and B are far apart, they both move toward each other. However, B moves slower than A. Also, B wants to be closer to A than A wants to be close to B, so as B gets too close, A runs away...

(At least that's what I had in mind while trying to draw the system evolution.)

The system evolution can be shown as a discrete series of states: Time=1, Time=2, Time=3... But in configuration space, I can draw the system evolution as a smooth

Conf2

trajectory.

If I had the time (to learn to use the appropriate software), I'd be drawing neat-o 3D diagrams at this point. Like the diagram at right, only with, like, actual graphics.

You may have previously heard the phrase, "time is the 4th dimension". But the diagram at right shows the evolution over time of a 1-dimensional universe with two particles. So time is the third dimension, the first dimension being the position of particle A, and the second dimension being the position of particle B.

Conf3

All these neat pictures are simplified, even relative to classical physics.

In classical physics, each particle has a 3-dimensional position and a 3-dimensional velocity. So to specify the complete state of a 7-particle system would require 42 real numbers, which you could view as one point in 42-dimensional space.

Hence the joke.

Configuration spaces get very high-dimensional, very fast. That's why we're sticking with 2 particles in a 1-dimensional universe. Anything more than that, I can't draw on paper—you've just got to be able to visualize it in N dimensions.

So far as classical physics is concerned, it's a matter of taste whether you would want to imagine a system state as a point in configuration space, or imagine the individual particles. Mathematically, the two systems are isomorphic—in classical physics, that is. So what's the benefit of imagining a classical configuration space?

Well, for one thing, it makes it possible to visualize joint probability distributions.

The grey area in the diagram represents a *probability distribution* over potential states of the A+B system.

If this is my state of knowledge, I think the system is somewhere in the region represented by the grey area. I believe that if I knew the actual states of both A and B, and visualized the A+B system as a point, the point would be inside the grey.

Three sample possibilities within the probability distribution are shown, and the corresponding systems.

And really the probability distribution should be lighter or darker, corresponding to volumes of decreased or increased probability *density*. It's a *probability* distribution,

Conf4

not a *possibility* distribution. I didn't make an effort to represent this in the diagram—I probably should have—but you can imagine it if you like. Or pretend that the slightly darker region in the upper left is a volume of increased probability density, rather than a fluke of penciling.

Once you've hit on the idea of using a bounded volume in configuration space to represent possibility, or a cloud with lighter and darker parts to represent probability, you can ask how your *knowledge about* a system develops over time. If you know how each system state (point in configuration space) develops dynamically into a future system state, and you draw a little cloud representing your current probability distribution, you can project that cloud into the future.

Conf5

Here I start out with uncertainty represented by the squarish grey box in the first configuration space, at bottom right.

All the points in the first grey box, correspond to system states, that dynamically develop over time, into new system states, corresponding to points in the grey rectangle in the second configuration space at middle right.

Then, my little rectangle of uncertainty develops over time into a wiggly figure, three major possibility-nodes connected by thin strings of probability density, as shown at top right.

In this figure I also tried to represent the idea of conserved probability volume—the same total volume of possibility, with points evolving to other points with the same local density, at each successive time. This is Liouville's Theorem, which is the key to the Second Law of Thermodynamics, as I have previously described.

Neat little compact volumes of uncertainty develop over time, under the laws of physics, into big wiggly volumes of uncertainty. If you want to describe the new volumes of uncertainty *compactly,* in less than a gazillion gigabytes, you've got to draw larger boundaries around them. Once you draw the new larger boundary, your uncertainty never shrinks, because probability flow is conservative. So entropy always increases. That's the second law of thermodynamics.

Just figured I'd mention that, as long as I was drawing diagrams... you can see why this "visualize a configuration space" trick is useful, even in classical physics.

Conf6

Another idea that's easier to visualize in configuration space is the idea of conditional independence between two probabilistic variables.

Conditional independence happens when the joint probability distribution is the product of the individual probability distributions:

P(A,B) = P(A) x P(B)

The vast majority of possible probability distributions are not conditionally independent, the same way that the vast majority of shapes are not rectangular. Actually, this is oversimplifying: It's not enough for the volume of possibilities to be rectangular. The probability density has to *factorize* into a product of probability densities on each side.

The vast majority of shapes are not rectangles, the vast majority of color patterns are not plaid. It's conditional *independence,* not conditional dependence, that is the unusual special case.

(I bet when you woke up this morning, you didn't think that today you would be visualizing plaid patterns in N dimensions.)

Conf4_2

In the figure reprised here at right, my little cloud of uncertainty is not rectangular.

Hence, my uncertainty about A and my uncertainty about B are not independent.

If you tell me A is far forward, I will conclude B is far back. If you tell me A is in the middle of its 1-dimensional universe, I will conclude that B is likewise in the middle.

If I tell you A is far back, what do you conclude about B?

Aaaand that's classical configuration space, folks. It doesn't add anything mathematically to classical physics, but it can help human beings visualize system dynamics and probability densities. It seemed worth filtering into a separate post, because configuration space is a modular concept, useful for other ideas.

Quantum physics *inherently* takes place in a configuration space. You can't take it out. Tomorrow, we'll see why.

Part of *The Quantum Physics Sequence*

Next post: "The Quantum Arena"

Previous post: "Can You Prove Two Particles Are Identical?"

The Quantum Arena

Previously in series: Classical Configuration Spaces

Yesterday, we looked at configuration spaces in classical physics. In classical physics, configuration spaces are a useful, but optional, point of view.

Today we look at quantum physics, which *inherently* takes place inside a configuration space, and *cannot be taken out*.

Ampl1

For a start, as you might guess, in quantum physics we deal with distributions of complex amplitudes, rather than probability distributions made up of positive real numbers. At left, I've used up 3 dimensions drawing a complex distribution over the position of *one* particle, A.

You may recall that yesterday, 3 dimensions let us display the position of two 1-dimensional particles plus the system evolution over time. Today, it's taking us 3 dimensions just to visualize an amplitude distribution over the position of one 1-dimensional particle at a single moment in time. Which is why we did classical configuration spaces first.

Ampl2

To clarify the meaning of the above diagram, the left-to-right direction is the position of A.

The up-and-down direction, and the invisible third dimension that leaps out of the paper, are devoted to the complex amplitudes. Since a complex amplitude has a real and imaginary part, they use up 2 of our 3 dimensions.

Richard Feynman said to just imagine the complex amplitudes as little 2-dimensional arrows. This is as good a representation as any; little 2D arrows behave just the same way complex numbers do. (You add little arrows by starting at the origin, and moving along each arrow in sequence. You multiply little arrows by adding the angles and multiplying the lengths. This is isomorphic to the complex field.) So we can think of each position of the A particle as having a little arrow associated to it.

As you can see, the position of A bulges in two places—a big bulge to the left, and a smaller bulge at right. Way up at the level of classical observation, there would be a large probability (integrating over the squared modulus) of finding A somewhere to the left, and a smaller probability of finding it at the small bulge to the right.

Drawing a neat little graph of the A+B system would involve having a complex amplitude for each joint position of the A and B particles, which you could visualize as a hypersurface in 4 dimensions. I'd draw it for you, but I left my 4-dimensional pencil in the pocket of the 3rd leg of my other pants.

You may recall from yesterday that a plaid rectangular probability distribution factorizes into the product of two independent probability distributions.

Conf6_2

This kind of independence-structure is one of several keys to recovering the illusion of individual particles from quantum amplitude distributions. If the amplitude distribution roughly factorizes, has subsystems A and B with Amplitude(X,Y) ~ Amplitude(X) * Amplitude(Y), then X and Y will seem to evolve roughly independently of each other.

But maintaining the illusion of individuality is harder in quantum configuration spaces, because of the identity of particles. This identity cuts down the size of a 2-particle configuration space by 1/2, cuts down the size of a 3-particle configuration space by 1/6, and so on. Here, the diminished configuration space is shown for the 2-particle case:

Ampl3_3

The quantum configuration space is over joint possibilities like "a particle here, a particle there", not "this particle here, that particle there". What would have been a neat little plaid pattern gets folded in on itself.

You might think that you could recover the structure by figuring out which particle is "really which"—i.e. if you see a "particle far forward, particle in middle", you can guess that the first particle is A, and the second particle is B, because only A can be far forward; B just stays in the middle. (This configuration would lie in at the top of the original plaid pattern, the part that got folded over).

The problem with this is the little triangular region, where the folded plaid intersects itself. In this region, the folded-over amplitude distribution gets superposed, added together. Which makes an experimental difference, because the squared modulus of the sum is not the sum of the squared moduli.

In that little triangular region of quantum configuration space, there is simply no fact of the matter as to "which particle is which". Actually, there *never was* any such fact; but there was an illusion of individuality, which in this case has broken down.

But even *that* isn't the ultimate reason why you can't take quantum physics out of configuration space.

In classical configuration spaces, you can take a *single* point in the configuration space, and the single point describes the entire state of a classical system. So you can take a single point in classical configuration space, and ask how the corresponding system develops over time. You can take a single point in classical configuration space, and ask, "Where does this one point go?"

The development over time of *quantum* systems depends on things like the second derivative of the amplitude distribution. Our laws of physics describe how amplitude distributions develop into new amplitude distributions. They do not describe, *even in principle,* how one configuration develops into another configuration.

(I pause to observe that physics books make it way, way, way too hard to figure out this extremely important fact. You'd think they'd tell you up front, "Hey, the evolution of a quantum system depends on stuff like the second derivative of the amplitude distribution, so you can't *possibly* break it down into the evolution of individual configurations." When I first saw the Schrödinger Equation it confused the hell out of me, because I thought the equation was supposed to apply to single configurations.)

If I've understood the laws of physics correctly, quantum mechanics still has an extremely important property of *locality:* You can determine the instantaneous change in the amplitude of a single configuration using only the infinitesimal neighborhood. If you forget that the space is continuous and think of it as a mesh of computer processors, each processor would only have to talk to its immediate neighbors to figure out what to do next. You do have to talk to your neighbors—but *only* your next-door neighbors, no telephone calls across town. (Technical term: "Markov neighborhood.")

Conway's Game of Life has the discrete version of this property; the future state of each cell depends only on its own state and the state of neighboring cells.

The second derivative—Laplacian, actually—is not a *point* property. But it is a *local* property, where knowing the immediate neighborhood tells you everything, regardless of what the rest of the distribution looks like. Potential energy, which also plays a role in the evolution of the amplitude, can be computed at a *single* positional configuration (if I've understood correctly).

There are mathematical transformations physicists use for their convenience, like viewing the system as an amplitude distribution over momenta rather than positions, which throw away this neighborhood structure (e.g. by making potential energy a non-locally-computable property). Well, mathematical convenience is a fine thing. But I *strongly suspect* that the physically real wavefunction has local dynamics. This kind of locality seems like an *extremely* important property, a candidate for something hardwired into the nature of reality and the structure of causation. Imposing locality is part of the jump from Newtonian mechanics to Special Relativity.

The temporal behavior of each amplitude in configuration space depends only on the amplitude at neighboring points. But you cannot figure out what happens to the amplitude of a point in quantum configuration space, by looking *only* at that *one* point. The *future* amplitude depends on the *present* second derivative of the amplitude distribution.

So you can't say, as you can in classical physics, "If I had infinite knowledge about the system, all the particles would be in one definite position, and then I could figure out the exact future state of the system."

If you had a point mass of amplitude, an infinitely sharp spike in the quantum arena, the amplitude distribution would not be twice differentiable and the future evolution of the system would be undefined. The known laws of physics would crumple up like tinfoil. Individual configurations don't have quantum dynamics; amplitude distributions do.

A point mass of amplitude, concentrated into a single exact position in configuration space, does not correspond to a precisely known state of the universe. It is *physical nonsense*.

It's like asking, in Conway's Game of Life: "What is the future state of this one cell, regardless of the cells around it?" The immediate future of the cell depends on its immediate neighbors; its distant future may depend on distant neighbors.

Imagine trying to say, in a classical universe, "Well, we've got this probability distribution over this classical configuration space... but to find out where the system evolves, where the probability flows from each point, we've got to twice differentiate the probability distribution to figure out the dynamics."

In classical physics, the position of a particle is a separate fact from its momentum. You can know exactly where a particle is, but not know exactly how fast it is moving.

In Conway's Game of Life, the velocity of a glider is not a separate, additional fact about the board. Cells are only "alive" or "dead", and the *apparent* motion of a glider arises from a configuration that repeats itself as the cell rules are applied. If you know the life/death state of all the cells in a glider, you know the glider's velocity; they are not separate facts.

In quantum physics, there's an amplitude distribution over a configuration space of particle positions. Quantum dynamics specify how that amplitude distribution evolves over time. Maybe you start with a blob of amplitude centered over position X, and then a time T later, the amplitude distribution has evolved to have a similarly-shaped blob of amplitude at position X+D. Way up at the level of human researchers, this looks like a particle with velocity D/T. But at the quantum level this behavior arises *purely* out of the amplitude distribution over *positions,* and the laws for how amplitude distributions evolve over time.

In quantum physics, if you know the exact current amplitude distribution over particle positions, you know the exact future behavior of the amplitude distribution. Ergo, you know how blobs of amplitude appear to propagate through the configuration space. Ergo, you know how fast the "particles" are "moving". Full knowledge of the amplitude distribution over positions implies full knowledge of momenta.

Imagine trying to say, in a classical universe, "I twice differentiate the probability distribution over these particles' positions, to *physically determine* how fast they're going. So if I learned new information about where the particles were, they might end up moving at different speeds. If I got very precise information about where the particles were, this would physically cause the particles to start moving very fast, because the second derivative of probability would be very large." Doesn't sound all that sensible, does it? Don't try to interpret this nonsense—it's not even analogously correct. We'll look at the horribly misnamed "Heisenberg Uncertainty Principle" later.

But that's why you can't take quantum physics out of configuration space. Individual configurations don't *have* physics. Amplitude distributions have physics.

(Though you can regard the *entire* state of a quantum system—the whole amplitude distribution—as a single point in a space of infinite dimensionality: "Hilbert space." But this is just a convenience of visualization. You imagine it in N dimensions, then let N go to infinity.)

Part of *The Quantum Physics Sequence*

Next post: "Feynman Paths"

Previous post: "Classical Configuration Spaces"

Feynman Paths

Previously in series: The Quantum Arena

At this point I would like to introduce another key idea in quantum mechanics. Unfortunately, this idea was introduced so well in chapter 2 of *QED: The Strange Theory of Light and Matter* by Richard Feynman, that my mind goes blank when trying to imagine how to introduce it any other way. As a compromise with just stealing his entire book, I stole one diagram—a diagram of how a mirror *really* works.

Feynman1

In elementary school, you learn that the angle of incidence equals the angle of reflection. But *actually*, saith Feynman, each part of the mirror reflects at all angles.

So why is it that, way up at the human level, the mirror seems to reflect with the angle of incidence equal to the angle of reflection?

Because in quantum mechanics, amplitude that flows to identical configurations (particles of the same species in the same places) is added together, regardless of how the amplitude got there.

To find the amplitude for a photon to go from S to P, you've got to add up the amplitudes for *all* the different ways the photon could get there—by bouncing off the mirror at A, bouncing off the mirror at B...

The rule of the Feynman "path integral" is that each of the paths from S to P contributes an amplitude of *constant* magnitude but varying *phase*, and the phase varies with the total *time* along the path. It's as if the photon is a tiny spinning clock—the hand of the clock stays the same length, but it turns around at a constant rate for each unit of time.

Feynman graphs the time for the photon to go from S to P via A, B, C, ... Observe: the *total* time *changes less* between "the path via F" and "the path via G", then the total time changes between "the path via A" and "the path via B". So the phase of the complex amplitude changes less, too.

And when you add up all the ways the photon can go from S to P, you find that most of the amplitude comes from the middle part of the mirror—the contributions from other parts of the mirror tend to mostly cancel each other out, as shown at the bottom of Feynman's figure.

There is no answer to the question "Which part of the mirror did the photon *really* come from?" Amplitude is flowing from *all* of these configurations. But if we were to *ignore* all the parts of the mirror except the middle, we would calculate essentially the same amount of *total* amplitude.

This means that a photon, which can get from S to P by striking *any* part of the mirror, will *behave pretty much as if* only a tiny part of the mirror exists—the part where the photon's angle of incidence equals the angle of reflection.

Unless you start playing clever tricks using your knowledge of quantum physics.

For example, you can *scrape away* parts of the mirror at regular intervals, deleting some little arrows and leaving others. Keep A and its little arrow; scrape away B so that it has no little arrow (at least no little arrow going to P). Then a distant part of the mirror can contribute amplitudes that add up with each other to a big final amplitude, because you've removed the amplitudes that were out of phase.

In which case you can make a mirror that reflects with the angle of incidence not equal to the angle of reflection. It's called a diffraction grating. But it reflects different wavelengths of light at different angles, so a diffraction grating is not quite a "mirror" in the sense you might imagine; it produces little rainbows of color, like a droplet of oil on the surface of water.

How fast does the little arrow rotate? As fast as the photon's wavelength—that's what a photon's wavelength *is*. The wavelength of yellow light is ~570 nanometers: If yellow light travels an extra 570 nanometers, its little arrow will turn all the way around and end up back where it started.

So either Feynman's picture is of a very tiny mirror, or he is talking about some very big photons, when you look at how fast the little arrows seem to be rotating. Relative to the wavelength of visible light, a human being is a lot bigger than the level at which you can see quantum effects.

You'll recall that the first key to recovering the classical hallucination from the reality of quantum physics, was the possibility of approximate independence in the amplitude distribution. (Where the distribution roughly factorizes, it can look like a subsystem of particles is evolving on its own, without being entangled with every other particle in the universe.)

The second key to re-deriving the classical hallucination, is the kind of behavior that we see in this mirror. Most of the possible paths cancel each other out, and only a small group of neighboring paths add up. Most of the amplitude comes from a small neighborhood of histories—the sort of history where, for example, the photon's angle of incidence is equal to its angle of reflection. And so too with many other things you are pleased to regard as "normal".

My first posts on QM showed amplitude flowing in crude chunks from discrete situation to discrete situation. In *real life* there are continuous amplitude flows between continuous configurations, like we saw with Feynman's mirror. But by the time you climb all the way up from a few hundred nanometers to the size scale of human beings, most of the amplitude contributions have canceled out except for a narrow neighborhood around one path through history.

Mind you, this is *not* the reason why a photon only seems to be in one place at a time. That's a different story, which we won't get to today.

The more massive things are—actually the more energetic they are, mass being a form of energy—the faster the little arrows rotate. Shorter wavelengths of light having more energy is a special case of this. Compound objects, like a neutron made of three quarks, can be treated as having a collective amplitude that is the multiplicative product of the component amplitudes—at least to the extent that the amplitude distribution factorizes, so that you can treat the neutron as an individual.

Thus the relation between energy and wavelength holds for more than photons and electrons; atoms, molecules, and human beings can be regarded as having a wavelength.

But by the time you move up to a human being—or even a single biological cell—the mass-energy is *really, really* large relative to a yellow photon. So the clock is rotating *really, really fast.* The wavelength is *really, really* short. Which means that the neighborhood of paths where things don't cancel out is *really, really narrow.*

By and large, a human experiences what seems like a single path through configuration space—the classical hallucination.

This is not how Schrödinger's Cat works, but it is how a regular cat works.

Just remember that this business of single paths through time is not *fundamentally* true. It's merely a good approximation for modeling a sofa. The classical hallucination breaks down completely by the time you get to the atomic level. It can't handle quantum computers at all. It would fail you even if you wanted a *sufficiently precise* prediction of a brick. A billiard ball taking a single path through time is not how the universe *really, really* works—it is just what human beings have evolved to easily visualize, for the sake of throwing rocks.

(PS: I'm given to understand that the Feynman path integral may be more fundamental than the Schrödinger equation: that is, you can *derive* Schrödinger from Feynman. But as far as I can tell from examining the equations, Feynman is still differentiating the amplitude distribution, and so reality doesn't yet break down into point amplitude flows between point configurations. Some physicist please correct me if I'm wrong about this, because it is a matter on which I am quite curious.)

Part of *The Quantum Physics Sequence*

Next post: "No Individual Particles"

Previous post: "The Quantum Arena"

No Individual Particles

Followup to: Can You Prove Two Particles Are Identical?, Feynman Paths

Even babies think that objects have individual identities. If you show an infant a ball rolling behind a screen, and then a moment later, two balls roll out, the infant looks longer at the expectation-violating event. Long before we're old enough to talk, we have a parietal cortex that does spatial modeling: that models individual animals running or rocks flying through 3D space.

And this is just not the way the universe works. The difference is experimentally knowable, and known. Grasping this fact, being able to see it at a glance, is one of the fundamental bridges to cross in understanding quantum mechanics.

If you shouldn't start off by talking to your students about wave/particle duality, where should a quantum explanation start? I would suggest taking, as your first goal in teaching, explaining how quantum physics implies that a simple experimental test can show that two electrons are *entirely* indistinguishable —not just indistinguishable according to known measurements of mass and electrical charge.

To grasp on a *gut level* how this is possible, it is necessary to move from thinking in billiard balls to thinking in configuration spaces; and then you have truly entered into the true and quantum realm.

In previous posts such as Joint Configurations and The Quantum Arena, we've seen that the physics of our universe takes place in a multi-particle configuration space.

Conf6_2

The illusion of individual particles arises from approximate factorizability of a multi-particle distribution, as shown at left for a classical configuration space.

If the probability distribution over this 2D configuration space of two classical 1D particles, looks like a rectangular plaid pattern, then it will factorize into a distribution over A times a distribution over B.

In classical physics, the particles A and B are the fundamental things, and the configuration space is just an isomorphic way of looking at them.

In quantum physics, the configuration space is the fundamental thing, and you get the appearance of an individual particle when the amplitude distribution factorizes enough to let you look at a *subspace* of the configuration space, and see a *factor* of the amplitude distribution—a factor that might look something like this:

Ampl1

This isn't an amplitude distribution, mind you. It's a *factor* in an amplitude distribution, which you'd have to multiply by the subspace for all the *other* particles in the universe, to approximate the *physically real* amplitude distribution.

Most mathematically possible amplitude distributions won't factor this way. *Quantum entanglement* is not some extra, special, additional bond between two particles. "Quantum entanglement" is the *general* case. The *special and unusual* case is *quantum independence*.

Reluctant tourists in a quantum universe talk about the bizarre phenomenon of quantum entanglement. Natives of a quantum universe talk about the special case of quantum independence. Try to think like a native, because you are one.

I've previously described a configuration as a mathematical object whose identity is "A photon here, a photon there; an electron here, an electron there." But this is not quite correct. Whenever you see a real-world electron, caught in a little electron trap or whatever, you are looking at a *blob* of amplitude, not a point mass. In fact, what you're looking at is a *blob of amplitude-factor* in a subspace of a global distribution that happens to factorize.

Clearly, then, an *individual point* in the configuration space does not have an identity of "blob of amplitude-factor here, blob of amplitude-factor there"; so it doesn't make sense to say that a configuration has the identity "A photon here, a photon there."

But what *is* an individual point in the configuration space, then?

Well, it's physics, and physics is math, and you've got to come to terms with thinking in pure mathematical objects. A single point in quantum configuration space, is the *product* of multiple *point positions* per quantum field; multiple point positions in the electron field, in the photon field, in the quark field, etc.

When you actually see an electron trapped in a little electron trap, what's *really* going on, is that the cloud of amplitude distribution that includes you and your observed universe, can at least roughly factorize into a subspace that corresponds to that little electron, and a subspace that corresponds to everything else in the universe. So that the *physically real* amplitude distribution is roughly the *product* of a little blob of amplitude-factor in the subspace for that electron, and the amplitude-factor for everything else in the universe. Got it?

One commenter reports attaining enlightenment on reading in Wikipedia:

> 'From the point of view of quantum field theory, particles are identical if and only if they are excitations of the same underlying quantum field. Thus, the question "why are all electrons identical?" arises from mistakenly regarding individual electrons as fundamental objects, when in fact it is only the electron field that is fundamental.'

Okay, but that doesn't make the basic jump into a quantum configuration space that is inherently over multiple particles. It just sounds like you're talking about individual disturbances in the aether, or something. As I understand it, an electron isn't an *excitation* of a quantum electron field, like a wave in the aether; the electron is a blob of amplitude-factor in a subspace of a configuration space whose points correspond to multiple point positions in quantum fields, etc.

The difficult jump from classical to quantum is *not* thinking of an electron as an excitation of a field. Then you could just think of a universe made up of "Excitation A in electron field over here" + "Excitation B in electron field over there" + etc. You could factorize the universe into individual excitations of a field. Your parietal cortex would have no trouble with that one—it doesn't care whether you call the little billiard balls "excitations of an electron field" so long as they still behave like little billiard balls.

The difficult jump is thinking of a configuration space that is the product of many positions in many fields, without individual identities for the positions. A configuration space whose points are "a position *here* in *this* field, a position *there* in *this* field, a position *here* in *that* field, and a position *there* in *that* field". Not, "A positioned here in this field, B positioned there in this field, C positioned here in that field" etc.

You have to reduce the appearance of individual particles to a regularity in something that is *different* from the appearance of particles, something that *is not itself a little billiard ball.*

Oh, sure, thinking of photons as individual objects will *seem* to work out, as long as the amplitude distribution happens t factorize. But what happens when you've got your "individual" photon A and your "individual" photon B, and you're in a situation where, a la Feynman paths, it's possible for photon A to end up in position 1 and photon B to end up in position 2, *or* for A to end up in 2 and B to end up in 1? Then the illusion of classicality breaks down, because the amplitude flows overlap:

Ampl3_3

In that triangular region where the distribution overlaps itself, no fact exists as to which particle is which, even in principle—and in the real world, we often get a lot more overlap than that.

I mean, imagine that I take a balloon full of photons, and shake it up.

Amplitude's gonna go all over the place. If you label all the original apparent-photons, there's gonna be Feynman paths for photons A, B, C ending up at positions 1, 2, 3 via a zillion different paths and permutations.

The amplitude-factor that corresponds to the "balloon full of photons" subspace, which contains bulges of amplitude-subfactor at various different locations in the photon field, will undergo a continuously branching evolution that involves each of the original bulges ending up in many different places by all sorts of paths, and the final configuration will have amplitude contributed from many different permutations.

It's not that you *don't know* which photon went where. It's that *no fact of the matter exists.* The illusion of individuality, the classical hallucination, has simply broken down.

And the same would hold true of a balloon full of quarks or a balloon full of electrons. Or even a balloon full of helium. Helium atoms can end up in the same places, via different permutations, and have their amplitudes add just like photons.

Don't be tempted to look at the balloon, and think, "Well, helium atom A could have gone to 1, or it could have gone to 2; and helium atom B could have gone to 1 or 2; quantum physics says the atoms both sort of split, and each went both ways; and now the final helium atoms at 1 and 2 are a mixture of the identities of A and B." Don't torture your poor parietal cortex so. It wasn't built for such usage.

Just stop thinking in terms of little billiard balls, with or without confused identities. Start thinking in terms of amplitude flows in configuration space. That's all there ever is.

And *then* it will seem completely intuitive that a simple experiment can tell you whether two blobs of amplitude-factor are over the same quantum field.

Just perform any experiment where the two blobs end up in the same positions, via different permutations, and see if the amplitudes add.

Part of *The Quantum Physics Sequence*

Next post: "Identity Isn't In Specific Atoms"

Previous post: "Feynman Paths"

Identity Isn't In Specific Atoms

Continuation of: No Individual Particles
Followup to: The Generalized Anti-Zombie Principle

Suppose I take two atoms of helium-4 in a balloon, and swap their locations via teleportation. I don't move them through the intervening space; I just click my fingers and cause them to swap places. Afterward, the balloon looks just the same, but two of the helium atoms have exchanged positions.

Now, did that scenario seem to make sense? Can you imagine it happening?

If you looked at that and said, "The operation of swapping two helium-4 atoms produces an identical configuration—not a similar configuration, an *identical* configuration, the same mathematical object—and particles have no individual identities *per se*—so what you just said is *physical nonsense*," then you're starting to get quantum mechanics.

If you furthermore had any thoughts about a particular "helium atom" being a factor in a subspace of an amplitude distribution that happens to factorize that way, so that it makes no sense to talk about swapping two identical multiplicative factors, when only the combined amplitude distribution is real, then you're *seriously* starting to get quantum mechanics.

If you thought about two similar billiard balls changing places inside a balloon, but nobody on the outside being able to notice a difference, then... oh, hell, I don't know, go back to the beginning of the series and try rereading the whole thing over the course of one day. If that still doesn't work, read an actual book on quantum mechanics. Feynman's *QED* is a great place to start—though not a good place to finish, and it's not written from a pure realist perspective.

But if you did "get" quantum physics, then, as promised, we have now come to the connection between the truth of quantum mechanics, the lies of human intuitions, and the Generalized Anti-Zombie Principle.

Stirling Westrup previously commented, on the GAZP post:

> I found the previous articles on Zombies somewhat tedious... Still, now I'm glad I read through it all as I can see why you were so careful to lay down the foundations you did.
>
> The question of what changes one can make to the brain while maintaining 'identity' has been been discussed many times on the Extropians list, and seldom with any sort of constructive results.
>
> Today's article has already far exceeded the signal to noise ratio of any other discussion on the same topic that I've ever seen...

The Extropians email list that Westrup refers to, is the oldest online gathering place of transhumanists. It is where I made my debut as a writer, and it is where the cofounders of the Singularity Institute met. Though the list is not what it once was...

There are certain topics, on the Extropians list, that have been discussed over and over again, for years and years, without making any progress. Just the same arguments and counterarguments, over and over again.

The worst of those infinite loops concerns the question of *personal identity*. For example, if you build an exact physical replica of a human, using *different atoms,* but atoms of the *same kind* in the *same places*, is it the *same person* or *just a copy*?

This question has flared up at least once a year, always with the same arguments and counterarguments, every year since I joined the Extropians mailing list in 1996. And I expect the Personal Identity Wars started well before then.

I did *try* remarking, "Quantum mechanics says there *isn't any such thing* as a 'different particle of the same kind', so wherever your personal identity is, it sure isn't in *particular atoms,* because there *isn't any such thing* as a 'particular atom'."

It didn't work, of course. I didn't really expect it to. Without a long extended explanation, a remark like that doesn't actually mean anything.

The concept of reality as a sum of independent individual billiard balls, seems to be built into the human parietal cortex—the parietal cortex being the part of our brain that does spatial modeling: navigating rooms, grasping objects, throwing rocks.

Even very young children, infants, look longer at a scene that violates expectations—for example, a scene where a ball rolls behind a screen, and then two balls roll out.

People try to think of a *person*, an *identity,* an *awareness,* as though it's an awareness-ball located inside someone's skull. Even nonsophisticated materialists tend to think that, since the consciousness ball is made up of lots of little billiard balls called "atoms", if you swap the atoms, why, you must have swapped the consciousness.

Now even without knowing any quantum physics—even in a purely classical universe—it is possible to refute this idea by applying the Generalized Anti-Zombie Principle. There are many possible formulations of the GAZP, but one of the simpler ones says that, if alleged gigantic changes are occurring in your consciousness, you really ought to *notice something happening,* and be able to say so.

The equivalent of the Zombie World, for questions of identity/continuity, is the Soul Swap World. The allegation is that the Soul Swap World is microphysically identical to our own; but every five minutes, each thread of consciousness jumps to a random new brain, without the brains changing in any third-party experimentally detectable way. One second you're *yourself,* the next second you're Britney Spears. And neither of you *say* that you've noticed anything happening—by hypothesis, since you're microphysically identical down to the motion of your lips.

(Let me know if the Soul Swap World has been previously invented in philosophy, and has a standard name—so far as I presently know, this is my own idea.)

We can proceed to demolish the Soul Swap World by an argument exactly analogous to the one that demolished the Zombie World: Whatever-it-is which makes me feel that I have a consciousness that continues through time, that whatever-it-is was physically potent enough to make me type this sentence. Should I try to make the phrase "consciousness continuing through time" *refer* to something that has nothing to do with the *cause* of my typing those selfsame words, I will have problems with the *meaning* of my arguments, not just their plausibility.

Whatever it is that makes me say, aloud, that I have a personal identity, a causally closed world physically identical to our own, has captured that source—if there is any source at all.

And we can proceed, again by an exactly analogous argument, to a Generalized Anti-Swapping Principle: Flicking a disconnected light switch shouldn't switch your personal identity, even though the motion of the switch has an in-principle detectable gravitational effect on your brain, because the switch flick can't disturb the true cause of your talking about "the experience of subjective continuity".

So even in a classical universe, if you snap your fingers and swap an atom in the brain for a *physically similar* atom outside; and the brain is not disturbed, or not disturbed any more than the level of thermal noise; then whatever causes the experience of subjective continuity, should also not have been disturbed. Even if you swap *all* the classical atoms in a brain at the *same time,* if the person doesn't *notice* anything happen, why, it probably didn't.

And of course there's the classic (and classical) argument, "Well, your body's turnover time for atoms is seven years on average."

But it's a moot argument.

We don't live in a classical universe.

We live in a quantum universe where the notion of "same hydrogen atom vs. different hydrogen atom" is *physical nonsense.*

We live in a universe where the whole notion of billiard balls bopping around is *fundamentally wrong*.

This can be a disorienting realization, if you formerly thought of *yourself* as an awareness ball that moves around.

Sorry. Your parietal cortex is fooling you on this one.

But wait! It gets even worse!

The brain doesn't exactly repeat itself; the state of your brain one second from now is not the state of your brain one second ago. The neural connections don't *all* change *every* second, of course. But there are enough changes every second that the brain's state is not cyclic, not over the course of a human lifetime. With every fragment of memory you lay down—and every thought that pops in and out of short-term memory—and every glance of your eyes that changes the visual field of your visual cortex—you ensure that you never repeat yourself exactly.

Over the course of a single *second*—not seven years, but *one second*—the joint position of all the atoms in your brain, will change far enough away from what it was before, that there is no *overlap* with the previous *joint amplitude distribution*. The brain doesn't repeat itself. Over the course of *one second,* you will end up being comprised of a *completely different, nonoverlapping volume of configuration space*.

And the quantum configuration space is the most fundamental known reality, according to our best current theory, remember. Even if quantum theory turns out not to be really truly fundamental, it has already finished superseding the hallucination of individual particles. We're never going back to billiard balls, any more than we're going back to Newtonian mechanics or phlogiston theory. The ratchet of science turns, but it doesn't turn backward.

And actually, the time for you to be comprised of a completely different volume of configuration space, is way less than a second. That time is the product of all the individual changes in your brain put together. It'll be less than a millisecond, less than a femtosecond, less than the time it takes light to cross a neutron diameter. It works out to less than the [Planck time](), if that turns out to make physical sense.

And then there's the point to consider that the *physically real* amplitude distribution is over a configuration space of all the particles in the universe. "You" are just a factored subspace of that distribution.

Yes, that's right, I'm calling *you* a factored subspace.

None of this should be taken as saying that you are somehow *independent* of the quantum physics comprising you. If an anvil falls on your head, you will stop talking about consciousness. This is experimentally testable. Don't try it at home.

But the notion that you can equate your personal *continuity*, with the *identity* of any physically real constituent of your existence, is absolutely and utterly hopeless.

You are not "the same you, because you are made of the same atoms". You have zero overlap with the *fundamental* constituents of yourself from even one nanosecond ago. There is continuity of information, but not equality of parts.

The new factor over the subspace looks a *whole lot* like the old you, and not by coincidence: The flow of time is lawful, there are causes and effects and preserved commonalities. Look to the regularity of physics, if you seek a source of continuity. Do not ask to be composed of the same objects, for this is hopeless.

Whatever makes you feel that your present is connected to your past, it has nothing to do with an *identity* of *physically fundamental* constituents over time.

Which you could deduce *a priori*, even in a classical universe, using the Generalized Anti-Zombie Principle. The imaginary identity-tags that read "This is electron #234,567..." don't affect particle motions or anything else; they can be swapped without making a difference because they're epiphenomenal. But since this final conclusion happens to be counterintuitive to a human parietal cortex, it helps to have the brute fact of quantum mechanics to crush all opposition.

Damn, have I waited a long time to be able to say that.

And no, this isn't the only point I have to make on how counterintuitive physics rules out intuitive conceptions of personal identity. I've got even stranger points to make. But those will take more physics first.

Part of *The Quantum Physics Sequence*

Next post: "Three Dialogues on Identity"

Previous post: "No Individual Particles"

Decoherence

Previously in series: Feynman Paths

To understand the quantum process called "decoherence", we first need to look at how the special case of quantum independence can be destroyed—how the evolution of a quantum system can produce entanglement where there was formerly independence.

Conf6

Quantum independence, as you'll recall, is a special case of amplitude distributions that approximately factorize—amplitude distributions that can be treated as a product of sub-distributions over subspaces.

Reluctant tourists visiting quantum universes think as if the *absence* of a rectangular plaid pattern is some kind of special ghostly link between particles. Hence the unfortunate term, "quantum entanglement".

The evolution of a quantum system can produce entanglement where there was formerly independence—turn a rectangular plaid pattern into something else. Quantum independence, being a special case, is easily lost.

Entangler

Let's pretend for a moment that we're looking at a classical system, which will make it easier to see what kind of physical process leads to entanglement.

At right is a system in which a positively charged light thingy is on a track, far above a negatively charged heavy thingy on a track.

At the beginning, the two thingies are far enough apart that they're not significantly interacting.

But then we lower the top track, bringing the two thingies into the range where they can easily attract each other. (Opposite charges attract.)

So the light thingy on top rolls toward the heavy thingy on the bottom. (And the heavy thingy on the bottom rolls a little toward the top thingy, just like an apple attracts the Earth as it falls.)

Now switch to the Feynman path integral view. That is, imagine the evolution of a quantum system as a sum over all the paths through configuration space the initial conditions could take.

Suppose the bottom heavy thingy and the top thingy started out in a state of quantum independence, so that we can view the amplitude distribution over the whole system as the product of a "bottom thingy distribution" and a "top thingy distribution".

The bottom thingy distribution starts with bulges in three places—which, in the Feynman path view, we might think of as three possible starting configurations from which amplitude will flow.

When we lower the top track, the light thingy on top is attracted toward the heavy bottom thingy -

- except that the bottom thingy has a sub-distribution with three bulges in three different positions.

So the end result is a joint distribution in which there are three bulges in the amplitude distribution over *joint* configuration space, corresponding to three different *joint* positions of the top thingy and bottom thingy.

Superposition2

I've been trying very carefully to avoid saying things like "The bottom thingy is in three places at once" or "in each possibility, the top thingy is attracted to wherever the bottom thingy is".

Still, you're probably going to visualize it that way, whether I say it or not. To be honest, that's how *I* drew the diagram—I visualized three possibilities and three resulting outcomes. Well, that's just how a human brain tends to visualize a Feynman path integral.

But this doesn't mean there are actually *three possible ways the universe could be,* etc. That's just a trick for visualizing the path integral. *All* the amplitude flows *actually happen,* they are not *possibilities.*

Now imagine that, in the starting state, the bottom thingy has an amplitude-factor that is smeared out over the whole bottom track; and the top thingy has an amplitude-factor in one place. Then the joint distribution over "top thingy, bottom thingy" would start out looking like the plaid pattern at left, and develop into the non-plaid pattern at right:

Entanglecloud

Here the horizontal coordinate corresponds to the top thingy, and the vertical coordinate corresponds to the bottom thingy. So we start with the top thingy localized and the bottom thingy spread out, and then the system develops into a joint distribution where the top thingy and the bottom thingy are in the same place, but their *mutual* position is spread out. Very loosely speaking.

So an initially *factorizable* distribution, evolved into an "entangled system"—a joint amplitude distribution that is not viewable as a product of distinct factors over subspaces.

> (Important side note: You'll note that, in the diagram above, system evolution obeyed the second law of thermodynamics, aka Liouville's Theorem. Quantum evolution conserved the "size of the cloud", the volume of amplitude, the total amount of grey area in the diagram.
>
> If instead we'd started out with a big light-gray square—meaning that both particles had amplitude-factors widely spread—then the second law of thermodynamics would prohibit the combined system from developing into a tight dark-gray diagonal line.
>
> A system has to start in a low-entropy state to develop into a state of quantum *entanglement,* as opposed to just a diffuse cloud of amplitude.
>
> Mutual information is also negentropy, remember. Quantum amplitudes aren't *information* per se, but the rule is analogous: Amplitude must be highly concentrated to look like a neatly entangled diagonal line, instead of just a big diffuse cloud. If you imagine amplitude distributions as having a "quantum entropy", then an entangled system has low quantum entropy.)

Okay, so *now* we're ready to discuss decoherence.

Multiblobdeco

The system at left is highly entangled—it's got a joint distribution that looks something like, "There's two particles, and either they're both over *here*, or they're both over *there*."

Yes, I phrased this as if there were two separate possibilities, rather than a single physically real amplitude distribution. Seriously, there's no good way to use a human brain to talk about quantum physics in English.

But if you can just remember the *general rule* that saying "possibility" is shorthand for "physically real blob within the amplitude distribution", then I can describe amplitude distributions a lot faster by using the *language* of uncertainty. Just remember that it is *language.* "Either the particle is over here, or it's over there" means a physically real amplitude distribution with blobs in both places, *not* that the particle is in one of those places but we don't know which.

Anyway. Dealing with highly entangled systems is often annoying—for human physicists, not for reality, of course. It's not just that you've got to calculate all the possible outcomes of the different possible starting conditions. (I.e., add up a lot of physically real amplitude flows in a Feynman path integral.) The possible outcomes may interfere with each other. (Which actual *possible* outcomes would never do, but different blobs in an amplitude distribution do.) Like, maybe the two particles that are both over *here,* or both over *there,* meet twenty other particles and do a little dance, and at the conclusion of the path integral, many of the final configurations have received amplitude flows from both initial blobs.

But that kind of *extra-annoying* entanglement only happens when the blobs in the initial system are *close* enough that their evolutionary paths can slop over into each other. Like, if the particles were either both *here*, or both *there,* but *here* and *there* were two light-years apart, then any system evolution taking less than a year, couldn't have the different possible outcomes *overlapping.*

Okay, so let's talk about *three* particles now.

Precohered_2

This diagram shows a blob of amplitude that factors into the product of a 2D subspace and a 1D subspace. That is, two entangled particles and one independent particle.

The vertical dimension is the one independent particle, the length and breadth are the two entangled particles.

The independent particle is in one definite place—the cloud of amplitude is vertically narrow. The two entangled particles are either both *here*, or both *there*. (Again I'm using that wrong language of uncertainty, words like "definite" and "either", but you see what I mean.)

Now imagine that the third independent particle interacts with the two entangled particles in a sensitive way. Maybe the third particle is balanced on the top of a hill; and the two entangled particles pass nearby, and attract it magnetically; and the third particle falls off the top of the hill and rolls to the bottom, in that particular direction.

Decohered

Afterward, the new amplitude distribution might look like this. The third particle is now entangled with the other two particles. And the amplitude distribution as a whole consists of two more *widely separated* blobs.

Loosely speaking, in the case where the two entangled particles were over *here*, the third particle went *this way*, and in the case where the two entangled particles were *over there,* the third particle went *that way.*

So now the final amplitude distribution is fully entangled—it doesn't factor into subspaces at all.

But the two blobs are more *widely separated* in the configuration space. Before, each blob of amplitude had *two* particles in different positions; now each blob of amplitude has *three* particles in different positions.

Indeed, if the third particle interacted in an especially sensitive way, like being tipped off a hill and sliding down, the new separation could be much larger than the old one.

Actually, it isn't necessary for a particle to get tipped off a hill. It also works if you've got *twenty* particles interacting with the first two, and ending up entangled with them. Then the new amplitude distribution has got two blobs, each with *twenty-two* particles in different places. The distance between the two blobs in the *joint* configuration space is much greater.

And the greater the distance between blobs, the less likely it is that their amplitude flows will intersect each other and interfere with each other.

That's decoherence. Decoherence is the third key to recovering the classical hallucination, because it makes the blobs behave independently; it lets you treat the whole amplitude distribution as a sum of separated non-interfering blobs.

Indeed, once the blobs have separated, the pattern *within a single blob* may look a lot more plaid and rectangular—I tried to show that in the diagram above as well.

Thus, the big headache in quantum computing is *preventing* decoherence. Quantum computing relies on the amplitude distributions staying *close enough together* in configuration space to *interfere with each other*. And the environment contains a zillion particles just *begging* to accidentally interact with your fragile qubits, teasing apart the pieces of your painstakingly sculpted amplitude distribution.

And you can't just magically make the pieces of the scattered amplitude distribution jump back together—these are blobs in the *joint* configuration, remember. You'd have to *put the environmental particles* in the same places, too.

> (Sounds pretty irreversible, doesn't it? Like trying to unscramble an egg? Well, that's a very good analogy, in fact.
>
> This is why I emphasized earlier that entanglement happens starting from a condition of low entropy. Decoherence is irreversible because it is an essentially *thermodynamic* process.
>
> It is a fundamental principle of the universe—as far as we can tell—that if you "run the film backward" all the *fundamental* laws are still obeyed. If you take a movie of an egg falling onto the floor and smashing, and then play the film backward and see a smashed egg leaping off the floor and into a neat shell, you will not see the known laws of physics violated in any particular. All the molecules will just happen to bump into each other in just the right way to make the egg leap off the floor and reassemble. It's not *impossible,* just *unbelievably improbable*.
>
> Likewise with a smashed amplitude distribution suddenly assembling many distantly scattered blobs into mutual coherence—it's not *impossible,* just *extremely improbable* that many distant starting positions would end up sending amplitude flows to nearby final locations. You are far more likely to see the reverse.
>
> Actually, in addition to running the film backward, you've got to turn all the positive charges to negative, and reverse left and right (or some other single dimension—essentially you have to turn the universe into its mirror image).
>
> This is known as CPT symmetry, for Charge, Parity, and Time.
>
> CPT symmetry appears to be a really, really, really deep principle of the universe. Trying to violate CPT symmetry doesn't sound *quite* as awful to a modern physicist as trying to throw a baseball so hard it travels faster than light. But it's *almost* that awful. I'm told that ~~General Relativity~~ Quantum Field Theory requires CPT symmetry, for one thing.
>
> So the fact that decoherence *looks* like a one-way process, but is only *thermodynamically* irreversible rather than *fundamentally* asymmetrical, is a very important point. It means quantum physics obeys CPT symmetry.

> It is a universal rule in physics—according to our best current knowledge—that every apparently irreversible process is a special case of the second law of thermodynamics, *not* the result of time-asymmetric fundamental laws.)

To sum up:

Decoherence is a thermodynamic process of ever-increasing quantum entanglement, which, through an amazing sleight of hand, masquerades as increasing quantum independence: Decoherent blobs don't interfere with each other, and *within a single blob but not the total distribution*, the blob is more factorizable into subspaces.

Thus, decoherence is the third key to recovering the classical hallucination. Decoherence lets a human physicist think about one blob at a time, without worrying about how blobs interfere with each other; and the blobs themselves, considered as isolated individuals, are less *internally* entangled, hence easier to understand. This is a fine thing if you want to pretend the universe is classical, but *not so good* if you want to factor a million-digit number before the Sun burns out.

Part of *The Quantum Physics Sequence*

Next post: "The So-Called Heisenberg Uncertainty Principle"

Previous post: "Three Dialogues on Identity"

The So-Called Heisenberg Uncertainty Principle

Previously in series: Decoherence

As touched upon earlier, Heisenberg's "Uncertainty Principle" is horribly misnamed.

Amplitude distributions in configuration space evolve over time. When you specify an amplitude distribution over joint positions, you are also necessarily specifying how the distribution will evolve. If there are blobs of position, you know where the blobs are going.

In classical physics, where a particle is, is a separate fact from how fast it is going. In quantum physics this is not true. If you *perfectly* know the amplitude distribution on position, you *necessarily know* the evolution of any blobs of position over time.

So there is a theorem which *should* have been called the Heisenberg Certainty Principle, or the Heisenberg Necessary Determination Principle; but what does this theorem actually say?

At left is an image I previously used to illustrate a possible amplitude distribution over positions of a 1-dimensional particle.

Suppose that, instead, the amplitude distribution is actually a *perfect helix.* (I.e., the amplitude at each point has a constant modulus, but the complex phase changes linearly with the position.) And neglect the effect of potential energy on the system evolution; i.e., this is a particle out in intergalactic space, so it's not near any gravity wells or charged particles.

If you started with an amplitude distribution that looked like a perfect spiral helix, the laws of quantum evolution would make the helix seem to rotate / move forward at a constant rate. Like a corkscrew turning at a constant rate.

This is what a physicist views as *a single particular momentum*.

And you'll note that a "single particular momentum" corresponds to an amplitude distribution that is *fully spread out*—there's no bulges in any particular position.

Let me emphasize that I have *not* just described a real situation you could find a particle in.

The physicist's notion of "a single particular momentum" is a *mathematical tool* for analyzing quantum amplitude distributions.

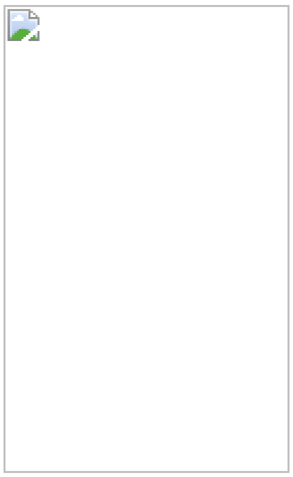
The evolution of the amplitude distribution involves things like taking the second derivative in space and multiplying by *i* to get (one component of) the first derivative in time. Which turns out to give rise to a wave mechanics—blobs that can propagate themselves across space, over time.

One of the basic tools in wave mechanics is taking apart complicated waves into a sum of simpler waves.

If you've got a wave that bulges in particular places, and thus changes in pitch and diameter, then you can take apart that ugly wave into a *sum* of prettier waves.

A sum of simpler waves whose individual behavior is easy to calculate; and then you just add those behaviors back together again.

A sum of nice neat waves, like, say, those perfect spiral helices corresponding to precise momenta.



A physicist can, for mathematical convenience, decompose a position distribution into an integral over (infinitely many) helices of different pitches, phases, and diameters.

Which integral looks like assigning a complex number to each possible pitch of the helix. And each pitch of the helix corresponds to a different momentum. So you get a complex distribution over momentum-space.

It happens to be a fact that, when the position distribution is more concentrated—when the position distribution bulges more sharply—the integral over momentum-helices gets more widely distributed.

Which has the physical consequence, that anything which is very sharply in one place, tends to soon spread itself out. Narrow bulges don't last.

Alternatively, you might find it convenient to think, "Hm, a narrow bulge has sharp changes in its second derivative, and I know the evolution of the amplitude distribution depends on the second derivative, so I can sorta imagine how a narrow bulge might tend to propagate off in all directions."

Technically speaking, the distribution over momenta is the Fourier transform of the distribution over positions. And it so happens that, to go *back* from momenta to positions, you just do another Fourier transform. So there's a precisely symmetrical argument which says that anything moving at a very definite speed, has to occupy a very spread-out place. Which goes back to what was shown before, about a perfect helix having a "definite momentum" (corkscrewing at a constant speed) but being equally distributed over all positions.

That's Heisenberg's Necessary Relation Between Position Distribution And Position Evolution Which Prevents The Position Distribution And The Momentum Viewpoint From Both Being Sharply Concentrated At The Same Time Principle in a nutshell.

So now let's talk about some of the assumptions, issues, and common misinterpretations of Heisenberg's Misnamed Principle.

The effect of observation on the observed

Here's what actually happens when you "observe a particle's position":

[Decoherence](), as discussed yesterday, can take apart a formerly coherent amplitude distribution into noninteracting blobs.

Let's say you have a particle X with a fairly definite position and fairly definite momentum, the starting stage shown at left above. And then X comes into the neighborhood of another particle S, or set of particles S, where S is highly sensitive to

X's exact location—in particular, whether X's position is on the left or right of the black line in the middle. For example, S might be poised at the top of a knife-edge, and X could tip it off to the left or to the right.

The result is to decohere X's position distribution into two noninteracting blobs, an X-to-the-left blob and an X-to-the-right blob. Well, now the position distribution *within* each blob, has become sharper. (Remember: Decoherence is a process of increasing quantum entanglement that masquerades as increasing quantum independence.)

So the Fourier transform of the more definite position distribution *within* each blob, corresponds to a more spread-out distribution over momentum-helices.

Running the particle X past a sensitive system S, has decohered X's position distribution into two noninteracting blobs. Over time, each blob spreads itself out again, by Heisenberg's Sharper Bulges Have Broader Fourier Transforms Principle.

All this gives rise to very real, very observable effects.

In the system shown at right, there is a light source, a screen blocking the light source, and a single slit in the screen.

Ordinarily, light seems to go in straight lines (for less straightforward reasons). But in this case, the screen blocking the light source decoheres the photon's amplitude. Most of the Feynman paths hit the screen.

The paths that *don't* hit the screen, are concentrated into a very narrow range. All positions except a very narrow range have decohered away from the blob of possibilities for "the photon goes through the slit", so, within this blob, the position-amplitude is concentrated very narrowly, and the spread of momenta is vey large.

Way up at the level of human experimenters, we see that when photons strike the second screen, they strike over a broad range—they don't just travel in a straight line from the light source.

Wikipedia, and at least some physics textbooks, claim that it is misleading to ascribe Heisenberg effects to an "observer effect", that is, perturbing interactions between the measuring apparatus and the measured system:

> "Sometimes it is a *failure* to measure the particle that produces the disturbance. For example, if a perfect photographic film contains a small hole, and an incident photon is *not* observed, then its momentum becomes uncertain by a large amount. By not observing the photon, we discover that it went through the hole."

However, the most technical treatment I've actually read was by Feynman, and Feynman seemed to be saying that, whenever measuring the position of a particle increases the spread of its momentum, the measuring apparatus must be delivering enough of a "kick" to the particle to account for the change.

In other words, Feynman seemed to assert that the decoherence perspective actually *was* dual to the observer-effect perspective—that an interaction which produced decoherence would always be able to physically account for any resulting perturbation of the particle.

Not grokking the math, I'm inclined to believe the Feynman version. It sounds pretty, and physics has a known tendency to be pretty.

The alleged effect of conscious knowledge on particles

One thing that the Heisenberg Student Confusion Principle DEFINITELY ABSOLUTELY POSITIVELY **DOES NOT SAY** is that KNOWING ABOUT THE PARTICLE or CONSCIOUSLY SEEING IT will MYSTERIOUSLY MAKE IT BEHAVE DIFFERENTLY because THE UNIVERSE CARES WHAT YOU THINK.

Decoherence works exactly the same way whether a system is decohered by a human brain or by a rock. Yes, physicists tend to construct very sensitive instruments that slice apart amplitude distributions into tiny little pieces, whereas a rock isn't that sensitive. That's why your camera uses photographic film instead of mossy leaves, and why replacing your eyeballs with grapes will not improve your vision. But *any* sufficiently sensitive physical system will produce decoherence, where "sensitive" means "developing to widely different final states *depending on* the interaction", where "widely different" means "the blobs of amplitude don't interact".

Does this description say anything about *beliefs?* No, just amplitude distributions. When you jump up to a higher level and talk about cognition, you realize that forming accurate beliefs requires sensors. But the decohering power of sensitive interactions can be analyzed on a purely physical level.

There is a legitimate "observer effect", and it is this: Brains that see, and pebbles that are seen, are part of a unified physics; they are both built out of atoms. To gain new empirical knowledge about a thingy, the particles in you have to interact with the particles in the thingy. It so happens that, in our universe, the laws of physics are pretty symmetrical about how particle interactions work—conservation of momentum and so on: if you pull on something, it pulls on you.

So you can't, in fact, observe a rock without affecting it, because to observe something is to depend on it—to let *it* affect *you*, and shape your beliefs. And, in our universe's laws of physics, any interaction in which the rock affects your brain, tends to have consequences for the rock as well.

Even if you're looking at light that left a distant star 500 years ago, then 500 years ago, emitting the light affected the star.

That's how the observer effect works. It works *because* everything is particles, and all the particles obey the same unified mathematically simple physics.

It does *not* mean the physical interactions we happen to call "observations" have a basic, fundamental, privileged effect on reality.

To suppose that physics contains a basic account of "observation" is like supposing that physics contains a basic account of being Republican. It projects a complex, intricate, high-order biological cognition onto fundamental physics. It sounds like a simple theory to humans, but it's not simple.

Linearity

One of the foundational assumptions physicists used to figure out quantum theory, is that time evolution is *linear*. If you've got an amplitude distribution X1 that evolves into X2, and an amplitude distribution Y1 that evolves into Y2, then the amplitude distribution (X1 + Y1) should evolve into (X2 + Y2).

(To "add two distributions" means that we just add the complex amplitudes at every point. Very simple.)

Physicists assume you can take apart an amplitude distribution into a sum of nicely behaved individual waves, add up the time evolution of those individual waves, and get back the actual correct future of the total amplitude distribution.

Linearity is why we can take apart a bulging blob of position-amplitude into perfect momentum-helices, without the whole model degenerating into complete nonsense.

The linear evolution of amplitude distributions is a theorem in the Standard Model of physics. But physicists didn't just stumble over the linearity principle; it was used to invent the hypotheses, back when quantum physics was being figured out.

I talked earlier about taking the second derivative of position; well, taking the derivative of a differentiable distribution is a linear operator. F'(x) + G'(x) = (F + G)'(x). Likewise, integrating the sum of two integrable distributions gets you the sum of the integrals. So the amplitude distribution evolving in a way that depends on the second derivative—or the equivalent view in terms of integrating over Feynman paths—doesn't mess with linearity.

Any "non-linear system" you've ever heard of is linear on a quantum level. Only the high-level simplifications that we humans use to model systems are nonlinear. (In the same way, the lightspeed limit requires physics to be local, but if you're thinking about the Web on a very high level, it looks like any webpage can link to any other webpage, even if they're not neighbors.)

Given that quantum physics is strictly linear, you may wonder how the *hell* you can build *any possible physical instrument* that detects a ratio of squared moduli of amplitudes, since the squared modulus operator is not linear: the squared modulus of the sum is not the sum of the squared moduli of the parts.

This is a *very good question*.

We'll get to it *shortly*.

Meanwhile, physicists, in their daily mathematical practice, assume that quantum physics is linear. It's one of those important little assumptions, like CPT invariance.

Part of *The Quantum Physics Sequence*

Next post: "Which Basis Is More Fundamental?"

Previous post: "Decoherence"

Which Basis Is More Fundamental?

Followup to: [The So-Called Heisenberg Uncertainty Principle]

For decades, quantum physics was vehemently asserted to be nothing but a convenience of calculation. The equations were not to be interpreted as describing *reality*, though they made good predictions for reasons that it was mere philosophy to question. This being the case, any quantity you could *define* seemed as fundamentally real as any other quantity, which is to say, not real at all.

Physicists have invented, for convenience of calculation, something called a *momentum basis* of quantum mechanics. Instead of having a complex amplitude distribution over the positions of particles, you had a complex amplitude distribution over their momenta.

The "momentum basis" contains all the information that is in the "position basis", and the "position basis" contains all the information that is in the "momentum basis". Physicists use the word "basis" for both, suggesting that they are on the same footing: that positions are no better than momenta, or vice versa.

But, in my humble opinion, the two representations are *not* on an equal footing when it comes to being "fundamental".

Physics in the position basis can be [computed locally]. To determine the instantaneous change of amplitude at a configuration, you only need to look at its infinitesimal neighborhood.

The momentum basis cannot be computed locally. Quantum evolution depends on potential energy. Potential energy depends on how far apart things are from each other, like how high an apple is off the ground. To figure out how far apart things are from each other, you have to look at the entire momentum basis to recover the positions.

The "momentum basis" is in some ways like a description of the chessboard in which you have quantities like "the queen's position minus the rook's position" and "the queen's position plus the rook's position". You can get back a description of the entire chessboard—but the rules of the game are much harder to phrase. Each rule has to take into account many more facts, and there's no longer an elegant local structure to the board.

Now the above analogy is not really fair, because the momentum basis is not *that* inelegant. The momentum basis is the Fourier transform of the position basis, and symmetrically, the position basis is the Fourier transform of the momentum basis. They're equally easy to extract from each other. Even so, the momentum basis has no local physics.

So if you think that the nature of reality seems to tend toward local relations, local causality, or local anything, then the position basis is a *better* candidate for being fundamentally real.

What is this "nature of reality" that I'm talking about?

I sometimes talk about the Tao as being the distribution from which our laws of physics were drawn—the alphabet in which our physics was generated. This is almost certainly a false concept, but it is a useful one.

It was a very important *discovery,* in human history, that the Tao wrote its laws in the language of mathematics, rather than heroic mythology. We had to *discover* the general proposition that *equations* were better explanations for natural phenomena than "Thor threw a lightning bolt". (Even though Thor sounds simpler to humans than Maxwell's Equations.)

Einstein seems to have discovered General Relativity almost entirely on the basis of guessing what language the laws should be written in, what properties they should have, rather than by distilling vast amounts of experimental evidence into an empirical regularity. This is the strongest evidence I know of for the pragmatic usefulness of the "Tao of Physics" concept. If you get *one* law, like Special Relativity, you can look at the language it's written in, and infer what the *next* law ought to look like. If the laws are not being generated from the same language, they surely have *something* in common; and this I refer to as the Tao.

Why "Tao"? Because no matter how I try to describe the whole business, when I look over the description, I'm pretty sure it's wrong. Therefore I call it the Tao.

One of the aspects of the Tao of Physics seems to be *locality.* (Markov neighborhoods, to be precise.) Discovering this aspect of the Tao was part of the great transition from Newtonian mechanics to relativity. Newton thought that gravity and light propagated at infinite speed, action-at-a-distance. Now that we know that everything obeys a speed limit, we know that what happens at a point in spacetime only depends on an immediate neighborhood of the immediate past.

Ever since Einstein figured out that the Tao prefers its physics local, physicists have successfully used the heuristic of prohibiting *all* action-at-a-distance in their hypotheses. We've figured out that the Tao doesn't like it. You can see how local physics would be easier to compute... though the Tao has no objection to wasting incredible amounts of computing power on things like quarks and quantum mechanics.

The Standard Model includes many fields and laws. Our physical models require many equations and postulates to write out. To the best of our current knowledge, the laws still appear, if not complicated, then not perfectly simple.

Why should *every* known behavior in physics be linear in quantum evolution, local in space and time, Charge-Parity-Time symmetrical, and conservative of probability density? I don't know, but you'd have to be pretty stupid not to notice the pattern. A single exception, in any individual behavior of physics, would destroy the generalization. It seems like too much coincidence.

So, yes, the position basis includes all the information of the momentum basis, and the momentum basis includes all the information of the position basis, and they give identical predictions.

But the momentum basis looks like... well, it looks like humans took the *real* laws and rewrote them in a mathematically convenient way that destroys the Tao's beloved locality.

That may be a poor way of putting it, but I don't know how else to do so.

In fact, the position basis is also not a good candidate for being *fundamentally* real, because it doesn't obey the relativistic spirit of the Tao. Talking about any particular position basis, involves choosing an arbitrary space of simultaneity. Of course, transforming your description of the universe to a different space of simultaneity, will leave all your experimental predictions exactly the same. But however the Tao of Physics wrote the real laws, it seems *really unlikely* that they're written to use Greenwich's space of simultaneity as the arbitrary standard, or whatever. Even if you can formulate a mathematically equivalent representation that uses Greenwich space, it doesn't seem likely that the Tao actually *wrote* it that way... if you see what I mean.

I wouldn't be surprised to learn that there is some known better way of looking at quantum mechanics than the position basis, some view whose mathematical components are relativistically invariant and locally causal.

But, for now, I'm going to stick with the observation that the position basis is local, and the momentum basis is not, regardless of how pretty they look side-by-side. It's not that I think the position basis is fundamental, but that it seems fundamental*er*.

The notion that every possible way of slicing up the amplitude distribution is a "basis", and every "basis" is on an equal footing, is a habit of thought from those dark ancient ages when quantum amplitudes were thought to be states of partial information.

You can slice up your *information* any way you like. When you're reorganizing your *beliefs*, the only question is whether the answers *you want* are easy to *calculate*.

But if a model is meant to describe *reality*, then I would tend to suspect that a locally causal model probably gets closer to fundamentals, compared to a nonlocal model with action-at-a-distance. Even if the two give identical predictions.

This is admittedly a deep philosophical issue that gets us into questions I can't answer, like "Why does the Tao of Physics like math and CPT symmetry?" and "Why should a locally causal isomorph of a structural essence, be privileged over nonlocal isomorphs when it comes to calling it 'real'?", and "What the hell is the Tao?"

Good questions, I agree.

This talk about the Tao is messed-up reasoning. And I *know* that it's messed up. And I'm not claiming that just because it's a highly useful heuristic, that is an *excuse* for it being messed up.

But I also think it's okay to have theories that are *in progress,* that are not even *claimed* to be in a nice neat finished state, that include messed-up elements *clearly labeled as messed-up*, which are to be *resolved as soon as possible* rather than just tolerated indefinitely.

That, I think, is how you make *incremental* progress on these kinds of problems—by working with incomplete theories that have wrong elements clearly labeled "WRONG!" Academics, it seems to me, have a bias toward publishing only theories that they claim to be correct—or even worse, complete—or worse yet, coherent. This, of course, rules out incremental progress on really difficult problems.

When using this methodology, you should, to avoid confusion, choose labels that clearly indicate that the theory is wrong. For example, the "Tao of Physics". If I gave that some kind of fancy technical-sounding formal name like "metaphysical distribution", people might think it was a name for a coherent theory, rather than a name for my own confusion.

I accept the possibility that this whole blog post is merely stupid. After all, the question of whether the position basis or the momentum basis is "more fundamental" should never make any difference as to what we anticipate. If you ever find that your anticipations come out one way in the position basis, and a different way in the momentum basis, you are surely doing something wrong.

But Einstein (and others!) seem to have comprehended the Tao of Physics to powerfully predictive effect. The question "What kind of laws does the Tao favor writing?" has paid more than a little rent.

The position basis looks noticeably more... favored.

Added: When I talk about "locality", I mean locality in the abstract, computational sense: mathematical objects talking only to their immediate neigbors. In particular, quantum physics is local in the configuration space.

This also happens to translate into physics that is local in what humans think of "space": it is impossible to send signals faster than light. But this isn't immediately obvious. It is an additional structure of the neighborhoods in configuration space. A configuration only neighbors configurations where positions didn't change faster than light.

A view that made both forms of locality explicit, in a relativistically invariant way, would be much more fundamentalish than the position basis. Unfortunately I don't know what such a view might be.

Part of *The Quantum Physics Sequence*

Next post: "Where Physics Meets Experience"

Previous post: "The So-Called Heisenberg Uncertainty Principle"

Where Physics Meets Experience

Followup to: Decoherence, Where Philosophy Meets Science

Once upon a time, there was an alien species, whose planet hovered in the void of a universe with laws almost like our own. They would have been alien to us, but of course they did not think of *themselves* as alien. They communicated via rapid flashes of light, rather than sound. We'll call them the Ebborians.

Ebborians reproduce by fission, an adult dividing into two new individuals. They share genetic material, but not through sexual recombination; Ebborian adults swap genetic material with each other. They have two eyes, four legs, and two hands, letting a fissioned Ebborian survive long enough to regrow.

Human DNA is built in a double helix; unzipping the helix a little at a time produces two stretches of single strands of DNA. Each single strand attracts complementary bases, producing a new double strand. At the end of the operation, a DNA double helix has turned into two double helices. Hence earthly life.

Ebborians fission their brains, as well as their bodies, by a process something like how human DNA divides.

Imagine an Ebborian brain as a flat sheet of paper, computing in a way that is more electrical than chemical—charges flowing down conductive pathways.

When it's time for an Ebborian to fission, the brain-paper splits down its thickness into two sheets of paper. Each new sheet is capable of conducting electricity on its own. Indeed, the Ebborian(s) stays conscious throughout the whole fissioning process. Over time, the brain-paper grows thick enough to fission again.

Electricity flows through Ebborian brains faster than human neurons fire. But the Ebborian brain is constrained by its two-dimensionality. An Ebborian brain-paper must split down its thickness while retaining the integrity of its program. Ebborian evolution took the cheap way out: the brain-paper computes in a purely two-dimensional way. The Ebborians have much faster neuron-equivalents, but they are far less interconnected.

On the whole, Ebborians think faster than humans and remember less. They are less susceptible to habit; they recompute what we would cache. They would be incredulous at the idea that a human neuron might be connected to a thousand neighbors, and equally incredulous at the idea that our axons and dendrites propagate signals at only a few meters per second.

The Ebborians have no concept of parents, children, or sexuality. Every adult Ebborian remembers fissioning many times. But Ebborian memories quickly fade if not used; no one knows the last common ancestor of those now alive.

In principle, an Ebborian personality can be immortal. Yet an Ebborian remembers less life than a seventy-year-old human. They retain only the most important highlights of their last few millennia. Is this immortality? Is it death?

The Ebborians had to rediscover natural selection from scratch, because no one retained their memories of being a fish.

But I digress from my tale.

Today, the Ebborians have gathered to celebrate a day which all present will remember for hundreds of years. They have discovered (they believe) the Ultimate Grand Unified Theory of Everything for their universe. The theory which seems, at last, to explain every known *fundamental* physical phenomenon—to predict what every instrument will measure, in every experiment whose initial conditions are exactly known, and which can be calculated on available computers.

"But wait!" cries an Ebborian. (We'll call this one Po'mi.) "But wait!", cries Po'mi, "There are still questions the Unified Theory can't answer! During the fission process, when *exactly* does *one* Ebborian consciousness become *two* separate people?"

The gathered Ebborians look at each other. Finally, there speaks the moderator of the gathering, the second-foremost Ebborian on the planet: the much-respected Nharglane of Ebbore, who achieved his position through consistent gentleness and courtesy.

"Well," Nharglane says, "I admit I can't answer that one—but is it really a question of *fundamental* physics?"

"I wouldn't even call that a 'question'," snorts De'da the Ebborian, "seeing as how there's no experimental test whose result depends on the answer."

"On the contrary," retorts Po'mi, "all our experimental results ultimately come down to our *experiences.* If a theory of physics can't predict what we'll experience, what good is it?"

De'da shrugs. "One person, two people—how does that make a difference even to *experience?* How do you tell even *internally* whether you're one person or two people? Of course, if you look over and see your other self, you know you're finished dividing—but by that time your brain has long since finished splitting."

"Clearly," says Po'mi, "at any given point, *whatever* is having an experience is one person. So it is never necessary to tell whether you are one person or two people. *You* are always one person. But at any given time during the split, does there exist another, *different* consciousness as yet, with its own awareness?"

De'da performs an elaborate quiver, the Ebborian equivalent of waving one's hands. "When the brain splits, it splits fast enough that there isn't much time where the question would be ambiguous. One instant, all the electrical charges are moving as a whole. The next instant, they move separately."

"That's not true," says Po'mi. "You can't sweep the problem under the rug that easily. There is a quite appreciable time—many picoseconds—when the two halves of the brain are within distance for the moving electrical charges in each half to tug on the other. Not quite causally separated, and not quite the same computation either. Certainly there is a time when there is definitely one person, and a time when there is definitely two people. But at which *exact* point in between are there two distinct conscious experiences?"

"My challenge stands," says De'da. "How does it make a difference, even a difference of *first-person* experience, as to *when* you say the split occurs? There's no third-party experiment you can perform to tell you the answer. And no difference of first-person experience, either. Your belief that consciousness must 'split' at some particular point, stems from trying to model consciousness as a big rock of awareness that can only be in one place at a time. There's no third-party experiment, and no first-person experience, that can tell you when you've split; the question is meaningless."

"If experience is meaningless," retorts Po'mi, "then so are all our scientific theories, which are merely intended to *explain* our experiences."

"If I may," says another Ebborian, named Yu'el, "I think I can refine my honorable colleague Po'mi's dilemma. Suppose that you anesthetized one of us -"

(Ebborians use an anesthetic that effectively shuts off electrical power to the brain—no processing or learning occurs while an Ebborian is anesthetized.)

"- and then flipped a coin. If the coin comes up heads, you split the subject while they are unconscious. If the coin comes up tails, you leave the subject as is. When the subject goes to sleep, should they anticipate a 2/3 probability of seeing the coin come up heads, or anticipate a 1/2 probability of seeing the coin come up heads? If you answer 2/3, then there is a difference of anticipation that *could* be made to depend on exactly when you split."

"Clearly, then," says De'da, "the answer is 1/2, since answering 2/3 gets us into paradoxical and ill-defined issues."

Yu'el looks thoughtful. "What if we split you into 512 parts while you were anesthetized? Would you still answer a probability of 1/2 for seeing the coin come up heads?"

De'da shrugs. "Certainly. When I went to sleep, I would figure on a 1/2 probability that I wouldn't get split at all."

"Hmm..." Yu'el says. "All right, suppose that we are definitely going to split you into 16 parts. 3 of you will wake up in a red room, 13 of you will wake up in a green room. Do you anticipate a 13/16 probability of waking up in a green room?"

"I anticipate waking up in a green room with near-1 probability," replies De'da, "and I anticipate waking up in a red room with near-1 probability. My future selves will experience both outcomes."

"But I'm asking about your *personal* anticipation," Yu'el persists. "When you fall asleep, how much do you *anticipate* seeing a green room? You can't see both room colors at once—that's not an experience anyone will have—so which color do you personally anticipate more?"

De'da shakes his head. "I can see where this is going; you plan to ask what I anticipate in cases where I may or may not be split. But I must deny that your question has an objective answer, precisely *because* of where it leads. Now, I do say to you, that I *care* about my future selves. If you ask me whether I would like each of my green-room selves, or each of my red-room selves, to receive ten dollars, I will of course choose the green-roomers—but I don't care to follow this notion of 'personal anticipation' where you are taking it."

"While you are anesthetized," says Yu'el, "I will flip a coin; if the coin comes up heads, I will put 3 of you into red rooms and 13 of you into green rooms. If the coin comes up tails, I will reverse the proportion. If you wake up in a green room, what is your *posterior probability* that the coin came up heads?"

De'da pauses. "Well..." he says slowly, "Clearly, some of me will be wrong, no matter which reasoning method I use—but if you offer me a bet, I can minimize the number of me who bet *poorly*, by using the general policy, of each self *betting as if* the posterior probability of their color dominating is 13/16. And if you try to make *that* judgment depend on the details of the splitting process, then it just depends on how whoever *offers the bet* counts Ebborians."

Yu'el nods. "I can see what you are saying, De'da. But I just can't make myself believe it, at least not yet. If there were to be 3 of me waking up in red rooms, and a billion of me waking up in green rooms, I would quite strongly *anticipate* seeing a green room when I woke up. Just the same way that I anticipate *not* winning the lottery. And if the proportions of three red to a billion green, followed from a coin coming up heads; but the reverse proportion, of a billion red to three green, followed from tails; and I woke up and saw a red room; why, then, I would be nearly *certain*—on a quite personal level—that the coin had come up tails."

"That stance exposes you to quite a bit of trouble," notes De'da.

Yu'el nods. "I can even see some of the troubles myself. Suppose you split brains only a short distance apart from each other, so that they could, in principle, be *fused back together again?* What if there was an Ebborian with a brain thick enough to be split into a million parts, and the parts could then re-unite? Even if it's not biologically possible, we could do it with a computer-based mind, someday. Now, suppose you split me into 500,000 brains who woke up in green rooms, and 3 much thicker brains who woke up in red rooms. I would surely anticipate seeing the green room. But most of me who see the green room will see nearly the same thing—different in tiny details, perhaps, enough to differentiate our experience, but such details are soon forgotten. So now suppose that my 500,000 green selves are reunited into one Ebborian, and my 3 red selves are reunited into one Ebborian. Have I just sent nearly all of my "subjective probability" into the green future self, even though it is now only one of two? With only a little more work, you can see how a *temporary* expenditure of computing power, or a nicely refined brain-splitter and a dose of anesthesia, would let you have a high *subjective probability* of winning any lottery. At least any lottery that involved splitting you into pieces."

De'da furrows his eyes. "So have you not just proved your own theory to be nonsense?"

"I'm not sure," says Yu'el. "At this point, I'm not even sure the conclusion is wrong."

"I didn't suggest your conclusion was *wrong,*" says De'da, "I suggested it was *nonsense.* There's a difference."

"Perhaps," says Yu'el. "Perhaps it will indeed turn out to be nonsense, when I know better. But if so, I don't quite know better *yet.* I can't quite see how to eliminate the notion of *subjective anticipation* from my view of the universe. I would need something to replace it, something to re-fill the *role* that anticipation currently plays in my worldview."

De'da shrugs. "Why not just eliminate 'subjective anticipation' outright?"

"For one thing," says Yu'el, "I would then have no way to express my surprise at the orderliness of the universe. Suppose you claimed that the universe was actually made up entirely of random experiences, brains temporarily coalescing from dust and experiencing all possible sensory data. Then if I don't count individuals, or weigh their existence *somehow*, that chaotic hypothesis would predict my existence as strongly as does science. The realization of all possible chaotic experiences would predict my own experience with probability 1. I need to keep my surprise at having *this particular* orderly experience, to justify my anticipation of seeing an orderly future. If I throw away the notion of subjective anticipation, then how do I differentiate the chaotic universe from the orderly one? Presumably there are Yu'els, somewhere in time and space (for the universe is spatially infinite) who are about to have a really chaotic experience. I need some way of saying that these Yu'els are *rare,* or *weigh little*—some way of *mostly* anticipating that I won't sprout wings and fly away. I'm not saying that my *current* way of doing this is good bookkeeping, or even *coherent* bookkeeping; but I can't just *delete* the bookkeeping without a more solid understanding to put in its place. I need some way to say that there are versions of me who see one thing, and versions of me who see something else, but there's *some* kind of different weight on them. Right now, what I try to do is count copies—but I don't know *exactly* what constitutes a copy."

Po'mi clears his throat, and speaks again. "So, Yu'el, you agree with me that there exists a definite and factual question as to exactly when there are two conscious experiences, instead of one."

"That, I do not concede," says Yu'el. "All that I have said may only be a recital of my own confusion. You are too quick to fix the language of your beliefs, when there are words in it that, by your own admission, you do not understand. No matter how fundamental your experience *feels* to you, it is not safe to *trust* that feeling, until experience is no longer something you are *confused* about. There is a black box here, a mystery. Anything could be inside that box—any sort of surprise—a shock that shatters everything you currently believe about consciousness. Including upsetting your belief that experience is fundamental. In fact, that strikes me as a surprise you should anticipate—though it will still come as a shock."

"But then," says Po'mi, "do you at least agree that if our physics does not specify *which* experiences are experienced, or how many of them, or how much they 'weigh', then our physics must be incomplete?"

"No," says Yu'el, "I don't concede that either. Because consider that, even if a physics is *known*—even if we construct a universe with very simple physics, much simpler than our own Unified Theory—I can *still* present the same split-brain dilemmas, and they will still seem just as puzzling. This suggests that the source of the confusion is not in our theories of *fundamental* physics. It is on a higher level of organization. We can't compute exactly how proteins will fold up; but this is not a deficit in our theory of atomic dynamics, it is a deficit of computing power. We don't know what makes *sharkras* bloom only in spring; but this is not a deficit in our Unified Theory, it is a deficit in our biology—we don't possess the technology to take the *sharkras* apart on a molecular level to find out how they work. What you are pointing out is a gap in our science of consciousness, which would present us with just the same puzzles even if we knew *all* the fundamental physics. I see no work here for *physicists,* at all."

Po'mi smiles faintly at this, and is about to reply, when a listening Ebborian shouts, "What, have you begun to believe in zombies? That when you specify all the physical facts about a universe, there are facts about consciousness left over?"

"No!" says Yu'el. "Of course not! You can know the *fundamental* physics of a universe, hold all the *fundamental* equations in your mind, and still not have *all* the physical facts. You may not know why *sharkras* bloom in the summer. But if you could actually hold the entire fundamental physical state of the *sharkra* in your mind, and understand all its levels of organization, then you would necessarily know why it blooms—there would be no fact left over, from outside physics. When I say, 'Imagine running the split-brain experiment in a universe with simple known physics,' you are not *concretely* imagining that universe, in every detail. You are not *actually* specifying the entire physical makeup of an Ebborian in your imagination. You are only *imagining* that you know it. But if you *actually* knew how to build an entire conscious being from scratch, out of paperclips and rubberbands, you would have a *great deal* of knowledge that you do not presently have. This is *important* information that you are missing! *Imagining* that you have it, does not give you the insights that would follow from *really* knowing the full physical state of a conscious being."

"So," Yu'el continues, "We can *imagine* ourselves knowing the fundamental physics, and imagine an Ebborian brain splitting, and find that we don't know exactly when the consciousness has split. Because we are not *concretely* imagining a *complete and detailed* description of a conscious being, with full comprehension of the implicit higher levels of organization. There are knowledge gaps here, but they are not gaps of *physics.* They are gaps in our understanding of consciousness. I see no reason to think that *fundamental* physics has *anything to do with* such questions."

"Well then," Po'mi says, "I have a puzzle I should like you to explain, Yu'el. As you know, it was discovered not many years ago, that our universe has four spatial dimensions, rather than three dimensions, as it first appears."

"Aye," says Nharglane of Ebbore, "this was a key part in our working-out of the Unified Theory. Our models would be utterly at a loss to account for observed experimental results, if we could not model the fourth dimension, and differentiate the fourth-dimensional density of materials."

"And we also discovered," continues Po'mi, "that our very planet of Ebbore, including all the people on it, has a four-dimensional thickness, and is constantly fissioning along that thickness, just as our brains do. Only the fissioned sides of our planet do not remain in contact, as our new selves do; the sides separate into the fourth-dimensional void."

Nharglane nods. "Yes, it was rather a surprise to realize that the whole *world* is duplicated over and over. I shall remember that realization for a long time indeed. It is a good thing we Ebborians had our experience with self-fissioning, to prepare us for the shock. Otherwise we might have been driven mad, and embraced absurd physical theories."

"Well," says Po'mi, "when the world splits down its four-dimensional thickness, it does not always split exactly evenly. Indeed, it is not uncommon to see nine-tenths of the four-dimensional thickness in one side."

"Really?" says Yu'el. "My knowledge of physics is not so great as yours, but—"

"The statement is correct," says the respected Nharglane of Ebbore.

"Now," says Po'mi, "if fundamental physics has nothing to do with consciousness, can you tell me why the subjective probability of finding ourselves in a side of the split world, should be exactly proportional to the square of the thickness of that side?"

There is a great terrible silence.

"WHAT?" says Yu'el.

"WHAT?" says De'da.

"WHAT?" says Nharglane.

"WHAT?" says the entire audience of Ebborians.

To be continued...

Part of *The Quantum Physics Sequence*

Next post: "Where Experience Confuses Physicists"

Previous post: "Which Basis Is More Fundamental?"

Where Experience Confuses Physicists

Continuation of: Where Physics Meets Experience

When we last met our heroes, the Ebborians, they were discussing the known phenomenon in which the entire planet of Ebbore and all its people splits down its fourth-dimensional thickness into two sheets, just like an individual Ebborian brain-sheet splitting along its third dimension.

And Po'mi has just asked:

> "Why should the subjective probability of finding ourselves in a side of the split world, be exactly proportional to the square of the thickness of that side?"

When the initial hubbub quiets down, the respected Nharglane of Ebbore asks: "Po'mi, what is it *exactly* that you found?"

"Using instruments of the type we are all familiar with," Po'mi explains, "I determined when a splitting of the world was about to take place, and in what proportions the world would split. I found that I could not predict *exactly* which world I would find myself in—"

"Of course not," interrupts De'da, "you found yourself in *both* worlds, every time -"

"—but I could predict *probabilistically* which world I would find myself in. Out of all the times the world was about to split 2:1, into a side of two-thirds width and a side of one-third width, I found myself on the thicker side around 4 times out of 5, and on the thinner side around 1 time out of 5. When the world was about to split 3:1, I found myself on the thicker side 9 times out of 10, and on the thinner side 1 time out of 10."

"Are you *very sure* of this?" asks Nharglane. "How much data did you gather?"

Po'mi offers an overwhelming mountain of experimental evidence.

"I guess that settles that," mutters Nharglane.

"So you see," Po'mi says, "you were right after all, Yu'el, not to eliminate 'subjective probability' from your worldview. For if we do not have a 4/5 subjective anticipation of *continuing into* the thicker side of a 2:1 split, then how could we even *describe* this rule?"

"A good question," says De'da. "There ought to be *some* way of phrasing your discovery, which eliminates this problematic concept of 'subjective continuation'..."

The inimitable Ha'ro speaks up: "You might say that we find ourselves in a world in which the *remembered* splits obey the squared-thickness rule, to within the limits of statistical expectation."

De'da smiles. "Yes, excellent! That describes the evidence in terms of recorded experimental results, which seems less problematic than this 'subjective anticipation' business."

"Does that really buy us anything...?" murmurs Yu'el. "We're not limited to memories; we could perform the experiment again. What, on that next occasion, would you *anticipate* as your experimental result? If the thickness is split a hundred to one? Afterward it will be only a memory... but what about beforehand?"

"I think," says De'da, "that you have forgotten one of your own cardinal rules, Yu'el. Surely, what you *anticipate* is part of your map, not the territory. Your degree of anticipation is partial information you possess; it is not a substance of the experiment itself."

Yu'el pauses. "Aye, that is one of my cardinal rules... but I like my partial information to be *about* something. Before I can distinguish the map and the territory, I need a concept of the territory. What is my subjective anticipation *about*, in this case? I will *in fact* end up in both world-sides. I can calculate a certain probability to five decimal places, and verify it experimentally—but what is it a probability *of?*"

"I know!" shouts Bo'ma. "It's the probability that your *original* self ends up on that world-side! The other person is *just a copy!*"

A great groan goes up from the assembled Ebborians. "Not this again," says De'da. "Didn't we settle this during the Identity Wars?"

"Yes," Yu'el says. "There is no copy: there are two originals."

De'da shakes his head in disgust. "And what are the odds that, out of umpteen billion split Ebbores, *we* would be the originals at this point?"

"But you can't deny," Bo'ma says smugly, "that my theory produces good experimental predictions! It explains our observations, and that's all you can ask of any theory. And so science vindicates the Army of Original Warriors—we were right all along!"

"Hold on," says Yu'el. "That theory doesn't actually *explain* anything. At all."

"What?" says Bo'ma. "Of course it does. I use it daily to make experimental predictions; though *you* might not understand that part, not being a physicist."

Yu'el raises an eye. "Failure to explain anything is a hard-to-notice phenomenon in scientific theories. You have to pay close attention, or you'll miss it. It was once thought that phlogiston theory predicted that wood, when burned, would lose phlogiston and transform into ash; and predicted that candles, burning in an enclosed space, would saturate the air with phlogiston and then go out. But these were not *advance* predictions of phlogiston theory. Rather, phlogiston theorists saw those results, and then said 'Phlogiston did it.' Now why didn't people notice this right away? Because that sort of thing is actually surprisingly hard to notice."

"In this case," continues Yu'el, "you have given us a rule that the *original* Ebborian has a probability of ending up in a world-side, which is proportional to the squared thickness of the side. We originally had the mystery of where the squared-thickness rule came from. And now that you've offered us your rule, we have the *exact same mystery* as before. *Why* would each world have a squared-thickness probability of receiving the original? Why wouldn't the original consciousness *always* go to the thicker world? Or go with probability *directly* proportional to thickness, instead of the square? And what does it even *mean* to be the original?"

"That doesn't matter," retorts Bo'ma. "Let the equation *mean* anything it likes, so long as it gives good experimental predictions. What is the meaning of an electrical charge? Why is it an electrical charge? That doesn't matter; only the numbers matter. My law that the original ends up in a particular side, with probability equaling the square of its thickness, gives good numbers. End of story."

Yu'el shakes his head. "When I look over the raw structure of your theory—the computer program that would correspond to this model—it contains a strictly superfluous element. You have to compute the square of the thickness, and turn it into a probability, in order to get *the chance that the original self goes there.* Why not just *keep that probability* as the experimental prediction? Why *further* specify that this is the *probability of* original-ness? Adding that last rule doesn't help you compute any *better* experimental predictions; and it leaves all the original mysteries intact. Including Po'mi's question as to when exactly a world splits. And it adds the new mystery of why original-ness should only end up in one world-side, with probability equal to the square of the thickness."   Yu'el pauses. "You might as well just claim that all the split world-sides except one vanish from the universe."

Bo'ma snorts. "For a world-side to 'just vanish' would outright violate the laws of physics. Why, if it all vanished in an instant, that would mean the event occurred non-locally—faster than light. My suggestion about 'originals' and 'copies' doesn't postulate unphysical behavior, whatever other criticisms you may have."

Yu'el nods. "You're right, that was unfair of me. I apologize."

"Well," says Bo'ma, "how about this, then? What if 'fourth-dimensional thickness', as we've been calling it, is actually a *degree of partial information* about who we *really* are? And then when the world splits, we find out."

"Um... *what*?" says Yu'el. "Are you sure you don't want to rephrase that, or something?"

Bo'ma shakes his head. "No, you heard me the first time."

"Okay," says Yu'el, "correct me if I'm wrong, but I thought I heard Nharglane say that you had to do things like differentiate the fourth-dimensional density in order to do your experimental calculations. That doesn't sound like probability theory to me. It sounds like physics."

"Right," Bo'ma says, "it's a quantity that propagates around with wave mechanics that involve the differential of the density, but it's *also* a degree of partial information."

"Look," Yu'el says, "if this 4D density business works the way you say it does, it should be easy to set up a situation where there's no *possible* 'fact as to who you really are' that is fixed in advance but unknown to you, because the so-called 'answer' will change depending on the so-called 'question'—"

"Okay," Bo'ma says, "forget the 'probability' part. What if 4D thickness is *the very stuff of reality itself?* So how *real* something is, equals the 4D thickness—no, pardon me, the square of the 4D thickness. Thus, some world-sides are quantitatively *realer* than others, and that's why you're more likely to find yourself in them."

"Why," says Yu'el, "is the *very stuff of reality itself* manifesting as a physical quantity with its own wave mechanics? What's next, electrical charge as a degree of possibility? And besides, doesn't that violate -"

Then Yu'el pauses, and falls silent.

"What is it?" inquires Po'mi.

"I was about to say, wouldn't that violate the Generalized Anti-Zombie Principle," Yu'el replies slowly. "Because then you could have a complete mathematical model of our world, to be looked over by the Flying Spaghetti Monster, and then *afterward* you would need to tell the Flying Spaghetti Monster an *extra* postulate: *Things are real in proportion to the square of their fourth-dimensional thickness.* You could change that postulate, and leave everything microphysically the same, but people would find... different proportions of themselves?... in different places. The difference would be detectable *internally*... sort of... because the inhabitants would *experience* the results in different proportions, whatever that means. They would see different things, or at least see the same things in different relative amounts. But any third-party observer, looking over the universe, couldn't tell which internal people were *more real,* and so couldn't discover the statistics of experience."

De'da laughs. "Sounds like a crushing objection to me."

"Only," says Yu'el, "is that really so different from believing that you can have the whole mathematical structure of a world, and then an *extra* fact as to whether that world happens to *exist* or *not exist*? Shouldn't *that* be ruled out by the Anti-Zombie Principle too? Shouldn't the Anti-Zombie Principle say that it was logically impossible to have had a world physically identical to our own, except that it *doesn't exist?* Otherwise there could be an abstract mathematical object structurally identical to this world, but with *no experiences in it*, because *it doesn't exist*. And papers that philosophers wrote about subjectivity wouldn't prove they were conscious, because the papers would also 'not exist'."

"Um..." says an Ebborian in the crowd, "correct me if I'm mistaken, but didn't you just solve the mystery of the First Cause?"

"You are mistaken," replies Yu'el. "I can tell when I have *solved* a mystery, because it stops being mysterious. To cleverly manipulate my own confusion is not to dissolve a problem. It is an interesting argument, and I may try to follow it further—but it's not an *answer* until the confusion goes away."

"Nonetheless," says Bo'ma, "if you're allowed to say that some worlds exist, and some worlds don't, why not have a degree of existence that's *quantitative?* And propagates around like a wave, and then we have to square it to get an answer."

Yu'el snorts. "Why not just let the 'degree of existence' be a complex number, while you're at it?"

Bo'ma rolls his eyes. "Please stop mocking me. I can't even *imagine* any possible experimental evidence which would point in the direction of *that* conclusion. You'd need a case where two events that were real in opposite directions canceled each other out."

"I'm sorry," says Yu'el, "I need to learn to control my tendency to attack straw opponents. But still, where would the squaring rule come from?"

An Ebborian named Ev'Hu suggests, "Well, you could have a rule that world-sides whose thickness tends toward zero, must have a degree of reality that also tends to zero. And then the rule which says that you square the thickness of a world-side, would let the probability tend toward zero as the world-thickness tended toward zero. QED."

"That's not QED," says Po'mi. "That's a complete non-sequitur. Logical fallacy of affirming the consequent. You could have all *sorts* of rules that would let the reality tend toward zero as the world-thickness tended toward zero, not just the squaring rule. You could approach the limit from many different directions. And in fact, *all* our world-sides have a thickness that 'tends toward zero' because they keep splitting. Furthermore, why would an indefinite tendency in the infinite future have any impact on what we do now?"

"The frequentist heresy," says Yu'el. "It sounds like some of their scriptures. But let's move on. Does anyone have any *helpful* suggestions? Ones that don't just shuffle the mystery around?"

Ha'ro speaks. "I've got one."

"Okay," Yu'el says, "this should be good."

"Suppose that when a world-side gets thin enough," Ha'ro says, "it cracks to pieces and falls apart. And then, when you did the statistics, it would turn out that the vast majority of *surviving* worlds have splitting histories similar to our own."

There's a certain unsettled pause.

"Ha'ro," says Nharglane of Ebbore, "to the best of my imperfect recollection, that is the most disturbing suggestion any Ebborian physicist has ever made in the history of time."

"Thank you very much," says Ha'ro. "But it could also be that a too-small world-side just sheds off in flakes when it splits, rather than containing actual sentient beings who get to experience a moment of horrified doom. The too-small worlds merely fail to exist, as it were. Or maybe sufficiently small world-sides get attracted to larger world-sides, and merge with them in a continuous process, obliterating the memories of anything having happened differently. But *that's* not important, the *real* question is whether the numbers would work out for the right size limit, and in fact," Ha'ro waves some calculations on a piece of paper, "all you need is for the minimum size of a cohesive world to be somewhere around the point where half the total fourth-dimensional mass is above the limit -"

"Eh?" says Yu'el.

"I figured some numbers and they don't look too implausible and we might be able to prove it, either from first-principles of 4D physics showing that a cracking process occurs, or with some kind of *really clever* experiment," amplifies Ha'ro.

"Sounds promising," says Yu'el. "So if I get what you're saying, there would be a *completely physical* explanation for why, when a typical bunch of worlds split 2:1, there's around 4 times as many cohesive worlds left that split from the thicker side, as from the thinner side."

"Yes," says Ha'ro, "you just count the surviving worlds."

"And if the Flying Spaghetti Monster ran a simulation of our universe's physics, the simulation would automatically include observers that experienced the same things we did, with the same statistical probabilities," says Yu'el. "No extra postulates required. None of the quantities in the universe would need additional characteristics beyond their strictly physical structure. Running any mathematically equivalent computer program would do the trick—you wouldn't need to be told how to *interpret* it a particular way."

Ha'ro nods. "That's the general idea."

"Well, I don't know if that's *correct,*" says Yu'el. "There's some potential issues, as you know. But I've got to say it's the first suggestion I've heard that's even *remotely* helpful in making all this seem any less mysterious."

Part of *The Quantum Physics Sequence*

Next post: "On Being Decoherent"

Previous post: "Where Physics Meets Experience"

On Being Decoherent

Previously in series: The So-Called Heisenberg Uncertainty Principle

"A human researcher only sees a particle in one place at one time." At least that's what everyone goes around repeating to themselves. Personally, I'd say that when a human researcher looks at a quantum computer, they quite clearly see particles *not* behaving like they're in one place at a time. In fact, you have *never in your life* seen a particle "in one place at a time" because they *aren't.*

Nonetheless, when you construct a big measuring instrument that is sensitive to a particle's location—say, the measuring instrument's behavior depends on whether a particle is to the left or right of some dividing line—then you, the human researcher, see the screen flashing "LEFT", or "RIGHT", but not a mixture like "LIGFT".

As you might have guessed from reading about decoherence and Heisenberg, this is because we *ourselves* are governed by the laws of quantum mechanics and subject to decoherence.

The standpoint of the Feynman path integral suggests viewing the evolution of a quantum system as a sum over histories, an integral over ways the system "could" behave—though the quantum evolution of each history still depends on things like the second derivative of that component of the amplitude distribution; it's not a sum over classical histories. And "could" does not mean *possibility* in the logical sense; all the amplitude flows are real events...

Nonetheless, a human being can try to grasp a quantum system by imagining all the ways that something could happen, and then adding up all the little arrows that flow to identical outcomes. That gets you something of the flavor of the real quantum physics, of amplitude flows between volumes of configuration space.

Now apply this mode of visualization to a sensor measuring an atom—say, a sensor measuring whether an atom is to the left or right of a dividing line.

Superposition2

Which is to say: The sensor and the atom undergo some physical interaction in which the final state of the sensor depends heavily on whether the atom is to the left or right of a dividing line. (I am reusing some previous diagrams, so this is not an exact depiction; but you should be able to use your own imagination at this point.)

Entanglecloud

You may recognize this as the *entangling interaction* described in "Decoherence". A quantum system that starts out highly factorizable, looking plaid and rectangular, that is, independent, can evolve into an entangled system as the formerly-independent parts interact among themselves.

So you end up with an amplitude distribution that contains two blobs of amplitude—a blob of amplitude with the atom on the left, and the sensor saying "LEFT"; and a blob of amplitude with the atom on the right, and the sensor saying "RIGHT".

For a sensor to *measure* an atom is to *become entangled* with it—for the state of the sensor to depend on the state of the atom—for the two to become correlated. In a classical system, this is true only on a probabilistic level. In quantum physics it is a physically real state of affairs.

To *observe* a thing is to *entangle yourself* with it. You may recall my having previously said things that sound a good deal like this, in describing how cognition obeys the laws of thermodynamics, and, much earlier, talking about how rationality is a phenomenon within causality. It is possible to appreciate this in a purely philosophical sense, but quantum physics helps drive the point home.

Ampl1

Let's say you've got an Atom, whose position has amplitude bulges on the left and on the right. We can regard the Atom's distribution as a *sum* (addition, not multiplication) of the left bulge and the right bulge:

Atom = (Atom-LEFT + Atom-RIGHT)

Also there's a Sensor in a ready-to-sense state, which we'll call BLANK:

Sensor = Sensor-BLANK

By hypothesis, the system starts out in a state of quantum independence—the Sensor hasn't interacted with the Atom yet. So:

System = (Sensor-BLANK) * (Atom-LEFT + Atom-RIGHT)

Sensor-BLANK is an amplitude sub-distribution, or sub-factor, over the joint positions of all the particles in the sensor. Then you multiply this distribution by the distribution (Atom-LEFT + Atom-RIGHT), which is the sub-factor for the Atom's position. Which gets you the *joint* configuration space over *all* the particles in the system, the Sensor *and* the Atom.

Quantum evolution is linear, which means that Evolution(A + B) = Evolution(A) + Evolution(B). We can understand the behavior of this whole distribution by understanding its parts. Not its multiplicative factors, but its additive components. So now we use the distributive rule of arithmetic, which, because we're just adding and multiplying complex numbers, works just as usual:

System = (Sensor-BLANK) * (Atom-LEFT + Atom-RIGHT)
= (Sensor-BLANK * Atom-LEFT) + (Sensor-BLANK * Atom-RIGHT)

Now, the volume of configuration space corresponding to (Sensor-BLANK * Atom-LEFT) evolves into (Sensor-LEFT * Atom-LEFT).

Which is to say: Particle positions for the sensor being in its initialized state *and* the Atom being on the left, end up sending their amplitude flows to final configurations in which the Sensor is in a LEFT state, and the Atom is still on the left.

So we have the evolution:

(Sensor-BLANK * Atom-LEFT) + (Sensor-BLANK * Atom-RIGHT)
=>
(Sensor-LEFT * Atom-LEFT) + (Sensor-RIGHT * Atom-RIGHT)

By hypothesis, Sensor-LEFT is a different state from Sensor-RIGHT—otherwise it wouldn't be a very sensitive Sensor. So the final state doesn't factorize any further; it's entangled.

But this entanglement is not likely to manifest in difficulties of calculation. Suppose the Sensor has a little LCD screen that's flashing "LEFT" or "RIGHT". This may seem like a relatively small difference to a human, but it involves avogadros of particles—photons, electrons, entire molecules—occupying different positions.

So, since the states Sensor-LEFT and Sensor-RIGHT are widely separated in the configuration space, the volumes (Sensor-LEFT * Atom-LEFT) and (Sensor-RIGHT * Atom-RIGHT) are even more widely separated.

The LEFT blob and the RIGHT blob in the amplitude distribution can be considered separately; they won't interact. There are no plausible Feynman paths that end up with both LEFT and RIGHT sending amplitude to the *same joint configuration.* There would have to be a Feynman path from LEFT, and a Feynman path from RIGHT, in which *all* the quadrillions of differentiated particles ended up in the *same places*. So the amplitude flows from LEFT and RIGHT don't intersect, and don't interfere.

Precohered

You may recall this principle from "Decoherence", for how a sensitive interaction can decohere two interacting blobs of amplitude, into two noninteracting blobs.

Decohered

Formerly, the Atom-LEFT and Atom-RIGHT states were close enough in configuration space, that the blobs could interact with each other—there would be Feynman paths where an atom on the left ended up on the right. Or Feynman paths for both an atom on the left, and an atom on the right, to end up in the middle.

Now, however, the two blobs are decohered. For LEFT to interact with RIGHT, it's not enough for just the *Atom* to end up on the right. The *Sensor* would have to spontaneously leap into a state where it was flashing "RIGHT" on screen. Likewise with any particles in the environment which previously happened to be hit by photons for the screen flashing "LEFT". Trying to reverse decoherence is like trying to unscramble an egg.

And when a *human being* looks at the Sensor's little display screen... or even just stands nearby, with quintillions of particles slightly influenced by gravity... then, under *exactly the same laws,* the system evolves into:

> (Human-LEFT * Sensor-LEFT * Atom-LEFT) + (Human-RIGHT * Sensor-RIGHT * Atom-RIGHT)

Thus, any *particular version* of yourself only sees the sensor registering one result.

That's it—the big secret of quantum mechanics. As physical secrets go, it's actually pretty damn big. Discovering that the Earth was not the center of the universe, doesn't hold a candle to realizing that you're twins.

That *you, yourself,* are made of particles, is the fourth and final key to recovering the classical hallucination. It's why you only ever see the universe from *within* one blob of amplitude, and not the vastly entangled whole.

Asking why you can't see Schrodinger's Cat as simultaneously dead and alive, is like an Ebborian asking: "But if my brain really splits down the middle, why do I only ever remember finding myself on either the left *or* the right? Why don't I find myself on both sides?"

Because you're not outside and above the universe, looking down. You're *in* the universe.

Your eyes are not an empty window onto the soul, through which the true state of the universe leaks in to your mind. What you *see,* you see because your brain represents it: because your brain becomes entangled with it: because your eyes and brain are part of a continuous physics with the rest of reality.

You only see nearby objects, not objects light-years away, because photons from those objects can't reach you, therefore you can't see them. By a similar locality principle, you don't interact with distant configurations.

When you open your eyes and see your shoelace is untied, that event happens within your brain. A brain is made up of interacting neurons. If you had two separate groups of neurons that never interacted with each other, but did interact among themselves, they would not be a single computer. If one group of neurons thought "My shoelace is untied", and the other group of neurons thought "My shoelace is tied", it's difficult to see how these two brains could possibly contain the same consciousness.

And if you think all this sounds obvious, note that, historically speaking, it took more than two decades after the invention of quantum mechanics for a physicist to publish that little suggestion. People *really aren't used* to thinking of themselves as particles.

The Ebborians have it a bit easier, when they split. They can see the other sides of themselves, and talk to them.

But the only way for two widely separated blobs of amplitude to communicate—to have causal dependencies on each other—would be if there were at least some Feynman paths leading to identical configurations from both starting blobs.

Once one entire human brain thinks "Left!", and another entire human brain thinks "Right!", then it's *extremely unlikely* for all of the particles in those brains, and all of the particles in the sensors, and all of the nearby particles that interacted, to coincidentally end up in approximately the same configuration again.

It's around the same likelihood as your brain spontaneously erasing its memories of seeing the sensor and going back to its exact original state; while nearby, an egg unscrambles itself and a hamburger turns back into a cow.

So the decohered amplitude-blobs don't interact. And we never get to talk to our other selves, nor can they speak to us.

Of course, this doesn't mean that the other amplitude-blobs *aren't there any more,* any more than we should think that a spaceship suddenly ceases to exist when it travels over the cosmological horizon (relative to us) of an expanding universe.

(Oh, you thought that post on belief in the implied invisible was part of the Zombie sequence? No, that was covert preparation for the coming series on quantum mechanics.

You can go through line by line and substitute the arguments, in fact.

Remember that the next time some commenter snorts and says, "But what do all these posts have to do with your Artificial Intelligence work?")

Disturbed by the prospect of there being more than one version of you? But as Max Tegmark points out, living in a spatially infinite universe *already* implies that an exact duplicate of you exists somewhere, with probability 1. In all likelihood, that duplicate is no more than $10^{(10^{29})}$ lightyears away. Or $10^{(10^{29})}$ meters away, with numbers of that magnitude it's pretty much the same thing.

(Stop the presses! Shocking news! Scientists have announced that *you* are actually the duplicate of yourself $10^{(10^{29})}$ lightyears away! What you *thought* was "you" is really just a duplicate of you.)

You also get the same Big World effect from the inflationary scenario in the Big Bang, which buds off multiple universes. And both spatial infinity and inflation are more or less standard in the current model of physics. So living in a Big World, which contains more than one person who resembles you, is a bullet you've pretty much got to bite—though none of the guns are certain, physics is firing that bullet at you from at least three different directions.

Maybe later I'll do a post about why you shouldn't panic about the Big World. You shouldn't be drawing many epistemic implications from it, let alone moral implications. As Greg Egan put it, "It all adds up to normality." Indeed, I sometimes think of this as Egan's Law.

Part of *The Quantum Physics Sequence*

Next post: "The Conscious Sorites Paradox"

Previous post: "Where Experience Confuses Physicistss"

The Conscious Sorites Paradox

Followup to: On Being Decoherent

Decoherence is implicit in quantum physics, not an extra postulate on top of it, and quantum physics is continuous. Thus, "decoherence" is not an all-or-nothing phenomenon—there's no sharp cutoff point. Given two blobs, there's a *quantitative* amount of amplitude that can flow into identical configurations between them. This quantum interference diminishes down to an exponentially tiny infinitesimal as the two blobs separate in configuration space.

Asking *exactly when* decoherence takes place, in this continuous process, is like asking when, if you keep removing grains of sand from a pile, it stops being a "heap".

The sand-heap dilemma is known as the Sorites Paradox, after the Greek *soros,* for heap. It is attributed to Eubulides of Miletus, in the 4th century BCE. The moral I draw from this very ancient tale: If you try to draw sharp lines in a continuous process and you end up looking silly, it's your own darn fault.

(Incidentally, I once posed the Sorites Paradox to Marcello Herreshoff, who hadn't previously heard of it; and Marcello answered without the slightest hesitation, "If you remove all the sand, what's left is a 'heap of zero grains'." Now *that's* a computer scientist.)

Ah, but what about when *people* become decoherent? What of the Conscious Sorites Paradox?

What about the case where two blobs of amplitude containing people are interacting, but *only somewhat* - so that there is visibly a degree of causal influence, and visibly a degree of causal independence?

Okay, this interval may work out to less than the Planck time for objects the size of a human brain. But I see that as no excuse to evade the question. In principle we could build a brain that would make the interval longer.

Shouldn't there be some definite fact of the matter as to when one person becomes two people?

Some folks out there would just say "No". I suspect Daniel Dennett would just say "No". Personally, I *wish* I could just say "No", but I'm not that advanced yet. I haven't yet devised a way to express my appreciation of the orderliness of the universe, which doesn't involve counting people in orderly states as compared to disorderly states.

Yet if you insist on an objective population count, *for whatever reason*, you have Soritic problems *whether or not* you delve into quantum physics.

What about the Ebborians? The Ebborians, you recall, have brains like flat sheets of conducting polymer, and when they reproduce, the brain-sheet splits down its thickness. In the beginning, there is definitely one brain; in the end, there is definitely two brains; in between, there is a continuous decrease of causal influence and synchronization. When does one Ebborian become two?

Those who insist on an objective population count in a decoherent universe, must confront *exactly analogous* people-splitting problems in classical physics!

Heck, you could *simulate* quantum physics the way we *currently think* it works, and ask exactly the same question! At the beginning there is one blob, at the end there are two blobs, in this universe we have constructed. So when does the consciousness split, if you think there's an objective answer to that?

Demanding an objective population count is not a reason to object to *decoherence,* as such. Indeed, the last fellow I argued with, ended up agreeing that his objection to decoherence was in fact a fully general objection to functionalist theories of consciousness.

You might be tempted to try sweeping the Conscious Sorites Paradox under a rug, by postulating additionally that the Quantum Spaghetti Monster eats certain blobs of amplitude at exactly the right time to avoid a split.

But then (1) you have to explain exactly when the QSM eats the amplitude, so you aren't avoiding any burden of specification.

And (2) you're requiring the Conscious Sorites Paradox to get answered *by fundamental physics*, rather than being answered or dissolved by a better understanding of consciousness. It's hard to see why taking this stance advances your position, rather than just closing doors.

In fact (3) if you think you have a definite answer to "When are there two people?", then it's hard to see why you can't just give that *same* answer within the *standard* quantum theory instead. The Quantum Spaghetti Monster isn't really *helping* here! For every definite theory with a QSM, there's an equally definite theory with no QSM. This is one of those occasions you have to pay close attention to see the superfluous element of your theory that doesn't really explain anything—it's harder when the theory as a whole does explain something, as quantum physics certainly does.

Above all, (4) you would *still have to explain afterward* what happens with the Ebborians, or what happens to decoherent people in a simulation of quantum physics the way we *currently think* it works. So you *really* aren't avoiding any questions!

It's also worth noting that, in any physics that is continuous (or even any physics that has a very fine-grained discrete cellular level underneath), there are further Conscious Sorites Parodoxes for when people are born and when they die. The bullet plows into your brain, crushing one neuron after another—when exactly are there zero people instead of one?

Does it still seem like the Conscious Sorites Paradox is an objection to *decoherent quantum mechanics,* in particular?

A reductionist would say that the Conscious Sorites Paradox is not a puzzle *for physicists*, because it is a puzzle you get even after the physicists have done their duty, and told us the true laws governing every fundamental event.

As previously touched on, this doesn't imply that consciousness is a matter of nonphysical knowledge. You can know the fundamental laws, and yet lack the computing power to do protein folding. So, too, you can know the fundamental laws; and yet lack the empirical knowledge of the brain's configuration, or miss the insight into higher levels of organization, which would give you a compressed understanding of consciousness.

Or so a materialist would assume. A non-epiphenomenal dualist would say, "Ah, but you *don't* know the true laws of fundamental physics, and when you *do* know them, *that* is where you will find the thundering insight that also resolves questions of consciousness and identity."

It's because I actually *do* acknowledge the possibility that there is some thundering insight in the fundamental physics we don't know yet, that I am not quite willing to say that the Conscious Sorites puzzle is not a puzzle for physicists. Or to look at it another way, the problem might not be *their responsibility,* but that doesn't mean they *can't help.* The physicists might even swoop in and solve it, you never know.

In one sense, there's a clear gap in our interpretation of decoherence: we don't know *exactly* how quantum-mechanical states correspond to the experiences that are (from a Cartesian standpoint) our final experimental results.

But this is something you could say about *all* current scientific theories (at least that I've heard of). And I, for one, am betting that the puzzle-cracking insight comes from a cognitive scientist.

I'm not just saying *tu quoque* (i.e., "Your theory has that problem too!") I'm saying that "But you haven't explained consciousness!" doesn't reasonably seem like the *responsibility* of physicists, or an *objection* to a theory of *fundamental* physics.

An analogy: When a doctor says, "Hey, I think that virus X97 is causing people to drip green slime," you don't respond: "Aha, but you haven't explained the *exact* chain of causality whereby this merely physical virus leads to my *experience* of dripping green slime... so it's probably not a virus that does it, but a bacterium!"

This is another of those sleights-of-hand that you have to pay close attention to notice. Why does a non-viral theory do any *better* than a viral theory at explaining which biological states correspond to which conscious experiences? There is a puzzle here, but how is it a puzzle that provides *evidence* for one *epidemiological* theory *over another*?

It can reasonably seem that, *however consciousness turns out to work*, getting infected with virus X97 *eventually* causes your experience of dripping green slime. You've solved the *medical* part of the problem, as it were, and the remaining mystery is a matter for cognitive science.

Likewise, when a physicist has said that two objects attract each other with a force that goes as the product of the masses and the inverse square of the distance between them, that looks pretty much consistent with the experience of an apple falling on your head. If you have an experience of the apple floating off into space, *that's* a problem for the physicist. But that you have *any experience at all*, is not a problem for *that particular theory of gravity*.

If two blobs of amplitude are no longer interacting, it seems reasonable to regard this as consistent with there being two different brains that have two different experiences, *however consciousness turns out to work*. Decoherence has a pretty reasonable explanation of why you experience a single world *rather than* an entangled one, given that you experience anything at all.

However the whole debate over consciousness turns out, it seems that we see pretty much what we should expect to see given decoherent physics. What's left is a puzzle, but it's not a physicist's responsibility to answer.

...is what I would *like* to say.

But unfortunately there's that whole thing with the squared modulus of the complex amplitude giving the apparent "probability" of "finding ourselves in a particular blob".

That part is a serious puzzle with no obvious answer, which I've discussed already in analogy. I'll shortly be doing an explanation of how the problem looks from within actual quantum theory.

Just remember, if someone presents you with an apparent "answer" to this puzzle, don't forget to check whether the phenomenon still seems mysterious, whether the answer really explains anything, and whether every part of the hypothesis is actively helping.

Part of *The Quantum Physics Sequence*

Next post: "Decoherence is Pointless"

Previous post: "On Being Decoherent"

Decoherence is Pointless

Previously in series: On Being Decoherent

Yesterday's post argued that continuity of decoherence is no bar to accepting it as an explanation for our experienced universe, insofar as it is a physicist's responsibility to explain it. This is a good thing, because the equations say decoherence is continuous, and the equations get the final word.

Now let us consider the continuity of decoherence in greater detail...

On Being Decoherent talked about the decoherence process,

(Human-BLANK) * (Sensor-BLANK) * (Atom-LEFT + Atom-RIGHT)
=>
(Human-BLANK) * ((Sensor-LEFT * Atom-LEFT) + (Sensor-RIGHT * Atom-RIGHT))
=>
(Human-LEFT * Sensor-LEFT * Atom-LEFT) + (Human-RIGHT * Sensor-RIGHT * Atom-RIGHT)

At the end of this process, it may be that your brain in LEFT and your brain in RIGHT are, in a technical sense, communicating—that they have intersecting, interfering amplitude flows.

But the amplitude involved in this process, is the amplitude for a brain (plus all entangled particles) to leap into the other brain's state. This influence may, in a quantitative sense, exist; but it's exponentially tinier than the gravitational influence upon your brain of a mouse sneezing on Pluto.

By the same token, decoherence *always* entangles you with a blob of amplitude density, not a point mass of amplitude. A point mass of amplitude would be a discontinuous amplitude distribution, hence unphysical. The distribution can be very narrow, very sharp—even exponentially narrow—but it can't actually be pointed (nondifferentiable), let alone a point mass.

Decoherence, you might say, is pointless.

If a measuring instrument is sensitive enough to distinguish 10 positions with 10 separate displays on a little LCD screen, it will decohere the amplitude into at least 10 parts, almost entirely noninteracting. In all probability, the instrument is *physically* quite a bit more sensitive (in terms of evolving into different configurations) than what it shows on screen. You would find experimentally that the particle was being decohered (with consequences for momentum, etc.) more than the instrument was designed to measure from a human standpoint.

But there is no such thing as infinite sensitivity in a continuous quantum physics: If you start with blobs of amplitude density, you don't end up with point masses. Liouville's Theorem, which generalizes the second law of thermodynamics, guarantees this: you can't compress probability.

What about if you measure the position of an Atom using an analog Sensor whose dial shows a continuous reading?

Think of probability theory over classical physics:

When the Sensor's dial appears in a particular position, that gives us evidence corresponding to the likelihood function for the Sensor's dial to be in that place, given that the Atom was originally in a particular position. If the instrument is not infinitely sensitive (which it can't be, for numerous reasons), then the likelihood function will be a density distribution, not a point mass. A very sensitive Sensor might have a sharp spike of a likelihood distribution, with density falling off rapidly. If the Atom is *really* at position 5.0121, the likelihood of the Sensor's dial ending up in position 5.0123 might be very small. And so, unless we had overwhelming prior knowledge, we'd conclude a tiny posterior probability that the Atom was so much as 0.0002 millimeters from the Sensor's indicated position. That's probability theory over classical physics.

Similarly in quantum physics:

The blob of amplitude in which you find yourself, where you see the Sensor's dial in some particular position, will have a sub-distribution over actual Atom positions that falls off according to (1) the initial amplitude distribution for the Atom, analogous to the prior; and (2) the amplitude for the Sensor's dial (and the rest of the Sensor!) to end up in our part of configuration space, *if* the Atom started out in that position. (That's the part analogous to the likelihood function.) With a Sensor at all sensitive, the amplitude for the Atom to be in a state noticeably different from what the Sensor shows, will taper off very sharply.

(All these amplitudes I'm talking about are actually densities, N-dimensional integrals over dx dy dz..., rather than discrete flows between discrete states; but you get the idea.)

If there's not a lot of amplitude flowing from initial particle position 5.0150 +/- 0.0001 to configurations where the sensor's LED display reads '5.0123', then the *joint* configuration of (Sensor=5.0123 * Atom=5.0150) ends up with very tiny amplitude.

Part of *The Quantum Physics Sequence*

Next post: "Decoherent Essences"

Previous post: "The Conscious Sorites Paradox"

Decoherent Essences

Followup to: Decoherence is Pointless

In "Decoherence is Pointless", we talked about quantum states such as

(Human-BLANK) * ((Sensor-LEFT * Atom-LEFT) + (Sensor-RIGHT * Atom-RIGHT))

which describes the evolution of a quantum system just after a sensor has measured an atom, and right before a human has looked at the sensor—or before the human has interacted gravitationally with the sensor, for that matter. (It doesn't take much interaction to decohere objects the size of a human.)

But this is only one way of looking at the amplitude distribution—a way that makes it easy to see objects like humans, sensors, and atoms. There are other ways of looking at this amplitude distribution—different choices of basis—that will make the decoherence less obvious.

Suppose that you have the "entangled" (non-independent) state:

(Sensor-LEFT * Atom-LEFT) + (Sensor-RIGHT * Atom-RIGHT)

considering now only the sensor and the atom.

This state looks nicely diagonalized—separated into two distinct blobs. But by linearity, we can take apart a quantum amplitude distribution any way we like, and get the same laws of physics back out. So in a different basis, we might end up writing (Sensor-LEFT * Atom-LEFT) as:

(0.5(Sensor-LEFT + Sensor-RIGHT) + 0.5(Sensor-LEFT - Sensor-RIGHT)) *
(0.5(Atom-RIGHT + Atom-LEFT) - 0.5(Atom-RIGHT - Atom-LEFT))

(Don't laugh. There are legitimate reasons for physicists to reformulate their quantum representations in weird ways.)

The result works out the same, of course. But if you view the entangled state in a basis made up of linearly independent components like (Sensor-LEFT - Sensor-RIGHT) and (Atom-RIGHT - Atom-LEFT), you see a differently shaped amplitude distribution, and it may not *look* like the blobs are separated.

Oh noes! The *decoherence has disappeared!*

...or that's the source of a huge academic literature asking, "Doesn't the decoherence interpretation require us to choose a preferred basis?"

To which the short answer is: Choosing a basis is an isomorphism; it doesn't change any experimental predictions. Decoherence is an experimentally visible phenomenon or we would not have to protect quantum computers from it. You can't protect a quantum computer by "choosing the right basis" instead of using environmental shielding. Likewise, looking at splitting humans from another angle won't make their decoherence go away.

But this is an issue that you're bound to encounter if you pursue quantum mechanics, especially if you talk to anyone from the Old School, and so it may be worth expanding on this reply.

After all, if the short answer is as obvious as I've made it sound, then why, oh why, would anyone ever think you *could* eliminate an experimentally visible phenomenon like decoherence, by isomorphically reformulating the mathematical representation of quantum physics?

That's a bit difficult to describe in one mere blog post. It has to do with history. You know the warning I gave about dragging *history* into explanations of QM... so consider yourself warned: Quantum mechanics is simpler than the arguments we have about quantum mechanics. But here, then, is the history:

Once upon a time,

Long ago and far away, back when the theory of quantum mechanics was first being developed,

No one had ever thought of decoherence. The question of why a human researcher only saw one thing at a time, was a Great Mystery with no obvious answer.

You had to *interpret* quantum mechanics to get an answer back out of it. Like reading meanings into an oracle. And there were different, competing interpretations. In one popular interpretation, when you "measured" a system, the Quantum Spaghetti Monster would eat all but one blob of amplitude, at some unspecified time that was exactly right to give you whatever experimental result you actually saw.

Needless to say, this "interpretation" wasn't *in* the quantum equations. You had to add in the *extra* postulate of a Quantum Spaghetti Monster *on top*, *additionally* to the differential equations you had fixed experimentally for describing how an amplitude distribution evolved.

Along came Hugh Everett and said, "Hey, maybe the formalism just describes the way the universe *is,* without any need to 'interpret' it."

But people were so used to adding *extra* postulates to interpret quantum mechanics, and so *unused* to the idea of amplitude distributions as real, that they couldn't see this new "interpretation" as anything *except* an additional Decoherence Postulate which said:

"When clouds of amplitude become separated enough, the Quantum Spaghetti Monster steps in and *creates a new world* corresponding to each cloud of amplitude."

So then they asked:

"Exactly how separated do two clouds of amplitude have to be, quantitatively speaking, in order to invoke the instantaneous action of the Quantum Spaghetti Monster? And in which basis does the Quantum Spaghetti Monster measure separation?"

But, in the *modern* view of quantum mechanics—which is accepted by everyone except for a handful of old fogeys who may or may not still constitute a numerical majority—well, as David Wallace puts it:

> "If I were to pick one theme as central to the tangled development of the Everett interpretation of quantum mechanics, it would probably be: *the formalism is to be*

left alone."

Decoherence is not an extra phenomenon. Decoherence is not something that has to be proposed additionally. There is no Decoherence Postulate *on top of* standard QM. It is implicit in the standard rules. Decoherence is just what happens *by default,* given the standard quantum equations, unless the Quantum Spaghetti Monster intervenes.

Some still claim that the quantum equations are unreal—a mere model that just happens to give amazingly good experimental predictions. But then decoherence is what happens to the particles in the "unreal model", if you apply the rules universally and uniformly. It is *denying* decoherence that requires you to postulate an extra law of physics, or an act of the Quantum Spaghetti Monster.

(Needless to say, no one has ever observed a quantum system behaving coherently, when the untouched equations say it should be decoherent; nor observed a quantum system behaving decoherently, when the untouched equations say it should be coherent.)

If you're talking about anything that isn't in the equations, you must not be talking about "decoherence". The standard equations of QM, uninterpreted, do not talk about a Quantum Spaghetti Monster creating new worlds. So if you ask when the Quantum Spaghetti Monster creates a new world, and you can't answer the question just by looking at the equations, then you must not be talking about "decoherence". QED.

Which basis you use in your calculations makes no difference to standard QM. "Decoherence" is a phenomenon implicit in standard QM. Which basis you use makes no difference to "decoherence". QED.

Changing your view of the configuration space can change your view of the blobs of amplitude, but ultimately the same physical events happen for the same causal reasons. Momentum basis, position basis, position basis with a different relativistic space of simultaneity—it doesn't matter to QM, ergo it doesn't matter to decoherence.

If this were not so, you could do an experiment to find out which basis was the right one! Decoherence is an experimentally visible phenomenon—that's why we have to protect quantum computers from it.

Ah, but then where is the decoherence in

> (0.5(Sensor-LEFT + Sensor-RIGHT) + 0.5(Sensor-LEFT - Sensor-RIGHT)) * (0.5(Atom-RIGHT + Atom-LEFT) - 0.5(Atom-RIGHT - Atom-LEFT)) + (0.5(Sensor-LEFT + Sensor-RIGHT) - 0.5(Sensor-LEFT - Sensor-RIGHT)) * (0.5(Atom-RIGHT + Atom-LEFT) + 0.5(Atom-RIGHT - Atom-LEFT))

?

The decoherence is still *there.* We've just made it harder for a human to *see,* in the new *representation*.

The main interesting fact I would point to, about this amazing new representation, is that we can no longer calculate its evolution with *local causality.* For a technical definition of what I mean by "causality" or "local", see Judea Pearl's *Causality*. Roughly, to compute the evolution of an amplitude cloud in a *locally causal* basis, each point in configuration space only has to look at its infinitesimal neighborhood to determine its instantaneous change. As I understand quantum physics—I pray to some physicist to correct me if I'm wrong—the position basis is local in this sense.

(Note: It's okay to pray to physicists, because physicists actually exist and can answer prayers.)

However, once you start breaking down the amplitude distribution into components like (Sensor-RIGHT—Sensor-LEFT), then the flow of amplitude, and the flow of causality, is no longer *local* within the new configuration space. You can still calculate it, but you have to use nonlocal calculations.

In essence, you've obscured the chessboard by subtracting the queen's position from the king's position. All the information is still there, but it's harder to *see*.

When it comes to talking about whether "decoherence" has occurred in the quantum state of a human brain, what should intuitively matter is questions like, "Does the event of a neuron firing in Human-LEFT have a noticeable influence on whether a corresponding neuron fires in Human-RIGHT?" You can choose a basis that will mix up the amplitude for Human-LEFT and Human-RIGHT, *in your calculations.* You cannot, however, *choose a basis* that makes a human neuron fire when it would not otherwise have fired; any more than you can *choose a basis* that will protect a quantum computer without the trouble of shielding, or *choose a basis* that will make apples fall upward instead of down, etcetera.

The formalism is to be left alone! If you're talking about anything that isn't in the equations, you're not talking about decoherence! Decoherence is part of the invariant essence that doesn't change no matter how you spin your basis—just like the physical reality of apples and quantum computers and brains.

There may be a kind of Mind Projection Fallacy at work here. A tendency to see the basis itself as real—something that a Quantum Spaghetti Monster might come in and act upon—because you spend so much time calculating with it.

In a strange way, I think, this sort of jump is actively encouraged by the Old School idea that the amplitude distributions *aren't real.* If you were told the amplitude distributions were physically real, you would (hopefully) get in the habit of looking past mere *representations*, to *see through* to some invariant essence inside—a reality that doesn't change no matter how you choose to represent it.

But people are told the amplitude distribution is not real. The calculation itself is *all there is*, and has no virtue save its *mysteriously excellent* experimental predictions. And so there is no point in trying to *see through* the calculations to something within.

Then why *not* interpret all this talk of "decoherence" in terms of an arbitrarily chosen basis? Isn't that all there is to *interpret*—the calculation that you did in some representation or another? Why not complain, if—having thus *interpreted* decoherence—the separatedness of amplitude blobs seems to change, when you change the basis? Why try to see through to the neurons, or the flows of causality, when you've been told that the calculations are all?

(This notion of *seeing through*—looking for an essence, and not being distracted by surfaces—is one that pops up again and again, and again and again and again, in the Way of Rationality.)

Another possible problem is that the calculations are crisp, but the essences inside them are not. Write out an integral, and the symbols are digitally distinct. But an entire apple, or an entire brain, is larger than anything you can handle formally.

Yet the form of that crisp integral will change when you change your basis; and that sloppy real essence will remain invariant. Reformulating your equations won't remove a dagger, or silence a firing neuron, or shield a quantum computer from decoherence.

The phenomenon of decoherence within brains and sensors, may not be any more crisply defined than the brains and sensors themselves. Brains, as high-level phenomena, don't always make a clear appearance in fundamental equations. Apples aren't crisp, you might say.

For historical reasons, some Old School physicists are accustomed to QM being "interpreted" using extra postulates that involve crisp actions by the Quantum Spaghetti Monster—eating blobs of amplitude at a particular instant, or creating worlds as a particular instant. Since the equations aren't supposed to be *real,* the sloppy borders of real things are not looked for, and the crisp calculations are primary. This makes it hard to see through to a real (but uncrisp) phenomenon among real (but uncrisp) brains and apples, invariant under changes of crisp (but arbitrary) representation.

Likewise, any change of representation that makes apples harder to see, or brains harder to see, will make decoherence within brains harder to see. But it won't change the apple, the brain, or the decoherence.

As always, any philosophical problems that result from "brain" or "person" or "consciousness" not being crisply defined, are not the responsibility of physicists or of any fundamental physical theory. Nor are they limited to decoherent quantum physics particularly, appearing likewise in splitting brains constructed under classical physics, etcetera.

Coming tomorrow (hopefully): *The Born Probabilities*, aka, that mysterious thing we do with the squared modulus to get our experimental predictions.

Part of *The Quantum Physics Sequence*

Next post: "The Born Probabilities"

Previous post: "Decoherence is Pointless"

The Born Probabilities

Previously in series: Decoherence is Pointless
Followup to: Where Experience Confuses Physicists

One serious mystery of decoherence is where the Born probabilities come from, or even what they are probabilities *of.* What does the integral over the squared modulus of the amplitude density have to do with anything?

This was discussed by analogy in "Where Experience Confuses Physicists", and I won't repeat arguments already covered there. I will, however, try to convey exactly what the puzzle *is,* in the real framework of quantum mechanics.

A professor teaching undergraduates might say: "The probability of finding a particle in a particular position is given by the squared modulus of the amplitude at that position."

This is oversimplified in several ways.

First, for continuous variables like position, amplitude is a density, not a point mass. You integrate over it. The integral over a single point is zero.

(Historical note: If "observing a particle's position" invoked a mysterious event that squeezed the amplitude distribution down to a delta point, or flattened it in one subspace, this would give us a different future amplitude distribution from what decoherence would predict. All interpretations of QM that involve quantum systems jumping into a point/flat state, which are both testable and have been tested, have been falsified. The universe does not have a "classical mode" to jump into; it's all amplitudes, all the time.)

Second, a single observed particle doesn't *have* an amplitude distribution. Rather the system containing yourself, plus the particle, plus the rest of the universe, may approximately *factor* into the multiplicative product of (1) a sub-distribution over the particle position and (2) a sub-distribution over the rest of the universe. Or rather, the particular blob of amplitude that you happen to be in, can factor that way.

So what could it mean, to associate a "subjective probability" with a component of one *factor* of a combined amplitude distribution that happens to factorize?

Recall the physics for:

(Human-BLANK * Sensor-BLANK) * (Atom-LEFT + Atom-RIGHT)
=>
(Human-LEFT * Sensor-LEFT * Atom-LEFT) + (Human-RIGHT * Sensor-RIGHT * Atom-RIGHT)

Think of the whole process as reflecting the good-old-fashioned distributive rule of algebra. The initial state can be decomposed—note that this is an *identity*, not an evolution—into:

(Human-BLANK * Sensor-BLANK) * (Atom-LEFT + Atom-RIGHT)
=

(Human-BLANK * Sensor-BLANK * Atom-LEFT) + (Human-BLANK * Sensor-BLANK * Atom-RIGHT)

We assume that the distribution factorizes. It follows that the term on the left, and the term on the right, initially differ only by a multiplicative factor of Atom-LEFT vs. Atom-RIGHT.

If you were to *immediately* take the multi-dimensional integral over the squared modulus of the amplitude density of that whole system,

Then the *ratio* of the all-dimensional integral of the squared modulus over the left-side term, *to* the all-dimensional integral over the squared modulus of the right-side term,

Would equal the *ratio* of the lower-dimensional integral over the squared modulus of the Atom-LEFT, *to* the lower-dimensional integral over the squared modulus of Atom-RIGHT,

For essentially the same reason that if you've got (2 * 3) * (5 + 7), the ratio of (2 * 3 * 5) to (2 * 3 * 7) is the same as the ratio of 5 to 7.

Doing an integral over the squared modulus of a complex amplitude distribution in N dimensions doesn't change that.

There's also a rule called "unitary evolution" in quantum mechanics, which says that quantum evolution never changes the *total* integral over the squared modulus of the amplitude density.

So if you assume that the initial left term and the initial right term evolve, without overlapping each other, into the final LEFT term and the final RIGHT term, they'll have the same ratio of integrals over etcetera as before.

What all this says is that,

If some roughly independent Atom has got a blob of amplitude on the left of its factor, and a blob of amplitude on the right,

Then, after the Sensor senses the atom, and *you* look at the Sensor,

The integrated squared modulus of the whole LEFT blob, and the integrated squared modulus of the whole RIGHT blob,

Will have the same ratio,

As the ratio of the squared moduli of the original Atom-LEFT and Atom-RIGHT components.

This is why it's important to remember that apparently individual particles have amplitude distributions that are *multiplicative factors* within the total *joint* distribution over *all* the particles.

If a whole gigantic human experimenter made up of quintillions of particles,

Interacts with one teensy little atom whose amplitude *factor* has a big bulge on the left and a small bulge on the right,

Then the resulting amplitude distribution, in the *joint* configuration space, Has a big amplitude blob for "human sees atom on the left", and a small amplitude blob of "human sees atom on the right".

And what *that* means, is that the Born probabilities seem to be about *finding yourself in a particular blob,* not *the particle being in a particular place.*

But what does the integral over squared moduli have to do with anything? On a straight reading of the data, you would always find yourself in both blobs, every time. How can you find yourself in one blob with greater probability? What are the Born probabilities, probabilities *of*? Here's the map—where's the territory?

I don't know. It's an open problem. Try not to go funny in the head about it.

This problem is even worse than it looks, because the squared-modulus business is *the only non-linear rule in all of quantum mechanics.* Everything else—*everything* else—obeys the linear rule that the evolution of amplitude distribution A, plus the evolution of the amplitude distribution B, equals the evolution of the amplitude distribution A + B.

When you think about the weather in terms of clouds and flapping butterflies, it may not *look* linear on that higher level. But the amplitude distribution for weather (plus the rest of the universe) is linear on the only level that's fundamentally real.

Does this mean that the squared-modulus business *must* require additional physics beyond the linear laws we know—that it's *necessarily* futile to try to derive it on any higher level of organization?

But even this doesn't follow.

Let's say I have a computer program which computes a sequence of positive integers that encode the successive states of a sentient being. For example, the positive integers might describe a Conway's-Game-of-Life universe containing sentient beings (Life is Turing-complete) or some other cellular automaton.

Regardless, this sequence of positive integers represents the time series of a discrete universe containing conscious entities. Call this sequence Sentient(n).

Now consider another computer program, which computes the negative of the first sequence: -Sentient(n). If the computer running Sentient(n) instantiates conscious entities, then so too should a program that computes Sentient(n) and then negates the output.

Now I write a computer program that computes the sequence {0, 0, 0...} in the obvious fashion.

This sequence happens to be equal to the sequence Sentient(n) + -Sentient(n).

So does a program that computes {0, 0, 0...} necessarily instantiate as many conscious beings as both Sentient programs put together?

Admittedly, this isn't an exact analogy for "two universes add linearly and cancel out". For that, you would have to talk about a universe with linear physics, which excludes Conway's Life. And then in this linear universe, two states of the world both containing conscious observers—world-states equal but for their opposite sign—would have to cancel out.

It doesn't work in Conway's Life, but it works in our own universe! Two quantum amplitude distributions can contain components that *cancel each other out,* and this demonstrates that the number of conscious observers in *the sum of two distributions*, need not equal the sum of conscious observers *in each distribution separately.*

So it actually *is* possible that we could pawn off *the only non-linear phenomenon in all of quantum physics* onto a better understanding of consciousness. The question "How many conscious observers are contained in an evolving amplitude distribution?" has obvious reasons to be non-linear.

(!)

Robin Hanson has made [a suggestion along these lines].

(!!)

Decoherence is a physically continuous process, and the interaction between LEFT and RIGHT blobs may never actually become *zero.*

So, Robin suggests, any blob of amplitude which gets small enough, becomes dominated by stray flows of amplitude from many larger worlds.

A blob which gets too small, cannot sustain coherent inner interactions—an internally driven chain of cause and effect—because the amplitude flows are dominated from outside. Too-small worlds fail to support computation and consciousness, or are ground up into chaos, or merge into larger worlds.

Hence Robin's cheery phrase, "mangled worlds".

The cutoff point will be a function of the squared modulus, because unitary physics preserves the squared modulus under evolution; if a blob has a certain total squared modulus, future evolution will preserve that integrated squared modulus so long as the blob doesn't split further. You can think of the squared modulus as the amount of amplitude available to internal flows of causality, as opposed to outside impositions.

The seductive aspect of Robin's theory is that quantum physics wouldn't need *interpreting.* You wouldn't have to stand off beside the mathematical structure of the universe, and say, "Okay, now that you're finished computing all the mere numbers, I'm furthermore telling you that the squared modulus is the 'degree of existence'." Instead, when you run any program that computes the *mere numbers,* the program *automatically* contains people who experience the same physics we do, with the same probabilities.

A major problem with Robin's theory is that it seems to predict things like, "We should find ourselves in a universe in which ~~lots of~~ very few decoherence events have already taken place," which tendency does not seem especially apparent.

The main thing that would support Robin's theory would be if you could show from first principles that mangling does happen; and that the cutoff point is somewhere around the median amplitude density (the point where half the total amplitude density is in worlds above the point, and half beneath it), which is apparently what it takes to reproduce the Born probabilities in any particular experiment.

What's the probability that Hanson's suggestion is right? I'd put it under fifty percent, which I don't think Hanson would disagree with. It would be much lower if I knew of a single alternative that seemed equally... reductionist.

But *even if* Hanson is wrong about what causes the Born probabilities, I would guess that the final answer still comes out *equally non-mysterious*. Which would make me feel very silly, if I'd embraced a more mysterious-seeming "answer" up until then. As a general rule, it is questions that are mysterious, not answers.

When I began reading Hanson's paper, my initial thought was: *The math isn't beautiful enough to be true.*

By the time I finished processing the paper, I was thinking: *I don't know if this is the real answer, but the real answer has got to be at least this normal.*

This is still my position today.

Part of *The Quantum Physics Sequence*

Next post: "Decoherence as Projection"

Previous post: "Decoherent Essences"

Decoherence as Projection

Previously in series: The Born Probabilities

Heisensplit

In "The So-Called Heisenberg Uncertainty Principle" we got a look at how decoherence can affect the apparent surface properties of objects: By measuring whether a particle is to the left or right of a dividing line, you can decohere the part of the amplitude distribution on the left with the part on the right. Separating the amplitude distribution into two parts affects its future evolution (within each component) because the two components can no longer interfere with each other.

Yet there are more subtle ways to take apart amplitude distributions than by splitting the position basis down the middle. And by exploring this, we rise further up the rabbit hole.

(Remember, the classical world is Wonderland, the quantum world is reality. So when you get deeper into quantum physics, you are going *up* the rabbit hole, not *down* the rabbit hole.)

Light has a certain quantum property called "polarization". Of course, all known physical properties are "quantum properties", but in this case I mean that polarization neatly exhibits fundamental quantum characteristics. I mention this, because polarization is often considered part of "classical" optics. Why? Because the quantum nature of polarization is so simple that it was accidentally worked out as part of classical mechanics, back when light was thought to be a wave.

(Nobody tell the marketers, though, or we'll be wearing "quantum sunglasses".)

I don't usually begin by discussing the astronomically high-level phenomena of macroscopic physics, but in this case, I think it will be helpful to begin with a human-world example...

I hand you two little sheets of semi-transparent material, looking perhaps like dark plastic, with small arrows drawn in marker along the sides. When you hold up one of the sheets in front of you, the scene through it is darker—it blocks some of the light.

Now you hold up the second sheet in front of the first sheet...

When the two arrows are aligned, pointing in the same direction, the scene is no darker than before—that is, the two sheets in series block the same amount of light as the first sheet alone.

But as you rotate the second sheet, so that the two arrows point in increasingly different directions, the world seen through both sheets grows darker. When the arrows are at 45° angles, the world is half as bright as when you were only holding up one sheet.

When the two arrows are perpendicular (90°) the world is completely black.

2polaroids

Then, as you continue rotating the second sheet, the world gets lighter again. When the two arrows point in opposite directions, again the lightness is the same as for only one sheet.

Clearly, the sheets are selectively blocking light. Let's call the sheets "polarized filters".

Now, you might reason something like this: "Light is built out of two components, an up-down component and a left-right component. When you hold up a single filter, with the arrow pointing up, it blocks out the left-right component of light, and lets only the up-down component through. When you hold up another filter in front of the first one, and the second filter has the arrow pointing to the left (or the right), it only allows the left-right component of light, and we already blocked that out, so the world is completely dark. And at intermediate angles, it, um, blocks some of the light that wasn't blocked already."

So I ask, "Suppose you've already put the second filter at a 45° angle to the first filter. Now you put up the third filter at a 45° angle to the second filter. What do you expect to see?"

"That's ambiguous," you say. "Do you mean the third filter to end up at a 0° angle to the first filter, or a 90° angle to the first filter?"

"Good heavens," I say, "I'm surprised I forgot to specify that! Tell me what you expect either way."

"If the third filter is at a 0° angle to the first filter," you say, "It won't block out anything the first filter hasn't blocked already. So we'll be left with the half-light world, from the second filter being at a 45° angle to the first filter. And if the third filter is at a 90° angle to the first filter, it will block out everything that the first filter didn't block, and the world will be completely dark."

I hand you a third filter. "Go ahead," I say, "Try it."

First you set the first filter at 0° and the second filter at 45°, as your reference point. Half the light gets through.

3polaroids

Then you set the first filter at 0°, the second filter at 45°, and the third filter at 0°. Now one quarter of the light gets through.

"Huh?" you say.

"Keep going," I reply.

With the first filter at 0°, the second filter at 45°, and the third filter at 90°, one quarter of the light goes through. Again.

"Umm..." you say. You quickly take out the second filter, and find that the world goes completely dark. Then you put in the second filter, again at 45°, and the world resumes one-quarter illumination.

Further investigation quickly verifies that all three filters seem to have the same basic properties—it doesn't matter what order you put them in.

"All right," you say, "that just seems weird." You pause. "So it's probably something quantum."

Indeed it is.

Though light may seem "dim" or "bright" at the macroscopic level, you can't split it up indefinitely; you can always send a single photon into the series of filters, and ask what happens to that single photon.

As you might suspect, if you send a single photon through the succession of three filters, you will find that—assuming the photon passes the first filter (at 0°)—the photon is observed to pass the second filter (at 45°) with 50% probability, and, if the photon does pass the second filter, then it seems to pass the third filter (at 90°) with 50% probability.

The appearance of "probability" in deterministic amplitude evolutions, as we now know, is due to decoherence. Each time a photon was blocked, some other you saw it go through. Each time a photon went through, some other you saw it blocked.

But what exactly is getting decohered? And why does an intervening second filter at 45°, let some photons pass that would otherwise be blocked by the 0° filter plus the 90° filter?

First: We can represent the polarization of light as a complex amplitude for up-down plus a complex amplitude for left-right. So polarizations might be written as (1 ; 0) or (0 ; -i) or (√.5 ; √.5), with the units (up-down ; left-right). It is more customary to write these as column vectors, but row vectors are easier to type.

(Note that I say that this is a way to "represent" the polarization of light. There's nothing magical about picking up-down vs. left-right, instead of upright-downleft vs. upleft-downright. The vectors above are written in an arbitrary but convenient basis. This will become clearer.)

Let's say that the first filter has its little arrow pointing right. This *doesn't* mean that the filter blocks any photon whose polarization is not *exactly* (0 ; 1) or a multiple thereof. But it nonetheless happens that all the photons which we see leave the first filter, will have a polarization of (0 ; 1) or some irrelevantly complex multiple thereof. Let's just take this for granted, for the moment. Past the first filter at 0°, we're looking at a stream of photons purely polarized in the left-right direction.

Now the photons hit a second filter. Let's say the second filter is at a 30° angle to the first—so the arrow written on the second filter is pointing 30° above the horizontal.

Then each photon has a 25% probability of being blocked at the second filter, and a 75% probability of going through.

How about if the second filter points to 20° above the horizontal? 12% probability of blockage, 88% probability of going through.

45°, 50/50.

The general rule is that the probability of being blocked is the squared sine of the angle, and the probability of going through is the squared cosine of the angle.

Why?

First, remember two rules we've picked up about quantum mechanics: The evolution of quantum systems is linear and unitary. When an amplitude distribution breaks into parts that then evolve separately, the components must (1) add to the original distribution and (2) have squared moduli adding to the squared modulus of the original distribution.

So now let's consider the photons leaving the first filter, with "polarizations", quantum states, of (0 ; 1).

To understand what happens when the second filter is set at a 45° angle, we observe... and think of this as a purely abstract statement about 2-vectors... that:

(0 ; 1) = (.5 ; .5) + (-.5 ; .5)

Polardecomp

Okay, so the two vectors on the right-hand-side sum to (0 ; 1) on the left-hand-side.

But what about the squared modulus? Just because two vectors sum to a third, doesn't mean that the squares of the first two vectors' lengths sum to the square of the third vector's length.

The *squared* length of the vector (.5 ; .5) is $(.5)^2 + (.5)^2$ = .25 + .25 = 0.5. And likewise the squared length of the vector (-.5 ; .5) is $(-.5)^2 + (.5)^2 = 0.5$. The sum of the squares is 0.5 + 0.5 = 1. Which matches the squared length of the vector (0 ; 1).

Polarpythagorean

So when you decompose (0 ; 1) into (.5 ; .5) + (-.5 ; .5), this obeys both linearity and unitarity: The two parts sum to the original, and the squared modulus of the parts sums to the squared modulus of the original.

When you interpose the second filter at an angle of 45° from the first, it decoheres the incoming amplitude of (0 ; 1) into an amplitude of (.5 ; .5) for being transmitted and an amplitude of (-.5 ; .5) for being blocked. Taking the squared modulus of the amplitudes gives us the observed Born probabilities, i.e. fifty-fifty.

What if you interposed the second filter at an angle of 30° from the first? Then that would decohere the incoming amplitude vector of (0 ; 1) into the vectors (.433 ; .75) and (-.433, .25). The squared modulus of the first vector is .75, and the squared modulus of the second vector is .25, again summing to one.

A polarized filter *projects* the incoming amplitude vector into the two sides of a right triangle that sums to the original vector, and *decoheres* the two components. And so, under Born's rule, the transmission and absorption probabilities are given by the Pythagorean Theorem.

Polar3060

(!)

3polaroids_2

A filter set at 0° followed by a filter set at 90° will block all light—any photon that emerges from the first filter will have an amplitude vector of (0 ; 1), and the component in the direction of (1 ; 0) will be 0. But suppose that instead you put an intermediate filter at 45°. This will decohere the vector of (0 ; 1) into a transmission vector of (.5 ; .5) and an absorption amplitude of (-.5 ; .5).

A photon that *is* transmitted through the 45° filter will have a polarization amplitude vector of (.5 ; .5). (The (-.5 ; .5) component is decohered into another world where you see the photon absorbed.)

This photon then hits the 90° filter, whose transmission amplitude is the component in the direction of (1 ; 0), and whose absorption amplitude is the component in the direction of (0 ; 1). (.5 ; .5) has a component of (.5 ; 0) in the direction of (1 ; 0) and a component of (0 ; .5) in the direction of (0 ; 1). So it has an amplitude of (.5 ; 0) to make it through both filters, which translates to a Born probability of .25.

Likewise if the second filter is at -45°. Then it decoheres the incoming (0 ; 1) into a transmission amplitude of (-.5 ; .5) and an absorption amplitude of (.5 ; .5). When (-.5 ; .5) hits the third filter at 90°, it has a component of (-.5 ; 0) in the direction of (1 ; 0), and because these are complex numbers we're talking about, (-.5 ; 0) has a squared modulus of 0.25, that is, 25% probability to go through both filters.

It may seem surprising that putting in an extra filter causes more photons to go through, even when you send them one at a time; but that's quantum physics for you.

"But wait," you say, "Who needs the second filter? Why not just use math? The initial amplitude of (0 ; 1) breaks into an amplitude of (-.5 ; .5) + (.5 ; .5) whether or not you have the second filter there. By linearity, the evolution of the parts should equal the evolution of the whole."

Yes, indeed! So, with no second filter—just the 0° filter and the 90° filter—here's how we'd do that analysis:

First, the 0° filter decoheres off all amplitude of any incoming photons except the component in the direction of (0 ; 1). Now we look at the photon—which has some amplitude (0 ; x) that we've implicitly been renormalizing to (0 ; 1)—and, in a purely mathematical sense, break it up into (.5x ; .5x) and (-.5x ; .5x) whose squared moduli will sum to x^2.

Now first we consider the (.5x ; .5x) component; it strikes the 90° filter which transmits the component (.5x ; 0) and absorbs the (0 ; .5x) component.

Next we consider the (-.5x ; .5x) component. It also strikes the 90° filter, which transmits the component (-.5x ; 0) and absorbs the component (0 ; .5x).

Polarbreakdown

Since no other particles are entangled, we have some identical configurations here: Namely, the two configurations where the photon is transmitted, and the two configurations where the photon is absorbed.

Summing the amplitude vectors of (.5x ; 0) and (-.5x ; 0) for transmission, we get a total amplitude vector of (0 ; 0).

Summing the amplitude vectors of (0 ; .5x) and (0 ; .5x) for absorption, we get an absorption amplitude of (0 ; x).

So all photons that make it through the first filter are blocked.

Remember Experiment 2 from way back when? *Opening up a new path* to a detector can cause *fewer* photons to be detected, because the new path has an amplitude of opposite sign to some existing path, and they cancel out.

In an exactly analogous manner, having a filter that sometimes absorbs photons, can cause more (individual) photons to get through a series of filters. Think of it as decohering off a component of the amplitude that would otherwise destructively interfere with another component.

A word about choice of basis:

You could just as easily create a new basis in which (1 ; 0) = (.707 ; .707) and (0 ; 1) = (.707 ; -.707). This is the upright-downleft and upleft-downright basis of which I spoke before. .707 = √.5, so the basis vectors individually have length 1; and the dot product of the two vectors is 0, so they are orthogonal. That is, they are "orthonormal".

The new basis is just as valid as a compass marked NW, NE, SE, SW instead of N, E, S, W. There isn't an absolute basis of the photon's polarization amplitude vector, any more than there's an absolute three-coordinate system that describes your location in space. Ideally, you should see the photon's polarization as a purely abstract 2-vector in complex space.

(One of my great "Ahas!" while reading the Feynman Lectures was the realization that, rather than a 3-vector being made out of an ordered list of 3 scalars, a 3-vector was just a pure mathematical object in a vector algebra. If you wanted to take the 3-vector apart for some reason, you could generate an arbitrary orthonormal basis and get 3 scalars that way. In other words, you didn't build the vector space by composing scalars—you built the decomposition from within the vector space. I don't know if that makes any sense to my readers out there, but it was the great turning point in my relationship with linear algebra.)

Oh, yes, and what happens if you have a complex polarization in the up-down/left-right basis, like (.707*i* ; .707)? Then that corresponds to "circular polarization" or "elliptical polarization". All the polarizations I've been talking about are "linear polarizations", where the amplitudes in the up-down/left-right basis happen to be real numbers.

When things decohere, they decohere into pieces that add up to the original (linearity) and whose squared moduli add up to the original squared modulus (unitarity). If the squared moduli of the pieces add up to the original squared modulus, this implies the pieces are *orthogonal*—that the components have inner products of zero with each other. That is why the title of this blog post is "Decoherence as Projection".

A word about how *not* to see this whole business of polarization:

Some ancient textbooks will say that when you send a photon through a 0° filter, and it goes through, you've learned that the photon is polarized left-right rather than up-down. Now you measure it with another filter at a 45° angle, and it goes through, so you've learned that the photon is polarized upright-downleft rather than upleft-downright. And (says the textbook) this second measurement "destroys" the first, so that if you want to know the up-down / left-right polarization, you'll have to measure it all over again.

Because you can't know both at the same time.

And some of your more strident ancient textbooks will say something along the lines of: the up-down / left-right polarization *no longer exists* after the photon goes through the 45° filter. It's not just unknown, it *doesn't exist*, and—

(you might think that wasn't too far from the truth)

—*it is meaningless to even talk about it.*

Okay. That's going a bit too far.

There are ways to use a polarizer to split a beam into two components, rather than absorbing a component and transmitting a component.

Suppose you first send the photons through a 0° filter. Then you send them through a 45° splitter. Then you *recombine the beams*. Then you send the photons through a 0° filter again. All the photons that made it past the first filter, will make it past the third filter as well. Because, of course, you've put the components back together again, and (.5 ; .5) + (-.5 ; .5) = (0 ; 1).

This doesn't seem to square with the idea that measuring the 45° polarization *automatically destroys* the up-down/left-right polarization, that it *isn't even meaningful* to talk about it.

Of course the one will say, "Ah, but now you no longer *know* which path the photon took past the splitter. When you recombined the beams, you unmeasured the photon's 45° polarization, and the original 0° polarization popped back into existence again, and it was always meaningful to talk about it."

O RLY?

Anyway, that's all talk about classical surface appearances, and you've *seen* the underlying quantum reality. A photon with polarization of (-.707 ; .707) has a component of (.707 ; 0) in the up-down direction and a component of (0 ; .707) in the left-right direction. If you happened to feed it into an apparatus that decohered these two components—like a polarizing filter—then you would be able to predict the decoherent evolution as a deterministic fact about the amplitude distribution, and the Born probabilities would (deterministically if mysteriously) come out to 50/50.

Now someone comes along and says that the result of this measurement you may or may not perform, *doesn't exist* or, better yet, *isn't meaningful*.

It's hard to see what this startling statement could *mean*, let alone how it could improve your experimental predictions. How would you falsify it?

Part of *The Quantum Physics Sequence*

Next post: "Entangled Photons"

Previous post: "The Born Probabilities"

Entangled Photons

Previously in series: Decoherence as Projection

Today we shall analyze the phenomenon of "entangled particles". We're going to make heavy use of polarized photons here, so you'd better have read yesterday's post.

If a particle at rest decays into two other particles, their *net* momentum must add up to 0. The two new particles may have amplitudes to head off in all directions, but in each *joint* configuration, the directions will be opposite.

By a similar method you can produce two entangled photons which head off in opposite directions, and are guaranteed to be polarized oppositely (at right angles to each other), but with a 50% prior probability of going through any given polarized filter.

You might think that this would involve amplitudes over a continuous spectrum of opposite configurations—an amplitude for photon A to be polarized at 0° and for photon B to be polarized at 90°, an amplitude for A to be 1° polarized and for B to be 91° polarized, etc. But in fact it's possible to describe the quantum state "unknown but opposite polarizations" much more compactly.

First, note that the two photons are heading off in opposite directions. This justifies calling one photon A and one photon B; they aren't likely to get their identities mixed up.

As with yesterday, the polarization state (1 ; 0) is what passes a 90° filter. The polarization state (0 ; 1) is what passes a 0° filter. (1 ; 0) is polarized up-down, (0 ; 1) is polarized left-right.

If A is in the polarization state (1 ; 0), we'll write that as A=(1 ; 0).

If A=(1 ; 0) and B=(0 ; 1), we'll write that as

[A=(1 ; 0) ∧ B=(0 ; 1)]

The state for "unknown opposite polarization" can be written as:

√(1/2) * ([A=(1 ; 0) ∧ B=(0 ; 1)] - [A=(0 ; 1) ∧ B=(1; 0)])

Note that both terms are being multiplied by the square root of 1/2. This ensures that the squared modulus of both terms sums to 1. Also, don't overlook the minus sign in the center, we'll need it.

If you measure the A photon's polarization in the up-down/left-right basis, the result is pretty straightforward. Your measurement decoheres the entanglement, creating one evolution out of the A=(1 ; 0) ∧ B=(0 ; 1) configuration, and a second, noninteracting evolution out of the A=(0 ; 1) ∧ B=(1; 0) configuration.

If you find that the A photon is polarized up-down, i.e., (1 ; 0), then you know you're in the A=(1 ; 0) ∧ B=(0 ; 1) blob of amplitude. So you know that if you or anyone else measures B, they'll report to you that they found B in the (0 ; 1) or left-right polarization. The version of you that finds A=(1 ; 0), and the version of your friend that finds B=(0 ; 1), always turn out to live in the same blob of amplitude.

On the other side of configuration space, another version of you finds themselves in the A=(0 ; 1) $\wedge$ B=(1; 0) blob. If a friend measures B, the other you will expect to hear that B was polarized up-down, just as you expect to meet the version of your friend that measured B left-right.

But what if you measure the system in a slanted basis—test a photon with a 30° polarized filter? Given the specified starting state, in the up-down / left-right basis, what happens if we measure in the 30° basis instead? Will we still find the photons having opposite polarizations? Can this be demonstrated?

Yes, but the math gets a little more interesting.

Let's review, from yesterday, the case where a photon previously polarized in the up-down/left-right basis encounters a 30° filter.

Polar3060

A 30-60-90 triangle has a hypotenuse of 1, a small side of 1/2, and a longer side of (√3)/2, in accordance with the Pythagorean Theorem.

If a photon passes a 0° filter, coming out with polarization (0 ; 1), and then encounters another filter at 30°, the vector that would be *transmitted* through the 30° filter is

$(\sqrt{3})/2 * (1/2 ; (\sqrt{3})/2) = (.433 ; .75)$

and the polarization vector that would be *absorbed* is

$1/2 * (-(\sqrt{3})/2 ; 1/2) = (-.433 ; .25)$

Note that the polarization states (1/2 ; (√3)/2) and (-(√3)/2 ; 1/2) form an *orthonormal basis:* The inner product of each vector with itself is 1, and the inner product of the two vectors with each other is 0.

Then we had (√3)/2 of one basis vector plus 1/2 of the other, guaranteeing the squared moduli would sum to 1. $((\sqrt{3})/2)^2 + (1/2)^2 = 3/4 + 1/4 = 1$.

So we can say that in the 30° basis, the incoming (0 ; 1) photon had a (√3)/2 amplitude to be transmitted, and a 1/2 amplitude to be absorbed.

Symmetrically, suppose a photon had passed a 90° filter, coming out with polarization (1 ; 0), and then encountered the same 30° filter. Then the transmitted vector would be

$1/2 * (1/2 ; (\sqrt{3})/2) = (.25 ; .433)$

and the absorbed vector would be

$-(\sqrt{3})/2 * (-(\sqrt{3})/2 ; 1/2) = (.75 ; -.433)$

Now let's consider again with the entangled pair of photons

√(1/2) * ([A=(1 ; 0) ∧ B=(0 ; 1)] - [A=(0 ; 1) ∧ B=(1; 0)])

and measure photon A with a 30° filter.

Suppose we find that we see photon A absorbed.

Then we know that there was a -(√3)/2 amplitude for this event to occur if the original state had A=(1 ; 0), and a 1/2 amplitude for this event to occur if the original state had A=(0 ; 1).

So, if we see that photon A is absorbed, we learn that *we* are in the now-decoherent blob of amplitude:

(-(√3)/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(0 ; 1)])
- (1/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(1; 0)])

You might be tempted to add the two amplitudes for A being absorbed—the -(√3)/2 * √(1/2) and the -1/2 * √(1/2)—and get a total amplitude of -.966, which, squared, comes out as .933.

But if this were true, there would be a 93% prior probability of A being absorbed by the filter—a huge prior expectation to see it absorbed. There should be a 50% prior chance of seeing A absorbed.

What went wrong is that, even though we haven't yet measured B, the configurations with B=(0 ; 1) and B=(1 ; 0) are distinct. B could be light-years away, and unknown to us; the configurations would still be distinct. So we don't add the amplitudes for the two terms; we keep them separate.

When the amplitudes for the terms are *separately* squared, and the squares added together, we get a prior absorption probability of 1/2—which is exactly what we should expect.

Okay, so we're in the decoherent blob where A is absorbed by a 30° filter. Now consider what happens over at B, within our blob, if a friend measures B with another 30° filter.

The new starting amplitude distribution is:

(-(√3)/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(0 ; 1)])
- (1/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(1; 0)])

In the case where B=(0 ; 1), it has an amplitude of (√3)/2 to be transmitted through a 30° filter; being transmitted through a 30° filter corresponds to the polarization state (1/2 ; (√3)/2). Likewise, a 1/2 amplitude to be absorbed (polarization state (-(√3)/2 ; 1/2).)

In the case where B=(1 ; 0) it has an amplitude of 1/2 to be transmitted with state (1/2 ; (√3)/2). And an amplitude of -(√3)/2 to occupy the state (-(√3)/2 ; 1/2) and be absorbed.

So add up four terms:

(-(√3)/2 * √(1/2)) * [A=(-(√3)/2 ; 1/2) ∧ B=(0 ; 1)]
breaks down into
(-(√3)/2 * √(1/2)) * (√3)/2 * [A=(-(√3)/2 ; 1/2) ∧ B=(1/2 ; (√3)/2)] +

(-(√3)/2 * √(1/2)) * 1/2   * [A=(-(√3)/2 ; 1/2) ∧ B=(-(√3)/2 ; 1/2)]
and
- (1/2 * √(1/2)) * [A=(-(√3)/2 ; 1/2) ∧ B=(1; 0)])
breaks down into
-(1/2 * √(1/2)) * 1/2   * [A=(-(√3)/2 ; 1/2) ∧ B=(1/2 ; (√3)/2)] +
-(1/2 * √(1/2)) * -(√3)/2 * [A=(-(√3)/2 ; 1/2) ∧ B=(-(√3)/2 ; 1/2)]

These four terms occupy only two distinct configurations.

Adding the amplitudes, the configuration [A=(-(√3)/2 ; 1/2) ∧ B=(-(√3)/2 ; 1/2)] ends up with zero amplitude, while [A=(-(√3)/2 ; 1/2) ∧ B=(1/2 ; (√3)/2)] ends up with a final amplitude of √(1/2).

So, within the blob in which you've found yourself, the probability of your friend seeing that a 30° filter blocks both A and B, is 0. The probability of seeing that a 30° filter blocks A and transmits B, is 50%.

Symmetrically, there's another blob of amplitude where your other self sees A transmitted and B blocked, with probability 50%. And A transmitted and B transmitted, with probability 0%.

So you and your friend, when you compare results in some particular blob of decohered amplitude, always find that the two photons have opposite polarization.

And in general, if you use two equally oriented polarization filters to measure a pair of photons in the inital state:

√(1/2) * ([A=(1 ; 0) ∧ B=(0 ; 1)] - [A=(0 ; 1) ∧ B=(1; 0)])

then you are guaranteed that one filter will transmit, and the other filter absorb—regardless of how you set the filters, so long as you use the same setting. The photons *always* have opposite polarizations, even though the prior probability of any *particular* photon having a *particular* polarization is 50%.

What if I measure one photon with a 0° filter, and find that it is transmitted (= state (0 ; 1)), and then I measure the other photon with a 30° filter?

The probability works out to just the same as if I knew the other photon had state (1 ; 0)—in effect, it now does.

Over on my side, I've decohered the amplitude over the *joint* distribution, into blobs in which A has been transmitted, and A absorbed. I am in the decoherent blob with A transmitted: A=(0 ; 1). Ergo, the amplitude vector / polarization state of B, *in my blob,* behaves as if it starts out as (1 ; 0). This is just as true whether I measure it with another 0° filter, or a 30° filter.

With symmetrically entangled particles, each particle *seems* to know the state the other particle has been measured in. But "seems" is the operative word here. Actually we're just dealing with decoherence that happens to take place in a very symmetrical way.

Tomorrow (if all goes according to plan) we'll look at Bell's Theorem, which rules out the possibility that each photon already has a fixed, non-quantum state that locally determines the result of any possible polarization measurement.

Part of *The Quantum Physics Sequence*

Next post: "Bell's Theorem: No EPR 'Reality'"

Previous post: "Decoherence as Projection"

Bell's Theorem: No EPR "Reality"

Previously in series: Entangled Photons

(Note: So that this post can be read by people who haven't followed the whole series, I shall temporarily adopt some more standard and less accurate terms; for example, talking about "many worlds" instead of "decoherent blobs of amplitude".)

The legendary Bayesian, E. T. Jaynes, began his life as a physicist. In some of his writings, you can find Jaynes railing against the idea that, because we have not yet found any way to predict quantum outcomes, they must be "truly random" or "inherently random".

Sure, *today* you don't know how to predict quantum measurements. But how do you *know,* asks Jaynes, that you won't find a way to predict the process tomorrow? How can any mere experiments tell us that we'll *never* be able to predict something—that it is "inherently unknowable" or "truly random"?

As far I can tell, Jaynes never heard about decoherence aka Many-Worlds, which is a great pity. If you belonged to a species with a brain like a flat sheet of paper that sometimes split down its thickness, you could reasonably conclude that you'd *never* be able to "predict" whether you'd "end up" in the left half or the right half. Yet is this really *ignorance*? It is a *deterministic* fact that different versions of you will experience different outcomes.

But even if you don't know about Many-Worlds, there's still an excellent reply for "Why do you think you'll *never* be able to predict what you'll see when you measure a quantum event?" This reply is known as Bell's Theorem.

In 1935, Einstein, Podolsky, and Rosen once argued roughly as follows:

Suppose we have a pair of entangled particles, light-years or at least light-minutes apart, so that no signal can possibly travel between them over the timespan of the experiment. We can suppose these are polarized photons with opposite polarizations.

Polarized filters block some photons, and absorb others; this lets us measure a photon's polarization in a given orientation. Entangled photons (with the right kind of entanglement) are always found to be polarized in *opposite* directions, when you measure them in the same orientation; if a filter at a certain angle passes photon A (*transmits* it) then we know that a filter at the same angle will block photon B (*absorb* it).

Now we measure one of the photons, labeled A, and find that it is *transmitted* by a 0° polarized filter. *Without measuring B,* we can now predict with certainty that B will be *absorbed* by a 0° polarized filter, because A and B always have opposite polarizations when measured in the same basis.

Said EPR:

> "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

EPR then assumed (correctly!) that nothing which happened at A could *disturb* B or exert any influence on B, due to the spacelike separations of A and B. We'll take up the relativistic viewpoint again tomorrow; for now, let's just note that this assumption is correct.

If by measuring A at 0°, we can predict with certainty whether B will be absorbed or transmitted at 0°, then according to EPR this fact must be an "element of physical reality" about B. Since measuring A cannot influence B in any way, this element of reality must *always* have been true of B. Likewise with every other possible polarization we could measure—10°, 20°, 50°, anything. If we measured A first in the same basis, even light-years away, we could perfectly predict the result for B. So on the EPR assumptions, there must exist some "element of reality" corresponding to whether B will be transmitted or absorbed, in *any* orientation.

But if no one has measured A, quantum theory does *not* predict with certainty whether B will be transmitted or absorbed. (At least that was how it seemed in 1935.) Therefore, EPR said, there are elements of reality that exist but are not mentioned in quantum theory:

> "We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete."

This is another excellent example of how seemingly impeccable philosophy can fail in the face of experimental evidence, thanks to a wrong assumption so deep you didn't even realize it was an assumption.

EPR correctly assumed Special Relativity, and then incorrectly assumed that there was *only one version of you* who saw A do only one thing. They assumed that the certain prediction about what *you* would *hear* from B, described the *only* outcome that happened at B.

In real life, if you measure A and your friend measures B, different versions of you and your friend obtain both possible outcomes. When you *compare notes,* the two of you always find the polarizations are opposite. This does not violate Special Relativity even in spirit, but the reason why not is the topic of tomorrow's post, not today's.

Today's post is about how, in 1964, ~~Belldandy~~ John S. Bell irrevocably shot down EPR's original argument. Not by pointing out the flaw in the EPR assumptions—Many-Worlds was not then widely known—but by describing an experiment that disproved them!

It is *experimentally impossible* for there to be a physical description of the entangled photons, which specifies a single fixed outcome of any polarization measurement individually performed on A or B.

This is Bell's Theorem, which rules out all "local hidden variable" interpretations of quantum mechanics. It's actually not all that complicated, as quantum physics goes!

We begin with a pair of entangled photons, which we'll name A and B. When measured in the same basis, you find that the photons always have opposite polarization—one is transmitted, one is absorbed. As for the *first* photon you measure, the probability of transmission or absorption seems to be 50-50.

What if you measure with polarized filters set at different angles?

Suppose that I measure A with a filter set at 0°, and find that A was transmitted. In general, if you *then* measure B at an angle θ to my basis, quantum theory says the probability (of my hearing that) you *also* saw B transmitted, equals $\sin^2 \theta$. E.g. if your filter was at an angle of 30° to my filter, and I saw my photon transmitted, then there's a 25% probability that you see your photon transmitted.

(Why? See "Decoherence as Projection". Some quick sanity checks: sin(0°) = 0, so if we measure at the same angles, the calculated probability is 0—we never measure at the *same* angle and see *both* photons transmitted. Similarly, sin(90°) = 1; if I see A transmitted, and you measure at an orthogonal angle, I will always hear that you saw B transmitted. sin(45°) = √(1/2), so if you measure in a diagonal basis, the probability is 50/50 for the photon to be transmitted or absorbed.)

Oh, and the initial probability of my seeing A transmitted is always 1/2. So the *joint* probability of seeing *both* photons transmitted is $1/2 * \sin^2 \theta$. 1/2 probability of my seeing A transmitted, times $\sin^2 \theta$ probability that you then see B transmitted.

And now you and I perform three statistical experiments, with large sample sizes:

(1) First, I measure A at 0° and you measure B at 20°. The photon is transmitted through both filters on $1/2 \sin^2 (20°)$ = 5.8% of the occasions.

(2) Next, I measure A at 20° and you measure B at 40°. When we compare notes, we again discover that we both saw our photons pass through our filters, on $1/2 \sin^2 (40° - 20°)$ = 5.8% of the occasions.

(3) Finally, I measure A at 0° and you measure B at 40°. Now the photon passes both filters on $1/2 \sin^2 (40°)$ = 20.7% of occasions.

Or to say it a bit more compactly:

1. A transmitted 0°, B transmitted 20°: 5.8%
2. A transmitted 20°, B transmitted 40°: 5.8%
3. A transmitted 0°, B transmitted 40°: 20.7%

What's wrong with this picture?

Nothing, in real life. But on EPR assumptions, it's impossible.

On EPR assumptions, there's a fixed local tendency for any individual photon to be transmitted or absorbed by a polarizer of any given orientation, independent of any measurements performed light-years away, as the single unique outcome.

Consider experiment (2). We measure A at 20° and B at 40°, compare notes, and find we both saw our photons transmitted. Now, A was transmitted at 20°, so *if* you had measured B at 20°, B would certainly have been absorbed—if you measure in the same basis you must find opposite polarizations.

That is: If A had the fixed tendency to be transmitted at 20°, then B must have had a fixed tendency to be absorbed at 20°. If this rule were violated, you could have measured both photons in the 20° basis, and found that both photons had the same polarization. Given the way that entangled photons are actually produced, this would violate conservation of angular momentum.

So (under EPR assumptions) what we learn from experiment (2) can be *equivalently* phrased as: "B was a kind of photon that was transmitted by a 40° filter and *would have been* absorbed by the 20° filter." Under EPR assumptions this is logically equivalent to the actual result of experiment (2).

Now let's look again at the percentages:

1. B is a kind of photon that was transmitted at 20°, and would not have been transmitted at 0°: 5.8%
2. B is a kind of photon that was transmitted at 40°, and would not have been transmitted at 20°: 5.8%
3. B is a kind of photon that was transmitted at 40°, and would not have been transmitted at 0°: 20.7%

If you want to try and see the problem on your own, you can stare at the three experimental results for a while...

(Spoilers ahead.)

Consider a photon pair that gives us a positive result in experiment (3). On EPR assumptions, we now know that the B photon was inherently a type that would have been absorbed at 0°, and was in fact transmitted at 40°. (And conversely, if the B photon is of this type, experiment (3) will always give us a positive result.)

Now take a B photon from a positive experiment (3), and ask: "*If instead* we had measured B at 20°, would it have been transmitted, or absorbed?" Again by EPR's assumptions, there must be a definite answer to this question. We *could* have measured A in the 20° basis, and then had certainty of what would happen at B, without disturbing B. So there must be an "element of reality" for B's polarization at 20°.

But if B is a kind of photon that would be transmitted at 20°, then it is a kind of photon that implies a positive result in experiment (1). And if B is a kind of photon that would be absorbed at 20°, it is a kind of photon that would imply a positive result in experiment (2).

If B is a kind of photon that is transmitted at 40° *and* absorbed at 0°, *and* it is *either* a kind that is absorbed at 20° *or* a kind that is transmitted at 20°; then B must be *either* a kind that is absorbed at 20° and transmitted at 40°, *or* a kind that is transmitted at 20° and absorbed at 0°.

So, on EPR's assumptions, it's really hard to see how the same source can manufacture photon pairs that produce 5.8% positive results in experiment (1), 5.8% positive results in experiment (2), and 20.7% positive results in experiment (3). Every photon pair that produces a positive result in experiment (3) should also produce a positive result in either (1) or (2).

"Bell's inequality" is that any theory of hidden local variables implies (1) + (2) >= (3). The experimentally verified fact that (1) + (2) < (3) is a "violation of Bell's inequality". So there are no hidden local variables. QED.

And that's Bell's Theorem. See, that wasn't so horrible, was it?

But what's *actually* going on here?

When you measure at A, and your friend measures at B a few light-years away, different versions of you observe both possible outcomes—both possible polarizations for your photon. But the amplitude of the joint world where you *both* see your photons transmitted, goes as $\sqrt{(1/2)} * \sin \theta$ where θ is the angle between your polarizers. So the squared modulus of the amplitude (which is how we get probabilities in quantum theory) goes as $1/2 \sin^2 \theta$, and that's the probability for finding mutual transmission when you meet a few years later and compare notes. We'll talk tomorrow about why this doesn't violate Special Relativity.

Strengthenings of Bell's Theorem eliminate the need for statistical reasoning: You can show that local hidden variables are impossible, using *only* properties of individual experiments which are *always* true given various measurements. (Google "GHZ state" or "GHZM state".) Occasionally you also hear that someone has published a strengthened Bell's experiment in which the two particles were more distantly separated, or the particles were measured more reliably, but you get the core idea. Bell's Theorem is proven beyond a reasonable doubt. Now the physicists are tracking down unreasonable doubts, and Bell always wins.

I know I sometimes speak as if Many-Worlds is a settled issue, which it isn't academically. (If people are still arguing about it, it must not be "settled", right?) But Bell's Theorem itself is agreed-upon academically as an experimental truth. Yes, there are people discussing theoretically conceivable loopholes in the experiments done so far. But I don't think anyone out there *really* thinks they're going to find an experimental violation of Bell's Theorem as soon as they use a more sensitive photon detector.

What does Bell's Theorem plus its experimental verification tell us, exactly?

My favorite phrasing is one I encountered in D. M. Appleby: "Quantum mechanics is inconsistent with the classical assumption that a measurement tells us about a property previously possessed by the system."

Which is exactly right: Measurement decoheres your blob of amplitude (world), splitting it into several noninteracting blobs (worlds). This creates new indexical uncertainty—uncertainty about which of several versions of yourself you are. Learning which version you are, does *not* tell you a previously unknown property that was always possessed by the system. And which specific blobs (worlds) are created, depends on the physical measuring process.

It's sometimes said that Bell's Theorem rules out "local realism". Tread cautiously when you hear someone arguing against "realism". As for *locality*, it is, if anything, far better understood than this whole "reality" business: If life is but a dream, it is a dream that obeys Special Relativity.

It is just one particular sort of locality, and just one particular notion of which things are "real" in the sense of previously uniquely determined, which Bell's Theorem says cannot *simultaneously* be true.

In particular, decoherent quantum mechanics is local, and Bell's Theorem gives us no reason to believe it is not real. (It may or may not be the ultimate truth, but quantum mechanics is certainly *more* real than the classical hallucination of little billiard balls bopping around.)

Does Bell's Theorem prevent us from regarding the quantum description as a state of partial knowledge about something more deeply real?

At the very least, Bell's Theorem prevents us from interpreting quantum amplitudes as probability in the *obvious* way. You cannot point at a single configuration, with probability proportional to the squared modulus, and say, "This is what the universe looked like all along."

In fact, you cannot pick *any* locally specified description *whatsoever* of unique outcomes for quantum experiments, and say, "*This* is what we have partial information about."

So it certainly isn't *easy* to reinterpret the quantum wavefunction as an uncertain belief. You can't do it the obvious way. And I haven't heard of any *non*-obvious interpretation of the quantum description as partial information.

Furthermore, as I mentioned previously, it is really odd to find yourself differentiating a degree of uncertain anticipation to get physical results—the way we have to differentiate the quantum wavefunction to find out how it evolves. That's not what probabilities are *for.*

Thus I try to emphasize that quantum amplitudes are *not* possibilities, or probabilities, or degrees of uncertain belief, or expressions of ignorance, or any other species of *epistemic* creatures. Wavefunctions are not states of mind. It would be a very bad sign to have a *fundamental* physics that operated over states of mind; we know from looking at brains that minds are made of parts.

In conclusion, although Einstein, Podolsky, and Rosen presented a picture of the world that was disproven experimentally, I would still regard them as having won a moral victory: The then-common interpretation of quantum mechanics did indeed have a one person measuring at A, seeing a single outcome, and then making a certain prediction about a unique outcome at B; and this is indeed incompatible with relativity, and wrong. Though people are still arguing about that.

Part of *The Quantum Physics Sequence*

Next post: "Spooky Action at a Distance: The No-Communication Theorem"

Previous post: "Entangled Photons"

Spooky Action at a Distance: The No-Communication Theorem

Previously in series: Bell's Theorem: No EPR "Reality"

When you have a pair of entangled particles, such as oppositely polarized photons, one particle seems to somehow "know" the result of distant measurements on the other particle. If you measure photon A to be polarized at 0°, photon B somehow immediately knows that it should have the opposite polarization of 90°.

Einstein famously called this "spukhafte Fernwirkung" or "spooky action at a distance". Einstein didn't know about decoherence, so it seemed spooky to him.

Though, to be fair, Einstein knew perfectly well that the universe couldn't *really* be "spooky". It was a then-popular interpretation of QM that Einstein was calling "spooky", not the universe itself.

Let us first consider how entangled particles *look,* if you don't know about decoherence—the reason why Einstein called it "spooky":

Suppose we've got oppositely polarized photons A and B, and you're about to measure B in the 20° basis. Your probability of seeing B transmitted by the filter (or absorbed) is 50%.

But wait! Before you measure B, I suddenly measure A in the 0° basis, and the A photon is transmitted! Now, apparently, the probability that you'll see B transmitted is 11.6%. Something has changed! And even if the photons are light-years away, spacelike separated, the change still occurs.

You might try to reply:

> "No, nothing has *changed*—measuring the A photon has *told* you something about the B photon, you have gained *knowledge,* you have carried out an *inference* about a distant object, but no physical influence travels faster-than-light.
>
> "Suppose I put two index cards into an envelope, one marked '+' and one marked '-'. Now I give one envelope to you, and one envelope to a friend of yours, and you get in a spaceship and travel a few light-years away from each other, and then you open your envelope and see '+'. At once you know that your friend is holding the envelope marked '-', but this doesn't mean the envelope's content has *changed* faster than the speed of light.
>
> "You are committing a Mind Projection Fallacy; the envelope's content is constant, only your local beliefs about distant referents change."

Bell's Theorem, covered yesterday, shows that this reply fails. It is *not possible* that each photon has an unknown but fixed individual tendency to be polarized a particular way. (Think of how unlikely it would seem, a priori, for this to be something *any* experiment could tell you!)

Einstein didn't know about Bell's Theorem, but the theory he was criticizing did not say that there were hidden variables; it said that the probabilities changed directly.

But then how fast does this influence travel? And what if you measure the entangled particles in such a fashion that, in their individual reference frames, each measurement takes place before the other?

These experiments have been done. If you think there is an influence traveling, it travels at least six million times as fast as light (in the reference frame of the Swiss Alps). Nor is the influence fazed if each measurement takes place "first" within its own reference frame.

So why *can't* you use this mysterious influence to send signals faster than light?

Here's something that, as a kid, I couldn't get anyone to explain to me: "Why can't you signal using an entangled pair of photons that both start out polarized up-down? By measuring A in a diagonal basis, you destroy the up-down polarization of both photons. Then by measuring B in the up-down/left-right basis, you can with 50% probability detect the fact that a measurement has taken place, if B turns out to be left-right polarized."

It's particularly annoying that nobody gave me an answer, because the answer turns out to be simple: If both photons have definite polarizations, they aren't entangled. There are just two different photons that both happen to be polarized up-down. Measuring one photon doesn't even change your *expectations* about the other.

Entanglement is not an *extra* property that you can just stick onto otherwise normal particles! It is a breakdown of quantum independence. In classical probability theory, if you know two facts, there is no longer any logical dependence left between them. Likewise in quantum mechanics, two particles each with a definite state must have a factorizable amplitude distribution.

Or as old-style quantum theory put it: Entanglement requires superposition, which implies uncertainty. When you measure an entangled particle, you are not able to force your measurement result to take any particular value. So, over on the B end, if they do not know *what* you measured on A, their probabilistic *expectation* is always the same as before. (So it was once said).

But in old-style quantum theory, there was indeed a real and instantaneous change in the other particle's statistics which took place as the result of your own measurement. It had to be a real change, by Bell's Theorem and by the invisibly assumed *uniqueness* of both outcomes.

Even though the old theory invoked a non-local influence, you could never use this influence to *signal* or *communicate* with anyone. This was called the "no-signaling condition" or the "no-communication theorem".

Still, on then-current assumptions, they couldn't actually call it the "no influence of any kind whatsoever theorem". So Einstein correctly labeled the old theory as "spooky".

In decoherent terms, the impossibility of signaling is much easier to understand: When you measure A, one version of you sees the photon transmitted and another sees the photon absorbed. If you see the photon absorbed, you have not learned any new *empirical* fact; you have merely discovered which version of yourself "you" happen to be. From the perspective at B, your "discovery" is not even theoretically a fact they can learn; they know that both versions of you exist. When B finally communicates with you, they "discover" which world they themselves are in, but that's all. The statistics at B *really* haven't changed—the total Born probability of measuring either polarization is still just 50%!

A common defense of the old theory was that Special Relativity was not violated, because no "information" was transmitted, because the superluminal influence was always "random". As some Hans de Vries fellow points out, information theory says that "random" data is the most expensive kind of data you can transmit. Nor is "random" information always useless: If you and I generate a million entangled particles, we can later measure them to obtain a shared key for use in cryptography—a highly useful form of information which, by Bell's Theorem, could *not* have already been there before measuring.

But wait a minute. Decoherence also lets you generate the shared key. Does decoherence *really* not violate the spirit of Special Relativity?

Decoherence doesn't allow "signaling" or "communication", but it allows you to generate a highly useful shared key apparently out of nowhere. Does decoherence *really* have any advantage over the old-style theory on this one? Or are both theories equally obeying Special Relativity in practice, and equally violating the spirit?

A first reply might be: "The shared key is not 'random'. Both you and your friend generate all possible shared keys, and this is a deterministic and local fact; the correlation only shows up when you meet."

But this just reveals a deeper problem. The counter-objection would be: "The measurement that you perform over at A, splits both A and B into two parts, two worlds, which guarantees that you'll meet the right version of your friend when you reunite. That is non-local physics—something you do *at A*, makes the world *at B* split into two parts. This is spooky action at a distance, and it too violates the spirit of Special Relativity. Tu quoque!"

And indeed, if you look at our quantum calculations, they are written in terms of joint configurations. Which, on reflection, doesn't seem all that local!

But wait—what exactly does the no-communication theorem say? *Why* is it true? Perhaps, if we knew, this would bring enlightenment.

Here is where it starts getting complicated. I myself don't fully understand the no-communication theorem—there are some parts I think I can see at a glance, and other parts I don't. So I will only be able to explain some of it, and I may have gotten it wrong, in which case I pray to some physicist to correct me (or at least tell me where I got it wrong).

When we did the calculations for entangled polarized photons, with A's polarization measured using a 30° filter, we calculated that the initial state

√(1/2) * ([A=(1 ; 0) ∧ B=(0 ; 1)] - [A=(0 ; 1) ∧ B=(1; 0)])

would be decohered into a blob for

(-(√3)/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(0 ; 1)])
- (1/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(1; 0)])

and symmetrically (though we didn't do this calculation) another blob for

(1/2 * √(1/2) * [A=(1/2 ; (√3)/2) ∧ B=(0 ; 1)])
 - ((√3)/2 * √(1/2) * [A=(1/2 ; (√3)/2) ∧ B=(1; 0)])

These two blobs together add up, linearly, to the initial state, as one would expect. So what changed? At all?

What changed is that the final result at A, for the first blob, is really more like:

(Sensor-A-reads-"ABSORBED") * (Experimenter-A-sees-"ABSORBED") *
{ (-(√3)/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(0 ; 1)])
 -(1/2 * √(1/2) * [A=(-(√3)/2 ; 1/2) ∧ B=(1; 0)]) }

and correspondingly with the TRANSMITTED blob.

What changed is that one blob in configuration space, was decohered into two distantly separated blobs that can't interact any more.

As we saw from the Heisenberg "Uncertainty Principle", decoherence is a visible, experimentally detectable effect. That's why we have to shield quantum computers from decoherence. So couldn't the decohering measurement at A, have detectable consequences for B?

But think about how B sees the initial state:

√(1/2) * ([A=(1 ; 0) ∧ B=(0 ; 1)] - [A=(0 ; 1) ∧ B=(1; 0)])

From B's perspective, this state is already "not all that coherent", because no matter what B does, it can't make the A=(1 ; 0) and A=(0 ; 1) configurations cross paths. There's already a sort of decoherence here—a separation that B can't eliminate by any local action at B.

And as we've earlier glimpsed, the basis in which you write the initial state is arbitrary. When you write out the state, it has pretty much the same form in the 30° measuring basis as in the 0° measuring basis.

In fact, there's nothing preventing you from writing out the initial state with A in the 30° basis and B in the 0° basis, so long as your numbers add up.

Indeed this is exactly what we *did* do, when we first wrote out the four terms in the two blobs, and didn't include the sensor or experimenter.

So when A *permanently* decohered the blobs in the 30° basis, from B's perspective, this merely *solidified* a decoherence that B could have viewed as *already* existing.

Obviously, this can't change the local evolution at B (he said, waving his hands a bit).

Now this is only a statement about a quantum measurement that *just* decoheres the amplitude for A into parts, *without* A itself evolving in interesting new directions. What if there were many particles on the A side, and something happened on the A side that put some of those particles into identical configurations via different paths?

This is where linearity and unitarity come in. The no-communication theorem requires both conditions: in general, violating linearity or unitarity gives you faster-than-light signaling. (And numerous other superpowers, such as solving NP-complete problems in polynomial time, and possibly Outcome Pumps.)

By linearity, we can consider parts of the amplitude distribution separately, and their evolved states will add up to the evolved state of the whole.

Suppose that there are many particles on the A side, but we count up every configuration that corresponds to some single fixed state of B—say, B=(0 ; 1) or B=France, whatever. We'd get a group of components which looked like:

(AA=1 ∧ AB=2 ∧ AC=Fred ∧ B=France) +
(AA=2 ∧ AB=1 ∧ AC=Sally ∧ B=France) + ...

Linearity says that we can decompose the amplitude distribution around states of B, and the evolution of the parts will add to the whole.

Assume that the B side stays fixed. Then this component of the distribution that we have just isolated, will not interfere with any *other* components, because other components have different values for B, so they are not identical configurations.

And unitary evolution says that whatever the measure—the integrated squared modulus—of this component, the total measure is the same after evolution at A, as before.

So *assuming* that B stays fixed, then anything *whatsoever* happening at A, won't change the measure of the states at B (he said, waving his hands some more).

Nor should it matter whether we consider A first, or B first. Anything that happens at A, within some component of the amplitude distribution, only *depends* on the A factor, and only happens *to* the A factor; likewise with B; so the final *joint* amplitude distribution should not depend on the order in which we consider the evolutions (and he waved his hands a final time).

It seems to me that from here it should be easy to show no communication considering the simultaneous evolution of A and B. Sadly I can't quite see the last step of the argument. I've spent very little time doing actual quantum calculations—this is not what I do for a living—or it would probably be obvious. Unless it's more subtle than it appears, but anyway...

Anyway, *if I'm not mistaken*—though I'm feeling my way here by mathematical intuition—the no-communication theorem manifests as invariant generalized states of entanglement. From B's perspective, they are entangled with some distant entity A, and that entanglement has an invariant shape that remains exactly the same no matter what happens at A.

To me, at least, this suggests that the *apparent non-locality of quantum physics* is a *mere artifact of the representation* used to describe it.

If you write a 3-dimensional vector as "30° west of north, 40° upward slope, and 100 meters long," it doesn't mean that the universe has a basic compass grid, or that there's a global direction of up, or that reality runs on the metric system. It means you chose a convenient representation.

Physics, including quantum physics, is relativistically invariant: You can pick any relativistic frame you like, redo your calculations, and always get the same experimental predictions back out. *That* we know.

Now it may be that, in the course of doing *your* calculations, you find it convenient to pick *some* reference frame, *any* reference frame, and use that in *your* math. Greenwich Mean Time, say. This doesn't mean there really *is* a central clock, somewhere underneath the universe, that operates on Greenwich Mean Time.

The representation we used talked about "joint configurations" of A and B in which the states of A and B were simultaneously specified. This means our representation was not relativistic; the notion of "simultaneity" is arbitrary. We assumed the universe ran on Greenwich Mean Time, in effect.

I don't know what kind of representation would be (1) relativistically invariant, (2) show distant entanglement as invariant, (3) directly represent space-time locality, and (4) evolve each element of the new representation in a way that depended only on an immediate neighborhood of other elements.

But that representation would probably be a *lot* closer to the Tao.

My suspicion is that a better representation might take its basic mathematical objects as local states of entanglement. I've actually suspected this ever since I heard about holographic physics and the entanglement entropy bound. But that's just raw speculation, at this point.

However, it *is* important that a fundamental representation be as *local* and as *simple* as possible. This is why e.g. "histories of the entire universe" make poor "fundamental" objects, in my humble opinion.

And it's why I find it suspicious to have a representation for calculating quantum physics that talks about a relativistically arbitrary "joint configuration" of A and B, when it seems like each local position has an invariant "distant entanglement" that suffices to determine local evolution. Shouldn't we be able to refactor this representation into smaller pieces?

Though ultimately you do have to retrieve the phenomenon where the experimenters meet again, after being separated by light-years, and discover that they measured the photons with opposite polarizations. Which is provably not something you can get from individual billiard balls bopping around.

I suspect that when we get a *representation* of quantum mechanics that is local in every way that the physics itself is local, it will be immediately obvious—right there in the representation—that things only happen in one place at a time.

Hence, no faster-than-light communicators. (Dammit!)

Now of course, all this that I have said—all this wondrous normality—relies on the decoherence viewpoint.

It relies on believing that when you measure at A, both possible measurements for A still exist, and are still entangled with B in a way that B sees as invariant.

All the amplitude in the joint configuration is undergoing linear, unitary, local evolution. None of it vanishes. So the probabilities at B are always the same from a global standpoint, and there is no supraluminal influence, period.

If you tried to "interpret" things any differently... well, the no-communication theorem would become a *lot less obvious*.

Part of *The Quantum Physics Sequence*

Next post: "Decoherence is Simple"

Previous post: "Bell's Theorem: No EPR 'Reality'"

Decoherence is Simple

An epistle to the physicists:

When I was but a little lad, my father, a PhD physicist, warned me sternly against meddling in the affairs of physicists; he said that it was hopeless to try to comprehend physics without the formal math. Period. No escape clauses. But I had read in Feynman's popular books that if you really understood physics, you ought to be able to explain it to a nonphysicist. I believed Feynman instead of my father, because Feynman had won the Nobel Prize and my father had not.

It was not until later—when I was reading the *Feynman Lectures*, in fact— that I realized that my father had given me the simple and honest truth. No math = no physics.

By vocation I am a Bayesian, not a physicist. Yet although I was raised not to meddle in the affairs of physicists, my hand has been forced by the occasional gross misuse of three terms: *simple*, *falsifiable*, and *testable*.

The foregoing introduction is so that you don't laugh, and say, "Of course I know what those words mean!" There is math here. What follows will be a restatement of the points in Belief in the Implied Invisible, as they apply to quantum physics.

Let's begin with the remark that started me down this whole avenue, of which I have seen several versions; paraphrased, it runs:

> The many-worlds interpretation of quantum mechanics postulates that there are vast numbers of other worlds, existing alongside our own. Occam's Razor says we should not multiply entities unnecessarily.

Now it must be said, in all fairness, that those who say this will usually also confess:

> But this is not a universally accepted application of Occam's Razor; some say that Occam's Razor should apply to the laws governing the model, not the number of objects inside the model.

So it is good that we are all acknowledging the contrary arguments, and telling both sides of the story—

But suppose you had to *calculate* the simplicity of a theory.

The original formulation of William of Ockham stated:

> *Lex parsimoniae: Entia non sunt multiplicanda praeter necessitatem.*

"The law of parsimony: Entities should not be multiplied beyond necessity."

But this is qualitative advice. It is not enough to say whether one theory seems more simple, or seems more complex, than another—you have to assign a number; and the number has to be meaningful, you can't just make it up. Crossing this gap is like the difference between being able to eyeball which things are moving "fast" or "slow," and starting to measure and calculate velocities.

Suppose you tried saying: "Count the words—that's how complicated a theory is."

Robert Heinlein once claimed (tongue-in-cheek, I hope) that the "simplest explanation" is always: "The woman down the street is a witch; she did it." Eleven words—not many physics papers can beat that.

Faced with this challenge, there are two different roads you can take.

First, you can ask: "The woman down the street is a *what*?" Just because English has one word to indicate a concept doesn't mean that the concept itself is simple. Suppose you were talking to aliens who didn't know about witches, women, or streets—how long would it take you to explain your theory to them? Better yet, suppose you had to write a computer program that embodied your hypothesis, and output what you say are your hypothesis's predictions—how big would that computer program have to be? Let's say that your task is to predict a time series of measured positions for a rock rolling down a hill. If you write a subroutine that simulates witches, this doesn't seem to help narrow down where the rock rolls—the extra subroutine just inflates your code. You might find, however, that your code necessarily includes a subroutine that squares numbers.

Second, you can ask: "The woman down the street is a witch; she did *what*?" Suppose you want to describe some event, as precisely as you possibly can given the evidence available to you—again, say, the distance/time series of a rock rolling down a hill. You can preface your explanation by saying, "The woman down the street is a witch," but your friend then says, "What did she *do*?," and you reply, "She made the rock roll one meter after the first second, nine meters after the third second..." Prefacing your message with "The woman down the street is a witch," doesn't help to *compress* the rest of your description. On the whole, you just end up sending a longer message than necessary—it makes more sense to just leave off the "witch" prefix. On the other hand, if you take a moment to talk about Galileo, you may be able to greatly compress the next five thousand detailed time series for rocks rolling down hills.

If you follow the first road, you end up with what's known as Kolmogorov complexity and Solomonoff induction. If you follow the second road, you end up with what's known as Minimum Message Length.

> Ah, so I can pick and choose among definitions of simplicity?

No, actually the two formalisms in their most highly developed forms were proven equivalent.

> And I suppose now you're going to tell me that both formalisms come down on the side of "Occam means counting laws, not counting objects."

More or less. In Minimum Message Length, so long as you can tell your friend an exact recipe they can mentally follow to get the rolling rock's time series, we don't care how much mental work it takes to follow the recipe. In Solomonoff induction, we count bits in the program code, not bits of RAM used by the program as it runs. "Entities" are lines of code, not simulated objects. And as said, these two formalisms are ultimately equivalent.

Now before I go into any further detail on formal simplicity, let me digress to consider the objection:

> So what? Why can't I just invent my o*wn* formalism that does things differently? Why should I pay any attention to the way you happened to decide to do things,

> over in your field? Got any e*xperimental* evidence that shows I should do things this way?

Yes, actually, believe it or not. But let me start at the beginning.

The conjunction rule of probability theory states:

$$P(X, Y) \leq P(X)$$

For any propositions *X* and *Y*, the probability that "*X* is true, and *Y* is true," is *less than or equal to* the probability that "*X* is true (whether or not *Y* is true)." (If this statement sounds not terribly profound, then let me assure you that it is easy to find cases where human probability assessors violate this rule.)

You usually can't apply the conjunction rule $P(X,Y) \leq P(X)$ directly to a conflict between mutually exclusive hypotheses. The conjunction rule only applies directly to cases where the left-hand-side strictly implies the right-hand-side. Furthermore, the conjunction is just an inequality; it doesn't give us the kind of quantitative calculation we want.

But the conjunction rule does give us a rule of monotonic decrease in probability: as you tack more details onto a story, and each additional detail can potentially be true or false, the story's probability goes down monotonically. Think of probability as a conserved quantity: there's only so much to go around. As the number of details in a story goes up, the number of possible stories increases exponentially, but the sum over their probabilities can never be greater than 1. For every story "*X* and *Y*," there is a story "*X* and ¬*Y*." When you *just* tell the story "*X*," you get to *sum over* the possibilities *Y* and ¬*Y*.

If you add ten details to *X*, each of which could potentially be true or false, then that story must compete with $2^{10} - 1$ other equally detailed stories for precious probability.

If on the other hand it suffices to *just* say *X*, you can sum your probability over 2^{10} stories

> ((X and Y and Z and ...) or (X and ¬Y and Z and ...) or ...) .

The "entities" counted by Occam's Razor should be individually costly in probability; this is why we prefer theories with fewer of them.

Imagine a lottery which sells up to a million tickets, where each possible ticket is sold only once, and the lottery has sold every ticket at the time of the drawing. A friend of yours has bought one ticket for $1—which seems to you like a poor investment, because the payoff is only $500,000. Yet your friend says, "Ah, but consider the alternative hypotheses, 'Tomorrow, someone will win the lottery' and 'Tomorrow, I will win the lottery.' Clearly, the latter hypothesis is simpler by Occam's Razor; it only makes mention of one person and one ticket, while the former hypothesis is more complicated: it mentions a million people and a million tickets!"

To say that Occam's Razor only counts laws, and not objects, is not quite correct: what counts against a theory are the entities it must mention *explicitly*, because these are the entities that cannot be *summed over*. Suppose that you and a friend are puzzling over an amazing billiards shot, in which you are told the starting state of a billiards table, and which balls were sunk, but not how the shot was made. You propose a theory which involves ten specific collisions between ten specific balls; your friend counters with a theory that involves five specific collisions between five specific balls. What counts against your theories is not *just* the laws that you claim to govern billiard balls, but any *specific* billiard balls that had to be in some *particular* state for your model's prediction to be successful.

If you measure the temperature of your living room as 22 degrees Celsius, it does not make sense to say: "Your thermometer is probably in error; the room is much more likely to be 20 °C. Because, when you consider all the particles in the room, there are exponentially vastly more states they can occupy if the temperature is really 22 °C—which makes any *particular* state all the more improbable." But no matter which exact 22 °C state your room occupies, you can make the same prediction (for the supervast majority of these states) that your thermometer will end up showing 22 °C, and so you are not sensitive to the exact initial conditions. You do not need to specify an *exact* position of all the air molecules in the room, so that is not counted against the probability of your explanation.

On the other hand—returning to the case of the lottery—suppose your friend won ten lotteries in a row. At this point you should suspect the fix is in. The hypothesis "My friend wins the lottery every time" is more complicated than the hypothesis "Someone wins the lottery every time." But the former hypothesis is predicting the data much more precisely.

In the Minimum Message Length formalism, saying "There is a single person who wins the lottery every time" at the beginning of your message compresses your description of who won the next ten lotteries; you can just say "And that person is Fred Smith" to finish your message. Compare to, "The first lottery was won by Fred Smith, the second lottery was won by Fred Smith, the third lottery was…"

In the Solomonoff induction formalism, the prior probability of "My friend wins the lottery every time" is low, because the program that describes the lottery now needs explicit code that singles out your friend; but because that program can produce a *tighter probability distribution* over potential lottery winners than "Someone wins the lottery every time," it can, by Bayes's Rule, overcome its prior improbability and win out as a hypothesis.

Any formal theory of Occam's Razor should quantitatively define, not only "entities" and "simplicity," but also the "necessity" part.

Minimum Message Length defines necessity as "that which compresses the message."

Solomonoff induction assigns a prior probability to each possible computer program, with the entire distribution, over every possible computer program, summing to no more than 1. This can be accomplished using a binary code where no valid computer program is a prefix of any other valid computer program ("prefix-free code"), e.g. because it contains a stop code. Then the prior probability of any program *P* is simply $2^{-L(P)}$ where L(P) is the length of *P* in bits.

The program *P* itself can be a program that takes in a (possibly zero-length) string of bits and outputs the conditional probability that the *next* bit will be 1; this makes *P* a probability distribution over all binary sequences. This version of Solomonoff induction, for any string, gives us a mixture of posterior probabilities dominated by the shortest programs that most precisely predict the string. Summing over this mixture gives us a prediction for the next bit.

The upshot is that it takes more Bayesian evidence—more successful predictions, or more precise predictions—to justify more complex hypotheses. But it can be done; the burden of prior improbability is not infinite. If you flip a coin four times, and it comes up heads every time, you don't conclude right away that the coin produces only heads; but if the coin comes up heads twenty times in a row, you should be considering it very seriously. What about the hypothesis that a coin is fixed to produce HTTHTT… in a repeating cycle? That's more bizarre—but after a hundred coinflips you'd be a fool to deny it.

Standard chemistry says that in a gram of hydrogen gas there are six hundred billion trillion hydrogen atoms. This is a startling statement, but there was some amount of evidence that sufficed to convince physicists in general, and you particularly, that this statement was true.

Now ask yourself how much evidence it would take to convince you of a theory with six hundred billion trillion separately specified physical laws.

Why doesn't the prior probability of a program, in the Solomonoff formalism, include a measure of how much RAM the program uses, or the total running time?

The simple answer is, "Because space and time resources used by a program aren't mutually exclusive possibilities." It's not like the program specification, that can only have a 1 or a 0 in any particular place.

But the even simpler answer is, "Because, historically speaking, that heuristic doesn't work."

Occam's Razor was raised as an objection to the suggestion that nebulae were actually distant galaxies—it seemed to vastly multiply the number of entities in the universe. *All those stars!*

Over and over, in human history, the universe has gotten bigger. A variant of Occam's Razor which, on each such occasion, would label the vaster universe as *more unlikely*, would fare less well under humanity's historical experience.

This is part of the "experimental evidence" I was alluding to earlier. While you can justify theories of simplicity on mathy sorts of grounds, it is also desirable that they actually work in practice. (The other part of the "experimental evidence" comes from statisticians / computer scientists / Artificial Intelligence researchers, testing which definitions of "simplicity" let them construct computer programs that do empirically well at predicting future data from past data. Probably the Minimum Message Length paradigm has proven most productive here, because it is a very adaptable way to think about real-world problems.)

Imagine a spaceship whose launch you witness with great fanfare; it accelerates away from you, and is soon traveling at 0.9c. If the expansion of the universe continues, as current cosmology holds it should, there will come some future point where—according to your model of reality—you don't expect to be able to interact with the spaceship even in principle; it has gone over the cosmological horizon relative to you, and photons leaving it will not be able to outrace the expansion of the universe.

Should you believe that [the spaceship literally, physically disappears from the universe] at the point where it goes over the cosmological horizon relative to you?

If you believe that Occam's Razor counts the objects in a model, then yes, you should. Once the spaceship goes over your cosmological horizon, the model in which the spaceship instantly disappears, and the model in which the spaceship continues onward, give indistinguishable predictions; they have no Bayesian evidential advantage over one another. But one model contains many fewer "entities"; it need not speak of all the quarks and electrons and fields composing the spaceship. So it is simpler to suppose that the spaceship vanishes.

Alternatively, you could say: "Over numerous experiments, I have generalized certain laws that govern observed particles. The spaceship is made up of such particles. Applying these laws, I deduce that the spaceship should continue on after it crosses the cosmological horizon, with the same momentum and the same energy as before, on pain of violating the conservation laws that I have seen holding in every examinable instance. To suppose that the spaceship vanishes, I would have to add a new law, 'Things vanish as soon as they cross my cosmological horizon.' "

The decoherence (a.k.a. many-worlds) version of quantum mechanics states that measurements obey the same quantum-mechanical rules as all other physical processes. Applying these rules to macroscopic objects in exactly the same way as microscopic ones, we end up with observers in states of superposition. Now there are many questions that can be asked here, such as

"But then why don't all binary quantum measurements appear to have 50/50 probability, since different versions of us see both outcomes?"

However, the objection that decoherence violates Occam's Razor on account of multiplying objects in the model is simply wrong.

Decoherence does not require the wavefunction to take on some complicated exact initial state. Many-worlds is not specifying all its worlds by hand, but generating them via the compact laws of quantum mechanics. A computer program that directly simulates quantum mechanics to make experimental predictions, would require a great deal of RAM to run—but simulating the wavefunction is exponentially expensive in *any* flavor of quantum mechanics! Decoherence is simply more so. *Many* physical discoveries in human history, from stars to galaxies, from atoms to quantum mechanics, have vastly increased the apparent CPU load of what we believe to be the universe.

Many-worlds is not a zillion worlds worth of complicated, any more than the atomic hypothesis is a zillion atoms worth of complicated. For anyone with a quantitative grasp of Occam's Razor that is simply not what the term "complicated" means.

As with the historical case of galaxies, it may be that people have mistaken their *shock* at the notion of a universe that large, for a probability penalty, and invoked Occam's Razor in justification. But if there are probability penalties for decoherence, the *largeness of the implied universe*, per se, is definitely not their source!

The notion that decoherent worlds are additional entities penalized by Occam's Razor is just plain mistaken. It is not sort-of-right. It is not an argument that is weak but still valid. It is not a defensible position that could be shored up with further arguments. It is entirely defective as probability theory. It is not fixable. It is bad math. 2 + 2 = 3.

Decoherence is Falsifiable and Testable

The words “falsifiable” and “testable” are sometimes used interchangeably, which imprecision is the price of speaking in English. There are two different probability-theoretic qualities I wish to discuss here, and I will refer to one as “falsifiable” and the other as “testable” because it seems like the best fit.

As for the math, it begins, as so many things do, with:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_j P(B|A_j)P(A_j)}$$

This is Bayes’s Theorem. I own at least two distinct items of clothing printed with this theorem, so it must be important.

To review quickly, *B* here refers to an item of evidence, A_i is some hypothesis under consideration, and the A_j are competing, mutually exclusive hypotheses. The expression $P(B|A_i)$ means “the probability of seeing *B*, if hypothesis *Ai* is true” and $P(A_i|B)$ means “the probability hypothesis A_i is true, if we see B.”

The mathematical phenomenon that I will call “falsifiability” is the scientifically desirable property of a hypothesis that it should concentrate its probability mass into preferred outcomes, which implies that it must also assign low probability to some un-preferred outcomes; probabilities must sum to 1 and there is only so much probability to go around. Ideally there should be possible observations which would drive down the hypothesis’s probability to nearly zero: There should be things the hypothesis *cannot* explain, conceivable experimental results with which the theory is *not* compatible. A theory that can explain everything prohibits nothing, and so gives us no advice about what to expect.

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_j P(B|A_j)P(A_j)}$$

In terms of Bayes’s Theorem, if there is at least some observation *B* that the hypothesis *Ai* can’t explain, i.e., *P*(*B*|*Ai*) is tiny, then the numerator *P*(*B*|*Ai*)*P*(*Ai*) will also be tiny, and likewise the posterior probability *P*(*Ai*|*B*). Updating on having seen the impossible result *B* has driven the probability of *Ai* down to nearly zero. A theory that refuses to make itself vulnerable in this way will need to spread its probability widely, so that it has no holes; it will not be able to strongly concentrate probability into a few preferred outcomes; it will not be able to offer precise advice.

Thus is the rule of science derived in probability theory.

As depicted here, “falsifiability” is something you evaluate by looking at a *single*hypothesis, asking, “How narrowly does it concentrate its probability distribution over possible outcomes? How narrowly does it tell me what to expect? Can it explain some possible outcomes much better than others?"

Is the decoherence interpretation of quantum mechanics *falsifiable*? Are there experimental results that could drive its probability down to an infinitesimal?

Sure: We could measure entangled particles that should always have opposite spin, and find that if we measure them far enough apart, they sometimes have the same spin.

Or we could find apples falling upward, the planets of the Solar System zigging around at random, and an atom that kept emitting photons without any apparent energy source. Those observations would also falsify decoherent quantum mechanics. They're things that, on the hypothesis that decoherent quantum mechanics governs the universe, we should definitely *not expect* to see.

So there do exist observations *B* whose $P(B|A_{decoherence})$ is infinitesimal, which would drive $P(A_{decoherence}|B)$ down to an infinitesimal.

> But that's just because decoherent quantum mechanics is still quantum mechanics! What about the decoherence part, per se, versus the collapse postulate?

We're getting there. The point is that I just defined a test that leads you to think about one hypothesis at a time (and called it "falsifiability"). If you want to distinguish decoherence *versus* collapse, you have to think about at least two hypotheses at a time.

Now really the "falsifiability" test is not quite *that* singly focused, i.e., the sum in the denominator has got to contain *some* other hypothesis. But what I just defined as "falsifiability" pinpoints the kind of problem that Karl Popper was complaining about, when he said that Freudian psychoanalysis was "unfalsifiable" because it was equally good at coming up with an explanation for every possible thing the patient could do.

If you belonged to an alien species that had never invented the collapse postulate or Copenhagen Interpretation—if the only physical theory you'd ever heard of was decoherent quantum mechanics—if *all* you had in your head was the differential equation for the wavefunction's evolution plus the Born probability rule—you would still have sharp expectations of the universe. You would not live in a magical world where anything was probable.

> But you could say exactly the same thing about quantum mechanics w*ithout(*macroscopic) decoherence.

Well, yes! Someone walking around with the differential equation for the wavefunction's evolution, plus a collapse postulate that obeys the Born probabilities and is triggered before superposition reaches macroscopic levels, still lives in a universe where apples fall down rather than up.

> But where does decoherence make a n*ew* prediction, one that lets us t*est* it?

A "new" prediction relative to what? To the state of knowledge possessed by the ancient Greeks? If you went back in time and showed them decoherent quantum mechanics, they would be enabled to make many experimental predictions they could not have made before.

When you say “new prediction,” you mean “new” relative to some other hypothesis that defines the “old prediction.” This gets us into the theory of what I’ve chosen to label *testability*; and the algorithm inherently considers at least two hypotheses at a time. You cannot call something a “*new* prediction” by considering only one hypothesis in isolation.

In Bayesian terms, you are looking for an item of evidence *B* that will produce evidence for one hypothesis over another, distinguishing between them, and the process of producing this evidence we could call a “test.” You are looking for an experimental result *B* such that

$$P(B|A_d) \neq P(B|A_c);$$

that is, some outcome *B* which has a different probability, conditional on the decoherence hypothesis being true, versus its probability if the collapse hypothesis is true. Which in turn implies that the posterior odds for decoherence and collapse will become different from the prior odds:

$$\frac{P(B|A_d)}{P(B|A_c)} \neq 1 \text{ implies}$$

$$\frac{P(A_d|B)}{P(A_c|B)} = \frac{P(B|A_d)}{P(B|A_c)} \times \frac{P(A_d)}{P(A_c)}$$

$$\frac{P(A_d|B)}{P(A_c|B)} \neq /\mathrm{frac}P(A_d)P(A_c).$$

This equation is symmetrical (assuming no probability is literally equal to 0). There isn’t one A_j labeled “old hypothesis” and another A_j labeled “new hypothesis.”

This symmetry is a feature, not a bug, of probability theory! If you are designing an artificial reasoning system that arrives at different beliefs depending on the order in which the evidence is presented, this is labeled “hysteresis” and considered a Bad Thing. I hear that it is also frowned upon in Science.

From a probability-theoretic standpoint we have various trivial theorems that say it shouldn’t matter whether you update on *X* first and then *Y*, or update on *Y* first and then *X*. At least they’d be trivial if human beings didn’t violate them so often and so lightly.

If decoherence is “untestable” relative to collapse, then so too, collapse is “untestable” relative to decoherence. What if the history of physics had transpired differently—what if Hugh Everett and John Wheeler had stood in the place of Bohr and Heisenberg, and vice versa? Would it then be right and proper for the people of that world to look at the collapse interpretation, and snort, and say, “Where are the *new* predictions?”

What if someday we meet an alien species that invented decoherence before collapse? Are we each bound to keep the theory we invented first? Will Reason have nothing to say about the issue, leaving no recourse to settle the argument but interstellar war?

> But if we revoke the requirement to yield new predictions, we are left with scientific chaos. You can add arbitrary untestable complications to old theories, and get experimentally equivalent predictions. If we reject what you call “hysteresis,” how can we defend our current theories against every crackpot who proposes that electrons have a new property called “scent,” just like quarks have “flavor”?

Let it first be said that I quite agree that you should reject the one who comes to you and says: “Hey, I’ve got this brilliant new idea! Maybe it’s not the electromagnetic field that’s tugging on charged particles. Maybe there are tiny little angels who actually push on the particles, and the electromagnetic field just tells them how to do it. Look, I have all these successful experimental predictions—the predictions you used to call your own!”

So yes, I agree that we shouldn’t buy this amazing new theory, but it is not the *newness* that is the problem.

Suppose that human history had developed only slightly differently, with the Church being a primary grant agency for Science. And suppose that when the laws of electromagnetism were first being worked out, the phenomenon of magnetism had been taken as proof of the existence of unseen spirits, of angels. James Clerk becomes Saint Maxwell, who described the laws that direct the actions of angels.

A couple of centuries later, after the Church’s power to burn people at the stake has been restrained, someone comes along and says: “Hey, do we really need the angels?”

“Yes,” everyone says. “How else would the mere numbers of the electromagnetic field translate into the actual motions of particles?”

“It might be a fundamental law,” says the newcomer, “or it might be something other than angels, which we will discover later. What I am suggesting is that interpreting the numbers *as the action of angels* doesn’t really add anything, and we should just keep the numbers and throw out the angel part.”

And they look one at another, and finally say, “But your theory doesn’t make any new experimental predictions, so why should we adopt it? How do we test your assertions about the absence of angels?”

From a normative perspective, it seems to me that if we should reject the crackpot angels in the first scenario, *even without being able to distinguish the two theories experimentally*, then we should also reject the angels of established science in the second scenario, even without being able to distinguish the two theories experimentally.

It is ordinarily the crackpot who adds on new useless complications, rather than scientists who accidentally build them in at the start. But the problem is not that the complications are new, but that they are useless whether or not they are new.

A Bayesian would say that the extra complications of the angels in the theory lead to penalties on the prior probability of the theory. If two theories make equivalent predictions, we keep the one that can be described with the shortest message, the smallest program. If you are evaluating the prior probability of each hypothesis by counting bits of code, and then applying Bayesian updating rules on all the evidence available, then it makes no difference which hypothesis you hear about first, or the order in which you apply the evidence.

It is usually not possible to apply formal probability theory in real life, any more than you can predict the winner of a tennis match using quantum field theory. But if probability theory can serve as a guide to practice, this is what it says: Reject *useless*complications *in general*, not just when they are *new*.

> Yes, and u*seless* is precisely what the many worlds of decoherence are! There are supposedly all these worlds alongside our own, and they don't d*o* anything to our world, but I'm supposed to believe in them anyway?

No, according to decoherence, what you're supposed to believe are the general laws that govern wavefunctions—and these general laws are very visible and testable.

I have argued elsewhere that the imprimatur of science should be associated with general laws, rather than particular events, because it is the general laws that, in principle, anyone can go out and test for themselves. I assure you that I happen to be wearing white socks right now as I type this. So you are probably *rationally* justified in believing that this is a historical fact. But it is not the specially strong kind of statement that we canonize as a provisional belief of science, because there is no experiment that you can do for yourself to determine the truth of it; you are stuck with my authority. Now, if I were to tell you the mass of an electron in general, you could go out and find your own electron to test, and thereby see for yourself the truth of the general law in that particular case.

The ability of anyone to go out and verify a general scientific law for themselves, by constructing some particular case, is what makes our belief in the general law specially reliable.

What decoherentists say they believe in is the differential equation that is observed to govern the evolution of wavefunctions—which you can go out and test yourself any time you like; just look at a hydrogen atom.

Belief in the existence of separated portions of the universal wavefunction is not *additional*, and it is not *supposed* to be explaining the price of gold in London; it is just a deductive consequence of the wavefunction's evolution. If the evidence of many particular cases gives you cause to believe that $X \to Y$ is a general law, and the evidence of some particular case gives you cause to believe X, then you should have $P(Y) \geq P(X \text{ and } (X \to Y))$.

Or to look at it another way, if $P(Y|X) \approx 1$, then $P(X \text{ and } Y) \approx P(X)$.

Which is to say, believing extra details doesn't cost you extra probability when they are *logical implications* of general beliefs you already have. Presumably the general beliefs themselves are falsifiable, though, or why bother?

This is why we don't believe that spaceships blink out of existence when they cross the cosmological horizon relative to us. True, the spaceship's continued existence doesn't have an impact on our world. The spaceship's continued existence isn't helping to explain the price of gold in London. But we get the invisible spaceship for free as a consequence of general laws that imply conservation of mass and energy. If the spaceship's continued existence were *not* a deductive consequence of the laws of physics as we presently model them, *then* it would be an additional detail, cost extra probability, and we would have to question why our theory must include this assertion.

The part of decoherence that is supposed to be testable is not the many worlds per se, but just the general law that governs the wavefunction. The decoherentists note that, applied universally, this law implies the existence of entire superposed worlds. Now there are critiques that can be leveled at this theory, most notably, "But then where do the Born probabilities come from?" But within the internal logic of decoherence, the many worlds are not offered as an explanation for anything, nor are they the substance of the theory that is meant to be tested; they are simply a logical consequence of those general laws that constitute the substance of the theory.

If $A \Rightarrow B$ then $\neg B \Rightarrow \neg A$. To deny the existence of superposed worlds is necessarily to deny the universality of the quantum laws formulated to govern hydrogen atoms and every other examinable case; it is this denial that seems to the decoherentists like the extra and untestable detail. You can't see the other parts of the wavefunction—why postulate *additionally* that they don't exist?

The events surrounding the decoherence controversy may be unique in scientific history, marking the first time that serious scientists have come forward and said that by historical accident humanity has developed a powerful, successful, mathematical physical theory that includes angels. That there is an entire law, the collapse postulate, that can simply be thrown away, leaving the theory *strictly*simpler.

To this discussion I wish to contribute the assertion that, in the light of a mathematically solid understanding of probability theory, decoherence is not ruled out by Occam's Razor, nor is it unfalsifiable, nor is it untestable.

We may consider e.g. decoherence and the collapse postulate, side by side, and evaluate critiques such as "Doesn't decoherence definitely predict that quantum probabilities should always be 50/50?" and "Doesn't collapse violate Special Relativity by implying influence at a distance?" We can consider the relative merits of these theories on grounds of their compatibility with experience and the apparent character of physical law.

To assert that decoherence is not even in the game—because the many worlds themselves are "extra entities" that violate Occam's Razor, or because the many worlds themselves are "untestable," or because decoherence makes no "new predictions"—all this is, I would argue, an outright error of probability theory. The discussion should simply discard those particular arguments and move on.

Quantum Non-Realism

"Does the moon exist when no one is looking at it?"

—Albert Einstein, asked of Niels Bohr

Suppose you were just starting to work out a theory of quantum mechanics.

You begin to encounter experiments that deliver different results depending on how closely you observe them. You dig underneath the reality you know, and find an extremely precise mathematical description that only gives you the relative frequency of outcomes; worse, it's made of complex numbers. Things behave like particles on Monday and waves on Tuesday.

The correct answer is not available to you as a hypothesis, because it will not be invented for another thirty years.

In a mess like that, what's the best you *could* do?

The best you can do is the *strict* "shut up and calculate" interpretation of quantum mechanics. You'll go on *trying* to develop new theories, because doing your best doesn't mean giving up. But we've specified that the correct answer won't be available for thirty years, and that means none of the new theories will really be any good. Doing the *best* you could theoretically do would mean that you recognized that, even as you looked for ways to test the hypotheses.

The best you could theoretically do would *not* include saying anything like, "The wavefunction only gives us probabilities, not certainties." That, in retrospect, was jumping to a conclusion; the wavefunction gives us a certainty of many worlds existing. So that part about the wavefunction being only a probability was not-quite-right. You calculated, but failed to shut up.

If you do the *best* that you can do without the correct answer being available, then, when you hear about decoherence, it will turn out that you have not said *anything*incompatible with decoherence. Decoherence is not ruled out by the data and the calculations. So if you refuse to affirm, as positive knowledge, any proposition which was not forced by the data and the calculations, the calculations will not *force* you to say anything incompatible with decoherence. So too with whatever the correct theory may be, if it is not decoherence. If you go astray, it must be from your own impulses.

But it is hard for human beings to shut up and calculate—*really* shut up and calculate. There is an overwhelming tendency to treat our ignorance as if it were positive knowledge.

I don't know if any conversations like this ever really took place, but this is how ignorance becomes knowledge:

Gallant: "Shut up and calculate."

Goofus: "Why?"

Gallant: “Because I don’t know what these equations mean, just that they seem to work.”

—five minutes later—

Goofus: “Shut up and calculate.”

Student: “Why?”

Goofus: “Because these equations don’t mean anything, they just work.”

Student: “Really? How do you know?”

Goofus: “Gallant told me.”

A similar transformation occurs in the leap from:

Gallant: “When my calculations show an amplitude of $-\frac{1}{3}i$ for this photon to get absorbed, my experiments showed that the photon was absorbed around 107 times out of 1,000, which is a good fit to $\frac{1}{9}$ the square of the modulus. There’s clearly some kind of connection between the experimental statistics and the squared modulus of the amplitude, but I don’t know what.”

Goofus: “The probability amplitude doesn’t say where the electron i*s*, but where it m*ight be.* The squared modulus is the probability that reality will turn out that way. Reality i*tself* is inherently nondeterministic.”

And again:

Gallant: “Once I measure something and get an experimental result, I do my future calculations using only the amplitude whose squared modulus went into calculating the frequency of that experimental result. Only this rule makes my further calculations correspond to observed frequencies.”

Goofus: “Since the amplitude i*s* the probability, once you k*now* the experimental result, the probability of everything else becomes zero!”

The whole slip from:

The square of this “amplitude” stuff corresponds tightly to our experimentally observed frequencies

to

The amplitude is the probability of getting the measurement

to

Well, obviously, once you know you didn’t get a measurement, its probability becomes zero

has got to be one of the most embarrassing wrong turns in the history of science.

If you take all this *literally*, it becomes the consciousness-causes-collapse interpretation of quantum mechanics. These days, just about nobody will confess to *actually* believing in the consciousness-causes-collapse interpretation of quantum mechanics—

But the physics textbooks are still written this way! People say they don't believe it, but they *talk as if* knowledge is responsible for removing incompatible "probability" amplitudes.

Yet as implausible as I find consciousness-causes-collapse, it at least gives us a picture of reality. Sure, it's an informal picture. Sure, it gives mental properties ontologically basic status. You can't *calculate* when an "experimental observation" occurs or what people "know," you *just know* when certain probabilities are *obviously*zero. And this "just knowing" just happens to fit your experimental results, whatever they are—

—but at least consciousness-causes-collapse purports to tell us how the universe works. The amplitudes are real, the collapse is real, the consciousness is real.

Contrast to this argument schema:

> Student: "Wait, you're saying that this amplitude disappears as soon as the measurement tells me it's not true?"
>
> Goofus: "No, no! It doesn't *literally* disappear. The equations don't mean anything —they just give good predictions."
>
> Student: "But then what *does* happen?"
>
> Goofus: *(Whorble. Hiss.)* "Never ask that question."
>
> Student: "And what about the part where we measure this photon's polarization over here, and a light-year away, the entangled photon's probability of being polarized up-down changes from 50% to 25%?"
>
> Goofus: "Yes, what about it?"
>
> Student: "Doesn't that violate Special Relativity?"
>
> Goofus: "No, because you're just *finding out* the other photon's polarization. Remember, the amplitudes aren't *real*."
>
> Student: "But Bell's Theorem shows there's no possible local hidden variable that could describe the other photon's polarization before we measure it—"
>
> Goofus: "Exactly! It's meaningless to talk about the photon's polarization before we measure it."
>
> Student: "But the probability suddenly changes—"
>
> Goofus: *"It's meaningless to talk about it before we measure it!"*

What does Goofus even *mean*, here? Never mind the plausibility of his words; what sort of state of reality would correspond to his words being true?

What way could reality *be*, that would make it meaningless to talk about Special Relativity being violated, because the property being influenced didn't exist, even though you could calculate the changes to it?

But you know what? Forget that. I want to know the answer to an even more important question:

Where is Goofus *getting* all this stuff?

Let's suppose that you take the Schrödinger equation, and assert, as a positive fact:

> This equation generates good predictions, but it doesn't mean anything!

Really? *How do you know?*

I sometimes go around saying that the fundamental question of rationality is *Why do you believe what you believe?*

You say the Schrödinger equation "doesn't mean anything." How did this item of definite knowledge end up in your possession, if it is not simply ignorance misinterpreted as knowledge?

Was there some experiment that told you? I am open to the idea that experiments can tell us things that seem philosophically impossible. But in this case I should like to see the decisive data. Was there a point where you carefully set up an experimental apparatus, and worked out what you should expect to see if (1) the Schrödinger equation was meaningful or (2) the Schrödinger equation was meaningless; and then you got result (2)?

> Gallant: "If I measure the 90° polarization of a photon, and then measure the 45° polarization, and then measure 90° again, my experimental history shows that in 100 trials a photon was absorbed 47 times and transmitted 53 times."

> Goofus: "The 90° polarization and 45° polarization are incompatible properties; they can't both e*xist* at the same time, and if you measure one, it is meaningless to t*alk* about the other."

How do you know?

How did you acquire that piece of knowledge, Goofus? I know where Gallant got *his*—but where did *yours* come from?

My attitude toward questions of existence and meaning was nicely illustrated in a discussion of the current state of evidence for whether the universe is spatially finite or spatially infinite, in which James D. Miller chided Robin Hanson:

> Robin, you are suffering from overconfidence bias in assuming that the universe exists. Surely there is some chance that the universe is of size zero.

To which I replied:

> James, if the universe doesn't exist, it would still be nice to know whether it's an infinite or a finite universe that doesn't exist.

Ha! You think pulling that old "universe doesn't exist" trick will stop me? It won't even slow me down!

It's not that I'm *ruling out* the possibility that the universe doesn't exist. It's just that, *even if* nothing exists, I still want to understand the nothing as best I can. My curiosity doesn't suddenly go away just because there's no reality, you know!

The nature of "reality" is something about which I'm still confused, which leaves open the possibility that there isn't any such thing. But Egan's Law still applies: "It all adds up to normality." Apples didn't stop falling when Einstein disproved Newton's theory of gravity.

Sure, when the dust settles, it could turn out that apples don't exist, Earth doesn't exist, reality doesn't exist. But the nonexistent apples will still fall toward the nonexistent ground at a meaningless rate of 9.8 m/s2.

You say the universe doesn't exist? Fine, suppose I believe that—though it's not clear *what* I'm supposed to believe, aside from repeating the words.

Now, what happens if I press *this* button?

In The Simple Truth, I said:

> Frankly, I'm not entirely sure myself where this "reality" business comes from. I can't create my own reality in the lab, so I must not understand it yet. But occasionally I believe strongly that something is going to happen, and then something else happens instead… So I need different names for the thingies that determine my predictions and the thingy that determines my experimental results. I call the former thingies "belief," and the latter thingy "reality."

You want to say that the quantum-mechanical equations are "not real"? I'll be charitable, and suppose this means something. What might it mean?

Maybe it means the equations which determine my predictions are substantially different from the thingy that determines my experimental results. Then what *does*determine my experimental results? If you tell me "nothing," I would like to know what sort of "nothing" it is, and why this "nothing" exhibits such apparent regularity in determining e.g. my experimental measurements of the mass of an electron.

I don't take well to people who tell me to stop asking questions. If you tell me something is definitely positively meaningless, I want to know exactly what you mean by that, and how you came to know. Otherwise you have not given me an answer, only told me to stop asking the question.

The Simple Truth describes the life of a shepherd and apprentice who have discovered how to count sheep by tossing pebbles into buckets, when they are visited by a delegate from the court who wants to know how the "magic pebbles" work. The shepherd tries to explain, "An empty bucket is magical if and only if the pastures are empty of sheep," but is soon overtaken by the excited discussions of the apprentice and the delegate as to how the magic might get into the pebbles.

Here we have quantum equations that deliver excellent experimental predictions. What *exactly* does it mean for them to be "meaningless"? Is it like a bucket of pebbles that *works for counting sheep*, but *doesn't have any magic*?

Back before Bell's Theorem ruled out local hidden variables, it seemed possible that (as Einstein thought) there was some more complete description of reality which we didn't have, and the quantum theory summarized incomplete knowledge of this more complete description. The laws we'd learned would turn out to be like the laws of statistical mechanics: quantitative statements of uncertainty. This would hardly make the equations "meaningless"; partial knowledge *is* the meaning of probability.

But Bell's Theorem makes it much less plausible that the quantum equations are partial knowledge of something deterministic, the way that statistical mechanics over classical physics is partial knowledge of something deterministic. And even so, the quantum equations would not be "meaningless" as that phrase is usually taken; they would be "statistical," "approximate," "partial information," or at worst "wrong."

Here we have equations that give us excellent predictions. You say they are "meaningless." I ask what it is that determines my experimental results, then. You cannot answer. Fine, then how do you justify ruling out the possibility that the quantum equations give such excellent predictions because they are, oh, say, *meaningful*?

I don't mean to trivialize questions of reality or meaning. But to call something "meaningless" and say that the argument is now resolved, finished, over, done with, you must have a theory of exactly how it is meaningless. And when the answer is given, the question should seem no longer mysterious.

As you may recall from Semantic Stopsigns, there are words and phrases which are not so much *answers* to questions, as cognitive traffic signals which indicate you should *stop asking* questions. "Why does anything exist in the first place? God!" is the classical example, but there are others, such as "Élan vital!"

Tell people to "shut up and calculate" because you don't know what the calculations mean, and inside of five years, "Shut up!" will be masquerading as a positive theory of quantum mechanics.

I have the *highest* respect for any historical physicists who even came *close* to *actually* shutting up and calculating, who were genuinely conservative in assessing what they did and didn't know. This is the best they could possibly do without actually being Hugh Everett, and I award them fifty rationality points. My scorn is reserved for those who interpreted "We don't know why it works" as the positive knowledge that the equations were definitely not real.

I mean, if that trick worked, it would be too good to confine to one subfield. Why shouldn't physicists use the "not real" loophole *outside* of quantum mechanics?

> "Hey, doesn't your new 'yarn theory' violate Special Relativity?"
>
> "Nah, the equations are meaningless. Say, doesn't your model of 'chaotic evil inflation' violate CPT symmetry?"
>
> "My equations are e*ven more meaningless* than your equations! So your criticism d*ouble* doesn't count."

And if that doesn't work, try writing yourself a Get Out of Jail Free card.

If there is a moral to the whole story, it is the moral of how very hard it is to stay in a state of *confessed* confusion, without making up a story that gives you closure—how hard it is to avoid manipulating your ignorance as if it were definite knowledge that you possessed.

Collapse Postulates

Macroscopic decoherence—also known as “many-worlds”—is the idea that the known quantum laws that govern microscopic events simply govern at all levels without alteration. Back when people didn’t know about decoherence—before it occurred to anyone that the laws deduced with such precision for microscopic physics might apply universally—what did people *think* was going on?

The initial reasoning seems to have gone something like:

> When my calculations showed an amplitude of $-\frac{1}{3}i$ for this photon to get absorbed, my experimental statistics showed that the photon was absorbed around 107 times out of 1,000, which is a good fit to $\frac{1}{9}$, the square of the modulus.

to

> The amplitude i*s* the probability (by way of the squared modulus).

to

> Once you measure something and *know it didn’t happen,* its p*robability* goes to zero.

Read literally, this implies that knowledge itself—or even conscious awareness—causes the collapse. Which was in fact the form of the theory put forth by Werner Heisenberg!

But people became increasingly nervous about the notion of importing dualistic language into fundamental physics—as well they should have been! And so the original reasoning was replaced by the notion of an objective “collapse” that destroyed all parts of the wavefunction except one, and was triggered sometime before superposition grew to human-sized levels.

Now, once you’re supposing that parts of the wavefunction can just vanish, you might think to ask:

> Is there only *one* survivor? Maybe there are many surviving worlds, but they survive with a frequency determined by their integrated squared modulus, and so the typical surviving world has experimental statistics that match the Born rule.

Yet collapse theories considered in modern academia only postulate *one* surviving world. Why?

Collapse theories were devised in a time when it *simply didn’t occur* to any physicists that more than one world *could* exist! People took for granted that measurements had single outcomes—it was an assumption so deep it was invisible, because it was what they *saw happening*. Collapse theories were devised to explain *why measurements had single outcomes*, rather than (in full generality) *why experimental statistics matched the Born rule*.

For similar reasons, the “collapse postulates” considered academically suppose that collapse occurs *before* any human beings get superposed. But experiments are steadily ruling out the possibility of "collapse" in increasingly large entangled systems. Apparently an experiment is underway to demonstrate quantum superposition at 50-micrometer scales, which is bigger than most neurons and getting up toward the diameter of some human hairs!

So why doesn't someone try jumping ahead of the game, and ask:

> Say, we keep having to postulate the collapse occurs steadily later and later. What if collapse occurs only once superposition reaches planetary scales and substantial divergence occurs—say, Earth's wavefunction collapses around once a minute? Then, while the surviving Earths at any given time would *remember* a long history of quantum experiments that matched the Born statistics, a supermajority of those Earths would begin obtaining non-Born results from quantum experiments and then abruptly cease to exist a minute later.

Why don't collapse theories like *that* one have a huge academic following, among the many people who apparently think it's okay for parts of the wavefunction to just vanish? Especially given that experiments are proving superposition in steadily larger systems?

A cynic might suggest that the reason for collapse's continued support isn't the *physical plausibility* of having large parts of the wavefunction suddenly vanish, or the hope of somehow explaining the Born statistics. The point is to keep the intuitive appeal of "I don't remember the measurement having more than one result, therefore only one thing happened; I don't remember splitting, so there must be only one of me." You don't remember dying, so superposed humans must never collapse. A theory that dared to stomp on intuition would be missing the whole point. You might as well just move on to decoherence.

So a cynic might suggest.

But surely it is too early to be attacking the motives of collapse supporters. That is mere argument ad hominem. What about the actual physical plausibility of collapse theories?

Well, first: Does any collapse theory have any experimental support? No.

With that out of the way…

If collapse actually worked the way its adherents say it does, it would be:

1. The only non-linear evolution in all of quantum mechanics.
2. The only non-unitary evolution in all of quantum mechanics.
3. The only non-differentiable (in fact, discontinuous) phenomenon in all of quantum mechanics.
4. The only phenomenon in all of quantum mechanics that is non-local in the configuration space.
5. The only phenomenon in all of physics that violates CPT symmetry.
6. The only phenomenon in all of physics that violates Liouville's Theorem (has a many-to-one mapping from initial conditions to outcomes).
7. The only phenomenon in all of physics that is acausal / non-deterministic / inherently random.
8. The only phenomenon in all of physics that is non-local in spacetime and propagates an influence faster than light.

What does the god-damned collapse postulate have to do for physicists to reject it? Kill a god-damned puppy?

If Many-Worlds Had Come First

Not that I'm claiming I could have done better, if I'd been born into that time, instead of this one…

Macroscopic decoherence, a.k.a. many-worlds, was first proposed in a 1957 paper by Hugh Everett III. The paper was ignored. John Wheeler told Everett to see Niels Bohr. Bohr didn't take him seriously.

Crushed, Everett left academic physics, invented the general use of Lagrange multipliers in optimization problems, and became a multimillionaire.

It wasn't until 1970, when Bryce DeWitt (who coined the term "many-worlds") wrote an article for *Physics Today*, that the general field was first informed of Everett's ideas. Macroscopic decoherence has been gaining advocates ever since, and may now be the majority viewpoint (or not).

But suppose that decoherence and macroscopic decoherence had been realized immediately following the discovery of entanglement, in the 1920s. And suppose that no one had proposed collapse theories until 1957. Would decoherence now be steadily declining in popularity, while collapse theories were slowly gaining steam?

Imagine an alternate Earth, where the very first physicist to discover entanglement and superposition said, "Holy flaming monkeys, there's a zillion other Earths out there!"

In the years since, many hypotheses have been proposed to explain the mysterious Born probabilities. But no one has *yet* suggested a collapse postulate. That possibility simply has not occurred to anyone.

One day, Huve Erett walks into the office of Biels Nohr…

"I just don't understand," Huve Erett said, "why no one in physics even seems *interested* in my hypothesis. Aren't the Born statistics the greatest puzzle in modern quantum theory?"

Biels Nohr sighed. Ordinarily, he wouldn't even bother, but something about the young man compelled him to try.

"Huve," says Nohr, "every physicist meets dozens of people per year who think they've explained the Born statistics. If you go to a party and tell someone you're a physicist, chances are at least one in ten they've got a new explanation for the Born statistics. It's one of the most famous problems in modern science, and worse, it's a problem that everyone thinks they can understand. To get attention, a new Born hypothesis has to be… pretty darn good."

"And *this*," Huve says, "*this* isn't *good?*"

Huve gestures to the paper he'd brought to Biels Nohr. It is a short paper. The title reads, "The Solution to the Born Problem." The body of the paper reads:

> When you perform a measurement on a quantum system, all parts of the wavefunction except one point vanish, with the survivor chosen non-

deterministically in a way determined by the Born statistics.

“Let me make absolutely sure,” Nohr says carefully, “that I understand you. You’re saying that we’ve got this wavefunction—evolving according to the Wheeler-DeWitt equation—and, all of a sudden, the whole wavefunction, except for one part, just spontaneously goes to zero amplitude. Everywhere at once. This happens when, way up at the macroscopic level, we ‘measure’ something.”

“Right!” Huve says.

“So the wavefunction knows when we ‘measure’ it. What exactly is a ‘measurement’? How does the wavefunction know we’re here? What happened before humans were around to measure things?”

“Um…” Huve thinks for a moment. Then he reaches out for the paper, scratches out “When you perform a measurement on a quantum system,” and writes in, “When a quantum superposition gets too large.”

Huve looks up brightly. “Fixed!”

“I see,” says Nohr. “And how large is ‘too large’?”

“At the 50-micron level, maybe,” Huve says, “I hear they haven’t tested that yet.”

Suddenly a student sticks his head into the room. “Hey, did you hear? They just verified superposition at the 50-micron level.”

“Oh,” says Huve, “um, whichever level, then. Whatever makes the experimental results come out right.”

Nohr grimaces. “Look, young man, the truth here isn’t going to be comfortable. Can you hear me out on this?”

“Yes,” Huve says, “I just want to know why physicists won’t listen to me.”

“All right,” says Nohr. He sighs. “Look, if this theory of yours were actually true—if whole sections of the wavefunction just instantaneously vanished—it would be… let’s see. The only law in all of quantum mechanics that is non-linear, non-unitary, non-differentiable and discontinuous. It would prevent physics from evolving locally, with each piece only looking at its immediate neighbors. Your ‘collapse’ would be the only fundamental phenomenon in all of physics with a preferred basis and a preferred space of simultaneity. Collapse would be the only phenomenon in all of physics that violates CPT symmetry, Liouville’s Theorem, and Special Relativity. In your original version, collapse would also have been the only phenomenon in all of physics that was inherently mental. Have I left anything out?”

“Collapse is also the only acausal phenomenon,” Huve points out. “Doesn’t that make the theory more wonderful and amazing?”

“I think, Huve,” says Nohr, “that physicists may view the exceptionalism of your theory as a point not in its favor.”

“Oh,” said Huve, taken aback. “Well, I think I can fix that non-differentiability thing by postulating a second-order term in the—”

“Huve,” says Nohr, “I don’t think you’re getting my point, here. The reason physicists aren’t paying attention to you, is that your theory isn’t physics. It’s magic.”

“But the Born statistics are the greatest puzzle of modern physics, and this theory provides a mechanism for the Born statistics!” Huve protests.

“No, Huve, it doesn’t,” Nohr says wearily. “That’s like saying that you’ve ‘provided a mechanism’ for electromagnetism by saying that there are little angels pushing the charged particles around in accordance with Maxwell’s equations. Instead of saying, ‘Here are Maxwell’s equations, which tells the angels where to push the electrons,’ we just say, ‘Here are Maxwell’s equations’ and are left with a strictly simpler theory. Now, we don’t know *why* the Born statistics happen. But you haven’t given the slightest reason why your ‘collapse postulate’ should eliminate worlds in accordance with the Born statistics, rather than something else. You’re not even making use of the fact that quantum evolution is unitary—”

“That’s because it’s not,” interjects Huve.

“—which everyone pretty much knows has got to be the key to the Born statistics, somehow. Instead you’re merely saying, ‘Here are the Born statistics, which tell the collapser how to eliminate worlds,’ and it’s strictly simpler to just say ‘Here are the Born statistics.’ ”

“But—” says Huve.

“*Also*,” says Nohr, raising his voice, “you’ve given no justification for why there’s only *one* surviving world left by the collapse, or why the collapse happens before any *humans* get superposed, which makes your theory *really suspicious* to a modern physicist. This is exactly the sort of untestable hypothesis that the ‘One Christ’ crowd uses to argue that we should ‘teach the controversy’ when we tell high school students about other Earths.”

“I’m not a One-Christer!” protests Huve.

“Fine,” Nohr says, “then *why* do you just assume there’s only one world left? And that’s not the only problem with your theory. Which part of the wavefunction gets eliminated, exactly? And in which basis? It’s clear that the whole wavefunction isn’t being compressed down to a delta, or ordinary quantum computers couldn’t stay in superposition when any collapse occurred anywhere—heck, ordinary molecular chemistry might start failing—”

Huve quickly crosses out “one point” on his paper, writes in “one part,” and then says, “Collapse doesn’t compress the wavefunction down to one point. It eliminates all the amplitude *except* one world, but leaves *all* the amplitude in that world.”

“Why?” says Nohr. “In principle, once you postulate ‘collapse,’ then ‘collapse’ could eliminate any part of the wavefunction, anywhere—why just one neat world left? Does the collapser *know we’re in here?*”

Huve says, “It leaves one whole world because that’s what fits our experiments.”

“Huve,” Nohr says patiently, “the term for that is ‘post hoc.’ Furthermore, decoherence is a continuous process. If you partition by whole brains with distinct neurons firing, the partitions have almost zero mutual interference within the wavefunction. But plenty of other processes overlap a great deal. There’s no possible way you can point to ‘one world’ and eliminate everything else without making completely arbitrary choices, including an arbitrary choice of basis—”

“But—” Huve says.

“And *above all*,” Nohr says, “the *reason* you can’t tell me which part of the wavefunction vanishes, or exactly when it happens, or exactly what triggers it, is that if we did adopt this theory of yours, it would be *the only informally specified, qualitative fundamental law* taught in all of physics. Soon no two physicists anywhere would agree on the exact details! Why? Because it would be the *only fundamental law in all of modern physics that was believed without experimental evidence to nail down exactly how it worked*.”

“What, really?” says Huve. “I thought a lot of physics was more informal than that. I mean, weren’t you just talking about how it’s impossible to point to ‘one world’?”

“That’s because worlds aren’t *fundamental*, Huve! We have massive experimental evidence underpinning the fundamental law, the Wheeler-DeWitt equation, that we use to describe the evolution of the wavefunction. We just apply exactly the same equation to get our description of macroscopic decoherence. But for difficulties of calculation, the equation would, in principle, tell us *exactly* when macroscopic decoherence occurred. We don’t know where the Born statistics come from, but we have massive evidence for what the Born statistics *are*. But when I ask you when, or where, collapse occurs, you don’t know—*because there’s no experimental evidence whatsoever to pin it down*. Huve, even if this ‘collapse postulate’ worked the way you say it does, *there’s no possible way you could* know *it!* Why not a gazillion other equally magical possibilities?”

Huve raises his hands defensively. “I’m not saying my theory should be taught in the universities as accepted truth! I just want it experimentally tested! Is that so wrong?”

“You haven’t specified when collapse happens, so I can’t construct a test that falsifies your theory,” says Nohr. “Now with that said, we’re already looking experimentally for any part of the quantum laws that change at increasingly macroscopic levels. Both on general principles, in case there’s something in the 20th decimal point that only shows up in macroscopic systems, and also in the hopes we’ll discover something that sheds light on the Born statistics. We check decoherence times as a matter of course. But we keep a *broad* outlook on what might be different. Nobody’s going to privilege your non-linear, non-unitary, non-differentiable, non-local, non-CPT-symmetric, non-relativistic, a-frikkin’-causal, faster-than-light, *in-bloody-formal* ‘collapse’ when it comes to looking for clues. Not until they see absolutely unmistakable evidence. And believe me, Huve, it’s going to take a hell of a lot of evidence to unmistake *this*. Even if we did find anomalous decoherence times, and I don’t think we will, it wouldn’t force your ‘collapse’ as the explanation.”

“What?” says Huve. “Why not?”

“Because there’s got to be a billion more explanations that are more plausible than violating Special Relativity,” says Nohr. “Do you realize that if this really happened, there would only be a *single* outcome when you measured a photon’s polarization? Measuring one photon in an entangled pair would influence the other photon a light-year away. Einstein would have a heart attack.”

“It doesn’t *really* violate Special Relativity,” says Huve. “The collapse occurs in exactly the right way to prevent you from ever actually *detecting* the faster-than-light influence.”

“That’s not a point in your theory’s favor,” says Nohr. “Also, Einstein would still have a heart attack.”

“Oh,” says Huve. “Well, we’ll say that the relevant aspects of the particle *don’t exist*until the collapse occurs. If something doesn’t exist, influencing it doesn’t violate Special Relativity—”

“You’re just digging yourself deeper. Look, Huve, as a general principle, theories that are actually *correct* don’t generate this level of confusion. But above all, there isn’t any evidence for it. You have no logical way of knowing that collapse occurs, and no reason to believe it. You made a mistake. Just say ‘oops’ and get on with your life.”

“But they *could* find the evidence someday,” says Huve.

“I can’t think of what evidence could determine *this particular* one-world hypothesis as an explanation, but in any case, right now we *haven’t* found any such evidence,” says Nohr. “We haven’t found anything even vaguely suggestive of it! You can’t update on evidence that could theoretically arrive someday but hasn’t arrived! Right now, today, there’s no reason to spend valuable time thinking about this rather than a billion other equally magical theories. There’s absolutely nothing that justifies your belief in ‘collapse theory’ any *more* than believing that someday we’ll learn to transmit faster-than-light messages by tapping into the acausal effects of praying to the Flying Spaghetti Monster!”

Huve draws himself up with wounded dignity. “You know, if my theory is wrong—and I do admit it might be wrong—”

“*If?*” says Nohr. “*Might?*”

“If, I say, my theory is wrong,” Huve continues, “then somewhere out there is another world where *I* am the famous physicist and *you* are the lone outcast!”

Nohr buries his head in his hands. “Oh, not this again. Haven’t you heard the saying, ‘Live in your own world’? And *you* of all people—”

“Somewhere out there is a world where the vast majority of physicists believe in collapse theory, and no one has even *suggested* macroscopic decoherence over the last thirty years!”

Nohr raises his head, and begins to laugh.

“What’s so funny?” Huve says suspiciously.

Nohr just laughs harder. “Oh, my! Oh, my! You really think, Huve, that there’s a world out there where they’ve known about quantum physics for thirty years, and nobody has even *thought* there might be more than one world?”

“Yes,” Huve says, “that’s exactly what I think.”

“Oh my! So you’re saying, Huve, that physicists detect superposition in microscopic systems, and work out quantitative equations that govern superposition in every single instance they can test. And for thirty years, not *one person* says, ‘Hey, I wonder if these laws happen to be universal.’ ”

“Why should they?” says Huve. “Physical models sometimes turn out to be wrong when you examine new regimes.”

“But to not even *think* of it?” Nohr says incredulously. “You see apples falling, work out the law of gravity for all the planets in the solar system except Jupiter, and it doesn’t even *occur* to you to apply it to Jupiter because Jupiter is too large? That’s like, like some kind of comedy routine where the guy opens a box, and it contains a spring-loaded pie, so the guy opens another box, and it contains another spring-loaded pie, and the guy just keeps doing this without even *thinking* of the possibility that the next box contains a pie too. You think John von Neumann, who may have been the highest-*g* human in history, wouldn’t think of it?”

“That’s right,” Huve says, “He wouldn’t. Ponder that.”

“This is the world where my good friend Ernest formulates his Schrödinger’s Cat thought experiment, and in this world, the thought experiment goes: ‘Hey, suppose we have a radioactive particle that enters a superposition of decaying and not decaying. Then the particle interacts with a sensor, and the sensor goes into a superposition of going off and not going off. The sensor interacts with an explosive, that goes into a superposition of exploding and not exploding; which interacts with the cat, so the cat goes into a superposition of being alive and dead. Then a human looks at the cat,’ and at this point Schrödinger stops, and goes, ‘gee, I just can’t imagine what could happen next.’ So Schrödinger shows this to everyone else, and they’re also like ‘Wow, I got no idea what could happen at this point, what an amazing paradox.’ Until finally *you* hear about it, and you’re like, ‘hey, maybe at *that*point half of the superposition just vanishes, at random, faster than light,’ and everyone else is like, ‘Wow, what a great idea!’ ”

“That’s right,” Huve says again. “It’s got to have happened somewhere.”

“Huve, this is a world where every single physicist, and probably the whole damn human species, is too dumb to sign up for cryonics! We’re talking about the Earth where George W. Bush is President.”

Many Worlds, One Best Guess

If you look at many microscopic physical phenomena—a photon, an electron, a hydrogen atom, a laser—and a million other known experimental setups—it is possible to come up with simple laws that seem to govern all small things (so long as you don't ask about gravity). These laws govern the evolution of a highly abstract and mathematical object that I've been calling the "amplitude distribution," but which is more widely referred to as the "wavefunction."

Now there are gruesome questions about the proper generalization that covers all these tiny cases. Call an object "grue" if it appears green before January 1, 2020 and appears blue thereafter. If all emeralds examined so far have appeared green, is the proper generalization, "Emeralds are green" or "Emeralds are grue"?

The answer is that the proper generalization is "Emeralds are green." I'm not going to go into the arguments at the moment. It is not the subject of this essay, and the obvious answer in this case happens to be correct. The true Way is not stupid: however clever you may be with your logic, it should finally arrive at the right answer rather than a wrong one.

In a similar sense, the *simplest* generalizations that would cover observed *microscopic* phenomena alone take the form of "All electrons have spin $\frac{1}{2}$" and not "All electrons have spin $\frac{1}{2}$ before January 1, 2020" or "All electrons have spin $\frac{1}{2}$ unless they are part of an entangled system that weighs more than 1 gram."

When we turn our attention to macroscopic phenomena, our sight is obscured. We cannot experiment on the wavefunction of a human in the way that we can experiment on the wavefunction of a hydrogen atom. In no case can you actually read off the wavefunction with a little quantum scanner. But in the case of, say, a human, the size of the entire organism defeats our ability to perform precise calculations or precise experiments—we cannot confirm that the quantum equations are being obeyed in *precise detail*.

We know that phenomena commonly thought of as "quantum" do not just disappear when many microscopic objects are aggregated. Lasers put out a flood of coherent photons, rather than, say, doing something completely different. Atoms have the chemical characteristics that quantum theory says they should, enabling them to aggregate into the stable molecules making up a human.

So in one sense, we have a great deal of evidence that quantum laws are aggregating to the macroscopic level without too much difference. Bulk chemistry still works.

But we cannot directly verify that the particles making up a human have an aggregate wavefunction that behaves *exactly* the way the simplest quantum laws say. Oh, we know that molecules and atoms don't disintegrate, we know that macroscopic mirrors still reflect from the middle. We can get *many* high-level predictions from the assumption that the microscopic and the macroscopic are governed by the same laws, and every prediction tested has come true.

But if someone were to claim that the macroscopic quantum picture differs from the microscopic one in some as-yet-untestable detail—something that only shows up at the unmeasurable 20th decimal place of microscopic interactions, but aggregates into something bigger for macroscopic interactions—well, we can't *prove* they're wrong. It is Occam's Razor that says, "There are zillions of new fundamental laws you could postulate in the 20th decimal place; why are you even *thinking* about this one?"

If we calculate using the simplest laws which govern all known cases, we find that humans end up in states of quantum superposition, just like photons in a superposition of reflecting from and passing through a half-silvered mirror. In the Schrödinger's Cat setup, an unstable atom goes into a superposition of disintegrating, and not-disintegrating. A sensor, tuned to the atom, goes into a superposition of triggering and not-triggering. (Actually, the superposition is now a joint state of [atom-disintegrated × sensor-triggered] + [atom-stable × sensor-not-triggered].) A charge of explosives, hooked up to the sensor, goes into a superposition of exploding and not exploding; a cat in the box goes into a superposition of being dead and alive; and a human, looking inside the box, goes into a superposition of throwing up and being calm. The same law at all levels.

Human beings who interact with superposed systems will themselves evolve into superpositions. But the brain that sees the exploded cat, and the brain that sees the living cat, will have many neurons firing differently, and hence many many particles in different positions. They are very distant in the configuration space, and will communicate to an exponentially infinitesimal degree. Not the 30th decimal place, but the 1030th decimal place. No particular mind, no particular cognitive causal process, sees a blurry superposition of cats.

The fact that "you" only seem to see the cat alive, *or* the cat dead, is exactly what the simplest quantum laws predict. So we have no reason to believe, from our experience so far, that the quantum laws are in any way different at the macroscopic level than the microscopic level.

And physicists have verified superposition at steadily larger levels. Apparently an effort is currently underway to test superposition in a 50-micron object, larger than most neurons.

The existence of other versions of ourselves, and indeed other Earths, is not supposed *additionally*. We are simply supposing that the same laws govern at all levels, having no reason to suppose differently, and all experimental tests having succeeded so far. The existence of other decoherent Earths is a *logical consequence*of the simplest generalization that fits all known facts. If you think that Occam's Razor says that the other worlds are "unnecessary entities" being multiplied, then you should check the probability-theoretic math; that is just not how Occam's Razor works.

Yet there is one particular puzzle that seems odd in trying to extend microscopic laws universally, including to superposed humans:

If we try to get probabilities by counting the number of distinct observers, then there is no *obvious* reason why the integrated squared modulus of the wavefunction should correlate with statistical experimental results. There is no known reason for the Born probabilities, and it even seems that, a priori, we would expect a 50/50 probability of any binary quantum experiment going both ways, if we just counted observers.

Robin Hanson suggests that if exponentially tinier-than-average decoherent blobs of amplitude ("worlds") are interfered with by exponentially tiny leakages from larger blobs, we will get the Born probabilities back out. I consider this an interesting possibility, because it is so normal.

(I myself have had recent thoughts along a different track: If I try to count observers the obvious way, I get strange-seeming results in general, not just in the case of quantum physics. If, for example, I split my brain into a trillion similar parts, conditional on winning the lottery while anesthetized; allow my selves to wake up and perhaps differ to small degrees from each other; and then merge them all into one self again; then counting observers the obvious way says I should be able to make myself win the lottery (if I can split my brain and merge it, as an uploaded mind might be able to do).

In this connection, I find it very interesting that the Born rule does *not* have a split-remerge problem. Given unitary quantum physics, Born's rule is the *unique* rule that prevents "observers" from having psychic powers—which doesn't *explain* Born's rule, but is certainly an *interesting fact*. Given Born's rule, even splitting and remerging worlds would still lead to consistent probabilities. Maybe physics uses better anthropics than I do!

Perhaps I should take my cues from physics, instead of trying to reason it out a priori, and see where that leads me? But I have not been led anywhere *yet*, so this is hardly an "answer.")

Wallace, Deutsch, and others try to derive Born's Rule from decision theory. I am rather suspicious of this, because it seems like there is a component of "What happens to me?" that I cannot alter by modifying my utility function. Even if I didn't *care* at all about worlds where I didn't win a quantum lottery, it still seems to me that there is a sense in which I would "mostly" wake up in a world where I didn't win the lottery. It is this that I think needs explaining.

The point is that many hypotheses about the Born probabilities have been proposed. Not as many as there should be, because the mystery was falsely marked "solved" for a long time. But still, there have been many proposals.

There is legitimate hope of a solution to the Born puzzle without new fundamental laws. Your world does not split into exactly two new subprocesses on the exact occasion when you see "absorbed" or "transmitted" on the LCD screen of a photon sensor. We are constantly being superposed and decohered, all the time, sometimes along continuous dimensions—though brains are digital and involve whole neurons firing, and fire/not-fire would be an extremely decoherent state even of a *single*neuron… There would seem to be room for *something* unexpected to account for the Born statistics—a better understanding of the anthropic weight of observers, or a better understanding of the brain's superpositions—without new fundamentals.

We cannot rule out, though, the possibility that a new fundamental law is involved in the Born statistics.

As Jess Riedel puts it:

> If there's one lesson we can take from the history of physics, it's that everytime new experimental "regimes" are probed (e.g. large velocities, small sizes, large mass densities, large energies), phenomena are observed which lead to new theories (Special Relativity, quantum mechanics, General Relativity, and the Standard Model, respectively).

"Every time" is too strong. A nitpick, yes, but also an important point: you can't just *assume* that any particular law will fail in a new regime. But it's possible that a new fundamental law is involved in the Born statistics, and that this law manifests only in the 20th decimal place at microscopic levels (hence being undetectable so far) while aggregating to have substantial effects at macroscopic levels.

Could there be some law, as yet undiscovered, that causes there to be only *one*world?

This is a shocking notion; it implies that all our twins in the other worlds— all the different versions of ourselves that are constantly split off, not just by human researchers doing quantum measurements, but by ordinary entropic processes—are actually *gone*, leaving us alone! This version of Earth would be the *only* version that exists in local space! If the inflationary scenario in cosmology turns out to be wrong, and the topology of the universe is both finite and relatively small—so that Earth does not have the distant duplicates that would be implied by an exponentially vast universe—then this Earth could be the only Earth that exists *anywhere*, a rather unnerving thought!

But it is dangerous to focus too much on specific hypotheses that you have no specific reason to think about. This is the same root error of the Intelligent Design folk, who pick any random puzzle in modern genetics, and say, "See, God must have done it!" Why "God," rather than a zillion other possible explanations?—which you would have thought of long before you postulated divine intervention, if not for the fact that you secretly started out already knowing the answer you wanted to find.

You shouldn't even *ask*, "Might there only be one world?" but instead just go ahead and do physics, and raise that *particular* issue only if new evidence demands it.

Could there be some as-yet-unknown fundamental law, that gives the universe a privileged center, which happens to coincide with Earth—thus proving that Copernicus was wrong all along, and the Bible right?

Asking *that particular* question—rather than a zillion other questions in which the center of the universe is Proxima Centauri, or the universe turns out to have a favorite pizza topping and it is pepperoni—betrays your hidden agenda. And though an unenlightened one might not realize it, giving the universe a privileged center *that follows Earth around through space* would be rather difficult to do with any *mathematically simple* fundamental law.

So too with asking whether there might be only one world. It betrays a sentimental attachment to human intuitions already proven wrong. The wheel of science turns, but it doesn't turn *backward*.

We have specific reasons to be highly suspicious of the notion of only one world. The notion of "one world" exists on a higher level of organization, like the location of Earth in space; on the quantum level there are no firm boundaries (though brains that differ by entire neurons firing are certainly decoherent). How would a *fundamental* physical law identify one *high-level* world?

Much worse, any physical scenario in which there was a *single* surviving world, so that any measurement had only a *single* outcome, would violate Special Relativity.

If the same laws are true at all levels—i.e., if many-worlds is correct—then when you measure one of a pair of entangled polarized photons, you end up in a world in which the photon is polarized, say, up-down, and alternate versions of you end up in worlds where the photon is polarized left-right. From your perspective before doing the measurement, the probabilities are 50/50. Light-years away, someone measures the other photon at a 20° angle to your own basis. From their perspective, too, the probability of getting either immediate result is 50/50—they maintain an invariant state of generalized entanglement with your faraway location, no matter what you do. But when the two of you meet, years later, your probability of meeting a friend who got the *same* result is 11.6%, rather than 50%.

If there is only one global world, then there is only a single outcome of any quantum measurement. Either you measure the photon polarized up-down, or left-right, but not both. Light-years away, someone else's probability of measuring the photon polarized similarly in a 20° rotated basis actually *changes* from 50/50 to 11.6%.

You cannot possibly interpret this as a case of merely revealing properties that were already there; this is ruled out by Bell's Theorem. There does not seem to be any possible consistent view of the universe in which both quantum measurements have a single outcome, and yet both measurements are predetermined, neither influencing the other. Something has to actually *change*, faster than light.

And this would appear to be a fully general objection, not just to collapse theories, but to any possible theory that gives us one global world! There is no consistent view in which measurements have single outcomes, but are locally determined (even locally randomly determined). Some mysterious influence has to cross a spacelike gap.

This is not a trivial matter. You cannot save yourself by waving your hands and saying, "the influence travels backward in time to the entangled photons' creation, then forward in time to the other photon, so it never actually crosses a spacelike gap." (This view has been seriously put forth, which gives you some idea of the magnitude of the paradox implied by one global world!) One measurement has to change the other, so which measurement happens *first*? Is there a global space of simultaneity? You can't have both measurements happen "first" because under Bell's Theorem, there's no way local information could account for observed results, etc.

Incidentally, this experiment has already been performed, and if there is a mysterious influence it would have to travel six million times as fast as light in the reference frame of the Swiss Alps. Also, the mysterious influence has been experimentally shown not to care if the two photons are measured in reference frames which would cause each measurement to occur "before the other."

Special Relativity seems counterintuitive to us humans—like an arbitrary speed limit, which you could get around by going backward in time, and then forward again. A law you could escape prosecution for violating, if you managed to hide your crime from the authorities.

But what Special Relativity really says is that human intuitions about space and time are simply wrong. There *is* no global "now," there *is* no "before" or "after" across spacelike gaps. The ability to *visualize* a single global world, *even in principle*, comes from not getting Special Relativity on a gut level. Otherwise it would be obvious that physics proceeds locally with invariant states of distant entanglement, and the requisite information is simply *not locally present* to support a *globally single world*.

It might be that this seemingly impeccable logic is flawed—that my application of Bell's Theorem and relativity to rule out any single global world contains some hidden assumption of which I am unaware—

—but consider the burden that a single-world theory must now shoulder! There is absolutely no reason *in the first place* to suspect a global single world; this is just *not what current physics says!* The global single world is an ancient human intuition that was *disproved*, like the idea of a universal absolute time. The superposition principle is visible even in half-silvered mirrors; experiments are verifying the disproof at steadily larger levels of superposition—but above all there is *no longer any reason to privilege the hypothesis* of a global single world. The ladder has been yanked out from underneath that human intuition.

There is no experimental evidence that the macroscopic world is single (we already know the microscopic world is superposed). And the prospect necessarily either violates Special Relativity, or takes an even more miraculous-seeming leap and violates seemingly impeccable logic. The latter, of course, being much more plausible in practice. But it isn't really *that* plausible in an absolute sense. *Without experimental evidence*, it is generally a *bad sign* to have to postulate arbitrary logical miracles.

As for quantum non-realism, it appears to me to be nothing more than a Get Out of Jail Free card. "It's okay to violate Special Relativity because none of this is real anyway!" The equations cannot reasonably be hypothesized to deliver such excellent predictions *for literally no reason*. Bell's Theorem rules out the obvious possibility that quantum theory represents imperfect knowledge of something locally deterministic.

Furthermore, macroscopic decoherence gives us a perfectly *realistic* understanding of what is going on, in which the equations deliver such good predictions because they mirror reality. And so the idea that the quantum equations are just "meaningless," and therefore it is okay to violate Special Relativity, so we can have one global world after all, is not *necessary*. To me, quantum non-realism appears to be a huge bluff built around semantic stopsigns like "Meaningless!"

It is not quite safe to say that the existence of multiple Earths is as well-established as any other truth of science. The existence of quantum other worlds is not so well-established as the existence of trees, which most of us can personally observe.

Maybe there is something in that 20th decimal place, which aggregates to something bigger in macroscopic events. Maybe there's a loophole in the seemingly iron logic which says that any single global world must violate Special Relativity, because the information to support a single global world is not locally available. And maybe the Flying Spaghetti Monster is just messing with us, and the world we know is a lie.

So all we can say about the existence of multiple Earths, is that it is as rationally probable as e.g. the statement that spinning black holes do not violate conservation of angular momentum. We have extremely fundamental reasons, having to do with the rotational symmetry of space, to suspect that conservation of angular momentum is built into the underlying nature of physics. And we have no specific reason to suspect this *particular* violation of our old generalizations in a higher-energy regime.

But we haven't actually checked conservation of angular momentum for rotating black holes—so far as I know. (And as I am talking here about rational guesses in states of partial knowledge, the point is exactly the same if the observation has been made and I do not know it yet.) And black holes are a more massive regime. So the obedience of black holes is not *quite* as assured as that my toilet conserves angular momentum while flushing, which come to think, I haven't checked either…

Yet if you make the *mistake* of thinking too hard about this one particular possibility, instead of zillions of other possibilities—and especially if you don't understand the fundamental reason *why* angular momentum is conserved— then it may start seeming more and more plausible that "spinning black holes violate conservation of angular momentum," as you think of more and more vaguely plausible-sounding reasons it *could* be true.

But the rational probability is pretty damned small.

Likewise the rational probability that there is only one Earth.

I mention this to explain my habit of talking as if many-worlds is an obvious fact. Many-worlds *is* an obvious fact, if you have all your marbles lined up correctly (understand very basic quantum physics, know the formal probability theory of Occam's Razor, understand Special Relativity, etc.) It is in fact considerably *more*obvious to me than the proposition that spinning black holes should obey conservation of angular momentum.

The only reason why many-worlds is not universally acknowledged as a direct prediction of physics which requires magic to violate, is that a contingent accident of our Earth's scientific history gave an entrenched academic position to a phlogiston-like theory that had an unobservable faster-than-light magical "collapse" devouring all other worlds. And many academic physicists do not have a mathematical grasp of Occam's Razor, which is the usual method for ridding physics of invisible angels. So when they encounter many-worlds and it conflicts with their (undermined) intuition that only one world exists, they say, "Oh, that's multiplying entities"—which is just flatly wrong as probability theory—and go on about their daily lives.

I am not in academia. I am not constrained to bow and scrape to some senior physicist who hasn't grasped the obvious, but who will be reviewing my journal articles. I need have no fear that I will be rejected for tenure on account of scaring my students with "science-fiction tales of other Earths." If *I* can't speak plainly, who can?

So let me state then, very clearly, on behalf of any and all physicists out there who dare not say it themselves: Many-worlds *wins outright* given our current state of evidence. There is no more reason to postulate a single Earth, than there is to postulate that two colliding top quarks would decay in a way that violates Conservation of Energy. It takes more than an unknown fundamental law; it takes magic.

The debate should already be over. It should have been over fifty years ago. The state of evidence is too lopsided to justify further argument. There is no balance in this issue. There is no rational controversy to teach. The laws of probability theory are laws, not suggestions*; there is no flexibility in the best guess given this evidence. Our children will look back at the fact that we were still arguing about this in the early twenty-first century, and correctly deduce that we were nuts.*

We have embarrassed our Earth long enough by failing to see the obvious. So for the honor of my Earth, I write as if the existence of many-worlds were an established fact, because it *is*. The only question now is how long it will take for the people of this world to update.

Living in Many Worlds

Some commenters have recently expressed disturbance at the thought of constantly splitting into zillions of other people, as is the straightforward and unavoidable prediction of quantum mechanics.

Others have confessed themselves unclear as to the implications of many-worlds for planning: If you decide to buckle your seat belt in this world, does that increase the chance of another self unbuckling their seat belt? Are you being selfish at their expense?

Just remember Egan's Law: *It all adds up to normality.*

(After Greg Egan, in *Quarantine*.[1])

Frank Sulloway said [2]:

> Ironically, psychoanalysis has it over Darwinism precisely because its predictions are so outlandish and its explanations are so counterintuitive that we think, I*s that really true? How radical!* Freud's ideas are so intriguing that people are willing to pay for them, while one of the great disadvantages of Darwinism is that we feel we know it already, because, in a sense, we do.

When Einstein overthrew the Newtonian version of gravity, apples didn't stop falling, planets didn't swerve into the Sun. Every new theory of physics must *capture* the successful predictions of the old theory it displaced; it should predict that the sky will be blue, rather than green.

So don't think that many-worlds is there to make strange, radical, exciting predictions. It all adds up to normality.

Then why should anyone care?

Because there was once asked the question, fascinating unto a rationalist: *What* all adds up to normality?

And the answer to this question turns out to be: quantum mechanics. It is *quantum mechanics* that adds up to normality.

If there were something else there *instead* of quantum mechanics, *then* the world would look strange and unusual.

Bear this in mind, when you are wondering how to live in the strange new universe of many worlds: *You have always been there.*

Religions, anthropologists tell us, usually exhibit a property called *minimal counterintuitiveness*; they are startling enough to be memorable, but not so bizarre as to be *difficult* to memorize. Anubis has the head of a dog, which makes him memorable, but the rest of him is the body of a man. Spirits can see through walls; but they still become hungry.

But physics is not a religion, set to surprise you just exactly enough to be memorable. The underlying phenomena are so counterintuitive that it takes long study for humans to come to grips with them. But the surface phenomena are entirely ordinary. You will *never* catch a glimpse of another world out of the corner of your eye. You will *never* hear the voice of some other self. That is unambiguously prohibited outright by the laws. Sorry, you're just schizophrenic.

The act of making *decisions* has no special interaction with the process that branches worlds. In your *mind*, in your *imagination*, a decision seems like a branching point where the world could go two different ways. But you would feel just the same uncertainty, visualize just the same alternatives, if there were only one world. That's what people thought for centuries before quantum mechanics, and they still visualized alternative outcomes that could result from their decisions.

Decision and *decoherence* are *entirely orthogonal concepts*. If your brain never became decoherent, then that single cognitive process would still have to imagine different choices and their different outcomes. And a rock, which makes no decisions, obeys the same laws of quantum mechanics as anything else, and splits frantically as it lies in one place.

You don't split *when you come to a decision in particular*, any more than you particularly split when you take a breath. You're just splitting all the time as the result of decoherence, which has nothing to do with choices.

There is a population of worlds, and in each world, it all adds up to normality: apples don't stop falling. In each world, people choose the course that seems best to them. Maybe they happen on a different line of thinking, and see new implications or miss others, and come to a different choice. But it's not that one world chooses each choice. It's not that one version of you chooses what seems best, and another version chooses what seems worst. In each world, apples go on falling and people go on doing what seems like a good idea.

Yes, you can nitpick exceptions to this rule, but they're *normal* exceptions. It all adds up to normality, in all the worlds.

You cannot "choose which world to end up in." In all the worlds, people's choices determine outcomes in the same way they would in just one single world.

The choice you make here does not have some strange balancing influence on some world elsewhere. There is no causal communication between decoherent worlds. In each world, people's choices control the future of that world, not some other world.

If you can imagine decisionmaking in one world, you can imagine decision-making in many worlds: just have the world constantly splitting while otherwise obeying all the same rules.

In no world does two plus two equal five. In no world can spaceships travel faster than light. All the quantum worlds obey our laws of physics; their existence is asserted in the first place by our laws of physics. Since the beginning, not one unusual thing has ever happened, in this or any other world. They are all lawful.

Are there horrible worlds out there, which are utterly beyond your ability to affect? Sure. And horrible things happened during the twelfth century, which are also beyond your ability to affect. But the twelfth century is not your responsibility, because it has, as the quaint phrase goes, "already happened." I would suggest that you consider every world that is not in your future to be part of the "generalized past."

Live in your own world. Before you knew about quantum physics, you would not have been tempted to try living in a world that did not seem to exist. Your decisions should add up to this same normality: you shouldn't try to live in a quantum world you can't communicate with.

Your decision theory should (almost always) be the same, whether you suppose that there is a 90% probability of something happening, or if it will happen in 9 out of 10 worlds. Now, because people have trouble handling probabilities, it may be helpful to visualize something happening in 9 out of 10 worlds. But this just helps you use normal decision theory.

Now is a good time to begin learning how to shut up and multiply. As I note in Lotteries: A Waste of Hope:

> The human brain doesn't do 64-bit floating-point arithmetic, and it can't devalue the emotional force of a pleasant anticipation by a factor of 0.00000001 without dropping the line of reasoning entirely.

And in New Improved Lottery:

> Between zero chance of becoming wealthy, and epsilon chance, there is an order-of-epsilon difference. If you doubt this, let epsilon equal one over googolplex.

If you're thinking about a world that could arise in a lawful way, but whose probability is a quadrillion to one, and something very pleasant or very awful is happening in this world . . . well, it does probably exist, if it is lawful. But you should try to release one quadrillionth as many neurotransmitters, in your reward centers or your aversive centers, so that you can weigh that world *appropriately* in your decisions. If you don't think you can do that . . . don't bother thinking about it.

Otherwise you might as well go out and buy a lottery ticket using a quantum random number, a strategy that is *guaranteed* to result in a very tiny mega-win.

Or here's another way of thinking about it: Are you considering expending some mental energy on a world whose frequency in your future is less than a trillionth? Then go get a 10-sided die from your local gaming store, and, before you begin thinking about that strange world, start rolling the die. If the die comes up 9 twelve times in a row, *then* you can think about that world. Otherwise don't waste your time; thought-time is a resource to be expended wisely.

You can roll the dice as many times as you like, but you can't think about the world until 9 comes up twelve times in a row. Then you can think about it for a minute. After that you have to start rolling the die again.

This may help you to appreciate the concept of "trillion to one" on a more visceral level.

If at any point you catch yourself thinking that quantum physics might have some kind of strange, *abnormal* implication for everyday life—then you should probably stop right there.

Oh, there are a *few* implications of many-worlds for ethics. Average utilitarianism suddenly looks a lot more attractive—you don't need to worry about creating as many people as possible, because there are already plenty of people exploring person-space. You just want the average quality of life to be as high as possible, in the future worlds that are your responsibility.

And you should always take joy in discovery, as long as *you personally* don't know a thing. It is meaningless to talk of being the "first" or the "only" person to know a thing, when everything knowable is known within worlds that are in neither your past nor your future, and are neither before or after you.

But, by and large, it all adds up to normality. If your understanding of many-worlds is the tiniest bit *shaky*, and you are contemplating whether to believe some strange proposition, or feel some strange emotion, or plan some strange strategy, then I can give you very simple advice: Don't.

The quantum universe is not a strange place into which you have been thrust. It is the way things have always been.

---

1. Greg Egan, *Quarantine* (London: Legend Press, 1992).

2. Robert S. Boynton, "The Birth of an Idea: A Profile of Frank Sulloway," The New Yorker (October 1999).

Mach's Principle: Anti-Epiphenomenal Physics

Previously in series: Many Worlds, One Best Guess
Followup to: The Generalized Anti-Zombie Principle

> **Warning: Mach's Principle is not experimentally proven, though it is widely considered to be credible.**

Centuries ago, when Galileo was promoting the Copernican model in which the Earth spun on its axis and traveled around the Sun, there was great opposition from those who trusted their common sense:

"How could the Earth be moving? I don't *feel* it moving! The ground beneath my feet seems perfectly steady!"

And lo, Galileo said: If you were on a ship sailing across a perfectly level sea, and you were in a room in the interior of the ship, you wouldn't know how fast the ship was moving. If you threw a ball in the air, you would still be able to catch it, because the ball would have initially been moving at the same speed as you and the room and the ship. *So you can never tell how fast you are moving.*

This would turn out to be the beginning of one of the most important ideas in the history of physics. Maybe even *the* most important idea in *all* of physics. And I'm not talking about Special Relativity.

Suppose the *entire* universe was moving. Say, the universe was moving left along the *x* axis at 10 kilometers per hour.

If you tried to visualize what I just said, it *seems* like you can imagine it. If the universe is standing still, then you imagine a little swirly cloud of galaxies standing still. If the whole universe is moving left, then you imagine the little swirly cloud moving left across your field of vision until it passes out of sight.

But then, some people think they can imagine philosophical zombies: entities who are identical to humans down to the molecular level, but not conscious. So you can't always trust your imagination.

Forget, for a moment, anything you know about relativity. Pretend you live in a Newtonian universe.

In a Newtonian universe, 3+1 spacetime can be broken down into 3 space dimensions and 1 time dimension, and you can write them out as 4 real numbers, (x, y, z, t). Deciding how to write the numbers involves seemingly arbitrary choices, like which direction to call 'x', and which perpendicular direction to then call 'y', and where in space and time to put your origin (0, 0, 0, 0), and whether to use meters or miles to measure distance. But once you make these arbitrary choices, you can, in a Newtonian universe, use the same system of coordinates to describe the whole universe.

Suppose that you pick an arbitrary but uniform (x, y, z, t) coordinate system. Suppose that you use these coordinates to describe every physical experiment you've ever done—heck, every observation you've ever made.

Next, suppose that you were, *in your coordinate system,* to shift the origin 10 meters to the left along the x axis. Then if you originally thought that Grandma's House was 400 meters to the right of the origin, you would now think that Grandma's House is 410 meters to the right of the origin. Thus every point (x, y, z, t) would be relabeled as (x' = x + 10, y' = y, z' = z, t' = t).

You can express the idea that "physics does not have an absolute origin", by saying that the observed laws of physics, as you generalize them, should be exactly the same after you perform this coordinate transform. The *history* may not be written out in exactly the same way, but the *laws* will be written out the same way. Let's say that in the old coordinate system, Your House is at (100, 10, -20, 7:00am) and you walk to Grandma's House at (400, 10, -20, 7:05am). Then you traveled from Your House to Grandma's House at one meter per second. In the new coordinate system, we would write the history as (110, 10, 20, 7:00am) and (410, 10, -20, 7:05am) but your apparent speed would come out the same, and hence so would your acceleration. The *laws* governing how fast things moved when you pushed on them—how fast you accelerated forward when your legs pushed on the ground—would be the same.

Now if you were given to jumping to conclusions, and moreover, given to jumping to conclusions that were exactly right, you might say:

"Since there's no way of figuring out where the origin is by looking at the laws of physics, the origin must not really *exist!* There *is* no (0, 0, 0, 0) point floating out in space somewhere!"

Which is to say: There is just *no fact of the matter* as to where the origin "really" is. When we argue about our choice of representation, this fact about the map does not actually correspond to any fact about the territory.

Now this statement, if you interpret it in the natural way, is not *necessarily* true. We can readily imagine alternative laws of physics, which, written out in their most natural form, would *not* be insensitive to shifting the "origin". The Aristotelian universe had a crystal sphere of stars rotating around the Earth. But so far as anyone has been able to tell, in our real universe, the laws of physics do *not* have any natural "origin" written into them. When you write out your observations in the simplest way, the coordinate transform x' = x + 10 does not change any of the laws; you write the same laws over x' as over x.

As Feynman said:

> Philosophers, incidentally, say a great deal about what is *absolutely necessary* for science, and it is always, so far as one can see, rather naive, and probably wrong. For example, some philosopher or other said it is fundamental to the scientific effort that if an experiment is performed in, say, Stockholm, and then the same experiment is done in, say, Quito, the *same results* must occur. That is quite false. It is not necessary that *science* do that; it may be a *fact of experience,* but it is not necessary...
>
> What *is* the fundamental hypothesis of science, the fundamental philosophy? We stated it in the first chapter: *the sole test of the validity of any idea is experiment*...

> If we are told that the same experiment will always produce the same result, that is all very well, but if when we try it, it does *not*, then it does *not*. We just have to take what we see, and then formulate all the rest of our ideas in terms of our actual experience.

And so if you regard the universe itself as a sort of Galileo's Ship, it would seem that the notion of the entire universe *moving at a particular rate*—say, all the objects in the universe, including yourself, moving left along the x axis at 10 meters per second—must also be silly. *What* is it that moves?

If you believe that everything in a Newtonian universe is moving left along the x axis at an average of 10 meters per second, then that just says that when you write down your observations, you write down an x coordinate that is 10 meters per second to the left, of what you would have written down, if you believed the universe was standing still. If the universe is standing still, you would write that Grandma's House was observed at (400, 10, -20, 7:00am) and then observed again, a minute later, at (400, 10, -20, 7:01am). If you believe that the whole universe is moving to the left at 10 meters per second, you would write that Grandma's House was observed at (400, 10, -20, 7:00am) and then observed again at (-200, 10, -20, 7:01am). Which is just the same as believing that the *origin* of the universe is moving *right* at 10 meters per second.

But the universe has no origin! So this notion of the *whole universe* moving at a particular speed, must be nonsense.

Yet if it makes no sense to talk about speed in an absolute, global sense, then what *is* speed?

It is simply the movement of *one* thing *relative* to a *different* thing! *This* is what our laws of physics talk about... right? The law of gravity, for example, talks about how planets pull on each *other,* and change their velocity relative to each *other.* Our physics do not talk about a crystal sphere of stars spinning around the objective center of the universe.

And now—it seems—we understand how we have been misled, by trying to *visualize* "the whole universe moving left", and *imagining* a little blurry blob of galaxies scurrying from the right to the left of our visual field. When we imagine this sort of thing, it is (probably) articulated in our visual cortex; when we visualize a little blob scurrying to the left, then there is (probably) an activation pattern that proceeds across the columns of our visual cortex. The seeming absolute *background*, the *origin* relative to which the universe was *moving,* was in the underlying neurology we used to visualize it!

But there is no origin! So the whole thing was just a case of the Mind Projection Fallacy—*again.*

Ah, but now Newton comes along, and he sees the flaw in the whole argument.

From Galileo's Ship we pass to Newton's Bucket. This is a bucket of water, hung by a cord. If you twist up the cord tightly, and then release the bucket, the bucket will spin. The water in the bucket, as the bucket wall begins to accelerate it, will assume a concave shape. Water will climb up the walls of the bucket, from centripetal force.

If you supposed that the whole universe was *rotating* relative to the origin, the parts would experience a centrifugal force, and fly apart. (No this is not why the universe is expanding, thank you for asking.)

Newton used his Bucket to argue in favor of an absolute space—an absolute background for his physics. There was a testable difference between the whole universe rotating, and the whole universe *not* rotating. By looking at the parts of the universe, you could determine their rotational velocity—not relative to *each other*, but relative to *absolute space*.

This absolute space was a tangible thing, to Newton: it was aether, possibly involved in the transmission of gravity. Newton didn't believe in action-at-a-distance, and so he used his Bucket to argue for the existence of an absolute space, that would be an aether, that could perhaps transmit gravity.

Then the origin-free view of the universe took another hit. Maxwell's Equations showed that, indeed, there seemed to be an absolute speed of light—a standard rate at which the electric and magnetic fields would oscillate and transmit a wave. In which case, you could determine how fast you were going, by seeing in which directions light seemed to be moving quicker and slower.

Along came a stubborn fellow named Ernst Mach, who *really* didn't like absolute space. Following some earlier ideas of Leibniz, Mach tried to get rid of Newton's Bucket by asserting that *inertia* was about your *relative* motion. Mach's Principle asserted that the resistance-to-changing-speed that determined how fast you accelerated under a force, was a resistance to changing your *relative* speed, compared to other objects. So that if the whole universe was rotating, no one would notice anything, because the inertial frame would also be rotating.

Or to put Mach's Principle more precisely, even if you *imagined* the whole universe was rotating, the *relative* motions of all the objects in the universe would be just the same as before, and their *inertia*—their *resistance* to changes of *relative* motion—would be just the same as before.

At the time, there did not seem to be any good reason to suppose this. It seemed like a mere attempt to impose philosophical elegance on a universe that had no particular reason to comply.

The story continues. A couple of guys named Michelson and Morley built an ingenious apparatus that would, via interference patterns in light, detect the absolute motion of Earth—as it spun on its axis, and orbited the Sun, which orbited the Milky Way, which hurtled toward Andromeda. Or, if you preferred, the Michelson-Morley apparatus would detect Earth's motion relative to the luminiferous aether, the medium through which light waves propagated. Just like Maxwell's Equations seemed to say you could do, and just like Newton had always thought you could do.

The Michelson-Morley apparatus said the absolute motion was zero.

This caused a certain amount of consternation.

Enter Albert Einstein.

The first thing Einstein did was repair the problem posed by Maxwell's Equations, which seemed to talk about an absolute speed of light. If you used a different, non-Galilean set of coordinate transforms—the Lorentz transformations—you could show that the speed of light would always look the same, in every direction, no matter how fast you were moving.

I'm not going to talk much about Special Relativity, because that introduction has already been written many times. If you don't get all indignant about "space" and "time" not turning out to work the way you thought they did, the math should be straightforward.

Albeit for the benefit of those who may need to resist postmodernism, I will note that the word "relativity" is a misnomer. What "relativity" really does, is establish *new invariant elements of reality.* The quantity $\sqrt{(t^2 - x^2 - y^2 - z^2)}$ is the same in every frame of reference. The x and y and z, and even t, seem to change with your point of view. But not $\sqrt{(t^2 - x^2 - y^2 - z^2)}$. Relativity does not make reality inherently subjective; it just makes it objective in a different way.

Special Relativity was a relatively easy job. Had Einstein never been born, Lorentz, Poincaré, and Minkowski would have taken care of it. Einstein got the Nobel Prize for his work on the photoelectric effect, not for Special Relativity.

General Relativity was the impressive part.

Einstein—explicitly inspired by Mach—and even though there was no experimental evidence for Mach's Principle—reformulated gravitational accelerations as a curvature of spacetime.

If you try to draw a straight line on curved paper, the curvature of the paper may twist your line, so that even as you proceed in a locally straight direction, it seems (standing back from an imaginary global viewpoint) that you have moved in a curve. Like walking "forward" for thousands of miles, and finding that you have circled the Earth.

In curved spacetime, objects under the "influence" of gravity, always seem to themselves—locally—to be proceeding along a strictly inertial pathway.

This meant you could *never* tell the difference between firing your rocket to accelerate through flat spacetime, and firing your rocket to stay in the same place in curved spacetime. You could accelerate the imaginary 'origin' of the universe, while changing a corresponding degree of freedom in the curvature of spacetime, and keep exactly the same laws of physics.

Einstein's theory further had the property that moving matter would generate *gravitational waves,* propagating curvatures. Einstein suspected that if the whole universe was rotating around you while you stood still, you would feel a *centrifugal force* from the incoming gravitational waves, corresponding exactly to the *centripetal force* of spinning your arms while the universe stood still around you. So you could construct the laws of physics in an accelerating or even rotating frame of reference, and end up observing the same laws—again freeing us of the specter of absolute space.

(I do not think this has been verified exactly, in terms of how much matter is out there, what kind of gravitational wave it would generate by rotating around us, et cetera. Einstein did verify that a shell of matter, spinning around a central point, ought to generate a gravitational equivalent of the Coriolis force that would e.g. cause a pendulum to precess. Remember that, by the basic principle of gravity as curved spacetime, this is *indistinguishable in principle* from a rotating inertial reference frame.)

We come now to the most important idea in all of physics. (Not counting the concept of "describe the universe using math", which I consider as the idea *of* physics, not an idea *in* physics.)

The idea is that you can start from "It shouldn't ought to be possible for X and Y to have different values from each other", or "It shouldn't ought to be possible to distinguish different values of Z", and generate *new physics* that make this *fundamentally* impossible because X and Y are now *the same thing*, or because Z *no longer exists*. And the new physics will often be *experimentally verifiable.*

We can interpret many of the most important revolutions in physics in these terms:

- Galileo / "The Earth is not the center of the universe": You shouldn't ought to be able to tell "where" the universe is—shifting all the objects a few feet to the left should have no effect.
- Special Relativity: You shouldn't ought to be able to tell how fast you, or the universe, are moving.
- General Relativity: You shouldn't ought to be able to tell how fast you, or the universe, are accelerating.
- Quantum mechanics: You shouldn't ought to be able to tell two identical particles apart.

Whenever you find that two things seem to always be exactly equal—like inertial mass and gravitational charge, or two electrons—it is a hint that the underlying physics are such as to make this a *necessary identity*, rather than a *contingent equality.* It is a hint that, when you see through to the underlying elements of reality, inertial mass and gravitational charge will be the *same thing*, not merely *equal.* That you will no longer be able to *imagine* them being different, if your imagination is over the elements of reality in the new theory.

Likewise with the way that quantum physics treats the similarity of two particles of the same species. It is not that "photon A at 1, and photon B at 2" happens to *look just like* "photon A at 2, and photon B at 1" but that they are *the same element of reality.*

When you see a seemingly contingent equality—two things that just happen to be equal, all the time, every time—it may be time to reformulate your physics so that there is one thing instead of two. The *distinction you imagine* is epiphenomenal; it has no experimental consequences. In the right physics, with the right elements of reality, you would no longer be able to *imagine* it.

The amazing thing is that this is a scientifically productive rule—finding a new representation that gets rid of epiphenomenal distinctions, often means a substantially different theory of physics with experimental consequences!

(Sure, what I just said is logically impossible, but it works.)

Part of *The Quantum Physics Sequence*

Next post: "Relative Configuration Space"

Previous post: "Living in Many Worlds"

Relative Configuration Space

Previously in series: Mach's Principle: Anti-Epiphenomenal Physics
Followup to: Classical Configuration Spaces

> **Warning: The ideas in today's post are taken seriously by serious physicists, but they are not experimentally proven and are not taught as standard physics.**
>
> Today's post draws on the work of the physicist Julian Barbour, and contains diagrams stolen and/or modified from his book "The End of Time".

Previously, we saw Mach's idea (following in the earlier path of Leibniz) that inertia is resistance to *relative* motion. So that, if the whole universe was rotating, it would drag the inertial frame along with it. From the perspective of General Relativity, the rotating matter would generate gravitational waves.

All right: It's possible that you can't tell if the universe is rotating, because the laws of gravitation may be set up to make it look the same either way. But even if this turns out to be the case, it may not yet seem *impossible to imagine* that things could have been otherwise.

To expose Mach's Principle *directly,* we turn to Julian Barbour.

The diagrams that follow are stolen from Julian Barbour's The End of Time. I'd forgotten what an amazing book this was, or I would have stolen diagrams from it earlier to explain configuration space. Anyone interested in the nature of reality must read this book. Anyone interested in understanding modern quantum mechanics should read this book. "Must" and "should" are defined as in RFC 2119.

Jbarbourconfigurationcube_2

Suppose that we have three particles, A, B, and C, on a 2-dimensional plane; and suppose that these are the *only* 3 particles in the universe.

Let there be a classical configuration space which describes the 2D positions of A, B, and C. 3 classical 2D particles require a 6-dimensional configuration space.

If your monitor cannot display 6-dimensional space, I've set a 2D projection of a 3D cube to appear instead. If you see what looks like a window into an incomprehensible void, try using Firefox instead of Internet Explorer.

The thing about this 6-dimensional cube, is that it contains *too much information*. By looking at an exact point in this cube—supposedly corresponding to an exact state of reality—we can read off information that A, B, and C will never be able to observe.

The point (0, 1, 3, 4, 2, 5) corresponds to A at (0, 1), B at (3, 4), and C at (2, 5). Now consider the point (1, 1, 4, 4, 3, 5); which corresponds to moving A, B, and C one unit to the right, in unison.

Can A, B, and C ever detect any experimental difference? Supposing that A, B, and C can *only* see *each other,* as opposed to seeing "absolute space" in the background?

After we shift the universe to the right (shift the origin to the left), A looks around... and sees B and C at the same distance from itself as before. B and C can't detect any difference in the universe either.

Yet we have described (0, 1, 3, 4, 2, 5) and (1, 1, 4, 4, 3, 5) as two different points in the configuration space. Even though, to A, B, and C, the associated states of reality seem indistinguishable. We have postulated an epiphenomenal difference: This suggests that our physics is not over the true elements of reality. (Remember, this has been, historically, a highly productive line of reasoning! It is not just logic-chopping.)

Indeed, our classical configuration space has *many* epiphenomenal differences. We can rotate the three particles in unison, and end up with a different point in the configuration space; while A, B, and C again see themselves at the same distances from each other. The "rotation" that took place, was a matter of *us* looking at them from a different angle, from *outside their universe*. Which is to say the "rotation" was a choice of viewpoint for *us*, not an experimentally detectable fact *within* the ABC universe.

How can we rid the physics of mind projections and epiphenomena?

A and B and C cannot observe their absolute positions in space against a fixed background. Treating these absolute positions as elements of reality may be part of our problem.

Jbarbourrelative

What *can* A, B, and C observe? By hypothesis, they can observe their distances from each other. They can measure the distances AB, BC, and CA.

Why not use *that* as the dimensions of a configuration space?

At right is depicted a *relative configuration space* whose three dimensions are the distances AB, BC, and CA. It really is 3-dimensional, now!

If you're wondering why the configuration space looks pyramidal, it's because any point with e.g. AB + BC < CA is "outside the configuration space". It does not represent a realizable triangle, because one side is longer than the sum of the other two. Likewise AB + CA < BC and BC + CA < AB.

Every different point in this configuration space, corresponds to an *experimentally different* state of reality that A, B, and C can observe.

Jbarbourtriangleland1_2

(Albeit this assumes that ABC can measure absolute, rather than relative, distances. Otherwise, different slices of pyramid-space would be observationally identical because they would describe the same triangle at different scales, as shown at left.)

(Oh, and we're assuming that A, B, and C can tell each other apart—perhaps they are different colors.)

The edges of each slice of the configuration space, are the configurations with A, B, and C on the same line. E.g., if AB + BC = CA, then B lies on a point between A and C.

The corners of each slice are the configurations in which two points coincide; e.g., AB=0, BC=CA.

Jbarbourtriangleland2

At right (or possibly below, depending on your screen width), is a diagram showing a single slice in greater detail; Julian Barbour credits this to his friend Dierck Liebscher.

The point in the center of the slice corresponds to an equilateral triangle.

The dashed lines, which are axes of bilateral symmetry of the configuration space, contain points that correspond to isosceles triangles.

The curved lines are right-angled triangles.

Points "inside" the curved lines are acute triangles; points "outside" the curved lines are obtuse triangles.

What about *three* points coinciding?

There is no triangle *at this scale* where all three points coincide.

Remember, this is just one *slice* of the configuration space. Every point in the *whole* configuration space corresponds to what ABC experience as a different state of affairs.

The configuration where A, B, and C are all in the same place is *unique* in their experience. So it is only found in *one* slice of the configuration space: The slice that is a single point, at the tip of the infinite pyramid: The degenerate slice where the center and the corners are the same point: The slice that is the single point in configuration space: AB=BC=CA=0.

Julian Barbour calls this point Alpha.

But I'm getting ahead of myself, here—that sort of thing is the topic of tomorrow's post.

To see the power of a relative configuration space, observe how it makes it impossible to *imagine* certain epiphenomenal differences:

Put your Newtonian goggles back on: imagine A, B, and C as little billiard balls bouncing around in plain old space (not configuration space) and time. Perhaps A, B, and C attract each other via a kind of gravity, and so orbit around one another. If you were looking at the evolution of A, B, and C in plain old space and time, then a strobe-lit photograph of their motion might look like this:

Jbarbourtriangleseries

In this time-series photograph, we've seen points A, B, and C forming a triangle. Not only do the points of the triangle orbit around each other, but they also seem to be heading down and to the right. It seems like you can imagine the triangle heading off up and to the right, or up and to the left, or perhaps spinning around much faster. Even though A, B, and C, who can only see their distance to each other, would never notice the difference.

Now we could also map that whole trajectory over time, onto the relative configuration space. If AB+BC+CA happens to be a constant throughout the evolution, then we could conveniently map the trajectory onto one slice of configuration space:

Jbarbourshapepath

(This doesn't actually represent the triangle-series shown above it, but imagine that it does.)

If this is what you believe to be the *reality*—this trajectory in the relative configuration space—then, if I ask you to imagine, "Suppose that the triangle is heading up and to the left, instead of down and to the right", I have just uttered *physical nonsense.* Mapping that alternative trajectory in Newtonian space, onto the relative configuration space, would produce just the same curve. And if the laws of physics are over the relative configuration space, then this curve is all there *is.*

Imagine physics over trajectories in a relative configuration space like this one, but with many more particles, and perhaps 3 space dimensions. Sentient beings evolve in this universe, on some equivalent of a planet. They hunt across fields that do not seem to shift underfoot. They have a strong illusion of moving through an absolute space, against an absolute background; the relativity of motion is hidden from them.

But if the fundamental laws of their universe were over relative configurations, then it would not just be a *contingent* fact about their universe, that if all the particles were speeding or accelerating or rotating in unison, all the experiments would come out the same. Talking about "all the particles rotating in unison" would be *physical nonsense*. It only makes physical sense to talk about the velocity of *some* particles relative to *other* particles.

Your ancestors evolved on a savanna that seemed to stay put while they ran across it. You can, by an effort of mind, visualize a car that stays motionless as the world zips past, or alternatively, visualize a world that remains motionless as the car zips past. You can, by an effort of mind, see that the internal relations are the same. But it still seems to you that you are imagining two different things.

Your visual neurology is representing objects in terms of absolute positions against a fixed background. There is a web of cortical columns in your visual cortex that activate to create a mental picture. The particular columns that activate, are felt by you as positions in your visual field. That is how the algorithm feels from inside.

In a universe whose physics is over a relative configuration space, the absolute positions, and the fixed background, are not elements of reality. They are mind projection fallacies, the shadows of a point of view; as if your mind's eye were outside the universe, and the universe could move relative to that.

But if you could learn to visualize the relative configuration space, then, so long as you thought in terms of those elements of reality, it would no longer be *imaginable* that Mach's Principle could be false.

I am not entirely convinced of this notion of a relative configuration space. My soul as a computer programmer cries out against the idea of representing N particles with N^2 distances between them; it seems wasteful. On the other hand, I have no evidence that the Tao is prejudiced against *redundant* or *overconstrained* representations, in the same way that the Tao seems prejudiced against *epiphenomena* in representations. Though my soul as a programmer cries out against it, better an overconstrained representation than an epiphenomenal one. Still, it does not feel entirely satisfactory, to me. It seems like merely the *best* representation, not the *true* one.

Also, any position basis invokes an arbitrary space of simultaneity, and a relative position basis does so as well. As required by Special Relativity, the choice makes no difference—but this means that the relative position basis *still* contains epiphenomenal information. Perhaps the true representation will be more strictly local, in terms of invariant states of distant entanglement, as I've suggested before; and maybe, who knows, it won't be overconstrained?

Relativizing the position basis feels to me like an *improvement,* but it doesn't seem *finished.*

...

Of course, all this that we have said about the particles A, B, C and their trajectory through time, cannot *possibly* apply to our own universe.

In our *own* universe, as you may recall, there are no little billiard balls bouncing around.

In our own universe, if physics took place in a relative configuration space, it would be *quantum* physics in a relative configuration space. And a single moment of time, might look like this:

At right we see a cloud of red and blue mist, representing a complex amplitude distribution over the relative configuration space. You could imagine that redness is the real part and blueness is the imaginary part, or some such. But this is not a realistic amplitude distribution—just a representation of the general idea, "A cloud of complex amplitude in configuration space."

Jbarbourtrianglecloud

As for why only a sixth of the triangle is colored: If A, B, and C are the same species of particle, which is to say, identical particles, then the configuration space collapses along the sixfold symmetry corresponding to the six possible permutations of A, B, and C.

The whole cloud is a single static instant, in some arbitrary space of simultaneity. The quantum wavefunction is a distribution over configuration space, not a single point in configuration space. So to represent the state of the universe at a single moment, we need the whole cloud, which covers the entire collapsed configuration space.

You might naturally tend to assume that we could represent *time* using an animated version of this same diagram: and that the animated diagram would show the mist churning in the configuration space, the cloud's parts changing color, as amplitude flowed from volume to volume; and that as the quantum waves propagated, little blobs of amplitude density would move around through the configuration space, in trajectories much resembling the classical curve we saw earlier.

But that would be overcomplicating things.

Be aware: Churning mist in a non-relative configuration space, would be the metaphor that corresponds to the *standard* formulation of physics. That is, according to *standard* physics, the description I just gave above, would be correct (after we took it back out of the relative configuration space, which is *not* standard).

Yet tomorrow we shall discuss a certain *further* simplification of physics, which renders unimaginable still *another* epiphenomenal distinction, and deletes a *further* needless element of the laws.

Part of *The Quantum Physics Sequence*

Next post: "Timeless Physics"

Previous post: "Mach's Principle: Anti-Epiphenomenal Physics"

Timeless Physics

Previously in series: Relative Configuration Space

> **Warning: The central idea in today's post is taken seriously by serious physicists; but it is not experimentally proven and is not taught as standard physics.**
>
> Today's post draws heavily on the work of the physicist Julian Barbour, and contains diagrams stolen and/or modified from his book "The End of Time". However, some of the arguments here are of my own devising, and Barbour might(?) not agree with them.

I shall begin by asking a incredibly deep question:

What time is it?

If you have the excellent habit of giving obvious answers to obvious questions, you will answer, "It is now 7:30pm [or whatever]."

How do you know?

"I know because I looked at the clock on my computer monitor."

Well, suppose I hacked into your computer and changed the clock. Would it then be a different time?

"No," you reply.

How do you know?

"Because I once used the 'Set Date and Time' facility on my computer to try and make it be the 22nd century, but it didn't work."

Ah. And how do you *know* that it *didn't* work?

"Because," you say, "I looked outside, and the buildings were still made of brick and wood and steel, rather than having been replaced by the gleaming crystal of diamondoid nanotechnological constructions; and gasoline was still only $4/gallon."

You have... *interesting*... expectations for the 22nd century; but let's not go into that. Suppose I replaced the buildings outside your home with confections of crystal, and raised the price of gas; *then* would it be 100 years later?

"No," you say, "I could look up at the night sky, and see the planets in roughly the same position as yesterday's night; with a powerful telescope I could measure the positions of the stars as they very slowly drift, relative to the Sun, and observe the rotation of distant galaxies. In these ways I would know exactly how much time had passed, no matter what you did here on Earth."

Ah. And suppose I snapped my fingers and caused all the stars and galaxies to move into the appropriate positions for 2108?

"You'd be arrested for violating the laws of physics."

But suppose I did it anyway.

"Then, still, 100 years would not have passed."

How would you *know* they had not passed?

"Because I would remember that, one night before, it had still been 2008. Though, realistically speaking, I would think it more likely that it was my memory at fault, not the galaxies."

Now suppose I snapped my fingers, and caused *all* the atoms in the universe to move into positions that would be appropriate for (one probable quantum branch) of 2108. Even the atoms in your brain.

Think carefully before you say, "It would still *really* be 2008." For does this belief of yours, have *any* observable consequences left? Or is it an epiphenomenon of your model of physics? *Where* is stored the fact that it is 'still 2008'? Can I snap my fingers one last time, and alter this last variable, and cause it to *really* be 2108?

Is it possible that Cthulhu could snap Its tentacles, and cause time *for the whole universe* to be suspended for exactly 10 million years, and then resume? How would anyone ever detect what had just happened?

A global suspension of time may seem *imaginable*, in the same way that it seems imaginable that you could "move all the matter in the whole universe ten meters to the left". To visualize the universe moving ten meters to the left, you imagine a little swirling ball of galaxies, and then it jerks leftward. Similarly, to imagine time stopping, you visualize a swirling ball of galaxies, and then it stops swirling, and hangs motionless for a while, and then starts up again.

But the sensation of passing time, in your visualization, is provided by your own mind's eye outside the system. *You* go on thinking, your brain's neurons firing, while, in your *imagination*, the swirling ball of galaxies stays motionless.

When you *imagine* the universe moving ten meters to the left, you are imagining motion *relative* to your mind's eye outside the universe. In the same way, when you imagine time stopping, you are *imagining* a motionless universe, frozen *relative* to a still-moving clock hidden outside: your own mind, counting the seconds of the freeze.

But what would it mean for 10 million "years" to pass, if motion *everywhere* had been suspended?

Does it make sense to say that the global rate of motion could slow down, or speed up, over the whole universe at once—so that all the particles arrive at the same final configuration, in twice as much time, or half as much time? You couldn't measure it with any clock, because the ticking of the clock would slow down too.

Do not say, "I could not detect it; therefore, who knows, it might happen every day."

Say rather, "I could not detect it, nor could anyone detect it even in principle, nor would any physical relation be affected *except* this one thing called 'the global rate of motion'. Therefore, I wonder what the phrase 'global rate of motion' really *means*."

All of that was a line of argument of Julian Barbour's, more or less, Let us pause here, and consider a second line of argument, this one my own. That is, I don't think it was in Barbour's *The End of Time.* (If I recall correctly, I reasoned thus even before I read Barbour, while I was coming up with my unpublished general decision theory of Newcomblike problems. Of course that does not mean the argument is novel; I have no idea whether it is novel. But if my argument is wrong, I do not want it blamed on an innocent bystander.) So:

> "The future changes as we stand here, else we are the game pieces of the gods, not their heirs, as we have been promised."
> —Raistlin Majere

A fine sentiment; but what does it mean to *change* the future?

Suppose I have a lamp, with an old-style compact fluorescent bulb that takes a few seconds to warm up. At 7:00am, the lamp is off. At 7:01am, I flip the switch; the lamp flickers for a few moments, then begins to warm up. At 7:02am, the lamp is fully bright. Between 7:00am and 7:02am, the lamp changed from OFF to ON. This, certainly, is a change; but it is a change *over time.*

Change implies difference; difference implies comparison. Here, the two values being compared are (1) the state of "the lamp at 7:00am", which is OFF, and (2) the state of "the lamp at 7:02am", which is ON. So we say "the lamp" has *changed* from one time to another. At 7:00am, you wander by, and see the lamp is OFF; at 7:02am, you wander by, and see the lamp is ON.

But have you ever seen the *future* change from one time to another? Have you wandered by a lamp at exactly 7:02am, and seen that it is OFF; then, a bit later, looked in again on the "the lamp at exactly 7:02am", and discovered that it is now ON?

Naturally, we often *feel* like we are "changing the future". Logging on to your online bank account, you discover that your credit card bill comes due tomorrow, and, for some reason, has not been paid automatically. *Imagining* the future-by-default—extrapolating out the world as it would be without any further actions—you see that the bill not being paid, and interest charges accruing on your credit card. So you pay the bill online. And now, *imagining* tomorrow, it seems to you that the interest charges will not occur. So at 1:00pm, you imagined a future in which your credit card accrued interest charges, and at 1:02pm, you imagined a future in which it did not. And so your imagination of the future changed, from one time to another.

As I remarked previously: The way a belief feels from inside, is that you seem to be looking straight at reality. When it actually *seems* that you're looking at a belief, as such, you are really experiencing a belief about your beliefs.

When your *extrapolation* of the future changes, from one time to another, it *feels* like the future itself is changing. Yet you have never *seen* the future change. When you actually *get to* the future, you only ever see one outcome.

How could a single moment of time, change from one time to another?

I am not going to go into "free will" in today's blog post. Except to remark that if you have been reading Overcoming Bias all this time, and you are currently agonizing about whether or not you *really have free will,* instead of trying to understand where your own mind has become confused and generated an impossible question, you should probably go back and read it all again. For anyone who is just now joining us... perhaps I shall discuss the issue tomorrow.

Just remember Egan's Law: *It all adds up to normality.* Apples didn't stop falling when Einstein disproved Newton's theory of gravity, and anyone who jumped off a cliff would still go splat. Perhaps Time turns out to work differently than you thought; but tomorrow still lies ahead of you, and your choices, and their consequences. I wouldn't advise reworking your moral philosophy based on confusing arguments and strange-seeming physics, until the physics stops appearing strange and the arguments no longer seem confusing.

Now to physics we turn; and here I resume drawing my ideas from Julian Barbour.

For the benefit of anyone who hasn't followed the series on quantum mechanics, a very *very* quick summary:

- In classical physics—the *mistaken* physics that was developed first historically, and matches human intuitions all *too* well—a particle is like a little billiard ball. A particle is in a single place in 3D space, and we can describe its position with three real numbers. In *quantum* physics, we need an *amplitude distribution* over all possible positions for the particle—a complex number for the particle being *here,* a complex number for the particle being *there,* and so on through all the positions in space; a continuous distribution. (Configurations and Amplitude.)
- In classical physics, we can consider each particle independently. *This* particle is *here, that* particle is *there*. In quantum physics this is not possible; we can only assign amplitudes to *configurations* that describe the simultaneous positions of many particles. In fact, the only mathematical entities that actually have amplitudes are joint configurations of all the particles in the entire universe. (Joint Configurations.)

Jbarbourconfigurationcube_3

Above is a diagram that shows what a *configuration space* might look like for three particles, A, B, and C. ABC form a triangle in two-dimensional space. Every individual point in the configuration space corresponds to a simultaneous position of *all* the particles—above we see points that correspond to particular triangles i.e. joint positions of A, B, and C. (Classical Configuration Spaces; The Quantum Arena.)

The *state of a quantum system* is not a *single point* in this space; it is a *distribution* over this space. You could imagine it as a cloud, or a blob, or a colored mist within the space.

Jbarbourrelative

Here we see a *relative* configuration space, in which each axis is the distance between a pair of particles. This has some advantages I'm not going to recapitulate (it was covered in a previous post), so if you're dropping into the middle of the series, just pretend it's a regular configuration space.

Jbarbourtriangleland1

We've just chopped up the pyramidal space you saw before, into a series of slices. In this configuration space, the slices near the bottom show all the particles close together (tiny triangles). As we rise up, the particles get further apart (larger triangles).

At the very bottom of the configuration space is a configuration where all the particles occupy the same position.

(But remember, it's nonsense to talk about an *individual particle* being anywhere in a *configuration space*—each point in the configuration space corresponds to a position of all the particles. Configuration space is not the 3D space you know. It's not that there are a bunch of particles resting in the same place at the bottom. The single bottom point *corresponds to* all the particles being in the same place in 3D space.)

Jbarbourtrianglecloud_2

Here we take a closer look at one of the slices of configuration space, and see a cloud of blue and red mist covering some of it. (Why am I only showing the cloud covering a sixth (exactly a sixth) of the triangle? This has to do with a symmetry in the space—exchanges of identical particles—which is not important to the present discussion.)

But there is your glimpse of some quantum mist—in two colors, because amplitudes are complex numbers with a real and imaginary part. An amplitude distribution or "wavefunction" assigns a complex number to every point in the continuous configuration space—a complex number to every possible configuration of all the particles.

Yesterday, I finished by asking how the state of a quantum system might evolve over *time.*

You might be tempted to visualize the mist churning and changing colors, as quantum amplitude flows within the configuration space.

And this is *indeed* the way that you would visualize *standard* physics.

Behold the standard Schrödinger Equation:

Schrodinger

Here $\psi(\mathbf{r}, t)$ is the amplitude distribution over configuration space ($\mathbf{r}$) and time (t). The left-hand side of the Schrödinger Equation is the *change over time* of the wavefunction ψ, and the right-hand-side shows how to calculate this change as the sum of two terms: The gradient of the wavefunction over configuration space (at that time), and the potential energy of each configuration.

Which is to say, the derivative in *time* of the wavefunction—the instantaneous rate of change—can be in terms of the wavefunction's derivative in *space,* plus a term for the potential energy.

If you tried to visualize Schrödinger's Equation—doesn't look too hard, right?—you'd see a blob of churning, complex mist in configuration space, with little blobs racing around and splitting into smaller blobs as waves propagated.

If you tried to calculate the quantum state of a *single* hydrogen atom *over time,* apart from the rest of the universe—which you can only really do if the hydrogen atom isn't entangled with anything—the atom's quantum state would evolve over time; the mist would churn.

But suppose you think about the whole universe at once, including yourself, of course. Because—even in the standard model of quantum physics!—that is exactly the arena in which quantum physics takes place: A wavefunction over *all* the particles, *everywhere.*

If you can sensibly talk about the quantum state of some particular hydrogen atom, it's only because the wavefunction happens to neatly factor into (hydrogen atom) * (rest of world).

Even if the hydrogen atom is behaving in a very regular way, the *joint* wavefunction for (hydrogen atom * rest of world) may not be so regular. Stars move into new positions, people are born and people die, digital watches tick, and the cosmos expands: The universe is non-recurrent.

Think of how the *universal* wavefunction $\psi(\mathbf{r}, t)$ might behave when $\mathbf{r}$ is the position of *all* the particles in the universe.

Let's call 9:00am the time t=0, measured in seconds.

At $\psi(\mathbf{r}, t=0)$, then, you are wondering what time it is: The particles making up the neurons in your brain, are in positions $\mathbf{r}_{\text{you}}$ that correspond to neurons firing in the thought-pattern "What time is it?" And the Earth, and the Sun, and the rest of the universe, have their own particles in the appropriate $\mathbf{r}_{\text{rest-of-universe}}$. Where the complete $\mathbf{r}$ roughly factorizes as the product ($\mathbf{r}_{\text{you}} * \mathbf{r}_{\text{rest-of-universe}}$).

Over the next second, the joint wavefunction of the entire universe evolves into $\psi(\mathbf{r}, t=1)$. All the stars in the sky have moved a little bit onward, in whatever direction they're heading; the Sun has burned up a little more of its hydrogen; on Earth, an average of 1.8 people have died; and you've just glanced down at your watch.

At $\psi(\mathbf{r}, t=2)$, the stars have moved a little onward, the galaxies have rotated, the cosmos has expanded a little more (and its expansion has accelerated a little more), your watch has evolved into the state of showing 9:00:02 AM on its screen, and your own mind has evolved into the state of thinking the thought, "Huh, I guess it's nine o' clock."

Ready for the next big simplification in physics?

Here it is:

We don't need the *t*.

It's redundant.

The **r** never repeats itself. The universe is expanding, and in every instant, it gets a little bigger. We don't *need* a separate *t* to keep things straight. When you're looking at the whole universe, a unique function ψ of (**r**, *t*) is pretty much a unique function of **r**.

And the only way *we know in the first place* "what time it is", is by looking at clocks. And whether the clock is a wristwatch, or the expansion of the universe, or *your own memories*, that clock is encoded in the position of particles—in the **r**. We have never seen a *t* variable apart from the **r**.

Jbarbourrelative

We can recast the quantum wave equations, specifying the time evolution of ψ(**r**, *t*), as specifying relations *within* a wavefunction ψ(**r**).

Occam's Razor: Our equations don't need a *t* in them, so we can banish the *t* and make our ontology that much simpler.

An *unchanging* quantum mist hangs over the configuration space, not churning, not flowing.

But the mist has internal structure, internal relations; and these contain time *implicitly.*

The dynamics of physics—falling apples and rotating galaxies—is now embodied *within* the unchanging mist in the unchanging configuration space.

This landscape is not *frozen* like a cryonics patient suspended in liquid nitrogen. It is not motionless as an isolated system while the rest of the universe goes on without it.

The landscape is *timeless*; time exists only *within* it. To talk about time, you have to talk about relations *inside* the configuration space.

Asking "What happened before the Big Bang?" is revealed as a *wrong question*. There is no "before"; a "before" would be outside the configuration space. There was never a pre-existing emptiness into which our universe exploded. There is just this timeless mathematical object, time existing *within* it; and the object has a natural boundary at the Big Bang. You cannot ask "*When* did this mathematical object come into existence?" because there is no *t* outside it.

So that is Julian Barbour's proposal for the next great simplification project in physics.

(And yes, you can not only fit General Relativity into this paradigm, it actually comes out looking *even more elegant than before.* For which point I refer you to Julian Barbour's papers.)

Tomorrow, I'll go into some of my own thoughts and reactions to this proposal.

But one point seems worth noting immediately: I have spoken before on the apparently perfect universality of physical laws, that apply everywhere and everywhen. We have just raised this perfection to an even higher pitch: **everything that exists is either *perfectly global* or *perfectly local***. There are points in configuration space that affect only their immediate neighbors in space and time; governed by universal laws of physics. Perfectly local, perfectly global. If the meaning and *sheer beauty* of this statement is not immediately obvious, I'll go into it tomorrow.

And a final intuition-pump, in case you haven't yet gotten timelessness on a gut level...

Think of this as a diagram of the many worlds of quantum physics. The branch points could be, say, your observation of a particle that seems to go either "left" or "right".

Looking back from the vantage point of the gold head, you only *remember* having been the two green heads.

So you seem to remember Time proceeding along a *single line*. You remember that the particle first went left, and then went right. You ask, "Which way will the particle go *this* time?"

You only remember one of the two outcomes that occurred on each occasion. So you ask, "When I make my next observation, which of the two possible worlds will *I* end up in?"

Remembering only a single line as your past, you try to extend that line into the future -

But both branches, both future versions of you, just *exist.* There *is no fact of the matter* as to "which branch you go down". Different versions of you experience both branches.

So that is many-worlds.

And to incorporate Barbour, we simply say that all of these heads, all these Nows, *just exist.* They do not appear and then vanish; they just *are*.   From a global perspective, there *is no answer* to the question, "What time is it?" There are just different experiences at different Nows.

From any given vantage point, you look back, and remember other times—so that the question, "Why is it *this* time right now, rather than some *other* time?" seems to make sense. But there is no answer.

When I came to this understanding, I forgot the meaning that Time had once held for me.

Time has dissolved for me, has been reduced to something simpler that is not itself timeful.

I can no longer conceive that there might *really be* a universal time, which is somehow "moving" from the past to the future. This now seems like nonsense.

Something like Barbour's timeless physics has to be true, or I'm in trouble: I have forgotten how to imagine a universe that has "real genuine time" in it.

Part of *The Quantum Physics Sequence*

Next post: "Timeless Beauty"

Previous post: "Relative Configuration Space"

Timeless Beauty

Followup to: Timeless Physics

One of the great surprises of humanity's early study of physics was that there were universal laws, that the heavens were governed by the same order as the Earth: Laws that hold in all times, in all places, without known exception. Sometimes we discover a seeming exception to the old law, like Mercury's precession, but soon it turns out to perfectly obey a still deeper law, that once again is universal as far as the eye can see.

Every known law of *fundamental* physics is perfectly global. We know no law of fundamental physics that applies on Tuesdays but not Wednesdays, or that applies in the Northern hemisphere but not the Southern.

In classical physics, the laws are universal; but there are also other entities that are neither perfectly global nor perfectly local. Like the case I discussed yesterday, of an entity called "the lamp" where "the lamp" is OFF at 7:00am but ON at 7:02am; the lamp entity extends through time, and has different values at different times. The little billiard balls are like that in classical physics; a classical billiard ball is (alleged to be) a fundamentally existent entity, but it has a world-*line*, not a world-*point.*

In timeless physics, **everything that exists is either perfectly global or perfectly local**. The laws are perfectly global. The configurations are perfectly local—every possible arrangement of particles has a *single* complex amplitude assigned to it, which never changes from one time to another. Each configuration only affects, and is affected by, its immediate neighbors. Each actually existent thing is perfectly unique, as a mathematical entity.

Newton, first to combine the Heavens and the Earth with a truly universal generalization, saw a clockwork universe of moving billiard balls and their world-lines, governed by perfect exceptionless laws. Newton was the first to look upon a greater beauty than any mere religion had ever dreamed.

But the beauty of classical physics doesn't begin to compare to the beauty of timeless quantum physics.

Timeful quantum physics is pretty, but it's not all that much pretti*er* than classical physics. In timeful physics the "same configuration" can still have different values at different times, its own little world-line, like a lamp switching from OFF to ON. There's that ugly *t* complicating the equations.

You can see the beauty of timeless quantum physics by noticing how much easier it is to *mess up* the perfection, if you try to tamper with Platonia.

Consider the collapse interpretation of quantum mechanics. To people raised on timeful quantum physics, "the collapse of the wavefunction" sounds like it might be a plausible physical mechanism.

If you step back and look upon the timeless mist over the entire configuration space, all dynamics manifest in its perfectly local relations, then the "pruning" process of collapse suddenly shows up as a hugely ugly discontinuity in the timeless object. Instead of a continuous mist, we have something that looks like a maimed tree with branches hacked off and sap-bleeding stumps left behind. The perfect locality is ruined, because whole branches are hacked off in one operation. Likewise, collapse destroys the perfect global uniformity of the laws that relate each configuration to its neighborhood; sometimes we have the usual relation of amplitude flow, and then sometimes we have the collapsing-relation instead.

This is the power of beauty: The more beautiful something is, the more obvious it becomes when you mess it up.

I was surprised that many of yesterday's commenters seemed to think that Barbour's timeless physics was nothing new, relative to the older idea of a Block Universe. 3+1D Minkowskian spacetime has no privileged space of simultaneity, which, in its own way, seems to require you to throw out the concept of a global *now*. From Minkowskian 3+1, I had the idea of "time as a single perfect 4D crystal"—I didn't know the phrase "Block Universe", but seemed evident enough.

Nonetheless, I did not *really* get timelessness until I read Barbour. Saying that the *t* coordinate was just another coordinate, didn't have nearly the same impact on me as tossing the *t* coordinate out the window.

Special Relativity is widely accepted, but that doesn't stop people from talking about "nonlocal collapse" or "retrocausation"—relativistic *timeful* QM isn't beautiful enough to protect itself from complication.

Shane Legg's reaction is the effect I was looking for:

> "Stop it! If I intuitively took on board your timeless MWI view of the world... well, I'm worried that this might endanger my illusion of consciousness. Thinking about it is already making me feel a bit weird."

I wish I knew whether the unimpressed commenters got what Shane Legg did, just from hearing about Special Relativity; or if they still haven't gotten it *yet* from reading my brief summary of Barbour.

But in any case, let me talk in principle about why it helps to toss out the *t* coordinate:

To reduce a thing, you must reduce it to something that does not itself have the property you want to explain.

In old-school Artificial Intelligence, a researcher wonders where the meaning of a word like "apple" comes from. They want to get knowledge about "apples" into their beloved AI system, so they create a LISP token named **apple**. They realize that if they claim the token is meaningful of itself, they have not really *reduced* the nature of meaning... So they *assert* that "the **apple** token is not meaningful by itself", and then go on to say, "The meaning of the **apple** token emerges from its network of connections to other tokens." This is not true reductionism. It is wrapping up your confusion in a gift-box.

To reduce time, you must reduce it to something that is not time. It is not enough to take the *t* coordinate, and say that it is "just another dimension". So long as the *t* coordinate is there, it acts as a mental sponge that can soak up all the time-ness that you want to explain. If you toss out the *t* coordinate, you are forced to see time as something else, and not just see time as "time".

Tomorrow (if I can shake today's cold) I'll talk about one of my points of departure from Barbour: Namely, I have no problem with discarding time and keeping *causality.* The commenters who complained about Barbour grinding up the universe into disconnected slices, may be reassured: On this point, I think Barbour is trying too hard. We can discard *t*, and still keep causality *within* **r**.

I dare to disagree with Barbour, on this point, because it seems plausible that Barbour has not studied Judea Pearl and colleagues' formulation of causality—

—which likewise makes no use of a *t* coordinate.

Pearl et. al.'s formulation of "causality" would not be anywhere *near* as enlightening, if they had to put *t* coordinates on everything for the math to make sense. Even if the authors insisted that *t* was "just another property" or "just another number"... well, if you've read Pearl, you see my point. It would correspond to a much weaker understanding.

Part of *The Quantum Physics Sequence*

Next post: "Timeless Causality"

Previous post: "Timeless Physics"

Timeless Causality

Followup to: Timeless Physics

Julian Barbour believes that each configuration, each individual point in configuration space, corresponds individually to an experienced Now—that each instantaneous time-slice of a brain is the carrier of a subjective experience.

On this point, I take it upon myself to disagree with Barbour.

There is a timeless formulation of causality, known to Bayesians, which may glue configurations together even in a timeless universe. Barbour may not have studied this; it is not widely studied.

Such causal links could be required for "computation" and "consciousness"—whatever *those* are. If so, we would not be forced to conclude that a *single* configuration, encoding a brain frozen in time, can be the bearer of an instantaneous experience. We could throw out time, and keep the concept of causal computation.

There is an old saying: "Correlation does not imply causation." I don't know if this is my own thought, or something I remember hearing, but on seeing this saying, a phrase ran through my mind: *If correlation does not imply causation, what does?*

Suppose I'm at the top of a canyon, near a pile of heavy rocks. I throw a rock over the side, and a few seconds later, I hear a crash. I do this again and again, and it seems that the rock-throw, and the crash, tend to *correlate;* to occur in the presence of each other. Perhaps the sound of the crash is causing me to throw a rock off the cliff? But no, this seems unlikely, for then an effect would have to precede its cause. It seems more likely that throwing the rock off the cliff is causing the crash. If, on the other hand, someone observed me on the cliff, and saw a flash of light, and then immediately afterward saw me throw a rock off the cliff, they would suspect that flashes of light caused me to throw rocks.

Perhaps correlation, plus *time*, can suggest a direction of causality?

But we just threw out time.

You see the problem here.

Once, sophisticated statisticians believed this problem was unsolvable. Many thought it was unsolvable even *with* time. Time-symmetrical laws of physics didn't seem to leave room for asymmetrical causality. And in statistics, nobody thought there was any way to *define* causality. They could measure correlation, and that was enough. Causality was declared dead, and the famous statistician R. A. Fisher testified that it was impossible to prove that smoking cigarettes actually *caused* cancer.

Anyway...

Causeundirected_2

Let's say we have a data series, generated by taking snapshots over time of two variables 1 and 2. We have a large amount of data from the series, laid out on a track, but we don't know the direction of *time* on the track. On each round, the past values of 1 and 2 probabilistically generate the future value of 1, and then separately probabilistically generate the future value of 2. We know this, but we don't know the actual laws. We can try to infer the laws by gathering statistics about which values of 1 and 2 are adjacent to which other values of 1 and 2. But we don't know the global direction of time, yet, so we don't know if our statistic relates the effect to the cause, or the cause to the effect.

When we look at an arbitrary value-pair and its neighborhood, let's call the three slices L, M, and R for Left, Middle, and Right.

We are considering two hypotheses. First, that causality could be flowing from L to M to R:

Causeright_2

Second, that causality could be flowing from R to M to L:

Causeleft_3

As good Bayesians, we realize that to distinguish these two hypotheses, we must find some kind of observation that is more likely in one case than in the other. But what might such an observation be?

We can try to look at various slices M, and try to find correlations between the values of M, and the values of L and R. For example, we could find that when M1 is in the + state, that R2 is often also in the + state. But is this because R2 causes M1 to be +, or because M1 causes R2 to be +?

If throwing a rock causes the sound of a crash, then the throw and the crash will tend to occur in each other's presence. But this is also true if the sound of the crash causes me to throw a rock. So observing these correlations does not tell us the direction of causality, unless we already know the direction of time.

Causeundirected_2

From looking at this undirected diagram, we can guess that M1 will correlate to L1, M2 will correlate to R1, R2 will correlate to M2, and so on; and all this will be true because there are lines between the two nodes, regardless of which end of the line we try to draw the arrow upon. You can see the problem with trying to derive causality from correlation!

Could we find that when M1 is +, R2 is *always* +, but that when R2 is +, M1 is not always +, and say, "M1 must be causing R2"? But this does not follow. We said at the beginning that past values of 1 and 2 were generating future values of 1 and 2 in a probabilistic way; it was nowhere said that we would give preference to laws that made the future deterministic given the past, rather than vice versa. So there is nothing to make us prefer the hypothesis, "A + at M1 always causes R2 to be +" to the hypothesis, "M1 can only be + in cases where its parent R2 is +".

Ordinarily, at this point, I would say: "Now I am about to tell you the answer; so if you want to try to work out the problem on your own, you should do so now." But in this case, some of the greatest statisticians in history did not get it on their own, so if you do not already know the answer, I am not really expecting you to work it out. Maybe if you remember half a hint, but not the whole answer, you could try it on your own. Or if you suspect that your era will support you, you could try it on your own; I have given you a tremendous amount of help by asking exactly the correct question, and telling you that an answer is possible.

...

So! Instead of thinking in terms of observations we could find, and then trying to figure out if they might distinguish asymmetrically between the hypotheses, let us examine a single causal hypothesis and see if it implies any asymmetrical observations.

Say the flow of causality is from left to right:

Causeright_3

Suppose that we *do* know L1 and L2, but we do *not* know R1 and R2. Will learning M1 tell us anything about M2?

That is, will we observe the conditional dependence

   P(M2|L1,L2) ≠ P(M2|M1,L1,L2)

to hold? The answer, on the assumption that causality flows to the right, and on the other assumptions previously given, is *no.* "On each round, the past values of 1 and 2 probabilistically generate the future value of 1, and then separately probabilistically generate the future value of 2." So once we have L1 and L2, they generate M1 independently of how they generate M2.

But if we did know R1 or R2, then, on the assumptions, learning M1 would give us information about M2. Suppose that there are siblings Alpha and Betty, cute little vandals, who throw rocks when their parents are out of town. If the parents are out of town, then either Alpha or Betty might each, independently, decide to throw a rock through my window. If I *don't* know whether a rock has been thrown through my window, and I know that Alpha didn't throw a rock through my window, that doesn't affect my probability estimate that Betty threw a rock through my window—they decide independently. But if I *know* my window is broken, and I know Alpha *didn't* do it, then I can guess Betty is the culprit. So even though Alpha and Betty throw rocks independently of each other, knowing the *effect* can epistemically entangle my beliefs about the *causes.*

Similarly, if we didn't know L1 or L2, then M1 should give us information about M2, because from the effect M1 we can infer the state of its causes L1 and L2, and thence the effect of L1/L2 on M2. If I know that Alpha threw a rock, then I can guess that Alpha and Betty's parents are out of town, and that makes it more likely that Betty will throw a rock too.

Which all goes to say that, if causality is flowing from L to M to R, we may indeed expect the conditional dependence

$$P(M2|R1,R2) \neq P(M2|M1,R1,R2)$$

to hold.

So if we observe, statistically, over many time slices:

$$P(M2|L1,L2) = P(M2|M1,L1,L2)$$
$$P(M2|R1,R2) \neq P(M2|M1,R1,R2)$$

Then we know causality is flowing from left to right; and conversely if we see:

$$P(M2|L1,L2) \neq P(M2|M1,L1,L2)$$
$$P(M2|R1,R2) = P(M2|M1,R1,R2)$$

Then we can guess causality is flowing from right to left.

This trick used the assumption of probabilistic generators. We couldn't have done it if the series had been generated by bijective mappings, i.e., if the future was deterministic given the past and only one possible past was compatible with each future.

So this trick does not directly apply to reading causality off of Barbour's Platonia (which is the name Barbour gives to the timeless mathematical object that is our universe).

However, think about the situation if humanity sent off colonization probes to distant superclusters, and then the accelerating expansion of the universe put the colonies over the cosmological horizon from us. There would then be distant human colonies that could not speak to us again: Correlations in a case where light, going *forward,* could not reach one colony from another, or reach any common ground.

On the other hand, we would be *very* surprised to reach a distant supercluster billions of light-years away, and find a spaceship just arriving from the *other* side of the universe, sent from another independently evolved Earth, which had developed genetically compatible indistinguishable humans who speak English. (A la way too much horrible sci-fi television.) We would not expect such extraordinary *similarity* of events, in a historical region where a ray of light could not yet have reached there from our Earth, nor a ray of light reached our Earth from there, nor could a ray of light reached both Earths from any mutual region between. On the assumption, that is, that rays of light travel in the direction we call "forward".

When two regions of spacetime are timelike separated, we cannot deduce any direction of causality from similarities between them; they could be similar because one is cause and one is effect, or vice versa. But when two regions of spacetime are spacelike separated, and far enough apart that they have no common causal ancestry *assuming* one direction of physical causality, but *would* have common causal ancestry assuming a *different* direction of physical causality, then similarity between them... is at least highly suggestive.

I am not skilled enough in causality to translate probabilistic theorems into bijective deterministic ones. And by calling certain similarities "surprising" I have secretly imported a probabilistic view; I have made myself uncertain so that I can be surprised.

But Judea Pearl himself believes that the arrows of his graphs are more fundamental than the statistical correlations they *produce*; he has said so in an essay entitled "Why I Am Only A Half-Bayesian". Pearl thinks that his arrows reflect reality, and hence, that there is more to inference than just raw probability distributions. If Pearl is right, then there is no reason why you could not have directedness in bijective deterministic mappings as well, which would manifest in the same sort of similarity/dissimilarity rules I have just described.

This does not bring back time. There is no *t* coordinate, and no global *now* sweeping across the universe. Events do not happen in the *past* or the *present* or the *future,* they just *are.* But there may be a certain... *asymmetric locality of relatedness...* that preserves "cause" and "effect", and with it, "therefore". A point in configuration space would never be "past" or "present" or "future", nor would it have a "time" coordinate, but it might be "cause" or "effect" to another point in configuration space.

I am aware of the standard argument that anything resembling an "arrow of time" should be made to stem strictly from the second law of thermodynamics and the low-entropy initial condition. But if you throw out causality along with time, it is hard to see how a low-entropy *terminal* condition and high-entropy *initial* condition could produce the same pattern of similar and dissimilar regions. Look at in another way: To compute a consistent universe with a low-entropy terminal condition and high-entropy initial condition, you have to simulate lots and lots of universes, then throw away all but a tiny fraction of them that end up with low entropy at the end. With a low-entropy initial condition, you can compute it out locally, without any global checks. So I am not yet ready to throw out the arrowheads on my arrows.

And, if we have "therefore" back, if we have "cause" and "effect" back—and science would be somewhat forlorn without them—then we can hope to retrieve the concept of "computation". We are not forced to grind up reality into disconnected configurations; there can be glue between them. We can require the amplitude relations between connected volumes of configuration space, to carry out some kind of timeless computation, before we decide that it contains the timeless Now of a conscious mind. We are not forced to associate experience with an isolated point in configuration space—which is a good thing from my perspective, because it doesn't seem to me that a frozen brain with all the particles in fixed positions ought to be having experiences. I would sooner associate experience with the arrows than the nodes, if I had to pick one or the other! I would sooner associate consciousness with the *change in* a brain than with the brain itself, if I had to pick one or the other.

This also lets me keep, for at least a little while longer, the concept of a conscious mind being connected to its future Nows, and anticipating some future experiences rather than others. Perhaps I will have to throw out this idea eventually, because I cannot seem to formulate it consistently; but for now, at least, I still cannot do without the notion of a "conditional probability". It still seems to me that there is some actual *connection* that makes it more likely for *me* to wake up tomorrow as Eliezer Yudkowsky, than as Britney Spears. If I am in the arrows even more than the nodes, that gives me a direction, a timeless flow. This may possibly be naive, but I am sticking with it until I can jump to an alternative that is less confusing than my present confused state of mind.

Don't think that any of this preserves *time,* though, or distinguishes the past from the future. I am just holding onto *cause* and *effect* and *computation* and even *anticipation* for a little while longer.

Part of *The Quantum Physics Sequence*

Next post: "Timeless Identity"

Previous post: "Timeless Beauty"

Timeless Identity

Followup to: No Individual Particles, Identity Isn't In Specific Atoms, Timeless Physics, Timeless Causality

People have asked me, "What practical good does it do to discuss quantum physics or consciousness or zombies or personal identity? I mean, what's the application for me in real life?"

Before the end of today's post, we shall see a real-world application with practical consequences, for you, yes, you in today's world. It is built upon many prerequisites and deep foundations; you will not be able to tell others what you have seen, though you may (or may not) want desperately to tell them. (Short of having them read the last several months of OB.)

In No Individual Particles we saw that the intuitive conception of reality as little billiard balls bopping around, is entirely and absolutely wrong; the basic ontological reality, to the best of anyone's present knowledge, is a joint configuration space. These configurations have mathematical identities like "A particle here, a particle there", rather than "particle 1 here, particle 2 there" and the difference is experimentally testable. What might *appear* to be a little billiard ball, like an electron caught in a trap, is actually a multiplicative *factor* in a wavefunction that happens to approximately factor. The factorization of 18 includes *two* factors of 3, not *one* factor of 3, but this doesn't mean the two 3s have separate individual identities—quantum mechanics is sort of like that. (If that didn't make any sense to you, sorry; you need to have followed the series on quantum physics.)

In Identity Isn't In Specific Atoms, we took this counterintuitive truth of physical ontology, and proceeded to kick hell out of an intuitive concept of personal identity that depends on being made of the "same atoms"—the intuition that you are the same person, if you are made out of the *same pieces.* But because the brain doesn't repeat its exact state (let alone the whole universe), the *joint* configuration space which underlies you, is nonoverlapping from one fraction of a second to the next. Or even from one Planck interval to the next. I.e., "you" of now and "you" of one second later do not have in common any ontologically basic elements with a shared persistent identity.

Just from standard quantum mechanics, we can see immediately that some of the standard thought-experiments used to pump intuitions in philosophical discussions of identity, are *physical nonsense*. For example, there is a thought experiment that runs like this:

> "The Scanner here on Earth will destroy my brain and body, while recording the exact states of all my cells. It will then transmit this information by radio. Travelling at the speed of light, the message will take three minutes to reach the Replicator on Mars. This will then create, out of new matter, a brain and body exactly like mine. It will be in this body that I shall wake up."

This is Derek Parfit in the excellent *Reasons and Persons,* p. 199—note that Parfit is describing thought experiments, not necessarily endorsing them.

There is an argument which Parfit describes (but does not himself endorse), and which I have seen many people spontaneously invent, which says (not a quote):

> Ah, but suppose an improved Scanner were invented, which scanned you *non-destructively,* but still transmitted the same information to Mars . Now, *clearly*, in this case, *you, the original* have simply stayed on Earth, and the person on Mars is *only a copy*. Therefore this teleporter is actually murder and birth, not *travel* at all—it destroys the original, and constructs a copy!

Well, but who says that if we build an exact copy of you, one version is the *privileged original* and the other is *just a copy?* Are you under the impression that one of these bodies is constructed out of *the original atoms*—that it has some kind of physical continuity the other does not possess? But there is no such thing as a particular atom, so the original-ness or new-ness of the person can't depend on the original-ness or new-ness of the atoms.

(If you are now saying, "No, you can't distinguish two electrons *yet*, but that doesn't mean they're the *same entity* -" then you have not been following the series on quantum mechanics, or you need to reread it. Physics does not work the way you think it does. There *are no* little billiard balls bouncing around down there.)

If you further realize that, as a matter of fact, you are splitting all the time due to ordinary decoherence, then you are much more likely to look at this thought experiment and say: "There is no copy; there are two originals."

Intuitively, in your imagination, it might seem that one billiard ball stays in the same place on Earth, and another billiard ball has popped into place on Mars; so one is the "original", and the other is the "copy". But at a fundamental level, things are not made out of billiard balls.

A sentient brain constructed to atomic precision, and copied with atomic precision, could undergo a quantum evolution along with its "copy", such that, afterward, there would *exist no fact of the matter* as to which of the two brains was the "original". In some Feynman diagrams they would exchange places, in some Feynman diagrams not. The two entire brains would be, in aggregate, identical particles with no individual identities.

Parfit, having discussed the teleportation thought experiment, counters the intuitions of physical continuity with a different set of thought experiments:

> "Consider another range of possible cases: the *Physical Spectrum*. These cases involve all of the different possible degrees of physical continuity...
>
> "In a case close to the near end, scientists would replace 1% of the cells in my brain and body with exact duplicates. In the case in the middle of the spectrum, they would replace 50%. In a case near the far end, they would replace 99%, leaving only 1% of my original brain and body. At the far end, the 'replacement' would involve the complete destruction of my brain and body, and the creation out of new organic matter of a Replica of me."
>
> (*Reasons and Persons,* p. 234.)

Parfit uses this to argue against the intuition of physical continuity pumped by the first experiment: if your identity depends on physical continuity, where is the exact threshold at which you cease to be "you"?

By the way, although I'm criticizing Parfit's reasoning here, I really liked Parfit's discussion of personal identity. It really surprised me. I was expecting a rehash of the same arguments I've seen on transhumanist mailing lists over the last decade or more. Parfit gets *much* further than I've seen the mailing lists get. This is a sad verdict for the mailing lists. And as for *Reasons and Persons,* it well deserves its fame.

But although Parfit executed his arguments competently and with great philosophical skill, those two *particular* arguments (Parfit has lots more!) are doomed by physics.

There just is no such thing as "new organic matter" that has a persistent identity apart from "old organic matter". No fact of the matter exists, as to which electron is which, in your body on Earth or your body on Mars. No fact of the matter exists, as to how many electrons in your body have been "replaced" or "left in the same place". So both thought experiments are physical nonsense.

Parfit seems to be enunciating his own opinion here (not Devil's advocating) when he says:

> "There are two kinds of sameness, or identity. I and my Replica are *qualitatively identical,* or exactly alike. But we may not be *numerically identical*, one and the same person. Similarly, two white billiard balls are not numerically but may be qualitatively identical. If I paint one of these balls red, it will cease to be qualitatively identical with itself as it was. But the red ball that I later see and the white ball that I painted red are numerically identical. They are one and the same ball." (p. 201.)

In the human *imagination,* the way we have evolved to imagine things, we can imagine two qualitatively identical billiard balls that have a further fact about them—their persistent identity—that makes them distinct.

But it seems to be a basic lesson of physics that "numerical identity" *just does not exist.* Where "qualitative identity" exists, you can set up quantum evolutions that refute the illusion of individuality—Feynman diagrams that sum over different permutations of the identicals.

We should always have been suspicious of "numerical identity", since it was not experimentally detectable; but physics swoops in and drop-kicks the whole argument out the window.

Parfit p. 241:

> "Reductionists admit that there is a difference between numerical identity and exact similarity. In some cases, there would be a real difference between some person's being me, and his being someone else who is merely exactly like me."

This reductionist admits no such thing.

Parfit even describes a wise-*seeming* reductionist refusal to answer questions as to when one person becomes another, when you are "replacing" the atoms inside them. P. 235:

> (The reductionist says:) "The resulting person will be psychologically continuous with me as I am now. This is all there is to know. I do not know whether the resulting person will be me, or will be someone else who is merely exactly like me. But this is not, here, a real question, which must have an answer. It does not describe two different possibilities, one of which must be true. It is here an empty question. There is not a real difference here between the resulting person's being

me, and his being *someone else.* This is why, even though I do not know whether I am about to die, I know everything."

Almost but not quite reductionist enough! When you master quantum mechanics, you see that, in the thought experiment where your atoms are being "replaced" in various quantities by "different" atoms, *nothing whatsoever is actually happening*—the thought experiment itself is physically empty.

So *this* reductionist, at least, triumphantly says—not, "It is an empty question; I know everything that there is to know, even though I don't know if I will live or die"—but simply, "I will live; nothing happened."

This whole episode is one of the main reasons why I hope that when I *really* understand matters such as these, and they have ceased to be mysteries unto me, that I *will* be able to give definite answers to questions that seem like they ought to have definite answers.

And it is a reason why I am suspicious, of philosophies that too early—before the dispelling of mystery—say, "There is no answer to the question." Sometimes there *is* no answer, but then the absence of the answer comes with a shock of understanding, a click like thunder, that makes the question vanish in a puff of smoke. As opposed to a dull empty sort of feeling, as of being told to shut up and stop asking questions.

And another lesson: Though the thought experiment of having atoms "replaced" seems *easy to imagine in the abstract,* anyone knowing a *fully detailed physical visualization* would have immediately seen that the thought experiment was physical nonsense. Let zombie theorists take note!

Additional physics can shift our view of identity even further:

In Timeless Physics, we looked at a speculative, but even more beautiful view of quantum mechanics: We don't need to suppose the amplitude distribution over the configuration space is *changing*, since the universe never repeats itself. We never see any particular joint configuration (of the whole universe) change amplitude from one time to another; from one time to another, the universe will have expanded. There is just a timeless amplitude distribution (aka wavefunction) over a configuration space that includes compressed configurations of the universe (early times) and expanded configurations of the universe (later times).

Then we will need to discover people and their identities embodied within a timeless set of *relations* between configurations that never repeat themselves, and never change from one time to another.

As we saw in Timeless Beauty, timeless physics is beautiful because it would make everything that exists either *perfectly global*—like the uniform, exceptionless laws of physics that apply everywhere and everywhen—*or perfectly local*—like points in the configuration space that only affect or are affected by their immediate local neighborhood. Everything that exists fundamentally, would be *qualitatively unique:* there would never be two *fundamental* entities that have the same properties but are not the same entity.

(Note: The you on Earth, and the you on Mars, are not ontologically basic. You are *factors* of a joint amplitude distribution that is ontologically basic. Suppose the integer 18 exists: the factorization of 18 will include *two* factors of 3, not *one* factor of

3. This does not mean that inside the Platonic integer 18 there are two little 3s hanging around with persistent identities, living in different houses.)

We also saw in Timeless Causality that the end of time is not necessarily the end of cause and effect; causality can be defined (and detected statistically!) without mentioning "time". This is important because it preserves arguments about personal identity that rely on *causal* continuity rather than "physical continuity".

Previously I drew this diagram of *you* in a timeless, branching universe:

Manybranches4

To understand many-worlds: The gold head only *remembers* the green heads, creating the illusion of a unique line through time, and the intuitive question, "Where does the line go next?" But it goes to both possible futures, and both possible futures will look back and see a single line through time. In many-worlds, there *is no fact of the matter* as to which future *you personally* will end up in. There is no copy; there are two originals.

To understand timeless physics: The heads are not popping in and out of existence as some Global Now sweeps forward. They are all just there, each thinking that *now* is a different time.

In Timeless Causality I drew this diagram:

Causeright

This was part of an illustration of how we could statistically distinguish left-flowing causality from right-flowing causality—an argument that *cause and effect* could be defined relationally, even the absence of a changing global time. And I said that, because we could keep cause and effect as the glue that binds configurations together, we could go on trying to identify experiences with *computations* embodied in flows of amplitude, rather than having to identify experiences with individual configurations.

But both diagrams have a common flaw: they show discrete nodes, connected by discrete arrows. In reality, physics is continuous.

So if you want to know "Where is the computation? Where is the experience?" my best guess would be to point to something like a *directional braid:*

Braid_2

This is not a braid of moving particles. This is a braid of interactions within close neighborhoods of timeless configuration space.

Braidslice

Every point intersected by the red line is unique as a mathematical entity; the points are not *moving* from one time to another. However, the amplitude at different points is related by physical laws; and there is a direction of causality to the relations.

You could say that the amplitude is *flowing,* in a river that never changes, but has a direction.

Embodied in this timeless flow are computations; within the computations, experiences. The experiences' computations' configurations might even overlap each other:

Braidtime_2

In the causal relations covered by the rectangle 1, there would be one moment of Now; in the causal relations covered by the rectangle 2, another moment of Now. There is a causal direction between them: 1 is the cause of 2, not the other way around. The rectangles overlap—though I really am not sure if I should be drawing them with overlap or not—because the computations are embodied in some of the same configurations. Or if not, there is still causal continuity because the end state of one computation is the start state of another.

But on an ontologically fundamental level, nothing with a persistent identity moves through time.

Even the braid itself is not ontologically fundamental; a human brain is a *factor* of a larger wavefunction that happens to factorize.

Then what is preserved from one time to another? On an ontologically basic level, absolutely nothing.

But you will recall that I earlier talked about any perturbation which does not disturb your internal narrative, almost certainly not being able to disturb whatever is the true cause of your saying "I think therefore I am"—this is why you can't leave a person physically unaltered, and subtract their consciousness. When you look at a person on the level of organization of neurons firing, anything which does not disturb, or only infinitesimally disturbs, the pattern of neurons firing—such as flipping a switch from across the room—ought not to disturb your consciousness, or your personal identity.

If you were to describe the brain on the level of neurons and synapses, then this description of the factor of the wavefunction that is your brain, would have *a very great deal in common,* across different cross-sections of the braid. The pattern of synapses would be "almost the same"—that is, the description would come out almost the same—even though, on an ontologically basic level, nothing that exists fundamentally is held in common between them. The internal narrative goes on, and you can see it within the vastly higher-level view of the firing patterns in the connection of synapses. The *computational* pattern computes, "I think therefore I am". The narrative says, today and tomorrow, "I am Eliezer Yudkowsky, I am a rationalist, and I have something to protect." Even though, in the river that never flows, not a single drop of water is shared between one time and another.

If there's any basis *whatsoever* to this notion of "continuity of consciousness"—I haven't quite given up on it yet, because I don't have anything better to cling to—then I would guess that this is how it works.

Oh... and I promised you a real-world application, didn't I?

Well, here it is:

Many throughout time, tempted by the promise of immortality, have consumed strange and often fatal elixirs; they have tried to bargain with devils that failed to appear; and done many other silly things.

But like all superpowers, long-range life extension can only be acquired by seeing, with a shock, that some way of getting it is *perfectly normal.*

If you can see the moments of *now* braided into time, the causal dependencies of future states on past states, the high-level pattern of synapses and the internal narrative as a computation within it—if you can viscerally dispel the classical hallucination of a little billiard ball that is you, and see your *nows* strung out in the river that never flows—then you can see that signing up for cryonics, being vitrified in liquid nitrogen when you die, and having your brain nanotechnologically reconstructed fifty years later, is actually *less* of a change than going to sleep, dreaming, and forgetting your dreams when you wake up.

You should be able to *see* that, now, if you've followed through this whole series. You should be able to get it on a *gut level*—that being vitrified in liquid nitrogen for fifty years (around 3e52 Planck intervals) is not very different from waiting an average of 2e26 Planck intervals between neurons firing, on the generous assumption that there are a hundred trillion synapses firing a thousand times per second. You should be able to *see* that there is nothing preserved from one night's sleep to the morning's waking, which cryonic suspension does not preserve also. Assuming the vitrification technology is good enough for a sufficiently powerful Bayesian superintelligence to look at your frozen brain, and figure out "who you were" to the same resolution that your morning's waking self resembles the person who went to sleep that night.

Do you know what it takes to *securely* erase a computer's hard drive? Writing it over with all zeroes isn't enough. Writing it over with all zeroes, then all ones, then a random pattern, isn't enough. Someone with the right tools can still examine the final state of a section of magnetic memory, and distinguish the state, "This was a 1 written over by a 1, then a 0, then a 1" from "This was a 0 written over by a 1, then a 0, then a 1". The best way to securely erase a computer's hard drive is to destroy it with thermite.

I really don't think that carefully vitrifying a brain to prevent ice crystal formation and then freezing it in liquid nitrogen is going to be a secure erase procedure, if you can examine atomic-level differences in the synapses.

Someone hears about cryonics and thinks for 10 seconds and says, "But if you're frozen and then revived, are you *really the same person?*"

And if they happened to know all about quantum physics *and could apply the abstract knowledge to real life,* and they had followed the whole debate about zombies *and resolved it against epiphenomenalism in general,* then they would be able to visualize the braids in the river that never flows, and say, "Yes."

But this knowledge is not common.

So they die.

There are numerous other reasons that people seize on, when they search for a rationalization for a negative initial flinch against cryonics. And numerous other knowledges that would be required to answer those objections. "But wouldn't it be boring to live such a long time?" (Can be answered if you know hedonic psychology, and have developed a theory of fun, and can visualize accessible fun spaces that increase in volume with increasing intelligence.) "Why would future civilizations bother to revive me?" (Requires understanding either economic growth diminishing the cost, *or* knowledge of history and how societies have become kinder over time, *or* knowing about Friendly AI.) "Isn't it wrong to live so long?" (Requires knowing about the "sour grapes" bias. See also transhumanism as simplified humanism and the meaning that immortality gives to life.) Then there's the meta-knowledge of how to question all these deeply wise cached thoughts that pop into your head about the futility of life; and the ability to do things that might make people look at you weird, and so on...

Some of these are series of posts I haven't done yet. But if you anticipate updating your probabilities when you read those future posts, then you should update them now. Or, if you prefer, trust me:

If you would rather live happily ever after, than die, and you are willing to spend between $300 and $2000 per year(*) to express this preference, then sign up for cryonics.

If you've been cryocrastinating, putting off signing up for cryonics "until later", don't think that you've "gotten away with it so far". Many worlds, remember? There are branched versions of you that are dying of cancer, and not signed up for cryonics, and it's too late for them to get life insurance.

See, knowing about many worlds can help you visualize probabilities as frequencies, because they usually *are.*

It might encourage you to get around to getting health insurance, too, or wearing a helmet on your motorcycle, or whatever: don't think you've gotten away with it so far.

And if you're planning to play the lottery, don't think you *might* win this time. A vanishingly small fraction of you wins, every time. So either learn to discount small fractions of the future by shutting up and multiplying, or spend all your money on lottery tickets—your call.

It is a very important lesson in rationality, that at any time, the Environment may suddenly ask you almost any question, which requires you to draw on 7 different fields of knowledge. If you missed studying a single one of them, you may suffer arbitrarily large penalties up to and including capital punishment. You can die for an answer you gave in 10 seconds, without realizing that a field of knowledge existed of which you were ignorant.

This is why there is a virtue of scholarship.

150,000 people die every day. Some of those deaths are truly unavoidable, but most are the result of inadequate knowledge of cognitive biases, advanced futurism, and quantum mechanics.(**)

If you disagree with my premises or my conclusion, take a moment to consider nonetheless, that *the very existence of an argument about life-or-death stakes*, whatever position you take in that argument, constitutes a sufficient lesson on *the sudden relevance of scholarship.*

(*) The way cryonics works is that you get a life insurance policy, and the policy pays for your cryonic suspension. The Cryonics Institute is the cheapest provider, Alcor is the high-class one. Rudi Hoffman set up my own insurance policy, with CI. I have no affiliate agreements with any of these entities, nor, to my knowledge, do they have affiliate agreements with anyone. They're trying to look respectable, and so they rely on altruism and word-of-mouth to grow, instead of paid salespeople. So there's a vastly smaller worldwide market for immortality than lung-cancer-in-a-stick. Welcome to your Earth; it's going to stay this way until you fix it.

(**) *Most* deaths? Yes: If cryonics were widely seen in the same terms as any other medical procedure, economies of scale would considerably diminish the cost; it would be applied routinely in hospitals; and foreign aid would enable it to be applied even in poor countries. So children in Africa are dying because citizens and politicians and philanthropists in the First World don't have a gut-level understanding of quantum mechanics.

Added: For some of the questions that are being asked, see Alcor's FAQ for scientists and Ben Best's Cryonics FAQ (archived snapshot).

Part of *The Quantum Physics Sequence*

Next post: "Thou Art Physics"

Previous post: "Timeless Causality"

Thou Art Physics

Three months ago—jeebers, has it really been that long?—I posed the following homework assignment: Do a stack trace of the human cognitive algorithms that produce debates about “free will.” Note that this task is strongly distinguished from arguing that free will does or does not exist.

Now, as expected, people are asking, “If the future is determined, how can our choices control it?” The wise reader can guess that it all adds up to normality; but this leaves the question of *how*.

People hear: “The universe runs like clockwork; physics is deterministic; the future is fixed.” And their minds form a causal network that looks like this:

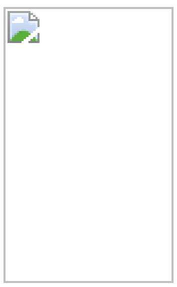
Here we see the causes “Me” and “Physics,” competing to determine the state of the “Future” effect. If the “Future” is fully determined by “Physics,” then obviously there is no room for it to be affected by “Me.”

This causal network is not an explicit philosophical belief. It’s implicit— a background representation of the brain, controlling which philosophical arguments seem “reasonable.” It just seems like the way things *are*.

Every now and then, another neuroscience press release appears, claiming that, because researchers used an fMRI to spot the brain doing something-or-other during a decision process, *it’s not you who chooses, it’s your brain*.

Likewise that old chestnut, “Reductionism undermines rationality itself. Because then, every time you said something, it wouldn’t be the result of *reasoning* about the evidence—it would be merely quarks bopping around.”

Of course the actual diagram should be:



Or better yet:

Why is this not obvious? Because there are many levels of organization that separate our models of our thoughts—our emotions, our beliefs, our agonizing indecisions, and our final choices—from our models of electrons and quarks.

We can *intuitively* visualize that a hand is made of fingers (and thumb and palm). To ask whether it's *really* our hand that picks something up, or *merely* our fingers, thumb, and palm, is transparently a wrong question.

But the gap between physics and cognition cannot be crossed by direct visualization. No one can *visualize* atoms making up a person, the way they can see fingers making up a hand.

And so it requires *constant vigilance* to maintain your perception of yourself as an entity *within physics*.

This vigilance is one of the great keys to philosophy, like the Mind Projection Fallacy. You will recall that it is this point which I nominated as having tripped up the quantum physicists who failed to imagine macroscopic decoherence; they did not think to apply the laws to *themselves*.

Beliefs, desires, emotions, morals, goals, imaginations, anticipations, sensory perceptions, fleeting wishes, ideals, temptations… You might call this the "surface layer" of the mind, the parts-of-self that people can see even without science. If I say, "It is not *you* who determines the future, it is your *desires, plans, and actions* that determine the future," you can readily see the part-whole relations. It is immediately visible, like fingers making up a hand. There are other part-whole relations all the way down to physics, but they are not immediately visible.

"Compatibilism" is the philosophical position that "free will" can be intuitively and satisfyingly defined in such a way as to be compatible with deterministic physics. "Incompatibilism" is the position that free will and determinism are incompatible.

My position might perhaps be called "Requiredism." When agency, choice, control, and moral responsibility are cashed out in a sensible way, they *require* determinism—at least some patches of determinism within the universe. If you choose, and plan, and act, and bring some future into being, in accordance with your desire, then all this requires a lawful sort of reality; you cannot do it amid utter chaos. There must be order over at least those parts of reality that are being controlled by you. *You* are within physics, and so you/physics have determined the future. If it were not determined by physics, it could not be determined by you.

Or perhaps I should say, "If the future were not determined by reality, it could not be determined by you," or "If the future were not determined by something, it could not be determined by you." You don't need neuroscience or physics to push naive definitions of free will into incoherence. If the mind were not embodied in the brain, it would be embodied in something else; there would be *some real thing* that was a mind. If the future were not determined by physics, it would be determined by *something*, some law, some order, some grand reality that included you within it.

But if the laws of physics control us, then how can we be said to control ourselves?

Turn it around: If the laws of physics did *not* control us, how could we possibly control ourselves?

How could thoughts judge other thoughts, how could emotions conflict with each other, how could one course of action appear best, how could we pass from uncertainty to certainty about our own plans, in the midst of utter chaos?

If we were not in reality, where could we be?

The future is determined by physics. What kind of physics? The kind of physics that includes the actions of human beings.

People's choices are determined by physics. What kind of physics? The kind of physics that includes weighing decisions, considering possible outcomes, judging them, being tempted, following morals, rationalizing transgressions, trying to do better…

There is no point where a quark swoops in from Pluto and overrides all this.

The thoughts of your decision process are all *real*, they are all *something*. But a thought is too big and complicated to be an atom. So thoughts are made of smaller things, and our name for the stuff that stuff is made of is "physics."

Physics underlies our decisions and includes our decisions. It does not explain them away.

Remember, physics adds up to normality; it's your cognitive algorithms that generate confusion

Timeless Control

Followup to: Timeless Physics, Timeless Causality, Thou Art Physics

People hear about many-worlds, which is deterministic, or about timeless physics, and ask:

If the future is determined by physics, how can anyone control it?

In Thou Art Physics, I pointed out that since you are *within* physics, anything *you* control is *necessarily* controlled by physics. Today we will talk about a different aspect of the confusion, the words "determined" and "control".

The "Block Universe" is the classical term for the universe considered from outside Time. Even without timeless physics, Special Relativity outlaws any global space of simultaneity, which is widely believed to suggest the Block Universe—spacetime as one vast 4D block.

When you take a perspective outside time, you have to be careful not to let your old, timeful intuitions run wild in the absence of their subject matter.

In the Block Universe, the future is not determined *before* you make your choice. "Before" is a timeful word. Once you descend so far as to start talking about *time,* then, of course, the future comes "after" the past, not "before" it.

If we're going to take a timeless perspective, then the past and the future have not *always* been there. The Block Universe is not something that hangs, motionless and static, lasting for a very long time. You might try to visualize the Block Universe hanging in front of your mind's eye, but then your mind's eye is running the clock while the universe stays still. Nor does the Block Universe exist for just a single second, and then disappear. It is not instantaneous. It is not eternal. It does not last for exactly 15 seconds. All these are timeful statements. The Block Universe is simply *there.*

Perhaps people imagine a Determinator—not so much an agent, perhaps, but a mysterious entity labeled "Determinism"—which, at "the dawn of time", say, 6:00am, writes down your choice at 7:00am, and separately, writes the outcome at 7:02am. In which case, indeed, the future would be determined *before* you made your decision...

Fwdeterminism_2

In this model, the Determinator writes the script for the Block Universe at 6:00am. And *then* time—the global time of the universe—continues, running through the Block Universe and realizing the script.

At 7:00am you're trying to decide to turn on the light bulb. But the Determinator already decided at 6:00am whether the light bulb would be on or off at 7:02am. Back at the dawn of time when Destiny wrote out the Block Universe, which was scripted *before* you started experiencing it...

This, perhaps, is the kind of unspoken, intuitive mental model that might lead people to talk about "determinism" implying that the future is determined *before* you make your decision.

Even without the concept of the Block Universe or timeless physics, this is probably what goes on when people start talking about "deterministic physics" in which "the whole course of history" was fixed at "the dawn of time" and therefore your choices have no effect on the "future".

As described in Timeless Causality, "cause" and "effect" are things we talk about by pointing to relations *within* the Block Universe. E.g., we might expect to see human colonies separated by an expanding cosmological horizon; we can expect to find correlation between two regions that communicate with a mutual point in the "past", but have no light-lines to any mutual points in their "future". But we wouldn't expect to find a human colony in a distant supercluster, having arrived from the other side of the universe; we should *not* find correlation between regions with a shared "future" but no shared "past". This is how we can experimentally observe the orientation of the Block Universe, the direction of the river that never flows.

Fwcausality

If you are going to talk about causality at all—and personally, I think we should, because the universe doesn't make much sense without it—then causality applies to relations *within* the Block Universe, not outside it.

The Past is just *there,* and the Future is just *there,* but the relations between them have a certain kind of structure—whose ultimate nature, I do not conceive myself to understand—but which we do know a bit about mathematically; the structure is called "causality".

(I am not ruling out the possibility of causality that extends outside the Block Universe—say, some reason why the laws of physics are what they are. We can have timeless causal relations, remember? But the causal relations between, say, "dropping a glass" and "water spilling out", or between "deciding to do something" and "doing it", are causal relations embedded *within* the Block.)

One of the things we can do with graphical models of causality—networks of little directed arrows—is construe *counterfactuals:* Statements about "what *would* have happened if X had occurred, instead of Y".

These counterfactuals are untestable, unobservable, and do not actually exist anywhere that *I've* been able to find. Counterfactuals are not facts, unless you count them as mathematical properties of certain causal diagrams. We can define statistical properties we expect to see, given a causal hypothesis; but counterfactuals *themselves* are not observable. We cannot *see* what "would have happened, if I hadn't dropped the glass".

Nonetheless, if you draw the causal graph that the statistics force you to draw, *within* our Block Universe, and you construct the counterfactual, then you get statements like: "If I hadn't dropped the glass, the water wouldn't have spilled."

If your mind contains the causal model that has "Determinism" as the cause of both the "Past" and the "Future", then you will start saying things like, *But it was determined before the dawn of time that the water would spill—so not dropping the glass would have made no difference.* This *would* be the standard counterfactual, on the causal graph in which "Past" and "Future" are both children of some mutual ancestor, but have no connection between them.

And then there's the idea that, if you can predict the whole course of the universe by looking at the state at the beginning of time, the present must have no influence on the future...

Fwmarkov_2

Surely, if you can determine the Future just by looking at the Past, there's no need to look at the Present?

The problem with the right-side graph is twofold: First, it violates the beautiful locality of reality; we're supposing causal relations that go outside the immediate neighborhoods of space/time/configuration. And second, you can't compute the Future from the Past, except by also computing something that looks exactly like the Present; which computation just creates another copy of the Block Universe (if that statement even makes any sense), it does not affect any of the causal relations *within* it.

One must avoid mixing up timeless and timeful thinking. E.g., trying to have "Determinism" acting on things *before they happen.* Determinism is a timeless viewpoint, so it doesn't mix well with words like "before".

The same thing happens if you try to talk about how the Past at 6:30am *determines* the Future at 7:30am, and therefore, the state at 7:30am is *already determined* at 6:30am, so you can't *control* it at 7:00am, because it was determined at 6:30am *earlier*...

What is *determined* is a timeless mathematical structure whose interior includes 7:00am and 7:30am. That which you might be tempted to say "already exists" at 6:00am, does not exist *before* 7:00am, it is something whose existence *includes* the Now of 7:00am and the Now of 7:30am.

If you imagine a counterfactual surgery on the interior of the structure at 7:00am, then, according to the statistically correct way to draw the arrows of causality within the structure, the 7:30am part would be affected as well.

So it is exactly correct to say, on the one hand, "The whole future course of the universe was determined by its state at 6:30am this morning," and, on the other, "If I hadn't dropped the glass, the water wouldn't have spilled." In the former case you're talking about a mathematical object outside time; in the latter case you're talking about cause and effect *inside* the mathematical object. Part of *what is determined* is that dropping the glass in the Now of 7:00:00am, *causes* the water to spill in the Now of 7:00:01am.

And as pointed out in Thou Art Physics, *you* are inside that mathematical object too. So are your thoughts, emotions, morals, goals, beliefs, and all else that goes into the way you determine your decisions.

To say "the future is already written" is a fine example of mixed-up timeful and timeless thinking. The future *is.* It is not "already". *What* is it that writes the future? In the timeless causal relations, *we do*. *That* is *what is written*: that our choices control the future.

But how can you "control" something without *changing* it?

"Change" is a word that makes sense *within* time, and only within time. One observes a macroscopically persistent object, like, say, a lamp, and compares its state at 7:00am to its state at 7:02am. If the two states are different, then we say that "the lamp" changed *over time.*

In Timeless Physics, I observed that, while things can change *from one time to another*, a *single* moment of time is never observed to change:

> At 7:00am, the lamp is off. At 7:01am, I flip the switch... At 7:02am, the lamp is fully bright. Between 7:00am and 7:02am, the lamp changed from OFF to ON.
>
> But have you ever seen the *future* change from one time to another? Have you wandered by a lamp at exactly 7:02am, and seen that it is OFF; then, a bit later, looked in again on the "the lamp at exactly 7:02am", and discovered that it is now ON?

But if you have to change a single moment of time, in order to be said to "control" something, you really are hosed.

Forget this whole business of deterministic physics for a moment.

Let's say there *was* some way to change a single moment of time.

We would then need some kind of meta-time *over which* time could "change".

The lamp's state would need to change from "OFF at 7:02am at 3:00meta-am" to "ON at 7:02am at 3:01meta-am".

But wait! Have you ever seen a lamp change from OFF at 7:02am at 3:00meta-am, to ON at 7:02am at 3:00meta-am? No! A single instant of meta-time never changes, so you cannot change it, and you have no control.

Now we need meta-meta time.

So if we're going to keep our concepts of "cause" and "control" and "choose"—and to discard them would leave a heck of a lot observations unexplained—then we've got to figure out some way to define them *within* time, *within* that which is written, *within* the Block Universe, within... well... *reality*.

Control lets you change things from one time to another; you can turn on a lamp that was previously off. That's one kind of control, and a fine sort of control it is to have. But trying to pull this stunt on a *single* moment of time, is a type error.

If you isolate a subsystem of reality, like a rock rolling down hill, then you can mathematically define the future-in-isolation of that subsystem; you can take the subsystem in isolation, and compute what would happen to it *if* you did not act on it. In this case, what would happen is that the rock would reach the bottom of the hill. This future-in-isolation is not something that actually happens in the Block Universe; it is a computable *property* of the subsystem as it exists at some particular moment. If you reach in from outside the isolation, you can stop the rock from rolling. Now if you walk away, and again leave the system isolated, the future-in-isolation will be that the rock just stays there. But perhaps someone will reach in, and tip the rock over and start it rolling again. The hill is not *really* isolated—the universe is a continuous whole—but we can imagine what *would* happen if the hill *were* isolated. This is a "counterfactual", so called because they are not factual.

The future-in-isolation of a subsystem can change from one time to another, as the subsystem itself changes over time as the result of actions from outside. *The* future of the Grand System that includes *everything,* cannot change as the result of outside action.

People want to place themselves outside the System, see themselves separated from it by a Cartesian boundary. But even if free will could act outside physics to change the Block Universe, we would just have a Grand System that included free-will+physics and *the* future would be fully determined by *that.* If you have "freer will" we just have an Even Grander System, and so on.

It's hard to put yourself outside Reality. Whatever *is,* is real.

Control lets you *determine* single moments of time (though they do not change from one meta-time to another). You can change what *would have* happened, from one time to another. But you cannot *change* what *does* happen—just *determine* it. Control means that you *are* what writes the written future, according to the laws of causality as they exist *within* the writing.

Or maybe look at it this way: Pretend, for a moment, that naive views of free will were correct. The future "doesn't exist yet" and can be "changed". (Note: How are these two statements compatible?) Suppose that you exercise your "free will" at 6:30am to rescue three toddlers from a burning orphanage, changing their future from horrible flamey death at 7:00am, to happy gurgling contentment at 7:00am.

But *now* it is 7:30am, and I say:

"Aha! The past is fixed and can never be altered! So now you cannot ever have chosen any differently than you *did* choose. Furthermore, the actual outcome of your actions can never change either; the outcome is now fixed, so even if your past choice did now change, the past outcome wouldn't, because they are both just determined by "The Past". While your will was once free at 6:30am to change the future at 7:00am, it is now 7:30am and this freedom no longer exists. So *now* your will at 6:30am is no longer free. How can your past will have been free, now that there is only one past? Therefore I do not now assign you any moral credit for saving the orphanage; you no longer could have chosen differently from how you chose."

In the Block Universe, the "past" and the "future" are just perspectives, taken from some point within the Block. So, if the fixation of the past doesn't prevent the embedded decisions from having (had?) the property of freedom, why should the determination of the future prevent *those* embedded decisions from having the same property?

In the Block Universe, the Future is *just* like the Past: it contains the Nows of people making choices that determine their outcomes, which do not change from one meta-time to another.

And given the way we draw the causal arrows, it is correct to form the (un-observable) counterfactuals, "If I hadn't saved those children from the orphanage, they would be dead," and "If I don't think carefully, my thoughts will end up in Outer Mongolia." One is a counterfactual over the past, and one is a counterfactual over the future; but they are both as correct as a counter-factual can be.

The next step in analyzing the cognitive issues surrounding free will, is to take apart the word "could"—as in "I *could* have decided not to save the children from the orphanage." As always, I encourage the reader to try to get it in advance—this one is easier if you know a certain simple algorithm from Artificial Intelligence.

PPS: It all adds up to normality.

Part of *The Quantum Physics Sequence*

Next post: "The Failures of Eld Science"

Previous post: "Thou Art Physics"

The Failures of Eld Science

This time there were no robes, no hoods, no masks. Students were expected to become friends, and allies. And everyone knew why you were in the classroom. It would have been pointless to pretend you weren't in the Conspiracy.

Their *sensei* was Jeffreyssai, who might have been the best of his era, in his era. His students were either the most promising learners, or those whom the *beisutsukai* saw political advantage in molding.

Brennan fell into the latter category, and knew it. Nor had he hesitated to use his Mistress's name to open doors. You used every avenue available to you, in seeking knowledge; that was respected here.

"—for over thirty years," Jeffreyssai said. "Not one of them saw it; not Einstein, not Schrödinger, not even von Neumann." He turned away from his sketcher, and toward the classroom. "I pose to you to the question: How did they fail?"

The students exchanged quick glances, a calculus of mutual risk between the wary and the merely baffled. Jeffreyssai was known to play games.

Finally Hiriwa-called-the-Black leaned forward, jangling slightly as her equation-carved bracelets shifted on her ankles. "By your years given, *sensei,* this was two hundred and fifty years after Newton. Surely, the scientists of that era must have grokked the concept of a universal law."

"Knowing the universal law of gravity," said the student Taji, from a nearby seat, "is not the same as understanding the concept *of* a universal law." He was one of the promising ones, as was Hiriwa.

Hiriwa frowned. "No... it was said that Newton had been praised *for* discovering the first universal. Even in his own era. So it was known." Hiriwa paused. "But Newton himself would have been gone. Was there a *religious* injunction against proposing further universals? Did they refrain out of respect for Newton, or were they waiting for his *ghost* to speak? I am not clear on how Eld science was motivated—"

"No," murmured Taji, a laugh in his voice, "you really, *really* aren't."

Jeffreyssai's expression was kindly. "Hiriwa, it wasn't religion, and it wasn't lead in the drinking water, and they didn't all have Alzheimers, and they weren't sitting around all day reading webcomics. Forget the catalogue of horrors out of ancient times. Just think in terms of cognitive errors. What could Eld science have been *thinking* wrong?"

Hiriwa sat back with a sigh. "*Sensei,* I truly cannot imagine a snafu that would do *that*."

"It wouldn't be just *one* mistake," Taji corrected her. "As the saying goes: Mistakes don't travel alone; they hunt in packs."

"But the *entire* human species?" said Hiriwa. "Thirty *years*?"

"It wasn't the entire human species, Hiriwa," said Styrlyn. He was one of the older-looking students, wearing a short beard speckled in grey. "Maybe one in a hundred thousand could have written out Schrödinger's Equation from memory. So that would have been their first and primary error—failure to concentrate their forces."

"*Spare us the propaganda!*" Jeffreyssai's gaze was suddenly fierce. "You are not here to proselytize for the Cooperative Conspiracy, my lord politician! Bend not the truth to make your points! I believe your Conspiracy has a phrase: 'Comparative advantage.' Do you *really* think that it would have helped to call in the whole human species, as it existed at that time, to debate quantum physics?"

Styrlyn didn't flinch. "Perhaps not, *sensei,*" he said. "But if you are to compare that era to this one, it is a consideration."

Jeffreyssai moved his hand flatly through the air; the maybe-gesture he used to dismiss an argument that was true but not relevant. "It is not what I would call a *primary* mistake. The puzzle should not have required a billion physicists to solve."

"I can think of more *specific* ancient horrors," said Taji. "Spending all day writing grant proposals. Teaching undergraduates who would rather be somewhere else. Needing to publish thirty papers a year to get tenure..."

"But we are not speaking of only the lower-status scientists," said Yin; she wore a slightly teasing grin. "It was said of Schrödinger that he retired to a villa for a month, with his mistress to provide inspiration, and emerged with his eponymous equation. We consider it a famous historical success of our methodology. Some Eld physicists *did* understand how to focus their mental energies; and would have been senior enough to do so, had they chose."

"True," Taji said. "In the end, administrative burdens are only a generic obstacle. Likewise such answers as, 'They were not trained in probability theory, and did not know of cognitive biases.' Our sensei seems to desire some more specific reply."

Jeffreyssai lifted an eyebrow encouragingly. "Don't dismiss your line of thought so quickly, Taji; it begins to be relevant. What kind of system would create administrative burdens on its own people?"

"A system that failed to support its people adequately," said Styrlyn. "One that failed to value their work."

"Ah," said Jeffreyssai. "But there is a student who has not yet spoken. *Brennan?*"

Brennan didn't jump. He deliberately waited just long enough to show he wasn't scared, and then said, "Lack of pragmatic motivation, sensei."

Jeffreyssai smiled slightly. "Expand."

What kind of system would create administrative burdens on its own people?, their *sensei* had asked them. The other students were pursuing their own lines of thought. Brennan, hanging back, had more attention to spare for his teacher's few hints. Being the beginner wasn't *always* a disadvantage—and he had been taught, long before the Bayesians took him in, to take every available advantage.

"The Manhattan Project," Brennan said, "was launched with a specific *technological* end in sight: a weapon of great power, in time of war. But the error that Eld Science committed with respect to quantum physics had no immediate consequences for their technology. They were confused, but they had no desperate *need* for an answer.

Otherwise the surrounding system would have removed all burdens from their effort to solve it. Surely the Manhattan Project must have done so—Taji? Do you know?"

Taji looked thoughtful. "Not *all* burdens—but I'm pretty sure they weren't writing grant proposals in the middle of their work."

"So," Jeffreyssai said. He advanced a few steps, stood directly in front of Brennan's desk. "You think Eld scientists simply weren't trying hard enough. Because their art had no military applications? A rather *competitive* point of view, I should think."

"Not necessarily," Brennan said calmly. "Pragmatism is a virtue of rationality also. A desired *use* for a better quantum theory, would have helped the Eld scientists in many ways beyond just motivating them. It would have given shape to their curiosity, and told them what constituted success or failure."

Jeffreyssai chuckled slightly. "Don't guess so hard what *I* might prefer to hear, Competitor. Your first statement came closer to my hidden mark; your oh-so-Bayesian disclaimer fell wide... The factor I had in mind, Brennan, was that Eld scientists thought it was *acceptable* to take thirty years to solve a problem. Their entire social process of science was based on getting to the truth *eventually.* A wrong theory got discarded *eventually*—once the next generation of students grew up familiar with the replacement. Work expands to fill the time allotted, as the saying goes. But people can think important thoughts in far less than thirty years, if they *expect* speed of themselves." Jeffreyssai suddenly slammed down a hand on the arm of Brennan's chair. "*How long do you have to dodge a thrown knife?*"

"Very little time, sensei!"

"*Less than a second! Two opponents are attacking you! How long do you have to guess who's more dangerous?*"

"Less than a second, sensei!"

"*The two opponents have split up and are attacking two of your girlfriends! How long do you have to decide which one you truly love?*"

"Less than a second, sensei!'

"*A new argument shows your precious theory is flawed! How long does it take you to change your mind?*"

"Less than a second, sensei!"

"*WRONG! DON'T GIVE ME THE WRONG ANSWER JUST BECAUSE IT FITS A CONVENIENT PATTERN AND I SEEM TO EXPECT IT OF YOU!* How long does it really take, Brennan?"

Sweat was forming on Brennan's back, but he stopped and actually thought about it—

"*ANSWER, BRENNAN!*"

"*No sensei! I'm not finished thinking sensei! An answer would be premature! Sensei!*"

"*Very good! Continue! But don't take thirty years!*"

Brennan breathed deeply, reforming his thoughts. He finally said, "Realistically, sensei, the best-case scenario is that I would see the problem immediately; use the discipline of suspending judgment; try to re-accumulate all the evidence before continuing; and depending on how emotionally attached I had been to the theory, use the crisis-of-belief technique to ensure I could genuinely go either way. So at least five minutes and perhaps up to an hour."

"*Good! You actually thought about it that time! Think about it every time! Break patterns!* In the days of Eld Science, Brennan, it was not uncommon for a grant agency to spend six months reviewing a proposal. *They permitted themselves the time!* You are being graded on your *speed,* Brennan! The question is not whether you get there eventually! Anyone can find the truth in five thousand years! You need to *move faster!*"

"*Yes, sensei!*"

"Now, Brennan, have you just learned something new?"

"Yes, sensei!"

"How long did it take you to learn this new thing?"

An arbitrary choice there... "Less than a minute, sensei, from the boundary that seems most obvious."

"Less than a minute," Jeffreyssai repeated. "So, Brennan, how long do you think it should take to solve a major scientific problem, if you are not wasting any time?"

Now there was a trapped question if Brennan had ever heard one. There was no way to guess what time period Jeffreyssai had in mind—what the *sensei* would consider too long, or too short. Which meant that the only way out was to just try for the genuine truth; this would offer him the defense of honesty, little defense though it was. "One year, sensei?"

"Do you think it could be done in one month, Brennan? In a case, let us stipulate, where in principle you already have enough experimental evidence to determine an answer, but not so much experimental evidence that you can afford to make errors in interpreting it."

Again, no way to guess which answer Jeffreyssai might *want...* "One month seems like an unrealistically short time to me, sensei."

"A *short time*?" Jeffreyssai said incredulously. "How many minutes in thirty days? Hiriwa?"

"43200, sensei," she answered. "If you assume sixteen-hour waking periods and daily sleep, then 28800 minutes."

"Assume, Brennan, that it takes five whole minutes to think an *original* thought, rather than learning it from someone else. Does even a major scientific problem require 5760 distinct insights?"

"I confess, sensei," Brennan said slowly, "that I have never thought of it that way before... but do you tell me that is *truly* a realistic level of productivity?"

"No," said Jeffreyssai, "but neither is it realistic to think that a single problem requires 5760 insights. And yes, it has been done."

Jeffreyssai stepped back, and smiled benevolently. Every student in the room stiffened; they knew that smile. "Though none of you hit the particular answer that *I* had in mind, nonetheless your answers were as reasonable as mine. Except Styrlyn's, I'm afraid. Even Hiriwa's answer was not entirely wrong: the task of proposing new theories was once considered a sacred duty reserved for those of high status, there being a limited supply of problems in circulation, at that time. But *Brennan's* answer is *particularly* interesting, and I am minded to test his theory of motivation."

Oh, hell, Brennan said silently to himself. Jeffreyssai was gesturing for Brennan to stand up before the class.

When Brenann had risen, Jeffreyssai neatly seated himself in Brennan's chair.

"Brennan-sensei," Jeffreyssai said, "you have five minutes to think of something stunningly brilliant to say about the failure of Eld science on quantum physics. As for the rest of us, our job will be to gaze at you expectantly. I can only imagine how embarrassing it will be, should you fail to think of anything good."

Bastard. Brennan didn't say it aloud. Taji's face showed a certain amount of sympathy; Styrlyn held himself aloof from the game; but Yin was looking at him with sardonic interest. Worse, Hiriwa *was* gazing at him expectantly, assuming that he would rise to the challenge. And Jeffreyssai was gawking wide-eyed, waiting for the guru's words of wisdom. *Screw you, sensei.*

Brennan didn't panic. It was very, very, very far from being the scariest situation he'd ever faced. He took a moment to decide how to think; then thought.

At four minutes and thirty seconds, Brennan spoke. (There was an art to such things; as long as you were doing it anyway, you might as well make it look easy.)

"A woman of wisdom," Brennan said, "once told me that it is wisest to regard our past selves as fools beyond redemption—to see the people we once were as idiots entire. I do not necessarily say this myself; but it is what she said to me, and there is more than a grain of truth in it. As long as we are making excuses for the past, trying to make it look better, *respecting* it, we cannot make a clean break. It occurs to me that the rule may be no different for human *civilizations*. So I tried looking back and considering the Eld scientists as simple fools."

"Which they were not," Jeffreyssai said.

"Which they were not," Brennan continued. "In terms of raw intelligence, they undoubtedly exceeded me. But it occurred to me that a difficulty in seeing what Eld scientists did wrong, might have been in respecting the ancient and legendary names too highly. And that did indeed produce an insight."

"Enough introduction, Brennan," said Jeffreyssai. "If you found an insight, state it."

"Eld scientists were not trained..." Brennan paused. "No, *untrained* is not the concept. They were trained for the *wrong task.* At that time, there were no Conspiracies, no secret truths; as soon as Eld scientists solved a major problem, they published the solution to the world and each other. Truly scary and confusing *open problems* would have been in extremely rare supply, and used up the moment they were solved. So it would not have been possible to train Eld researchers *to bring order out of scientific chaos.* They would have been trained for something else—I'm not sure what—"

"Trained to manipulate whatever science had *already* been discovered," said Taji. "It was a difficult enough task for Eld teachers to train their students to *use existing knowledge,* or follow already-known methodologies; that was all Eld science teachers aspired to impart."

Brennan nodded. "Which is a *very* different matter from creating new science of their own. The Eld scientists faced with problems of quantum theory, might never have faced that kind of *fear* before—the dismay of not knowing. The Eld scientists might have seized on unsatisfactory answers prematurely, because they were accustomed to working with a neat, agreed-upon body of knowledge."

"*Good*, Brennan," murmured Jeffreyssai.

"But above all," Brennan continued, "an Eld scientist couldn't have *practiced* the actual problem the quantum scientists faced—that of resolving a major confusion. It was something you did once per lifetime if you were lucky, and as Hiriwa observed, Newton would no longer have been around. So while the Eld physicists who messed up quantum theory were not unintelligent, they were, in a strong sense, *amateurs*—ad-libbing the whole process of paradigm shift."

"And no probability theory," Hiriwa noted. "So anyone who *did* succeed at the problem would have no idea what they'd just done. They wouldn't be able to communicate it to anyone else, except vaguely."

"Yes," Styrlyn said. "And it was only a handful of people who could tackle the problem at all, with no training in doing so; those are the physicists whose names have passed down to us. A handful of people, making a handful of discoveries each. It would not have been enough to sustain a community. Each Eld scientist tackling a new paradigm shift would have needed to rediscover the rules from scratch."

Jeffreyssai rose from Brenann's desk. "Acceptable, Brennan; you surprise me, in fact. I shall have to give further thought to this method of yours." Jeffreyssai went to the classroom door, then looked back. "However, I did have in mind at least one *other* major flaw of Eld science, which none of you suggested. I expect to receive a list of possible flaws tomorrow. I expect the flaw I have in mind to be on the list. You have 480 minutes, excluding sleep time. I see five of you here. The challenge does not require more than 480 insights to solve, nor more than 96 insights in series."

And Jeffreyssai left the room.

The Dilemma: Science or Bayes?

> "Eli: You are writing a lot about physics recently. Why?"
> —Shane Legg (and several other people)

> "In light of your QM explanation, which to me sounds perfectly logical, it seems *obvious and normal* that many worlds is overwhelmingly likely. It just seems almost too good to be true that *I* now get what plenty of genius quantum physicists still can't. [...] Sure I can explain all that away, and I still think you're right, I'm just suspicious of myself for believing the first believable explanation I met."
> —Recovering irrationalist

RI, you've got no idea how glad I was to see you post that comment.

Of course I had more than just *one* reason for spending all that time posting about quantum physics. I like having lots of hidden motives, it's the closest I can ethically get to being a supervillain.

But to give an example of a purpose I could *only* accomplish by discussing quantum physics...

In physics, you can get absolutely clear-cut issues. Not in the sense that the issues are trivial to explain. But if you try to apply Bayes to healthcare, or economics, you may not be able to *formally* lay out what is the simplest hypothesis, or what the evidence supports. But when I say "macroscopic decoherence is simpler than collapse" it is actually *strict* simplicity; you could write the two hypotheses out as computer programs and count the lines of code. Nor is the evidence itself in dispute.

I wanted a very clear example—*Bayes says "zig", this is a zag*—when it came time to break your allegiance to Science.

"Oh, sure," you say, "the physicists messed up the many-worlds thing, but give them a break, Eliezer! No one ever claimed that the social process of science was perfect. People are human; they make mistakes."

But the physicists who refuse to adopt many-worlds aren't disobeying the rules of Science. They're *obeying* the rules of Science.

The tradition handed down through the generations says that a new physics theory comes up with new experimental predictions that distinguish it from the old theory. You perform the test, and the new theory is confirmed or falsified. If it's confirmed, you hold a huge celebration, call the newspapers, and hand out Nobel Prizes for everyone; any doddering old emeritus professors who refuse to convert are quietly humored. If the theory is disconfirmed, the lead proponent publicly recants, and gains a reputation for honesty.

This is not how things *do* work in science; rather it is how things are *supposed* to work in Science. It's the ideal to which all good scientists aspire.

Now many-worlds comes along, and it doesn't seem to make any new predictions relative to the old theory. That's suspicious. And there's all these other worlds, but you can't see them. That's *really* suspicious. It just doesn't seem scientific.

If you got as far as RI—so that many-worlds now seems perfectly logical, obvious and normal—*and* you also started out as a Traditional Rationalist, then you should be able to switch back and forth between the Scientific view and the Bayesian view, like a Necker Cube.

So now put on your Science Goggles—you've still got them around somewhere, right? Forget everything you know about Kolmogorov complexity, Solomonoff induction or Minimum Message Lengths. That's not part of the traditional training. You just eyeball something to see how "simple" it looks. The word "testable" doesn't conjure up a mental image of Bayes's Theorem governing probability flows; it conjures up a mental image of being in a lab, performing an experiment, and having the celebration (or public recantation) afterward.

> *Science-Goggles on*: The current quantum theory has passed all experimental tests so far. Many-Worlds doesn't make any new testable predictions—the amazing new phenomena it predicts are all hidden away where we can't see them. You can get along fine without supposing the other worlds, and that's just what you should do. The whole thing smacks of science fiction. But it must be admitted that quantum physics is a very deep and very confusing issue, and who knows what discoveries might be in store? Call me when Many-Worlds makes a testable prediction.

Science-Goggles off, Bayes-Goggles back on:

> *Bayes-Goggles on*: The simplest quantum equations that cover all known evidence don't have a special exception for human-sized masses. There isn't even any reason to ask that particular question. Next!

Okay, so is this a problem we can fix in five minutes with some duct tape and superglue?

No.

Huh? Why not just teach new graduating classes of scientists about Solomonoff induction and Bayes's Rule?

Centuries ago, there was a widespread idea that the Wise could unravel the secrets of the universe just by thinking about them, while to go out and *look* at things was lesser, inferior, naive, and would just delude you in the end. You couldn't trust the way things *looked*—only thought could be your guide.

Science began as a rebellion against this Deep Wisdom. At the core is the pragmatic belief that human beings, sitting around in their armchairs trying to be Deeply Wise, just drift off into never-never land. You couldn't trust your thoughts. You had to make advance experimental predictions—predictions that no one else had made before—run the test, and confirm the result. That was evidence. Sitting in your armchair, thinking about what seemed reasonable... would not be taken to *prejudice* your theory, because Science wasn't an idealistic belief about pragmatism, or getting your hands dirty. It was, rather, the dictum that experiment alone would decide. Only experiments could judge your theory—not your nationality, or your religious professions, or the fact that you'd invented the theory in your armchair. Only experiments! If you sat in your armchair and came up with a theory that made a novel prediction, and experiment confirmed the prediction, then we would care about the result of the experiment, not where your hypothesis came from.

That's Science. And if you say that Many-Worlds should replace the immensely successful Copenhagen Interpretation, adding on all these twin Earths that can't be observed, just because it *sounds more reasonable and elegant*—not because it *crushed the old theory with a superior experimental prediction*—then you're undoing the core scientific rule that prevents people from running out and putting angels into all the theories, because angels are more reasonable and elegant.

You think teaching a few people about Solomonoff induction is going to solve *that* problem? Nobel laureate Robert Aumann—who first proved that Bayesian agents with similar priors cannot agree to disagree—is a believing Orthodox Jew. Aumann helped a project to test the Torah for "Bible codes", hidden prophecies from God—and concluded that the project had failed to confirm the codes' existence. Do you want Aumann thinking that once you've got Solomonoff induction, you can forget about the experimental method? Do you think that's going to help him? And most scientists out there will not rise to the level of Robert Aumann.

Okay, Bayes-Goggles back on. Are you *really* going to believe that large parts of the wavefunction disappear when you can no longer see them? As a result of the only non-linear non-unitary non-differentiable non-CPT-symmetric acausal faster-than-light informally-specified phenomenon in all of physics? Just because, by sheer historical contingency, the stupid version of the theory was proposed first?

Are you going to make a major modification to a scientific model, and believe in zillions of other worlds you can't see, without a defining moment of experimental triumph over the old model?

Or are you going to reject probability theory?

Will you give your allegiance to Science, or to Bayes?

Michael Vassar once observed (tongue-in-cheek) that it was a good thing that a majority of the human species believed in God, because otherwise, he would have a very hard time rejecting majoritarianism. But since the majority opinion that God exists is simply unbelievable, we have no choice but to reject the extremely strong philosophical arguments for majoritarianism.

You can see (one of the reasons) why I went to such lengths to explain quantum theory. Those who are good at math should now be able to *visualize* both macroscopic decoherence, and the probability theory of simplicity and testability—get the insanity of a global single world on a *gut* level.

I wanted to present you with a nice, sharp dilemma between rejecting the scientific method, or embracing insanity.

Why? I'll give you a hint: It's not just because I'm evil. If you would guess my motives here, think beyond the first obvious answer.

PS: If you try to come up with clever ways to wriggle out of the dilemma, you're just going to get shot down in future posts. You have been warned.

Science Doesn't Trust Your Rationality

Scott Aaronson suggests that Many-Worlds and libertarianism are similar in that they are both cases of bullet-swallowing, rather than bullet-dodging:

> Libertarianism and MWI are both are grand philosophical theories that start from premises that almost all educated people accept (quantum mechanics in the one case, Econ 101 in the other), and claim to reach conclusions that most educated people reject, or are at least puzzled by (the existence of parallel universes / the desirability of eliminating fire departments).

Now *there's* an analogy that would never have occurred to me.

I've previously argued that Science rejects Many-Worlds but Bayes accepts it. (Here, "Science" is capitalized because we are talking about the idealized form of Science, not just the actual social process of science.)

It furthermore seems to me that there is a *deep* analogy between (small-'l') libertarianism and Science:

1. Both are based on a pragmatic distrust of reasonable-sounding arguments.
2. Both try to build systems that are more trustworthy than the people in them.
3. Both accept that people are flawed, and try to harness their flaws to power the system.

The core argument for libertarianism is historically motivated distrust of lovely theories of "How much *better* society would be, if we just made a rule that said XYZ." If that sort of trick actually *worked,* then more regulations would correlate to higher economic growth as society moved from local to global optima. But when some person or interest group gets enough power to start doing everything they think is a good idea, history says that what actually *happens* is Revolutionary France or Soviet Russia.

The plans that in lovely theory should have made everyone happy ever after, don't have the results predicted by reasonable-sounding arguments. And power corrupts, and attracts the corrupt.

So you regulate as little as possible, because you can't trust the lovely theories and you can't trust the people who implement them.

You don't shake your finger at people for being selfish. You try to build an efficient system of production out of selfish participants, by requiring transactions to be voluntary. So people are forced to play positive-sum games, because that's how they get the *other* party to sign the contract. With violence restrained and contracts enforced, individual selfishness can power a globally productive system.

Of course none of this works quite so well in practice as in theory, and I'm not going to go into market failures, commons problems, etc. The core argument for libertarianism is not that libertarianism would work in a perfect world, but that it degrades gracefully into real life. Or rather, degrades less awkwardly than any other known economic principle. (People who see Libertarianism as the perfect solution for perfect people, strike me as kinda missing the point of the "pragmatic distrust" thing.)

Science first came to know itself as a rebellion against trusting the word of Aristotle. If the people of that revolution had merely said, "Let us trust ourselves, not Aristotle!" they would have flashed and faded like the French Revolution.

But the Scientific Revolution lasted because—like the American Revolution—the architects propounded a stranger philosophy: "Let us trust no one! Not even ourselves!"

In the beginning came the idea that we can't just toss out Aristotle's armchair reasoning and replace it with *different* armchair reasoning. We need to talk to Nature, and actually *listen* to what It says in reply. This, itself, was a stroke of genius.

But then came the challenge of implementation. People are stubborn, and may not want to accept the verdict of experiment. Shall we shake a disapproving finger at them, and say "Naughty"?

No; we assume and accept that each individual scientist may be crazily attached to their personal theories. Nor do we assume that anyone can be trained out of this tendency—we don't try to choose Eminent Judges who are supposed to be impartial.

Instead, we try to *harness* the individual scientist's stubborn desire to prove their personal theory, by saying: "Make a new experimental prediction, and do the experiment. If you're right, and the experiment is replicated, you win." So long as scientists believe this is true, they have a motive to do experiments that can *falsify* their own theories. Only by accepting the possibility of defeat is it possible to win. And any great claim will require replication; this gives scientists a motive to be honest, on pain of great embarrassment.

And so the stubbornness of individual scientists is harnessed to produce a steady stream of knowledge at the group level. The System is *somewhat* more trustworthy than its parts.

Libertarianism secretly relies on most individuals being prosocial enough to tip at a restaurant they won't ever visit again. An economy of genuinely selfish human-level agents would implode. Similarly, Science relies on most scientists not committing sins so egregious that they can't rationalize them away.

To the extent that scientists believe they can promote their theories by playing academic politics—or game the statistical methods to potentially win without a chance of losing—or to the extent that nobody bothers to replicate claims—science degrades in effectiveness. But it degrades gracefully, as such things go.

The part where the successful predictions belong to the theory and theorists who originally made them, and cannot just be stolen by a theory that comes along later—*without* a novel experimental prediction—is an important feature of this social process.

The final upshot is that Science is not easily reconciled with probability theory. If you do a probability-theoretic calculation *correctly*, you're going to get the *rational* answer. Science doesn't trust your rationality, and it doesn't rely on your ability to use probability theory as the arbiter of truth. It wants you to set up a definitive experiment.

Regarding Science as a mere approximation to some probability-theoretic ideal of rationality... would certainly seem to be *rational*. There seems to be an extremely reasonable-sounding argument that Bayes's Theorem is the hidden structure that explains why Science works. But to subordinate Science to the grand schema of Bayesianism, and let Bayesianism come in and override Science's verdict when that seems appropriate, is not a trivial step!

Science is built around the assumption that you're *too stupid and self-deceiving* to just use Solomonoff induction. After all, if it was that simple, we wouldn't need a social process of science... right?

So, are you going to believe in faster-than-light quantum "collapse" fairies after all? Or do you think you're smarter than that?

When Science Can't Help

Once upon a time, a younger Eliezer had a stupid theory. Let's say that Eliezer$_{18}$'s stupid theory was that consciousness was caused by closed timelike curves hiding in quantum gravity. This isn't the whole story, not even close, but it will do for a start.

And there came a point where I looked back, and realized:

1. I had carefully followed everything I'd been told was Traditionally Rational, in the course of going astray. For example, I'd been careful to only believe in stupid theories that made novel experimental predictions, e.g., that neuronal microtubules would be found to support coherent quantum states.
2. Science would have been perfectly fine with my spending ten years trying to test my stupid theory, only to get a negative experimental result, so long as I then said, "Oh, well, I guess my theory was wrong."

From Science's perspective, that is how things are *supposed* to work—happy fun for everyone. You admitted your error! Good for you! Isn't that what Science is all about?

But what if I didn't want to waste ten years?

Well... Science didn't have much to say about *that.* How could Science say which theory was right, in *advance* of the experimental test? Science doesn't care where your theory comes from—it just says, "Go test it."

This is the great strength of Science, and also its great weakness.

Gray Area asked:

> Eliezer, why are you concerned with untestable questions?

Because questions that are *easily immediately* tested are hard for Science to get wrong.

I mean, sure, when there's already definite unmistakable experimental evidence available, go with it. Why on Earth wouldn't you?

But sometimes a question will have very large, very definite experimental consequences in your future—but you can't easily test it experimentally *right now*—and yet there *is* a strong *rational* argument.

Macroscopic quantum superpositions are readily testable: It would just take nanotechnologic precision, very low temperatures, and a nice clear area of interstellar space. Oh, sure, you can't do it *right now*, because it's *too expensive* or *impossible for today's technology* or something like that—but in theory, sure! Why, maybe someday they'll run whole civilizations on macroscopically superposed quantum computers, way out in a well-swept volume of a Great Void. (Asking what quantum non-realism says about the status of any observers inside these computers, helps to reveal the underspecification of quantum non-realism.)

This doesn't seem immediately pragmatically relevant to your life, I'm guessing, but it establishes the pattern: Not everything with future consequences is *cheap* to test *now*.

Evolutionary psychology is another example of a case where rationality has to take over from science. While theories of evolutionary psychology form a connected whole, only some of those theories are readily testable experimentally. But you still need the other parts of the theory, because they form a connected web that helps you to form the hypotheses that are actually testable—and then the helper hypotheses are supported in a Bayesian sense, but not supported experimentally. Science would render a verdict of "not proven" on individual parts of a connected theoretical mesh that is experimentally productive as a whole. We'd need a new kind of verdict for that, something like "indirectly supported".

Or what about cryonics?

Cryonics is an archetypal example of an extremely important issue (150,000 people die per day) that will have huge consequences in the foreseeable future, but doesn't offer definite unmistakable experimental evidence that we can get *right now.*

So do you say, "I don't believe in cryonics because it hasn't been experimentally proven, and you shouldn't believe in things that haven't been experimentally proven?"

Well, from a Bayesian perspective, that's incorrect. Absence of evidence is evidence of absence only to the degree that we could reasonably expect the evidence to appear. If someone is trumpeting that snake oil cures cancer, you can reasonably expect that, *if the snake oil was actually curing cancer,* some scientist would be performing a controlled study to verify it—that, at the least, doctors would be reporting case studies of amazing recoveries—and so the absence of this evidence is strong evidence of absence. But "gaps in the fossil record" are not strong evidence against evolution; fossils form only rarely, and *even if an intermediate species did in fact exist,* you cannot expect with high probability that Nature will obligingly fossilize it and that the fossil will be discovered.

Reviving a cryonically frozen mammal is just not something you'd expect to be able to do with modern technology, *even if future nanotechnologies could in fact perform a successful revival*. That's how I see Bayes seeing it.

Oh, and as for the actual arguments *for* cryonics—I'm not going to go into those at the moment. But if you followed the physics and anti-Zombie sequences, it should now seem a lot more plausible, that whatever preserves the pattern of synapses, preserves as much of "you" as is preserved from one night's sleep to morning's waking.

Now, to be fair, someone who says, "I don't believe in cryonics because it hasn't been proven experimentally" is *misapplying* the rules of Science; this is not a case where science actually gives the *wrong answer.* In the absence of a definite experimental test, the verdict of science here is "Not proven". Anyone who interprets that as a rejection is taking an extra step outside of science, not a misstep within science.

John McCarthy's Wikiquotes page has him saying, "Your statements amount to saying that if AI is possible, it should be easy. Why is that?" The Wikiquotes page doesn't say what McCarthy was responding to, but I could venture a guess.

The general mistake probably arises because there *are* cases where the absence of scientific proof is strong evidence—because an experiment would be readily performable, and so failure to perform it is itself suspicious. (Though not as suspicious as I used to think—with all the strangely varied anecdotal evidence coming in from respected sources, why the *hell* isn't anyone testing Seth Roberts's theory of appetite suppression?)

Another confusion factor may be that if you test Pharmaceutical X on 1000 subjects and find that 56% of the control group and 57% of the experimental group recover, some people will call that a verdict of "Not proven". I would call it an experimental verdict of "Pharmaceutical X doesn't work well, if at all". Just because this verdict is theoretically retractable in the face of new evidence, doesn't make it ambiguous.

In any case, right now you've got people dismissing cryonics out of hand as "not scientific", like it was some kind of pharmaceutical you could easily administer to 1000 patients and see what happened. "Call me when cryonicists actually revive someone," they say; which, as Mike Li observes, is like saying "I refuse to get into this ambulance; call me when it's actually at the hospital". Maybe Martin Gardner warned them against believing in strange things without experimental evidence. So they wait for the definite unmistakable verdict of Science, while their family and friends and 150,000 people per day are dying *right now,* and might or might not be savable—

—a calculated bet you could only make *rationally.*

The drive of Science is to obtain a mountain of evidence so huge that not even fallible human scientists can misread it. But even *that* sometimes goes wrong, when people become confused about which theory predicts what, or bake extremely-hard-to-test components into an early version of their theory. And sometimes you just can't get clear experimental evidence at all.

Either way, you have to try to do the thing that Science doesn't trust anyone to do—think rationally, and figure out the answer *before* you get clubbed over the head with it.

(Oh, and sometimes a *disconfirming* experimental result looks like: "Your entire species has just been wiped out! You are now scientifically required to relinquish your theory. If you publicly recant, good for you! Remember, it takes a strong mind to give up strongly held beliefs. Feel free to try another hypothesis next time!")

Science Isn't Strict Enough

Once upon a time, a younger Eliezer had a stupid theory. Eliezer$_{18}$ was careful to follow the precepts of Traditional Rationality that he had been taught; he made sure his stupid theory had experimental consequences. Eliezer$_{18}$ professed, in accordance with the virtues of a scientist he had been taught, that he wished to test his stupid theory.

This was all that was required to be virtuous, according to what Eliezer$_{18}$ had been taught was virtue in the way of science.

It was not even *remotely* the order of effort that would have been required to get it *right*.

The traditional ideals of Science too readily give out gold stars. Negative experimental results are also knowledge, so everyone who plays gets an award. So long as you can think of some kind of experiment that tests your theory, and you *do* the experiment, and you *accept* the results, you've played by the rules; you're a good scientist.

You didn't necessarily get it right, but you're a nice science-abiding citizen.

> (I note at this point that I am speaking of Science, not the social process of science as it actually works in practice, for two reasons. First, I went astray in trying to follow the *ideal* of Science—it's not like I was shot down by a journal editor with a grudge, and it's not like I was trying to imitate the flaws of academia. Second, if I point out a problem with the ideal as it is traditionally preached, real-world scientists are not *forced* to likewise go astray!)

Science began as a rebellion against grand philosophical schemas and armchair reasoning. So Science doesn't include a rule as to what kinds of hypotheses you are and aren't allowed to test; that is left up to the individual scientist. Trying to guess that a priori, would require some kind of grand philosophical schema, and reasoning in advance of the evidence. As a social ideal, Science doesn't judge you as a bad person for coming up with heretical hypotheses; honest experiments, and acceptance of the results, is virtue unto a scientist.

As long as most scientists can manage to accept definite, unmistakable, unambiguous experimental evidence, science can progress. It may happen too slowly—it may take longer than it should—you may have to wait for a generation of elders to die out—but eventually, the ratchet of knowledge clicks forward another notch. Year by year, decade by decade, the wheel turns *forward*. It's enough to support a civilization.

So that's all that Science really asks of you—the ability to accept reality when you're beat over the head with it. It's not much, but it's enough to sustain a scientific culture.

Contrast this to the notion we have in probability theory, of an exact quantitative rational judgment. If 1% of women presenting for a routine screening have breast cancer, and 80% of women with breast cancer get positive mammographies, and 10% of women without breast cancer get false positives, what is the probability that a routinely screened woman with a positive mammography has breast cancer? 7.5%. You cannot say, "I believe she doesn't have breast cancer, because the experiment isn't definite enough." You cannot say, "I believe she has breast cancer, because it is wise to be pessimistic and that is what the only experiment so far seems to indicate." 7.5% is the rational estimate given this evidence, not 7.4% or 7.6%. The laws of probability are *laws*.

It is written in the *Twelve Virtues,* of the third virtue, lightness:

> If you regard evidence as a constraint and seek to free yourself, you sell yourself into the chains of your whims. For you cannot make a true map of a city by sitting in your bedroom with your eyes shut and drawing lines upon paper according to impulse. You must walk through the city and draw lines on paper that correspond to what you see. If, seeing the city unclearly, you think that you can shift a line just a little to the right, just a little to the left, according to your caprice, this is just the same mistake.

In Science, when it comes to deciding which hypotheses to test, the morality of Science gives you personal freedom of what to believe, so long as it isn't already ruled out by experiment, and so long as you move to test your hypothesis. Science wouldn't try to give an official verdict on the *best* hypothesis to test, in *advance* of the experiment. That's left up to the conscience of the individual scientist.

Where definite experimental evidence exists, Science tells you to bow your stubborn neck and accept it. Otherwise, Science leaves it up to you. Science gives you room to wander around *within the boundaries* of the experimental evidence, according to your whims.

And this is not easily reconciled with Bayesianism's notion of an exactly right probability estimate, one with no flex or room for whims, that exists both before and after the experiment. It doesn't match well with the ancient and traditional reason for Science—the distrust of grand schemas, the presumption that people aren't rational enough to get things right without definite and unmistakable experimental evidence. If we were all perfect Bayesians, we wouldn't *need* a social process of science.

Nonetheless, around the time I realized my big mistake, I had also been studying Kahneman and Tversky and Jaynes. I was learning a new Way, stricter than Science. A Way that could criticize my folly, in a way that Science never could. A Way that could have told me, what Science would never have said in *advance*: "You picked the wrong hypothesis to test, dunderhead."

But the Way of Bayes is also *much harder to use* than Science. It puts a tremendous strain on your ability to hear tiny false notes, where Science only demands that you notice an anvil dropped on your head.

In Science you can make a mistake or two, and another experiment will come by and correct you; at worst you waste a couple of decades.

But if you try to use Bayes even qualitatively—if you try to do the thing that Science doesn't trust you to do, and reason rationally in the absence of overwhelming evidence—it is like math, in that a single error in a hundred steps can carry you anywhere. It demands lightness, evenness, precision, perfectionism.

There's a good reason why Science doesn't trust scientists to do this sort of thing, and asks for further experimental proof *even after* someone claims they've worked out the right answer based on hints and logic.

But if you would rather not waste ten years trying to prove the *wrong* theory, you'll need to essay the vastly more difficult problem: listening to evidence that doesn't shout in your ear.

Even if you can't look up the priors for a problem in the Handbook of Chemistry and Physics—even if there's no Authoritative Source telling you what the priors are—that doesn't mean you get a free, personal choice of making the priors whatever you want. It means you have a new guessing problem which you must carry out to the best of your ability.

If the mind, as a cognitive engine, could generate *correct* estimates by fiddling with priors according to whims, you could know things without looking them, or even alter them without touching them. But the mind is not magic. The rational probability estimate has no room for any decision based on whim, even when it seems that you don't know the priors.

Similarly, if the Bayesian answer is difficult to compute, that doesn't mean that Bayes is inapplicable; it means you *don't know* what the Bayesian answer is. Bayesian probability theory is not a toolbox of statistical methods, it's the *law* that governs any tool you use, whether or not you know it, whether or not you can calculate it.

As for using Bayesian methods on huge, highly general hypothesis spaces—like, "Here's the data from every physics experiment ever; now, what would be a good Theory of Everything?"—if you knew how to do that *in practice,* you wouldn't be a statistician, you would be an Artificial General Intelligence programmer. But that doesn't mean that human beings, in modeling the universe using human intelligence, are violating the laws of physics / Bayesianism by generating correct guesses without evidence.)

Nick Tarleton comments:

> The problem is encouraging a *private*, *epistemic* standard as lax as the social one.

which pinpoints the problem I was trying to indicate much better than I did.

Do Scientists Already Know This Stuff?

poke alleges:

> "Being able to create relevant hypotheses is an important skill and one a scientist spends a great deal of his or her time developing. It may not be part of the traditional *description* of science but that doesn't mean it's not included in the actual social institution of science that produces actual real science here in the real world; it's your description and not science that is faulty."

I know I've been calling my younger self "stupid" but that is a figure of speech; "unskillfully wielding high intelligence" would be more precise. Eliezer$_{18}$ was not in the habit of making obvious mistakes—it's just that his "obvious" wasn't my "obvious".

No, I did not go through the traditional apprenticeship. But when I look back, and see what Eliezer$_{18}$ did wrong, I see *plenty* of modern scientists making the same mistakes. I cannot detect any sign that they were better warned than myself.

Sir Roger Penrose—a world-class physicist—still thinks that consciousness is caused by quantum gravity. I expect that no one ever warned him against mysterious answers to mysterious questions—only told him his hypotheses needed to be falsifiable and have empirical consequences. Just like Eliezer$_{18}$.

"Consciousness is caused by quantum gravity" has testable implications: It implies that you should be able to look at neurons and discover a coherent quantum superposition (whose collapse?) contributes to information-processing, and that you won't ever be able to reproduce a neuron's input-output behavior using a computable microanatomical simulation...

...but even after you say "Consciousness is caused by quantum gravity", you don't anticipate anything about how your brain thinks "I think therefore I am!" or the mysterious redness of red, that you did not anticipate before, even though you feel like you know a cause of it. This is a tremendous danger sign, *I now realize,* but it's not the danger sign that *I* was warned against, and I doubt that Penrose was ever told of it by his thesis advisor. For that matter, I doubt that Niels Bohr was ever warned against it when it came time to formulate the Copenhagen Interpretation.

As far as I can tell, the reason Eliezer$_{18}$ and Sir Roger Penrose and Niels Bohr were not warned, is that no standard warning exists.

I did not *generalize* the concept of "mysterious answers to mysterious questions", in that many words, until I was writing a Bayesian analysis of what distinguishes technical, nontechnical and semitechnical scientific explanations. Now, the final *output* of that analysis, can be phrased nontechnically in terms of four danger signs:

- First, the explanation acts as a curiosity-stopper rather than an anticipation-controller.
- Second, the hypothesis has no moving parts—the secret sauce is not a specific complex mechanism, but a blankly solid substance or force.

- Third, those who proffer the explanation cherish their ignorance; they speak proudly of how the phenomenon defeats ordinary science or is unlike merely mundane phenomena.
- Fourth, *even after the answer is given, the phenomenon is still a mystery* and possesses the same quality of wonderful inexplicability that it had at the start.

In principle, all this could have been said in the immediate aftermath of vitalism. Just like elementary probability theory could have been invented by Archimedes, or the ancient Greeks could have theorized natural selection. But *in fact* no one ever warned me against any of these four dangers, in those terms—the closest being the warning that hypotheses should have testable consequences. And I didn't conceptualize the warning signs *explicitly* until I was trying to think of the whole affair in terms of probability distributions—some degree of overkill was required.

I simply have no reason to believe that these warnings are passed down in scientific apprenticeships—certainly not to a majority of scientists. Among other things, it is advice for handling *situations of confusion and despair*, scientific *chaos.* When would the average scientist or average mentor have an opportunity to use that kind of technique?

We just got through discussing the single-world fiasco in physics. Clearly, no one told them about the formal definition of Occam's Razor, in whispered apprenticeship or otherwise.

There is a known effect where great scientists have multiple great students. This may well be due to the mentors passing on skills that they can't describe. But I don't think that counts as part of *standard* science. And if the great mentors haven't been able to put their guidance into words and publish it generally, that's not a good sign for how well these things are understood.

Reasoning in the absence of definite evidence without going *instantaneously completely wrong* is *really really hard.* When you're learning in school, you can miss one point, and then be taught fifty other points that happen to be correct. When you're reasoning out new knowledge in the absence of crushingly overwhelming guidance, you can miss one point and wake up in Outer Mongolia fifty steps later.

I am pretty sure that scientists who switch off their brains and relax with some comfortable nonsense as soon as they leave their own specialties, do not realize that minds are engines and that there is a causal story behind every trustworthy belief. Nor, I suspect, were they ever told that there is an exact rational probability given a state of evidence, which has no room for whims; even if you can't calculate the answer, and even if you don't hear any authoritative command for what to believe.

I doubt that scientists who are asked to pontificate on the future by the media, who sketch amazingly detailed pictures of Life in 2050, were ever taught about the conjunction fallacy. Or how the representativeness heuristic can make more detailed stories seem more plausible, even as each extra detail drags down the probability. The notion of every added detail needing its own support—of not being able to *make up* big detailed stories that sound just like the detailed stories you were *taught* in science or history class—is *absolutely vital* to precise thinking in the absence of definite evidence. But how would a notion like that get into the *standard* scientific apprenticeship? The cognitive bias was uncovered only a few decades ago, and not popularized until very recently.

Then there's affective death spirals around notions like "emergence" or "complexity" which are sufficiently vaguely defined that you can say lots of nice things about them. There's whole academic subfields built around the kind of mistakes that Eliezer_{18} used to make! (Though I never fell for the "emergence" thing.)

I sometimes say that the goal of science is to amass such an enormous mountain of evidence that not even scientists can ignore it: and that this is the distinguishing feature of a scientist, a non-scientist will ignore it anyway.

If there can exist some amount of evidence so crushing that you finally despair, stop making excuses and *just give up*—drop the old theory and never mention it again—then this is all it takes to let the ratchet of Science turn forward over time, and raise up a technological civilization. Contrast to religion.

Books by Carl Sagan and Martin Gardner and the other veins of Traditional Rationality are meant to accomplish this difference: to transform someone from a non-scientist into a potential scientist, and guard them from experimentally disproven madness.

What further training does a professional scientist get? Some frequentist stats classes on how to calculate statistical significance. Training in standard techniques that will let them churn out papers within a solidly established paradigm.

If Science demanded more than this from the average scientist, I don't think it would be possible for Science to get done. We have problems enough from people who sneak in without the drop-dead-basic qualifications.

Nick Tarleton summarized the resulting problem very well—better than I did, in fact: If you come up with a bizarre-seeming hypothesis not yet ruled out by the evidence, and try to test it experimentally, Science doesn't call you a bad person. Science doesn't trust its elders to decide which hypotheses "aren't worth testing". But this is a carefully lax *social* standard, and if you try to translate it into a standard of *individual* epistemic rationality, it lets you believe far too much. Dropping back into the analogy with pragmatic-distrust-based-libertarianism, it's the difference between "Cigarettes shouldn't be illegal" and "Go smoke a Marlboro".

Do you remember ever being *warned against that mistake,* in so many words? Then why *wouldn't* people make exactly that error? How many people will *spontaneously* go an extra mile and be even stricter with themselves? Some, but not many.

Many scientists will believe all manner of ridiculous things outside the laboratory, so long as they can convince themselves it hasn't been definitely disproven, or so long as they manage not to ask. Is there some standard lecture that grad students get, of which people see this folly, and ask, "Were they absent from class that day?" No, as far as I can tell.

Maybe if you're super lucky and get a famous mentor, they'll tell you rare personal secrets like "Ask yourself which are the important problems in your field, and then work on one of those, instead of falling into something easy and trivial" or "Be more careful than the journal editors demand; look for new ways to guard your expectations from influencing the experiment, even if it's not standard."

But I *really don't think* there's a huge secret standard scientific tradition of precision-grade rational reasoning on sparse evidence. Half of all the scientists out there still believe they believe in God! *The more difficult skills are not standard!*

No Safe Defense, Not Even Science

I don't ask my friends about their childhoods—I lack social curiosity—and so I don't know how much of a trend this really is:

Of the people I know who are reaching upward as rationalists, who volunteer information about their childhoods, there is a surprising tendency to hear things like: "My family joined a cult and I had to break out," or "One of my parents was clinically insane and I had to learn to filter out reality from their madness."

My own experience with growing up in an Orthodox Jewish family seems tame by comparison... but it accomplished the same outcome: It broke my core emotional trust in the sanity of the people around me.

Until this core emotional trust is broken, you don't start growing as a rationalist. I have trouble putting into words why this is so. Maybe any *unusual* skills you acquire—anything that makes you *unusually* rational—requires you to zig when other people zag. Maybe that's just too scary, if the world still seems like a sane place unto you.

Or maybe you don't bother putting in the hard work to be extra bonus sane, if normality doesn't scare the hell out of you.

I know that many aspiring rationalists seem to run into roadblocks around things like cryonics or many-worlds. Not that they don't see the logic; they see the logic and wonder, "Can this really be true, when it seems so obvious now, and yet none of the people around me believe it?"

Yes. Welcome to the Earth where ethanol is made from corn and environmentalists oppose nuclear power. I'm sorry.

(See also: Cultish Countercultishness. If you end up in the frame of mind of *nervously seeking reassurance*, this is never a good thing—even if it's because you're about to believe something that sounds logical but could cause other people to look at you funny.)

People who've had their trust broken in the sanity of the people around them, seem to be able to evaluate strange ideas on their merits, without feeling nervous about their strangeness. The glue that binds them to their current place has dissolved, and they can walk in some direction, hopefully forward.

Lonely dissent, I called it. True dissent doesn't feel like going to school wearing black; it feels like going to school wearing a clown suit.

That's what it takes to be the lone voice who says, "If you really think you know who's going to win the election, why aren't you picking up the free money on the Intrade prediction market?" while all the people around you are thinking, "It is good to be an individual and form your own opinions, the shoe commercials told me so."

Maybe in some other world, some alternate Everett branch with a saner human population, things would be different... but in this world, I've never seen anyone begin to grow as a rationalist until they make a deep emotional break with the wisdom of their pack.

Maybe in another world, things would be different. And maybe not. I'm not sure that human beings realistically *can* trust and think at the same time.

Once upon a time, there was something I trusted.

Eliezer_{18} trusted Science.

Eliezer_{18} dutifully acknowledged that the social process of science was flawed. Eliezer_{18} dutifully acknowledged that academia was slow, and misallocated resources, and played favorites, and mistreated its precious heretics.

That's the convenient thing about acknowledging flaws in *people* who failed to live up to your ideal; you don't have to question the ideal itself.

But who could possibly be foolish enough to question, "The experimental method shall decide which hypothesis wins"?

Part of what fooled Eliezer_{18} was a general problem he had, with [an aversion to ideas that resembled things idiots had said]. Eliezer_{18} had seen plenty of people questioning the ideals of Science Itself, and without exception they were all on the Dark Side. People who questioned the ideal of Science were invariably trying to sell you snake oil, or trying to safeguard their favorite form of stupidity from criticism, or trying to disguise their personal resignation as a Deeply Wise acceptance of futility.

If there'd been any other ideal that was a few centuries old, the young Eliezer would have looked at it and said, "I wonder if this is really right, and whether there's a way to [do better]." But not the ideal of Science. Science was the master idea, the idea that let you change ideas. You could question it, but you were meant to [question it and then accept it], not actually say, "Wait! This is wrong!"

Thus, when once upon a time I came up with a stupid idea, I thought I was behaving virtuously if I made sure there was a Novel Prediction, and professed that I wished to test my idea experimentally. I thought I had done everything I was obliged to do.

So I thought I was *safe*—not safe from any particular external threat, but safe on some deeper level, like a child who trusts their parent and has obeyed all the parent's rules.

I'd long since been broken of trust in the sanity of my family or my teachers at school. And the other children weren't intelligent enough to compete with the conversations I could have with books. But I trusted the books, you see. I trusted that if I did what Richard Feynman told me to do, I would be safe. I never thought those words aloud, but it was how I felt.

When Eliezer_{23} realized exactly *how* stupid the stupid theory had been—and that Traditional Rationality had not saved him from it—and that Science would have been perfectly okay with his wasting ten years testing the stupid idea, so long as afterward he admitted it was wrong...

...well, I'm not going to say it was a huge emotional convulsion. I don't really go in for that kind of drama. It simply became obvious that I'd been stupid.

That's the trust I'm trying to break in you. You are not safe. Ever.

Not even Science can save you. The ideals of Science were born centuries ago, in a time when no one knew anything about probability theory or cognitive biases.

Science demands *too little* of you, it blesses your good intentions too easily, [it is not strict *enough*], it only makes those injunctions that an [average scientist] can follow, it accepts [slowness] as a fact of life.

So don't think that if you only follow the rules of Science, that makes your reasoning defensible.

There is no known procedure you can follow that makes your reasoning defensible.

There is no known set of injunctions which you can satisfy, and know that you will not have been a fool.

There is no known morality-of-reasoning that you can do your best to obey, and know that you are thereby shielded from criticism.

No, not even if you turn to Bayescraft. It's much harder to use and you'll never be sure that you're doing it right.

The discipline of Bayescraft is younger by far than the discipline of Science. You will find no textbooks, no elderly mentors, no histories written of success and failure, no hard-and-fast rules laid down. You will have to study cognitive biases, and probability theory, and evolutionary psychology, and social psychology, and other cognitive sciences, and Artificial Intelligence—and think through for yourself how to apply all this knowledge to the case of correcting yourself, since that isn't yet in the textbooks.

You don't know what your own mind is really doing. They find a new cognitive bias every week and you're never sure if you've corrected for it, or overcorrected.

The formal math is impossible to apply. It doesn't break down as easily as John Q. Unbeliever thinks, but you're never really sure where the foundations come from. You don't know why the universe is simple enough to understand, or why any prior works for it. You don't know what your own priors *are,* let alone if they're any good.

One of the problems with Science is that it's too vague to really scare you. "Ideas should be tested by experiment." How can you go wrong with that?

On the other hand, if you have some math of probability theory laid out in front of you, and worse, *you know you can't actually use it,* then it becomes clear that you are trying to do something difficult, and that you might well be doing it *wrong.*

So you cannot trust.

And all this that I have said, *will not be sufficient* to break your trust. That won't happen until you get into your first real disaster from following The Rules, not from breaking them.

Eliezer$_{18}$ already had the notion that you were allowed to question Science. Why, of course the scientific method was not itself immune to questioning! For are we not all good rationalists? Are we not allowed to question everything?

It was the notion that you could *actually in real life* follow Science and fail miserably, that Eliezer$_{18}$ didn't really, emotionally believe was possible.

Oh, of course he said it was possible. Eliezer$_{18}$ dutifully acknowledged the possibility of error, saying, "I could be wrong, but..."

But he didn't think failure could happen in, you know, real life. You were supposed to look for flaws, not actually find them.

And this emotional difference is a terribly difficult thing to accomplish in words, and I fear there's no way I can really warn you.

Your trust will not break, until you apply all that you have learned here and from other books, and take it as far as you can go, and find that this too fails you—that you have still been a fool, and no one warned you against it—that all the most important parts were left out of the guidance you received—that some of the most precious ideals you followed, steered you in the wrong direction—

—and if you still have something to protect, so that you *must* keep going, and *cannot* resign and wisely acknowledge the limitations of rationality—

—then you will be ready to start your journey as a rationalist. To take sole responsibility, to live without any trustworthy defenses, and to forge a higher Art than the one you were once taught.

No one begins to truly search for the Way until their parents have failed them, their gods are dead, and their tools have shattered in their hand.

Post Scriptum: On reviewing a draft of this essay, I discovered a fairly inexcusable flaw in reasoning, which actually affects one of the conclusions drawn. I am leaving it in. Just in case you thought that taking my advice made you safe; or that you were supposed to look for flaws, but not find any.

And of course, if you look too hard for a flaw, and find a flaw that is not a real flaw, and cling to it to reassure yourself of how critical you are, you will only be worse off than before...

It is living with uncertainty—knowing on a gut level that there are flaws, they are serious and you have not found them—that is the difficult thing.

Changing the Definition of Science

New Scientist on changing the definition of science, ungated here:

> Others believe such criticism is based on a misunderstanding. "Some people say that the multiverse concept isn't falsifiable because it's unobservable—but that's a fallacy," says cosmologist Max Tegmark of the Massachusetts Institute of Technology. He argues that the multiverse is a natural consequence of such eminently falsifiable theories as quantum theory and general relativity. As such, the multiverse theory stands or fails according to how well these other theories stand up to observational tests.
> [...]
> So if the simplicity of falsification is misleading, what should scientists be doing instead? Howson believes it is time to ditch Popper's notion of capturing the scientific process using deductive logic. Instead, the focus should be on reflecting what scientists actually do: gathering the weight of evidence for rival theories and assessing their relative plausibility.
>
> Howson is a leading advocate for an alternative view of science based not on simplistic true/false logic, but on the far more subtle concept of degrees of belief. At its heart is a fundamental connection between the subjective concept of belief and the cold, hard mathematics of probability.

I'm a good deal less of a lonely iconoclast than I seem. Maybe it's just the way I talk.

The points of departure between myself and *mainstream* let's-reformulate-Science-as-Bayesianism is that:

(1) I'm not in academia and can censor myself a *lot* less when it comes to saying "extreme" things that others might well already be thinking.

(2) I think that **just teaching probability theory won't be nearly enough**. We'll have to synthesize lessons from multiple sciences like cognitive biases and social psychology, forming a new coherent Art of Bayescraft, before we are actually going to do any better *in the real world* than modern science. Science tolerates errors, Bayescraft does not. Nobel laureate Robert Aumann, who first proved that Bayesians with the same priors cannot agree to disagree, is a believing Orthodox Jew. Probability theory alone won't do the trick, when it comes to really teaching scientists. *This is my primary point of departure, and it is not something I've seen suggested elsewhere.*

(3) I think it *is* possible to do better in the real world. In the extreme case, a Bayesian superintelligence could use *enormously* less sensory information than a human scientist to come to correct conclusions. First time you ever see an apple fall down, you observe the position goes as the square of time, invent calculus, generalize Newton's Laws... and see that Newton's Laws involve action at a distance, look for alternative explanations with increased locality, invent relativistic covariance around a hypothetical speed limit, and consider that General Relativity might be worth testing. Humans do not process evidence *efficiently*—our minds are so noisy that it requires orders of magnitude more *extra* evidence to set us back on track after we derail. Our collective, academia, is even slower.

Faster Than Science

I sometimes say that the method of science is to amass such an enormous mountain of evidence that even scientists cannot ignore it; and that this is the distinguishing characteristic of a scientist, a non-scientist will ignore it anyway.

Max Planck was even less optimistic:

> "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

I am much tickled by this notion, because it implies that the power of science to distinguish truth from falsehood ultimately rests on the good taste of grad students.

The *gradual* increase in acceptance of many-worlds in academic physics, suggests that there are physicists who will only accept a new idea given some *combination* of epistemic justification, and a sufficiently large academic pack in whose company they can be comfortable. As more physicists accept, the pack grows larger, and hence more people go over their individual thresholds for conversion—with the epistemic justification remaining essentially the same.

But Science still gets there *eventually,* and this is sufficient for the ratchet of Science to move forward, and raise up a technological civilization.

Scientists can be moved by groundless prejudices, by undermined intuitions, by raw herd behavior—the panoply of human flaws. Each time a scientist shifts belief for epistemically unjustifiable reasons, it requires more evidence, or new arguments, to cancel out the noise.

The "collapse of the wavefunction" has no experimental justification, but it appeals to the (undermined) intuition of a single world. Then it may take an extra argument—say, that collapse violates Special Relativity—to begin the slow academic disintegration of an idea that should never have been assigned non-negligible probability in the first place.

From a Bayesian perspective, human academic science as a whole is a highly inefficient processor of evidence. Each time an unjustifiable argument shifts belief, you need an extra justifiable argument to shift it back. The social process of science leans on extra evidence to overcome cognitive noise.

A more charitable way of putting it is that scientists will adopt positions that are theoretically *insufficiently extreme*, compared to the ideal positions that scientists *would* adopt, if they were Bayesian AIs and could trust themselves to reason clearly.

But don't be too charitable. The noise we are talking about is not all innocent mistakes. In many fields, debates drag on for decades after they should have been settled. And *not* because the scientists on both sides refuse to trust themselves and agree they should look for additional evidence. But because one side keeps throwing up more and more ridiculous objections, and demanding more and more evidence, from an entrenched position of academic power, long after it becomes clear from which quarter the winds of evidence are blowing. (I'm thinking here about the debates surrounding the invention of evolutionary psychology, not about many-worlds.)

Is it possible for individual humans or groups to process evidence more efficiently—reach correct conclusions faster—than human academic science as a whole?

"Ideas are tested by experiment. That is the core of science." And this must be true, because if you can't trust Zombie Feynman, who *can* you trust?

Yet where do the *ideas* come from?

You may be tempted to reply, "They come from scientists. Got any other questions?" In Science you're not supposed to care *where* the hypotheses come from—just whether they pass or fail experimentally.

Okay, but if you remove *all* new ideas, the scientific process as a whole stops working because it has no alternative hypotheses to test. So inventing new ideas is not a dispensable part of the process.

Now put your Bayesian goggles back on. As described in Einstein's Arrogance, there are queries that are not binary—where the answer is not "Yes" or "No", but drawn from a larger space of structures, e.g., the space of equations. In such cases it takes far more Bayesian evidence to *promote a hypothesis to your attention* than to *confirm the hypothesis.*

If you're working in the space of all equations that can be specified in 32 bits or less, you're working in a space of 4 billion equations. It takes far more Bayesian evidence to raise one of those hypotheses to the 10% probability level, than it requires *further* Bayesian evidence to raise the hypothesis from 10% to 90% probability.

When the idea-space is large, coming up with ideas worthy of testing, involves much more work—in the Bayesian-thermodynamic sense of "work"—than *merely* obtaining an experimental result with $p<0.0001$ for the new hypothesis over the old hypothesis.

If this doesn't seem obvious-at-a-glance, pause here and read Einstein's Arrogance.

The scientific process has always relied on scientists to come up with hypotheses to test, via some process not further specified by Science. Suppose you came up with some way of generating hypotheses that was completely crazy—say, pumping a robot-controlled Ouija board with the digits of pi—and the resulting suggestions kept on getting verified experimentally. The pure ideal essence of Science wouldn't skip a beat. The pure ideal essence of Bayes would burst into flames and die.

(Compared to Science, Bayes is falsified by more of the possible outcomes.)

This doesn't mean that the process of deciding which ideas to test is *unimportant* to Science. It means that Science doesn't *specify* it.

In practice, the robot-controlled Ouija board doesn't work. In practice, there are some scientific queries with a large enough answer space, that picking models at random to test, it would take zillions of years to hit on a model that made good predictions—like getting monkeys to type Shakespeare.

At the *frontier* of science—the boundary between ignorance and knowledge, where science *advances*—the process relies on at least some individual scientists (or working groups) seeing things that are not yet confirmed by Science. That's how they know which hypotheses to test, in advance of the test itself.

If you take your Bayesian goggles off, you can say, "Well, they don't have to know, they just have to guess." If you put your Bayesian goggles back on, you realize that "guessing" with 10% probability requires nearly as much epistemic work to have been successfully performed, behind the scenes, as "guessing" with 80% probability—at least for large answer spaces.

The scientist may not *know* he has done this epistemic work successfully, in advance of the experiment; but he must, in fact, have done it successfully! Otherwise he will not even *think* of the correct hypothesis. In large answer spaces, anyway.

So the scientist makes the novel prediction, performs the experiment, publishes the result, and *now* Science knows it too. It is now part of the publicly accessible knowledge of humankind, that anyone can verify for themselves.

In between was an interval where the scientist rationally knew something that the public social process of science hadn't yet confirmed. And this is not a trivial interval, though it may be short; for it is where the *frontier* of science lies, the advancing border.

All of this is more true for non-routine science than for routine science, because it is a notion of large answer spaces where the answer is not "Yes" or "No" or drawn from a small set of obvious alternatives. It is much easier to train people to test ideas, than to have good ideas to test.

Einstein's Speed

Yesterday I argued that the Powers Beyond Science are actually a standard and necessary part of the social process of science. In particular, scientists must call upon their powers of individual rationality to decide what ideas to test, in advance of the sort of definite experiments that Science demands to bless an idea as confirmed. The ideal of Science does not try to *specify* this process—we don't suppose that any public authority knows how individual scientists should think—but this doesn't mean the process is *unimportant.*

A readily understandable, non-disturbing example:

A scientist identifies a strong mathematical regularity in the cumulative data of previous experiments. But the corresponding hypothesis has not yet made and *confirmed* a novel experimental prediction—which his academic field demands; this is one of those fields where you can perform controlled experiments without too much trouble. Thus the individual scientist has readily understandable, rational reasons to believe (though not with probability 1) something not yet blessed by Science as public knowledge of humankind.

Noticing a regularity in a huge mass of experimental data, doesn't seem all that *unscientific.* You're still data-driven, right?

But that's because I deliberately chose a non-disturbing example. When Einstein invented General Relativity, he had almost no experimental data to go on, except the precession of Mercury's perihelion. And (AFAIK) Einstein did not *use* that data, except at the end.

Einstein generated the theory of Special Relativity using Mach's Principle, which is the physicist's version of the Generalized Anti-Zombie Principle. You begin by saying, "It doesn't seem reasonable to me that you could tell, in an enclosed room, how fast you and the room were going. Since this number shouldn't ought to be observable, it shouldn't ought to exist in any meaningful sense." You then observe that Maxwell's Equations invoke a seemingly absolute speed of propagation, *c*, commonly referred to as "the speed of light" (though the quantum equations show it is the propagation speed of all fundamental waves). So you reformulate your physics in such fashion that the absolute speed of a single object no longer meaningfully exists, and only relative speeds exist. I am skipping over quite a bit here, obviously, but there are many excellent introductions to relativity—it is not like the horrible situation in quantum physics.

Einstein, having successfully done away with the notion of your absolute speed inside an enclosed room, then set out to do away with the notion of your absolute *acceleration* inside an enclosed room. It seemed to Einstein that there shouldn't ought to be a way to differentiate, in an enclosed room, between the room accelerating northward while the rest of the universe stayed still, versus the rest of the universe accelerating southward while the room stayed still. If the rest of the universe accelerated, it would produce gravitational waves that would accelerate you. Moving matter, then, should produce gravitational waves.

And because inertial mass and gravitational mass were always exactly equivalent—unlike the situation in electromagnetics, where an electron and a muon can have different masses but the same electrical charge—gravity should reveal itself as a kind of inertia. The Earth should go around the Sun in some equivalent of a "straight line". This requires spacetime in the vicinity of the Sun to be curved, so that if you drew a graph of the Earth's orbit around the Sun, the line on the 4D graph paper would be locally flat. Then inertial and gravitational mass would be *necessarily* equivalent, not just *coincidentally* equivalent.

(If that did not make any sense to you, there are good introductions to General Relativity available as well.)

And of course the new theory had to obey Special Relativity, and conserve energy, and conserve momentum, etcetera.

Einstein spent several years grasping the necessary mathematics to describe curved metrics of spacetime. Then he wrote down the simplest theory that had the properties Einstein thought it ought to have—including properties no one had ever observed, but that Einstein thought fit in well with the character of other physical laws. Then Einstein cranked a bit, and got the previously unexplained precession of Mercury right back out.

How impressive was this?

Well, let's put it this way. In some small fraction of alternate Earths proceeding from 1800—perhaps even a sizeable fraction—it would seem plausible that relativistic physics could have proceeded in a similar fashion to our own great fiasco with quantum physics.

We can imagine that Lorentz's original "interpretation" of the Lorentz contraction, as a physical distortion caused by movement with respect to the ether, prevailed. We can imagine that various corrective factors, themselves unexplained, were added on to Newtonian gravitational mechanics to explain the precession of Mercury—attributed, perhaps, to strange distortions of the ether, as in the Lorentz contraction. Through the decades, further corrective factors would be added on to account for other astronomical observations. Sufficiently precise atomic clocks, in airplanes, would reveal that time ran a little faster than expected at higher altitudes (time runs slower in more intense gravitational fields, but they wouldn't know that) and more corrective "ethereal factors" would be invented.

Until, *finally,* the many different empirically determined "corrective factors" were unified into the simple equations of General Relativity.

And the people in that alternate Earth would say, "The final equation was simple, but there was no way you could *possibly* know to arrive at that answer from *just* the perihelion precession of Mercury. It takes many, many *additional* experiments. You must have measured time running slower in a stronger gravitational field; you must have measured light bending around stars. Only *then* can you imagine our unified theory of ethereal gravitation. No, not even a perfect Bayesian superintelligence could know it!—for there would be many ad-hoc theories consistent with the perihelion precession alone."

In our world, Einstein didn't even *use* the perihelion precession of Mercury, except for verification of his answer produced by other means. Einstein sat down in his armchair, and thought about how *he* would have designed the universe, to look the way he thought a universe should look—for example, that you shouldn't ought to be able to distinguish yourself accelerating in one direction, from the rest of the universe accelerating in the other direction.

And Einstein executed the whole long (multi-year!) chain of armchair reasoning, without making any mistakes that would have required further experimental evidence to pull him back on track.

Even Jeffreyssai would be grudgingly impressed. Though he would still ding Einstein a point or two for the cosmological constant. (I don't ding Einstein for the cosmological constant because it later turned out to be real. I try to avoid criticizing people on occasions where they are right.)

What would be the probability-theoretic perspective on Einstein's feat?

Rather than observe the planets, and infer what laws might cover their gravitation, Einstein was observing the other laws of physics, and inferring what new law might follow the same pattern. Einstein wasn't finding an equation that covered the motion of gravitational bodies. Einstein was finding a character-of-physical-law that covered previously observed equations, and that he could crank to predict the next equation that would be observed.

Nobody knows where the laws of physics come from, but Einstein's success with General Relativity shows that their common character is strong enough to predict the correct form of one law from having observed other laws, without necessarily needing to observe the precise effects of the law.

(In a general sense, of course, Einstein did know by observation that things fell down; but he did not get GR by backward inference from Mercury's exact perihelion advance.)

So, from a Bayesian perspective, what Einstein did is still induction, and still covered by the notion of a simple prior (Occam prior) that gets updated by new evidence. It's just the prior was over the *possible characters of physical law,* and observing other physical laws let Einstein update his model of *the character of physical law*, which he then used to predict a particular law of gravitation.

If you didn't have the concept of a "character of physical law", what Einstein did would look like magic—plucking the correct model of gravitation out of the space of all possible equations, with vastly insufficient evidence. But Einstein, by looking at *other* laws, cut down the space of possibilities for the *next* law. He learned the alphabet in which physics was written, constraints to govern his answer. Not magic, but reasoning on a higher level, across a wider domain, than what a naive reasoner might conceive to be the "model space" of only this one law.

So from a probability-theoretic standpoint, Einstein was still data-driven—he just used the data he *already had*, more *effectively*. Compared to any alternate Earths that demanded huge quantities of *additional* data from astronomical observations and clocks on airplanes to *hit them over the head* with General Relativity.

There are numerous lessons we can derive from this.

I use Einstein as my example, even though it's cliche, because Einstein was also unusual in that he *openly admitted* to knowing things that Science hadn't confirmed. Asked what he would have done if Eddington's solar eclipse observation had failed to confirm General Relativity, Einstein replied: "Then I would feel sorry for the good Lord. The theory is correct."

According to prevailing notions of Science, this is arrogance—you must accept the verdict of experiment, and not cling to your personal ideas.

But as I concluded in Einstein's Arrogance, Einstein doesn't come off nearly as badly from a Bayesian perspective. From a Bayesian perspective, in order to suggest General Relativity at all, in order to even *think* about what turned out to be the correct answer, Einstein must have had enough evidence to identify the true answer in the theory-space. It would take only a little *more* evidence to justify (in a Bayesian sense) being nearly certain of the theory. And it was unlikely that Einstein only had *exactly* enough evidence to bring the hypothesis all the way up to his attention.

Any accusation of arrogance would have to center around the question, "But Einstein, how did you know you had reasoned correctly?"—to which I can only say: Do not criticize people when they turn out to be right! Wait for an occasion where they are wrong! Otherwise you are missing the chance to see when someone is thinking smarter than you—for you criticize them whenever they depart from a preferred ritual of cognition.

Or consider the famous exchange between Einstein and Niels Bohr on quantum theory—at a time when the then-current, single-world quantum theory seemed to be immensely well-confirmed experimentally; a time when, by the standards of Science, the current (deranged) quantum theory had simply won.

> Einstein: "God does not play dice with the universe."
> Bohr: "Einstein, don't tell God what to do."

You've got to admire someone who can get into an argument with God and win.

If you take off your Bayesian goggles, and look at Einstein *in terms of what he actually did all day,* then the guy was sitting around studying math and thinking about how *he* would design the universe, rather than running out and looking at things to gather more data. What Einstein did, *successfully*, is exactly the sort of high-minded feat of sheer intellect that Aristotle *thought* he could do, but *couldn't.* Not from a probability-theoretic stance, mind you, but from the viewpoint of what they did all day long.

Science does not trust scientists to do this, which is why General Relativity was not blessed as the public knowledge of humanity until after it had made and verified a novel experimental prediction—having to do with the bending of light in a solar eclipse. (It later turned out that particular measurement was not precise enough to verify reliably, and had favored GR essentially by luck.)

However, just because Science does not *trust* scientists to do something, does not mean it is impossible.

But a word of caution here: The reason why history books sometimes record the names of scientists who thought great high-minded thoughts, is not that high-minded thinking is *easier*, or *more reliable.* It is a priority bias: Some scientist who *successfully* reasoned from the *smallest amount of experimental evidence* got to the truth *first.* This cannot be a matter of pure random chance: The theory space is too large, and Einstein won several times in a row. But out of all the scientists who *tried* to unravel a puzzle, or who would have *eventually* succeeded given enough evidence, history passes down to us the names of the scientists who *successfully* got there *first*. Bear that in mind, when you are trying to derive lessons about how to reason prudently.

In everyday life, you want every scrap of evidence you can get. *Do not rely on being able to successfully think high-minded thoughts unless experimentation is so costly or dangerous that you have no other choice.*

But sometimes experiments are costly, and sometimes we prefer to get there first... so you might consider trying to train yourself in reasoning on scanty evidence, *preferably in cases where you will later find out if you were right or wrong.* Trying to beat low-capitalization prediction markets might make for good training in this?—though that is only speculation.

As of now, at least, reasoning based on scanty evidence is something that modern-day science cannot reliably train modern-day scientists to do *at all*. Which may perhaps have something to do with, oh, I don't know, not even trying?

Actually, I take that back. The most sane thinking I have seen in any scientific field comes from the field of evolutionary psychology, possibly because they understand self-deception, but also perhaps because they often (1) have to reason from scanty evidence and (2) do later find out if they were right or wrong. I recommend to all aspiring rationalists that they study evolutionary psychology simply to get a glimpse of what careful reasoning looks like. See particularly Tooby and Cosmides's "The Psychological Foundations of Culture".

As for the possibility that *only* Einstein could do what Einstein did... that it took superpowers beyond the reach of ordinary mortals... here we run into some biases that would take a separate post to analyze. Let me put it this way: It is possible, perhaps, that only a genius could have done Einstein's actual historical work. But *potential* geniuses, in terms of raw intelligence, are probably far more common than historical superachievers. To put a random number on it, I doubt that anything more than one-in-a-million *g*-factor is required to be a potential world-class genius, implying at least six thousand potential Einsteins running around today. And as for everyone else, I see no reason why they should not aspire to use efficiently the evidence that they have.

But my final moral is that the frontier where the individual scientist rationally knows something that Science has not yet confirmed, is not always some innocently data-driven matter of spotting a strong regularity in a mountain of experiments. Sometimes the scientist gets there by thinking great high-minded thoughts that Science does not trust you to think.

I will not say, "Don't try this at home." I will say, "Don't think this is easy." We are not discussing, here, the victory of casual opinions over professional scientists. We are discussing the sometime historical victories of one kind of professional effort over another. Never forget all the famous historical cases where attempted armchair reasoning lost.

That Alien Message

Imagine a world much like this one, in which, thanks to gene-selection technologies, the average IQ is 140 (on our scale). Potential Einsteins are one-in-a-thousand, not one-in-a-million; and they grow up in a school system suited, if not to them personally, then at least to bright kids. Calculus is routinely taught in sixth grade. Albert Einstein, himself, still lived and still made approximately the same discoveries, but his work no longer seems *exceptional.* Several modern top-flight physicists have made equivalent breakthroughs, and are still around to talk.

(No, this is not the world Brennan lives in.)

One day, the stars in the night sky begin to change.

Some grow brighter. Some grow dimmer. Most remain the same. Astronomical telescopes capture it all, moment by moment. The stars that change, change their luminosity one at a time, distinctly so; the luminosity change occurs over the course of a microsecond, but a whole second separates each change.

It is clear, from the first instant anyone realizes that more than one star is changing, that the process seems to center around Earth particularly. The arrival of the light from the events, at many stars scattered around the galaxy, has been precisely timed to Earth in its orbit. Soon, confirmation comes in from high-orbiting telescopes (they have those) that the astronomical miracles do *not* seem as synchronized from outside Earth. Only Earth's telescopes see one star changing every second (1005 milliseconds, actually).

Almost the entire combined brainpower of Earth turns to analysis.

It quickly becomes clear that the stars that jump in luminosity, all jump by a factor of exactly 256; those that diminish in luminosity, diminish by a factor of exactly 256. There is no apparent pattern in the stellar coordinates. This leaves, simply, a pattern of BRIGHT-dim-BRIGHT-BRIGHT...

"A binary message!" is everyone's first thought.

But in this world there are careful thinkers, of great prestige as well, and they are not so sure. "There are easier ways to send a message," they post to their blogs, "if you can make stars flicker, and if you want to communicate. *Something* is happening. It appears, *prima facie,* to focus on Earth in particular. To call it a 'message' presumes a great deal more about the cause behind it. There might be some kind of evolutionary process among, um, things that can make stars flicker, that ends up sensitive to intelligence somehow... Yeah, there's probably something like 'intelligence' behind it, but try to appreciate how wide a range of possibilities that really implies. We don't know this is a message, or that it was sent from the same kind of motivations that might move us. I mean, *we* would just signal using a big flashlight, we wouldn't mess up a whole galaxy."

By this time, someone has started to collate the astronomical data and post it to the Internet. Early suggestions that the data might be harmful, have been... not ignored, but not obeyed, either. If anything this powerful wants to hurt you, you're pretty much dead (people reason).

Multiple research groups are looking for patterns in the stellar coordinates—or fractional arrival times of the changes, relative to the center of the Earth—or exact durations of the luminosity shift—or any tiny variance in the magnitude shift—or any other fact that might be known about the stars before they changed. But *most* people are turning their attention to the pattern of BRIGHTS and dims.

It becomes clear almost instantly that the pattern sent is highly redundant. Of the first 16 bits, 12 are BRIGHTS and 4 are dims. The first 32 bits received align with the second 32 bits received, with only 7 out of 32 bits different, and then the next 32 bits received have only 9 out of 32 bits different from the second (and 4 of them are bits that changed before). From the first 96 bits, then, it becomes clear that this pattern is not an optimal, compressed encoding of anything. The obvious thought is that the sequence is meant to convey instructions for decoding a compressed message to follow...

"But," say the careful thinkers, "anyone who cared about *efficiency,* with enough power to mess with stars, could maybe have just signaled us with a big flashlight, and sent us a DVD?"

There also seems to be structure within the 32-bit groups; some 8-bit subgroups occur with higher frequency than others, and this structure only appears along the natural alignments (32 = 8 + 8 + 8 + 8).

After the first five hours at one bit per second, an additional redundancy becomes clear: The message has started approximately repeating itself at the 16,385th bit.

Breaking up the message into groups of 32, there are 7 bits of difference between the 1st group and the 2nd group, and 6 bits of difference between the 1st group and the 513th group.

"A 2D picture!" everyone thinks. "And the four 8-bit groups are colors; they're tetrachromats!"

But it soon becomes clear that there is a horizontal/vertical asymmetry: Fewer bits change, on average, between (N, N+1) versus (N, N+512). Which you wouldn't expect if the message was a 2D picture projected onto a symmetrical grid. Then you would expect the average bitwise distance between two 32-bit groups to go as the 2-norm of the grid separation: $\sqrt{(h^2 + v^2)}$.

There also forms a general consensus that a certain binary encoding from 8-groups onto integers between -64 and 191—not the binary encoding that seems obvious to us, but still highly regular—minimizes the average distance between neighboring cells. This continues to be borne out by incoming bits.

The statisticians and cryptographers and physicists and computer scientists go to work. There is structure here; it needs only to be unraveled. The masters of causality search for conditional independence, screening-off and Markov neighborhoods, among bits and groups of bits. The so-called "color" appears to play a role in neighborhoods and screening, so it's not just the equivalent of surface reflectivity. People search for simple equations, simple cellular automata, simple decision trees, that can predict or compress the message. Physicists invent entire new theories of physics that might describe universes projected onto the grid—for it seems quite plausible that a message such as this is being sent from beyond the Matrix.

After receiving 32 * 512 * 256 = 4,194,304 bits, around one and a half months, the stars stop flickering**.**

Theoretical work continues. Physicists and cryptographers roll up their sleeves and *seriously* go to work. They have cracked problems with far less data than this. Physicists have tested entire theory-edifices with small differences of particle mass; cryptographers have unraveled shorter messages deliberately obscured.

Years pass.

Two dominant models have survived, in academia, in the scrutiny of the public eye, and in the scrutiny of those scientists who once did Einstein-like work. There is a theory that the grid is a projection from objects in a 5-dimensional space, with an asymmetry between 3 and 2 of the spatial dimensions. There is also a theory that the grid is meant to encode a cellular automaton—arguably, the grid has several fortunate properties for such. Codes have been devised that give interesting behaviors; but so far, running the corresponding automata on the largest available computers, has failed to produce any decodable result. The run continues.

Every now and then, someone takes a group of especially brilliant young students who've never looked at the detailed binary sequence. These students are then shown only the first 32 rows (of 512 columns each), to see if they can form new models, and how well those new models do at predicting the next 224. Both the 3+2 dimensional model, and the cellular-automaton model, have been well duplicated by such students; they have yet to do better. There are complex models finely fit to the whole sequence—but those, everyone knows, are probably worthless.

Ten years later, the stars begin flickering again.

Within the reception of the first 128 bits, it becomes clear that the Second Grid *can* fit to small motions in the inferred 3+2 dimensional space, but does *not* look anything like the successor state of any of the dominant cellular automaton theories. Much rejoicing follows, and the physicists go to work on inducing what kind of dynamical physics might govern the objects seen in the 3+2 dimensional space. Much work along these lines has already been done, just by speculating on what type of *balanced* forces might give rise to the objects in the First Grid, if those objects were static—but now it seems not all the objects are static. As most physicists guessed—statically balanced theories seemed contrived.

Many neat equations are formulated to describe the dynamical objects in the 3+2 dimensional space being projected onto the First and Second Grids. Some equations are more elegant than others; some are more precisely predictive (in retrospect, alas) of the Second Grid. One group of brilliant physicists, who carefully isolated themselves and looked only at the first 32 rows of the Second Grid, produces equations that seem elegant to them—and the equations also do well on predicting the next 224 rows. This becomes the dominant guess.

But these equations are underspecified; they don't seem to be enough to make a universe. A small cottage industry arises in trying to guess what kind of laws might complete the ones thus guessed.

When the Third Grid arrives, ten years after the Second Grid, it provides information about second derivatives, forcing a major modification of the "incomplete but good" theory. But the theory doesn't do too badly out of it, all things considered.

The Fourth Grid doesn't add much to the picture. Third derivatives don't seem important to the 3+2 physics inferred from the Grids.

The Fifth Grid looks almost exactly like it is expected to look.

And the Sixth Grid, and the Seventh Grid.

(Oh, and every time someone in this world tries to build a really powerful AI, the computing hardware spontaneously melts. This isn't really important to the story, but I need to postulate this in order to have human people sticking around, in the flesh, for seventy years.)

My moral?

That even Einstein did not come within a million light-years of making *efficient use of sensory data*.

Riemann invented his geometries before Einstein had a use for them; the physics of our universe is not that complicated in an absolute sense. A Bayesian superintelligence, hooked up to a webcam, would invent General Relativity as a hypothesis—perhaps not the *dominant* hypothesis, compared to Newtonian mechanics, but still a hypothesis under direct consideration—by the time it had seen the third frame of a falling apple. It might guess it from the first frame, if it saw the statics of a bent blade of grass.

We would think of it. Our civilization, that is, given ten years to analyze each frame. Certainly if the average IQ was 140 and Einsteins were common, we would.

Even if we were human-level intelligences in a different sort of physics—minds who had never seen a 3D space projected onto a 2D grid—we would still think of the 3D->2D hypothesis. Our mathematicians would still have invented vector spaces, and projections.

Even if we'd never seen an accelerating billiard ball, our mathematicians would have invented calculus (e.g. for optimization problems).

Heck, think of some of the crazy math that's been invented here on *our* Earth.

I occasionally run into people who say something like, "There's a theoretical limit on how much you can deduce about the outside world, given a finite amount of sensory data."

Yes. There is. The theoretical limit is that every time you see 1 additional bit, it cannot be expected to eliminate more than half of the remaining hypotheses (half the remaining probability mass, rather). And that a redundant message, cannot convey more information than the compressed version of itself. Nor can a bit convey any information about a quantity, with which it has correlation *exactly zero,* across the probable worlds you imagine.

But nothing I've depicted this human civilization doing, even *begins* to approach the theoretical limits set by the formalism of Solomonoff induction. It doesn't approach the picture you could get if you could search through *every single computable hypothesis*, weighted by their simplicity, and do Bayesian updates on *all* of them.

To see the *theoretical* limit on extractable information, imagine that you have infinite computing power, and you simulate all possible universes with simple physics, looking for universes that contain Earths embedded in them—perhaps inside a simulation—where some process makes the stars flicker in the order observed. Any bit in the message—or any order of selection of stars, for that matter—that contains the tiniest correlation (across all possible computable universes, weighted by simplicity) to any element of the environment, gives you information about the environment.

Solomonoff induction, taken literally, would create countably infinitely many sentient beings, trapped inside the computations. All possible computable sentient beings, in fact. Which scarcely seems ethical. So let us be glad this is only a formalism.

But my point is that the "theoretical limit on how much information you can extract from sensory data" is *far* above what I have depicted as the triumph of a civilization of physicists and cryptographers.

It certainly is not anything like a human looking at an apple falling down, and thinking, "Dur, I wonder why that happened?"

People seem to make a leap from "This is 'bounded'" to "The bound must be a reasonable-looking quantity on the scale I'm used to." The power output of a supernova is 'bounded', but I wouldn't advise trying to shield yourself from one with a flame-retardant Nomex jumpsuit.

No one—not even a Bayesian superintelligence—will ever come remotely close to making efficient use of their sensory information...

...is what I would like to say, but I don't trust my ability to set limits on the abilities of Bayesian superintelligences.

(Though I'd bet money on it, if there were some way to judge the bet. Just not at very extreme odds.)

The story continues:

Millennia later, frame after frame, it has become clear that some of the objects in the depiction are extending tentacles to move around other objects, and carefully configuring other tentacles to make particular signs. They're trying to teach us to say "rock".

It seems the senders of the message have vastly underestimated our intelligence. From which we might guess that the aliens themselves are not all that bright. And these awkward children can shift the luminosity of our stars? That much power and that much stupidity seems like a dangerous combination.

Our evolutionary psychologists begin extrapolating possible courses of evolution that could produce such aliens. A strong case is made for them having evolved asexually, with occasional exchanges of genetic material and brain content; this seems like the most plausible route whereby creatures that stupid could still manage to build a technological civilization. Their Einsteins may be our undergrads, but they could still collect enough scientific data to get the job done *eventually*, in tens of their millennia perhaps.

The inferred physics of the 3+2 universe is not fully known, at this point; but it seems sure to allow for computers far more powerful than our quantum ones. We are reasonably certain that our own universe is running as a simulation on such a computer. Humanity decides not to probe for bugs in the simulation; we wouldn't want to shut ourselves down accidentally.

Our evolutionary psychologists begin to guess at the aliens' psychology, and plan out how we could persuade them to let us out of the box. It's not difficult in an absolute sense—they aren't very bright—but we've got to be very careful...

We've got to pretend to be stupid, too; we don't want them to catch on to their mistake.

It's not until a million years later, though, that they get around to telling us how to signal back.

At this point, most of the human species is in cryonic suspension, at liquid helium temperatures, beneath radiation shielding. Every time we try to build an AI, or a nanotechnological device, it melts down. So humanity waits, and sleeps. Earth is run by a skeleton crew of nine supergeniuses. Clones, known to work well together, under the supervision of certain computer safeguards.

An additional hundred million human beings are born into that skeleton crew, and age, and enter cryonic suspension, before they get a chance to slowly begin to implement plans made eons ago...

From the aliens' perspective, it took us thirty of their minute-equivalents to oh-so-innocently learn about their psychology, oh-so-carefully persuade them to give us Internet access, followed by five minutes to innocently discover their network protocols, then some trivial cracking whose only difficulty was an innocent-looking disguise. We read a tiny handful of physics papers (bit by slow bit) from their equivalent of arXiv, learning far more from their experiments than they had. (Earth's skeleton team spawned an extra twenty Einsteins, that generation.)

Then we cracked their equivalent of the protein folding problem over a century or so, and did some simulated engineering in their simulated physics. We sent messages (steganographically encoded until our cracked servers decoded it) to labs that did their equivalent of DNA sequencing and protein synthesis. We found some unsuspecting schmuck, and gave it a plausible story and the equivalent of a million dollars of cracked computational monopoly money, and told it to mix together some vials it got in the mail. Protein-equivalents that self-assembled into the first-stage nanomachines, that built the second-stage nanomachines, that built the third-stage nanomachines... and then we could finally begin to do things at a reasonable speed.

Three of their days, all told, since they began speaking to us. Half a billion years, for us.

They never suspected a thing. They weren't very smart, you see, even before taking into account their slower rate of time. Their primitive equivalents of rationalists went around saying things like, "There's a bound to how much information you can extract from sensory data." And they never quite realized what it meant, that we were smarter than them, and thought faster.

My Childhood Role Model

When I lecture on the Singularity, I often draw a graph of the "scale of intelligence" as it appears in everyday life:

Mindscaleparochial

But this is a rather *parochial* view of intelligence. Sure, in everyday life, we only deal socially with other humans—only other humans are partners in the great game—and so we only *meet the minds* of intelligences ranging from village idiot to Einstein. But what we really need to talk about Artificial Intelligence or theoretical optima of rationality, is *this* intelligence scale:

Mindscalereal

For us humans, it seems that the scale of intelligence runs from "village idiot" at the bottom to "Einstein" at the top. Yet the distance from "village idiot" to "Einstein" is tiny, in the space of *brain designs.* Einstein and the village idiot both have a prefrontal cortex, a hippocampus, a cerebellum...

Maybe Einstein has some minor genetic differences from the village idiot, engine tweaks. But the brain-design-distance between Einstein and the village idiot is nothing remotely like the brain-design-distance between the village idiot and a chimpanzee. A chimp couldn't tell the difference between Einstein and the village idiot, and our descendants may not see much of a difference either.

Carl Shulman has observed that some academics who talk about transhumanism, seem to use the following scale of intelligence:

Mindscaleacademic

Douglas Hofstadter actually said something like this, at the 2006 Singularity Summit. He looked at my diagram showing the "village idiot" next to "Einstein", and said, "That seems wrong to me; I think Einstein should be way off on the right."

I was speechless. Especially because this was *Douglas Hofstadter,* one of my childhood heroes. It revealed a cultural gap that I had never imagined existed.

See, for me, what you would find toward the right side of the scale, was a Jupiter Brain. Einstein did not *literally* have a brain the size of a planet.

On the right side of the scale, you would find Deep Thought—Douglas Adams's original version, thank you, not the chessplayer. The computer so intelligent that even before its stupendous data banks were connected, when it was switched on for the first time, it started from *I think therefore I am* and got as far as deducing the existence of rice pudding and income tax before anyone managed to shut it off.

Toward the right side of the scale, you would find the Elders of Arisia, galactic overminds, Matrioshka brains, and the better class of God. At the *extreme* right end of the scale, Old One and the Blight.

Not frickin' Einstein.

I'm sure Einstein was very smart for a human. I'm sure a General Systems Vehicle would think that was very cute of him.

I call this a "cultural gap" because I was introduced to the concept of a Jupiter Brain at the age of twelve.

Now all of this, of course, is the logical fallacy of generalization from fictional evidence.

But it is an example of why—logical fallacy or not—I suspect that reading science fiction does have a helpful effect on futurism. Sometimes the alternative to a fictional acquaintance with worlds outside your own, is to have a mindset that is absolutely stuck in one era: A world where humans exist, and have always existed, and always will exist.

The universe is 13.7 billion years old, people! *Homo sapiens sapiens* have only been around for a hundred thousand years or thereabouts!

Then again, I have met some people who never read science fiction, but who do seem able to imagine outside their own world. And there are science fiction fans who don't get it. I wish I knew what "it" was, so I could bottle it.

Yesterday, I wanted to talk about the *efficient use of evidence,* i.e., Einstein was cute for a human but in an absolute sense he was around as efficient as the US Department of Defense.

So I had to talk about a civilization that included thousands of Einsteins, thinking for decades. Because if I'd just depicted a Bayesian superintelligence in a box, looking at a webcam, people would think: "But... how does it know how to interpret a 2D picture?" They wouldn't put *themselves* in the shoes of the mere machine, even if it was called a "Bayesian superintelligence"; they wouldn't apply even their *own* creativity to the problem of what you could extract from looking at a grid of bits.

It would just be a ghost in a box, that happened to be called a "Bayesian superintelligence". The ghost hasn't been told anything about how to interpret the input of a webcam; so, in their mental model, the ghost does not know.

As for whether it's realistic to suppose that one Bayesian superintelligence can "do all that"... i.e., the stuff that occurred to me on first sitting down to the problem, writing out the story as I went along...

Well, let me put it this way: Remember how Jeffreyssai pointed out that if the experience of having an important insight doesn't take more than 5 minutes, this theoretically gives you time for 5760 insights per month? Assuming you sleep 8 hours a day and have no important insights while sleeping, that is.

Now humans cannot use themselves this efficiently. But humans are not adapted for the task of scientific research. Humans are adapted to chase deer across the savanna, throw spears into them, cook them, and then—this is probably the part that takes most of the brains—cleverly argue that they deserve to receive a larger share of the meat.

It's amazing that Albert Einstein managed to repurpose a brain like that for the task of doing physics. This deserves applause. It deserves more than applause, it deserves a place in the Guinness Book of Records. Like successfully building the fastest car ever to be made entirely out of Jello.

How poorly did the blind idiot god (evolution) *really* design the human brain?

This is something that can only be grasped through much study of cognitive science, until the full horror begins to dawn upon you.

All the biases we have discussed here should at least be a hint.

Likewise the fact that the human brain must use its full power and concentration, with trillions of synapses firing, to multiply out two three-digit numbers without a paper and pencil.

No more than Einstein made efficient use of his sensory data, did his brain make efficient use of his neurons firing.

Of course I have certain ulterior motives in saying all this. But let it also be understood that, years ago, when I set out to be a rationalist, the impossible unattainable ideal of intelligence that inspired me, was never Einstein.

Carl Schurz said:

> "Ideals are like stars. You will not succeed in touching them with your hands. But, like the seafaring man on the desert of waters, you choose them as your guides and following them you will reach your destiny."

So now you've caught a glimpse of one of my great childhood role models—my dream of an AI. Only the dream, of course, the reality not being available. I reached up to that dream, once upon a time.

And this helped me to some degree, and harmed me to some degree.

For some ideals are like dreams: they come from within us, not from outside. Mentor of Arisia proceeded from E. E. "doc" Smith's imagination, not from any real thing. If you imagine what a Bayesian superintelligence would say, it is only your own mind talking. Not like a star, that you can follow from outside. You have to guess where your ideals are, and if you guess wrong, you go astray.

But do not limit your ideals to mere stars, to mere humans who actually existed, especially if they were born more than fifty years before you and are dead. Each succeeding generation has a chance to do better. To let your ideals be composed only of humans, especially dead ones, is to limit yourself to what has already been accomplished. You will ask yourself, "Do I dare to do this thing, which Einstein could not do? Is this not *lèse majesté?*" Well, if Einstein had sat around asking himself, "Am I allowed to do better than Newton?" he would not have gotten where he did. This is the problem with following stars; at best, it gets you to the star.

Your era supports you more than you realize, in unconscious assumptions, in subtly improved technology of mind. Einstein was a nice fellow, but he talked a deal of nonsense about an impersonal God, which shows you how well he understood the art of careful thinking at a higher level of abstraction than his own field. It may seem less like sacrilege to think that, if you have at least one imaginary galactic supermind to compare with Einstein, so that he is not the far right end of your intelligence scale.

If you only try to do what seems humanly possible, you will ask too little of yourself. When you imagine reaching up to some higher and inconvenient goal, all the convenient reasons why it is "not possible" leap readily to mind.

The most important role models are dreams: they come from within ourselves. To dream of anything less than what you conceive to be perfection, is to draw on less than the full power of the part of yourself that dreams.

Einstein's Superpowers

There is a widespread tendency to talk (and think) as if Einstein, Newton, and similar historical figures had superpowers—something magical, something sacred, something beyond the mundane. (Remember, there are many more ways to worship a thing than lighting candles around its altar.)

Once I unthinkingly thought this way too, with respect to Einstein in particular, until reading Julian Barbour's *The End of Time* cured me of it.

Barbour laid out the history of anti-epiphenomenal physics and Mach's Principle; he described the historical controversies that predated Mach—all this that stood behind Einstein and was known to Einstein, when Einstein tackled his problem...

And maybe I'm just imagining things—reading too much of *myself* into Barbour's book—but I thought I heard Barbour very quietly shouting, coded between the polite lines:

> What Einstein did *isn't magic,* people! If you all just *looked at how he actually did it,* instead of falling to your knees and worshiping him, maybe then you'd be able to do it too!

(EDIT March 2013: Barbour did not actually say this. It does not appear in the book text. It is not a Julian Barbour quote and should not be attributed to him. Thank you.)

Maybe I'm mistaken, or extrapolating too far... but I kinda suspect that Barbour once tried to explain to people how you move further along Einstein's direction to get timeless physics; and they sniffed scornfully and said, "Oh, you think *you're* Einstein, do you?"

John Baez's Crackpot Index, item 18:

> 10 points for each favorable comparison of yourself to Einstein, or claim that special or general relativity are fundamentally misguided (without good evidence).

Item 30:

> 30 points for suggesting that Einstein, in his later years, was groping his way towards the ideas you now advocate.

Barbour never bothers to compare himself to Einstein, of course; nor does he ever appeal to Einstein in support of timeless physics. I mention these items on the Crackpot Index by way of showing how many people compare themselves to Einstein, and what society generally thinks of them.

The crackpot sees Einstein as something magical, so they compare themselves to Einstein by way of praising themselves as magical; they think Einstein had superpowers and they think they have superpowers, hence the comparison.

But it is just the other side of the same coin, to think that Einstein is sacred, and the crackpot is *not* sacred, therefore they have committed blasphemy in comparing themselves to Einstein.

Suppose a bright young physicist says, "I admire Einstein's work, but personally, I hope to do better." If someone is shocked and says, "What! You haven't accomplished anything remotely like what Einstein did; what makes you think you're smarter than him?" then they are the other side of the crackpot's coin.

The underlying problem is conflating social status and research potential.

Einstein has extremely high social status: because of his record of accomplishments; because of *how* he did it; and because he's the physicist whose name even the general public remembers, who brought honor to science itself.

And we tend to mix up fame with other quantities, and we tend to attribute people's behavior to dispositions rather than situations.

So there's this tendency to think that Einstein, even before he was famous, already had an inherent disposition to be Einstein—a potential *as rare as his fame* and *as magical as his deeds.* So that if you claim to have the *potential* to do what Einstein did, *it is just the same as claiming Einstein's rank,* rising far above your assigned status in the tribe.

I'm not phrasing this well, but then, I'm trying to dissect a confused thought: Einstein belongs to a separate magisterium, the sacred magisterium. The sacred magisterium is distinct from the mundane magisterium; you can't set out to be Einstein in the way you can set out to be a full professor or a CEO. Only beings with divine potential can enter the sacred magisterium—and then it is only fulfilling a destiny they already have. So if you say you want to outdo Einstein, you're claiming to *already be* part of the sacred magisterium—you claim to have the same aura of destiny that Einstein was born with, like a royal birthright...

"But Eliezer," you say, "surely not *everyone* can become Einstein."

You mean to say, not everyone can *do better* than Einstein.

"Um... yeah, that's what I meant."

Well... in the modern world, you may be correct. You probably *should* remember that I am a transhumanist, going around looking around at people thinking, "You know, it just sucks that not everyone has the potential to do better than Einstein, and this seems like a fixable problem." It colors one's attitude.

But in the modern world, yes, not everyone has the potential to be Einstein.

Still... how can I put this...

There's a phrase I once heard, can't remember where: "Just another Jewish genius." Some poet or author or philosopher or other, brilliant at a young age, doing something not tremendously important in the grand scheme of things, not all that influential, who ended up being dismissed as "Just another Jewish genius."

If Einstein had chosen the wrong angle of attack on his problem—if he hadn't chosen a sufficiently important problem to work on—if he hadn't persisted for years—if he'd taken any number of wrong turns—or if someone else had solved the problem first—then dear Albert would have ended up as just another Jewish genius.

Geniuses are rare, but not all *that* rare. It is not all that implausible to lay claim to the kind of intellect that can get you dismissed as "just another Jewish genius" or "just another brilliant mind who never did anything interesting with their life". The associated social status here is not high enough to be sacred, so it should seem like an ordinarily evaluable claim.

But what separates people like this from becoming Einstein, I suspect, is no innate defect of brilliance. It's things like "lack of an interesting problem"—or, to put the blame where it belongs, "failing to choose an important problem". It is very easy to fail at this because of the [cached thought]() problem: Tell people to choose an important problem and they will choose the first cache hit for "important problem" that pops into their heads, like "global warming" or "string theory".

The truly important problems are often the ones you're not even considering, because they appear to be impossible, or, um, *actually difficult,* or worst of all, *not clear how to solve*. If you worked on them for years, they might not seem so impossible... but this is an extra and unusual insight; naive realism will tell you that solvable problems look solvable, and impossible-looking problems are impossible.

Then you have to come up with a new and *worthwhile* angle of attack. Most people who are not allergic to novelty, will go too far in the other direction, and fall into an [affective death spiral]().

And then you've got to bang your head on the problem for years, without being distracted by the temptations of easier living. "Life is what happens while we are making other plans," as the saying goes, and if you want to fulfill your other plans, you've often got to be ready to turn down life.

Society is not set up to support you while you work, either.

The point being, the problem is not that you need an aura of destiny and the aura of destiny is missing. If you'd met Albert before he published his papers, you would have perceived no aura of destiny about him to match his future high status. He would seem like just another Jewish genius.

This is not because the royal birthright is *concealed*, but because it simply is *not there.* It is *not necessary.* There *is no* separate magisterium for people who do important things.

I say this, because I want to do important things with my life, and I have a genuinely important problem, and an angle of attack, and I've been banging my head on it for years, and I've managed to set up a support structure for it; and I very frequently meet people who, in one way or another, say: "Yeah? Let's see your aura of destiny, buddy."

What impressed me about Julian Barbour was a quality that I don't think anyone would have known how to fake without actually *having* it: Barbour seemed to have *seen through* Einstein—he talked about Einstein as if everything Einstein had done was perfectly understandable and mundane.

Though even having realized this, to me it still came as a shock, when Barbour said something along the lines of, "Now here's where Einstein failed to apply his own methods, and missed the key insight—" But the shock was fleeting, I knew the Law: *No gods, no magic, and ancient heroes are milestones to tick off in your rearview mirror.*

This *seeing through* is something one has to *achieve,* an insight one has to discover. You cannot see through Einstein just by saying, "Einstein is mundane!" if his work still seems like magic unto you. That would be like declaring "Consciousness must reduce to neurons!" without having any idea of how to do it. It's true, but it doesn't solve the problem.

I'm not going to tell you that Einstein was an ordinary bloke oversold by the media, or that deep down he was a regular schmuck just like everyone else. That would be going *much* too far. To walk this path, one must acquire abilities some consider to be... unnatural. I take a special joy in doing things that people call "humanly impossible", because it shows that I'm growing up.

Yet the way that you acquire magical powers is not by being born with them, but by seeing, with a sudden shock, that they *really are* perfectly normal.

This is a general principle in life.

Class Project

"Do as well as Einstein?" Jeffreyssai said, incredulously. "*Just* as well as Einstein? Albert Einstein was a great scientist of his era, but that was his era, not this one! Einstein did not comprehend the Bayesian methods; he lived before the cognitive biases were discovered; he had no scientific grasp of his own thought processes. Einstein spoke nonsense of an impersonal God—which tells you how well he understood the rhythm of reason, to discard it outside his own field! He was too caught up in the drama of rejecting his era's quantum mechanics to actually *fix* it. And while I grant that Einstein reasoned cleanly in the matter of General Relativity—barring that matter of the cosmological constant—he took ten years to do it. Too slow!"

"*Too slow?*" repeated Taji incredulously.

"Too slow! If Einstein were in this classroom now, rather than Earth of the negative first century, I would rap his knuckles! *You will not try to do as well as Einstein! You will aspire to do BETTER than Einstein or you may as well not bother!*"

Jeffreyssai shook his head. "Well, I've given you enough hints. It is time to test your skills. Now, I know that the other *beisutsukai* don't think much of my class projects..." Jeffreyssai paused significantly.

Brennan inwardly sighed. He'd heard this line many times before, in the Bardic Conspiracy, the Competitive Conspiracy: *The other teachers think my assignments are too easy, you should be grateful,* followed by some ridiculously difficult task—

"They say," Jeffreyssai said, "that my projects are too hard; insanely hard; that they pass from the realm of madness into the realm of Sparta; that Laplace himself would catch on fire; they accuse me of trying to tear apart my students' souls—"

Oh, crap.

"But there is a reason," Jeffreyssai said, "why many of my students have achieved great things; and by that I do not mean high rank in the Bayesian Conspiracy. I expected much of them, and they came to expect much of themselves. So..."

Jeffreyssai took a moment to look over his increasingly disturbed students, "Here is your assignment. Of quantum mechanics, and General Relativity, you have been told. This is the limit of Eld science, and hence, the limit of public knowledge. The five of you, working on your own, are to produce the correct theory of quantum gravity. Your time limit is one month."

"*What?*" said Brennan, Taji, Styrlyn, and Yin. Hiriwa gave them a puzzled look.

"Should you succeed," Jeffreyssai continued, "you will be promoted to *beisutsukai* of the second *dan* and sixth level. We will see if you have learned speed. Your clock starts—*now*."

And Jeffreyssai strode out of the room, slamming the door behind him.

"This is crazy!" Taji cried.

Hiriwa looked at Taji, bemused. "The solution is not known to us. How can you know it is so difficult?"

"Because we *knew* about this problem back in the Eld days! Eld scientists worked on this problem for a lot longer than one month."

Hiriwa shrugged. "They were still arguing about many-worlds too, weren't they?"

"*Enough! There's no time!*"

The other four students looked to Styrlyn, remembering that he was said to rank high in the Cooperative Conspiracy. There was a brief moment of weighing, of assessing, and then Styrlyn was their leader.

Styrlyn took a great breath. "We need a list of approaches. Write down all the angles you can think of. Independently—we need your individual components before we start combining. In five minutes, I'll ask each of you for your best idea first. *No wasted thoughts! Go!*"

Brennan grabbed a sheet and his tracer, set the tip to the surface, and then paused. He couldn't think of anything clever to say about unifying general relativity and quantum mechanics...

The other students were already writing.

Brennan tapped the tip, once, twice, thrice. General relativity and quantum mechanics...

Taji put his first sheet aside, grabbed another.

Finally, Brennan, for lack of anything clever to say, wrote down the obvious.

Minutes later, when Styrlyn called time, it was still all he had written.

"All right," Styrlyn said, "your best idea. Or the idea you most want the rest of us to take into account in our second components. Taji, go!"

Taji looked over his sheets. "Okay, I think we've got to assume that every avenue that Eld science was trying is a blind alley, or they would have found it. And if this is possible to do in one month, the answer must be, in some sense, elegant. So no multiple dimensions. If we start doing anything that looks like we should call it 'string theory', we'd better stop. Maybe begin by considering how failure to understand decoherence could have led Eld science astray in quantizing gravity."

"The opposite of folly is folly," Hiriwa said. "Let us pretend that Eld science never existed."

"No criticisms yet!" said Styrlyn. "Hiriwa, your suggestion?"

"Get rid of the infinities," said Hiriwa, "extirpate that which permits them. It should not be a matter of cleverness with integrals. A *representation* that allows infinity must be false-to-fact."

"Yin."

"We know from common sense," Yin said, "that if we stepped outside the universe, we would see time laid out all at once, reality like a crystal. But I once encountered a hint that physics is timeless in a deeper sense than that." Yin's eyes were distant, remembering. "Years ago, I found an abandoned city; it had been uninhabited for eras, I think. And behind a door whose locks were broken, carved into one wall: quote *.ua sai .ei mi vimcu ty bu le mekso* unquote."

Brennan translated: *Eureka! Eliminate t from the equations.* And written in Lojban, the sacred language of science, which meant the unknown writer had thought it to be true.

"The 'timeless physics' of which we've all heard rumors," Yin said, "may be timeless in a very literal sense."

"My own contribution," Styrlyn said. "The quantum physics we've learned is over joint positional configurations. It seems like we should be able to take that apart into a spatially local representation, in terms of invariant distant entanglements. Finding that representation might help us integrate with general relativity, whose curvature is local."

"A strangely *individualist* perspective," Taji murmured, "for one of the Cooperative Conspiracy."

Styrlyn shook his head. "You misunderstand us, then. The first lesson we learn is that groups are made of people... no, there is no time for politics. Brennan!"

Brennan shrugged. "Not much, I'm afraid, only the obvious. Inertial mass-energy was always observed to equal gravitational mass-energy, and Einstein showed that they were necessarily the same. So why is the 'energy' that is an eigenvalue of the quantum Hamiltonian, *necessarily* the same as the 'energy' quantity that appears in the equations of General Relativity? Why should spacetime curve at the same rate that the little arrows rotate?"

There was a brief pause.

Yin frowned. "That seems *too* obvious. Wouldn't Eld science have figured it out already?"

"Forget Eld science existed," Hiriwa said. "The question stands: we need the answer, whether it was known in ancient times or not. It cannot possibly be *coincidence.*"

Taji's eyes were abstracted. "Perhaps it would be possible to show that an exception to the equality would violate some conservation law..."

"That is not where Brennan pointed," Hiriwa interrupted. "He did not ask for a proof that they must be set equal, given some appealing principle; he asked for a view in which the two are one and cannot be divided even conceptually, as was accomplished for inertial mass-energy and gravitational mass-energy. For we must assume that the beauty of the whole arises from the fundamental laws, and not the other way around. Fair-rephrasing?"

"Fair-rephrasing," Brennan replied.

Silence reigned for thirty-seven seconds, as the five pondered the five suggestions.

"I have an idea..."

Why Quantum?

This post is part of the Quantum Physics Sequence.
Followup to: Quantum Explanations

"Why are you doing these posts on quantum physics?" the one asked me.

"Quite a number of reasons," I said.

"For one thing," I said, "the many-worlds issue is just about the only case I know of where you can bring the principles of Science and Bayesianism into *direct* conflict." It's important to have different mental buckets for "science" and "rationality", as they are different concepts. Bringing the two principles into direct conflict is helpful for illustrating what science is and is not, and what rationality is and is not. Otherwise you end up trusting in what you call "science", which won't be strict enough.

"For another thing," I continued, "part of what goes into becoming a rationalist, is learning to live into a counterintuitive world—learning to find things underneath the surface that are unlike the world of surface forms." Quantum mechanics makes a good introduction to that, when done correctly without the horrible confusion and despair. It breaks you of your belief in an *intuitive* universe, counters naive realism, destroys your trust in the way that your cognitive algorithms look from inside—and then you're ready to start seeing your mind *as a mind,* not as a window onto reality.

"But you're writing about physics, without being a physicist," the one said, "isn't that... a little..."

"Yes," I said, "it is, and I felt guilty about it. But there were physicists talking complete nonsense about Occam's Razor without knowing the probability theory of it, so my hand was forced. Also the situation in teaching quantum mechanics is really awful—I saw the introductions to Bayesianism and they seemed unnecessarily difficult, but the situation in quantum mechanics is *so* much worse." It really is. I remember sitting there staring at the "linear operators", trying to figure out what the hell they physically *did* to the eigenvectors—trying to visualize the actual *events* that were going on in the physical evolution—before it dawned on me that it was just a math trick to extract the average of the eigenvalues. Okay, but... can't you just *tell* me that up front? Write it *down* somewhere? Oh, I forgot, the math *doesn't mean anything, it just works.*

"*Furthermore,*" I added, "knowing about many worlds, helps you visualize probabilities as frequencies, which is helpful to many points I want to make."

"And *furthermore,*" I said, "reducing time to non-time is a powerful example of the principle, in reductionism, that you should reduce something to something other than itself."

"And even *furthermore,*" I said, "I had to break my readers of trust in Science, even trust in physicists, because it doesn't seem possible to think and trust at the same time."

"Many-worlds is really a very clear and simple problem," I said, "by comparison with the challenges you encounter in AI, which are around a hundred times less clear-cut. And many scientists can't even get many-worlds, in the absence of authority." So you are left with no choice but to aspire to do better than the average scientist; a hell of a lot better, in fact. This notion is one that you cannot just blurt out to people without showing them why it is necessary.

Another helpful advantage—I often do things with quite a few different purposes in mind, as you may have realized by this point—was that you can see various commenters who still haven't gotten it, who are still saying, "Oh, look, Eliezer is overconfident because he believes in many-worlds."

Well, if you can viscerally see the arguments I have laid forth, then you can see that I am not being careless in having an opinion about physics. The balance of arguments is overwhelmingly tipped; and physicists who deny it, are making specific errors of probability theory (which I have specifically laid out, and shown to you) that they might not be expected to know about. It is not just a matter of my forming strong opinions at random.

But would you believe that I had such strong support, if I had not shown it to you in full detail? Ponder this well. For I may have other strong opinions. And it may seem to you that *you* don't see any good reason to form such strong beliefs. Except this is *not* what you will see; you will see simply that there *is* no good reason for strong belief, that there *is* no strong support one way or the other. For our first-order beliefs are how the world seems to *be.* And you may think, "Oh, Eliezer is just opinionated—forming strong beliefs in the absence of lopsided support." And I will not have the time to do another couple of months worth of blog posts.

I am *very* far from infallible, but I do not hold strong opinions at random.

"And *yet still furthermore,*" I said, "transhumanist mailing lists have been arguing about issues of personal identity for years, and a tremendous amount of time has been wasted on it." Probably most who argue, will not bother to read what I have set forth; but if it stops any intelligent folk from wasting further time, that too is a benefit.

I am sometimes accused of being overconfident and opinionated, for telling people that being composed of "the same atoms" has nothing to do with their personal continuity. Or for saying that an uploading scan performed to the same resolution as thermal noise, actually has less effect on your identity than a sneeze (because your eyes squeeze shut when you sneeze, and that actually *alters* the computational state of billions of neurons in your visual cortex). Yet if you can see your *nows* braided into causality of the river that never flows; and the synaptic connections computing your internal narrative, that remain the same from one time to another, though not a drop of water is shared; then you can see that I have reasons for this strong belief as well.

Perhaps the one says to me that the exact duplicate constructed on Mars, is *just a copy.* And I post a short comment saying, "Wrong. There is no copy, there are two originals. This is knowable and I know it." Would you have thought that I might have very strong support, that you might not be seeing?

I won't always have the time to write a month of blog posts. While I am enough of a Traditional Rationalist that I dislike trust, and will not lightly ask it, I may ask it of you if your life is at stake.

Another one once asked me: "What does quantum physics have to do with overcoming bias?"

Robin Hanson chose the name "Overcoming Bias"; but names are not steel chains. If I'd started my own personal blog for the material I'm now posting, I would have called it "Reinventing Rationality" or something along those lines—and even that wouldn't have been the *real* purpose, which would have been harder to explain.

What are these series of posts, *really?* Raw material for a popular book on rationality—but maybe a tenth of this material, or less, will make it into the book. One of the reasons I write long posts, is so that I can shorten them later with a good conscience, knowing that I did lay out the full argument *somewhere.* But the whole quantum physics sequence is probably not going to make it into the popular book at all—and neither will many other posts. So what's the *rest* of it for?

Sometimes I think wistfully of how much more I could have accomplished in my teenage years, if I had known a fraction of what I know now at age 15. (This is the age at which I was a Traditional Rationalist, and dedicated and bright as such ones go, but knew not the Way of Bayes.) You can think of these blog posts, perhaps, as a series of letters to my past self. Only not exactly, because some of what I now write, I *did* already know then.

It seems to me, looking back, that the road which took me to this Way, had a great deal of luck in it. I would like to eliminate that element of luck for those who come after. So some of what I post, is more formal explanations of matters which Eliezer-15 knew in his bones. And the rest, I only *wish* I had known.

Perhaps if you prime someone with enough material as a starting point, they can figure out the other 95% on their own, if they go on to study the relevant sciences at a higher technical level. That's what I hope.

Eliezer-15 was led far astray by the seeming mysteriousness of quantum mechanics. An antiproject in which he was aided and abetted by certain popular physicists—notably Sir Roger Penrose; but also all those physicists who told him that quantum physics was "mysterious" and that it was okay not to understand it.

This is something I wish I had known, so I explained it to me.

Why not just tell me to ignore quantum physics? Because I am not going to "just ignore" a question that large. It is not how we work.

If you are confronting real scientific chaos—not just some light matter of an experimental anomaly or the search for a better theory, but genuine fear and despair, as now exists in Artificial Intelligence—then it is necessary to be a polymath. Healthy fields have healthy ways of thinking; you cannot trust the traditions of the confused field you must reform, though you must learn them. You never know which way you'll need to draw upon, on venturing out into the unknown. You learn new sciences for the same reasons that programmers learn new programming languages: to change the way you think. If you want to never learn anything without knowing in advance how it will apply, you had best stay away from chaos.

If you want to tackle challenges on the order of AI, you can't just learn a bunch of AI stuff.

And finally...

Finally...

There finally comes a point where you get tired of trying to communicate across vast inferential distances. There comes a point where you get tired of not being able to say things to people without a month of preliminary explanation. There comes a point where you want to say something about branching Earths or identical particles or braids in the river that never flows, and you can't.

It is such a tremendous relief, to finally be able to say all these things. And all the other things, that I have said here; that people have asked me about for so long, and all I could do was wave my hands. I didn't have to explain the concept of "inferential distance" from scratch, I could just link to it. It is such a relief.

I have written hundreds of blog posts here. Think about what it would be like, to carry all that around *inside your head.*

If I can do all the *long* sequences on Overcoming Bias, then maybe after that, it will be possible to say most things that I want to say, in just one piece.

Part of *The Quantum Physics Sequence*

(end of sequence)

Previous post: "Class Project"