Enter Heisenberg, Exit Common Sense

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1 Unanswered Questions

The questions raised to date which still have not been answered are as follows:

1. The basic building blocks of matter, called elementary particles, must all have zero volume. What, then, prevents them from piling in so closely together that the matter they form does *not* have zero volume?
2. How does a nucleus hold itself together, if the electromagnetic force trying to push the protons apart is so much stronger than gravity, and gravity is the only attractive force we know of that applies?
3. Why aren't electrons ever found in a nucleus?
4. How does information about particle positions get exchanged between particles? That would seem to violate energy conservation.
5. How are new particles created? *Answer currently incomplete.*
6. Can the physical laws of the Universe truly allow a random process?
7. What force(s) do neutrinos experience?

At the end of the previous lesson, we learned that radioactive decay is a random process, which takes place at seemingly arbitrary times. This opens up a whole range of possibilities: if there is one random process in nature, then it stands to reason that there would be others.

2 Determinism

The first concept this challenges is determinism. Determinism is the belief that everything that happens in nature is absolute, and that a sufficiently advanced scientific model paired with sufficiently complete experimental observations could be used to accurately predict all future events. This has long been an assumption of scientists, but radioactive decay makes it appear to be incorrect. Granted, radioactive decay is not *completely* random,[1] but the inability to accurately predict the moment of decay for any single nucleus is disturbing to many scientists.

To press forward, let us re-examine two of our unanswered questions from the first two lessons:

1. How does information about particle positions get exchanged between particles? That would seem to violate energy conservation.
2. How are new particles created? *(The answer to this one is, at the moment, incomplete.)*

These two questions can actually be cleared up if we can accept uncertainty in the universe we live in.

3 Limitations on Experimental Observations

To make any measurement of a system, one must interact with that system. In doing so, you alter that system. Let's look at a circuit as an example.

There are three main quantities that can be measured in any electric circuit: voltage, current and resistance. Resistance is purely a result of the materials the circuit has been constructed from. Materials with high resistance make it difficult for current to pass through, and often get warm in the process. (Toasters, light bulbs, stoves and ovens are essentially based on this principle.) Current is, essentially, a measure of how many electrons are moving through the circuit at a time. Voltage, finally, is a measure of how much potential energy is available to make the electrons move, or, if you prefer, it a measure of how strongly the electrons are pushed through the circuit. These three variables are related in such a way that you can't change one of the three without changing at least one of the other two.[2]

[1] We can define a meaningful half-life for the decay rate of any given isotope.

[2] Mathematically, the relationship can be written as $V = IR$, where V is voltage, I is current, and R is resistance.

Electric circuits also form an example of experimental limitations. To measure the current in a circuit, one must put the measurement tool in the circuit along the path the electrons travel. This allows the experimenter to confidently "count" all of the electrons in motion and determine the current. However, this also means increasing the total resistance of the circuit by the resistance of your measurement tool, making it impossible to measure the natural voltage of the circuit.[3] Similarly, to measure the voltage, we must put our measurement tool in parallel in the circuit, meaning the circuit must be altered to fork into the voltage meter before forking back into a single path. Although this measures the voltage well, the current in either half of the fork alone would not be representative of the current in the entire circuit. If you were to try to measure both current and voltage simultaneously, you would exaggerate both effects.

In short, it is impossible to measure both voltage and current in a circuit with arbitrary accuracy. They can be measured with *high* accuracy, but there will be imperfections in the combined measurements that can never be entirely eliminated.

4 The Heisenberg Uncertainty Principle and Measurements

It is not difficult to imagine that similar limitations as that on measuring voltage and current as described above would exist in other situations, as well. When you get down to the quantum mechanical level, in which distances and subjects are so incredibly small, it is not hard to imagine that there would be more significant limitations of this type.

Any time we take a measurement, we alter the subject of that measurement. In the case of subatomic particles, the effect is significant. As we've already deduced, elementary particles must have zero volume. There's not a microscope in the world that can magnify zero into something greater than zero, so we have to get creative if we want to determine where a particle is. We have to force it to interact with something else that has a known position and calculate where it is. In doing so, the interaction changes the energy of that particle, making it difficult to measure that particle's momentum with any accuracy. Similarly, if one attempts to measure the momentum of a particle, then one disturbs the position of the particle, limiting the accuracy of that measurement.

Werner Heisenberg[4] was the first to formulate a mathematical relationship

[3] Well made equipment can keep these distortions at very low levels, to the point where it's well below the threshold of the tools to measure, but all equipment has some impact.

[4] Unrelated trivia: Werner Heisenberg was the scientist in charge of the Nazi atomic bomb project in World War II. At one point, the Nazi project was more advanced than the Allied

that determines exactly how limited our measurements of related variables can get. The uncertainty principle he derived still bears his name.

The logic for the principle is pretty straightforward. If measuring the same two quantities in two different orders alters the results, then we can define that uncertainty in terms of the difference between these two orders. We look at the results if we measure position (x) first and momentum (p) second, and multiply them together. (For example, let's pretend this gave us measurements of 50 and 20 respectively, in some appropriate set of units, multiplying out to 1000.) Then, we look at the results if we measure momentum first and position second, and multiply those together. (For example, measuring 21 and 48 respectively, in the same units as our first pair, whatever they may be. These multiply out to 1008.) If we subtract these, we will then have some idea of the degree of our uncertainties. The difference between the two measurements is at least 8 (in appropriate units), so the average uncertainty in one pair of measurements is at least 4 (in the same units.) If our equipment is precise enough that we can measure position within 2 units, then our uncertainty in momentum must be at least $4 \div 2 = 2$ units. If our equipment can measure position within 1 unit, then our uncertainty in momentum must be at least $4 \div 1 = 4$ units. At this point, the principle is logical and easy to accept. There is one other aspect of the principle that tends to throw our instincts out of whack, however.

This is not just a limitation on our ability to measure particles, this is a limitation on the *existence* of subatomic particles. The reasons for this are, unfortunately, best left for later lessons.[5]

5 The Heisenberg Uncertainty Principle and Existence

We have already seen that radioactive decay involved a random element subject to well defined constraints. (i.e. any individual unstable particle may or may not decay at any given time, but the probability of the decay is defined well enough to produce a measurable half life.) That phenomena demands a level of random, uncertain behaviour crop up in the scientific theory itself. The Heisenberg Uncertainty Principle is what governs that behaviour. This explains why there

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project, but was abandoned when a test bomb failed to detonate. It was later shown that it failed because Heisenberg made a mistake in his calculations relating to the amount of radioactive fuel required, and the bomb only had 10% of the uranium required for proper detonation. It is still unclear whether or not this calculational error was accidental.

[5]The unfortunate part about trying to build a model of the Universe one block at a time is that the Universe has already been built and exists. All of the building blocks in the model already exist, and sometimes we hit phenomena in combinations that cannot be properly explained in a linear order. Be patient, and we *will* get there.

is random behaviour, why there are limits on how random that behaviour can get, and why we don't notice this behaviour during our day to day life.

Because the uncertainties in quantities are defined in pairs, there is always an indeterminate "wiggle room" for each individual measurement. The particles in question cannot be described in absolutes. They exist in an indeterminant state. That is why we can't predict exactly when an unstable particle will decay; the current state of any given particle is in flux. The flux is limited by the Heisenberg principle, and the limits of the Heisenberg principle are so tight that they are unnoticeable on normal distance scales. This seems to contradict one idea of science: we have always assumed that we can take measurements as precisely as we like (given proper equipment) and that we can then predict the future of a system with absolute certainty. We can't. This is not a limitation on modern technology, nor is it something which merely requires more research. This is the way our world works, like it or not. So, some might ask, what is the point of continuing if we can't make absolute predictions? Well, although we cannot measure within this range of random behaviour, we *can* measure the probabilities of the outcomes of this behaviour with all the accuracy we require. It is with this mindset that we can happily continue our research.

5.1 Philosophical and Theological Interpretations

The Heisenberg Uncertainty Principle is still a subject of debate. There are three different schools of thought that seem to prevail:

- Some people believe that events taking place within these limits is entirely random.
- Some people believe that there is nothing truly random going on, but that there are "hidden variables" within these limits that we can never measure, but which govern the results of these questions. This allows the Universe to remain a place of absolute rules, even if we can never access all of the information we need to act on all of those rules.
- Some people believe that this "uncertain realm" is the area in which the deity of choice steers the course of reality. Again, we'll never be able to directly measure what's going on in this realm, but the Universe is no longer random.

Due to the nature of the Heisenberg Uncertainty Principle, it is impossible for science to distinguish between these three viewpoints. The author's preference for the first interpretation will almost undoubtedly come through as a bias in the verbiage chosen, but this preference is a completely aesthetic choice. Each reader is encouraged to choose among these viewpoints, or to develop a new one, based on his or her own aesthetic preferences. In short, science and religion are, indeed, compatible, and neither science nor religion will ever be able to describe existence in its totality. No warranty is expressed or implied. Your mileage may vary.

6 Next time

Next week, we address three questions from our list:

1. How does information about particle positions get exchanged between particles? That would seem to violate energy conservation.
2. How are new particles created? *(The answer to this one is, at the moment, incomplete.)*
3. What force(s) do neutrinos experience?

The answers to these questions will, however, lead us to ask entirely new questions in the process.