The Big Questions
Spring 2008

Lecture Notes 3: Are There Parallel Universes?

1 The Level I Multiverse

Throughout these notes, I've been talking about this pretty big thing, called the "Universe." I discussed its history, its possible beginning and end, its size, and its shape. Just to recap: according to our standard picture of the Universe, which we've accumulated over the past century, the Universe *did* have a beginning — we call it "'Big Bang" — and it will have *no* end. It is also infinite and "flat." At the end of *Lecture Notes 2*, I briefly mentioned that if you think a little harder about what the Big Bang really *was*, you realize that that, in fact, we don't really understand it, because all of our best physics theories no longer work at the high energies assumed to be present at the Big Bang, and we don't yet know what the right theory to use to describe the Big Bang is. People have come up with theories to describe the very early Universe, but we don't know if they're right — they're plausible, but ultimately they need to be tested experimentally, which they haven't been yet. So, at this moment in time, in 2008, we currently don't know if the Universe had a beginning, although we think it won't have an end — all of our theories seem to say that.

In these notes, I'd like to describe some very interesting features that emerge with the assumption that the Universe that is infinite, or, at least, *very large* in size. For the remainder of these notes, I'll assume that the Universe *is* actually infinite — which it could very well be, and which all of our observations are consistent with — but the things which I'll describe will also be true in a universe that is not infinite but still sufficiently big.

In an infinite universe, the wildest things happen. Anything that *can* happen *does* happen. You can say that, if it doesn't happen here, it happens in a "parallel universe." I'll be more precise about what I mean by "parallel" and "universe" in a minute.

As I sit here typing these notes, it's quite possible I'll get bored and want to do something else, like walk over to the lounge watch TV. (In fact, there's a good deal of experimental evidence to support this.) So, if the Universe is infinite, then in a parallel universe I *do* do that! Fortunately, that's not this universe, so you get a full set of lecture notes instead!

Let me be a little bit more precise now. First, we must distinguish between the *whole* Universe and the *observed* universe[1] The whole Universe is exactly what it sounds like — it's the whole Universe! Unfortunately, we can't *observe* the whole Universe because light has only had a finite amount of time to reach us from wherever it's coming from since the Big Bang, which happened about 13.7 billion years. (Strictly speaking, it's the time of recombination that's important — not the Big Bang itself — but this is a detail.) However, we do observe all the light that *has* had time to reach us, and so we call all the points in space where light has had the time to reach us the "observed" universe. It forms a sphere around us. This sphere is actually increasing in size — for every year, light from even farther places has a little more time to reach us, and so it eventually does.

Now, in principle, the only things which we know for sure exist are the objects in the observed Universe — we can't directly see anything outside of it, because light from there hasn't had time to reach us, so it's logically possible that the Universe just *stops* at the edge of the observed Universe. In other words, it could be that the observed Universe *is* the whole Universe — that the whole Universe is a giant sphere centered around us. (And how delightful it is to be the center of the Universe!)

So, *can* we know if there's anything beyond the horizon which separates the observed from the unobserved? Well, as I discussed in *Lecture Notes 2*, none of our theories about the large-scale structure of the Universe predict a finite universe like this, *i.e.*, a finite universe with a boundary. Even the finite possibility that I talked about is different from this type of finite, where the Universe just stops. That type of finite is finite in the same way a sphere is — finite and closed, rather than finite with a boundary or a "stop sign." Furthermore, we now have very good evidence that the Universe is flat and infinite, or at least, very very large, much larger than the observed universe.

[1] More commonly, you'll hear the observed universe called the "observable" universe. I personally . . . add more later

So, even though we don't have direct evidence that the Universe doesn't just stop, we certainly have *indirect* evidence.

Now, according to our best theories on the early Universe, matter and energy were spread around pretty randomly right after the Big Bang to create all possible arrangements of matter — infinitely many times! More precisely, consider some kind of a box. (Add figure...) Say only 4 atoms can fit inside of it, so that they can only go in some "slots." How many possible arrangements of matter are there? Well, you can either have an atom here or not — so that's 2 possibilities for this slot. And there are 4 slots, so there are $2 \times 2 \times 2 \times 2 = 16$ total possibilities for this box. There are 16 different ways you can arrange matter in this box. Now you can consider a larger volume, say, with 10 slots — then there would be $2^{10} = 1,024$ possibilities. And you can think about even bigger boxes.

The point is that, in an infinite universe, these different arrangements eventually start to repeat themselves. And, in fact, they will repeat themselves infinitely many times. So, after the Big Bang, every possible arrangement of matter existed for any size of box you consider. Now, some arrangements of matter are very unlikely to form. For example, there is a slight chance that all the air molecules in the room will rush away from me, suffocating me in a gruesome death. It's very improbable that that will happen, but it's possible. In an infinite universe, everything that is possible happens. The probability of all the air rushing towards me might be something like one in a billion trillion trillion [actually, it's much, much lower]. But, if you considered a billion trillion trillion copies of this room, then you'd actually have a good chance of finding it happening eventually. And, if you considered more identical rooms, the chance is even higher. If you considered infinitely many rooms, then it has to happen — infinitely many times!

This means that all possible arrangements of matter are still present. If there was the slightest chance for one arrangement of matter to form into any other, then it would have happened, and it occurs in infinitely many regions in the universe. This also means that every possible "history" of an arrangement of matter has also happened. If there was a slight chance for some matter to do some thing, then it did. If there was a slight chance for some matter to do something else, then it did. Furthermore, every possible "future" of arrangements of matter will happen as well. More precisely, all possible arrangements that could be produced in all possible finite volumes of space were produced (infinitely many times!). Therefore, all possible arrangements still exist. Also, all possible histories of these volumes of space have occurred (and all possible futures will occur), where “history” (and “future”) can simply be understood to refer to the motion of the matter present inside the volume.

This makes sense: it’s as though you started off with many shuffled decks of cards and then just kept individually shuffling them — after you’ve done this many times, they’ll still all be quite shuffled. Here each deck corresponds to a particular arrangement of matter inside a particular volume, and one shuffle corresponds to a small amount of time passing by in the universe: shuffle the deck and you change the arrangement. Since there are so many volumes, this means that at any given moment of time, you’re bound to find a particular arrangement of matter inside some volume; because there are infinitely many volumes, youll find that particular arrangement of matter inside infinitely many volumes. You can also imagine how any possible set out of outcomes of the shufflings would arise from numerous shufflings. This corresponds to all “histories” of a volume playing out.

So here we are, in an infinite Universe where all possible arrangements of matter with all possible histories and futures occur infinitely many times. This realization leads to some quite profound and counter-intuitive conclusions. For example, according to the modern scientific understanding of biology, we humans are nothing but a particular arrangement of various molecules, which are in turn some particular arrangement of various atoms, which in turn are some particular arrangement of fundamental particles like electrons and quarks. It’s true that those particles are arranged in an enormously complex way — somehow intelligence, consciousness, etc. emerge from them — but in principle you could be described completely in terms of them. Thus, your arrangement of matter will eventually repeat itself infinitely many times, and so the universe is filled with infinitely many clones of you (and me)!

Now, they’re not really “you”; *you’re* you. But they are copies (or “counterparts”) of you that think the same way that you do, that like the same kinds of food as you, and that even have the same memories of you. However, while in our universe you may grow up to be a doctor, a counterpart of you may grow up to be a physicist. If there’s the slightest chance that this would happen our universe, then it does happen in another universe. (Of course, it may very well happen in our universe as well.)

The set of all these universes I just described form what’s called the Level I multiverse. It arises simply by assuming an infinite universe where all initial conditions occurred. And these are reasonably uncontroversial assumptions.

2 The Level II Multiverse

The idea that you and I and the observable universe have an infinite number of clones in the universe certainly sounds strange, but the Level I multiverse is actually the *least* controversial level thats been proposed[2] Whereas the universes that compose the Level I multiverse differ in their initial conditions (i.e., initial arrangements of matter and energy), the universes that make up the Level II multiverse differ in their physical *constants* and spacetime *dimensionalities*. Some universes have 5 space dimensions and 14 time dimensions, in some the speed of light is only 25 mph, and in others the electron has the same mass as a rhinoceros in our universe. All of this, of course, sounds crazy, so why should we even consider it?

Well, the reason is that all of these scenarios are a consequence of a certain model of the universe which predicts many things quite accurately. And when one has model that makes so many successful predictions, one should at least suspect that other predictions the model makes — radical though they may be — might be true. The model I'm referring to here is called chaotic eternal inflation, which is a modification of the standard Big Bang theory. "Inflation" refers to an extremely fast stretching of space, caused by really weird particles that were present in the very early universe. These particles actually had *repulsive* gravity; we are used to thinking of gravity as always being attractive, but in our high-energy particle physics theories, particles can actually emerge which gravitationally repel one another. It turns out that by hypothesizing such a process, one can answer a number of seemingly impossible questions — for example, why is the universe so large, and why is it so uniform?

Several versions of inflationary models have been proposed. In the so-called chaotic eternal inflation model, the whole universe is expanding and will do so forever. But because of "quantum fluctuations," some regions of space eventually stop expanding and then develop into "island universes," each of which is a (possibly infinite) Level I multiverse! Furthermore, through a process called "symmetry breaking" (which is also a result of quantum fluctuations), the Level I multiverses will develop with a distribution of physical constants and spacetime dimensionalities. This ensemble of Level I multiverses forms the Level II multiverse.

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[2]By the way, the classification of "levels" of multiverses as I'm describing them is due to Max Tegmark. See, for example, his Scientific American article *Parallel Universes* (2003).

So, what are these parallel Level I multiverses like? Well, if you make the assumption that the laws of physics are the same for each multiverse, but simply change some parameters, you can actually answer that question by working through the equations and deriving what would happen. For example, it can be shown that in a world completely identical to us in every way except for having one extra time dimension, events would be completely unpredictable — every prediction you made about the outcome of an experiment would necessarily have an infinite error bar attached to it. In a world where there are 5 space dimensions and 4 time dimensions, atoms couldn't exist; they would decay in a split second. In a world where the electromagnetic force is stronger than the strong nuclear force, carbon would be unstable.

In fact, our Level I multiverse seems uncannily fit for life — it has just the right constants and dimensionality. People have been puzzled over this for a long time: why these constants and not others? Well, the chaotic eternal inflationary model of the universe (well, Level II multiverse) finally gives an answer. First, we shouldn't be surprised to find ourselves in a multiverse we're able to inhabit, because if it were otherwise, we would not be here! Second, Level I multiverses with other constants do exist. However, intelligent life simply does not arise in the vast majority of these multiverses, because the constants aren't suitable, the dimensionality isn't suitable, and so on. Only in those with the right combination of physical parameters can intelligent life develop.

Many people, however, don't like this answer and consider it somewhat of a cop-out. Many people feel that all of the physical parameters of our universe should be *derivable* from fundamental principles, not the result of some kind of random process. I won't say more about this debate, but it's an important one.

3 The Level III Multiverse

Yes, there are more levels to the *whole* Universe. The Level III multiverse is a consequence of the so-called "many-worlds interpretation of quantum mechanics, which in itself actually isn't so weird. Quantum mechanics is the theory that was developed in the 1920s that has proven enormously successful in describing the very small. It is one of the two most successful physics theories ever proposed (the other being general relativity, which I talked about last time). Now, although quantum mechanics has really only been tested on small things, it's reasonable to think that it applies to bigger things. After all, bigger things are made up of smaller things! So, in principle, not just atoms and electrons are describable by quantum mechanics. Dogs, cats, humans, and even the *Universe* should in principle be describable by quantum mechanics.

Now, according to quantum mechanics, there's a fundamental random aspect to nature. It's impossible to know, even in *principle*, what the result of a given measurement will be. You can calculate probabilities of certain things happening — and, in some cases, these probabilties may be very high (for example, if I drop a chalk, it will very probably fall down) — but you generally never know for sure what will happen. Now there's a tool in quantum mechanics to calculate these probabilities, and it's called the "wavefunction. The wave function tells you the probability that you'll measure a given thing, like the probability you'll measure an electron to be over here. However, there's nothing random about how this wave function changes in time; there's a simple equation (called the Schrodinger equation) which says how it changes. The wavefunction changes in time in a completely predictable way. However, once you make a measurement on an object, the object's wavefunction is said to "collapse," and the result of the measurement is not known with complete certainty. This collapse underlies the random aspect of quantum mechanics.

This is the traditional way of thinking about how things change according to quantum mechanics. The collapse itself is not described much more than how I just described it. In this view, measurement is an extremely peculiar process, and mathematically it's very different (and far less elegant) than the simple evolution of the wavefunction. Well, this "collapse" that I referred to has been confusing physicists for a long time, and people have tried for years to understand the true nature of measurement.

In the 1950s, an alternative interpretation of quantum mechanics was proposed, and today it's known as the many-worlds interpretation. The many-worlds interpretation of quantum mechanics does away with this collapse postulate. It holds that theres only *one* process that occurs in nature — time evolution of the wavefunction according to Schrdingers equation. Measurement in this view is still rather complicated (hey, the world is a complicated place!), but it is process which is understandable.

Now, in both the traditional and the many-worlds interpretations, there exist states of systems called superpositions. These are kind of like mixtures of different states. For example, a cat being alive is one state of a cat, the cat being dead is another state, and, interestingly, the cat being alive and dead at the same time is another! [3] Whats different between the two interpretations is what happens to the cat in the superposition of dead and alive states once you actually measure the cats “aliveness” or “deadness.”

In the traditional interpretation, you measure the cat to be either alive or dead; the original superposition collapses either into an alive state or a dead state, and the superposition is gone. [4] However, in the many- worlds interpretation, although youll measure the cat to be either alive or dead, in reality — the reality defined by quantum mechanics — the cat will remain in the superposition. You, a subjective observer, merely perceive the cat to be in one of the two states; you perceive a “classical” reality.

Suppose you measure the cat to be alive. According to the many-worlds interpretation, in another “universe” you will measure the cat to be dead. Furthermore, the totality of the quantum object that is “you” is really a superposition of many states, corresponding to different possible subjective realities which you had the possibility of experiencing, had you made different decisions from the ones you did. Indeed, in other universes, you did make other decisions, and the “you”s in those universes are quite different from the “you” in this universe. As Tegmark says, “every conceivable way that the world could be (within the scope of quantum mechanics) corresponds to a different universe.”

These universes differ from the universes of the Level I and Level II multiverses in that theyre really members of the abstract quantum space of the whole universe, by which I mean all of the Level II multiverses. In fact, superpositions associated with Level II multiverses do occur, according to many-worlds quantum mechanics. The set of all these superpositions is the Level III multiverse.

Note that what you perceive in a Level III multiverse actually isnt dif-

[3] This is related to the famous “Schrodinger cat” (thought) experiment, which describes how to actually get a cat into such a superposition. The way you do this is you find a cat, put it in a box, and also put some radioactive poison in the box. Now seal the box, so that you have no knowledge of whether the poison has decayed. Suppose that, within a given hour, the poison has a probability of 50% of decaying. Then, an hour after youve sealed the box, the cat will be in an equal superposition between the alive and dead states.

[4] Thus, if you measure the cat to be dead, one could accuse you of killing the cat by measuring it. This is one of the many reasons we must always distinguish between real experiments and thought experiments.

ferent from what youd perceive if many-worlds quantum mechanics werent true. (And we dont know that its true, by the way, but experiments are in very good agreement with it.) In both the traditional interpretation and the many-worlds interpretation, youll still perceive a classical reality, which is merely a small part of the true quantum reality.

Think about that tonight.

4 The Level IV Multiverse

At last we reach the highest level multiverse— in fact, the theoretically highest level. Recall that the Level I universes differ from one another because they had different initial conditions. The Level II universes differ from each other because they have different spacetime dimensionalities and other physical parameters. And the Level III multiverse is simply many-worlds quantum mechanics applied to the Level II multiverses (which contain the Level I multiverses). Nevertheless, strikingly different though may seem, the laws of physics of all these universes are the same. This immediately begs the question: what if we consider universes with different *laws of physics*?

For example, maybe in another universe classical physics is sufficient to describe the world. Or maybe there's a universe where a Flying Spaghetti Monster was responsible for the creation of humanity. It's been said that gravitation is not responsible for people falling in love. Perhaps there's a universe where it is. All of these possibilities are realized if our (Level III) universe is but one of many universes composing a Level IV multiverse. The Level IV multiverse is a consequence of a very simple postulate (proposed by Tegmark):

All structures that exist mathematically also exist physically.

Mathematical structures are abstract objects, like the set of real numbers, or a triangle; they're sets of entities with relations among the entities. The laws of physics are described by mathematical structures. General relativity, for example, is described the mathematics (differential geometry) of curved higher-dimensional spaces. And quantum mechanics is described by linear algebra (if you know what that is). According to the above postulate, not only is the universe *described* by mathematical structures — the universe *is* a mathematical structure. We don't know exactly what mathematical structure our universe is, because we dont yet have a theory combining general relativity and quantum theory, but we do know that it is approximated by the structures of general relativity and quantum mechanics. The hope is that some day a "theory of everything" will be discovered, thereby unraveling the mathematical structure that is our universe. (Some feel, for example, that string theory may one day develop into this theory of everything. I'll say more about this in *Lecture Notes 7*.)

Now, just as you can ask about the constants and spacetime dimensionalities of our universe, so you can ask: why is our universe this mathematical structure and not some other structure? Equivalently, why does our universe obey these laws of physics and not others? According to Tegmark's postulate, all structures exist both mathematically and physically. So, only in mathematical structures which are complex enough to contain "self-aware substructures" will there be any subjective appearance of physical reality. We just happen to be in such a structure. As you can imagine, the Level IV multiverse is the most controversial of the levels. However, it does rather elegantly provide an explanation as to why our universe is described by a particular set of laws and not others, and it does provide a very pleasing closure to the multiverse levels.