Note: A good portion of these notes and the lecture are based on Max Tegmark's *Scientific American* article "Parallel Universes" (2003), which I highly recommend to everyone!

Parallel Universes

One of the niftiest things about quantum mechanics is that it allows, via quantum tunneling (described in the Quantum Notes and in the lecture), many seemingly impossible events to occur, like walking through a brick wall, surviving after getting shot in the face, and meeting the girl of your dreams. Continuing on the theme of "possibility," these notes describe parallel universes, in which even *crazier* things are possible.

The Level I Multiverse

What do I mean by "parallel universes"? Well, first, we need to distinguish between the *whole* universe and the *observable* universe. Because the Big Bang occurred only a finite amount of time ago (approximately 14 billion years), light has simply not had the time to reach us from all the points in the universe. The points where light has had the time to reach us form the observable universe, and this is what we mean when we speak of "our" universe.

Now, strictly speaking, the only things which we know *for sure* exist are the objects in *our* universe – we can't directly observe anything in the unobservable universe, so how could we know if there's anything beyond the horizon which separates the observable from the unobservable? The key word here is "directly." One could ask if there exists any *indirect* evidence which points towards either direction. Well, it turns out there is!

By studying the radiation known as cosmic microwave background – certain microwaves which are relics of the Big Bang and which arrive at us from *everywhere* in space, regardless of where you point your telescope – cosmologists have been able to test (in quite amazing ways, which I can't go into here) various models of the *whole* universe. For instance, one could postulate that the universe is finite and has the geometry of a 4-dimensional sphere, which would mean, for example, that if you traveled in any one direction long enough, then you'd eventually return to your initial spot. (Think about little ants walking along the surface of a balloon and eventually returning to their initial spot – then mentally increase the dimension by one. Unfortunately, the only way we can "visualize" higher-dimensional objects is by appealing to analogies like this.) Or the universe could by finite and shaped like a donut. Or it could be infinite and shaped like a plane; such a universe would then be infinite and *flat*. In fact, predictions made with the flat infinite models of the universe fit the CMB data extremely well, so it looks as though the universe is infinite – there exist stuff past the horizon!

Now, according to modern theories of the early universe, processes shortly after the Big Bang randomly spread matter (and energy) around to create all possible arrangements of matter – infinitely many times! 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, you'll 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, "you" are nothing but a particular arrangement of various particles.* 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, so the universe is filled with infinitely many clones of you (and me)! Also, infinitely many such clones of you with infinitely many different histories (infinitely many of which were the same as yours) are to be found! So, while in this universe you may live to be 84 and have a life of somewhat-above-average interestingness, involving, say, financial engineering, in another universe you lived to be 97 and had an *extraordinarily* interesting life, working as physicist during the day and a secret agent during the night.

(*Footnote: At least, this is the "materialist" viewpoint of the world which physics takes; for those who don't subscribe to it, the conclusions regarding humans won't apply. (One must, of course, always be politically correct.)

The set of all these "universes" described form the *Level I multiverse*. It arises simply by assuming an infinite universe where all initial conditions occurred.

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 that's been proposed. 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 occurred in the very early universe. 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 an (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*.

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 fitted 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? 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, by the considerations of the previous paragraph, intelligent life simply does not arise in the vast majority of these multiverses. Only in those with the right combination of physical parameters can intelligent life develop.

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. Recall that in quantum mechanics the state of an object is described by an abstract wavefunction. This state evolves deterministically in time – so that, for example, the probability distribution of where you'll find an electron changes in a predictable manner – according to an equation called the Schrödinger equation. However, once you make a measurement on the object, its wavefunction is said to "collapse," and the result of the measurement is not known with complete certainty.

This is the traditional way of thinking about how things change according to quantum mechanics. The collapse itself is not described in 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 a quantum state that the Schrödinger equation gives.

The many-worlds interpretation of quantum mechanics does away with this collapse postulate. It holds that there's only *one* process that occurs in nature – time evolution of the wavefunction according to Schrödinger's 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, "superpositions" (which are kind of like mixtures) of states are as perfectly good states as the states which make up the superpositions; i.e., the superpositions are also "physically real" 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!* [*Footnote. This is related to the famous "Schrödinger 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 you've sealed the box, the cat will be in an equal superposition between the "alive" and "dead" states.] What's different between the two interpretations is what happens to the cat in the superposition of dead and alive states once you actually *measure* the cat's "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. (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.) However, in the many-worlds interpretation, although you'll 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 they're 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 isn't different from what you'd perceive if many-worlds quantum mechanics weren't true. (And we don't know that it's true, by the way, but experiments are in pretty good agreement with it.) In both the traditional interpretation and the many-worlds interpretation, you'll still perceive a classical reality, which is merely a small part of the true quantum reality.

Think about that tonight.

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).

Well, 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 don't 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.)

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.

(And, of course, it goes without saying that the Level IV multiverse is very fun to think about!)