What is the difference between classical physics and quantum physics?

1. Classical physics is causal; complete knowledge of the past allows computation of the future. Likewise, complete knowledge of the future allows precise computation of the past. (Chaos theory is irrelevant to this statement; it talks about how well you can do with incomplete knowledge.)

Not so in quantum physics. Objects in quantum physics are neither particles nor waves; they are a strange combination of both. Given complete knowledge of the past, we can make only probabilistic predictions of the future.

In classical physics, two bombs with identical fuses would explode at the same time. In quantum physics, two absolutely identical radioactive atoms can and generally will explode at very different times. Two identical atoms of uranium-238 will, on average, undergo radioactive decay separated by billions of years, despite the fact that they are identical.

There is a rule that physicist often use to separate classical physics from quantum. If Planck's constant appears in the equations, it is quantum physics. If it doesn't, it is classical physics.

Most physicists believe that quantum physics is the right theory, even though many details are yet to be worked out. Classical physics can be derived from quantum physics in the limit that the quantum properties are hidden. That fact is called the "correspondence principle."

2. Quantum physics is the revolution that overthrew classical physics. Describing the difference between them is like describing the difference between the Bolsheviks and the Tsars. Where do we even begin?

On the one hand, we have the Newtonian picture of a clockwork universe. In this paradigm, all of physical reality is a giant machine that ticks forward in time, changing its configuration predictably according to deterministic laws. Newton saw his god as a mathematician who constructed the cosmos out of physical elements, setting them in motion according to a small set of simple mathematical laws. These laws are ultimately responsible for all the complexity and diversity of natural phenomena. Likewise, all phenomena, no matter how complex, can be understood in terms of these simple laws. "All discord," wrote Alexander Pope, is "harmony not understood."

On the other hand, we have the quantum universe, which from our perspective, seems to resemble more of a slot machine than a clock. In the quantum universe, we see the machinery as fundamentally probabilistic. If there is harmony underlying quantum discord, it is inaccessible to the experimenter.

In fact, the quantum revolution goes much deeper than merely introducing probability as a fundamental feature. It altogether trashes the Newtonian clock, replacing it with a completely alien device built out of much more advanced mathematics. The quantum revolution tells us that the classical perspective isn't just wrong, it is *fundamentally unsalvageable*.

Lets proceed by discussing some Newtonian components to be thrown in the trash:

1. **Particles and fields possess well defined dynamic variables at all times**. Dynamic variables are the quantities used to describe the motion of objects, such as position, velocity, momentum, and energy. Classical physics presupposes that the dynamic variables of a system are well defined and can be measured to perfect precision. For example, at any given point in time, a classical particle exists at a single point in space and travels with a single velocity. Even if the exact values of the variables are uncertain, we assume that they exist and only take one specific value.
2. **Particles as point-like objects following predictable trajectories**. In classical mechanics, a particle is treated as a dimensionless point. This point travels from A to B by tracing out a continuous path through the intermediate space. A billiard ball traces out a straight line as it rolls across the table, a satellite in orbit traces out an ellipse, and so on. The idea of a definite trajectory presupposes well defined dynamic variables, and so once the first point above is abandoned, the idea of a definite trajectory must be discarded as well.
3. **Dynamic variables as continuous real numbers**. In classical physics, dynamic variables are smoothly varying continuous values. Quantum physics takes its name from the observation that certain quantities, most notably energy and angular momentum, are restricted to certain discrete or 'quantized' values under special circumstances. The in-between values are forbidden.

4. **Particles and waves as separate phenomena**. Classical physics has one framework for particles and a different framework for waves and fields. This matches the intuitive notion that a billiard ball and a water wave move from A to B in completely different fashions. In quantum physics however, these two phenomena are synthesized and treated under a unified, magnificent framework. All physical entities are particle/wave hybrids.
5. **Newton's Second Law**. Without the four kinematic features mentioned above, $\sum F=ma\sum F=ma$ is more than wrong, it's nonsensical. A radically different dynamics must be developed that is governed by a very different equation of motion.
6. **Predictability of measurement outcomes**. In classical physics, the outcomes of measurements can be predicted perfectly, assuming full knowledge of the system beforehand. In quantum mechanics, even if you have full knowledge of a system, the outcomes of certain measurements will be impossible to predict.

With the above list in mind, its no wonder that quantum mechanics took an international collaboration several decades to develop. How do you build a coherent model of the universe without these features?

Well, thankfully, not quite *everything* from classical physics had to be scrapped. The conservation laws are preserved (or Great Conservation Principles as Feynman called them, always capitalized to highlight their centrality to all areas of physics). Quantum physics conserves things like momentum, energy, and electric charge as perfectly as classical physics.

Also, while Newton's formulation of classical mechanics is completely abandoned, the conservation laws encourage us adapt tools from the more mathematically elegantHamiltonian and Lagrangian formulations of classical mechanics. Erwin Schrodinger chose to adapt the Hamiltonian formalism which led to his eponymous equation. Richard Feynman adapted Lagrangian mechanics which led to his path integral formulation. Heisenberg developed his own esoteric approach called matrix mechanics.

All three approaches to quantum mechanics are mathematically equivalent and useful in their own right (there's more than three, but these are the standard formulations). Schrodinger's formulation of quantum mechanics is usually the one everyone encounters first, and his is the formalism most widely used in the field. So lets go back through the list above, and replace Newton's components with Schrodinger's:

1. **Particles possess a wave function** $\Psi(x,t)\Psi(x,t)$ **at all times.** The wave function assigns a complex number to each point in space at each moment in time. This function contains within it all available information about the particle. Everything that can be known about the particle's motion is extracted from $\Psi(x,t)\Psi(x,t)$. To recover dynamic information, we use Born's rule and calculate $\Psi\Psi*\Psi\Psi*$ to get the probability density of the particle's position, and we calculate $\phi\phi*\phi\phi*$ to get the probability density of the particle's momentum, where $\phi(p,t)\phi(p,t)$ is the Fourier transform of the wave function. This is a radically different approach to kinematics than in classical mechanics, which describes particles by listing off the values of the dynamic variables.

2. **Trajectories are replaced with wave function evolution**. As the wave function changes in time, so do the probabilities of observing particular positions and momenta for the particle. The evolution equation is the time-dependent Schrodinger equation: $i\hbar\dot{\Psi}(x,t)=H\Psi(x,t)i\hbar\dot{\Psi}(x,t)=H\Psi(x,t)$. HH is the Hamiltonian operator for the system, i.e. the self-adjoint operator corresponding to the total energy of the system (described in point 3 below).
3. **Dynamic variables are Hermitian matrices**. Instead of real-valued, continuously evolving dynamic variables, Schrodinger uses fixed Hermitian matrices (or self-adjoint operators) to represent observable quantities. Each observable such as position, momentum, energy, etc has a corresponding matrix/operator. The eigenvalues of the matrix/operator determines the allowed values of the corresponding observable. The energy levels of atoms, for example, are eigenvalues of the Hamiltonian operator. This is another completely radical shift from how classical physics treats motion.
4. **Unification of particles and waves**. A mathematical analysis of the Schrodinger equation reveals that it has wavelike solutions, and so particles propagate as waves. This means that we shouldn't picture particles as tiny spheres bouncing around their environment. The closest you can get to visualizing a particle is by visualizing its wave function. As stated previously in the first point above, the wave function assigns a complex number to each point in space. This field of complex numbers evolves in time. *What does this evolution look like?* Well, if you are familiar with phasors, it looks like a field of rapidly rotating phasors (excellent visualization). To be more specific, the field of phasors for a particular particle looks like a screw that twists in the direction of motion.
5. **The time-dependent Schrodinger equation replaces Newton's second law**.
6. **Measurement is random**. Even if you have full knowledge of a quantum system prior to measurement (i.e. you know $\Psi(x,t)\Psi(x,t)$), you still will not be able to predict the outcomes of measurements in general. The outcome of the measurement is probabilistic. The possible outcomes are determined by the eigenvalues of the operator you are observing (see point 3), and the probability of each outcome is determined by the projection of the wave function onto the eigenvectors of that operator.

So this is a sketch of what Schrodinger's quantum mechanics looks like. Alternate formulations would have different details, but the gist is the same.

Hopefully it is now clear that the differences between classical physics and quantum physics are vast. The quantum revolution is really one of the most stunning intellectual developments of the 20th century, and in many ways the effects of the revolution have yet to be fully felt. Quantum computing, for example, is one ramification that hasn't quite yet materialized. The philosophical and technological ramifications will most certainly continue to transform the 21st century in extraordinary ways.

3. I am going to make this as simple as possible and not throw a lot of math at you.

In classical physics, there is an "in-principle" determinism. If you had N atoms of neon in a gas canister, and you knew the position, and momentum of every one, *in principle* you could describe the history fully for all time.

That doesn't mean that you can't use statistical methods or treat the motions as random (to treat them deterministically you'd need to keep track of 6N numbers as a function of time!). And in fact, such methods are extremely useful in classical physics. It just means that there are exact knowable properties such as position and momentum that are measurable to any accuracy, independent of the process of observation.

In classical physics, things like electrons and atoms were supposed to be treated as strictly particles, and things like light and other forms of electromagnetic radiation treated strictly as waves. (It turns out that there are a *lot* of things that happen with light and electrons that cannot be properly explained in classical physics!)

Classical physics. Each particle has an exact position and momentum. The pool table has an almost completely uniform coefficient of friction, and the collisions are approximately elastic. True, some of the tricks with backspin appear a little freaky....

In quantum physics, there properties such as position and momentum that are NOT measurable to any accuracy, independent of the process of observation. Specifically in the case of position and momentum, there is a limit on how accurately you can measure both at once.

You can think of a particle as being described as a wave, which encodes the probability of making a specific measurement. Possible observations are determined by the probabilities, and are not determinate. There is no "trajectory" between subsequent observations.

The variation becomes significant on the atomic scale and below. Large macroscopic objects that have, say maybe 7,000,000,000,000,000,000,000,000,000 atoms in them, like you and me, can have variations due to quantum uncertainty that are such a tiny fraction of them, they can effectively be treated as classical objects for almost all purposes. Indeed, the formula for the wave associated with a human body, or a pool ball or table, gives a wavelength that is so incredibly short, that the quantum calculations approximate the classical ones for these large objects to a tremendous degree of accuracy.

The double slit experiment. A wave that strikes a surface with two small nearby openings will interfere with itself, producing interference fringes. In this video electrons are fired at a pair of slits one at a time. Electrons are definitely particles! Yet, the electrons don't seem to follow a definite trajectory, and show up randomly. When a lot have been transmitted, they form interference fringes!

4. Classical physics took form when Newton developed his theory of gravity and the mathematics we commonly known as calculus. Newtonian physics were three dimensional: width, height and depth, Energy comes in tiny lumps, in packets whereas a single packet is a quantum and Planck's ideas were soon called the "quantum theory." Quanta can behave like particles and quanta can behave like waves. It seems counter-intuitive, but, light can be both particles and waves and the difference depends fundamentally on how it is studied.

5. There is a huge difference between Classical and Quantum Theory.

1. In classical theory, a body always chooses the least action path and there is only one path. In Quantum theory, a particle also always chooses the least action path and it chooses multiple least action paths simultaneously.

2. If there are 9 boxes and 10 pigeons, then at least one box will end up with two pigeons. This is in Classical Theory. No such thing happens in Quantum Theory. We can pass infinite electrons just from two boxes.

3. We can determine position and velocity of a particle simultaneously with great accuracy in Classical Physics. Quantum Physics follows the Heisenberg Uncertainty Principle.

4. Classical Physics is applicable to macroscopic particles. Quantum Physics is applicable to microscopic particles.

6. Here's a simple analogy.

Suppose you are playing squash with a sponge ball. And you wish to build a machine that can play it with you, the first thing you would need is to mathematically model the mechanics of the sponge ball so that you can incorporate it in the design of the machine. For this a classical model would suffice.

Now lets go quantum, if you want to replace the sponge ball with an electron, the classical model of a sponge ball breaks apart.

First of there is no deterministic way of knowing the location of the ball before it hits your bat. Then there is a probability that it will tunnel through your bat even if you got it right. So we have just started with the long list of phenomenon unseen in classical mechanics. These phenomenon are modelled into the mathematics in QM and for a probabilistic theory it does explain why things happen beautifully.

The problem however is that with this new model, the world looks like a much stranger place. The ball is no longer a ball anymore, but an eigenvalue in a wave equation. It's nothing like the world that we are familiar with. This posts interesting puzzles on what the mathematics mean. It's both mind bending and confusing to visualize yet so intriguing because it's very counter intuitive.