Fundamental Physics and the Nature of Reality – Part 3
Quantum Mechanics

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Preamble

In the last block we explored the picture of physics that we get when we leave Newtonian physics behind and head for first high speeds (Special Relativity) and then the largest spatial and temporal scales (General Relativity and Cosmology). Now we head in the opposite direction, investigating the even stranger world we encounter when we look at the world on the very smallest scales.

Quantum Mechanics is remarkable in being hugely successful as a physical theory at the same time as its fundamental objects are barely understood, or even discussed. Here we have a theory which can be firmly divided into two areas, namely a particularly successful set of mathematical techniques, and a much more troublesome set of philosophical questions, which reach to the very heart of the problem 'what is the world *really* like?' I'll first give you an overview, of the phenomenology of quantum mechanics – what it says happens in the world. This is puzzling enough, but I'll then move on to talk about what this seems to tell us about the natural world, and address the question: just what *is* the quantum world made of?

In this block, I will concentrate exclusively on *non*-relativistic quantum mechanics, rather than its relativistic counterpart, Quantum Field Theory. This is the extension of quantum mechanics which brings it into conformity with Special Relativity, and which underlies our understanding of fundamental particle physics. I have done this, not only because field theory is more difficult to talk about, but also because the real puzzles about our world can be satisfactorily and clearly exposed by quantum mechanics. I could not leave such a topic out entirely, however, so in Sect. 3 I describe the view of the world which modern particle physics gives us.

Physicists often talk of beauty and simplicity as guides in evaluating mathematical theories. This may seem odd to you, but it is why I have repeatedly emphasised the simplicity of Special Relativity in being derived from a single pair of axioms, and why I emphasise the almost equal simplicity of quantum mechanics below. This simplicity comes at a cost, however, as the few fundamental ideas involved in a 'simple' theory are almost inevitably very distant from our everyday experience.

1 Quantum Theory

1.1 Introduction

In 1901, Lord Kelvin remarked[1] that “The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds. I. The first involves the question, How could the earth move through an elastic solid, such as essentially is the luminiferous ether? II. The second is the Maxwell-Boltzmann doctrine regarding the partition of energy.”[2] The first of these problems concerned theoretical and practical difficulties with the assumed properties of the ether, which was assumed to exist in order to allow light waves (newly described by James Clerk Maxwell) to have a medium though which to propagate; a complex of problems related to this were only resolved by Einstein’s special theory of relativity, first published in 1905.

The second complex of problems also involved light: Kelvin’s remarks refer, amongst other things, to the failure of thermodynamics and classical statistical mechanics to account for the spectrum of black-body radiation, which is the spectrum (how much red, how much blue, how much ultra-violet, and so on) of the light given off by an idealised object heated until it glows. This may seem an uninspiring problem, but its fundamental aspects led the greatest physicists of the time to make contributions to its solution. The contribution we are most concerned with is Max Planck’s huge intuitive leap that “energy is forced at the outset to remain together in certain quanta.”[3] This assumption, that energy may take only certain values, rather than the continuum assumed by classical electrodynamics, made Planck very uncomfortable, and he did not regard it, at the time, as having much physical significance: “This was purely a formal assumption, and I did not give it much thought except that no

[1] Philosophical Magazine (6) **2**, 1 (1901)

[2] The situation in physics at the end of the ninteenth century was not, in fact, quite as clear at this remark might suggest. Although Thermodynamics, Classical Dynamics and Maxwell’s Electromagnetism are particularly successful theories, and we can now see that they can gracefully account for most of the observed physics of the ninteenth century, there were sufficient problems with them that there was no such consensus amongst physicists of the time; indeed there was not even an consensus that objects like atoms really existed. Nonetheless, the remark *does* neatly illustrate the points where ninteenth century physical theories run out of steam.

[3] Planck, writing in a letter to R. W. Wood in 1931

matter what the cost, I must bring about a positive result.”

The historical development of Quantum Mechanics is very interesting, but having set its beginnings in context, we shall largely skip over the contributions of Einstein, Bohr, Schrödinger and Dirac, and describe some of the mechanics of quantum theory.

I will describe quantum mechanics by describing a series of measurements one might make, with a collection of ordinary Polaroids, on photons. Remember that most of what I have to say also applies to other quantum mechanical particles; I am going to talk about photons because (i) they illustrate the behaviour of quantum-mechanical particles whilst being relatively familiar, and (ii) the quantum mechanical explanation of their behaviour can be usefully contrasted with the classical description. Before I describe the quantum mechanical interpretation of these measurements in Sect. 1.4, however, I will describe how they are understood classically.

1.2 Classical polarization

Light, in classical electrodynamics, is a combination of oscillating electric and magnetic fields. Vertically and horizontally polarized light is understood classically as having the electric field oscillating in a vertical and a horizontal direction, respectively. We can manipulate and detect the polarization of light using a piece of Polaroid, which is an otherwise transparent film coated with a polymer which absorbs one polarization and not the other. Light polarized in any arbitrary direction can be regarded as composed of appropriate components of vertical and horizontal polarization, so when this light is shone on a Polaroid set to transmit only vertically polarized light, only this component will go through, and the light on the far side of the Polaroid will be purely vertically polarized, and of lower intensity. As Fig. 1 demonstrates, this means that (unless the light falling on a polarizer happens to be perpendicular to the transmission axis of the Polaroid) the light leaving a polarizer is always aligned along the transmission axis.

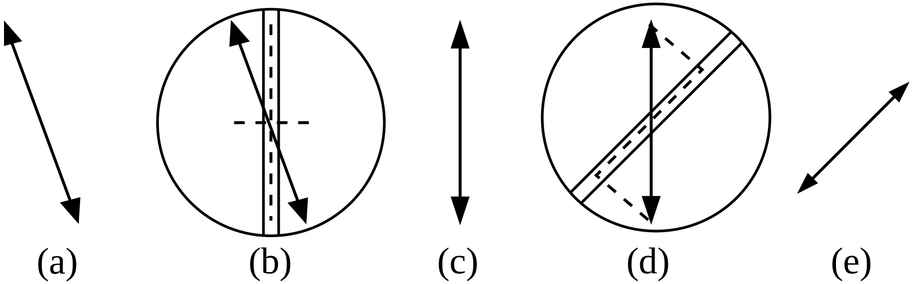

Figure 1: Classical polarization. Light of an arbitrary polarization (a) falls on a polarizer (b), which is set to allow only the vertical component of the light to go through, so that the light on the far size of the polarizer (c) is vertically polarized, and of slightly lower intensity. This light then falls on a polarizer (d) set to allow only that component of the light which is polarized at 45^o to pass through, so that the light on the far side of *that* polarizer (e) is polarized in that direction, and of lower intensity again.

1.3 From classical to quantum mechanics

The description of classical polarization that I gave above included features, such as the notion of a directional electric field, or of resolution into components, which are possibly new to you. It does not, however, include features which are fundamentally antagonistic to our normal understanding of how things behave in the world. There are two features of the quantum world which readily distinguish it from the classical one.

1.3.1 Positivism

Positivism is the philosophical notion that we can know nothing of the world other than the results of our measurements on it; that is, that we can know nothing of any underlying reality, which it is therefore meaningless to talk of. It was developed towards the end of the ninteenth century, though it has antecedents in Hume in the eighteenth; and it influenced Einstein to some extent, and is related to the concentration on observers' *measurements* with clocks and rulers in special relativity. Quantum mechanics may be described as a positivist theory since, depending on the interpretation you choose, you may either say that one *may not* discuss the physical properties of an object independently of the measurement of them, or take the more extreme position that there is nothing to discuss – that an object simply *does not have* any properties independently of measurement. If this were all the difference between classical and quantum physics, however, the latter would not be nearly so strange.

1.3.2 Quantum measurements

When we make a classical measurement, perhaps measuring the temperature of the coffee in my cup, we make two assumptions. Firstly, we assume that in principle the measurement need not affect the quantity being measured; although measuring the temperature of my coffee with a cold thermometer would cool the coffee down, we can at least in principle compensate for that and gain an accurate measurement. Secondly, we assume that we can, again in principle, make more careful measurements to determine the temperature to any accuracy we want, which also assumes that there is a continuous range of values the measurements may have. These assumptions fail when we make quantum measurements: such a measurement will typically have only a limited number of possible outcomes, and (unless the object is already in one of these allowed, or 'pure' states) the measurement will *change* the measured object from a general state into one of those allowable states.

I will attempt to illustrate these properties by giving the quantum mechanical description of polarization.

1.4 Photon polarization

In quantum mechanics, light is not a continuous wave, but a stream of tiny packets of energy, called *photons*; the energy in an individual photon is given by $E = h\nu = hc/\lambda$, where h and c are fundamental constants of nature, and ν and λ are respectively the frequency and wavelength of the light (this means, incidentally, that short-wavelength photons, such as in ultra-violet or X-radiation for example, have much more energy than infra-red photons). Photons have other measurable properties, including polarization.

In the classical case, note that I showed the light as having a perfectly well-defined polarization in Fig. 1a, and that the function of the polarizers was to extract and transmit some component of the wave incident on them. It is axiomatic in quantum mechanics that one should not, and cannot, talk of any property of a particle without talking about *measuring* that property. Now, it turns out that in quantum mechanics a photon's polarisation can have one of only two values, so that sending a photon through a vertical polarizer, say, is interpreted as measuring *whether or not* that photon has a vertical polarization: if it has, it will be transmitted unchanged, and if it has not, it will be absorbed completely; no other answers are possible.

In this description, the decrease in intensity of the light on the far side of the polarizer is not because the individual photons have a lower energy – this could not be the case without their wavelength being changed as well – but because we see fewer photons on the far side, since some proportion of them (half, on average, if the light was initially unpolarized) will have been absorbed by the polarizer.

I want to emphasise the difference between the classical and quantum descriptions. In the classical case, the light has a perfectly well-defined polarization, and the polarizer simply selects and transmits one component of it. In the quantum case, the photon before it reaches the polarizer does not have a well-defind polarization, but is instead a *mixture* of the two *alternatives*, one of which is randomly selected by the measuring instrument, and a photon in that pure state is passed on.

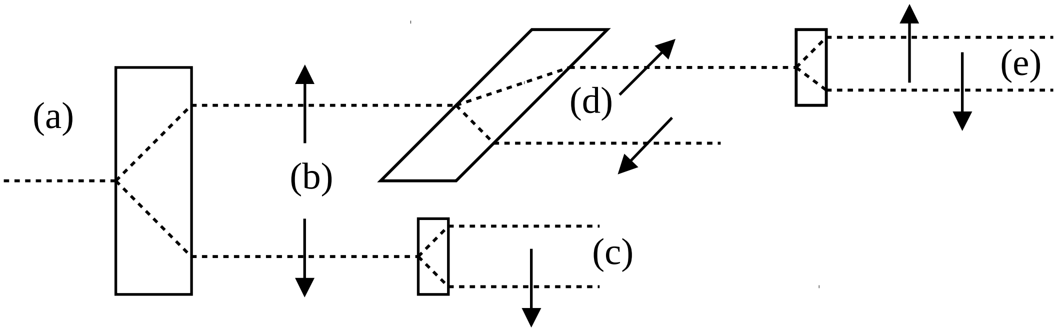

Figure 2: Quantum mechanical polarization. The path of protons through a Stern-Gerlach analyser.

1.5 Spin and the Stern-Gerlach experiment

To further investigate the properties of quantum particles, I will leave photons and polarization behind, and instead describe the process of measuring the quantum-mechanical *spin* of a particle (for definiteness, I will refer to a proton in what follows, though the discussion can be made more general). Quantum-mechanical 'spin' is so called because its behaviour is in many ways analogous to the ordinary spin, of a gyroscope for example, that we are used to – however, it is *not* the same thing. Like ordinary, or classical, spin, quantum-mechanical spin is a vector quantity, in that it has both magnitude and direction ('how much' spin there is, and which axis it is spinning about).

We can experimentally determine the vertical component of the proton's spin using a *Stern-Gerlach* analyser, in which a carefully shaped magnetic field deflects the proton to a degree dependent on the size of the proton's spin in the vertical direction (that is, on the extent to which the proton is spinning along a vertical axis). If the proton spins are in random orientations as they approach the apparatus (see Fig. 2a), then we would expect them to be deflected by equally random amounts. This we do not observe.

What we do observe is that the protons are deflected either one way or the other, with nothing in between. That is, all the protons seem to be aligned with *all* their spin pointing either vertically upwards or vertically downwards (Fig. 2b) – since they were supposed to be in random orientations initially, this is rather strange. We could now turn the apparatus on its side, and measure the components of the protons' spins in the horizontal direction (though we might not expect to find any horizontal spin, if we've convinced ourselves that the protons are spinning purely vertically, for some reason). We would find almost the same result: the horizontal component of the protons' spin seems to account for the total amount of spin the protons have – that is, the protons now seem to be spinning purely in the horizontal plane transverse to the proton beam. What is happening?

You might think that the protons are somehow unstable, and the direction of their spins is constantly changing. This is not the case, as we can take repeated mesurements of a proton's spin by, for example, measuring the vertical component of spin of one of the beams coming from an earlier analyser (Fig. 2c), and we would find that an analyser measuring a pure 'spin-down' state will deflect all the protons into the 'spin-down' direction.

Things get stranger when we take one of the deflected beams, say the one with its spins pointing upwards, and pass it through another analyser (Fig. 2d) to measure the *horizontal* component of the spins. We would find that, although we are taking the beam with all its polarisations upwards, and although repeated measurements of the vertical polarisation would agree that all the protons' spin is purely vertically upwards, a measurement of the components of the protons' spin in the horizontal would find that all the spin was concentrated in the 'spin-left' and the 'spin-right' directions, producing the conclusion that the protons are spinning purely horizontally with, moreover, random orientations in that plane. Finally, if we were now to carry on and measure the vertical polarisation of one of these beams (Fig. 2e) we would find that, once again, the vertical polarisations would be random, either purely upwards or purely downwards.

The results of these experiments could lead us to make two (true) assertions:

- the act of measurement affects the system being measured;
- some pairs of measurements (here two perpendicular spin components) are incompatible.

The first point shows that our first assumption in Sect. 1.3 about classical measurements is not true of quantum measurements. Secondly, our polarisation experiments here suggest, and other quantum-mechanical experiments confirm, that quantum-mechanical measurements can have a *limited number of outcomes*, that an experimental apparatus will 'choose' randomly between the available possibilities, and that different sets of possibilities can be incompatible.

In our measurements, the vertical analyser can give the two answers 'spin-up' or 'spin-down' and nothing in between, and if we pass the 'spin-up' protons through another vertical analyser, it will agree with the first one. If we pass the (now polarised) protons through a horizontal analyser, which can give only the two answers 'spin-left' and 'spin-right', then those are the answers which it will give (Fig. 2d). Now, it is *not* the case that the protons are still polarised vertically but the horizontal polariser simply cannot measure it, because if we pass these horizontally polarised protons through another vertical polariser (Fig. 2e), then will come out with random polarisations. In other words, we cannot measure both the horizontal and the vertical components of the protons' spins, in the way that we *are* able to measure, for example, both the vertical component of a proton's spin, and its momentum.

Quantum mechanics has many of these incompatible pairs of measurements, and the best known is the position and momentum of a particle. Although measurement of these properties for a free particle results in smoothly varying values, rather than the discrete values we obtain for the protons' polarisations, it turns out that increased accuracy for a position measurement can be obtained only at the expense of decreased accuracy for a simultaneous measurement of momentum, and *vice versa.* This is the physical content of Heisenberg's famous uncertainty principle.

1.6 The wavefunction

The way that all this is dealt with mathematically is to introduce the notion of a *wavefunction*, which contains all that there is of the particle and which is, in a sense, interrogated by measuring instruments which, by interrogating it, change it into, in our case, the wavefunction of a vertically polarised proton. The wavefunction evolves perfectly deterministically, and randomness enters in the probabilistic *collapse of the wavefunction* into one of the states which can pass through the measuring apparatus.

When our protons arrived at the first analyser, they were in a mixture – technically, a *superposition* – of the two states 'spin-up' and 'spin-down' which could be measured by the analyser. After a proton has left the vertical analyser, it is in only one of these states, selected at random by the analyser. If this pure state ('spin-up', say) arrives at another vertical analyser it will be passed unchanged and that proton's spin will again be measured as 'up'. However, this state can itself be taken to be a superposition of the 'spin-left' and 'spin-right' states measurable by a horizontal analyser, and so when this 'spin-up' state arrives at such a analyser, one of the two will be selected at random, the wavefunction that leaves will be one of those two states, and the proton's horizontal component of spin will have been measured.

1.7 More questions than answers

This account of the measurement process in quantum mechanics raises more questions than it answers. What is the ontological status of the wavefunction – is it a real thing, or a mathematical construct that does nothing more than codify our ignorance of the state of the quantum system? Can we really be said to 'measure' quantum mechanical parameters, in the sense that we can say that the proton had a perfectly well defined spin before we measured it, which we did no more than reveal? Since the proton had to go through a number of other 'measurements' before we became aware of the results – it had to hit a photographic plate or other detector before the results arrived at our eye – at what point, exactly, did the wavefunction collapse? What on earth does all this mean? And what does it tell us about reality?

1.8 Summary of quantum mechanics

In 1932, *John von Neumann* published *Mathematical Foundations of Quantum Mechanics*, which systematised the rather messy subject, and gave it a firm axiomatic foundation (rather as the two very clear axioms that Einstein proposed for Special Relativity allowed us to derive the rest of the theory using clear logical arguments). I will not summarise these axioms directly here, but simply emphasise that the formalism of quantum mechanics rests on a very small number of very clear ideas.

The wavefunction of a system contains all there is to know about that system. That is, when we make measurements on a system, we are simply ‘interrogating’ the wavefunction. This statement implicitly says that there are no hidden variables governing the system’s behaviour.

The wavefunction evolves deterministically, under the control of the Schrödinger equation. It is only in the act of measurement (which we will have a lot more to say about later), that any randomness enters the theory.

A ‘measurement’ performed on a wavefunction has the effect of collapsing that wavefunction into one of a number of ‘eigenstates’. The eigenstates are particular wavefunctions that have the property of passing through the measuring apparatus unchanged (ie, without any further collapse), and as such, they are characteristic of a particular experimental setup. In the case of polarization, the two ‘eigenstates’ are the ‘vertical polarization’ and ‘horizontal polarization’. Before the collapse, the wavefunction can be taken to be in a *superposition* of the eigenstates peculiar to the apparatus, and although the precise state into which it collapses is ‘chosen’ randomly, the probability of its collapse into one or other of those eigenstates is governed, loosely speaking, by the amount of that eigenstate in the superposition. Since the base eigenstates into which a wavefunction can be decomposed are specific to a particular apparatus, it follows that the ‘measurement’ which is the result of the collapse is not an intrinsic property of the wavefunction before it is measured, but is a *joint* property of the wavefunction and the apparatus. The collapse of the wavefunction is taken to be instantaneous, even though the wavefunction may have ‘spread out’ over a huge distance. Some measurements, such as the position or momentum of a free particle, have a continuum of eigenstates, and hence a continuum of experimental results. More typically, however, a quantum measurement (a polarization, perhaps) has a finite number (two? three? ten million?) of eigenstates, so that the measurement can have only certain discrete outcomes – this is the 'quantum' in quantum mechanics.

Some pairs of measurements are incompatible. Some pairs of measurements are compatible in the sense that they *share* eigenstates, so that a wavefunction can pass through both measurements unchanged. Other pairs do not have this property, so that when both measurements are done on a wavefunction, one after the other, the eigenstate which is the result of the first measurement is newly collapsed by the second. Whichever eigenstate of the second measurement is selected, that state would *again* undergo a collapse if it were sent through the first apparatus again, and this eigenstate would possibly be different from the result of the initial measurement. Since the eigenstate which is selected by a measurement corresponds to the *result* of that measurement, we cannot simultaneously know the results of two incompatible measurements.

2 The interpretation of quantum mechanics

2.1 Positivism, realism, and the Copenhagen interpretation

The description I have just given provides most of the technical 'bones' of quantum mechanics. It undermines the familiar classical notions of particles and waves, but it replaces them with a wavefunction which has no stronger claim to real existence than any other piece of mathematics. Similarly, the process of measurement – which needed no explanation or interpretation in classical mechanics – becomes an obscure and mysterious thing, and loses physical intelligibility even as it gains mathematical clarity. As we come to the crux of this discussion, and move from the mechanics of quantum theory to its meaning, we inevitably move from physics to philosophy. The two antagonistic approaches which most clearly define the interpretation of quantum mechanics are *positivism* and *realism*.

Positivism is the doctrine that the only scientific statements that may be made about the world, are those which are verifiable by direct observation or measurement. A theory, from this point of view, is merely a mathematical device for summarising past observations, and using them to predict the results of future ones. The objects of the theory (such as wavefunctions) have no existence away from the mathematician's notebook, and to talk of them as physically real things is to indulge (and there is a pronounced hint of opprobium here) in metaphysics[4]. The positivists are not idealists – they do not deny that there is a real world out there – but they do deny that we can have scientific knowledge about the real nature of that world.

Realism, on the other hand, declares that there is a real world, that we can sensibly discuss and even know its nature, that there is some physical thing in the world that corresponds to the wavefunction (for example), and that it has real properties whether or not we measure them (or even, whether or not we *can* measure them).

The *Copenhagen interpretation* is the orthodox position on the matter[5]. This (positivist)

[4]The positivists denied, for example, the existence of atoms, and it was only in 1905, with Einstein's publication of work on Brownian motion, that the notion of atoms as physically real objects became generally accepted.

[5]I hesitate to use the word 'orthodox', as it naturally suggests the sequence 'heterodox', 'heresy' and 'fire'. Far from being so concerned with philosophical coherence and consensus, the physicist on the silicon-valley omnibus

interpretation, which is associated with *Niels Bohr*, concentrates on the measurements we make, rather than the object we measure, and states that since we cannot observe any reality independent of these, it is *meaningless* to talk of it. For example, we can measure either the horizontal or the vertical component of a proton's spin, but we cannot ascribe a well-defined value, in the sense of a repeatably measureable value, to both at once. We might say that "we cannot measure both at once: two components do not *exist* both at once", but this means either 'therefore the two components do not exist…' or 'because…'. The latter seems to be making a definite metaphysical statement about the world, and the former seems to tend toward the idea of a reality constructed by us, and both are notions repellent to hard-headed positivism, which simply refuses to discuss the matter. Heisenberg said that we could understand classical waves and particles, but that we could only understand any quantum observation once it had been translated into those classical terms. Bohr simply declared "there is no quantum world".

Bohr talked a lot of *complementarity* as a fundamental feature of quantum mechanics. At base, this is simply an extension of the observation that some pairs of operators are incompatible, and that we cannot consistently measure both at once. Horizontal and vertical spin components are an example of two complementary measurements, and so are the position and momentum of a particle. The notion expands to the remark that wave and particle properties are complementary, and if we seek to measure a wave property, such as the wavelength, the measured system will behave like a wave, but if we measure a particle property, such as the momentum, the system will obligingly switch to behaving like a particle. It can be quantified in Heisenberg's famous uncertainty relation.

The Copenhagen interpretation is therefore straightforwardly positivist, and resolves the problem of interpretation by saying there is no problem and refusing to discuss the matter further. This is philosophically consistent, but it is also completely unsatisfactory – we do not study physics merely in order to learn how to relate observations. If you share this dissatisfac-

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would be inclined to regard talk of interpretive underpinnings as a sign that everyone's had quite enough to drink thank you very much, and would anyone like some tea?

tion, you are in good company, as both Einstein steadfastly held out against the Copenhagen interpretation (Schrödinger, in a letter to Bohr, said “If we are still going to have to put up with these damn quantum jumps, I am sorry that I ever had anything to do with quantum theory”). After a long-running debate with Bohr, Einstein failed to show that quantum mechanics was inconsistent; he accepted that it wasn’t, but then tried to show that it must instead be *incomplete*.

2.2 The EPR paradox and local realism

2.2.1 The EPR paradox

In 1935, Einstein, *Boris Podolsky* and *Nathan Rosen* (EPR) published a paper which purported to show that there must be 'more' reality than quantum mechanics was able to describe, and that the latter was therefore incomplete. EPR said "If, without in any way disturbing a system, we can predict with certainty. . . the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" and went on to describe a thought experiment in which quantum theory made some very unpalatable predictions. We can describe a more practical version of their thought experiment now.

We can arrange for an atom to emit two photons in opposite directions, in such a way that the atom has the same intrinsic angular momentum before as after. Since angular momentum is conserved, the photons, which can carry angular momentum, must have equal and opposite momenta, or equal and opposite circular polarization. If, some distance away, we arrange to measure the photons' linear (that is, vertical or horizontal) polarization then, as we saw last week, we will get a random answer, with the photon's wavefunction randomly collapsing into one of the two possibilities. It turns out, however, that if one photon (call it A) is measured to have a vertical polarization, then the second photon (B, say) must *also* have vertical polarization, if angular momentum is to be conserved. That is, we know that the two photons must be measured to have the *same* polarization, even though we cannot know in advance what that polarization is.

When we make the measurement of photon A (and remember that the result of this measurement is random, and though it is governed by the wavefunction it is *not* deterministic), we turn its linear polarization from a potentiality to a reality, in the sense that we now know with certainty the result of any future measurement of that photon's linear polarization. However, if we measure photon A fractionally before[6] we measure B, then we know in advance what

[6]This staggering of the measurements is not necessary for the EPR experiment, but it makes this explanation a little easier.

the result of that second measurement must be: it must have the same linear polarization as photon A, and so its polarization state must, by EPR's reasonable definition, be an element of physical reality. We have done something very bizarre, here – by making a measurement on A, we have *instantly*, and without any measurement, made real the polarization state of photon B which, depending on the size of our laboratory, could be in the next galaxy. It is quite upsetting enough to say that we adjudicate on what is real at A, without quantum mechanics suggesting that we influence reality at B, as well.

This conclusion was so unpalatable to EPR that they concluded that the photons' polarization states must, in some way not directly accessible to experiment, be already real *before* they are measured; that is, unless the photons were somehow instantaneously communicating with each other, they must somehow be carrying information within themselves which is not contained within the wavefunction, contrary to von Neumann's first postulate of quantum mechanics. Note that EPR were not saying that the experiment as described would not work – they were not suggesting that quantum mechanics would predict the wrong answer – they were instead suggesting that the experiment could not work *in the way quantum mechanics said it would*, and that the quantum mechanical description in terms of a wavefunction must therefore be *incomplete*.

2.2.2 Hidden variables and Bell's inequality

Given that you don't believe in 'spooky action at a distance', the obvious resolution of the EPR problem is to invoke some *hidden variables* within the quantum system which, although they are not themselves measureable, predetermine the result of some future measurement of, say, polarization. Using the EPR experiment as an example, if the photon's state, including all its hidden variables, is set at the point of emission from the atom, then quantum mechanics reverts to being a completely deterministic and locally real, and the randomness it exhibits is merely statistical (the polarizations exhibited by a stream of photons seem quite random to us, but that is only because we don't know until we measure them, what the predetermined polarizations are)[7]. Here, the term *locally real* refers to the demand that measurable things have real values which do not depend on any instantaneous (or other faster-than-light) propagation of information; that is, there is no action at a distance.

Attractive as this picture is, in restoring some of our classical certainties to the quantum world, it transpires that it cannot be true, and that locally realistic (hidden-variable) theories are ruled out by experiment.

How can we come to this very general conclusion? In a paper which appeared in 1966, *John S. Bell* produced a very simple inequality, which is satisfied by *all* local hidden-variable theories. This inequality, now called Bell's Theorem, refers to correlations between measurements of polarizations (for example; it is more general than this, however, and applies to pairs of socks as well). The predictions of quantum theory *violate* this inequality: if the theory's predictions can be confirmed by experiment to be correct, we can conclude from the violation of Bell's inequality that quantum theory *cannot* be a local hidden-variable theory.

2.2.3 The experimental support

Bell's theorem is such an important result, that it instantly became vital to check explicitly that, as expected, quantum theory's predictions were in fact correct. In a very careful series of experiments in 1981 and 1982, *Alain Aspect* and collaborators at Université Paris-Sud showed essentially this. In the final form of their experiments, which were very similar to the thought experiment I have described above, they used equipment which effectively changed the orientation of the analysers, and hence which polarization components they measured, whilst the photons were in flight; and they made the measurements on the two photons sufficiently close together in time (less than 20 ns apart, or 20 billionths of a second) that there was no time for a signal travelling at the speed of light to pass between the photons.

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[7] It seems that Einstein never explicitly advocated a hidden-variable theory, nor did he put forward precisely this statistical interpretation. However, they are both heavily implicit within the EPR paper, and are both to some extent associated with him.

The only way that hidden-variable theories can still be tenable is to imagine that the photons somehow ‘know’ in advance what polarizations will be measured, and collaborate before setting off, but even this grand conspiracy on the part of the photons can be ruled out by other so-called ‘delayed-choice’ experiments, in which the measurement that is to be made is decided, randomly, only after the photons have entered the apparatus.

So, to summarize: quantum theory’s predictions are correct, Bell’s inequality is violated, and so the theory cannot be locally real. What that means, in turn (accepting for the moment that the wavefunction is a real thing), is that the wavefunction of the two photons does not split into two independent wavefunction as they separate, but instead remains a single object; and when a measurement is made on ‘one of the photons’, the wavefunction as a whole instantly collapses, no matter how far apart the photons now are[8].

This is a trifle odd.

[8]This rather suggests that a suitably cunning arrangement of atoms and polarizers would allow you to send messages instantly across half the galaxy. All you’d have to do is switch your own polarizer back and forth, and your friend on Betelgeuse would note down the correlations on his or her polarizer. Well, although it is true that if you measure a photon to be vertically polarized, that photon’s partner on Betelgeuse must also be measured to be vertical, before you rush to the patent office, remember that you cannot *control* whether you measure a vertical or a horizontal photon, so that you cannot control your friend’s polarizer, and so cannot send any message this way.

Despite this, there is an application for quantum mechanics in communication, in the field of quantum cryptography. For a useful review, see *New Scientist* October? 1999.

2.3 Pilot waves and propensities

If it were your particular aim to go back in time and thoroughly upset a 19th-century classical physicist, it is difficult to see how you could do better than to describe the orthodox interpretation of quantum mechanics. It is non-deterministic, non-local, and it includes a strong demarcation between a classical world we can know, and a quantum world we cannot. We have examined the philosophical background to the Copenhagen interpretation, and we have seen how the EPR paradox and the Aspect experiment damn the simplest reinterpretation of the formalism of quantum mechanics (*sc.* a locally-realistic hidden-variable theory). After these experiments, is there any freedom left for interpretive alternatives?

There is. The only substantial alternative to the conventional formulation of quantum mechanics, as far as I am aware, is the theory of *pilot waves*, which was originally suggested by *de Broglie*, but which was developed by, and is more closely associated with, *David Bohm*. In this picture, the particle we detect in our apparatus is a *real* particle, with perfectly well-defined position and momentum. It does not propagate freely through space, however, but is guided in its motion by a familiar classical potential, as well as a newly-introduced quantum potential. The motion of the particle is thus a perfectly deterministic function of its initial position, and the randomness we see in the quantum world is due to our inability to determine the particle's initial position accurately. When a measurement is made on the particle, the quantum potential governing it instantly changes, thus affecting measurements made on a corresponding particle elsewhere – we can see that the quantum potential therefore takes on some of the role of the wavefunction in the conventional formalism, but is at the same time a type of hidden-variable. We can thus see that the pilot wave theory is deterministic and realist but, in the instantaneous change of the quantum potential, not *locally* real. The notion of the pilot wave is part of the larger and more fundamental cosmological system that Bohm developed, which he described in his book *Wholeness and the Implicate Order*. It is a holistic theory, which talks of a degree of order which exists at some hidden fundamental level, which is constantly enfolded and unfolded around us.

Karl Popper (whom we will return to in later weeks) claimed that the interpretive problems in quantum mechanics were instead problems in the interpretation of probability. If you imagine a sloping board with a regular array of pins driven into it, and imagine rolling a small ball down through the pins, then you can see that we could work out the various probabilities of the ball emerging at various points along the bottom edge of the board. If we remove one of the pins in the middle of the array, we can see that this would affect the ball's probable paths, whether or not the ball went close to that missing pin: in Popper's terms, the missing pin has instantly, and far from mysteriously, changed the *propensity* of the system as a whole to produce a particular result. This idea can be developed using notions of propensity waves, but the properties that have to be assumed for those waves, to make them fit the phenomenology of quantum mechanics, means that Popper's theory comes more and more to resemble Bohm's.

2.4 Measurement and the collapse of the wavefunction

In our discussions above, we have been principally concerned with the nature and behaviour of the wavefunction. It is now time to turn to the other great mystery of quantum mechanics: the act of measurement. One of the axioms of quantum mechanics blithely states that the act of measurement causes the wavefunction to collapse into one of the eigenstates appropriate to the measurement that is being made, and hence the apparatus that is being used. At the formal level, that is all that has to be said, but if we step back, we can see that this statement does little other than raise questions: what exactly causes the collapse? when does the collapse happen? which measurements can, and which cannot, cause a collapse? It is questions such as these, and some of the possible answers, that are partly responsible for the recently-renewed general interest in quantum mechanics.

Before we go on to look at some of the solutions, however, it would good to look at a famous statment of the problem.

2.4.1 Schrödinger's cat

Imagine putting one of our proton polarizers into a box, and firing a single proton in to be measured. We arrange things so that if the proton is measured to be spin-up, a red light goes on, and if it is measured to be spin-down, a green light goes on. Before the proton is measured, as we know, it is in a superposition of the eigenstates spin-up and spin-down, which the measurement is supposed to resolve into one or the other. But the detector and the light-bulbs are fundamentally governed by the same physics, so that they must be quantum systems, as well, and so before they are measured (by us, or by some robot) they must *also* be in a superposition of the eigenstates spin-up-red-light and spin-down-green-light, which the observation of the lights collapses. We know that we only see one of the possible results of the measurement: the question is where, along this chain of measurements of measurements, does this single result emerge? Where does the wavefunction collapse, and why?

Schrödinger chose to illustrate the seriousness of this problem by imagining a rather different sort of detector – a cat. We put a cat in the box along with the apparatus, and arrange that if the detector measure the proton to be spin-up, then as well as lighting the red lamp, it will smash a phial of some poisonous gas. Exactly the same analysis as before goes through, except that now we must say that, before we make a measurement on this larger and furrier apparatus, the system as a whole is a superposition of the eigenstates spin-up-red-light-cat-dead, and spin-down-green-light-cat-alive, which our measurement resolves. Whilst we may be happy with the notion that the proton can be both spin-up and spin-down before its measurement, and vaguely reconciled to the notion that both lamps can be 'half-lit', I at least am not at all happy with the notion that the cat is simultaneously alive and dead, and that it is only our final measurement of the system as a whole that forces it to be one or the other.

I want to emphasise that, from the formal point of view, this is a perfectly acceptable analysis of the problem. Schrödinger is using this example to demonstrate that this formal analysis cannot be reasonable, or at least cannot be complete. The Copenhagen interpretation suggests that the reduction takes place when the quantum system encounters a classical (ie, a large) system but is, as ever, maddeningly vague on any details, and seems to suggest that the measurement problem is just another feature of 'the quantum world' that, as good positivists, we cannot reasonably enquire after. This is just hocus-pocus.

2.4.2 Thermodynamics and statistics

The formalism of quantum mechanics says nothing at all about where the collapse takes place, and so it cannot itself produce any resolution to the problem. Such resolutions can therefore only come from modifications to the basics of quantum mechanics, or additions to it. Some of these resolutions – perhaps the more respectable ones – are rather technical, and concerned with subtle uncertainties in the fundamentals of quantum mechanics; I shall not be able to discuss these in much depth here, but I shall describe them briefly before going on to the more 'romantic' answers. The latter hope to find dramatic insights into other problems, and other areas of human experience.

Ilya Prigogine talks of complementarity, but this time a complementarity between being (dynamical processes such as a ball being thrown, which look the same when viewed forwards and backwards in time) and becoming ('thermodynamic' processes such as an ink-drop disappearing in a bowl of water, which do not look the same when run backwards). He remarks that, in mechanics, the latter irreversibility is seen as an illusion: the laws of mechanics are perfectly reversible, and it is only our inability to measure the positions and momenta of all the molecules in the bowl of water that stops us being able to reverse all those momenta and watch the process undo itself. On the contrary, he suggests that irreversibility is fundamental, and that it is the apparent reversibility of mechanics that is the illusion, engendered by the extreme simplicity of the systems. Accordingly, he suggests explicitly incorporating thermodynamics within quantum mechanics, which would rather naturally result in an explanation for the irreversible collapse of the wavefunction.

On the same general lines, others have suggested incorporating non-linear terms within the Schrödinger equation, which are ignorably small when we are dealing with quantum systems, but which naturally account for the collapse when the equation is applied to larger systems. *GRW theory* (due to Ghiradi, Rimini and Weber) is well known amongst these. GRW suggest that the wavefunction spontaneously collapses with a frequency that increases with the number of particles involved. Thus the wavefunction of something as simple as a single proton would take billions of years to decay, but one the size of a cat, say, would collapse almost immediately.

There are other suggestions, which are in this section because they come under the heading of 'technical', but which are really no less exotic than the ones to follow. *Roger Penrose*, for example, has suggested that it is extreme curvature of spacetime that causes the collapse, that this might be provided by a pervasive background of baby black holes suggested by Hawking and Coleman in another context, and that it is the mass of the graviton that sets the scale for this.

The suggested solutions that follow are some of the best known ones, partly because they make good newspaper copy, but also because in making them, physics seems to step outside its normal bounds, and barge its way into other rooms of the academy. Physics is not used to the Argument From Authority, but it still seems worth pointing out that, although they are particularly exotic, all these notions have been advocated at one time or another, by fairly exalted physicists.

2.4.3 Consciousness

Eugene Wigner took Schrödinger's cat paradox one step further, by having not a cat, but some helpful friend, observe which light was lit. Since the friend was fully conscious, and knew all about quantum mechanics, he could stand in for any of us, and it is purely solipsistic to suggest that the wavefunction had not collapsed by the time Wigner's friend was aware of which light was lit, but waited until Wigner himself asked the result. He concluded from this that the wavefunction must collapse as or before it reaches its first conscious mind.

In 1932, John von Neumann declared that quantum mechanics should indeed work with macroscopic systems such as lightbulbs and your optic nerve, and that a description in terms of superpositions of states was appropriate even after the signal had left your eye en route for your brain. The wavefunction, he said, only collapses when it strikes something quantum mechanics does *not* describe, such as a conscious mind.

2.4.4 Many-worlds

In 1957, *Hugh Everett III* insisted that the Schrödinger equation by itself was enough for a complete theory. In this picture, observers have no special status: when a measurement is made, the states of the measured system and the observer simply become entangled, and are never collapsed. The observer sees only one of the possible results, because when the measurement happens, the entire universe splits – *all* the possibilies happen, each in a marginally different universe. *John Wheeler* has championed this interpretation for its great economy of ideas, and it is popular with quantum cosmologists, who like to talk of the wavefunction of the entire universe, but it gives most physicists fainting fits, and it has been described as 'very economical with concepts, but quite prodigal with universes'. *David Deutsch* has described a variant of this, in which there are a finite number of parallel universes, and the terms of the wavefunction are somehow partitioned between them, allowing the possibility of remixing them at some later stage.

2.4.5 God

"Are we missing the ultimate hidden variable?" (Baggott)

Paul Davies has remarked that "Science offers a surer path to God than religion does", and more scientists than you might expect have what one might call religiosity, which may not fit neatly in any church, but which surely has some of the same motivations. This is not the place for an account of the philosphy of religion, and nor am I the person to deliver it, but there are two philosophers of the Enlightenment whose remarks on religion I believe have some relevance here.

Spinoza claimed that God and Nature were different (in this context we might almost say 'complementary') aspects of the same substance, and so that the mental and physical worlds are really two different ways of looking at the same thing, God-or-Nature. Einstein, for example, seems to have had a personal picture of God in nature which Spinoza would have recognised.

On another tack, *Kant* claimed that there are limits to what we can know through reason alone, but that this does not mean that we should simply stop at this border, and dismiss everything beyond as metaphysical. We can (or must) still *think* of things as existing in fact, even if we cannot perceive or experience them directly. It is practical faith which makes the connection between things-as-they-appear, and the inaccessible things-in-themselves, and this is a remark which can as happily apply to physics as to conventional religion.

3 Elementary particle physics

I now want to describe the *phenomenology* of Elementary Particle Physics – the behaviour of subatomic and subnuclear particles moving with very high energies – as a preface to describing and discussing the physics in the next two meetings. The notion seems so obvious to us now, that it seems strange that anyone could have doubted that (at least some aspects of) the physical world could be explained by explaining the behaviour of its various components. The search for a set of truly fundamental components has been a long one, but I shall describe the most fundamental model which is generally agreed on, the *Standard Model*, which accounts for all the particles and forces we know about in terms of just four fundamental forces. After that, I'll describe the attempt to reunify these four forces into just one truly fundamental, and deeply hidden, force.

3.1 The Particle Zoo

The search for the elementary constituents of matter began, probably, with Democritus, who elaborated the earlier notion that the world is composed of individual and indivisible *atoms*. John Dalton (1766–1844) offered indirect evidence for atoms when he observed that atoms can combine and recombine in certain fixed proportions to make up the compounds that we see around us. Mendeleev systematised chemical knowledge by recognising the patterns within the chemical properties of matter, and laying the atoms out in a regular form – the periodic table of the elements. Mendeleev recognised that the regularity of the pattern was important, and used the presence of gaps in the pattern to successfully predict both the existence and chemical properties of hitherto unknown elements, to fill those gaps. The regularity of the pattern suggested that there was some more fundamental structure, and this was borne out in the early part of this century with the detection by Thomson, Rutherford and Chadwick of, respectively, the *electron*[9], the *nucleus* and the nuclear atom, and the *neutron*. At that point, all matter could be said to be composed of combinations of just three particles, the protons and neutrons within the nucleus, and the electrons orbiting around it.

In 1930, experiments on neutron decay seemed to suggest that the process violated the principle of the conservation of energy. To rescue this principle, Wolfgang Pauli proposed the existence of the *neutrino*, a ghostly particle which interacts only very weakly with other matter. It is consequently very difficult to detect, and that was only done in 1956. Dirac's relativistic mechanics introduced the idea of *antiparticles* – partners of each of the normal particles, which have opposite values for all of their quantum parameters except mass. When people were able to detect very high energy cosmic rays in cloud chambers they found the *muon* and the *pion*. The list of fundamental particles has become rather long.

Then the particle accelerator was invented.... When physicists were able to probe to higher energies, a host of new particles tumbled out, each with as much of a claim as any

[9] Incidentally, J J Thomson was given the Nobel prize in 1906 for showing in 1897 that the electron was a particle. Thirty-one years later, his son G P Thomson shared the Nobel prize for an electron diffraction experiment which showed that the electron was a wave.

other to fundamental status. The current Particle Data Group summary of particle properties is 184 pages. It started to look as some more fundamental structure had to be found.

3.2 Classifying particles

The particles that flooded out of accelerators can be classified according to their properties. Particles have mass, charge, quantum mechanical spin, strangeness.... The last two properties are unfamiliar, as they have no counterparts in the classical world. Quantum mechanical spin is analogous to ordinary spin, and it has some of the same effects, but it is completely different in detail.

'Strangeness' was invented in an attempt to systematise the particles and collisions observed in greater and greater numbers in accelerators. People discovered that they could assign quantities of strangeness to different particles in such a way that, although the identities of particles coming out of a collision might be different from the ones going in, the total amount of strangeness stayed the same, *unless* the collision involved the so-called weak interaction, or weak nuclear force (about which more later). In this respect, strangeness is broadly similar to electric charge, although that charge is conserved in *every* collision.

Particles could also be divided into three groups.

leptons For example, the electron, muon and neutrino. These particles have very small masses, and seem to be truly fundamental.

hadrons For example, the proton, neutron and pion. These are split into two groups, the *baryons* and the *mesons*, and have substantially larger masses than the leptons. These particles feel the 'strong nuclear force' described below.

'gauge bosons' The photon, the W and Z particles and the gluon (see below). These are the particles which carry the fundamental forces.

With this classification, and others, the particles could be grouped suggestively together, in much the same way that Mendeleev grouped the elements, and with a broadly similar effect.

At first merely descriptive, but later with more theoretical support, the notion of *quarks* appeared. In this picture, the various groups of particles with similar properties are created by combining more fundamental objects. With three quarks, called *up*, *down* and *strange*, you can make a neutron by binding an up to two downs, or a sigma particle Σ^+ with two ups and a strange, and generally create all of the known baryons with a suitable combination of three quarks. Each of these quarks has its antiparticle, and the mesons are created by combining a quark and an antiquark – a pion π^+, for example, is an up bound to an antidown. As with Mendeleev's periodic table, the tableaux constructed by these methods had some gaps, and this allowed Murray Gell-Mann to predict (in the 1960s) the existence and mass of the so-called Ω^-.

Quarks started off as a purely mathematical construction – purely as marks on paper – as a way of constructing things with the correct properties. No-one started off saying anything about them *existing* (and they shouldn't be observable in principle), but now physicists routinely think precisely that, in the sense that the quarks are taken to be the things within the proton and friends.

As more new particles appeared, more quarks were needed, and the charm, the top and the bottom quarks (also sometimes more poetically referred to as the truth and beauty quarks) were suggested. With the addition of a couple more leptons, that seems to be it: although there's no theoretical reason why the sequence should stop there, it seems that our world is constructed from a relatively small set of particles. Grouped into three families, they are

u, d	s, c	t, b
e, ν_e	μ, ν_μ	τ, ν_τ

That is, the up and down quarks are associated with the electron and the electron neutrino (the first neutrino to be discovered, and named by Pauli), the strange and charm quarks are associated with the muon and its neutrino, and the top and bottom quarks with the tau, and its neutrino. If you don't count these particles' antiparticles as being distinct, this comes to a total of 12 fundamental particles which make up the universe.

3.3 The four forces

According to the so-called Standard Model, all the matter in the universe is comprised of a few truly fundamental particles, and all the forces are manifestations of a set of four fundamental forces.

3.3.1 Gravity

Felt by everything

Strength $\sim 10^{-40}$

Range infinite

The 'strength' I've quoted here is intended to suggest how weak the force of gravity is compared to the so-called 'strong nuclear force', which holds the nucleus together.

The best theory of gravity we have is still Einstein's classical one – we do not have a fully successful quantum theory of gravity. In this picture, gravity is the stage on which all of the rest of physics takes place, and in consequence *everything* feels its effects, even the massless photon. 'Space tells matter how to move; matter tells space how to curve.'

3.3.2 Electromagnetism

Felt by charges

Strength $\sim 1/137$

Range infinite

Carried by massless photons

This is the force that drives motors, comprises radio waves, keeps the electrons circling the nucleus, and stops us falling through the floor. James Clerk Maxwell produced a beautiful and effective classical theory of electromagnetism, but the version of the theory that is used in high-energy particle collisions is known as QED, for Quantum Electrodynamics. In this theory, charged particles interact with each other by exchanging photons. It is a stunningly successful theory, in terms of the hugely accurate agreement between theory and experiment.

The *range* of the electromagnetic force is given here as infinite (a fact which is intimately related to the masslessness of the photon). Since it is so much stronger than gravity, why does it not dominate the universe? The answer is that it would, if there were substantial accumulations of charge anywhere. Almost all the charge in the universe, however, is closely associated with equal amounts of opposite charge, giving an overall neutrality.

3.3.3 Weak nuclear force

Felt by hadrons and leptons (ie, all matter)

Strength $\sim 10^{-6}$

Range $\sim 10^{-18}\,\mathrm{m}$

Carried by $W^{\pm}$ and Z^0, about 90 times the mass of the proton

The prosaically named weak nuclear force is the force responsible for radioactive decay, when a neutron decays into a proton, and electron, and a neutrino. It is also through the weak force that the ghostly neutrino interacts with the nuclei of atoms, and it is because the force is so weak, that that interaction is so fragile. The weak force can act on all hadrons and leptons – in other words, on all matter. A notable feature of the weak interaction is that that it does not conserve strangeness – it can turn a strange quark into an up quark.

3.3.4 Strong nuclear force

Felt by quarks, and hence the particles (hadrons) made from them

Strength 1

Range nucleus

Carried by gluons

The strong nuclear force is the force that keeps nuclei firmly in one piece against the huge electrostatic repulsive force. The theory that describes it is known as QCD, for Quantum Chromodynamics, which is like a more complicated version of QED, with a 'colour' charge instead of the electric charge.

3.3.5 Does the standard model work?

Yes. . . and no. The standard model works very well indeed, in the sense that it predicts experimentally measurable quantities with staggering accuracy (the magnetic moment of the electron has been calculated and measured to more than one part in a thousand million).

When the standard model was first proposed, it was believed in by theoreticians because it was too beautiful to be false, but not by experimentalists, because there was little support for it. Since then, the theory has been modified here and there, as constrained by a great deal of experimental work, until now experimentalists believe in the model because of its huge experimental support, but theorists no longer do, because after all the modifications that have been made to it, the model is now too ugly to be true.

This remark is not entirely whimsical. It is almost a principle of physics that a truly fundamental theory will have a spartan simplicity that commands belief. This has been true in the past (classical mechanics, Maxwell's electromagnetism, relativity, and QED are all fundamental, insightful, theories commonly exclaimed by physicists to be truly beautiful things), and has possibly found its most extreme statement in Dirac's remark 'It is more important to have beauty in one's equations, than to have them fit experiment'.

Many folk believe that the standard model *must* be wrong, but are hampered by being unable to find any chink in its success which might lead to a specific theoretical problem. Instead, they try to dig under its foundations, by investigating its fundamentals, and aiming for *unification.*

3.4 Unification and quantum gravity

When they were first discovered, electricity and magnetism were naturally thought to be distinct phenomena. It was Michael Faraday and James Clerk Maxwell who, at the end of the ninteenth century, showed experimentally and theoretically that they were in fact just different aspects of a single force, electromagnetism. In the same way, the electromagnetic force and the weak nuclear force discovered in accelerator experiments were experimentally and theoretically shown, in the 60s, 70s and 80s to be different manifestations of a single electroweak force. Thus, there are actually only three fundamental forces, rather than the four I've described. There is a history of unification in Fig. 3.

The strong force shares many fundamental mathematical features with the electroweak force, and there are a number of reasonable candidates for a theory which will unify the two forces, but because the energies and timescales involved are so huge, experimental confirmation would have to be indirect.

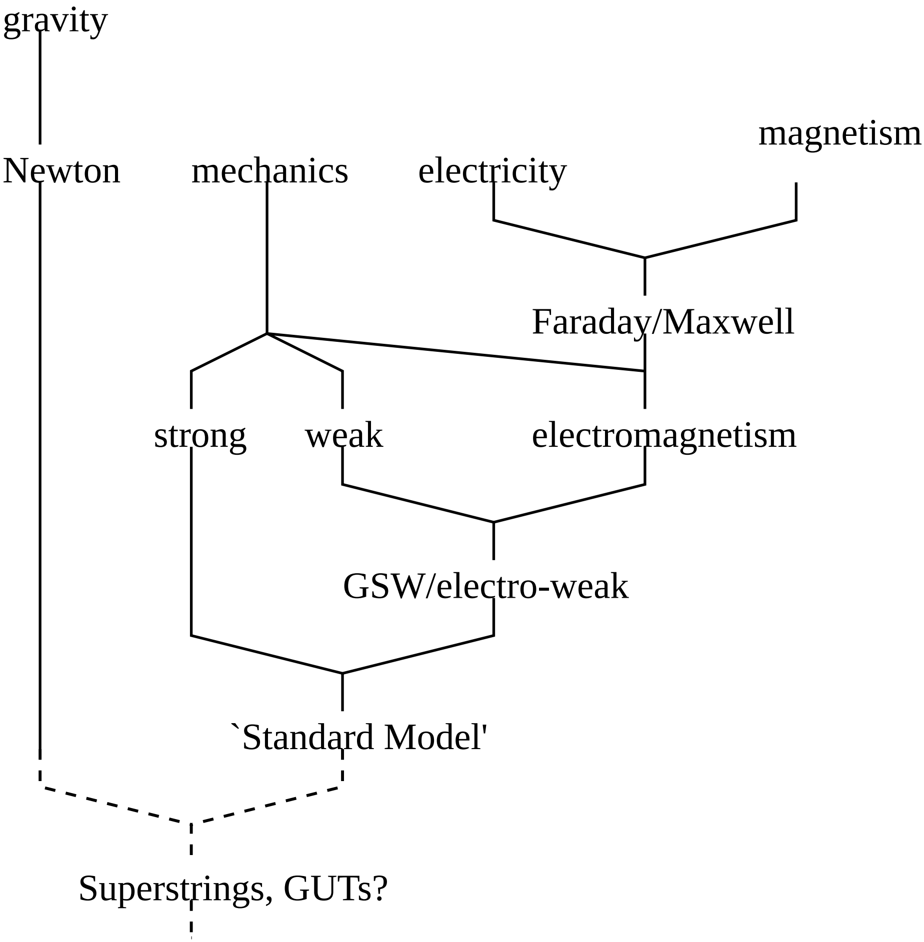
Gravity is a great problem. Although it shares some features with the other forces, it has important differences, and its status as a background for the rest of physics makes a quantum theory of gravity a very difficult proposition. This has not stopped folk from trying to develop such theories, but they are necessarily very exotic, very speculative, and very far from experimental confirmation.

Scales

- Particle physics experiments work at up to TeV scale, or 10^{12}eV, on length scales of an atom (10^{-10}m), or a nucleus (10^{-15}m) or a little smaller.

- Gravity works on scales of 10^{3}m to 10^{10} parsecs, or 10^{26}m.

- The 'unification scale' is where the various Standard Model theories converge: Planck energy: $\hbar c^5/G = 10^{28}$eV


gravity
magnetism
Newton
mechanics
electricity
Faraday/Maxwell
strong
weak
electromagnetism
GSW/electro-weak
`Standard Model'
Superstrings, GUTs?

- Planck length: $\sqrt{\hbar G/c^3} = 10^{-35}$m; time, $\sqrt{\hbar G/c^5} = 10^{-44}$s; mass, $\sqrt{\hbar c/G} = 10^{-7}$kg
- …not directly accessible by experiment, but they *do* involve G!

3.4.1 Superstrings

Strings

- Comes from particle physics, and is a modification of standard quantum mechanics.
- It is a response to the perplexing observation that the ‘fundamental’ particles do have a lot of properties: spin, parity, colour, charge, hypercharge.
- Surely the Planck scale is where the internal machinery lives.
- Instead of point particles (zero dimensions) being the fundamental objects, have strings (one dimension) instead – immediately gives much richer structure.
- But it only makes sense in 10 dimensions.
- Strings can’t interact with particles, so either all matter (particles and photons) is stringy, or none of it is.

Dimensions

- Compactification: like a hosepipe
- Kaluza-Klein
- Reduce number of observable dimensions, but still have dynamics in all 10. Explains ‘internal’ properties.

Black holes

- Hawking radiation: black holes evaporate, and return their energy to the universe
- And they have an *entropy*: Bekenstein-Hawking equation, $S = Ak_b c^3/4\hbar G$
- A black hole constructed from D-branes has precisely this entropy!

Too many theories

- The problem is that there are too many possibilities – something like 10^{100} possible vacua, and no *a priori* way of distinguishing between them
- ‘Pocket universes’; anthropic arguments?

3.4.2 Loop quantum gravity

A different approach

- Superstring theory assumes a simple background space – a flat stage – and has exotic objects moving around in it
- Loop quantum gravity talks of quantising space itself, completing (?) the transition from Newton’s space, to Einstein’s, and beyond

Spin networks

- We intuit that in space we can move from one point, continuously, to any other point
- Replace this with a network of nodes and links: space consists of the collection of nodes, and we can only move from one node to another to which it connected by a link
- Natural quantisation of space, into volumes around each node (around the size of the Planck length) and areas corresponding to each link, forming the boundaries of a cell

Successes

- Has also derived the Bekenstein-Hawking equation (once a free parameter has been fixed)
- ‘Spinfoam’ is the history of a spin network, and allows you to calculate ‘sum over histories’

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