In this review of present ideas and questions for the future my theme will be the search for unity in our description of elementary particle physics. Everything in the Universe, including ourselves, is made of elementary particles, each kind behaving in exactly the same way in every part of the Universe, as far as we can tell from the light reaching us from the most distant galaxies. The laws of these elementary particles and of the forces governing their behaviour constitute the fundamental principles of microscopic physics. If we adjoin to these the principles of cosmology, in particular the boundary condition that about 15 000 million years ago the Universe was a tiny, hot, dense, expanding ball, then we have all the fundamental laws of physics. They underlie not only the rest of physics, but also astronomy, chemistry, geology, biology, ... in fact all of natural science. When Dirac wrote his relativistic equation for the electron in 1928 he commented modestly that his equation explained most of physics and the whole of chemistry.

In this enterprise of discovery, as in natural sciences generally, the experimental and theoretical contributions go hand in hand; these days they are usually made by different sets of people. Sometimes the theorists are ahead, with correct predictions, but occasionally the experimentalists spring a surprise that sends the theorists back to the drawing board. I do not have time to discuss the experimental data supporting the theoretical ideas that I will mention; some of them have been described in earlier chapters. I will, however, take care to distinguish those ideas that have some appreciable experimental support and are probably right, or nearly right, from those ideas that are highly speculative and must be tested in future experiments. It is very important to draw that distinction because the two kinds of ideas may sound equally crazy.

In elementary particle theory one assumes the validity of three principles that appear to be exactly correct.

(1) Quantum mechanics, that mysterious, confusing discipline, which
none of us really understands but which we know how to use. It works perfectly, as far as we can tell, in describing physical reality, but it is a 'counter-intuitive discipline', as the social scientists would say. Quantum mechanics is not a theory, but rather a framework within which we believe any correct theory must fit.

(2) Relativity. Seventy-five years after Einstein's first work on relativity, we have no reason to doubt it.

(3) Causality, the simple principle that causes must precede their effects.

These three principles together constitute the basis of Quantum Field Theory and all respectable speculation in our field is carried out in the context of quantum field theories. Here each force is communicated through the exchange of a quantum; for example, for electromagnetism that quantum is the photon. The quantum field theory of electrons and photons has existed for a little over 50 years and is called quantum electrodynamics. It deserves its nickname of QED because it agrees fantastically well with experiments, to a precision of many decimal places. In QED, as in other quantum field theories, we can use the little pictures invented by my colleague Richard Feynman, which are supposed to give the illusion of understanding what is going on in quantum field theory. In Fig. 8.1, for example, an electron emits a photon which is then absorbed by another electron, giving rise to the electromagnetic force between the two electrons. Strict energy and momentum conservation would appear to forbid the one electron from emitting the photon and the other from absorbing it; however, in the Pickwickian sense of quantum mechanics such happenings are allowed and the effect is a force between the two electrons.

![Fig. 8.1.](image)

Matter as we see it is made of molecules or crystals, and these are made of atoms or ions, which in turn are made of nuclei surrounded by electrons. The nuclei, as we have known for almost 50 years, are made of neutrons and protons. All of these are composite structures (except the electrons) and the proton and neutron are made, in their turn, of quarks. (Quark is an obvious name for the fundamental constituents of the neutron and proton!) The recipe for making a neutron out of quarks is to take one of charge $+2/3$, called a u quark, and two each of charge $-1/3$, d quarks; for the proton just interchange u and d quarks. The total charges add to 0 and +1 respectively. (We use units in which the proton charge is +1; the sign was determined arbitrarily by Benjamin Franklin.)
The u and d quarks are known as 'flavours' of quark and there are other flavours, in addition to these two.

There is another distinguishing characteristic of quarks, known by another pet name, 'colour'. Colour has no more to do with real colour than flavour has to do with real flavour; they are just convenient names for physical variables each with several values. In the case of colour we know how many values: exactly three. So we can name the three colours arbitrarily 'red', 'green', and 'blue', which are supposed to be the primary colours of human vision.

To continue the recipe for building protons and neutrons, the three quarks we take must each have a different colour, and they are assembled in

<table>
<thead>
<tr>
<th>Neutron and proton are made of quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
</tr>
<tr>
<td>Proton</td>
</tr>
</tbody>
</table>

There is one quark in each of three 'colour' states (say: 'red', 'green', or 'blue') and the over-all colour of the proton or neutron must always be neutral (or 'white').
such a way that the colour 'averages out'; the resulting neutron or proton must have no net colour. Continuing the metaphor, it must be 'white'.

The quarks naturally have to be held together by some kind of force, and, in quantum field theory, that force has to arise from the exchange of certain quanta. In this case they are called 'gluons', because they glue the quarks together inside the neutron and proton. Again we can draw a Feynman diagram (Fig. 8.2), showing the exchange of a gluon between quarks.

\[ u_R \quad \text{Gluon} \quad d_R \]

\[ u_R \quad (R \bar{R}) \quad d_R \]

\[ d_G \quad \text{Gluon} \quad d_G \]

\[ d_G \quad (B \bar{G}) \quad d_G \]

**Fig. 8.2.**

The flavour makes no difference because the gluon forces are completely indifferent to flavour. However colour is very important; for different colour situations we have different gluons. There are eight different sorts of gluon corresponding to different colour combinations.

A definite quantum field theory has been proposed over the past ten or fifteen years for the coupling of quarks and gluons; it is called quantum colour dynamics or quantum chromodynamics (QCD) and is closely analogous to QED. So far it seems to be working extremely well and it is probably right. The analogy can be seen in the following way: instead of the electron of QED we have the quarks, with their various flavours and their three colours; in place of the photon, the quantum of QED, we have the eight colourful gluons.

The two theories are actually very similar. QED of course makes use of the quantum version of James Clerk Maxwell's equations for electrodynamics and the equations for QCD are not so very different from Maxwell's. The important distinction is that whereas the photon, responsible for electromagnetism, is itself electrically neutral, the gluons, which carry the colour force, are themselves colourful and couple to that force; this adds a couple of extra terms to the equations, which are then no longer identical to Maxwell's. The solutions are profoundly affected by the existence of these extra terms.

In the case of QCD we know how to solve the equations at very small distances, that is, when the quarks are separated by a distance much smaller than 10^{-13} \text{cm}. (Anything bigger than 10^{-13} \text{cm}, about the size of the proton or neutron, is, in particle physics, a huge distance.) Now at very small distances, deep inside the neutron or proton, the effective gluon–quark coupling strength tends to zero in QCD. The quarks, consequently, act as nearly free in the deep interior of the neutron or proton. This notion of 'asymptotic freedom' suggested by the theory has been amply confirmed by experiment over the past twelve years or so.
The coupling strength, which gets very small as the distance between the quarks gets small, likewise grows much larger as the distance increases, until ultimately we cannot follow it by calculation any more; it becomes so large we no longer know how to solve the equations correctly. Nevertheless at large distances we suppose that the coupling strength keeps on increasing so rapidly that, unlike all other interactions, the force does not decline at large distances. If that is true it would result in the confinement of quarks and gluons. Coloured quarks and colourful gluons would be permanently trapped inside ‘white’ objects like the neutron and proton, and they could never be got out. They could then be detected only indirectly, through experiments on, for example, protons and neutrons, which would act as though made of quarks interacting through gluon forces. In fact that is exactly how neutrons and protons do behave. The indirect detection of quarks, and more recently of gluons, has been carried very far experimentally so that it looks practically impossible now to abandon the notion of a quark. Even the gluon now has very considerable experimental support.

If we are right, indirect evidence is all there ever will be. This of course does not make QCD an unsuitable scientific theory because the predictions are quite definite about how observable objects should behave. Of course some of them still require theoretical work, namely those concerned with the large-distance behaviour.

It should be mentioned that both experimentally and theoretically there is still the possibility that confinement of colour is only approximate, that some small leakage effect permits a detection of individual quarks, and that bulk matter contains a tiny proportion of unconfined quarks. In fact, in one experiment on niobium spheres at Stanford such a result is claimed. If quarks really are sometimes unconfined, that would not only affect fundamental physical theory but lead, most probably, to practical consequences as well. At least one fractionally charged particle would be perfectly stable, because of electric charge conservation, and would have striking chemical properties. It has been debated whether such particles could catalyse thermonuclear fusion. In any case, we can imagine the growth of a prosperous quarkonics industry. However, for the rest of this talk I shall assume that colour confinement is perfect.

We may remark that the old problem of the ‘nuclear force’ is solved in principle in the sense that we now believe the binding of neutrons and protons to form the nucleus is an indirect consequence of the basic quark-gluon interaction, described in QCD. Such a situation is not at all unprecedented: inter-atomic and inter-molecular forces, so dear to the chemists, are of the same kind; they also are not fundamental, but just indirect consequences of electromagnetism, as treated in QED.

Besides the neutron and proton, and the central nucleus made of them, there are also of course the electrons that surround the nucleus to form the atom. Here we turn to another part of the elementary particle system.

The electron does not have colour and does not feel the nuclear force. But
### Table 8.3
Particles and forces

<table>
<thead>
<tr>
<th>Forces</th>
<th>QED Electromagnetic</th>
<th>QCD Colour force</th>
<th>QED Electro-weak or Flavour force</th>
<th>QCD Colour force</th>
<th>Einstein's theory of Gravitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchange quanta, the mediators of quantum field theories.</td>
<td>Name</td>
<td>Photon</td>
<td>( \gamma )</td>
<td>( X^+, Z^0 )</td>
<td>Gluons</td>
</tr>
<tr>
<td></td>
<td>Photon</td>
<td>0</td>
<td>80</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Spin</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Quarks. (3 Colours)</td>
<td>charge ( +\frac{2}{3} )</td>
<td>( u ), ( c ), ( t )</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>charge ( -\frac{1}{3} )</td>
<td>( d ), ( s ), ( b )</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Elementary particles (all spin ( \frac{1}{2} )) and forces they experience</td>
<td>0</td>
<td>( \nu_e ), ( \nu_\mu ), ( \nu_\tau )</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>( -1 )</td>
<td>( e^- ), ( \mu^- ), ( \tau^- )</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Plus antiquarks and antileptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Gravitation couples to energy of massless neutrinos.
Questions for the Future

in a very important sense it has flavour, like the quarks. Just as the u and d quarks are flavour partners, so the electron has a flavour partner, the electron-neutrino, \( \nu_e \). The electron-neutrino, like the electron, lacks colour and feels neither the nuclear force, nor, since it is electrically neutral, the electromagnetic force; it can pass right through the Earth with very little chance of interacting. That stimulated John Updike to write this poem about it:

**Cosmic Gall**

_by John Updike_

Neutrinos, they are very small.  
They have no charge and have no mass  
And scarcely* interact at all.  
The earth is just a silly ball  
To them, through which they simply pass,  
Like dustmaids down a drafty hall  
Or photons through a sheet of glass.  
They snub the most exquisite gas,  
Ignore the most substantial wall,  
Cold-shoulder steel and sounding brass,  
Insult the stallion in his stall,  
And, scorn ing barriers of class,  
Infiltrate you and me! Like tall  
and painless guillotines, they fall  
Down through our heads into the grass.  
At night, they enter at Nepal  
And pierce the lover and his lass  
From underneath the bed—you call  
It wonderful; I call it crass.

The neutrinos do of course interact—they can be produced, and so, by a kind of reverse process, they can be detected. They interact through the weak force, which can cause a neutrino to turn into its flavour partner the electron while a neutron changes into a proton. Actually the basic interaction (Fig. 8.3) involves a d quark turning into a u quark; flavour exchange takes place as the electron-neutrino turns into an electron and the d turns into the u. In a quantum field theory context this occurs with the exchange of a particle called X\(^+\); there is, of course also an X\(^-\). These quanta are heavy, electrically charged and predicted to be found in the next few years in experiments just higher in energy than those being done now. They must be found! These are not hidden particles trapped inside matter; they must be observed individually, or else large numbers of us theoreticians will fall on

* The original reads 'And do not interact at all'. This change is made by scientific licence.
our fountain pens. (For clarity, I should say there are some misguided colleagues who refer to the \(X^+\) and \(X^-\) as \(W^+\) and \(W^-\); this, I'm sure, will stop.)

The electromagnetic and weak forces are 'flavour forces': the electric charge of a particle depends on its flavour; weak forces are flavour exchange forces. Altogether, then, we have a set of flavour forces that we can think of as the electro-weak force. A quantum flavour-dynamics (QFD) has been formulated for the electro-weak interaction; it includes QED and a description of the weak force as well. It has made many successful predictions, for example the existence of a new flavour force, discovered in 1973, in which neutrinos can simply scatter off quarks without exchanging flavour, without turning into electrons. In terms of quantum field theory the neutrino and quark are exchanging another intermediate quantum (of a new weak force) called \(Z^0\) (Fig. 8.4).

Again, the \(Z^0\) is supposed to be a real object with a definite mass, about 90 GeV (nearly 100 times the proton mass) and during the coming decade experiments at high energy are supposed to produce it, otherwise we are in deep trouble. In fact the various laboratories are now disputing which one will have the strongest production of the \(Z^0\) quanta in order to be able to use them to study other things; you see how much confidence they have in us theoreticians!

The proposed quantum flavour dynamics has four quanta: the photon, already familiar, and the other three, \(X^\pm\) and \(Z^0\), soon to be discovered. The theory, QFD, has certain features connected with the violation of symmetry that may require, if not modification, at least further specification. It cries out, in any case, to be imbedded in a bigger and better scheme. But at low energies it is certainly the right theory, or very close to it, and in 1979 Glashow, Salam, and Weinberg were awarded the Nobel Prize for their contributions to its formulation.
Now let us sum up what we have found so far (Table 8.4). There are the two flavours, electron and electron-neutrino, of what are called, misleadingly, leptons; lepton means light in weight but they are not all light, as we shall see. Then there are two flavours of quark, u and d. (See, quark is a much better name because it is not misleading!) Operating on the colour variable we have colour forces carried by colourful gluons and described by QCD. Working across the table are the flavour forces, carried by the photon, for electromagnetism, and by the $X^2$ and $Z^0$ for the weak interaction; all are described within QFD. The quarks and gluons are thought to be confined but all the others must be observable.

Table 8.4

<table>
<thead>
<tr>
<th>Leptons</th>
<th>$e^-$</th>
<th>$\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks</td>
<td>$d^u_{b^0}$</td>
<td>$u^u_{b^0}$</td>
</tr>
<tr>
<td></td>
<td>$d^s_{b^0}$</td>
<td>$u^s_{b^0}$</td>
</tr>
<tr>
<td></td>
<td>$d^b_{b^0}$</td>
<td>$u^b_{b^0}$</td>
</tr>
</tbody>
</table>

Colour forces (QCD) carried by colourful gluons.

Flavour forces (QFD) carried by photon, $X^2$, and $Z^0$.

Why not stop here? For some reason Nature does not find herself satisfied with this relatively brief list of particles. There are other leptons. The muon, which is just like the electron but 200 times heavier, was discovered at Caltech in 1937, was promptly mistaken by theoreticians for something they had been wanting, and caused tremendous confusion for ten years or so. It is accompanied by its own neutrino, labelled $\nu_\mu$.

More recently, in 1975, experiments at SLAC in Stanford, California, discovered the $\tau$-lepton, very heavy, about twenty times the mass of the muon. Its partner the $\tau$-neutrino, $\nu_\tau$, has not yet been demonstrated very well experimentally but no doubt exists. There might even be a few more flavours of leptons, although there are cosmological reasons for believing the list may stop here. As I. I. Rabi said about the muon, ‘Who ordered that?’ We may well ask now ‘Who ordered this replication of families? Why does Nature want so many flavours?’

The quarks are in almost exactly the same situation: we have the u and the d with charges of $+2/3$ and $-1/3$; we know the strange (s) and charmed (c) quarks also have to be there, the s with charge $-1/3$ like the d, and the c with charge $+2/3$, like the u quark. Recently experimentalists discovered, with very little encouragement from theoreticians, another quark, b, with charge $-1/3$, and many people believe, rather plausibly, that the b will have a partner, t, which will have a charge $+2/3$. There will then be three pairs of flavours of quarks and three pairs of flavours of leptons.
In addition to all these of course we must remember the antiparticles. In quantum field theory there is always a symmetry between particles and their so-called antiparticles. And of course the particles are the antiparticles of antiparticles; it is just a reciprocal symmetry. Under this symmetry the electric charge turns into its opposite, the mass remains the same, you have to turn left into right and forward-time into backward-time, but I won’t dwell on these aspects. For some neutral particles, for example the photon, the antiparticle and particle are one and the same; but in most cases particle and antiparticle are distinct objects. For instance the proton is distinct from the antiproton, the neutron is distinct from the antineutron, the quarks are distinct from the antiquarks. The antiproton is made of three antiquarks, as the proton is made of three quarks, and so on.

If we take ordinary matter and replace electrons by their antitelectrons, the positrons, and replace protons and neutrons by their antiparticles we get ‘antimatter’. In isolation, antimatter looks very much like matter, but of course if you brought a lump of antimatter and a lump of matter together they would annihilate with a release of energy, most of it finally assuming the form of photons, neutrinos, and antineutrinos.

In principle, complex antimatter objects could be made. The most complex nucleus that I believe has actually been made at a high energy accelerator is the anti-helium nucleus (or anti-alpha particle), which consists of two antiprotons and two antineutrons. With enough time, trouble, and expenditure, you could in principle make an anti-dust mote, or perhaps even an anti-organism. Here is another poem, this time by a physicist, on matter and antimatter.

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**PERILS OF MODERN LIVING**

by

_Harold P. Furth_

Well up beyond the tropopause
There is a region stark and stellar
Where, on a streak of anti-matter
Lived Dr. Edward Anti-Teller.

Remote from Fusion’s origin,
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from Earth.
Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.

Now why has Nature not taken the trouble to make a lot of antimatter and put it near us somewhere? If there were a lot of anti-stars in the Galaxy, or a lot of anti-galaxies in a cluster, then when matter and antimatter stars or galaxies collide, as ordinary ones sometimes are observed to do, the annihilation would generate radiation that could be detected. From the lack of such radiation it looks as if, at least in our part of the Universe, there is not much antimatter; perhaps nowhere in the Universe is there much anti-matter. An important question is why?

For the first time an answer to that question may now be available. But let me first take up the natural question of why are there so many kinds of elementary particles; this will be the main theme of the rest of this chapter.

One possible and rather obvious answer is that in fact the quarks and leptons are themselves composite. They show absolutely no sign of that so far, but at very high energies they might begin to do so. Until recently, theories that treated them as composite taught us very little, but now somewhat more interesting suggestions are being made, and perhaps we should take the idea more seriously. In the People's Republic of China, under the rule of the notorious Gang of Four (G 4), the belief in compositeness was almost compulsory—not only that but one had to follow an idea attributed to Chairman Mao (based on the thinking of earlier Communist leaders) that underneath each level of reality there exists another level, with the particles being made up of sub-particles in an infinite 'chain of being'. That notion is no longer compulsory in China under the more liberal rule of today's authorities. It might of course be right, but we have no particular reason for thinking so except that it would represent a sort of historical continuity; what has always happened in the past is that apparently fundamental entities turned out to be composed of still smaller objects.

Another possibility is that there is some completely new way of looking at things that will be pointed out by a brilliant young scientist who will show us that we are just asking all the wrong questions. There is a story about Pauli in Heaven, that he was accused of asking the wrong questions. The story was told, while he was still alive, that he died, went to Heaven, and, very impatiently, demanded to see God. After making his way through the bureaucracy he was admitted to the presence of God and immediately asked him why He had made the particles the way He had—in particular why was there a muon? God listened to all of this, naturally with infinite patience, and then delivered a lecture to Pauli on elementary particles. According to the story Pauli is supposed to have nodded, frequently, during the first part of the lecture, even when God said 'The trouble, Pauli, is that you are asking the wrong questions' he still nodded. Eventually, though, as God got into
the deeper mathematics of the theory Pauli began to shake his head, indicating that he found something the matter; presently he couldn’t contain himself any more and he stood up and yelled ‘Aber das ist ganz falsch!’ (That’s completely false!) And he pointed out the mistake.

Let me now consider at some length a third possibility we can envisage, namely, that we can utilize the particles that appear elementary today, along with others, to construct some sort of unified quantum field theory.

We note first that the theory of QCD and the theory of QFD are very similar mathematically; they belong to the same class of theories. They are called Yang-Mills theories after two people who introduced them to physics in the 1950s; some people call them ‘gauge theories’, not a very good name because there are actually other gauge theories. QCD is a Yang-Mills theory with perfect colour symmetry, that is, the three colours are treated in an absolutely symmetrical fashion. In QFD this is not the case; Nature is quite unsymmetrical with respect to the flavours. The photon has zero rest mass while the $X^+, X^-, Z^0$ are supposed to have gigantic rest masses, of about 80 or 90 GeV; the neutrino is massless, or very nearly so, while the charged leptons have considerable mass. So there is a great deal of asymmetry in the case of flavour and none in the case of colour.

Many people are searching for a unified scheme, a sort of ‘Grand Design’ that would embrace flavour dynamics and colour dynamics together, as well as new forces. Unification of colour and flavour would take place in an over-all quantum unified dynamics, which would be a Yang-Mills theory with broken symmetry, like the flavour dynamics but much bigger and including colour. The colour portion would be exactly symmetrical but the rest of the symmetry would be largely broken.

This is the point where I must deliver my warning. From now on we are talking about ideas that are not supported by experimental evidence and could be completely wrong. How is such speculation carried out? Perhaps you have already seen this picture (Fig. 8.5), much publicized in 1979, the centenary of Einstein’s birth.

The picture shows the master at work on his theory... you see how the inappropriate theories are discarded and finally a correct one is found. The most important tool of our trade is the waste basket, into which we throw all the theories which fail to be self-consistent, or fail to be consistent with some well-established body of evidence. The remainder is small, but includes presumably, that which we want to keep.

One problem with unified Yang-Mills theories is that the effective unification between colour and flavour, which have very different coupling strengths, can take place only at a very, very high energy. This is because in quantum field theories coupling strengths change very slowly with energy and in order for weak interactions and strong interactions to come together at some common value of the coupling strengths one has to move over an enormous range of energies, up to something like $10^{15}$ GeV. The most important question about this kind of work is how can we have the nerve to
believe that our physical ideas, developed at lower energies where experimental confirmation is possible (up to energies of 10 GeV or so) could possibly be correctly extrapolated over a factor of $10^{14}$ until we reach $10^{15}$ GeV. Very unlikely, one would think! Nevertheless people try and the results are very interesting. Another question we might ask is what about experimental tests: between present energies and the unification energies what sort of experimental tests can we have? It is difficult to imagine any way in which even the world budget would allow the construction of machines capable of verifying behaviour at $10^{15}$ GeV! We are lucky if we can get to $10^3$ GeV.

Certain experiments performed without accelerators may help to test consequences of a unified Yang-Mills theory. In particular, two cases have been discussed in previous chapters; let me refer to them again. The first has to do with proton stability. In constructing a unified Yang-Mills theory of colour and flavour, it is possible to stabilize the proton, but it takes a certain amount of effort on the part of the theoretician. It is more natural, in such a
theory, for the proton to decay. But of course we all believe, on the basis of extremely sound experimental evidence, even the evidence of our own senses, the evidence of our own existence, that the proton is stable, or nearly so. If the proton decays, but slowly enough, that could be compatible with everything we know.

Now the present upper limit for the decay rate of the proton is near the ridiculously small number of $10^{-20}$ per year. In a unified Yang–Mills theory of colour and flavour, the proton decays at a rate of about $10^{-25}$ per year, not very far below the present experimental limit. Therefore it is worthwhile to try to perform experiments to look for proton decay, to improve the present limit, and see if one actually observes proton decay; such an observation would totally change our impression of what the world is like. Such experiments are being organized in the United States (there is one in a silver mine in Utah and one in a salt mine in Ohio) and there may be experiments soon in Europe as well, perhaps in a tunnel under the Alps. These experiments are supposed to search for an occasional decay of a single proton in a thousand or more tons of water or iron.

Another point, very important, follows if there is proton instability. Suppose you also assume that the evolution of the Universe in its very early moments took place under non-equilibrium conditions and that the so-called CP violation, that is the slight asymmetry that has been observed between matter and antimatter, persists up to very high temperature. Then it has been pointed out that one may be able to construct an explanation of why the Universe seems to consist mostly of matter rather than antimatter. The first person to put these three assumptions together and reach this conclusion was Sakharov, the Soviet physicist who is nowadays noted mostly for activities outside physics. He did this work in 1969 when he had already partially turned from physics to other matters; it was ignored for a long time and only recently has the mainstream of theoretical physics taken it up.

It is now a popular idea that maybe the notion of a unified Yang–Mills theory is right, maybe the proton does decay, and maybe that will help to explain why the Universe is asymmetric between matter and antimatter. But, of course, real conviction depends to a great extent on a successful result of the experimental search for proton decay.

The other experiment is also in a mine, this time a gold mine, the Homestake Mine in Lead, South Dakota, where for many years a team has been searching for neutrinos from the Sun, those self-same neutrinos from the Sun about which John Updike wrote his poem, coming from above during the day and from below at night. Not enough solar neutrinos are found to agree with astrophysical and elementary particle theory. Although the errors are still fairly large, the discrepancy may well be significant. How can we explain the result?

One possibility is that the astrophysical theory of the Sun may have some flaws. The most radical suggestion was that made in desperation by my
colleague Willy Fowler, that the Sun has gone out! If the thermonuclear
reactor in the centre of the Sun had gone out, permanently or temporarily,
we would know that immediately by the cessation of the production of
neutrinos, but it would take a million years or so for the news to reach the
surface and stop the shining of the Sun in electromagnetic radiation. The
proposal was that we are somewhere in that million-year period. When the
news reaches the surface, the Sun would turn off its electromagnetic radia-
tion and we should be left with a really serious energy crisis! One can of
course discuss less drastic modifications of astrophysical theory.

Another possibility is that the experiment is wrong. This is the only team
of experimentalists in the world clever enough to detect one atom that has
been transformed in a car-load of cleaning fluid, and since nobody else can
check their results, they could conceivably be wrong. A clever, but rather
ruthless experimental physicist proposed, presumably in jest, to take into
the mine a very strong radio-active source and, without notifying the mine
authorities, the health authorities, or the miners, place it near the experi-
ment to see if the neutrinos from the source would be properly detected.
Needless to say that hasn’t been done; instead the same team has con-
structed an apparatus that is to be exposed to the accelerator at Los Alamos
to see if the neutrinos there will set it off in the proper way.

Yet another possibility is that there is something interesting in particle
physics that is responsible for the failure to find enough neutrinos. In unified
Yang–Mills theories it can very easily happen that the three neutrinos we
know about don’t have exactly zero rest mass, that is, they don’t travel
always with the velocity of light. They could have very very small rest-
masses, perhaps of about 1 eV, which would have escaped observation.
Not only that, they may have so-called ‘transition masses’, that is to say,
probabilities for transforming from one species into another as they move
through space. If that is true then the electron-neutrinos emitted by the sun
could be transforming themselves into, for example, τ-neutrinos on their
way to the Earth. The ν_e would not be detected by the apparatus in the gold
mine and in that way one could account for a modest factor of suppression in
the number of neutrinos observed, using this very interesting phenomenon
of ‘neutrino oscillation’. There are now experiments under way at various
nuclear reactors to search for neutrino oscillation.

So although the unified theories deal with unification at fantastically high
energies, they have a certain number of rather interesting consequences that
might be detectable at ordinary energies and might in fact revolutionize our
ideas about the Universe.

What about more general unification? Let me say just a few words about
that, to summarize it. I have to add one more bit of physics. Each kind of
particle has a definite amount of ‘spin’ angular momentum; in quantum
mechanics that is quantized and in the appropriate units the spin is 0, 1/2,
1, 3/2, 2... and so on; an integer or half integer.

The photon, the X^± and Z^0, and the gluons all have spin 1; the quarks and
the leptons all have spin 1/2. In fact all the elementary particles that we have mentioned so far have spin 1/2 or 1.

However, there are reasons to discuss also spin 0 and spin 2. The spin 0 particles come in from spontaneously broken symmetry, discussed by Chris Llewellyn Smith and Abdus Salam in chapters 3 and 5. In theories with spontaneously broken symmetry we try to use exactly symmetrical equations to produce unsymmetrical effects, a very subtle process; the mechanism for achieving this requires the presence of spin 0 particles. In today’s theories they are introduced in what I consider to be a rather deplorable way; the spin 0 particles are dragged in, ad hoc, with numerous arbitrary parameters being adjusted to explain some of the quantities we observe. I think that can’t last. To avoid such arbitrariness in the discussion of these spinless particles some theorists are trying to explain them as bound states of other particles, perhaps new ones, or to find some symmetry principle that requires their existence.

There is also a very important reason for studying spin 2, namely to incorporate Einstein’s theory of gravitation, which he liked to call General Relativity, into the framework of quantum mechanics. This requires the graviton, the quantum of gravitation, and because of the nature of Einstein’s theory the graviton must have spin 2. It is difficult to find the graviton experimentally because the gravitational coupling is so small for little bits of matter; for a whole planet, of course, there is a sizeable coupling to gravity but an electron, with its tiny mass, couples very weakly to gravity. Consequently the experimental discovery of the graviton must be postponed to a later age. Nevertheless, if you believe both Einstein’s theory of gravity and quantum mechanics you must have a graviton; therefore some theorists have engaged in an even more ambitious unification scheme that involves putting gravitation (Einstein’s theory) as well as the colour and flavour forces all together in one theory. That theory should include not only all the quanta but also the quarks and leptons as well as the spinless particles we believe we need for spontaneous symmetry breaking. If some or all of these particles are composite, then their fundamental constituents would be described by the theories. The aim is to incorporate all fundamental objects, including the graviton, into one single, truly unified theory. One makes use of ‘super-symmetry’, a symmetry connecting particles of different spins, to relate the various elementary particles to one another.

The biggest and best such theory to have been found so far is called \( N = 8 \) super-gravity and contains fundamental fields corresponding to:

1 graviton of spin 2;
8 new objects of spin 3/2, called gravitinos;
28 quanta of spin 1;
56 particles and antiparticles of spin 1/2;
and 70 objects of spin 0, possibly useful for symmetry breaking.

The gravitinos of spin 3/2 are a welcome addition from the point of view of
simplicity: when we discussed only spins 2, 1, 1/2, and 0 we had an ugly gap at spin 3/2.

Now, if we try to interpret the 28 quanta of spin 1 as including the gluon, the $X^\pm$, the $Z^0$, and the photon, we find that the mathematics is too restrictive. At least the $X^\pm$ would have to be left out. Likewise, if we try to interpret all or most of the 56 particles and antiparticles of spin 1/2 as leptons, antileptons, quarks, and antiquarks, we find that we cannot accommodate enough flavours to agree with the observed list.

The $N = 8$ super-gravity theory comes remarkably close to fulfilling our present-day version of Einstein’s dream of unifying all the forces of Nature in a single equation. However, it does not quite work if we try to identify today’s elementary particles of spin 1/2 and spin 1 with those of the theory. Either we have to look further for the right unified field theory or else we have to admit that some or all of our ‘elementary particles’ are not really fundamental.

Let me mention that in super-gravity, or any unified scheme including Einsteinian gravity, the energy of effective unification is even higher than before; we need even more nerve to believe in this kind of theory than we did for the unified Yang–Mills theory unifying just colour and flavour forces; here we are extrapolating from the 10 GeV or so of present experimental knowledge to something like $10^{19}$ GeV, an even larger factor.

Where do we stand then, in the quest for unity in the description of the elementary particles that make up the world? Some immediate issues, as I see them, are the following.

I would like to know, better than the present theories tell us, what is the right way to look at spontaneous symmetry breaking. If we really have spontaneous symmetry breaking induced by spinless particles, are those introduced into the theory as elementary objects? If so, do they have a reason for being in the theory because of something like supersymmetry or, if not, do they result from the binding of other particles in the theory? I find it very hard to believe that they need to be dragged in ad hoc with numerous arbitrary parameters having to be adjusted to fit the data.

What produces this curious replication of quark and lepton flavours? Why do we have not just $u$ and $d$ quarks, but also $c$ and $s$, $b$ and probably $t$ quarks? Why, for the leptons, do we again have three pairs of flavours: electron and its neutrino, muon and its neutrino, $\tau$ and its neutrino? Does the replication, somehow, go on further? We note that cosmologists don’t want us to have more than three or four neutrino types.

How do we explain the curious mass spectrum of the quarks and leptons: light ones, medium light ones, heavy ones? Where do these strange mass ratios come from?

We really have, I think, very little idea of the answer to any of these questions. The big questions, of course, relate to unification and to the identification of fundamental entities. Will the attempts at over-all unification or the slightly more modest attempts at unification without gravitation...
succeed? In a proposed unified theory can we figure out the relation between the elementary objects in the theory and the particles that would appear at present or future experimental energies as elementary? Not only composite objects but other particle-like solutions of the fundamental equation may masquerade as elementary and produce confusion. Nevertheless we still hope to discover a single elegant mathematical equation with a unique structure that will account for the three colours, the right number of flavours, and all the other special features of particle physics. It would be an equation for a giant superfield with many components representing different elementary entities unified by a basic symmetry of Nature. If our efforts succeed, then simplicity will lie not in economy of particles but in economy of principle.

Let me finish by saying that it is a curious thought that we might, conceivably, come to the end of the description. It is much easier to imagine an unending search, level after level of reality, as in Chairman Mao’s ‘straton’ picture. But we can try to envisage the possibility of solving completely the problem of the fundamental physical laws.

What would it be like? We can only describe it operationally, at least those of us who are not philosophers. Operationally it would look like this: with further experimental support for today’s theories at present energies, we theoreticians would propose a unified theory of everything, compatible with all the known facts and predicting a number of new ones. Experiments would be done over a reasonable period of time and costing a reasonable sum of money and would confirm the theory. This would continue for a while, with no exceptions being found. (Of course that has never happened before but it is conceivable.) Eventually, there would be a limit to human patience and to the resources that would be expended in trying further to check this successful theory. Humanity would proclaim it to be the final fundamental physical theory!
Glossary and notes

These definitions and notes summarize and, in some cases, expand on explanations given in the main text. The aim is to help the reader to gain a qualitative feeling for unfamiliar terms and concepts. Words which are themselves treated elsewhere in the glossary are written in italics.

Angular momentum measures the tendency of a body to maintain its state of rotational motion. It is a vector quantity with a direction along the axis of rotation chosen so that the rotation appears clockwise when viewed in that direction. It is conserved and is quantized in units of $\hbar$. (See also spin.)

Annihilation. The process in which a particle antiparticle disappear and their total mass is converted into energy or new particles and antiparticles.

Antiparticle. A particle and its antiparticle have certain opposite attributes such as sign of electric charge, magnetic moment, flavour (e.g. strangeness of $+1$ or $-1$), lepton number, baryon number, etc. But mass, spin, and lifetime must be identical. Normal matter is composed of protons, neutrons, and electrons; antimatter would be composed of the corresponding antiparticles: antiprotons, antineutrons, and antielectrons, or positrons. The choice of which to call 'particle' is a matter of convenience and the antiparticle of the antiparticle is the particle. In certain cases, for example the photon and neutral pion, the two conditions are not distinguished; such particles are their own antiparticles.

Baryon. One of the two sub-classes of the hadrons. The lightest baryon state is the proton which is apparently stable; its lifetime is at least $10^{30}$ years. This stability, which may not be absolute, is associated with a rule called conservation of baryon number, $B$; baryons and antibaryons have opposite baryon number ($+1$ or $-1$) and the total baryon number is a constant, so they can be destroyed (as in annihilation) or created only in baryon plus antibaryon pairs. Baryons have an internal structure containing 3 quarks, each of baryon number $1/3$; antibaryons contain 3 antiquarks of baryon number $-1/3$.

Big Bang. See Expansion of the Universe.

Black hole. A source of gravitational field so intense that photons (light rays) cannot escape.

Boson. The name given to particles which do not obey the Pauli exclusion principle. All bosons have integer spin ($0, 1, 2, \ldots$) in units of $\hbar$. Examples are the photon, of spin 1, and all mesons.

C. Charge-conjugation. The operation which transforms particles into antiparticles and vice-versa.

c. The speed of light: 186 000 miles/s or $2.998 \times 10^5$ km/s.

Charge. Electric charge is the source of the electromagnetic force. There is only one sort of electric charge and, by convention, that carried by the proton is defined as
positive while the electron carries the anti-charge, equal in magnitude but negative in sign. Electric charge is conserved and is quantized, that is it only occurs in Nature in amounts which are integer multiples of the magnitude of the electron’s (or proton’s) charge, e. The only exceptions occur for the quarks which have charges of 2/3 and 1/3 of e, but these, it is believed, are permanently confined within the hadrons. The electric charge determines the strength of the electric force between two charge-carrying bodies and it is to the charge that the exchanged virtual photon mediating the force couples. By analogy the word charge is often used for the equivalent concept in other forces as, for example, in ‘colour charge’ for the strong force. In particle physics the magnitude of the electron’s charge is adopted as the unit of electric charge; in standard units it is $1.602 \times 10^{-19}$ coulomb.

**Chiral.** The name given to an approximate hidden symmetry—see chapter 3, page 69.

**Colour** is an attribute of quarks (and has no connection whatever with the normal meaning of the word). There are three varieties of colour (and three anti-colours carried by the antiquarks). It is believed to be the source, or charge, of the strong force as described by the theory called quantum chromodynamics or QCD.

**Conservation law.** A quantity is said to be conserved if, within a system free from external interference, it remains constant in time. For example the total electric charge (the sum of all positive charges minus the sum of all negative charges) of an isolated system must remain constant.

**Cosmic radiation.** A continuous rain of particles arriving at the Earth from outer space. A low-energy component originates in the Sun but the more energetic ones, (90 per cent protons, 9 per cent helium nuclei, 1 per cent heavier nuclei) have their source in poorly understood astrophysical processes elsewhere in the Galaxy or, for those of highest energy, perhaps in other galaxies.

**Coupling.** A term used to describe the interaction between the exchange particle of a field (e.g. virtual photon) and the particle experiencing the force (e.g. electron); hence also coupling constant, specifying the strength of the interaction.

**CP.** A combination of the two transformations C and P carried out one after the other in either order.

**Cross-section.** A measure of the probability for a given process to take place. The concept is a very simple one: the chance that a random dart-thrower will hit the dart board is proportional to the area of the board. Roughly 1600 cm$^2$, but his chance of hitting the ‘bull’s-eye’ is more than 1000 times less since its area is only a little more than 1 cm$^2$. Typical cross-sections in particle physics are: $3 \times 10^{-26}$ cm$^2$ for the interaction of two high-energy protons, which is comparable to their actual geometric ‘target area’; or $10^{-39}$ cm$^2$ for a 10 GeV neutrino to interact with a proton, showing that the neutrino, which can only interact through the weak force, will on average pass through about $10^{11}$ protons before anything happens. The standard unit for cross-section is the barn (as in ‘barn door’) which is $10^{-24}$ cm$^2$; a more useful size for particle physics, at least for strong interaction processes, is the millibarn, mb, $10^{-27}$ cm$^2$.

**Density of states factor.** A particle emitted in a reaction may have one of many possible directions in space and a range of possible values of momentum. In quantum mechanics the probability for the reaction to take place is proportional to the
‘volume’ defined in an abstract space, formed from the three dimensions of ordinary space and the three corresponding components of momentum, accessible to each of the particles emitted. This space is called ‘phase space’, or ‘momentum space’, and the number of possible states is the accessible volume divided by the minimum ‘volume element’ in this space which is $h^3$.

$e$. The magnitude of the electron’s electric charge.

*Electron*. The electron is a member of the *lepton* class of particles and is the chemically active component of atoms, bound by electrostatic attraction to the central nucleus. It carries a negative electric charge, $e$, of $1.602 \times 10^{-19}$ coulombs, its mass $(m_e)$ is 0.511 MeV/c$^2$ (or $9.1095 \times 10^{-28}$ gm), it has a spin of $1/2\hbar$, and a magnetic moment of $-1.00115965241 \ (e\hbar/2m_e)$ which agrees, to the last decimal place, with the value expected for a point-like, structureless particle. Because there is no less-massive particle which carries electric charge the conservation of electric charge requires the electron to be stable.

*Energy*. Energy is an agent, or a product, of change: either it is required to make changes occur or it is released when they happen. Mass is equivalent to energy, a sort of stored energy with a very high conversion efficiency: $E = mc^2$. All processes of change are in fact transformations between mass and energy brought about through the agency of one of the four basic forces in Nature and the total mass-energy of an isolated system is conserved. The standard scientific unit of measure for energy is the joule; a 100 watt light bulb consumes 100 joules of energy every second. But the joule is too big to be useful in atomic and particle physics where we use instead the electron-volt, eV. One eV is the energy acquired by a particle carrying a positive electric charge, equal in magnitude to that of an electron, in falling through a potential difference of 1 volt. 1 eV is equivalent to $1.602 \times 10^{-19}$ joules. In fact, for particle physics, the most convenient units are $10^4$ eV (1 MeV) and $10^9$ eV (1 GeV).

*eV, electron-volt*. See Energy.

*Expansion of the Universe*. Measurements of the wavelengths (colour) of light from distant galaxies show the emission spectra characteristic of specific atoms to be shifted towards longer wavelengths, that is, towards the red end of the spectrum. This red shift is believed to be a Doppler effect, like the fall in pitch of a train whistle as the train rushes past and speeds rapidly away. The red shift shows that most of the galaxies are receding from each other, the Universe is expanding. The speed of recession is greatest for the most distant galaxies and is equal to the distance multiplied by the Hubble constant: about 20 km per second per million light-years. Allowing for some uncertainty in the Hubble constant and for the speed of recession to have been somewhat greater in the past, this implies that the matter in the Universe originated from the same place in a ‘Big Bang’ between 10 and 20 times $10^9$ years ago.

*Fermi interaction*. The first, and very successful, theory of the weak force, due to Fermi.

*Fermion*. The name given to particles which obey the *Pauli exclusion principle*. All fermions have half-integer ($1/2, 3/2, 5/2 \ldots$) spin in units of $\hbar$. Examples are the electron and proton with spin $1/2$, and the $\Delta^-$ baryon state with spin $3/2$.

*Field*. The region of influence of a force; for example the electric field surrounding an electric charge. In quantum field theory the force is propagated by exchange of particles: the field quanta (e.g. photon, the quantum of the electromagnetic field).
Glossary and notes

Fine structure constant, \( \alpha \). This is the quantity \( e^2/\hbar c \), a dimensionless number with the value 1/137.036. Its name derives from the fact that it determines the magnitude of the splitting, or fine structure, of atomic energy levels caused by the electron’s magnetic moment. In quantum electrodynamics its value is a measure of the strength of the interaction between two electronic charges (\( e \)) arising from the exchange of a single virtual photon. The importance of this number, a dimensionless quantity formed from the three fundamental quantities \( e, \hbar \), and \( c \), strongly suggests that there must be a fundamental relationship between them.

Flavour. The quality which distinguishes different types of quark: up, down, strange, charmed, bottom (or beauty), and (yet to be discovered but strongly anticipated) top (or truth). The term can be extended to include, as additional flavours, the six types of lepton: electron and electron-neutrino, muon and muon-neutrino, tau and tau-neutrino. Flavour and electric charge are related. Quark and lepton flavours and charges can be changed by the weak interaction and the electro-weak theory which unifies the weak and electromagnetic forces is also called quantum flavour dynamics, or QFD.

Gauge transformation. In an electric field there is no way of defining, no way of measuring, an absolute value for the electrostatic potential; all phenomena are invariant to global changes in the value of the potential. This is a kind of gauge invariance and in the case of electrostatics it can be shown that the law of conservation of electric charge is a consequence of this symmetry. In quantum field theory there is another form of gauge invariance which has to do with the phase of the functions describing particles and their propagation (the phase determines the state of the wave associated with the propagation of a particle, say ‘crest’ or ‘trough’, at a chosen reference point). There is no way to measure an absolute phase and so the theory is required to be invariant to operations which change the phase. In fact the most interesting, and very restricting, form of gauge invariance is not global, but local; that is, invariance is required to phase changes which may differ from point to point and at different times. The establishment of a local gauge symmetry requires the existence of a force, called a ‘gauge force’ mediated by exchange of ‘gauge particles’. The word ‘gauge’ was originally introduced by Hermann Weyl in the context of a theory requiring invariance to certain changes in the scale of space, like the choice of different ‘gauge blocks’ used for calibration by machinists. It no longer has this significance in modern theories but the name remains.

Gluon. The field quantum or exchange particle mediating the postulated ‘colour force’ which binds quarks to form hadrons and which is the primary form of the strong force. Quarks carry one of three colours and antiquarks the corresponding anti-colours. The colour force is propagated by the exchange of coloured gluons: they form a set of eight, corresponding to eight different colour plus anti-colour combinations belonging to an octet multiplet of the symmetry group SU(3). The three colours and three anti-colours can also be combined in a ninth way, to form a singlet of SU(3), but this is ‘white’, or neutral in the colour charge and so plays no part in the force. The SU(3) symmetry of colour is exact and free gluons would have zero mass, however, like quarks, they are believed permanently confined within hadrons. The gluons have spin 1\( \hbar \), zero electric charge, and no electromagnetic or weak interaction.

Graviton. The quantum of the gravitational field. In a quantum field theory of gravity the force would be propagated by the exchange of a graviton, a particle with zero mass, zero charge, and spin 2\( \hbar \).
\( h, \ h \) Planck's constant \( h = 6.626 \times 10^{-34} \) joule seconds or \( 4.136 \times 10^{-11} \) MeV seconds. The magnitude of this quantity determines the scale of phenomena for which ordinary mechanics is no longer a good approximation and must be replaced by quantum mechanics. It has the same dimensions as angular momentum which is quantized in units of \( h \), equal to \( h/2\pi \).

**Hadron.** The class of particles which experience the strong force. These are the baryons, composed of three quarks, and the mesons, composed of a quark and an antiquark.

**Heisenberg's uncertainty principle.** See chapter 2, page 39.

**Intermediate vector bosons.** These are the three spin 1 particles acting as mediators of the weak force: \( W^+, W^- \) and \( Z^0 \) (Note: in chapter 8, Gell-Mann prefers the letter X to denote the Ws.) In the electro-weak theory of Salam and Weinberg the \( W^\pm \) and \( Z^0 \) masses are predicted to be about 80 GeV/c^2 and 90 GeV/c^2, respectively.

**Lepton.** The class of point-like particles with spin 1/2 which do not experience the strong force. There are three pairs of leptons: electron and electron-neutrino, muon and muon-neutrino, tau and tau-neutrino and also the corresponding three pairs of antileptons. The reason for three pairs of leptons is not understood. Neither is it known why there are three pairs of quarks (one of which is still to be discovered) but there are good reasons to expect the same numbers of both lepton and quark pairs. For each of the three families there is a lepton number, \( L \), which appears to be conserved just as baryon number is conserved.

**Lepto-quark.** The name sometimes used for the mediators of the postulated electro-nuclear force in the 'Grand Unified Theory' which is an attempt to unify the electromagnetic, weak, and strong (colour) forces. Their mass is supposed to be about \( 10^{15} \) GeV, they have spin 1 and are usually denoted by the letter X (except in chapter 8 where Gell-Mann uses X for the mediators of the electro-weak force).

**Lifetime.** The spontaneous decay of radioactive nuclei, or of unstable particles, is characterized by the average time before decay or mean lifetime. The distribution in actual lifetimes for a large sample of the same state is exponential. If \( N_0 \) are present at time zero then there will be a number \( N = N_0 e^{-\lambda t} \) after a time \( t \), where \( \lambda \) is the mean lifetime.

**Light year.** Astronomical unit of distance equal to the distance travelled by a light ray in one year: \( 9.46 \times 10^{12} \) km.

**Magnetic moment.** A rotating body carrying electric charge, such as an electron orbiting in an atom or a spinning particle or nucleus, generates a magnetic field rather like that of an ordinary bar-magnet. The familiar magnetism of iron has its source in the magnetic moment associated with the intrinsic spin of the electron. The strength of such a source of magnetism and its direction (pointing in the same or the opposite direction as the spin) are specified by the magnetic moment. The usual unit is the magneton, \( eB/2mc \), where \( m \) is the mass of the particle.

**Mass** is a measure of inertia, that is, of the reluctance of a body to change its motion; the force required to achieve a given acceleration is proportional to mass. The mass of a particle depends on its speed relative to the observer, thus when a particle's mass is given it is understood that this is the value which would be obtained under
conditions (in a 'frame of reference') in which its speed is zero. This is called the 'rest mass', $m_0$. Then, at a speed $v$ the 'relativistic mass', $m$, is given by:

$$m = m_0 \sqrt{1 - v^2/c^2}.$$  

So, as long as $v$ is very much less than $c$ the relativistic mass and the rest mass are the same, which is the case for all situations of interest outside a particle physics laboratory, and the reason that Newtonian mechanics works so well is that $c$ is a very large number. Mass and energy are equivalent; the total energy of a particle is given by $E = mc^2$, where $m$ is the relativistic mass, and $E$ is the sum of the kinetic energy (that associated with the motion) and the rest mass energy $E_0 = m_0c^2$. Thus energy also has inertia; for example, a photon of energy $e$ has a relativistic mass of $e/c^2$ and behaves like a particle with this mass in, say, a collision with an electron. The rest mass of the photon is zero ($m_0 = 0$) but there is no physical meaning to a frame of reference in which the photon, or any particle of zero mass, is 'at rest': its speed is always that of light, $v = c$. Mass also features in physics in another, and seemingly quite different way: it is the charge for the gravitational force. Thus the inertia of energy also places it under the influence of gravity. The present attempts to build a unified theory of the forces are based on fundamental symmetries which require all particles to be massless (i.e. zero rest mass). In these theories mass is introduced by 'symmetry breaking' mechanisms which are among the least well understood corners of the present scene; the very origin of mass is one of the profoundest mysteries and one which seems unlikely to be solved until the relationship of gravitation to the other forces is properly understood. The standard unit of mass is the kilogram (kg) but in particle physics it is more convenient to use a much smaller unit derived from that of energy: eV/c^2. In these units the mass of the electron, for example, is 0.51 MeV/c^2. In practice the speed of light, $c$, is often set to unity and then the mass unit is written in eV (or MeV or GeV).

**Meson.** One of the two classes of hadrons (the others are baryons) these are particles with integer spin (0, 1, 2, ...) in units of $\hbar$ and are composed of one quark and one antiquark. There is no conservation law for mesons: they may be created singly and all are unstable.

**Momentum.** The product of mass and velocity, momentum is a vector with the same direction as the velocity. It measures the inertia of a body in motion and the force required to change such motion is proportional to the rate of change of the momentum (equal to the mass times the acceleration). Like mass-energy it is a conserved quantity with the added requirement that the momentum, say before and after a collision of two billiards balls, must balance in every direction.

**Neutrino.** A neutral lepton. Three varieties are known: the electron-neutrino, muon-neutrino, and tau-neutrino. They have spin $1/2$ and experience only the weak interaction. It is usually assumed that the neutrinos have zero mass but there is no understanding of why this should be and a recent experiment, yet to be confirmed, suggests the mass of the electron-neutrino is between 14 eV/c^2 and 46 eV/c^2. The experimental upper limits on the muon-neutrino and tau-neutrino masses are 0.57 MeV/c^2 and 250 MeV/c^2 respectively.

**Neutron.** The neutron is the neutral companion of the proton with which it forms the nuclei of atoms. It is a baryon with spin $1/2$ and a mass of 939.57 MeV/c^2. It has a size of about $10^{-13}$ cm, a magnetic moment of $-1.913 \, (e\hbar/2M_c)$ and its quark composition is (uud).

**Nucleon.** Neutron or proton.
Numbers. To cope in a concise way with the very large range of magnitudes found in physics numbers are expressed powers of ten, rather than using long strings of zeros. A number written as $10^n$ is the same as $1$ followed by $n$ zeros. Thus $10^2 = 100$, $10^5 = 1000000$; ten thousand million (the approximate age of the universe in years) is $100000000000000 = 10^{18}$. The number $299792458$; the speed of light in metres per second, is $2.9979 	imes 10^8$. Numbers less than 1 are written using a negative sign in front of the $n$; so $10^{-2}$ is $1$ divided by $100$, that is, $1/100$ or $0.01$; $10^{-1}$ is $1/1000000$ or $0.000001$. The mass of the electron expressed as a fraction of the proton mass is $5.446 	imes 10^{-4}$.

$P$. The parity transformation, which is equivalent to reflection in a mirror (plus a rotation).

Pauli’s exclusion principle. This principle was first deduced empirically by Pauli from an examination of atomic spectra. Certain transitions are systematically absent, all of them involving energy levels of the atom in which two electrons would have been in exactly the same physical state. Pauli concluded that electrons are indistinguishable one from another and, in particular, that two, or more, were forbidden to occupy the same state of motion. The exclusion principle applies to all particles of half-integer spin, or fermions, but not to particles of integer spin, the bosons, any number of which may occupy the same physical state.

Photon. The quantum of the electromagnetic field. Virtual photons mediate the electromagnetic force; real photons transmit the energy of electromagnetic radiation. The photon has zero electric charge, spin 1, zero mass, and is always moving with the speed of light, $c$. If the photon had mass this would result in small departures from the expected fall-off in strength of an electromagnetic field with distance from its source. The current best experimental upper limit to the mass of the photon is $8 	imes 10^{-50}$ gm, or $4 	imes 10^{-16}$ eV/c$^2$; this astonishingly small number is derived from the analysis of measurements of the shape of the magnetic field of the planet Jupiter, obtained during the Pioneer 10 fly-by in 1973.

Pion. The pion, or $\pi$-meson, was the first meson state to be discovered and was identified with the exchange particle predicted by Yukawa as mediator of the nuclear force, binding protons and neutrons in the nucleus. Its exchange, as a virtual state, contributes to this force but the basic strong interaction is now thought to be due to the exchange of coloured gluons between quarks.

Planck mass. The effects of gravity are felt in the macroscopic world of large masses and distances. The smallness of Planck’s constant ensures that quantum effects are significant only for atomic and sub-atomic phenomena where, on the contrary, gravitational effects are negligible. The gravitational force between two masses at a given separation is proportional to Newton’s universal constant of gravitation, $G$, whose value is $6.67 	imes 10^{-11}$ cm$^3$/gm s$^2$. The value of $h$ is $1.05 	imes 10^{-27}$ gm cm$^2$/s. To obtain a guide to the scale of phenomena at which gravitation and quantum effects may ‘meet’ we can, from $G$, $h$, and the speed of light $c$ ($2.998 	imes 10^{10}$ cm/s), calculate a mass:

$$M_P = \sqrt{(hcG)}.$$ 

This is called the Planck mass and its value is about $2 	imes 10^{-5}$ gm. It is very small and for masses greater than this quantum effects in gravitation are negligible. However, looked at from the viewpoint of particle physics this is the huge mass of $10^{19}$ GeV/c$^2$ and warns that when we consider masses, or equivalent energies, approaching this then gravitational effects can no longer be ignored. For time intervals less than $h/M_P c^2$, that is about $10^{-44}$ seconds, Heisenberg’s uncertainty principle allows
vacuum fluctuations to reach the Planck mass within regions of space smaller than $c \times 10^{-44}$, or about $10^{-33}$ cm. Within such minute intervals of space-time both gravitation and quantum effects are expected to be significant.

**Planck's constant.** See $h$.

**Positron.** The antiparticle of the electron. It has the same mass as the electron, electric charge of equal magnitude but positive in sign instead of negative, spin 1/2 $h$ and magnetic moment opposite in sign to the electron's.

**Proton.** The nucleus of the hydrogen atom and, with the neutron, constituent of all atomic nuclei. It is a baryon of mass 938.28 MeV/c^2 (or $1.67 \times 10^{-24}$ gm), spin 1/2 $h$, positive electric charge equal in magnitude to the electron's charge ($e$), and a magnetic moment 2.79 ($e\hbar/2M_p c$). If it were a structureless, point-like particle the magnetic moment would be close to 1. Its size is about $10^{-13}$ cm and it has three quark constituents: (uud). The experimental upper limit for any difference in magnitude of the proton and electron charges is about $10^{-31} \times e$.

**Quantum.** A small, discrete quantity, usually of energy or angular momentum. For example, the energy carried by a photon is $E = hv$, where $v$ is the frequency of the associated electromagnetic radiation.

**Quantum mechanics.** The set of rules and procedures for describing and predicting the behaviour of matter. Newtonian mechanics, familiar as a prescription for calculations dealing with everyday phenomena, is strictly an approximation which becomes inadequate at atomic and sub-atomic levels where Planck's constant, $h$, is no longer small enough to be ignored. An alternative term sometimes used is 'wave mechanics' because there are mathematical similarities to the equations describing wave propagation.

**Quark.** Quarks are believed to be the basic constituents of all hadronic matter, in particular of the protons and neutrons which constitute the nuclei of atoms. They have spin 1/2 $h$, fractional electric charge, and five different flavours are known. A sixth flavour probably exists since there is good reason to believe they form flavour-pairs like the leptons. Quarks also carry one of three colours. There is a corresponding set of five, or six, antiquarks. Their attributes are summarized in Table G.1.

### Table G1

#### Quarks and antiquarks

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Antiquarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flavour pairs</strong></td>
<td><strong>Colour triplets</strong></td>
</tr>
<tr>
<td>up</td>
<td>$u_u$</td>
</tr>
<tr>
<td>down</td>
<td>$d_u$</td>
</tr>
<tr>
<td>charmed</td>
<td>$c_u$</td>
</tr>
<tr>
<td>strange</td>
<td>$s_u$</td>
</tr>
<tr>
<td>top(?)</td>
<td>$t_u$</td>
</tr>
<tr>
<td>bottom</td>
<td>$b_u$</td>
</tr>
</tbody>
</table>


Relativistic. The term used to refer to a situation in which particle speeds approach the speed of light.

Scattering. In particle physics this describes the deflection in the path of a particle by collision with a nucleus or other particle.

Spin. Most particles spin like a top. This is an intrinsic angular momentum as distinct from 'orbital' angular momentum which, for example, may be associated with the motion of an electron in an atom or the relative motion of quarks inside a hadron. Spin can take half-integer \((1/2, 3/2, 5/2, \ldots)\) or integer \((0, 1, 2, \ldots)\) values of angular momentum (in units of \(\hbar\)) whereas only integer values are possible for orbital angular momentum.

Strong force. The force responsible for binding protons and neutrons to form nuclei (sometimes called the nuclear force) and binding quarks to form hadrons (including the proton and neutron).

\(SU(3)\). The name for a particular group of symmetry transformations acting on a set of three entities. Larger ensembles of entities which are also symmetric to the same group of transformations are sometimes referred to as multiplets. Multiplets of the \(SU(3)\) symmetry group include ones containing 8 and 10 entities. Examples are the baryon multiplets of size 8 and 10 made up from the 3 quarks u, d, and s; this symmetry is only approximate. An example of an exact \(SU(3)\) symmetry is that of the 3 colours of quarks with the coloured gluons of quantum chromodynamics (QCD) forming a multiplet of 8 entities.

\(T\). The operation of reversal in time. This was assumed to be an absolute symmetry of Nature until found to be violated, along with the combined \(CP\) symmetry, in neutral K-meson (K+) decay.

Temperature. Within an assembly of particles (e.g. atoms or molecules) if there is no net transfer of energy from any one region of the system to any other the assembly is said to be in thermal equilibrium and all regions are at the same temperature. The temperature of an assembly of particles is determined by the internal energy of the system, that is the energy associated with the particle motions and states of vibration or rotation. The connection between temperature and energy is made through Boltzmann's constant, \(k\), which has the value of \(1.38 \times 10^{-23}\) joules per kelvin or, in the energy units used in particle physics, \(8.62 \times 10^{-5}\) eV per kelvin.

Torr. A unit of pressure. Normal atmospheric pressure at sea level is 760 Torr.

Units. The basic units of length, mass, and time used in this book are as follows.

- **Length:** centimetre, cm; metre, m; kilometre, km; also Ångström, Å is \(10^{-10}\) cm.
- **Mass:** gram, gm; kilogram, kg (see also *mass*).
- **Time:** second, s.

Vector. A quantity with both magnitude and direction. Common examples are wind velocity (55 m.p.h. from the south-west) or force (the tension in a fishing line). In particle physics the word is also used to denote particles of spin 1 with properties under the spatial transformations of rotation and reflection the same as those of a vector in three dimensions.
W. The letter usually used to denote the charged mediators ($W^\pm$) of the weak force. (Note: in Chapter 8 Gell-Mann uses the letter X instead.) Its mass is predicted to be about 80 GeV/c$^2$.

*Weak force.* The force responsible for radioactive decay of nuclei with the emission of an *electron* and an antineutrino (or a *positron* and *neutrino*).

X. See *lepto-quark* (and $W$).

Z. The letter used to denote the neutral mediator of the weak force ($Z^0$). Its mass is predicted to be about 90 GeV/c$^2$. 


Bibliography

A selection of books and articles for further reading. Most of those in section 5 require familiarity with particle physics or cosmology and contain references to original sources.

1. Books for the general reader.
   (Mysteries of relativity and quantum mechanics are illustrated by Gamow's imaginative construction of a dream world in which the velocity of light is much less, and the Planck's constant much bigger, than in the real world.)
   (Although not up to date this is a very readable introduction to the formation of the elements in the early Universe by one of the originators of this idea.)
   (Story, with many illustrations, of the construction of the CERN 400 GeV proton accelerator.)
   Segrè, E. From X-rays to Quarks—modern physicists and their discoveries, W. H. Freeman, 1980.
   (An outstanding book on the Big Bang by one of the winners of the 1979 Nobel Physics Prize.)

2. Introductory books and reviews—a little more technical.

3. Recent Scientific American articles.
Glashow, S. *Quarks with Colour and Flavour*, October 1975.
t'Hooft, G. *Gauge Theories of the Forces Between Elementary Particles*, June 1980.

4. Review articles in *Nature*—these usually include references to original publications.

5. Review articles for physicists, with references to original sources.
(i) Reviews of Modern Physics

(ii) Annual Review of Nuclear and Particle Science
Kleinknecht, K. *CP Violation and K0 Decays*, 26, 1, 1976.
(A source for some results quoted by J. Ellis in chapter 6.)