A great many tacit assumptions are made in science. They are not often called into question unless some difficulty is encountered. It is remarkable, if one looks back, how quickly and how successfully physicists in particular have arrived at important generalizations, often from scant evidence, guided by some widely believed tacit assumptions such as that mathematics is applicable to any physically definable situation, or that the fundamental laws are simple and beautiful — though we are more ready to give up simplicity than beauty, as Dirac has pointed out. When, however, a tacit assumption is found to break down, we consider this to be very revolutionary. Thus classical mechanics, which was tacitly assumed to hold for small distances, had to be replaced by quantum mechanics; and the assumption that arbitrarily large velocities are possible had to be replaced by the assumption of a limiting velocity in relativity theory. After parity conservation was discovered to hold for electromagnetic interactions, it was tacitly believed to hold for all interactions, but this belief had to be given up for the weak interactions.

Questioning a truth is different from doubting it — a subtle difference which is sometimes forgotten. Many tacit assumptions have been often questioned but found to be quite resilient. Without attempting to be exhaustive, I should like to discuss some examples of assumptions which are often taught as if they were self-evident, e.g., the early generalization that the exponent n in Coulomb's law $F = \frac{e_1 \cdot e_2}{r^n}$ is the
integer 2, or that the limiting velocity $c_E$ in Einstein's theory of 
relativity is the velocity of light $c$.\(^1\) In fact, these two assumptions 
are related. Experimentally we cannot show that a number that a priori 
could be anything is an integer, except within some error, nor that the 
mass of the photon is zero (another integer), except that empirically,\(^2\) 
$m_v \leq 4 \times 10^{-48}$ g. Thus we may say that Einstein made the tacit assumption 
that the mass of the photon is zero, which would follow from 
Maxwell's equations or Coulomb's law but cannot be explicitly shown 
experimentally. Certainly $c_E = c$, though not proven explicitly, holds 
well enough that we can usually neglect any possible difference. But it 
is worth keeping in mind that the equality sign used here is not neces-
sarily equivalent to that used to express a mathematical equality such 
as $2^3 = 8$. It might therefore be useful to introduce a sign for empiri-
cal equality, and I propose the sign $\equiv$ (read: empirically equal), 
meaning equal "as far as we can see" (aided, of course, by the best 
available "microscopes"). Thus in Coulomb's law $n \equiv 2$, and in 
Einstein's relativity equations $c_E \equiv c$.

Table 1 (taken from ref. 2) summarizes the many attempts made over 
the years to find out whether the exponent of the Coulomb law deviates 
from 2. It shows experimental limits on $q$, where $n = 2 + q$.

Let us discuss a somewhat different example. Soon after 
A. H. Becquerel discovered the emission of $\beta$ rays from radioactive sub-
stances, he assumed from a rough measurement of their magnetic deflection 
that $\beta$ rays were the same as the electrons that J. J. Thomson had ex-
tracted from atoms. Over the years many people measured $e/m$ with in-
creasing accuracy and were unable, within experimental limits, to
find any difference between $\beta$ rays and atomic electrons. But the question remained whether the identity of these particles could be proved more directly. Pauli's exclusion principle, which states that identical fermions cannot have the same four quantum numbers (three corresponding to spatial coordinates and one to spin direction), provides a powerful tool for checking identity of particles of different origin. In an experiment in which $\beta$ rays were brought to rest in lead, an unsuccessful search was made for $x$ rays. Had the stopped $\beta$ rays been able to fall into the K shell, they would have emitted $x$ rays. Since the K shell of a Pb atom is already filled with two atomic electrons of opposite spin, it cannot — according to the exclusion principle — accept one more electron. We can therefore conclude that, at the end of their path, $\beta$ rays are identical with atomic electrons.

When two tacit assumptions collide, one or the other may first be tentatively discarded. For example, in $\beta$ decay, where the electrons cover an energy continuum, the tacit assumption that energy is conserved in all processes was tentatively given up (Bohr, Kramers, and Slater). Alternatively, the tacit assumption that protons, electrons, and photons are the only particles in Nature was abandoned: a new particle, the neutrino, was assumed to be emitted simultaneously with the electron, sharing the transition energy (Pauli). The second, less radical hypothesis won out. This is not always the case. For example, to understand the variety of $K$-meson decays found ($K \rightarrow 2\pi$, $K \rightarrow 3\pi$, etc.), one could assume the existence either of many different particles or of a single particle with many decay modes. The second assumption implied...
giving up parity conservation in K-meson decay (Lee and Yang), and this
time the more radical assumption won out.

A number of interactions are found in Nature; the well-established
ones are shown in table 2, with the families of particles given in order
of increasing number of interactions. The graviton is the hypothetical
particle that mediates the gravitational interaction existing between
all particles. The photon mediates electromagnetic interactions, which
exist between electric charges as well as currents. The leptons mediate
weak interactions and the mesons, strong interactions. The hadrons con-
sist of baryons of half-integer spin and mesons of integer spin. Some
theories suggest that the weak interactions are of second order, in-
volving in first order a hypothetical intermediate vector boson and a
strength equal to electromagnetic interactions. If this should be con-

Some conservation laws are believed to be absolute, and others are
known to be only approximate and to be broken by some of these interac-
tions. The algebraic sums of the elementary electric charges (Q),
baryon numbers (B), and lepton numbers (L) are believed to be absolutely
conserved in fundamental particle interactions, as summarized in the
following equations:

\[ Q + B + L = 0 \]
\[
\sum Q_i = \text{constant in time,}
\]
\[
\sum B_i = \text{constant in time,}
\]
\[
\sum L_i = \text{constant in time.}
\]

If these equations hold, then any independent set of linear combinations of these numbers, such as
\[
Q_i' = a_1Q_i + b_1B_i + c_1L_i,
\]
\[
B_i' = a_2Q_i + b_2B_i + c_2L_i,
\]
\[
L_i' = a_3Q_i + b_3B_i + c_3L_i,
\]
will also be constant in time. Thus, because of the conservation of baryons and leptons, the application of conservation of charge to the known reactions involving elementary particles does not, of itself, determine the ratio of the charges of all elementary particles; instead, two ratios are left arbitrary by all known reactions (see ref. 4).

Some reactions show that particles exist for which all absolutely conserved quantum numbers have the value zero, e.g., \(\nu\) and \(\pi^0\). This is shown by reactions such as
\[
e + e \rightarrow e + e + \gamma \quad \text{and} \quad p + p \rightarrow p + p + \pi^0.
\]

It can be further concluded that all particles and their antiparticles have opposite charge since they can be "materialized" in pairs from photons.

The apparent absence of the reaction \(p \rightarrow e^+ + \pi^0\) and of similar processes leaves the ratio of the charges of \(p\) and \(\nu^0\) undetermined. After the scale of charge is fixed by measuring in terms of \(Q_e\), two charges

\[
\text{...}
\]
are left undetermined which can be chosen as $Q_p$ and $Q_n$.

The tacit assumption is usually made that $Q_p = -Q_e$ and $Q_n = 0$, i.e., that the hydrogen atom and the neutron are electrically neutral. This assumption can be tested by direct experiment to a considerable degree of accuracy. If the neutron carried a small electric charge, this might be detected by deflecting a neutron beam by a homogeneous electric field. Such an experiment was carried out by Shapiro and Estulin, who found an upper limit for the charge of the neutron of $Q_n < 6 \times 10^{-12} |Q_e|$.

Fraser et al. carried out similar experiments for the "neutral" atoms $^{39}K$ and $^{133}Cs$ and found (with the net charge of the hydrogen atom being $\delta q = Q_p + Q_e$ and that of the neutron $Q_n$)

$$Q \left( ^{39}_{19}K_{20} \right) = 19 \delta q + 20 Q_n = (0.84 \pm 0.78) \times 10^{-18} Q_e,$$

$$Q \left( ^{133}_{55}Cs_{78} \right) = 55 \delta q + 78 Q_n = (1.62 \pm 0.70) \times 10^{-18} Q_e.$$

It follows that

$$\delta q = (0.9 \pm 2.0) \times 10^{-19} Q_e;$$

$$Q_n = (0.4 \pm 1.5) \times 10^{-19} Q_e.$$

With charge conservation assumed in the neutron decay $n \rightarrow \mu + e^- + \bar{\nu}_e$ it can be further concluded that

$$Q_{e^-} = -(0.5 \pm 3) \times 10^{-19} Q_e.$$
These results give considerable support to the generalization that all the known particles have charge ± $Q_e$ or 0, and reinforce group theoretical considerations which imply integral charges.

This generalization would also follow from charge conservation alone if the conservation of baryons and leptons were only approximate, i.e., if processes like $p \rightarrow e^+ + \pi^0$ were observable. Conversely, if it were found that the electric charges of the baryons were all slightly displaced from their usually accepted values, say by a common small value $e$, the conservation of baryons would follow from the conservation of charge instead of being an independent physical principle. In light of such considerations, it is worthwhile to ask how well — within what numerical limits — charge, baryon number, and lepton number are conserved.

If electric charge or baryon number were not absolutely conserved, then individual electrons or baryons would be expected to decay into lighter particles with a total energy equal to the rest mass of the decaying particle. One way of detecting such processes, regardless of the decay modes, would be by noting the filling of a "hole" left behind if either an electron or a nucleon disappeared from a bound state. Disappearance of an electron, e.g., from the K shell of an atom, would be followed by detectable K x rays. Disappearance of a bound nucleon from a nucleus would leave behind nuclear excitation sufficient in a heavy nucleus like $^{232}$Th to induce an apparently "spontaneous" fission, which could be detected. Another approach good for both bound and unbound particles involves the detection of some of the radiations that might be emitted as decay products of either electrons or nucleons.
Both approaches have been used and give very high lower limits on the lifetime of these particles (see tables 3 and 4). Thus, if any forces should exist which could induce the decay of either electrons or nucleons, they must be extremely weak, comparable to or weaker than the weakest force we know, the gravitational force. For the lepton number \( L \) the most direct tests of conservation are not very stringent.

Pati and Salam\(^8\) have suggested that baryon decay may be a higher-order process. The quark theory of nucleon structure permits an estimate of nucleon lifetime if free quarks are assumed to be unstable, decaying into leptons sufficiently rapidly to have so far escaped detection. Pati and Salam estimate on this basis that a proton could have a half-life of the order of \( 10^{30} \) years, with its three quarks decaying simultaneously into leptons. Since, if angular momentum and electric charge are conserved, such a decay would contain at least one charged lepton, Reines and Crouch\(^9\) have searched for positive muons from proton decay. They find a lower limit of \( 2 \times 10^{30} \) years for such a process and are pursuing this question further.

We have seen how yesterday's generalizations become today's tacit assumptions. Though inspiration might have early led to an "ultimate truth," our belief in it is strengthened by experimental tests. As long as we do not forget their empirical origins, we can use tacit assumptions with considerable confidence; at the same time we should continue to test them with more and more accuracy whenever this is possible. While negative results seem disappointing to most experimenters, they nevertheless help channel the imagination and contribute to the physicist's surefootedness.
FOOTNOTES


TABLE 1

EXPERIMENTAL LIMITS ON DEVIATIONS FROM COULOMB'S LAW

\[ F = \frac{e_1 \cdot e_2}{r^n} \], WHERE \( n = 2 + q \). THE AUTHORS' NAMES ARE GIVEN IN THE ORDER IN WHICH THE RESULTS BECAME PUBLIC, BUT THE DATES REFER TO THE YEAR THE EXPERIMENT WAS CARRIED OUT. (FROM A. S. GOLDHABER AND M. NIETO, REF. 2)

<table>
<thead>
<tr>
<th>AUTHOR</th>
<th>DATE</th>
<th>q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb</td>
<td>1785</td>
<td>(1 \times 10^{-1})</td>
</tr>
<tr>
<td>Robison</td>
<td>1769</td>
<td>(6 \times 10^{-2})</td>
</tr>
<tr>
<td>Cavendish</td>
<td>1773</td>
<td>(3 \times 10^{-2})</td>
</tr>
<tr>
<td>Maxwell</td>
<td>1873</td>
<td>(5 \times 10^{-5})</td>
</tr>
<tr>
<td>Plimpton et al.</td>
<td>1936</td>
<td>(2 \times 10^{-9})</td>
</tr>
<tr>
<td>Cochran et al.</td>
<td>1968</td>
<td>(9 \times 10^{-12})</td>
</tr>
<tr>
<td>Bartlett et al.</td>
<td>1970</td>
<td>(1 \times 10^{-13})</td>
</tr>
<tr>
<td>Williams et al.</td>
<td>1971</td>
<td>(6 \times 10^{-16})</td>
</tr>
</tbody>
</table>
## TABLE 2

THE RELATIVE STRENGTHS OF THE WELL-ESTABLISHED FORCES IN NATURE

<table>
<thead>
<tr>
<th>FORCE</th>
<th>RELATIVE STRENGTH OF FORCES</th>
<th>GRAVITON</th>
<th>PHOTON</th>
<th>LEPTONS</th>
<th>HADRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAVITY</td>
<td>$10^{-40}$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EL-MAGN.</td>
<td>$10^{-2}$</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WEAK</td>
<td>$10^{-6}$</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>STRONG</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
## Table 3
### Summary of Experimental Limits for Electron Half-lives

<table>
<thead>
<tr>
<th>Experimenters</th>
<th>Electron half-life (yr)</th>
<th>Detection Method</th>
<th>Electron Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. der Mateosian and M. Goldhaber, unpublished (See also ref. 4)</td>
<td>$&gt; 10^{19}$</td>
<td>Search for K x rays of iodine (in NaI(Tl) scintillator).</td>
<td>NaI crystal</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10^{20}$</td>
<td>Search for $\gamma$ rays from process $e^{-} \rightarrow \nu + \gamma$.</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>$&gt; 4 \times 10^{22}$</td>
<td>Search for $\gamma$ rays from process $e^{-} \rightarrow \nu + \gamma$.</td>
<td>&quot;</td>
</tr>
<tr>
<td>Experimenters</td>
<td>Nucleon half-life (yr)</td>
<td>Nucleon decay detection method</td>
<td>Nucleon source</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------</td>
</tr>
<tr>
<td>Goldhaber (1954)</td>
<td>$&gt; 1.4 \times 10^{18}$*</td>
<td>Spontaneous fission of $^{232}\text{Th}$ after excitation by nucleon decay.</td>
<td>Toluene in detector and surrounding paraffin.</td>
</tr>
<tr>
<td>Reines, Cowan, and Goldhaber (1954)</td>
<td>$&gt; 1 \times 10^{22}$</td>
<td>High-energy decay fragment. Liquid scintillation, 30 m below surface.</td>
<td>Water, lead, and rock.</td>
</tr>
<tr>
<td>Reines, Cowan, and Kruse (1957)</td>
<td>$&gt; 4 \times 10^{23}$</td>
<td>Proton decay in deuteron. High-energy fragment plus neutron left over from deuteron after decay of proton. Delayed coincidence and liquid scintillation, 61 m below surface.</td>
<td>Water, lead, and rock.</td>
</tr>
<tr>
<td>Backenstoss, Frauenfelder, Hyams, Koester, and Marin (1960)</td>
<td>$&gt; 2.8 \times 10^{26}$</td>
<td>High-energy fragment; upward going particles. Čerenkov and scintillation, 800 m below surface. At least 250 MeV assumed to be available to decay particle. Result based on combined measurements for neutrons and protons.</td>
<td>Water, lead, and rock.</td>
</tr>
<tr>
<td>Giamati and Reines (1962)</td>
<td>$&gt; 1 \times 10^{26}$ to $&gt; 7 \times 10^{27}$, depending on mode.</td>
<td>High-energy fragment. Liquid scintillation with anticoincidence shield, 585 m below surface.</td>
<td>Decalin in detector and surrounding iron.</td>
</tr>
<tr>
<td>Kropp and Reines (1964)</td>
<td>$&gt; 6 \times 10^{27}$ to $&gt; 4 \times 10^{28}$, depending on mode.</td>
<td>High-energy fragment. Liquid scintillation with anticoincidence shield, 585 m below surface.</td>
<td>Decalin in detector and surrounding iron.</td>
</tr>
<tr>
<td>Dix and Reines (private communication)</td>
<td>In progress.</td>
<td>Neutron left over from deuteron after decay of proton. Not dependent on decay mode.</td>
<td>Heavy water in detector.</td>
</tr>
<tr>
<td>Present experiment</td>
<td>$&gt; 2 \times 10^{28}$ to $&gt; 8 \times 10^{29}$, depending on mode.</td>
<td>High-energy fragment. Liquid scintillation, 3200 m below surface. Horizontally going particles.</td>
<td>Surrounding rock, mineral oil scintillator, and detector box.</td>
</tr>
</tbody>
</table>

*An improved limit $>10^{23}$ yr for decay of a nucleon "into anything" can be deduced from the limit on spontaneous fission of Th$^{232}$ obtained by G. N. Flerov et al., Soviet Physics Doklady 3 (1958): p. 79.*