Fire

Dry

Hot

Earth

Air

Cold

Wet

Water

Getting to Know

by ROBERT L. JAFFE

Humankind has wondered since the beginning of history what are the fundamental constituents of matter. Today's list includes about 25 elementary particles. Tomorrow's list promises to be longer still, with no end in sight.

THE URGE TO REDUCE THE FORMS of matter to a few elementary constituents must be very ancient. By 450 BCE, Empedocles had already developed or inherited a "standard model" in which everything was composed of four elements—Air, Earth, Fire, and Water. Thinking about the materials available to him, this is not a bad list. But as a predictive model of Nature, it has some obvious shortcomings. Successive generations have evolved increasingly sophisticated standard models, each with its own list of "fundamental" constituents. The length of the list has fluctuated over the years, as shown on the next page. The Greeks are actually tied for the minimum with four. The chemists of the 19th century and the particle physicists of the 1950s and 1960s pushed the number up toward 100 before some revolutionary development reduced it dramatically. Today's list includes about 25 elementary particles, though it could be either higher or lower depending on how you count. Tomorrow's list—the product of the next generation of accelerators—promises to be longer still, with no end in sight. In fact, modern speculations always seem to increase rather than decrease the number of fundamental constituents. Superstring theorists dream of unifying all the forces and forms of matter into a single essence, but so far they have little clue how the diversity of our observed world would devolve from this perfect form. Others have pointed out that Nature at the shortest distances and highest energies might be quite random and chaotic, and that the forces we feel and the particles we observe are special only in that they persist longer and propagate further than all the rest.

Two lessons stand out in this cartoon history. First, what serves as a "fundamental constituent" changes with time and depends on what sorts of questions one asks. The older

Your Constituents

models are not really inferior to today's Standard Model within the context of the world they set out to describe. And, second, there always seems to be another layer. In the early years of the 21st century particle physicists will be probing deeply into the physics of the current Standard Model of particle physics with new accelerators like the B-factories of SLAC and KEK and the Large Hadron Collider at CERN. Now seems like a good time to reflect on what to expect.

It is no accident, nor is it a sign of our stupidity, that we have constructed "atomic" descriptions of Nature on several different scales only to learn that our "atoms" were composed of yet more fundamental constituents. Quantum mechanics itself gives rise to this apparently layered texture of Nature. It also gives us very sophisticated tools and tests with which to probe our constituents for substructure. Looking back at the "atoms" of previous generations, we can see where the hints of substructure first appeared and how our predecessors were led to the next layer. Looking forward from our present crop of elementary particles, we see some suggestions of deeper structure beneath, but—tantalizingly—other signs suggest that today's fundamental constituents, numerous as they

A schematic history of the concept of an elementary constituent, from the four elements of the Greeks to today's Standard Model. The number has gone up and down over the years.
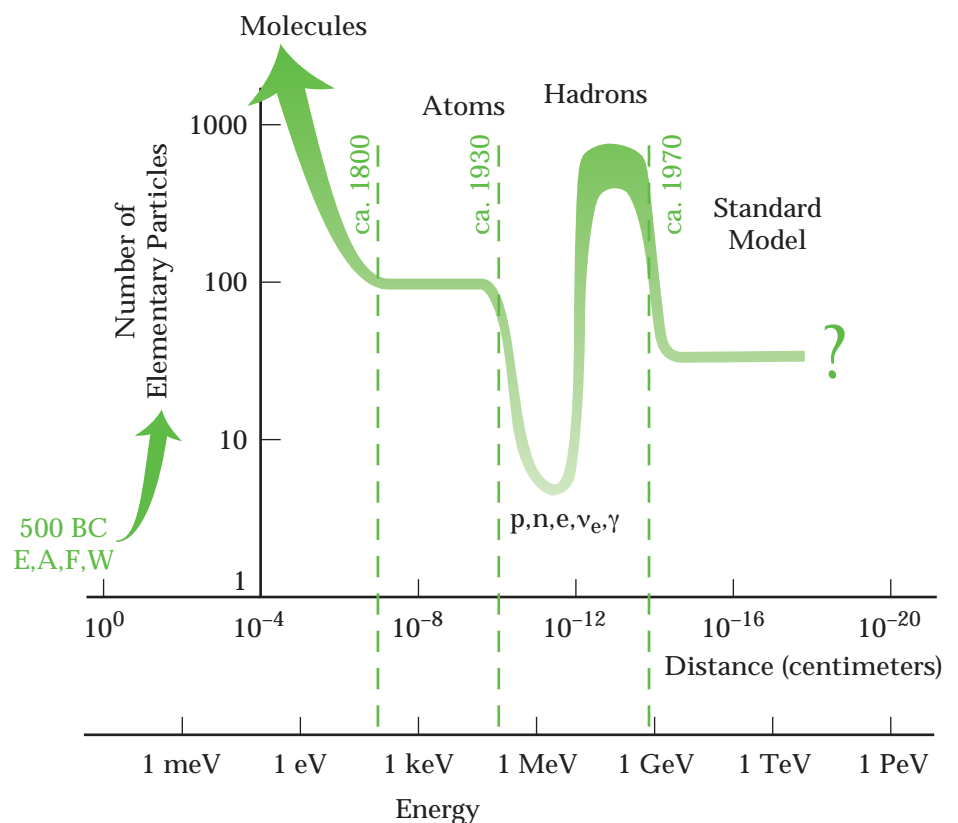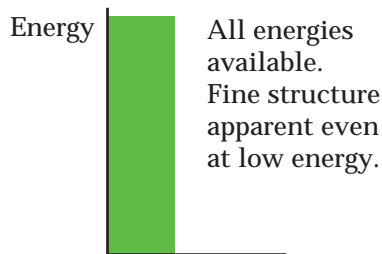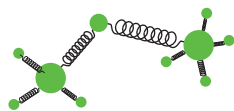
are, may be more fundamental than yesterday's.

BEFORE LOOKING at where we are today, let's take a brief tour of the two most useful "atomic" descriptions of the past: the standard models of chemistry and nuclear physics, shown below. Both provide very effective descriptions of phenomena within their range of applicability. Actually the term "effective" has a technical meaning here. For physicists an "effective theory" is one based on building blocks known not to be elementary, but which can be treated as if

they were, in the case at hand. "Effective" is the right word because it means both "useful" and "standing in place of," both of which apply in this case. The chemical elements are very useful tools to understand everyday phenomena, and they "stand in place of" the complex motions of electrons around atomic nuclei, which are largely irrelevant for everyday applications.
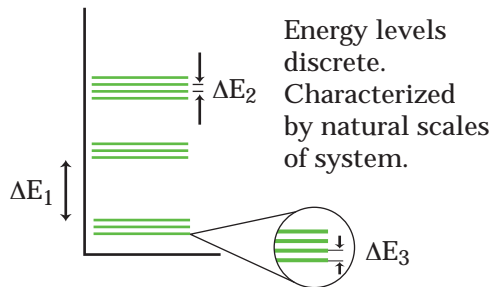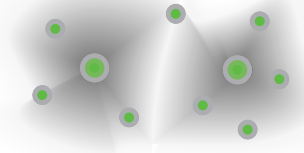
Chemistry and nuclear physics are both "effective theories" because quantum mechanics shields them from the complexity that lies beneath. This feature of quantum mechanics is largely responsible for the orderliness we perceive in the physical world, and it deserves more discussion. Consider a familiar substance such as water. At the simplest level, a chemist views pure water as a vast number of identical molecules, each composed of two hydrogen atoms bound to an oxygen atom. Deep within the atoms are nuclei: eight protons and eight neutrons for an oxygen nucleus, a single proton for hydrogen. Within the protons and neutrons are quarks and gluons. Within the quarks and gluons, who knows what? If classical mechanics described the world, each degree of freedom in this teeming microcosm could have an arbitrary amount of excitation energy. When disturbed, for example by a collision with another molecule, all the motions within the water molecule could be affected. In just this way, the Earth and everything on it would be thoroughly perturbed if our solar system collided with another.

Below: The "elementary" particles of the four schemes that have dominated modern science.

Scheme	Constituents	Date of Dominance	Domain of Applicability
Chemistry	92 Elements	Antiquity ~ 1900	$\gtrsim 10^{-8}$ cm
Nuclear	p, n, e, ν_e, γ	1900–1950	$\gtrsim 10^{-12}$ cm
Hadronic	$p, n, \Lambda, \Sigma, \pi, \rho, \dots$	1950–1970	$\gtrsim 10^{-13}$ cm
Standard Model	Quarks, Leptons	1970–?	$\gtrsim 10^{-17}$ cm

Energy

All energies available. Fine structure apparent even at low energy.

Energy Levels of a Classical System

ΔE_2

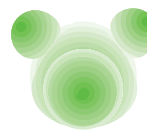ΔE_1

ΔE_3

Energy levels discrete. Characterized by natural scales of system.

Energy Levels of a Quantum System

Left: A schematic view of the energy levels of classical and quantum systems.

States of Water

	microwave meV	visible eV	soft γ-ray MeV	hard γ-ray GeV
Molecular	Active	Irrelevant	Irrelevant	Irrelevant
Atomic	Frozen	Active	Irrelevant	Irrelevant
Nuclear	Frozen	Frozen	Active	Irrelevant
Hadronic	Frozen	Frozen	Frozen	Active

The "quantum ladder" of water—the important degrees of freedom change with the scale on which it is probed, described here by the wavelength of light.

Quantum mechanics, on the other hand, does not allow arbitrary disruption. All excitations of the molecule are quantized, each with its own characteristic energy. Motions of the molecule as a whole—rotations and vibrations—have the lowest energies, in the 1–100 milli-electron volt regime (1 meV = 10^{-3} eV). An electron volt, abbreviated eV, is the energy an electron gains falling through a potential of one volt and is a convenient unit of energy for fundamental processes. Excitation of the electrons in the hydrogen and oxygen atoms come next, with characteristic energies ranging from about 10^{-1} to 10^3 eV. Nuclear excitations in oxygen require millions of electron volts (10^6 eV = 1 MeV), and excitations of the quarks inside a proton require hundreds of MeV. Collisions between water molecules at room temperature transfer energies of order 10^{-2} eV, enough to excite rotations and perhaps vibrations, but too small to involve any of the deeper excitations except very rarely. We say that these variables—the electrons, the nuclei, the quarks—are "frozen." The energy levels of a classical and quantum system are compared in the bottom illustration on the previous page. They are inaccessible and unimportant. They are not static—the quarks inside the nuclei of water molecules are whizzing about at speeds approaching the speed of light—however their state of motion cannot be changed by everyday processes. Thus there is an excellent description of molecular rotations and vibrations that knows little about electrons and nothing about nuclear structure, quarks, or gluons. Light quanta make a particularly good probe of this "quantum ladder," as

Victor Weisskopf called it. As summarized in the illustration above, as we shorten the wavelength of light we increase the energy of light quanta in direct proportion. As we move from microwaves to visible light to X rays to gamma rays we probe successively deeper layers of the structure of a water molecule. The appropriate constituent description depends on the scale of the probe. At one extreme, we cannot hope to describe the highest energy excitations of water without knowing about quarks and gluons; on the other hand, no one needs quarks and gluons to describe the way water is heated in a microwave oven.

PERHAPS THE MOST effective theory of all was the one invented by the nuclear physicists in the 1940s. It reigned for only a few years, before the discovery of myriad excited states of the proton and neutron led to its abandonment and eventual replacement with today's Standard Model of quarks and leptons. The nuclear standard model was based on three constituents: the proton (p); the neutron (n); and the electron (e). The neutrino (ν_e) plays a bit part in radioactive decays, and perhaps one should count the photon (γ), the quantum of the electromagnetic field. So the basic list is three, four, or five, roughly as short as Empedocles' and far more effective at explaining Nature. Most of nuclear physics and astrophysics and

all of atomic, molecular, and condensed matter physics can be understood in terms of these few constituents. The nuclei of atoms are built up of protons and neutrons according to fairly simple empirical rules. Atoms, in turn, are composed of electrons held in orbit around nuclei by electromagnetism. All the different chemical elements from hydrogen (the lightest) to uranium (the heaviest naturally occurring) are just different organizations of electrons around nuclei with different electric charge. Even the radioactive processes that transmute one element into another are well described in the $pnev_e\gamma$ world.

The nuclear model of the world was soon replaced by another. Certain tell-tale signatures that emerged early in the 1950s made it clear that these "elementary" constituents were not so elementary after all. The same signatures of compositeness have repeated every time one set of constituents is replaced by another:

Excitations. If a particle is composite, when it is hit hard enough its component parts will be excited into a quasi-stable state, which later decays by emitting radiation. The hydrogen atom provides a classic example. When hydrogen atoms are heated so that they collide with one another violently, light of characteristic frequencies is emitted. As soon as it was understood that the light comes from the de-excitation of its inner workings, hydrogen's days as an elementary particle were over. Similarly, during the 1950s physicists discovered that when a proton or neutron is hit hard enough, excited states are formed and characteristic radiation (of light or other hadrons)

There is tantalizing evidence that new relationships await discovery.

is emitted. This suggest that protons and neutrons, like hydrogen, have inner workings capable of excitation and de-excitation. Of course, if only feeble energies are available, the internal structure cannot be excited, and it will not be possible to tell whether or not the particle is composite. So an experimenter needs a high-energy accelerator to probe compositeness by looking for excitations.

Complex force laws. We have a deep prejudice that the forces between elementary particles should be simple, like Coulomb's law for the electrostatic force between point charges: $F_{12} = q_1 q_2/r_{12}^2$. Because they derive from the complex motion of the electrons within the atom, forces between atoms are not simple. Nor, it turns out, are the forces between protons and neutrons. They depend on the relative orientation of the particles and their relative velocities; they are complicated functions of the distance between them. Nowadays the forces between the proton and neutron are summarized by pages of tables in the *Physical Review*. We now understand that they derive from the

complex quark and gluon substructure within protons and neutrons.

The complicated features of force laws die away quickly with distance. So if an experimenter looks at a particle from far away or with low resolution, it is not possible to tell whether it is composite. A high-energy accelerator is needed to probe short distances and see the deviations from simple force laws that are telltale signs of compositeness.

Form factors. When two structureless particles scatter, the results are determined by the simple forces between them. If one of the particles has substructure, the scattering is modified. In general the probability of the scattered particle retaining its identity—this is known as "elastic scattering"—is reduced, because there is a chance that the particle will be excited or converted into something else. The factor by which the elastic scattering probability is diminished is known as a "form factor." Robert Hofstadter first discovered that the proton has a form factor in experiments performed at Stanford in the 1950s. This was incontrovertible evidence that the proton is composite.

If, however, one scatters lightly from a composite particle, nothing new is excited, and no form factor is observed. Once again, a high-energy accelerator is necessary to scatter hard enough to probe a particle's constituents.

Deep inelastic scattering. The best proof of compositeness is, of course, to detect directly the sub-constituents out of which a particle is composed. Rutherford found the nucleus of the atom by scattering α particles from a gold foil and

finding that some were scattered directly backwards, a result that would only be possible if the gold atoms contained a heavy concentration of mass—the nucleus—at their core. The famous SLAC experiments led by Jerome Friedman, Henry Kendall, and Richard Taylor found the analogous result for the proton: when they scattered electrons at large angles they found telltale evidence of pointlike quarks inside.

By the early 1970s mountains of evidence had forced the physics community to conclude that protons, neutrons, and their ilk are not fundamental, but are instead composed of quarks and gluons. During that decade Burton Richter and Sam Ting and their collaborators separately discovered the charm quark; Leon Lederman led the team that discovered the bottom quark; and Martin Perl's group discovered the third copy of the electron, the tau-lepton or tauon. The mediators of the weak force, the *W* and *Z* bosons, were discovered at CERN. The final ingredients in our present Standard Model are the top quark, recently discovered at Fermilab, and the Higgs boson, soon to be discovered at Fermilab or CERN. As these final blocks fall into place, we have a set of about 25 constituents from which all matter is built up.

THE STANDARD Model of particle physics is incredibly successful and predictive, but few believe it is the last word. There are too many particles—about 25—and too many parameters—also about 25 masses, interaction strengths, and orientation angles—for a fundamental theory.

	Excitation Spectrum	Form Factors	Complex Force Laws
92 Elements	Yes	Yes	Yes
p,n,e	Yes	Yes	Yes
Standard Model	No	No	No

Evidence for underlying structure in models of elementary constituents.

Particle physicists have spent the last quarter century looking for signs of what comes next. So far, they have come up empty—no signs of an excitation spectrum, complex force laws, or form factors have been seen in any experiment. The situation is summarized above. The Standard Model was discovered when physicists attempted to describe the world at distances smaller than the size of the proton, about 10^{-13} cm. Modern experiments have probed to distances about four orders of magnitude smaller, 10^{-17} cm, without evidence for substructure.

There is tantalizing evidence that new relationships await discovery. For example, the Standard Model does not require the electric charges of the quarks to be related to the electric charge of the electron. However, the sum of the electric charges of the three quarks that make up the proton has been measured by experiment to be the exact opposite of the charge on the electron to better than one part in 10^{20}. Such a relationship would follow naturally either if quarks and electrons were composed of common constituents or if they were different excitations states of some "ur" particle. Equally intriguing is that each quark and lepton seems to come in three versions with identical properties, differing only in mass. The three charged leptons, the electron, the muon and the tauon,

are the best-known example, but the same holds for the up, charm, and top quarks, the down, strange, and bottom quarks, and the neutrinos associated with each lepton. The pattern looks very much like one of internal excitation—as if the muon and tauon are "excited electrons". However, extremely careful experiments have not been able to excite an electron into a muon or a tauon. The limits on these excitation processes are now extremely strong and pretty much rule out simple models in which the electron, muon, and tauon are "made up of" the same subconstituents in a straightforward way.

Building structures that relate the elementary particles of the Standard Model to one another is the business of modern particle theory. Supersymmetry (SUSY) combined with Grand Unification is perhaps the most promising approach. It removes some of the most troubling incongruities in the Standard Model. However, the cost is high—if SUSY is right, a huge number of new particles await discovery at the LHC or at the Next Linear Collider. The list of "elementary constituents" would more than double, as would the number of parameters necessary to describe their interactions. The situation would resemble the state of chemistry before the understanding of atoms, or of hadron physics before the discovery of quarks: a huge number of constituents, grouped into families, awaiting the next simplifying discovery of substructure.

One of the most striking properties of the Standard Model is the simplicity of the force laws. All the known forces between quarks and

leptons are generalizations of Coulomb's Law. They all follow from symmetry considerations known as "gauge principles." Even gravity, which rests uneasily in the Standard Model, follows from the gauge principle that Einstein called "general covariance." The simplicity of the forces in the Standard Model has been mistaken for evidence that at last we have reached truly elementary constituents, and that there is no further substructure to be found. After all, the argument goes, "How could composite particles behave so simply?" Unfortunately, it turns out that it is quite natural for composite particles to mimic fundamental ones if we do not probe them deeply enough. The forces between atoms and nuclei look simple if one does not look too closely. Models with quite arbitrary interactions defined at very short distances produce the kind of forces we see in the Standard Model when viewed from far away. In a technical sense, the deviations from the forces that follow from the "gauge principle" are suppressed by factors like Λ/ℓ , where ℓ is the typical length scale probed by an experiment (ℓ scales like the inverse of the energy of the colliding particles), and Λ is the distance scale of the substructure. Holgar Nielsen and his collaborators have followed this thread of logic to an extreme, by exploring the extent to which an essentially random theory defined at the shortest distance scales will present itself to our eyes with gauge interactions like the Standard Model and gravity. These exercises show how much room there is for surprise when we probe

the next level beyond the Standard Model.

We are poised rather uncomfortably upon a rung on Viki Weisskopf's Quantum Ladder. The world of quarks, leptons, and gauge interactions does a wonderful job of explaining the rungs below us: the nuclear world of $pnev_e\gamma$, the world of atoms, and chemistry. However, the internal consistency of the Standard Model and the propensity of quantum mechanics to shield us from what lies beyond, leave us without enough wisdom to guess what we will find on the next rung, or if, indeed, there is another rung to be found. Hints from the Standard Model suggest that new constituents await discovery with the next round of accelerator experiments. Hope from past examples motivates theorists to seek simplifications beyond this proliferation. Past experience cautions that we are a long way from the end of this exploration.