**The Heart of Chemistry**

WHILE EINSTEIN AND Hubble were productively unraveling the large-scale structure of the cosmos, others were struggling to understand something closer to hand but in its way just as remote: ***the tiny and ever- mysterious atom.***

The great Caltech physicist Richard Feynman once observed that if you had to reduce scientific history to one important statement it would be “All things are made of atoms.” They are everywhere and they constitute everything. Look around you. It is all atoms. Not just the solid things like walls and tables and sofas, but the air in between. And they are there in numbers that you really cannot conceive.

The basic working arrangement of atoms is the molecule (from the Latin for “little mass”). A molecule is simply two or more atoms working together in a more or less stable arrangement: add two atoms of hydrogen to one of oxygen and you have a molecule of water. Chemists tend to think in terms of molecules rather than elements in much the way that writers tend to think in terms of words and not letters, so it is molecules they count, and these are numerous to say the least. At sea level, at a temperature of 0 degree Celsius, one cubic centimeter of air (that is, a space about the size of a sugar cube) will contain 45 billion billion molecules. And they are in every single cubic centimeter you see around you. Think how many cubic centimeters there are in the world outside your window—how many sugar cubes it would take to fill that view. Then think how many it would take to build a universe. Atoms, in short, are very abundant.

They are also fantastically durable.

Because they are so long lived, atoms really get around. Every atom you possess has almost certainly passed through several stars and been part of millions of organisms on its way to becoming you. We are each so atomically numerous and so vigorously recycled at death that a significant number of our atoms—up to a billion for each of us, it has been suggested—probably once belonged to Shakespeare. A billion more each came from Buddha and Genghis Khan and Beethoven, and any other historical figure you care to name. (The personages have to be historical, apparently, as it takes the atoms some decades to become thoroughly redistributed; however much you may wish it, you are not yet one with Elvis Presley.)

So we are all reincarnations—though short-lived ones. When we die our atoms will disassemble and move off to find new uses elsewhere—as part of a leaf or other human being or drop of dew. Atoms, however, go on practically forever. Nobody actually knows how long an atom can survive, but according to Martin Rees it is probably about 1035 years—a number so big that even I am happy to express it in notation.

Above all, atoms are tiny—very tiny indeed. Half a million of them lined up shoulder to shoulder could hide behind a human hair. On such a scale an individual atom is essentially impossible to imagine, but we can of course try.

Start with a millimeter, which is a line this long: -. Now imagine that line divided into a thousand equal widths. Each of those widths is a micron. This is the scale of microorganisms. A typical paramecium, for instance, is about two microns wide, 0.002 millimeters, which is really very small. If you wanted to see with your naked eye a paramecium swimming in a drop of water, you would have to enlarge the drop until it was some forty feet across. However, if you wanted to see the atoms in the same drop, you would have to make the drop fifteen miles across.

It is of course the abundance and extreme durability of atoms that makes them so useful, and the tininess that makes them so hard to detect and understand. The realization that atoms are these three things—small, numerous, practically indestructible—and that all things are made from them first occurred not to Antoine-Laurent Lavoisier, as you might expect, or even to Henry Cavendish or Humphry Davy, but rather to a spare and lightly educated English Quaker named John Dalton.

Let us pause for a moment and consider the structure of the atom as we know it now. Every atom is made from three kinds of elementary particles: protons, which have a positive electrical charge; electrons, which have a negative electrical charge; and neutrons, which have no charge. Protons and neutrons are packed into the nucleus, while electrons spin around outside. The number of protons is what gives an atom its chemical identity. An atom with one proton is an atom of hydrogen, one with two protons is helium, with three protons is lithium, and so on up the scale. Each time you add a proton you get a new element. (Because the number of protons in an atom is always balanced by an equal number of electrons, you will sometimes see it written that it is the number of electrons that defines an element; it comes to the same thing. The way it was explained to me is that protons give an atom its identity, electrons its personality.)

Neutrons don’t influence an atom’s identity, but they do add to its mass. The number of neutrons is generally about the same as the number of protons, but they can vary up and down slightly. Add a neutron or two and you get an isotope. The terms you hear in reference to dating techniques in archeology refer to isotopes—carbon-14, for instance, which is an atom of carbon with six protons and eight neutrons (the fourteen being the sum of the two).

Neutrons and protons occupy the atom’s nucleus. The nucleus of an atom is tiny—only one millionth of a billionth of the full volume of the atom—but fantastically dense, since it contains virtually all the atom’s mass. As Cropper has put it, if an atom were expanded to the size of a cathedral, the nucleus would be only about the size of a fly—but a fly many thousands of times heavier than the cathedral. It was this spaciousness—this resounding, unexpected roominess—that had Rutherford scratching his head in 1910.

It is still a fairly astounding notion to consider that atoms are mostly empty space, and that the solidity we experience all around us is an illusion. When two objects come together in the real world—billiard balls are most often used for illustration—they don’t actually strike each other. “Rather,” as Timothy Ferris explains, “the negatively charged fields of the two balls repel each other . . . were it not for their electrical charges they could, like galaxies, pass right through each other unscathed.” When you sit in a chair, you are not actually sitting there, but levitating above it at a height of one angstrom (a hundred millionth of a centimeter), your electrons and its electrons implacably opposed to any closer intimacy.

The picture that nearly everybody has in mind of an atom is of an electron or two flying around a nucleus, like planets orbiting a sun. This image was created in 1904, based on little more than clever guesswork, by a Japanese physicist named Hantaro Nagaoka. It is completely wrong, but durable just the same. As Isaac Asimov liked to note, it inspired generations of science fiction writers to create stories of worlds within worlds, in which atoms become tiny inhabited solar systems or our solar system turns out to be merely a mote in some much larger scheme. Even now CERN, the European Organization for Nuclear Research, uses Nagaoka’s image as a logo on its website. In fact, as physicists realized, electrons are not like orbiting planets at all, but more like the blades of a spinning fan, managing to fill every bit of space in their orbits simultaneously (but with the crucial difference that the blades of a fan only seem to be everywhere at once; electrons are).

Needless to say, very little of this was understood in 1910 or for many years afterward. Clearly whatever was going on down there in the world of the very small was not governed by the laws that applied in the macro world where our expectations reside.

As physicists began to delve into this subatomic realm, they realized that it wasn’t merely different from anything we knew, but different from anything ever imagined. “Because atomic behavior is so unlike ordinary experience,” Richard Feynman once observed, “it is very difficult to get used to and it appears peculiar and mysterious to everyone, both to the novice and to the experienced physicist.” When Feynman made that comment, physicists had had half a century to adjust to the strangeness of atomic behavior.

The atom turned out to be quite unlike the image that most people had created. The electron doesn’t fly around the nucleus like a planet around its sun, but instead takes on the more amorphous aspect of a cloud. The “shell” of an atom isn’t some hard shiny casing, as illustrations sometimes encourage us to suppose, but simply the outermost of these fuzzy electron clouds. The cloud itself is essentially just a zone of statistical probability marking the area beyond which the electron only very seldom strays. Thus an atom, if you could see it, would look more like a very fuzzy tennis ball than a hard-edged metallic sphere (but not much like either or, indeed, like anything you’ve ever seen; we are, after all, dealing here with a world very different from the one we see around us).

This is CRAZY! And this is what we will explore throughout the year… ☺