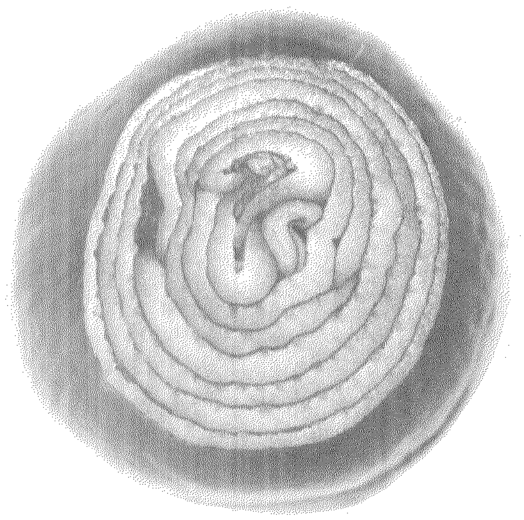


Onions or Plum Puddings?

by David J. Stevenson

ONE RECIPE in the Betty Crocker guide to planets might feature the liliaceous herb of the genus *Allium* pictured above — the onion. This onion is layered, and it is possible that the concentric layers may be similar to the distribution of material within a planet dictated by gravity. An alternative planetary structure might be more like a plum pudding, which has a matrix with inclusions of a material of a different composition. If you have ever tried to make a structure like this, you know that if you make the mixture too runny, the raisins will settle out before the cooking process "lithifies" the matrix and causes the raisins to stay in place.

These gastronomical examples can serve as models for an age-old puzzle: What is the internal structure of planets? For thousands of years man has looked up to the heavens and pondered the nature of stars. Perhaps to a lesser extent, but more importantly, he has looked down and wondered what is below him. This wonderment is evident in both the scientific and popular literature throughout the ages. A typical example comes from a 1922 novel by Edgar Rice Burroughs, *At the Earth's Core* (recently made into a particularly bad movie).

> The earth was once a nebulous mass. It cooled, and as it cooled, it shrank. At length a thin crust of solid matter formed upon its outer surface as a sort of shell. But within it was partially molten matter and highly expanded gases. As it continued to cool, what happened? Centrifugal force held the particles of the nebulous center toward the crust as rapidly as they approached the solid state. You have seen the same principles practically applied in the modern cream separator. Presently there was only a small superheated core of gaseous matter remaining within a huge vacant interior left by the contraction of the cooling gases. The equal attraction of the solid crust from all directions maintained this luminous core in the exact center of the hollow globe.

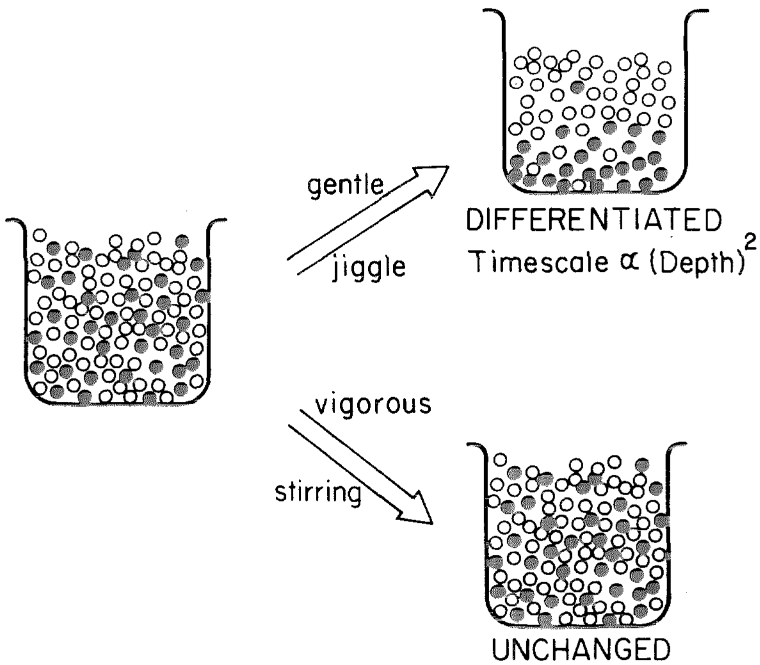
There are two interesting things about this extract. One is that it's complete nonsense, and could be said to be complete nonsense even in 1922. But it does mention two crucial issues for understanding the recipes of planets. One is the temperature and state of the material that goes into making the planet. The other is the extent to which the forces acting on that material (primarily gravity rather than centrifugal forces as Burroughs supposed) determine the distribution of the constituents within the planet.

This can be illustrated by several thought experiments (although the experiments can be and have been done in reality). Say you have a beaker containing a mixture of balls, or atoms, that are identical except that some are heavier than others. If you jiggle the system gently (that is to say that each one of these atoms has some kinetic energy associated with it) and then wait long enough, the system will tend to differentiate under the action of gravity. The heavier atoms tend to accumulate towards the bottom. But this process, called diffusion, is a random walk process, and as a consequence the atoms don't go down to the bottom of the system as quickly as they could. The time it takes to go from one state to the other is proportional to the square of the depth of the system. If you do this in a laboratory where the size of the system is quite small, the process doesn't take too long. But if you imagine trying to do it on the scale of a planet, you find that the time it takes for the heavier things to settle out is longer than the age of the solar system. It would take about 10^{12} years or more to do this process in a planet even if you set the conditions up right, that is, that you don't stir the system too vigorously. So the conclusion you reach is that you can't separate the heavy atoms from the light ones by a process that involves purely a simple diffusive process, because it takes too long.

Actually the situation is even worse because in many cases, including planets and including our own lower atmosphere, the stirring is sufficiently vigorous that the diffusive process cannot succeed for any time scale, and the system just stays well stirred. Therefore, in order to hypothesize that a planet actually manages to get its heavy constituents to the bottom under the action of gravity, you have to look at some other way of doing it.

There is a very simple way of doing it that unquestionably works. Let's suppose that the heavy atoms can stick to each other. They stick to other heavy atoms, but they don't stick to the lighter atoms, and the light atoms do not stick to each other. Then, with the same setup as before, when our beaker of atoms is jiggled, the heavy atoms will come into contact with each other. They will stick to each other and develop clusters that are more able to settle out through the system. And you can accumulate this mass of material at the bottom of the beaker on a shorter time scale than in the previous example.

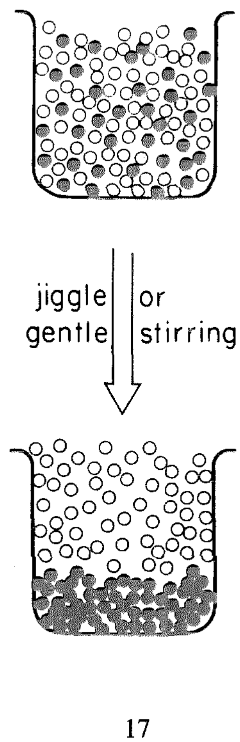
This is the same process that is responsible for getting water out of the earth's atmosphere onto the earth's surface in the form of rainfall. In fact, if the random walk process of the previous example applied to water, the water would go up because it's lighter than most of the other molecules in the earth's atmosphere. But when material accumulates into clusters, that is, undergoes a phase transition, then separation occurs.

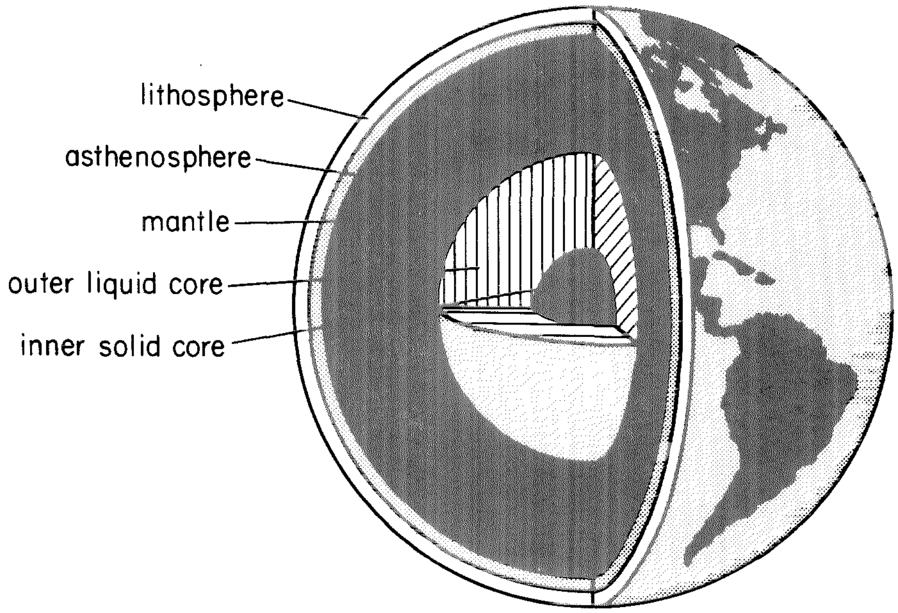


If we move away from atoms and look at the way the system behaves macroscopically, there are two possible situations. One is an assemblage of solid particles with interstitial liquid. If the liquid is less dense than the solid, the solid can settle out of the system, and the liquid can settle up to the top. This is the process whereby melt is separated in a partially molten rock, which leads eventually to volcanic activity. The other situation involves snow or rain settling out to form a sedimentary layer. These processes can indeed happen in a time scale that is less than the age of the solar system. It can still be a very long time, but it will be much shorter than the time scale that relies on purely atomic processes.

Still another thought experiment illustrates what would happen if you had light material underlying heavy material. In general, gravity would prefer to have the heavy material at the bottom, because that is an energetically more preferable situation. How does the system try and adjust so as to go to the state where the heavy stuff is at the bottom and the light stuff is at the top? The answer depends on how the overlying material can deform. If it can behave as a fluid, the system can change through diapiric activity, that is, a large blob of light fluid moving up into the heavy material. This doesn't necessarily require the heavier material to be fluid like water; it could be deformable on a long time scale like the solid material inside the earth. If the heavy material does not behave like a fluid, a crack could form spontaneously. The fluid can rise up through the crack, and the crack can extend itself verti-

If the black balls, or atoms (above), are heavier than the white ones, jiggling the beaker will cause the black atoms to settle to the bottom by diffusion. This would take a long time if the beaker were a planet, and with vigorous stirring, which characterizes many planets, the heavier atoms will not settle out at all. If, however, the heavier atoms can stick to each other (below), they will form clusters and fall to the bottom relatively quickly.





An onion? This cross-section drawing of the earth shows the small solid core surrounded by the larger, primarily iron, liquid core. The mantle overlying that consists of silicates similar to the rock of the earth's surface. Of the two outermost layers, the asthenosphere is a region of partial melting, and the lithosphere is the cold, rigid layer.

cally, allowing the light material to escape.

We've known for a long time that the earth has a dense core. Already at the turn of the century, rudimentary seismic data and other information had revealed that the central part of the earth was much more dense than the outer regions. It was suspected that this would be a region of iron, and the modern view is not very much different from this. Except for a smaller inner solid region, the central part of the earth is a primarily liquid core, which has iron as its major constituent. Overlying that is "rock," consisting of silicates, material very similar to that on the earth's surface. How was this state created? How did this heavy, iron material find its way to the center of the earth?

One possible hypothesis is that the core formed directly, and then the silicate outer material was added later. Based on what we currently understand about the way in which planets were put together, this is improbable. The solar system probably started out with a very large number of small bodies of iron and silicates orbiting the newly formed sun, or the region in which the sun was about to form. Because there were so many of them, they would frequently collide with each other. As a result of these collisions, the bodies would get larger and larger, and fewer and fewer, eventually reaching something like the present solar system.

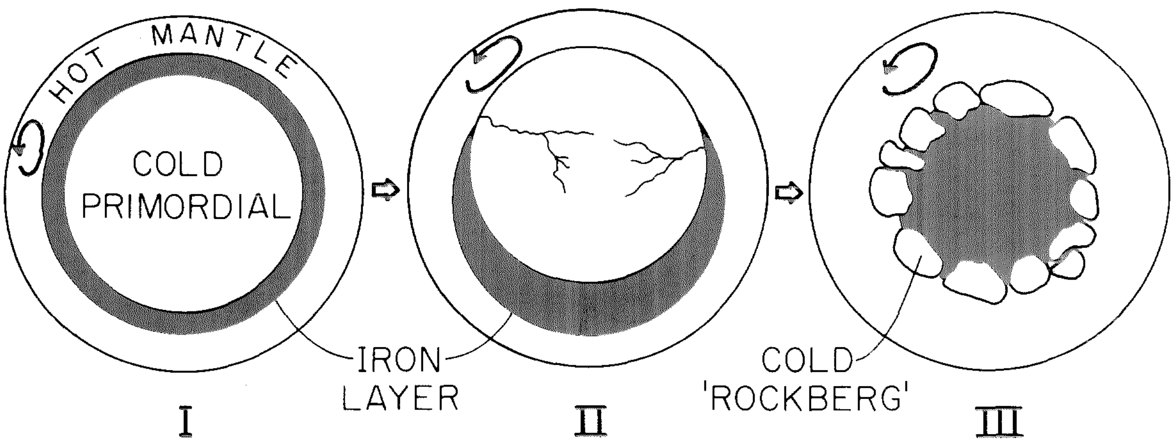
This sequence of steps is very efficient in homogenizing the material that goes into forming the planets. So you would expect that when you make a planet by this process, a planet like the earth, it will start out as a uniform mixture of silicate and iron. It will not have an iron core to begin with.

The other thing that we can expect on the basis of this sequence of steps is that the outer region of the earth is going to be very hot because of the collisions as it forms. The outer regions will actually be hotter than the inside, because the deeper regions are formed from bodies that collided at much lower velocities. So, before the earth reaches its final size, you can expect to get melting in the *outer* regions, sort of like a baked Alaska. As the iron in that hot outer region melts, the silicate and iron will separate into layers, and the iron will try to find its way down to the center of the earth. But it is going to have trouble doing so because the central, uniformly mixed part of the earth is much colder than the outer region and will be reluctant to let the iron pass through.

But we know that the iron *is*, in fact, at the center, so how does it get there? One possible mechanism, which was thought of primarily by the geophysicist Walter Elsasser of Johns Hopkins University, is that the material migrates down by deforming the cold inner region as though this cold region were behaving like a fluid. And in that way you might imagine a large blob eventually finding its way to the center of the earth. This process is a very slow one — on the order of a billion years. Another possibility is that silicate grains detach themselves from the cold primordial core and rise up through the liquid iron layer. As a consequence, the liquid iron layer slowly migrates down toward the center of the earth, eating away the material in the central part, the silicate portion of which then gets displaced upwards into the outer region. This would also take about a billion years. A billion years is a lot less than the age of the earth, which is 4½ billion years, but we still might wonder whether there is a faster way of doing it.

And there is. The process that I favor would take more like a million years. I call it a "catastrophic asymmetry," and it happens because there is a lower energy state. This state is reached when the central primordial region migrates spontaneously as a rigid body through the liquid iron layer. It will do so very rapidly in just the same way that a rubber ducky held down below the surface of the bathtub water and then let go would pop up to the surface. Since the material in the liquid layer can easily move out of the way of the core, the process can be very rapid. This spontaneous asymmetry makes the earth pear-shaped, which in turn creates very large stresses capable of fracturing the primordial core, which then breaks up into pieces. These pieces distribute themselves around the newly formed iron core. Basically what is happening here is that the earth's central region is turning itself inside out.

This process has important consequences for the origin of the earth's atmosphere, perhaps for the origin of the moon, and for the chemistry of the rocks that we see at the earth's surface. The core formation process can take place when the earth is a lot smaller than its present size. Subsequently, the earth continues to grow as bodies with iron in them hit the earth. That iron can separate out as blobs and drop down to the earth's core very rapidly. The mantle material, even though it's very hot, is compositionally similar to the present mantle of the earth, that is, the silicate outer region. This compositional similarity means that volcanic activity leads to the expelling of gases that are similar to the gases currently produced by the earth's volcanism. In particular, carbon dioxide would be the dominant form of expelled carbon.



"Catastrophic asymmetry" is one way for the heavy stuff to get to the center relatively quickly – about a million years. The central, primordial region could migrate as a rigid body through the liquid iron layer quite rapidly, creating an asymmetry that would fracture the core. The broken-up pieces of the old core – "rockbergs" – would then redistribute themselves around the new iron core.

D. J. Stevenson, Science, Nov. 6, 1981, Vol. 214, No. 4521, p. 612.

So the early atmosphere of the earth would have been rich in carbon dioxide, that is, in oxygen-bearing rather than hydrogen-bearing gases. This is very important for the origin of life. Until recently many scientists thought that perhaps the early earth had an atmosphere that was rich in such hydrogen-bearing gases as ammonia and methane. But now it seems more likely that the earth's core formed quickly in the way described above, with the early mantle and volcanic gases very similar to their present states. And it is indeed possible that life could form in that environment.

This model of the earth's formation also provides a scenario for the creation of the moon out of the mantle material, which is compositionally correct for the moon's observed bulk composition. There are a number of ways that a substantial amount of the mantle might have been persuaded to leave the earth's surface.

The moon as we see it from earth consists of dark regions and light regions. The dark regions are the maria, which are produced by the basalt flowing out from the interior of the moon and filling in the lows in the topography, quite often very large impact basins. The light regions are older rocks. They are the highlands of the moon, compositionally distinct from the lowlands. The *other* side of the moon, however, consists almost entirely of the light regions. This fundamental asymmetry of the moon can be explained by the spontaneous asymmetry mentioned earlier, which would occur with the separation of the primordial core moving through the liquid iron layer. Since the moon is a lot smaller than the earth and the amount of iron is a lot less, this state will last for a long time and could evolve in such a way as to produce an asymmetry between the near side and the far side, just as is observed in the moon today.

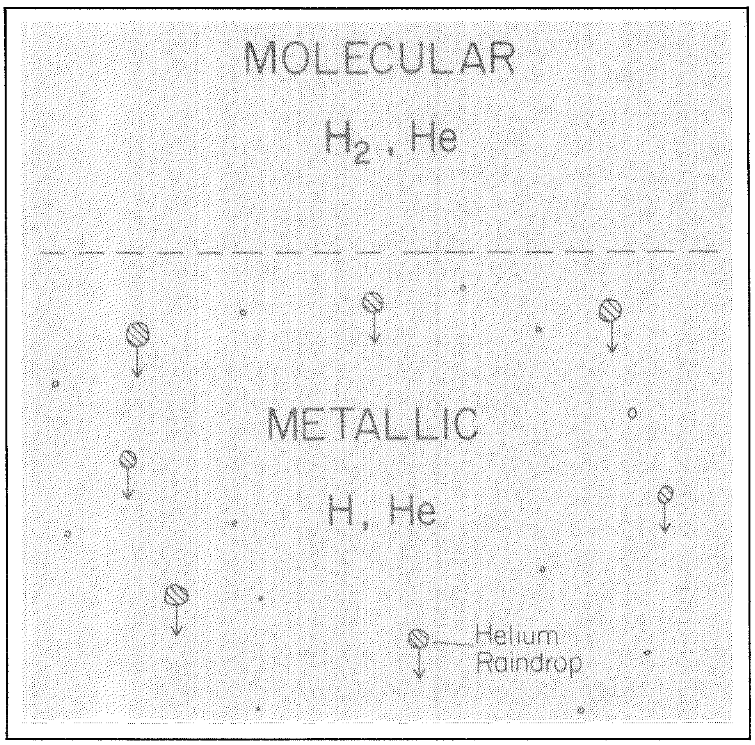
The behavior of the giant planets is completely different but still related to this theory of the earth's formation. When the two Voyager spacecraft flew by Jupiter and Saturn and measured the properties of these planets, they discovered a very important difference between them despite their superficial similarity. Jupiter can be understood simply as a large ball of gas, primarily hydrogen, which has been cooling off throughout geologic time. The heat coming out of this planet is exactly that which you would expect on the basis of starting from a hot state and cooling off. Jupiter's atmosphere is primarily a mixture of hydrogen and helium in the same ratio as existed when helium was created during the big bang that originated the universe.

Saturn is also a ball of hydrogen — hot and gradually cooling off, radiating excess energy into space, which we can measure. But Saturn is emitting an amount of energy larger than you would expect if it were just a hot ball of gas cooling down over geologic time. Furthermore, when we measure the composition of the atmosphere of

Saturn, we find that the amount of helium in the atmosphere is less than that in Jupiter by about a factor of two. These two facts together — too much heat and too little helium — lead us to suspect that differentiation is taking place. What is happening inside Saturn is directly analogous to the second thought experiment mentioned earlier, that is, the atoms are sticking together, resulting in a phase transition. In this case it's the helium atoms that are behaving as though they're sticky, and they do so because they find themselves in a metallic environment, where they would prefer to be with other helium atoms rather than mixed in with the hydrogen. That environment is metallic because of the very large pressure that occurs inside these planets. In the outermost region of these planets, the material we see in the atmosphere is molecular. The hydrogen is bound together in the form of molecules, and the helium is uniformly mixed in. But under higher pressures the hydrogen molecules break up into their constituent protons, and the electrons associated with these molecules get smeared out, distributed, as in a metallic state. This state is called metallic hydrogen, and it is an alkali metal just like sodium or potassium, except that the positive ions are bare protons.

Helium, on the other hand, prefers to retain its electrons, and so it doesn't like being in the metallic environment (helium gas is highly insoluble in any metal). What happens on Saturn, which is colder than Jupiter, is that the helium atoms stick together and then separate out into raindrops, and those raindrops settle down toward the center of the planet, depleting the helium in the uppermost region. Equally important is that, as these raindrops settle out, energy is released because heavy material is dropping through a gravitational field. That energy finds its way to the outside, and we observe it as an excess heat flow from the planet.

In the outer atmosphere of a planet like Saturn, the hydrogen exists as molecules, and the helium atoms are uniformly mixed in. At the higher pressures closer to the interior, the hydrogen molecules break up, creating a metallic state. In a metallic state, helium atoms prefer to be with other helium atoms; they separate out as helium raindrops and fall toward the center.

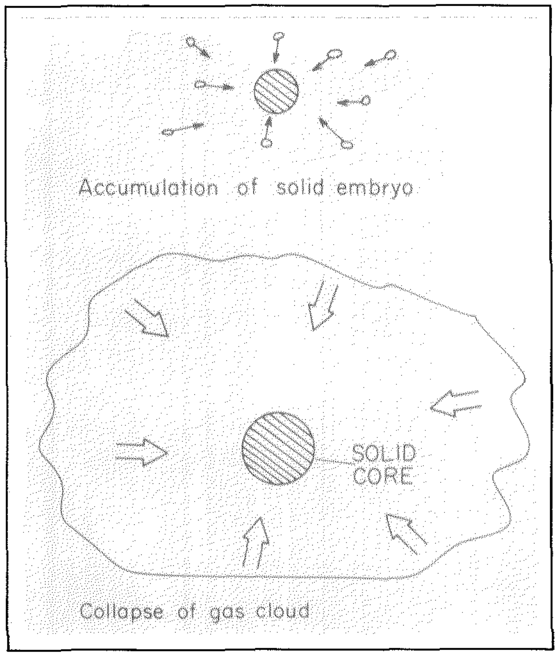


Jupiter and Saturn each have a very dense core equal to about 10 or perhaps 20 earth masses. We know that these cores exist from the observed gravity field external to the planets. The cores are very dense and consist of rock and possibly some water-ice at tens of millions of atmospheres of pressure. The temperature of this material is also very high — about 20,000°F in the case of Jupiter. But the interesting thing about the existence of these cores is that theoretically this material should get mixed upwards. If the atoms are not sticky, and if the material is being stirred by convection, then this core material should get dredged up. It has not been.

It turns out that the core in a giant planet like Jupiter or Saturn has to be made first. This is very different from the earth. In the case of the earth I argued that the core formed *after* the accumulation of the material that went into making the earth. In this case I'm arguing that because the material can mix, you have to make the core *first*. So in order to make a giant planet, you first have to accumulate a solid body in much the same way as you would accumulate the whole earth. And then you have to persuade the gas that resides everywhere in space during this process to collapse onto that solid core. It turns out that that is indeed possible if the solid core is massive enough — about 10 earth masses. If the earth had ever grown this large, and if there had been gas around, we would have ended up like Jupiter. But fortunately we did not.

Another member of the solar system that shows evidence of an interesting history is Titan, which is not a planet but a large satellite in orbit around Saturn. Titan's dense atmosphere makes it unique. From Voyager data we have some information about this atmosphere. The temperature at the surface is very cold — about 90 Kelvin or −300°F — and in the lowermost part of the atmosphere the pressure is similar to that on earth. The gas is primarily nitrogen but with a small amount of methane. How did this atmosphere come into existence?

When you put together a body, whether it is a giant planet or the earth or a satellite, you will always get very high temperatures. That temperature depends on the amount of energy released in the collision of the material that goes into making



The core in a giant planet is made first, as smaller bodies collide and accumulate. If this core is massive enough – about ten times the size of the earth – gas will collapse around it.

that body; in the case of Titan it would have been at least twice as hot as it is today — about 180 K or even hotter — for a period of time. Then you can expect to have a water-ammonia ocean — cleaning fluid — and an atmosphere that consists of a number of molecules — methane, ammonia, nitrogen, and some water vapor. This system too can undergo differentiation, which comes about because of a compound called clathrate. Clathrate is water-ice in which the structure of the ice has been modified so as to incorporate guest molecules, methane and nitrogen in this particular case. At about 180 K clathrate snow precipitates out of the oceans. Later on, when the ocean has mostly frozen, this material may become available for the outgasing of methane and nitrogen, which are the present constituents of the atmosphere. So this differentiation is a possible way of explaining the present atmosphere.

All these theories of planet composition are, of course, just theories, because we can't get inside planets to study them. But there are two new techniques that might lead to a better understanding of the interior of the earth. The primary technique currently applied is seismology. Seismology has many convenient attributes, but it also has a number of limitations in understanding composition. One new technique, which is already potentially available, although it is much more expensive than seismology, uses a beam of massless particles called neutrinos, which can be produced in a high-energy accelerator, such as Fermilab near Chicago. The neutrino beam goes in a straight line, and if you run it through the earth, you can measure the outcoming beam at the exact antipodes on the other side of the earth by placing detectors at the bottom of the ocean. By measuring the absorption of the neutrinos, you can learn something about the material inside the earth, because the absorption depends on the composition.

The other technique, perhaps somewhat bizarre from an engineering aspect, is to send a probe down into the interior. If you make a solid state probe (by which I mean something that is solid throughout with no cavities), and preferably quite large, say, 100 meters to a kilometer across, it can melt its way down into the interior of the earth and send information back up to the surface of the earth by seismic techniques or by very long wavelength electromagnetic radiation. With such a probe you would have in principle a way of sampling deep down within the earth, doing local measurements and sending the information back up to the eager people at the surface who would love to know what's going on down there.

This is a difficult engineering task and one not likely to come to pass in the very near future. But sending probes down into planets is potentially an important way of learning about their interiors. I'm even tempted to mention the idea, distasteful though it might be, of a new national agency. We already have NASA, which deals with outer space, and we have NOAA, which deals with oceans and atmospheres. Why not have NUA, which would be the National Underworld Administration?

So there is in fact a place for both onions and plum puddings in our solar system. Some of the planets (Jupiter is an example) are adolescent in the sense that they have not undergone the settling process; it has not yet separated except for the primordial core emplaced during the process of formation itself. The helium has not separated from the hydrogen; it is mixed in like the raisins in a plum pudding. On the other hand, the terrestrial planets, including the earth, do have something like the structure of an onion. □