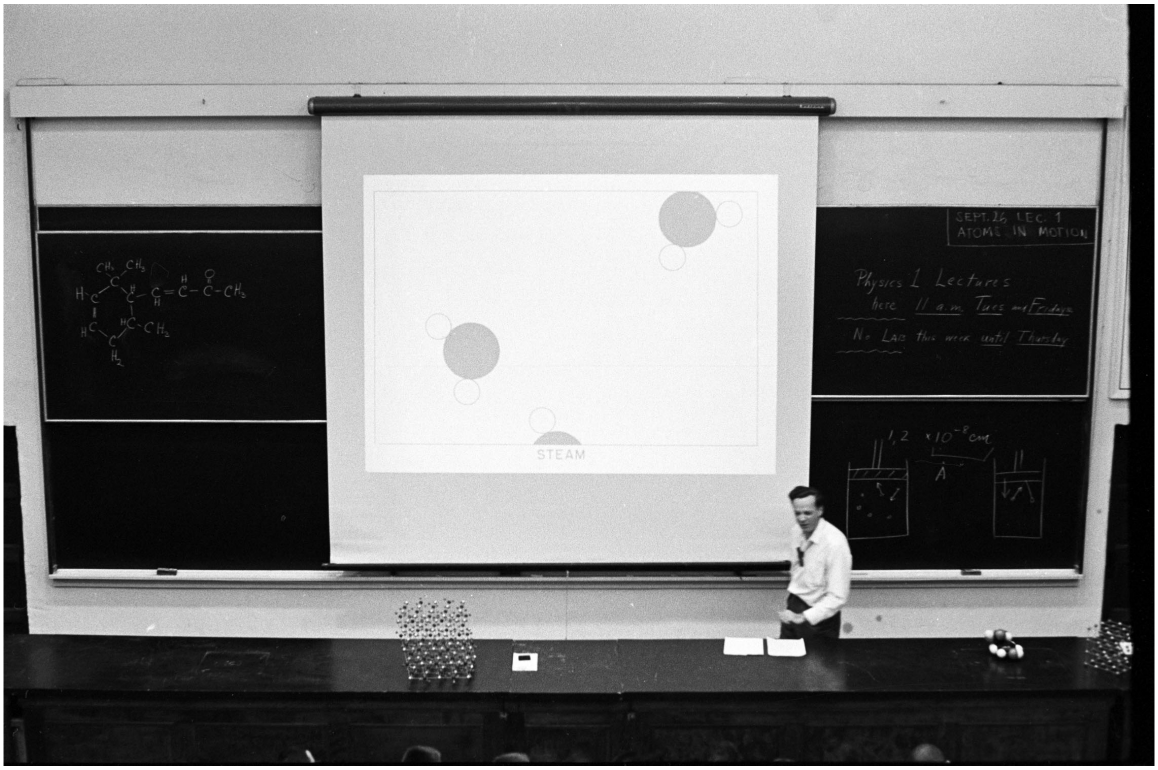
Atoms in Motion by Richard P. Feynman

The following is a transcript of Caltech Ph 1 Lecture #1, recorded on September 26, 1961, published in edited form as *The Feynman Lectures on Physics*, Vol. I, Chapter 1 (1963)
transcribed by Ralph Leighton, and edited by Michael Gottlieb.
(21 pages)



00:25

For two years I'm gonna lecture you on physics. I'm gonna lecture from the point of view uh that you are all going to be physicists—it's not the case, of course, but that's what every professor in every subject does. So, assuming that you're going to be physicists, we're gonna have a lot to study.

There's two hundred years of the most rapidly developing batch of knowledge that there is. So much, in fact, that you might think that you can't learn all of it in four years—and you can't: you have to go to graduate school, too. But the surprising thing is, that in spite of the tremendous amount of work that's been done for all this time, it *is* possible to summarize all this to a very large extent—and that is, to find some kind of laws which summarizes all our knowledge.

Nevertheless, it's still very hard—and it's unfair for you to start exploring this subject without some kind of a map, or an outline, of the relationship of one part of the subject of science to another. Therefore the first three lectures here will be in the form of outlining the relation of physics to the rest of the sciences, and the sciences to each other, and the meaning of science.

Incidentally, each lecture here will begin by some kind of a description of what the point of the lecture's going to be; then the lecture proper will start. uh Previous to that there'll be a summary of the previous lecture—the on– the bare minimum from the lecture before that uh is necessary to keep track of. In the first three lectures nothing is necessary to keep track of; no notes need be taken, because what we're trying to develop is a feel—a *feel*—for the subject. (Of course you can take down anything that you find interesting that you'd like to remember, but that's about it.) After two weeks or so, there will be the copy of these notes will be available—that we're gonna have some kind of a way of converting this, this, these words into print.

Now you might ask, "Why can't we teach physics by just giving the basic laws an– on page one, and then just showing how they work in all the various circumstances?"—something like Euclidean geometry: here are the axioms, and you make all the deductions.

Now you're not satisfied to learn it in four years; you wanna learn it in four minutes.

Well, we can't do it that way for two reasons.

First, we don't know all the basic laws—it's an ex– there's an expanding frontier of ignorance; that we still don't know the, the answer to everything.

03:01

Second, the correct statement of the laws of physics requires some very unfamiliar ideas, and requires advanced mathematics in their description. Therefore you need a considerable amount of training—first, in order to learn that what the words mean—so it is not possible to do it that way.

Therefore, we can only do it piece by piece, or…

Yet each piece, or part of the whole of nature, is only some kind of an *approximation* to the complete truth (or the complete truth as far as we know it); in fact, even everything that we know is only some kind of an approximation, because uh we know that we don't know all the laws yet. Therefore a great deal must be learned only to be unlearned again—or, more accurately, to be corrected.

Now, the principle of science—the definition, almost—is the following: *the test of all knowledge is experiment*. Experiment is the sole judge of "truth" with quotation marks—the quotation marks mean "scientific truth" or what we accept to be scientific. Anything is judged always by an experimental test.

But what is the *source* of the knowledge? Where did the laws come from that are going to be tested? Experiment, too, in a sense, produces these laws—in the sense that it gives hints. But you also need imagination to create from these hints the great generalizations—to guess at the wonderful, simple, yet very strange patterns beneath it all—and then to return to experiment to check again whether you got the right guess in your imagination.

This imagining process is so difficult, that there is today a partial division of labor in physics: there are theoretical physicists—who imagine, deduce, and guess at new laws, but don't experiment; and then there are experimenters—who experiment, imagine, deduce, and guess. (hmpf-hmpf)

Now, I said that the nature the laws of nature are approximate—and we first find the wrong ones, and then we find the right ones. Now, how can an experiment be "wrong"?

First, in a trivial way—that something was the matter with the apparatus that you didn't notice—but these things are easily fixed, and uh checked back and forth. So, gra– granting that the minor things are taken out, how can the law deduced from experiment be wrong?

Only by being inaccurate.

05:55

For example, the mass of an object never seemed to change—a spinning top, for example, has the same weight as a still one. So a law was ju– was invented: mass is constant, independent of speed. That is now found to be incorrect: the mass *does* increase with velocity, but appreciable increases require velocities nearly that of light.

A *true* law is: if an object moves less than a hundred miles a second, the mass is constant to within one part in a million. And, you see, in some *approximate* form is the correct law. So in practice, you see, you'd think that the new law made very little difference.

Well, yes and uh no: for ordinary speeds, we can certainly forget it, and use the simple constant law as a good approximation. Yet for high speeds we are wrong, and the higher the speed, the more completely wrong.

Finally, in a most interesting way, philosophically we are *completely* wrong with the approximate law: our entire picture of the world has to be altered when the mass is changed only by a little bit, if it isn't constant. That is the very peculiar thing about the philosophy, or the basic ideas, behind the laws: *very small effects require profound changes in our ideas*.

Well, what should we teach first, if we're going to teach? Shall we teach the correct, more exact law, with its strange and different, difficult conceptual ideas—for example, in this particular case, the theory of relativity, four-dimensional space-time, and so on—or shall we first teach the simpler constant-mass law, which is only approximate, but does not involve such difficult ideas? The first is more exciting and more wonderful, more fun—but the second is easier to get at at first, and is a first step to a real understanding of the first idea.

Now, this problem arises again and again in teaching physics, and at different times we'll have to resolve it in different ways. But in any case it's worth knowing at each stage what we are learning, how accurate it is, how it fits in to everything else, how it may be changed when we learn more. And therefore, in the first three lectures here, we're going to try to give an outline or a general map of our understanding of science today so that you can—in particular, physics, but other sciences at the periphery, uh from the point of view that we're taking here.

The purpose of this these first three lectures, then, is to get a feel for the whole thing, so that when we *do* concentrate and look very closely at a particular point, we have some idea of what the background is, and why that particular point is interesting, and how it fits into the big structure—so that's the purpose of the first three lectures.

In other words, the first three lectures are the main point *"what is our overall picture of the world?"*

09:05

Now, I'm a-going to begin this p– the first lecture—which is on atoms in motion.

If, in some cataclysm, all of the scientific knowledge is to be destroyed, but only one sentence is to be passed on to the next generations of creatures, what would be the best thing, the thing that contains the most information in the least number of words?

I believe it is the hyp– atomic hypothesis (or the atomic fact, or whatever you want to call it) that *all things are made out of atoms—little particles that move around, are in perpetual motion, attract each other when they are some distance apart, but repel being squeezed into one another*. In that one sentence you'll see there's an enormous amount of information about the world if just a little imagination and thinking is applied.

In order to… It's the purpose of this lecture to illustrate that idea, and uh I do it this way.

Suppose that we have a drop of water, say a quarter of an inch on a side, and if we look at it very closely, we see nothing but water—smooth, continuous water. Now, if we magnify it with the best microscope (light microscope, I mean) that's available, roughly two thousand times, then the water would drop would be forty feet across—about as big as a room, or so—and if we look uh at it closely, we would see that it is again a relatively smooth water, but here and there are small football-shaped things swimming back and forth—very interesting!—those are paramecia.

And you may stop off at this level and get so curious about the paramecia with their wiggling cilia and twisting bodies, that you don't go any further in this particular line—except to hope that you could make the paramecium still larger, and see what's inside. This of course is a subject of biology, but for the present lecture I must pass that and go down still further.

Magnif– Looking at the water material itself, and magnifying it uh two thousand times again, now the drop of water extends from here to Los Angeles, about fifteen miles across. And if you look very closely at it you'll see a kind of teeming—something that look, appears it's no longer smooth; that it's something like a crowd would appear at a football game, as seen from a very great distance.

In order to see what this "teeming" is about, we'll magnify it another two hundred and fifty times so we get a better look at this thing, and we'll see something like what's shown on the first slide.

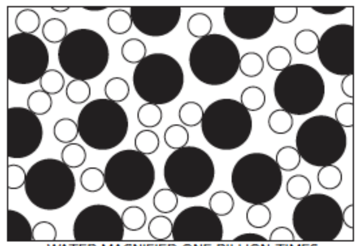


Figure 1-1

12:08

This picture of water magnified a billion times is idealized in several ways. In the first place, the particles are drawn in a simple manner, with sharp edges—which is inaccurate. Secondly, for simplicity I've sketched it almost schematically in a two-dimensional arrangement, but as you must appreciate, these things are moving around in three dimensions, and it's very much harder to draw—so this is not a real picture, but a kinda idealization.

I would like you to notice that there's two kinds of blobs, or circles, here—those are the atoms: there's a atom of oxygen, which is made in black, and an atom of hydrogen is pictured as a white circle—and you'll notice that each one that each white one has two hydrogens tied on to it.

There's another way in which this thing is idealized, and that is that the particles in this picture are really in fact 're always in motion: they're in a continuous jiggling and bouncing, turning and twisting around one another—so you'll have to imagine this in a dynamic way, rather than a static way.

Another thing that cannot be illustrated in a drawing is the fact that they are stuck together, that they attract each other—that this one is pulled toward this one, and b– and so forth, so that the whole bunch of them are glued sort of together, roughly, uh in a big clump.

On the opposite hand, they do not pass through each other: if you try to squeeze two of them too close together, they do repel. So we have this picture of jiggling balls bouncing around in the water. As a consequence, of course our drop of water fifteen miles across is now two hundred and fifty times fifteen, or from here to Chicago, approximately, or bigger.

And, uh you can remember the size of these atoms roughly this way: you can either remember that the atoms are from between one and two times ten to the minus eight centimeters in diameter— ten to the minus eight centimeters is also called an angstrom, so we say (just as another name), so we say they're about one or two angstroms in diameter. Another way to remember the size is this: if you take an apple and magnify it to the size of the earth, then the atoms in the apple are approximately the size of an apple—so that's another way—it's either way; you can remember it either way.

Now, you could imagine, then, this great drop of water, with all these things stuck together and tumbling over each other. The water keeps its volume: it doesn't pu– fall apart, because of the attraction of the ato– of the molecules or the atoms for each other.

15:02

Supposing if you had a slope, for example, that in the tumbling they can move the whole drop of water from one place to another—the water can flow—but it doesn't just disappear; the things don't just fly apart, on account of the attraction.

Now, the motion is what we represent—or what we notice, rather, as heat—and when we increase the temperature, we increase the motion. If we heat the water up, the jiggling increases, increases—the banging between the atoms or molecules increases all the time—until there comes a time when, in a collision, there's not en– there's so much speed that it's this pull between them is not enough to hold them together, and they fly apart and become separated from one another. Of course what I'm describing is the manufacture of steam out of water by increasing the temperature—the things flying apart because of the increased motions.

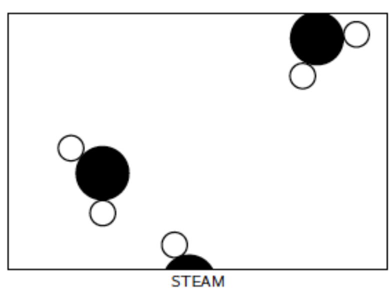


Figure 1-2

So in the next picture, we have a—next slide—, we have a picture of steam. Now it is much more clear how the molecules are formed. This picture of steam fails in one respect: the in ordinary pressures, this atmospheric pressure of steam, there might be only a few molier– not very many molecules in this whole room; there certainly wouldn't be as many as three—most squares of this size would contain nothing, and I accidentally have two and a half or three in the picture, but that's just so it isn't completely boring: you have *three* things to look at!

You see the characteristic molecules are much clearer in the case of steam than they are in the case of water. In this molecule I've drawn them on the slide so there's a hundred and twenty degree angle here, for simplicity. In actual fact the angle is a hundred and five degrees, three minutes—and the distance between the center of the hydrogen and the center of the oxygen is point nine five seven angstroms—so we know this molecule very well. In fact, we probably know it better, but I couldn't get more accurate figures in the short time available.

Now let's see what some of the properties are of steam vapor, or any other gas, because these things, having being separated from one another, will bounce against the walls: imagine this room with a number of tennis balls—or not very many; a hundred tennis balls, or something—bouncing around in all directions because of the heat that they have, in perpetual motion. Then they'll of course bounce against the walls and bombard it, and this rep– pushes the wall away. Of course you hold the wall back; that requires that means that the gas exerts a pressure, which our coarse senses (not having *ourselves* magnified a billion times), we feel it only as an average push. So in order to confine a gas, we have a pressure.

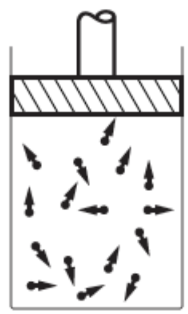


Figure 1-3

18:00

So here is a picture, for example, of a standard vessel for holding gases—in all textbooks—which consists of a cylinder with a piston head on it. (Or I don't know why all gases are always contained in cylinders with piston heads, but that's what we'll will represent here.)

Now, it doesn't make any difference what the shape of the water molecules are, so for simplicity I'll draw them as tennis balls or little dots, and these things are in perpetual motion in all directions. So, many of them are hitting all the time the top piston, and in order to keep it from from being patiently knocked out of the tank—slowly knocked out of the tank—by the continuous banging, I have to hold the piston down by a certain force which I call the pressure (or really the pressure times the area is the force, but never mind, it's—) Clearly the force… Clearly the force is proportional to the area if, when I increase the area, I keep the number of molecules per cc the same.

Now, if I put twice as many molecules in this tank at the same speed, that represents then the same temperature, but twice as number of atoms—that's twice the density—then, within an excellent approximation, the number of collisions will be twice as much, and they will be as energetic as before, and the pressure will be increased by a factor two. So the pressure is proportional to the density. Not exactly, because there are forces between these atoms; there's a certain density when you put too many in there, that one pulls the other back, and decreases the force that you'd expect, perhaps, over what you'll—or increases it because they take up each other's room—and so on. So that it's not so easy to tell *exactly*, but to an excellent approximation if the pressure's low enough that there are not many atoms, the force is proportional to the density.

Now you can see something else: if I increase the temperature without changing the density of the gas, that means if I increase the speed of the atoms, what's gonna happen to the pressure? Well, they hit harder because they're moving faster, so the pressure increases—you see how simple the ideas of atomic theory are.

Let me take another example that's still more… that's another…Well, let's consider another thing: suppose that the piston is moving down. Well, the atoms are being compressed into a smaller space. What happens when an atom hits a moving piston? If it's moving around like this, and it hits a moving mirror, or bounces off a moving wall, evidently it picks up speed from the collision—you can try it by bouncing a ping pong ball off a moving bowling ball, for example—and you'll find that it comes off with more speed than it went in. (Special example: if it happens to be standing still, and the piston hits *it*, it'll certainly go down.) So it's clear that it comes off on, in average, with more speed than it comes in. Therefore, after a while the atoms which are in here will have picked up speed. That means that when we compress a gas slowly, the temperature of the gas increases. So under com– slow compression a gas will increase its temperature.

21:04

And then the slow expansion, what? In the case of expansion, if the piston is moving up, then each atom which hits this piston, which is moving out, goes in—if I may crudely speak of it—into a yielding material (a place thing that's going back), and the energy that the atoms have is decreased. Therefore gases cool on expansion.

Now that's the di– direction of increasing the temperature of the water.

Let's look in the other direction. Suppose that we decrease the temperature. Suppose that the jiggling of the atoms—of the molecules, or the atoms in the water—is slowing down, slowing down all the time. Now, you know that the forces—there are forces of attraction between the atoms—and after a while they can't be able to jiggle so well—and d– what'll happen at very low temperatures is indicated in the next slide.

What happens is, that they lock in to a new pattern, what'sk a pattern of ss—(will you turn out the lights so we can see the ice better?)—to a… to a pattern which is solid.

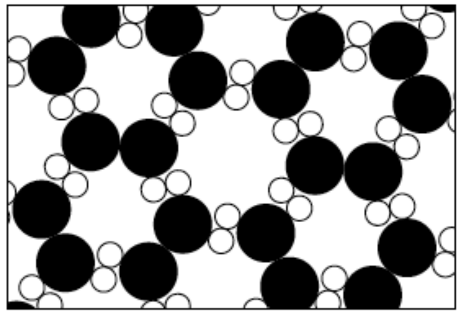


Figure 1-4

In this particular schematic diagram of ice—which is wrong because it's in two dimensions, but is right qualitatively (I have a three-dimensional model here too I'll explain perhaps later)—we have the oxygen atoms and the hydrogens, with two hydrogens on each oxygen as before, but they all are s– the hydrogens are touching each other, and the whole thing is stuck together in a certain array. This is not the *exact* array; of course it's a two-dimensional thing; the exact array of course is a *three*-dimensional thing that's hard to portray.

However, the point is is that's interesting is that the material has a definite *place* for every atom, and you can easily appreciate that if somehow or other I were to hold all these atoms in a certain arrangement, in a certain place, then because of the structure of interconnections, which is rigid, the other end—"miles" away—would have a definite location. So if I hold a piece of ice, or a needle of ice, at one end, the other end resists my pushing it down—unlike the case of water, in which this structure, because of the increased jiggling, is broken down so that the atoms all move around in all different ways. Then the organization of the atoms in this thing, even if they're held in place, will not pass itself from atom to atom in all directions to the other end, and our little crystal will just sag and drip down as we increase the temperature.

So the difference between solids and liquids is, tha– is that in a solid the atoms are arranged in some kind of an array and, uh, an array of what's is called a crystalline array—a crystalline array—and they do not have a random position at long distances, but the position of some of the atoms at a long distance away is lo– is determined by where the atoms are, some "millions of miles" on the other side of the crystal. (Of course I mean "millions of miles" at this scale, of course—a small distance in nature.)

24:17

This particular slide is an an invented arrangement for ice, and it contains several of the correct features of ice but is not the true arrangement. One of the correct features is that there's a pattern of symmetry that's hexagonal. You can see it if you turn this whole picture (I don't mean the out– the border, but the atoms themselves around an axis, say here, by thirty, by s– uh hundred and twenty degrees for example, then the picture returns to itself—so that there's a symmetry in the ice, a six-sided symmetry, which accounts for the six-sided appearance of snowflakes, for example. So in there is the form of snowflakes, hidden.

Another thing that's illustrated by this particular artificial model is the fact that, particularly, that ice *shrinks* when it melts. You'll note this particular pattern that's arranged here had lots of holes in it. Now, the true ice structure has a lotta holes in it, and when the organization breaks down, these holes can be occupied by the molecules—and so the volume of the water is less than that of ice. Most substances, with the exceptions of—common substances that are exceptions are are water, and type metal… Usually things contract expand when they melt, because usually the packing is tighter than this when it's cold, and when it melts it needs more room to jiggle around—so that usually it expands. But sometimes, when it's an open structure, it collapses when it melts, as it does in the case of water.

Finally, I may say that although this is how I keep talking about this as a rigid arrangement, ice temperature can change; ice has "heat" (if you wish), and you can change the amount of heat. What is the "heat" in the case of ice? Well, these things aren't really just standing still there; they're jiggling in place, vibrating, trying to get out of there—all jiggling, like a—wiggling, all the time, like a—oh, I don't know, you take a mattress springs, or something, and imagine them all wiggling all the time. So there's a definite order to the thing; it's got a structure, but they're all the things are jiggling in place.

As you increase the temperature they jiggle in place with a wider and wider shaking until the shaking is so wide, so big, that they pull themselves out of place, and we get the melting.

As you decrease the temperature the jiggling decreases and decreases, until at the absolute zero there's a minimum amount of jiggling that matter can have—not zero, but there's a certain *minimum* amount of jiggling that matter can have. As a matter of fact, this minimum amount of jiggling that a– things can have in all cases is not enough to melt the thing, so everything is solid at absolute zero with one exception, and that's helium. Helium never solidifies; the minimal jiggling at absolute zero is still enough to keep it meltin'. So helium, at zero temperature even, never freezes—unless the pressure is made so high as to help the things; they get squashed together—if you increase the pressure, then you can make it solidify.

27:18

Now, that's so much for the description of solids, liquids, and gases from the atomic point of view—but the atomic point of view also describes *processes*. And so I'd like to go and diss– look at a number of processes uh to see how they look from an atomic standpoint.

The first u– process that I would like to look at is associated with the surface of the water. What happens at the surface of the water? And this time I'll make the pictures more complicated and realistic by imagining that the surface is in air. And this is illustrated in the next picture.

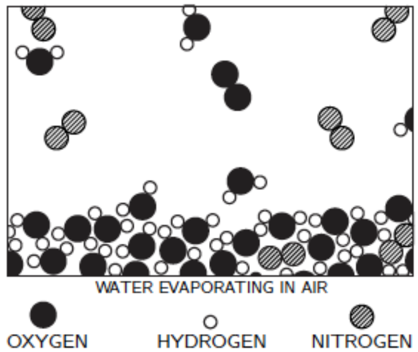


Figure 1-5

Here is a surface of water in air. You may rec– notice the water molecules as before, and down here, and below, is the liquid water—and this is the surface of it. Above you'll find a number of funny things.

First of all, there's some water molecules, like the steam—that's water vapor that's always there above water. There's a mixt– there's a equilibrium between the vapor—or steam vapor—and the liquid water, which I'll explain in a minute.

But in addition, you'll find some other thing. Here's two black ones stuck together; the black ones are called oxygen atoms, and two oxygen atoms stick together also by themself, forming another kinda molecule—or oxygen molecule. In addition there's these cross ha– cross-hatched things, which are nitrogen atoms, and they stick together in pairs, too, to make a molecule. Air consists almost entirely (with a fl– few uh impurities of different things) of… of, uh… nitrogen, oxygen, some water vapor, and few other things—carbon dioxide, argon, and traces of other thing . So here's the air, a gas containing some water vapor.

Now, what's happening in this picture? The molecules of the water are always jiggling around. From time to time in the jiggling, one near the surface happens to be hit a little harder on the accident (just an accident) a little harder than usual, and gets pushed away—say. (I mean, it's hard to say, 'cause it's a still picture, just what's happening here.) But this one has just been hit, for example, and it's flying out—or perhaps this one is the one is the one that's just been hit and flying out—so that, molecule by molecule, the water disappears. It evaporates.

29:43

But if we close the vessel above, after a while we have a large number of molecules of water amongst the air— because they have nowhere else to go. In other words, if we have a closed uh vessel, the wa– then what happens? Then—let me take this one—from time to time, one of them that's out here comes flying down into the water and gets stuck again. So that i– what looks like a dead, uninteresting thing—a glass of water with a cover that's been sitting there for twenty years—is a dynamic, ex– an interesting phenomenon going on all the time.

To our dumb eyes, our crude eyes, nothing's changing, but if you could see it a billion times magnified, you'd see that from its own point of view it's *always* changing: molecules are leaving the surface; molecules are coming back, back and forth. Why doesn't it change? Because just as many are leaving as are coming back, so in the long run, nothing happens.

If I then take the top of a vessel off, take the glass off, and blow the air away—if I make a stream that sweeps across here, and takes away these molecules of water, replacing 'em just by air—then the number that are leaving is still the same as it was before (because it depends on the jiggling of the water), but the number that are coming back is reduced very much, because there are so much fewer molecules above the water. Therefore there's more out than in, and it evaporates—hence, you want it to evaporate, turn on the fan.

Now there's something else: which molecules leave? When a molecule leaves, it's because of an accidental extra accumulation of a little bit more-than-ordinary knocking, or fo– banging. Therefore those that leave have, on the average, more energy than the average molecule that's in here. So the ones that are leaving take away energy, and leave the ones behind with a less average motion than they had before—the more uh mo– moving ones are the ones that leave. So the liquid gradually cools, if it evaporates.

Of course when one comes back, because of the attraction to the water below, when it comes in there's a sudden great attraction, and there's a snapping—in other words, a generation of heat. So when they're coming back they generate heat; when they leave they take away heat—and the result, of course, in the when there's no net evaporation, is nothing—there no change in temperature. But if I blow, so as to maintain a continuous increase in the number—there're more going out than coming in—then the water is cooled. Hence blow on soup, if you wanna cool it off.

I also want you to notice that the processes are more complicated. Not only does the water go into the air, but you can imagine among the collisions that from time to time, one of these molecules may come in here, get lost in the mer– in the mess, and work its way into the water, so that the air dissolves in the water—both oxygen, which is not illustrated, and nitrogen molecules will work their way into the water, and the water will contain nitrogen.

33:00

Of course if we suddenly take the air away, then these nitrogen molecules will leave more rapidly than they come in, and uh in doing so will make bubbles. This is uh very bad for divers, as you well know: when you have a high-pressure air, which you're breathing, then in the blood more nitrogen is dissolved than ordinarily, because high pressure just means a large density of the nitrogen—so that more of them are going in, when it's high. When you decrease the pressure, they try to come out, and make bubbles. So that's what happens, and the bubbles are not good for the heart.

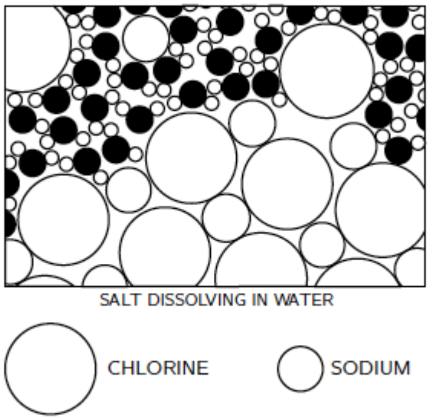


Figure 1-6

Crystal	●	○	a (Å)
Rocksalt	Na	Cl	5.64
Sylvine	K	Cl	6.28
	Ag	Cl	5.54
	Mg	O	4.20
Galena	Pb	S	5.97
	Pb	Se	6.14
	Pb	Te	6.34

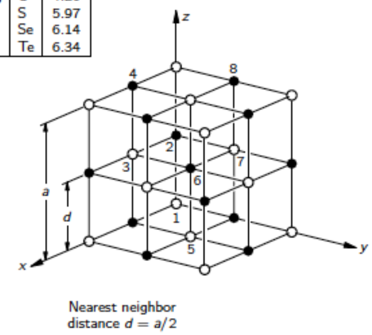


Figure 1-7

Now let me turn to another process. On the next slide we see another process from an atomic point of view—a solid dissolving in water. Suppose that we put a crystal of salt in the water. What happens? Salt is a solid; it's a crystal, and so there's an organized array, which is cubic arrangement here, of salt atoms. Here is an illustration, in three dimensions, of the salt—uh sodium and chlorine.

These are strictly speaking not atoms, but what we call ions. These uh… An ion is an atom which has either got an extra, or has lost a few, electrons—it has the wrong number of electrons. And uh this is a chlorine ion—it's a chlorine atom with an extra electron—and this is a sodium ion—that is to say, a sodium atom with one electron short.

Now, they all stick together by electrical attraction in the solid salt, but when you put it in the water, you'll find that because of the attractions of the negative oxygen and the positive hydrogens for the ions, there will be, gradually in the jiggling, some of these atoms will get loose. Here's a picture of one, the chlorine atom, getting loose—and uh there they are, floating in the water, in the form of ions.

You'll notice some very—these pictures are made with a great deal of care, heh—you notice some delicate features. For example, around the chlorine the hydrogen ends of the water are more likely to be there—while around the sodium, the oxygen end—because the sodium is positive, and the oxygen end of the water molecule is negative, and they electrically attract—so that there's that's the way it'll be, and it this more or less realistic. And uh we (Of course I han't think of everything, so I can only point out those things which *are* realistic in the slide; those things which aren't, I haven't thought of.)

Now, in this particular case, though, ion, or ion by ion, the sodium is dis– dis-eh-solved in the water. How can you tell from this picture whether this is salt dissolving in water, or salt crystallizing *out of* water, say, which is evaporating—an increase in the concentration of salt?

You cannot—because for while the atoms are leaving, other atoms are coming down; we still have this dynamic business, just as we had in the case of evaporation—and it depends upon whether there's more salt in the water, or less salt in the water, than the amount needed for equilibrium. By "equilibrium" I mean the rate at which they're leaving shall match the rate at which they're coming back. So, if there's hardly any salt in the water—if it's nearly pure water—more leave than come back, and the stuff dissolves. If, on the other hand, you've made it so there's too many atoms or too much in the water—then more come down, and the thing is crystallizing.

36:21

Notice that, by the way (if you're interested in molecules), that the concept of molecules is only approximate, and only exists for an certain number of substances. Although it's pretty clear in the case of water that those three atoms are stuck together, it's impossible to say, in the case of the sodium chloride, where the "molecule" is: there *is* no molecule of sodium chloride in the solid; there's just an arrangement of sodium and chlorine atoms in a pattern—uh the cubic pattern given here.

The… uh… If we increase the temperature, we increase the jiggling. Then the rate at which the things are taken away is increased—but so is the rate at which the things are brought back increased—and it turns out to be quite difficult in general to predict the general law as to which way it's going to go—when ya increase the temperature, whether you're gonna dissolve more, or dissolve less. Most substances dissolve more, but some substances dissolve less. So we can't tell, but we can guess that it'll change one way or the other, because it will be an accident of the greatest form if, when ya' increase the rate of jiggling, the rate at which they jiggle loose, and the rate at which they work their way back, happened to be uncha–n– balanced—changed both the same amount. Both rates are of course increased, but the question is, which increases the most.

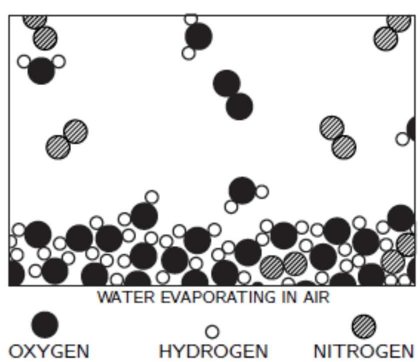


Figure 1-5

Now, in all the processes which I've described so far, the atoms or the ions have not "changed partners." That is, we have here a molecule of water with two oxygens and a hydrogen; we pointed out there was something like oxygen, which was two molec– two atoms of oxygen alone. But there *are* circumstances in which the atoms take up new combinations, forming new molecules.

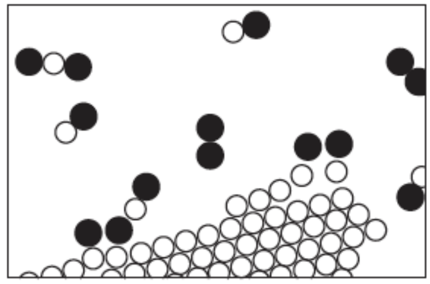


Figure 1-8

This is illustrated in the next slide—a situation in which the realignment of the pai– of the “partners” occurs. This is what we call a chemical reaction; the others we call a physical process, but there’s no sharp distinction between these things—nature doesn’t care what we call her; she just keeps on doing it whatever way she want.

Now, this is supposed to represent carbon. I didn’t bring a crystal of carbon; it’s diamond, for example. If you wanna burn a diamond in air, you can—but you’re kinda dopey.

Now, here is uh burning in oxygen. I’ve simplified: I haven’t got air—this is the oxygen. Now, in the case of oxygen these two oxygen atoms stick together very strongly. Why not three? Why not four stick together? That’s one of the very peculiar characteristics of uh interatomic forces: they’re very special, and they like certain particular partners in certain particular directions, and so on—and it’s the job of physics to analyze why each one “wants what it wants.” But at any rate, it forms—saturated, or “happy”—a pair. The carbon atoms in the crystal, which would be—the graphite, or… or diamond—looks like this.

39:24

Now, for example, one of these can come down to the carbon, and put and each one pick up a carbon atom, and go flying off in a new combination, carbon-oxygen—which is called the gas carbon monoxide (one oxygen for each carbon), and is given the chemical name CO—it’s very simple. This is practically a picture of that molecule.

The carbon attracts the oxygen much *more* than either the oxygen attracts the oxygen, or the carbon attracts the carbon. Therefore when this happens, this may come down with a small energy, but it may be able to pick up these things, and they will snap together with a tremendous vengeance, and jiggle—and anything else near them will pick up the energy away, because they hit if you hit something that’s jiggling hard, you pick up an energy. So there’s a trem–a–a a large amount of motion energy—kinetic energy in the gas is generated here. This, of course, is *burning*—we’re getting heat out from the combination of oxygen and carbon—the heat is in the form ordinarily of the high motion of the gas hot gas, but of course in certain circumstance it can be so enormous that it generates light—and so you get *flames* out of this.

In addition, the carbon monoxide is not quite "satisfied"—it is possible for it to attach another oxygen—so we might have a much more complicated reaction illustrated here, in which the oxygen is combining with the carbon—but we're not sure, and at the same time there's it happens to be a collision of a carbon monoxide, here—and we're not sure whether *this* oxygen is gonna end up attached to *this*, on this one to that, or how—but this *could* attach itself to this and form *this* molecule, which is one carbon and two oxygens, which is made in the form—CO_2—and is carbon dioxide. If you've got enough oxygen present, and you burn it continuously—you keep the reaction going—it'll form all carbon dioxide, ultimately. But if you burn the thing with very little oxygen, and uh do a very rapid reaction—like in a gas– for instance in an automobile engine, where the colli– where the explosion is so fast there isn't *time* for it to make mu– all the carbon dioxide—and a considerable amount of carbon monoxide comes out.

The main difference between this and other processes is the fact that new partners are formed to form *new* molecules, and this rearrangement is a called a chemical reaction—and, most interesting, in such rearrangements a very large amount of energy is released, forming explosions, and flames, and so forth, depending on the reactions.

42:02

Now, the chemists have studied these arrangements of the atoms, and find that *everything* can be understood—everything is some kind of an arrangement of atoms—and to illustrate this, I would like to just ex– take an example of something else. If we go in a field and smell violets, for example, what that smell is, is some kind of a molecule or arrangement of atoms that's worked its way into our nose. So, uh first of all, how does it work its way?

Well, that's pret– pretty easy: if there's some kind of a molecule or arrangement of atoms with that come off of a violet—since the gas has all the atoms pretty far apart it can—jiggling around and batting all over, wor– —accidentally work its way into the nose. There's no particular *desire* to get into the nose; it's merely—it's merely that they're a jostling crowd of atoms in molec– in the ga– in the air, and this particular chunk of stuff, working its way, gradually up into, uh happened to work its way into the nose.

Now, the chemists can take special molecules like the odor of violets, and analyze it, and tell you the exact arrangement *in space* of the atoms—just like we know that the carbon dioxide is a straight line from here to here; that can be determined easily physic– by physical methods, too. But in the very much more complicated arrangements of atoms that there are in chemistry, by a very remarkable process of detective work you can find the arrangements of the atoms.

First, let me deal wi- illustrate the picture of how what it looks like over a violet—what the air looks like in the neighborhood of a violet. That's illustrated in the next slide.

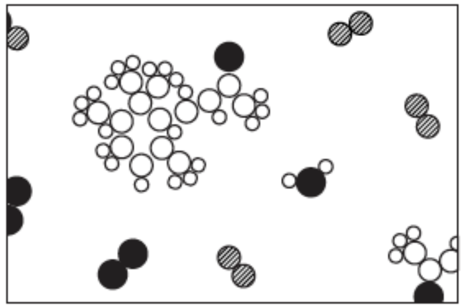


Figure 1-9

Here is uh nitrogen and oxygen of the air.

What’s that?

Well, water vapor.

What’s it doing?

Well, a violet is wet!

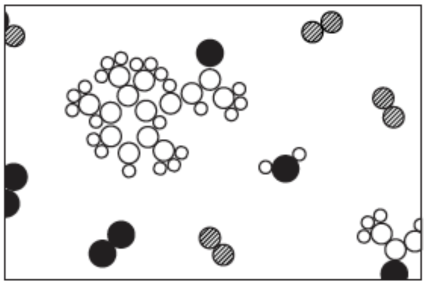
I mean uh you know, all plants transpire, and uh so there’s some water vapor in the air.

And then there’s this monster!

The(e) white circles are carbon atoms, the little circles are hydrogen atoms, and the black circle is an oxygen atom. And these, gentlemen, have pic– a certain particular pattern for them to arrange: it’s much more complicated than carbon dioxide; it’s an enormously complicated arrangement. Unfortunately, I cannot really picture all that is known about it chemically, because it is actually known, in *three* dimensions, the precise arrangement of those molec– those atoms—that is, whether, for examp–, you see I draw it in *two* dimensions, but *this* carbon and *that* one may be turned *this* way, relative to *this* carbon and *that* one, and so on. And these six carbons—which form a ring here—do not form a flat ring but a kind of puckered ring, and all the angles and distances are known (to uh say, a percent in this particular case).

45:03

However, for the excitement of the thing, I unfortunately made this slide some almost nine years ago, and it turns out that my in– my, uh respect for chemistry was a little bit exaggerated, because they since found that they had made a slight error in the arrangement of the odor of violets. (However, I’ll tell you what the error is; it’s not very great.) But I want to point out that what a chemical formula is, is merely a s*picture* of such a molecule. When the chemist writes this thing on the blackboard, he is trying to draw, roughly speaking, this: he’s not drawing it exactly in three dimensions, but tells you which atoms are touching which.



ODOR OF VIOLETS

Figure 1-9

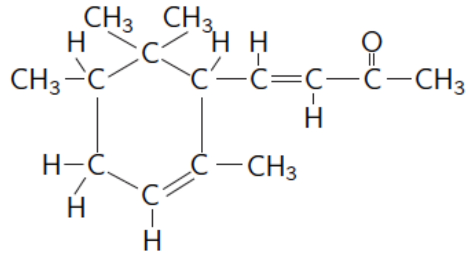


Fig. 1-10. The substance pictured is α-irone.

So I have, for example, a ring of six carbons, and a chain of carbons hanging out the end—and so you see a ring of six carbons, and a chain of carbons hanging out the end, with an oxygen second from the end—oxygen second from the end—three hydrogens tied to that carbon, two carbons and three hydrogens sticking up here, and so on. So the chemist, in writing this formula, has discovered the arrangement of the atoms in the fshape of the molecule.

How does he do it?

He mixes bottles full of stuff together, and if it turns red it tells him there's a group of one carbon and three hydrogens tied on here; if it turns blue, on the other hand, that's not the way it is at all. This is one of the most fantastic pieces of detective work that has ever been done—organic chemistry: to discover the arrangement of the atoms in these enormously complicated arrays by looking at what happens when you mix the different substances together. The physicist never quite believed that the chemist knew what he was talking about, when he told the arrangement of the atom. And in more or less recent years—in twenty years, thirty years—it's been possible, through electron diffraction, to kind of look at such molecules—not quite as complicated as this, but ones which contain parts of this. And it's been possible to loo– —(sometimes, nowadays, yes, even as complicated as this), and it's been possible to locate every k– atom by a physical method that has nothing to do with mixing and looking at the colors, but by measuring where they are. And, lo and behold, the chemists are almost always correct.

Incidentally, I must apologize for this particular one, the odor of violets being unknown then—it turned out that they had an error in analysis, and I picked the wrong molecule; I should have picked one nine years ago that they knew better. At any rate the correct picture of the odor of violets is given here. It's the same ring as before, same chain as before; if you look closely you'll see one difference: there's an extra CH_3 tied on here—there's a rearrangement of the hydrogens—there's none here, and there's an extra one here, and so on—but it's very close to the way it was before, and I'm sorry I could have made a new slide and not embarrassed the chemists.

The substance that I've drawn here is alpha irone. It turns out that there are, from the violet, three different molecules which have a slight difference in the arrangement of the hydrogen atoms—that's all; minor shifts—two hydrogen atoms—to the other form.

48:08

Now, an important problem in chemistry is to name the substance so you know what it is. uh Find a name for this shape—and ya appreciate the problem of finding a name for a shape—more than a shape, even: not only must you get the shape, but you haveta tell which is—"this is an oxygen, not a nitrogen"—exactly what they are. You need a name for the shape and the particular location of the atom. And so you can appreciate that, uh that the chemical names must be complex if they're complete. And so you see that the kname of this thing in a more complete form that'll tell you the form of it is four dash comma two two three six dash tetramethyl dash one dash cyclohexenyl close parentheses dash three dash butene dash two -o̲ne —and that tells you that this is the arrangement. But you can appreciate the difficulties that the chemists have, and also appreciate *why* the names are so long: it's not because they wanna be obstinate, but because they have an *extremely* difficult problem: to describe this thing, in words.

Why they don't just draw the pictures all the time, I don't know—it seems to me easier.

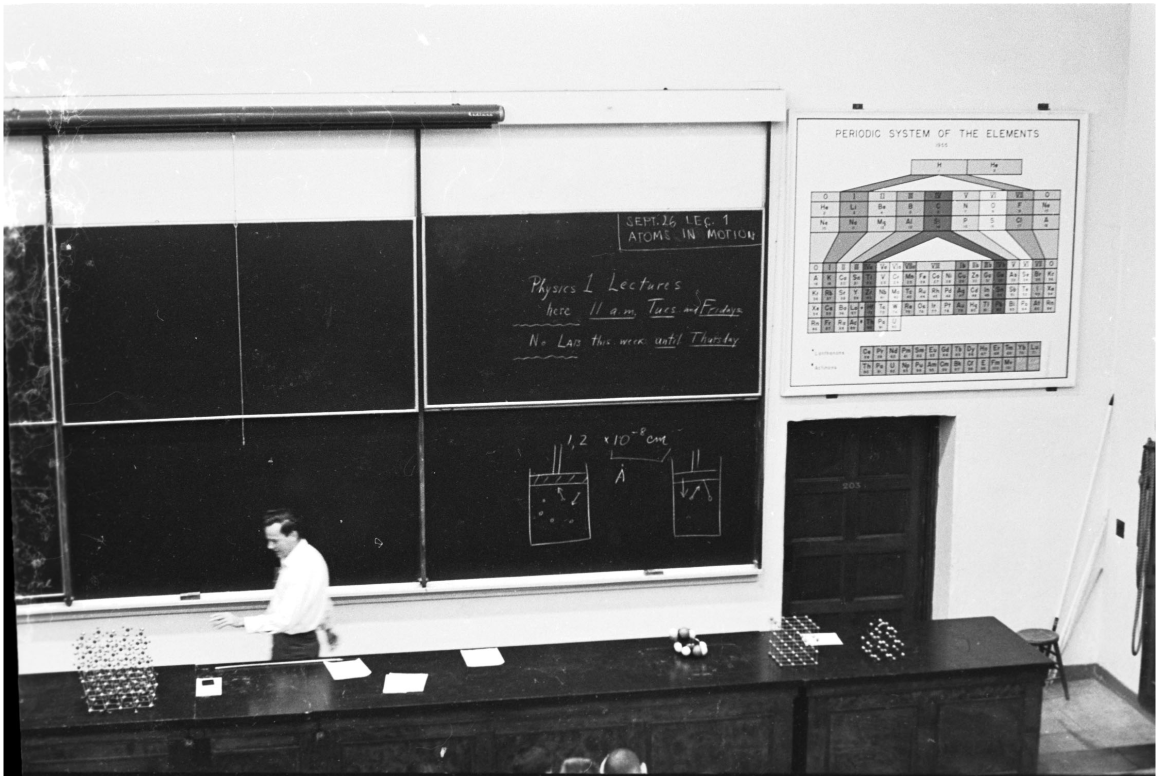
Now, how do we know that there *are* atoms?

By all of the effects that I talked about, we made a hypothesis that there are atoms—and one after the other, things come out the way we say. (They ought to, if they're made out of atoms—and that's the most of the evidence for atoms.)

There is somewhat more direct evidence; a good example of that is the following. The atoms are so small that you can't see them with a light microscope—an ordinary microscope—in fact even with today, with an electron microscope, you can't still see individual atom. But with a light microscope you can see something that's much bigger.

Now, if the atoms are always in motion, say in water, and I put a big ball of something in the water—much bigger than the atom—that ball will jiggle around, much like a push ball in that big game: you have a great big ball, a whole lot of people under it, all pushing in various directions, and the ball moves around the field in an irregular fashion. So in an irregular fashion a very large ball will move because of the accidental inequalities of the collisions on one side or the other. (A few more hit on one side than the other at a given moment and the ball starts moving *this* way; then it's quickly "change its mind," 'nd so on.) Therefore, by putting… if you look at very tiny particles of dirt (well, of stuff, of different things—colloids, or something) in water through an excellent microscope, you can see a perpetual jiggling of the particles, which is a result of the bombardment of the atoms.

That's the most direct evidence for the atoms, and I hope that they will it will be possible to arrange in a laboratory to set up a microscope so that you can take a look at these vibrating atoms.



51:00

I have uh here arrangements of the various, o– of some of the different kinds of solids. Here is a solid that's a little more complicated, which is calcite, and the actual crystal of true calcite sits here, and you can see the relation between the shape of the crystal, and the shape of the of the arrangement.

Here is another arrangement that the chemists are using to study the arrangement of the atoms in various molecules: this is about as complicated as irone; it happens to be an amino acid important in eh living p– things, called tyrosine—but it's merely illustrative of what we know about the atom.

Now, *everything* is made out of atoms—that's the key hypothesis. The most impressive hypothesis in all of biology, for example—the most important hypothesis—is, that everything that animals do, atoms do. In other words, that there's nothing that the living things do that cannot be *understood* from the point of view that they're made out of atoms jiggling according to the laws of physics. This has not been self-evident from the beginning; it took some experimenting to suggest this hypothesis, and now it is accepted and is the most useful for producing new ideas in the field of biology.

If a piece of steel or a piece of salt, consisting of atoms one next to the other, one next to the other, can have such interesting properties—or take water, which is nothing but these little blobs—mile upon mile of the same thing, repeated on an on—forms waves and foam, and makes rushing noises, and makes the funny patterns as it runs over cement; if all this all the life of a stream of water can be nothing but a pile of atoms, *how much more is possible?* If, instead of arranging the atoms in some definite pattern again and again repeated, on and on—or even in little lumps of complexity, like the odor of violets—we make an arrangement of atoms which is always *different* from place to place, with different kinds, and k– so on, in other words enormous arrays continuously changing, not repeating, how much more marvelous is it possible that these things behave? And is it possible that this *thing* that walking back and forth in front of you, talking to you, is a great glob of these things in a very complex arrangement—and that the sheer complexity of it staggers the imagination as to what it can do—so that when we say "I am a pile of atoms," I do not say I am *merely* a pile of atoms, because: a pile of atoms which is not repeated from one to the other might well have the possibilities which you see before you.

Thank you.