Lecture 5: The Distinction of Past and Future

[BBC TV Film Leader]
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The Distinction of Past and Future

Now, it's obvious to everybody that the phenomena of the world are evidently irreversible. By that I mean things happen that don't happen the other way: you drop a cup and it breaks, and you can sit there a long time waiting for the pieces to come together and come back into your hand. If you watch the waves breaking at the sea, you stand there and wait for the great moment when the foam collects together, rises up out of the sea, and falls back further out from the shore—it would be very pretty.

As a matter of fact, the demonstration of this in such lectures is usually made by having a section of moving picture, in which you take a number of phenomena, and running the thing backwards, and then see all the laughter—the laughter just means this ain't gonna happen in the real world.

But actually, that's a kind of a weak way to put something which is so obvious and deep as the difference between the past and the future. Because even without an experiment, our very experiences inside are completely different from past and future. We remember the past; we don't remember the future. We have a different kind of awareness about what might happen than we have of what most likely has happened. The past and future look completely different psychologically, [as do] the questions of memory, of apparent freedom of will, in the sense that we feel that we can do something to affect the future—but none of us, or very few of us, believe that there's anything you can do to affect the past.

Remorse, and regret, and hope are all words which distinguish perfectly obviously the past and the future. Now, if the world of nature is made of atoms (and we, too, are made of atoms that obey physical laws)—this obvious distinction between what happens in the past and the future, and this obvious irreversibility of all phenomena—you would think the most likely and obvious interpretation is that some laws—some of the motion laws of the atoms—are going one way, that the atom laws are not such that they can go either way, that there's somewhere in the works some kind of a principle that ooksels only make wooksels, and never vice versa, and so the world is turning from ooksely character to wooksely character all the time, and that this one—way business of the interactions of things is the thing that makes the whole phenomena of the world seem to go one way.

Yet we haven't found it yet. That is, in all the laws of physics that we've found so far, there doesn't seem to be any distinction of the past and the future, that the moving pictures should work the same way going both ways, and the physicist who looks at it should not laugh—details now to be explained.

Let us take the law of gravitation as our standard example. If I have a sun, and a planet that I started off in some direction going around to here, and then take a moving picture of this—say it gets to here. Now, take a moving picture of this backwards—take a moving picture of it, excuse me, and run the movie backwards—and look at it. What happens?

The planet goes around the sun in an ellipse. The speed of—this way, of course: starts here, goes to here, keeps on going around; goes in an ellipse—the speed of the planet is such that the area swept out by the radius is always the same in equal time. [It] just does exactly the way it ought to do, perfectly satisfactory; it cannot be distinguished from the one going the other way. So the law of gravitation is of such a kind that it doesn't make any difference if you show the phenomenon running—any phenomenon involving just gravitation—running backwards on a film, it'll look perfectly satisfactory. Put it precisely more this way: if at a given instance the particle moving this way—if all the particles in a more complicated situation—would have every one of their speeds reversed suddenly, then the thing will just unwind through all of the things that it wound up into. That is, if you have a lot of particles doing this, then you suddenly reverse the speeds, they will completely undo what they did before.

Now, this is in the laws of gravitation, which say now the velocity changes as a result of the forces, and so on; if I reverse the time, the forces are not changed, and so the changes in velocity are not altered at corresponding distances. And so each velocity then has its succession of alterations made in exactly the reverse way that they were made when this went out before, and it's easy to prove that the law of gravitation is time reversible.

The law of electricity and magnetism: time reversible. The laws of nuclear interaction: time reversible—as far as we can tell. The laws of beta decay that we talked about at a previous time: also time reversible; the difficulty of the experiments of a few months ago, which indicate that there's something the matter with—there's some unknown about—the law, suggests the possibility that, in fact, it may not be also time reversible, but we shall see.

But at least the following is true: this beta decay that we're talking about, which may not be time reversible (but I don't know), is a very unimportant phenomenon for most ordinary circumstances: the possibility of my talking to you does not depend on that happening; it does depend on chemical interactions; it depends on electrical forces; it doesn't actually depend much on nuclear forces at the moment, but it depends also on gravitation.

But, I am one-sided: I speak, and the voice goes out into the air and doesn’t come sucking back into my mouth when I open it. This irreversibility cannot be hung on the phenomena of beta decay. In other words, we believe that there are, in the world, most of the ordinary phenomena which are produced by atomic motions, which are according to laws which can be completely reversed.

So we have to look some more to find the explanation. If we look at this more carefully, and planets moving around the sun more carefully, you’ll soon find that it isn’t quite right: for example, the earth’s rotation on its axis is slightly slowing down—that’s due to tidal friction. You’ll see that friction is something which is obviously irreversible: if I took a heavy weight [block] on the [wood] floor, here, and pushed it, it would slide and stop; if I stand and wait for it, it doesn’t suddenly start up and speed up and come into my hand. So a frictional effect seems to be irreversible.

But a frictional effect, as we discussed at another time, is the result of enormous complexity of the interactions of the block with the wood, the jiggling of the atoms inside. That the organized motion of the wood—[I mean,] of the block—is changed into disorganized, irregular wiggle—waggles of the atoms in the wood. So that, therefore, we should look at the thing more closely.

As a matter of fact, we have here the clue to the apparent irreversibility. I take a simple example of—for example, if we have blue water, say ink, and white water, that’s water without ink, in a tank, with a little separation, and pull out the separation very delicately, then it starts out separate—blue on one side, white on the other side.

Wait a while. Gradually the blue mixes up with the white, and after a while the water is "lukeblue": I mean, it’s sort of 50/50 color, uniformly distributed throughout. Now if we wait long, for a long time, and watch this for a long time, it does not by itself separate. Oh, you can do something—you can get the blue separated again—you can evaporate the water and condense it somewhere else and collect the blue dye and dissolve it in half the water and put back this thing, and so on.

While you’re doing all that, however, you yourself are causing irreversible phenomena somewhere else. So by itself it doesn’t go the other way—and that gives us some clue.

Let’s look at the molecule. Suppose that we took a moving picture of the water—of the blue and the white water mixing: it would look funny if we ran it backwards, because we start with uniform water, and gradually the thing would separate, and would be obviously nutty. Now, we magnify the picture so that every physicist can watch, atom by atom, to find out what happened irreversibly—where the laws of balance of forward and backward broke down.

You start, and you look at the picture, and you have blue atoms (that’s ridiculous, but we’ll call it that)—we have atoms of one kind and atoms of another kind jiggling all the time, in thermal motion, wiggling and bouncing. If we were to start at the beginning, we would have mostly atoms of one kind on one side, and atoms of the other kind on the other side.

Now, these atoms are jiggling around—that's too small a box; you need more to get this effect—billions and billions of these atoms. Now, these atoms are jiggling around—I just put one more but I'm getting tired of making these. These atoms are jiggling around, and if we start all on one side and all on the other, we see, of course, that in their perpetual irregular motions, they'll get mixed up—and that's why it gets to be more or less uniformly blue. But let's watch any one collision.

Here's a particular collision selected from that picture: here's this molecule moving this way, and this one moving this way. They come together, say, in the moving picture, and they bounce off this way. Now you run that section of the film backwards, and you find a pair of molecules moving this way, bouncing off that way, and the physicist looks with his keen eye and measures everything and says, "That's all right; that's according to the laws of physics: if two molecules came this way, they would bounce that way, and if they came that way, they would bounce this way. It's reversible—the laws of molecular collision are reversible."

If you watch too carefully, you can't understand it at all, because every one of the collisions is absolutely reversible, and yet the whole moving picture shows something absurd, which is that the molecules start—in the reverse picture, the molecules start in this condition—blue, white, blue, white, and blue, white, and so on, all mixed up, and yet as time goes on, through all the collisions, the blue separates from the white—they can't do that!

That's not natural, that the accidents of life will be such that the blues will separate themselves from the whites, yet if you watch it move—this reverse movie—very carefully, every collision is okay. Well, you see that's all there is to it, that the irreversibility is caused by the general accidents of life: that if you start with a thing that's separated like this, and just make irregular changes, it gets more uniform, but if you start with something that's uniform, and make irregular changes, it doesn't get separated. It could get separated; it's not against the laws of physics that these things bounce around so that they separate; it's just unlikely. It just—it would never happen in a million years!—and that's the answer.

The things are irreversible only in the sense that going one way is likely to go, but going the other way, although is possible and is according to the laws of physics, wouldn't happen in a million years. It's just ridiculous to expect that if you sit there long enough, the jiggling of the atoms will separate a mixture, a uniform mixture, of ink and water into ink on one side, and water on the other.

Now, if I had put a box around here so that this was all the molecules that there were, as time went on they would get mixed up. But if you're patient, I think you could believe that in the perpetual, irregular collisions of these molecules, after some time (not necessarily a million years, maybe only a year), if you keep watching, accidentally they get back more or less like this—in the sense, at least; they get back far enough to say that if I drew a line through, all the whites on one side and all the blues on the other—it's not impossible. However, the actual objects with which we work have not only four or five blues and whites, but they have four or five million, million, million, million atoms. And it's just not likely that four or five million, million, million, million are all going to get separated like this.

So the apparent irreversibly of nature does not come from the irreversibility of the fundamental physical laws; it comes from the characteristic that if we start with an ordered system and have the irregularities of nature bouncing, then the thing goes one way.

Therefore, the next question is how did it get ordered in the first place? That is to say, why is it possible to start with the order? Because, you see, the difficulty is that we start with an ordered thing; we don't end with an ordered thing. One of the rules of the world is that the conditions at the beginning—I mean, that the thing goes from an ordered condition to a disordered [one].

(Incidentally, this word order, and disorder, is another one of those terms of physics which aren't exactly the same as it is in ordinary life: the order need not be interesting to you human beings; it's just a question that there's a definite situation—they're all on one side and all on the other, or they're mixed up—that's the order to disorder. Maybe you like it better mixed up, but that's not more ordered, anyhow.)

Now... ...the question is, then, how does the thing in the first place get ordered, and why, when we look at any ordinary situation which is only partly ordered, we can conclude that it probably came from more ordered. If I look at a tank of water in which it's very dark blue on this side, and very clear white water here, and sort of bluish water in between, and I know that that thing has been left alone for 20, 30 minutes, then I will guess that it got this way because it was bluer before—for instance, if I find—I mean, that the separation was more complete in the past. If I find, for example, two objects—well, this is as good an example as any. If I wait longer, then the blue and white would get more intermixed. If I know that this thing has been left alone for a sufficiently long time, I can conclude something about the past condition: the fact that it's smooth in here could only arise because it was much "better" in the past—much more satisfactorily separated—because if it weren't more satisfactorily separated in the past, in the time since then it would have gotten more mixed up than it is.

It is therefore possible to tell from the present something about the past, although physicists really do not do this much: physicists usually like to think that all you have to do is say, "These are the conditions, and what happens next?" But all our sister sciences have a completely different problem; in fact, all the other things that are studied—history, geology, and astronomical history—all have a problem of this kind: I find they're able to make predictions of a completely different type than a physicist.

A physicist says, "In this condition, I'll tell you what'll happen next." But a geologist will say something like this: "I have dug in the ground, and I've found certain kinds of bones. I predict that if you dig in the ground you'll find a similar kind of bone." A historian, although he talks about the past, can do it by talking about the future: when he says, "Napoleon exists," or "Napoleon was"—or that the French Revolution was in 1783, he means that if you look in another book about this French Revolution, you'll find that same date—1789, maybe. (That's pretty accurate for a physicist—to have the third decimal, to three figures.)

Now, the thing that he says is, he makes a kind of prediction about something he has never looked at before—documents that have still to be found. He predicts that the documents, if there's something written about Napoleon, will coincide with what is written in the other document. The question is how that's possible.

The only way that that's possible is to suggest that the past of the world was more organized in this sense than the present. Some people have proposed at one time (the physicists only have proposed this, some of the physicists) that the way it got ordered was this: that the whole universe is just irregular motions like this, and that if you see-if you wait long enough with five atoms, of course it can get separated accidentally.

All that has happened is that in the world has been going on and going on and going on and going on and going on, and it fluctuated—that's what this is called, when it gets a little bit out of ordinary—it fluctuated, and now we're watching the fluctuation undo itself again.

How do we know that isn't the case? You say, "Well, how long you would have to wait?" I know, but if it didn't fluctuate far enough to be able to produce evolution, to be able to produce an intelligent person, we wouldn't have noticed it—so we had to keep waiting until we were alive to notice it—so we have to have at least that big a fluctuation.

But this thing-this is incorrect, I believe; I think that's a ridiculous theory for the following reason. That if the world were much bigger, and there were atoms all over the place, and they started from a completely mixed-up condition—all over—and I happen only to look at the atoms here, and I find that the atoms here are separated, I have no way to conclude that the atoms anywhere else are separated.

In fact, if the thing were a fluctuation, and I noticed something odd, the most likely way that it got there is if there's nothing odd anywhere else. That is, I have to "borrow odds," so to speak, to get this lopsided, and there's no use on borrowing too much. It's much more likely of all the possible ways in which these six atoms can be on one side and these seven on the other side of all the possibilities, the most likely condition of the rest of the world is mixed up.

Therefore, an astronomer, looking at a star that he's never—although, when we look at the stars and we look at the world, we see it's ordered, there could be a fluctuation, the prediction would be that if we'd look at a place that we haven't looked at before, it'll be disordered, and a mess—that the separation of the matter into stars which are hot, and space which is cold, which we've seen—although, if you say it could be a fluctuation, then in places that we haven't looked we would expect that the stars are not separated from the space, since every time we make a prediction that in a place that we haven't looked, we'll see the same statement about Napoleon—we'll see stars in a similar condition—we'll see bones like the bones that we've seen before.

The success of all those sciences indicate that the world did not come from a fluctuation but came from a condition which was more separated, more organized in the past than at the present time.

Therefore, I think it's necessary that to add to the physical laws the hypothesis that in the past the universe was more ordered, in a technical sense—less mixed up—than it is today, that this statement is the added statement that's needed to make sense, and to make an understanding of the irreversibility. That statement, of course, is itself lopsided in time. It says something about the past is different than the future, but it comes outside of the province of what we ordinarily call physical laws, because we try, today, to distinguish (maybe someday we won't do that, but we do, today, distinguish) between the laws which tell how something moves if you start it in a certain way, and those statements about how the universe got the way it gets, or has been, what it was in the past, and what it's going to get to be—no, excuse me: the statement of the physical laws which govern the rules by which the universe develops, and the law which states the condition that the world was in the past, that's considered to be astronomical history. Perhaps someday that will also be a part of physical law.

Now, there are a number of interesting features of irreversibility that I think I would like to illustrate. One of them is to see how exactly an irreversible machine really works. Suppose that we built something that we know ought to work only one way. What I'm going to build is a wheel with a ratchet on it. A ratchet means just this—that we have a notched wheel with steps. (I've drawn the wrong way for what I'm used to thinking about it. No, I had it right, because this way there's another notch—a sawtooth wheel like this, with sharp up notches and relatively slow down notches, all the way around.)

And then—this is a wheel on a shaft—then on this thing there's a little piece of pawl, a thing called a pawl, which is on a pivot here, and which is held down by a spring. (It gets in the way of the wheel, but that's a small technical difficulty: this is two-dimensional, and actually it's set a little bit below.) Now, this wheel can only turn one way. If you try to turn it this way, then these straight—edged parts of the teeth get jammed against the pawl, and it doesn't go—whereas if you turn it the other way, it would just go right over the thing and—snap, snap, snap, pop, pop, pop—ping.

[This is why] they use them in clocks, so when you wind watches, they have this kind of a thing inside so that you can only wind it one way, and after you've wound it, it holds a spring.

Now, we want to discuss—you see, it's completely irreversible in the sense that the wheel can only turn one way. Now, this irreversible machine—this wheel that can only turn one way—has been imagined that you could use it for a very useful thing, say, a very interesting thing: because of molecular irregularities—because of molecular motion, perpetual motion—there's a perpetual motion of molecules.

And if you build a very delicate instrument, it will always jiggle, because it's being bombarded irregularly by the air molecules in the neighborhood. So, that's very clever; we'll connect this with a shaft, which is hard to illustrate in three dimensions; it goes way out here. You connect this to it with a shaft, with a vane, with a set—the wheel has four vanes (actually, my angles and things have gotten a little bit mixed up: look down on the shaft—this thing's got four vanes like this.) Those are bombarded—they're in a box of gas here, and they're bombarded all the time by the molecules, irregularly, so the thing is pushed sometimes one way, sometimes the other way.

[Now,] when it's pushed one way, this thing gets jammed, but when it's pushed the other way, it goes around. So we find the wheel perpetually going around, and we have a kind of perpetual motion. That's because this wheel is irreversible—but actually, we have to look into the details. The way this works is that when the wheel goes one way, it lifts the pawl up and then the pawl snaps down against the next tooth—and it will bounce, if it's perfectly elastic; it will go bounce, bounce, bounce, bounce, all the time.

The wheel could just go down around the other way when the pawl accidentally bounces up! This will not work unless it's true that when the pawl comes down it sticks, or stops, or bounces, and cuts out: if it bounces and cuts out, there must be what we call damping, or friction, again. And in the falling down and bouncing and stopping (which is the only way this will work one way), heat is generated by the friction: this part of the wheel, over here, will get hotter and hotter.

However, when it begins to get quite warm, something else happens: just as there's Brownian motion, or irregular motions in the gas here; so, whatever this is made out of—the parts that this is made out of—are getting hotter, and are becoming more irregular. So a time comes when this is hot enough, that the pawl is simply jiggling because of the molecular motions of the things on the inside. And so it bounces up and down on here because of molecular motion—the same thing that was making this vane turn around—and in bouncing up and down on here, it is up as much as it is down; when it is up as much as it is down, a tooth can go either way.

As a matter of fact, the thing will be driven backwards: if this one was hot and this one was cold, the wheel that you thought would go only one way would go the other way, because: in the terrible bouncing up and down on this wheel, every time it comes down it comes down on an incline plane—and so it pushes the wheel this way. Then it bounces up again, comes down another incline plane, and so on-and so if this side is hotter than this side, it'll go around this way.

What's it got to do with the temperature of this side—suppose they didn't have that at all? Oh: then, if it's pushed forward by falling on an incline plane, the next thing that will happen is, it will bounce against that tooth, and the wheel will bounce back. But in order to prevent the wheel from bouncing back, we put a damper on it: we put vanes in the air, so that it can't go. Then it can only- it will go one way, but the wrong way, and so it turns out that no matter how you design it, a wheel like this will go the one way if this side is hotter, and go the other way if this side is hotter.

But after there's a heat exchange between the two, and everything has calmed down, it will neither go one way or the other—that's the technical way in which the phenomena of nature will go one way as long as they're out of equilibrium, as long as one side is quieter than the other, or one side is bluer than the other. The conservation of energy would let us think that we have as much energy as we want—nature never loses or gains energy. Yet the energy of the sea, for example—the thermal motion of all the atoms in the sea—is practically unavailable to us: in order to get that energy organized—herded, used, make it useful, make it available for use—we have to have some place that's at a different temperature. We have to use a difference in temperature, or else we'll find that although the energy is there, we cannot make use of it. There's a great difference between energy and availability of energy.

The energy of the sea, for example, is a large amount, but it's not available to us. I think I can give an analogy, or give some idea of what the difficulty is, this way: the conservation of energy means that the total energy in the world is kept the same—but in the irregular jiggling, that energy can be spread about so uniformly that there's no (in certain circumstances) there's no way to make more go one way than the other; there's no way to control it anymore. I don't know if you've ever had this experience, but I have had, going to the beach with several, many towels, and so on, and sitting happily on the beach-and having a tremendous downpour suddenly come, picking up the towels as quickly as you can, and running into the bathhouse. Then you start to dry yourself, and you find that this towel is a little wet, but it's drier than you are. You keep drying this one; then you find that one's too wet—it's wetting you as much as it's drying you, and you try another one, and pretty soon you discover a horrible thing: all the towels are damp, and so are you. And as you keep picking them up and putting them down and rearranging them, and there's no way to get any drier, no matter how many towels—even though you have many towels—because there's no difference in some sense between the wetness of the towel and the wetness of yourself. I could invent a kind of a quantity which I could call "ease of removing water," or—yes, let's call it "ease of removing water": the towel has the same "ease of removing water" from it as you have. And so when you touch the towel to you, as much water comes off from the towel to you, as it does from you to the towel. It doesn't mean there's the same amount of water in the towel as there is on you-a big towel will have more water in it than a little towel—but they have the same dampness.

When things get to the same dampness, then there's nothing you can do any longer. Now, the water is like the energy, because the total amount of water isn't changing. But if we had a world which was limited—see, if the bathhouse door is open, and you can run into the sun and get dried out, or find another towel, you see, okay, that's different. Then you got saved. But if you have everything closed, and you can't get away from these towels—you can't get a new towel—so if you imagine this part of the world that was closed, wait long enough, and, in the accidents of the world, the energy, like the water, will be distributed all over, all of the parts, evenly.

There's nothing left of one—wayness; there's nothing left of the real interest of the world as we experience it. Thus, in this situation here, which is a limited one, in which nothing else is supposed to be involved, the temperatures gradually become equal on both sides, and the wheel doesn't go around either one way or the other. In the same way, the situation is, if you leave a system long enough, it gets the energy thoroughly mixed up in it, and no more energy is really available to do anything.

Incidentally, the thing that corresponds to the dampness is called the temperature. And although when I say two things [are] at the same temperature when things get balanced, it doesn't mean they have the same energy in them; it just means it's just as easy to pick energy off of one, as to pick it off the other. So if you put them next to each other, nothing apparently happens: they pass energy back and forth between them; the net result is nothing. When things have become all at the same temperature, then there's no more energy available to do anything.

The principle of irreversibility is that if things are at a different temperature and are left to themselves, as time goes on, they become more and more at the same temperature, and the availability of energy is perpetually decreasing. This is another name for what's called the entropy law, which says entropy is always increasing.

But never mind the words; to state it the other way, the availability of energy is always decreasing. That's a characteristic of the world, in the sense that it's due to the chaos of molecular irregular motions: things of different temperature, left to themselves, tend to become of the same temperature, but if you have two things at the same temperature, like water on an ordinary stove without a fire, the water isn't going to freeze and the stove get hot. (But if you have a hot stove with ice, it goes the other way.) The one-wayness is always the loss of the availability of energy.

Well, that's all I want to say on the subject, but I want to make a few remarks about some characteristics. Here we have an example in which an obvious effect—the irreversibility [of time]—is not an obvious consequence of the laws, but that the effect is rather far from the basic laws. It takes a lot of analysis to understand why this effect, and that the effect is of first importance-in the economy of the world, in the real behavior of the world, in all obvious things, my memory, my characteristics, the difference between past and future, are completely involved in this—and yet the understanding of it is not prima fascia available by knowing about the laws; it takes a lot of analysis.

It is often this way, that the laws of physics are different—the laws of physics do not have a direct obvious relevance to the experience, but that the laws are abstract from the experience to varying degrees. In this particular case, the fact that the laws are reversible, although the phenomena are not, is an example. There are often great distances between the details—the detailed laws—and the main aspects of real phenomena.

For example, it's something of this kind: that if you watch a glacier from a distance, and you see the big rocks falling into the sea and the way the ice moves and so forth and so on, it isn't really essential to remember that it's made out of little hexagonal ice crystals—that the ice crystals are hexagonal—and yet the character of a little hexagonal ice crystal, if understood well enough, is in fact—the consequence of this is, in fact—the motion of the glacier. But it takes quite a while to understand (in fact, nobody knows enough about ice, no matter how much they study the crystal—yet—to really understand) all the behavior of the glacier.

But the hope is that if we do understand the ice crystal, we'll ultimately understand the glacier. But there's a large—in fact, although we've been talking in these lectures about the fundaments of the physical laws, I must say immediately that one does not, by knowing all the fundamental laws as we know them today, immediately obtain an understanding of anything much: it takes a while, and even then it's only partial.

Nature, is as a matter of fact, seems to be so designed that the most important things in real world seem to be a kind of complicated accidental result of a lot of laws. To give an example: nuclei, which involve several nuclear particles—protons and neutrons—are very complicated; they have what we call energy levels. They can sit in states or conditions of different energy values. Various nuclei have various energy levels. It's a complicated mathematical problem, of which we only can partly solve, to find the position of the energy level.

Now, you can understand that it's complicated, and therefore there's no particular mystery about the fact that nitrogen with 15 particles inside happens to have a level at 2.4 million volts, and another level at 7.1, and so on; the exact position of the levels is obviously a consequence of an enormous complexity. But the remarkable thing about nature is that the whole universe, in its character, depends upon precisely the position of one particular level in one particular nucleus: in the carbon 12 nucleus there's a level at 7.82 million volts, it so happens-and that makes all the difference in the world!

The situation is the following: if we start with hydrogen (and it appears that in the beginning, or in the earliest times, the world was practically all hydrogen), then as the hydrogen condenses—comes together under gravity—and gets hotter, nuclear reactions can take place, and it can form helium. And then the helium can combine only partially with the hydrogen and produce a few more elements, a little heavier, but they disintegrate right away back into helium. So it was, for a while, a great mystery about where all the other elements in the world came from, because starting with hydrogen, the "cooking" processes inside the stars would not make much more than helium and a few others—half a dozen others; less, as a matter of fact—other elements.

Faced with this problem, Professor Hoyle said, that there is one way out (I think Edwin Salpeter also—he's here, so I have to be very careful). If three helium atoms could come together to form carbon, we can easily calculate how often that should happen in the star—and it turned out it should never happen much, except for one possible accident: if there happened to be an energy level at 7.82 million volts in carbon, then the three helium atoms would come together, would stay a little longer than they ought to—[or would] have, on the average, if there were no level there—before they come apart.

Staying there a little longer, there's enough time for something else to happen, and to make other elements: if there was a level of 7.82 million volts in carbon, then we could understand where all the other elements in the periodic table come from. And so, by a backhanded upside—down argument, it was predicted that there is in carbon a level of 7.82 million volts, and then experiments in the laboratory with carbon show indeed that there is. Therefore, the existence in the world of all these other elements is very closely related to the fact that there is this particular level in carbon. But the position of this particular level in carbon seems to us, after knowing the physical laws, to be a very complicated accident of 12 complicated particles interacting.

So I use to illustrate, by this example, that an understanding of the physical laws doesn't give an understanding in a sense of understanding significance of the world in any way. The details of real experience are very far, often, from the fundamental laws. There are, in a way of speaking, in the world—we have a way of discussing the world, which you could call—we discuss it at various hierarchies, or levels. Now, I don't mean to be very precise—there's a level, there's another level, and another level—but I will indicate by describing a set of ideas to you, just one after the other, what I mean by hierarchies of ideas.

For example, at one end, we have the fundamental laws of physics. Then we invent other terms for concepts which are approximate, which have, we believe, the ultimate explanation in terms of the fundamental laws. For instance, "heat"—heat is supposed to be the jiggling, and it's just a word for a hot thing—it is just a word for a mass of atoms which are jiggling. For all that, fundamentally, we should think of the atoms jiggling. But for a while, if we're talking about heat, we sometimes forget about the atoms jiggling, just like when we talk about the glacier, we don't always think of the hexagonal ice, the snowflakes which originally fell. Another example of the same thing is a "salt crystal": looked at fundamentally, it's a lot of protons, neutrons, and electrons. But we have this concept of "salt crystal," which carries a whole pattern already of fundamental interactions. Or [an] idea like pressure.

Now, if we go higher up from this, in another level, we have properties of substances like "refractive index"-how light is bent when it goes through something. Or "surface tension"-the fact that the water tends to pull itself together—is described by a number. I remind you, that we have to go through several laws down to find out that it's the pull of the atoms and so on, but we still say "surface tension," and don't worry when we're discussing surface tension of the inner workings, always-sometimes we do; sometimes we don’t. Go on up in the hierarchy. With the water we have the waves, and we have a thing like a storm. We have a word "storm," which represents an enormous mass of phenomena. Or "sunspot." Or "star," which is an accumulation of things, and it’s not worthwhile, always, to think of it way back.

In fact we can’t, because the higher up we go, we have too many steps in between, each one of which is a little weak, and we haven’t thought them all through yet. We go up in this hierarchy of complexity, we get the things like "frog," or "nerve impulse," which, you see, is an enormously complicated thing in the physical world, involving an organization of matter in a very elaborate complexity. Then we go on, and we come to things—words and concepts like "man," and "history," or "political expediency," and so forth—which is a series of concepts that we use to understand things at an ever higher level. Going on, we come to things like "evil," and "beauty," and "hope."

Now, which end is nearer to the ultimate creator, or the ultimate—or, I make a religious metaphor, which end is nearer to God? "Beauty" and "hope," or the fundamental laws? I think that the right way, of course, is to say that the whole structural interconnections of the thing is the thing that we have to look at, that the sequence of hierarchies, all the sciences and all the efforts—not just the sciences, but all the efforts of an intellectual kind—are to see the connections of the hierarchies, is to connect beauty to history, is to connect history to man’s psychology, the man’s psychology to the working of the brain, the brain to the neural impulse, the neural impulse to the chemistry, and so forth—up and down, both ways. Today, we cannot—and there’s no use making believe we can—draw carefully a line all the way from one end of this thing to the other; in fact, we’ve just begun to see that there is this relative hierarchy. And so I don’t think either end is nearer to God.

To stand at either end and to walk out off the end of the pier only, hoping out in that direction is the complete understanding, is a mistake. To stand with evil and beauty and hope, or to stand with the fundamental laws, hoping that way to get a deep understanding of the whole world with that aspect alone, is a mistake. It is not sensible either for the ones who specialize at one end, and the ones who specialize at the other end, to have such disregard for each other. (They don’t, actually, but the people say they do.)

But that actually, the great mass of workers in between, connecting one step to another, are improving all the time our understanding of the world—both from working at the ends, and working in the middle. In that way, we are gradually understanding this connection, this tremendous world of interconnecting hierarchies.

Thank you.