

## Emergence

The visible universe is 13.7 billion years old, and so far as we know, it originated from one point in space. Since light travels at a finite speed, whenever we look out into space, we look backward in time. It follows that if we had the right kind of eyes, we should be able to go outside on a clear night and see the beginning of the universe! That's not quite true because the universe was not always transparent as it is today, but we can see back to a time 350,000 years after creation, and what we see there is almost perfectly uniform; a very hot uniform ball of gas. There are slight fluctuations in temperature, but they are only a few parts in 100,000. Yet from this beginning we get galaxies, stars, planets, living cells, dinosaurs, republicans and democrats. How could this possibly happen? We understand part of the story. We are pretty sure we understand how galaxies form – there may be some technical difficulties to work out, but a complete understanding seems within our grasp. Stars and planets are more difficult, but no one expects that any fundamental changes in our understanding of astrophysics will be required. But how did microorganisms come about, and what about human brains and human intelligence? No one knows of course, but suppose we had a complete explanation of how these things came to be, what would this explanation look like? At this point there are several different schools of thought and many variations within those schools. If you are into philosophy, there is a lot to think about, and if you are into theology, as I assume you are, there are some heady theological ideas here as well. We need to start with physics and physics starts with Newton. According to Newton all matter is composed of particles. We know today that that's not too far from the truth. The job of physics then is to predict how these particles will move as they interact with one another. To this end he invented (or discovered) three laws of motion. The most important of which is  $F=ma$ . This is really a three-component, linear, second-order partial differential equation. That sounds bad, but as mathematics goes, it's really quite simple. In addition there is another law, the universal law of gravitation, which says that any two particles will attract one another according to a simple formula. Now suppose there is a system of particles behaving according to these two equations. In order to solve them you need two additional pieces of information; the position and velocity of each of the particles at any instant of time. Then the equations will predict the exact motion of all the particles for all subsequent time. We call this additional information the "initial conditions." In a nutshell, the initial conditions plus the equations of motion yield a complete description of the future.

Let's do a little thought experiment. Imagine a demon with a huge memory and vast computing power. The demon knows, never mind how, the position and velocity of all the particles in the universe at this moment of time. Then he can predict everything that will happen to you, everything you will do, and every thought you will ever have.

We have learned a lot since Newton. For one thing we know about electromagnetic forces. Most of the properties of matter are due to these, for example, all the properties of atoms. So in addition to the law of gravitation we will have to include electromagnetism. We also need to include the effects of relativity. All this makes the calculation much more difficult, but the paradigm is the same. We are always dealing with these partial differential equations. The present moment completely determines everything that will happen subsequently.

If this were true, of course, it would be impossible to prove that it was true or that it wasn't. Everything you would say would be just what you had been preprogrammed to say, regardless whether it was true or not. It seems to me that I do have free will, and that I can make informed judgments. I suppose that's the same for you, so let's just assume that that's the case. But if it is true, just what is wrong with the argument? Two things at least. For one thing, it doesn't take into account quantum mechanics. For another, it doesn't allow for what we now call chaos. I will come back to both of these points eventually. First I want to point out some paradoxical things about these laws.

The existence of universal mathematical laws is profoundly puzzling. I can write down these equations in a few lines using mathematics, which is presumably a human invention. But every particle in every star in every galaxy in the visible universe obeys these laws. How could this be? Is it possible that mathematics has some objective reality apart from us? Or has the universe been contrived in such a way that we can understand it? This is another one of these philosophical issues on which there are many schools of thought, and there are even some very speculative ideas to the effect that this question and the question of free will are somehow related. I'm not going to get in to that tonight.

Another puzzling point has to do with the nature of time. Starting with the initial conditions as I described, one cannot only predict the future, one can

predict the past. I use the word “predict” advisedly. These equations have a peculiar property we call time reversal invariance. They are equally valid whether time runs, as we would say, backwards or forwards. Put it another way, there is no real distinction between past and future. It’s arbitrary what you choose to call the future and what you decide to call the past. To quote T. S. Eliot (Burnt Norton)

Time present and time past  
Are both perhaps present in time future,  
And time future contained in time past.

There is a Christian idea about God and time going back at least to St. Augustine that God stands outside of time. All time, past and future, is one eternal present to God. This is as close as we can come to formulating this idea with mathematics.

This is completely counter to our experience. I invite you to think about unfrying an egg. As you stand by the skillet the egg turns raw and then jumps out of the pan into the half egg shell you are holding in your hand. The halves then knit up and go back into the fridge. This does not violate any of the basic laws of physics, but it just never happens. Why? Back in 1824 a Frenchman named Sadi Carnot thought about this in terms of simple processes involving heat. Heat flows from hot objects to cold objects but never the other way around. He turned this simple observation into a law of physics by inventing a quantity called entropy. When heat flows out of the hot object its entropy decreases. As it flows into the cold object its entropy increases. But the cold body always gains more entropy than the warm body loses so the total change is positive. The total entropy in a closed system always increases. This is the second law of thermodynamics. Heat always moves in such a way as to make it less useful. Your automobile engine runs because the temperature inside the cylinders is much higher than the temperature outside. If the temperature was the same inside and out the engine would not run no matter what that temperature was.

The second law gives us a real sense of past present and future. Everything will degrade, run down, become less effective, and approach a state in which everything is the same temperature and useful motion is impossible. That is the future. If we extrapolate it into the distant future we get what is sometimes called the heat death of the universe. The past – those were the good old days. From here on it’s all downhill.

This raises two huge questions. The first is how can it be that equations that are time-reversal invariant give rise to a universe that so clearly isn't? The modern way of looking at entropy is that it has to do with organization and information. This is easy to explain with a deck of cards. You all know what a royal flush is; the five highest card of a suit. Suppose I deal you five cards, what is the chance that you will get a royal flush in hearts? It works out to be one chance in 2.6 million. What is the chance that you will get any specified set of five cards? One chance in 2.6 million. The point is that there are so many more ways to get a worthless hand than there are ways to get a royal flush – or for that matter any hand that is organized in some specific way – that the royal flush is more valuable than a completely random assortment of cards. The higher the degree of organization, the smaller are your chances of getting it. Consequently it is more valuable. Finally, if you put a valuable hand like the royal flush back into the deck and shuffle it, chances are that the next hand will be worthless. We say that a valuable hand with its high degree of organization has small entropy and the random hand has large entropy. When you shuffle the deck, the overwhelming probability is that the degree of disorder will increase. This is the second law of thermodynamics. Any specific sequence of cards is as likely as any other, but a sequence that is organized in some special way is less likely than one that has no such organization, simply because there are so many more combinations that are random. Now let's go back to our original example of heat flow. If you have one hot object and one cold object, there is a certain degree of organization. Bringing them into contact with one another is like shuffling the deck. The overwhelming probability is that the heat will be uniformly distributed because this is the state with the least organization or the most disordered state.

This brings us back to the second huge question. It seems that the universe is running in the wrong direction! It has evolved from a state that was completely uniform to a state that has exquisitely organized structures such as us. How could that happen? This is the question of emergence.

One of the paradoxes of emergence is that the universe seems to have two arrows of time; or to put it another way, the universe is running in two opposite directions. On one hand there is the arrow of entropy; things are running down, energy is degraded and becoming useless, chaos is taking over from order. On the other hand, uniformity is breeding structure, order, and purpose. Primordial chaos leads to galaxies then to stars and planets then

to DNA and life, then to human intelligence, and then to society, culture and religion.

“After earths, not better earths but beasts; after beasts, not better beasts, but spirits. After a falling, not a recovery but a new creation. Out of the new creation, not a third but the mode of change itself is changed for ever.”

How can both of these things be happening at once?

Forgive me if I jump from the sublime to the almost ridiculous. There is a simple demonstration that physicists have known about for a century, the Benard cell. The idea is simple. Contain a fluid between two parallel, closely-spaced plates. Heat the bottom plate and cool the top plate. Warm fluid rises from the bottom plate. It is cooled at the top plate and sinks down to the bottom. So far, so good. Any beginning physics student could have predicted this. But here's what surprised Monsieur Benard. These little convection patterns arrange themselves into a regular lattice structure which usually, although not necessarily, has a hexagonal structure. A uniform liquid has spontaneously arranged itself into a regular array! This is puzzling for at least two reasons. First, where do the hexagons come from? These patterns appear with many different kinds of fluids, so there must be nothing particularly hexagonal about the individual molecules. Second, molecules interact by bumping into one another. They exert a force that is very short-ranged, very roughly on the order of a millionth of a centimeter. Yet the patterns extend over regions of several centimeters. How does an individual molecule “know” how to move so as to make and maintain the pattern?

The Benard cell is scarcely more than a toy to amaze undergraduates, but it makes at least seven points that are relevant to more complex systems. I will discuss them one at a time.

The second law of thermodynamics only applies to closed systems, and the Benard cell isn't. Heat is fed into the bottom of the cell and removed from the top. There is a constant flux of heat through the cell and with it a flux of entropy. The entropy of the universe increases while the fluid orders itself. The earth is just this sort of system. It absorbs heat from the sun and reradiates it back into space. Life evolves on earth while the entropy of the universe increases.

The equations that describe fluid flow have a special property. We say that they are non-linear. Without going into technical details, it means that in

some sense the whole is always more than the sum of its parts. The more parts – in this case the more tiny regions of fluid – the more complicated and unexpected the solutions are bound to be. This is typical of the laws of physics. Equations that describe single particles in simple situations are linear. When there are complicated interactions the equations become non-linear. Another important point is that non-linear equations are usually impossible to solve in the traditional way with pencil and paper. They can only be solved numerically with computers.

The Benard cell is far from equilibrium. Let me explain what that means by an example. Suppose you put some water in a jar, put the lid on, and let it sit quietly for a while at room temperature. The contents of the jar are at equilibrium. This means roughly that nothing is changing. There is a whole branch of physics called equilibrium thermodynamics that deals with situations like this. You see, there are so many molecules in the jar we could not hope to compute the behavior of any one of them, but the fact that the system is at equilibrium allows us to calculate a few simple properties of the system as a whole. For example, we could calculate the amount of water vapor mixed with the air. The Benard cell is not like that. There is a whole branch of physics that just doesn't apply. In situations like this one expects new phenomena.

There is the matter of scale. Benard convection doesn't happen in a drop of water. There is some critical threshold of size at which this occurs. This is paradigmatic. It takes a lot of atoms to make DNA. It takes a lot of molecules to make a living cell. It takes a lot of cells to make a living organism, etc. At each stage there is some critical size and level of complexity at which new and unexpected properties emerge.

There is an iterative feedback mechanism at work. Liquid is warmed and the warm liquid rises. When it gets to the top surface it is cooled and sinks. It reaches the bottom layer and the process repeats. When the cell is first set up this motion is random and chaotic, but as the liquid continues to circulate a regular pattern *emerges*.

You will notice that there are different patterns shown in the photographs. How is it that one cell can produce these different designs? It turns out to depend in a very sensitive and unpredictable way on exactly what state of motion and temperature the liquid was in when the circulation started. Perhaps it is true in principle that if we could reproduce *exactly* the same

initial conditions we would get *exactly* the same pattern, but this is an abstract meaningless statement, because the very act of manipulating the liquid to get these initial conditions would introduce a whole new level of unpredictability. This property is called “sensitivity to initial conditions,” and it seems to be a universal property of the sort of complex ordered systems we are talking about.

I have saved the most important point for last. You see – I have been lying to you. Those are not real photographs. They are computer simulations. So, we could not have predicted the Benard phenomenon if we had not first seen it; and we still can not give a completely intuitive explanation for it; but given the basic equations for fluid flow, a large enough computer, and a lot of fiddling with programs, we can reproduce it. Now here is an absolutely central question from the interaction of science and religion; is everything -- including our lives, intelligence, faith, hope and love -- like this? That is, can everything ultimately and in principle, be completely explained in terms of the laws of physics?

Think carefully before you answer! The philosophers have been going at this hammer-and-tongs for the last century. And I don't have to tell you, the way you think God interacts with his creation will depend very much on how you answer this question. Some of you no doubt have read *The Hitchhiker's Guide to the Galaxy*. You will know that Deep Thought, the second largest computer in the universe, was constructed to answer the question of life, the universe, and everything. Deep Thought worked on it for several million years and came up with the answer 42, partly because the question was not well-posed. The question I am asking you really is the question of life, the universe, and everything in a (somewhat) sharper formulation. Is everything ultimately reducible to physics? Is it?

I will take on the question presently, but first I would like to show you some things from mathematics. This is partly for your amusement and partly to illustrate some of the ideas above. Let's start with a famous example, the logistics map. This was first proposed by Robert May, a population biologist in 1976. Suppose you have some species, rabbits for example, which have a new litter every summer. Let's follow the progeny of a typical breeding pair. After a year the number of surviving rabbits will be equal to the two parents plus the number of offspring minus the number that have died for one reason or another. If this number is larger than two on average, the population will grow exponentially. If it is less than two the population will crash and the

rabbits will become extinct. Now let's make the very reasonable assumption that there is only a finite amount of food around. If there is a population explosion the food source will be decimated and the following generation of rabbits will starve. What happens as time goes by? May tried to model this with the following simple equation. The variable  $x$  is the number of rabbits scaled so that the maximum possible value is one. The parameter  $r$  is the average survival rate scaled in the same way. Start with any value of  $x$  between 0 and 1 and iterate.

-- Explain --

Notice that for some values of  $r$  the population remains steady. Year to year it's "same old, same old." Then the population flops between several stable values. Then at some critical threshold, all hell breaks loose. This is called the onset of chaos. Anything can happen. The population is unstable from year to year. Again this seems like a trivial exercise, but it makes several profound points.

Start with one value of  $x$ , call it  $x_0$ , with  $r$  in the chaotic region. As you iterate you will get a series of points  $x_1, x_2$ , etc. This sequence is called the *trajectory* of  $x_0$ . It turns out that the tiniest numerical error becomes enormously magnified as you continue to iterate. This is a simple example of the "butterfly effect." A more vivid way of imagining this is as follows. Imagine playing pool on a table without pockets. Also assume there is no friction. No energy is lost in any way. You make one shot and the balls bounce around forever. In principle it should be possible to calculate the trajectories of the balls for all time. The fact is that after a few minutes the trajectories are sensitive to the gravitational attraction of a single electron at the other side of the galaxy. The idea that everything that happens in the universe is determined by the laws of physics and the initial conditions is obviously wrong. Calculating everything in the universe would require a computer much larger than the universe itself!

And yet, in this chaotic regime there arises a complicated pattern of lines and voids. A kind of design arises from chaos! Many examples of this effect have been discovered. I will show you the most remarkable, the Mandelbrot set, in a minute.

One final point about the logistics map; both the chaos and the pattern come about because of the iterative interaction of two opposing forces, in this case

reproductive growth and food depletion. In fact there are innumerable examples of this paradigm in the life sciences. For example, in biochemistry there are many instances in which some catalyst causes a chemical reaction that produces a catalyst that inhibits the production of the first catalyst. In living organisms there are many of these catalytic cycles interlocked in complicated ways.

There is a fascinating example of how these feedback loops change the structure of societies. This is so remarkable that I need to tell you about it in detail. In central Africa there are two very similar species of apes, the chimpanzees and the bonobos. They seem to have diverged from a common ancestor about 2.5 million years ago. Today they are separated by the Zaire River, which neither species can cross. Chimpanzee society resembles ours in many troubling ways. Male-male alliances are central; males are extremely status-oriented; males dominate females and often force sexual intercourse; and males conduct warfare against neighboring communities. When Jane Goodall first studied the chimpanzees it was feared that these traits were inevitable among ape-descended life forms like us. However, across the river there lives another species, superficially identical but with a completely different social structure. The bonobos have a female-dominated society. Female alliances are strong; the highest status members of a community are all female; and females chose which males they will mate with. Male alliances are weak; usually a male's best ally is his mother who will defend him if another male attacks. If a male charges a female she usually just ignores him. If things get serious her girlfriends come beat him up! When a group from one community encounters a group from another, the males keep their distance. The females often mingle and engage in sexual encounters with both males and females from the other community. As several primatologists have noted, where chimps make war, bonobos make love!

Why the difference? One key observation is that the vast majority of sexual encounters among the bonobos is between females. The prevailing theory is that the vegetation in bonobo territory encouraged foraging in large parties. This is particularly true since, unlike chimpanzees, bonobos have never had to compete with gorillas for the same vegetation. These larger parties meant that females could spend much more time together. Apparently, simply being together more often created a novel opportunity for female bonobos to band together to reduce male aggression against them and their infants. Now let's look at the feedback loops. Enhanced female-female bonds lead to

enhanced female-female cooperation against males, which increased the value of female-female relationships, which favored enhanced female-female sexuality as a means of facilitation greater social tolerance among females, which in turn enhanced females' tendencies to spend time together, which then increased their ability to ally against males, which tended to promote greater female bonding and thus enhanced female-female sexuality, and so on. Unlike the previous examples, these are positive feedback loops. They were triggered by a slight difference in vegetation between chimpanzee and bonobo territory; but the process of iteration through successive breeding generations produced completely different societies.

I should summarize the argument so far. The dream of 19<sup>th</sup> century science was that everything that happens in the universe could be predicted in principle from the laws of physics. This turns out to be impossible for at least two reasons. The first is that events in the quantum mechanical regime happen in a way that is completely unpredictable. I will get back to that in another lecture. The second is the butterfly effect that I have been discussing. Nature is replete with iterative processes, and these tend to be unpredictable. We have also seen that order can arise from these chaotic processes in many surprising ways. Nonetheless, in all these examples (leaving aside the bonobos) can be understood, if not necessarily predicted, from basic science. We cannot predict how any particular Benard cell will develop, but the final configuration of convection cells can be completely understood using the equations for fluid flow. The problem comes when we move up to higher levels of complexity. Can the structure of DNA, in principle, be completely understood on the basis of the laws of chemistry in the same way that the Benard cell can be understood in terms of the laws of physics? And if DNA, then what about living cells? And if living cells, then what about the human mind?

Of course, we don't really know. The day-to-day working hypothesis of most scientists is that of course, everything can ultimately be explained scientifically. But it seems to me to be logically contradictory to claim that it can be scientifically proved that there is nothing that can't be proved scientifically. Thus there is lots of elbow room for the philosophers; and philosophers rush in where scientists fear to tread. With that I would like to move away from hard science and into the realm of philosophy and from there to theology.

One traditional explanation is that there are two kinds of “stuff” in the universe. There is the stuff of physics that ultimately is composed of elementary particles, and some other stuff which has been given various names. Let’s just call it “soul.” This is called dualism. We are two separate things. We have a body and quite separately, we have a soul. Your mind (as opposed to your brain) is part of your soul. No one in science likes this idea anymore. For one thing it has been shown how our thoughts and feelings are tightly correlated with our brain’s neurochemistry. I am chary about the idea for theological reasons as well. I was taught in Sunday school that when we died our bodies returned to the ground and our souls floated up to heaven like so much helium gas. I didn’t like the idea then and I still don’t.

A more contemporary point of view is that ultimately everything can be reduced to physics or explained in terms of physics. This is called reductionism or physicalism or monism (to distinguish it from dualism). A more colloquial term is “nothing but physics,” i.e. everything is nothing but physics. Of course it is impossible to start with elementary particle physics and derive the properties of the human brain. Everyone agrees with that. Everyone also agrees that it is often *useful* to speak of each level of emergent reality as if it had its own independent laws and principles. Chemists, for example, can talk about the rules of chemical reactions without regard to elementary particle physics. But everyone also agrees that these rules could, at least in principle, be derived from basic physics. I think that almost everyone would agree that higher organisms possess what could be called memory; that is they are partly the product of what happened to them in the past. But is that all? The reductionists would say yes.

I would like to advocate a third position. I believe that the causes and explanations of higher-order events, even in the long run, will have to be given in terms intrinsic to each particular level of natural reality. This is called emergentism (strictly speaking, strong emergentism.) Of course science will continue to make progress in elucidating the relations between different levels of reality, but, for example, it will never be possible to explain human thought and intelligence entirely in terms of neurology and neurochemistry. It will never be possible to explain the existence of life entirely in terms of the properties of organic molecules.

This is a wager. I might be wrong. I’d like to make four points to justify my belief. First, I claim that humans are rational, moral animals who often come to correct opinions based on rational thinking. The physicalist can only say

that what we call opinions are just the manifestation of some neurochemical state. If that is true then the physicalist's opinion on the matter is also just a state of brain chemistry and so should not be taken seriously! We also have the sense that we are self-conscious moral agents. We make things happen in the real world. It's hard to reconcile this with the doctrine that our sense of ourselves is just the cumulative effect of our brain chemistry.

Now how can we say that our thoughts are correct except that we live in a universe that is rational so that the word "correct" has meaning. We suppose a fit between our thoughts and the external world. If there is such a thing as reason it is a local activity of finite creatures that somehow enables them to make contact with universal truths, often of infinite range. Naturalism has no resources to explain such a thing.

These things that are inexplicable within naturalism have a natural explanation if one postulates the existence of a transcendent mind. The universe is rational because God created it that way. Our existence as independent moral agents capable of rational reflection is a result of the "top-down" influence of God. This in itself does not answer the difficult question of exactly how God interacts with the world. Here there are several theological camps. I would like to finish by reviewing them. You will see a progression from what I might call "less religious" to "more religious."

One could simply equate God with Nature. Nature is all there is. Our worship should be directed to the recurrent miracle of emergence. Nature becomes 'the divine'.

Another point of view, although not one widely held, is that God like human intelligence is also an emergent property of the universe. Evolution has not stopped with us. God will emerge from human intelligence as human intelligence has emerged from lower life forms.

A more traditional view is that God eternal and timeless, outside of time as St. Augustine claimed. God created the universe and the laws by which it operates, but it operates on its own. A good analogy would be to a man who invents a game like chess: God sets up the rules while leaving open the space for the self-development of the game of creation.

I think the majority position among theologians today could be called temporal theism. This view, which would have been shocking during the

Middle Ages, is that God has two natures, a 'primordial nature' which is essentially unchanging, and a temporal nature that changes and evolves through its interaction with the created world. God is omniscient in the sense that He knows all that is logically possible. But so far as the future is not yet determined prior to the actual selection of emergent possibilities, God cannot know all future actualities. God creates the world by setting nature free for a process of fertile self-exploration, this limitation is not external to God; it is ultimately rooted in the generosity of divine love. Being immanent in the world, God is ubiquitously present and incessantly active as God works out the divine intentions 'in, with, and under' the nexus of nature as a whole.

Finally, there is a more mystical view that some have called eschatological theism. We think of present occurrences as resulting from what has happened in the past. This point of view holds that the future must also be regarded as a causal agent.

The most famous representative of this point of view was the Jesuit paleontologist and theologian Teilhard de Chardin. In his posthumously published book, *The Phenomenon of Man*, Teilhard writes of the unfolding of the material cosmos, from primordial particles to the development of life, human beings and the [noosphere](#), and finally to his vision of the [Omega Point](#) in the future, which is "pulling" all creation towards it. I will finish this talk and this lecture series with an extended quote from Teilhard's *Human Energy*

The universe is fundamentally and primarily living, and in its complete history is ultimately nothing but an immense psychic exercise. From this point of view man is nothing but the point of emergence in nature, at which this deep cosmic evolution culminates and declares itself. From this point onwards man ceases to be a spark fallen by chance on earth and coming from another place. He is the flame of a general fermentation of the universe which breaks out suddenly on earth.