Introduction to Complexity and Applied Complexity, Spring 2021

Module 1 — Reductionism and Emergence

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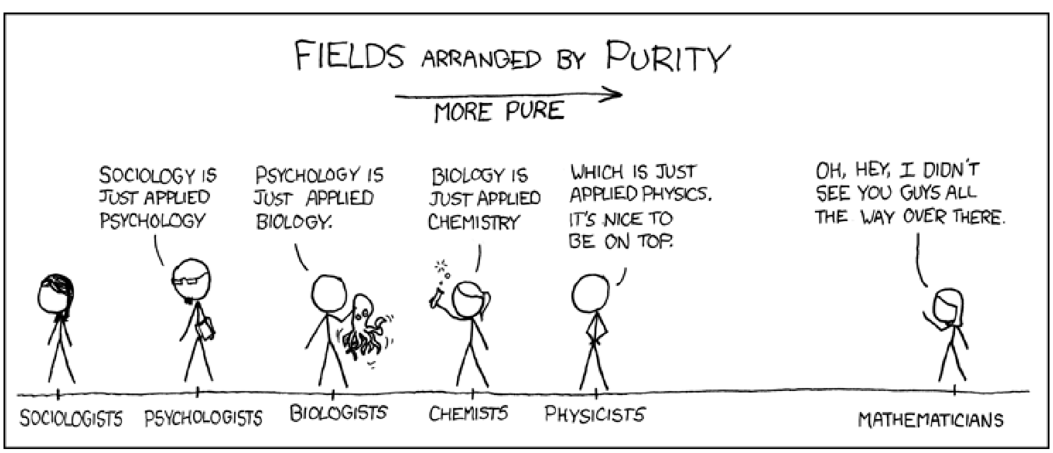
Readings

- **Life Itself, Chapter 1** — Robert Rosen
- **More Is Different** — P. W. Anderson
- **Emergence is coupled to scope, not level** — Alex Ryan

Different Approaches to Looking at the World

How do we study the world scientifically? The world, for our purposes, is the actual thing that we engage with. It's not necessarily these hidden quantum effects or something that you never actually see, but like, the world — our world. The world we interact with every day.



Let’s first look at the structure of science. Why are the sciences structured as they are? In this XKCD comic, we have, supposedly, the fields arranged by purity. Sociology is just applied psychology, psychology is just applied biology, and at the end it's all really just math. But there's actually something very wrong with this picture. If it were true that math is the purest field, then it’d follow that everyone should just be studying math (or at the very least physics) because everything else could be derived from there. But in fact, at each new scale of observation, we find novel things that weren't predicted by the previous scale. Therefore, sociology is *not* just applied psychology, psychology is *not* just applied biology. There seems to be something different at work, and it’s essential that we start grappling with it if we are to understand what's going on at all. This comic communicates one of our hidden assumptions that we talked about previously, and that assumption turns out to be wrong.

Overview of the Readings

There are three readings in this module. Let’s look at representative quotes from each — quotes that communicate the essence of the reading. There's obviously more content in each reading than one can capture in a single quote, but these are the main ideas...

In Rosen's chapter from his book *Life Itself*, he makes the assertion that:

“*System theory is the study of organization per se.*”

We’re used to seeing things broken down in the standard ‘university department’ way. What makes someone a chemist, for example? Well, they’re studying chemicals, molecules, atoms, and the interaction thereof. If they were studying organisms instead of chemicals, they would be biologists. Traditionally, we break down the sciences by the ‘stuff’ — the material — one is studying. Systems science takes a different approach. It’s not about the stuff you are studying, but how that stuff is organized. What are the interactions among those things? The material itself mostly takes a backseat, and you're much more interested in how things fit together into a bigger picture. The details of the material that comprise systems are more or less enabling certain patterns to exist, but they don't account for them.

This other paper is a classic from 1972 by P. W. Anderson — '*More is Different*'. This is one of those cliches we'll keep coming back to when studying systems science. More is not just more — it's not just a quantitative thing. As things increase either in size or quantity, there's a qualitative difference that needs to be accounted for, or at least appreciated and recognized. The quote I pulled from this one is:

"*At each level of complexity, entirely new properties appear.*"

The idea that we're indoctrinated into for most of our coursework — from grade school, to college, even to graduate school — is that the emergence of new properties is this sort of mysterious thing. If we're trying to get to the fundamentals of something, how can new properties emerge? As it turns out, it's not mysterious at all. To be fair, there are things about the world that are mysterious. There is, in fact, some irreducible amount of mystery that we're always faced with, and we'll look at where the limit of that is. But in essence, this idea of emergence can be made very non mysterious, and we'll try to do that going forward.

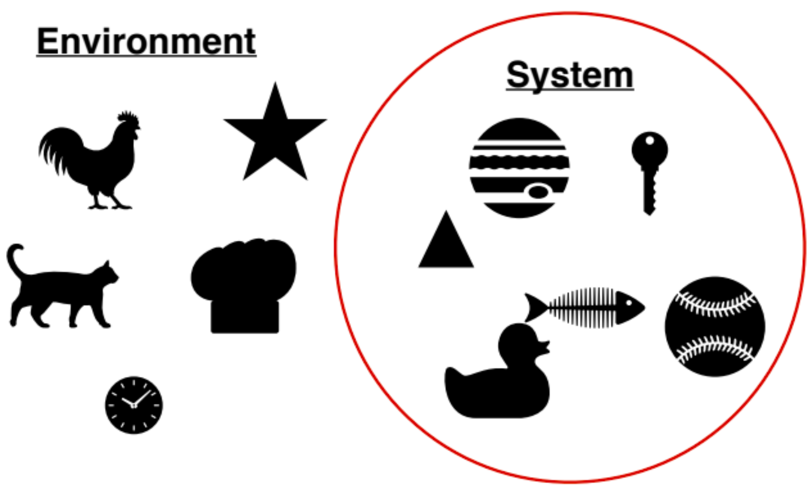
Finally, we have this 2006 paper '*Emergence is coupled to scope, not level*' from Alex Ryan. He's very crisp about his terminology, and that actually resolves a lot of tension that comes out of different usages of common words. One of the perennial difficulties is: emergence means one thing to one scientist and another thing to another. How do we find a common ground to talk about these things more clearly? His taxonomy is quite useful in clearing some of that confusion up. And, in the interest of relieving some of that more mysterious, more mystical side of things, he makes the very straightforward assertion:

"*Emergent properties are simply a difference between global and local structure.*"

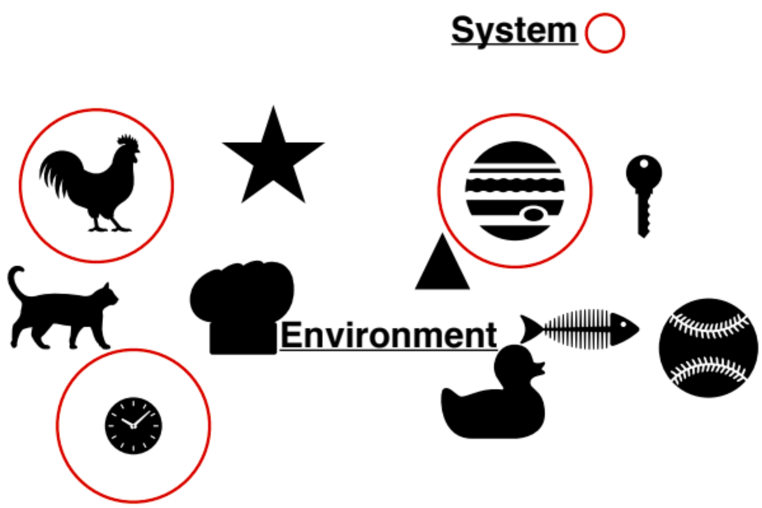
What is a System?

Often, we use the word system kind of offhandedly. When we use that word, what are we really saying? As we stumble upon the world, unanalyzed, we can see that there's stuff going on. Let's call it ***the ambience***.

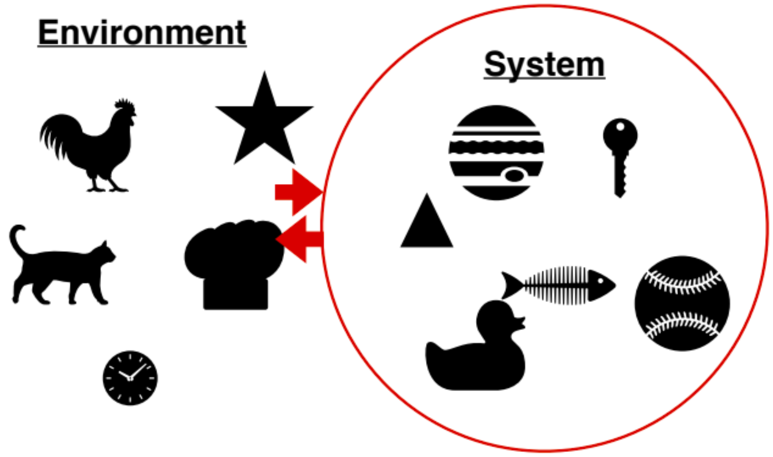
So what do we mean when we say system? What we're really saying — in the most fundamental sense — is that we're drawing some kind of a boundary in our analysis around some portion of the ambience, and calling it the system.



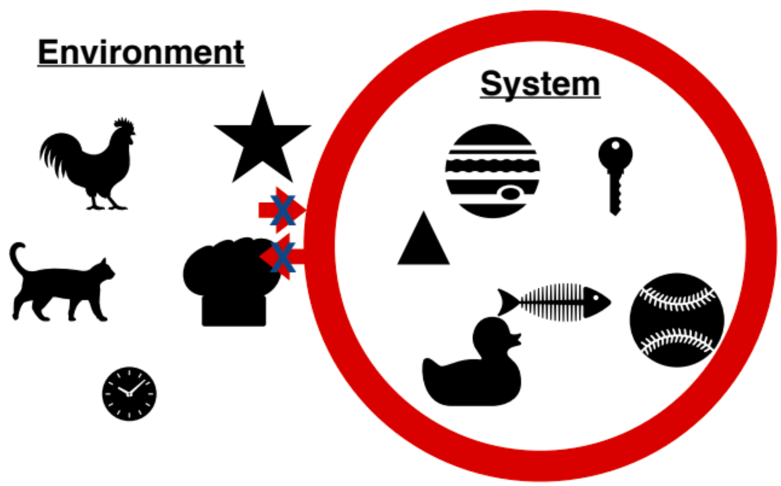
We partition the world (the ambience) into two sets, calling one ***the system*** and one ***the environment***. This is almost universally done in an intuitive, common sense way. It's very rare that you see someone deeply analyze what the boundary should be. It's kind of a presupposition in most approaches. But in fact, the question about where to draw the boundary turns out to be a deeply philosophical and important one. When you ask questions to the system (i.e. "will X happen?"), where you end up drawing your boundary between environment and system matters a lot. If you draw the boundary differently, you'll get a different answer.



Things are drawn nearby and orderly in that first picture. But of course, a distributed system could be all over the place. But again, this is all typically up to some kind of a judgment call of the analyst, or the scientist or whoever is looking, and it's not at all obvious where those boundaries should or do exist.



In addition, when we have a system and environment pair, we often have a kind of interaction where the system behaves and acts on the environment, and the environment has behaviors and properties that act on the system. Yet often, we try our best to build thicker boundaries around our systems. This thinker boundary indicates a kind of isolation and insulation of a system so that we can try and neglect its interactions with the environment.



There are things we can learn by doing that, but it also means that there are things we're missing by removing this interaction.

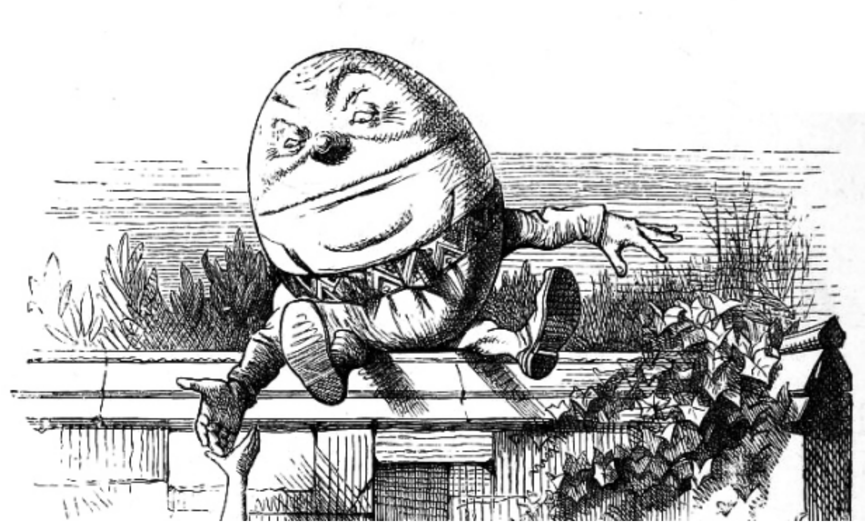
Another kind of nuance of this is that in so much of our traditional science — reductionist science — the results come from assuming an isolated system. In experimental work, stuff like classical thermodynamics for instance, it takes a lot of effort to create a system that is approximately isolated. This connects to a larger theme: how many systems that we're interested in are actually isolated systems? It's a number approaching zero. The world is a very interconnected place, almost nothing is in pure isolation. This calls into question the utility of studying isolated systems — there are some important kernels of insight that come from studying them, but in general systems are not isolated.

What makes a system complex?

Basically, complexity is the science of Humpty Dumpty. As the old nursery rhyme goes:

> *Humpty Dumpty sat on a wall,*
> *Humpty Dumpty had a great fall.*
> *All the king's horses and all the king's men*
> *Couldn't put Humpty together again.*

Reductionist science is all under the illusion that we can put Humpty Dumpty back together. We have all the parts, nothing was destroyed, so we can just put them back together. But it turns out to be more difficult than that.



So what makes a system complex? It's when the organization and the relationship of the parts of a system to each other *become essential for understanding its properties or behavior.*

If you don't need to look at those interactions to understand the properties of the system, then it is de facto not a complex system — you can just study the parts and know everything you need to know. If those interactions are essential for understanding, then indeed, you've crossed into the realm of complexity.

Emergent Properties and Reduction

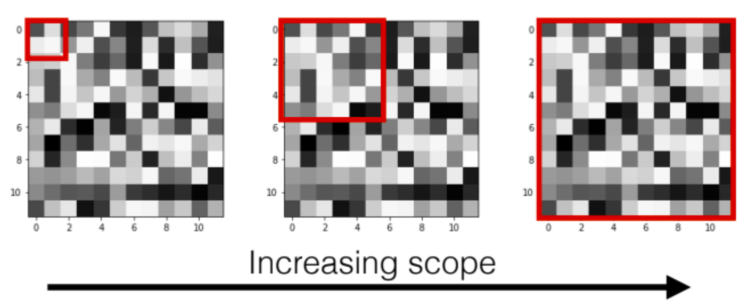
Reduction is just an activity, a way of analyzing a system, and it has no philosophical commitments. But reduction*ism* is meant to indicate that there is some kind of a philosophical and epistemological commitment to this process of reducing a system in order to study it. So really, reductionism is an assumption about how the world works — to understand any system first decompose it into its parts, then study the properties of these parts in isolation. Implication being that once you do that, putting the system back together into a coherent whole — putting Humpty Dumpty together again — is trivial.

If reductionism holds — if a system is truly reducible in full — then you might break it down into parts, and then if you really want to understand it, you break those parts into parts, and you keep doing that until you get to the ultimate base parts. And if you just study those parts enough, everything else will follow. That's reductionism. We'll find that, in most cases, reductionism doesn't work. A fundamental property of the world is that you can't break it down into parts and study it piecemeal.

Let's now introduce some crucial terminology to which we'll come again and again — courtesy of Alex Ryan. *Scope*, *resolution* and *state*.

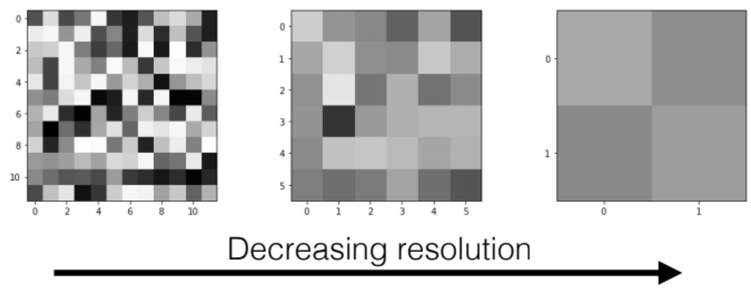
Let's look at a random pixel image, where each pixel in this 10 by 10 picture is, say, a random number between zero and one. We assign a shade of gray accordingly to represent that. We'll call this our universe. And let's just assume that these pixels are the ground truth of our universe. There's no smaller information to be found.

Our system, then, is defined by the ***scope*** — the boundary we draw around a set of pixels in our universe. As we expand the boundary, we increase our scope. Notice that the size of our universe stays the same, only the boundary grows.



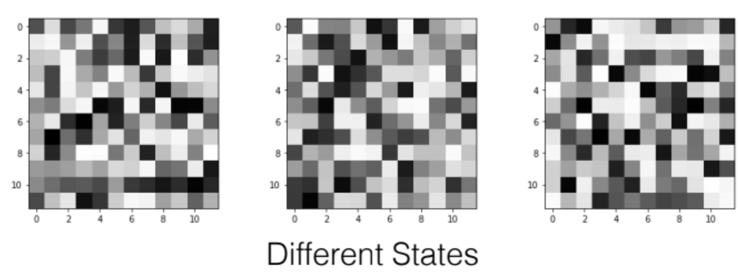
This is one way in which you might *move up a level* as you consider systems. But here you see the problem with terminology — *level* is ambiguous. Scope is one of the things someone might mean when they say something like "looking at greater levels".

Another is ***resolution***. Decreasing resolution has to do with washing away the details of what we're looking at. Again though, the size of our universe stays the same. This is another thing someone might mean by "changing levels".

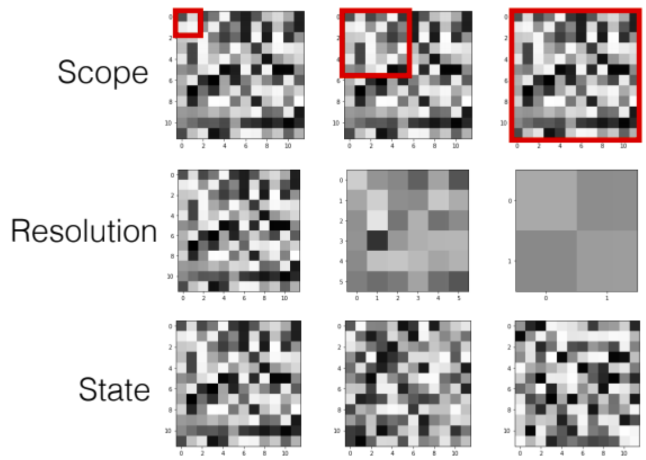


Despite the fact that you lose detail as you move to lower resolutions, what often happens is that by washing away details, you reveal some of the large-scale behaviors of the system. It's a forest for the trees thing — if you're looking very closely at all the trees, then you can miss the forest. Even if you're looking at all the trees in the forest, there're just so many details that it often becomes unclear what the large scale patterns are.

Now let's look at ***state***. Here, we have the same universe, but each pixel has a different value at each state — a different color. Systems are obviously dynamic — they change over time. So the state is a representation of a system at a given moment in time.

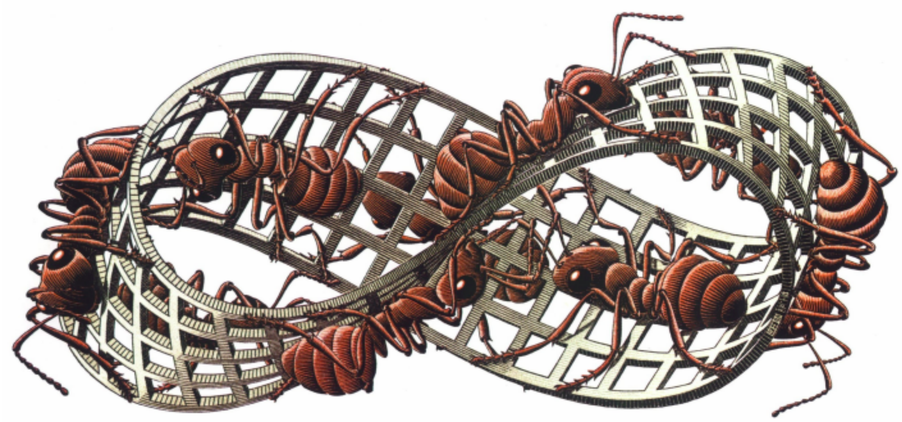


So there we have it. *Scope*, *resolution* and *state*.



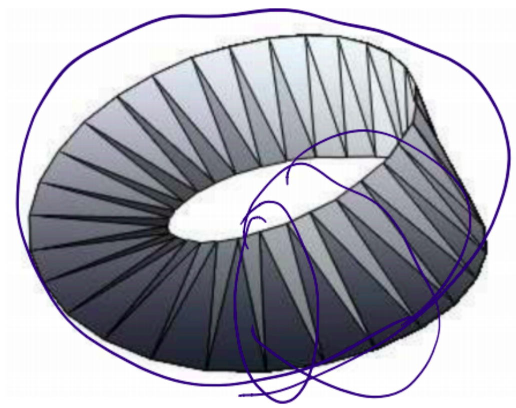
Strongly Emergent Properties

Let's take another example that Alex Ryan offers, and talk about this idea of emergent properties. And specifically, the idea of novel emergent properties, or **strongly emergent properties**.



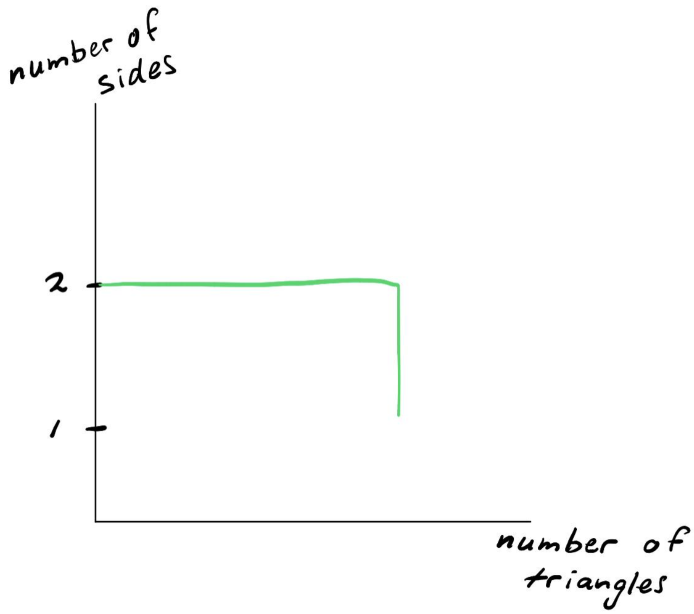
What we have here is a drawing by M.C. Escher — an ant crawling along a mobius strip. A mobius strip is a geometric object, with the interesting property that topologically, it's one sided. You can imagine this one ant crawling around at different moments in time: he starts on the top, he crawls around the curve, now he's around the back. And then he comes back around almost to where he was, but on the opposite side — or what we perceive to be the opposite side! He never actually had to crawl over the edge to get from what we perceive to be side to side.

Let's imagine that this mobius strip is some system we've stumbled across in nature, and we want to ask: what makes this system one sided? Well, if you proceeded with a reductionist approach, what you would do is start cutting up the Mobius strip. You could break it down into some set of triangles, for example, that would approximate this manifold.



And then you could look at the properties of a triangle, in an attempt to find what makes the mobius strip one-sided. Where is the one-sidedness in a triangle?

What we find is that any triangle, or in fact, any set of triangles that don't comprise the entire mobius strip are not one sided, but two sided. So depending on how we've scoped our analysis, we get two different answers. If our scope is anything less than the whole strip, we have a two sided object. But as soon as we've scoped the entire strip, we have a one sided object. This is why Ryan says that *emergence is nothing more than a difference between a local property and a global property*. This is also why he's adamant that this idea of strongly emergent properties is related to increasing our scope. Eventually, once we've scoped the whole thing, the property that we're measuring abruptly shifts.



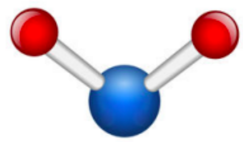
We can draw a graph where the number of triangles we're including in our scope is on the x-axis, and the number of sides of our object (the mobius strip) on the y-axis. We find that as you increase the number of triangles, you keep seeing two sides, two sides, two sides, until all of a sudden — when you get to the total number of triangles representing the mobius strip — the number of sides drops down to one! We get an abrupt shift in some property of the system.

Now let's imagine that instead of changing the scope of this system, we change the resolution (say, the size of the triangle into which the strip is broken). As long as you have enough triangles to reasonably represent this manifold, you will get the same answer for the number of sides, regardless of resolution.

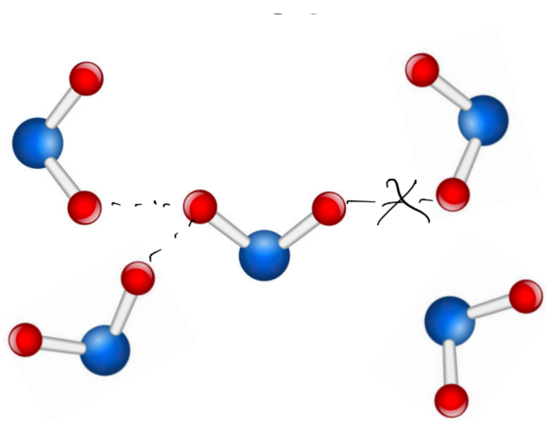
This is hopefully a bit of a demystification of this idea of emergent properties. There's nothing mysterious about this object, and there's nothing mysterious about the idea of looking at it as a whole or looking at it in terms of isolated parts. But depending on which approach we take, we end up with different answers.

Another Example

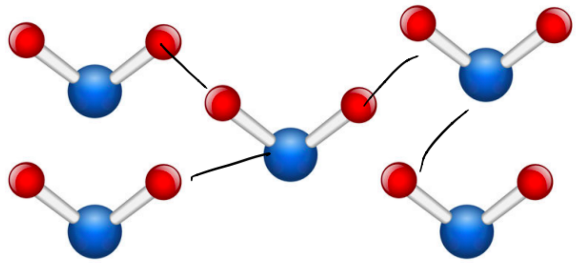
Here we have an H_2O molecule — water. Let's say it's sitting at room temperature.



We know that water at room temperature is a liquid. Would it make sense to say that this water molecule is in a liquid state? No — it's an ill-formed question. To start to address this question properly we have to have a collection of molecules that are interacting. The state of the substance comes out of the interactions of the molecules. The properties of the molecules enable this behavior, but they don't account for it in and of themselves. You have to look at them behaving together to see liquidity.



Now let's lower the temperature on this water and see what happens. All of a sudden, we get a solid state. There emerge stronger interactions among the molecules, inducing crystallization. Now they're very well ordered.



Notice that we have the same system, we're just varying one parameter — in this case, temperature. As we do that, we get a shift from one emergent property — liquidity — to a different emergent property — solidity. Same molecules, same laws, yet a different parameter, and hence a different emergent property. Again, we start to see here how the study of complexity focuses on the interactions, organization and relations among things, and how they give rise to properties and behaviors. The ‘things’ themselves take a back seat, instead we focus on the patterns that the ‘things’ embody.

Special vs General

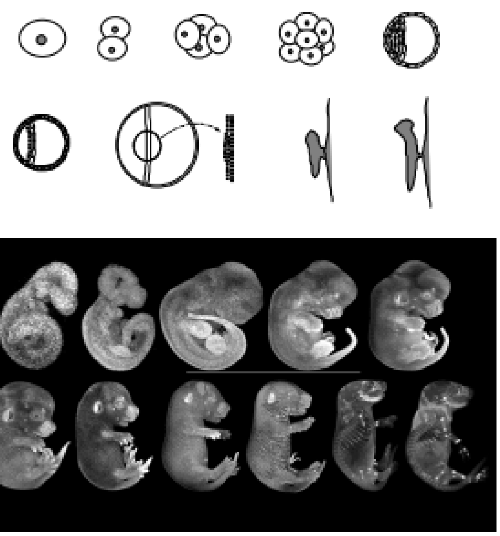
Stephen Hawking once said:

> *“I think the next century will be the century of complexity. We have already discovered the basic laws that govern matter and understand all the normal situations. We don't know how the laws fit together, and what happens under extreme conditions.”*

It’s of course very flattering to have Stephen Hawking — someone who a lot of people look up to — say this kind of thing about complexity. But there are multiple things we might take issue with here. For one, we might take issue with the notion that we have discovered all basic laws — maybe we have, maybe we haven’t. But the more crucial issue here is the way he orients his assumption around what is normal and what is extreme. This was a guy who studied black holes, right? A black hole, one might argue, is quite an extreme condition, not a normal situation. We should cultivate the frame of mind where we treat these isolated, basic laws of matter — situations where laws don't need to fit together — as very special cases instead of general cases. What science is mostly shining a light on are highly abnormal situations, highly contrived situations, situations that happen to fit the tools we have and are comfortable with, but are actually very rare, or at least very special. Again, it takes a lot of work to isolate a system. The mindset that we've inherited from recent science is this idea that what the physicists have studied are the normal things and now we need to fit them all together in a way that represents the world. It's actually the other way around. Hence, complex systems are typically described by the negation of terms that describe properties: *Irreducible, Nonlinear, Nonergodic, Nondeterministic, Nonstationary, Irreversible, Noncommutative, Nonisolated, Asymmetric.*

The Machine Metaphor

Another piece that will come up again and again is that our way of thinking has revolved around the machine metaphor. Things come into being by taking parts that already exist and assembling them. Let's say you're building a car: someone else fabricates the parts, you take them, put them together into the right configuration and get a complete, functioning system. This process is certainly something that exists, but again, it's not a general case of how order emerges.



Look at the process of development of a single organism. As the system grows, it's differentiating internally into various parts that play functional roles in the system. It's very unlike a machine in this way. You can't, for instance, disassemble the system and reassemble it. There's a strong interdependence between the parts — a strong link between the internal interactions of the system and its behavior. So much so that in living systems, if you destroy the interactions, you don't only destroy some of the properties, you actually disintegrate the system. The system disappears — there's no system anymore.

The machine metaphor sits in the background of a lot of our thinking. And indeed, the mathematics that we'll jump into in the next module is an effort to describe machines fully. Thinking about systems in terms of machines does take you a long way, but we still need to put a limit on how much we buy into this conceptualization — it’s not a big enough container to describe all things.