History of Complexity Science

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FFR 141

1) History leading up to mainstream complexity science
2) Some important concepts
3) Brief alternative recent history
4) A palette of techniques

-= Break =-

4) Simulation, Agent-Based Modeling
5) Cellular Automata
6) Network theory
7) Adaptation via natural selection
8) Mimicking nature

Today we will explore the history of complexity science, leading up to some of the central concepts in CAS – concepts that you will work with in the CAS programme.

After the break we will briefly cover some major methods and theories – just to outline them and familiarize you with the terminology somewhat.

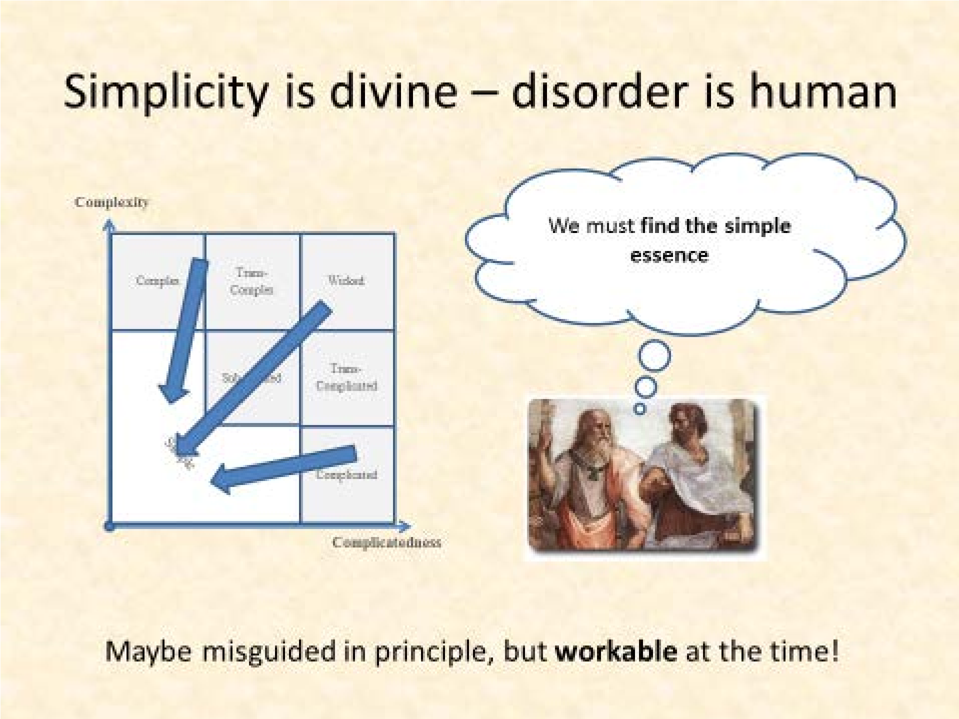
Let’s begin at the beginning… at least the beginning of recorded systematic thinking: the Greeks.

The relative neglect of complexity in science and philosophy today is not primarily because complexity is hard to see in the world.

The world has always struck observers as complex, but the question is what we do with complexity? How we interpret it...

Here we see represented two early competing views about the world... The complexity-oriented one clearly lost out...

Heraclitos is by no means forgotten, but it’s Aristotle that’s considered to be the ”father of science” and the stature of Plato can hardly be overestimated.



Why? I'd say because Heraclitos' path was less workable – it was harder to make headway.

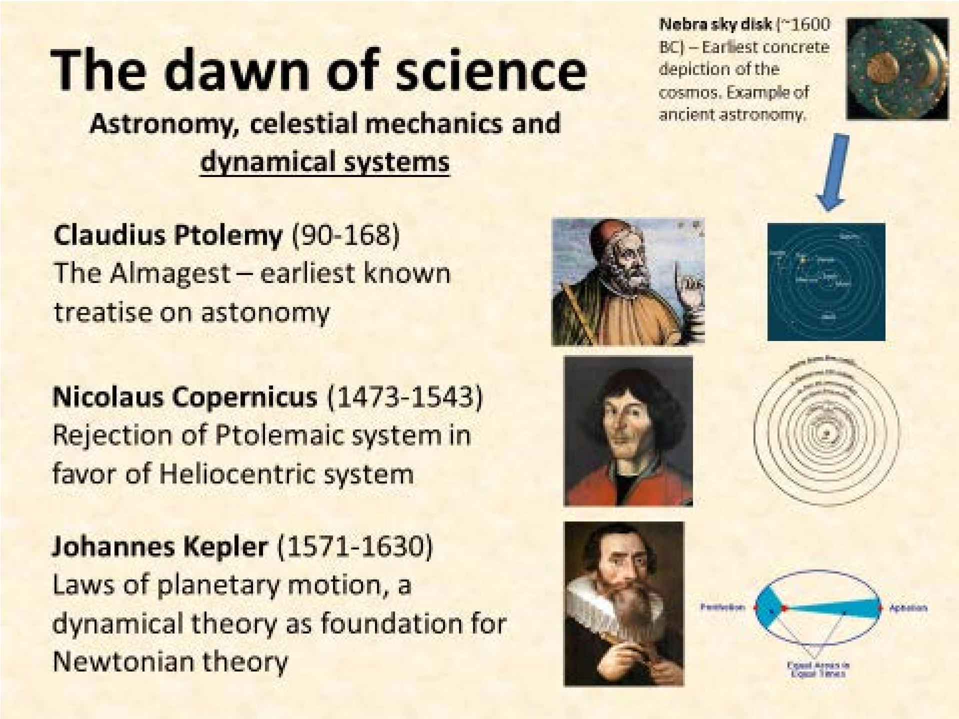
If you, as the Platonic school did, view complexity simply as noise that obscures a well-ordered and clear essence – and the task of philosophy to be to uncover that essence, then it's easier to get to work...

...and even if that view is misguided in certain fundamental ways - there are plenty of problems out there that **can** be worked from such a standpoint:

Problems where we can indeed find governing principles and models that cut away variability and complexity as a layer of dirt that can be dealt with for example statistically.

The coupling between that outlook and a tradition of empirical observation turned out to be explosively fruitful!

So what was it used for?



Well, religion was a prime mover of disciplined thought in those days, and prediction of the motion of celestial bodies had always had a particular significance in that context.

Imagine being able to predict uncanny or even frightening events such as lunar and solar eclipses in those days.

What better way to demonstrate your connection and insight in the divine area? What better way to maintain a worldly authority that stemmed precisely from a claim to be in direct connects with divine authority?

So the quest to understand celestial mechanics had been central and institutionalized since forever – at the top you see a depiction of the “Nebra sky disk” dating to the northern European Bronze Age.

Astronomy was an area that received funding and prestige... And it was the engine of much of our current understanding of the world.

Of course, as soon as you look closer at something, you are likely to sooner or later discover something that your patrons didn’t have in mind...

Perhaps even something that appears to work against the ends that they counted upon you to legitimize with your studies!

The idea that the sun is in the middle of the solar system was clearly one such idea... As was the preposterous idea that planets did not have the beautifully elegant circular orbits that one saw as evidence for the perfection of the Creator... But wobbly elliptical orbits! What blasphemy!

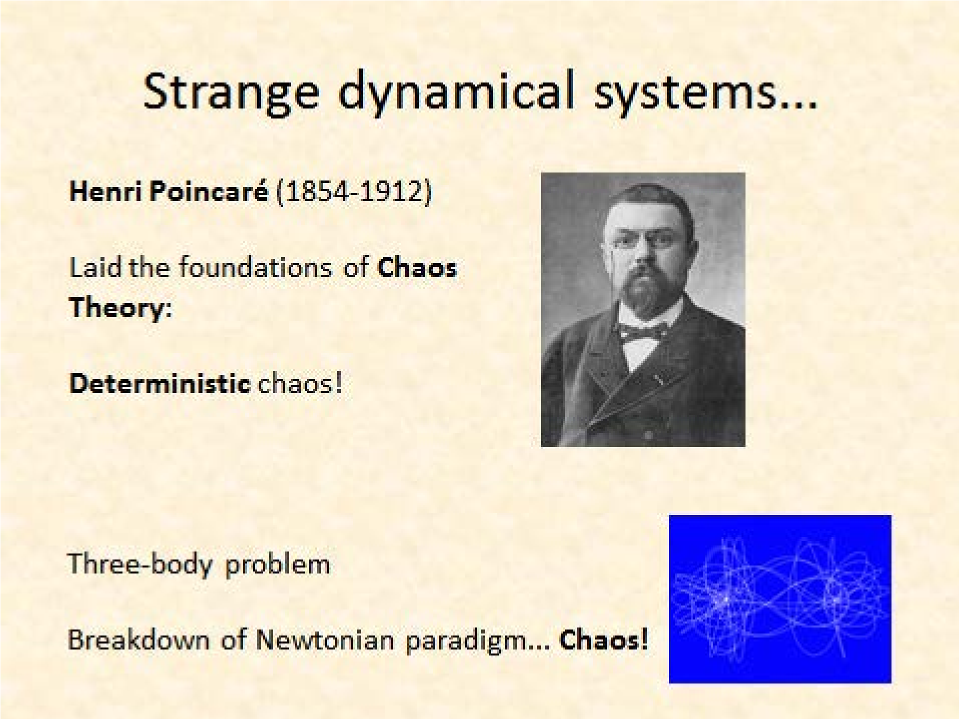
Nevertheless... Bit by bit, religiously motivated and funded inquiry bit its own tail… yielding more and more generative and more and more powerful and general theories and tools!

The big landmark here was the Cartesian-Newtonian paradigm that both serves and constrains us strongly today!

Modern science would be unthinkable without the contributions that we associate with these gentlemen.

It allows us to understand dynamical systems, subject to certain strong assumptions, in great detail and with very high accuracy!

Newton of course still remains with us today... Much less than proving Newton to be wrong, relativity theory turns Newton into a special case and explains how Newton's equations – although they lack a term – still work perfectly in the environments where we usually operate.



I recently stated that religion managed to bite its own tail by aiding and abetting inquiry into the divine perfection of celestial mechanics.

But it's not only religion that bites its own tail in such a way...

Scientific paradigms also do... Inquiry bit by bit tends to expose the limits of paradigms – the points where they break down.

Butting heads against such limitations has historically always been what has led to radical re-thinking of fundamental assumptions and well entrenched methodologies.

As many of you probably know, it's not exactly hard to cause Newtonian mechanics to break down: you only need to go from a two-body to a n-body problem… n=3 suffices to mess things up seriously.

...This was not just a philosophical problem – it had, for example, to do with the big problem of determining longitude at sea! The position of the moon would be eminently useful for doing this – but the motion of the moon is strongly influenced by both the sun and the earth!

None less than the Swedish (and Norwegian in those days) King – Oscar II – established a prize for anybody that solved the general n-body problem!

Poincaré received the prize… but a serious error was soon detected in his work. After working frantically at correcting this error, Poincaré failed to do so, but succeeded in making a string of fundamental mathematical discoveries that form the basis of **chaos theory**!

The three-body problem gives us a taste of **chaos**! A monster that reared its ugly head here and there to render analytical prediction impossible...

Problems tend to be avoided until they simply cannot be avoided any longer.

Typically this has to do with them getting in the way for solving some problem of great practical importance to somebody with assets.

Celestial mechanics had been such a problem… and so was making nuclear weapons in the 20th century!

Nuclear chain reactions, of course, are tremendously non-linear!

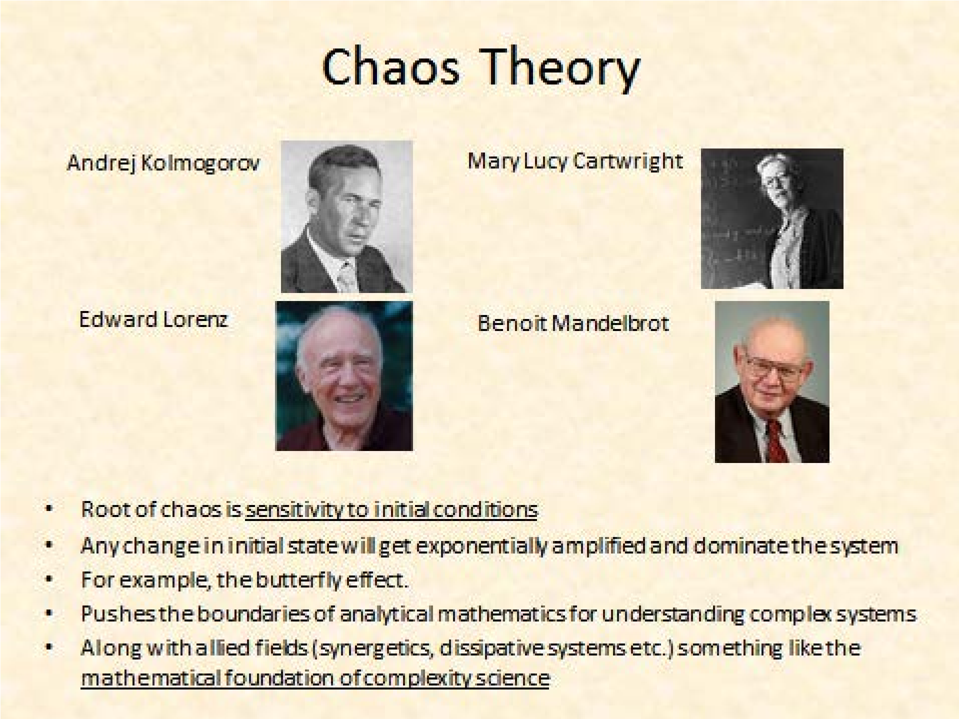
Nukes are dangerous and the raw material is expensive and slow to manufacture... Which rules out an experimental approach.

Analytics doesn't work because of chaos... One is forced to adopt **numerical** approaches!

It should be added that – at the time – numerical techniques, which were manual before computers, had an exceptionally low standing in mathematics!

And manual numerics is way too slow of course – so computers were pressed into action along with algorithms to automate numerics into the shape that we know it today.

Nuclear weapons and nuclear energy was a problem area that generated a whole new way of thinking about nature, systems and the world...



Out of all of this we got, for example, chaos theory... building upon Poincaré's work for example.

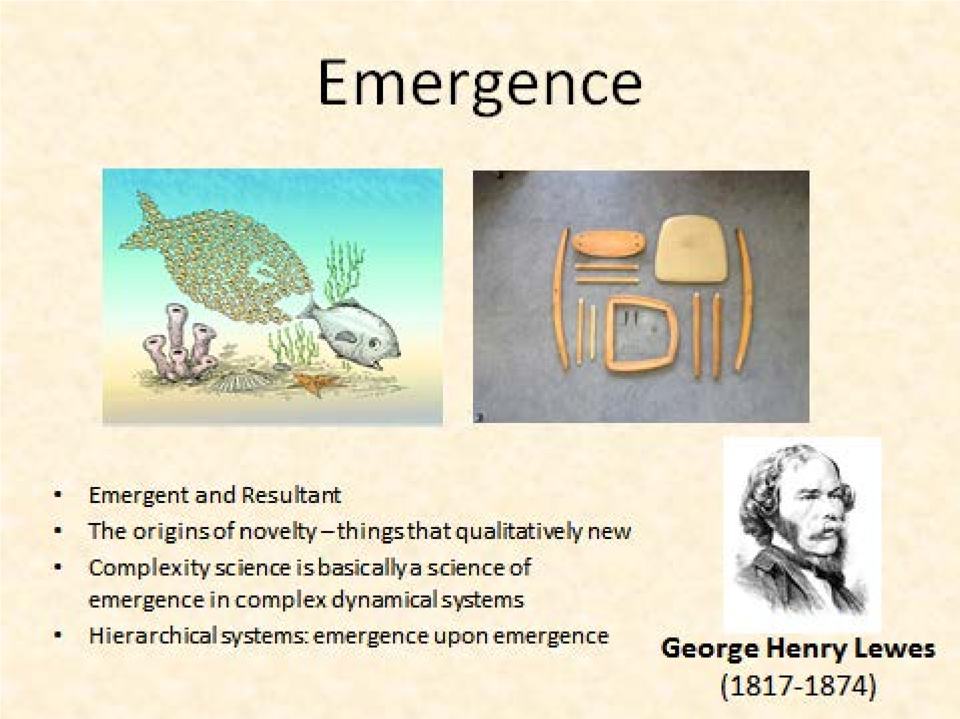
Eventually, people from the Los Alamos National Laboratory would go on to found the Santa Fe Institute in the 1980's – a place that we will return to and that's highly significant in the history of complexity science.

As you may see in the bullet point list – the issues now begin to look familiar!

These are issues that you will encounter in the CAS programme in various shapes and forms.

Chaos theory can be described as the mathematical foundation of CAS

It isn't to be considered as a part of CAS – it's to CAS more like what calculus is for physics.



But one thing that chaos theory is NOT concerned with, and that complexity science IS concerned with is Emergence.

In fact, no term is more central to complexity science than EMERGENCE:

What emergence is can be described breifly as follows: ”The whole is DIFFERENT from the sum of the parts”.

Emergence is an eminently QUALITATIVE thing – while chaos is and eminently QUANTITATIVE thing.

Emergence was initially introduced by philosopher **George Henry Lewes** and gave rise to a small school of ”emergentists” that had at least some lasting impact when **Emile Durkheim** used these arguments to motivate why a field of sociology was needed: why social systems cannot be reduced to, say, biology or chemistry.

An emergent property, Lewes stated, is one that **arises only at a certain level of organization**.

It is differentiated from ”**resultant**” properties which can simply be added through levels of organization.

Let’s take a system that’s eminently not dynamical – at least you don’t want it to be! A CHAIR

The chair is a **complicated** system, not a complex system… although it’s not highly complicated.

The property of a chair **that you can sit in it is emergent**. You can’t sit in any of its parts, and ”affording sitting” is not a property of wood, metal, hide or whatever chairs can be made of.

Unless you recognize the set of parts in the slide as pieces that will yield a chair when assembled... There is no general way to determine what the emergent property of an assembly are without actually assembling them.

But you won’t be dealing much with static systems like chairs in the CAS programme.

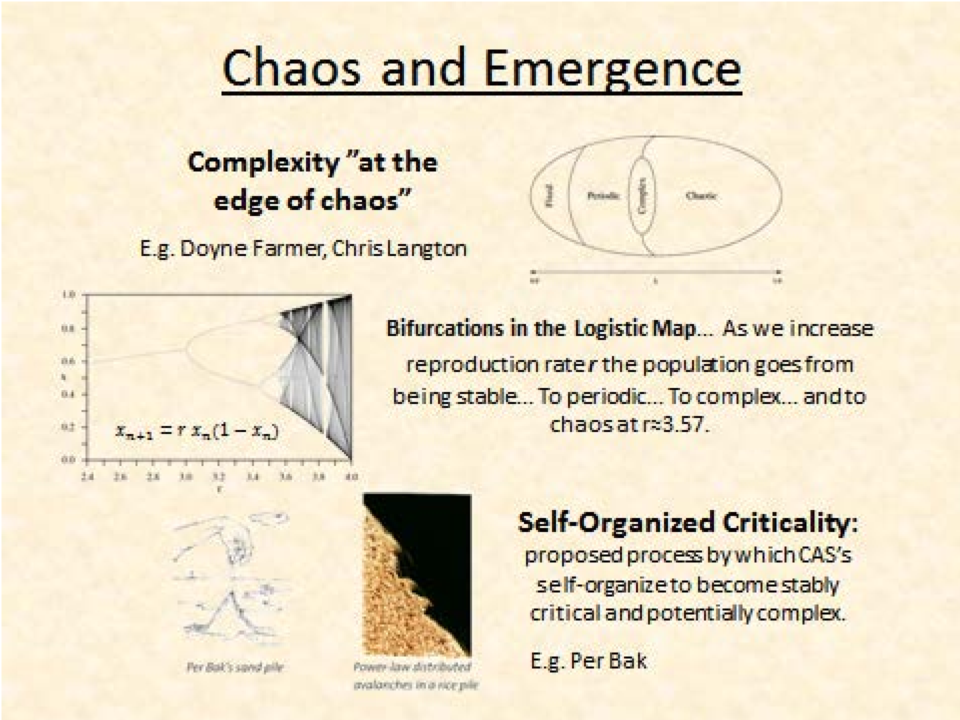
So how is emergence linked to non-linearity and chaos?

Non-linear systems are simply notorious producers of emergence... and emergence is a **different source of unpredictablility** than chaos!

So when we deal with non-linear systems we face two main hurdles to understanding, and these are, precisely: **chaos and emergence**.

Is there then a link **between chaos and emergence**?

Yes, there is a famed proposed link!



Complexity has been proposed to arise in dynamical systems that are "**on the edge of chaos**"!

What does this mean?

Let's look at a phase diagram that, if you haven't seen it already, you probably will soon: the period doublings – or bifurcations – in the **logistic map**.

As we increase the parameter "r", the system's dynamics become more and **more restless and rich** one might say.

At **first** it goes to a stable fixed point that varies smoothly with "r"... **Then** it becomes periodic, shifting between two values of x... **Then** four, then eight... And so on... Still mostly smoothly varying with "r".

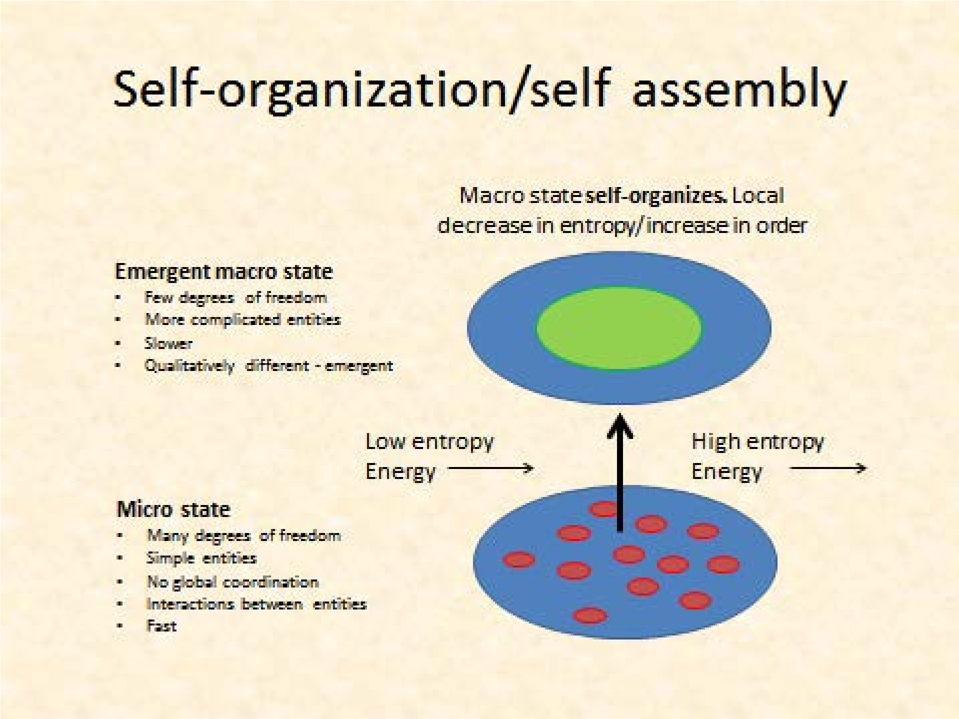
But eventually it all **breaks down in to chaos**: tiny changes in "r" produce entirely different orbits.

This basically captures the essence of deterministic chaos: the system is fully known **and we still cannot predict it**!

Why, then, do we have complex and rich behavior – what we need for example for adaptation – at the "edge of chaos"?

Well, in the chaotic regime no systematic adaptive process can operate…

…and the simple and dull periodic and static regimes are barren and devoid of complex structure.



So emergence is about components coming together to produce wholes that are different from the sum of their parts!

But **how** do the components come together?

In CAS we're usually talking about something called "**self-organization**"

This means organization that is not imposed from the top down, but that simply **arises from local interactions** as the system is "driven".

The significance of self-organization is hard to overstate: it's a source of order that does not come easily to the human mind!

We like to think of most things as designed top-down: it's how WE create things that have functions...

In other words, we tend to default to **complicatedness** as the principle of design.

So when we see things in nature that either have functions – biological things – or intricate structure that is non-random, like mountains, rivers, space...

...we've always imagined that they too must have arisen in a similar way.

In fact, self-organization, unless you pause to consider it, doesn't even appear as a potential explanation for order in nature.

So let's look at the slide:

We have a **collection of simple micro-level entities**... For example cells.

The system is **driven**... But not just in any way – it's **weakly driven**... You can't just blow up a bomb on it...

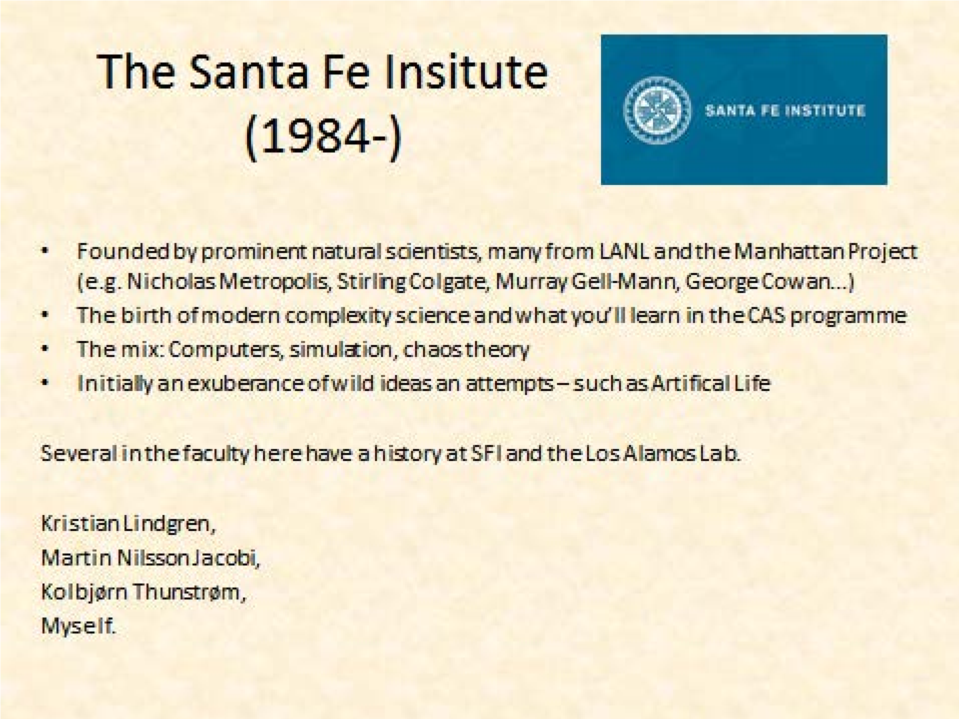
...and it's driven by ”**low entropy energy**” – often highly refined stuff that can be put to specific uses, such as glycogen and such... Not mere heat for instance.

Things move and interacts... Giving off **high-entropy energy**, which would be heat, detritus and stuff like that...

...and **large-scale patterns form**, making it possible for us to observe the system on a new level of observation!

For example... **The development of an organism during embryogenesis**: you take an egg, you keep it at a constant specific temperature for a specific period of time...

And out emerges a chicken! Who would have guessed from a microscopic perspective... Say from just looking at the chemical composition.



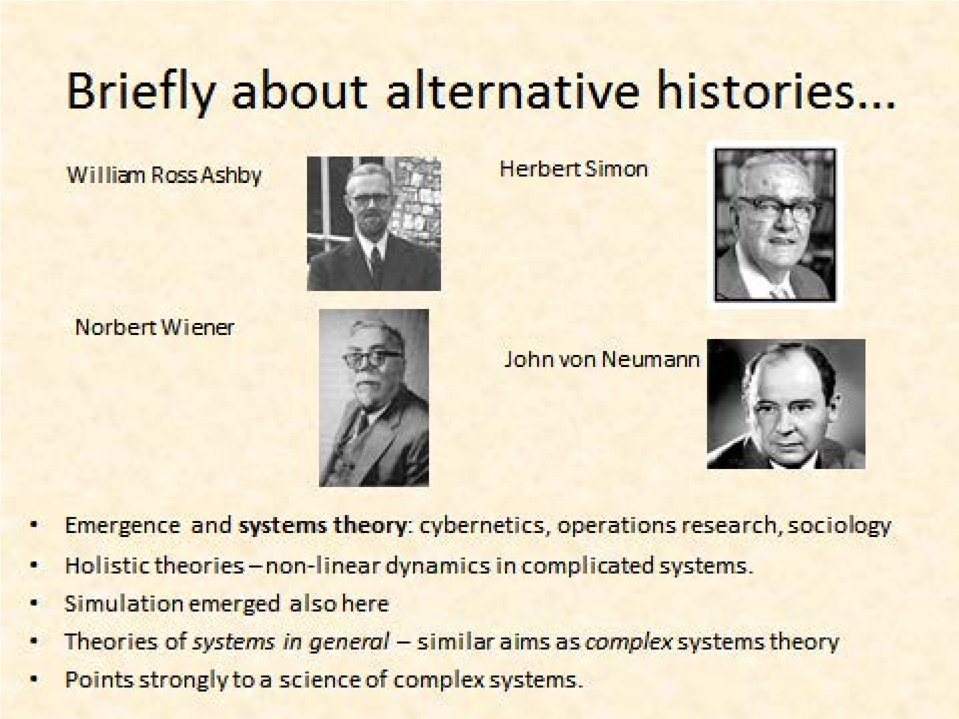
Much of what we have talked about in CAS so far has come out of – or in tight relation to – the **Santa Fe Institute** in New Mexico.

Many of us teachers here in the CAS programme have a history there. Myself I was there 1998-2001 and from time to time.

It's not as centrally important as it used to be – thanks to its success CAS research is now highly disseminated over the globe – but historically it's immensely important!

The birth of complexity science saw an exuberance of wild ideas and goose chases! Those were incredibly stimulating times...

Today CAS is still fascinating of course, but it's more mature and less playful... Even if it's more playful than a lot of other things out there!



But there are other ways of telling the history of CAS!

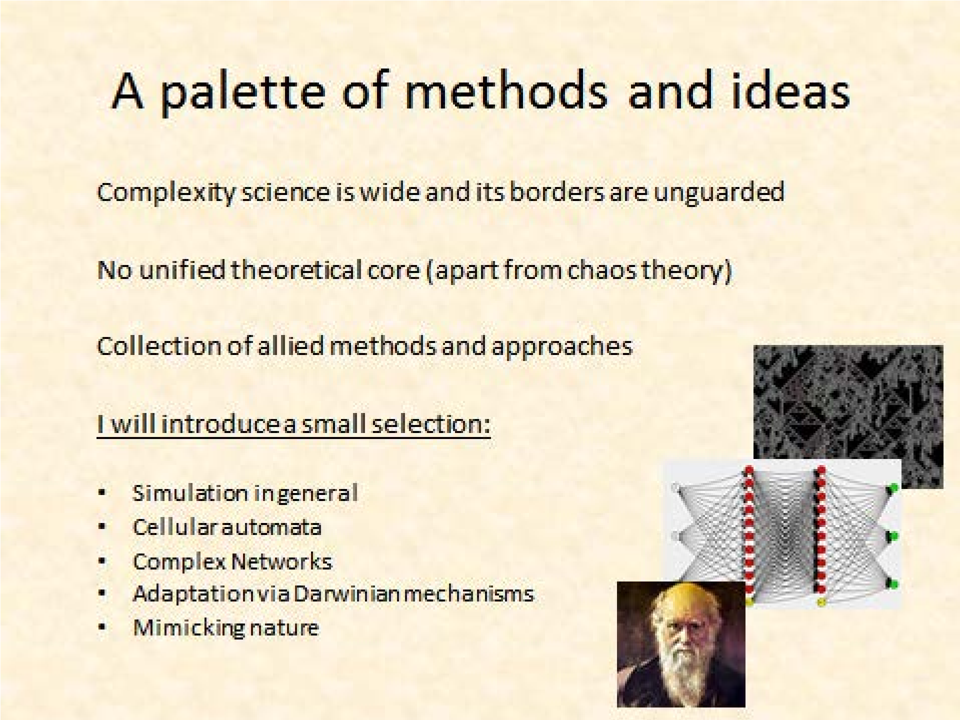
We've told the history that runs from the Atom Bomb to the Santa Fe Institute...

There is a story that goes from General Systems Theory to slightly different flavors of complexity theory.

These different lineages have interacted and intermixed quite a bit - but one can still tell the difference in how the initial questions were posed.

If your quest is to understand society and technology by figuring out what its components are and how they interact, you run into the problem of complexity and emergence from a different direction!

Indeed, you'll run into it from the **wicked direction** rather than from what we tend to refer to as complexity in CAS.

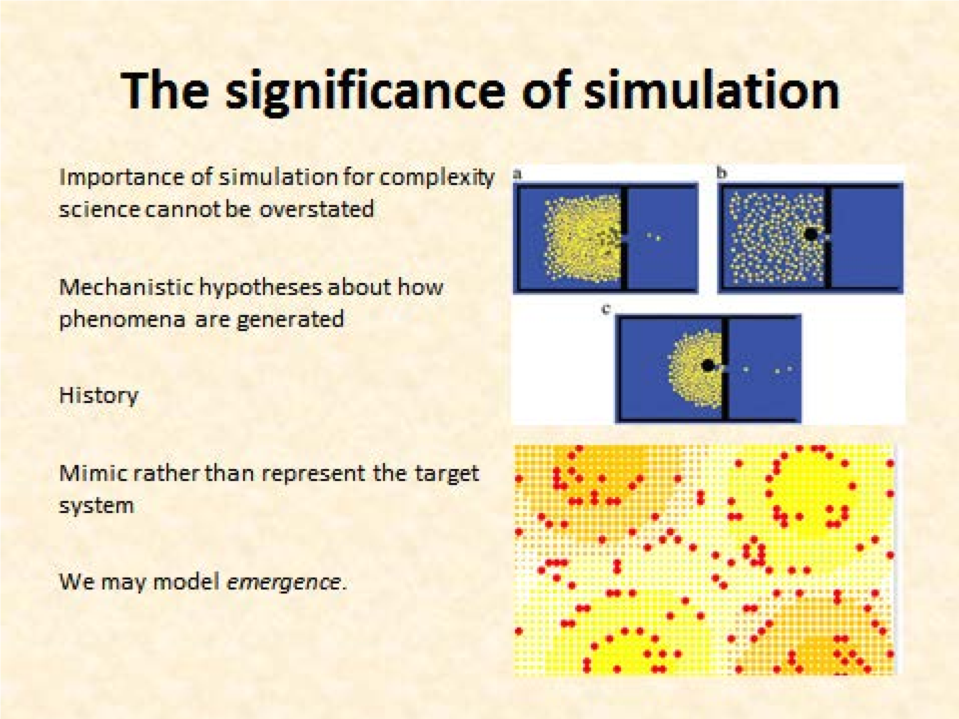


So let us summarize with some cuncluding observations before the break!

After the break we will go through a small selection of methods and approaches... Held together more along the lines of Wittgenstein’s Familiennähnlichkeit than as a classical category...

That is, more like fibers in a piece of cloth than like balls in a bucket.

BREAK



On the background of how I described self-organization and its significance – it is not hard to see why simulation is central to complexity science!

Look at the crowd simulation for example at the top...

How would you imagine what happens if 200 people try to get out of a room?

What happens if you place a pillar before the opening?

Right... There is no way we can even begin considering such things using our cognitive capabilities alone.

Can we put it down as equations and solve it? No, not really...

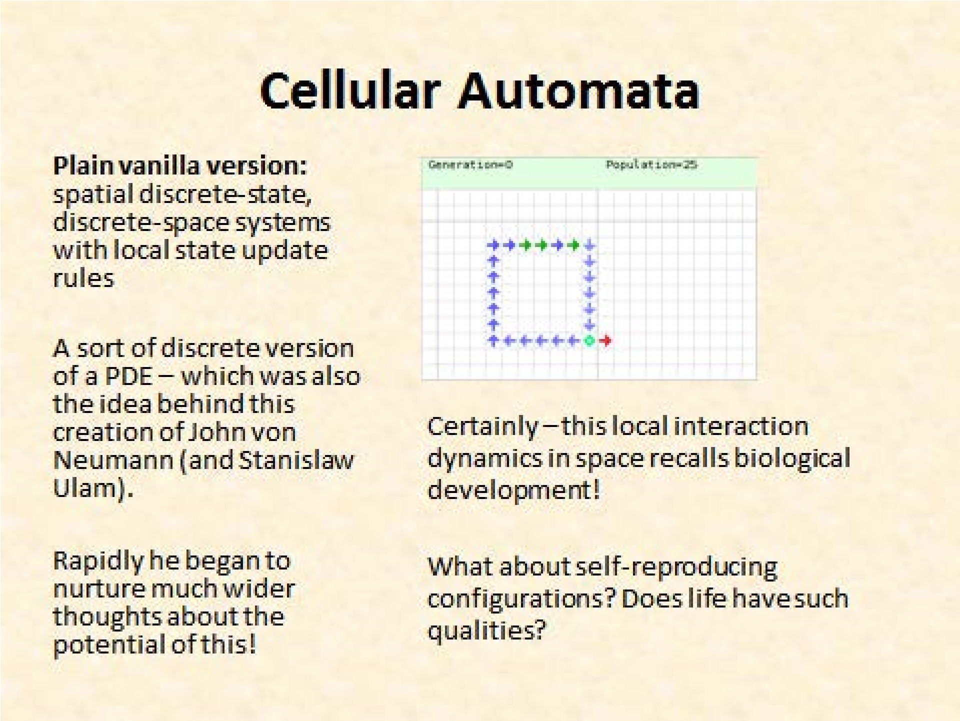
Can we make an experiment? Conceivably in this case... But shift to galaxies in a galaxy cluster, or cultural evolution across 100 millennia, and you see that experiments are not a general solution.

Simulation allows us **to mimic systems** on the microlevel, put it all into motion, and observe what happens!

We can see chaotic behavior, emergent patterns and whatever else appears.

We may even be able to discover mathematical ways of expressing what happens in the end – *with the aid of* simulations.

So let's go through some approaches where simulation plays a central role.



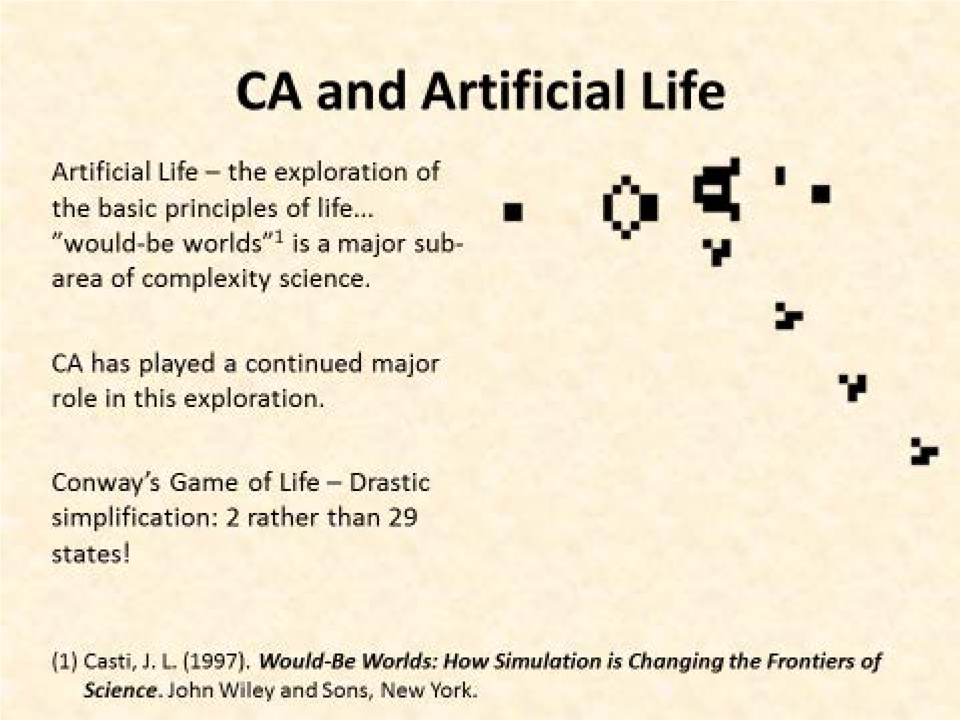
We begin with a plain Cellular Automaton

Originally the idea was to have a discrete type of PDE really – one that could be run exactly on a computer.

But this system turned out to be immensely interesting in itself!

It yielded completely different ideas and openings!

Does it maybe capture something important about things like self-reproduction and life?

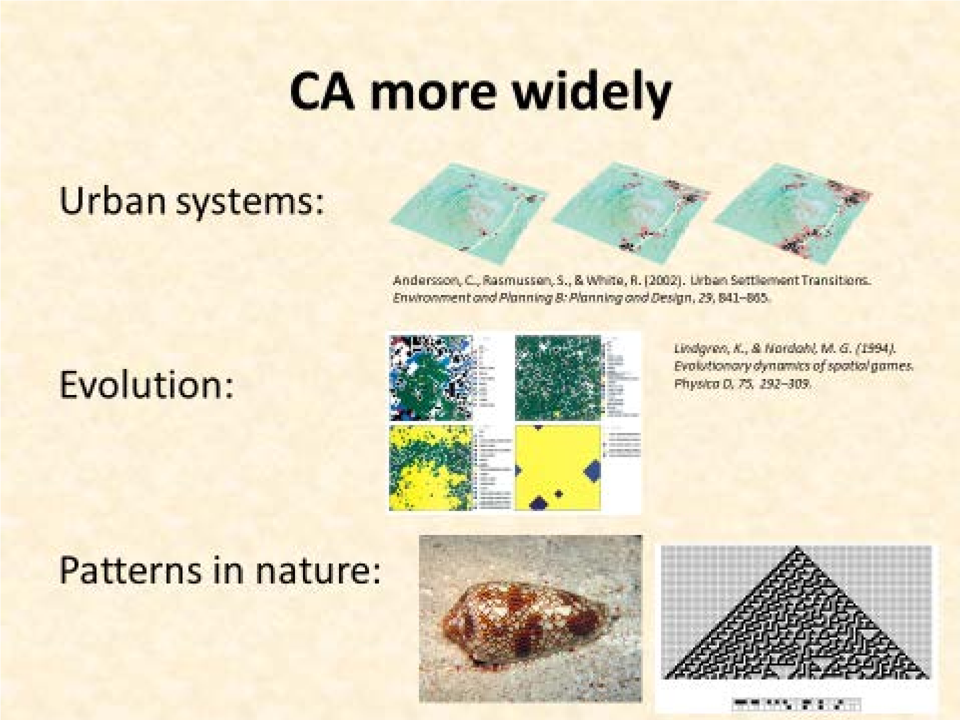


Cellular Automata have been essential in the area called ”Artificial Life”: the exploration of life in abstract ”would-be-worlds”.

Conway’s ”game of life” is probably the most famous Cellular Automaton...

Employing spatiality in intricate ways, ”machines” can reproduce with only 2 states!

Today,Turing Machines have been implemented in this artificial medium – proving that it in principle is powerful enough to solve ANY problem!



The practice of embedding local interaction rules into a cellular space is highly central to CAS research.

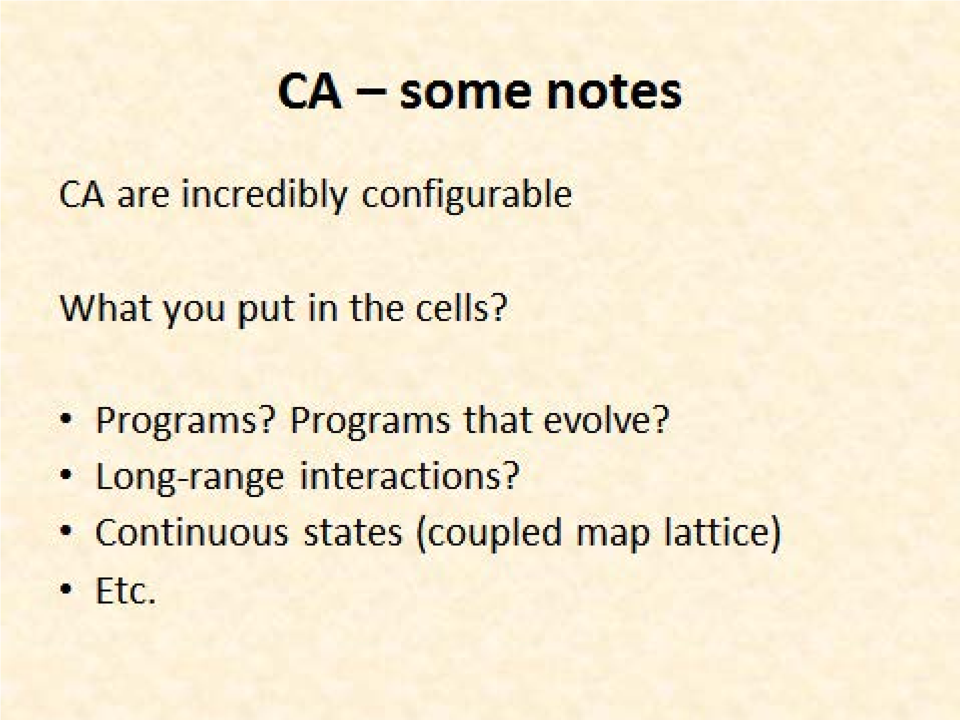
It can be taken in just about any direction!

We here see three examples…

Urban Systems – interactions between land uses and infrastructure to simulate urban change, something that I have worked extensively with.

We have the exploration of evolutionary phenomena in space, which Kristian Lindgren has made ground-breaking contributions to.

We also have for example the exploration of pattern formation in nature…



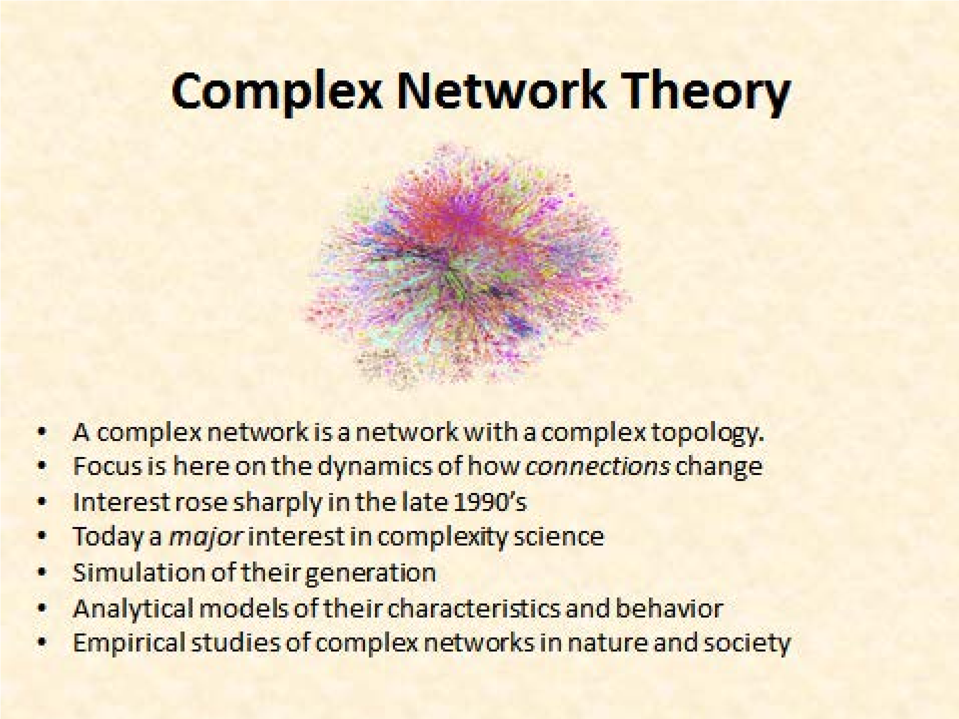
So in summary you can put just about anything into the cells of cellular automata…

They are the foundation of spatial simulation!

But you may of course use the same principles in other topologies.

In fact, the parallel update and local interaction that is central to CA, is also the foundation of **Agent-Based Simulation.**

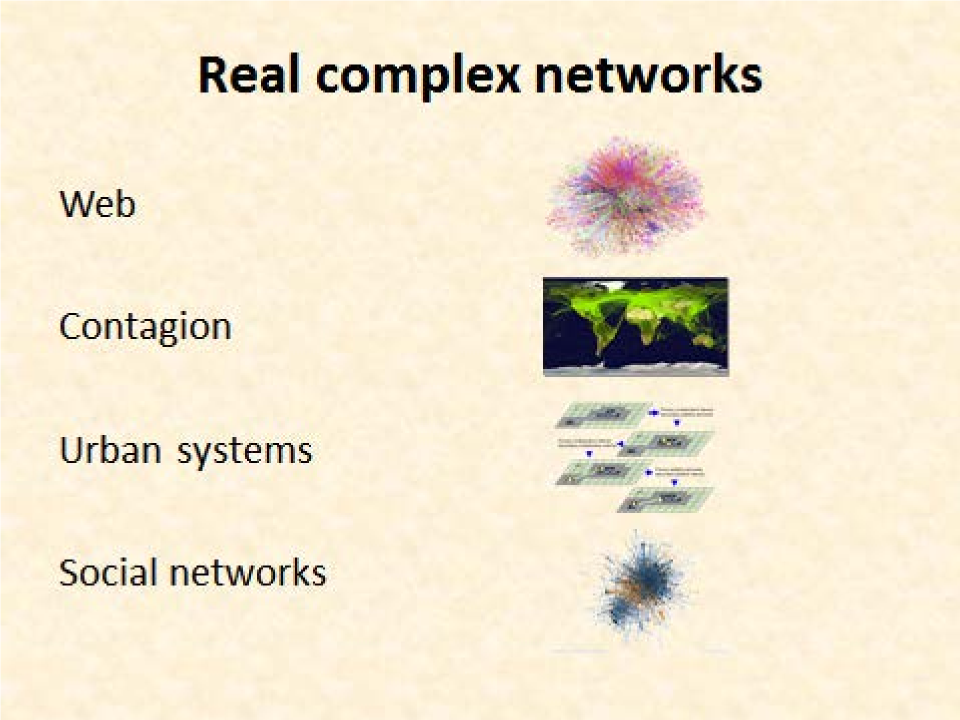
That is, **simulation from the perspective of agents**.



Network theory became a major topic in CAS in the end of the 90’s and the beginning of the 00’s

Sometimes it feels as if CAS is all about networks today.

Complex Networks refers to the self-organization of graphs, one might say – graphs that grow from the bottom up, and the properties that such networks have.



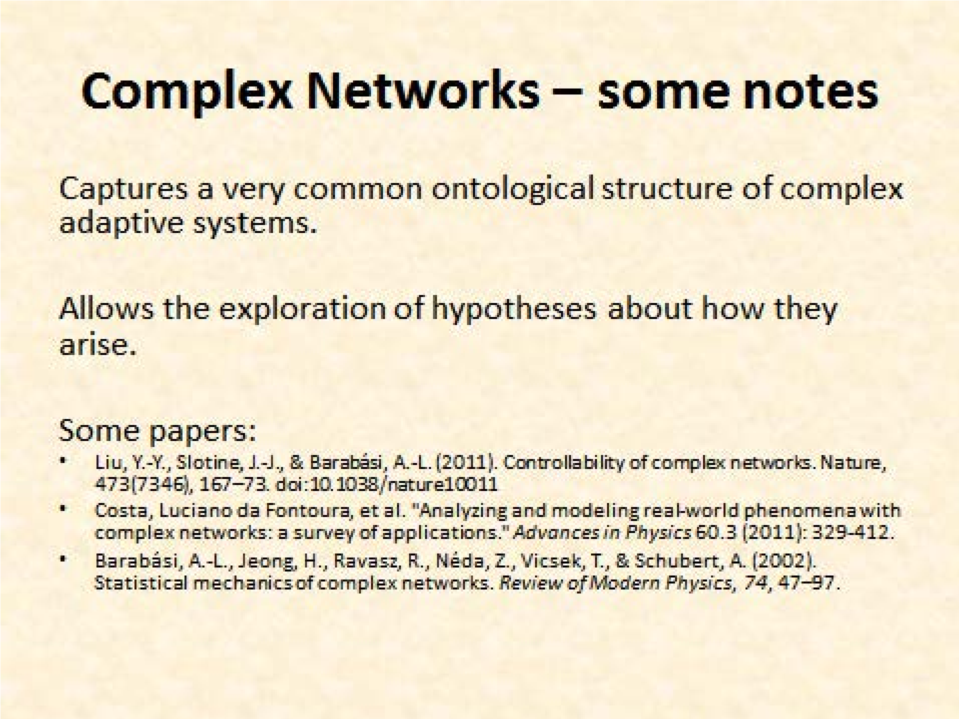
Some important examples…

Note how all of these are generated historically mostly be local initiatives based on local considerations.

They self-organize from the bottom up – they are complex…

But in all these cases, except contagion which is a biological phenomenon, we also have elements of top-down control in attempts to channel and direct their generation and behavior.

So they all edge somewhat toward a trans-complex ontology.



So in summary, complex networks capture a very common ontological structure of the world, and not least in the area of human social interactions.

Here are some important reviews and papers.

Adaptation

Adaptation is central to many issues in complexity science

What is it for a complex system to be adaptive?

(1) The system is adaptive; i.e. it adapts.
(2) The system is adaptive; i.e. it lends itself to some sort of functionality.

Techniques

Genetic algorithms

Genetic programming

Used extremely widely along with other tools: cellular automata, neural networks, particle swarm optimization…

Usually it's there in one form or the other.

And of course in the **study of natural systems with natural selection**!

Mimicking Nature

We've already mentioned natural selection...

But there are other examples

For example, **Particle Swarm Optimization**

Began as model of social insects, e.g. bees or ants.

Combines distributed information gathering with adaptation in a system that makes minimal assumptions about the system.

System behavior is adaptive and emergent – it solves a global task that the agents neither see nor understand.