Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

Introduction to self-organising systems

Lecture 1.01

EEU45C09 / EEP55C09
Self Organising Technological Networks

CONNECT
Networks of the Future

Nicola Marchetti
nicola.marchetti@tcd.ie

Let Us Begin…

https://www.youtube.com/watch?v=rl0yFwcGx_o&list=PLsJWgOB5mIMDRt8-DBLLVfh-XeKs2YAcg&index=8

https://www.youtube.com/watch?v=ybV4NA30jdc&t=8s

Ants

- The ant researcher Nigel Franks wrote that “The solitary army ant is behaviourally one of the least sophisticated animals imaginable…
- if 100 army ants are placed on a flat surface, they will walk around and around in never decreasing circles until they die of exhaustion.
- In extremely high numbers, however, it is a different story.”

Ants (2)

- Here, for example, is a colony of army ants, building a tunnel

- Each ant on its own is very simple, but the colony as a whole can work together cooperatively to accomplish very complex tasks

- *Without any central control*; that is, without any ant or group of ants being in charge

Ants (3)

- In other words, ant colonies can organize themselves to produce structures much more complicated than any single ant could produce

- Here's an example of ants building a bridge with their bodies so that other members of the colony can cross the gap between two leaves

- The ants gradually add themselves to the structure

- Each ant is secreting chemicals to communicate with the other ants, and the whole bridge is built without any central control

- We call this a "**decentralized, self-organizing system**"

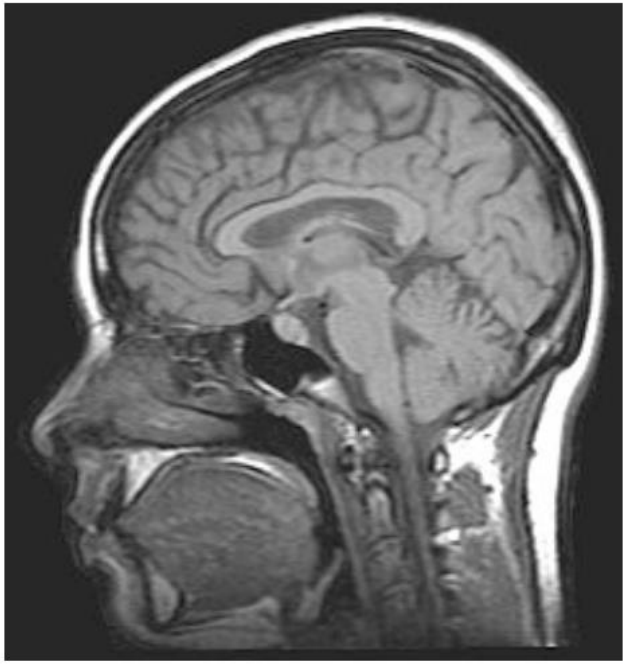
CONNECT Networks of the Future

Termites

- Other social insects produce similar behaviour
- For example, here is an example of the kind of complex living structure built by termites ➔ Termite mound
- A major focus of complex systems is to understand *how individually simple agents produce complex behaviour without central control*?
- Here the simple agents are insects, but we'll see many other kinds

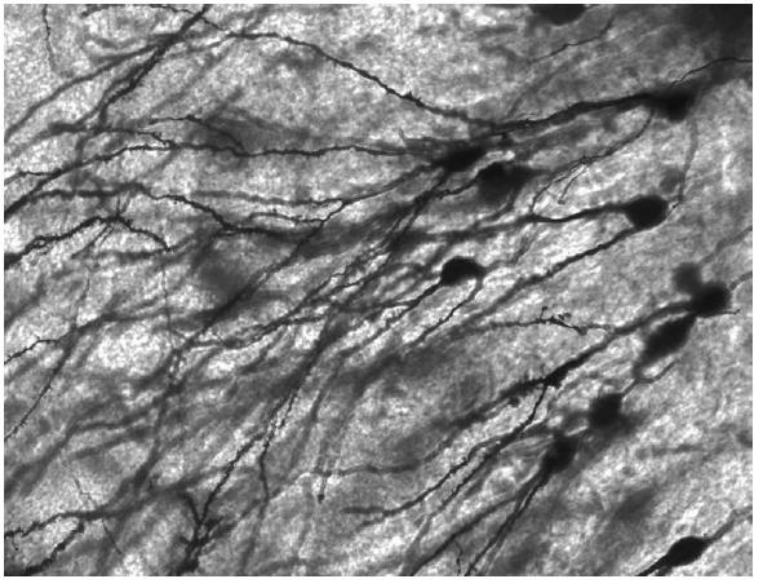
The brain

- Another classic example of a complex system is the brain
- Here the *individual simple agents* are neurons



The brain (2)

- The human brain consists of about 100 billion neurons and 100 trillion connections between those neurons



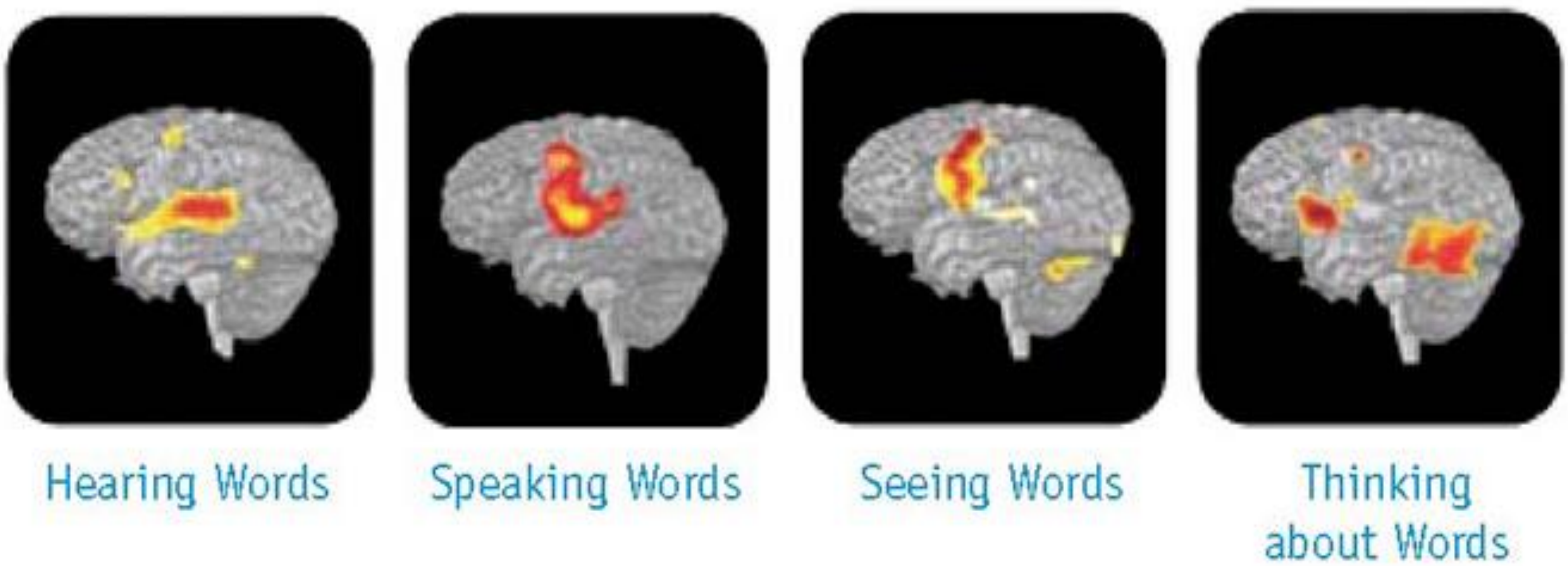
- Each neuron is relatively simple (compared to the whole brain) and, again, there is no central control

- Somehow the huge ensemble of neurons and connections gives rise to the complex behaviours we call "cognition" or "intelligence" or even "creativity"

The brain (3)

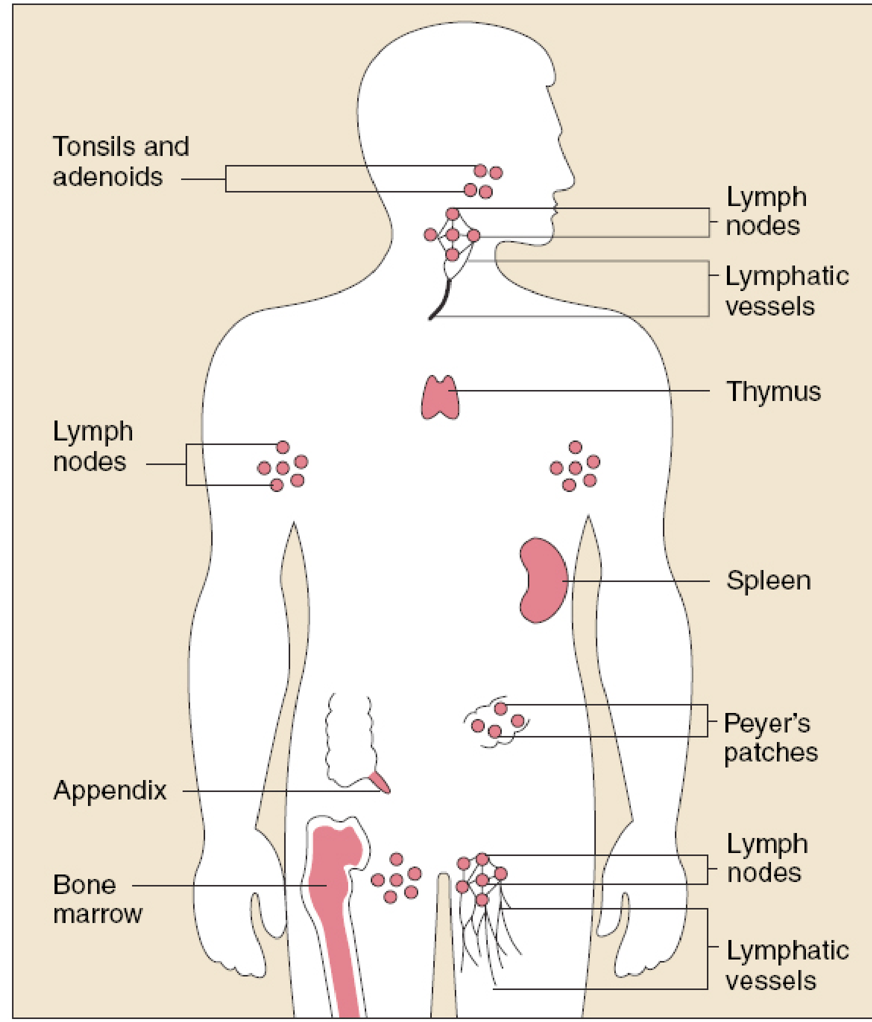
- Brain imaging has shown that these neurons have organized themselves into different functional areas

- Just like the ants or termites, *neurons can self-organize into complex structures* that help the species function and survive



Immune System

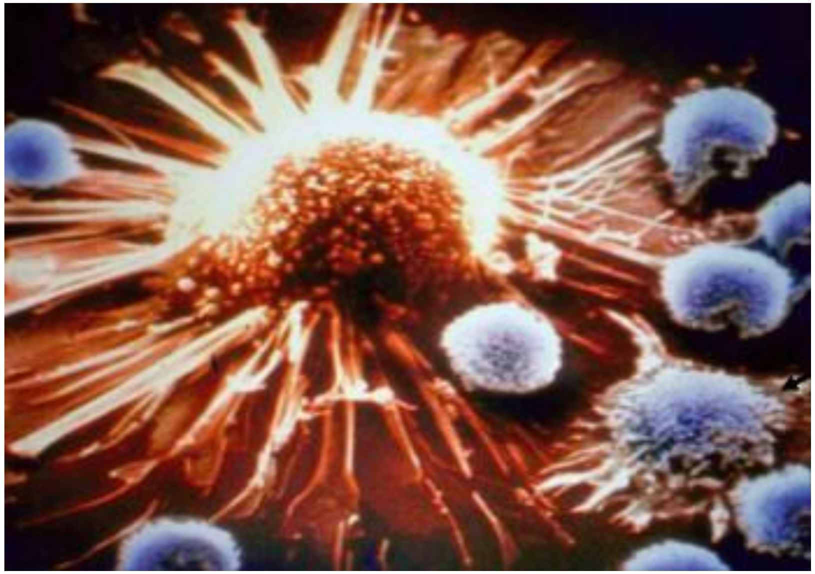
- Yet another complex system is the immune system
- The immune system is distributed across the body, involving many different organs, as shown in this picture, and trillions of cells moving around in the blood stream or lymphatic system, protecting and healing the body from damage or disease



Immune System (2)

- For example, this is a picture of immune system cells attacking a cancer cell

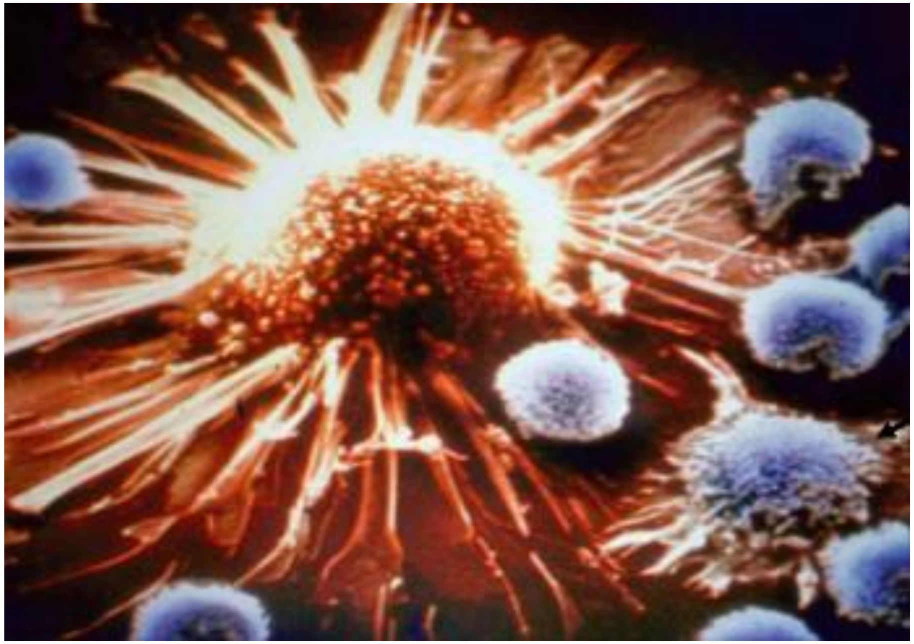
- Like the ants we saw before, immune system cells communicate with one another through chemical signals, and work together, without any central control, to launch coordinated attacks on what they perceive as threats to the body



Immune System (3)

- In addition, the population of immune system cells in the body is able to change, or adapt itself, in response to what that population of cells perceives in its environment

- This kind of *adaptation* is another key characteristic of complex systems

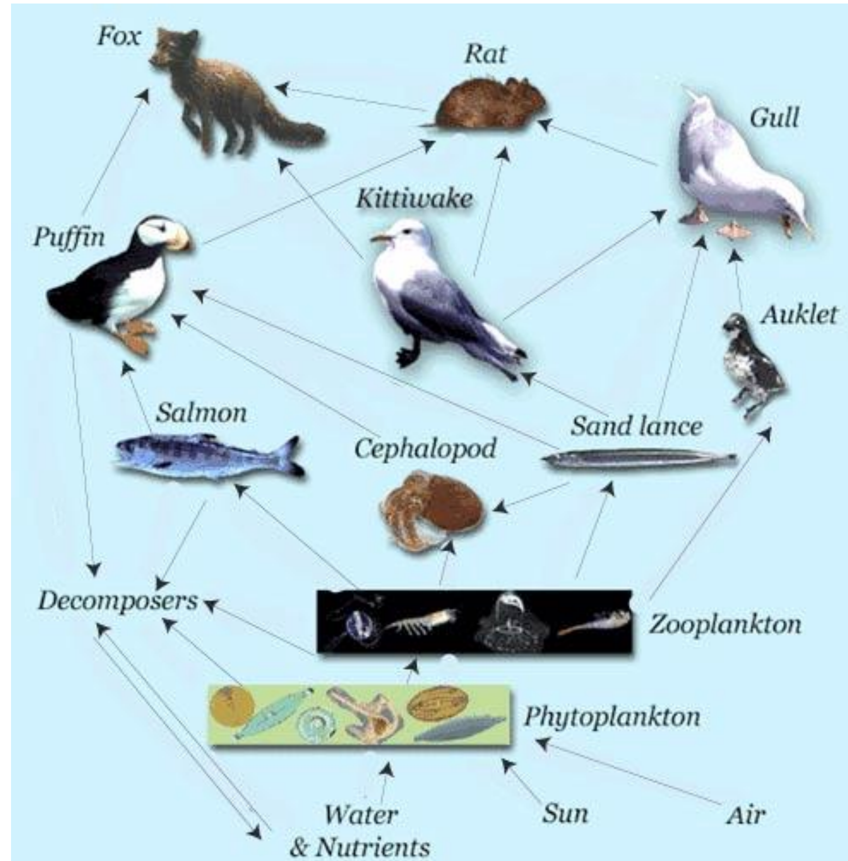


Food Web

- The idea of networks is central to the study of complexity in nature

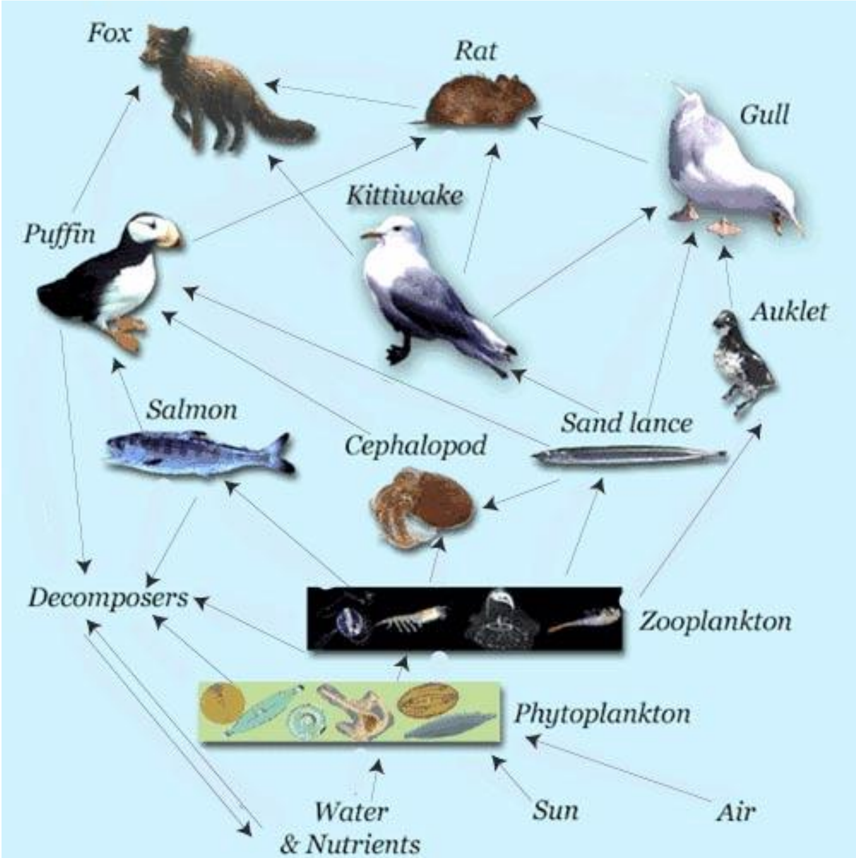
- Here is another kind of network, a food web

- Here, each node in the network is a particular group of species, and the arrows represent who eats whom



Food Web (2)

- If one species group points to another, that means the first is food for the second
- For example you can see that foxes are at the top of this particular Alaskan food web, since they eat several kinds of animals, but nothing eats them, at least on this chart



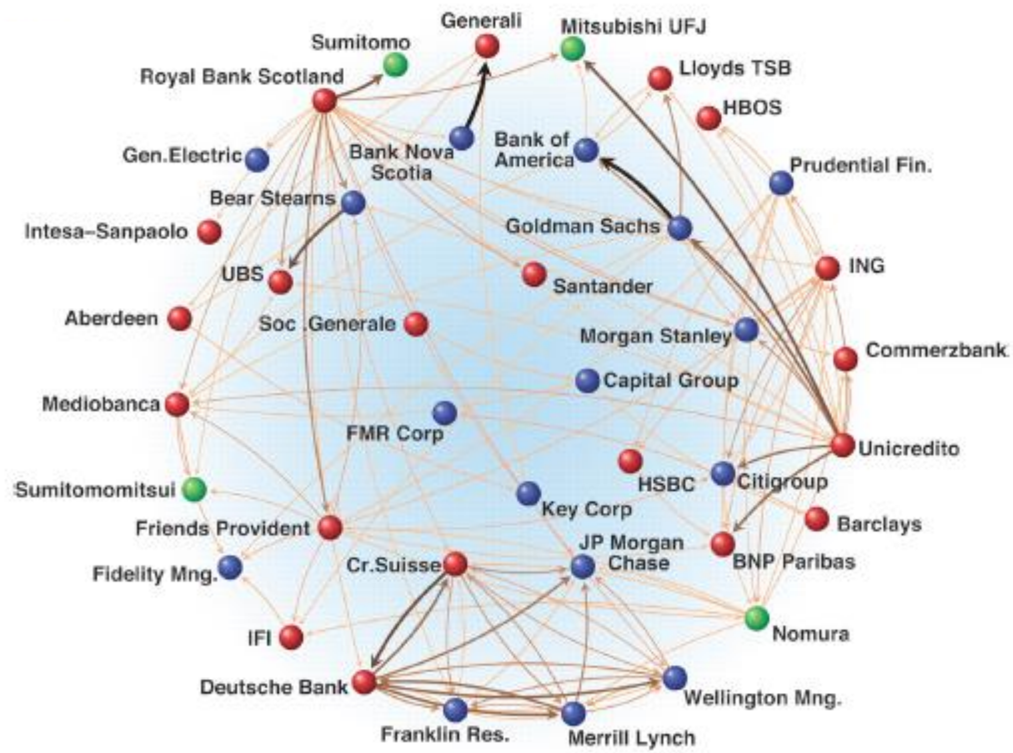
Facebook

Facebook "friend" links

- Complex systems scientists are very interested in studying large social networks, such as Facebook, to understand their *structure*, how such networks form, how they *change over time*, and how *information* is transmitted in such networks, among many other questions

Financial Institution Network

- Economies are another type of complex system in which networks of interactions are fundamental
- Here we see a sample of the international financial network



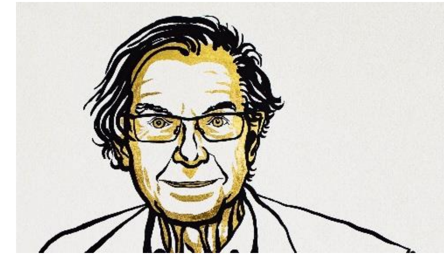
Financial Institution Network (2)

- Nodes represent financial institutions and links represent relations among them – for example, if a bank owns shares of another bank

- It turns out that the amount of connectivity in such a network, as well as the kinds of links present, can have a big effect on *how stable the network is to changes*, such as a bank going out of business

- The *interdisciplinary* field of network science, which has arisen from the complex systems research community, studies these kinds of phenomena in networks from many different disciplines





“What I try to do … is to trace the chain of relationships running from elementary particles, fundamental building blocks of matter everywhere in the universe, such as quarks, all the way to complex entities, and in particular complex adaptive systems like jaguars”.
(*Murray Gell-Mann*, Nobel Prize in Physics in 1969)

“I think the next century will be the century of complexity.”
(*Stephen Hawking,* 2000)

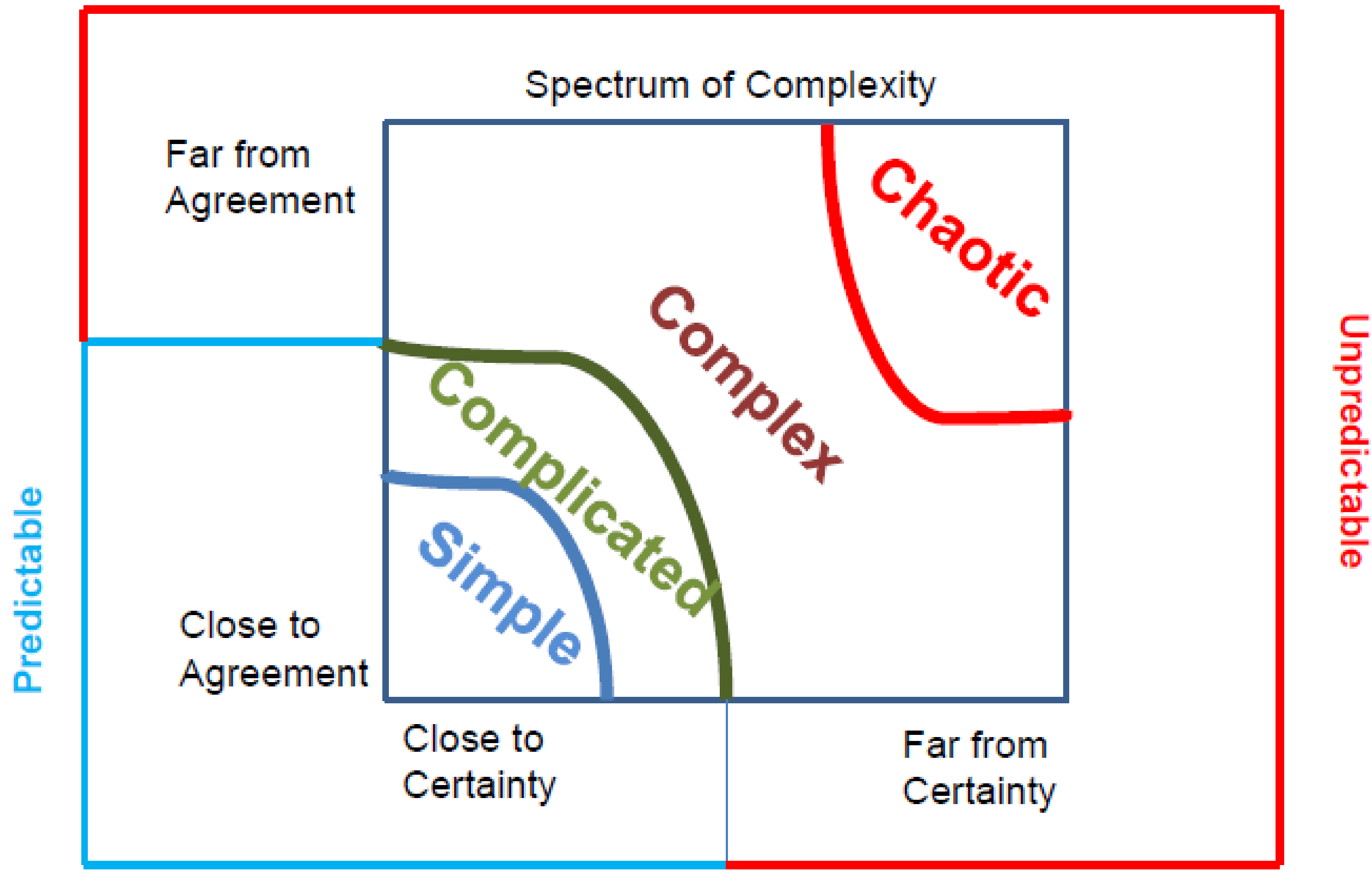
“We have a closed circle of consistency here: the laws of physics produce complex systems, and these complex systems lead to consciousness, which then produces mathematics, which can then encode in a succinct and inspiring way the very underlying laws of physics that gave rise to it.”
(*Roger Penrose*, Nobel Prize in Physics in 2020)

System Complexity

"Science has explored the microcosms and the macrocosms: we have a good sense of the lay of the land. The great unexplored frontier is complexity"

(Heinz R. Pagels, The Dreams of Reason, 1988)

Types of Systems



Complex Adaptive Systems

1. Non-linearity
This construct means that small actions can stimulate large reactions (otherwise known as the butterfly effect) in which highly improbable, unpredictable and unexpected events have huge impacts.

2. Emergence
The appearance of patterns occurs due to the collective behavior What emerges cannot be planned or intended. The whole of the interactions becomes greater than the sum of the separate parts.

3. Dynamical systems change
Interactions within, between and among subsystems and parts are volatile, turbulent, and cascade rapidly and unpredictably.

Complex Adaptive Systems

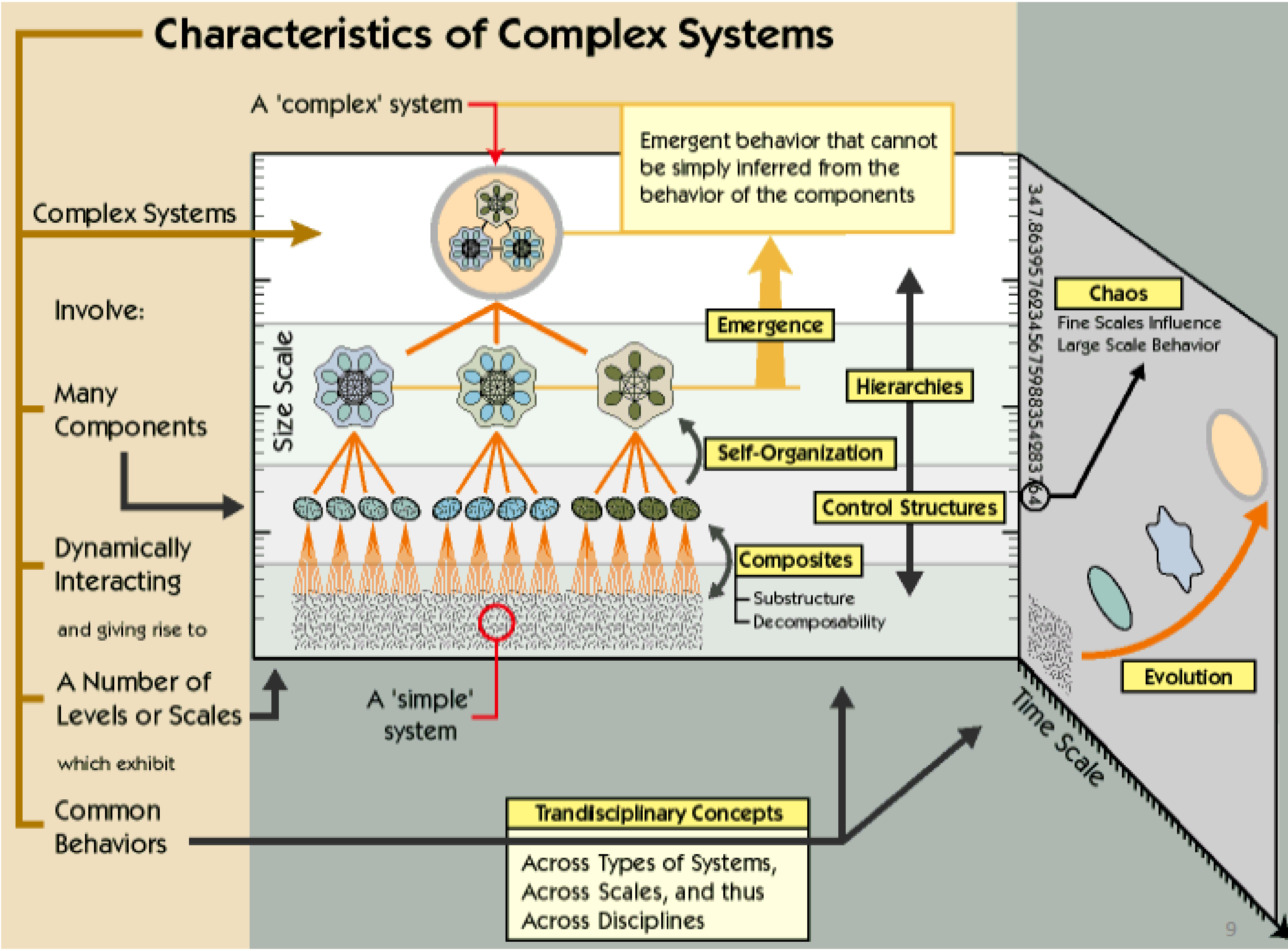
4. Adaptation
Interacting elements respond and adapt to each other so that what emerges and evolves is a function of ongoing adaptation among both interacting elements and the elements and their environment.

5. Uncertainty
Processes and outcomes are unpredictable, uncontrollable and unknowable in advance. There is no clear idea what might happen or how likely possible outcomes are.

6. Co-evolutionary
As interacting and adaptive agents self organize, ongoing connections emerge that become co-evolutionary as the agents evolve together (co-evolve) within and as part of the whole system over time.

Applications

- Complexity Theory appears in many fields
  - The more traditional ones: physics, biology, computer science
- Other examples include (besides Telecom ☺)
  - Transportation Systems
  - (Joseph Sussman, Professor Civil and Environmental Engineering, MIT)
    - Transport systems are complex networks, internally interconnected at different scales
    - The system is stochastic by nature and policy-makers introduce strategies that affect the overall behavior of the system
  - Dynamic Markets and Firms
  - (Chris Meyer, E&Y Partner and Director of the Center for Business Innovation)
    - The market is ever changing, defined by firm interaction
    - Inside the firm: make boundaries permeable, allow the bottom-up flow of ideas, give up of the idea of equilibrium


Characteristics of Complex Systems
A 'complex' system
Emergent behavior that cannot be simply inferred from the behavior of the components
Complex Systems
Involve:
Many Components
Dynamically Interacting
and giving rise to
A Number of Levels or Scales
which exhibit
Common Behaviors
Size Scale
Emergence
Hierarchies
Self-Organization
Control Structures
Composites
Substructure
Decomposability
Chaos
Fine Scales Influence Large Scale Behavior
Evolution
Time Scale
A 'simple' system
Trandisciplinary Concepts
Across Types of Systems, Across Scales, and thus Across Disciplines
9

Properties Common to Complex Systems

- *Simple components* or agents (simple relative to whole system)
- *Nonlinear interactions* among components
- *No central control*
- *Emergent* behaviours
  - Hierarchical organization
  - Information processing
  - Dynamics
  - Evolution and learning

CONNECT Networks of the Future

Measures of Complexity

- Shannon information
- Algorithmic complexity
- Minimum description length
- Fractal dimension
- Logical depth
- Thermodynamic depth
- Effective complexity
- Degree of hierarchy
- Etc...

Seth Lloyd,
"Measures of Complexity: A Nonexhaustive List",
***IEEE Control Systems Magazine*,**
Aug. 2001

Ackowledgement

- Melanie Mitchell, Santa Fe Institute