Tronc commun scientifique 5IF – TCS2

What is a complex system?

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INSA – INRIA – LIRIS – BEAGLE – IXXI

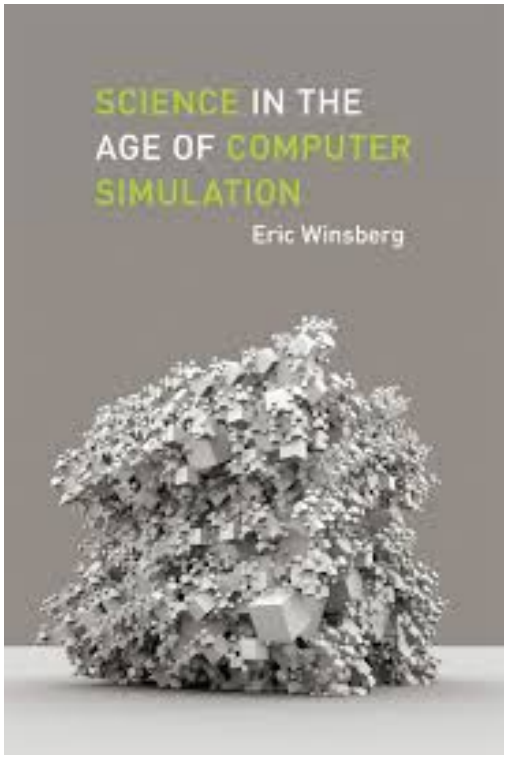
Préambule

"I think the next century will be the century of complexity"

Stephen Hawking,
January 2000

→ *On October 5, 2021, the Nobel Prize in physics was awarded to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi for their work on complex systems...*

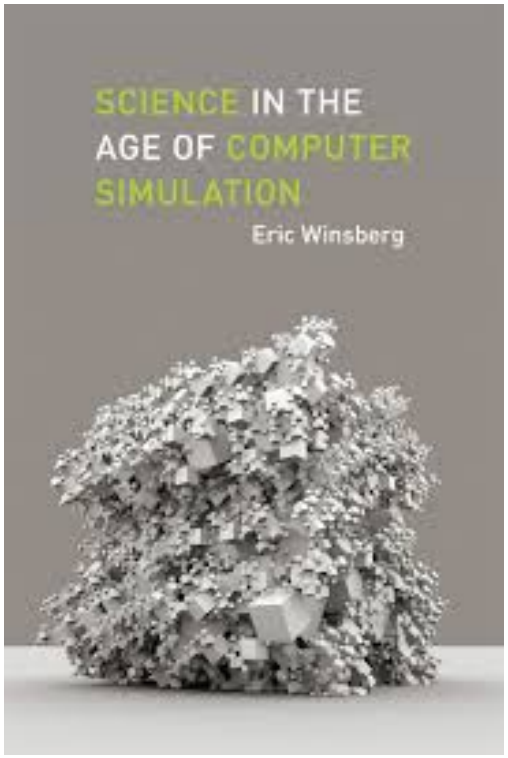
The age of computer simulations



"Over the last fifty years, however, there has been a revolutionary development affecting almost all of the sciences […]. *The development I am speaking of is the astonishing growth, in almost all of the sciences, of the use of the digital computer to study phenomena of great complexity – the rise of computer simulations. More and more scientific "experiments" are, to use the vernacular of the day, being carried out "in silico"* […] *An avalanche aided in no small part by our increasing ability to use the digital computer to build tractable models of greater and greater complexity."*

(Winsberg 2010)

The age of computer simulations



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What is a complex system?

- Definitions are important because:
  - The term is widely used in science: "*I think the next century will be the century of complexity*" [S. Hawking, 2001]
  - The relationship of complex systems science with other sciences is often difficult (need to identify the differences)
  - Politics need maps to define global scientific policy
  - Complex systems are ubiquitous; Is there a global definition? A global question?
    - If no, there is no such thing as a complex systems science!
    - If yes, what is it?
- But, in fact, there is no universally accepted definition!
  - And lots of problems and conflicts!

Definition

- The latin root: “complexus”
  - Entangled, entwined, embracing …

The New Oxford American Dictionary

SECOND EDITION

com•plex

adjective |käm'pleks; kəm'pleks; 'käm,pleks|

1 consisting of many different and connected parts : *a complex network of water channels.*
- not easy to analyze or understand; complicated or intricate : *a complex personality* | *the situation is more complex than it appears.*

2 Mathematics denoting or involving numbers or quantities containing both a real and an imaginary part.

3 Chemistry denoting an ion or molecule in which one or more groups are linked to a metal atom by coordinate bonds.

[…]

ORIGIN mid 17th cent. (in the sense [group of related elements]): from Latin ***complexus***, past participle (used as a noun) of ***complectere 'embrace, comprise,'*** later associated with ***complexus 'plaited'***; the adjective is partly via French ***complexe***.

Definition

- Most definitions are based on these two basic properties

"A set of items interacting via simple local rules in which emergent properties cannot be directly deduced from the local rules"

[M. Morvan, founder of the IXXI]

"Complex systems are systems with multiple interacting components whose behavior cannot be simply inferred from the behavior of the components"

[NECSI]

"A system is complex if it exhibits nontrivial emergent and self-organizing behavior"

[M. Mitchell, SFI, 2009]

But

- All these definitions contain terms like:
  - “directly deduced”, “simply inferred”, “difficult to”, “essential property”, “emergent behavior”, “non-trivial behavior”, …
- All these terms either
  - Depend on the cognitive abilities of the observer and on his scientific knowledge
  - Are not really defined (or defined as antonyms of “complex”)
- These definitions are subjective, self-referent and, actually, dangerous!

“A complex system is a system in which large networks of components with no central control and simple rules of operation give rise to a complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.”

[M.Mitchell, 2009]

So, what is a complex system?

(my definition)

- General agreement on:
  - The structure of the system (“many elements”)
  - Some subjective judgment (not always clearly accepted)
  - Something “emerges” (but the word may be rejected)
  - Something is dynamic and “self-organized”…

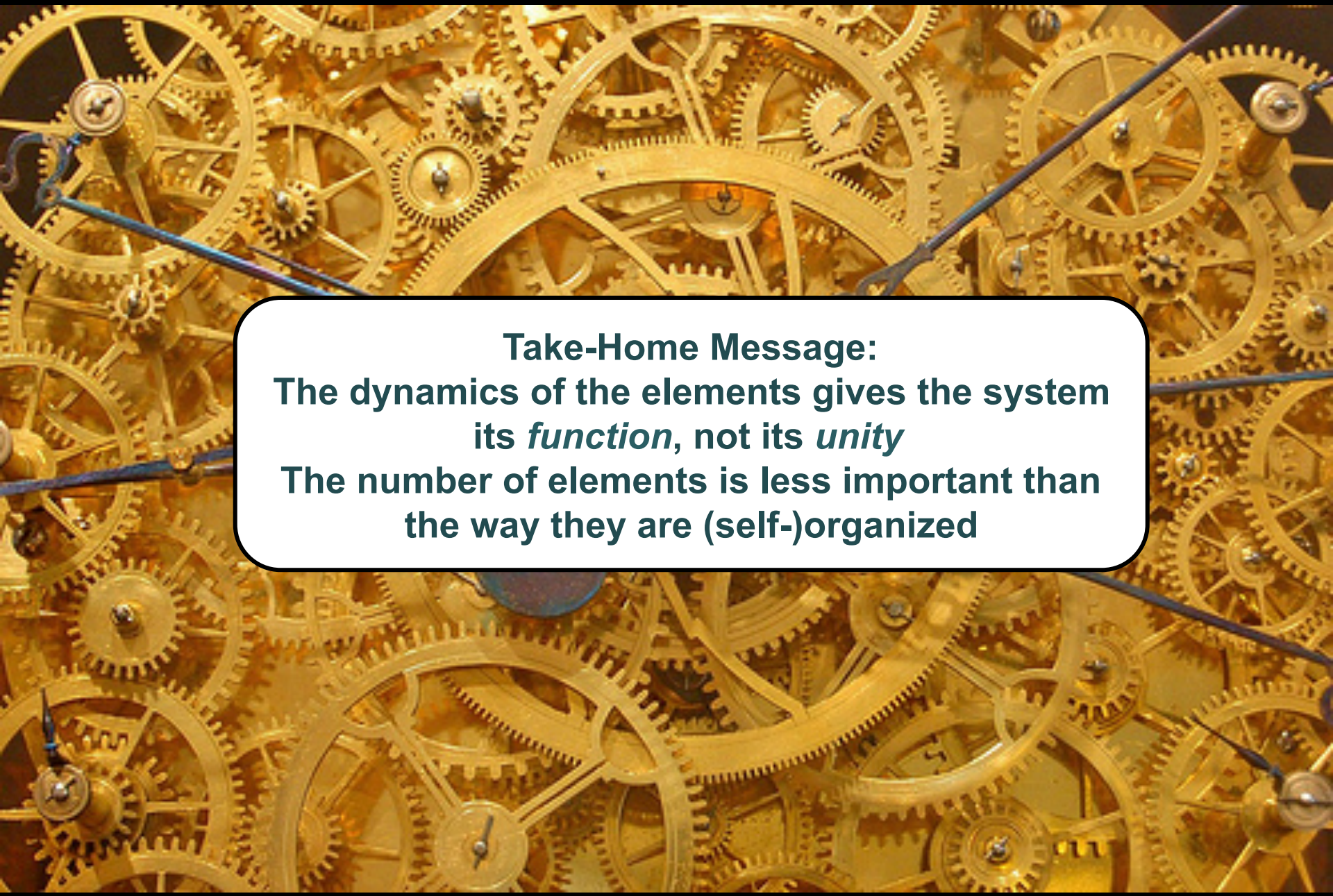
“*A system is a complex system if it is made of multiple interacting elements and if the dynamics of the interactions govern the behavior of the system, giving to it an appearance of unity from the point of view of an external observer*.”

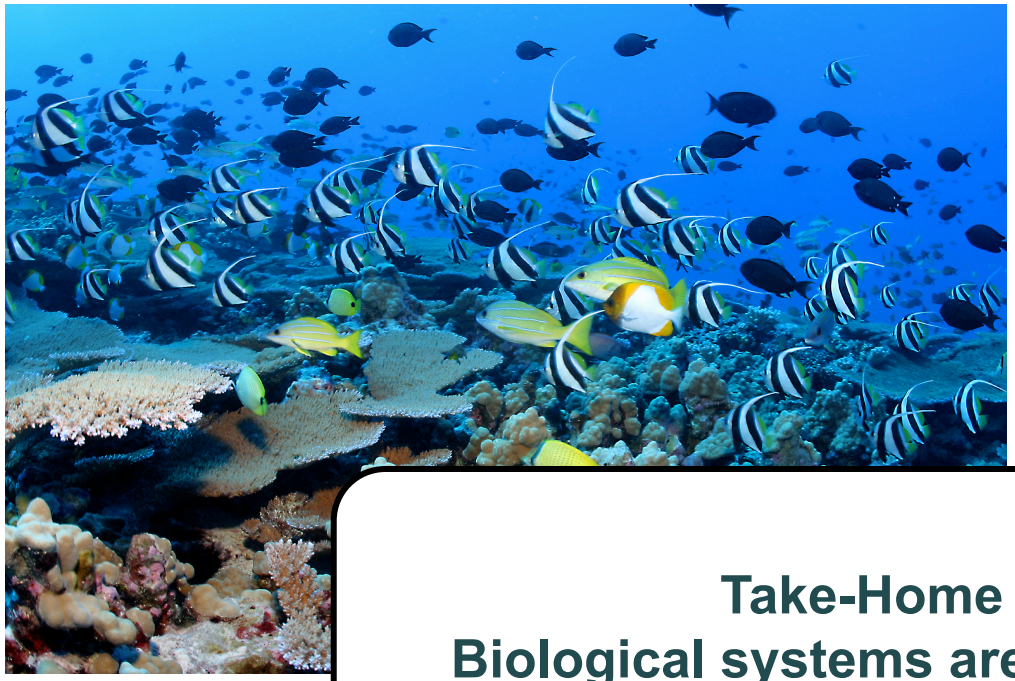
Why this definition?

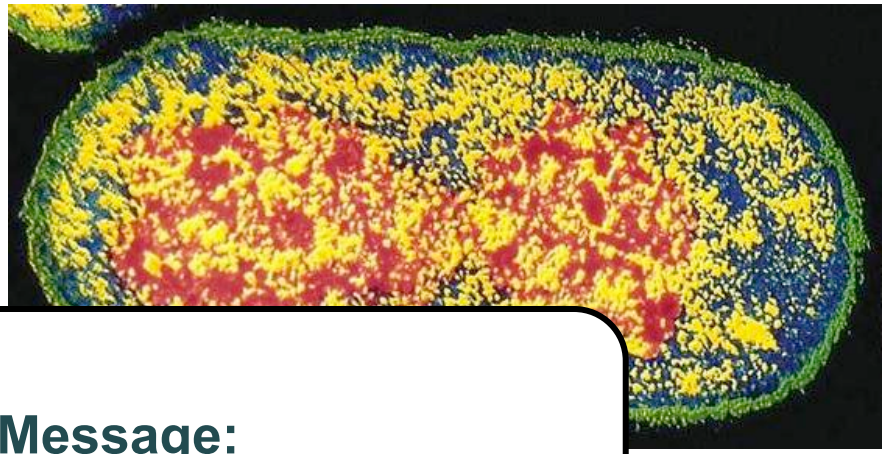
"*A system is a complex system if it is made of multiple interacting elements and if the dynamics of the interactions govern the behavior of the system, giving to it an appearance of unity from the point of view of an external observer*."

- Defines the structure of the system
  - But the structure is not enough: we also need dynamic interactions
- Subjectivity is clearly introduced
  - But it does not depend on our scientific knowledge
  - The scientist is external to the definition
- Raises ontological/epistemological questions

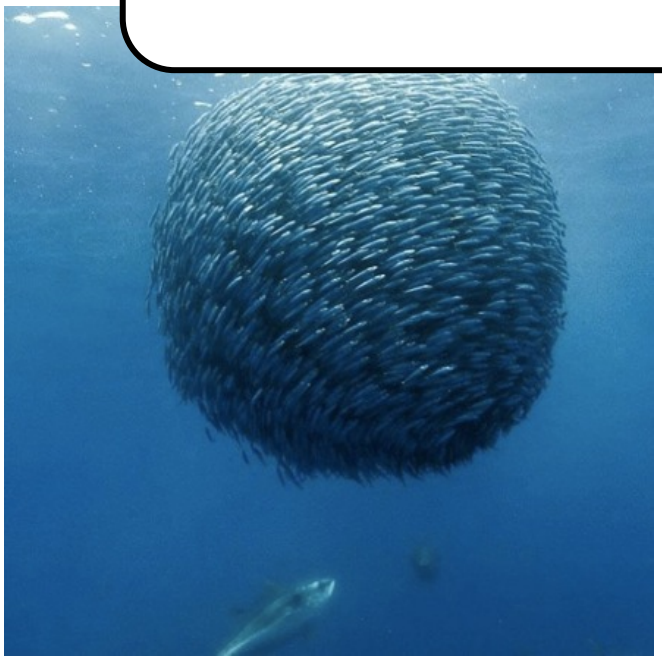
→ examples


Take-Home Message:
The dynamics of the elements gives the system its *function*, not its *unity*
The number of elements is less important than the way they are (self-)organized



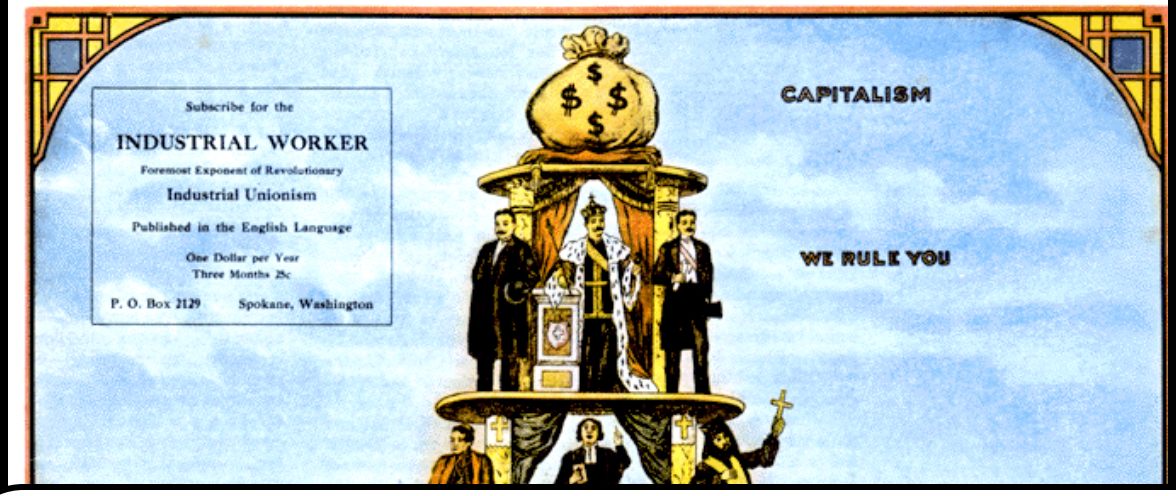


Take-Home Message:
Biological systems are always complex (?)



Take-Home Message:
The system is complex – or not – depending on the frontiers we (decide to) give it

Take-Home Message:
Social systems are always complex (?)



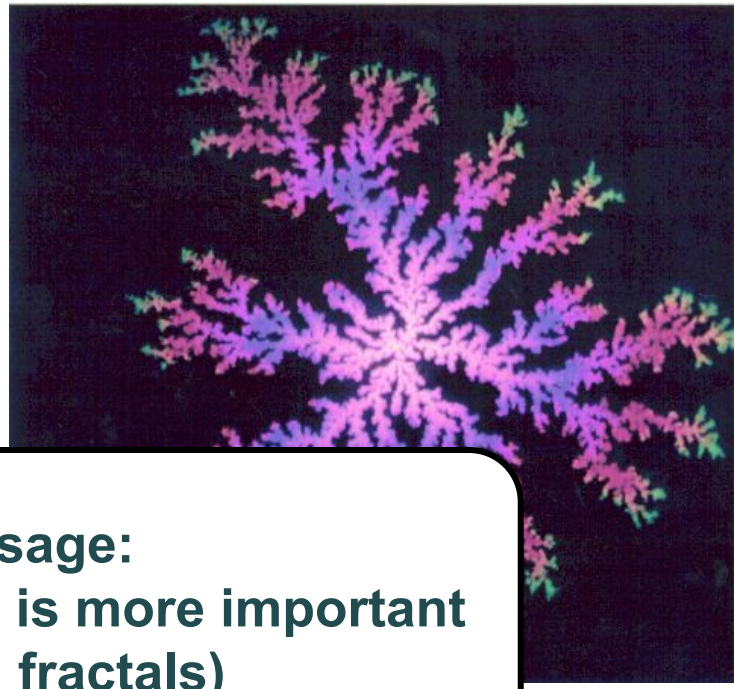
Take-Home Message:
Complex systems may (do?) not exit elsewhere than in our perception… and our perception depends on non-scientific elements (history, political opinion…)

Take-Home Message:
Complex systems can be "simple"
(Warren Weaver, 1968: disorganized complexity vs. organized complexity)

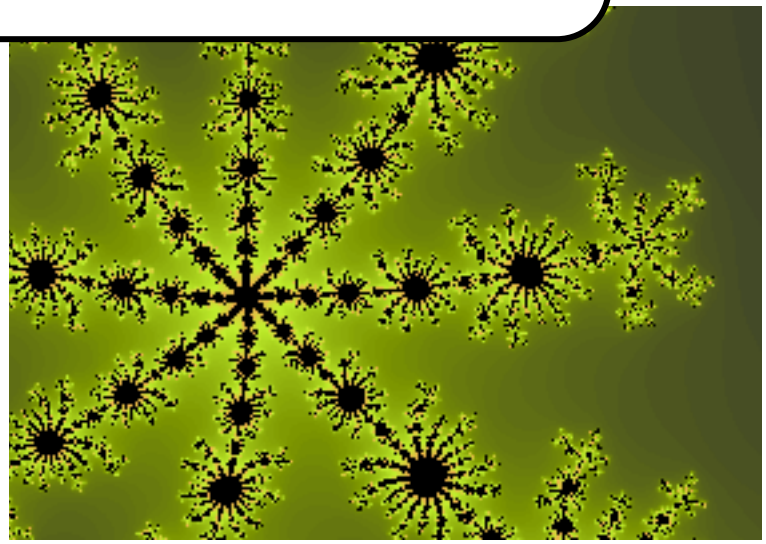
Take-Home Message:
A non-complex system can contain a complex system

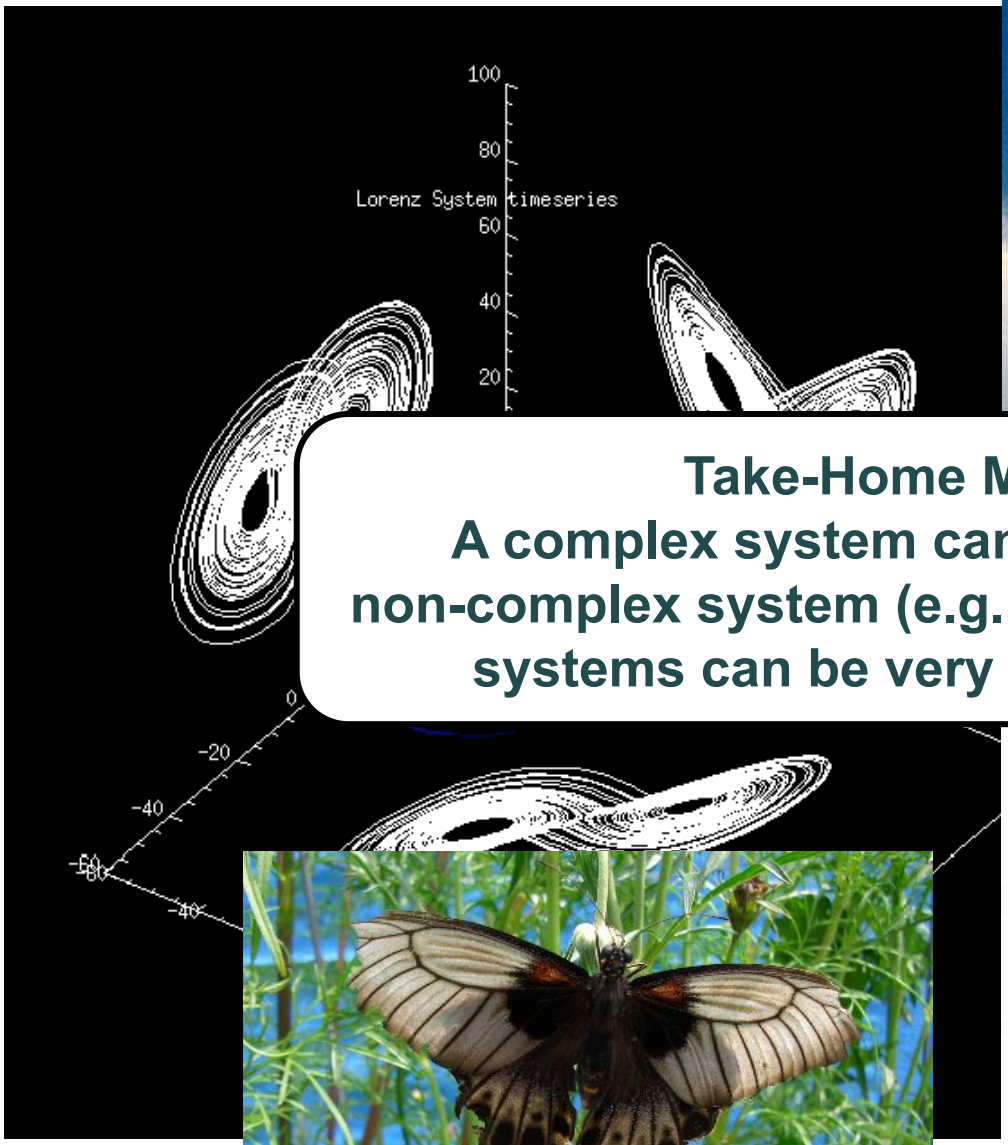
Take-Home Message:
A system can be complex – or not – depending on some of its parameters (here density)


Take-Home Message:
Engineers try to avoid complexity…
…with a mitigated success: Any (real)
system is complex at some point/scale

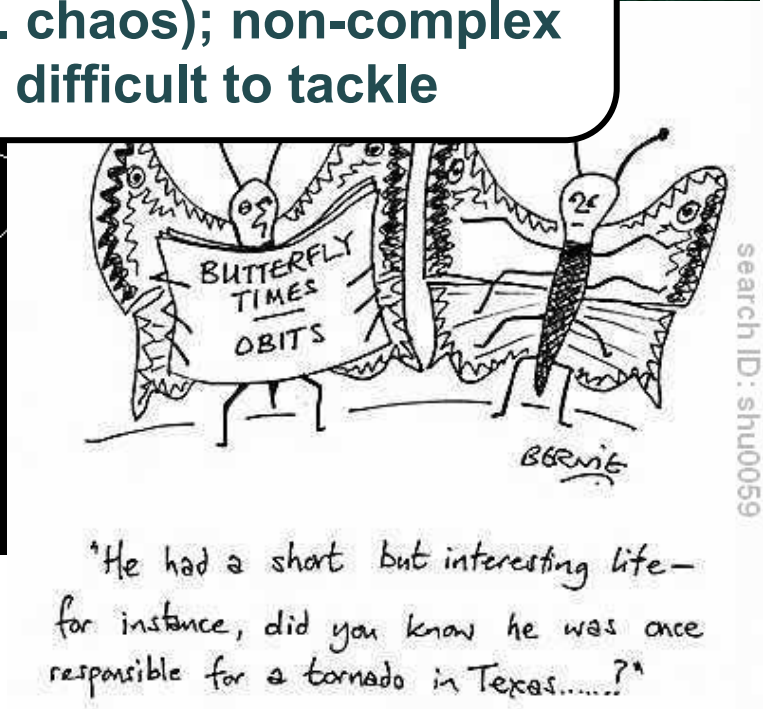


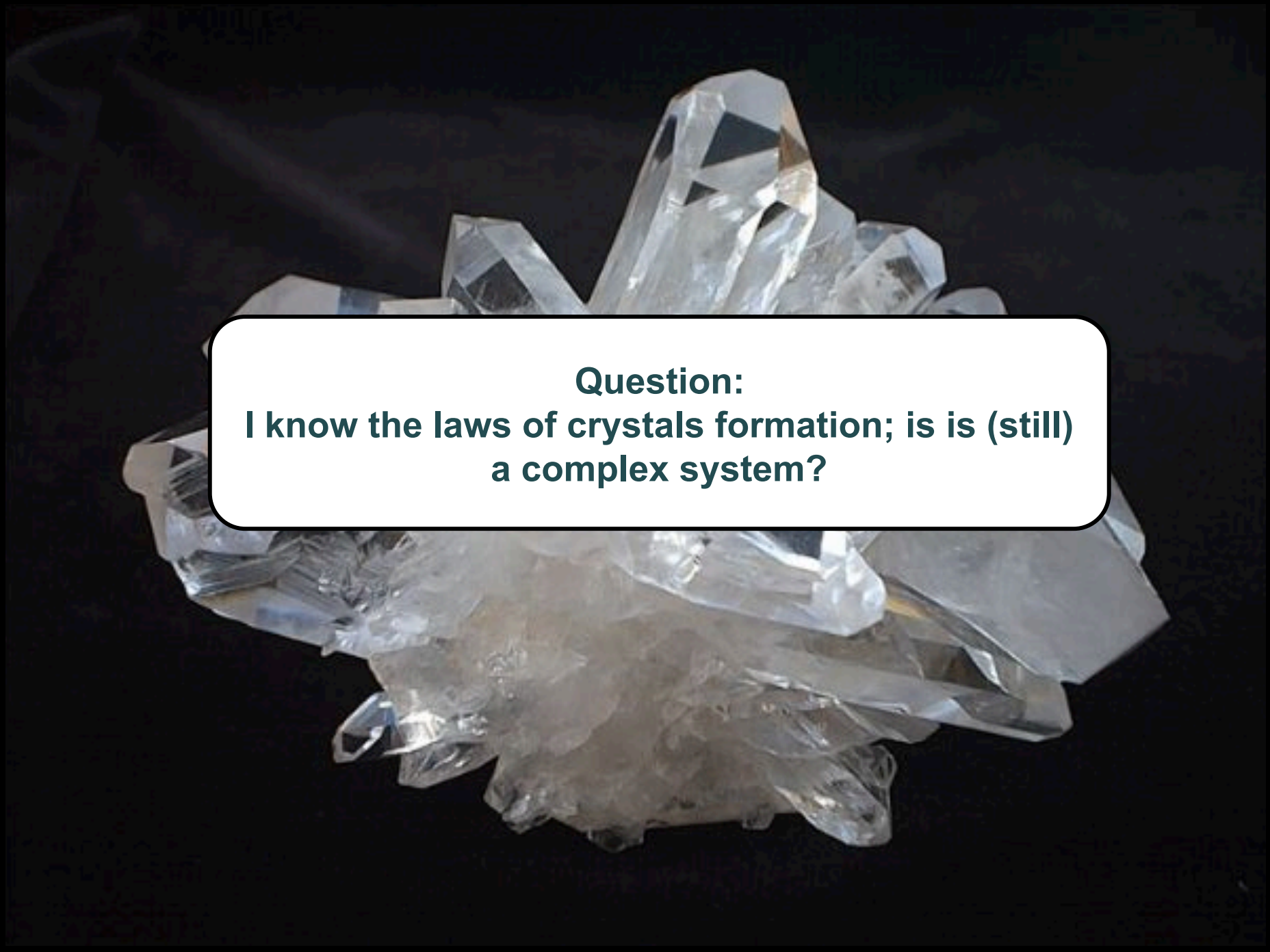
Take-Home Message:
The way a shape is produced is more important than the shape (e.g. fractals)





Take-Home Message:
A complex system can be modeled by a non-complex system (e.g. chaos); non-complex systems can be very difficult to tackle




Question:
I know the laws of crystals formation; is is (still)
a complex system?

Complex ≠ unkown

- Remember: Complex systems are ***NOT*** unexplained systems!
  - There are (fortunately) complex systems which behavior is explained
    - Any idea ?
  - There are (fortunately) open questions on systems that are NOT complex
    - Any idea ?
- Explained complex systems can be very useful to help us designing methodological principles…
  - Proof of concepts
  - Success stories

Complex ≠ complicated

- Complicated systems are “composed of a large number of elements”
- Complicated systems have “an appearance of unity from the point of view of an external observer”
- So what is the difference?
  - The unity does not come from the dynamics of the interactions
  - Complicated systems can be understood by division
- BUT: objects are not perfects …
  - Complicated objects are often *also* complex
  - Most of the work of engineers is to maintain complicated objects out of the complex regime!
- The distinction is not so clear!

Measuring complexity?

- (Quite) all the definitions of complexity are qualitative…
  - Can we give a quantitative definition of complexity?

  "*A complex system becomes more complex as the number of distinctions (distinct components, states, or aspects) and the number of relations or connections increases.*"

  [F. Heylighen, 2007]
- But these quantities are not objectively defined
  - They depend on the way you look at the system
  - The measure depends on the measurer; it is often chosen to match our subjective judgment (see next part: the C-value paradox)
- Would you say that a tiger is more alive than a bacteria?
  - Do we really need a scale of complexity?

Measuring complexity?

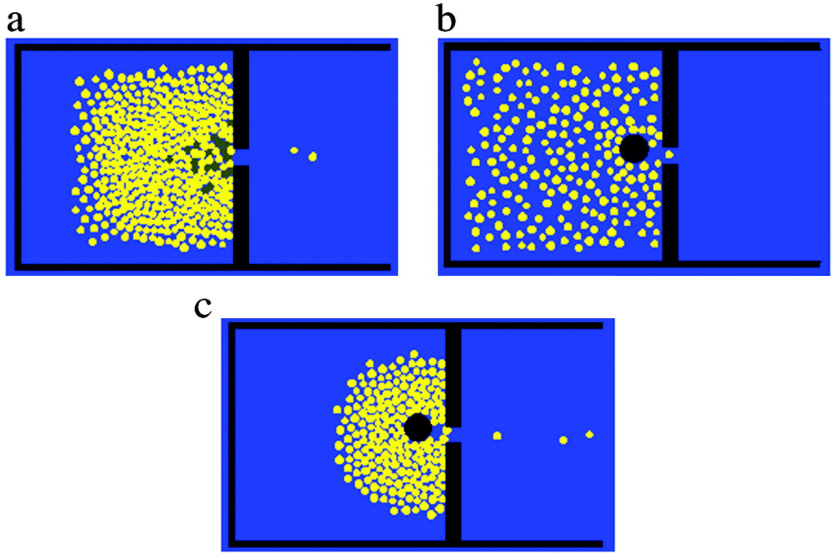
- Complexity can be measured on specific systems
  - Algorithmic complexity (time to execute a program)
  - Kolmogorov-Chaïtin complexity (size of the smallest program)
  - Bennett's logical depth (time to execute the smallest program)
- Not clear that they measure what we call complexity!
  - You can have classes without order… (e.g., biology)
- Actually, we are only able to measure complexity of idealized objects
  - Is the complexity of the model of the object equal to the complexity of the object?
  - "Le kantisme a les mains pures mais il n'a pas de main" (C. Péguy)
- Not sure complexity is a quantitative property!
  - Is it interesting to search for a measure? Probably yes!
  - We will learn a lot and get a deeper understanding of our field!

Why studying complex systems?

- "Because it's there" (George Mallory)
  - Science studies things that are there …

Why studying complex systems?

- "Because it's there" (George Mallory)
  - Science studies things that are there …
- Because they are prone to "natural interpretations"
  - Too complex for the human brain…
  - Avoiding such natural interpretation may help managing complex systems



Bonabeau E PNAS 2002;99:7280-7287

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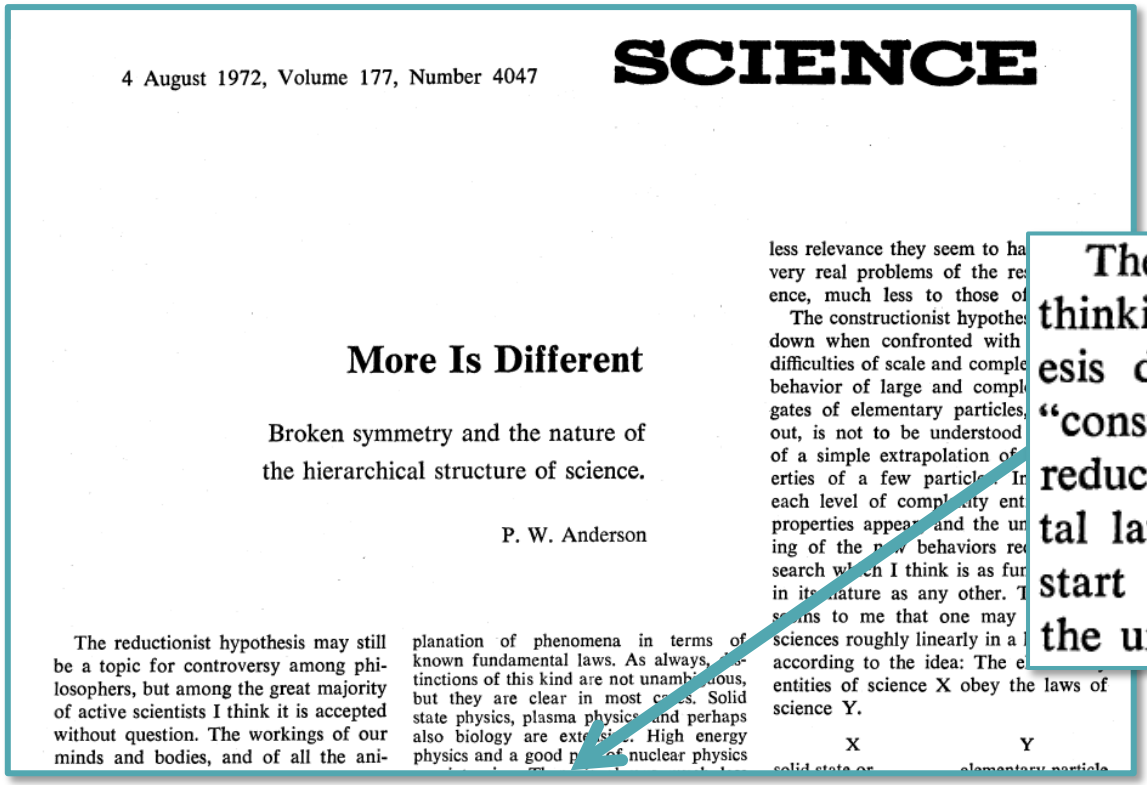
  - Science studies things that are there …
- Because they are prone to "natural interpretations"
  - Too complex for the human brain…
  - Avoiding such natural interpretation may help managing complex systems
- Because they have properties that we would like to understand/control/create …
  - Robustness (but fragility to some specific perturbations)
  - Resilience
  - Adaptability
  - Self-organization
  - Self-X properties …

Why studying complex systems now?

- Complex systems have always existed… why is it important to study them *now*?
  1. We are reaching the limits of reductionisms



4 August 1972, Volume 177, Number 4047 **SCIENCE**

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the ani-

planation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are exte… High energy physics and a good p… of nuclear physics

less relevance they seem to ha… very real problems of the re… ence, much less to those of…

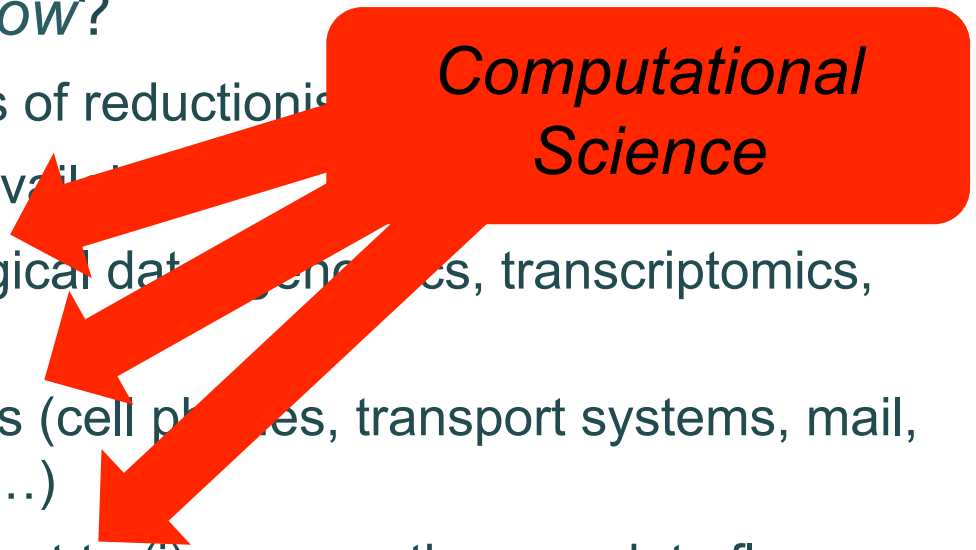
The constructionist hypothes… down when confronted with … difficulties of scale and comple… behavior of large and compl… gates of elementary particles, … out, is not to be understood … of a simple extrapolation of … erties of a few particle… In… each level of compl…ity ent… properties appear… and the un… ing of the n… behaviors re… search w…ch I think is as fun… in its …ature as any other. T… s…ms to me that one may … sciences roughly linearly in a … according to the idea: The e… entities of science X obey the laws of science Y.

X	Y
solid state or…	elementary particle…

> The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.

Why studying complex systems now?

- Complex systems have always existed… why is it important to study them *now*?
  1. We are reaching the limits of reductionis
  2. New data are becoming ava
     - High throughput biological dat es, transcriptomics, ecology…)
     - Large social databases (cell p es, transport systems, mail, social networks, WoS…)
  3. Computer power is sufficient to (i) manage the new data fluxes and (2) simulate large sets of elements (model emergent behavior)
  4. Theoretical models (statistical physics, computer science) start to get out of their original field to be applied to e.g. biological systems or social science



The science of complex systems

- We can (more or less) define a “complex system” but what is the “science of complex systems”
  - ~any system is a complex system at some levels of description
  - Does it implies that “science of complex systems = science”?
  - Hope you’ll agree that it is absurd! (at least)
- How can you define a science?
  - E.g., Biology, Chemistry and Physics are all working on DNA
  - A science is not defined by its objects but rather by its questions
- The science of complex systems is ***NOT*** the science of complex objects ***NOR*** the science of complex questions!
  - It is the science of questions that are specific to complex systems

Back to the definition

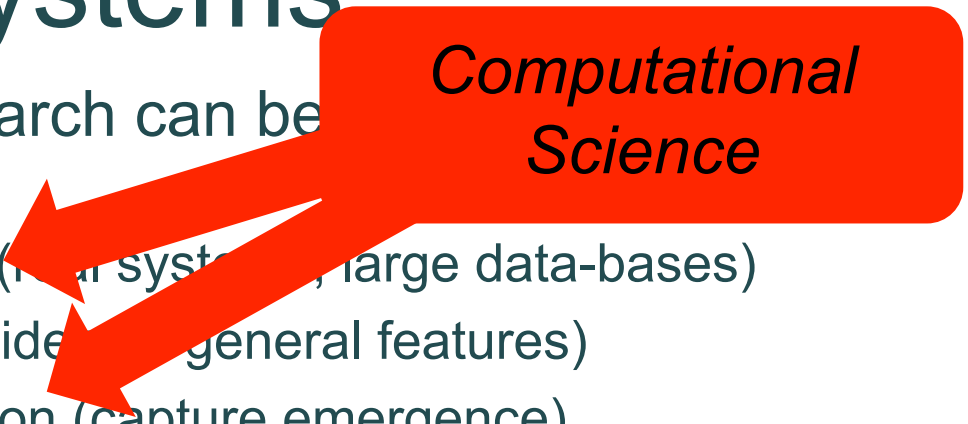
“A system is a complex system if it is made of a large number of interacting elements and if the dynamics of these interactions govern the behavior of the system, giving to it an appearance of unity from the point of view of an external observer.”

Back to the definition

"A system is a complex system if it is made of a ***large number of interacting elements*** and if the dynamics of these interactions govern the behavior of the system, giving to it ***an appearance of unity*** from the point of view of an external observer."

- So the question is:
  - Given the elements and their interactions, how can we quantify/ understand/reproduce the appearance of unity?
- From this general question, we can derive
  - More specific questions (field specific, intermediate)
  - Differences from other fields (possibly looking at the same object, e.g., molecular biology vs. systems biology)
  - The embryo of a methodology to study complex systems…

The science of complex systems



- Different kind of research can be
complex systems
  - Data-driven research (
large data-bases)
  - Theoretical research (ide
general features)
  - Modeling and simulation (capture emergence)
- Objectives:
  - Predict
  - Control
  - Design
- A science intrinsically interdisciplinary…
  - The real difficulty in CSS is interdisciplinarity…

Interdisciplinarity

- Interdisciplinarity is often promoted
  - But rarely realized (powerful and dangerous)
- Crossing disciplines boundaries is a difficult exercise that needs **time** and **tact**…
  - Be modest: All scientific disciplines have a long history
  - Be open-minded: All scientific disciplines have their own habits
  - Be honest: What do you want to show? (where do you want to publish? To whom to you want to explain your results?)
  - **Never suppose you can provoke a scientific revolution from the outside!**

"The burden of proof [in alife] is on us to explain our results to biologists in their own language and in their our journals"

[Miller, 1995]

Methodology

- Applied CSS: Three main questions can be derived from the central one:
  1. Description: What is the "unity" of the system? What are the elements? How can we describe both levels accurately?
  2. Understanding: What is the link between the dynamic of local interactions and the unity of the global system?
  3. Why do we perceive this system as a "unity"? What is "emergence"? (coping with the subjective part of the definition)
- Theoretical CSS: Can we identify universal features (laws) in complex systems
  1. Toy models: understand the laws
  2. Formal models: prove the laws
  3. Measures and tools to cope with a large amount of data

Research in complex systems (1): describe the system

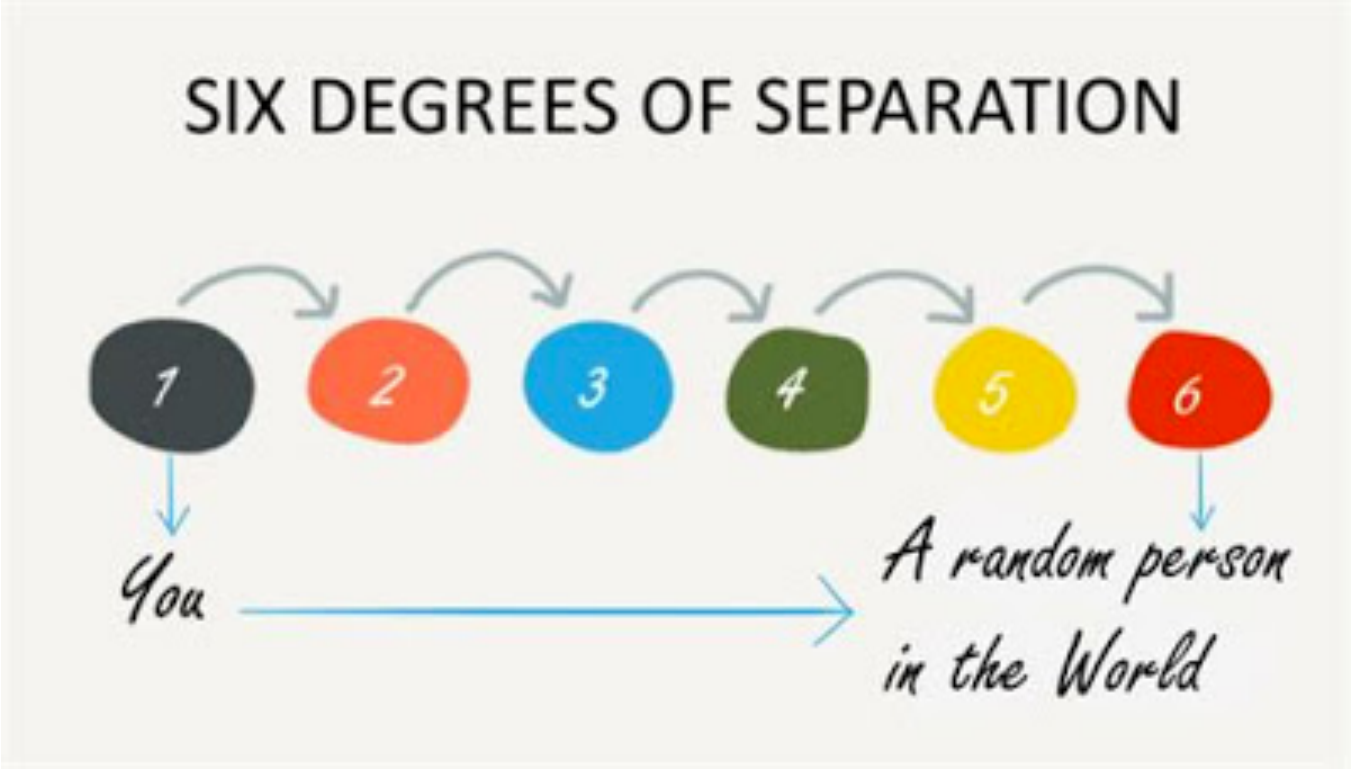
- Build an “exhausitive” description of the system
  - At the local level (what are the elements?)
  - At the global level (what is the unity?)
- Remember that you can miss important points! To draw a “complete” description, you MUST be very careful…
  - You must have a very good knowledge of the system…

    → Back to the problem of interdisciplinarity…
- Remember that a description is always
  - A subjective selection (of properties, scales, frontiers,…)
  - Dependent on the point of view (position, scale, time, science…)

    → Back to the problem of interdisciplinarity!

... partant d'un regard sceptique sur le monde...

- Six degrés de séparation...
- Théorie développée en 1929 par Frigyes Karinthy (écrivain, poète, dramaturge hongrois) dans « chaines »



https://intheloop888.blogspot.com/

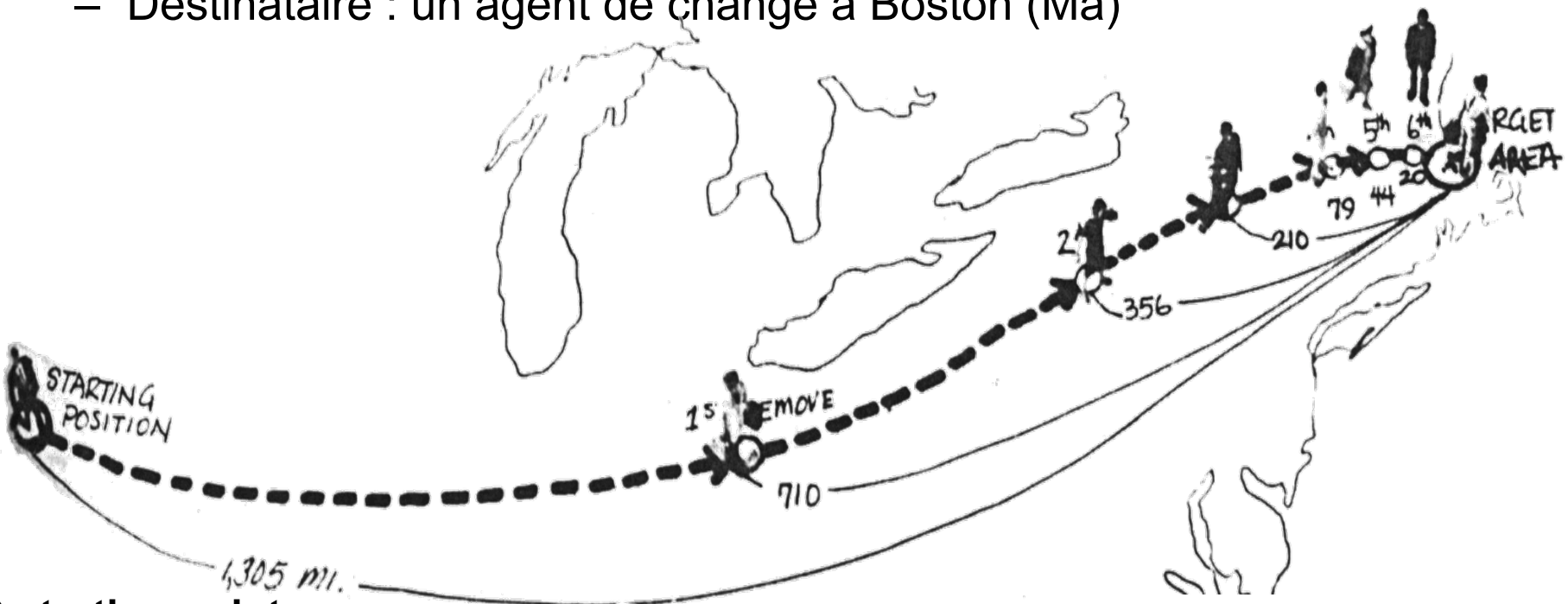
Research in complex systems (1): describe the system

- Six degrés de séparation ...
- Comment tester expérimentalement la théorie ?

Stanley Milgram, 1967

Research in complex systems (1): describe the system

- Comment tester expérimentalement la théorie ?
  - 160 lettres confiées à des habitants d'Omaha (Nebraska)
  - Règles de propagation strictes
  - Destinataire : un agent de change à Boston (Ma)



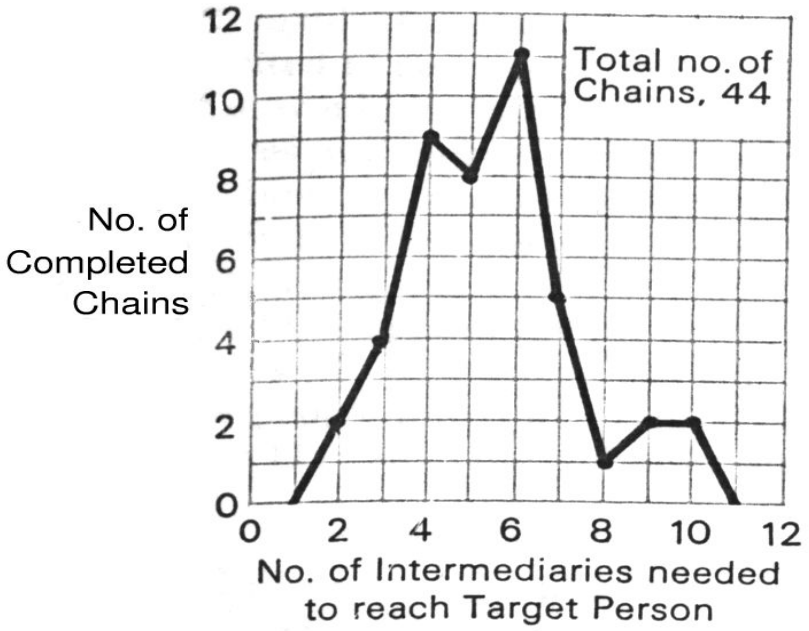
[Stanley Milgram, 1967]

Research in complex systems (1): describe the system

- Comment tester expérimentalement la théorie ?
  - 160 lettres confiées à des habitants d'Omaha (Nebraska)
  - Règles de propagation strictes
  - Destinataire : un agent de change à Boston (Ma)
- Résultats :
  - 44/160 lettres arrivées à destination
  - Nombre de sauts moyen : 5.43
  - Nombre de sauts médian : 5

→ « Six degrés de séparation »

→ Réseau « petit monde » : $l \sim \log N$

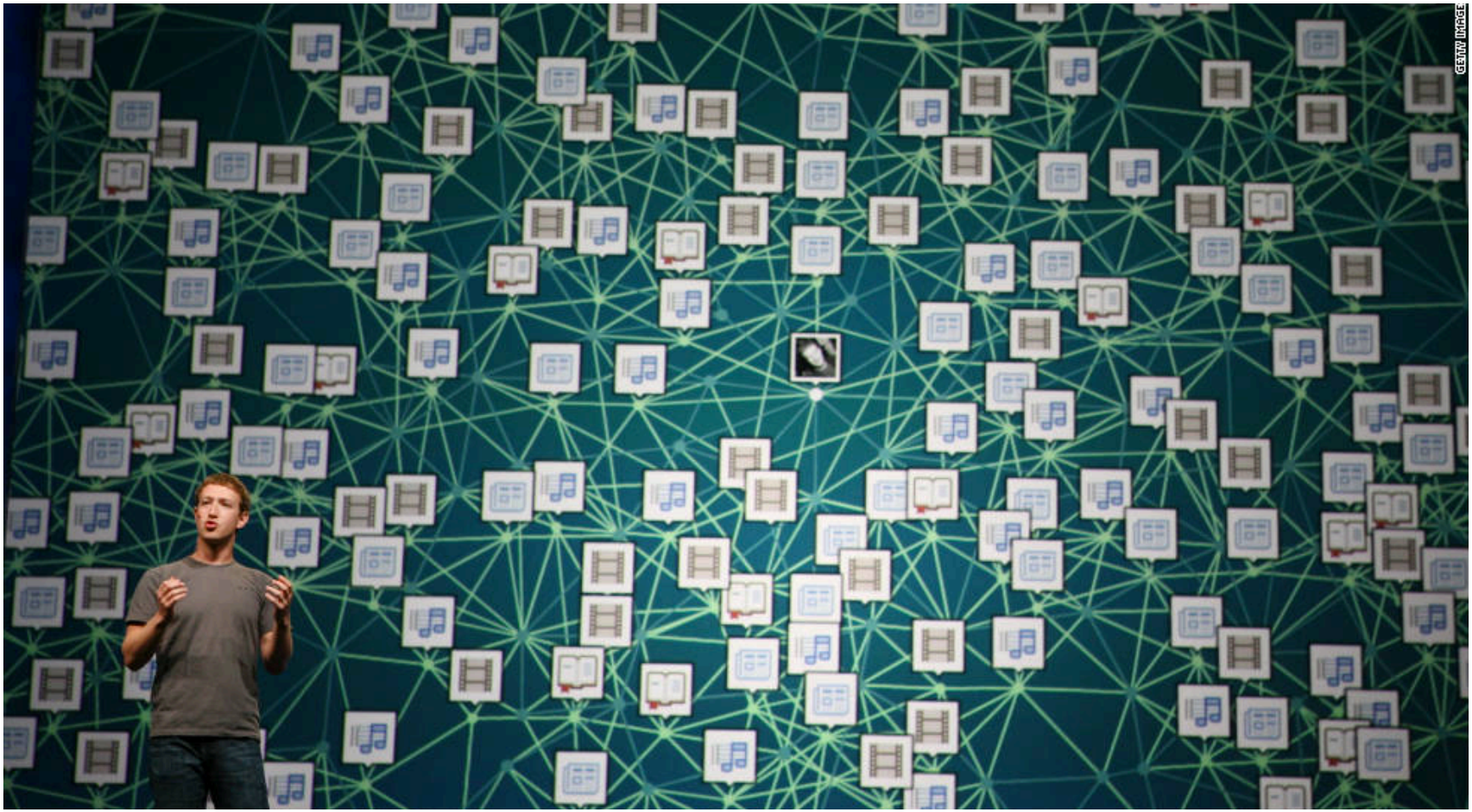


In the Nebraska Study the chains varied from two to 10 intermediate acquaintances with the median at five.

[Stanley Milgram, 1967]

Research in complex systems (1): describe the system

“On Facebook, it's now 4.74 degrees of separation” (CNN 2011)



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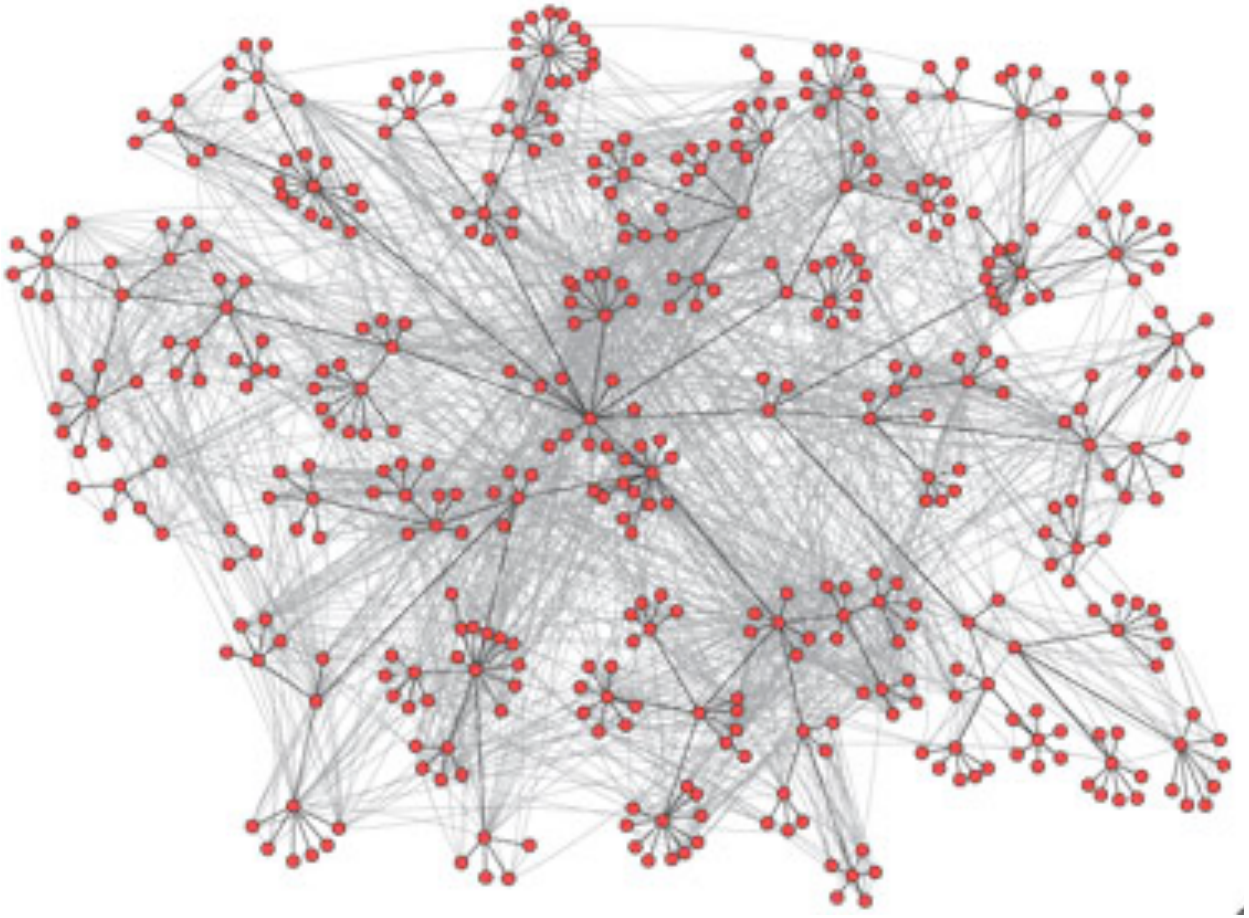
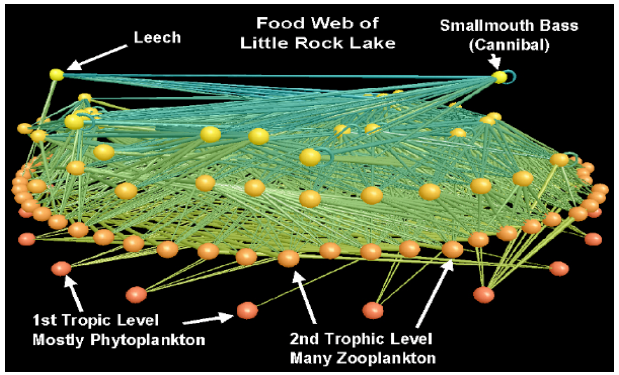
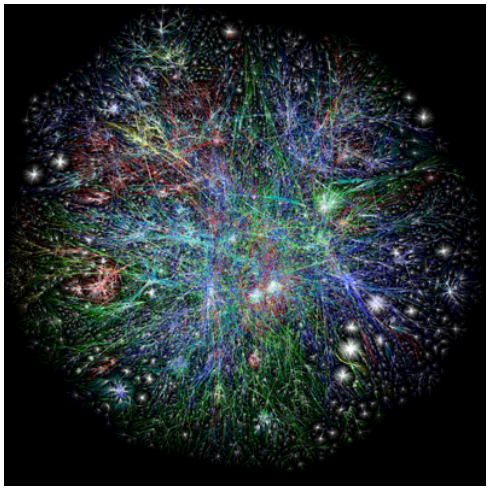


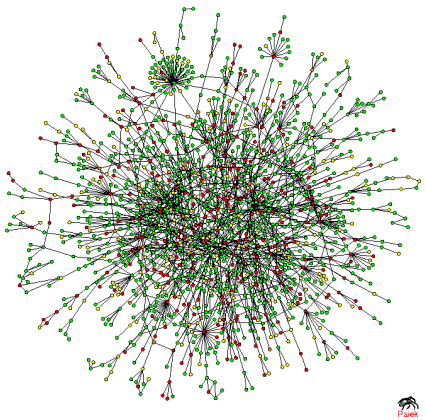
La numérisation des échanges permet un nouveau regard sur les systèmes sociaux
Exemple : échanges de mails entre 436 employés de Hewlett-Packard Research Lab.

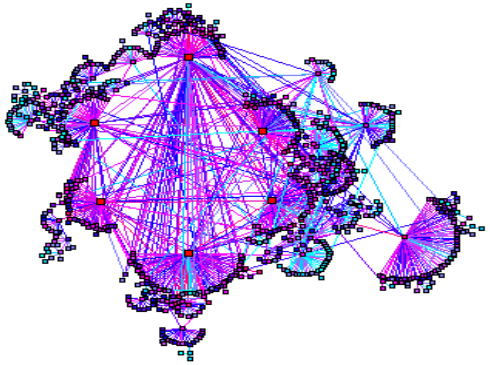
Research in complex systems (1): describe the system

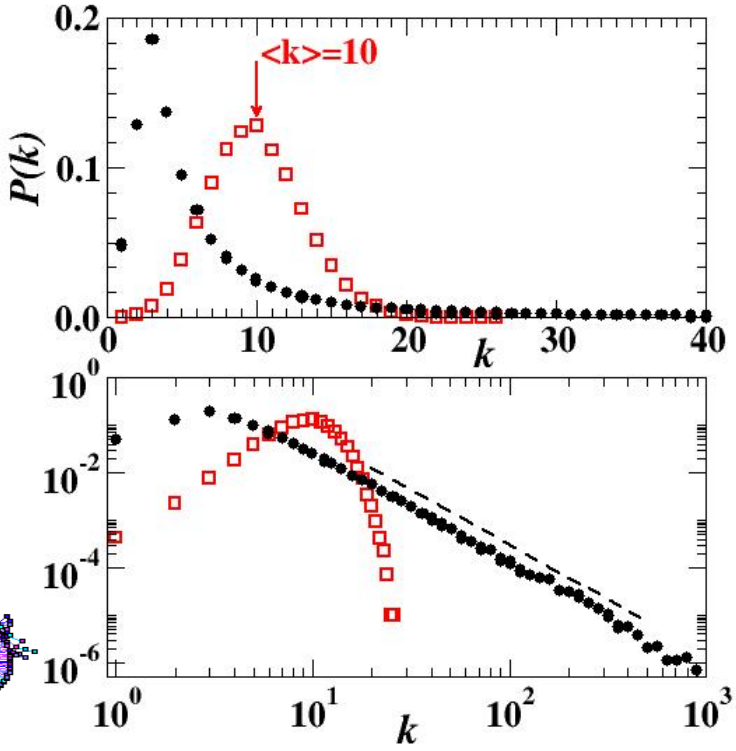
- Lots of real networks are **scale-free** and **small world** …









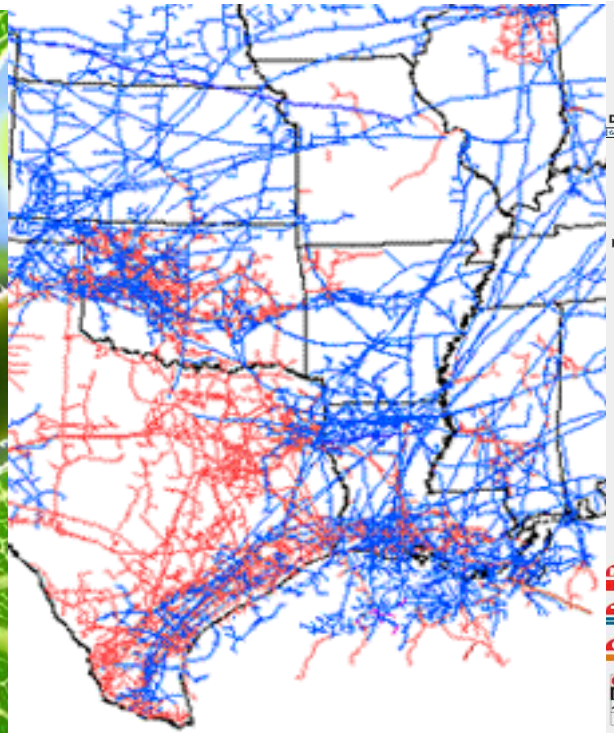


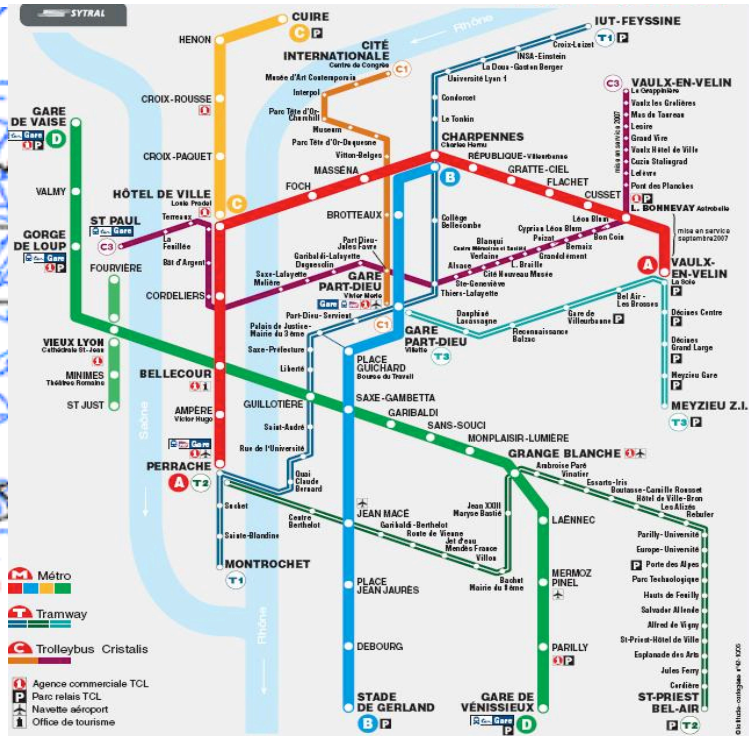
Research in complex systems (1): describe the system

- Once you have collected the data, you can browse the description and seek for hidden structures
  - E.g., in the context of social networks
    - Community detection
    - Invariant characteristics
    - Scale laws, hubs,…
- Then you can search for an origin of these structures
  - Switch to question 2 …
  - Note that the origin of the structures may not be “complex” !

Research in complex systems (2): Understanding

- Example of complex (social) networks (continued)
  - Networks share (or not) some common principles (e.g. branching)
  - Can these principles explain the global structure?



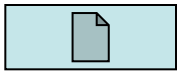


Research in complex systems (2): Understanding

- Probably the main goal!
- How can we do?
  - Complex systems are often difficult to tackle (either experimentally or by though experiments)
  - Dynamic non-linear interactions may contradict our intuition
  - We need tools to explore the behavior of the system and to explain the emergent comportment
- We need “models” to help us to understand the behavior of the system…
  - How can models help us to understand something?
  - How to use models in science?

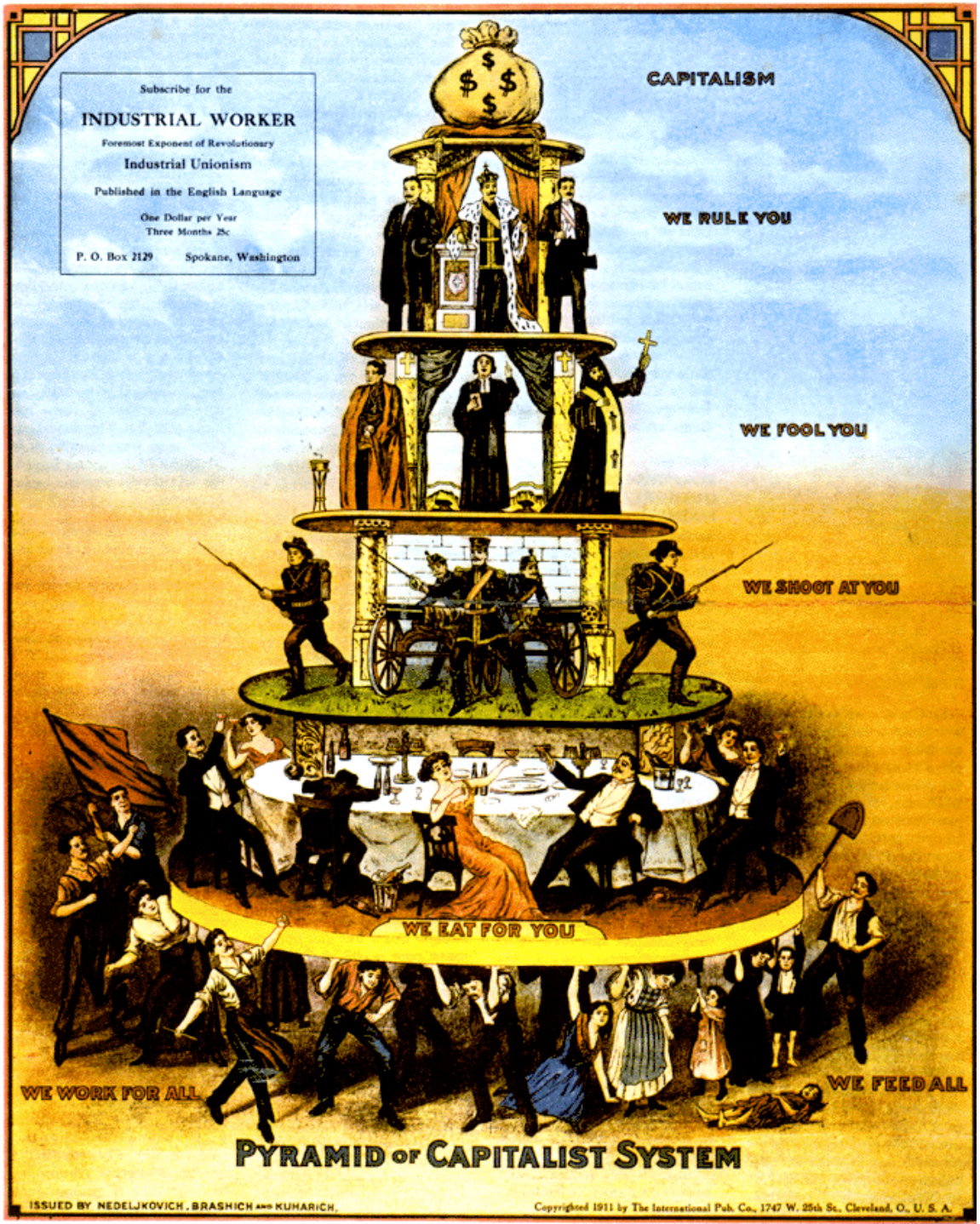
Research in complex systems (3) : cognitive science?

- "[…] ***an appearance of unity*** from the point of view of an external observer"
  - Why do we see a unity there but not there?
  - What are the limits of the system?
  - A trivial example : the game of life



- Can the science of complex systems help us to understand how our brain work?
  - Our brain actually is a complex system (but this is question 2!)
  - Our brain is the product of evolution; it's structure and behavior have been selected because they efficiently categorize the world… that is a complex system!
- Difficult epistemological questions (what is emergence? What is a frontier? What is a system?)


steinmann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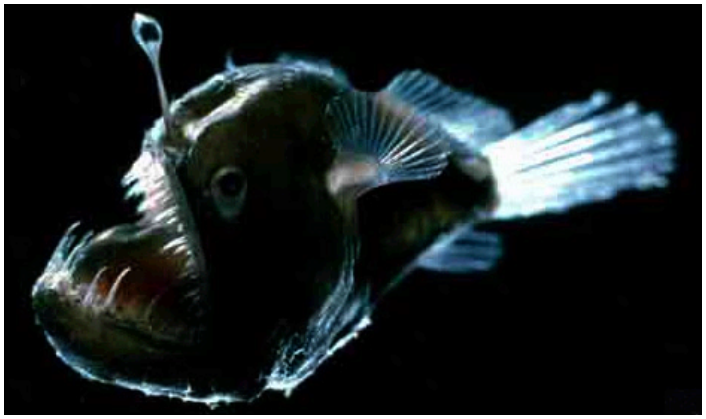
The notion of (complex) system questions our classifications

- Thinking “complex” often means crossing the frontiers of the considered system…
  - E.g., organism/ecosystems
  - E.g., petri dish/human gut
  - E.g., web site/web network

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