United Nations
Educational, Scientific and
Cultural Organization

UNESCO Chair
in Anticipatory Systems

UNIVERSITY OF TRENTO - Italy

project
ANTICIPATION

1.Understanding Systems

Roberto Poli

My short course

- **Understanding Systems**
  - What is a System?
  - Structure and Function
  - Complicated vs. Complex Systems
- **Toward a Paradigm Shift?**
  - Psychology (M. Seligman)
  - Anthropology (A. Appadurai)
  - Economics (J. Beckert)
- **Anticipation: Complexity and the Future**
  - Forecasting; Foresight 1.0; Foresight 2.0
  - Futures Literacy

Where we are

- The extraordinary success of modern science partly depends from the simplifications introduced by Galilei and Newton
  - Efficient cause only
  - One science only (Galilei: "The unique object of science is the book of nature")
  - Purely deterministic framework (natural laws are absolute; no exception allowed)
- The scientific development of the (19th and) 20th century has overcome most of these constraints
  - Variety of sciences
  - Failure of absolute determinism
- Today we start addressing the "multiple causes" issue

Science changes

- The main lesson to be learnt is that science has changed many times in the past and **continues to change**
- Today's science is different from the science of the 20th century
- Contemporary science is but a stage of a broader process
- Different positions are presently fighting one against the other and nobody knows which of them will eventually win

- "Science changes" → What does it really mean?

Science

Depew and Weber, *Darwinism evolving: System dynamics and the genealogy of natural selection*, MIT, 1994
Ulanowicz, *Ecology. The ascendent perspective*, Columbia UP, 1997

- According to Newtonian science, natural systems are
  - **Closed** (only efficient causality is accepted; bottom-up, top-down, "final" causes are forbidden)
  - **Atomic** (fractionable)
  - **Reversible** (no intrinsic temporal direction)
  - **Deterministic** (given enough information about initial and boundary conditions, the future evolution of the system can be specified with any required precision)
  - **Universal** (they apply everywhere, at all times and scales)

- Contemporary science shows that **all** these claims are false, in the sense that they are **not generic** (they work for **some special kind of system** only)

What is a System?

- General theory of systems
- The theory of specific kinds of system

- Three theses about systems

- Systems are everywhere
- (Many) Systems are encapsulated
- (Most) Systems are self-referential

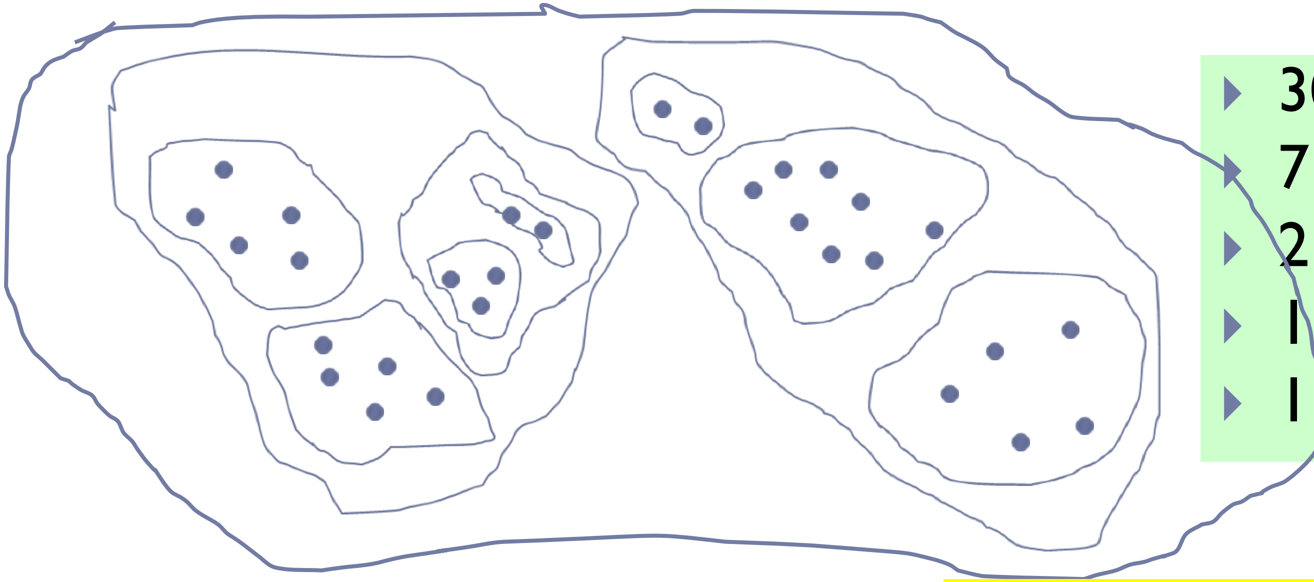
Systems are everywhere

- Political s.
- Geographic s.
- Linguistic s.
- Economic s.
- Cultural s.
- Social s.
- Planetary s.
- Digestive s.
- Immunitary s.
- Atomic s.
- Brake s.
- Electric s.

- Cosmological, physical, chemical, biological, psychological, social, political, economic …
- "System" crosses disciplinary boundaries

(Many) Systems are encapsulated

The intuitive (or naive) idea of system



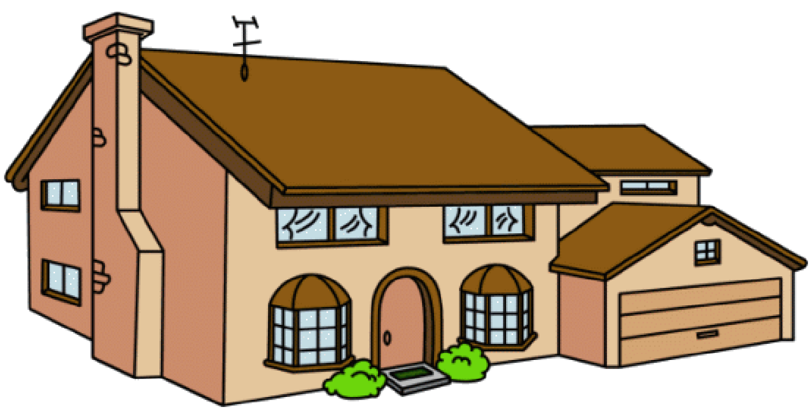
- 30 1st level systems
- 7 2nd level systems
- 2 3rd level systems
- 1 4th level system
- 1 5th level system

- Atom-molecule-cell
- Cell-organ-organism-population
- Person-group-organization
- Soldier-squad-platoon-company-…
- Believer-priest-bishop-pope

- While these encapsulations are locally correct, it is impossible to put them together into one global structure
- (I will come back to it)

(most) Systems are self-referential

- Two kinds of systems
  - Parts-first: start from a suitable collection of parts and assemble them in the proper order (house)
  - Whole-first: (1) the system is generated by another system; (2) the parts are produced by the system itself



(most) Systems are self-referential

- Two forms of constitution
  - ↑ from the parts to the whole: a system is a set of interacting elements (elements plus relations, that is structure)
  - ↓ from the whole to its elements: a system is an entity able to generate its parts (and their relations)
- In the former case a system <u>is</u> a structure; in the latter case a system <u>generates</u> (and modifies) its structures – which implies that the system is not limited to its structure. I shall call 'function' this extra component

A self-referential system:
- is a system that produces its own parts
- includes both structure and function

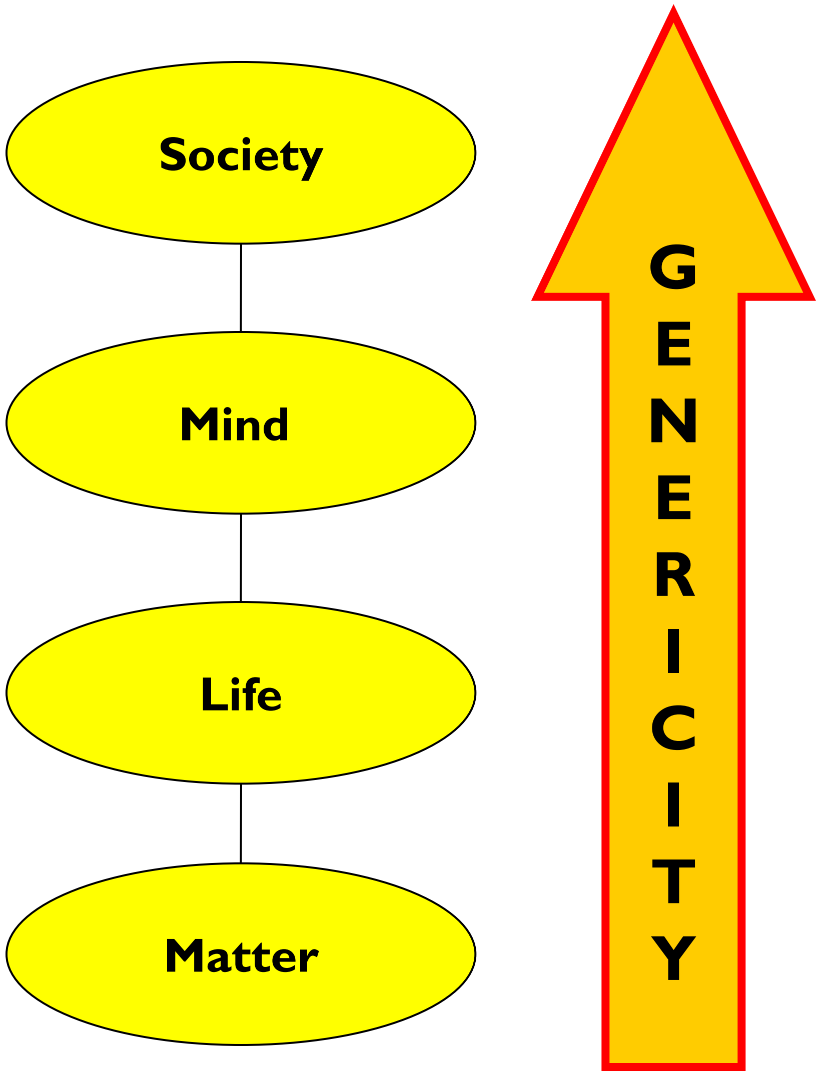
Two strategies

- How science develops? – The primary strategy adopted by science proceeds through analysis: take the system you would like to understand and divide (fragment) it into pieces
- The underlying ideas are that
  - Pieces are simpler than the original system. If a piece is still to complicated to understand, one can divide it again into subpieces until one arrives at a simple enough element she can understand
  - One can always get the original system by recomposing the pieces and sub-sub-pieces together
  - i.e. $\sigma\alpha(S) = S$ – the sinthesis of the products obtained by the analysis of a system S gives back S again

Two Strategies

- However, we all know that the duality between analysis and synthesis may fail – if you take the cat of my previous exemplification, fragment it into pieces and then put them together the original cat will not come back again
- Something is missing from this picture
  - The procedure above presented considers only structures, functions are missing
  - (We need a framework in which analysis and synthesis are not dual operators. Note that the duality between analysis and synthesis is a constraint. By getting rid of it, one obtains a more general framework)

The overall strategy



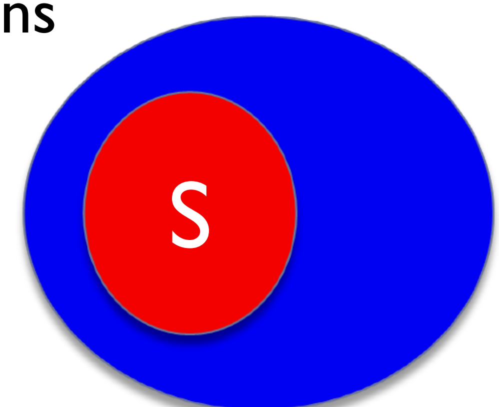
- Releave the overall theory from unneeded constraints
- Develop more general theoretical frameworks
- Search for a framework based on open, non-fractionable, irreversible, non-deterministic types of systems
- (In this sense the idea can make sense that, say, biology is more general than physics; required constraints may always be added for specific types of systems)
- (The math we know has been developed having in mind physical problems; we may new entirely new kinds of math))

Apropos Reductionism

- Reductionism = look for structures only
- The reductionistic strategy has proved enormously successful and its abandonment would be irresponsible
- On the other hand, the problems that are refractory to a reductionistic treatment are growing, and this asks for the availability of complementary non-reductionist strategies
- Reductionistic methods works well when a system can be decomposed (fragmented) without losing information
- For many systems, any fragmentation loses information
  - Supplement analytic methods with synthetic methods
  - Supplement structural analysis with functional analysis

Functional analysis (First step)

- Given a system S, look at the role that S plays within the higher system to which it pertains



- A system S may play different roles with reference to different higher-order systems (each of us is a citizen, family member, researcher, game-player etc). These roles may cohere or, more likely, conflict/interfere one another (e.g., there never is enough time for doing everything)
- S may be aware of the role it plays within the higher-order system. However, most systems are unaware of their roles

An exemplification

- Consider the difference between ear and organism
- Both are systems. Ears can be studied in order to understand what they are and do. One can divide an ear into its parts and see how they are made and what they do. The same works for organisms
- Both are authentic systems, both can be subjected to structural and functional analysis
- On the other hand, it seems correct to claim that organisms are more completely systems than ears are for a variety of different reasons, including the existential priority of organisms over ears

Question

- What is the ear supposed to do? Ears are such that they make the organism able to perceive sounds
- This answer has two sides
  - First, ears play some role within organisms. Like everything else, they need systems of which to be parts. Moreover, organisms build ears, not the other way round
  - Second, by having a role to play, ears constrain their own parts in such a way that they end up forming a structure that is putatively able to play the role that it has to play. Parts should further constrain their subparts so that they can play their own roles. And so on and so forth

Two more observations

- Firstly, the constraining procedure may always fail. For any level, the constraints imposed by the relevant system may not be able to steer the appropriate developments
- This may imply that the organ 'ear' fails to play its role, and this may further imply that the organism must either forget the perception of sounds or explore other avenues (e.g., different kinds of perception, or different kinds of ears)
- Secondly, the phenomenon of biological convergence, according to which the most diverse biological species discover the same solutions, shows that higher-order constraints are at work (see Conway Morris, 2003 and Conway Morris, 2008)
- When searching for a solution to its problems, life apparently does not traverse the entire combinatorial space of possibilities, but **continues to discover the same solutions** which suggest that optimality criteria (or variational principles) are at work

Life

- While life is in accordance with the laws of physics, physics cannot predict life
- Therefore, something is missing from the mainstream picture (things become worse as soon as mind and society are considered)

- The simplest way to see that biology requires its own categorical framework is to perform a couple of calculations

Two Simple Calculations

- The first calculation
  - From the point of view of organic chemistry, living tissue is composed (up to about 99%) by four types of atoms alone, namely C, O, H, and N
  - Between any two adjacent atoms there can be one of three possible ties, namely single bond, double bond or no bond at all
  - A single cell contains some 10^12 atoms
  - The combinatorial space arising from these number comprises 10^12^4^3 patterns, which is a finite numbers that extend beyond imagination
- The second calculation
  - Consider the four molecules that make up the DNA.
  - They form the twenty-odd amino acids which form the proteins
  - Let us assume that a protein is composed of a hundred amino acids (a very cautious estimate)
  - The combinatorial space arising from these numbers is 20^100 ca, which is equivalent to 10^130

Consequences

- Both calculations yield the same qualitative result: there are far too many combinations
- In both cases, the numbers obtained are much larger than the estimated number of particles composing the whole universe (estimated to be 10^80)
- These numbers are "uncomfortably large" as Conway Morris aptly puts it (*Life's solution. Inevitable humans in a lonely universe*, Cambridge University Press, 2003, p. 9)
- Interestingly, however, those combinatorial state spaces <u>are almost entirely void</u>: only a "comfortably" tiny fraction of those spaces has actually been explored by life
- Organisms use only a tiny fraction of the theoretically available state space. Why it is so?

Reasons

- Reason: most combinations are unsuitable for life
  - Given the watery milieu of the cell, a protein must be <u>soluble</u>
  - Furthermore, a protein must be chemically active (a chemically <u>inert</u> protein does nothing)
  - Etc
- "Let us … suppose that only one in a million proteins will be soluble, a necessary prerequisite for the watery milieu of a cell … of these again only one in a million has a configuration suitable for it to be chemically active … how many potentially enzymatically active soluble proteins … could we expect to be available to life? … the total far exceed the number of stars in the universe"
  - (Conway Morris, 2003, p. 9)

State Space

$$10^{130}$$

State Space Minus Non-Soluble Proteins

$$10^{124}$$

… Minus Inactive Proteins

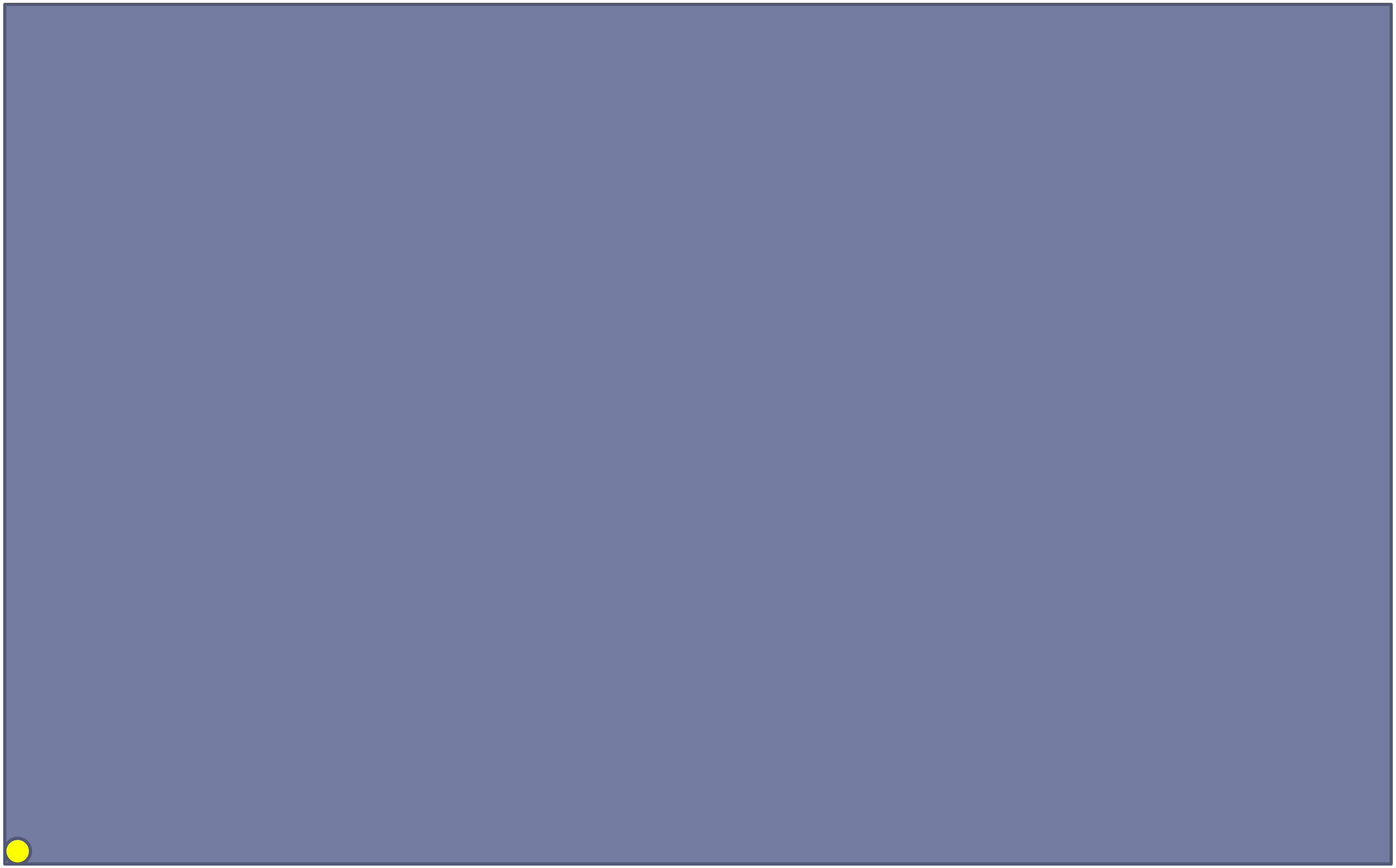
10^{118}

Conclusion

- The conclusion seems rather obvious
- There is a difference between physics and biology; a difference that does not invalidate physics but requires something **new** that cannot be explained by the former theory

- **<u>striking difference</u> between the combinatorial amount of possible chemical cases and the remarkably small sections actually traversed by biological phenomena**

State Space



Conclusion

- **Properly biological laws must be at work, able to dramatically filter the space of chemical combinations**
- How to find properly biological laws is one of those slippery questions that one does not know how to frame
  - Classically analytic frames may not be suitable candidates
- Evolution is the best starting point currently available, but it is itself in need of further developments, as shown by the cases of empathy, intelligence and anticipation
- What else is needed, apart from variation and selection?

Two types of complexity

Complexity$_1$

Simple vs. complex$_1$ systems

- Single cause and single effect (one-to-one connection)
- Small changes in the cause imply small changes in the effects

- These two properties implies that the system's behavior will not be surprising, i.e., that it is <u>predictable</u>
- Every system that is not simple is complex
  - The cause-effect connection is many-to-many
  - For a large class of complex systems, effects are fed back to modify causes (<u>*circular causality*</u>) – in this way causes and effects intermingle
  - A small change in the cause may imply dramatic effects
  - Emergence and unpredictability

Complex$_1$ systems

- Unpredictable behavior (which we try to predict anyway)
- Possible uncontrolled explosions (earthquake eruptions, epilepsy seizures, stock market crashes)
- [Formally speaking: Asymmetric power law distribution]
  - Many simple systems present a Gaussian distribution
  - Many social systems present a skewed pattern (80% of the income is made by 20% of the people, 80% of flights land at 20% of the airports)
  - Phenomena described by asymmetric (skewed) power law distributions
    - Power law distribution $y = ax^k$ (a,k constants)
- Problem: How to understand, control, manage, decompose, predict the behavior of complex$_1$ systems

Emergence of complexity$_1$

- Collections of entities have properties not shared by the individuals composing the collection
  - One molecule of H2O is not liquid
  - One amino acid is not alive
- How do system properties arise from the properties of their components?
- Sometime they emerge as a consequence of local interactions among parts, without external command
  - Self-organization
- Second: evolution of complexity through time
  - No ability to predict the next step in the evolutionary chain

Physics and complexity

- Hardcore physicsts admit that the laws of physics are not sufficient to explain emerging complexity
  - P. Anderson, "More is different", *Science*, 177, 1972, 393-396; N. Goldenfeld, L. Kadanoff, "Simple lessons from complexity", *Science*, 284, 1999, pp. 87-89; R. Laughlin, D. Pines, "The theory of everything and its critique", PNAS, 97, 2000, 28-31; E. Dagotto, "Complexity in strongly correlated electronic systems", *Science*, 309, 2005, 257-262
- Anderson: "the ability to reduce everything to simple fundamental laws does not imply the ability to start from these laws and reconstruct the universe"
- Laughlin and Pines: "emergent physical phenomena regulated by higher organizing principles have a property, namely their insensitivity to microscopic variations, that is relevant to the broad question of what is knowlable in the deepest sense of the term"
- "The solution may require a collaboration of reductionists and emergentists, is they can be persuaded to talk one another"

Two types of complexity

Complexity$_2$

Structure and function 1

- The axiom of reductionism – $\sigma\alpha(S) = S$ – implies that there is no need to look for functions because functions are entirely captured by structures (one-one correspondence between structure and function)
- As soon as the duality between analysis and synthesis is denied – that is $\sigma\alpha(S) \neq S$ – the one-one correspondence between structure and function fails as well
- The same structure may support different functions; the same function may be realized by different structures

Exemplification

- Consider a company
- To survive and develop, it should perform a variety of different functional activities, including the design of new products, producing, storing and circulating them, managing employees and workers, etc.
- Any of these activities may be performed by a specialized unit, or it may be split among a variety of units in many different ways. Companies make different choices in this regard
- All the possibly different structural choices notwithstanding, the functions to be performed are analogous
- Structures divide, functions unify

Structure and function 2

- The analytic decompositionof a structure produces a set of elements ($\alpha(S) = \{s_1, \ldots s_n\}$ and their relations)
- However, as soon as functions are properly introduced (that is, without assuming the one-one correspondence between individual structures and functions), the analysis of a function does not generate a given set of elements
- Even if one crystalizes a function F by deciding that F is realized by the structure S, the elements generated by the analysis of S may realize other functions different from F – which implies that these systems can always generate unintended consequences

Problem

- A problem remains, however
- Whichever strategy one adopts (downward, looking for structures; upward, looking for functions) no overall smooth transition arises among the many systems we detect
- There always are jumps
  - Atom – molecule – cell – organism – population
  - Where is mind? Where is society? (politics, art, religion, etc)
- Levels of reality – the world is organized into a series of irreducible levels: physical—biological—psychological—social
- There are both relations of (existential) dependence and relations of (categorical) independence among the levels
- Trading a X problem for a Y problem is a categorical mistake

The constitution of systems

- Two directions of systems' constitution
- Upward constitution (from elements to their system)
  - "A system is a collection of interacting elements"
- Downward constitution (from the system to its elements)
  - From the already constituted system to the underlining interactions (modification of the rules of interaction, adding of specific constraints, generation of new types of interaction)

- Together, the two constitutive directions (upward and downward) form a loop, a cycle
- I call 'self-referential' the systems using both constitutions
  - Structural analysis 'freeze' a system and decomposes it into its parts

Mechanisms

- Structural analysis is much simpler than functional analysis
- I call ‘mechanical’ or ‘mechanism’ a system that can be understood only through structural analysis
- The math learnt by engineers and physicists is a powerful framework for understanding and modeling mechanisms
- In principle, mechanisms admit maximal models, i.e. models capturing all the relevant information
  - Mechanisms can be completely known through suitable algorythmic models
  - Note that an algorythm is itself a mechanism, a rote set of instructions producing for each input a given output

Self-referential systems

- Following Rosen, I shall call self-referential systems ‘organisms’
- My claim is that everything above physics (including biology, psychology and sociology) requires self-referential systems
- Self-referential systems raise many deep scientific problems
  - The math for self-referential systems is more complex than the math for mechanical systems
  - The main problem however is that self-referential systems do not admit maximal models
  - Models are ‘static’ pictures of a system – self-referential systems are **creative**: every ‘static’ picture captures only some aspects of the system (technically, the system’s state space changes)
- On the other hand, if my claim that everything above physics is self-referential, MOST systems are self-referential and we should develop suitable theories and tools to better understand them

Terminology

- Machines (mechanical systems) are called simple
  - They may be exceedingly complicated, but they are not $complex_2$
  - $Complex_1$ systems pertain to this class (because they are based on a purely mechanical (algorythmic) internal machinery
- Organisms (self-referential systems) are called $complex_2$

- Sharp thresholf between simple and $complex_2$ systems
- Simple systems do not become $complex_2$ by making them more complicated, in the same way in which a finite series does not become infinite by adding +1, +1, etc
- A simple system becomes $complex_2$ only if self-referential loops are added to the system, that is only if it is no more simple

Simple vs. complex$_2$ systems

- The theory of simple systems (including complex$_1$ systems) is a mathematical fiction (locally or heuristically helpful, but nevertheless false as a claim on reality)
- Simple systems presuppose closure (no or predetermined interaction with their environment, that is with other systems)
- Most systems are complex$_2$ (simple systems are rare) because they are open to interactions with other systems
- System theory has been developed with the intent of **controlling** real systems
- However, there is no chance to control a complex$_2$ system – move from control to dance

Complex systems

- By not admitting maximal models, $complex_2$ systems can <u>never</u> be <u>entirely</u> captured by any scientific model
- This is not to say that modeling is useless
- It only means that models are <u>always</u> partial (they can never be taken as the last word about the system)
- The partiality of models is constitutive and does not depend on missing information or data
- This limiting result has major consequences for decision-making, policy and ethics