

# What is complexity and why doesn't it exist in physics?

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# Phenomenology and taxonomy

**Two different types: “physical”  
and “symbolic”**

# ¿What is certainly complex?

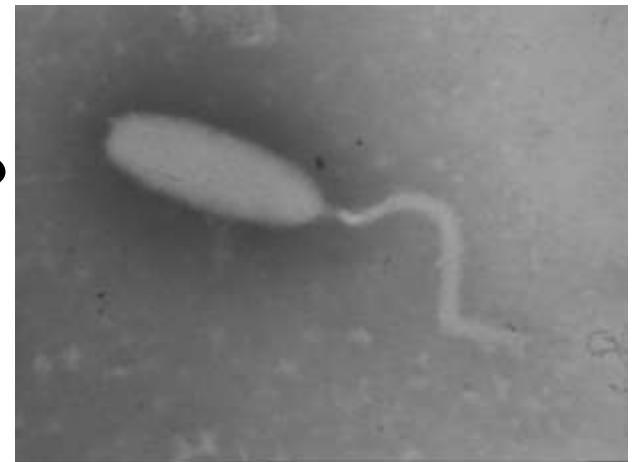
**This...?**



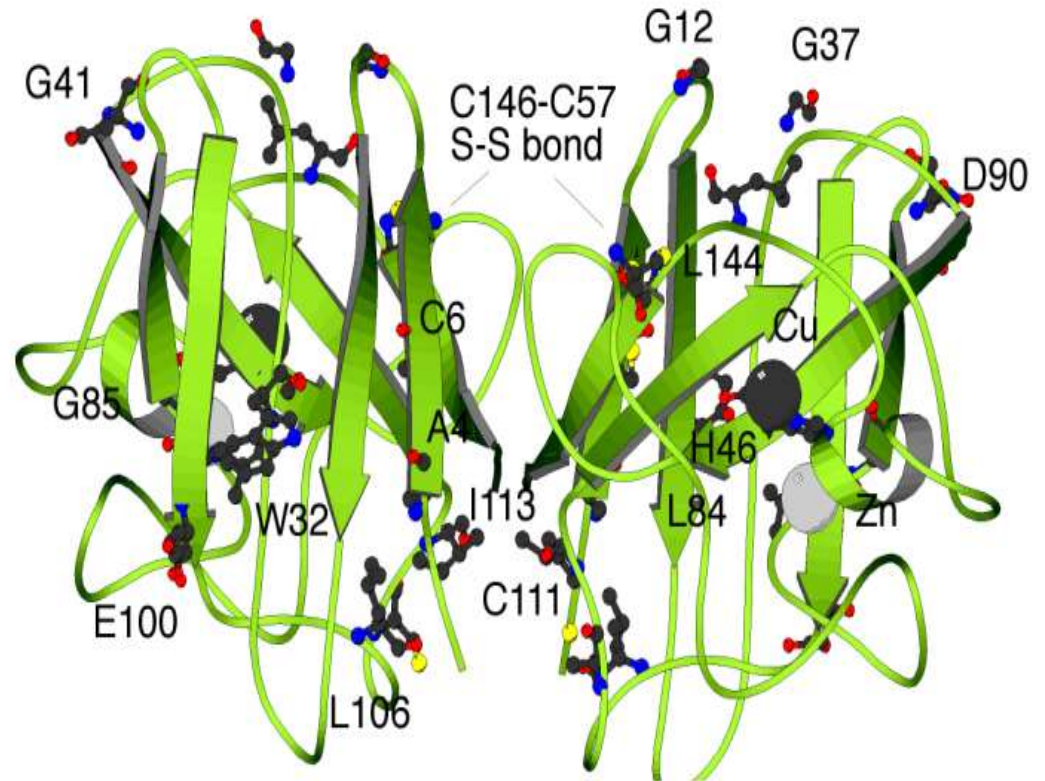
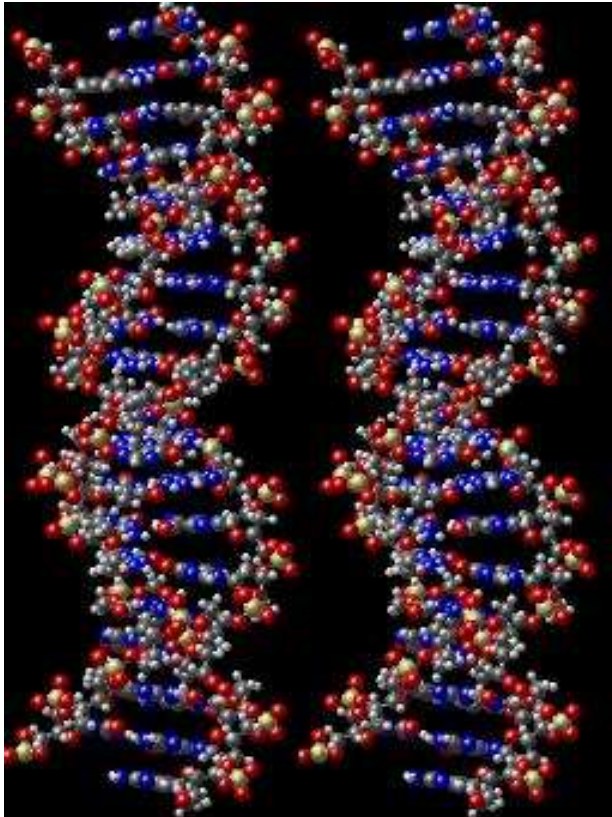
**No, what about this...?**



**And this...?**

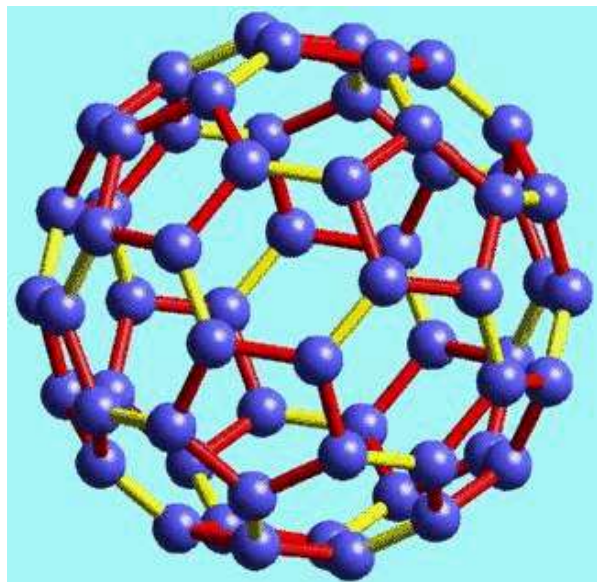


# And these?

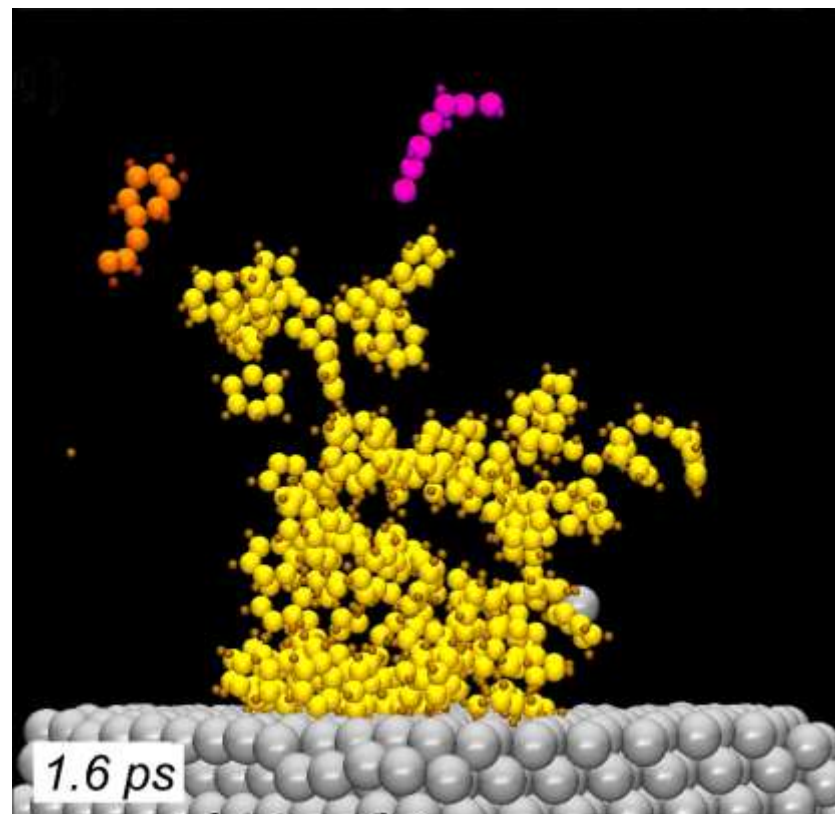


Model illustrating the formation of a misfolded species (M) from a folding intermediate (I). The region of the protein that misfolds is shown in red. The misfolded protein itself, or a self-assembled form, may be toxic to cells, leading to disease. The black arrows represent the relative rates of the various conformational events under native physiological conditions in the absence of mutation. The blue dash arrows represent the possible effects of mutation.

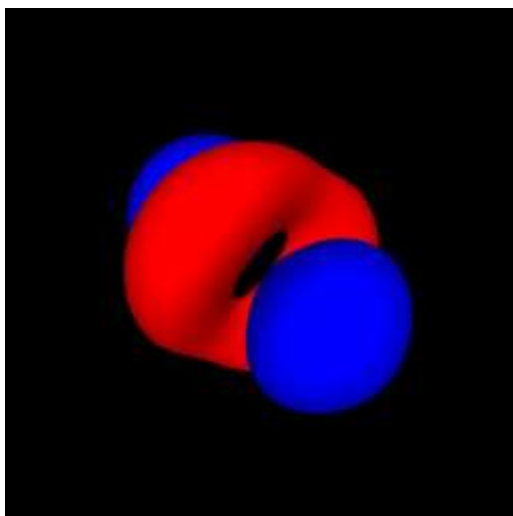
And what about these?



Buckyball  $C_{60}$



Polystyrene on a silver surface

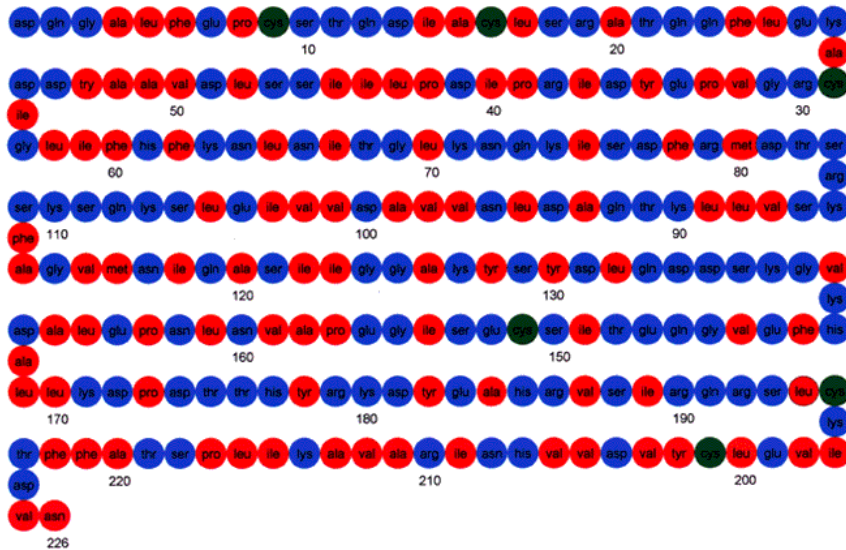


$n=3, l=2$  energy level of H

To be, or not to be--that is the question:  
 Whether 'tis nobler in the mind to suffer  
 The slings and arrows of outrageous fortune  
 Or to take arms against a sea of troubles  
 And by opposing end them. To die, to sleep--  
 No more--and by a sleep to say we end  
 The heartache, and the thousand natural shocks  
 That flesh is heir to. 'Tis a consummation  
 Devoutly to be wished. To die, to sleep--  
 To sleep--perchance to dream: ay, there's the rub,  
 For in that sleep of death what dreams may come  
 When we have shuffled off this mortal coil,  
 Must give us pause.

# What about complexity In this case?

Amino Acid Sequence of hJHBP



Human nucleotide sequence

```

AAAAGAAAAGGTTAGAAAAGATGAGAGATGATAAAAGGGTCCATTTGAGGTTAGGTAAT
ATGGTTTGGTATCCCTGTAGTTAAAAGTTTTTGTCTTATTTTAGAATAC TGTGACTA
TTTCTTTAGTATTAATTTTTCCTTC TGTTCCTCATCTAGGGAACCCCAAGGCAT
CCAATAGAAGCTGTGCAATTATGTAAAATTTTCAACTGTC TTCCTCAAATAAAGAA
GTATGGTAATCTTTACCTGTATACAGTGCAGAGCCTTC CAGAAGCACAGAATATTT
TTATAATTTCTTTATGTGAATTTTTAAGCTGCAAATCTGATGGCC TTAATTTCTTT
TTGACACTGAAAAGTTTTGTAAAAGAAATCATGTC CATA CACTTTGTTGCAAGATGTG
AATTAATTGACACTGAACTTAATAAC TGTGTACTGTTTCGGAAGGGGTTCC TCAAATTT
TTTGACTTTTTTTGTATG TGTGTGTTTTTCTTTTTTTTTTAAGTTCTTA TGAGGAGGGA
GGGTAAATAAACCACTGTGCGTC TTGGTGTAATTTGAAGATTGCCCATCTAGACTA
GCAATCTCTTCATTATCTCTGCTATATA TAAAA CGGTGCTGTGAGGAGGGGAAAA
GCAATTTTCAATATATGAAC TTTTGTACTGAATTTTTTTGTAATAAGCAATCAAGG
TTATAATTTTTTTTTAAAA TAGAAATTTTGTAA GAAGGCAATATTAACCTAATCACCA
TGTAAGCACTCTGGATGATGGATTCCACAAA ACTTGGTTTTATGGTTACTTCTTCTC
TTAGATTCTTAAATTCATGAGGAGGGTGGGGAGGGAGGTGGAGGGAGGGAAGGGTTT
CTCTATTAATGCAATTCGTTGTGTTTTTTAAGATA GTGTAAC TTGCTAAAATTTCTT
ATGTGACATTAACAAA TAAAAAGCTCTTTTAAATATTAGATAA
  
```

# ...and here?

aaaa aaaa aaaa aaaa aaaa aaaa aaaa... "ordered"

asmjgre fj sdjf s rege geoiie rgeasdffi... "disordered"

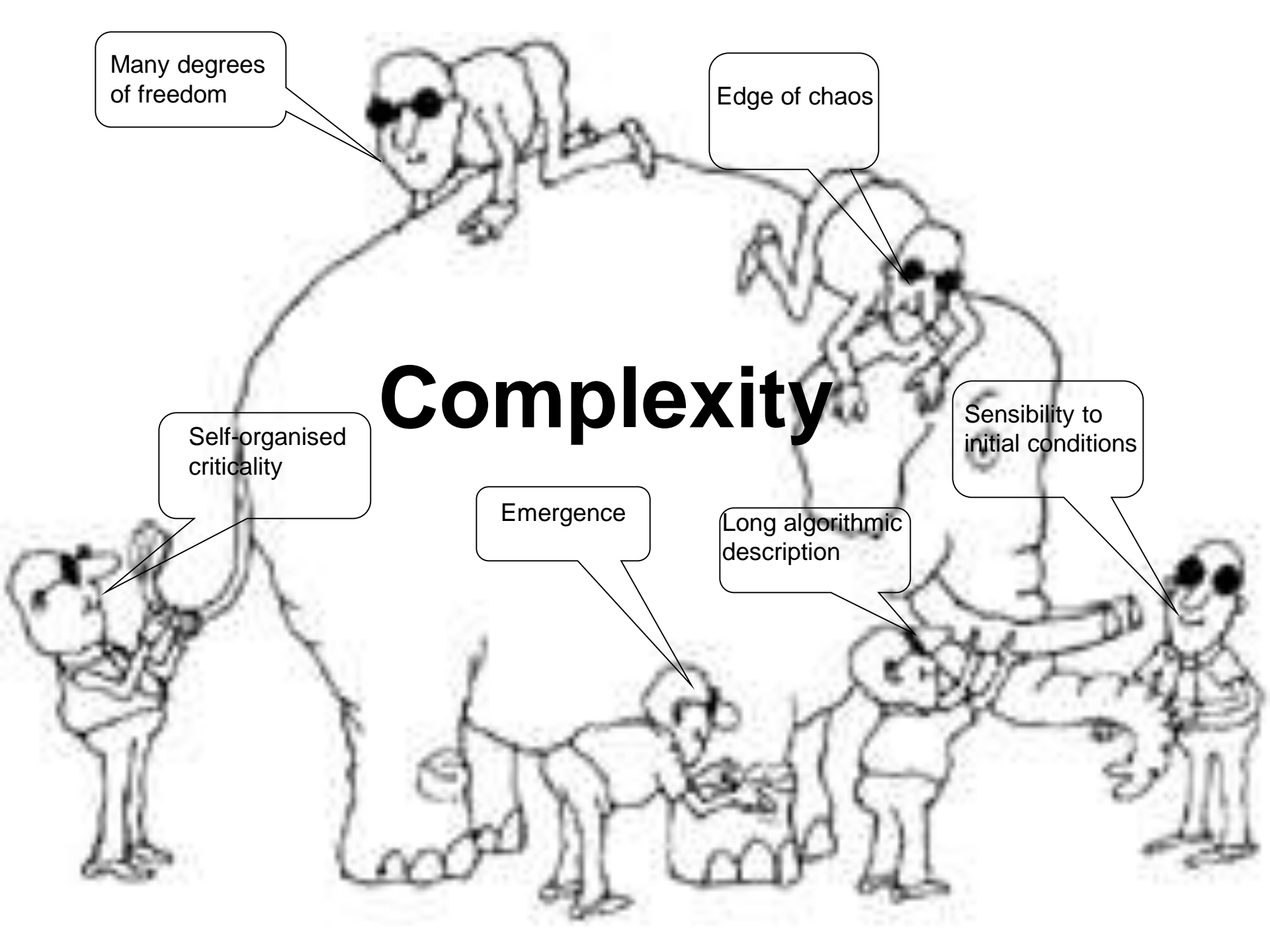
... \_ \_ \_ ... \_ \_ \_ ... \_ \_ \_ ... \_ \_ \_ ... "layered"

1001 110 11001 1111 10101 1 10010 101 1101 1 10010 10010 ... "?"

If you are married or are a man and woman living together as "complex"  
if you are married you must claim jointly ...

How do we recognise "complexity"?





Many degrees of freedom

Edge of chaos

# Complexity

Self-organised criticality

Sensibility to initial conditions

Emergence

Long algorithmic description

**So, maybe we can agree on what is definitely complex, and what is definitely not complex. But where do we change from one to the other?**

*The "Edge of Chaos"*

Flying speed of insects

Species extinctions

Electromagnetism

# The Edge of Chaos

Word frequency  
distributions

Fluids

Sandpiles

Prices in  
Financial  
markets

City populations

gravity

Ferromagnets

earthquakes

Metabolic rate

Income Distribution

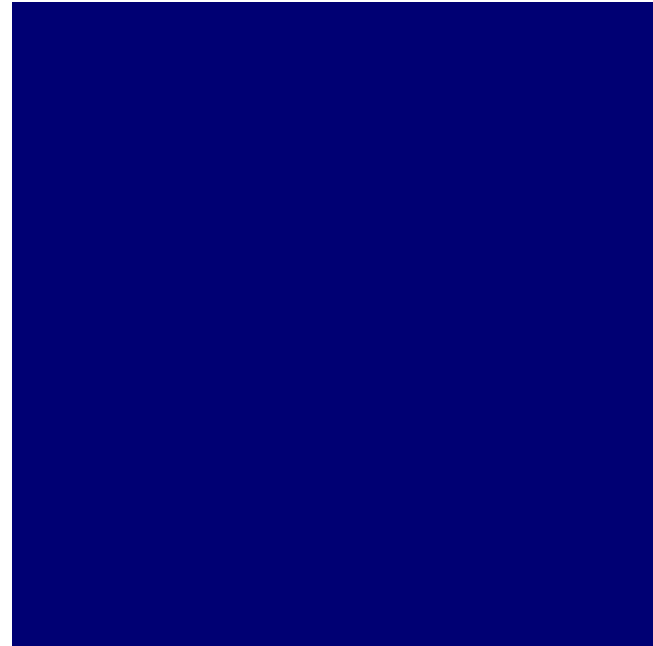
# On the “Edge of Chaos” in “micro”-physics?

Barkhausen effect – “avalanches” of magnetic domains

“Dirty”



Near  
critical



Typical critical phenomenon showing  
collective behavior and scaling  $Y \sim X^a$

**But...**

- Only one important length scale – the correlation length – that governs the scale of “collectivity”; Scale invariant near critical point (phase transition) – maximal “collectivity”
- Only one type of effective degree of freedom – a magnetic domain “avalanche”, but ...
- Complex? Once the spectrum of “avalanche” sizes is given then there’s nothing much more to be said. Not very interesting living on the “Edge” in physics!
- The same is true for other canonical critical or self-organised critical phenomena

# The “symbolic” Edge of Chaos?

el el el el el el el el el el ....

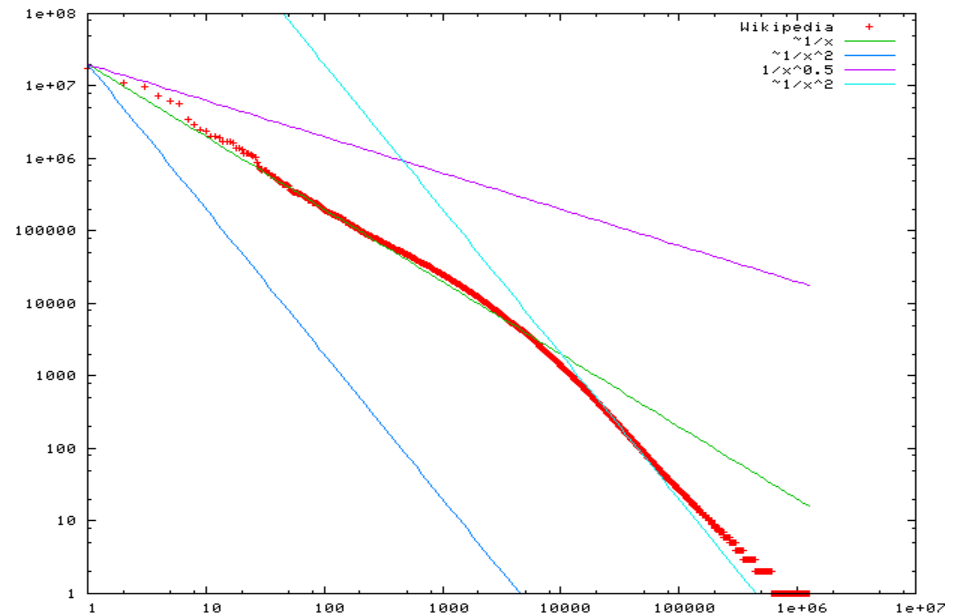
ordered

frame ridicule artillery parade strike unconscious what...

disordered

Parameter to distinguish between ordered and disordered...

s – where:



Zipf's law may be stated mathematically as:

$$f(k; s, N) = \frac{1/k^s}{\sum_{n=1}^N 1/n^s}$$

where  $N$  is the number of elements,  $k$  is their rank, and  $s$  is the exponent characterizing the distribution. In the example of the frequency of words in the English language,  $N$  is the number of words in the English language and, if we use the classic version of Zipf's law, the exponent  $s$  will be equal to unity.  $f(k; s, N)$  will then be the fraction of the time the  $k$ th most common word occurs.

In Hamlet (and in general in natural languages)  
 $s$  is about 1

So, language is on the “Edge of Chaos”!

Does this give an adequate description of Hamlet? That we need only state that the frequency distribution of words is scale invariant with exponent  $s$ ?

**NO!**

So, What's in Hamlet that's not in a “sandpile”?

# ¿What distinguishes complex from non-complex phenomena?

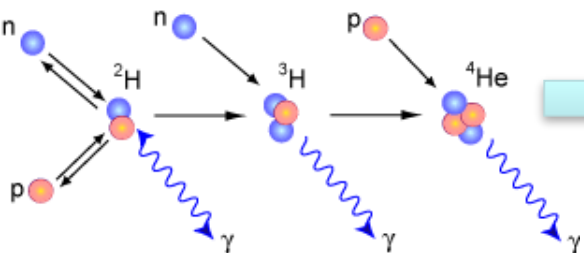
- Structural properties
  - A “hierarchy” of many different scales
  - Effective degrees of freedom (“collectivity”) that are qualitatively different at different scales
  - Hierarchies of **building blocks** (modularity)
  - Interactions that are stronger “intra-block” than “inter-block”
  - The micro and macro and linked through feedback (fitness, meaning,...)
- Functional properties
  - Systems that are **adaptive**
  - A dynamics that depends on many different **rules/strategies**
  - Systems that “**learn**” (feedback from the environment to the system that is used to update the rules)
  - The micro and macro and linked through feedback (fitness, meaning,...)
  - More complex behaviour (the “phenotype”)
  - Better described by what they **DO** than what they **ARE**



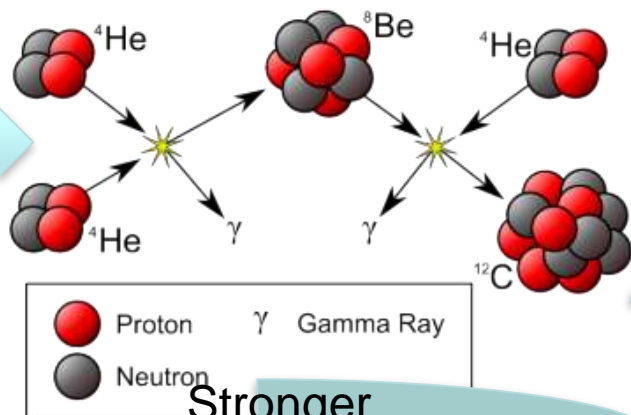
# **Building Block Hierarchies**

# Construction of the Universe through Building Blocks

## Big Bang Nucleosynthesis



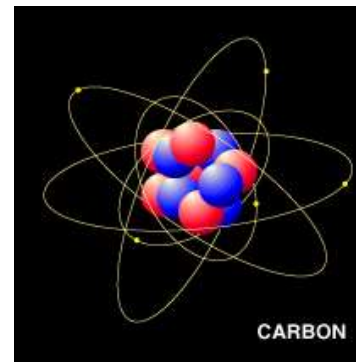
This shows one of the reaction sequences that produces a helium-4 nucleus from protons and neutrons. Other sequences are possible. The first stage is reversible due to photodisintegration by gamma photons.



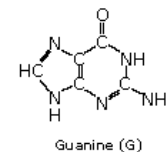
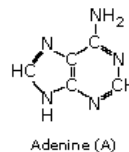
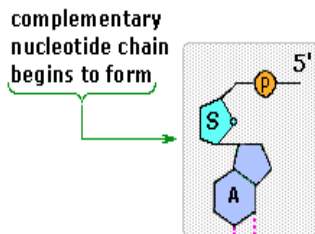
● Proton     $\gamma$  Gamma Ray  
● Neutron

These events are **recombination** events where something new is created from existing **building blocks**

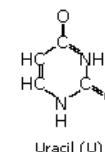
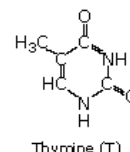
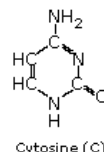
Stronger  
Interactions  
Weaker



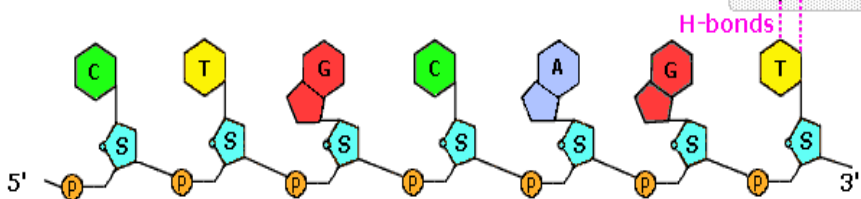
P = phosphate  
S = 2'-deoxyribose  
 bases = T thymine    C cytosine    G guanine    A adenine



Purine bases (two rings)



Pyrimidine bases (one rings)



unwound DNA strand

Botany, Ecology, Biology

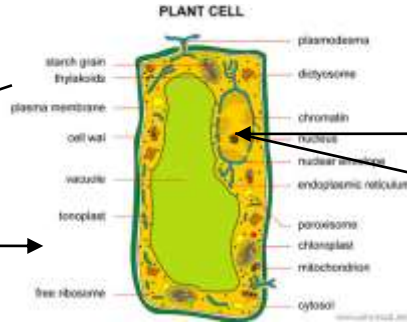


10<sup>-1</sup>m

Colour, size, form, leaves, roots, fruits, number of petals, number of cell types, number of genes, number of types of synthesized proteins ...

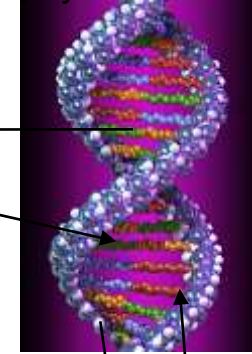
**“Reductionism”**

Cell Biology, Genetics



10<sup>-5</sup>m

Biochemistry, biophysics, molecular physics



Macromolecule composed of 4 bases C, G, T y U  
H,  
C, N y O.

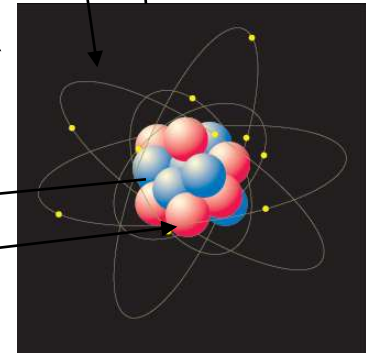
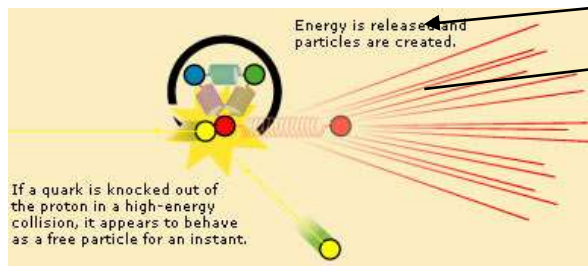
10<sup>-9</sup>m

Chemistry, atomic physics, nuclear physics

**“Agentes”**

Building Blocks

Física de partículas



10<sup>-10</sup>m

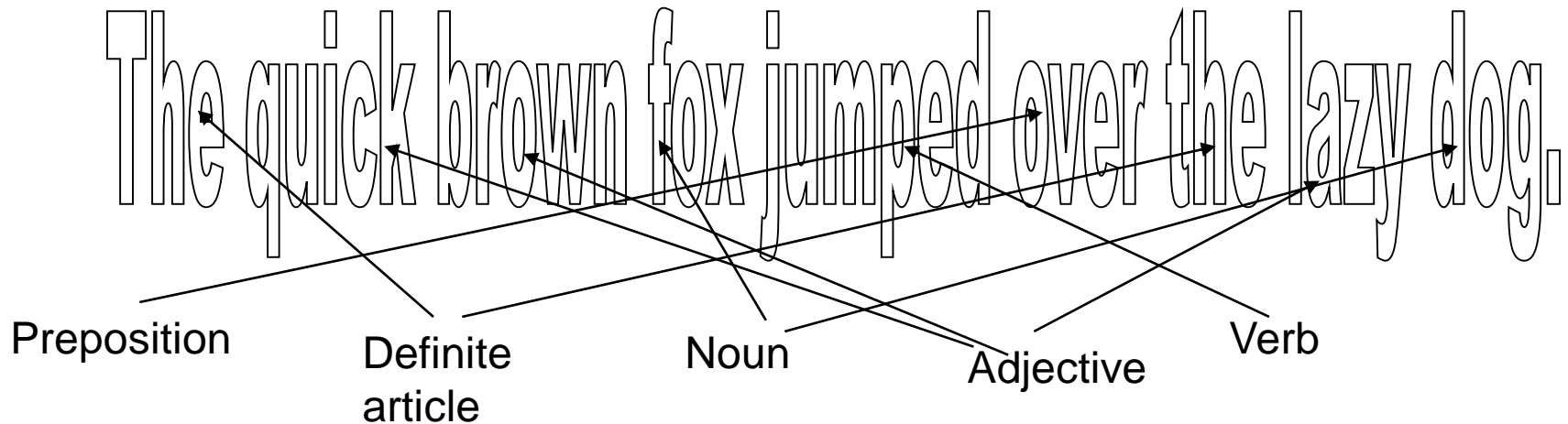
Number of electrons, number of protons and neutrons, their masses, charges

- Why is everything composed of Building Blocks?
- It's the **only** way to construct something complex
  - Example: construction of an iron nucleus
  - Example: construction of a cell

Permits functional specialization

# Complexity: Linking the “micro” to the “macro”

# Building Blocks in language



34 letters – 15 distinct types: classification a, b, c, ...

8 words – 7 distincts types: classification abacus, abalone, ...

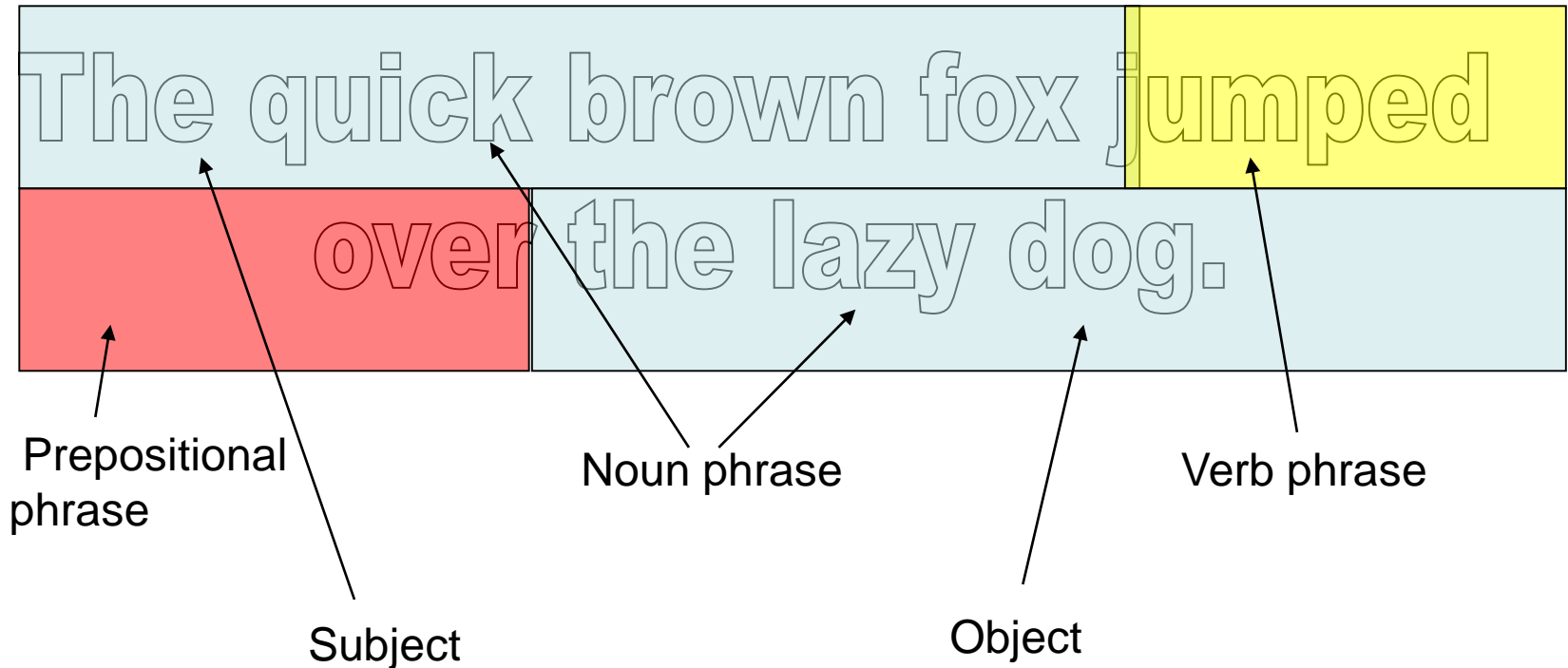
What other classifications are there?

Letters – consonants versus vowels

Words – grammatical classification

At the moment there are no interactions beyond the level of letters in a word

# Interactions between Building Blocks in language



**Interactions induced by grammar**

# Interactions between Building Blocks in language

The quick brown fox jumped  
over the lazy dog.  
The dog awoke startled.

Utah State university is located in Logan.

**There are no grammatical interactions between these sentences. They are  
However, logically distinct.**

**Semantics creates “long range” interactions**



# **Is complexity a scientific concept?**

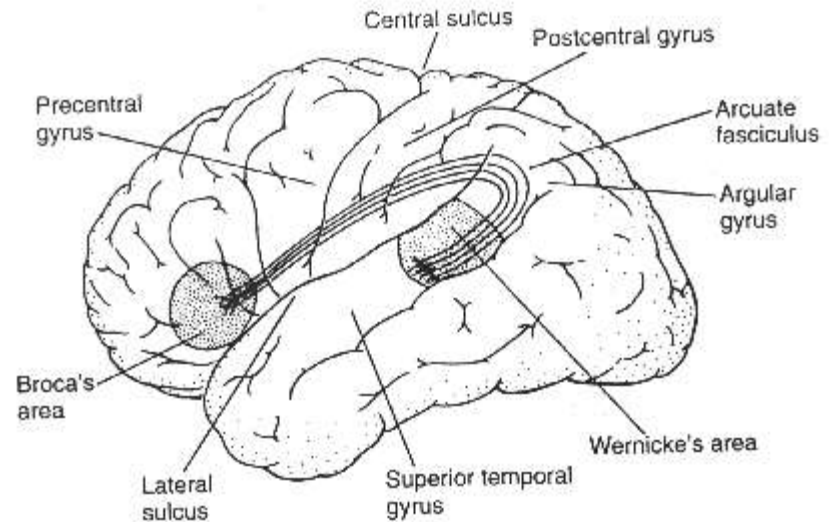
**If it is, then...**

**How do we measure it?**

**What is a good measuring  
apparatus...?**

# ...For symbolic complexity

To be or not to be that is the question.

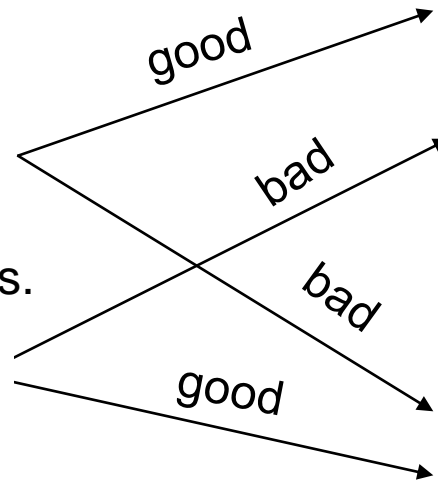


This apparatus is surely capable of measuring complexity. Or maybe not...?

# How good is your apparatus?

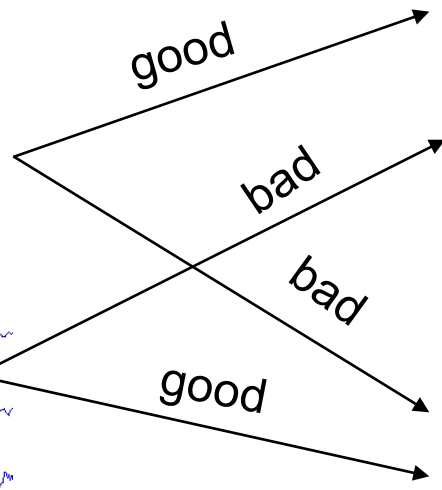
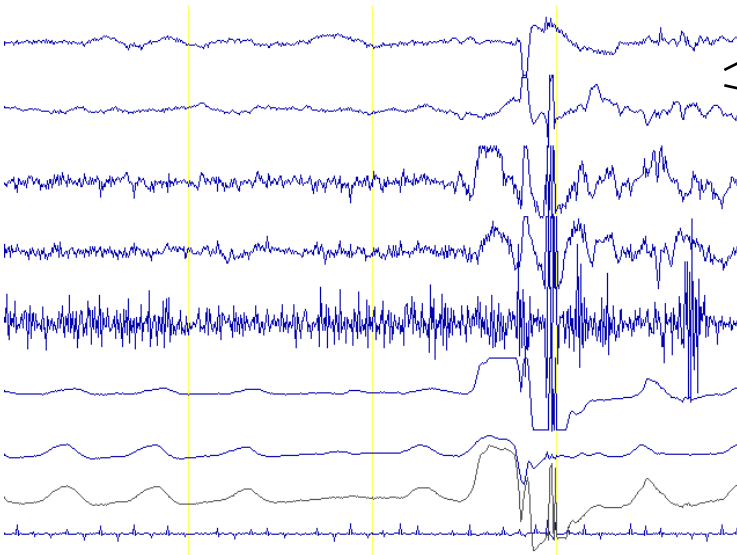
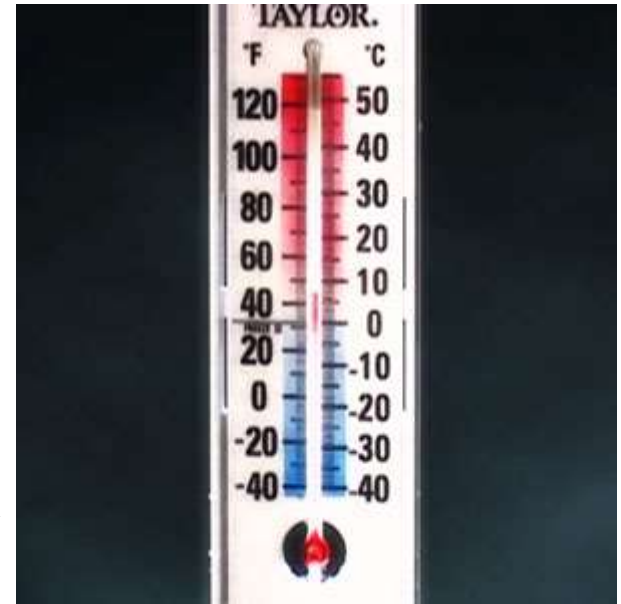
- To be or not to be that is the question.
- Para ser o no ser que es la pregunta.
- Om te zijn of te zijn niet dat de vraag is.

あるためまたはないため質問である



- Because of a certain or because it is not, it is question.
- Because or it is not for the sake of, that having asked and being convinced.
- Being not to be for the sake of, or that that, you ask, are convinced.
- It is that without having for the sake of, or, you ask, are convinced.

# But is this really any different to physics?



# **Modelling complexity and complex systems**

Consider this “simple” dynamic model...

$$\mathbf{d}_i(t + \Delta t) = \sum_{j \neq i} \frac{\mathbf{c}_j(t) - \mathbf{c}_i(t)}{|\mathbf{c}_j(t) - \mathbf{c}_i(t)|} + \sum_{j=1} \frac{\mathbf{v}_j(t)}{|\mathbf{v}_j(t)|}$$

Competition between an effective repulsion and attraction between “particles”

$$\hat{\mathbf{d}}_i(t + \Delta t) = \mathbf{d}_i(t + \Delta t) / |\mathbf{d}_i(t + \Delta t)|$$

$$\mathbf{d}_i'(t + \Delta t) = \frac{\hat{\mathbf{d}}_i(t + \Delta t) + \omega \mathbf{g}_i}{|\hat{\mathbf{d}}_i(t + \Delta t) + \omega \mathbf{g}_i|}$$

Equation for “charged” particles in an external field  $\mathbf{g}_i$

**Couzin, I.D.**, Krause, J., Franks, N.R. & Levin, S.A.  
(2005) *Nature*, **433**, 513-516.

**Does this represent a  
“complex” system?**



**Moral: It's important to distinguish between a description of complexity and a non-complex description of a phenomenon or behaviour associated with a complex system.**



# **The tyranny of the laws of physics and the difference between “being” and “doing”**

## The mechanical

## The adaptive

The cat obeys exactly the same laws of physics as the basketball

One can describe many of the processes that occur in the cat's fall in terms of known science – neurobiology, physiology, physics,...

So... What is the difference?

Although one can describe, up to a certain point, with the cat how it does it we don't understand "why" it does it






**Evolved strategies**

# Evolved Virtual Creatures

Examples from  
work in progress

# The difference between “being” and “doing”

In biological, economic and social systems, i.e., complex adaptive systems, organismos exhibit a great diversity of **STRATEGIES** (rules/models)

The dynamical state of an individual at  $t+1$  depends not only on the state of the individual at other times  $t$  but also on the strategy (update rule) selected at time  $t$ , that in turn depends on the rules of others at  $t$   it is necessary to work in a space of states AND strategies/rules/models – sounds like game theory but ...

We don't know what this space is!

Besides, the payoff for a strategy is **RELATIVE** not absolute. Payoff (fitness) should be an emergent property. Imagine at the beginning of life trying to specify a priori the fitness of a lion or an ant!

# Challenges for modelling complexity

## Phenomenology:

- Understand what are “necessary” and “sufficient” conditions for complexity
- Adaptation – What is it and how does it come about?
- Modularity – understand how different parts of a system come to have different functionalities and then join together as building blocks to form more complex objects – the role of multi-tasking
- Fitness as an emergent phenomenon
- The problem of statistical inference in the observation of complexity

# Challenges for modelling complexity

## Theory

- What paradigms are useful for modelling complexity? From physics? From biology? ...

All? None?

- Developing mathematical frameworks in which one works in a space of states and “laws”
- To describe a “game” where the rules change and we don't know the payoffs
- To understand how to do a “coarse graining” (renormalization group) to study the emergence of qualitatively different effective degrees of freedom



# ¿Podemos imaginar lo Complejo?

- Vivimos el complejo cada día
  - Todos los procesos autonómicos
    - Involucran un sinnúmero de factores a múltiples escalas
    - Metabolismo, sistema inmune, respirar
  - Todos los procesos “semi-autonómicos”
    - Involucran un sinnúmero de factores a múltiples escalas
    - Manejar, caminar, sonreír
  - Todos los procesos conscientes
    - “No involucran tantos factores”
    - Hablar, calcular
  - La relación entre el consciente y el inconsciente