

# Computational Methods for Complex Systems



# What is a complex system?

## Oxford Dictionary:

Consisting of many different and connected parts.  
“A complex network of water channels”

## Cambridge Dictionary:

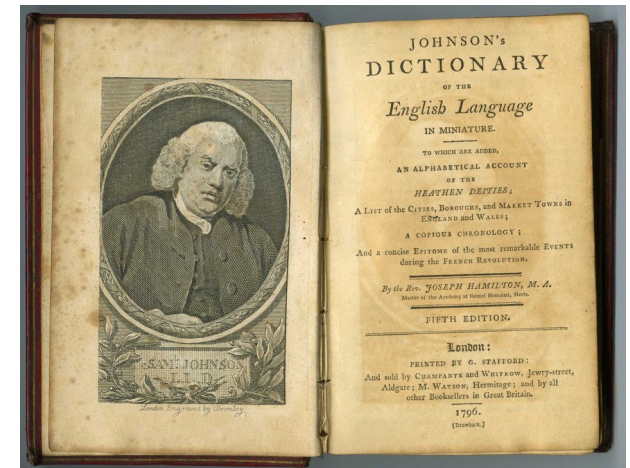
Involving a lot of different but related parts:  
“A complex molecule/carbohydrate”  
“A complex network of roads”  
“A complex procedure”  
“The company has a complex organizational structure.”

## Merrian Webster Dictionary:

A whole made up of complicated or interrelated parts.  
“A complex of welfare programs”  
“The military-industrial complex”

## Urban Dictionary:

- When one believes that many people around one hates one.  
“Stop ignoring your friend, you're going to give her a complex.”  
- Having many simple parts.  
“He kept throwing terms at me until I was blinded by how complex it was”.

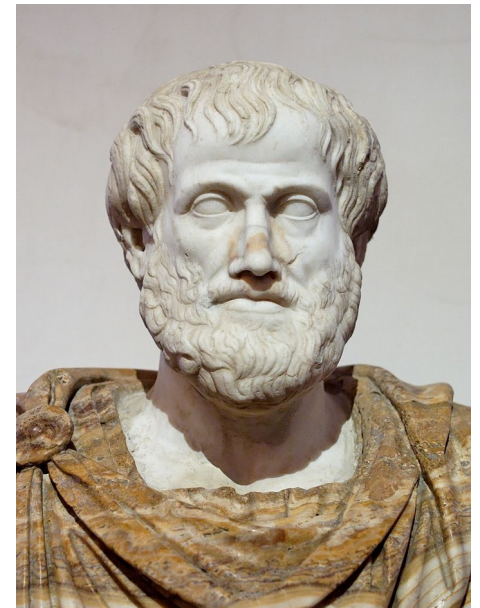


# What is a complex system?

Complexity is emerging as a post-Newtonian paradigm for approaching from a unifying point of view a large body of phenomena occurring in systems constituted by several subunits, at the crossroads of physical, engineering, environmental, life and human sciences. For a long time the idea prevailed that the perception of systems of this kind as complex arises from incomplete information, in connection with the presence of a large number of variables and parameters masking the underlying regularities. Over the years experimental data and theoretical breakthroughs challenging this view have become available, showing that Complexity is on the contrary rooted into the fundamental laws of physics. This realization opens the way to a systematic study of Complexity, which constitutes today a highly interdisciplinary, fast growing branch of science, drawing on the cross-fertilization of concepts and tools from nonlinear dynamics, statistical physics, probability and information theories, data analysis and numerical simulation.

Gregoire Nicolis and Catherine Rouvas-Nicolis (2007),  
Scholarpedia, 2(11):1473.

The whole is greater  
than the sum of its  
parts.



Aristotle

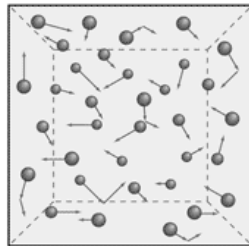
# What is a complex system?



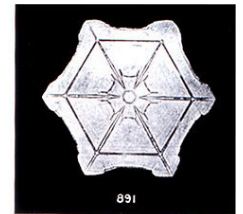
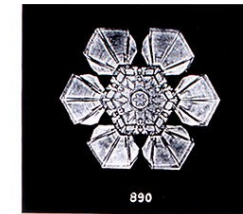
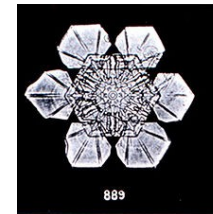
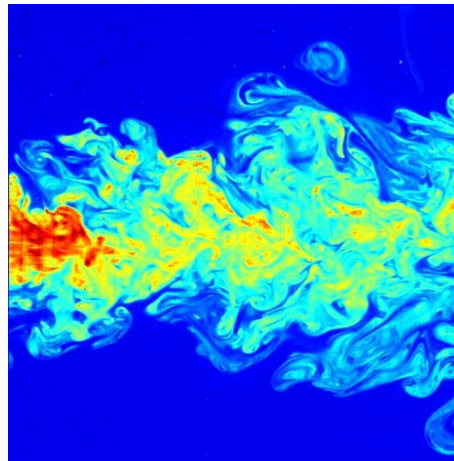
## The Ideal Gas Law

$$PV = nRT$$

- $P$  = pressure
- $V$  = volume
- $T$  = temperature
- $n$  = # of moles of gas
- $R$  = ideal gas constant  
[8.31 J/mole · K]  
[0.082 liter · atm/mole · K]

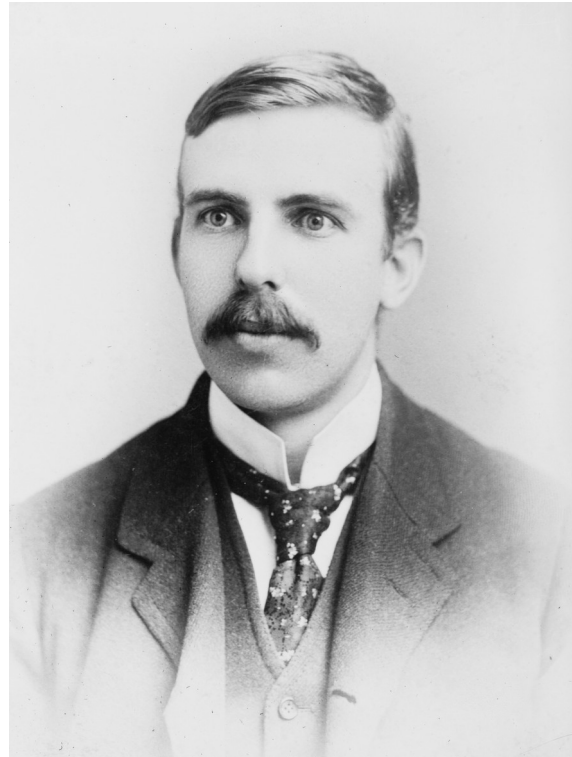


1 mole of an ideal gas occupies 22.4 liters at STP.



# What is a complex system?

All science is either physics or stamp collecting.



Ernest Rutherford (1908)

When we have found how the nucleus of atoms is built up we shall have found the greatest secret of all - except life.

# What is a complex system?

## Emergence

In philosophy, systems theory, science, and art, emergence is a process whereby larger entities, patterns, and regularities arise through interactions among smaller or simpler entities that themselves do not exhibit such properties.

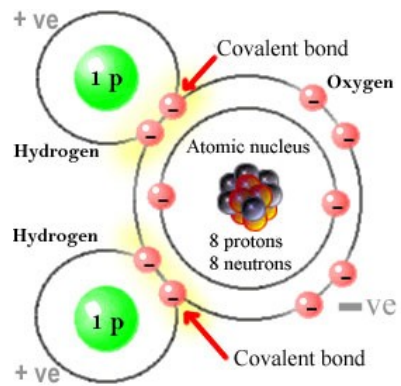
Emergence is central in theories of integrative levels and of complex systems. For instance, the phenomenon life as studied in biology is commonly perceived as an emergent property of interacting molecules as studied in chemistry, whose phenomena reflect interactions among elementary particles, modeled in particle physics, that at much higher mass—via substantial conglomeration—exhibit motion as modeled in gravitational physics. Neurobiological phenomena are often presumed to suffice as the underlying basis of psychological phenomena, whereby economic phenomena are in turn presumed to principally emerge.

<https://en.wikipedia.org/wiki/Emergence>

## Reductionism vs Emergentism

# What is a complex system?

## Reductionism



## Emergentism



# What is a complex system?

## Self-organization

Self-organization is the spontaneous often seemingly purposeful formation of spatial, temporal, spatiotemporal structures or functions in systems composed of few or many components. In physics, chemistry and biology self-organization occurs in open systems driven away from thermal equilibrium. The process of self-organization can be found in many other fields also, such as economy, sociology, medicine, technology.

Many objects in our surrounding and daily life such as furniture, houses, cars, TV-sets, computers are man made. On the other hand, especially in the animate world, objects grow, acquire their form, and function without being created by humans. The animal kingdom abounds of examples. It is increasingly recognized that even the human brain may be considered as a self-organizing system as well as quite a number of manifestations of human activity, such as in economy and sociology. But processes of self-organization can be found also in the inanimate world: formation of cloud streets, planetary systems, galaxies etc. A fundamental question is: Are there general principles for self-organization?

Hermann Haken (2008), Scholarpedia, 3(8):1401.



# What is a complex system?



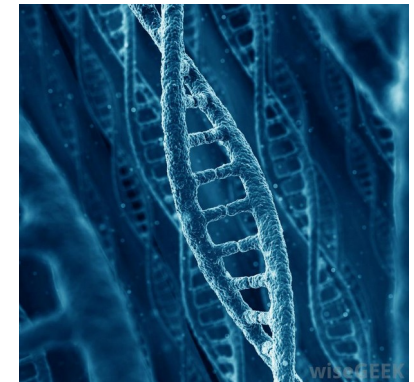
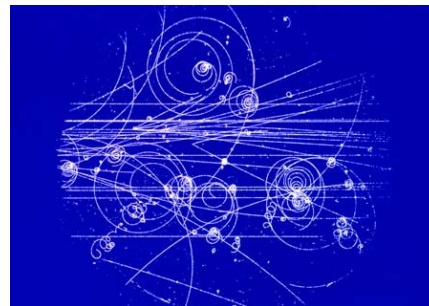
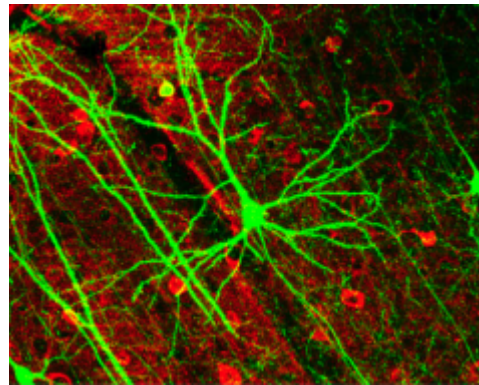
Philip W. Anderson

## More Is Different

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

P. W. Anderson

*Science* (1972) 177: 393–396.



# What is a complex system?

The rich are different from us.

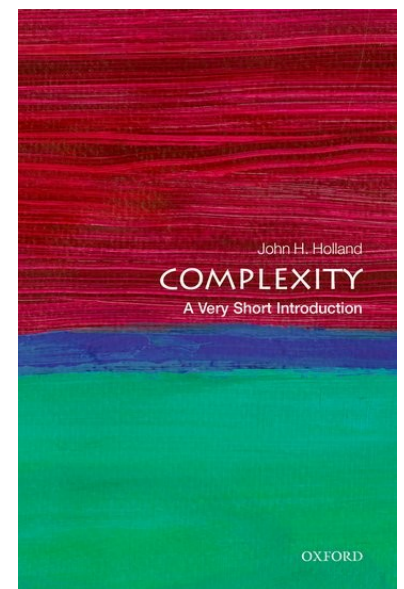
Yes: they have more money.



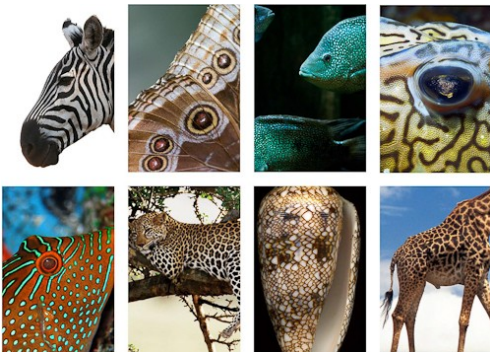
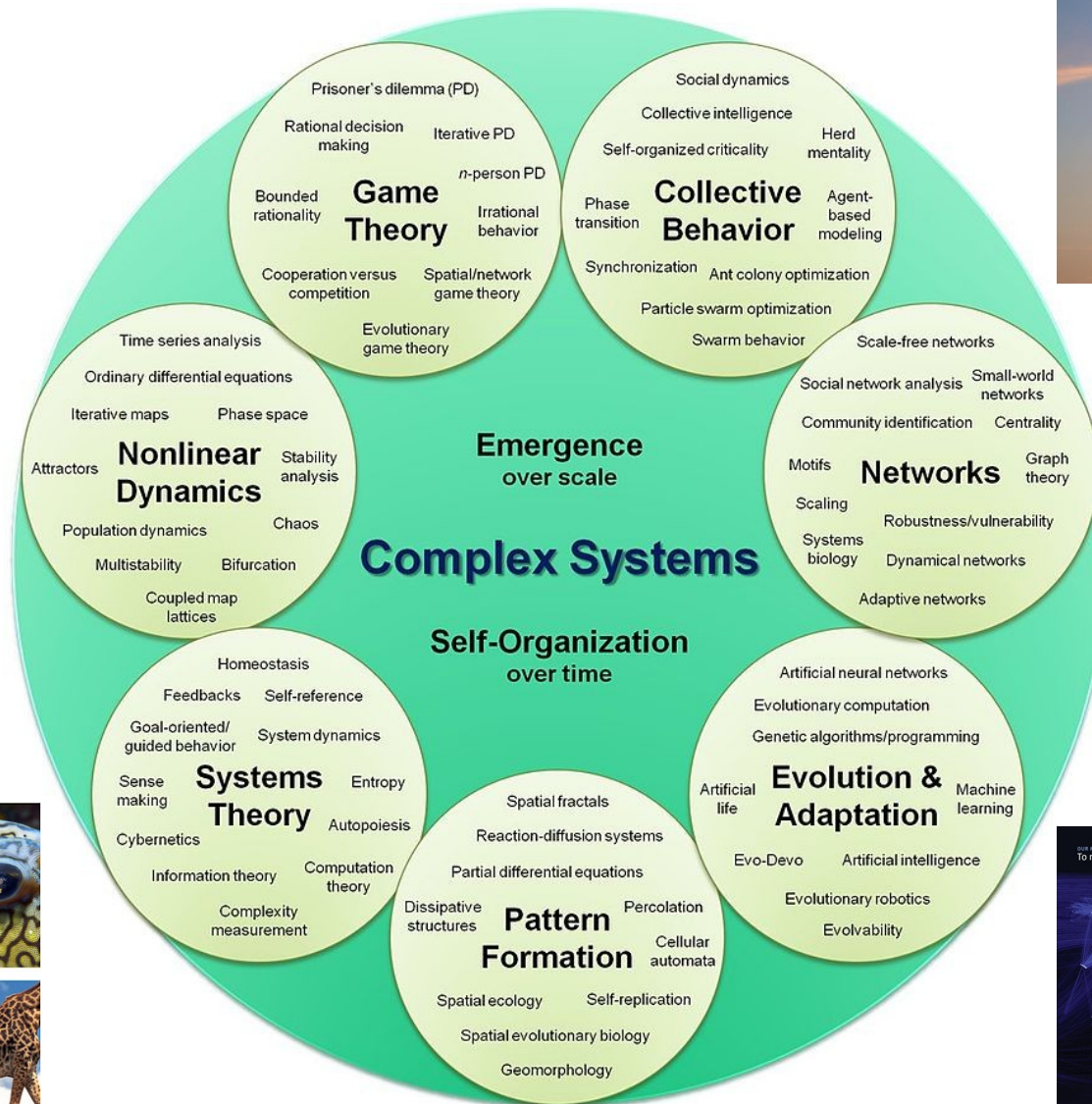
John H. Holland



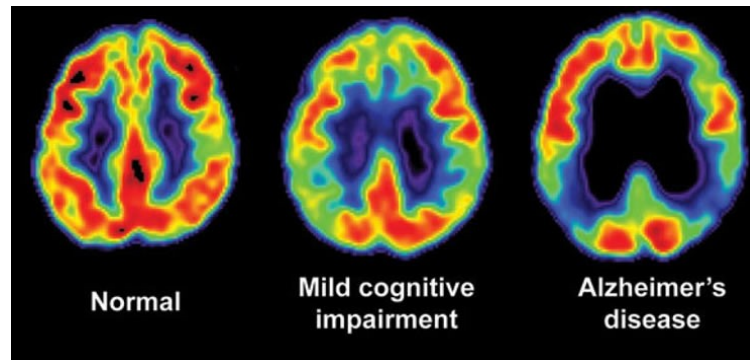
E. Hemingway & F. Scott Fitzgerald (1925)



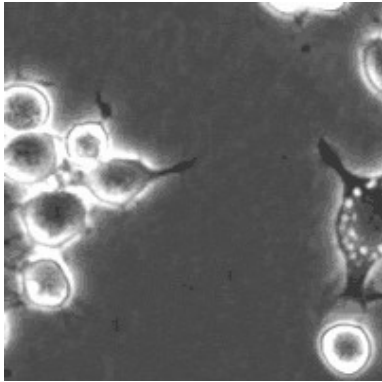
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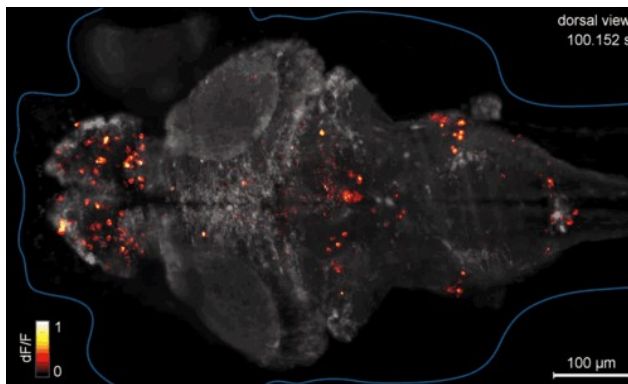
Life, biology, medicine;



Ecology, collective behaviour;



Climate, biosphere, geology;



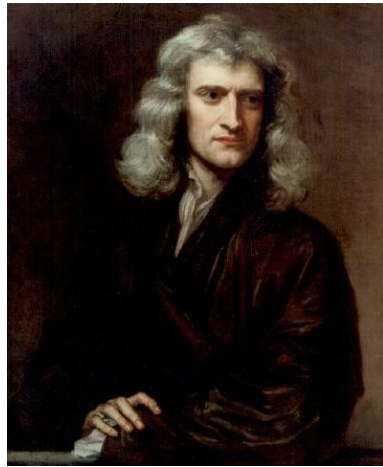
Neuroscience, the mind,  
psychology, consciousness;



Human behaviour,  
society, economy;



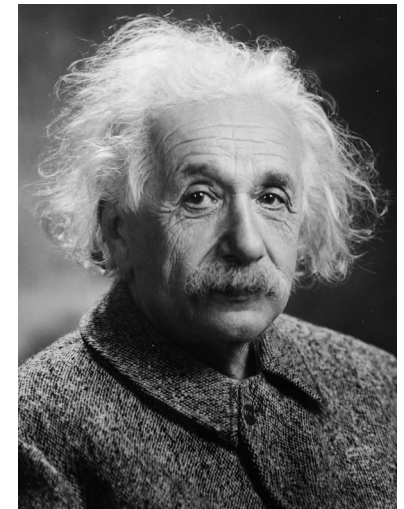
Engineering, artificial  
intelligence;



Isaac Newton

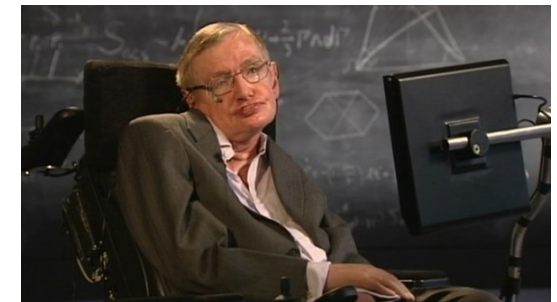
My head never ached but with my studies on the Moon.

When the number of factors coming into play in a phenomenological complex is too large scientific method in most cases fails. One need only think of the weather, in which case the prediction even for a few days ahead is impossible.



Albert Einstein

Even the smallest insect, with its intricate structure, is far more complex than either an atom or a star.

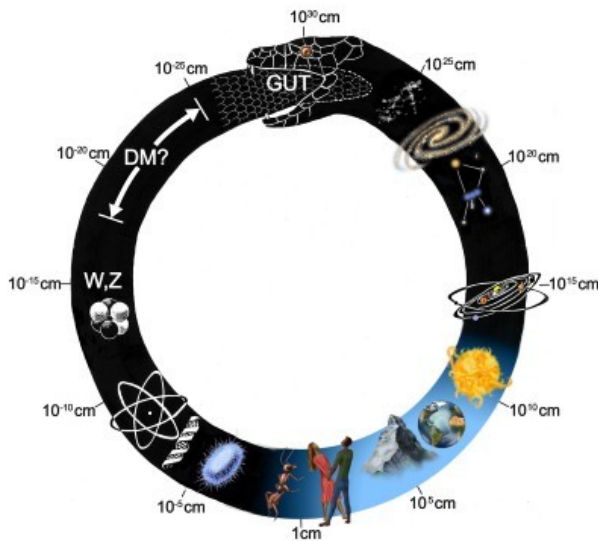


Stephen Hawking

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



Martin Rees





Shroud of Turin

Jesus of Nazareth?

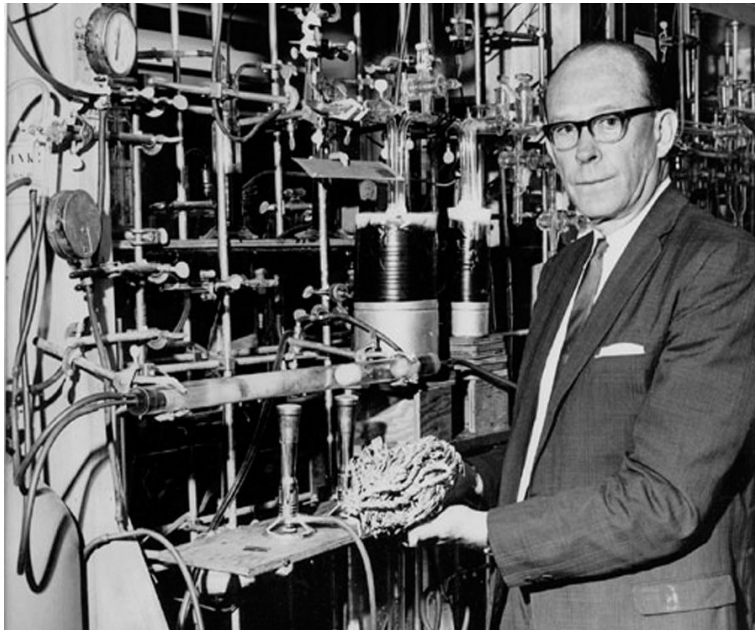
Radiocarbon dating



Made between 1260 and 1390 AD



Probably mediaeval forgery



Willard Libby  
(1908 - 1980)

Marie Curie  
(1867 - 1934)





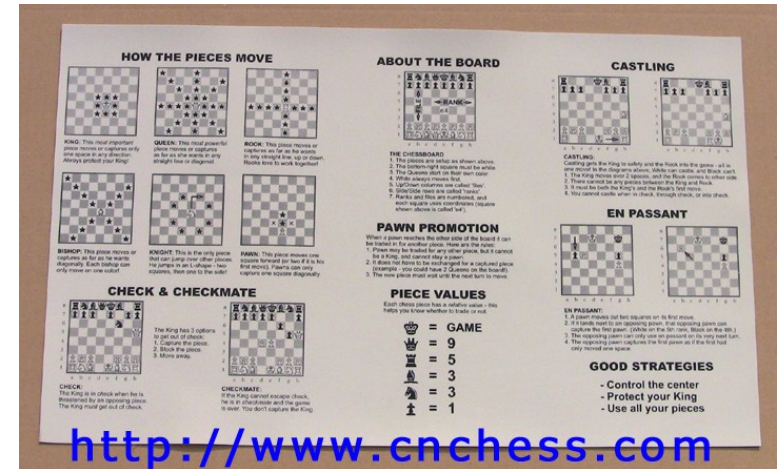
Garry Kasparov vs Deep Blue (1997)





Garry Kasparov vs Deep Blue (1997)

- Basic laws acting on simple elements: complex behaviour emerges from interactions.



12 rules, 32 pieces of 6 kinds,  
 8x8 lattice.  
 50 moves  $\sim 10^{50}$  sequences  $\gg$   
 # atoms in universe.



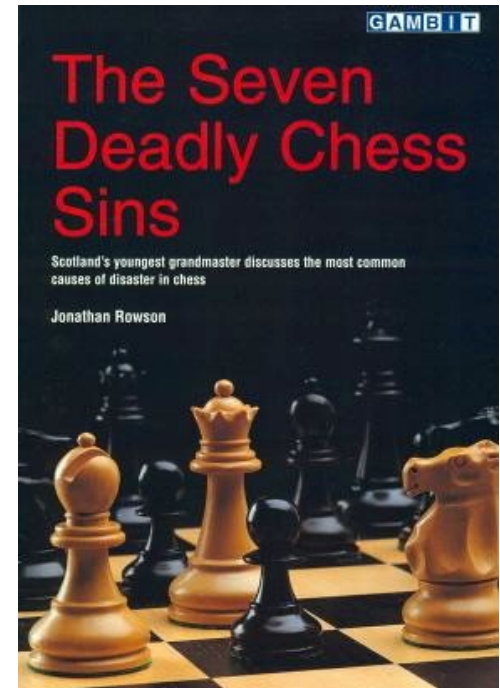
## Garry Kasparov vs Deep Blue (1997)

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- Perpetual novelty.



## Garry Kasparov vs Deep Blue (1997)

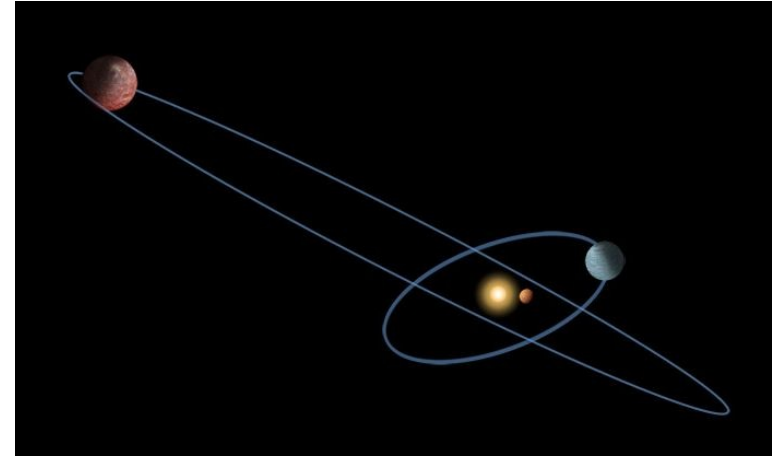
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## Garry Kasparov vs Deep Blue (1997)

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- Rules and configurations analogous to laws and states in physics.





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- Nonlinearity often makes use of PDEs difficult or impossible. Computer models or grammars natural descriptions.

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\epsilon} \quad (\text{Gauss' Law})$$

$$\nabla \cdot \mathbf{H} = 0 \quad (\text{Gauss' Law for Magnetism})$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (\text{Faraday's Law})$$

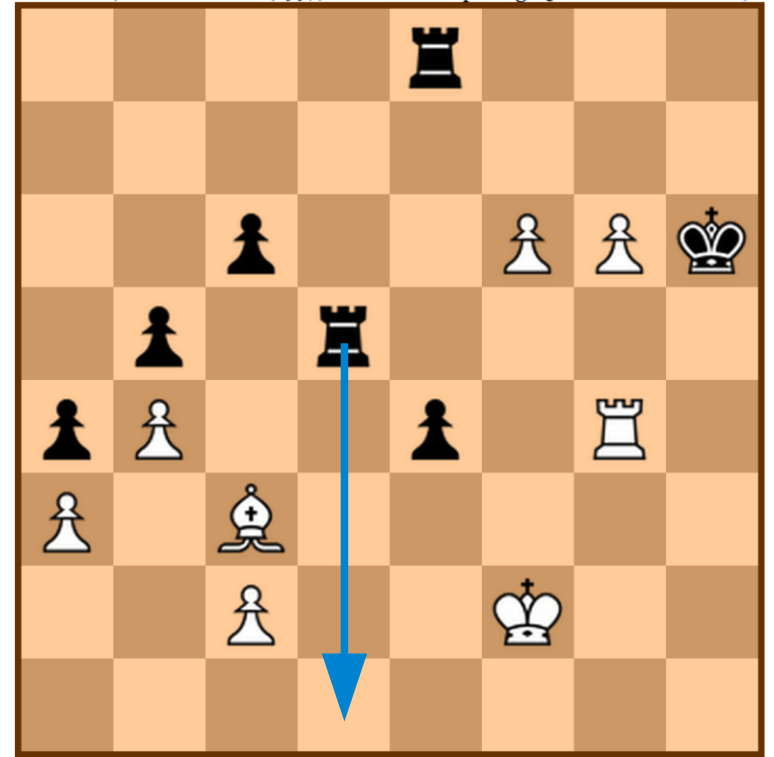
$$\nabla \times \mathbf{H} = \mathbf{J} + \epsilon \frac{\partial \mathbf{E}}{\partial t} \quad (\text{Ampere's Law})$$

1.Nf3 d5 2.g3 Bg4 3.b3 Nd7 4.Bb2 e6 5.Bg2 Ngf6  
 6.0-0 c6 7.d3 Bd6 8.Nbd2 0-0 9.h3 Bh5 10.e3 h6  
 11.Qe1 Qa5 12.a3 Bc7 13.Nh4 g5 14.Nhf3 e5 15.e4  
 Rfe8 16.Nh2 Qb6 17.Qc1 a5 18.Re1 Bd6 19.Ndf1  
 dxe4 20.dxe4 Bc5 21.Ne3 Rad8 22.Nhf1 g4 23.hxg4  
 Nxc4 24.f3 Nxe3 25.Nxe3 Be7 26.Kh1 Bg5 27.Re2  
 a4 28.b4 f5 29.exf5 e4 30.f4 Bxe2 31.fxc5 Ne5 32.g6  
 Bf3 33.Bc3 Qb5 34.Qf1 Qxf1+ 35.Rxf1 h5 36.Kg1 Kf8  
 37.Bh3 b5 38.Kf2 Kg7 39.g4 Kh6 40.Rg1 hxg4  
 41.Bxc4 Bxc4 42.Nxc4+ Nxc4+ 43.Rxc4 Rd5 44.f6  
 Rd1 45.g7 1-0



Deep Blue vs Garry Kasparov (1997)

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- Role of stochasticity.

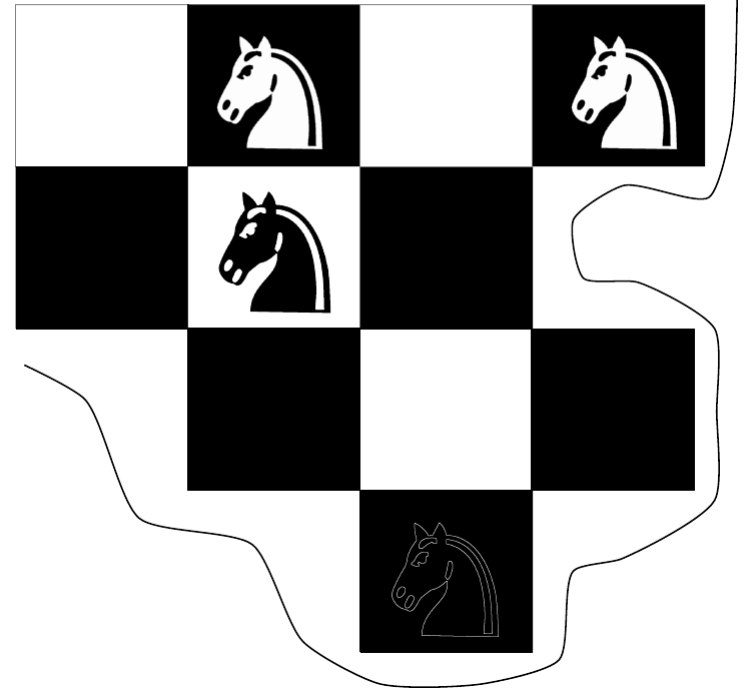




Deep Blue vs Garry Kasparov (1997)

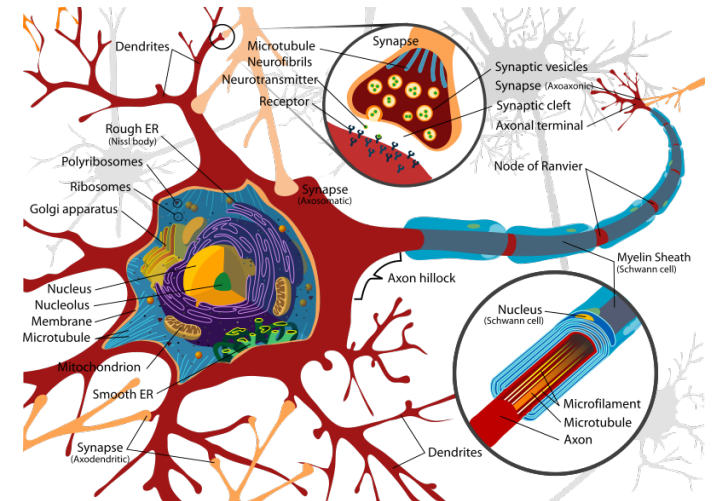
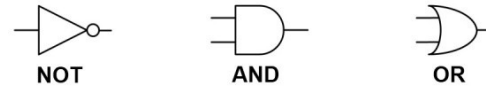
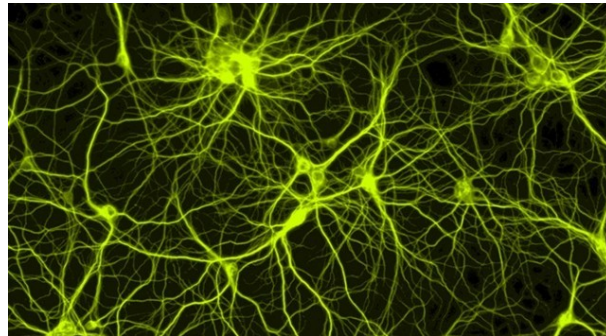
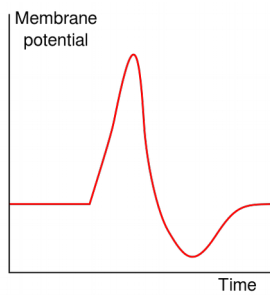
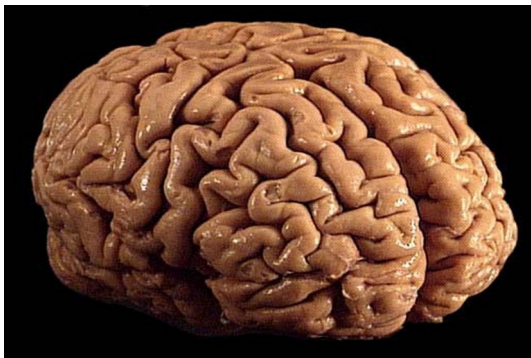
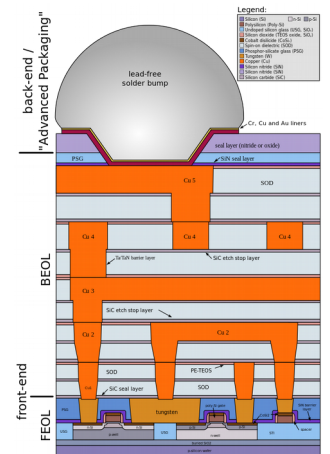
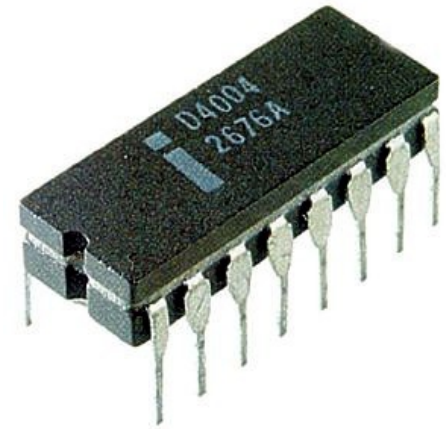
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- Nonlinearity often makes use of PDEs difficult or impossible. Computer models or grammars natural descriptions.
- Role of stochasticity.
- Importance of finding good representations.

A chess puzzle: swap the positions of black and white knights





Deep Blue vs Garry Kasparov (1997)



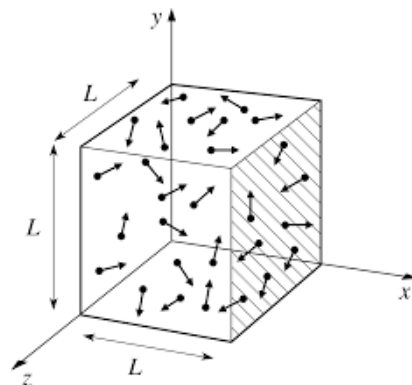
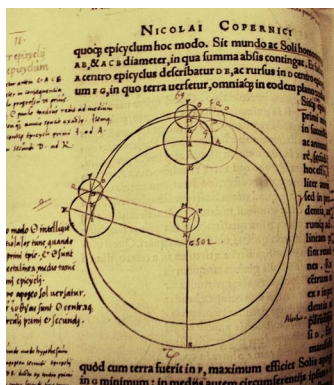
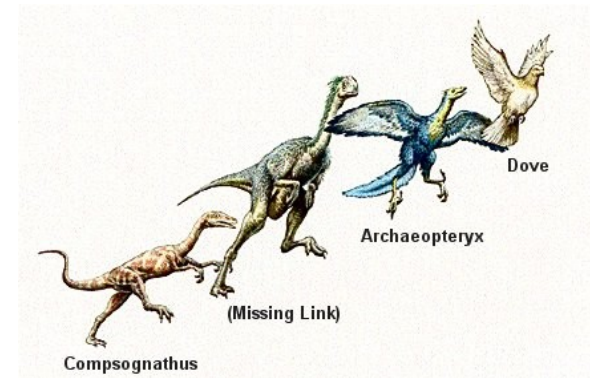
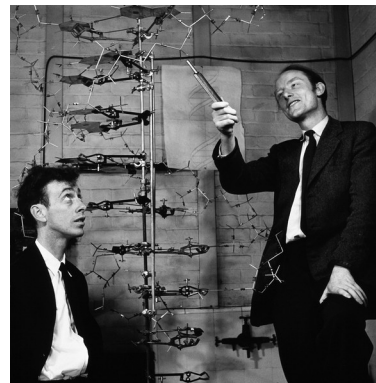
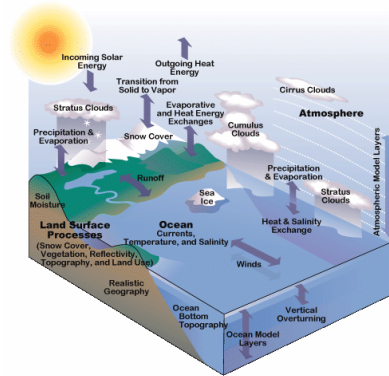
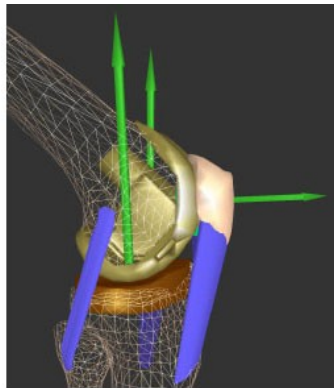


# What are models for?

Oxford Dictionary:

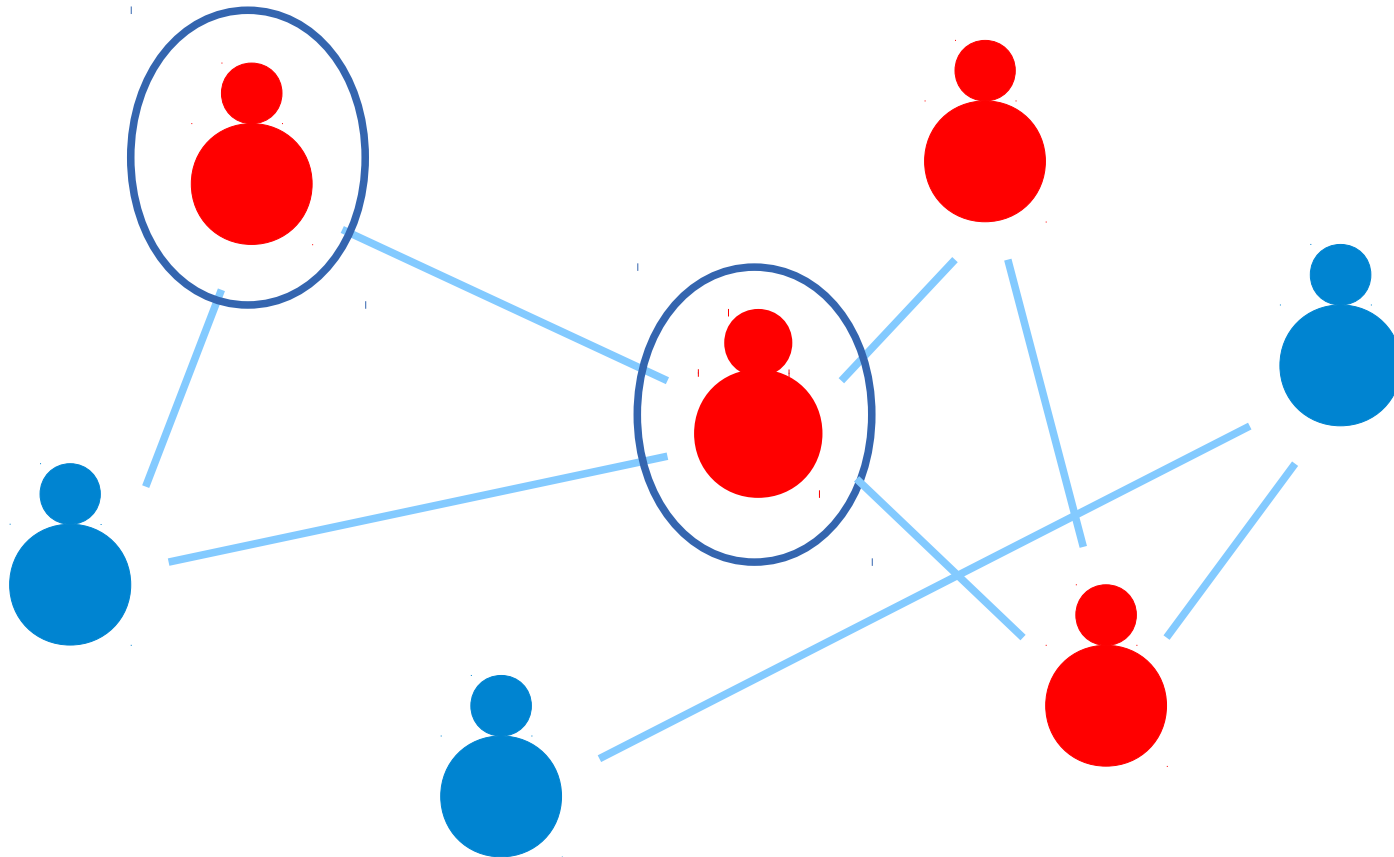
**Model** (noun): A simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions:

“a statistical model used for predicting the survival rates of endangered species”

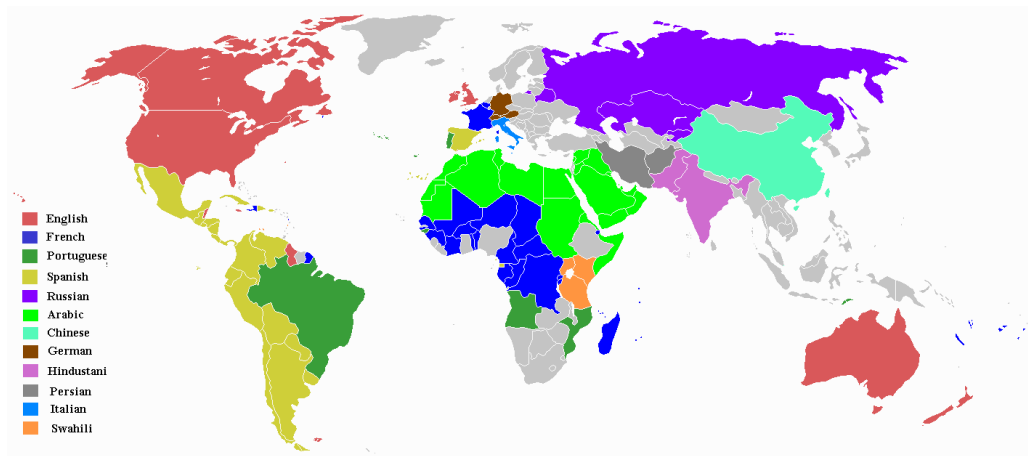
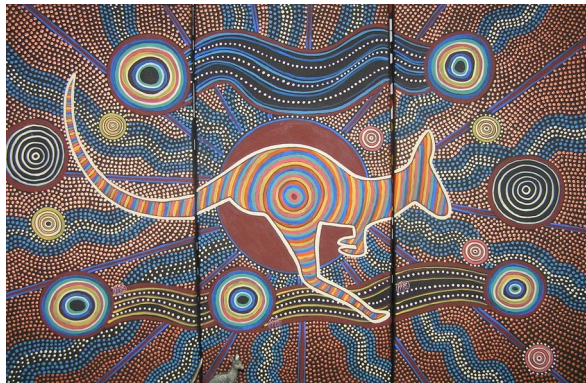


- Investigate specific real systems
- Understand underlying mechanisms

# An example: culture



# An example: culture



# An example: culture



## Axelrod's model

**The Dissemination of Culture: A Model with Local Convergence and Global Polarization**

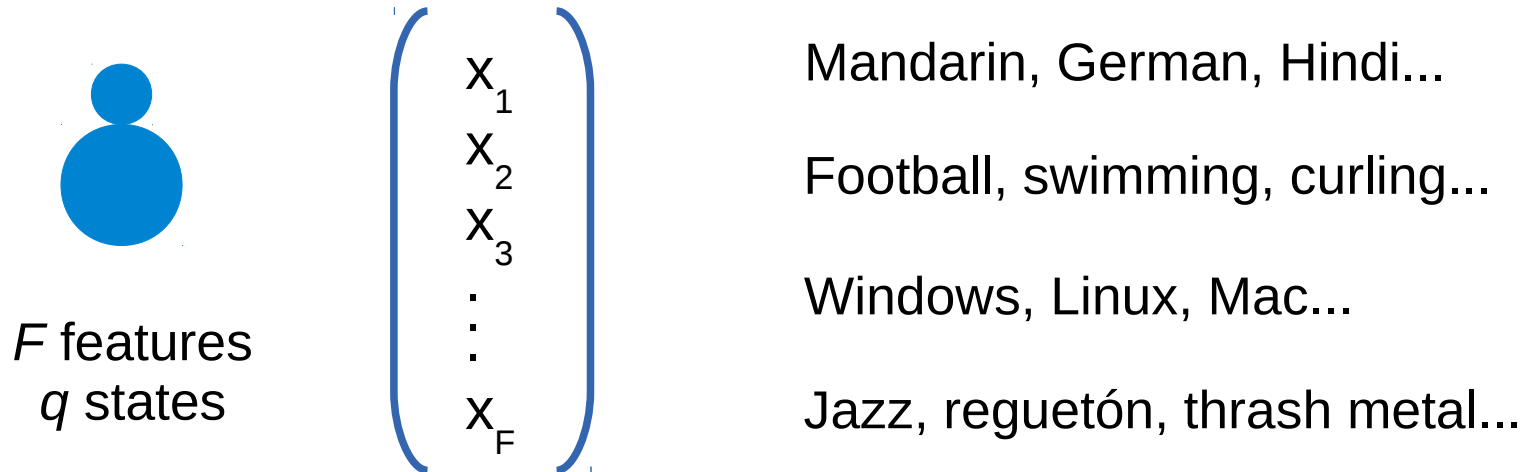
Robert Axelrod

*The Journal of Conflict Resolution*, Volume 41, Issue 2 (Apr., 1997), 203-226.



# An example: culture

## Axelrod's model



1. Choose random pair
2. If at least one feature in common, copy another one

# An example: culture

Axelrod's model

