# Thinking about Thought

## Theories of Brain, Mind, Consciousness

**May 12, 2015**

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**www.scaruffi.com**

Part 5.

Machine Intelligence

Self-organizing Systems

Relativity and Quantum Theories

# Video

Paul Wegener: Der Golem (1914) - Golem

Fritz Lang: Metropolis (1927) - Maria

Victor Fleming: The Wizard of Oz (1939) - The Tin Man

Robert Wise: The Day The Earth Stood Still (1951) - Gort

Fred Wilcox: Forbidden Planet (1956) - Robby the Robot

Kurt Neumann: Kronos (1957)

Jean-Luc Godard: Alphaville  (1965) - Alpha 60

Stanley Kubrick: 2001 A Space Odyssey (1968) - HAL

George Lucas: Star Wars (1977) - C-3P0

# Mind and Machines

Is our mind a machine?

Can we build one?

Mathematical models of the mind

- Descartes: water fountains
- Freud: a hydraulic system
- Pavlov: a telephone switchboard
- Wiener: a steam engine
- Simon: a computer

The computer is the first machine that can be programmed to perform different tasks

# A Brief History of Logic

Pythagoras’s' theorem (6th c BC): a relationship between physical quantities that is both abstract and eternal

Euclides' "Elements" (350 BC), the first system of Logic, based on just 5 axioms

Aristoteles' "Organon" (4th c BC): syllogisms

William Ockham's "Summa Totius Logicae" (1300 AD) on how people reason and learn

Francis Bacon’s "Novum Organum" (1620)

Rene' Descartes’ "Discours de la Methode" (1637): the analytic method over the dialectic method

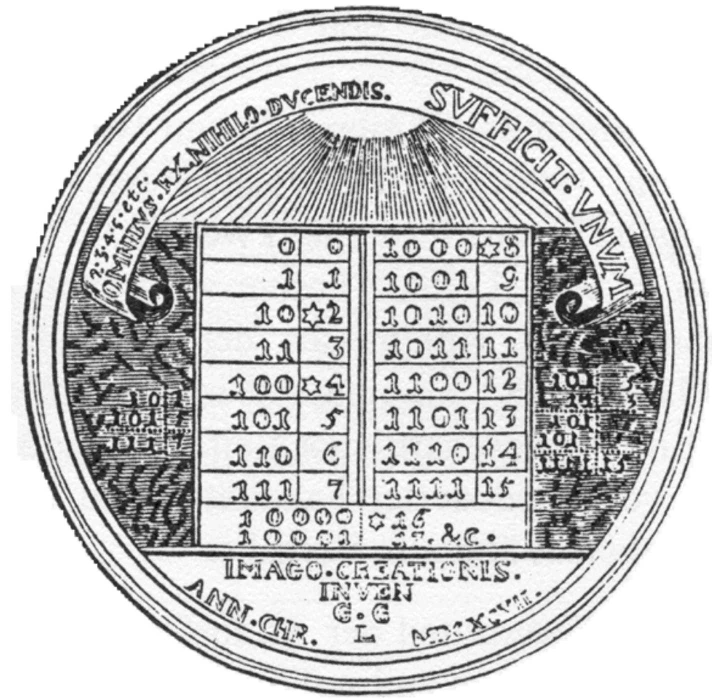
Gottfried Leibniz ‘s "De Arte Combinatoria" (1676)

Leonhard Euler (1761) how to do symbolic logic with diagrams

Augustus De Morgan's "The Foundations of Algebra" (1844)

# A Brief History of Logic

Gottfried Leibniz

# A Brief History of Logic

George Boole's "The Laws Of Thought" (1854): the laws of logic “are” the laws of thought

Propositional logic and predicate logic: true/false!

| | | |
|---|---|---|
| $F \vee G = G \vee F$; | $F \wedge G = G \wedge F$. | **commutativity** |
| $(F \vee G) \vee H = F \vee (G \vee H)$; | $(F \wedge G) \wedge H = F \wedge (G \wedge H)$. | **associativity** |
| $F \vee (G \wedge H) = (F \vee G) \wedge (F \vee H)$. | | **distributivity** |
| $F \wedge (G \vee H) = (F \wedge G) \vee (F \wedge H)$. | | **distributivity** |
| $\neg (F \vee G) = \neg F \wedge \neg G$; | $\neg (F \wedge G) = \neg F \vee \neg G$. | **De Morgan** |

**connectives** = $\{\supset, \neg, \vee, \wedge, \equiv\}$

**quantifiers** = $\{\forall, \exists\}$

$$(\exists x)\mathrm{Tet}(x)$$
$$(\forall x)(\mathrm{Tet}(x) \to \mathrm{Large}(x))$$
$$((\forall x)(\mathrm{Tet}(x) \to \mathrm{Large}(x)) \to (\mathrm{Tet}(x) \to \mathrm{Large}(x))$$
$$\mathrm{Tet}(x) \to \mathrm{Large}(x)$$
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$$\mathrm{Tet}(x) \to (\exists x)\mathrm{Large}(x)$$
$$(\exists x)\mathrm{Tet}(x) \to (\exists x)\mathrm{Large}(x)$$
$$(\exists x)\mathrm{Large}(x)$$

# A Brief History of Logic

Axiomatization of Thought:

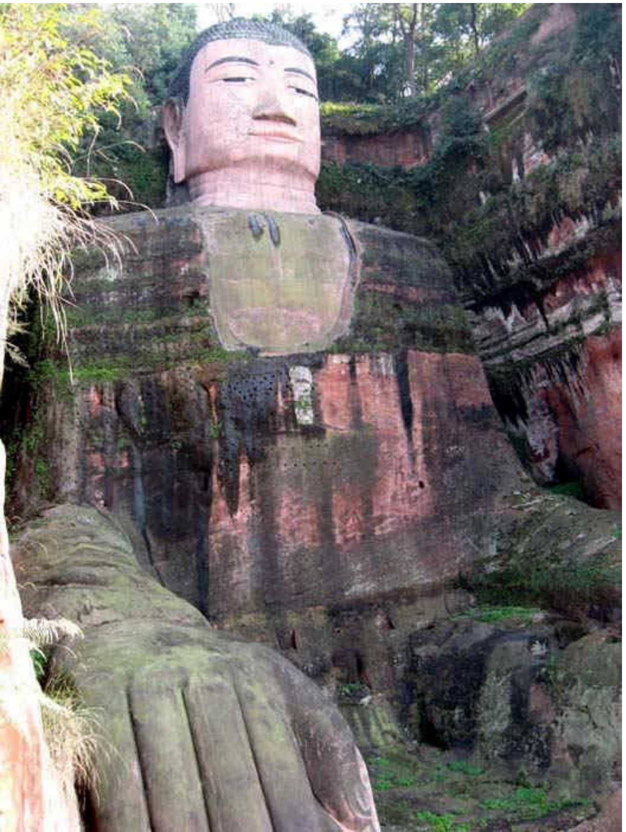
- Gottlob Frege's "Foundations of Arithmetic" (1884)
- Giuseppe Peano's "Arithmetices Principia Nova Methodo Exposita" (1889)
- Bertrand Russell's "Principia Mathematica" (1903)

# The Axiomatic Method

- David Hilbert (1928)
  - Entscheidungsproblem problem: the mechanical procedure for proving mathematical theorems
  - An algorithm, not a formula
  - Mathematics = blind manipulation of symbols
  - Formal system = a set of axioms and a set of inference rules
  - Propositions and predicates
  - Deduction = exact reasoning
  - Logic emancipated from reality by dealing purely with abstractions

# The Axiomatic Method

- Paradoxes
  - ”I am lying"
  - The class of classes that do not belong to themselves (the barber who shaves all barbers who do not shave themselves)
  - The omnipotent god



# The Axiomatic Method

- Kurt Goedel (1931)
  - Any formal system contains an “undecidable” proposition
  - A concept of truth cannot be defined within a formal system
  - Impossible to reduce logic to a mechanical procedure to prove theorems (“decision problem”)

# The Axiomatic Method

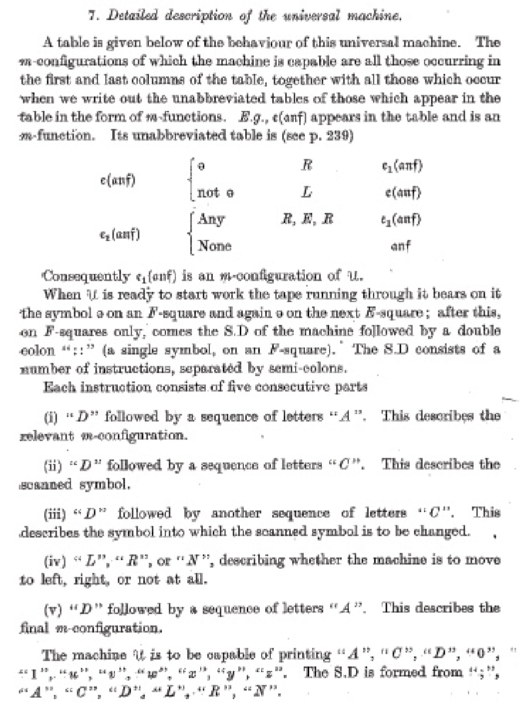
- Alan Turing (1936)
  - Hilbert's challenge (1928): an algorithm capable of solving all the mathematical problems
  - Turing Machine (1936): a machine whose behavior is determined by a sequence of symbols and whose behavior determines the sequence of symbols
  - A universal Turing machine (UTM) is a Turing machine that can simulate an arbitrary Turing machine

# The Axiomatic Method

- Alan Turing (1936)
  - Computation = the formal manipulation of symbols through the application of formal rules
  - Turing machine = a machine that is capable of performing any type of computation
  - Turing machine = the algorithm that Hilbert was looking for
  - Hilbert’s program reduced to manipulation of symbols
  - Problem solving = symbol processing

# The Axiomatic Method

- The Turing machine:
  - …an infinite tape (an unlimited memory capacity)
  - … marked out into squares, on each of which a symbol can be printed…
  - The machine can read or write one symbol at a time
  - At any moment there is one symbol in the machine, the scanned symbol
  - The machine can alter the scanned symbol based on that symbol and on a table of instructions
  - The machine can also move the tape back and forth



7. *Detailed description of the universal machine.*

A table is given below of the behaviour of this universal machine. The *m*-configurations of which the machine is capable are all those occurring in the first and last columns of the table, together with all those which occur when we write out the unabbreviated tables of those which appear in the table in the form of *m*-functions. *E.g.*, $\mathfrak{e}(\mathfrak{anf})$ appears in the table and is an *m*-function. Its unabbreviated table is (see p. 239)

| | | | |
|---|---|---|---|
| $\mathfrak{e}(\mathfrak{anf})$ | ə | $R$ | $\mathfrak{e}_1(\mathfrak{anf})$ |
| | not ə | $L$ | $\mathfrak{e}(\mathfrak{anf})$ |
| $\mathfrak{e}_1(\mathfrak{anf})$ | Any | $R, E, R$ | $\mathfrak{e}_1(\mathfrak{anf})$ |
| | None | | $\mathfrak{anf}$ |

Consequently $\mathfrak{e}_1(\mathfrak{anf})$ is an *m*-configuration of $\mathfrak{U}$.

When $\mathfrak{U}$ is ready to start work the tape running through it bears on it the symbol ə on an *F*-square and again ə on the next *E*-square; after this, on *F*-squares only, comes the S.D of the machine followed by a double colon "::" (a single symbol, on an *F*-square). The S.D consists of a number of instructions, separated by semi-colons.

Each instruction consists of five consecutive parts

(i) "*D*" followed by a sequence of letters "*A*". This describes the relevant *m*-configuration.

(ii) "*D*" followed by a sequence of letters "*C*". This describes the scanned symbol.

(iii) "*D*" followed by another sequence of letters "*C*". This describes the symbol into which the scanned symbol is to be changed.

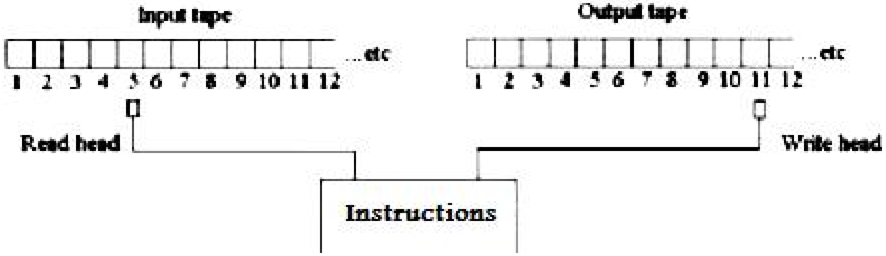
(iv) "*L*", "*R*", or "*N*", describing whether the machine is to move to left, right, or not at all.

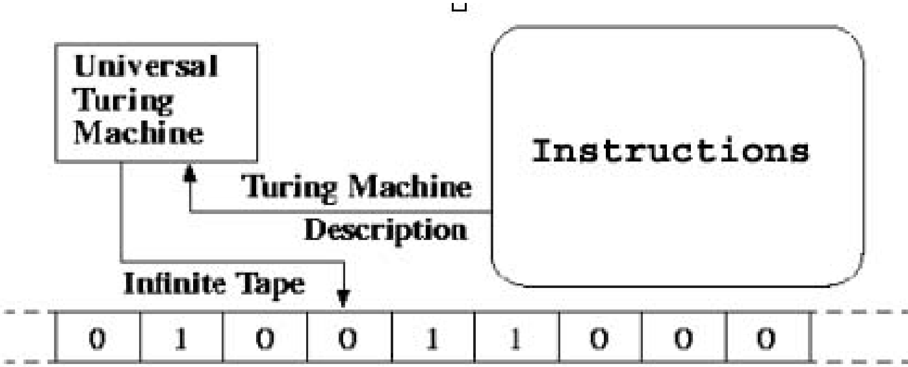
(v) "*D*" followed by a sequence of letters "*A*". This describes the final *m*-configuration.

The machine $\mathfrak{U}$ is to be capable of printing "*A*", "*C*", "*D*", "0", "1", "*u*", "*v*", "*w*", "*x*", "*y*", "*z*". The S.D is formed from ";", "*A*", "*C*", "*D*", "*L*", "*R*", "*N*".

# The Axiomatic Method

- Alan Turing (1936)
  - Universal Turing Machine: a Turing machine that is able to simulate any other Turing machine
  - The universal Turing machine reads the description of the specific Turing machine to be simulated




Turing Machine

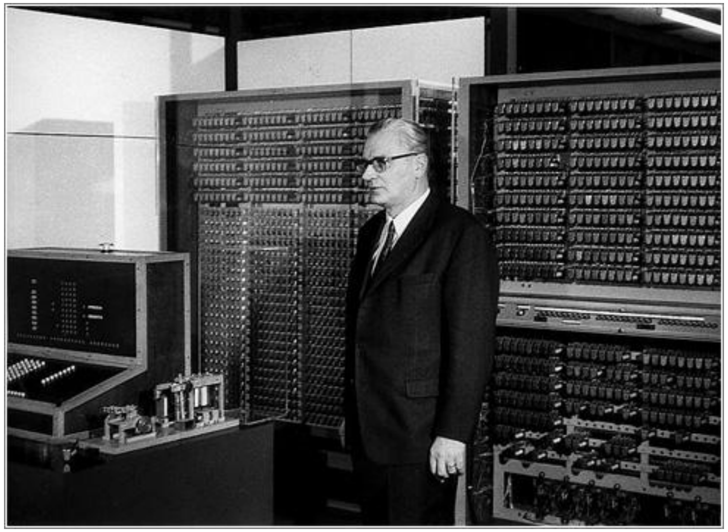
# The Axiomatic Method

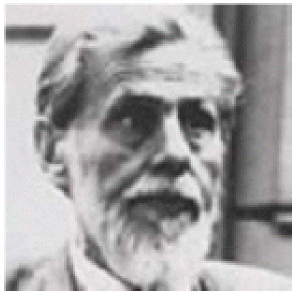
- Turing machines in nature: the ribosome, which translates RNA into proteins
  - Genetic alphabet: nucleotides ("bases"): A, C, G, U
  - The bases are combined in groups of 3 to form "codons“
  - RNA is composed of a string of nucleotides ("bases") according to certain rules
  - There are special carrier molecules ("tRNA") that are attached to specific aminoacids (proteins)
  - The start codon encodes the aminoacid Methionine
  - A codon is matched with a specific tRNA
  - The new aminoacid is attached to the protein
  - The tape then advances 3 bases to the next codon, and the process repeats
  - The protein keeps growing
  - When the “stop” codon is encountered, the ribosome dissociates from the mRNA

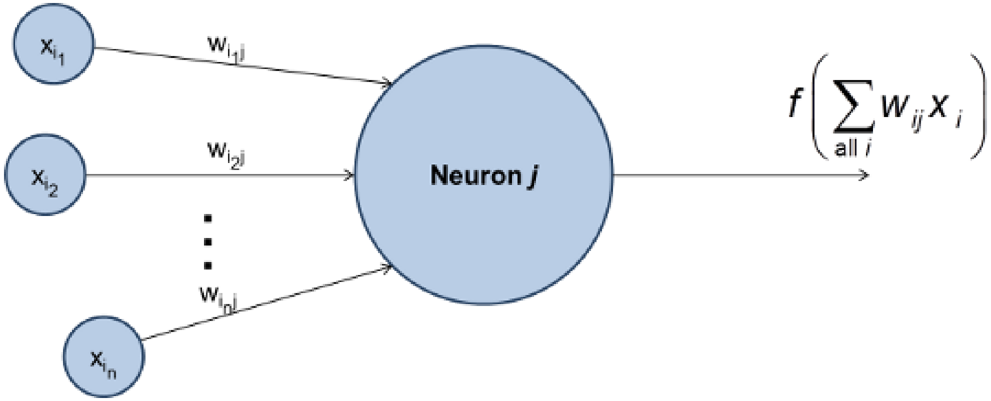
# Computer Science

1941: Konrad Zuse's Z3 programmable electronic computer

1943: Warren McCulloch's and Walter Pitts' binary neuron



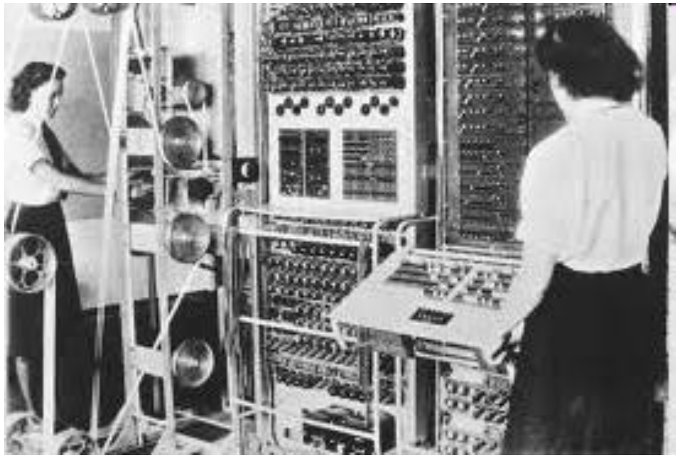




# Computer Science

Replica of the Bombe

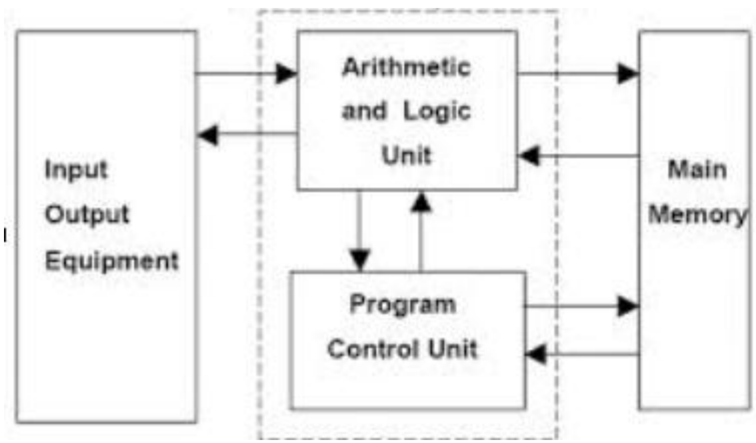
- World War II:
  - Breaking the Enigma code (Bombe)
  - Turing worked at Bletchley Park where the Colossus was built but it was not a universal Turing machine (not general purpose)

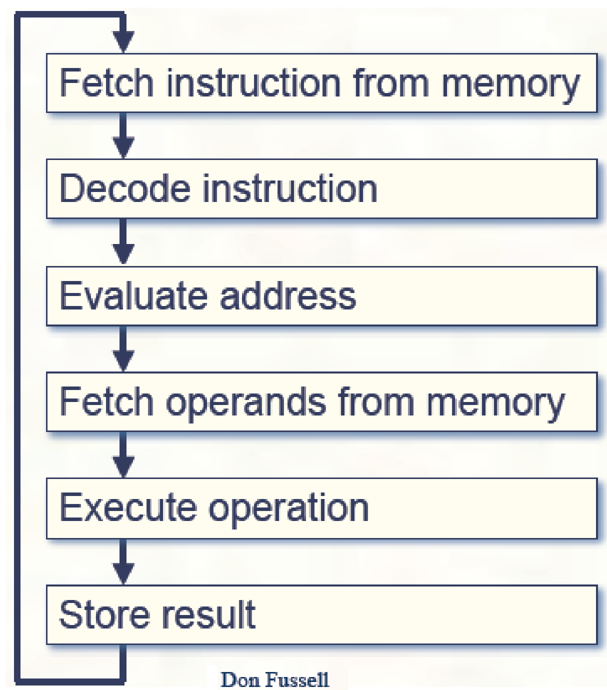


# Computer Science

## 1945: John Von Neumann's computer architecture

- Separation of instructions and data (although both are sequences of 0s and 1s)
- Sequential processing

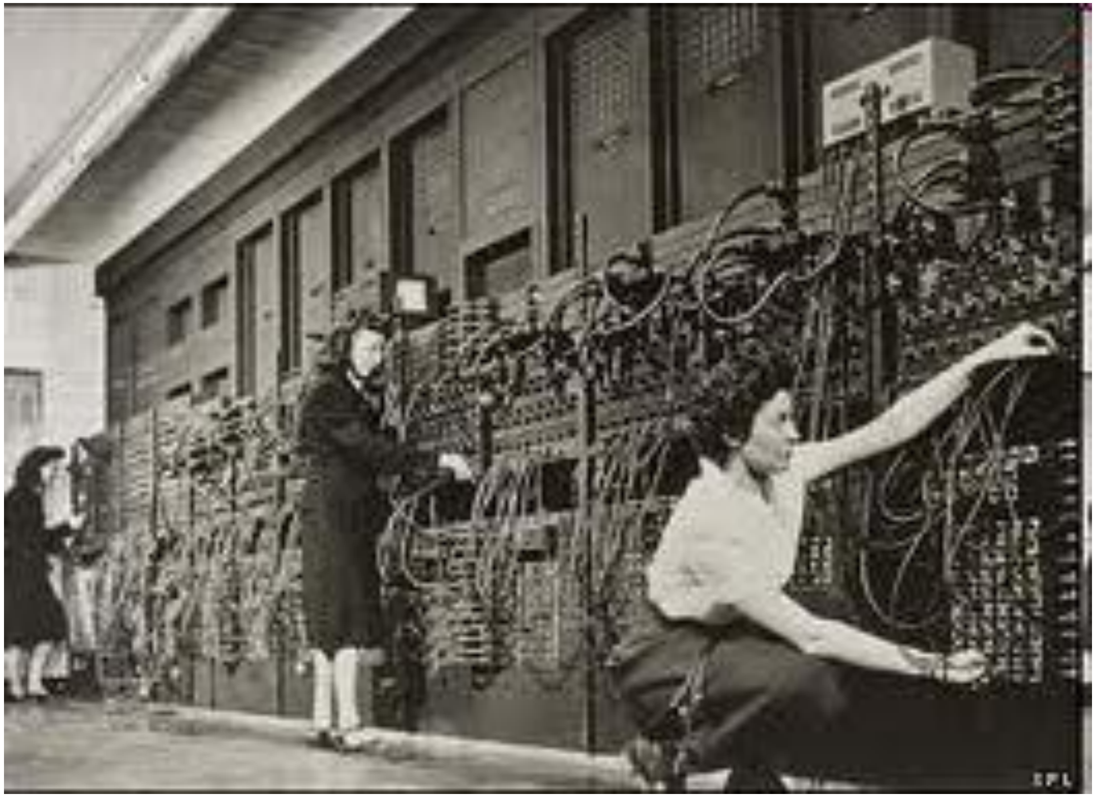



Control unit:
- reads an instruction from memory
- interprets/executes the instruction
- signals the other components what to do

# Computer Science

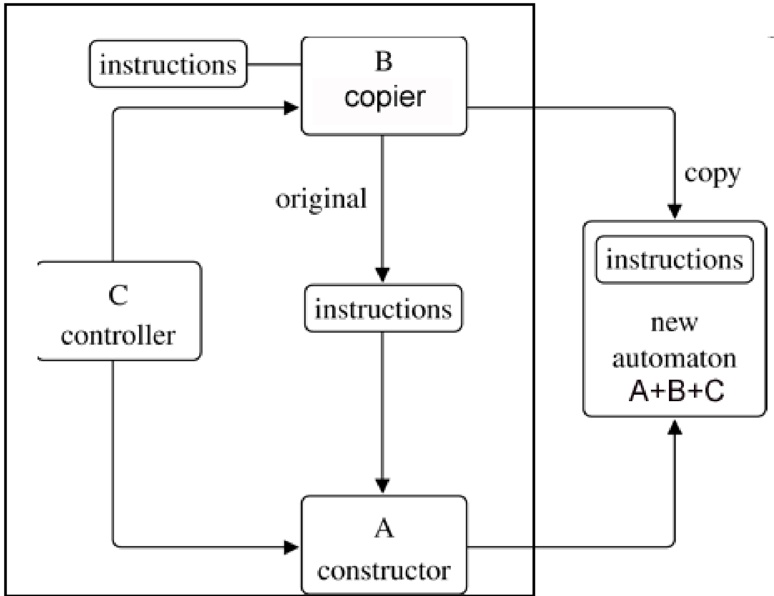
- The first non-military computer, ENIAC, by John Mauchly and Presper Eckert (1946)



# Computer Science

1947: John Von Neumann's self-reproducing automata

1. A universal constructor A, which can construct another automaton according to instruction I.
2. A copier B, which can make a copy of the instruction tape I.
3. A controller C, which combines A and B and allows A to construct a new automaton according to I, B to copy instructions from I and attach them to the newly created automaton
4. An instruction tape describing how to construct automaton A+B+C



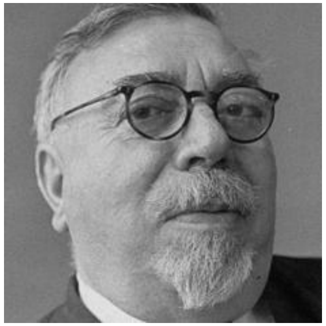
# Cybernetics

1943: Beginning of Cybernetics

1946: The first Macy Conference on Cybernetics

- John von Neumann (computer science),
- Norbert Wiener, Walter Pitts (mathematics),
- Rafael Lorente de No, Ralph Gerard, etc (neurology),
- Warren McCulloch (neuropsychiatry),
- Gregory Bateson, Margaret Mead (anthropology),
- Heinrich Kluever, Lawrence Kubie, etc (psychology)
- Filmer Northrop (philosophy),
- Lawrence Frank, Paul Lazarsfeld (sociology)

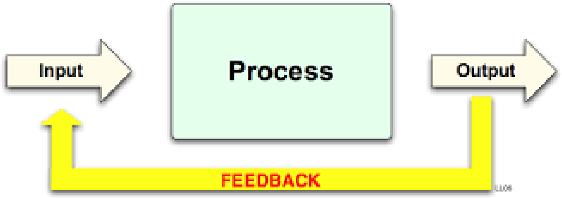
# Cybernetics



Norbert Wiener (1947)

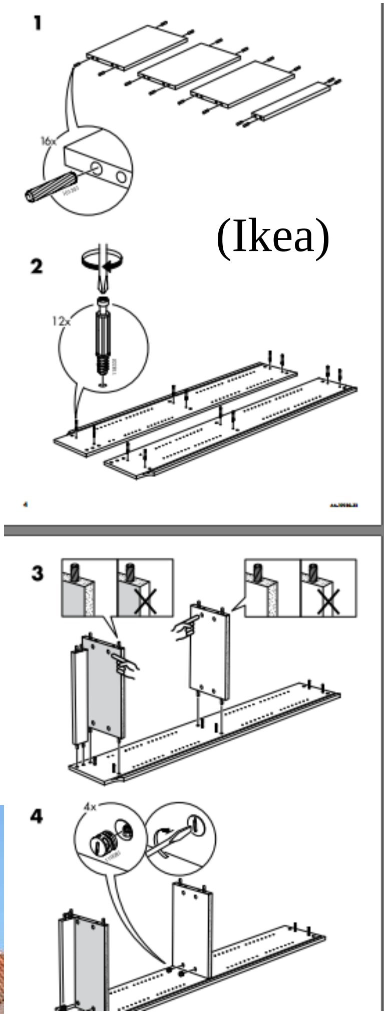
- To unify machines and nature, "artificial" systems and natural systems
- Feedback, by sending back the output as input, helps control the work of the machine
- A control system  is realized by a loop of action and feedback
- A control system is capable of achieving a "goal", is capable of "purposeful" behavior
- Living organisms are control systems
- Your brain is a control system

vs



# Cybernetics

- Paradigm shift from the world of continuous laws to the discrete world of algorithms
- The effect of an algorithm is to turn time's continuum into a sequence of discrete quanta, and, correspondingly, to turn an analog instrument into a digital instrument
- A watch is the digital equivalent of a sundial: the sundial marks the time in a continuous way, the watch advances by units.




(Ikea)

# Cybernetics

Cybernetics

- An analog instrument can be precise, and there is no limit to its precision.
- A digital instrument can only be approximate, its limit being the smallest magnitude it can measure




Titan Octane 9308KM01

# Cybernetics

Ross Ashby (1952)

- Both machines and living beings tend to change in order to compensate variations in the environment, so that the combined system is stable
- The "functioning" of both living beings and machines depends on feedback processes
- The system self-organizes

# Information Theory

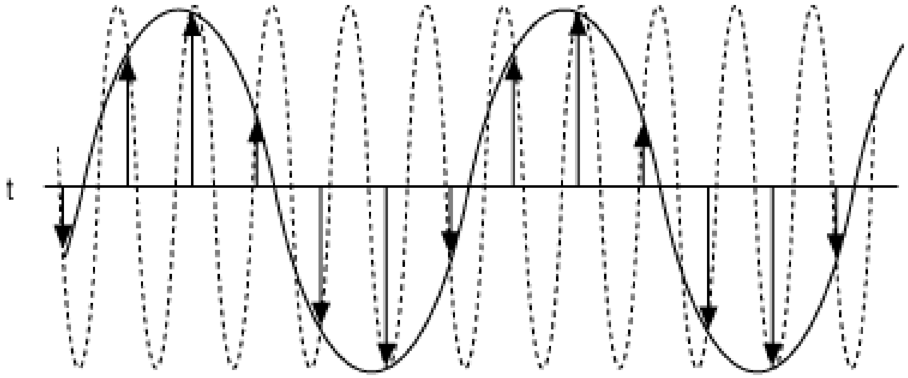
Claude Shannon (1949)

- Shannon defines information as chaos (entropy), Wiener and Brillouin define information as order (negentropy)

# Information Theory

Vladimir Kotelnikov (1933)

- The “Nyquist–Shannon” sampling theorem: how to convert continuous signals (analog domain) into discrete signals (digital domain) and back without losing fidelity



# Questions?

# History of Artificial Intelligence

1950: Alan Turing's "Computing Machinery and Intelligence" (the "Turing Test")

A. M. Turing (1950) Computing Machinery and Intelligence. *Mind 49:* 433-460.

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**COMPUTING MACHINERY AND INTELLIGENCE**

**By A. M. Turing**

**1. The Imitation Game**

I propose to consider the question, "Can machines think?" This should begin with definitions of the meaning of the terms "machine" and "think." The definitions might be framed so as to reflect so far as possible the normal use of the words, but this attitude is dangerous, If the meaning of the words "machine" and "think" are to be found by examining how they are commonly used it is difficult to escape the conclusion that the meaning and the answer to the question, "Can machines think?" is to be sought in a statistical survey such as a Gallup poll. But this is absurd. Instead of attempting such a definition I shall replace the question by another, which is closely related to it and is expressed in relatively unambiguous words.

# History of Artificial Intelligence

The Turing Test (1950)

- A machine can be said to be “intelligent” if it behaves exactly like a human being
- Hide a human in a room and a machine in another room and type them questions: if you cannot find out which one is which based on their answers, then the machine is intelligent

VOL. LIX. No. 236.] [October, 1950

MIND

A QUARTERLY REVIEW

OF

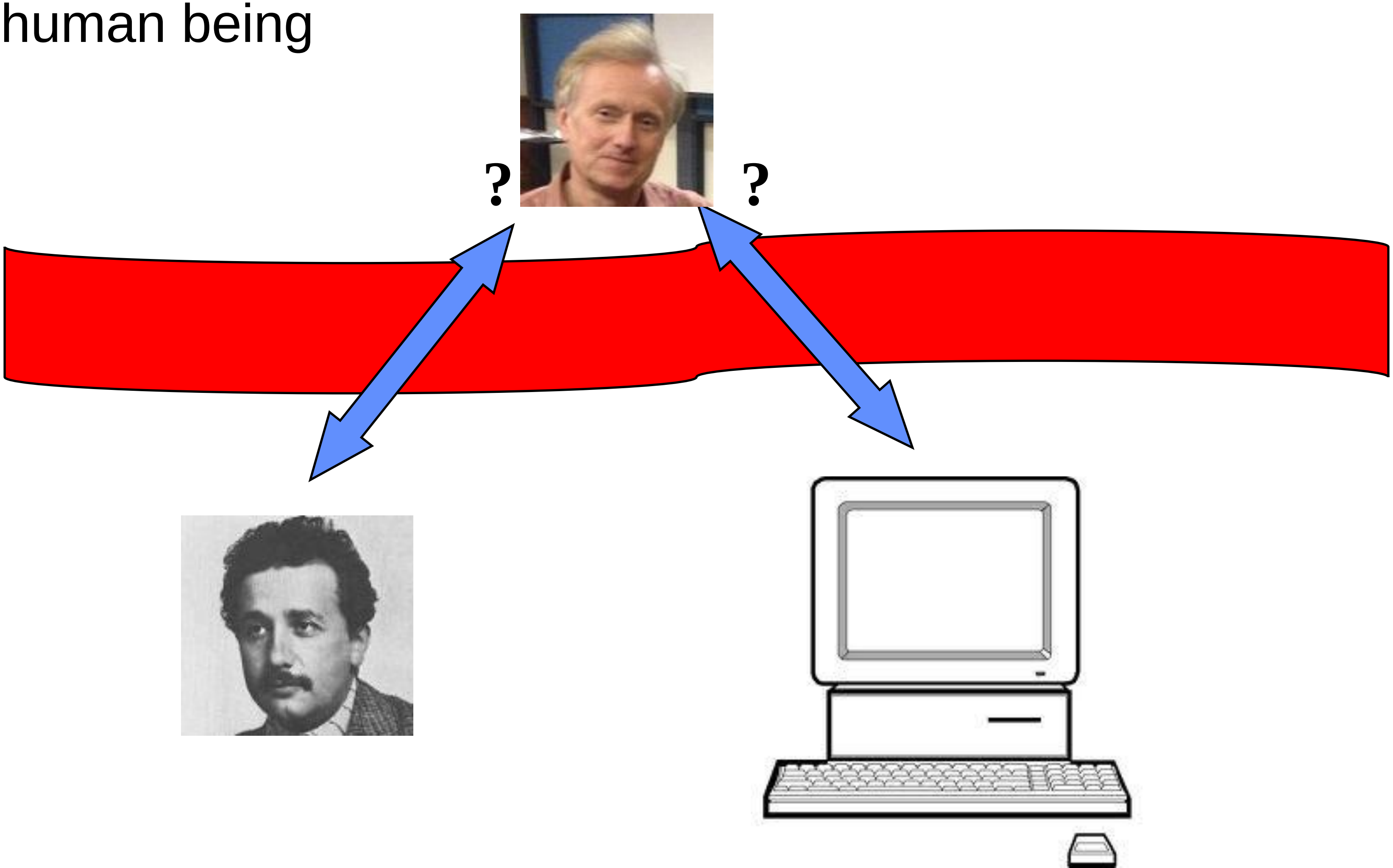
PSYCHOLOGY AND PHILOSOPHY

I.—COMPUTING MACHINERY AND INTELLIGENCE

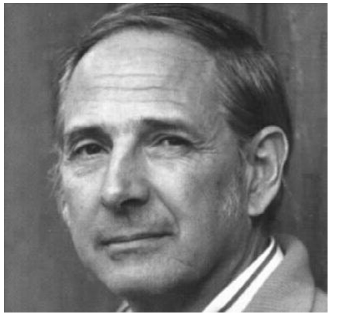
BY A. M. TURING

# History of Artificial Intelligence

The “Turing point”: a computer can be said to be intelligent if its answers are indistinguishable from the answers of a human being



# History of Artificial Intelligence



The Turing Test

- John Searle’s Chinese room (1980)
  - Whatever a computer is computing, the computer does not "know" that it is computing it
  - A computer does not know what it is doing, therefore “that” is not what it is doing
  - Objection: The room + the machine “knows”

# History of Artificial Intelligence

The Turing Test

- Hubert Dreyfus (1972):
  - Experience vs knowledge
  - Meaning is contextual
  - Novice to expert
  - Minds do not use a theory about the everyday world
  - Know-how vs know that

- Terry Winograd
  - Intelligent systems act, don't think.
  - People are “thrown” in the real world

# History of Artificial Intelligence

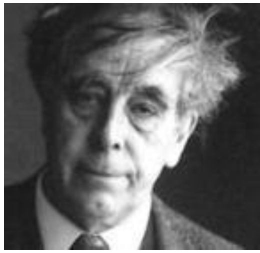
The Turing Test

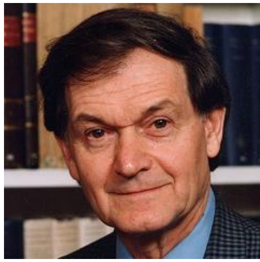
- Rodney Brooks (1986)
  - Situated reasoning
  - Intelligence cannot be separated from the body.
  - Intelligence is not only a process of the brain, it is embodied in the physical world
  - Cognition is grounded in the physical interactions with the world
  - There is no need for a central representation of the world
  - Objection: Brooks' robots can't do math

# History of Artificial Intelligence

The Turing Test

- John Randolph Lucas (1961) & Roger Penrose
  - Goedel’s limit: Every formal system (>Arithmetic) contains a statement that cannot be proved
  - Some logical operations are not computable, nonetheless the human mind can treat them (at least to prove that they are not computable)
  - The human mind is superior to a computing machine





# History of Artificial Intelligence

The Turing Test

- John Randolph Lucas (1961) & Roger Penrose
  - Objection: a computer can observe the failure of “another” computer’s formal system
  - Goedel’s theorem is about the limitation of the human mind: a machine that escapes Goedel’s theorem can exist and can be discovered by humans, but not built by humans

# History of Artificial Intelligence

The Turing Test

- What is measured: intelligence, cognition, brain, mind, or consciousness?
- What is measured: one machine, ..., all machines?
- What is intelligence? What is a brain? What is a mind? What is life?
- Who is the observer? Who is the judge?
- What is the instrument (instrument = observer)?
- What if a human fails the Turing test?

# History of Artificial Intelligence

The ultimate Turing Test

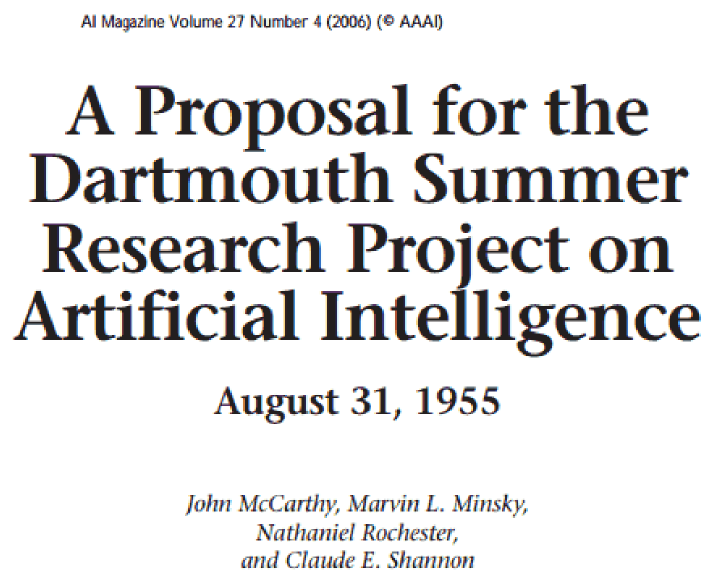
- Build a machine that reproduces my brain, neuron by neuron, synapses by synapses
- Will that machine behave exactly like me?
- If yes, is that machine “me”?

# History of Artificial Intelligence

1954: Demonstration of a machine-translation system by Leon Dostert's team at Georgetown University and Cuthbert Hurd's team at IBM

1956: Dartmouth conference on Artificial Intelligence

Artificial Intelligence (1956): the discipline of building machines that are as humans



AI Magazine Volume 27 Number 4 (2006) (© AAAI)

A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence

August 31, 1955

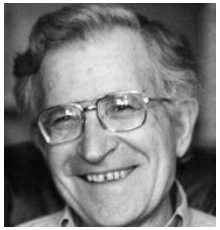
*John McCarthy, Marvin L. Minsky, Nathaniel Rochester, and Claude E. Shannon*

# History of Artificial Intelligence

1956: Allen Newell and Herbert Simon demonstrate the "Logic Theorist“, the first A.I. program, that uses “heuristics” (rules of thumb) and proves 38 of the 52 theorems in Whitehead’s and Russell’s “Principia Mathematica”

1957: “General Problem Solver” (1957): a generalization of the Logic Theorist but now a model of human cognition

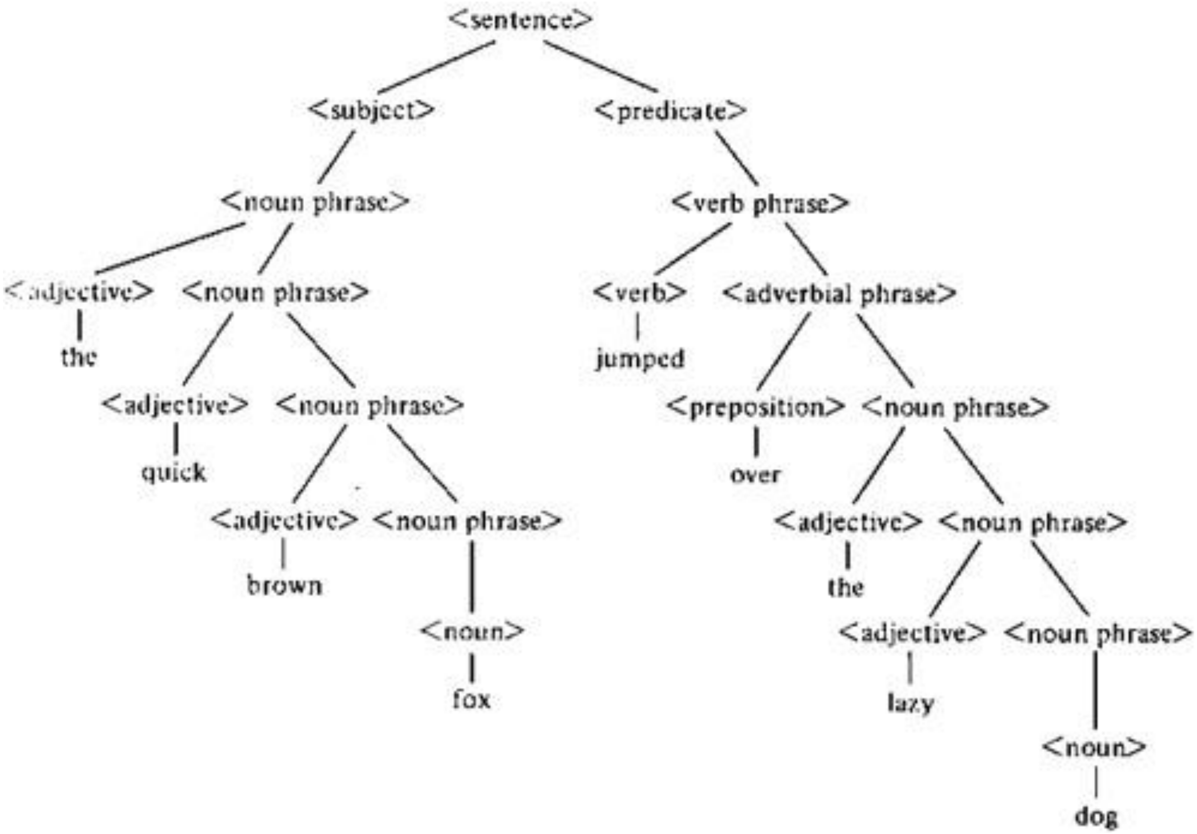
# History of Artificial Intelligence



## 1957: Noam Chomsky's "Syntactic Structures"

(1) S $\rightarrow$ NP + VP
(2) VP $\rightarrow$ Verb + NP
(3) NP $\rightarrow$ Det + N
(4) Verb $\rightarrow$ Aux + V
(5) Det $\rightarrow$ *the*, *a*, . . .
(6) N $\rightarrow$ *man*, *ball*, . . .
(7) Aux $\rightarrow$ *will*, *can*, . . .
(8) V $\rightarrow$ *hit*, *see*, . . .

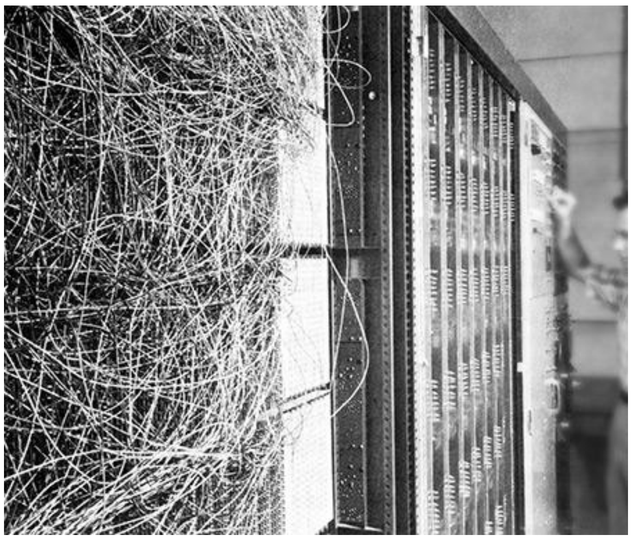
(1) $S \rightarrow A + B$
(2) $B \rightarrow C + D$
(3) $A \rightarrow a + b$
(4) $C \rightarrow c + e + f$
(5) $D \rightarrow d + g + h$

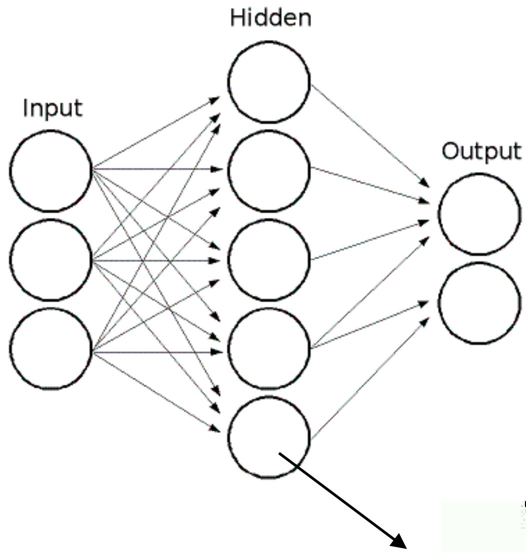


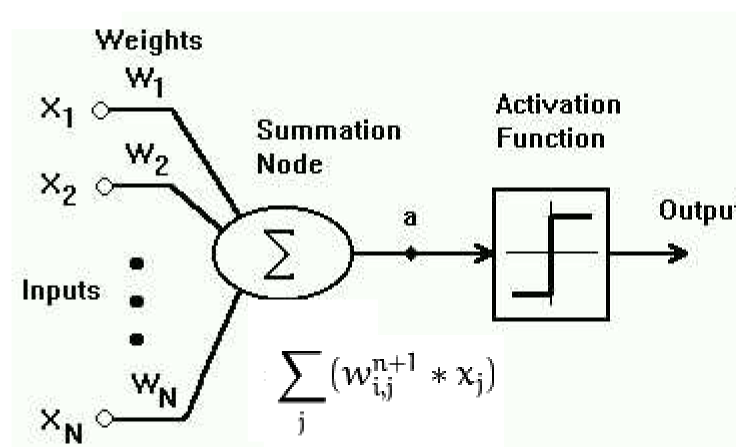

S stands for Sentence, NP for Noun Phrase, VP for Verb Phrase, Det for Determiner, Aux for Auxiliary (verb), N for Noun, and V for Verb stem

# History of Artificial Intelligence

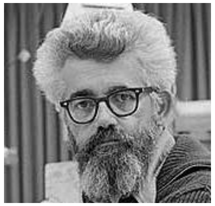
1957: Frank Rosenblatt's Perceptron, the first artificial neural network





# History of Artificial Intelligence



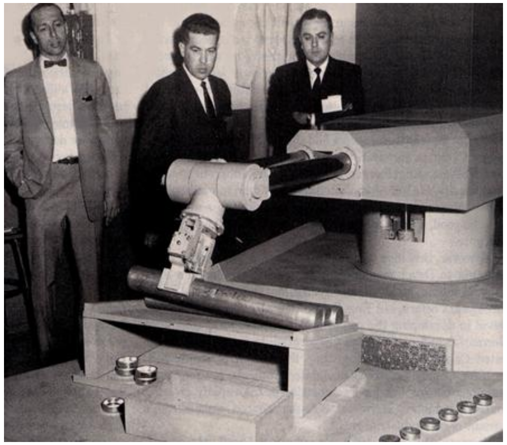
1959: John McCarthy's "Programs with Common Sense" (1949) focuses on knowledge representation

1959: Arthur Samuel's Checkers, the world's first self-learning program

1960: Hilary Putnam's Computational Functionalism

(see chapter on “Philosophy of Mind”)

1962: Joseph Engelberger deploys the industrial robot Unimate at General Motors

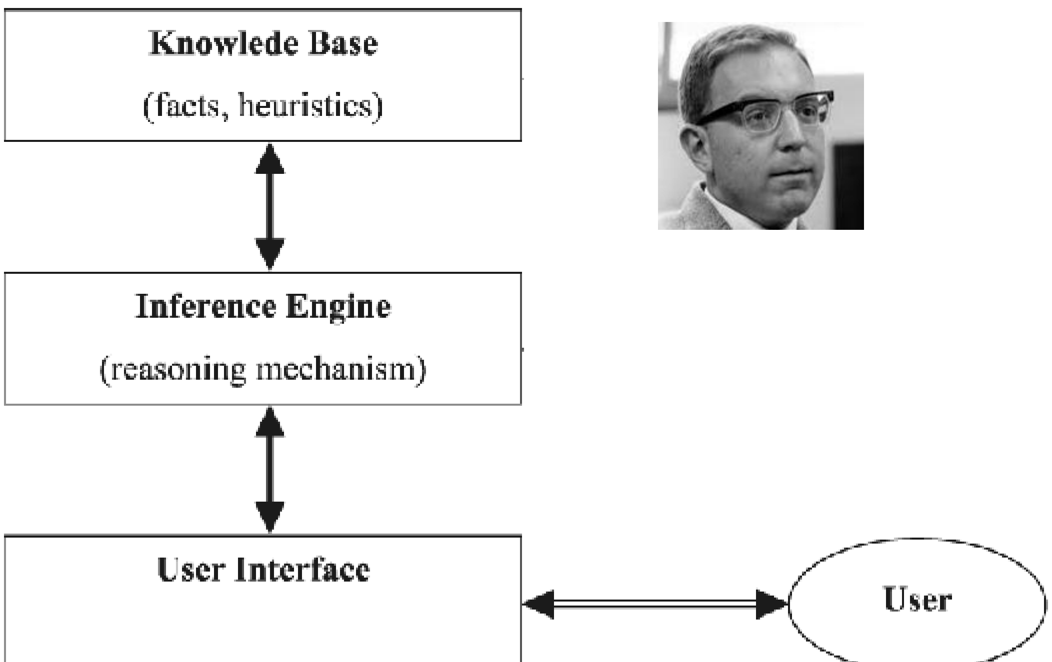


# History of Artificial Intelligence

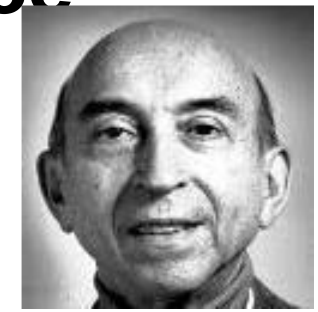
1963 Irving John Good speculates about "ultraintelligent machines" (the "singularity")

1964: IBM's "Shoebox" for speech recognition

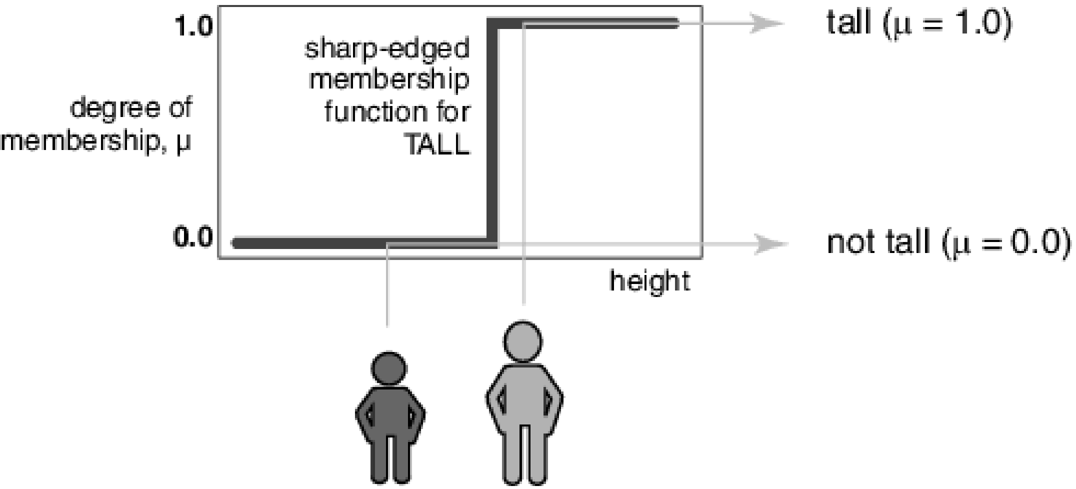
1965: Ed Feigenbaum's Dendral expert system: domain-specific knowledge

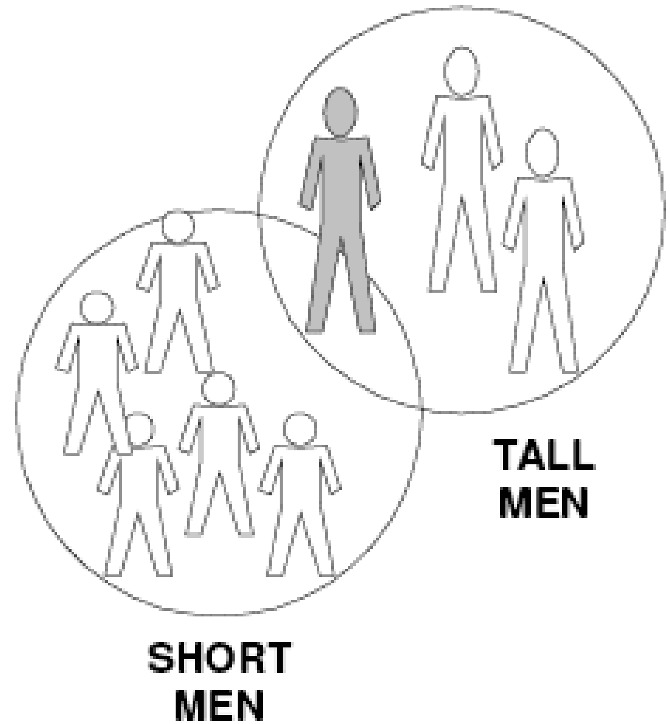



# History of Artificial Intelligence

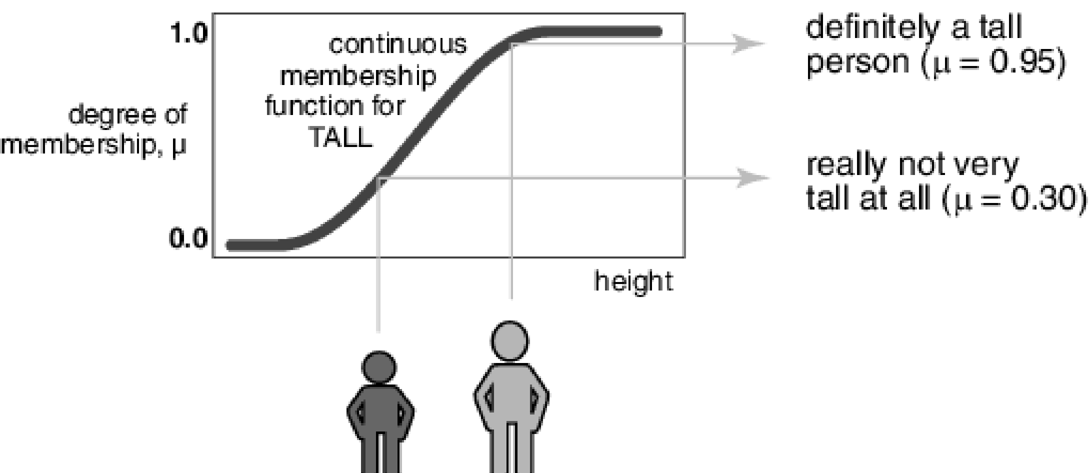


## 1965: Lotfi Zadeh's Fuzzy Logic



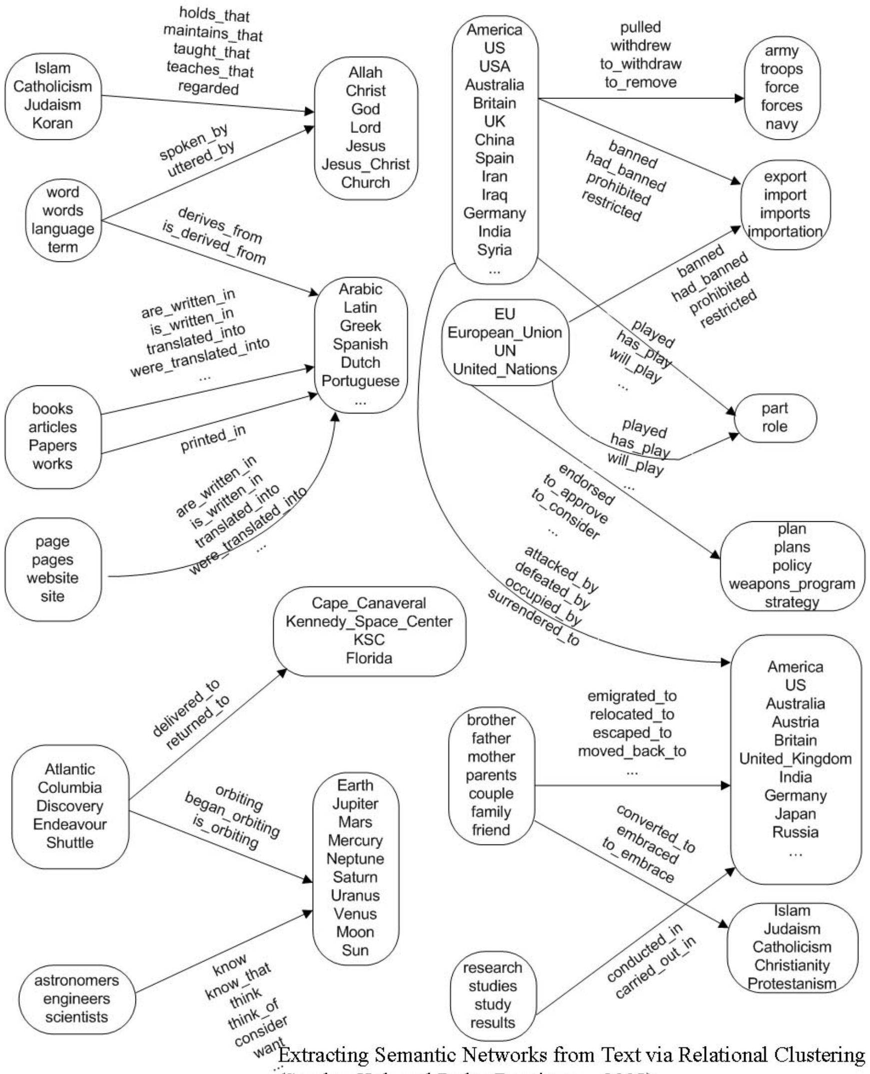




or, better:



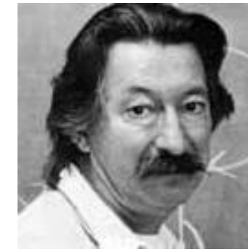
# History of Artificial Intelligence

1966: Ross Quillian's semantic networks




Extracting Semantic Networks from Text via Relational Clustering
(Stanley Kok and Pedro Domingos , 2008)

# History of Artificial Intelligence



1966: Joe Weizenbaum's Eliza

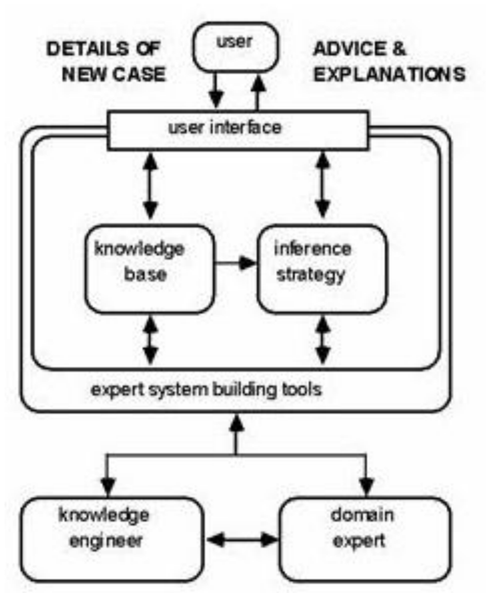

1968: Peter Toma founds Systran to commercialize machine-translation systems

# History of Artificial Intelligence

1969: Marvin Minsky & Samuel Papert's "Perceptrons" kill neural networks

1969: Stanford Research Institute's Shakey the Robot

1972: Bruce Buchanan's MYCIN




- a knowledge base
- a patient database
- a consultation/explanation program
- a knowledge acquisition program

Knowledge is organised as a series of IF THEN rules

# History of Artificial Intelligence

1972: Terry Winograd's Shrdlu

Person: PICK UP A BIG RED BLOCK.

Computer: OK. (does it)

Person: GRASP THE PYRAMID.

Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.

Person: FIND A BLOCK WHICH IS TALLER THAN THE ONE YOU ARE HOLDING AND PUT IT INTO THE BOX.

Computer: BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.

Computer: OK. (does it)

Person: WHAT DOES THE BOX CONTAIN?

Computer: THE BLUE PYRAMID AND THE BLUE BLOCK.

Person: WHAT IS THE PYRAMID SUPPORTED BY?

Computer: THE BOX.

Person: HOW MANY BLOCKS ARE NOT IN THE BOX?

Computer: FOUR OF THEM.

Person: IS AT LEAST ONE OF THEM NARROWER THAN THE ONE WHICH I TOLD YOU TO PICK UP?

Computer: YES, THE RED CUBE.

Person: IS IT SUPPORTED?

Computer: YES, BY THE TABLE.

Person: CAN THE TABLE PICK UP BLOCKS?

Computer: NO.

Person: CAN A PYRAMID BE SUPPORTED BY A BLOCK?

Computer: YES.

Person: CAN A PYRAMID SUPPORT A PYRAMID?

Computer: I DON'T KNOW.

Person: STACK UP TWO PYRAMIDS.

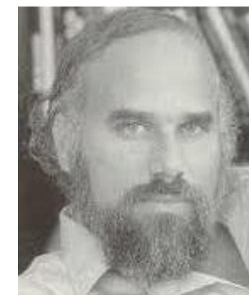
Computer: I CAN'T.

Person: WILL YOU PLEASE STACK UP BOTH OF THE RED BLOCKS AND EITHER A GREEN CUBE OR A PYRAMID?

Computer: OK. (does it)

Person: WHICH CUBE IS SITTING ON THE TABLE?

# History of Artificial Intelligence



1972: Hubert Dreyfus's "What Computers Can't Do"

1974: Marvin Minsky's Frame (see chapter on "Cognition")

1975: Roger Schank's Script (see chapter on "Cognition")

1975: John Holland's Genetic Algorithms

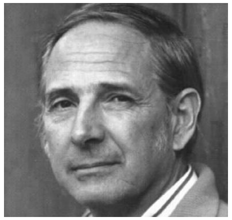
1976: Doug Lenat's AM

1979: Cordell Green's system for automatic programming

1979: Drew McDermott's non-monotonic logic

1979: David Marr's theory of vision

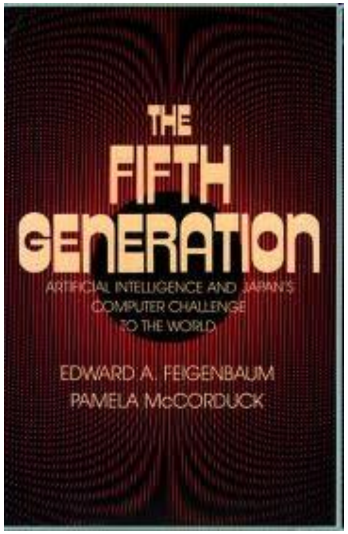
# History of Artificial Intelligence



1980: John Searle’s "Chinese Room"

1980: Intellicorp, the first major start-up for Artificial Intelligence

1982: Japan's Fifth Generation Computer Systems project



# History of Artificial Intelligence

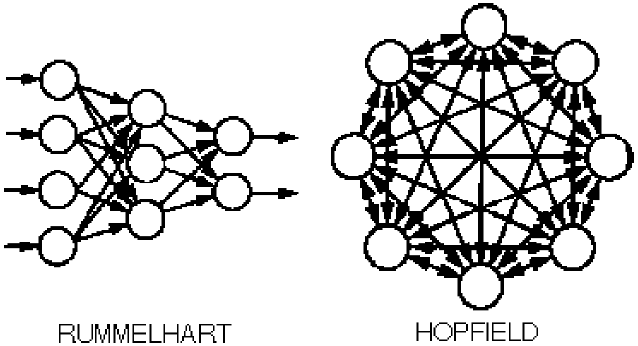
1982: John Hopfield describes a new generation of neural networks, based on a simulation of annealing

1983: Geoffrey Hinton's and Terry Sejnowski's Boltzmann machine for unsupervised learning

1986: Paul Smolensky's Restricted Boltzmann machine

1986: David Rumelhart's "Parallel Distributed Processing"

Rummelhart network
Neurons arranged in layers, each neuron linked to neurons of the neighboring layers, but no links within the same layer
Requires training with supervision




Hopfield networks
Multidirectional data flow
Total integration between input and output data
All neurons are linked between themselves
Trained with or without supervision

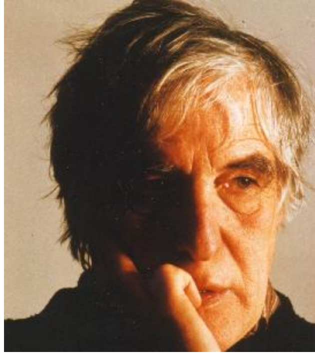
# History of Artificial Intelligence

Genealogy of Intelligent Machines

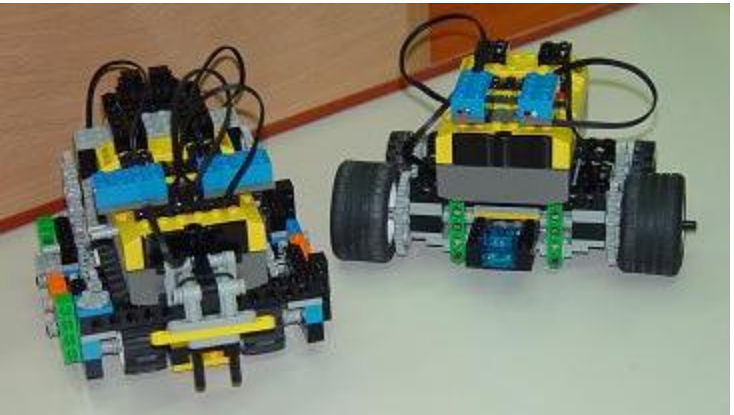
Hydraulic machines
↓
Steam engines
↓
Cybernetics
↓
Neural networks

Logic
↓
Hilbert
↓
Turing Machine
↓
Computers
↓
Expert Systems

# History of Artificial Intelligence



- Valentino Breitenberg's "vehicles" (1984)
  - Vehicle 1:  a motor and a sensor
  - Vehicle 2: two motors and two sensors
  - Increase little by little the circuitry, and these vehicles seem to acquire not only new skills, but also a personality.



# History of Artificial Intelligence

1985: Judea Pearl's "Bayesian Networks"

1987: Chris Langton coins the term "Artificial Life"

1987: Rodney Brooks' robots

1990: Carver Mead describes a neuromorphic processor

1992: Thomas Ray develops "Tierra", a virtual world

# History of Artificial Intelligence

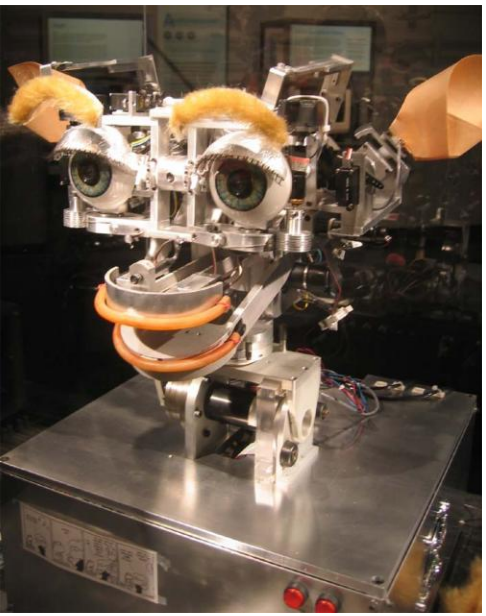
1997: IBM's "Deep Blue" chess machine beats the world's chess champion, Garry Kasparov

2011: IBM's Watson debuts on a tv show

# History of Artificial Intelligence

2000: Cynthia Breazeal's emotional robot, "Kismet"

2003: Hiroshi Ishiguro's Actroid, a young woman



# History of Artificial Intelligence

2004: Mark Tilden's biomorphic robot Robosapien

2005: Honda's humanoid robot "Asimo"

# History of Artificial Intelligence

2005: Boston Dynamics' quadruped robot "BigDog"

2010: Lola Canamero's Nao, a robot that can show its emotions

2011: Osamu Hasegawa's SOINN-based robot that learns functions it was not programmed to do

2012: Rodney Brooks' hand programmable robot "Baxter"


# History of Artificial Intelligence

- Rod Brooks/ Rethink Robotics (2012)
  - Vision to locate and grasp objects
  - Can be taught to perform new tasks by moving its arms in the desired sequence

# History of Artificial Intelligence



Deep Learning

- 1998: Yann LeCun 's second generation Convolutional Neura Networks
- 2006: Geoffrey Hinton's Geoffrey Hinton's Deep Belief Networks
- 2007: Yeshua Bengio's Stacked Auto-Encoders

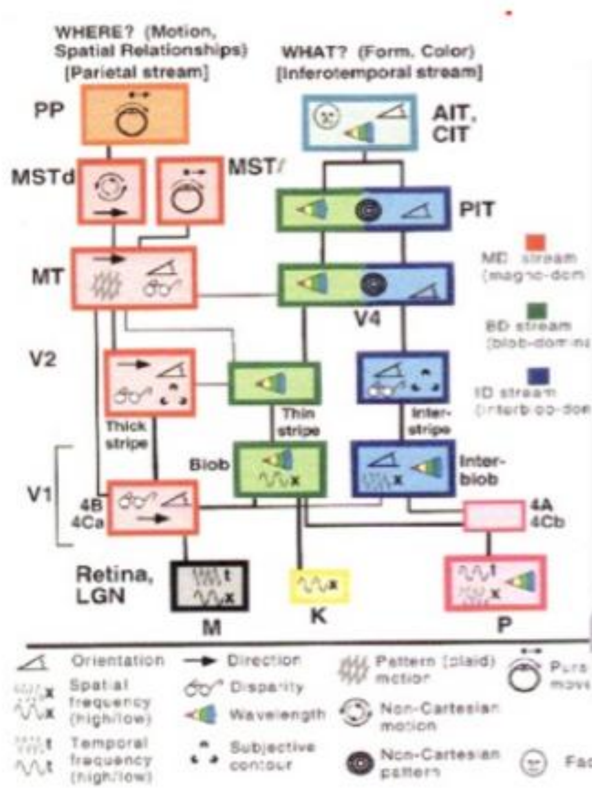
Error rates on the ILSVRC-2012 competition

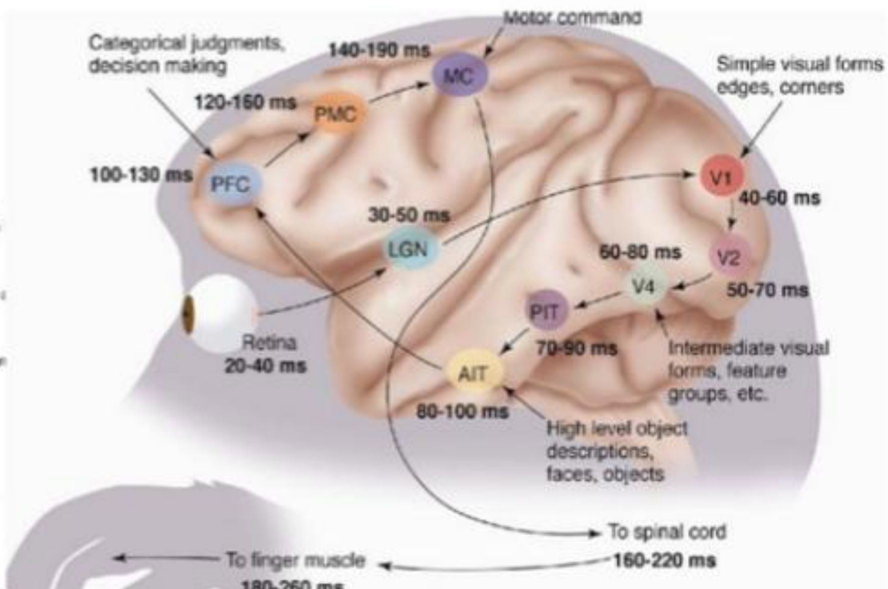
Deep Learning →

| | |
|---|---|
| Krizhevsky et. al. | 16.4% |
| much bigger gap | |
| University of Tokyo | 26.1% |
| Oxford University Vision Group | 26.9% |
| INRIA + XRCE | 27.0% |
| University of Amsterdam | 29.5% |

# History of Artificial Intelligence

Deep Learning mimics the workings of the brain: the audiovisual cortex works in multiple hierarchical stages




[picture from Simon Thorpe]

[Gallant & Van Essen]

# History of Artificial Intelligence

2014: Vladimir Veselov's and Eugene Demchenko's program Eugene Goostman, which simulates a 13-year-old Ukrainian boy, passes the Turing test at the Royal Society in London

2014: Li Fei-Fei's computer vision algorithm that can describe photos ("Deep Visual-Semantic Alignments for Generating Image Descriptions", 2014)

2014: Alex Graves, Greg Wayne and Ivo Danihelka publish a paper on "Neural Turing Machines"

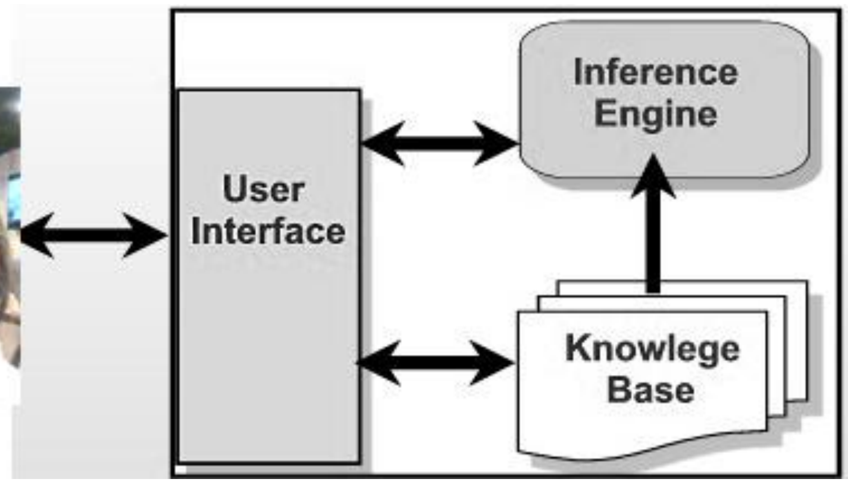
2014: Jason Weston, Sumit Chopra and Antoine Bordes publish a paper on "Memory Networks"

2014: Microsoft demonstrates a real-time spoken language translation system

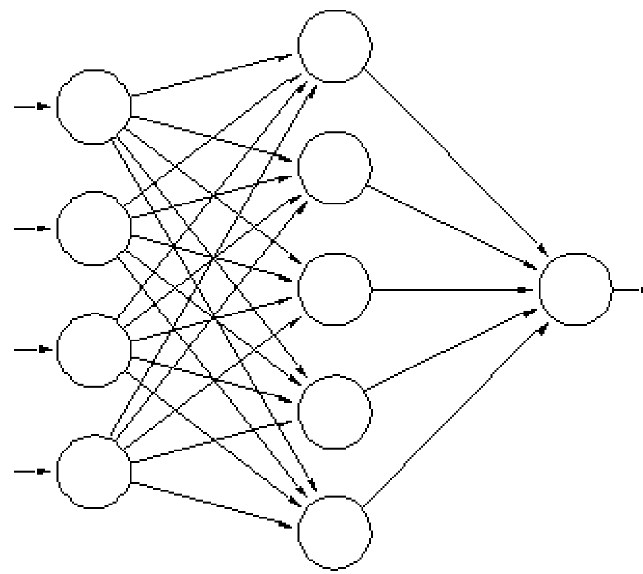
2014: *GoogLeNet*, a 22 layers convolutional network, wins Imagenet 2014, almost doubling the mean average precision of the previous year’s winner

# Questions?

# Artificial Intelligence




VS



# Knowledge-based Systems

"General problem solver": the program capable of solving all problems

→ Intelligence = reasoning about knowledge

→ Domain knowledge and domain experts

→ Knowledge Representation

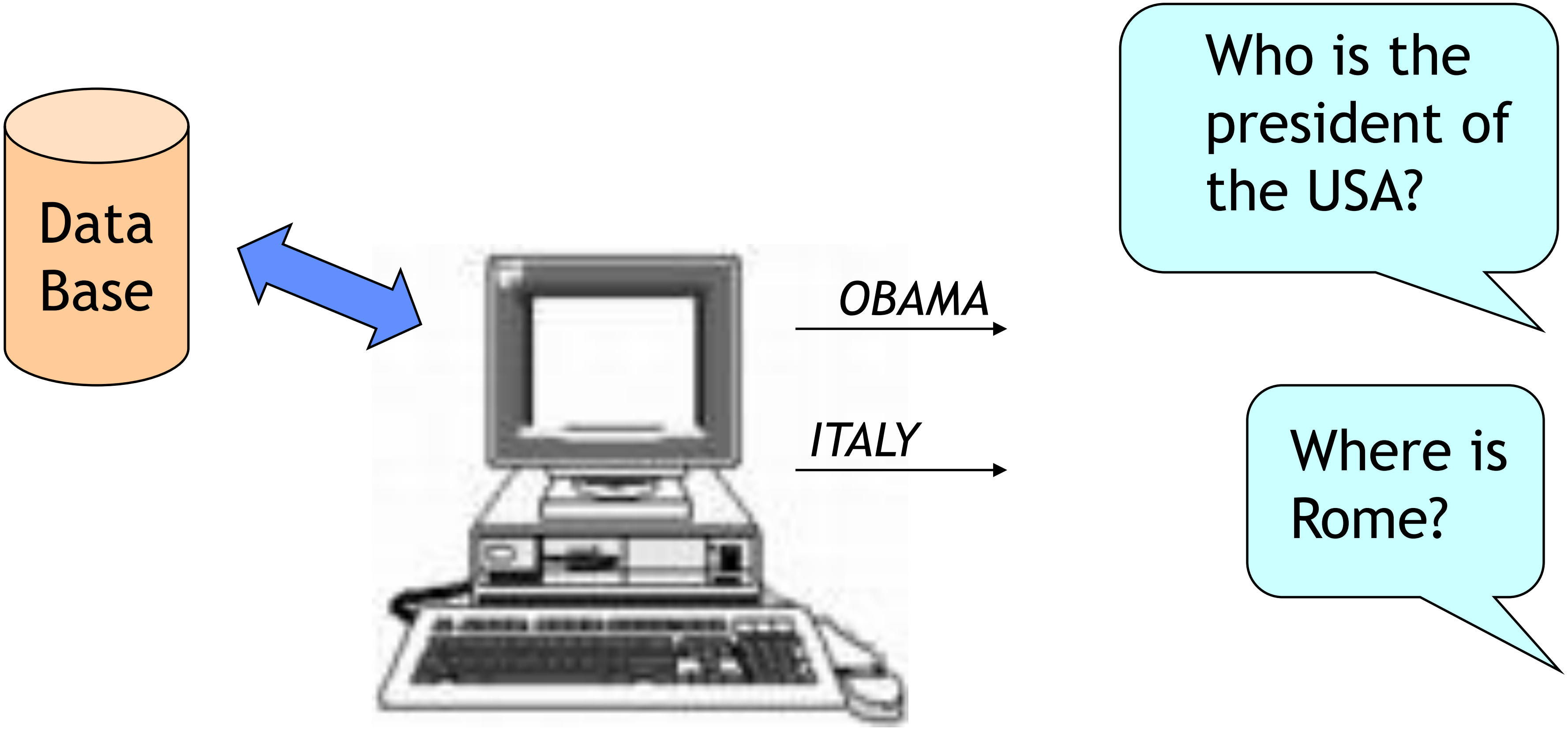
→ Knowledge-based systems (expert systems)

→ Knowledge Engineering

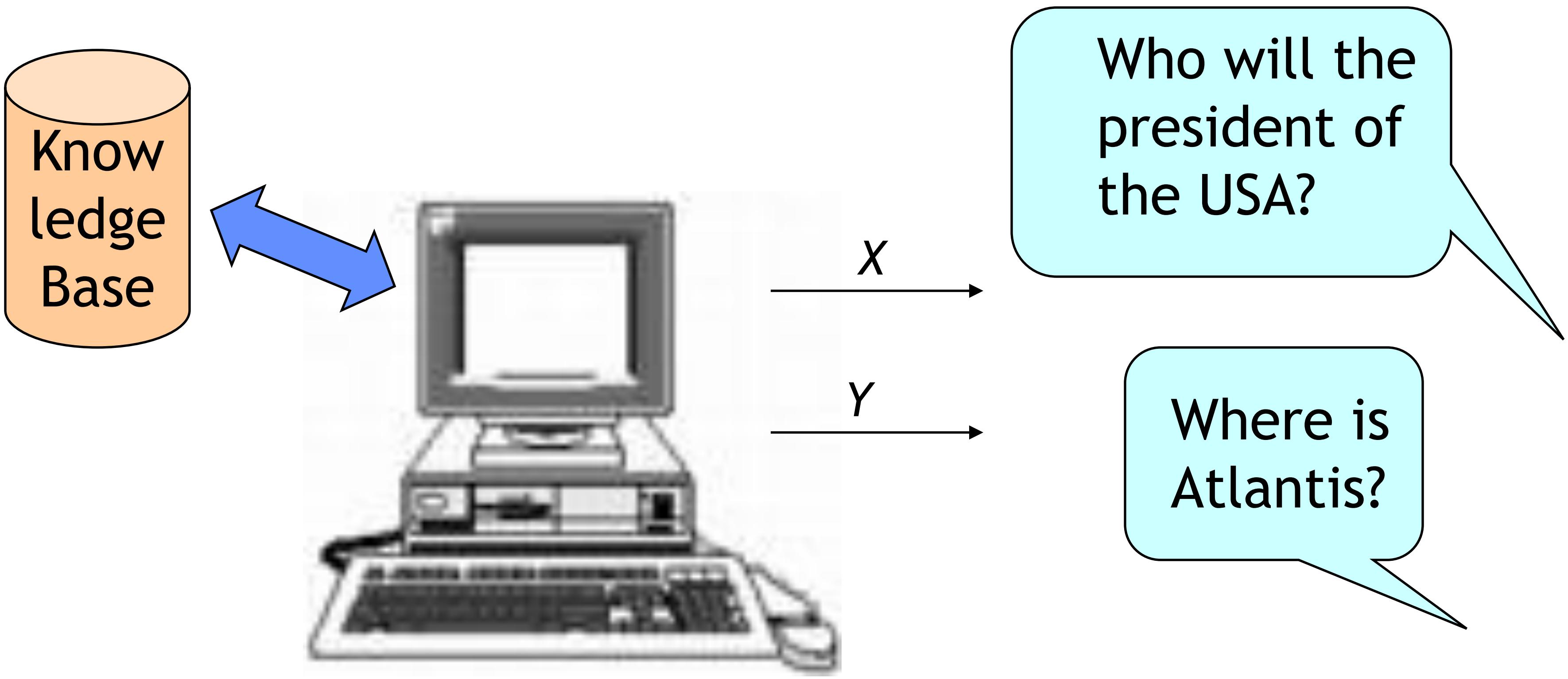
# Knowledge-based Systems

- Knowledge representation
  - Predicates
  - Production rules
  - Semantic networks
  - Frames
- Inference engine: reasoning mechanisms
- Common sense & heuristics
- Uncertainty
- Learning

# Information-based System



# Knowledge-based System



# Information Processing
# vs
# Knowledge Processing

Puzzle: What is the Italian word “PNAATEI”?

1)

AAEINPT
AAEINTP
AAEITPN
…

PIANETA

7!=5000

A
abaco
ad
addobbo
…
mangia…
zucchero

No know-ledge of Italian

2)

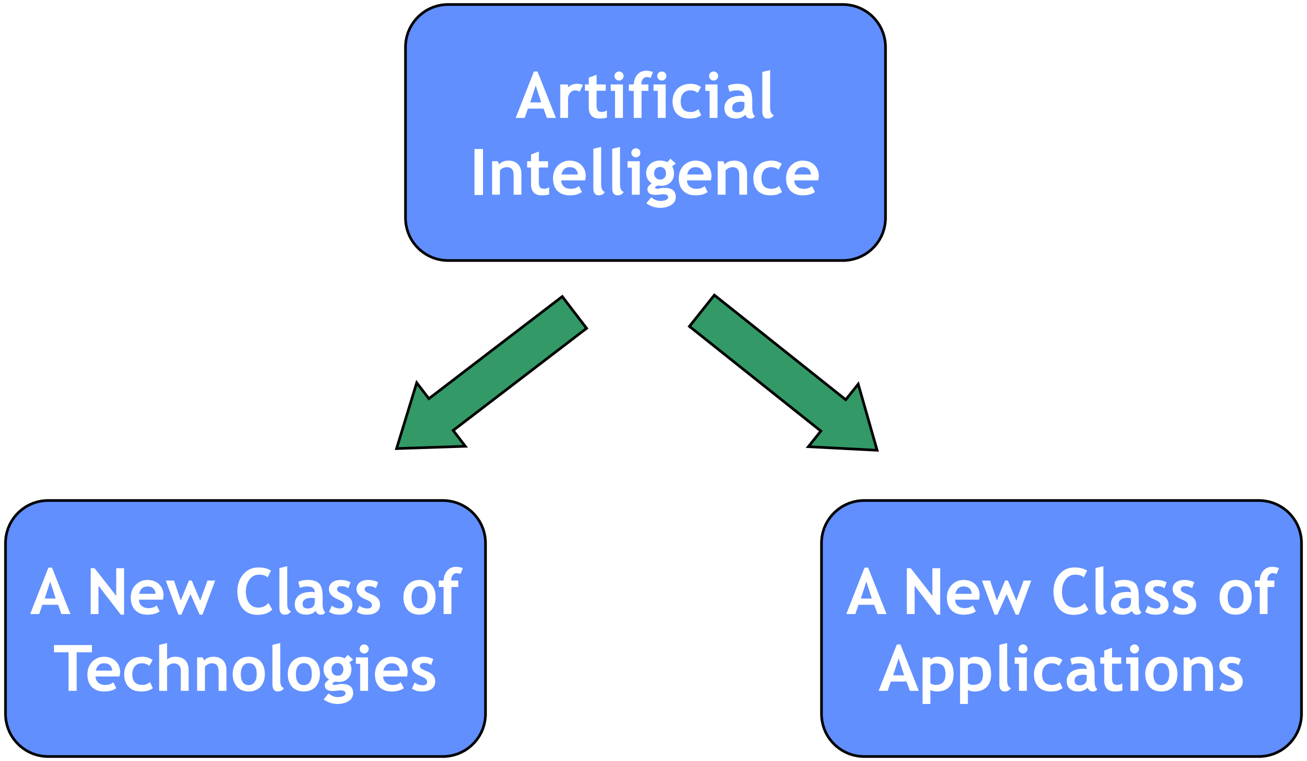
PANIETA
NAPIETA
TANIEPA
PENIATA
…

PIANETA

Less than 100

How Italian words look like

# Artificial Intelligence



# Artificial Intelligence

## A New Class of Applications

### Expert Tasks

- The algorithm does not exist
- A medical encyclopedia is not equivalent to a physician

### Heuristics

- There is an algorithm but it is “useless”
- Don’t touch boiling water

### Uncertainty

- The algorithm is not possible
- Italy will win the next world cup

### “Complex” Problem Solving

- The algorithm is too complicated
- Design a cruise ship

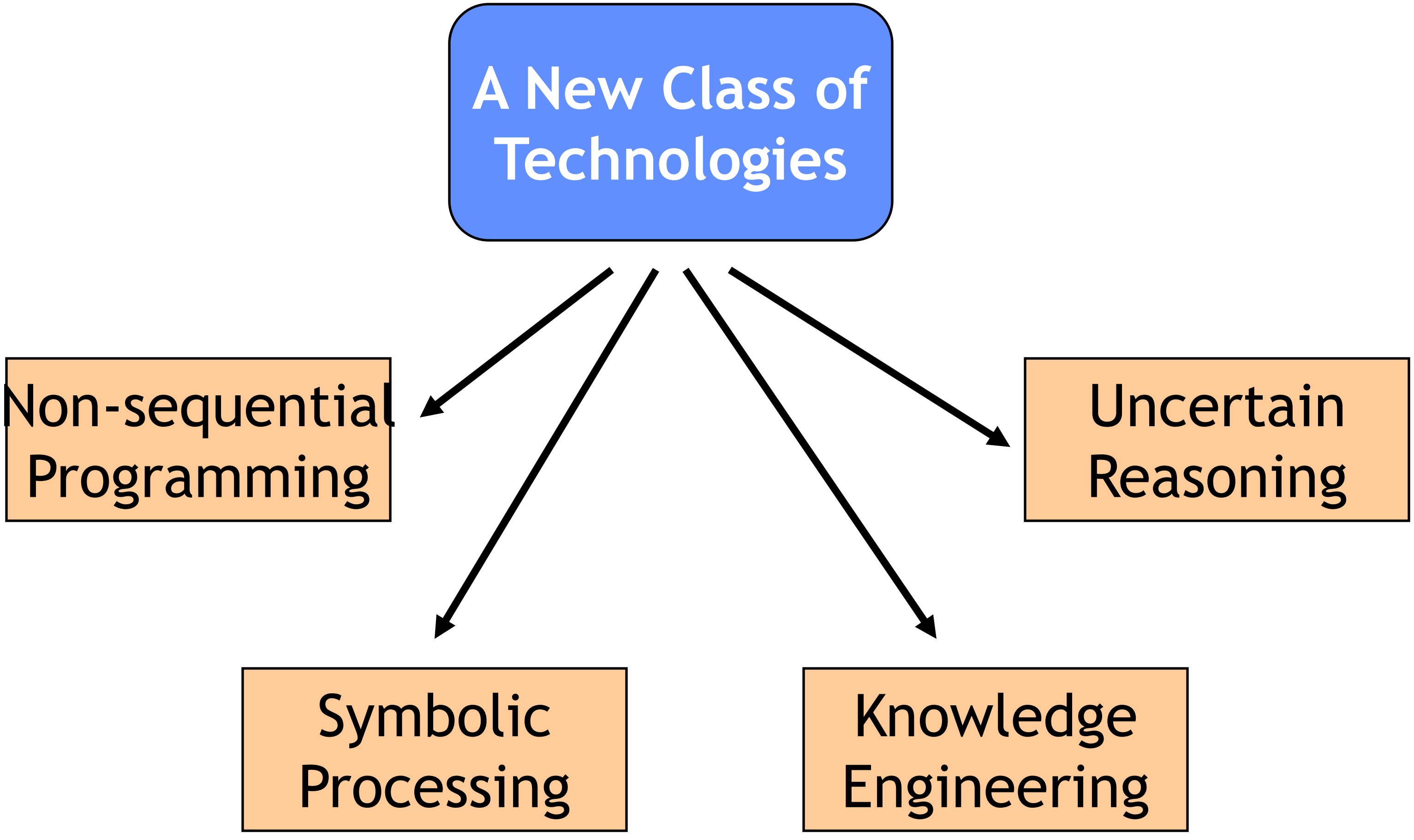
# Artificial Intelligence

**A New Class of Applications**

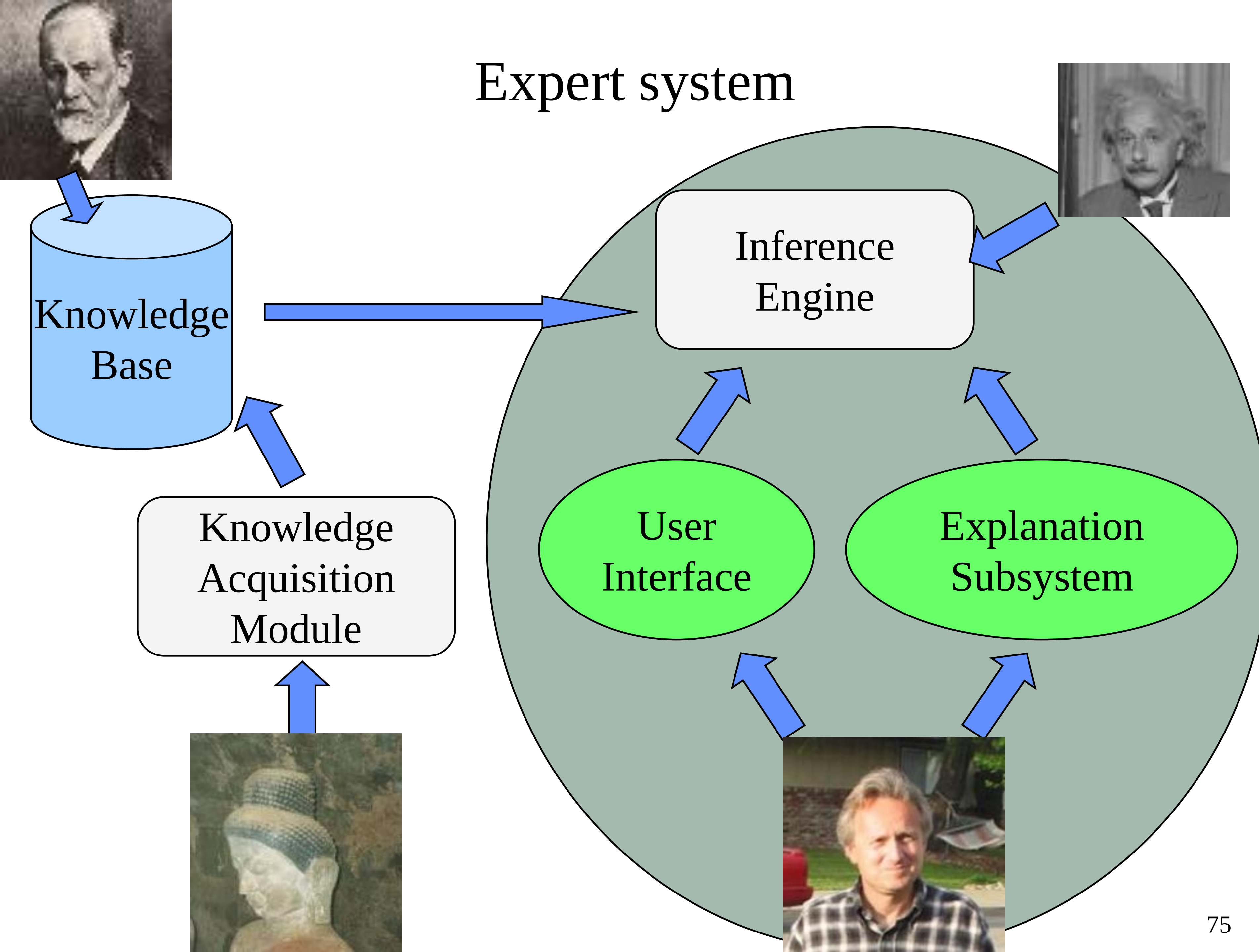
| Expert Tasks | Heuristics | Uncertainty | "Complex" Problem Solving |
| --- | --- | --- | --- |



# Artificial Intelligence



# Expert system



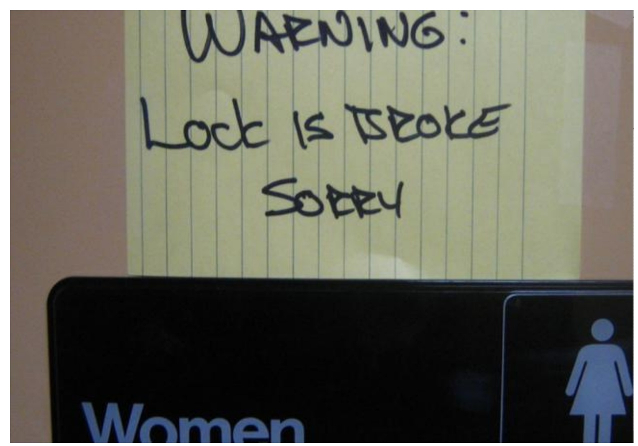
# Questions?

# Common Sense

*Small minds are concerned with the extraordinary, great minds with the ordinary"*
(Blaise Pascal)

# Common Sense

- In which cases it is perfectly logical to find a woman in the men's restrooms?


# Common Sense

- How easy is it to build a robot that can make these trivial inferences?

# Common Sense

- What is wrong about this picture?

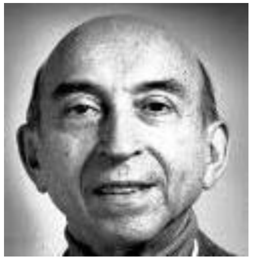
Communication tower
on top of Mt Diablo (2015)

# Common Sense

- Deduction is a method of exact inference  (classical logic)
  - All Greeks are humans and Socrates is a Greek, therefore Socrates is a human
- Induction infers generalizations from a set of events (science)
  - Water boils at 100 degrees
- Abduction infers plausible causes of an effect (medicine)
  - You have the symptoms of a flue

# Common Sense

- Classical Logic is inadequate for ordinary life
- Intuitionism (Luitzen Brouwer, 1925)
- Frederick and Barbara Hayes-Roth (1985): opportunistic reasoning
- Non- monotonic Logic
- Fuzzy Logic (Lofti Zadeh)



# Common Sense

The Frame Problem

– Classical logic deducts all that is possible from all that is available
– In the real world the amount of information that is available is infinite
– It is not possible to represent what does “not” change in the universe as a result of an action ("ramification problem“)
– Infinite things change, because one can go into greater and greater detail of description
– The number of preconditions to the execution of any action is also infinite, as the number of things that can go wrong is infinite ("qualification problem“)

# Common Sense

Uncertainty

- “Maybe i will go shopping”
- “I almost won the game”
- “This cherry is red”
- “piero is an idiot”

Probability

- Probability measures "how often" an event occurs
- But we interpret probability as “belief”

# Common sense

Principle of Incompatibility (Pierre Duhem)

- The certainty that a proposition is true decreases with any increase of its precision
- The power of a vague assertion rests in its being vague (“I am not tall”)
- A very precise assertion is almost never certain (“I am 1.71cm tall)

# Common Sense

Heuristics

- Knowledge that humans tend to share in a natural way: rain is wet, lions are dangerous, politicians are crooks, carpets get stained…
- Rules of thumbs

György Polya (1940s): “Heuretics“ - the nature, power and behavior of heuristics: where it comes from, how it becomes so convincing, how it changes

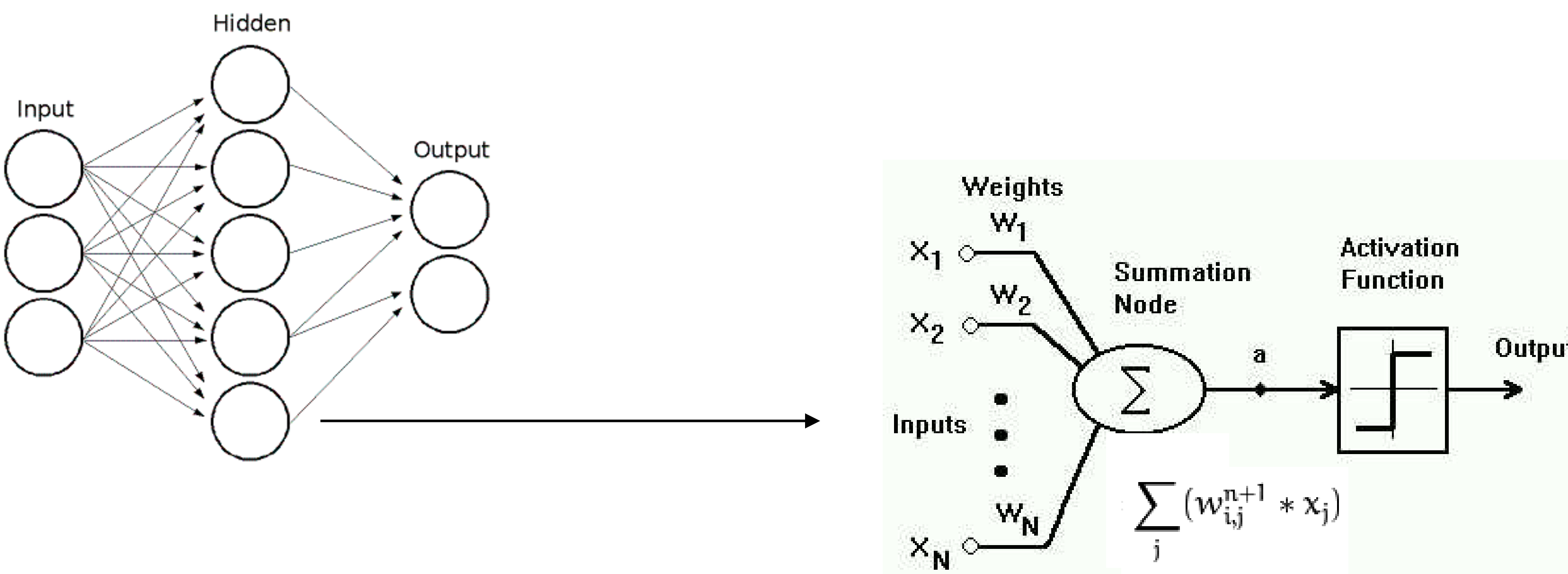
# Questions?

# Connectionism

A neural network is a set of interconnected neurons (simple processing units)

Each neuron receives signals from other neurons and sends an output to other neurons

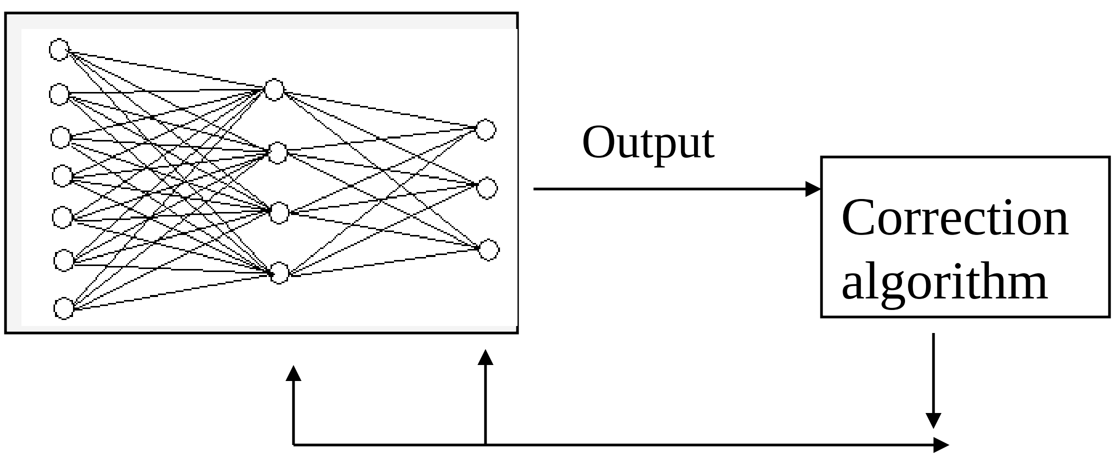
The signals are “amplified” by the “strength” of the connection



# Connectionism

The strength of the connection changes over time according to a feedback mechanism (output desired minus actual output)

The net can be "trained"



# Connectionism

- Distributed memory
- Nonsequential programming
- Fault-tolerance
- Recognition
- Learning

# Connectionism

Where are we?

Largest neural network:

- 1,000,000,000,000 neurons

Worm's brain:

- 1,000 neurons

But the worm's brain outperforms neural networks on most tasks

Human brain:

- 100,000,000,000 neurons
- 200,000,000,000,000 connections

# Artificial Intelligence

- Notes…
  - How many people can fly and land upside down on a ceiling? Don’t underestimate the brain of a fly.
  - Computers don’t grow up. Humans do.

# Questions?

# A Brief History of Bionic Beings

1957: The first electrical implant in an ear (André Djourno and Charles Eyriès)

1961: William House invents the "cochlear implant", an electronic implant that sends signals from the ear directly to the auditory nerve (as opposed to hearing aids that simply amplify the sound in the ear)

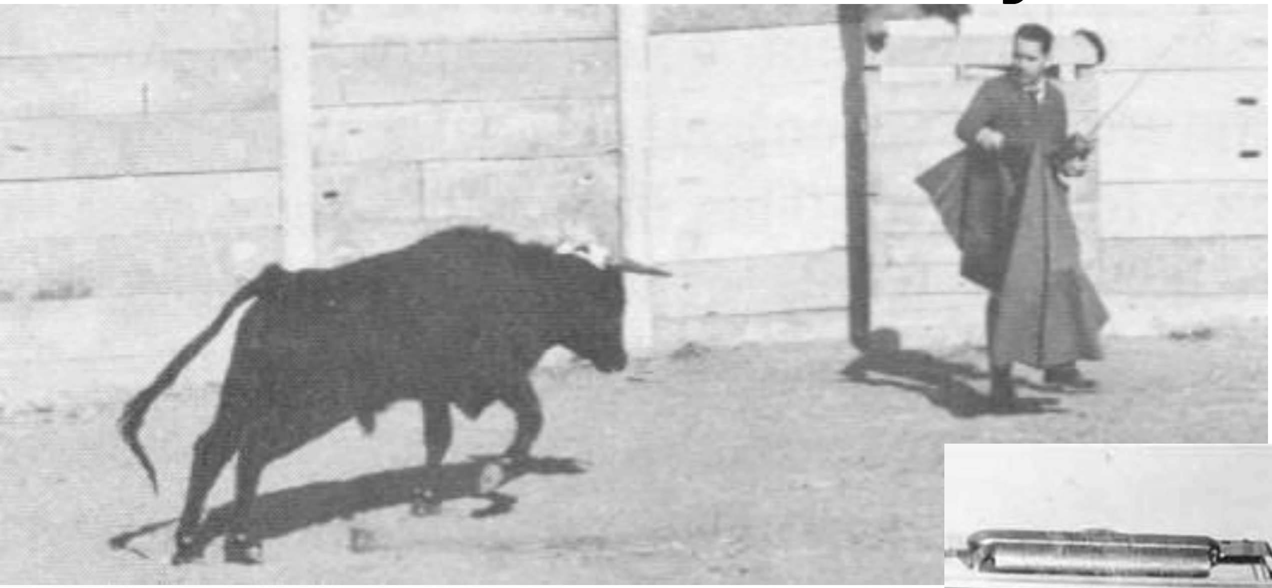
1952: Jose Delgado publishes the first paper on implanting electrodes into human brains: "Permanent Implantation of Multi-lead Electrodes in the Brain"

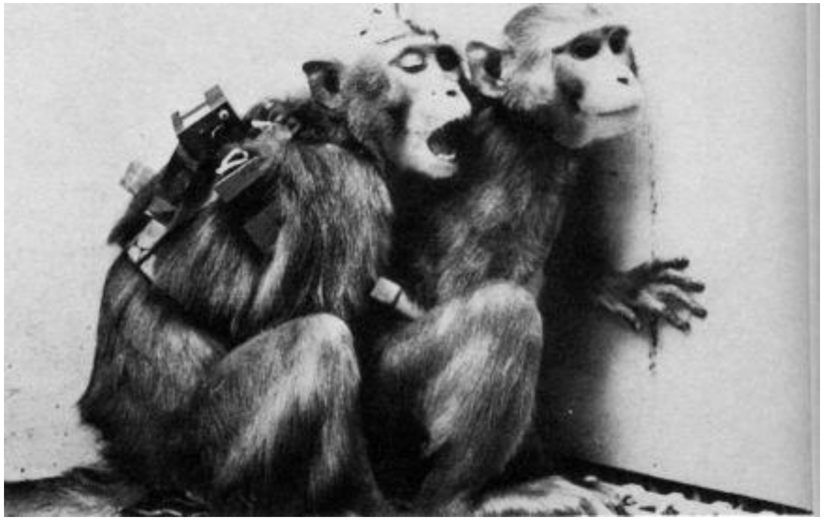
1965 : Jose Delgado controls a bull via a remote device, injecting fear at will into the beast's brain

1969: Jose Delgado’s book "Physical Control of the Mind - Toward a Psychocivilized Society"

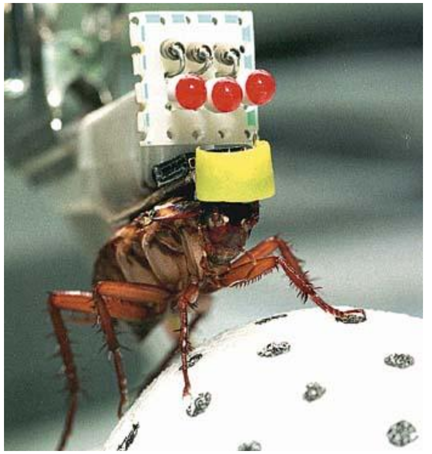
1969: Jose Delgado implants devices in the brain of a monkey and then sends signals in response to the brain's activity, thus creating the first bidirectional brain-machine-brain interface.

# A Brief History of Bionics





# A Brief History of Bionics



1997: Remotely controlled cockroaches at Univ of Tokyo

1998: Philip Kennedy develops a brain implant that can capture the "will" of a paralyzed man to move an arm (output neuroprosthetics: getting data out of the brain into a machine)

# A Brief History of Bionics

2000: William Dobelle develops an implanted vision system that allows blind people to see outlines of the scene. His patients Jens Naumann and Cheri Robertson become "bionic" celebrities.

2002: John Chapin debuts the "roborats", rats whose brains are fed electrical signals via a remote computer to guide their movements

# A Brief History of Bionics


2002: Miguel Nicolelis makes a monkey's brain control a robot's arm via an implanted microchip

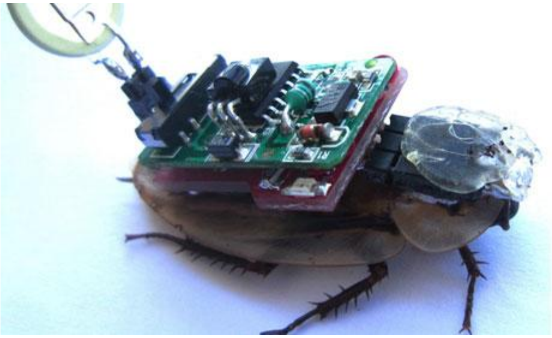
2005: Cathy Hutchinson, a paralyzed woman, receives a brain implant from John Donoghue's team that allows her to operate a robotic arm (output neuroprosthetics)

2004: Theodore Berger demonstrates a hippocampal prosthesis that can provide the long-term-memory function lost by a damaged hippocampus

# A Brief History of Bionics

The age of two-way neural transmission…

2006: The Defense Advanced Research Projects Agency (Darpa) asks scientists to submit "innovative proposals to develop technology to create insect-cyborgs



2013: Miguel Nicolelis makes two rats communicate by capturing the "thoughts" of one rat's brain and sending them to the other rat's brain over the Internet


# A Brief History of Bionics

The age of two-way neural transmission…

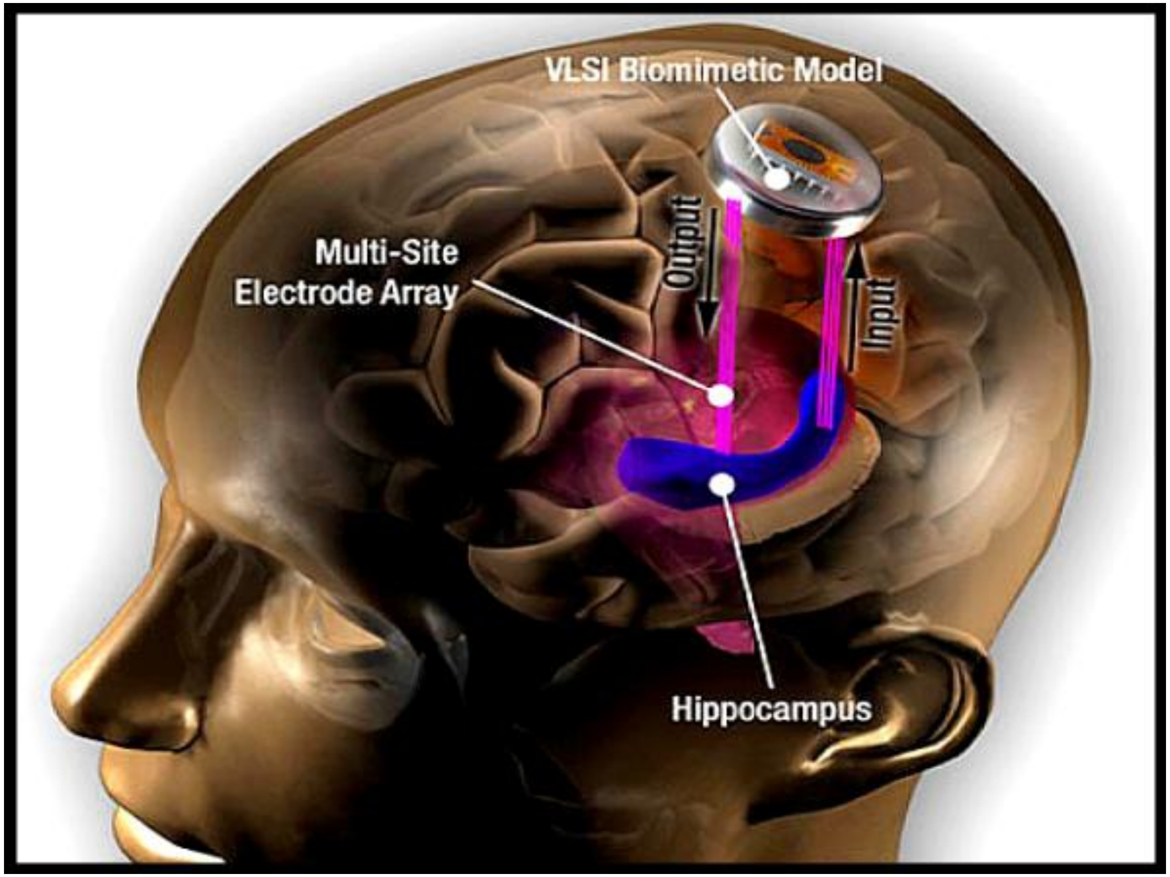
2013: Rajesh Rao and Andrea Stocco devise a way to send a brain signal from Rao's brain to Stocco's hand over the Internet, i.e. Rao makes Stocco's hand move, the first time that a human controls the body part of another human

2014: An amputee, Dennis Aabo, receives an artificial hand from Silvestro Micera's team capable of sending electrical signals to the nervous system so as to create the touch sensation

# A Brief History of Bionics

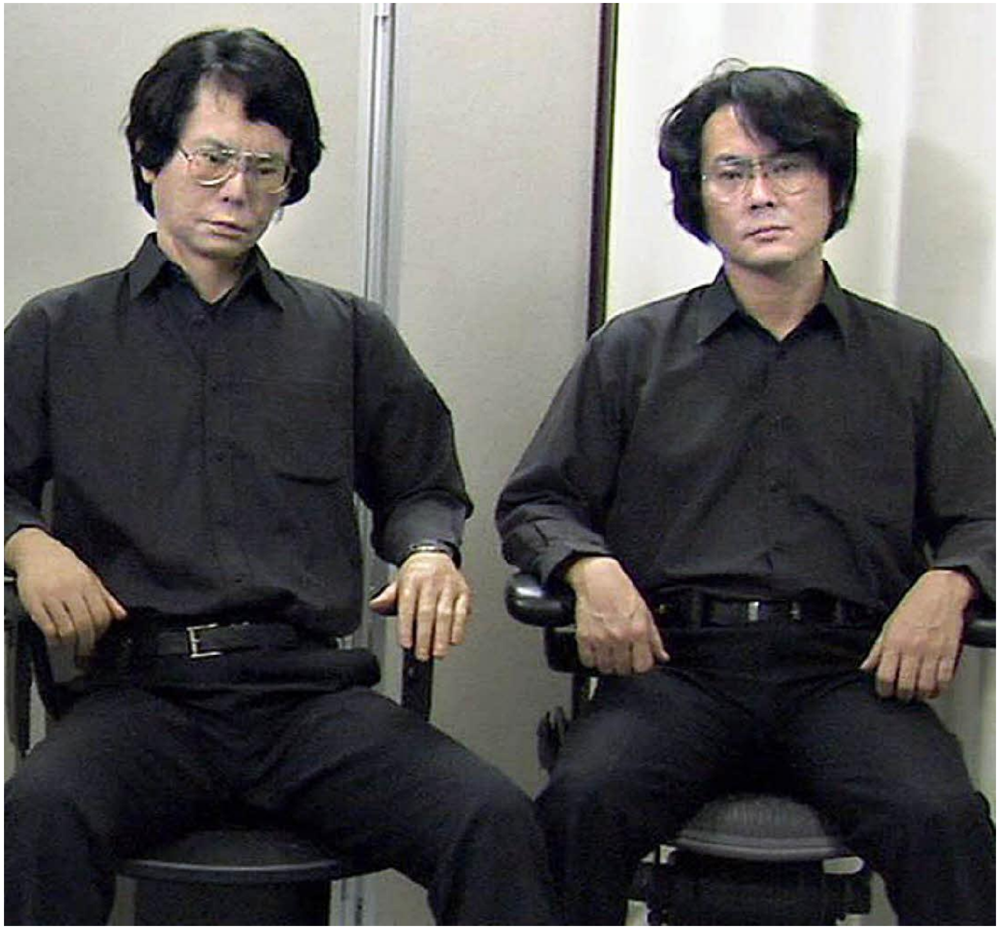
Neuro-engineering?

(http://its-interesting.com)




(http://targetedindividualscanada.com)

# Which one is the robot and which is the person?



# Questions?

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# Machine Intelligence

*"The person who says it cannot be done should not interrupt the person doing it"* (Chinese proverb)

# Break


*"There is more stupidity than hydrogen in the universe, and it has a longer shelf life"*
(Frank Zappa)

# Self-organization

# Or

# The Science Of Emergence

# Entropy: the Curse of Irreversibility

- Thermodynamics studies macroscopic systems that cannot easily reduced to their microscopic constituents

# Entropy: the Curse of Irreversibility

Entropy

- Sadi Carnot:
  - Heat flows spontaneously from hot to cold bodies, but the opposite never occurs
  - Any transformation of energy has an energetic cost
  - There are no reversible processes in nature
- "*I propose to name the quantity S the entropy of the system, after the Greek word [τροπη trope], the transformation*" (Rudolf Clausius, 1865)
- Natural processes generate entropy

# Entropy: the Curse of Irreversibility

Entropy

- Ludwig Boltzmann's statistical definition
  - Many different microscopic states of a system result in the same macroscopic state
  - The entropy of a macrostate is the logarithm of the number of its microstates
  - Entropy = the number of molecular degrees of freedom
  - Entropy is a probability function
  - A system tends to drift towards the most probable state, which happens to be a state of higher entropy

$$\boxed{S \propto \log \Omega}$$

# Entropy: the curse of irreversibility

- The second law of Thermodynamics (1852)
  - Some processes are not symmetric in time
  - Change cannot always be bi-directional
  - We cannot always replay the history of the universe backwards
  - Some things are irreversible

$$dS \geq 0$$

# The Second Law

- Entropy can never decrease
- Transformation processes cannot be run backwards, cannot be "undone"
- Young people age, elderly people cannot rejuvenate
- Buildings don't improve over the years, they decay
- Scrambled eggs cannot be unscrambled and dissolved sugar cubes cannot be recomposed

# Entropy

Entropy and Information

- Order is directly related to information
- Entropy is therefore related to information
- Entropy = a measure of disorder = a measure of the lack of information
- Entropy measures the amount of disorder in a physical system; i.e. entropy measures *the lack of information* about the structure of the system

$$\boxed{\text{Entropy} = -\ \text{Information}}$$

# The Origin of Order

- Classical physics: order can be built only rationally, by application of a set of fundamental laws of physics
  - Order needs to be somehow created by external forces

- Darwin: order can build itself spontaneously, e.g. Evolution
  - Spontaneous "emergence" of order.

$$\cancel{dS \geq 0}$$

# Chaos and Complexity

- Need for a new science:
  - A mathematical model of phenomena of emergence (the spontaneous creation of order)
  - A justification of their dynamics (which violates the second law of Thermodynamics)

# Chaos and Complexity

- Henri Poincare`'s "chaos" theory (1900s): a slight change in the initial conditions results in large-scale differences
- Very "disordered" systems spontaneously "crystallize" into a higher degree of order
- Complexity: a system must be complex enough for any property to “emerge” out of it
- Complexity can be formally defined as nonlinearity

# Dissipative Systems

- Ilya Prigogine's non-equilibrium thermodynamics (1960s)
  - Classical physics: the world is a static and reversible system that undergoes no evolution, whose information is constant in time
  - Classical physics is the science of being
  - Thermodynamics describes an evolving world in which irreversible processes occurs
  - Thermodynamics is the science of becoming

# Dissipative Systems

- Ilya Prigogine (1960s)
  - Order can come either from equilibrium systems or from non-equilibrium systems that are sustained by a constant source (by a persistent dissipation) of matter/energy
  - All living organisms are non-equilibrium systems
  - The distance from equilibrium and the nonlinearity of a system drive the system to ordered configurations, i.e. create order

# Complex Systems

- Per Bak (1987)
  - The collapse of a pile of sand under the weight of a new randomly placed grain is unpredictable
  - However, when it happens, the pile reorganizes itself
  - No external force is shaping the pile of sand: it is the pile of sand that organizes itself.

# Complex Systems

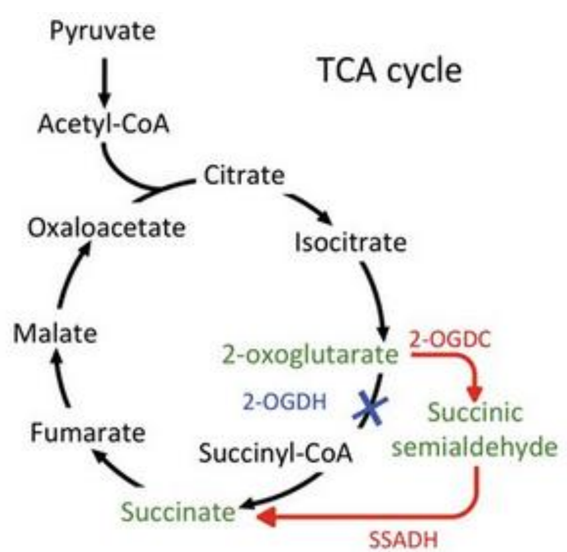
- Chris Langton (1989)
  - When ice turns into water, the atoms have not changed, but the system as a whole has undergone a phase transition
  - The state between order and chaos (the "edge of chaos") is sometimes a very "informative" state, because the parts are not as rigidly assembled as in the case of order and, at the same time, they are not as loose as in the case of chaos.
  - The system is stable enough to keep information and unstable enough to dissipate it.
  - The system at the edge of chaos is both a storage and a broadcaster of information.

# Complex Systems

- Chris Langton (1989)
  - The edge of chaos is where the system can perform computation, can metabolize, can adapt, can evolve
  - In a word: these systems can be “alive”
  - Phenomena such as life can only exists in a very narrow boundary between chaos and order

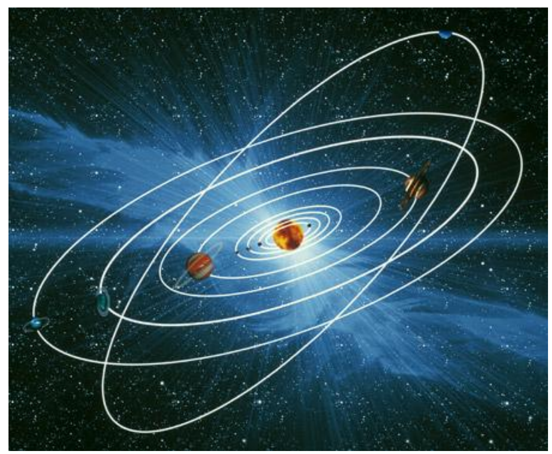
# Synchronized Oscillators

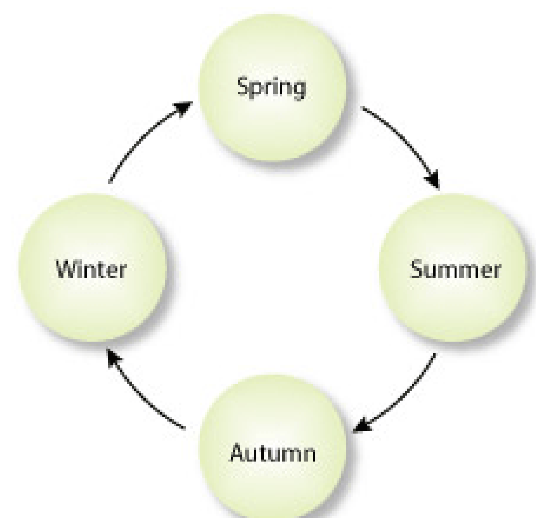
- Clocks and cycles are pervasive in our universe, from biological clocks to the cycles of electrons around the nucleus




The tricarboxylic acid (TCA) cycle includes a series of chemical reactions that are used for metabolism by most forms of life,

courtesy of Bryant Lab, Penn State University.



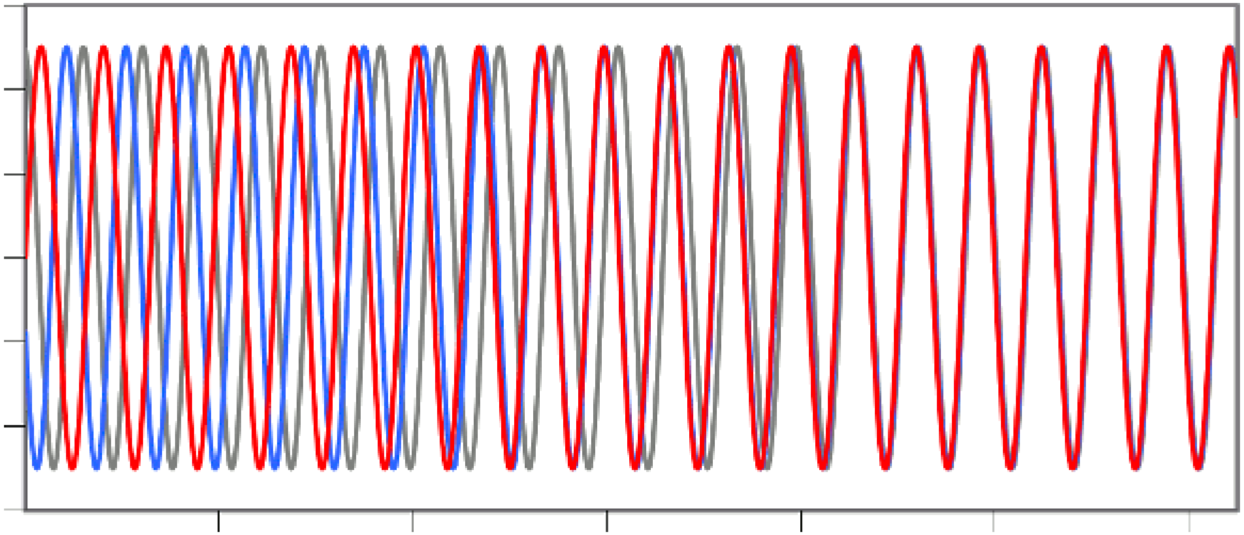


# Synchronized Oscillators

- Populations of synchronized oscillators are pervasive in nature
  - Biological clocks are regulated by populations of interacting neurons
  - The rhythm of the heart is set by the collective behavior of a group of cells
  - The suprachiasmatic nucleus is made of a large population of independent oscillators
  - At low temperatures all bosons behave like one (Bose-Einstein)
- The population does not need any leader in order to achieve synchronization

# Synchronized Oscillators

- Order emerges from the synchronized behavior of "coupled oscillators“
- The advantage of having a population of clocks: fault tolerance



# Synchronized Oscillators

- Yoshiki Kuramoto (1984): There is a threshold value for a chaotic system of oscillators, below which a solution of complete synchronization exists and above which it does not exist

- Steven Strogatz (2003): Synchronicity "will" emerge at some point in any system that exhibits partial synchronicity above the threshold

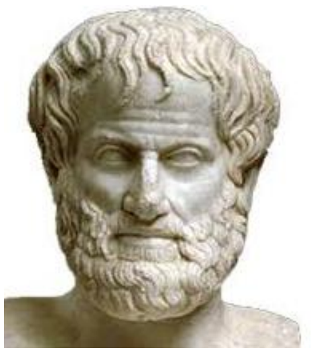
# Synchronized Oscillators

- Self-organization can be achieved in time or in space.
  - Some interacting molecules, cells and atoms achieve self-organization in space through spontaneous reorganization
  - Some coupled oscillators achieve self-organization in time through spontaneous synchrony

# Questions?

*"The beaver told the rabbit as they stared at the Hoover Dam: No, I didn't build it myself, but it's based on an idea of mine"*
(Charles Townes)

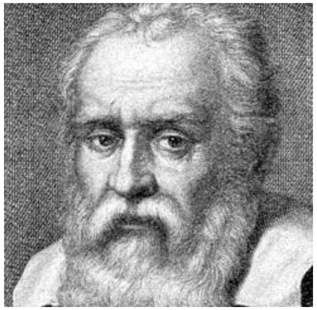
# The Classical World: Utopia



- Aristoteles
  - There is a reality that exists apart from anyone experiencing it, and human senses are capable of accessing it
  - The natural state of things is rest
  - The natural state of the heavens is uniform circular motion
  - Heavier bodies of a given material fall faster than lighter ones

Schema huius præmissæ diuisionis Sphærarum.

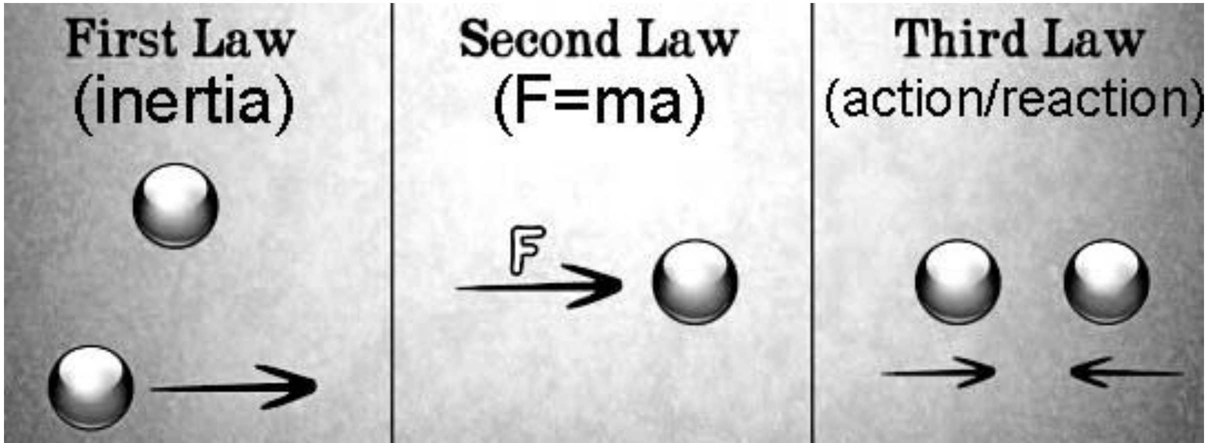
# The Classical World: Utopia



- Galileo Galilei
  - A body in free motion does not need any force to continue moving: the natural state of things is uniform linear motion
  - If a force is applied, then what will change is the acceleration, not the velocity
  - All bodies fall with the same acceleration
  - Space and time are independent

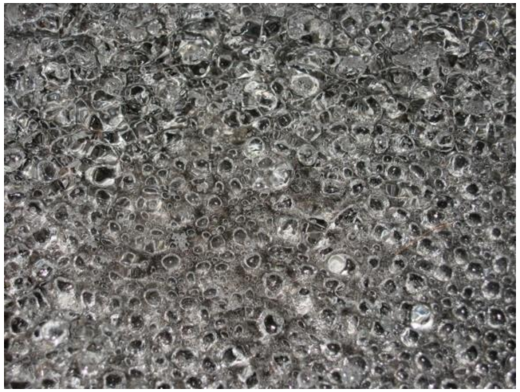
# The Classical World: Utopia

- Isaac Newton
  - Differential calculus and Euclid's geometry
  - Three fundamental laws
  - Exact mathematical relationships
  - The dynamic equation that mathematically describes the motion of a system
  - Newton’s world is a deterministic machine

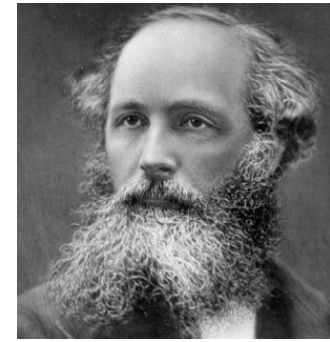


# The End of Utopia

- Gas
  - Gas: a system made of many minuscule particles in very fast motion and in continuous interaction
  - Classical approach abandoned in favor of a stochastic approach
  - All quantities that matter (from temperature to heat) are statistical quantities



# The End of Utopia



- Electromagnetism
  - Electric bodies radiate invisible waves of energy through space (fields)
  - James Maxwell (1873): field equations (distribution of electric and magnetic charges)
  - The number of coordinates needed to determine a wave is infinite

**Maxwell's Equations**

1. $$\frac{\nabla \mathrm{x} \underline{B}}{\mu} = \underline{j} + \frac{\partial}{\partial t}(\mathring{a}\underline{E})$$

2. $$\nabla \mathrm{x} \underline{E} = -\frac{\partial B}{\partial t}$$

3. $$\nabla . \underline{B} = 0$$

4. $$\nabla . \underline{E} = \frac{\ell_c}{\mathring{a}}$$

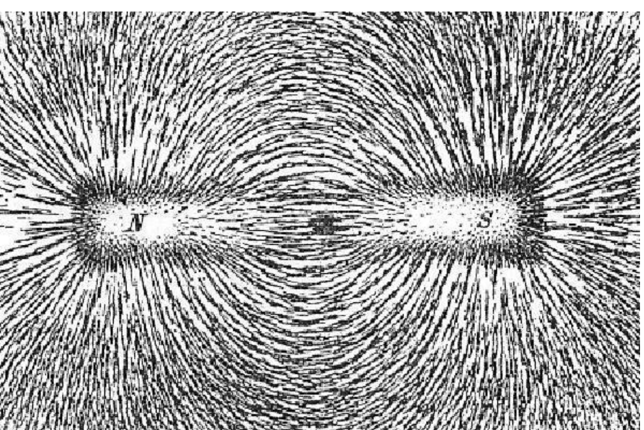
here $\underline{D} = \mathring{a}\underline{E}$ and $\underline{B} = \mu \underline{H}$

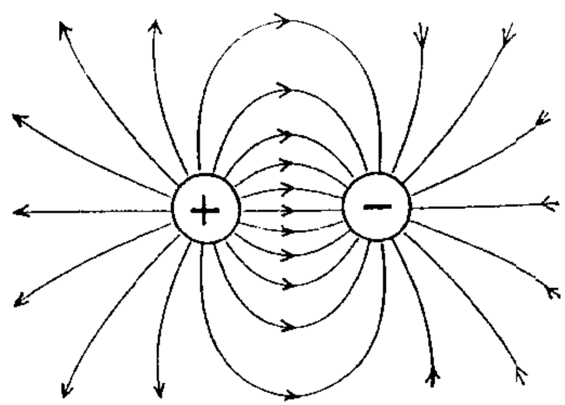
is the magnetic induction. $\underline{E}$ is the electric field.

is the electric displacement. $\underline{H}$ is the magnetic field.

is the electric current. $\ell_c$ is the charge density.

$\mu$ and $\mathring{a}$ are constants.



# The End of Utopia

- Erwin Schroedinger: classical science relies on two fundamental postulates:
  - object and subject can be separated (i.e., the subject can look at the object as if it were a completely disconnected entity);
  - the subject is capable of knowing the object (i.e., the subject can look at the object in a way that creates a connection, one leading to knowledge)

# Relativity: the Primacy of Light

- Special theory of relativity (1905)

*"On the Electrodynamics of Moving Bodies".*

**3. *Zur Elektrodynamik bewegter Körper;***
***von A. Einstein.***

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

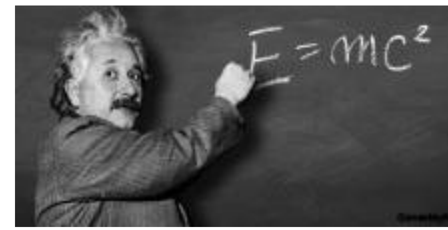
# Relativity: the Primacy of Light

- Special theory of relativity (1905)
  1. Laws of nature must be uniform
  2. Laws must be the same in all frames of reference that are "inertial"
  3. The speed of light is always the same

# Relativity: the Primacy of Light

- To unify Newton's equations for the dynamics of bodies and Maxwell's equations for the dynamics of electromagnetic waves in one set of equations
- Different observers see different things depending on their state of motion
- All quantities are decomposed into a time component and a space component, but how that occurs depends on the observer's state of motion.

# Relativity: the Primacy of Light




- Distortions of space and time
- "Now" is a meaningless concept
- The past determines the future
- Matter = energy
- Nothing can travel faster than light

# General Relativity: Gravity Talks

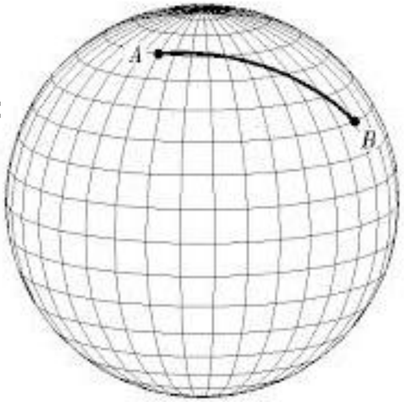
- General Relativity is ultimately about the nature of gravitation
- Relativity explains gravitation in terms of curved space-time, i.e. Geometry
- Free falls as natural motions, as straight lines in spacetime

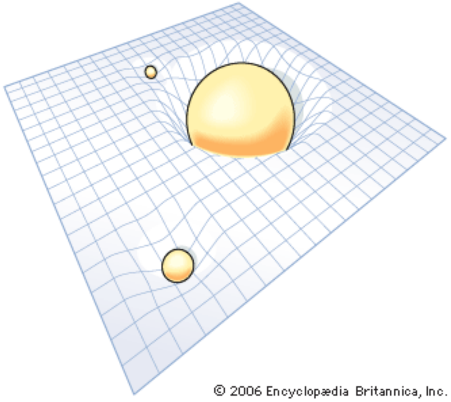
CURVATURE = ENERGY-MOMENTUM

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

# General Relativity: Gravity Talks

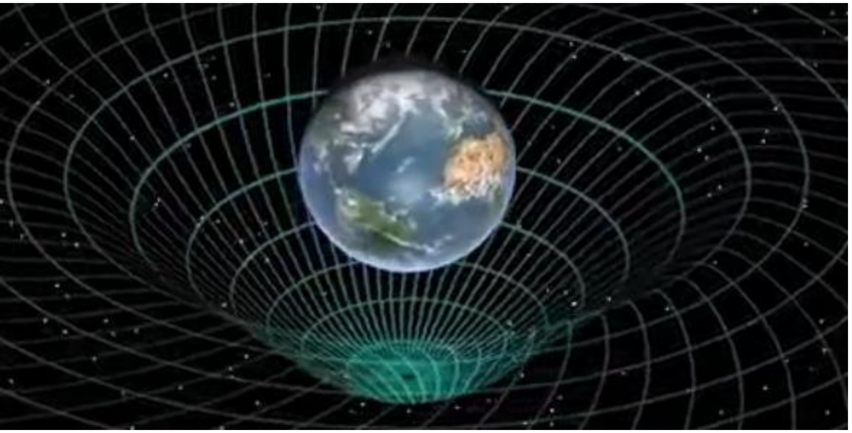
- The effect of a gravitational field is to produce a curvature of spacetime
- The straight line becomes a “geodesic”, the shortest route between two points on a warped surface
- Bodies not subject to forces other than a gravitational field move along geodesics of spacetime

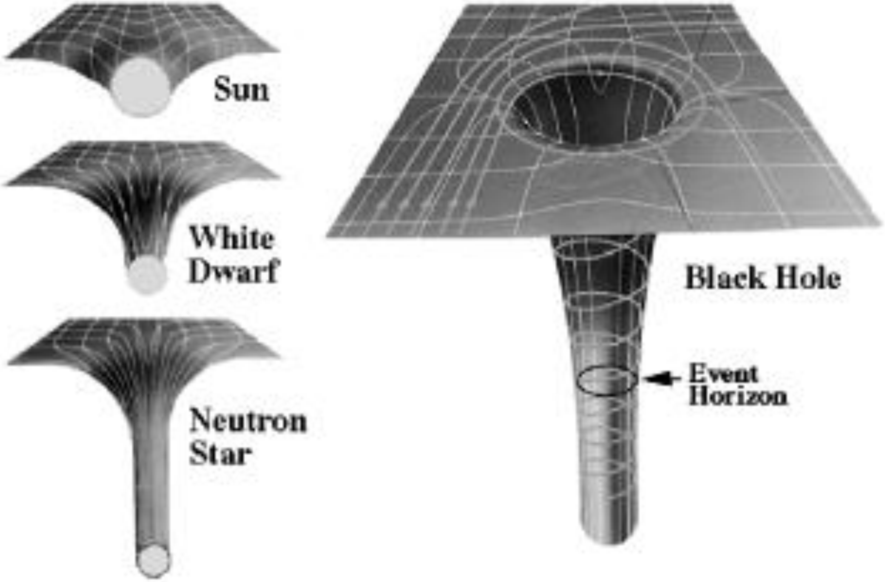



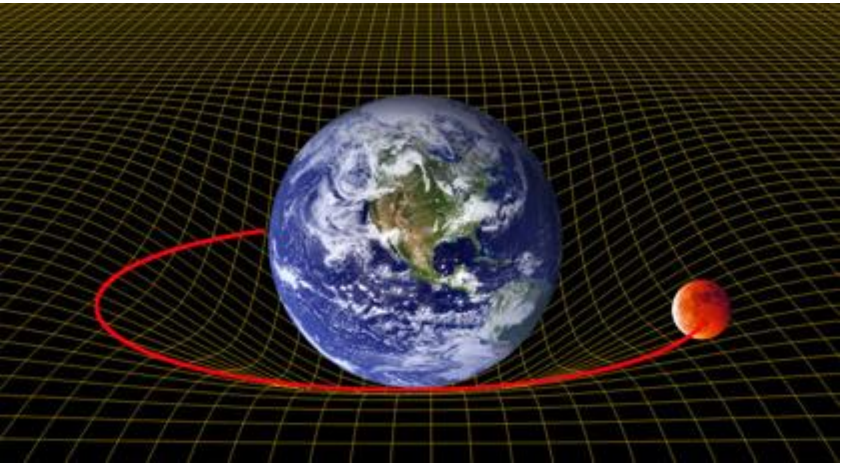



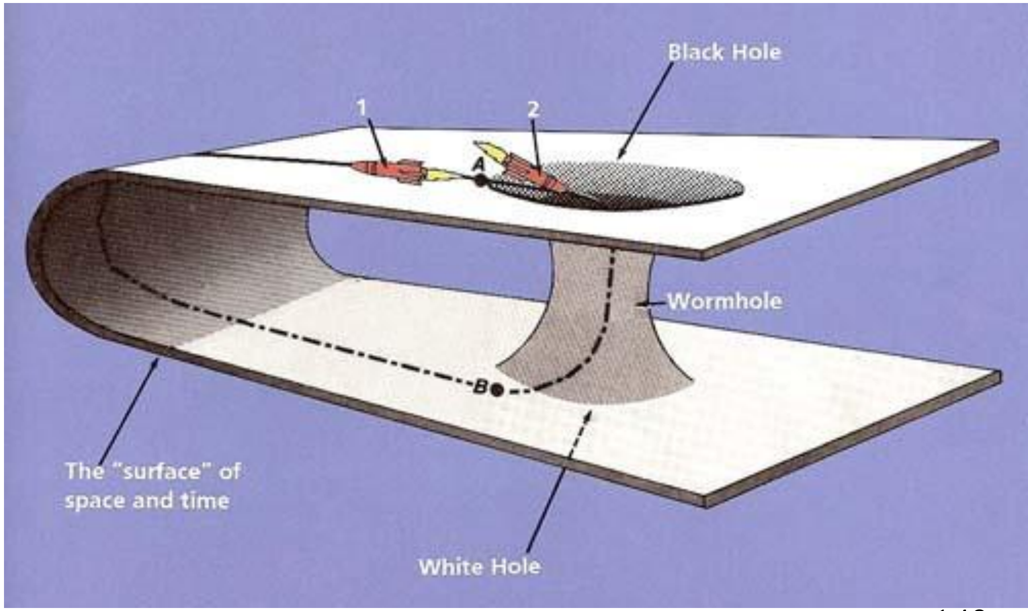
# General Relativity: Gravity Talks

- Spacetime warp



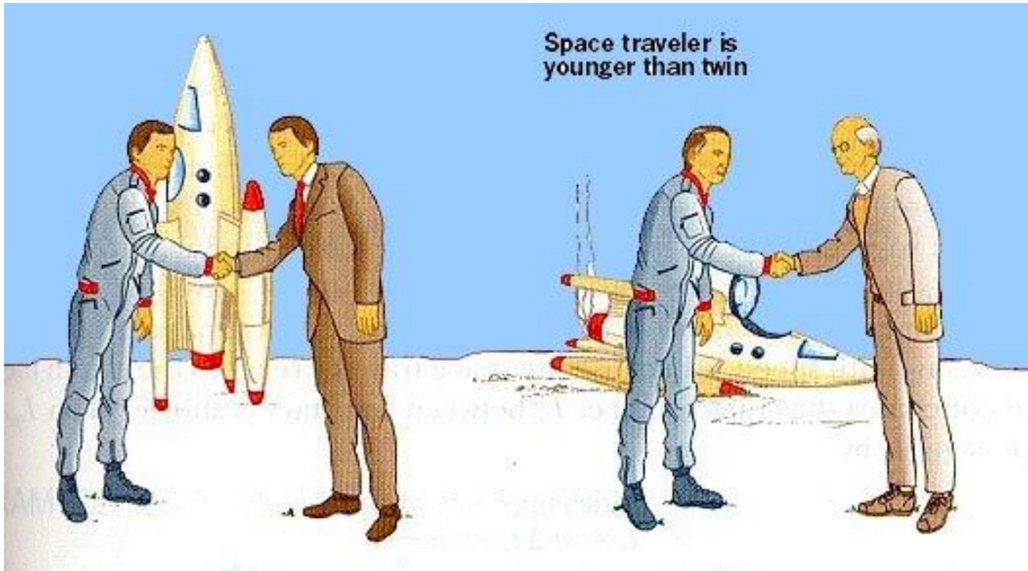




# General Relativity: Gravity Talks

- What causes the "warps" is energy-mass
- "Force" becomes an effect of the geometry of space
- A "force" is the manifestation of a distortion in the geometry of space
- Clocks are slowed down by "gravity" (i.e. by spacetime warps)



# Summarizing Einstein...





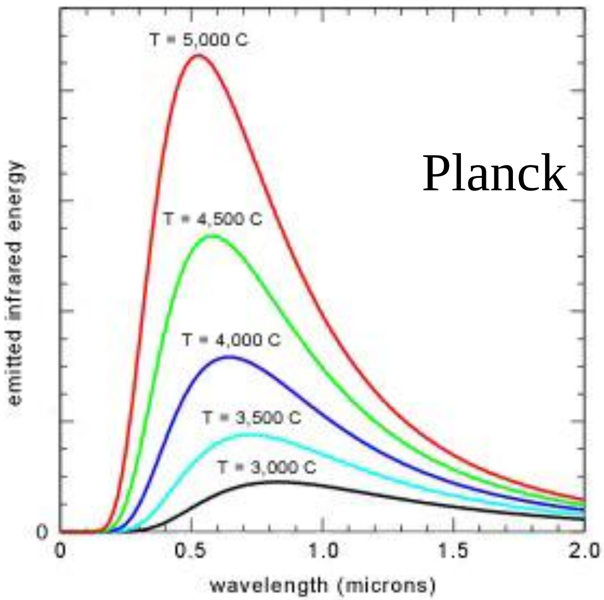
- The dynamics of matter is determined by the geometry of space-time
- Geometry is in turn determined by the distribution of matter
- Space-time acts like an intermediary device that relays the existence of matter to other matter

Matter → Spacetime geometry → Matter

# Questions?

# Quantum Theory: Enter Probabilities

- Any field of force manifests itself in the form of discrete particles (“quanta”)




Planck

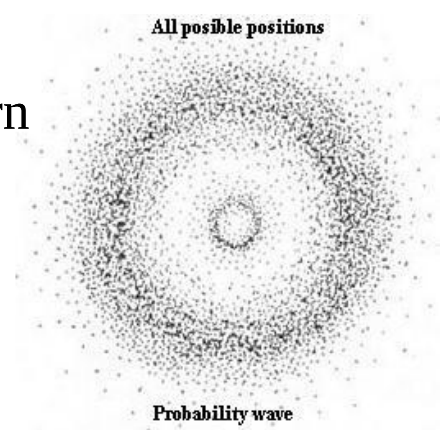
$$mc^2 = h\nu$$

DeBroglie

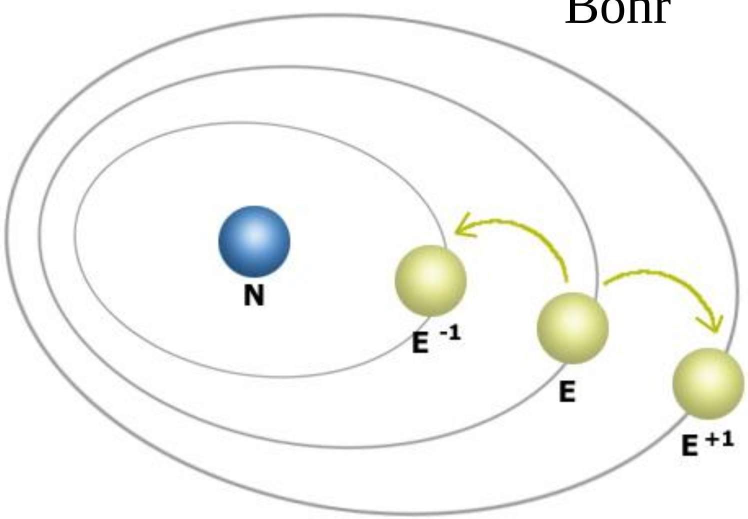
$$E = h\nu$$

Einstein

Born




Bohr



# Quantum Theory: Enter Probabilities

- Forces are manifestations of exchanges of discrete amounts of energy (Max Planck, 1900)
- Equivalent descriptions: energy and mass, frequency and wavelength (Einstein, 1905)
- Electrons are permitted to occupy only some orbits around the nucleus (Niels Bohr, 1913)
- Waves and particles are dual aspects (Louis de Broglie, 1923)
- The wave associated to a particle is a wave of probabilities (Max Born, 1926)





# Quantum Theory: Enter Probabilities

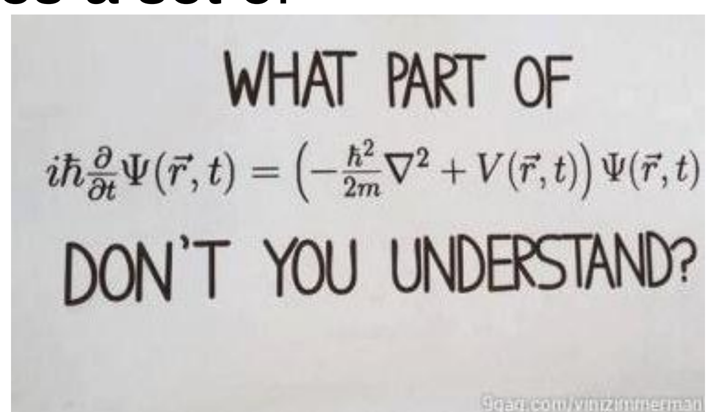
- 1925 equations to replace Newton's (or, better, Hamilton's) equations and predict the state of the system at a later time given the current state
  - Werner Heisenberg's equation (based on matrix algebra): the result of a physical experiment depends on the order in which the calculations are performed
  - Erwin Schroedinger (based on wave mechanics): an object is a wave spread in space

$$X_{nm}(t) = e^{2\pi i(E_n - E_m)t/h} X_{nm}(0)$$

$$i\hbar \frac{\partial}{\partial t} \psi(\mathbf{r},t) = -\frac{\hbar^2}{2m} \nabla^2 \psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

# Quantum Theory: Enter Probabilities

- The state of a particle is a “superposition” of alternatives
- The state of a particle is described by a “wave function” which summarizes (superposes) all the alternatives and their probabilities
- Erwin Schroedinger's equation describes how this wave function evolves in time
- The wave function describes a set of possibilities



# Quantum Theory: Enter Uncertainty

- An observable quantity can assume a range of values (its “eigenvalues”), each one with a given probability
- An observer can measure at the same time only observables which are compatible: indeterminacy of incompatible observables
- Werner Heisenberg’s "uncertainty principle": there is a limit to the precision with which we can measure quantities
- The degree of uncertainty is proportional to the Planck constant

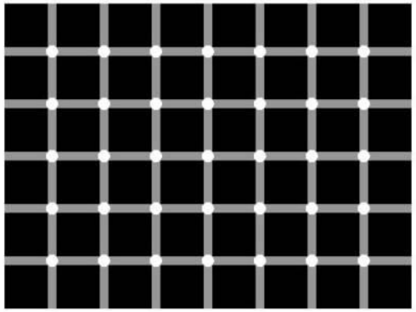
$$\Delta E\,\Delta t \geq \frac{\hbar}{2} \qquad \Delta\chi\Delta\rho \geq \frac{\hbar}{2}$$

# Quantum Theory: Enter Uncertainty

- The degree of uncertainty is proportional to the Planck constant
- Below a quantity proportional to the Planck constant the physical laws stop working altogether
- This implies that there is a limit to how small a physical system can be

# Quantum Theory: Enter Uncertainty

- The Planck constant
  - Newton and Einstein physics assumed that the most fundamental units of the universe were the point and the instant
  - Quantum Theory introduces a fundamental unit that is bigger than a point and an instant
  - There is a limit to how small an object can be and to how short an interval can be
  - Einstein had warped space and time, Quantum Theory it turned them into grids.
  - The Planck constant has a size: a length, height and width of $10^{-33}$ centimeters and a time interval of $10^{-43}$ seconds



# Quantum Theory: Enter Uncertainty

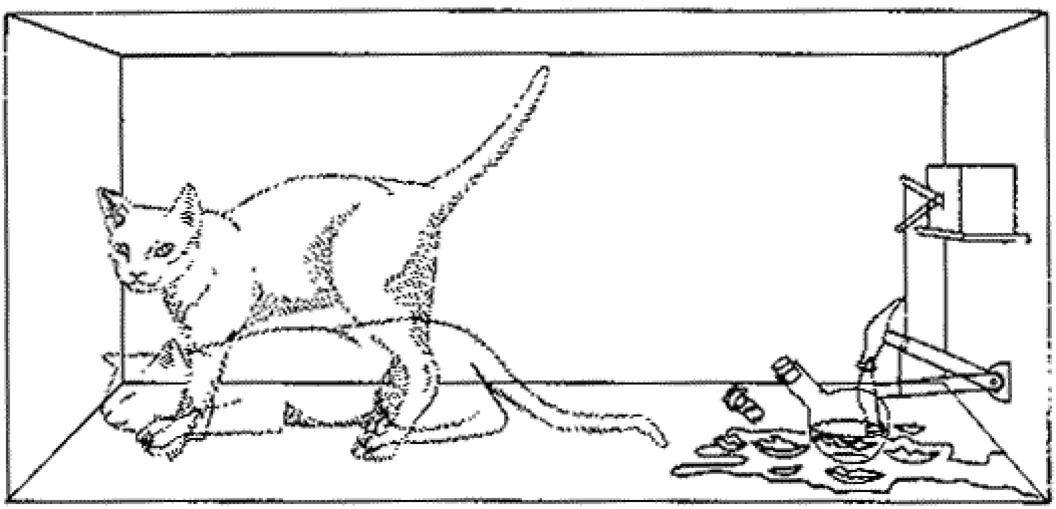
- The vacuum
  - Paul Dirac (1930)
  - If you remove all particles, i.e. you have absolute certainty about the position of particles, then you know nothing about momentum and therefore about energy
  - Kinetic and potential energy cannot both be zero at the same time
  - There has to be a minimum amount of energy: the zero-point energy
  - The vacuum is not empty
  - Hendrik Casimir (1948): the vacuum generates a force

$$E_0 = \int_{\omega=0}^{\omega_{cutoff}} \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega$$

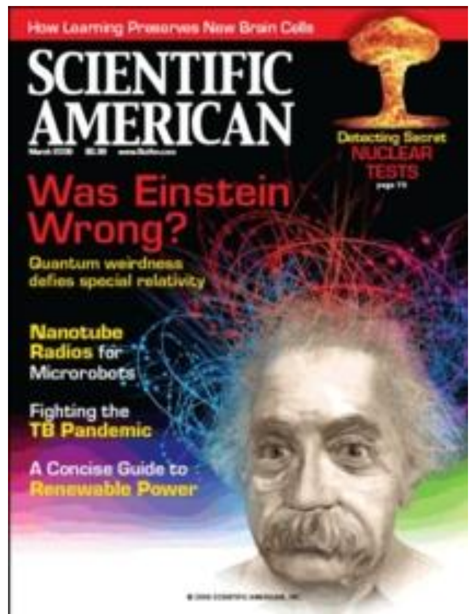
Energy Density from the Quantum Vacuum Advanced Propulsion Physics: Harnessing the Quantum Vacuum H. White, P. March

# Quantum Theory: Enter Uncertainty

- Randomness
- Schroedinger's cat
- Non-locality

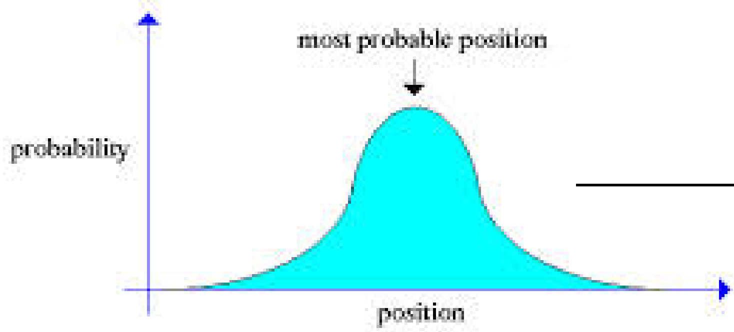


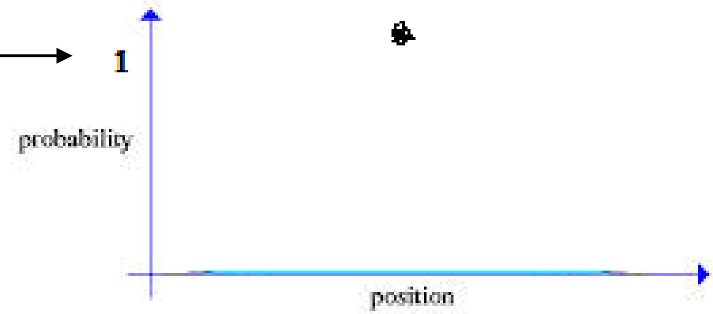
upscale.utoronto.ca

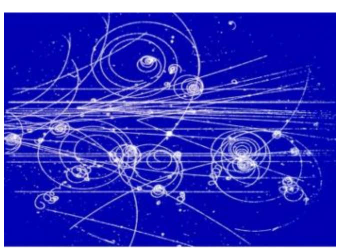


# The Measurement Problem

- A measurement causes a “collapse” (reduction) of the wave function: only one eigenvalue is possible after the measurement, the one that is measured
- A measurement introduces irreversibility in nature: collapse cannot be undone

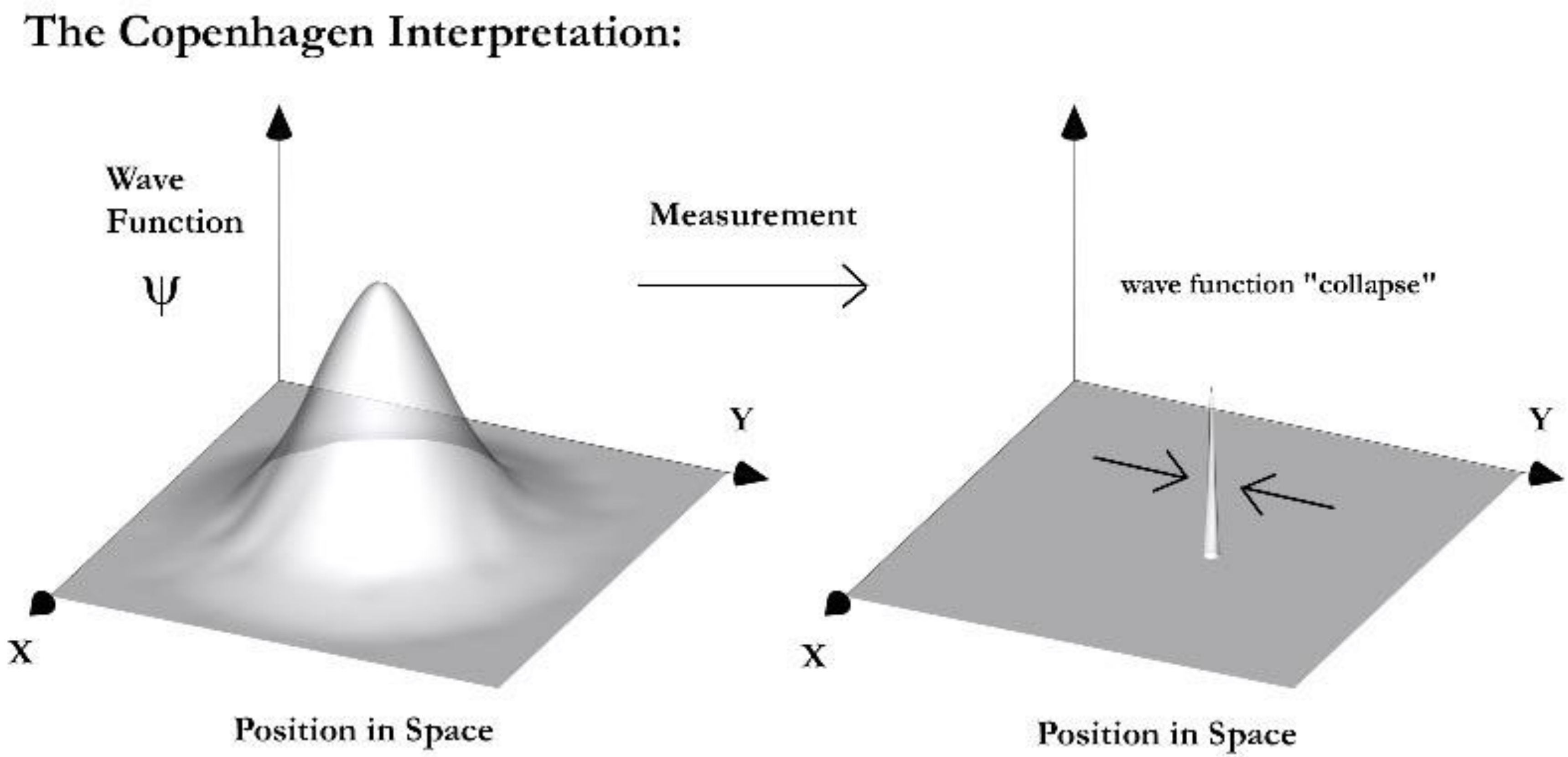


# The Measurement Problem

- The collapse of the wave:

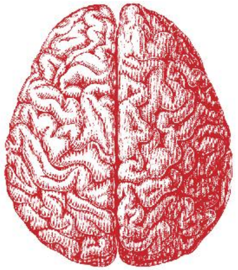


# The Measurement Problem

- John von Neumann (1932)
  - The flow of time is mysteriously altered by measurements
  - The classical world emerges from the quantum world thanks to measurement
  - A continuous process of the probabilistic kind gives rise to a discontinuous process of the deterministic kind

# The Measurement Problem

- John von Neumann
  - Measurement of a system consists in a chain of interactions between the instrument and the system, whereby the states of the instrument become dependent on the states of the system
  - Eventually, states of the observer’s consciousness are made dependent on states of  the system, and the observer “knows” what the value of the observable is
  - Somewhere between the system and the observer’s consciousness the “collapse” occurs



# The Measurement Problem

- Is it something that only humans have?
- If not, what is the smallest object that can collapse a wave?
- What is the measuring apparatus in quantum physics?
- How does nature know which of the two systems is the measurement system and which one is the measured system?
- A privilege of the human mind?

# Interpretations of Quantum Theory




- Niels Bohr: only phenomena are real
- Werner Heisenberg: the world "is" made of possibility waves (particles are merely "potentialities")
- Paul Dirac: a description of our knowledge of a system
- Hugh Everett: multiverse
- etc

# Quantum Theory: Enter Entanglement

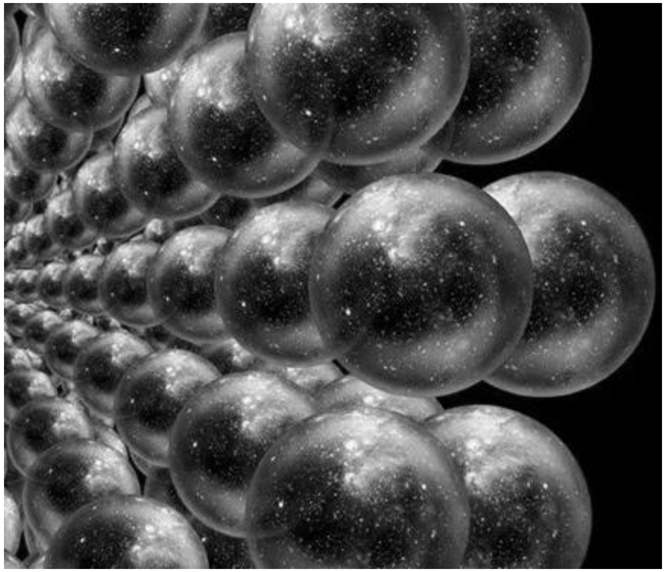
- Albert Einstein (1935)
  - Paradox: once entangled, the states of two particles would be entangled forever, no matter how far from each other (EPR paper: 5 citations in 20 years, more than 300 in 2014)
- Schroedinger (1935)
  - Entanglement is the most fundamental feature of Quantum Mechanics
- John Bell (1964)
  - Yep, that’s the way it is!

# Quantum Theory: Enter Entanglement

- A brief history of teleportation
  - Impossible according to Heisenberg’s uncertainty principle (the very act of measuring its state destroys it so it is impossible to make an exact replica)
  - William Wootters: Entanglement offers a way around it (1993)
  - (“Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels”, 1993). In 1998 the team led by US physicist Jeff Kimble teleports a photon for about one meter (1993)
  - Nicolas Gisin teleports a photon to 2 kms (2003)
  - Anton Zeilinger teleports a photon to 143 kms (2012)

# The Quest for Certainty

- Hugh Everett's “multi-verse” (1957)
  - If something physically can happen, it does: in some universe
  - Each measurement splits the universe in many universes



# The Quest for Certainty

- Hugh Everett's “multi-verse” (1957)
  - We exist in one copy for each universe and observe all possible outcomes of a situation
  - No collapse of the wave function
  - The universe can unfold in an infinite number of ways
  - Quantum theory becomes deterministic
  - The role of the observer is vastly reduced

# The Quest for Certainty

Michael Lockwood (1986)

- Each measurement splits the observer, not the universe

# The Quest for Certainty

- David Bohm (1952)
  - The quantum "wave" is a real wave, due to a real field, that acts upon particles the same way a classical potential does
  - This field is due to a potential that permeates the universe
  - Position and momentum of a particle are no longer incompatible
  - Bohm's wave is a real wave that guides the particle (the "pilot-wave")
  - Everything is both a particle and a wave, and is acted upon by both a classical potential and a quantum potential

# The Quest for Certainty

- David Bohm (1952)
  - Bohm's potential plays the role of Einstein's "hidden variables"
  - Bohm's quantum potential acts beyond the 4-dimensional geometry of spacetime
  - The quantum field is, in turn, affected by all particles
  - Everything in the universe is entangled in everything else
  - The universe is one indivisible whole

# The Quest for Certainty

- Eugene Wigner (1963) following Von Neumann:
  – Reality is just the content of consciousness
  – The evolution of the universe changed after the appearance of human beings (there was no collapse anywhere before mind appeared)

# The Quest for Certainty

- Transactional Interpretation
  - John Wheeler and Richard Feynman (1945)
    - Maxwell's equations of electromagnetism have two possible solutions: a retarded solution and an advanced one
    - A charged particle generates both waves that will arrive after the emission as well as other, perfectly symmetrical, waves that will arrive before the emission.
    - A radiation process is a "transaction" in which the emitter of the radiation and the absorber of the radiation exchange waves

# The Quest for Certainty

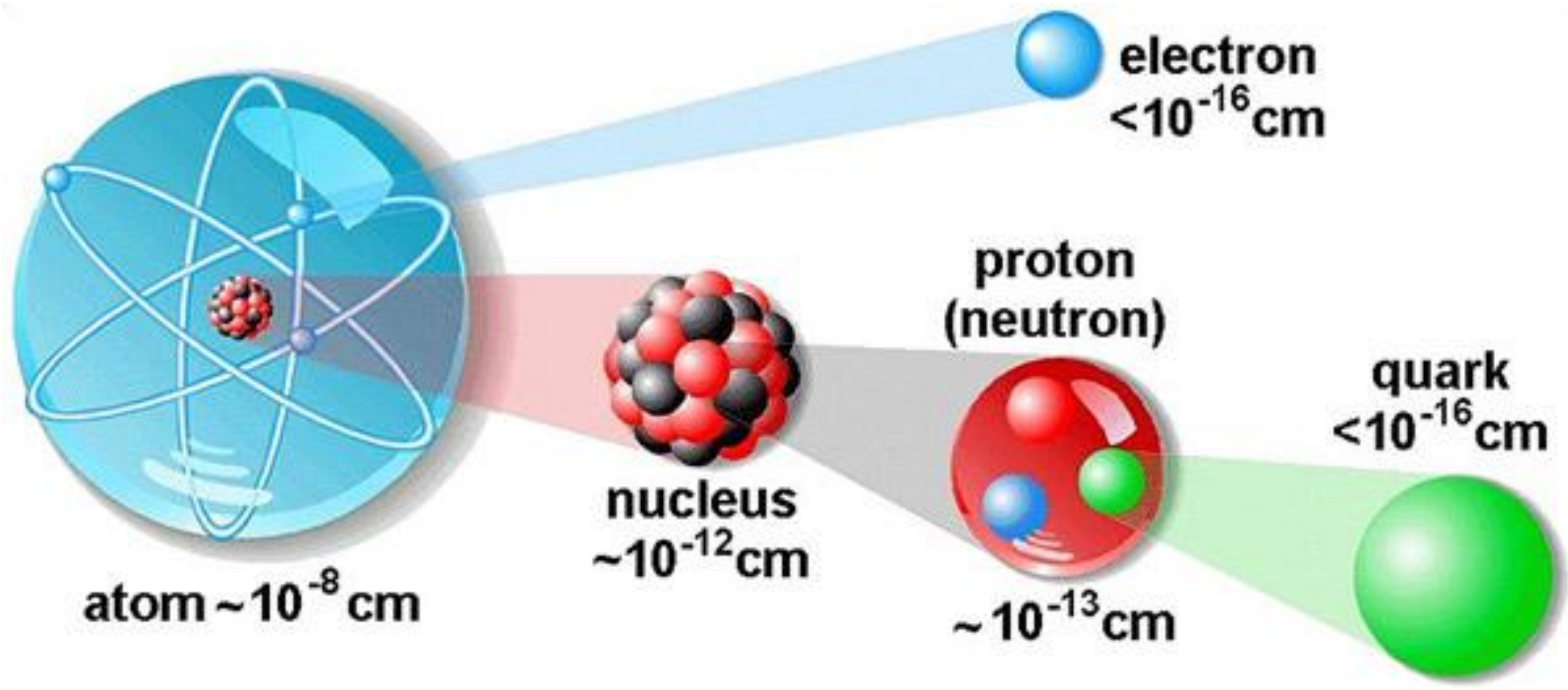
- John Wheeler (1994)
  - Ours is a "participatory" universe, one in which consciousness participates in creating reality
  - The observer and the phenomenon are engaged in a creative act that yields reality

# The Quest for Certainty

- Relativity, Quantum Physics and Thermodynamics: three disciplines that happen to pose limitations on the speed, amount and quality of information that can be transmitted in a physical process.

# Questions?

# The Physics of Elementary Particles

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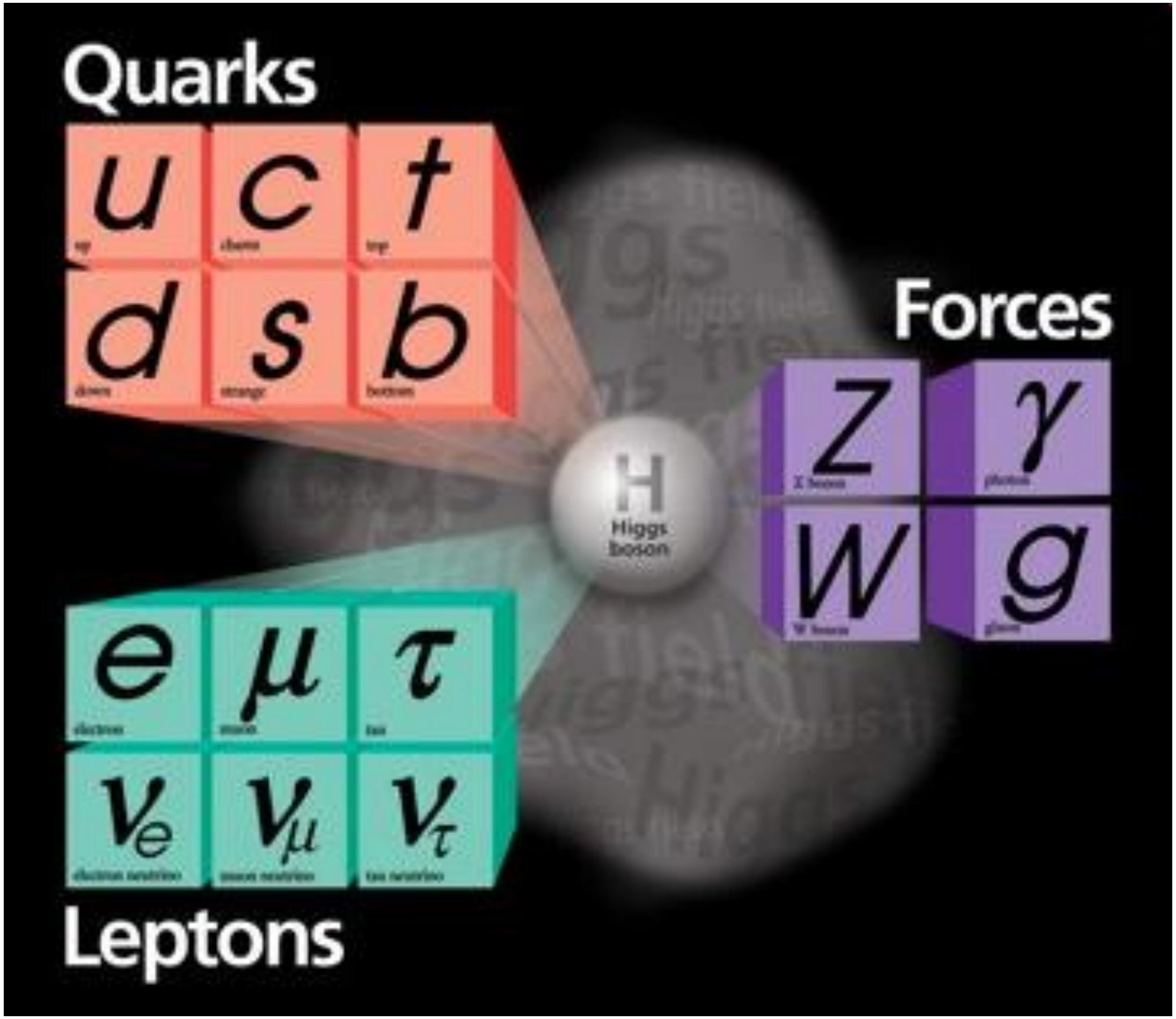
# The Physics of Elementary Particles

- Quantum Electrodynamics (Paul Dirac, 1928) and Quantum Chromodynamics (Murray Gellman, 1964)

# The Physics of Elementary Particles

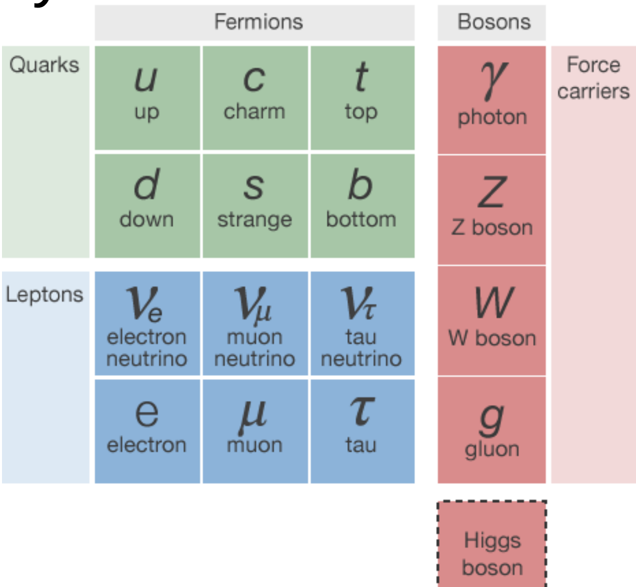
- Forces are mediated by discrete packets of energy (quanta: photon, w-/w+/z, graviton, gluons)
- Particles that make up matter belong to two families of fermions: leptons and quarks
- The world is made of six leptons, six times three quarks, four bosons for leptons and eight gluons for quarks (48 fermions and 12 bosons)
- The whole set of equations for these particles has 19 arbitrary constants

# The Physics of Elementary Particles



# Unification: In Search of Symmetry

- Peter Higgs  (1964)
  - The top quark is about 100,000 times "heavier" than the electron, and more than one trillion times heavier than the electron-neutrino
  - Mass measures the interaction with the all-pervasive Higgs field, mediated by the Higgs boson

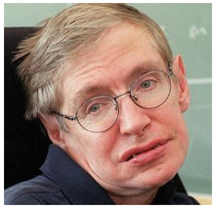



Source: AAAS

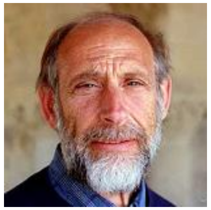
# Grand Unification

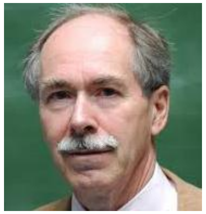
- The universe of Relativity is curved and continuous
- The universe of Quantum Theory is flat and granular
- Relativity prescribes that matter warps the continuum of spacetime, which in turns affects the motion of matter
- Quantum Theory prescribes that matter interacts via quanta of energy in a flat spacetime
- Quantum Theory does not explain gravity

# Black Holes and Entropy



- Jakob Bekenstein (1972): Black holes store a huge amount of entropy
- Stephen Hawking (1974): The area of the event horizon can never decrease
- The entropy of a black hole is proportional to the area of its event horizon.





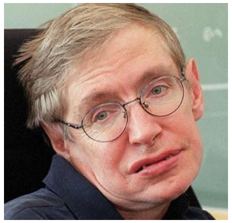
- Hawking (1974): Black holes evaporate
- Leonard Susskind and Gerard ’t Hooft (1993): A black hole is a hologram: information about what has been lost inside the black hole is encoded on the surface of the black hole

# Black Holes and Wormholes

- Karl Schwarzschild (1916): The "black hole"
- Einstein (1935): Black holes imply the existence of a "bridge" between our universe and a mirror universe which is hidden inside the black hole, and in which time runs backwards
- Kurt Goedel (1949): Space-time can curve to the point that a particle will return to a previous point in time; I.e., "wormholes" can connect two different points in time of the same universe
- John Wheeler (1950s): Two points in space can be connected through several different routes, because of the existence of  spatial wormholes




# Black Holes and Wormholes



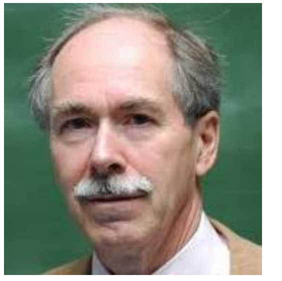
- Stephen Hawking (1988): Wormholes can connect different universes altogether

- Lee Smolin  (1992): Black holes are the birthplaces of offspring universes

- Kip Thorne (1994): A time machine capable of exploiting such time wormholes

- Andrew Strominger (1996): Black holes decay into strings and strings decay into black holes

# The Holographic Universe



- Gerard't Hooft (1993)
  - The horizon of a black hole (a two dimensional surface) stores all the information that ever fell into the hole
  - Generalizing: the informational content of a region of space can always be equivalently expressed by a theory that lives on the boundary of that region
  - The three-dimensional universe which we perceive might be encoded on a two-dimensional surface, like a hologram.

# Status

Science cannot account for:

Dark matter (perhaps 23% of the mass-energy of the universe and five times as abundant as matter) does not interact with ordinary matter, does not emit and does not reflect light (its gravitational effect has been inferred by observing the motion of galaxies)

Dark energy (about 73% of the mass-energy of the universe) is needed in order to account for the acceleration of the expansion of the universe

# Summary

- Classical Physics is continuous and objective
- Thermodynamics introduces entropy
- Entropy is related to order and information
- Darwin's theory was really a theory of how to create order
- Complex systems create order (self-organize) in special cases and yield new properties
- Self-organizing systems only happen at the edge of chaos
- Oscillators too can self-organize, not in space but in time
- Electromagnetism introduces fields

# Summary

- Relativity is based on the observer: even space and time are relative
- Quantum Mechanics is based on the observer: it is the act of measuring that creates reality
- There is a limit (uncertainty) to what we can know in Quantum Mechanics
- The result of a measurement (the collapse of the wave) is random
- The vacuum
- Entanglement
- Relativity and Quantum Physics contradict each other
- Physics is almost certainly incomplete (dark matter, dark energy)

# Questions?

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# Modern Physics

*"Time is the substance of which we are made"*
(Borges)

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