Artificial intelligence (CK0031)

Artificial intelligence

Francesco Corona

Artificial intelligence

- **Intelligence**: For thousands (2) of years, we have tried to understand how we think we think
- **Artificial intelligence**: An attempt not just to understand but also to build intelligent entities

AI is one of the newest fields in science and engineering

- Work started after World War II, the name was coined in 1956
- Along with molecular biology, AI is regularly cited as the 'field I would most like to be in' by scientists in other disciplines

Artificial intelligence (cont.)

AI currently encompasses a huge variety of subfields

- From the general (learning and perception) to the specific (playing chess, proving mathematical theorems, writing poetry, driving a car on a crowded street, diagnosing diseases, ...)

AI is relevant to any intellectual task: It is truly a universal field

What's AI?

Artificial intelligence

What's AI?

We can attempt a quadruple definition, along 2-by-2 dimensions

- **reasoning** v **behaviour**, vertically
- **humanity** v **ideality**, horizontally

A system that 'does the right thing' given what it knows has an ideal performance measure, which we can also call **rationality**

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What's AI? (cont.)

Thinking Humanly	**Thinking Rationally**
"The exciting new effort to make computers think . . . *machines with minds*, in the full and literal sense." (Haugeland, 1985) "[The automation of] activities that we associate with human thinking, activities such as decision-making, problem solving, learning . . ." (Bellman, 1978)	"The study of mental faculties through the use of computational models." (Charniak and McDermott, 1985) "The study of the computations that make it possible to perceive, reason, and act." (Winston, 1992)
Acting Humanly	**Acting Rationally**
"The art of creating machines that perform functions that require intelligence when performed by people." (Kurzweil, 1990) "The study of how to make computers do things at which, at the moment, people are better." (Rich and Knight, 1991)	"Computational Intelligence is the study of the design of intelligent agents." (Poole *et al.*, 1998) "AI . . . is concerned with intelligent behavior in artifacts." (Nilsson, 1998)

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What's AI? (cont.)

Historically, all of the four approaches to AI have been followed

Vertically
- **Thinking humanly and acting humanly**;
- **Thinking rationally and acting rationally**

- A *human* approach must be in part an empirical science, involving observations and hypotheses about human behaviour
- A *rational* approach must be in part a formal science, involving some combination of mathematics and engineering

Horizontally?
- **Thinking humanly and rationally**;
- **Acting humanly and rationally**

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Acting humanly

What's AI

Acting humanly

The **Turing test** was proposed by, ehm ... Alan Turing (1950)

- It was designed to provide a satisfactory operational definition of intelligence
- The details of the test can be used to discuss whether a computer would really be intelligent if it passed

- A computer passes the test if a human interrogator, after posing some written questions, cannot tell whether the written responses come from a person or from a computer

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Acting humanly (cont.)

Programming a computer to pass a rigorous test is not easy stuff

The computer would need to possess the following capabilities:

- **Natural language processing**, to communicate in English
- **Knowledge representation**, to store what it knows
- **Automated reasoning**, to use stored information to answer questions and draw new conclusions
- **Machine learning**, to adapt to new circumstances and to detect and extrapolate patterns

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Acting humanly (cont.)

Turing's test deliberately avoids direct physical interaction between the interrogator and the computer, because physical simulation of a person is unnecessary for intelligence

- The so-called **total Turing test** includes a video signal so that the interrogator can test the subject's perceptual abilities, as well as the opportunity for the interrogator to pass physical objects 'through the hatch'

To pass the total Turing test, the computer additionally will need

- **Computer vision**, to perceive objects
- **Robotics**, to manipulate objects and move about

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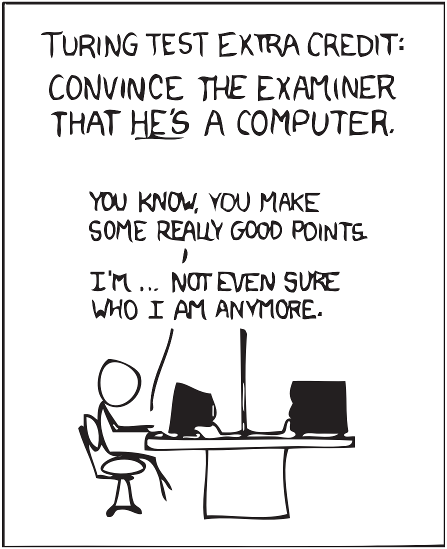
Acting humanly (cont.)

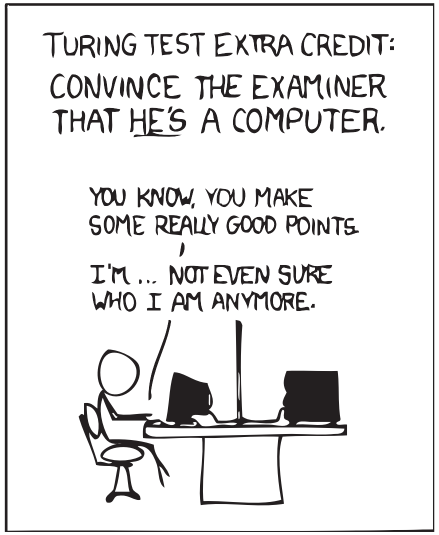
These six disciplines compose most of AI and Turing deserves credit for designing a test that remains relevant 60 years later

Acting humanly (cont.)



Hit Turing right in the test-ees

Acting humanly (cont.)



Hit Turing right in the test-ees

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Thinking humanly

What's AI

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Thinking humanly

If we are going to say that a given program thinks like a human, we must have some way of determining how humans think (doh!)

- We need to get inside the actual workings of human minds

There are three ways to do this, through:

- **Introspection**, trying to catch own thoughts as they go by;
- **Psychological experiments**, observing a person in action;
- **Brain imaging**, observing the brain in action

Once we have a sufficiently precise theory of the mind, then it may become possible to express the theory as a computer program

- If the program's input-output behaviour and corresponding human behaviour match, then there is evidence that some of the program's mechanisms could also be operating in humans

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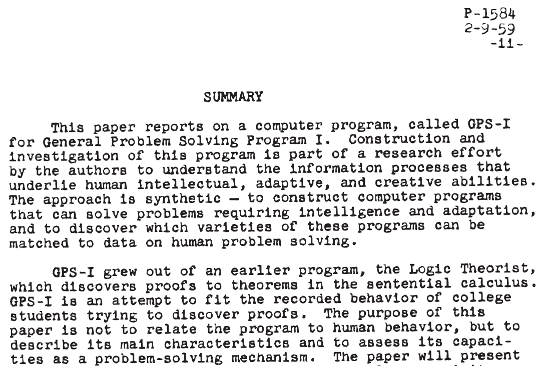
Thinking humanly (cont.)

Newell, Shaw and Simon, the guys who developed the **GPS**, the **General Problem Solver** (1959), were not content merely to have their program solve problems correctly

- They were more concerned with comparing the trace of its reasoning steps to traces of humans solving the same quiz



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SUMMARY

This paper reports on a computer program, called GPS-I for General Problem Solving Program I. Construction and investigation of this program is part of a research effort by the authors to understand the information processes that underlie human intellectual, adaptive, and creative abilities. The approach is synthetic — to construct computer programs that can solve problems requiring intelligence and adaptation, and to discover which varieties of these programs can be matched to data on human problem solving.

GPS-I grew out of an earlier program, the Logic Theorist, which discovers proofs to theorems in the sentential calculus. GPS-I is an attempt to fit the recorded behavior of college students trying to discover proofs. The purpose of this paper is not to relate the program to human behavior, but to describe its main characteristics and to assess its capacities as a problem-solving mechanism. The paper will present

Thinking humanly (cont.)

The interdisciplinary field of **cognitive science** brings together computer models from AI and experimental techniques from psychology to construct precise and testable theories of our mind

- We occasionally comment on similarities or differences between AI techniques and human cognition
- Real cognitive science is necessarily based on experimental investigation of actual humans or animals

Basically, we assume you have only a computer for experimentation

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Thinking humanly (cont.)

In early days there was often confusion between the approaches

- Somebody would argue that an algorithm performs well on a task and that it is thus a good model of human performance
- or vice versa

Modern authors separate the two kinds of claims

This distinction has allowed both AI and cognitive science to grow

- The two fields continue to fertilize each other (in computer vision, they incorporate neurophysiological evidence into computational models)

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Thinking rationally
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Thinking rationally

This is also called the **law of thought** approach and, as one of the first attempts to codify 'right thinking' as irrefutable reasoning processes it is due to the greek philosopher Aristotle

The **syllogism** provided patterns for argument structures that always yielded correct conclusions when given the right premises

- **Premises**: a) Socrates is a man and b) all men are mortal
- **Conclusion**: Socrates is mortal $\Longleftarrow$

These laws of thought were supposed to govern the operation of the mind and their study initiated the field called **logic**

Thinking rationally (cont.)

Logicians developed a precise notation for statements about all kinds of objects in the world and relations among them

- You can contrast this with ordinary arithmetic notation, which provides only for statements about numbers

By 1965, programs existed that could, in principle, solve any solvable problem described in logical notation

- Although if no solution exists, the program might loop forever

The **logicist** tradition within artificial intelligence aims at building on such programs to create intelligent systems

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Thinking rationally (cont.)

There are two main obstacles to this approach:

- First, it is hard to take informal knowledge and state it in the formal terms required by logical notation[1]
- Second, there is a difference between solving a problem 'in principle' and solving it in practice[2]

Such issue apply to any attempt to build computational reasoning systems, though they appeared first in the logicist tradition

[1] Particularly true when knowledge is less than 100% certain.

[2] Problems with a moderate number of facts can exhaust the resources of any computer, unless it has guidance as to which reasoning steps to try first.

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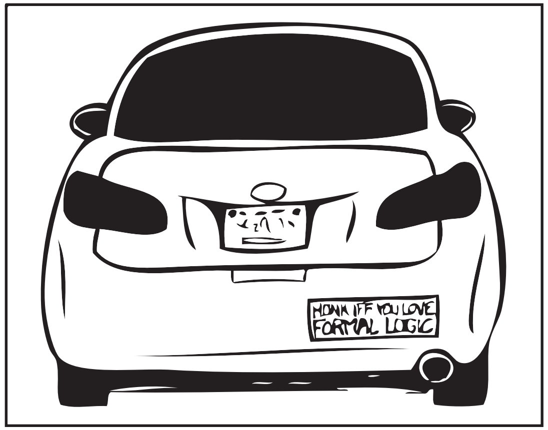
Thinking rationally (cont.)

Honk IFF you love formal logic



Note that this implies you should NOT honk
solely because I stopped for a pedestrian and you're behind me

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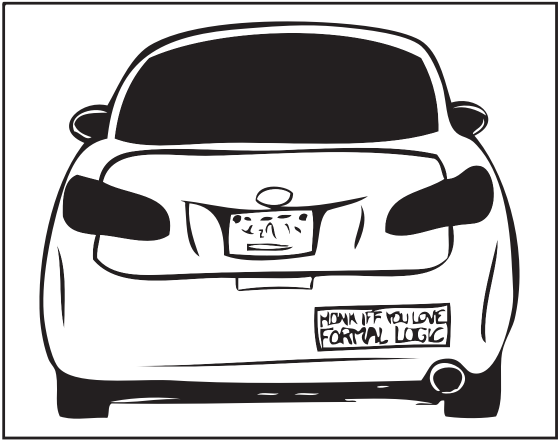
Acting rationally

What's AI

Thinking rationally (cont.)

Honk IFF you love formal logic



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Acting rationally

An **agent** is just something that acts (from Latin *agere*, to do)

Computer programs do something, computer agents must do more:

- They are expected to operate autonomously, to perceive their environment, to persist over a prolonged time period, to adapt to change, and to create and pursue goals

A **rational agent** is one that acts so as to achieve best outcomes

- when there is uncertainty, the best expected outcome

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Acting rationally (cont.)

In the 'thinking rationally' way, emphasis is on correct inferences

- Making correct inferences is part of being a rational agent: One way to act rationally is to reason logically to the conclusion that a given action will achieve one's goals and then to act on that conclusion
- Making correct inference is not all of rationality: In some situations, there is no provably correct thing to do, but something must still be done

There are ways of acting rationally that do not involve inference

- Recoiling from a hot stove is a reflex action: It is usually more successful than a slower action taken after careful deliberation

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Acting rationally (cont.)

All skills needed for the Turing test allow agents to act rationally

- Knowledge representation and reasoning enable agents to reach good decisions
- Natural language processing enables agents to generate comprehensible sentences
- Learning is needed not only for erudition, but also to improve ability to generate effective behaviour

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Acting rationally (cont.)

The rational-agent approach has two advantages over the others

1. More general than 'thinking rationally': Correct inference is just one possible mechanism for achieving rationality
2. More amenable to scientific development than are the other ways based on human behaviour or human thought

The standard of rationality is well defined (mathematically), it is completely general and it generates agents that provably achieve it

- Human behaviour is well adapted for one specific environment and is defined by the sum of all the things that humans do

Acting rationally (cont.)

Focus on general principles of rational agents and their parts

- Despite the apparent simplicity with which a problem can be stated, a variety of issues come up when we try to solve it
- Achieving perfect rationality, always the right thing, is not feasible in complex environments (computational demand)

Still, perfect rationality is a good starting point for analysis as it simplifies the problem and provides an appropriate setting

- **Limited rationality** deals with acting appropriately when there is not enough time to do all the computations

Foundations
Artificial intelligence

Foundations

The disciplines that contributed ideas, viewpoints, and techniques

- We concentrate on a small number of people, events, and ideas and we ignore others that also were important
- Around a series of questions, from such disciplines

- **Philosophy**
- **Mathematics**
- **Economics**
- **Neuroscience**
- **Psychology**
- **Computer engineering**
- **Control theory and cybernetics**
- **Linguistics**

Philosophy
Foundations

Philosophy

- Can formal rules be used to draw valid conclusions?
- How does the mind arise from physical brain?
- Where does knowledge come from?
- How does knowledge lead to action?

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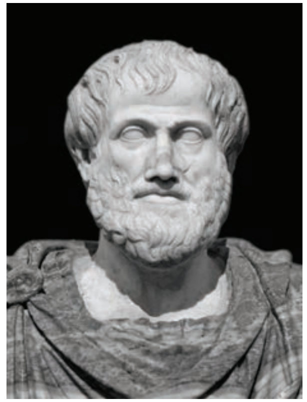
Philosophy (cont.)

Aristotle (-350): Set of laws driving the rational part of the mind

- The system of syllogisms for proper reasoning
- Generation of conclusions, given initial premises
- In principle, this could be dine mechanically



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Philosophy (cont.)

The idea that useful reasoning could actually be carried out by a mechanical artefact arrived much later, with Ramon Lull (1315)

Thomas Hobbes (1588-1679) proposed that reasoning was like numerical computation

- '*We add and subtract in our silent thoughts*'

The automation of computation itself was already well under way

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Philosophy (cont.)

Leonardo da Vinci (1452-1519) designed a mechanical calculator and recent reconstructions show the design to be functional

The first known calculating machine was constructed in 1623 by German scientist Wilhelm Schickard (1592 1635), though the Pascaline (1642), by Blaise Pascal (1623-1662), is more famous

- Pascal wrote that '*the arithmetical machine produces effects which appear nearer to thought than the actions of animals*'

Philosophy (cont.)

Gottfried Wilhelm Leibniz (1646-1716) built a mechanical device intended to carry out operations on concepts rather than numbers

- Leibniz did surpass Pascal by building a calculator that could add, subtract, multiply, and take roots
- The Pascaline could only add and subtract

In those times some speculated that machines might not just do calculations but actually be able to think and act, on their own!

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Philosophy (cont.)

- It's one thing to say that the mind operates, at least in part, according to logical rules, and to build physical systems that emulate some of those rules

It's another to say that the mind itself is such a physical system

Descartes (1596-1650) gave a clear discussion of the distinction between mind and matter and of the problems that arise

One problem with a purely physical conception of the mind is that it seems to leave little room for free will:

- If the mind is governed entirely by physical laws, then it has no more free will than a rock 'deciding' to fall toward the center of the earth

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Philosophy (cont.)

Descartes was a fan of the power of reasoning in understanding the world (**rationalism**), together with Aristotle and Leibniz

..., and he was also a proponent of **dualism**

He held that there is a part of the human mind (or soul or spirit) that is outside of nature, a part that is exempt from physical laws

- Animals, on the other hand, did not possess this dual quality and, as such they could be treated as machines

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Philosophy (cont.)

An alternative to dualism is **materialism**, which holds that brain's operation according to the laws of physics constitutes the mind

- Free will is simply the way that the *perception* of available choices appears to the choosing entity

Philosophy (cont.)

Given a physical mind that manipulates knowledge, the next problem is to establish the source of knowledge

- The **empiricism** movement, starting with Francis Bacon's (1561-1626) *Novum Organum*, is characterised by a dictum of John Locke (1632-1704): '*Nothing is in the understanding, which was not first in the senses*'
- David Hume's (1711-1776) *A Treatise of Human Nature* proposed what is now known as the principle of **induction**: that general rules are acquired by exposure to repeated associations between their elements

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Philosophy (cont.)

Building on the work of Ludwig Wittgenstein (1889-1951) and Bertrand Russell (1872-1970), the famous Vienna Circle, led by Rudolf Carnap (1891-1970), developed a novel doctrine

Logical positivism

- This doctrine holds that all knowledge can be characterised by logical theories connected, ultimately, to **observation sentences** that correspond to sensory inputs

Logical positivism: A combo of rationalism and empiricism, like

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Philosophy (cont.)

The **confirmation theory** of Carnap and Carl Hempel (1905-1997) attempted to analyse the acquisition of knowledge from experience

Carnap's book *The Logical Structure of the World* (1928) defined an explicit computational procedure for extracting knowledge from elementary experiences

- Probably the first theory of mind as a computational process

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Philosophy (cont.)

The final element in the philosophical picture of the mind is the connection between knowledge and action

- A vital question is vital to AI, as intelligence requires action as well as reasoning

Only by understanding how actions are justified can we understand how to build an agent whose actions are justifiable (or rational)

- Aristotle argued that actions are justified by a logical connection between goals and knowledge
- (in *De Motu Animalium*)

Philosophy (cont.)

Goal-based analysis does not say what to do when several actions will achieve the goal or when no action will achieve it completely

- Antoine Arnauld (1612-1694) described a quantitative formula for deciding what action to take in cases like this
- Stuart Mill's (1806-1873) *Utilitarianism* (1863) promoted the idea of rational decision criteria in all spheres of our activity

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Mathematics
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Mathematics

- What are the formal rules to draw valid conclusions?
- What can be computed?
- How do we reason with uncertain information?

If philosophers staked out some of the fundamental ideas of AI, the leap to formal science required mathematical formalisation

- Three areas: Logic, computation and probability

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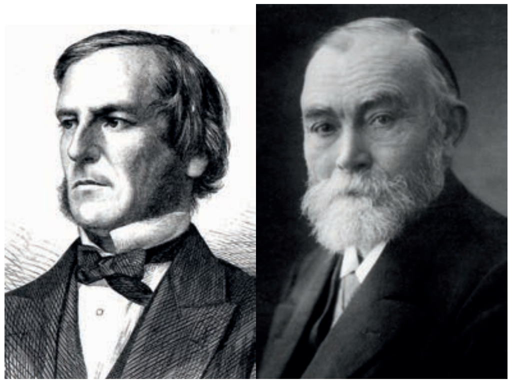
Mathematics (cont.)

The idea of formal logic can be tracked back to ancient Greece, mathematical development began with George Boole (1815-1864), who worked out **propositional** or **Boolean logic**

- In 1879, Gottlob Frege (1840-1925) extended Boole's logic to include objects and relations and created **first-order logic**



Mathematics (cont.)

Find the limits of what could be done with logic and computation

- The first nontrivial **algorithm** is thought to be Euclid's algorithm for computing greatest common divisors

The word algorithm (and the idea of studying them) comes from al-Khowarazmi, a Persian mathematician of the 9th century, whose writings also introduced Arabic numerals and algebra to Europe

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Mathematics (cont.)

- Boole and others discussed algorithms for logical deduction, and, by the late 19th century, efforts were under way to formalise general mathematical reasoning as logical deduction
- In 1930, Kurt Gödel (1906-1978) showed that there exists a procedure to prove any true statement in first-order logic, but first-order logic cannot capture the principle of mathematical induction needed to characterise the natural numbers

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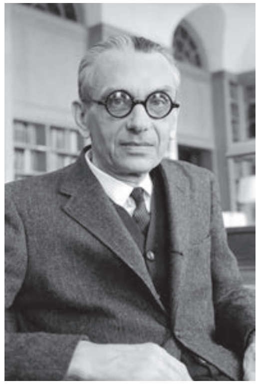
Mathematics (cont.)

In 1931, Kurt Gödel showed that limits on deduction do exist

His **incompleteness theorem** showed that in any formal theory as strong as Peano arithmetic (elementary theory of natural numbers), there exist true undecidable statements

- No proof within the theory



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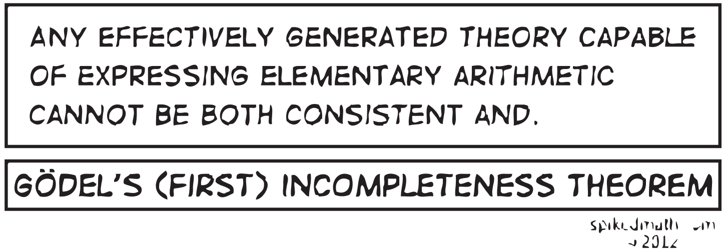
Mathematics (cont.)



Mathematics (cont.)

This motivated Alan Turing (1912-1954) to try to characterise which functions are **computable**, capable of being computed

- The notion is problematic because the notion of an effective procedure or computation cannot be given a formal definition

However, the Church-Turing thesis, which states that the Turing machine (Turing, 1936) is capable of computing any computable function, is generally accepted as providing a sufficient definition

There are some functions that no Turing machine can compute

- For example, no machine can tell in general whether a given program will return an answer on a given input or run forever

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Mathematics (cont.)

Though decidability and computability are vital to understand computation, the notion of **tractability** has a greater impact

- Roughly, a problem is called intractable if the time required to solve it grows exponentially with the size of the instances

This is truly serious stuff, exponential growth means that even mildly large instances cannot be solved in any reasonable time

- Strive to divide the overall problem of generating intelligent behaviour into tractable subproblems, r.t. intractable ones!

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Mathematics (cont.)

How can one recognize an intractable problem? Need a method ...

NP-completeness theory by S. Cook (1971) and R. Karp (1972)

- The existence of large classes of combinatorial search and reasoning problems that are NP-complete (NP + NP-hard)

Any problem class to which the class of NP-complete problems can be reduced is 'likely' to be intractable (there is yet no proof that NP-complete problems are necessarily intractable, but still ...)

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Mathematics (cont.)

These results contrast with the optimism with which the popular press greeted the first computers and yesterday's and today's AI

- Despite the increasing speed of computers, careful use of resources will characterise intelligent systems

Mathematics (cont.)

The third contribution of mathematics to AI is **probability theory**

- Gerolamo Cardano (1501-1576) framed the idea of probability, describing it in terms of the possible outcomes (gambling)
- Blaise Pascal (1623-1662), in a letter to Pierre Fermat (1601-1665), showed how to predict the future of an unfinished gambling game and assign average payoffs

Probability became invaluable to quantitative sciences, helping to deal with uncertain measurements and incomplete theories

- James Bernoulli (1654-1705), Pierre Laplace (1749-1827), and others advanced the theory and statistical methods
- Thomas Bayes (1702-1761) proposed a rule for updating probabilities in the light of new evidence

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Mathematics (cont.)

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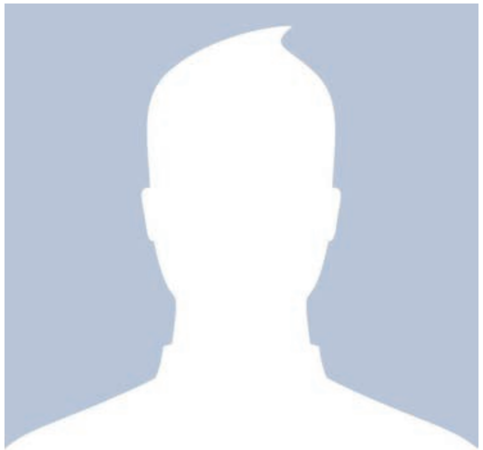
Mathematics (cont.)



Bayes' rule: In most modern approaches to uncertain reasoning

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Economics
Foundations

Economics

- How should we make decisions so as to maximise payoff?
- How should we do this when others may not go along?
- How we do this when the payoff may be far in the future?

The science of economics got its start in 1776, when Scottish philosopher Adam Smith (1723-1790) wrote his famous book

- '*An inquiry into the nature and causes of the wealth of nations*'

The ancient Greeks and others had made contributions to economic thought, Smith was first to treat it as a science

- The idea: Economies can be thought of as consisting of individual agents maximising own economic well-being

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Economics (cont.)

We think of economics as being about money, economists say that they study how people make choices that lead to desired outcomes

- When McDonald's offers a hamburger for a dollar, they are asserting that they would prefer the dollar and hoping that customers will prefer the hamburger

The mathematical treatment of 'preferred outcomes' or **utility** was formalised by L. Walras (1834-1910) and improved by F. Ramsey (1931) and later by von Neumann and Morgenstern in their book

- '*The theory of games and economic behavior*' (1944)

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Economics (cont.)

Decision theory combines probability theory with utility theory

- It provides a formal and complete framework for decisions (economic or otherwise) made under uncertainty
- That is, cases in which probabilistic descriptions capture appropriately the environment of the decision maker

This is suitable for 'large' economies where each agent need pay no attention to the actions of other agents as individuals

- For 'small' economies, the situation is much more like a **game** as the actions of one player can significantly affect the utility of another (either positively or negatively)

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Economics (cont.)

The development of Von Neumann and Morgenstern's **game theory** included the result that, for some games, a rational agent should adopt policies that appear to be randomised

- Unlike decision theory, game theory does not offer an unambiguous prescription for selecting actions

Economics (cont.)

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Economics (cont.)

For the most part, economists did not address the third question

- How to make rational decisions when payoffs from actions are not immediate but result from several sequential actions?

This topic was pursued in the field of operations research

- Richard Bellman (1957) formalised a class of sequential decision problems called **Markov decision processes**

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Economics (cont.)

Economics and operations research have contributed much to the notion of rational agents, yet AI developed along separate paths

One reason was the complexity of making rational decisions

- The pioneering AI researcher Herbert Simon (1916-2001) won the Nobel Prize in economics in 1978 for his work showing that models based on **satisficing** (making decisions that are 'good enough,' rather than laboriously calculating an optimal decision) gave a better description of actual human behaviour
- Since the 1990s, there has been a resurgence of interest in decision-theoretic techniques for agent systems

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Neuroscience

Foundations

Neuroscience

- How do brains process information?

Neuroscience studies the nervous system, particularly the brain

The exact way in which the brain enables thought is one of the mysteries of science, but the fact that it does enable thought has been appreciated for thousands (2) of years

- Evidence that head blows can lead to mental incapacitation

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Neuroscience (cont.)

It has also long been known that human brains are 'different'

- In $\sim$ -335 Aristotle wrote, '*Of all the animals, man has the largest brain in proportion to his size*'
- The largest brain, ... swing with it!

It was not until the middle of the 18th century that the brain was widely recognised as the seat of consciousness

- Before, candidate locations included heart and the spleen

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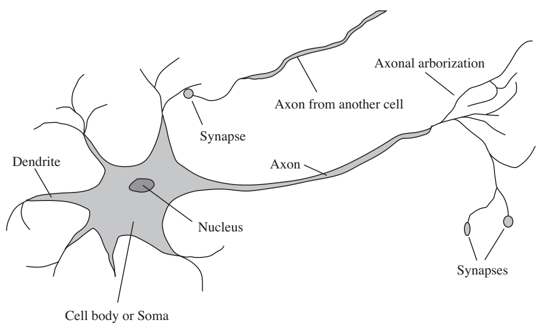
Neuroscience (cont.)

Studies in brain-damaged patients (1861) showed the existence of localised brain areas responsible for specific cognitive functions



By that time, we knew that the brain consisted of nerve cells, **neurons**, and in 1873 Golgi developed a staining technique allowing the observation of individual neurons in the brain

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Neuroscience (cont.)

Nicolas Rashevsky (1936 and 1938) was the first to apply mathematical models to the study of the nervous system

We have some data on the mapping between brain areas and the body parts that they control or from which receive sensory input

- Such mappings are able to change radically over the course of a few weeks, and some animals seem to have multiple maps
- Moreover, we do not fully understand how other areas can take over functions when one area is damaged
- Almost no theory on how an individual memory is stored

Neuroscience (cont.)

The measurement of intact brain activity began in 1929 with the invention by Hans Berger of the electroencephalograph (EEG)

The development of functional magnetic resonance imaging (fMRI, 2001) is giving unprecedentedly detailed images of brain activity

- Measurements that correspond to ongoing cognitive processes

There are the advances in single-cell recording of neuron activity

- Neurons are stimulated electrically, chemically and optically
- Allows neuronal input-output relationships to be mapped

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Neuroscience (cont.)

A long way from understanding how cognitive processes work

- A collection of simple cells can lead to thought
- Brains causes minds

These are our (rather amazing) conclusions today and the only real alternative theory is mysticism according to which minds operate in some mystical realm that is beyond physical science

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Neuroscience (cont.)

Brains and digital computers have somewhat different properties

	Supercomputer	Personal Computer	Human Brain
Computational units	10^4 CPUs, 10^{12} transistors	4 CPUs, 10^9 transistors	10^{11} neurons
Storage units	10^{14} bits RAM	10^{11} bits RAM	10^{11} neurons
	10^{15} bits disk	10^{13} bits disk	10^{14} synapses
Cycle time	10^{-9} sec	10^{-9} sec	10^{-3} sec
Operations/sec	10^{15}	10^{10}	10^{17}
Memory updates/sec	10^{14}	10^{10}	10^{14}

Computers have a cycle time that is a million times faster than a brain and the brain makes up for that with far more storage and interconnection than even a high-end personal computer

- Some supercomputers have a similar capacity to the brain's

The brain does not seem to use all of its neurons simultaneously

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Neuroscience (cont.)

Futurists make much of these numbers, pointing to approaching **singularity** at which computers reach a superhuman level of performance, but the comparisons are not terribly informative

- Even with a computer of virtually unlimited capacity, we still would not know how to achieve the brain's level of intelligence

Psychology

Foundations

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Psychology

- How do humans and animals think and act?

The origins of scientific psychology are traced to the physicists von Helmholtz (1821-1894) and Wundt (1832-1920)

- Helmholtz applied the scientific method to the study of human vision, his *Handbook of Physiological Optics* is even now described as '*the single most important treatise on the physics and physiology of human vision*'

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Psychology (cont.)

Wundt opened the first lab of experimental psychology (1879)

- Wundt insisted on carefully controlled experiments in which his workers would perform a perceptual or associative task while introspecting on their thought processes
- The careful controls went toward making psychology a science, but the subjective nature of the data made it unlikely that an experimenter would ever disconfirm his/her own theories

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Psychology (cont.)

Biologists studying animal behaviour, on the other hand, lacked introspective data and developed an objective methodology

- Described by H. S. Jennings (1906) in his work *Behavior of the Lower Organisms*

Applying this viewpoint to humans, the **behaviorism** movement, led by John Watson (1878-1958), rejected any theory involving mental processes: Introspection cannot provide reliable evidence

Behaviorists kept on studying objective measures of the percepts (or stimulus) given to animals and resulting actions (or response)

- Behaviorism discovered a lot about rats and pigeons
- They had less success at understanding humans

Psychology (cont.)

Cognitive psychology: Brains are information-processing devices

- It can be traced back at least to the works of William James (1842-1910)
- Helmholtz insisted that perception involved a form of unconscious logical inference

The cognitive viewpoint was largely eclipsed by behaviorism in the U.S., but at Cambridge's Applied Psychology Unit, directed by F. Bartlett (1886-969), cognitive modelling was able to flourish

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Psychology (cont.)

The Nature of Explanation, by Bartlett's student and successor Kenneth Craik (1943), forcefully reestablished the legitimacy of such 'mental' terms as beliefs and goals, arguing that they are just as scientific as, say, using pressure and temperature to talk about gases, despite their being made of molecules that have neither

Craik specified the three key steps of a knowledge-based agent:

1. The stimulus must be translated into internal representation;
2. The representation is manipulated by cognitive processes to derive new internal representations;
3. These are in turn retranslated back into action

He clearly explained why this was a good design for an agent

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Psychology (cont.)

Meanwhile, in the United States, the development of computer modelling led to the creation of the field of **cognitive science**

The field have started at a workshop in September 1956 at MIT

- At the workshop, G. Miller presented *The Magic Number Seven*, N. Chomsky presented *Three Models of Language*, and A. Newell and H. Simon presented *The Logic Theory Machine*

The papers showed how computer models can be used to address the psychology of memory, language, and logical thinking, rspctvly

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Psychology (cont.)

Among psychologists, it is now a common (though not universal) view that 'a cognitive theory should be like a computer program'

- it should describe a detailed information-processing mechanism whereby some cognitive function might be implemented

Computer engineering

Foundations

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Computer engineering

- **How do we build an efficient computer?**

For AI to succeed, two things:

- **Intelligence** and an **artefact**

Artefact of choice: **Computer**

The modern digital electronic computer was invented almost simultaneously by scientists in 3 countries embattled in WWII

- The first operational computer was the electromechanical **Heath Robinson**, built in 1940 by Alan Turing's team
- In 1943, the same group developed the **Colossus**, a general-purpose machine based on vacuum tubes
- The first working programmable computer was the **Z-3**, by Konrad Zuse in Germany (1941), who also invented floating - point numbers and the first high-level programming language

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Computer engineering (cont.)

- The first electronic computer, **ABC** (1942), was assembled by John Atanasoff and his student Clifford Berry at Iowa State
- The **ENIAC**, developed in a secret military project at UPenn by a team including John Mauchly and John Eckert, proved to be the most influential forerunner of modern computers

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Computer engineering (cont.)

Since then, each generation of computer hardware has brought an increase in speed and capacity and (somewhere) a price decrease

- Performance doubled approx. every 18 months until around 2005, when power dissipation problems led manufacturers to start multiplying CPU cores rather than clock speed

Current expectations are that future increases in power will come from massive parallelism (as in the brain?)

Computer engineering (cont.)

There were calculating devices before the electronic computer

- The earliest automated machines, from the 17th century
- The first programmable machine was a **loom**, devised in 1805 by Joseph Marie Jacquard (1752-1834), that used punched cards to store instructions for the pattern to be woven

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Computer engineering (cont.)

Charles Babbage (1792-1871) designed two machines, unfinished

- The **Difference engine** was intended to compute math tables for engineering and scientific projects. It was finally built in 1991 at the Science Museum in London (Swade, 2000)
- The **Analytical engine** was more ambitious and included addressable memory, stored programs, and conditional jumps and was the first artefact capable of universal computation

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Computer engineering (cont.)

Babbage's colleague Ada Lovelace was perhaps the world's first programmer and wrote programs for the unfinished Analytical engine and speculated that it could play chess or compose music

- The programming language Ada is named after her

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Computer engineering (cont.)

AI owes a debt to the software side of computer science, which has supplied the operating systems, programming languages, and tools

- This is one area where the debt has been repaid

Work in AI pioneered many ideas in mainstream computer science, including time sharing, interactive interpreters, personal computers with windows and pointer, development environments, the linked list data type, automatic storage management, and key concepts of symbolic, functional, declarative, and object-oriented programming

Control theory and cybernetics

Foundations

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Control theory and cybernetics

- How can artefacts operate under their own control?

Ktesibios of Alexandria (∼ -250) built a self-controlling machine

- a water clock with a regulator to keep a constant flow rate

This invention changed the definition of what an artefact could do

- Previously, only living things could modify their behaviour in response to changes in the environment

Other examples of self-regulating feedback control systems include the steam engine governor, created by James Watt (1736-1819), and the thermostat, invented by Cornelis Drebbel (1572-1633)

- The mathematical theory of stable feedback systems was developed in the 19th century

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Control theory and cybernetics (cont.)

A central figure in **control theory** is Norbert Wiener (1894-1964)

- A brilliant mathematician who worked with Bertrand Russell, among others, before developing an interest in biological and mechanical control systems and their connection to cognition

Wiener and his colleagues Rosenblueth and used control systems as psychological models and challenged the behaviourists

- They viewed purposive behaviour as arising from a regulatory mechanism trying to minimise some 'error', the difference between current state and goal/target state

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Control theory and cybernetics (cont.)

Control theory and cybernetics (cont.)

In the late 1940s, Wiener, along with McCulloch, Pitts and von Neumann, organised a series of influential conferences that explored mathematical and computational models of cognition

- Wiener's book Cybernetics (1948) became a bestseller and awoke the public to the possibility of AI machines

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Control theory and cybernetics (cont.)

Meanwhile, in Britain ...

W. Ross Ashby pioneered similar ideas and together with Turing, Walter, and others formed the Ratio Club (1940)

- '*For those who had Wiener's ideas, ... before Wiener's book appeared*'

Ashby's *Design for a brain* (1952): Intelligence can be created by the use of **homeostatic devices** containing appropriate feedback loops to achieve stable adaptive behaviour

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Control theory and cybernetics (cont.)

Modern control theory, especially stochastic optimal control, has as its goal systems that maximise an **objective function** over time

- This roughly matches our view of AI
- Design systems that behave optimally

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Control theory and cybernetics (cont.)

Why are AI and control theory two different fields then?

- Because of the coupling between math techniques familiar to the participants and sets of problems in each world view

Calculus and matrix algebra, tools of control, lend themselves to systems that are describable by fixed sets of continuous variables, AI arises partly as a way to escape from such perceived limitations

- The tools of logical inference and computation allowed AI to consider problems such as language, vision, and planning
- Stuff that fell outside the control theorist's purview

Linguistics
Foundations

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Linguistics

- How does language relate to thought?

B. F. Skinner published *Verbal behavior* (1957) a comprehensive, detailed account of the behaviourist approach to language learning

- A review of the book became as well known as the book itself, and served to almost kill off interest in behaviourism

The author of the review was the linguist Noam Chomsky, who had just published a book on his own theory *Syntactic structures*

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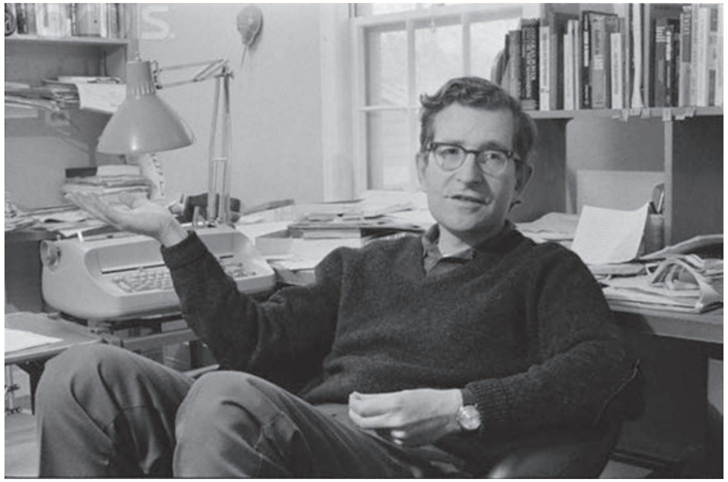
Linguistics (cont.)



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Linguistics (cont.)

Chomsky pointed out that the behaviourist theory did not address the notion of creativity in language

- It did not explain how a child could understand and make up sentences that he or she had never heard before

Chomsky's theory, based on syntactic models going back to the Indian linguist Panini ($\sim$ -350), could explain this

- Formal enough that it could in principle be programmed

Linguistics (cont.)

Modern linguistics and AI, then, were 'born' at about the same time, and grew up together, intersecting in a hybrid field called **computational linguistics** or **natural language processing**

- The problem of understanding language soon turned out to be considerably more complex than it seemed in 1957

Understanding language requires an understanding of the subject matter and context, not just the structure of sentences

- This might seem obvious, but it was not until the '60s
- Much of the early work in **knowledge representation** (how to put knowledge into a form for a computer to reason with) was tied to language and informed by research in linguistics

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History

- **The gestation of AI (1943-1955)**
- **The birth of AI (1956)**
- **Early enthusiasm, great expectations (1952-1969**
- **Back to reality (1966-1973)**
- **Knowledge-based systems (1969-1979)**
- **AI becomes an industry (1980-today)**
- **The return(s) of neural networks (1986-today)**
- **AI goes scientific (1987-today)**
- **The emergence of intelligent systems (1995-today)**
- **Big data, very big data (2001-today)**

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Gestation
History

Gestation (1943-1955)

The first work that is now generally recognised as AI was done by Warren McCulloch and Walter Pitts (1943)

They drew on three sources:

- Knowledge of the basic physiology and function of neurons in the brain;
- A formal analysis of propositional logic due to Russell and Whitehead;
- Turing's theory of computation

They proposed a model of artificial neurons where each neuron is characterised as '`on`' or '`off`', with a switch to '`on`' in response to stimulation by a sufficient number of neighbouring neurons

- The neuron state is conceived of as '*factually equivalent to a proposition which proposed its adequate stimulus*'

Gestation - 1943-1955 (cont.)

They showed that any computable function could be computed by some net of connected neurons, and that all logical connectives ('`and`', '`or`', '`not`', etc.) could be implemented by net structures

- McCulloch and Pitts also suggested that *suitably* defined neural networks could learn

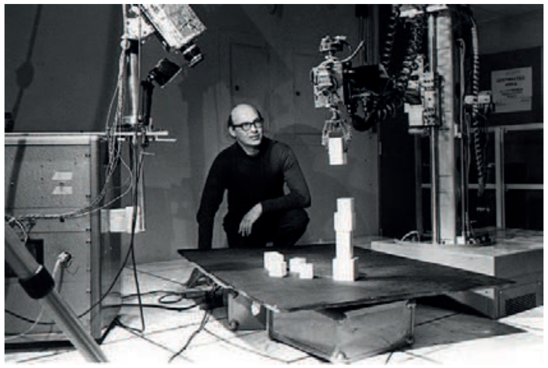
Donald Hebb (1949) demonstrated a simple updating rule for modifying the connection strengths between neurons

- **Hebbian learning** remains an influential model to this day

Gestation - 1943-1955 (cont.)

Two undergraduate students at Harvard, Marvin Minsky and Dean Edmonds, built the first neural network computer in 1950

- The SNARC: 3K vacuum tubes and a surplus automatic pilot mechanism from a B-24 bomber to simulate a 40-neuron net
- **Stochastic Neural Analog Reinforcement Calculator**



Gestation - 1943-1955 (cont.)

At Princeton, Minsky studied universal computation in neural nets

- His Ph.D. committee was skeptical about whether this kind of work should be considered mathematics, but von Neumann reportedly said, 'If it isn't now, it will be someday'

Minsky was later to prove influential theorems showing the limitations of neural network research

Gestation - 1943-1955 (cont.)

Other early examples of work that can also be characterised as AI

- Alan Turing's vision was perhaps the most influential

He lectured on the topic in 1947 at the London Mathematical Society and articulated a persuasive agenda in his 1950 article

- *Computing machinery and intelligence*
- Therein, he introduced the Turing test, machine learning, genetic algorithms, and reinforcement learning

He proposed the Child Programme idea, explaining '*Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulated the child's*?'

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Birth (1956)

Princeton was home to another figure in AI, John McCarthy

- After receiving his PhD in 1951 and working for two years as an instructor, McCarthy moved to Stanford and then to Dartmouth College, later the official birthplace of the field
- McCarthy convinced Minsky, Claude Shannon, and Nathaniel Rochester to help him bring together US researchers in automata theory, neural nets, and the study of intelligence

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Birth - 1956 (cont.)

They organised a 2-month workshop at Dartmouth, summer 1956

'*We propose that a 2 month, 10 man study of artificial intelligence be carried out during the summer of 1956 at Dartmouth College in Hanover, New Hampshire.*

The study is to proceed on the basis of the conjecture that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it.

An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves.

We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer'

Birth - 1956 (cont.)

There were 10 attendees in all, including More from Princeton, Samueln from IBM, and Solomonoff and Selfridge from MIT

- Two researchers from Carnegie Tech, Allen Newell and Herbert Simon, rather stole the show

Although the others had ideas and in some cases programs for particular applications such as checkers, Newell and Simon already had a reasoning program, the **Logic Theorist** (LT)

- '*We have invented a computer program capable of thinking non-numerically, and thereby solved the venerable mind-body problem*'

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Birth - 1956 (cont.)

Soon after, the program was able to prove most of the theorems in Chapter 2 of Russell and Whitehead's *Principia Mathematica*

- Russell was reportedly delighted when Simon showed him that the program had come up with a proof for one theorem that was shorter than the one in *Principia*

Remark

The editors of the *Journal of Symbolic Logic* were less impressed

- They rejected a paper coauthored by Newell, Simon, and Logic Theorist

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Birth - 1956 (cont.)

The Dartmouth workshop did not lead to any new breakthroughs, but it did introduce all the major figures to each other

- For the next 20 years, the field would be dominated by these people and their students at MIT, CMU, Stanford, and IBM

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Birth - 1956 (cont.)

Why was it necessary for AI to become a separate fiel?

- Why couldn't all the work done in AI have taken place under the name of control theory or operations research or decision theory, which, after all, have objectives similar to those of AI?
- Why isn't AI a branch of mathematics?

AI from the start embraced the idea of duplicating human faculties such as creativity, self-improvement, and language use

- None of the other fields were addressing these issues

The second answer is methodology, as AI is the only one of these fields that is clearly a branch of computer science

- AI is the only field to attempt to build machines that will function autonomously in complex, changing environments

Early enthusiasm and great expectations

History

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Early enthusiasm and great expectations (1952-1969)

The early years of AI were full of successes, in a limited way

Given the primitive computers and programming tools of the time

- Only a few years earlier computers were seen as things that could do arithmetic and no more

whenever a computer did anything remotely clever, it was a wow!

Remark

The intellectual establishment, by and large, preferred to believe that 'a machine can never do X'

- AI researchers naturally responded by demonstrating one X after another
- John McCarthy referred to this period as the 'Look, Ma, no hands!' era

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Early enthusiasm and great expectations - 1952-1969 (cont.)

Newell and Simon's early success was followed up with the GPS

- Unlike Logic Theorist, this program was designed from the start to imitate human problem-solving protocols
- Within the limited class of puzzles it could handle, it turned out that the order in which the program considered subgoals and possible actions was similar to that in which humans approached the same problems

Thus, GPS was probably the first program to embody the 'thinking humanly' approach

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Early enthusiasm and great expectations - 1952-1969 (cont.)

The success of GPS and others as models of cognition led Newell and Simon to formulate the **physical symbol system** hypothesis

- '*A physical symbol system has the necessary and sufficient means for general intelligent action*'

What they meant is that any system (human or machine) exhibiting intelligence must operate by manipulating data structures composed of symbols

- This hypothesis has been challenged from many directions

Early enthusiasm and great expectations - 1952-1969 (cont.)

At IBM, Rochester and colleagues produced the first AI programs

- Gelernter (1959) constructed the **Geometry Theorem Prover**, which was able to prove theorems that many students of mathematics would find quite tricky
- Starting in 1952, Samuel wrote a series of programs for checkers (draughts) that eventually learned to play at a strong amateur level

He disproved the idea that computers can do only what told to

- His program learned to play a better game than its creator

The program was demonstrated on television in February 1956

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Early enthusiasm and great expectation - 1952-1969 (cont.)

Remark

Like Turing, Samuel had trouble finding computer time

- Working at night, he used machines that were still on the testing floor at IBM's manufacturing plant

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Early enthusiasm and great expectation - 1952-1969 (cont.)

John McCarthy moved from Dartmouth to MIT and there made three crucial contributions in one historic year: 1958

In MIT AI LabMemo No. 1, McCarthy defined the high-level language **Lisp**, which was to become the dominant AI programming language for the next 30 years

- With Lisp, McCarthy had the tool he needed

Access to scarce and expensive computing resources was also a serious problem

- In response, he and others at MIT invented **time sharing**

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Early enthusiasm and great expectation - 1952-1969 (cont.)

In 1958, McCarthy published a paper entitled *Programs with Common Sense*, in which he described the **Advice Taker**, a hypothetical program (perhaps, the first complete AI system)

- Like the Logic Theorist and Geometry Theorem Prover, his program was designed to use knowledge to search for solutions to problems
- But unlike the others, it was to embody general knowledge of the world

For example, he showed how simple axioms would enable the program to generate a plan to drive to the airport

Early enthusiasm and great expectation - 1952-1969 (cont.)

The program was also designed to accept new axioms in the normal course of operation, thereby allowing it to achieve competence in new areas without being reprogrammed

The Advice Taker thus embodied the central principles of knowledge representation and reasoning:

- that it is useful to have a formal, explicit representation of the world and its workings and to be able to manipulate that representation with deductive processes

It is remarkable how much of the 1958 paper stays relevant today

Early enthusiasm and great expectation - 1952-1969 (cont.)

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1958 also marked the year that Marvin Minsky moved to MIT

- His initial collaboration with McCarthy did not last, tho

McCarthy stressed representation and reasoning in formal logic, whereas Minsky was more into getting programs to work

- In 1963, McCarthy started the AI lab at Stanford

His plan to use logic to build the ultimate Advice Taker was advanced by J. A. Robinson's discovery in 1965 of the **resolution method** (a theorem-proving algorithm for first-order logic)

Early enthusiasm and great expectation - 1952-1969 (cont.)

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Stanford emphasised general-purpose methods for logical reasoning

- Applications of logic included Cordell Green's question answering and planning systems (1969) and the Shakey robotics project at the Stanford Research Institute (SRI)

Shakey's project was the first one to demonstrate the complete integration of logical reasoning and physical activity

Early enthusiasm and great expectation - 1952-1969 (cont.)

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Minsky supervised a series of students who chose limited problems that appeared to require intelligence to solve

These limited domains became known as **micro-worlds**

- James Slagle's **Saint** program (1963) was able to solve closed-form calculus integration problems typical of first-year college courses
- Tom Evans's **Analogy** program (1968) solved geometric analogy problems that appear in IQ tests

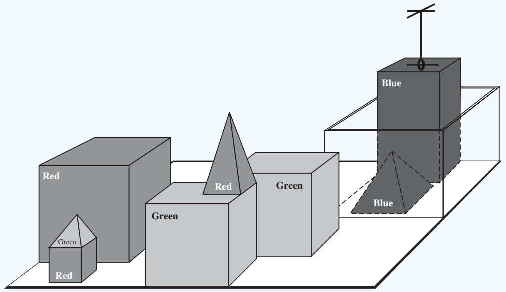
Daniel Bobrow's **Student** program (1967) solved algebra stories

- '*If the number of customers Tom gets is twice the square of 20 percent of the number of advertisements he runs, and the number of advertisements he runs is 45, what is the number of customers Tom gets?*'

Early enthusiasm and great expectation - 1952-1969 (cont.)

Typical task in the world of blocks: Rearrange blocks in a certain way, using a robot hand that can pick up one block at a time

Example



'Find a block that is taller than the one you're holding, and put it in the box

Early enthusiasm and great expectation - 1952-1969 (cont.)

The blocks world was home to the vision project of Huffman (1971), the vision and constraint propagation work of Waltz (1975), the learning theory of Winston (1970), the natural language understanding program of Winograd (1972), and the planner of Fahlman (1974)

Early enthusiasm and great expectation - 1952-1969 (cont.)

Work building on the neural nets of McCulloch and Pitts

- Winograd and Cowan (1963) showed how a large number of elements could collectively represent an individual concept, with a corresponding increase in robustness and parallelism
- Hebb's learning methods were enhanced by Widrow (1962), who called his networks **adalines**, and by Rosenblatt (1962) with his **perceptrons**

The perceptron convergence theorem (1962) says that the learning algorithm can adjust the connection strengths of a perceptron to match any input data, provided such a match exists

A dose of reality

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A dose of reality (1966-1973)

AI researchers were not shy about making predictions

The following statement by Herbert Simon in 1957 is often quoted

It is not my aim to surprise or shock you, but the simplest way I can summarise is to say that there are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until, in a visible future, the range of problems they can handle will be coextensive with the range to which the human mind has been applied

A dose of reality - 1966-1973 (cont.)

'Visible future' can be interpreted in various ways, but Simon also made more concrete predictions

... within 10 years a computer would be chess champion, and a significant mathematical theorem would be proved by machine

These predictions came true (or approximately true) within 40 years rather than 10 and Simon's overconfidence was due to the promising performance of early AI systems on simple examples

- In almost all cases, however, these early systems turned out to fail miserably when tried out on wider selections of problems and on more difficult problems

A dose of reality - 1966-1973 (cont.)

The first kind of difficulty arose because most early programs knew nothing of their subject matter

- They succeeded by means of simple syntactic manipulations

A typical story occurred in early machine translation efforts, which were generously funded by the U.S. National Research Council

- An attempt to speed up the translation of Russian papers in the wake of the Sputnik launch in 1957

It was thought that syntactic transformations based on the grammars of Russian and English, and word replacement from a dictionary, would suffice to preserve the meanings of sentences

- Thing is that translation requires background knowledge to resolve ambiguity and establish the content of sentences

A dose of reality - 1966-1973 (cont.)

Example

'*the spirit is willing but the flesh is weak?*'
'*the vodka is good but the meat is rotten*'

A dose of reality - 1966-1973 (cont.)

In 1966, a report by an advisory committee found that '*there has been no machine translation of general scientific text, and none is in immediate prospect?*'

- All U.S. government funding for academic translation projects was canceled

Remark

Today, machine translation is an imperfect but widely used tool for technical, commercial, government, and Internet documents

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A dose of reality - 1966-1973 (cont.)

The second kind of difficulty was the intractability of many of the problems that AI was attempting to solve

- Most of the early AI programs solved problems by trying out different combinations of steps until the solution was found

It worked initially because micro-worlds contained very few objects, very few possible actions and very short solution sequences

Before the theory of computational complexity was developed, it was widely thought that 'scaling up' to larger problems was simply a matter of faster hardware and larger memories

- The optimism from proving the resolution theorem, for example, was soon dampened when researchers failed to prove theorems involving more than a few dozen facts

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A dose of reality - 1966-1973 (cont.)

The fact that a program can find a solution, in principle, does not mean that the program contains any of the mechanisms needed to find it in practice

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A dose of reality - 1966-1973 (cont.)

The illusion of unlimited computational power was not confined to problem-solving programs

- Early experiments in machine evolution (now, **genetic algorithms**) based on the correct belief that by making a series of small mutations to a machine-code program, one can generate a program with good performance for any particular task

The idea was to try random mutations with a selection process to preserve mutations that seemed useful

- Despite thousands of hours of CPU time, almost no progress was demonstrated

Modern GA use better representations and shown more success

A dose of reality - 1966-1973 (cont.)

Failure to come to grips with the 'combinatorial explosion' was one of the main criticisms of AI contained in the Lighthill report

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A dose of reality - 1966-1973 (cont.)

A third difficulty arose because of some fundamental limitations on the basic structures being used to generate intelligent behaviour

Minsky and Papert's book *Perceptrons* (1969) proved that, though perceptrons (a simple neural net) could be shown to learn anything they were capable of representing, they could represent very little

- In particular, a two-input perceptron (restricted to be simpler than the form Rosenblatt originally studied) could not be trained to recognize when its two inputs were different

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A dose of reality - 1966-1973 (cont.)

Although their results did not apply to more complex, multilayer networks, research funding for neural-net research soon dwindled

- Ironically, the new back-propagation learning algorithms for multilayer networks that were to cause a resurgence in neural net research in the late 1980s (and today, and perhaps again in twenty years), were actually discovered first in 1969

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Knowledge-based systems

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Knowledge based systems (1969-1979)

The picture of problem solving that had arisen during the first decade of AI research was of a general-purpose search tool

- String together elementary reasoning steps to find complete solutions

Such approaches have been called **weak methods** because, though general, they do not scale up to large or difficult problem instances

The alternative to weak methods is to use more powerful, domain specific knowledge that allows larger reasoning steps and can more easily handle typically occurring cases in narrow areas of expertise

- One might say that to solve a hard problem, you have to almost know the answer already

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Knowledge based systems (1969-1979)

The **Dendral** program (1969) was an example of this approach

It was developed at Stanford, where Feigenbaum (a student of Simon), Buchanan (a philosopher turned computer scientist), and Lederberg (a Nobel laureate geneticist) teamed up

- Solve the problem of inferring molecular structure from the information provided by a mass spectrometer

The input to the program consisted of the elementary formula of a molecule (say, $C_6H_{13}NO_2$) and the mass spectrum giving the masses of the various fragments of the molecule

- The mass spectrum might contain a peak at $m = 15$, corresponding to the mass of a methyl (CH_3) fragment

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Knowledge based systems (1969-1979)

The naive version generated all possible structures consistent with the formula, and predicted what mass spectrum would be observed for each, comparing this with the actual spectrum

As expected, this is intractable for even moderate-sized molecules

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Knowledge based systems (1969-1979)

The Dendral researchers consulted analytical chemists and found that they worked by looking for well-known patterns of peaks in the spectrum that suggested common substructures

Example

The following rule is used to recognise a ketone ($C = O$) subgroup (which weighs 28):

If there are two peaks at x_1 and x_2 such that

- $x_1 + x_2 = M + 28$, with M the mass of the whole molecule
- $x_1 - 28$ is a high peak
- $x_2 - 28$ is a high peak
- At least one of x_1 and x_2 is high

then there is a ketone subgroup

Knowledge based systems (1969-1979)

Recognising that the molecule contains a particular substructure reduces the number of possible candidates enormously

- The Dendral was powerful

'*All the relevant theoretical knowledge to solve these problems has been mapped over from its general form in the [spectrum prediction component] ('first principles') to efficient special forms ('cookbook recipes')*'

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Knowledge based systems (1969-1979)

The Dendral was the first successful knowledge-intensive system

- Expertise derived from large numbers of special-purpose rules

Later systems also incorporated the main theme of McCarthy's Advice Taker approach, the clean separation of the knowledge (in the form of rules) from the reasoning component

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Knowledge based systems (1969-1979)

With this in mind, Feigenbaum and others at Stanford began the **Heuristic Programming Project** (HPP) to study the extent to which the new methodology of **expert systems** could be applied to other areas of human expertise

- The next major effort was in the area of medical diagnosis

Feigenbaum, Buchanan, and Dr. Shortliffe developed **MYCIN**

- Blood infection diagnosis
- With about 450 rules, MYCIN was able to perform as well as some experts, and considerably better than junior doctors

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Knowledge based systems (1969-1979)

MYCIN also contained two major differences from Dendral

- First, unlike the Dendral rules, no general theoretical model existed from which the MYCIN rules could be deduced

They had to be acquired from extensive interviewing of experts, who in turn acquired them from textbooks, other experts, etc.

- Second, the rules had to reflect the uncertainty associated with medical knowledge

MYCIN incorporated a calculus of uncertainty called **certainty factors**, which seemed (at the time) to fit well with how doctors assessed the impact of evidence on the diagnosis

Knowledge based systems (1969-1979)

Importance of domain knowledge: Understanding natural language

Although Winograd's **SHRDLU** system for understanding natural language had engendered excitement, its dependence on syntactic analysis caused some of the same problems as occurred in the early machine translation work

- It was able to overcome ambiguity and understand pronoun references, but this was mainly because it was designed specifically for one area, the blocks world

Several researchers, including Charniak, a student of Winograd's at MIT, suggested that robust language understanding would require general knowledge about the world

- and a general method for using that knowledge

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Knowledge based systems (1969-1979)

At Yale, linguist-turned-AI-researcher Roger Schank emphasized this point, claiming, '*There is no such thing as syntax*', which upset a lot of linguists but did serve to start a useful discussion

- Schank and his students built a series of programs (early 1980s), all had the task of understanding natural language

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Knowledge based systems (1969-1979)

The emphasis was less on language *per se* and more on the problems of representing and reasoning with the knowledge required for language understanding

Problems included representing stereotypical situations, describing human memory organization, and understanding plans and goals

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Knowledge based systems (1969-1979)

The growth of applications to real-world problems caused an increase in demand for knowledge representation schemes

- Different representation and reasoning languages appeared

Some were based on logic (for example, the Prolog was popular in Europe, and the Planner family in the U.S.)

Others, following Minsky's idea of **frames** (1975), adopted a more structured approach, assembling facts about particular object and event types and arranging the types into taxonomic hierarchies

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AI as an industry (1980-today)

The first successful commercial expert system **R1** began its operation at Digital Equipment Corporation (1982)

The program helped configure orders for new computer systems

- By 1986, it was saving the company an estimated \$40M/yr
- By 1988, DEC's AI group had +40 expert systems deployed

DuPont had 100 in use and 500 in development, saving ∼\$10M/yr

Nearly every major U.S. corporation had its own AI group and was either using or investigating expert systems, ... just like today!

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AI as an industry - 1980-today (cont.)

In 1981, the Japanese announced the 'Fifth Generation' project, a 10-year plan to build intelligent computers running Prolog

The US formed the Microelectronics and Computer Technology Corporation (MCC) as a research consortium designed to assure national competitiveness

- In both cases, AI was part of a broad effort, including chip design and human-interface research

In GB, the Alvey report reinstated funding (cut by Lighthill report)

In all three countries, the projects never met their ambitious goals

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AI as an industry - 1980-today (cont.)

Overall, the AI industry boomed from a few million dollars in 1980 to billions of dollars in 1988, including hundreds of companies

- ... building expert systems, vision systems, robots, and software and hardware specialised for these purposes

Soon after that came a period called the 'AI Winter', in which many companies failed to deliver on extravagant promises

The return of neural networks

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The return of neural networks (1986-today)

In the mid-80s at least four different groups reinvented the back - propagation learning algorithm found in 1969 by Bryson and Ho

- The algorithm was applied to many learning problems in computer science and psychology
- The dissemination of the results in the collection Parallel Distributed Processing (Rumelhart and McClelland, 1986) caused great excitement

These **connectionist** models of intelligent systems were seen by some as direct competitors both to symbolic models (Newell and Simon) and to the logicist approach (McCarthy and others)

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The return of neural networks - 1986-today (cont.)

It seems obvious that, at some level, humans manipulate symbols (Terrence Deacon's book *The Symbolic Species* in 1997 suggests that this is the defining characteristic of humans)

- Connectionists questioned whether symbol manipulation had any real explanatory role in detailed models of cognition
- The question remains unanswered, current view is that connectionist and symbolic approaches are complementary, not competing

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The return of neural networks - 1986-today (cont.)

As occurred with the separation of AI and cognitive science, modern neural network research has bifurcated into two fields

- One concerned with creating network architectures and algorithms and understanding their mathematical properties
- The other concerned with modelling of the empirical properties of actual neurons and ensembles of neurons

The scientific method

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The scientific method (1987-today)

Recent revolution in both content and methodology of work in AI

- More common to build on existing theories, than to propose brand-new ones
- More common to base claims on rigorous theorems or hard experimental evidence rather than on intuition
- More common to show relevance to real-world applications rather than toy examples

AI was founded also as a rebellion against the limitations of existing fields like control theory and statistics

- Now, it is embracing those fields

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The scientific method - 1987-today (cont.)

As David McAllester (1998) put it:

- *In the early period of AI it seemed plausible that new forms of symbolic computation, e.g., frames and semantic networks, made much of classical theory obsolete*
- *This led to a form of isolationism in which AI became largely separated from the rest of computer science.*
- *This isolationism is currently being abandoned*

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The scientific method - 1987-today (cont.)

There is a recognition that

- **Machine learning** should not be isolated from **information theory**
- **Uncertain reasoning** should not be isolated from **stochastic modelling**
- **Search** should not be isolated from classical **optimisation** and **control**
- **Automated reasoning** should not be isolated from **formal methods** and **static analysis**

The scientific method - 1987-today (cont.)

In terms of methodology, AI has come under the scientific method

To be accepted, hypotheses must be subjected to rigorous empirical experiments, and the results must be analyzed statistically for their importance (1995)

Remark

- **It is now possible to replicate experiments by using shared repositories of test data and code**

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The scientific method - 1987-today (cont.)

The field of speech recognition illustrates the pattern

- In the 1970s, a wide variety of different architectures and approaches were tried
- Many of these were rather *ad hoc* and fragile, and were demonstrated on only a few specially selected examples
- In recent years, approaches based on **hidden Markov models** (HMMs) have come to dominate the area

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The scientific method - 1987-today (cont.)

Two aspects of HMMs are relevant

- First, they are based on a rigorous mathematical theory

Speech builds on decades of mathematical results in other fields

- Second, they are generated by a process of training on a large corpus of real speech data

This ensures that the performance is robust, and in rigorous blind tests the HMMs have been improving their scores steadily

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The scientific method - 1987-today (cont.)

Speech technology and the related field of handwritten character recognition have made the transition to industrial/consumer apps

There is no claim that humans use HMMs to recognise speech

HMMs provide a mathematical framework for understanding the problem and support the engineering claim that they work well

The scientific method - 1987-today (cont.)

Machine translation follows the same course as speech recognition

- In the 1950s there was initial enthusiasm for an approach based on sequences of words, with models learned according to the principles of information theory
- That approach fell out of favor in the 1960s, but returned in the late 1990s and now dominates the field

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The scientific method - 1987-today (cont.)

Neural networks also fit this trend

- Much of the work on neural nets in the 1980s was done in an attempt to scope out what could be done and to learn how neural nets differ from 'traditional' techniques
- Using improved methodology and theoretical frameworks, the field arrived at an understanding in which neural nets can now be compared with corresponding techniques from statistics, pattern recognition, and machine learning, and the most promising technique can be applied to each application

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The scientific method - 1987-today (cont.)

As a result of these developments, so-called **data science** technology has spawned a vigorous new industry

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The scientific method - 1987-today (cont.)

Judea Pearl's (1988) *Probabilistic Reasoning in Intelligent Systems* led to a new acceptance of probability and decision theory in AI[3]

- The **Bayesian network** formalism was invented to allow efficient representation of, and rigorous reasoning with, uncertain knowledge
- This approach largely overcomes many problems of the probabilistic reasoning systems of the 1960s and 1970s

On top of AI research on uncertain reasoning and expert systems

The approach allows for learning from experience, and it combines the best of classical AI and neural nets

[3] A resurgence of interest epitomised by Peter Cheeseman's (1985) article *In Defense of Probability*.

The scientific method - 1987-today (cont.)

Work by Pearl, Horvitz and Heckerman promoted a new idea

- **Normative expert systems**, that act rationally according to laws of decision theory and do not try to imitate the thought steps of human experts

Modern operating systems includes several normative diagnostic expert systems for correcting problems

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The scientific method - 1987-today (cont.)

Robotics, computer vision, and knowledge representation, ... the same

- A better understanding of the problems and their complexity properties, combined with increased math sophistication, has led to workable research agendas and robust methods

Increased formalisation and specialisation led fields such as vision and robotics to become isolated from 'mainstream' AI in the '90s

- This trend has reversed in recent years as tools from machine learning in particular have proved effective for many problems

The process of reintegration is already yielding significant benefits

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Intelligent agents (1995-today)

Perhaps encouraged by the progress in solving subproblems of AI, researchers started to look at the 'whole agent' problem again

- Newell, Laird, and Rosenbloom **Soar**'s ($\sim$ 1990) is the best-known example of a complete agent architecture

Intelligent agents - 1995-today (cont.)

One important environment for intelligent agents is the Internet

- AI systems have become so common in apps that the '-bot' suffix has entered everyday language

Moreover, AI technologies underlie many Internet tools, such as search engines, recommender systems, and web site aggregators

Intelligent agents - 1995-today (cont.)

One effect of trying to build complete agents is the realisation that the previously isolated subfields of AI might need to be reorganised

- Their results are to be tied together
- It is now widely appreciated that sensory systems (vision, sonar, speech recognition, etc.) cannot deliver perfectly reliable information about the environment

Reasoning and planning systems must also handle uncertainty

Intelligent agents - 1995-today (cont.)

A second major consequence of the agent perspective is that AI has been drawn into much closer contact with other fields

- Control theory and economics, ...

Progress in robotic cars has derived from a mixture of approaches

- Better sensors, control-theoretic integration of sensing,
- Localisation and mapping, a degree of high-level planning

Intelligent agents - 1995-today (cont.)

Despite successes, influential founders of AI (Nilsson and Winston, McCarthy, Minsky) have expressed discontent with the AI progress

- AI should put less emphasis on creating ever-improved apps that are good at a specific task, such as driving a car, playing chess, or recognising speech
- AI should return to its roots of striving for, in Simon's words, '*machines that think, that learn and that create*'

They call the effort **human-level AI** (HLAI); their first met 2004

Intelligent agents - 1995-today (cont.)

A related idea is **Artificial General Intelligence** or AGI (2007), which held its first conference and organised the Journal of Artificial General Intelligence in 2008

- AGI looks for a universal algorithm for learning and acting in any environment, and has its roots in the work of Solomonoff (1964), an attendee of the 1956 Dartmouth conference

Guarantee that what we create is **friendly AI** is a concern (2008)

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Large datasets (2001-today)

Throughout the 60-year history of computer science, emphasis has been on the algorithm as the main subject of study

Some recent work in AI suggests that for many problems, it makes more sense to worry about data and be less picky about the algos

True because of the availability of very large data sources

- Trillions of words of English, billions of images from the Web (2006), billions of base pairs of genomic sequences (2003)

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Large datasets - 2001-today (cont.)

An influential paper: Yarowsky ('95) on word-sense disambiguation

- Given the use of the word 'plant' in a sentence, does that refer to flora or factory?

Previous approaches to the problem had relied on human-labeled examples combined with machine learning algorithms

- Yarowsky showed that the task can be done, with accuracy above 96%, with no labeled examples at all

Instead, given a very large corpus of un-annotated text and just the dictionary definitions of the two senses, 'works, industrial plant' and 'flora, plant life', one can label examples in the corpus

- From there, one can bootstrap to learn new patterns that help label new examples

Large datasets - 2001-today (cont.)

Banko and Brill (2001) show that techniques like this perform even better as the amount of available text goes up

- the increase in performance from using more data exceeds any difference in algorithm choice
- a mediocre algorithm with 100M words of un-labeled training data outperforms the best known algorithm with 1M words

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Large datasets - 2001-today (cont.)

Hays and Efros (2007) and the task of filling in holes in photos

Example

Suppose you use Photoshop to mask out an ex-friend from a group photo, but now you need to fill in the masked area with something that matches the background

- Hays and Efros defined an algorithm that searches through a collection of photos to find something that will match
- They found the performance of their algorithm was poor when they used a collection of only ten thousand photos
- They crossed a threshold into excellent performance when they grew the collection to two million photos

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Large datasets - 2001-today (cont.)

Work like this suggests that the 'knowledge bottleneck' in AI

- the problem of how to express all the knowledge that a system needs

may be solved in many applications by learning methods rather than hand- and hard-coded a priori knowledge engineering

- provided the algorithms have enough data to go on (2009)

Remark

Reporters have noticed the surge of new applications and have written that 'AI winter' may be yielding to a new spring (2005)

- Kurzweil (2005): '*today, many thousands of AI applications are deeply embedded in the infrastructure of every industry*'

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Artificial intelligence

Today

What can AI do today?
A concise answer is not difficult.
Lots!

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Today (cont.)

Robotic vehicles

- A driverless robotic car **STANLEY** sped through the rough terrain of the Mojave dessert at 22 mph, finishing the 132-mile course first in the 2005 DARPA Grand Challenge

Remark

STANLEY is a Volkswagen Touareg outfitted with cameras, radar, and laser rangefinders to sense the environment and onboard software to command steering, braking, and acceleration (2006)

- In 2007, CMU's **BOSS** won the Urban Challenge, driving in traffic through the streets of a closed UF-AF base, obeying traffic rules and avoiding pedestrians and other vehicles

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Today (cont.)

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Speech recognition

- A traveler calling United Airlines to book a flight can have the entire conversation guided by an automated speech recognition and dialog management system

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Autonomous planning and scheduling

- A 100 million miles from Earth, NASA's **REMOTE AGENT** program became first on-board autonomous planning program to control scheduling of operations of a spacecraft (2000)

The computer program plans from high-level goals specified from the ground and monitored the execution of those plans' including

- Detection, diagnosis, and recover from problems

Successor program **MAPGEN** (2004) plans the daily operations for NASA's Mars Exploration Rovers, and **MEXAR2** (2007) did mission planning, both logistics and science planning, for the European Space Agency's Mars Express mission in 2008

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Game playing

- IBM's **DEEP BLUE** became the first computer program to defeat the world champion in a chess match when it bested Garry Kasparov by a score 3.5 to 2.5 in an exhibition (1997)

Kasparov said he felt a 'new kind of intelligence' across the board from him, Newsweek magazine described the match as 'The brain's last stand and the value of IBM's stock increased by $18 billion

Remark

Human champions studied Kasparov's loss and were able to draw a few matches in subsequent years, but most recent human - computer matches have been won convincingly by the computer

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Today (cont.)

Spam fighting

- Each day, learning algorithms classify over a billion messages as spam, saving the recipient from wasting time deleting what, for many, could comprise 80% or 90% of all messages

Because the spammers are continually updating their tactics, it is difficult for a static programmed approach to keep up

- Learning algorithms work best (**SpamAssassin**, 2001)

Robotics

- The iRobot Corporation has sold over two million **ROOMBA** robotic vacuum cleaners for home use

Remark

They also deploy the PackBot to Iraq/Afghanistan, where it was/is used to handle hazardous materials, clear explosives, ...

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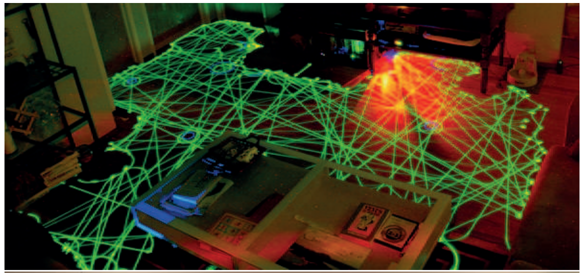

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Logistics planning

- During the Persian Gulf crisis of 1991, U.S. forces deployed a **Dynamic Analysis and Replanning Tool**, **DART** (1994), to do automated logistics planning and scheduling for transportation

Involved up to 50K vehicles, cargo, and people at a time, and had to account for starting points, destinations, routes, conflicts, etc.

- The AI planning techniques generated in hours a plan that would have taken weeks with older methods

Remark

The Defense Advanced Research Project Agency stated that this single application more than paid back 30-year investment in AI

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Machine translation

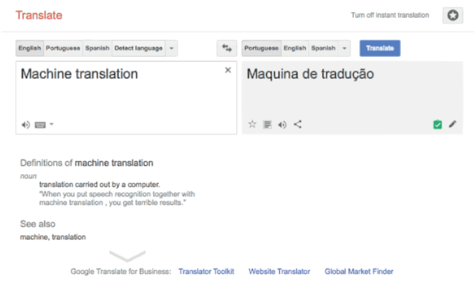
- In 2007, a computer program automatically translated from Arabic to English, allowing an English speaker to see '*Ardogan Confirms That Turkey Would Not Accept Any Pressure, Urging Them to Recognize Cyprus*'

A statistical model built from Arabic-to-English translations and from examples of English text totaling two trillion words

Remark

None of the computer scientists on the team speak Arabic, but they do understand statistics and machine learning algorithms

Today (cont.)



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Today (cont.)

Ken Jennings: Watson, Jeopardy and me, the obsolete know-it-all

Today (cont.)

Ken Jennings: Watson, Jeopardy and me, the obsolete know-it-all