Artificial intelligence

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What's AI?
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Thinking humanly
Thinking rationally
Acting rationally

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Today

Artificial intelligence
(CK0031/CK0248)

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Artificial intelligence

Intelligence

- For thousands (2) of years, understand how (we think) we think

Artificial intelligence

- 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

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Artificial intelligence (cont.)

AI: A huge variety of sub-fields

- 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

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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 study of mental faculties through the use of computational models." (Charniak and McDermott, 1985)
"[The automation of] activities that we associate with human thinking, activities such as decision-making, problem solving, learning . . ." (Bellman, 1978)	"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)	"Computational Intelligence is the study of the design of intelligent agents." (Poole *et al.*, 1998)
"The study of how to make computers do things at which, at the moment, people are better." (Rich and Knight, 1991)	"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

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.)

The test deliberately avoids physical interaction between interrogator and computer, as physical simulation of a person is unnecessary for intelligence

- The **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.)

Turing deserves credit for designing a test that stays relevant 60 years later

These six disciplines compose most of modern AI

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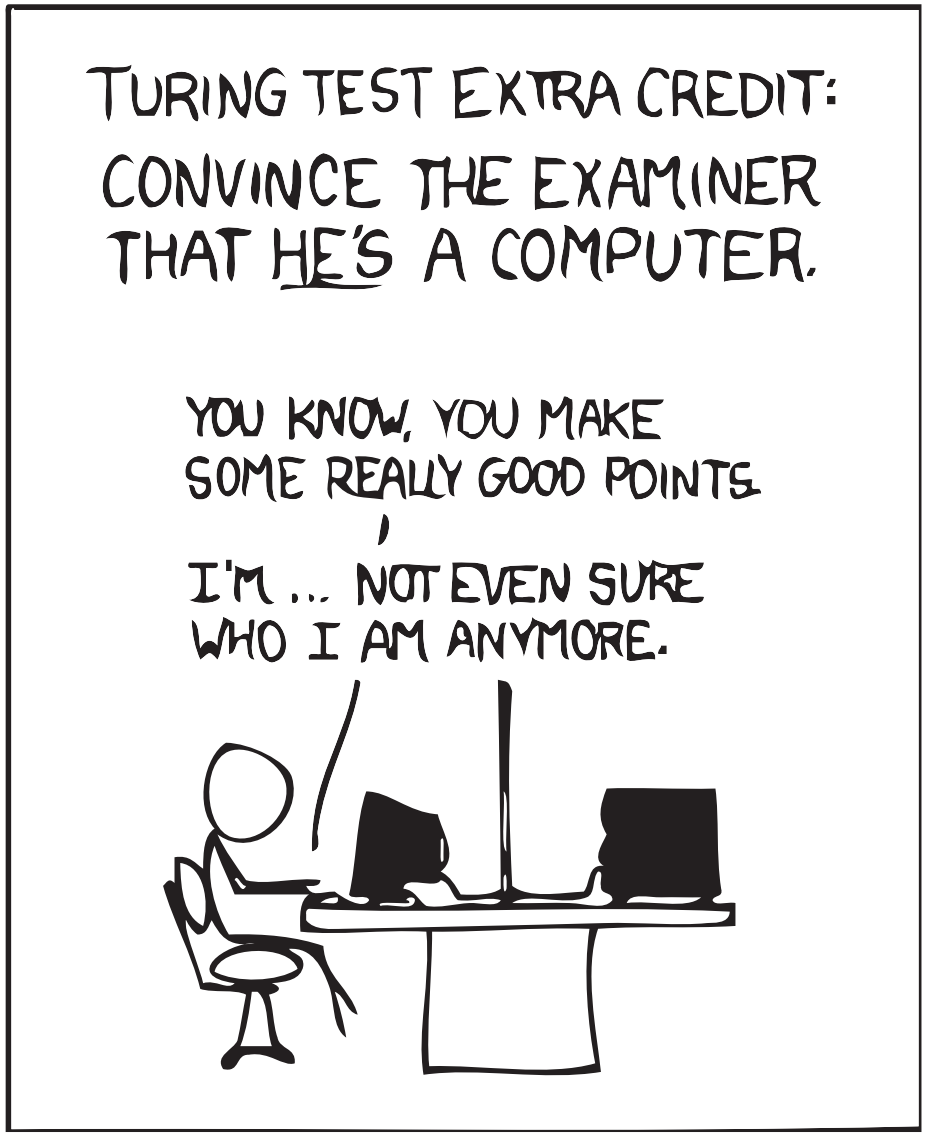
Acting humanly (cont.)



Hit Turing right in the test-ees

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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

First we need a sufficiently precise theory of the mind

⇝ Then, it may be possible to express the theory as a computer program

If the program's IO behaviour and corresponding human behaviour match

⇝ Then, there is evidence that some of the program's mechanisms could also be operating in humans

Thinking humanly (cont.)

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

- More concerned with studying the trace of its reasoning steps
- Compare them 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

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Thinking humanly (cont.)

The interdisciplinary field of **cognitive science** brings together i) computer models from AI and ii) experimental techniques from psychology

- To construct precise and testable theories of our mind

- We comment on similarities between AI and human cognition
- Cognitive science is necessarily based on experimental investigation
- (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

- An algorithm that performs well on a task is also 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

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

- Due to the greek philosopher Aristotle

The **syllogism** provided patterns for argument structures

- Always yielded correct conclusions, when given the right premises

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

These laws of thought were supposed to govern mind operation

- Their study initiated the field called **logic**

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Thinking rationally (cont.)

Logicians developed a notation for statements about all kinds of objects

- and relations among them

Contrast this with ordinary arithmetic notation

- (only for statements about numbers)

By 1965, programs existed that could solve any solvable problem

- The problem must be described in logical notation
- And, if no solution exists, the program might loop forever

The **logicist** tradition within AI aims at building on such programs

- This is how they create intelligent systems

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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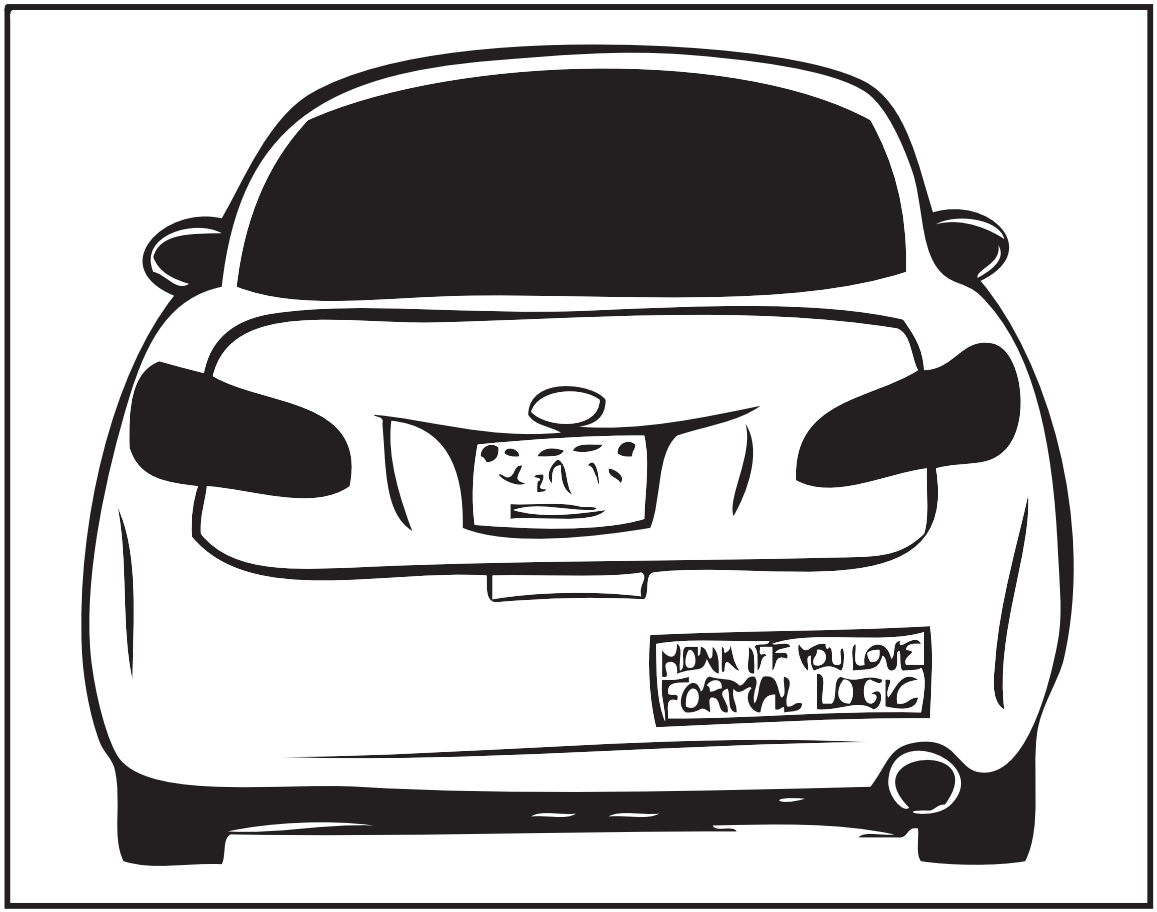
Thinking rationally (cont.)

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

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
- 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 cases, 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
- It generates agents that provably achieve it

Human behaviour is well adapted for one specific environment

- It is defined by the sum of all the things that humans do

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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

- 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

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Foundations

The disciplines that contributed ideas, viewpoints, and techniques

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

- **Philosophy**
- **Mathematics**
- **Economics**
- **Neuroscience**
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- **Computer engineering**
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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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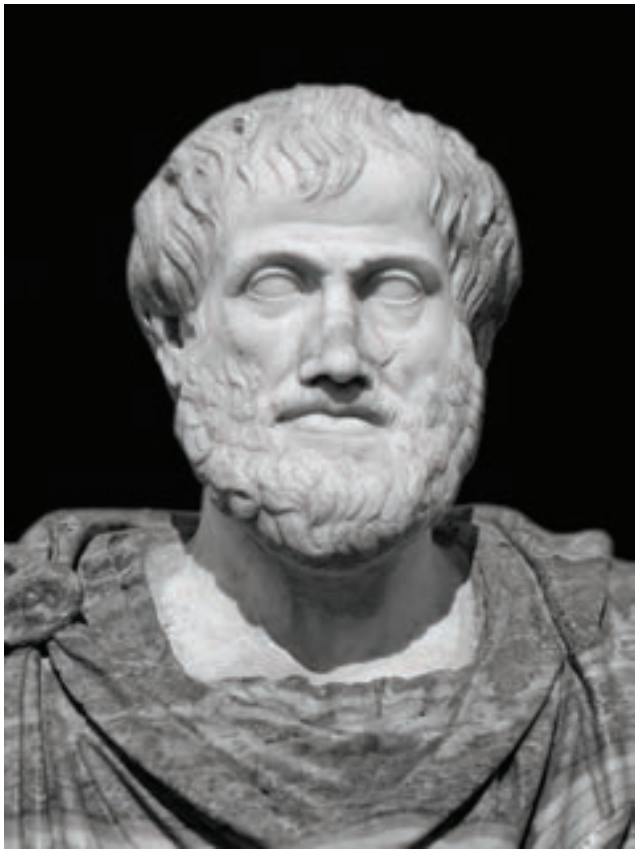
Philosophy (cont.)

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
- Could be done mechanically, in principle



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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): Reasoning is 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

- Recent reconstructions show the design to be functional

The first known calculating machine is by Wilhelm Schickard (1592-1635) in 1623, 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*'

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Philosophy (cont.)

Gottfried Wilhelm Leibniz (1646-1716) built a mechanical device

- 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 mind operates, at least partly, 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) discussed the distinction between mind and matter

$\rightsquigarrow$ And, the problems that arise

One main problem with a purely physical conception of the mind:

- It 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 centre 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 (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
- As such they could be treated as machines

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

⇝ Establish the source of knowledge

- The **empiricism** movement, 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**: General rules are acquired by exposure to repeated associations between their elements

Philosophy (cont.)

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

- They developed a novel doctrine

Logical positivism

- 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

Philosophy (cont.)

The **confirmation theory** of Carnap and Carl Hempel (1905-1997)

- An attempt to analyse the acquisition of knowledge from experience

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

- Probably the first theory of mind as a computational process

Philosophy (cont.)

The final element in the philosophical picture of the mind

⇝ The connection between knowledge and action

- 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
- Goals and knowledge of action's outcome are connected
- (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

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

Philosophers staked out some of the fundamental ideas of AI

- The leap to formal science required formalisation
- Three areas: Logic, computation and probability

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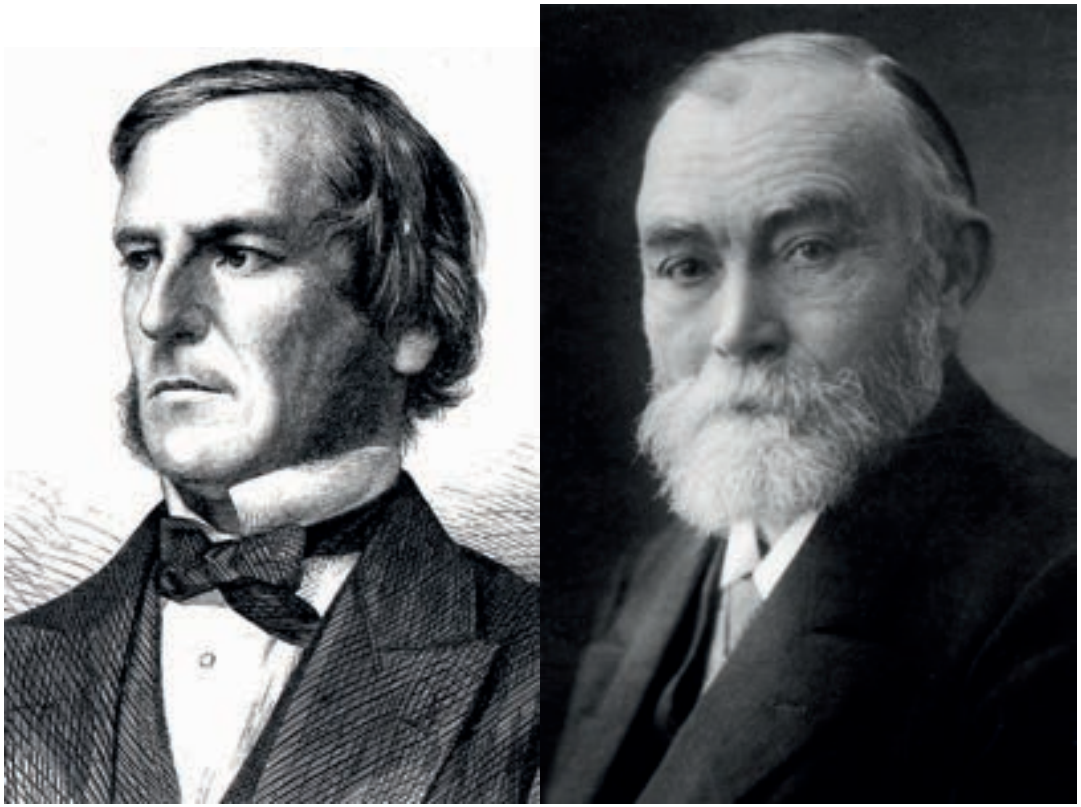
Mathematics (cont.)

The idea of formal logic can be tracked back to ancient Greece

- Mathematical development began with George Boole (1815-1864)
- He worked out **propositional** or **Boolean logic**



- In 1879, Gottlob Frege (1840-1925) extended Boole's logic
- Inclusion of objects and relations
- The creation of **first-order logic**

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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 a Persian

- His writings introduced Arabic numerals and algebra to Europe
- A mathematician of the 9th century, al-Khowarazmi

Mathematics (cont.)

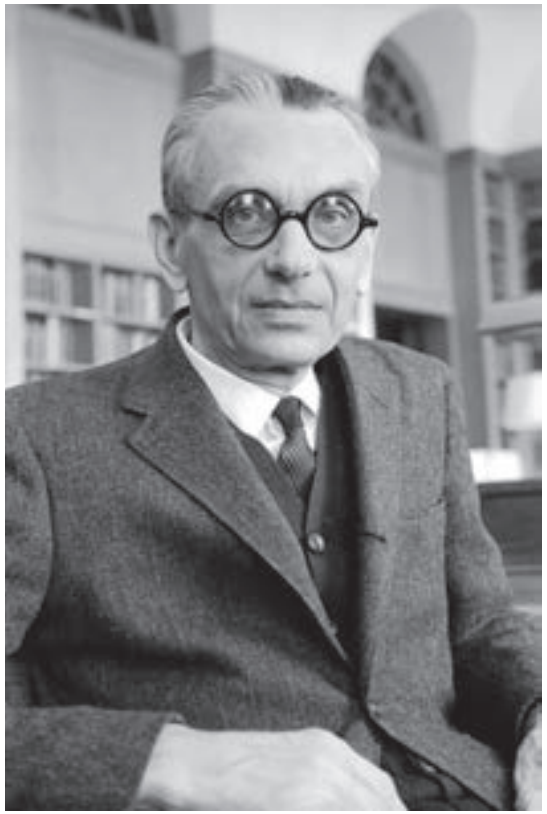
- Boole and others discussed algorithms for logical deduction
- By the late 19th century, efforts were under way to formalise general mathematical reasoning as logical deduction
- In 1930, Kurt Gödel (1906-1978) showed that there exists a procedure to prove any true statement in first-order logic
- But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

Mathematics (cont.)

Gödel: Limits on deduction do exist

The **incompleteness theorem**, 1931: In any formal theory as strong as Peano arithmetic (elementary theory of natural numbers), there are true undecidable statements

- No proof within the theory



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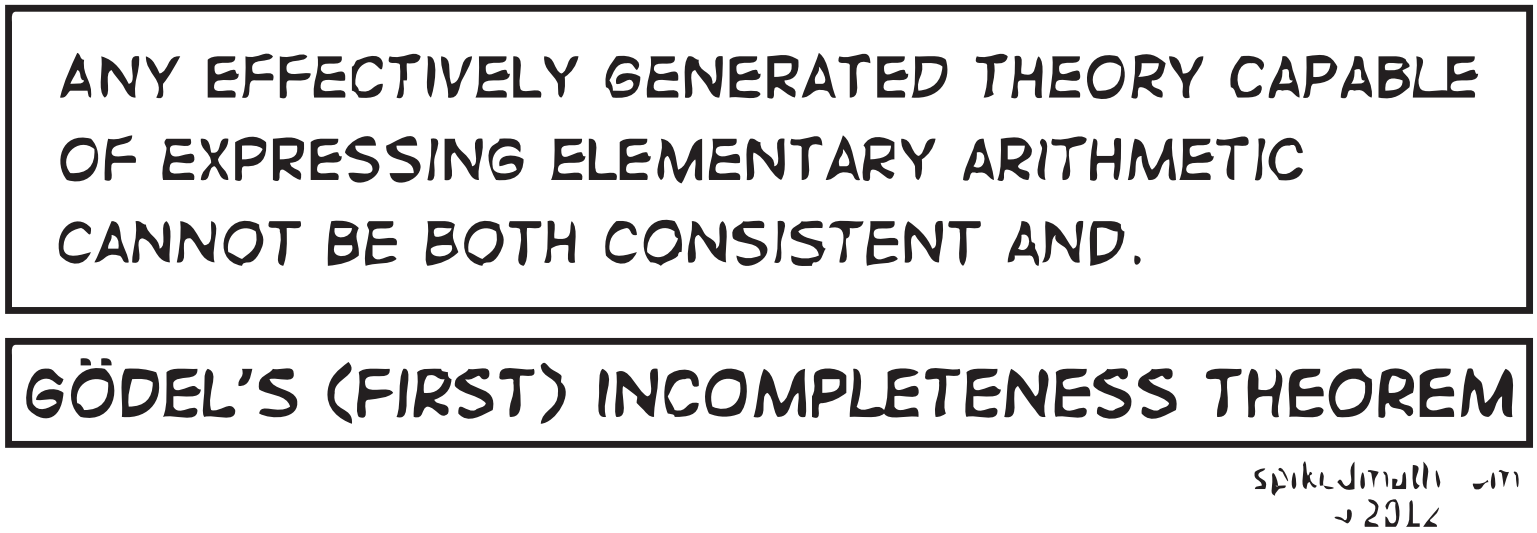

Mathematics (cont.)

Motivated Turing (1912-1954), characterise which funcs are **computable**

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

The Church-Turing thesis is accepted as providing a sufficient definition

- The Turing machine is capable of computing any computable function

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.)

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 mildly large instances cannot be solved

- At least, in any reasonable time
- Strive to divide the overall problem of generating intelligent behaviour into tractable subproblems

Mathematics (cont.)

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

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

A class of combinatorial search and reasoning problems 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 (yet no proof that NP-complete problems are necessarily intractable, but still ...)

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

Deal with uncertain measurements and incomplete theories

- James Bernoulli (1654-1705), Pierre Laplace (1749-1827) and others: Advance in the theory and statistical methods
- Thomas Bayes (1702-1761):
  Update of probabilities in the light of new evidence

Mathematics (cont.)

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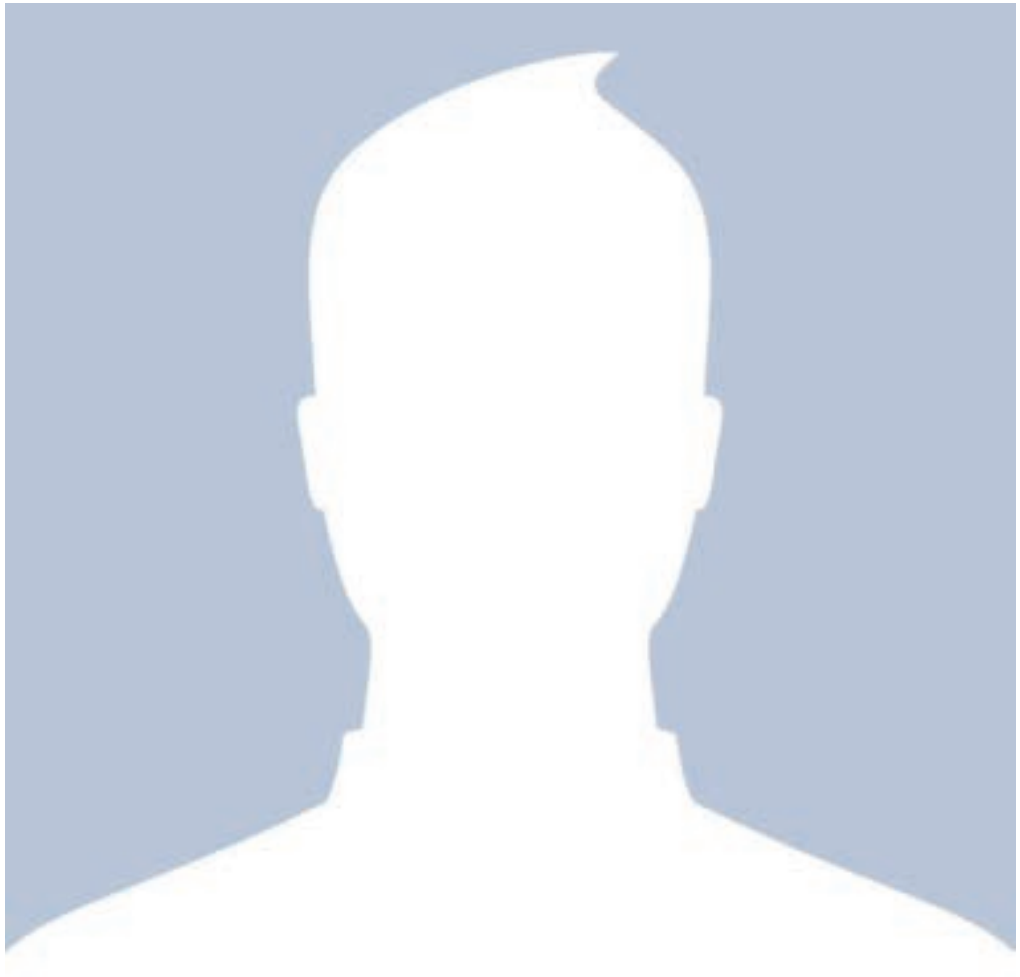

Bayes' rule: In most modern approaches to uncertain reasoning

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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

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 made contributions to economic thought

- Smith was first to treat it as a science
- Economies can be thought of as consisting of individual agents
- Agents maximise their own economic well-being

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 1$, they are asserting that they would prefer 1$ and hoping that you will prefer the hamburger

The math treatment of 'preferred outcomes' or **utility** was formalised

- L. Walras (1834-1910) and then improved by F. Ramsey (1931)

Later, von Neumann and Morgenstern and their book

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

Economics (cont.)

Decision theory combines probability theory with utility theory

- A formal and complete framework for decisions under uncertainty
- Situations in which probabilistic descriptions capture appropriately the environment of the decision maker

This is suitable for 'large' economies in which 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**

The actions of one player can significantly affect the utility of another

- (either positively or negatively)

Economics (cont.)

Von Neumann and Morgenstern's **game theory** showed 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.)

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

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

Economics (cont.)

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Economics (cont.)

Economics/operations research contributed 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
- 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

- How do brains process information?

Neuroscience studies the nervous system, particularly the brain

How the brain enables thought is one of the mysteries of science

- The fact that it does enable thought had been appreciated
- 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'

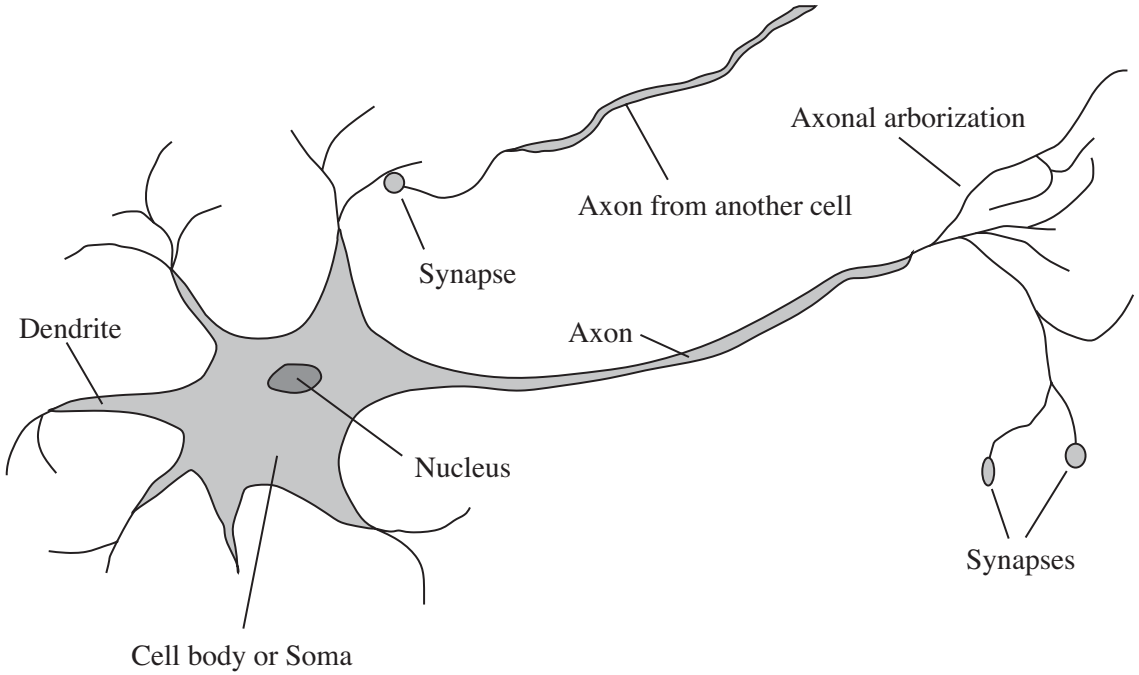
- In $\sim$ -335 Aristotle wrote, '*Of all the animals, man has the largest brain in proportion to his size*'
- The largest brain, ...!

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

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**

- In 1873 Golgi developed a technique to observe single neurons

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Neuroscience (cont.)

Nicolas Rashevsky (1936 and 1938): First to apply math models

- 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

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Neuroscience (cont.)

Measurement of intact brain activity: The electroencephalograph (EEG)

- Hans Berger, in 1929

The development of functional magnetic resonance imaging (fMRI, 2001)

- 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

Neuroscience (cont.)

A long way from understanding how cognitive processes work

These are our (rather amazing) conclusions today

- A collection of simple cells can lead to thought

$\rightsquigarrow$ Brains causes minds

The only real alternative theory is mysticism

- Minds operate in some mystical realm
- Beyond physical science

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

The brain makes up for that with far more storage and interconnection

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

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

Neuroscience (cont.)

Futurists make much of such numbers, pointing to incoming **singularity**

- Computers will soon reach a super-human level of performance
- Even with a computer of virtually unlimited capacity, we still would not know how to achieve the brain's level of intelligence
- Comparisons are not terribly informative

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Psychology

- How do humans and animals think and act?

Scientific psychology: By physicists von Helmholtz (1821-94) and Wundt (1832-1920)

- Helmholtz applied the scientific method to the study of human vision
- His *Handbook of Physiological Optics* is 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 controlled experiments in which his workers would perform a perceptual or associative task while introspecting
- The careful controls went toward making psychology a science
- 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 behaviou lacked introspective data

- They developed an objective methodology
- Described by H. S. Jennings (1906) in his work *Behavior of the Lower Organisms*

Applying this viewpoint to humans, the **behaviourism** movement, led by John Watson (1878-1958), rejected any theory involving mental processes

- Introspection cannot provide reliable evidence

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

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

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Psychology (cont.)

Cognitive psychology: Brains are information-processing devices

- Traced back at least to the works of William James (1842-1910)
- Perception involves a form of unconscious logical inference

The cognitive viewpoint was eclipsed by behaviourism in the U.S.

- Cognitive modelling was able to flourish at the Cambridge's Applied Psychology Unit, directed by F. Bartlett (1886-969)

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Psychology (cont.)

The Nature of Explanation, by Bartlett's student Kenneth Craik (1943), reestablished the legitimacy of such 'mental' terms as beliefs and goals

- They are 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;
3. The goal is to derive new internal representations;
4. These are in turn retranslated back into action

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

Psychology (cont.)

Meanwhile, in the United States, the development of computer modelling

$\rightsquigarrow$ The creation of the field of **cognitive science**

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

- G. Miller presented *The Magic Number Seven*
- N. Chomsky presented *Three Models of Language*
- 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 respectively

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Psychology (cont.)

- 'A cognitive theory should be like a computer program'

Among psychologists, it is now a common (though not universal) view

- 'a cognitive theory should be like a computer program'
- It should describe a detailed information-processing mechanism
- Some cognitive function might be implemented whereby

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Computer engineering

- How do we build an efficient computer?

For AI to succeed, two things:

- **Intelligence** + **artefact**

Artefact of choice: **Computer**

The modern digital electronic computer invented almost simultaneously

- By scientists in 3 countries embattled in WWII

The first operational computer: 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)

Zuse also invented the first high-level programming language

- And floating-point numbers

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Computer engineering (cont.)

The first electronic computer, **ABC** (1942):

- Assembled by John Atanasoff and his student Clifford Berry
- (at Iowa State)

The **ENIAC**, developed in a secret military project at UPenn

- A team including John Mauchly and John Eckert
- It 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
- 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?)

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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)
- It used punched cards to store instructions for the pattern to be woven

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

- The **Analytical engine** was more ambitious
- With addressable memory, stored programs, and conditional jumps
- The first artefact capable of universal computation

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Computer engineering (cont.)

Babbage's colleague Ada Lovelace: Perhaps, the world's first programmer

- She wrote programs for the unfinished Analytical engine
- She 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

- Time sharing, interactive interpreters, personal computers with windows and pointer, development environments
- Linked list data types, automatic storage management
- Key concepts of symbolic, functional, declarative
- Object-oriented programming

Control theory and cybernetics

Foundations

Control theory and cybernetics

- How can artefacts operate under their own control?

Ktesibios of Alexandria ($\sim$ -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

- The steam engine governor, created by James Watt (1736-1819)
- The thermostat, invented by Cornelis Drebbel (1572-1633)

The math theory of stable feedback systems was developed later

- In the 19th century

Control theory and cybernetics (cont.)

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

- A brilliant mathematician who worked also with Bertrand Russell
- Developed interest in biological and mechanical control systems
- He studied their connection to cognition

Wiener and colleagues used control systems as psychological models

- Purposive behaviour as arising from a regulatory mechanism
- An effort to try to minimise some 'error'
- (difference between current state and goal/target state)

They challenged the behaviourists

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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,

- A series of influential conferences

They explored mathematical and computational models of cognition

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

Control theory and cybernetics (cont.)

Meanwhile, in Britain ..., W. Ross Ashby pioneered similar ideas

The Ratio Club (1940): Together with Turing, Walter, and others

- '*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

- 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

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

Linguistics

- How does language relate to thought?

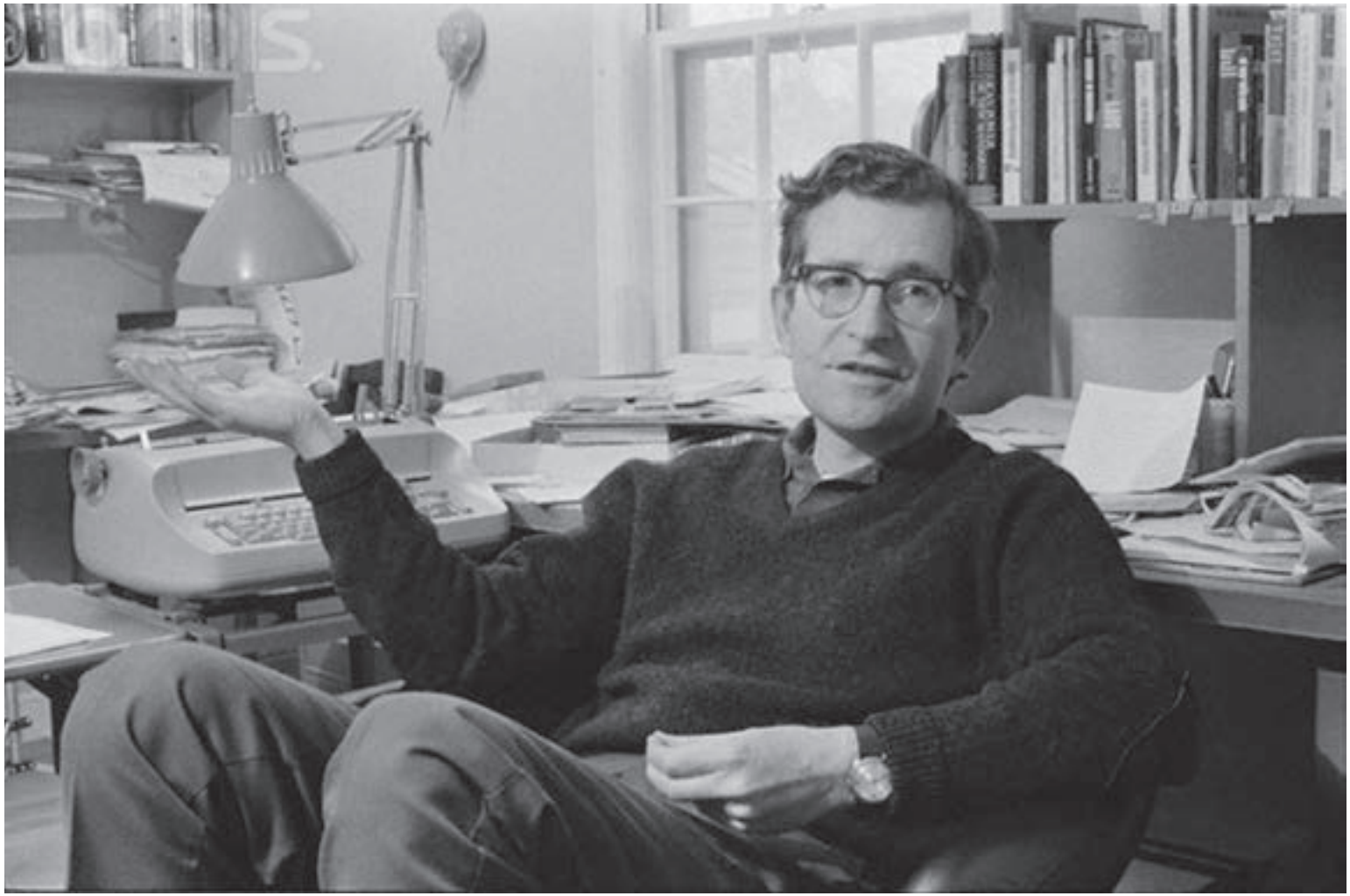
B. F. Skinner published *Verbal behavior* (1957) a comprehensive, detailed account of the behaviourist approach to language learning

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

The author of the review was the linguist Noam Chomsky

- He had just published a book on his own theory
- (*Syntactic structures*)

Linguistics (cont.)



Linguistics (cont.)

Behaviourist theories do not address the notion of creativity in language

- They do 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 could explain this

- Formal enough that it could in principle be programmed

Inspired by the Indian linguist Panini ($\sim$ -350)

Linguistics (cont.)

Modern linguistics and AI, then, were 'born' at about the same time

- The fields grew up together, intersecting in a hybrid field called
- **Computational linguistics** or **natural language processing**

Understanding language turned out to be more complex than it seemed

Understanding language needs understanding of subject matter/contex

- 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)
- Too tied to language and informed by research in linguistics

History
Artificial intelligence

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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 and birth
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Gestation (1943-1955)

The first work now generally recognised as AI

- 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 network of connected neurons, and that all logical connectives ('`and`', '`or`', '`not`', etc.) could be implemented by network structures

- McCulloch and Pitts also suggested that *suitably* defined artificial 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

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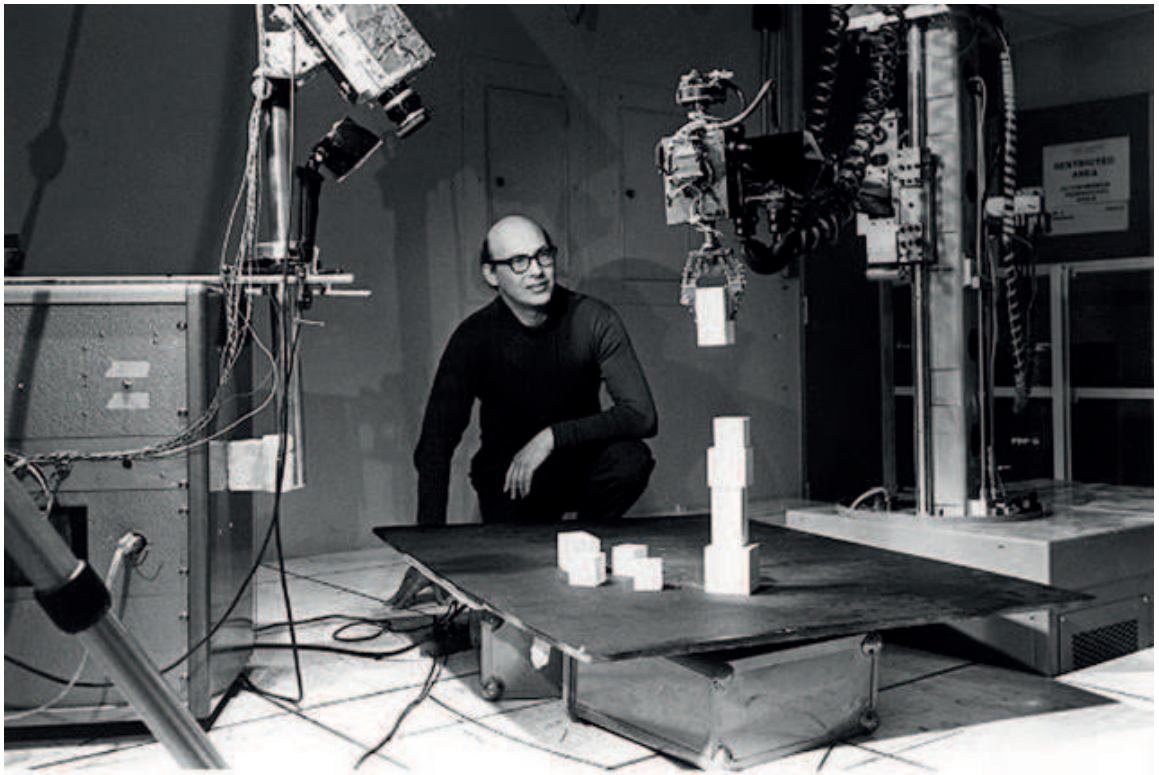
Gestation - 1943-1955 (cont.)

Two undergrad students at Harvard, Marvin Minsky and Dean Edmonds

- 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
- von Neumann reportedly said, 'If it isn't now, it will be someday'

Minsky was later to prove influential theorems

- limitations of neural network research

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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

- He 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

- '*Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulated the child's*?'

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 theory of automata, neural nets, and the study of intelligence

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 rather stole the show
- Allen Newell and Herbert Simon,

Although the others had ideas and in some cases programs for particular applications such as checkers, Newell and Simon 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*'

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 by Newell, Simon, and Logic Theorist

Birth - 1956 (cont.)

The Dartmouth workshop did not lead to any new breakthroughs

- 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?
- 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

AI is the only one of such fields that is a clear branch of computer science

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

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Early enthusiasm and great expectations

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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 only do arithmetic

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

Remark

The intellectual establishment believed that 'a machine can never do X'

- AI researchers responded by demonstrating one X after another
- John McCarthy referred to this 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
- In 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

GPS was the first program to embody the 'thinking humanly' approach

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*'

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**
- Able to prove theorems that many math students would find tricky
- Starting in 1952, Samuel wrote a series of programs for checkers (draughts/dama) that eventually learned to play at 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

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

John McCarthy moved from Dartmouth to MIT

- There he made three crucial contributions
- One historic year: 1958

In MIT AI LabMemo No. 1, McCarthy defined the high-level language **Lisp**, it became the AI programming language for the next 30 years

- With Lisp, McCarthy had the tool he needed

Access to scarce/expensive computing resources was a serious problem

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

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

In 1958, McCarthy published the paper *Programs with Common Sense*

- He described the **Advice Taker** (AT), a hypothetical program
- (perhaps, the first complete AI system)

Designed to use knowledge to search for solutions to problems

- But unlike the others, it was to embody knowledge of the world

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

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

The program was also designed to accept new axioms in the course of operation (allowing it to achieve competence in new areas)

- Without being reprogrammed

The AT embodied principles of knowledge representation and reasoning

- It is useful to have a formal, explicit representation of the world
- To be able to manipulate that representation with deductive processes

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

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

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

- 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.)

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

- Logical reasoning and physical activity

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

Minsky supervised a series of students who chose limited problems

- Intelligence was required to solve them

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% of the number of advertisements he runs, and the number of advertisements he runs is 45, what is the number of customers Tom gets?*'

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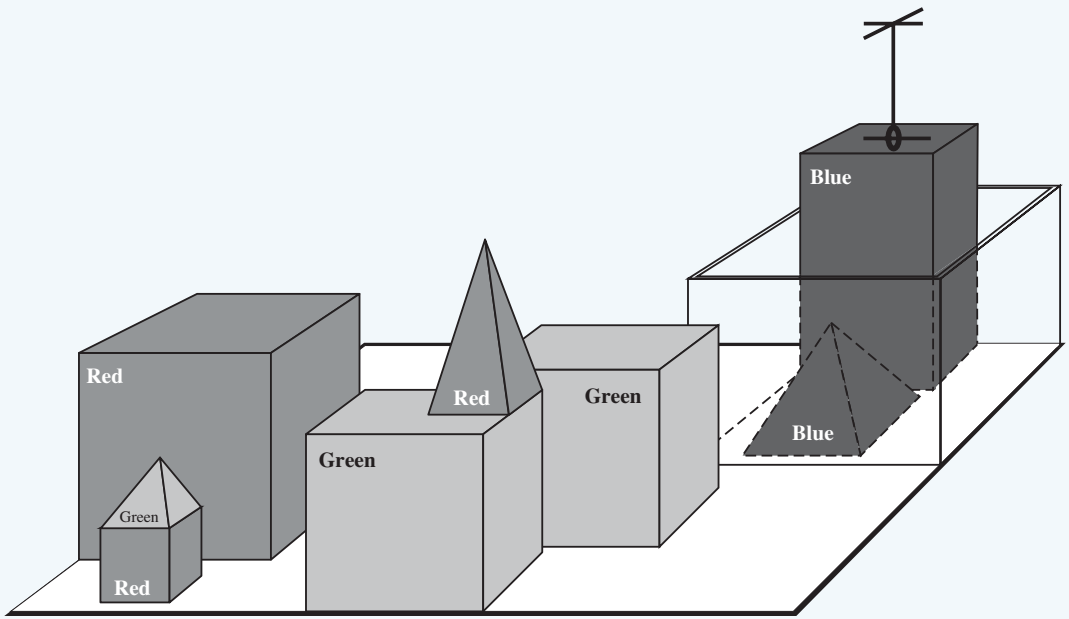
Early enthusiasm and great expectation - 1952-1969 (cont.)

Typical task in the world of blocks: Rearrange blocks in a certain way

- Use 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),
- The planner of Fahlman (1974)

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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 represent an individual concept
- With a corresponding increase in robustness and parallelism
- Hebb's learning methods were enhanced by Widrow (1962), with his **adalines**, and by Rosenblatt (1962) with his **perceptrons**

The perceptron convergence theorem (1962) says that the learning algo can adjust the connection strengths of a perceptron to match any input

A dose of reality
History

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

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

'Visible future' can be interpreted in various ways

- 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 (approximately) within 40 years rather than 10

Overconfidence was due to the promising performance on simple examples

- In almost all cases early systems failed miserably when tried out on wider selections of problems and on more difficult problems

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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

- An attempt to speed up the translation of Russian papers
- (At the time of the Sputnik launch in 1957)
- Generously funded by the US National Research Council

It was thought that syntactic transformations based on grammars and word replacement from dictionary, would preserve sentence meaning

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

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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*'

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

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

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

Remark

Today, machine translation is an imperfect but widely used tool

- Technical, commercial, government documents
- Internet documents

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

The second kind of difficulty was intractability of the problems

- 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

- and very few possible actions
- and very short solution sequences

Before the theory of computational complexity, it was believed that 'scaling up' to larger problems was just a matter of faster hardware/larger memories

- Optimism from proving the resolution theorem was dampened when researchers failed to prove theorems involving more than a few facts

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 power, not confined to problem-solving

- Early experiments in machine evolution (now, **genetic algorithms**)
- Based on a correct belief
- 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
- Thousands of hours of CPU time
- Almost no progress was proved

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'

- 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

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 diminished

- 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 (1969-1979)

Problem solving in the first decade of AI: A general-purpose search tool

- String together elementary reasoning steps, 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

- To solve a hard problem, you have to almost know the answer

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Knowledge based systems (1969-1979)

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

Developed at Stanford, Feigenbaum (Simon's student), Lederberg (Nobel laureate geneticist) and Buchanan (philosopher turned computer scientist)

- Infer molecular structures from data by a mass spectrometer

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

- 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)

Naive versions generated all possible structures consistent with the formula

- Predicted what mass spectrum would be observed for each
- By comparing this with the actual spectrum

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

Knowledge based systems (1969-1979)

The Dendral researchers consulted analytical chemists

- Chemists work by looking for patterns of peaks in the spectrum
- That was used to label common substructures

Example

This rule is used to recognise a ketone ($C = O$) subgroup (weight 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 incorporated the main theme of McCarthy's Advice Taker

- A separation of knowledge (rules) and reasoning components

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Knowledge based systems (1969-1979)

With this in mind, Feigenbaum and others at Stanford began the (HPP)

- **Heuristic Programming Project**
- Study the extent to which **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
- MYCIN was able to perform as well as some experts
- Considerably better than junior doctors
- About 450 rules

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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 in medical knowledge

MYCIN incorporated a calculus of uncertainty called **certainty factors**

- It seemed to fit well with how doctors assessed the impact of evidence

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Knowledge based systems (1969-1979)

Importance of domain knowledge: Understanding natural language

Winograd's **SHRDLU** for understanding natural language was exciting

- Yet, dependence on syntactic analysis caused some of the same problems that occurred in the early machine translation work
- Ability to overcome ambiguity and understand pronoun references
- Mainly because it was designed specifically for one area
- (the blocks world)

Several researchers (including Charniak, a Winograd's student at MIT) suggested that language understanding requires general knowledge

- 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 emphasised this point

- '*There is no such thing as syntax*'
- This served to start a discussion
- It upset a lot of linguists

Schank and his students built a series of programs (early 1980s)

- All had the task of understanding natural language

Knowledge based systems (1969-1979)

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

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

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Knowledge based systems (1969-1979)

Apps to real-world problems demanded for knowledge representation

- Different representation and reasoning languages appeared

Some were based on logic

- the Prolog was popular in Europe
- the Planner family in the US

Others followed Minsky's idea of **frames** (1975)

- Assembling facts about particular object and event types
- Then arranging the types into taxonomic hierarchies

A more structured approach

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AI as an industry (1980-today)

The first successful commercial expert system **R1** began operations, 1982

- At Digital Equipment Corporation (DEC)

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

- Either using or investigating expert systems
- ... just like today!

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

In 1981, Japan announced the 'Fifth Generation' project

- a 10-year plan to build intelligent computers running Prolog

The US formed Microelectronics and Computer Technology Corporation

- A research consortium designed to assure national competitiveness

In both cases, AI was part of a broad effort

- Both 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.)

AI industry boomed from a few million dollars in 1980 to billions in 1988

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

Soon after that came a period called the 'AI Winter'

- Many companies failed to deliver
- Too extravagant promises
- Hundreds of companies

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The return of neural networks (1986-today)

In the mid-80s at least four different groups reinvented back-propagation

- It is a learning algorithm found in 1969 by Bryson and Ho
- The algorithm was applied to many learning problems
- In computer science, psychology, ...

The results were reported in the collection Parallel Distributed Processing

- (Rumelhart and McClelland, 1986)
- The caused great excitement

These **connectionist** models of intelligent systems were seen by some as competitors both to symbolic models and to the logicist approach

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

It seems obvious that, at some level, humans manipulate symbols[3]

- 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

[3] Terrence Deacon's book *The Symbolic Species* in 1997 suggests that this is the defining characteristic of humans

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

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 same occurred with the separation of AI and cognitive science

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

- Stuff like control theory and statistics
- Now, it is embracing those fields

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**, from **stochastic modelling**
- **Search**, from classical **optimisation** and **control**
- **Automated reasoning**, from **formal methods** and **static analysis**

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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 experiments
- The results must be analysed statistically for importance (1995)

Remark

- **It is now possible to replicate experiments**
- **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, different architectures and approaches were tried
- Many were *ad hoc* and fragile
- Tested on a few selected examples

Recently, approaches based on **hidden Markov models** (HMMs)

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 trained on a large corpus of data

The performance is robust and it has been improving steadily

The scientific method - 1987-today (cont.)

Speech technology and related field of handwritten character recognition

- Transition to industrial/consumer apps

There is no claim that humans use HMMs to recognise speech

HMMs provide a math framework for understanding the problem

- A support to the engineering claim that they work well

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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 based on information theory
- That approach fell out of favor in the 1960s
- It only returned in the late 90's
- Today, it 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 be compared with related techniques from statistics and pattern recognition

The scientific method - 1987-today (cont.)

As a result, **data science** technology has spawned a vigorous new industry

The scientific method - 1987-today (cont.)

Judea Pearl's (1988) *Probabilistic Reasoning in Intelligent Systems*

- A new acceptance of probability and decision theory in AI[4]

- The **Bayesian network** formalism was invented to allow efficient representation of, and rigorous reasoning with, uncertain knowledge
- The approach overcomes issues of probabilistic systems from 60/70's

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

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

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The scientific method - 1987-today (cont.)

Work by Pearl, Horvitz and Heckerman promoted a new idea

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

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The scientific method - 1987-today (cont.)

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

- A better understanding of problems and their complexity
- Increased math sophistication

$\rightsquigarrow$ Towards a workable research agenda 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
- Machine learning tools 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)
- The best-known example of a complete agent architecture

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Intelligent agents - 1995-today (cont.)

One important environment for intelligent agents is the Internet

- AI systems have become so common in apps
- The '-bot' suffix entered everyday language

Moreover, AI technologies underlie many Internet tools

- Search engines, recommender systems, web site aggregators ...

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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 info

Reasoning and planning systems must also handle uncertainty

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Intelligent agents - 1995-today (cont.)

A second major consequence of the agent perspective

- AI has been drawn into closer contact with other fields
- Control theory, 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 hi-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, ...)
- AI should return to its roots
- '*... machines that think, that learn and that create*' (Simon's words)

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

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Intelligent agents - 1995-today (cont.)

A related idea is **Artificial General Intelligence** or AGI (2007)

- 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)

First conference, the Journal of Artificial General Intelligence: From 2008

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

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Large datasets (2001-today)

Throughout the 60 years of computer science, emphasis on the algorithm

Recent work in AI seem to suggest that for many problems, it makes more sense to worry about data and be less picky about the algorithms (does it?)

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)
- ...

Large datasets - 2001-today (cont.)

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

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

Previous approaches to the problem had relied on human-labeled examples

- Combined with machine learning algorithms

Yarowsky show that the task can be done with no labeled examples at all

- Accuracy +96%,

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Large datasets - 2001-today (cont.)

Banko and Brill (2001) show that techniques like this perform increasingly 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

- Now you need to fill in the masked area
- Something that matches the background

- Hays and Efros defined an algorithm that searches through a collection of photos to find something that will match
- Performance was poor when they used only $10K$ 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.)

Works like these suggest how to solve the 'knowledge bottleneck' in AI

- How to express all the knowledge that a system needs

Learning methods, not hand- and hard-coded a priori knowledge

- Algorithms need enough (good) data to go on (2009)

Remark

Reporters noticed the surge of new applications

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

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Robotic vehicles

- VOLKSWAGEN's **STANLEY**: First driverless robotic car in the DARPA Grand Challenge (2005), 132-mile course
- Rough terrain of the Mojave dessert at 22 mph

Remark

STANLEY is a Touareg with cameras, radar, and laser rangefinders to sense the environment and on-board software to command steering, braking, and acceleration

- CMU's **BOSS** won the Urban Challenge (2007): Driving in traffic, obeying traffic rules and avoiding pedestrians and other vehicles

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Today (cont.)

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Speech recognition

- Travellers calling airline companies to book a flight can have the entire conversation guided by dialog management systems
- Automated speech recognition systems
- ...

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Autonomous planning and scheduling

- NASA's **REMOTE AGENT**: First on-board autonomous planning program to control scheduling of operations of a spacecraft
- (2000, $100M$ miles from Earth)

Planning from hi-level goals from ground, monitoring execution on-board

- Detection, diagnosis, and recover from problems

Successor program **MAPGEN** plans daily operations (NASA's Mars Exploration Rovers, 2004) and **MEXAR2** did mission planning, logistics and science planning (European Space Agency's Mars Express mission, 2007-8)

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Game playing

- IBM's **DEEP BLUE**: First to beat the chess world champion
- It bested Garry Kasparov (3.5 to 2.5 in an exhibition, 1997)

Kasparov said he felt a 'new kind of intelligence' across the board

Newsweek described the match as 'The brain's last stand'

The value of IBM's stock increased by $\$18B$

Remark

Humans studied Kasparov's loss and drew a few matches in next years

- Recent human-computer matches have been won by the computer

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Spam fighting

- Each day, learning algorithms classify over $1B$ messages as spam
- Savings from wasting time deleting 80%-90% of all messages

Spammers update their tactics: Hard for a static approach to keep up

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

Robotics

- The iRobot Corporation: $+2M$ **ROOMBA** robotic vacuum cleaners

Remark

They also deploy the PackBot to Iraq/Afghanistan

- To handle hazardous materials, clear explosives, ...

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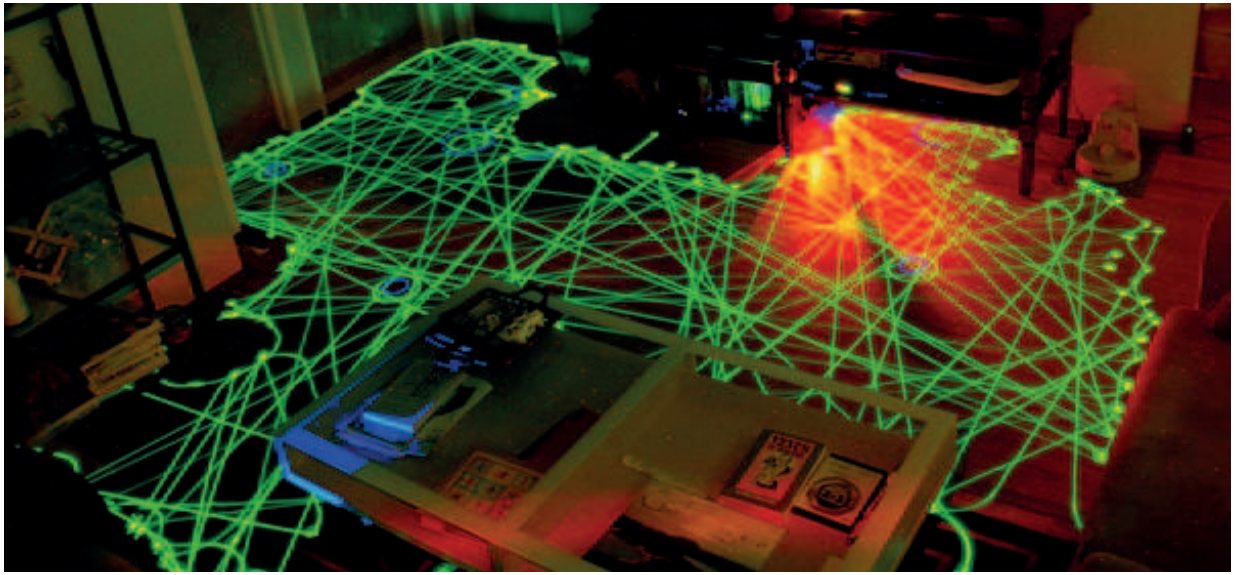

Today (cont.)

Logistics planning

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

Involved up to 50K vehicles, cargo, and people at a time

- Accounts for starting points, destinations, routes, conflicts, ..
- The AI planning techniques generated in hours a plan that would have taken weeks with older methods

Remark

The Defense Advanced Research Project Agency statement

- This single application more than paid back 30-year investment in AI

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Machine translation

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

A statistical model built from Arabic-to-English translations

- Examples of English text totalling two trillion words

Remark

None of the computer scientists on the team speak Arabic

- They did understand statistics and machine learning

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