Artificial intelligence
(CK0031/CK0248)

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What's AI?
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Thinking humanly
Thinking rationally
Acting rationally
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History

Artificial intelligence

Intelligence

- Understand how (we think) we think

Artificial intelligence

- Understand but also build intelligent entities

Artificial intelligence is one of the newest fields in science and engineering

- Work started after World War II, the name was coined in 1956
- 'The field I would most like to be in', by scientists in other disciplines

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Artificial intelligence (cont.)

AI consists of a huge variety of sub-fields

- From the general (perception, learning, deliberating and acting)
- 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?
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, can be understood as having 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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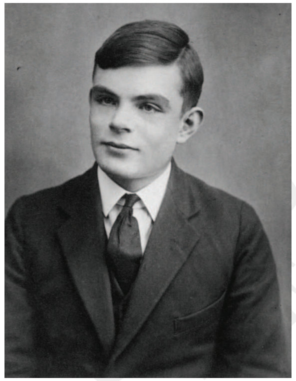
Acting humanly
What's AI

Acting humanly



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

- 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 cannot tell whether the written responses come from a person or from a computer
- (After posing some written questions,)

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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 a wide array 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 needs additional capabilities

⇝ **Computer vision**, to perceive objects

⇝ **Robotics**, to manipulate objects and move about

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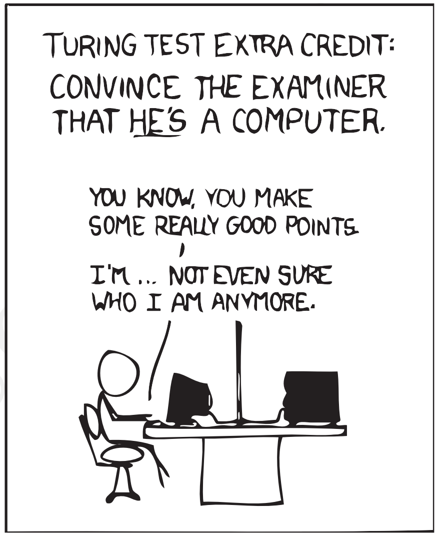
Acting humanly (cont.)

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

These (?) six disciplines compose most of modern AI

Acting humanly (cont.)



Hit Turing right in the test-ees

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Thinking humanly

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Thinking humanly

Suppose that we aim at saying that a given program thinks like a human

- ⇝ We must have some way of determining how humans think
- ⇝ We need to get inside the actual workings of human minds

There are three ways to do this (today, and as far as I know)

- ⇝ **Introspection**, try to catch own thoughts as they go by
- ⇝ **Psychological experiments**, observe a person in action
- ⇝ **Brain imaging**, observe 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

The program's IO behaviour and corresponding human behaviour matched?

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

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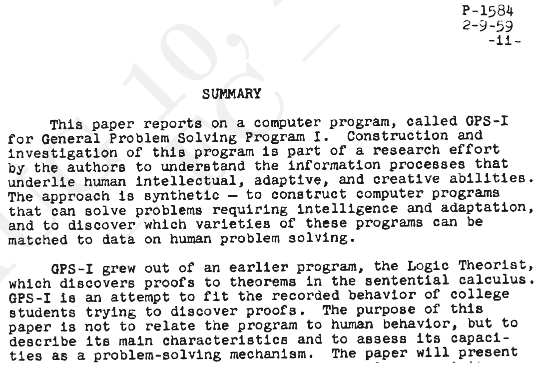
Thinking humanly (cont.)

Newell, Shaw and Simon, 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

Thinking humanly (cont.)

The field of **cognitive science** brings together various areas

- Computer models from AI
- Experimental techniques from psychology

The goal is to construct a precise and testable theory of 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 rationally

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Thinking rationally

Thinking rationally is also understood as the **law of thought** approach

It is one of the first attempts to codify 'right thinking' as irrefutable reasoning processes it (it all started with the greek philosopher Aristotle)

The **syllogism** provided patterns for argument structures

- It always yielded correct conclusions
- (When given the right premises)

Premises

- a) Socrates is a man
- b) All men are mortal

Conclusion

- ⇝ 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

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Thinking rationally (cont.)

It is believed that 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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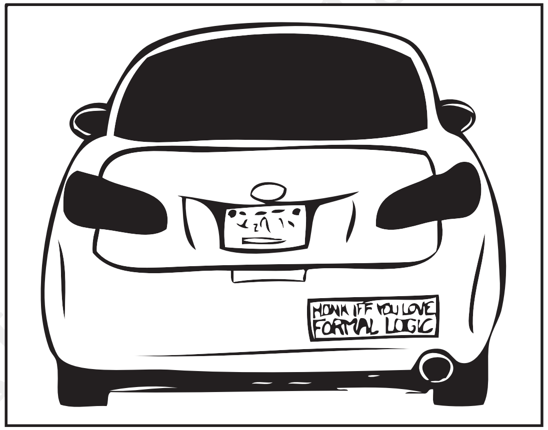
Thinking rationally (cont.)

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
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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

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

Foundations

Artificial intelligence

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**
- **Psychology**
- **Computer engineering**
- **Control and cybernetics**
- **Linguistics**

Philosophy

Foundations

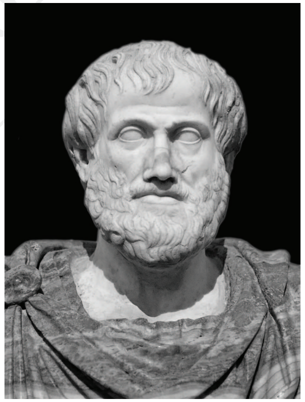
Philosophy

- 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?

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



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

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*'

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!

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

⇝ 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

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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

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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

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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

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Philosophy (cont.)

The final element in the philosophical picture of the mind

$\rightsquigarrow$ 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*)

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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

Mathematics

Foundations

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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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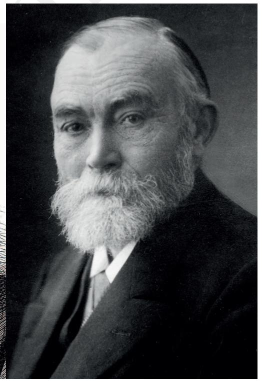
Mathematics (cont.)

The idea of formal logic can be tracked back all the way 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.)

Efforts to 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

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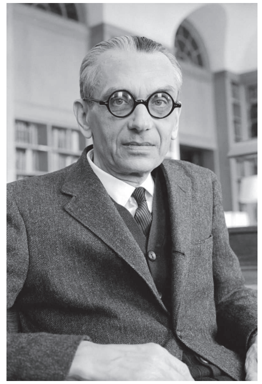
Mathematics (cont.)

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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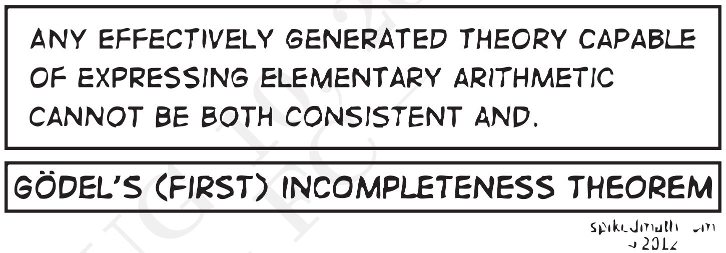
Mathematics (cont.)



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Mathematics (cont.)

Motivated Turing (1912-1954) to 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 can compute any computable function

There are some functions that Turing machines can not compute

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

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

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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)

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 ...)

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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 artificial intelligence

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

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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: Advances in the theory and statistical methods
- Thomas Bayes (1702-1761): Updates of probabilities in the light of new evidence

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Mathematics (cont.)

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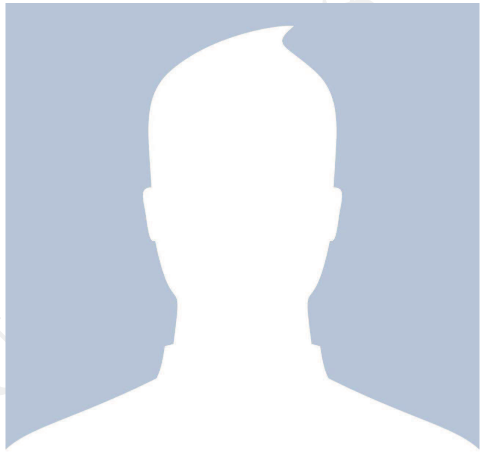
Mathematics (cont.)



Bayes' rule: In most modern approaches to uncertain reasoning

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Economics

⇝ 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 classic book

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

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Economics (cont.)

Decision theory combines probability theory with classic 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)

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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

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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 only 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

Neuroscience (cont.)

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

- In ∼ -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

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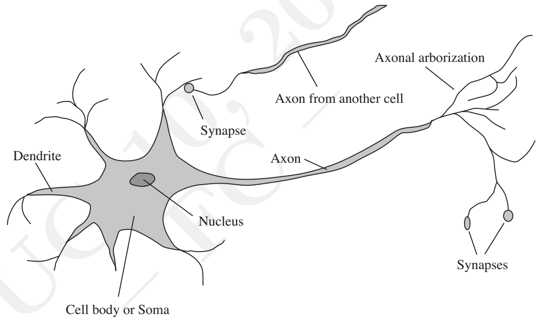
Neuroscience (cont.)

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**

- 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)

- Measurements that correspond to ongoing cognitive processes
- Unprecedentedly detailed images of brain activity

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.)

Still a long way from understanding how cognitive processes work

These are our (minimal but rather amazing) conclusions today

- A collection of simple cells can lead to thought

⇝ Brains causes minds

There is only one real alternative theory, mysticism

- Minds operate in some mystical realm
- 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

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

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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

Foundations

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.)

The biologists that were studying animal behaviour lacked introspective data

- They developed an objective methodology
- Described by H. S. Jennings (1906)
- *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 the resulting actions (responses)

- 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 flourished at the Cambridge's Applied Psychology Unit, directed by F. Bartlett (1886-969)

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

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

⇝ 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

Psychology (cont.)

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

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

- It should describe a detailed information-processing mechanism
- Some cognitive function might be implemented whereby

Computer engineering

Foundations

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

- It was invented almost simultaneously by 3 scientists
- (In 3 different countries, all 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

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Computer engineering (cont.)

The first 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)

The first electronic computer: The **ABC** (1942) from Iowa State University

- Assembled by John Atanasoff and his student Clifford Berry

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 already 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

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 a much more ambitious project
- Addressable memory, stored programs, 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 some 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.)

Artificial intelligence owes a debt to the software side of computer science, which 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
- Windows and the pointers, and development environments
- Linked list data types, automatic storage management
- Key concepts of symbolic, functional, declarative
- Object-oriented programming

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Control theory and cybernetics

Foundations

Control theory and cybernetics

⇝ How can artefacts operate under their own control?

Ktesibios of Alexandria (∼ -250) built the first 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)

Much later on 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

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Control theory and cybernetics (cont.)

A central figure in **control theory** is sublime 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.)

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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

Control theory and cybernetics (cont.)

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

- This view roughly matches our current view of AI
- Design systems that behave optimally
- (On average)

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Control theory and cybernetics (cont.)

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Thinking humanly
Thinking rationally
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Computer eng
Control, cybernetics
Linguistics
History

Why are artificial intelligence and control theory two different fields then?

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

Calculus and matrix algebra, the 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 inference and computation allowed artificial intelligence to consider problems such as language, vision, and planning
- Stuff that fell outside the control theorist's purview

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Linguistics

Foundations

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Linguistics

⇝ How does language relate to thought?

B. F. Skinner published *Verbal behavior* (1957) a comprehensive, a 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*)

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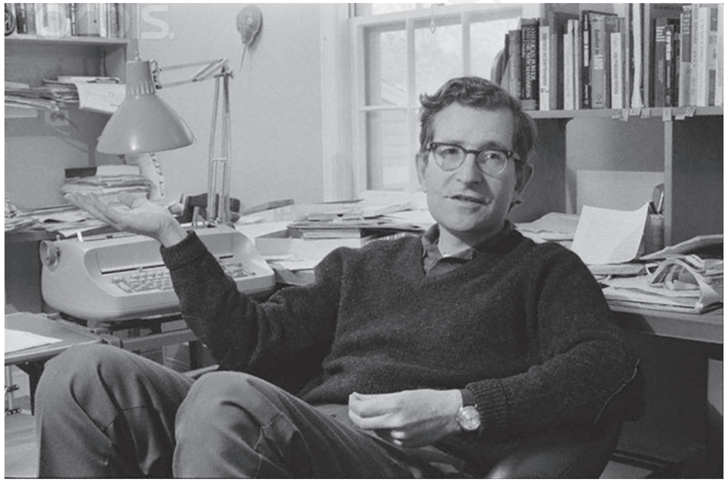
Linguistics (cont.)



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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)

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Linguistics (cont.)

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

The fields grew up together, intersecting in a hybrid field

- **Natural language processing**
- **Computational linguistics**

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)

- Approach 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)**