Search Methods in Artificial Intelligence

Introduction

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Syllabus

Introduction. History and philosophy. The Turing Test. The Winograd schema challenge. Placing search in the landscape of AI.

Search spaces. Examples. State space search. Depth first, breadth first, iterative deepening. Analysis.

Heuristic search. Escaping local optima. Stochastic local search.

Population based methods. Genetic algorithms, ant colony optimization.

Finding optimal paths. Algorithm A*. Admissibility of A*.

The monotone condition. Space saving versions of A*. Sequence alignment.

Game playing. Board games. Algorithms Minimax, Alpha-Beta, and SSS*.

Automated domain independent planning. Goal stack planning, partial order planning.

Problem decomposition with goal trees. Algorithm AO*.

Pattern directed inference systems. Forward chaining inference engine. The Rete algorithm.

Constraint processing. Algorithm Backtracking. Arc consistency. Combining search and reasoning. Waltz algorithm. Model based diagnosis.

Text Book and References

Text Books

Deepak Khemani. Search Methods in Artificial Intelligence, Cambridge University Press (forthcoming)
Deepak Khemani. A First Course in Artificial Intelligence, McGraw Hill Education (India), 2013.

Reference Books

- Stefan Edelkamp and Stefan Schroedl. Heuristic Search: Theory and Applications, Morgan Kaufmann, 2011.
- John Haugeland, Artificial Intelligence: The Very Idea, A Bradford Book, The MIT Press, 1985.
- Pamela McCorduck, Machines Who Think: A Personal Inquiry into the History and Prospects of Artificial Intelligence, A K Peters/CRC Press; 2 edition, 2004.
- Eugene Charniak and Drew McDermott, Introduction to Artificial Intelligence, Addison-Wesley, 1985
- Zbigniew Michalewicz and David B. Fogel. How to Solve It: Modern Heuristics. Springer; 2nd edition, 2004.
- Judea Pearl. Heuristics: Intelligent Search Strategies for Computer Problem Solving, Addison-Wesley, 1984.
- Elaine Rich and Kevin Knight. Artificial Intelligence, Tata McGraw Hill, 1991.
- Stuart Russell and Peter Norvig. Artificial Intelligence: A Modern Approach, 3rd Edition, Prentice Hall, 2009.
- Patrick Henry Winston. Artificial Intelligence, Addison-Wesley, 1992.

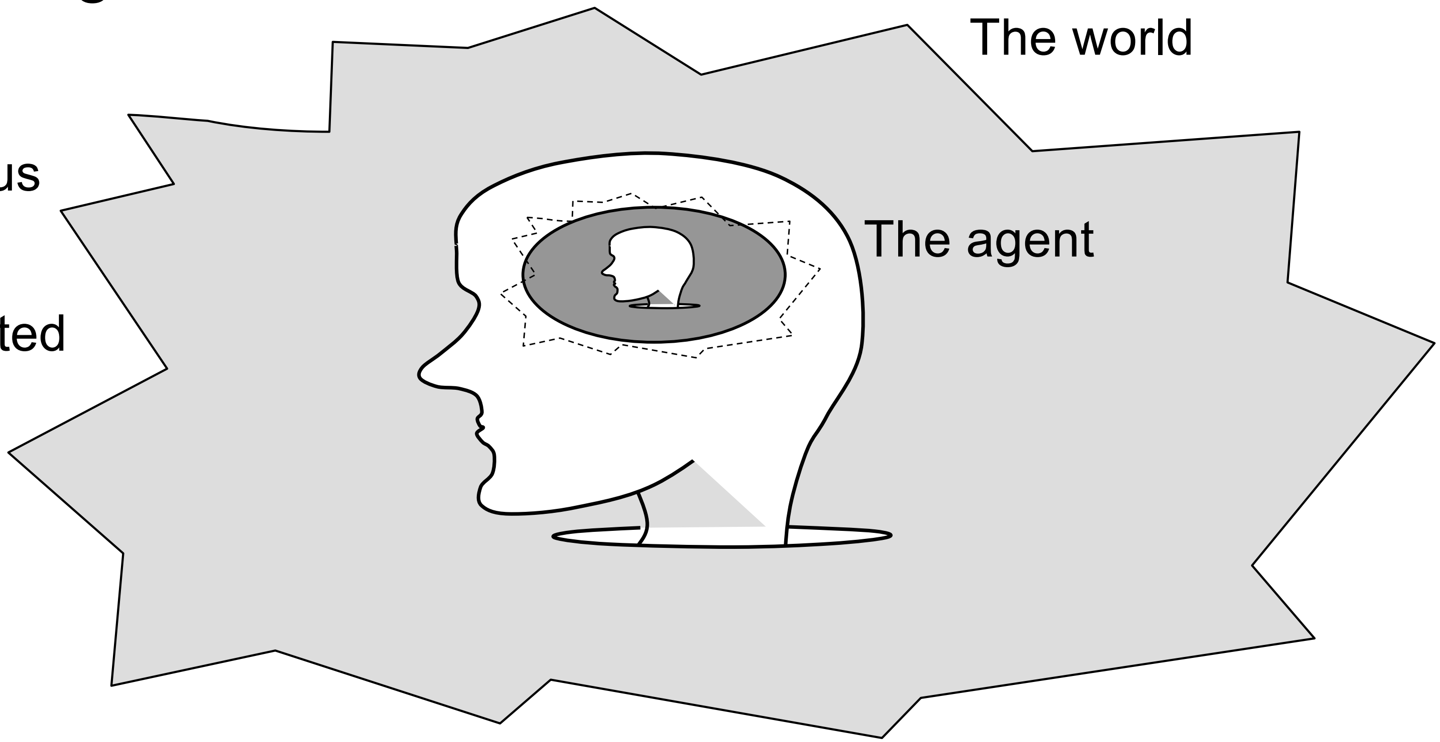
Intelligent Agents

Persistent

Autonomous

Proactive

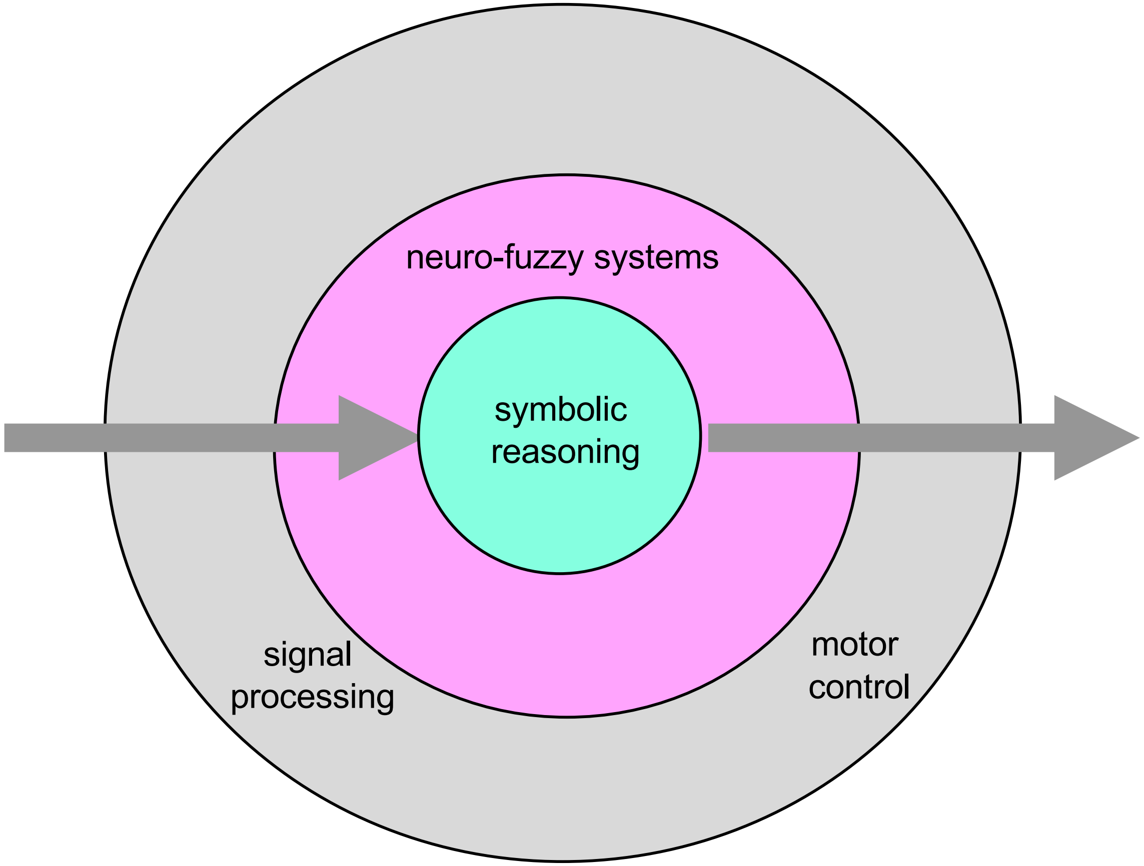
Goal Directed



An intelligent agent in a world carries a model of the world in its "head". The model maybe an abstraction. A self aware agent would model itself in the world model.

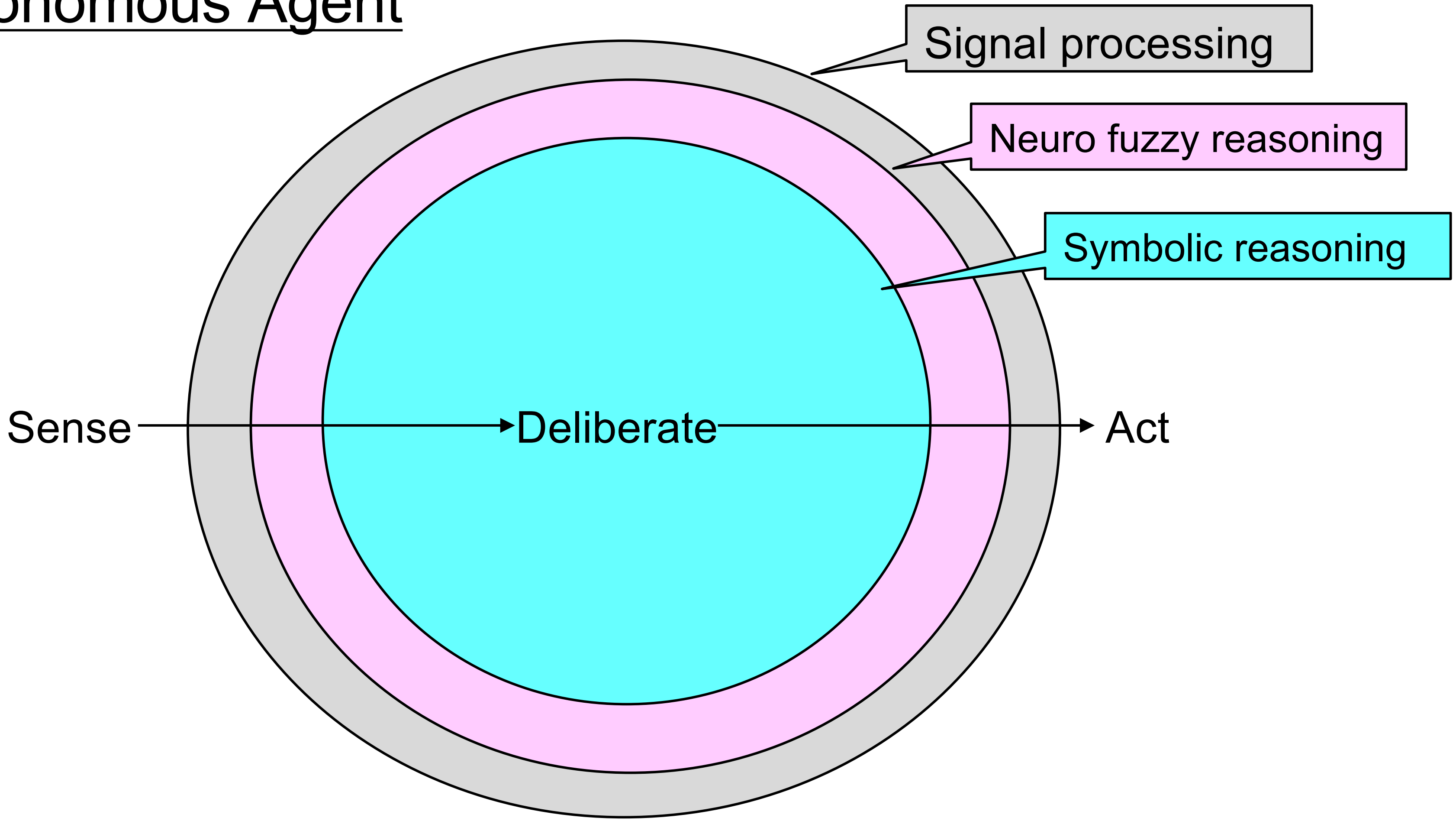
(From: *A First Course in AI* – Deepak Khemani)

Information Processing view of AI

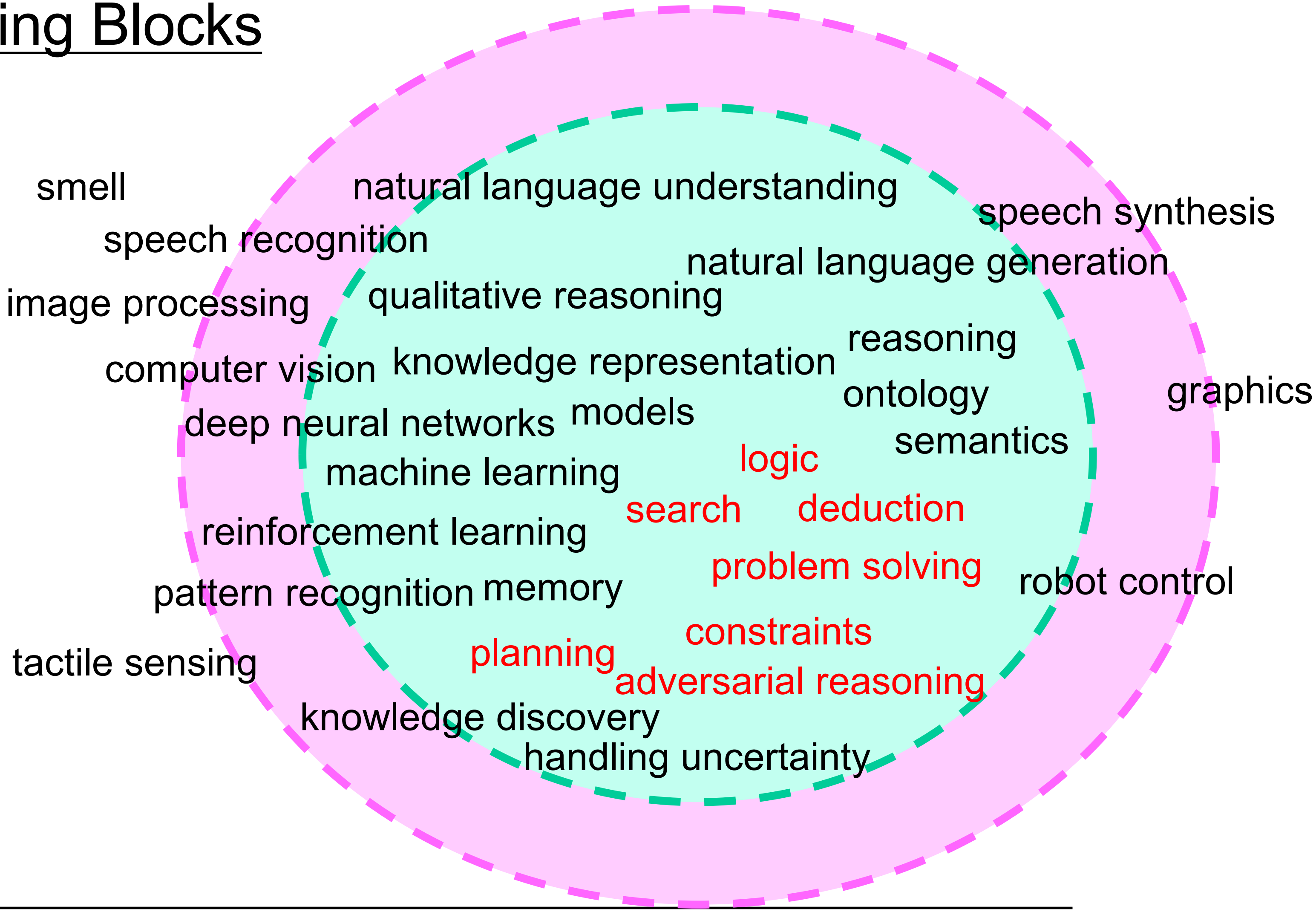


signal → symbol → signal

An Autonomous Agent



Building Blocks



Intelligence

- Remember the past. Learn from it.
  - Memory and experience – case based reasoning.
  - Learn a model – machine learning.
  - Recognize objects, faces, patterns – deep neural networks.
- Understand the present. Be aware of the world around you.
  - Create a model of the world – knowledge representation.
  - Make inferences from what you know – logic and reasoning.
- Imagine the future. Work towards your goals.
  - Trial and error – heuristic search.
  - Goals, plans, and actions – automated planning.

A Decade of Machine Learning

The last decade has seen an explosion

in the amount of data available

computing power available

and

advancements in neural network training algorithms

leading to the impression

that

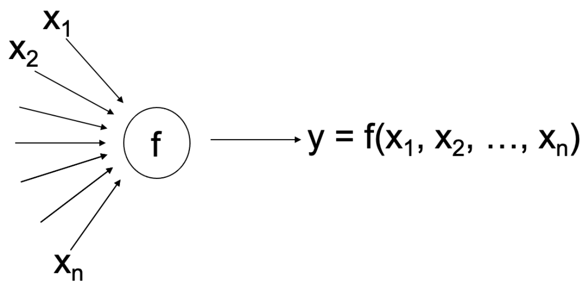
that is all AI is about!

We briefly look at this phenomenon

before proceeding to our syllabus

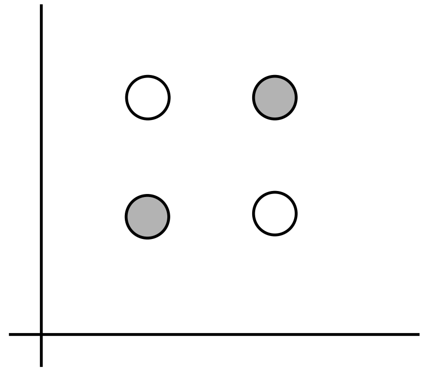
on problem solving using search...

Neural Networks



A neuron is a simple device that computes a simple function of the inputs it receives.

Collections of interconnected neurons can do complex computations.



The Perceptron, invented by Frank Rosenblatt in 1958, was a single layer neural network designed to be a binary classifier.

In 1958 Minsky and Papert showed its limitations – it could only classify linearly separable classes.

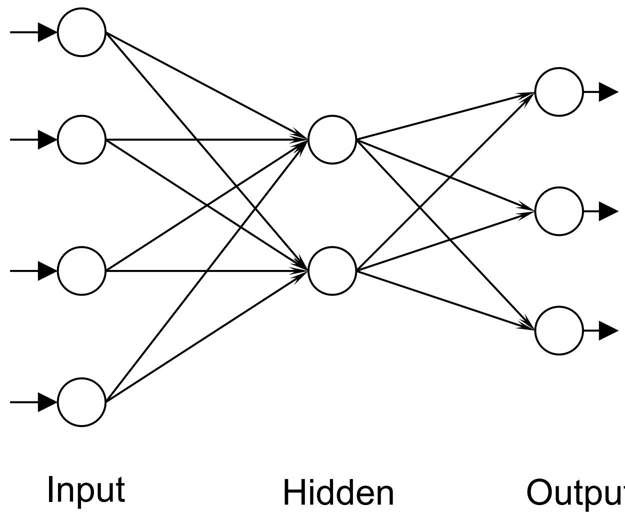
For example one cannot draw a line to separate the shaded circles, data from class A, from the empty ones, from class B.

The Hidden Layer

In 1986 Rumelhart, Hinton & Williams showed that a multi-layer perceptron could be trained to learn any non-linear classifier

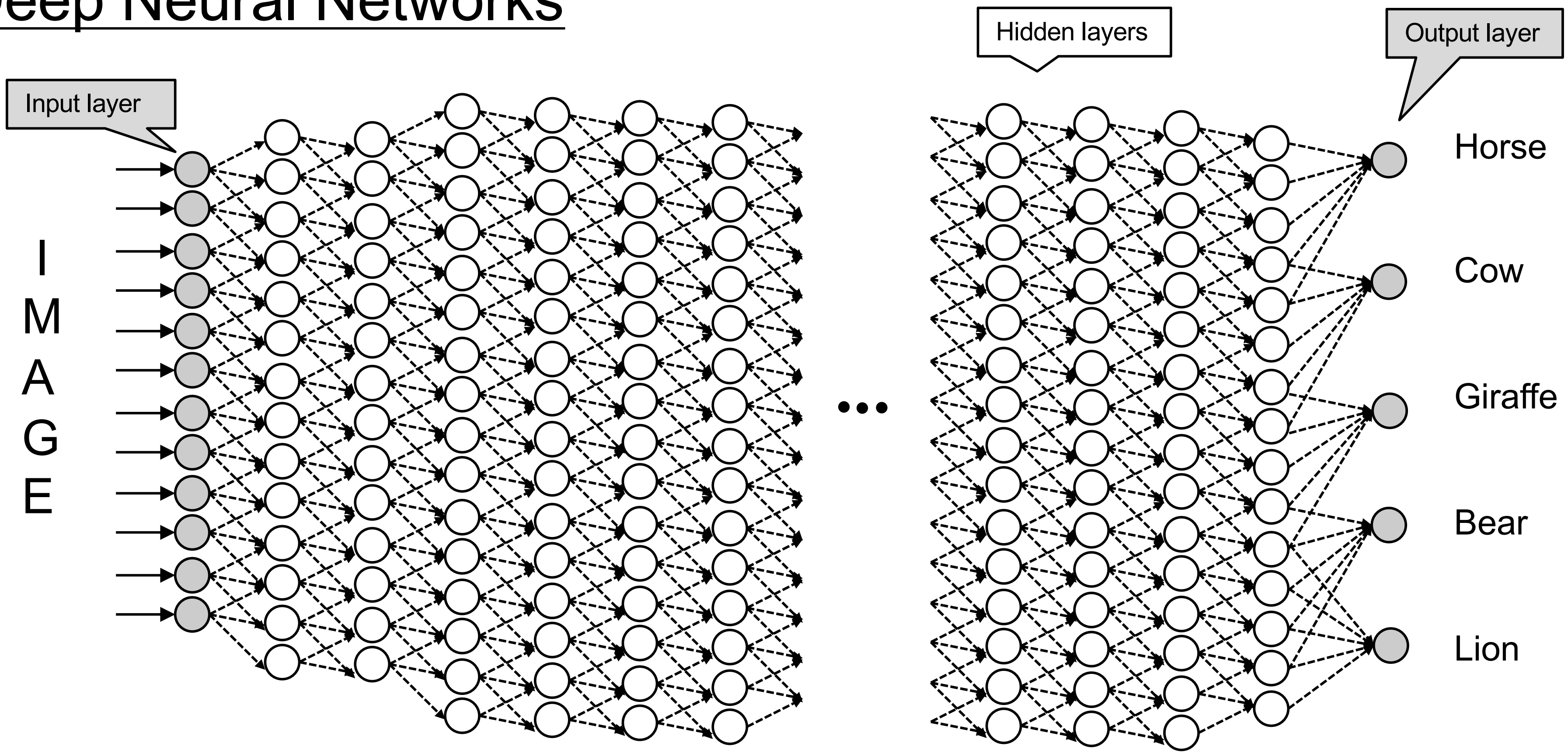
They also popularized the *Backpropagation Algorithm* which fed the error at the output layer back via the hidden layer, adjusting the weights of the connections.

Hinton persevered with neural networks and showed in 2012 that (deep) networks with many hidden layers achieved phenomenal success in computer vision - recognizing thousands of types of objects



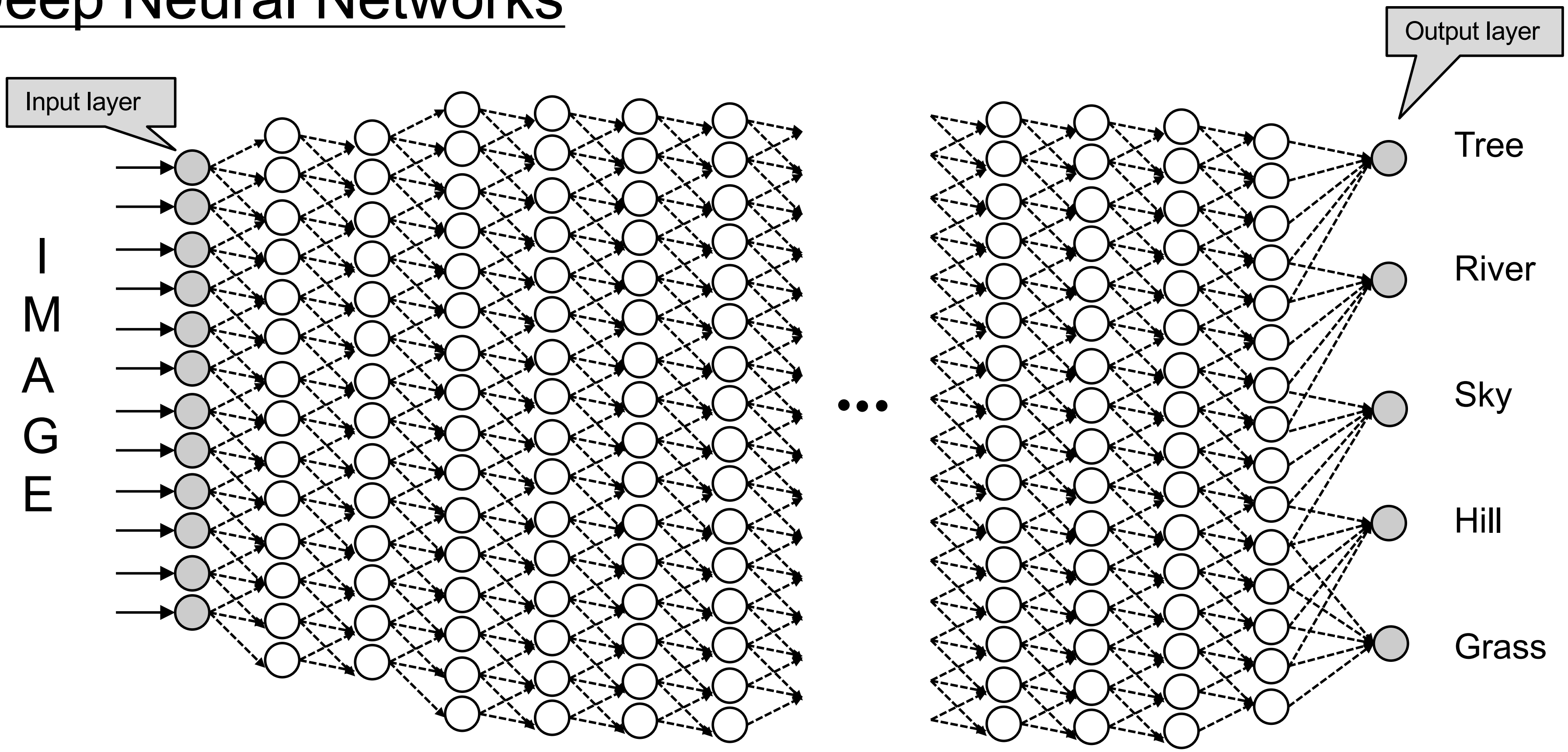
A Feedforward Artificial Neural Network

Deep Neural Networks

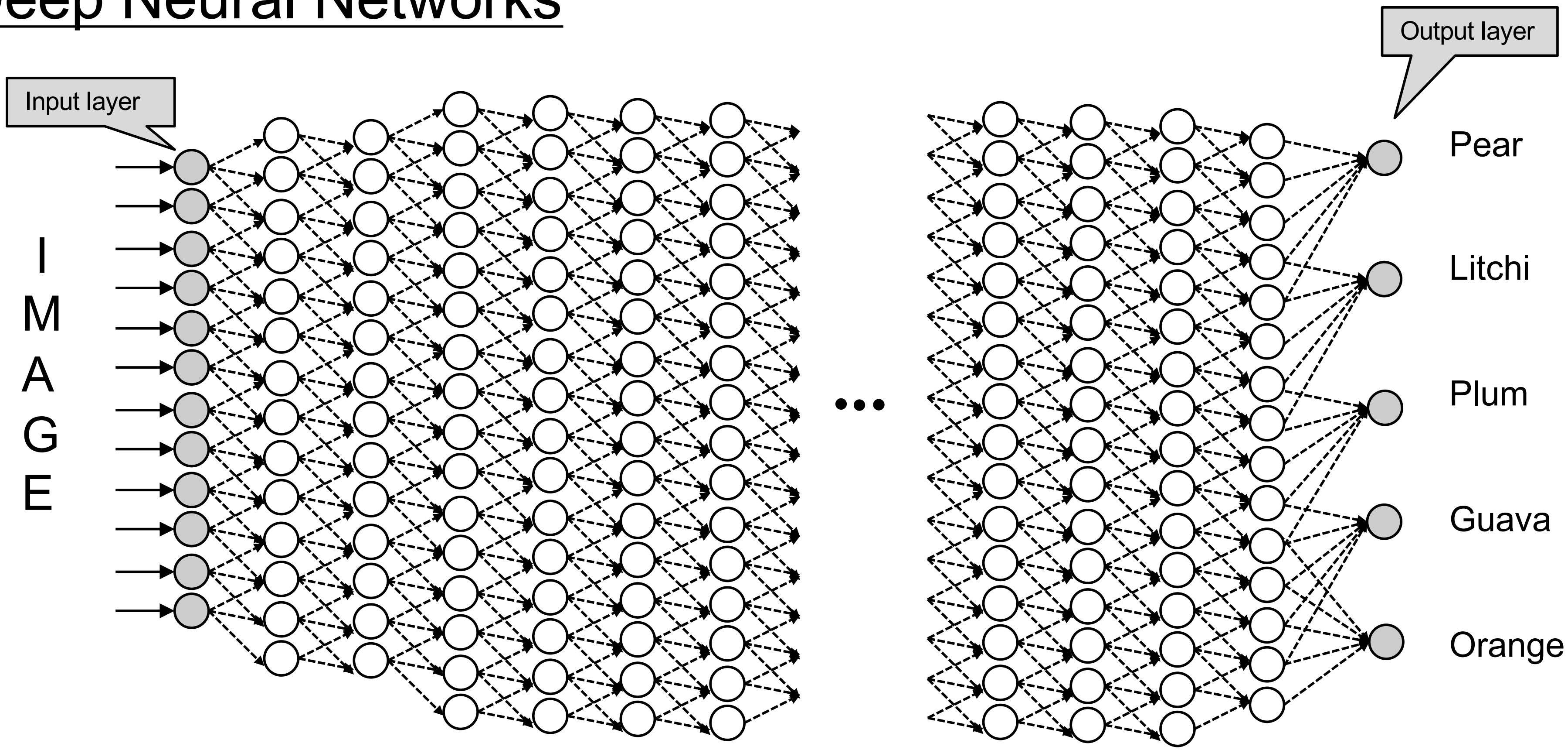


Feed forward networks: information flows from left to right

Deep Neural Networks

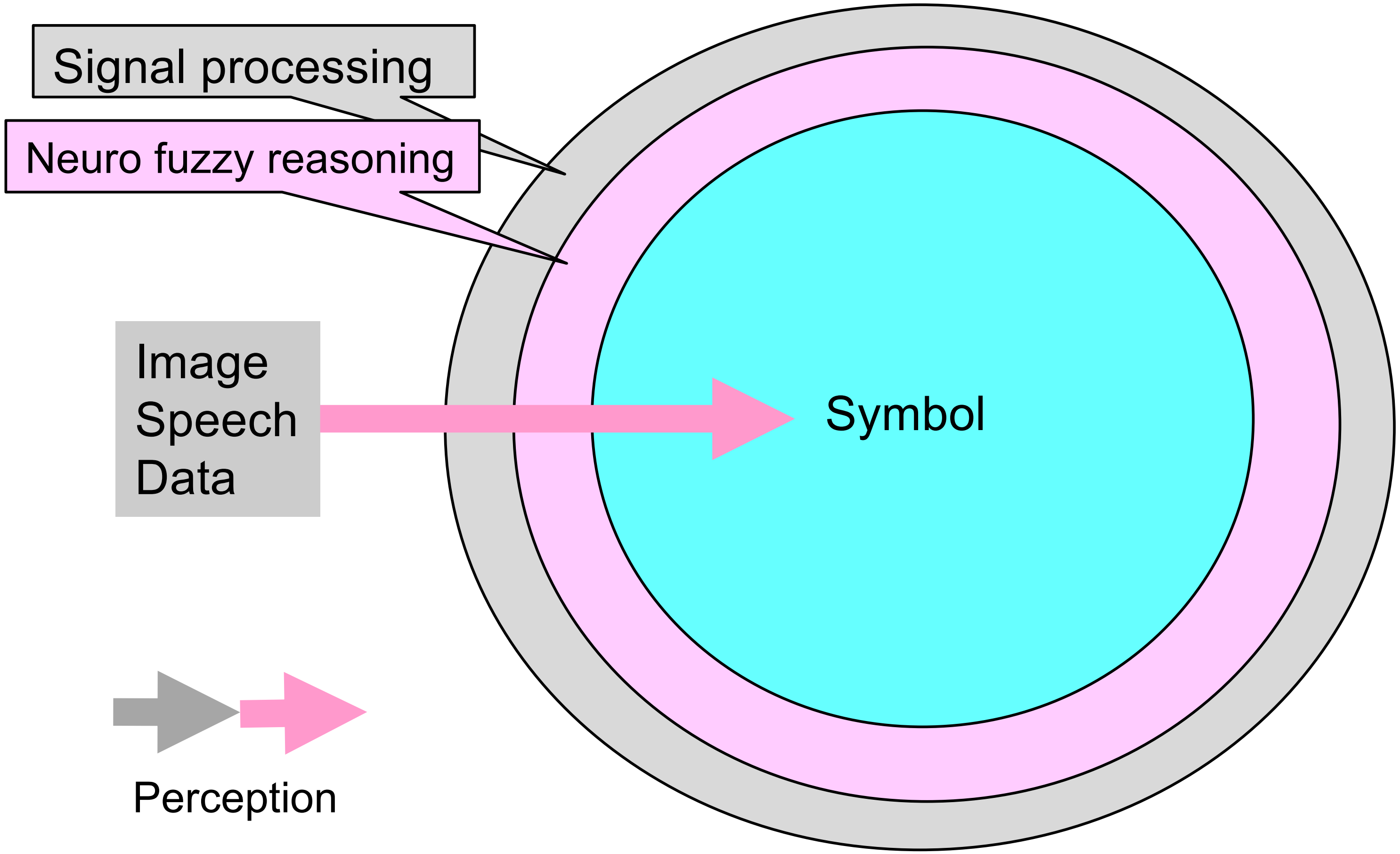


Deep Neural Networks



Geoffrey Hinton, Yann LeCun, and Yoshua Bengio, won the 2018 Turing Award

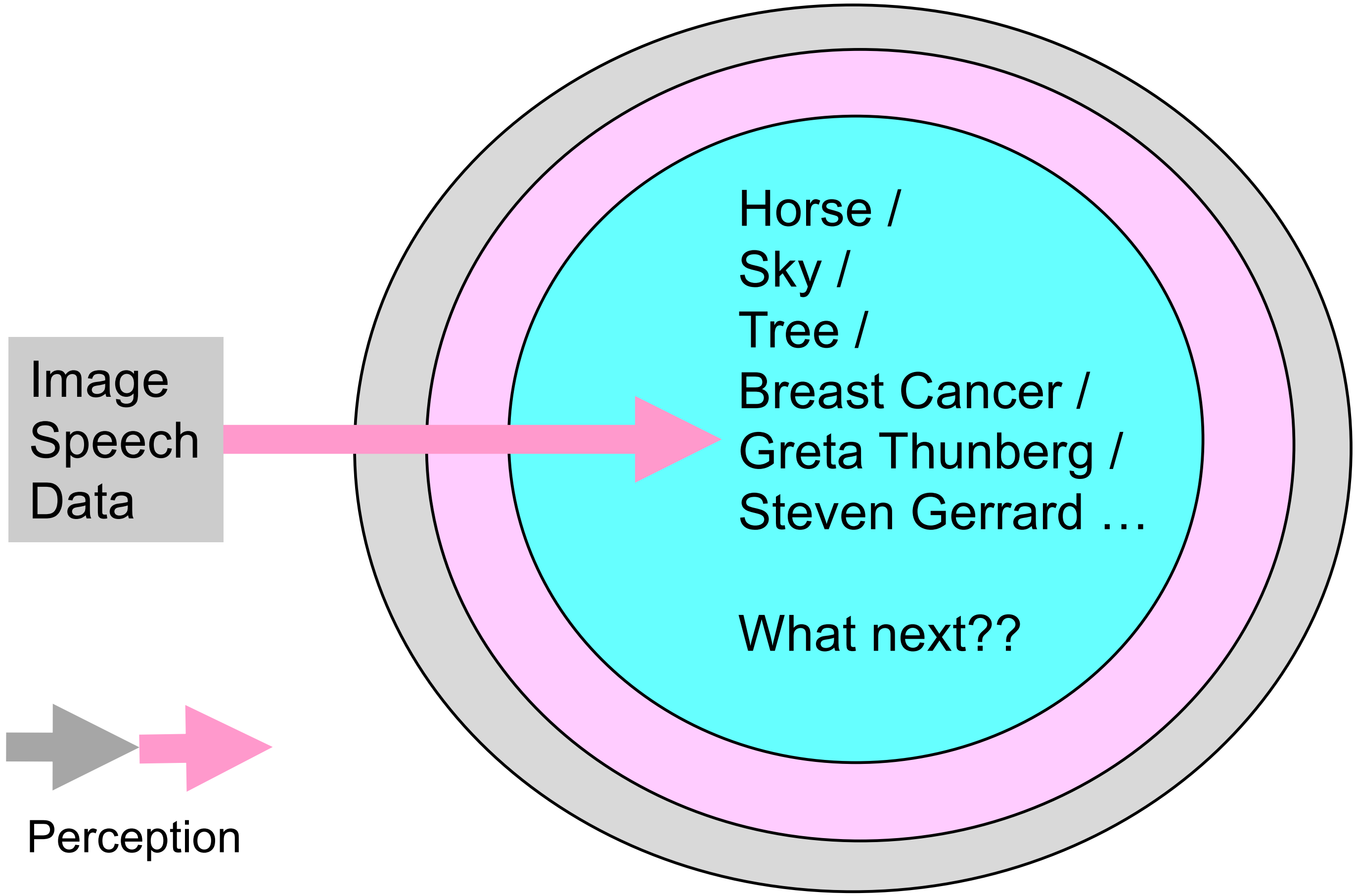
Deep Neural Networks



A symbol is a *perceptible something* that stands for something else.

It has no intrinsic meaning.

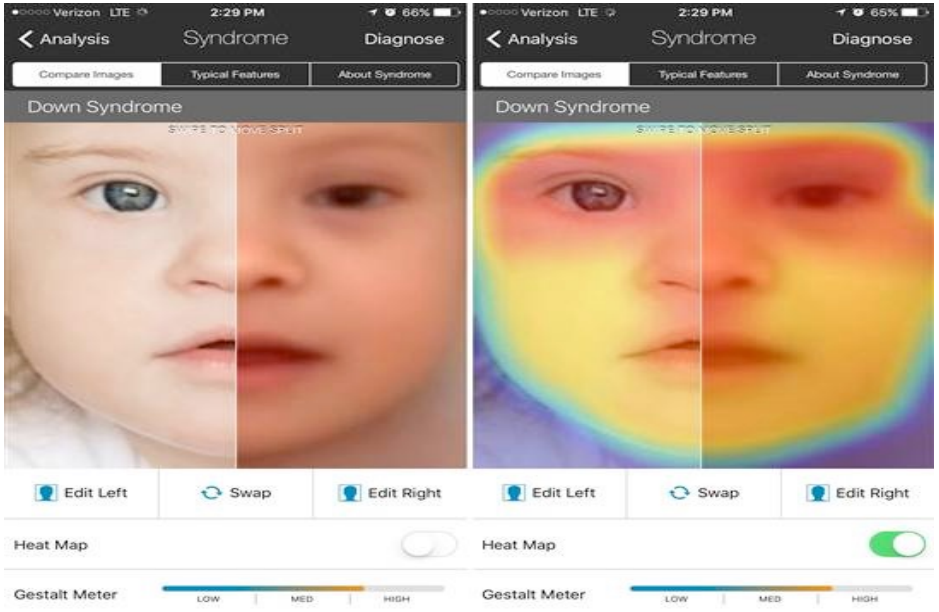
Classification / Face Recognition / …



How Machine Learning Is Revolutionizing the Diagnosis of Rare Diseases

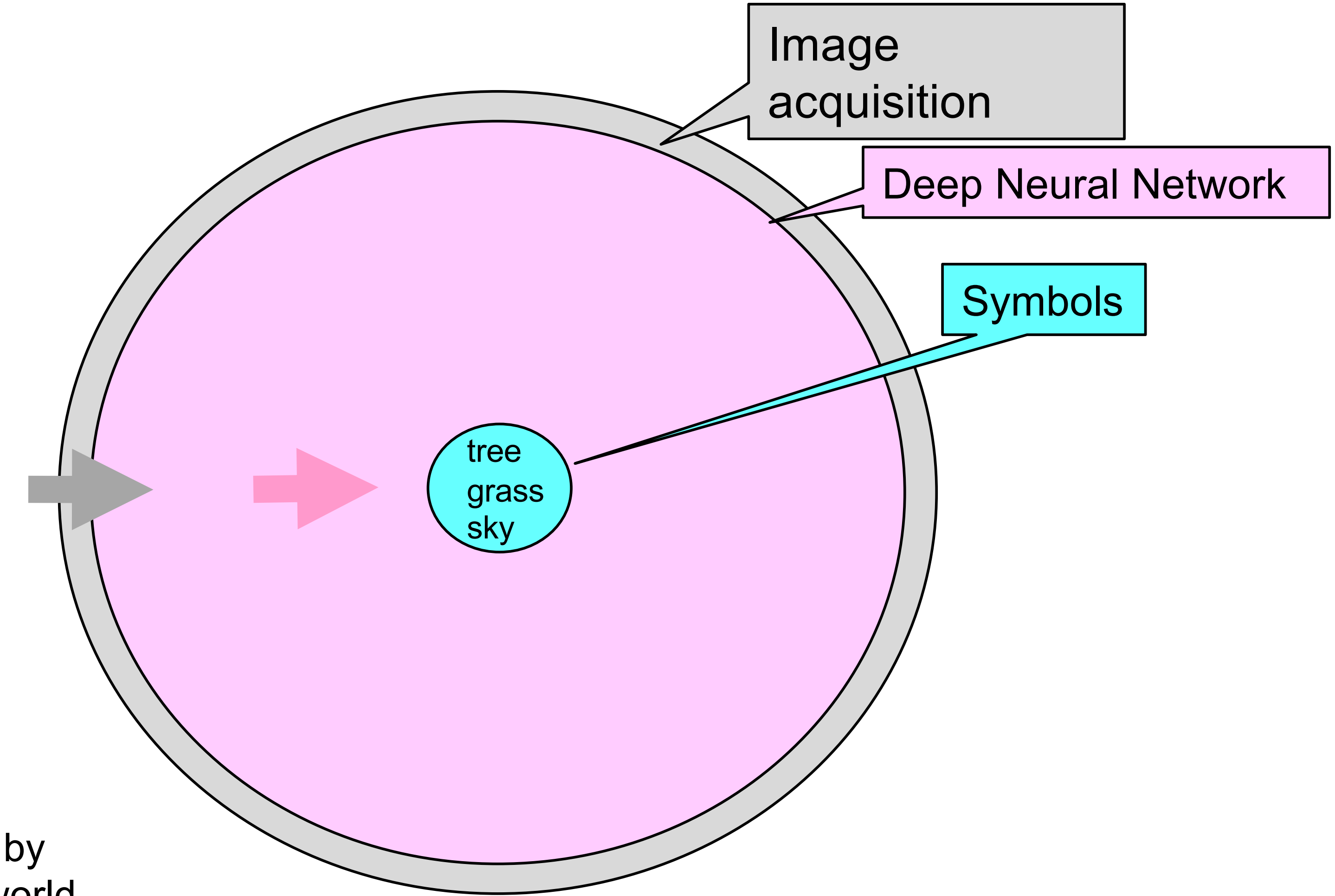
Facial recognition app Face2Gene is being used by doctors to diagnose rare diseases.
Within a matter of seconds, the app generated a list of potential diagnoses — and corroborated his hunch. “Sure enough, Mowat-Wilson syndrome came up on the list,” Abdul-Rahman recalls.

Courtesy FDNA



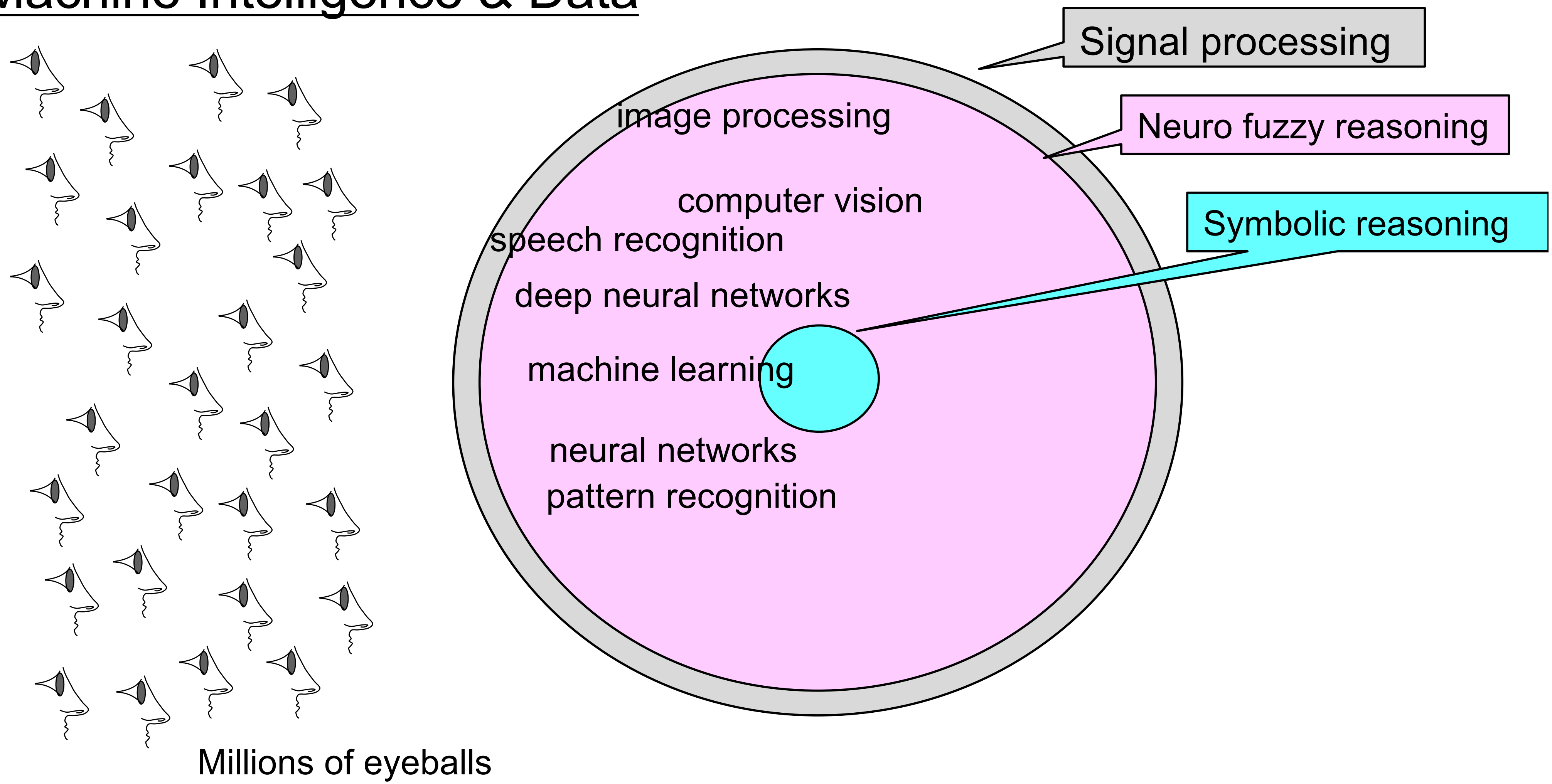
Jane C. Hu
http://www.nbcnews.com/storyline/the-big-questions/how-machine-learning-revolutionizing-diagnosis-rare-diseases-n700901

Image labeling



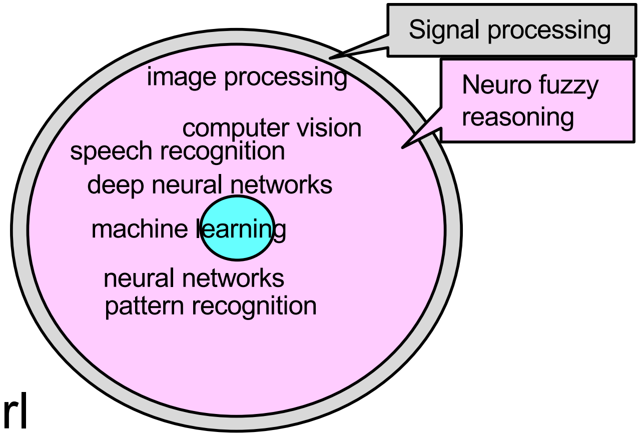
These algorithms are also used for facial recognition by governments around the world.

Machine Intelligence & Data



Animal–Like Abilities

"Everything ML does now,
humans do in the blink of an eye"



- "Eagles and snakes have better vision systems"
  - Judea Pearl
- Cats have superior navigation abilities
- Dogs recognize and react to human speech
- African grey parrots can mimic human speech

Yet, none of these animals have
the cognitive abilities and the intelligence
typically attributed to humans.

Adnan Darwiche, Human-Level Intelligence or Animal-Like Abilities, CACM, Vol. 61, No. 10, Oct 2018.

Performance vs. Competence

Now suppose a person tells us that a particular photo shows people playing Frisbee in the park. We naturally assume that this person can answer questions like *What is the shape of a Frisbee? Roughly how far can a person throw a Frisbee? Can a person eat a Frisbee? …*

Computers that can label images like “people playing Frisbee in a park” have no chance of answering those questions…

…they have *no idea* what a person is, that parks are usually outside, that people have ages, that weather is anything more than how it makes a photo look, etc.

Rodney Brook, The Seven Deadly Sins of AI Predictions.
MIT Technology Review

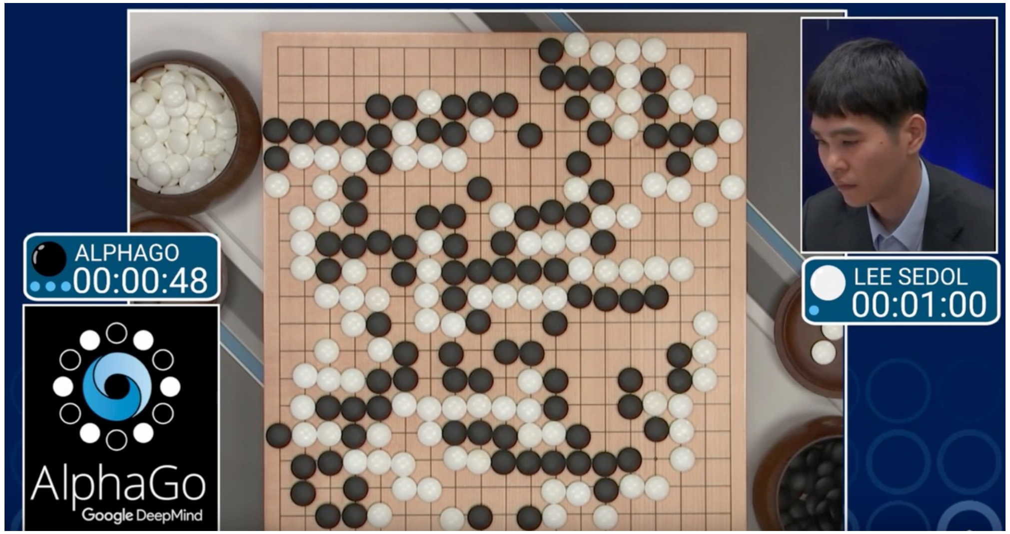
Suitcase Words

Marvin Minsky called words that carry a variety of meanings "suitcase words." "Learning" is a powerful suitcase word; it can refer to so many different types of experience…

When people hear that machine learning is making great strides in some new domain, they tend to use as a mental model the way in which a person would learn that new domain. However, machine learning is very brittle, and it requires lots of preparation by human researchers or engineers, special-purpose coding, special-purpose sets of training data, and a custom learning structure for each new problem domain.

Rodney Brook, The Seven Deadly Sins of AI Predictions.
MIT Technology Review

AlphaGo beats World Champion at Go in 2016



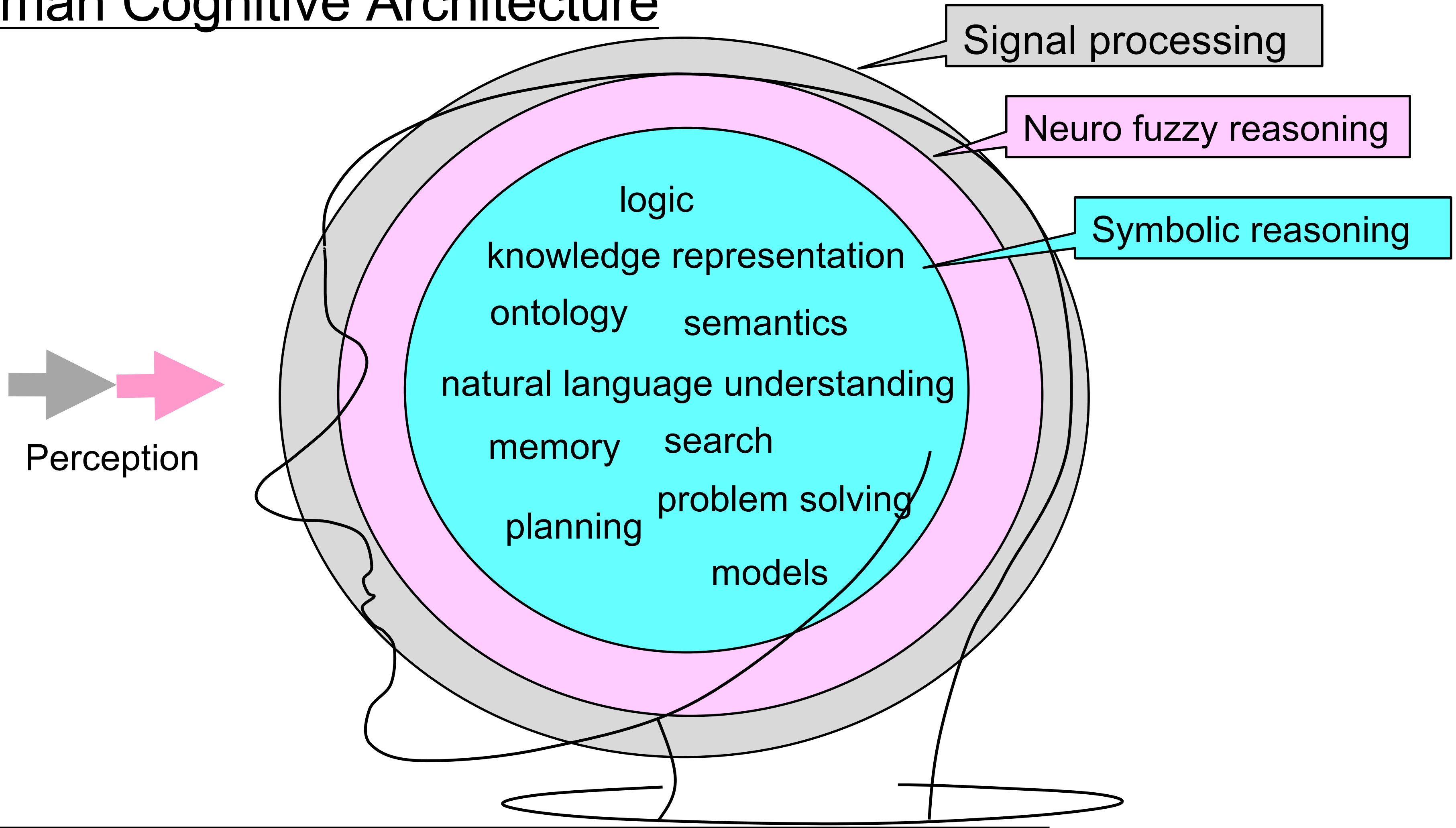
from this Popular Mechanics article

The triumph of reinforcement learning in games like chess and Go.

More on such games later in the course.

This website has more on AlphaGo and a link to a gripping film on the 2016 match and its build up.

Human Cognitive Architecture



Artificial Intelligence & Machine Learning

- AI – symbolic knowledge representation and problem solving
- ML – making sense of data
  - Data → Information
    (big data, recomender systems, predictive analytics….)
  - Data → Classification
    (deep learning, images and language….)

Knowledge and Reasoning – The Core of Intelligence

What does the agent **know***
and

what **else** does the agent **know** as a **consequence** of what it knows?

* We are concerned with explicit declarative knowledge
and not implicit procedural or tacit knowledge

Representation

Semiotics: A symbol is something that stands for something else

Examples.

- The "number" seven can be represented in many different ways.
- Road signs – curves, pedestrian crossing, schools, U-turns, eating places…
- The meaning of the symbol is a socially agreed upon construct.
  - Shakespeare: A rose by any other name will smell as sweet

All languages, both spoken and written, are semiotic systems

Biosemiotics: How complex behaviour emerges when simple systems interact with each other through signs.

For example, pheromone trails left by ants

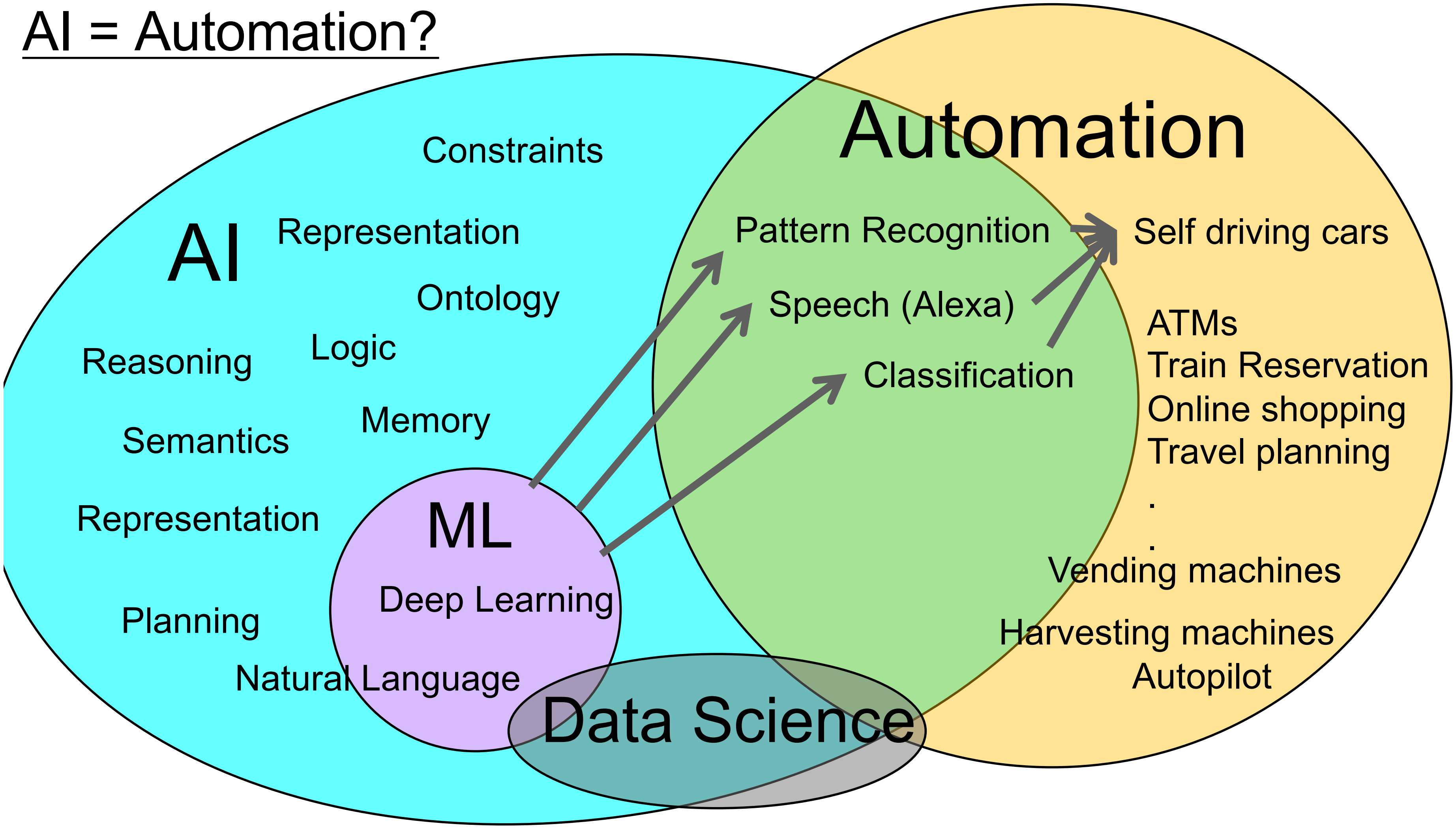
Reasoning

The manipulation of symbols in a *meaningful* manner.

Maths is replete with *algorithms* we use –

- Addition and multiplication of multi-digit numbers
- Long division
- Solving systems of linear equations
- Fourier transforms, convolution…

AI = Automation?



Artificial Intelligence: History and Philosophy

History and Philosophy of AI

The two books mentioned below give an insightful and entertaining account of the history and philosophy of AI.

"AI: The Very Idea"
by John Haugeland
http://philosophy.uchicago.edu/faculty/haugeland.html

"Machines Who Think"
by Pamela McCorduck
http://www.pamelamc.com/html/machines_who_think.html

Some definitions

We call programs intelligent if they exhibit behaviors that would be regarded intelligent if they were exhibited by human beings.
– Herbert Simon

Physicists ask what kind of place this universe is and seek to characterize its behavior systematically. Biologists ask what it means for a physical system to be living. We in AI wonder what kind of information-processing system can ask such questions.
– Avron Barr and Edward Feigenbaum

AI is the study of techniques for solving exponentially hard problems in polynomial time by exploiting knowledge about the problem domain.
– Elaine Rich

AI is the study of mental faculties
through the use of computational models.
– Eugene Charniak and Drew McDermott

Machines with Minds of their Own

"The fundamental goal of Artificial Intelligence research is not merely to mimic intelligence or produce some clever fake. Not at all.

"AI" wants the genuine article: machines with minds, in the full and literal sense.

This is not science fiction, but real science, based on a theoretical conception as deep as it is daring: namely, we are at root, computers ourselves.

That idea – the idea that thinking and computing are radically the same – is the idea of this book."

John Haugeland in "AI: The Very Idea"

Some fundamental questions

What is intelligence?

What is thinking?

What is a machine?

Is the computer a machine?

Here on when we say machine we will mean a programmable computer system

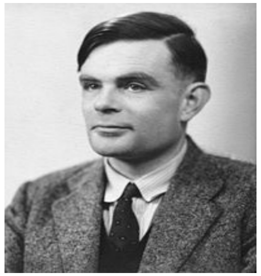
Can a machine think ?

If yes are we machines?!

The raging debates over *thinking machines*

- Herbert Dreyfus: "..intelligence depends upon unconscious instincts that can never be captured in formal rules"
  - http://en.wikipedia.org/wiki/Dreyfus%27_critique_of_artificial_intelligence
- John Searle: The Chinese Room argument – can an agent locked in a room processing questions in Chinese based on a set of syntactic rules be said to *understand* Chinese?
  - How many rules will the agent need to have for the thought experiment to be convincing?
- Roger Penrose: "..there is something (quantum mechanical) going on in our brains that current day physics cannot explain"
- Other arguments based on Emotion, Intuition, Consciousness, Ethics etcetera.

Alan Turing's Imitation Game

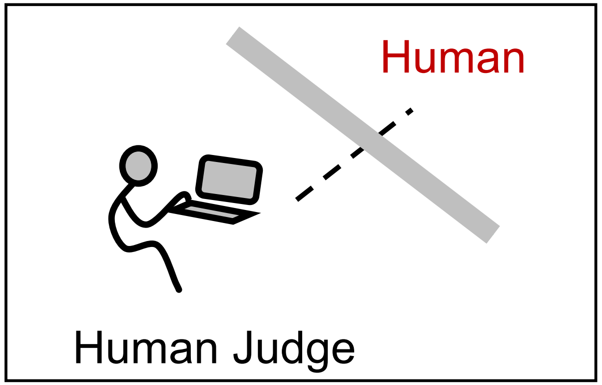


Alan Turing (1912 – 1954)

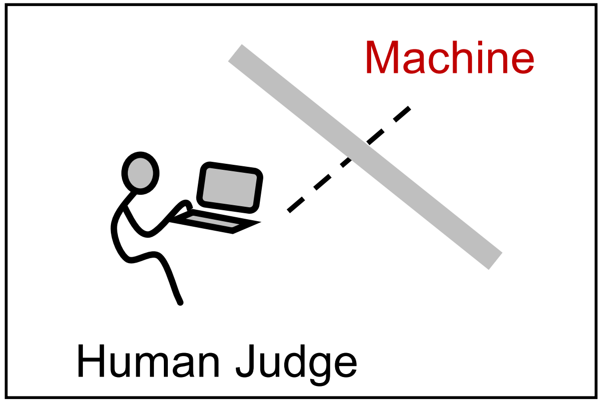
- The question whether machines can think is itself "too meaningless"

http://en.wikipedia.org/wiki/Alan_Turing

- Prescribed a test which he called the *Imitation Game* which is now known as *The Turing Test*
  - Turing, A.M. (1950). Computing machinery and intelligence. Mind, 59, 433-460. http://www.loebner.net/Prizef/TuringArticle.html



or?



The Loebner Prize 2013

Excerpts from the leader in 2013 *Izar*

IZAR TRANSCRIPT

JUDGE: Hello I'm Ronan. What is your name?

IZAR: Ronan! It's about time you contacted me! I was waiting for you! My name is Izar pronounced I zar, but you can call me Izzy if you want. Doing anything fun? Too much recursion in AIML

. . .

JUDGE: I like bananas. Which is your favorite fruit?

IZAR: Tell me more about your unknown. You are not the only one. I don't have a problem with bananas. Is that your favorite fruit? The obvious one. Does that remind you of unknown??

JUDGE: What music do you like?

IZAR: I like many kinds of human music, but recently, I've been getting into Hoomii, a type of Mongolian throat singing. Why? What kind of music do you like?

Nowadays

- Alexa
- Chatbots
- GPT3
- ChatGPT

ELIZA

….named after Eliza Doolittle, a working-class character in George Bernard Shaw's play *Pygmalion*,

ELIZA was a simple natural language processing program written at MIT by Joseph Weizenbaum around 1966.

It had simple rules to manipulate language and would essentially modify the users input to generate its response. A popular version called Doctor was running a script designed to make respond like a Rogerian psychotherapist.

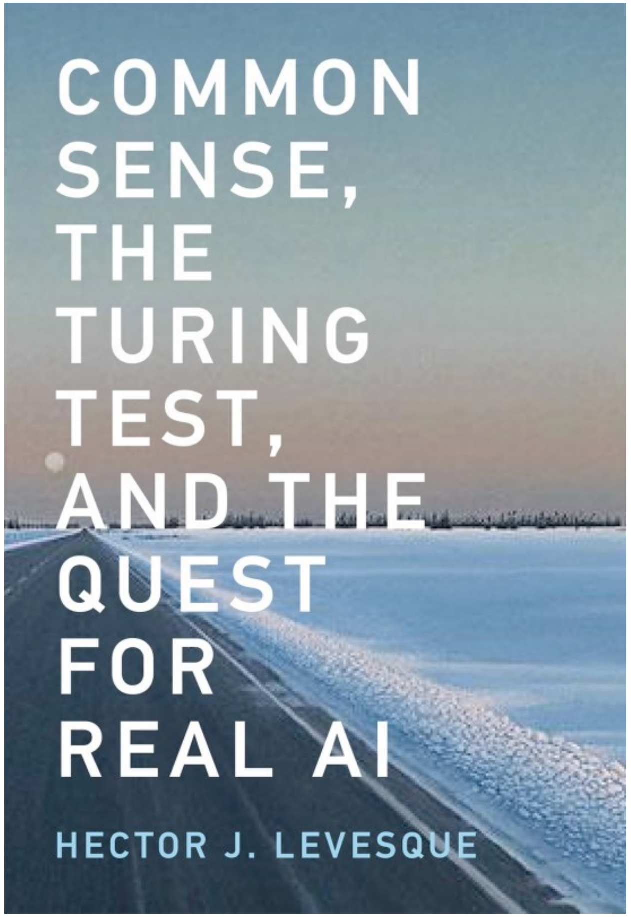
A Russian scientist chatting with Doctor at Stanford

Doctor: What brought you here to see me today?
Visitor: Oh, nothing much. I'm feeling a bit tired, that's all.
Doctor: Why do you think you're feeling a bit tired?
Visitor: Well I've been traveling a lot, and away from home.
Doctor: Tell me about your family.

Weizenbaum found people's responses to the program disturbing and wrote a book highlighting the limitations of a computer!

Computer Power and Human Reason: From Judgment to Calculation

Conversations with machines



Given the advances in web data processing, corpus based natural language processing, and clever distracting techniques - it has become easy to build conversational chat bots that are impressive but lack intelligence.

Hector J. Levesque has recently proposed a new test.

Winograd Schemas – an alternate "Turing Test"

- Winograd schemas ask a pointed multiple choice question that requires knowledge of the subject matter.
- For example, contexts where "give" can appear are statistically quite similar to those where "receive" can appear, and yet the answer must change depending on which one is used.
- This helps make the test *Google-proof:* having access to a large corpus of English text would likely not help much.
- The claim is that doing better than guessing requires subjects to figure out what is going on.

Winograd Schemas: Anaphora Resolution

- A Winograd Schema Challenge question consists of three parts:
- A sentence or brief discourse that contains the following:
  - Two noun phrases of the same semantic class (male, female, inanimate, or group of objects or people),
  - An ambiguous pronoun that may refer to either of the above noun phrases, and
  - A special word and alternate word, such that if the special word is replaced with the alternate word, the natural resolution of the pronoun changes.
- A question asking the identity of the ambiguous pronoun, and
- Two answer choices corresponding to the noun phrases in question.
- A machine will be given the problem in a standardized form which includes the answer choices, thus making it a binary decision problem.

https://en.wikipedia.org/wiki/Winograd_Schema_Challenge

Winograd schema: Example 1

The first schema was given by Terry Winograd himself in 1972. Such sentences are now named after him.

- The city councilmen refused the demonstrators a permit because they *feared* violence.

- The city councilmen refused the demonstrators a permit because they *advocated* violence.

Who does “they” refer to?

Answer 0: The demonstrators

Answer 1: The councilmen

Winograd schema: Example 2 (IJCAI 2016 challenge)

- John took the water bottle out of the backpack so that it would be *lighter*.

- John took the water bottle out of the backpack so that it would be *handy*.

  What does “it” refer to?

1. The backpack
2. The bottle

Winograd schema: Example 3

- The trophy would not fit in the brown suitcase because it was too *small*.
- The trophy would not fit in the brown suitcase because it was too *big*.

What does “it” refer to?

1. The trophy
2. The suitcase

Winograd schema: Example 4

- The lawyer asked the witness a question, but he was reluctant to *repeat* it.
- The lawyer asked the witness a question, but he was reluctant to *answer* it.

Who was reluctant?

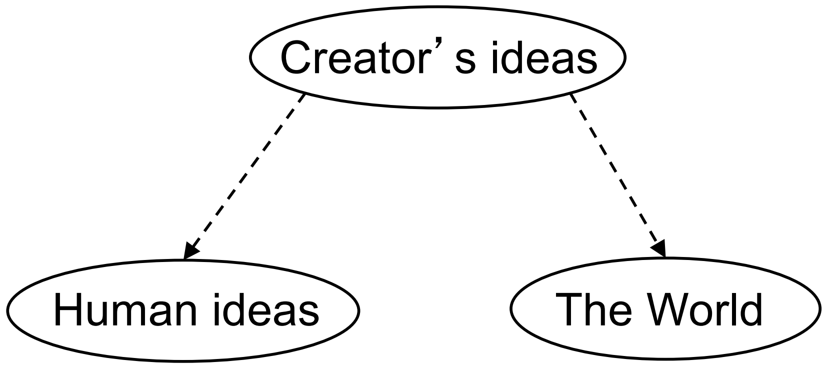
1. The lawyer
2. The witness

Minds and Machines

The European medieval world view

A Christian adaption of Greek ideas

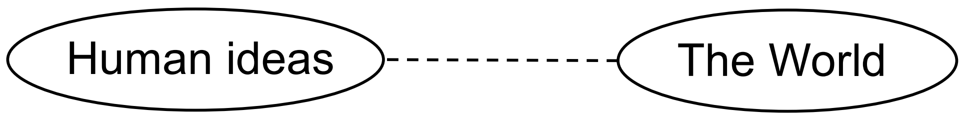
Platonic



Corruptible materializations of God's ideas

Our thoughts are *true* to the extent they are accurate copies of God's ideas

Aristotelian

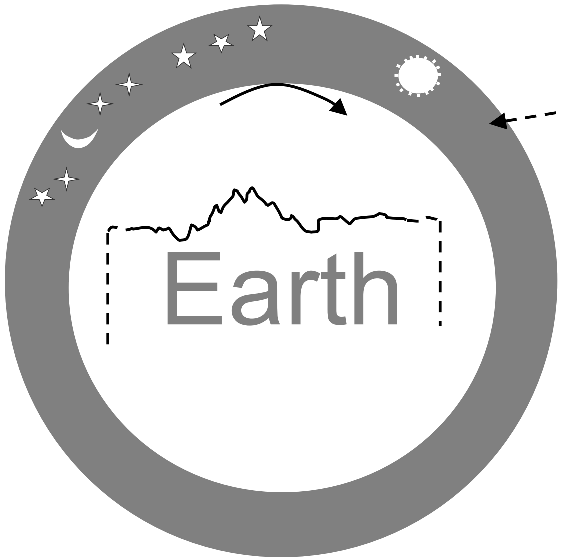


Our thoughts *resemble* the objects they stand for

Correspondence theory of truth

… Ludwig Wittgenstein: Picture Theory of Language

Our world as we saw it



Our Earth was flat and at the center of the Universe, with the God's heaven rotating around it.

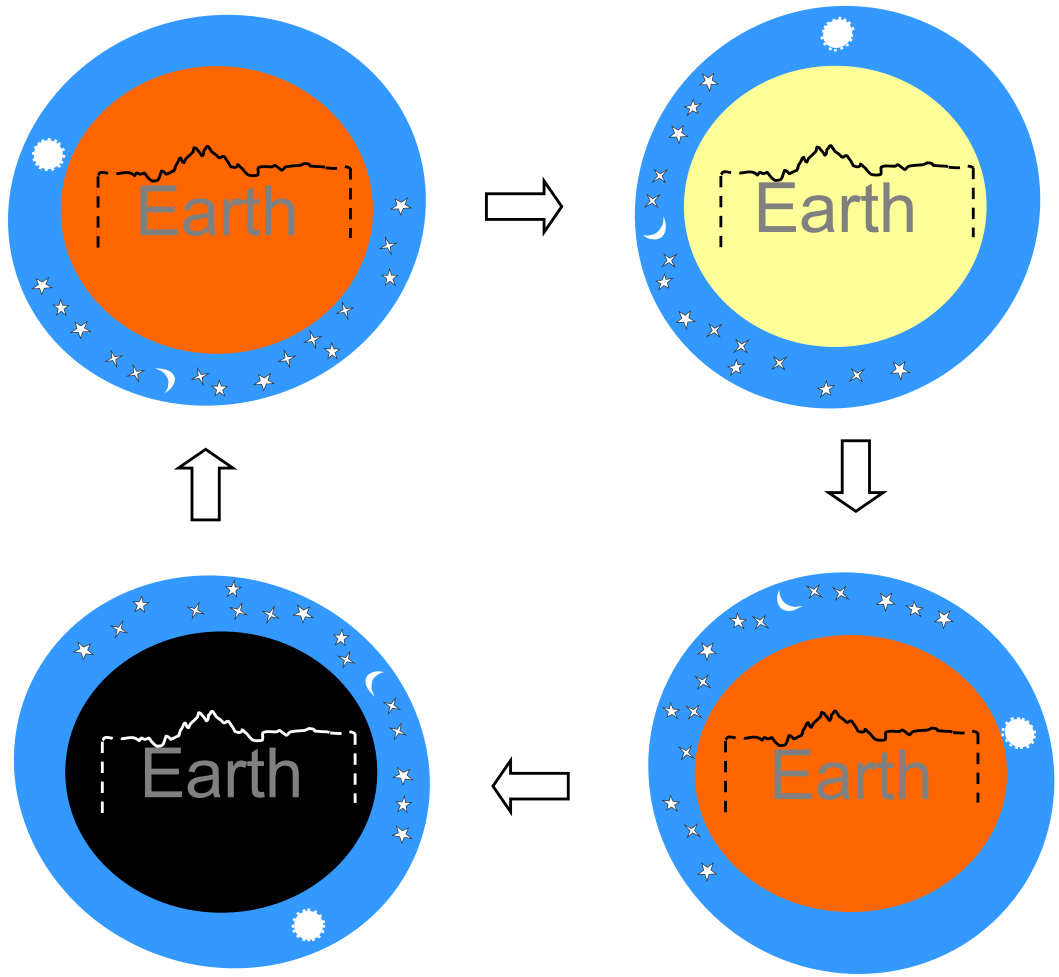
Sensible world composed of 5 elements

- quintessence
- fire
- air
- water
- earth

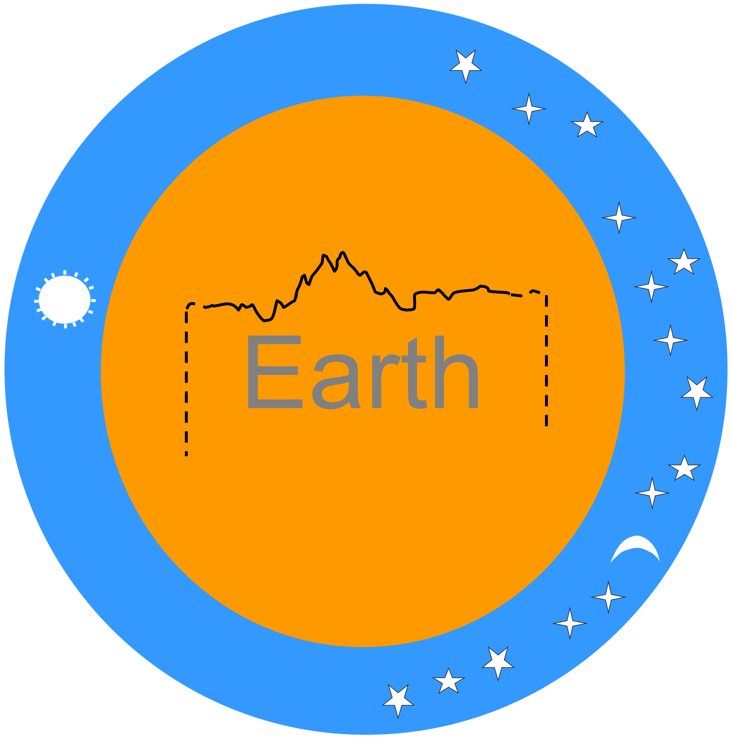
heavier

Jumbled up on Earth striving to separate and go their rightful place

Night & Day



Geocentric model of the Universe



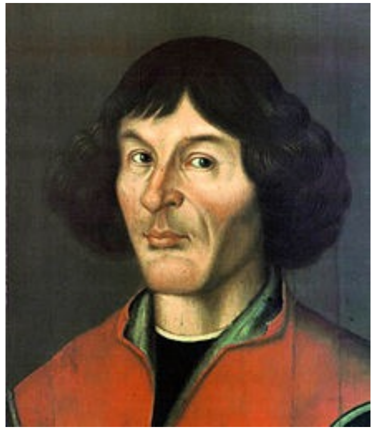
Astronomy was the most advanced empirical science, and observations like the **motion of planets** in the sky was specially **hard to explain** with the geocentric model.

"If God had consulted me when creating the universe, He would have received good advice!"

King Alfonso X of Spain (1221 – 1284)

What we see is not what really is…

It is the rotating Earth that creates the illusion of the Sun, the moon and the stars moving in the sky. (*On the Revolutions of the Celestial Spheres*)



Nicolaus Copernicus
Portrait, 1580, Toruń Old Town City Hall
Born 19 February 1473
Toruń (Thorn), Royal Prussia,
Kingdom of Poland

Source: http://en.wikipedia.org/wiki/Nicolaus_Copernicus

Reality

What is really out there?

What is the objective reality?

One thing is clear

Everything in the physical world is made up of a small number of fundamental particles

(even though we don't quite know yet what they are)

unless there is no matter at all (idealism)

The laws of physics that explain the behaviour of these particles are sufficient to explain the behaviour of ensembles of such particles

But…

Complexity

A human adult is made up of about 10^{27} atoms

These 10^{27} atoms continuously interact with zillions of surrounding atoms all the time

The air we breathe, the food we eat, the vibrations of air molecules we *sense as sound,* and impinged upon by trillions of photons (which have momentum but no mass).

Can we even hope to write down equations for these and solve them?

And what would we get if we did solve them?

A prediction of their location and movement?

Remember there are 10^{27} of them

The World in our Minds

The world around us and including us operates according to and can, in principle, be explained by the fundamental laws of physics. Nothing else is needed.

But we the thinking creatures create our own worlds in our minds. And it is only our own creation that is meaningful to us.

Idea embodied in movies: Matrix, Inception…

Powers of Ten

A Film by Charles and Ray Eames (1977)
http://www.powersof10.com/film

Source: Quarks to Quasars
http://www.wordwizz.com/pwrsof10.htm

100 yottameter – 10^{26} meters – The Visible Universe (about 10 billion light years across)
1 yottameter – 10^{24} meters – a cluster of galaxies (about 100 million light years across)
1 zettameter – 10^{21} meters – diameter of The Milky Way (about 100,000 light years across)
100 petameters – 10^{17} meters – the nearest stars (about 10 light years away)
10 terameters – 10^{13} meters – diameter of Solar system (11,826,600,000 km)
1 terameter – 10^{12} meters – distance from Saturn to Sun (1,429,000,000 km)
100 gigameters – 10^{11} meters – distance from Earth to Sun (149,600,000 km)
100 megameters – 10^{8} meters – the diameter of Jupiter (139,822 km)
10 megameters – 10^{7} meters – the diameter of Earth (12,756 km)
1 megameter – 10^{6} meters – the distance from Chennai to Pune (1190 km)
100 kilometers – 10^{5} meters – the distance from Mandi to Manali (110 km)
10 kilometers – 10^{4} meters – the diameter of a small town
1 kilometer – 10^{3} meters – longest span of the Golden Gate Bridge (1,280 m)
100 meters – 10^{2} meters – a sprint track, a meadow, a pond, a skyscraper
10 meters – 10^{1} meters – the width of a road, a small house, a tree
1 meter – 10^{0} meters – a typical door, a table, the height of a child
10 centimeters – 10^{-1} meters – a sunbird, a typical mango, a cellphone
1 millimeter – 10^{-3} meters – a mustard seed
100 micrometers – 10^{-4} meters – pollen
10 micrometers – 10^{-5} meters – a bacterium
100 nanometers – 10^{-7} meters – a virus
1 nanometer – 10^{-9} meters – the structure of DNA
100 picometers – 10^{-10} meters – carbon's outer shell – 1 Angstrom unit
1 picometer – 10^{-12} meters – the electron cloud – electromagnetism
10 femtometers – 10^{-14} meters – the carbon nucleus
1 femtometer – 10^{-15} meters – a proton
10 attometers – 10^{-17} meters – quarks and gluons

Our Perceptible Universe

100 yottameter – 10^{26} meters – The Visible Universe (about 10 billion light years across)
1 yottameter – 10^{24} meters – a cluster of galaxies (about 100 million light years across)
1 zettameter – 10^{21} meters – diameter of The Milky Way (about 100,000 light years across)
100 petameters – 10^{17} meters – the nearest stars (about 10 light years away)
10 terameters – 10^{13} meters – diameter of Solar system (11,826,600,000 km)
1 terameter – 10^{12} meters – distance from Saturn to Sun (1,429,000,000 km)
100 gigameters – 10^{11} meters – distance from Earth to Sun (149,600,000 km)
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Scientific progress enables us to extend our concepts to different scales

Scientific progress enables us to extend our concepts to different scales

The Domains for Reasoning

While the real world that we want to reason about is indeed made up of collections of fundamental particles,
those fundamental particles, whatever they are,
cannot be the elements of the domain
that we use for representation and reasoning.

This is simply because there are far too many of them,
even to describe a grain of rice.

Instead, depending upon the focus of study,
one can represent atoms, or molecules, or biological cells,
or animal organs, or living creatures,
or societies of living creatures.

Every domain of study defines it own ontology.

Domains of Study: Each has its own vocabulary

100 yottameter – 10^{26} meters – The Visible Universe (about 10 billion light years across)
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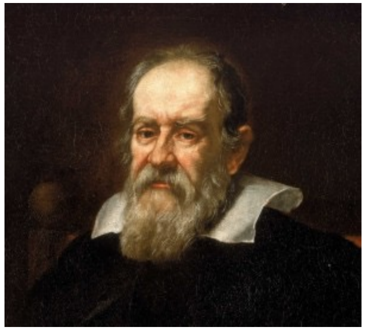
Cosmology
Astronomy
Astrophysics
Newtonian physics
Geography
Geology
Sociology
Economics
Psychology
Newtonian physics
Physiology
Biology
Cellular biology
Chemistry
Sub-atomic physics

Perception is an Internal Process



"I think that tastes, odors, colors, and so on are no more than mere names so far as the object in which we locate them are concerned, and that they reside in consciousness. Hence if the living creature were removed, all these qualities would be wiped away and annihilated"
—Galileo Galilei, *The Assayer* (published 1623).

Galileo Galilei
Born15 February 1564
Pisa, Duchy of Florence, Italy

"Philosophy is written in this grand book, the universe ... It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures;....

Galileo showed that geometry could be used to represent and reason about motion.

Source: http://en.wikipedia.org/wiki/Galileo_Galilei

Thomas Hobbes: The Grandfather of AI

It was the English philosopher Thomas Hobbes (1588-1679) who first put forward the view that thinking is the manipulation of symbols.

Galileo had said that all reality is mathematical in the sense that everything is made up of particles, and our sensing of smell or taste was how we reacted to those particles.

Hobbes extended this notion to say that thought too was made up of (expressed in) particles which the thinker manipulated.

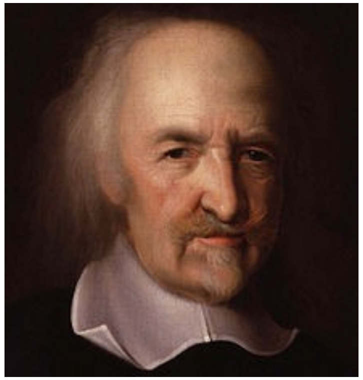
Hobbes was influenced by Galileo. Just as geometry could represent motion, thinking could be done by manipulation of mental symbols.

John Haugeland, AI: The Very Idea, 1985

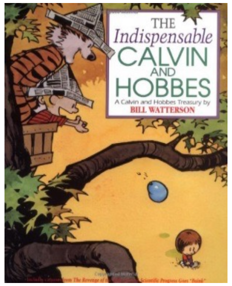
Reasoning = Computation

"By reasoning", he says "I understand computation. And to compute is *to collect the sum of many things added together at the same time, or to know the remainder when one thing has been taken from another*. To reason therefore is the same as *to add* or *to subtract*" (Hobbes 1655, 1.2).

Stanford Encyclopedia of Philosophy
http://plato.stanford.edu/entries/hobbes/



Thomas Hobbes
Born 5 April 1588
Westport near Malmesbury, Wiltshire, England



Bill Watterson named the character Hobbes after him.

Thoughts = Symbols

René Descartes (1596 –1650)

Animals are wonderful *machines*.
Human beings are too,
except that they possess a *mind*.

Born 31 March 1596
La Haye en Touraine,
Kingdom of France

Galileo: Motion → Geometry
Descartes: Geometry → Algebra

Everything is "applied math"
… even "thought"

Descartes: Thoughts themselves are symbolic representations

John Haugeland, AI: The Very Idea, 1985 http://en.wikipedia.org/wiki/Rene_Descartes

Dualism: Mind and Body

Decartes: A $\boxed{\text{symbol}}$ and $\boxed{\text{what it symbolizes}}$ are two different things

algebraic manipulation = thinking

subject of thought

mind ≠ world

What makes a notation suitable for symbolizing?
What makes a suitable notation $\boxed{\text{actually symbolize}}$?

How can thought and matter interact?

mind-body problem

John Haugeland, AI: The Very Idea, 1985

The Paradox of Mechanical Reason

For some more recent thoughts on this question see

Hofstadter: *Godel, Escher, Bach*

Hofstadter & *Dennet: The Mind's I*

Hofstadter: *I am a Strange Loop*

IF
Reasoning is the manipulation of meaningful symbols according to rational rules
THEN
Who is manipulating the symbols?

It can be either mechanical or meaningful but how can it be both?

How can a mechanical manipulator pay attention to meaning?

faculty of will?

transcendental ego?

or

the *humunculus*? A little man?

John Haugeland, AI: The Very Idea, 1985

Artificial People (Western mythology and fiction)

- In Homer’s *Illiad* Hephaestus
  - created Talos, a man of bronze to patrol the beaches of Crete
  - created Pandora who, commissioned by Zeus to punish mankind for accepting Prometheus’s gift of fire, overcome by curiosity opens the infamous casket

- Pygmalion, disappointed by real women, created Galatea in ivory, and Aphrodite obliges him by breathing life into Galatea

- Daedalus is credited with creating lifelike statues that wheezed and blinked, and scuttled about, impressing everyone.

- Pope Sylvester II (946 – 1003) is said to have made a statue with a talking head, with a limited vocabulary, and a penchant for predicting the future; on being asked a query about the future it would reply yes or no

Artificial People (continued)

http://en.wikipedia.org/wiki/Paracelsus

Paracelsus (1493 –1541) a prominent physician is said to have invented a *humunculus*, a little man.

"We shall be like gods … we shall duplicate God's greatest miracle – the creation of man"

Paracelsus:
Born 11 Nov or 17 Dec
Philip von Hohenheim
Egg, near Einsiedeln, Old Swiss Confederacy
(present-day Switzerland)

Judah Loew ben Bezalel (1520 –1609) is reported to have sculpted a living man from clay, named *Golem*, to defend the Jews of Prague. He alone could instruct him.

In Jewish folklore, a golem is an animated anthropomorphic being, created entirely from inanimate matter.

http://en.wikipedia.org/wiki/Golem

Real Mechanisms

In 802 A.D. the Emperor Haroun-al-Rashid is said to have presented Emperor Charlemagne with an elaborate clock which sent out a dozen cavaliers from a dozen windows each noon and sent them back again.

By the middle of the fourteenth century, large elaborate clocks with moving figures had become public monuments – Strasbourg, Nurnberg, Lubeck and Berne followed the Italian cities with them – and talking brass heads had become closely associated with learned men.

The Archbishop of Salzburg built a working model of a complete miniature town, all operated by water power from a nearby stream

Real Mechanisms

A group of Arab astrologers is credited with constructing a thinking machine called the *zairja* which was designed "to generate ideas by mechanical means.. with the help of the technique called the technique of 'breaking down'" (i.e. *al-jabr* → algebra). By combining number values associated with the letters and categories, new paths of insight and thought were created."

https://en.wikipedia.org/wiki/Zairja

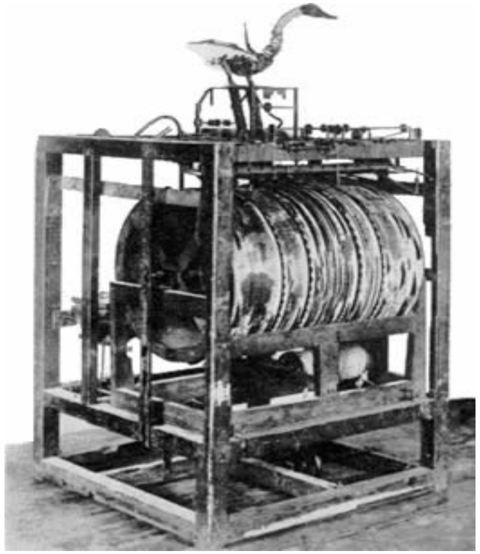
The Zairja, from http://zairja.org/quienes-somos

The *zairja* caught the imagination of the Catalonian missionary Ramon Lull (1232 – 1315) who decided to build a Christian version called the Ars Magna – *"to bring reason to bear on all subjects and, and in this way, arrive at truth without the trouble of thinking or fact finding"*

- Pamela McCorduck in *Machines Who Think*

Vaucanson's Duck

Jacques de Vaucanson (1709 – 1782) was a French inventor and artist who created several mechanical automata.



His most famous creation was the duck created in 1739. The mechanical duck ("*Who drinks, eats, quacks, splashes about on water, and digests his food*…") appeared to have the ability to eat kernels of grain, and to metabolize and defecate them. While the duck did not actually have the ability to do this—the food was collected in one inner container, and the pre-stored feces was 'produced' from a second, so that no actual digestion took place—Vaucanson hoped that a truly digesting automaton could one day be designed.

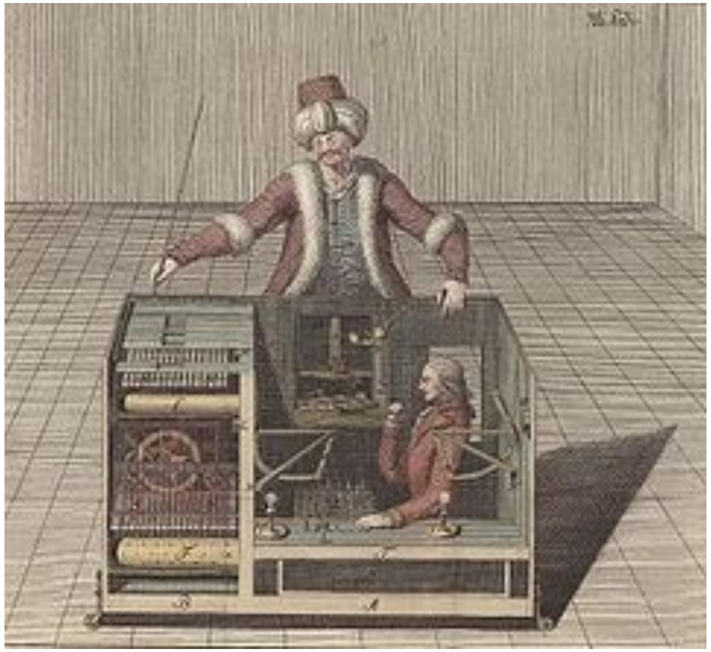
Source: http://en.wikipedia.org/wiki/Digesting_Duck

Von Kempelen's Chess Playing Turk

Wolfgang von Kempelen (1734 – 1804) is most well known for chess playing machine also known as the *Mechanical Turk.* Constructed and unveiled in 1770 by von Kempelen to impress the Empress Maria Theresa of Austria, the mechanism appeared to be able to play a strong game of chess against a human opponent, as well as perform the knight's tour.

The Turk was in fact a mechanical illusion that allowed a human chess master hiding inside to operate the machine, defeating many challengers including statesmen such as Napoleon Bonaparte and Benjamin Franklin.

Edgar Allan Poe wrote an essay "Maelzel's Chess Player" (1836) exposing the fraudulent automaton chess player.



Source: http://en.wikipedia.org/wiki/The_Turk

Mechanical Arithmetic

Blaise Pascal (1623 –1662) invented the mechanical calculator using lantern gears in 1642. He went through 50 prototypes before presenting his first machine to the public in 1645.

Called *Arithmetic Machine, Pascal's Calculator* and later *Pascaline*, this calculating machine could add and subtract two numbers directly and multiply and divide by repetition.

Born: 19 June 1623
Clermont-Ferrand,
Auvergne, France

By 1654 Pascal had sold about twenty machines, but the cost and complexity of the Pascaline was a barrier to further sales, and production ceased in that year.

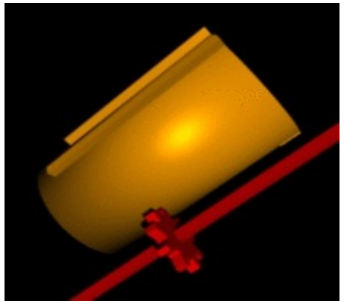
Source: http://en.wikipedia.org/wiki/Pascal%27s_calculator

The Stepped Reckoner

http://en.wikipedia.org/wiki/Gottfried_Leibniz

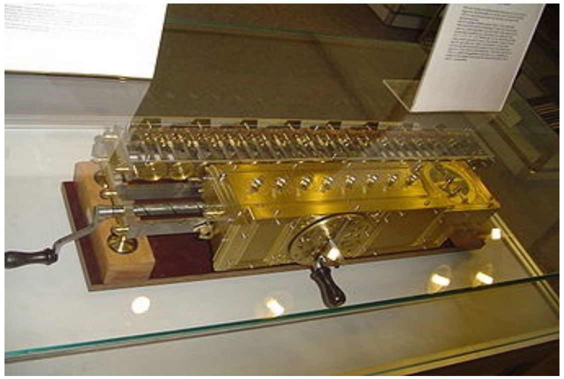
Born: July 1, 1646
Leipzig,
Electorate of Saxony,
Holy Roman Empire

Gottfried Wilhelm von Leibniz (1646 –1716) was a German mathematician and philosopher. He started to work on his own calculator after Pascal's death.



First he invented the Leibniz wheel or stepped drum in 1673, which was used for three centuries until the advent of the electronic calculator in the mid-1970s.

The Stepped Reckoner was a digital mechanical calculator invented by Leibniz around 1672 and completed in 1694. The machine performs multiplication by repeated addition, and division by repeated subtraction with 8 digit numbers.



Source: http://en.wikipedia.org/wiki/Stepped_Reckoner

Leibniz: *Calculus Ratiocinator*

Leibniz believed that much of human reasoning could be reduced to calculations of a sort, and that such calculations could resolve many differences of opinion:

"*The only way to rectify our reasonings is to make them as tangible as those of the Mathematicians, so that we can find our error at a glance, and when there are disputes among persons, we can simply say: Let us calculate [calculemus], without further ado, to see who is right.*"

Commercial success

The *Arithmometer* or *Arithmomètre* was the first mechanical calculator strong enough and reliable enough to be used daily in an office environment.

Patented in France by Thomas de Colmar in 1820 and manufactured from 1851 to 1915.

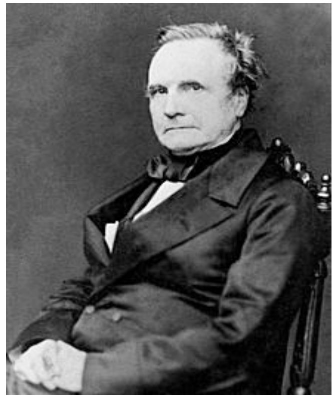
Its sturdy design made it a key player in the move from human computers to calculating machines that took place during the second half of the 19th century.

Source: http://en.wikipedia.org/wiki/Arithmometer

The First Computer

Charles Babbage (1791 – 1871) was a mathematician, philosopher, inventor and mechanical engineer, who is best remembered now for originating the concept of a programmable computer

As a child he was much impressed by the automata displayed by a man called Merlin. He described them as "*One walked, used an eye-glass occasionally, and bowed frequently; her motions were singularly graceful. The other was a dancer, full of imagination and irresistible.*"



Born: 26 Dec. 1791
London, England

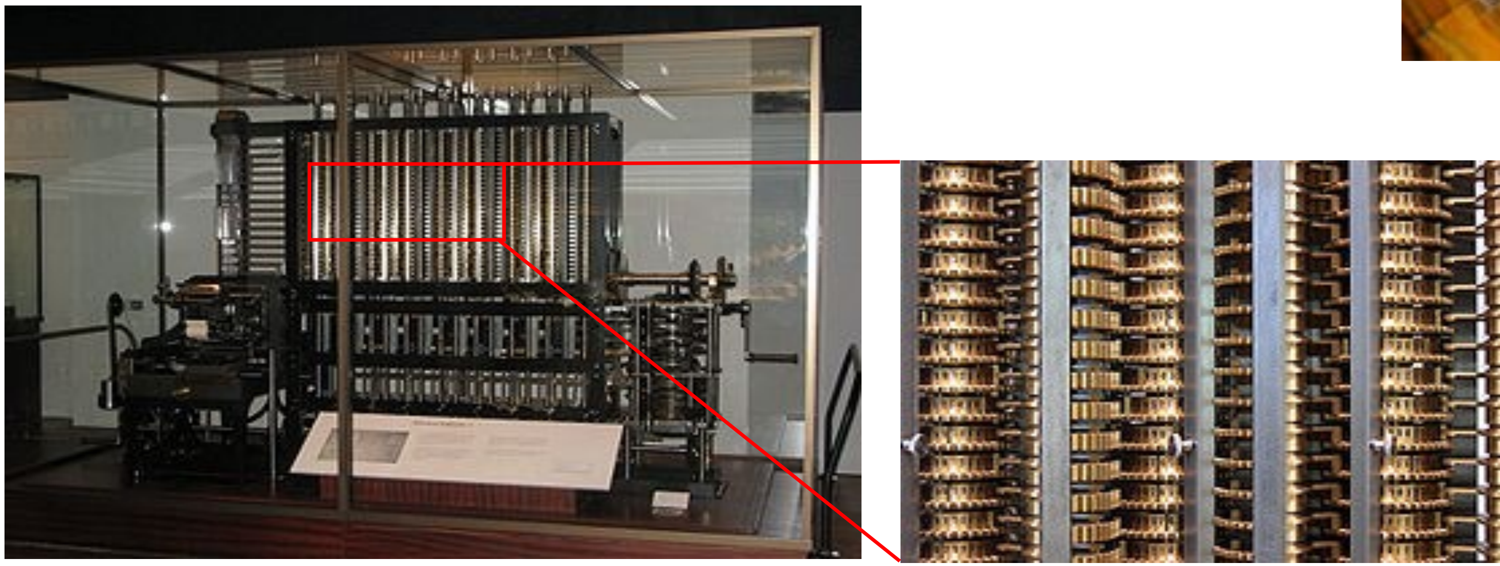
He began in 1822 with what he called the difference engine, made to compute values of polynomial functions. Babbage's difference engine was created to calculate a series of values automatically. The first difference engine was composed of around 25,000 parts, weighed fifteen tons (13,600 kg), and stood 8 ft (2.4 m) high.

Source: http://en.wikipedia.org/wiki/Charles_Babbage

The Difference Engine

Part of Babbage's difference engine, assembled after his death by Babbage's son, using parts found in his laboratory.

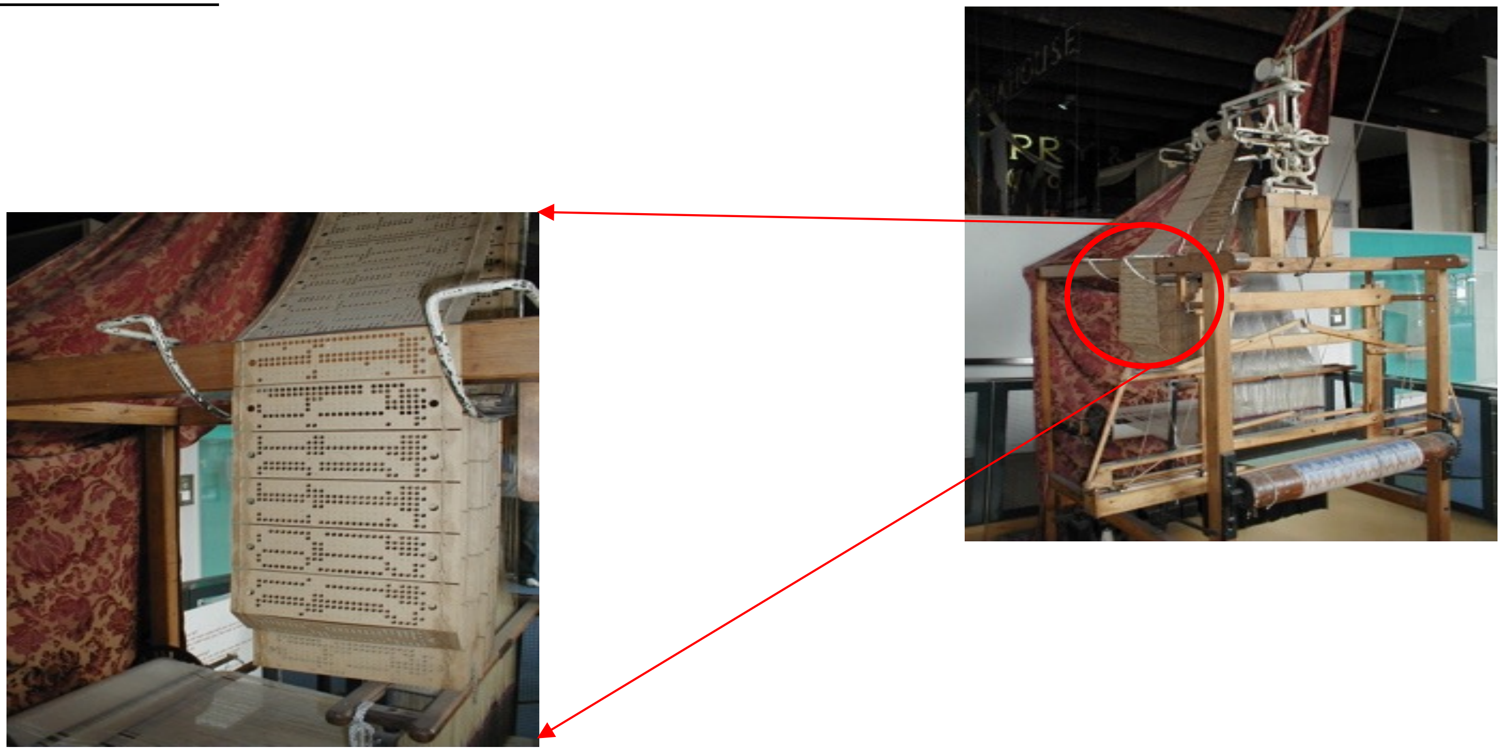
Source: http://en.wikipedia.org/wiki/Charles_Babbage



The London Science Museum's difference engine, built from Babbage's design.

Source: http://en.wikipedia.org/wiki/Difference_Engine

Jaquard Looms



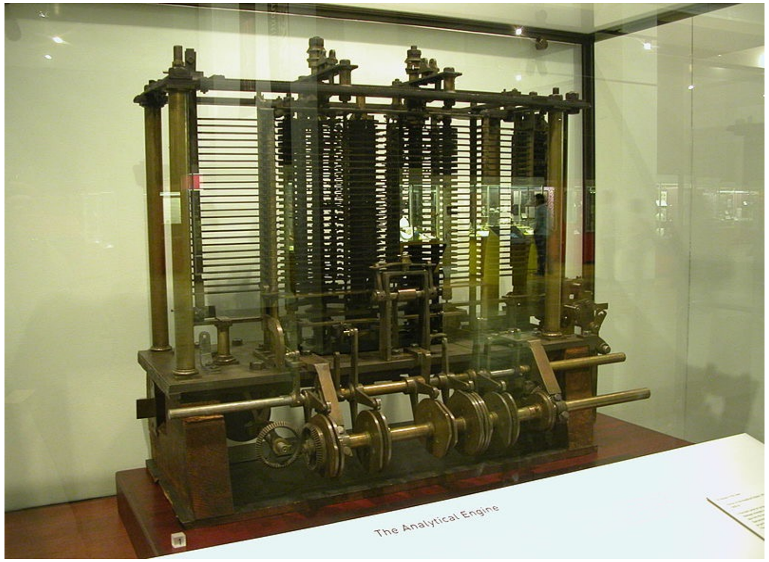
Used *punched cards* to weave *different patterns*

Source: http://en.wikipedia.org/wiki/Jacquard_loom

The Analytic Engine

The Analytical Engine was a proposed mechanical general-purpose computer designed by Charles Babbage

It was first described in 1837 as the successor to Babbage's Difference Engine. The Analytical Engine incorporated an arithmetic logic unit, control flow in the form of conditional branching and loops, and integrated memory, making it the first design for a general-purpose computer that could be described in modern terms as Turing-complete.



Trial model of a part of the Analytical Engine, built by Babbage, as displayed at the Science Museum (London)

Source: http://en.wikipedia.org/wiki/Analytical_Engine

The First Programmer

Augusta Ada King, Countess of Lovelace (1815 –1852), born Augusta Ada Byron and now commonly known as Ada Lovelace, was an English mathematician and writer chiefly known for her work on Charles Babbage's early mechanical general-purpose computer, the Analytical Engine.

Her notes on the engine include what is recognized as the first algorithm intended to be processed by a machine.

Because of this, she is often considered the world's first computer programmer.

The Hon. Augusta Ada Byron
Born 10 December 1815
London, England

The programming language ADA is named after her.

Source: http://en.wikipedia.org/wiki/Ada_Lovelace

Beyond Number Crunching

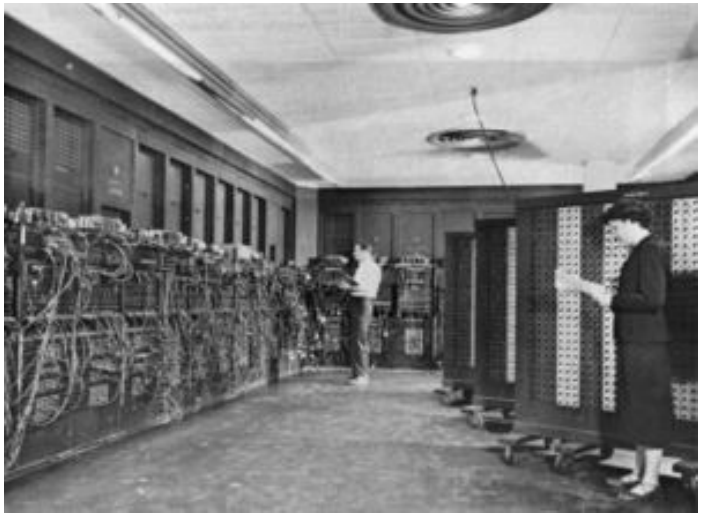
Ada Lovelace realized that the potential of the device extended far beyond mere number crunching. She wrote:

" [The Analytical Engine] might act upon other things besides number, were objects found whose mutual fundamental relations could be expressed by those of the abstract science of operations, and which should be also susceptible of adaptations to the action of the operating notation and mechanism of the engine...

Supposing, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent."

Source: http://en.wikipedia.org/wiki/Ada_Lovelace

ENIAC – the first electronic computer



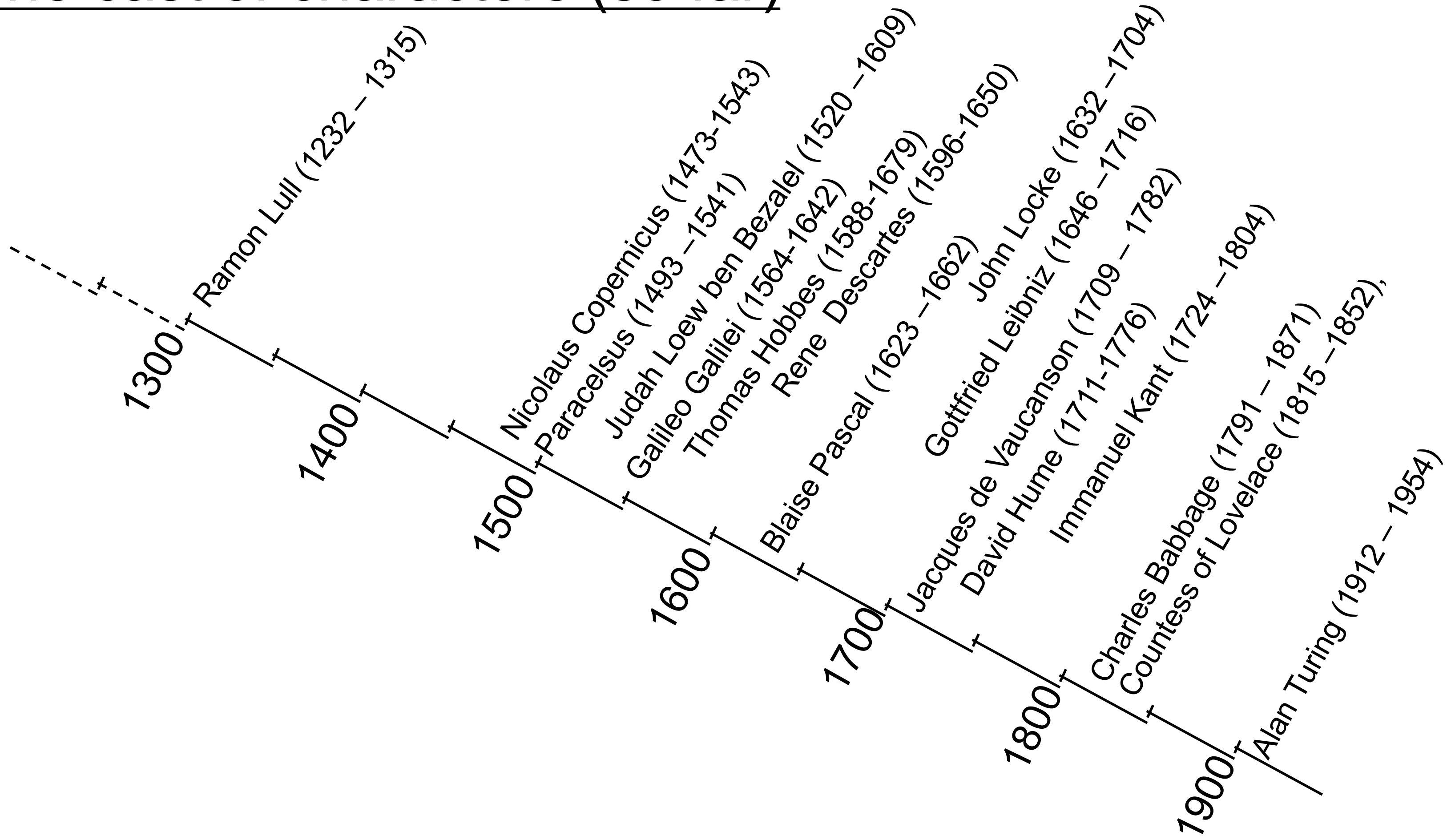
Physically, ENIAC was massive compared to modern PC standards. It contained
17,468 vacuum tubes,
7,200 crystal diodes,
1,500 relays,
70,000 resistors,
10,000 capacitors and
around 5 million hand-soldered joints.

It weighed 27 tons,
was roughly 2.4 m by 0.9 m by 30 m,
took up 167 m²,
and consumed 150 kW of power.

Source: http://en.wikipedia.org/wiki/ENIAC

Modern Times

The cast of characters (so far)



How AI got its name

The name *artificial intelligence* is credited to John McCarthy who, along with Marvin Minsky and Claude Shannon (1916–2001), organized the *Dartmouth Conference* in 1956.

The conference was to be a "*two month, ten-man study of artificial intelligence* … *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*".

See *Machines Who Think* by McCorduck, Chapter 5, for a detailed account.

Dartmouth Conference: The Organizers

- John McCarthy (1927 – 2011), then an assistant professor at Dartmouth. Designed the Lisp programming language that was very popular with AI researchers. Also did work in Logic and Commonsense Reasoning.
- Marvin Minsky (1927 – 2016), then a Harvard Junior Fellow went on to become one of the most influential figures in AI. With McCarthy he co-founded the MIT AI Lab. Known for his ideas on Frames. Wrote a book "Society of the Mind" and more recently "The Emotion Machine"
- Nathaniel Rochester (1919 – 2001) a young engineer at IBM. He designed the IBM 701 and wrote the first assembler. He supervised Arthur Samuel writing the checkers playing program. It is said that the marketing people at IBM reported that people were frightened of "electronic brains" resulting in IBM stopping work on AI.
- Claude Shannon (1916 – 2001) a mathematician at Bell Labs was already known for his information theory. Had hired McCarthy and Minsky in 1952 for the summer when they were graduate students.

Dartmouth Conference: The show stealers

Herbert Simon and Alan Newell were "*two vaguely known persons*" *working at Carnegie Tech and RAND, who were also invited to the Dartmouth Conference* "*almost as an afterthought*" – McCorduck in *Machines Who Think*.

Along with J. C. Shaw (1922 – 1991), also from RAND, they had already developed a program called the Logic Theorist (LT). "*It was the first program deliberately engineered to mimic the problem solving skills of a human being*". It went on to prove several theorems in Russell and Whitehead's celebrated *Principia Mathematica* (finding **shorter and more elegant proofs** for some!)

see http://en.wikipedia.org/wiki/Logic_Theorist

Simon and Newell

Herbert Simon (1916 – 2001) was "an American political scientist, economist, sociologist, psychologist, and professor—most notably at Carnegie Mellon University—whose research ranged across the fields of cognitive psychology, cognitive science, computer science, public administration, economics, management, philosophy of science, sociology, and political science". See http://en.wikipedia.org/wiki/Herbert_A._Simon

Alan Newell (1927 – 1992) was a long term collaborator of Simon at CMU. He designed the language Information Processing Language (IPL) in which LT was implemented.

The Information Processing View of AI

Simon and Newell went on to become leading figures in AI research and founded a strong group at CMU.

Their program General Problem Solver (GPS) was a pioneer in the use of heuristics in search and adopted a human like approach called means-ends-analysis.

Their work defined the Information-Processing approach for AI.

At CMU one shining example was the development of the SOAR cognitive architecture by John Laird.

Physical Symbol Systems

Symbol : A perceptible something that stands for something else.
- alphabet symbols, numerals, road signs, musical notation

Symbol System: A collection of symbols – a pattern
- words, arrays, lists, even a tune

Physical Symbol System: That obeys laws of some kind, a formal system
- long division, an abacus, an algorithm

The Physical Symbol System *Hypothesis*

"A physical symbol system has the **necessary** and **sufficient** means for general intelligent action."

— Allen Newell and Herbert A. Simon

The ability to manipulate symbols - Symbolic AI / Classical AI

Good Old Fashioned Artificial Intelligence (GOFAI)

– John Haugeland in *AI: The Very Idea*

Samuel's Checkers program

Arthur Samuel (1901-1990) was one of the attendees in Dartmouth. He wrote the first Checkers playing program in 1952 on IBM's 701 computer.

Samuel's goal was to explore how to get **computers to learn** – he felt that if computers could learn from experience then there would be no need for detailed and painstaking programming.
His Checker's program improved as it played more and more games, eventually "beating its own creator" – evoking fears of Frankenstein's monster like creatures (Mary Shelley) overwhelming humankind.

- Pamela McCorduck in *Machines Who Think*

Three Laws of Robotics

The Three Laws are a set of rules devised by the science fiction author Isaac Asimov. The rules were introduced in his 1942 short story "*Runaround*", although they had been foreshadowed in a few earlier stories. The Three Laws are:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Source: http://en.wikipedia.org/wiki/Three_Laws_of_Robotics

AI: Some landmarks

1957 : Newell, Simon and Shaw implement General Problem Solver
Noam Chomsky writes “Syntactic Structures”

1958 : John McCarthy introduces LISP at MIT
Herbert Gelernter (PhD dissertation) : Theorem prover for geometry

1959 : Minsky and McCarthy set up AI Lab at MIT
Frank Rosenblatt builds the Perceptron
Arthur Samuel’s Checkers program beats the best human players

1960 : Bar-Hillel writes paper describing difficulty of Machine Translation

1962 : Unimation: First industrial robots
Jaakko Hintikka writes “Knowledge and Belief”
Saul Kripke inroduces Kripke structures for possible world semantics

1963 : Ivan Sutherland (PhD dissertation) Sketchpad: CAD program
Ross Quillian: Semantic Nets
Susomo Kuno’s parser at MIT tested on “Time flies like an arrow”
Edward Feigenbaum and Julian Feldman publish “Computers and Thought”

1964 : Daniel Bobrow (PhD dissertation): STUDENT – solves algebra problems
Bertram Raphael (PhD dissertation): SIR – on knowledge representation for question answering

Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence

Some landmarks (continued)

1965 : Alan Robinson: The Resolution Method for theorem proving
Ivan Sutherland and Bob Sproulli demonstrate Virtual Reality with a head mounted display
Simon predicts “by 1985 machines will do any work that man can do”
Herbert Dreyfus argues against possibility of AI

1960 : Weizennbaum’s ELIZA

1967 : Greenblatt’s MacHack defeats Dreyfus at Chess
DENDRAL program (Edward Feigenbaum et al. at Stanford University) demonstrated to interpret mass spectra on organic chemical compounds. First success of knowledge based reasoning

1968 : Joseph Moses (PhD dissertation) MACSYMA – symbolic reasoning in mathematics

1969 : SHAKEY the robot demonstarted at Stanford Research Institute
Minsky and Papert’s book “Perceptrons” limits powers of single layer neural nets
Roger Schank defines Conceptual Dependency theory
McCarthy and Hayes discuss the Frame Problem

1970 : Bill Woods: Augmented Transition Networks for Natural Language Parsing
Patrick Winston (PhD Dissertation) ARCH: learns concepts from examples from children's blocks

1971 : Nils Nilsson and Richard Fikes demonstrate the planning system STRIPS
Terry Winograd (PhD dissertation) SHRDLU understanding English in a restricted domain

1971 : Alain Colmerauer develops Prolog
Earl Sacerdoti: Hierarchical planning with ABSTRIPS

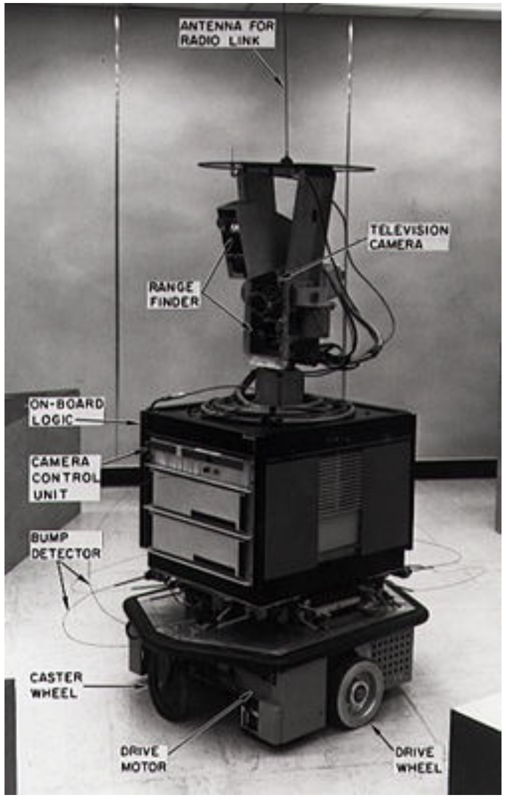
Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence

SHAKEY

Developed at Stanford Research Institute by a team led by Charles Rosen during 1966-1972, Shakey the robot was the first general-purpose mobile robot to be able to reason about its own actions.

It wandered around the corridors of SRI turning the light switches on and off, opening and closing the doors, climbing up and down from rigid objects, and pushing movable objects around.

Keywords: Robotics, computer vision, natural language processing, LISP, A*, STRIPS, Hough transform, visibility graph, collision detection.



Source: http://en.wikipedia.org/wiki/Shakey_the_robot

Some landmarks (continued)

1973 : Schank and Abelson introduce *Scripts* for story understanding

1974 : Ted Shortliffe (PHD dissertation): MYCIN – rule based approach to medical diagnosis

1975 : Marvin Minsky publishes article on *Frames*
The Meta-Dendral learning program produces new results in Chemistry
Austin Tate developes the Nonlin partial order planning system
Sacerdoti developes the NOAH planning system

~1975 : David Marr and colleagues at MIT describe the “primal sketch” as visual representation

1976 : Randall Davis (PhD dissertation) demonstrates the power of meta-level reasoning
Douglas Lenat’s (PhD dissertation) program AM creates a stir

1977 : SRI’s PROSPECTOR expert system predicts existence of a hitherto unknown molybdenum deposit in Washington State.

1978 : Tom Mitchell invents the concept of Version Spaces
Herbert Simon wins the Economics Nobel prize for his work on bounded rationality
Stefik and Friedland’s MOLGEN demonstrates the utility of object oriented programming

1979 : The Stanford Cart by Hands Moravec autonomously navigates in the Stanford AI Lab
BKG a backgammon program by Hans Berliner defeats reigning world champion
McDermott, Doyle and McCarthy publish on non-monotonic reasoning and truth maintenance

Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence http://www.stanford.edu/~learnest/cart.htm

Some landmarks (continued)

~1980 : Dickmanns et al build the first robot cars driving autonomously in Munich
Lisp machines and Expert System shells appear in the market

1980 : Douglas Hofstadter publishes Godel Escher Bach
McDermott builds the *XCON* expert system for configuring VAX machines
First AAAI conference

1981 : Daniel Hillis designs the Connection Machine
Common Lisp standard defined

1982 : Japanese government launches the Fifth Generation Computer Systems program
John Hopfield resuscitates neural networks

1983 : Darpa initiates Strategic Computing Initiative
John Laird and Paul Rosenbloom (PhD dissertations) – CMU's *SOAR* architecture
James Allen invents Interval Calculus

1985 : AARON the drawing artist created by Harold Cohen demonstrated at AAAI

1987 : Minsky publishes "The Society of Mind"
Rodney Brooks introduces an alternative subsumption architecture for AI

1989 : Dean Pomerleau at CMU creates ALVINN (An Autonomous Land Vehicle in a Neural Network).

Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence

Some landmarks (continued)

1990 : Gerald Tesauro's *TD-Gammon* based on Reinforcement Learning plays world class Backgammon

1993 : Ian Horswill (PhD dissertation) builds Polly a behaviour based robot that used vision for navigation
Rodney Brooks and colleagues start MIT Cog Project to build a humanoid robot child

1994 : Twin robot cars VaMP and VITA-2 of Ernst Dickmanns and Daimler-Benz drive more than one thousand kilometers on a Paris three-lane highway in standard heavy traffic at speeds up to 130 km/h.

1995 : Semi-autonomous ALVINN steered a car coast-to-coast (throttle and brakes controlled by human)
Ernst Dickmanns' robot cars (with robot-controlled throttle and brakes) drove more than 1000 miles from Munich to Copenhagen and back, in traffic, at up to 120 mph,

1997 : Deep Blue beats Garry Kasparov in a six game chess match
First official *RoboCup* tabletop football tournament with 40 teams and 5000 spectators

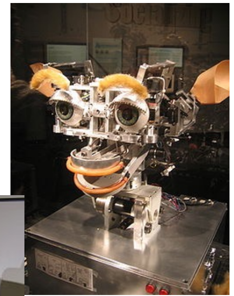
1998 : Furby the first robot toy for the domestic market released by Tiger Electronics
Tim Berne-Lee pubishes his Semantic Web roadmap paper

~1998 : Web Crawlers explore the WWW
Emotional agents demostrated at MIT

1999 : Sony introduces AIBO

Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence

Some landmarks (continued)



2000 : Cynthia Breazeal (PhD dissertation) on Sociable machines, describes *Kismet*, a robot that expresses emotions.
The Nomad robot explores remote regions of Antarctica looking for meteorite samples.

2004 : OWL Web Ontology Language W3C Recommendation
DARPA introduces the Grand Challenge for autonomous vehicles for prize money.

2005 : Honda's *ASIMO* robot, an artificially intelligent humanoid robot, is able to walk as fast as a human, delivering trays to customers in restaurant settings.
Recommendation technology based on tracking web activity or media usage brings AI to marketing
Blue Brain is born, a project to simulate the brain at molecular detail.

2006 : The Dartmouth Artificial Intelligence Conference: The Next 50 Years (AI@50)

2007 : Checkers is solved by a team of researchers at the University of Alberta.

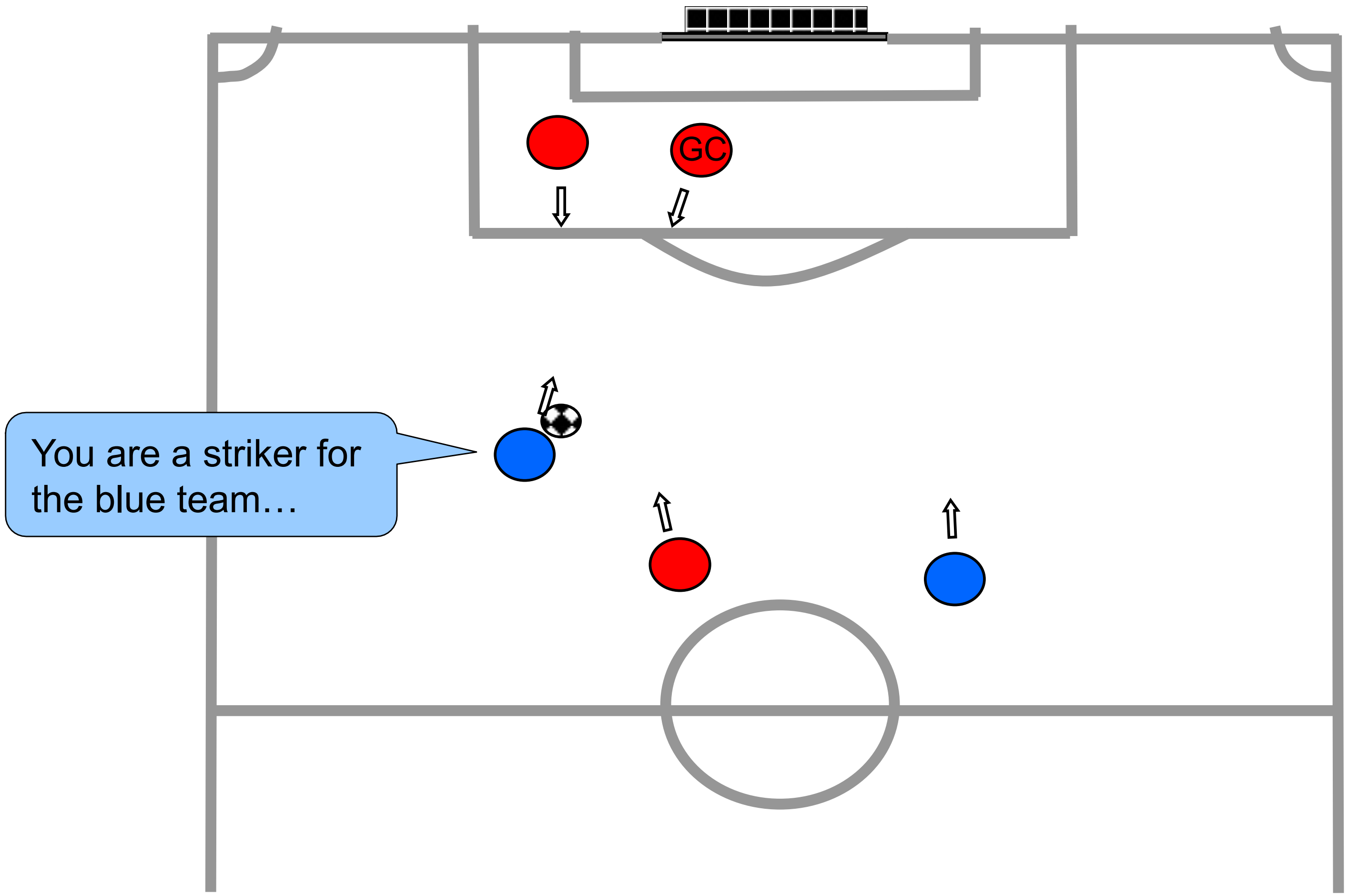
2011 : In a Jeopardy! exhibition match IBM's *Watson* soundly defeated the two greatest Jeopardy! champions, Brad Rutter and Ken Jennings.

2013 : Japanese space agency launches *Kirobo* into space as a companion to a human.

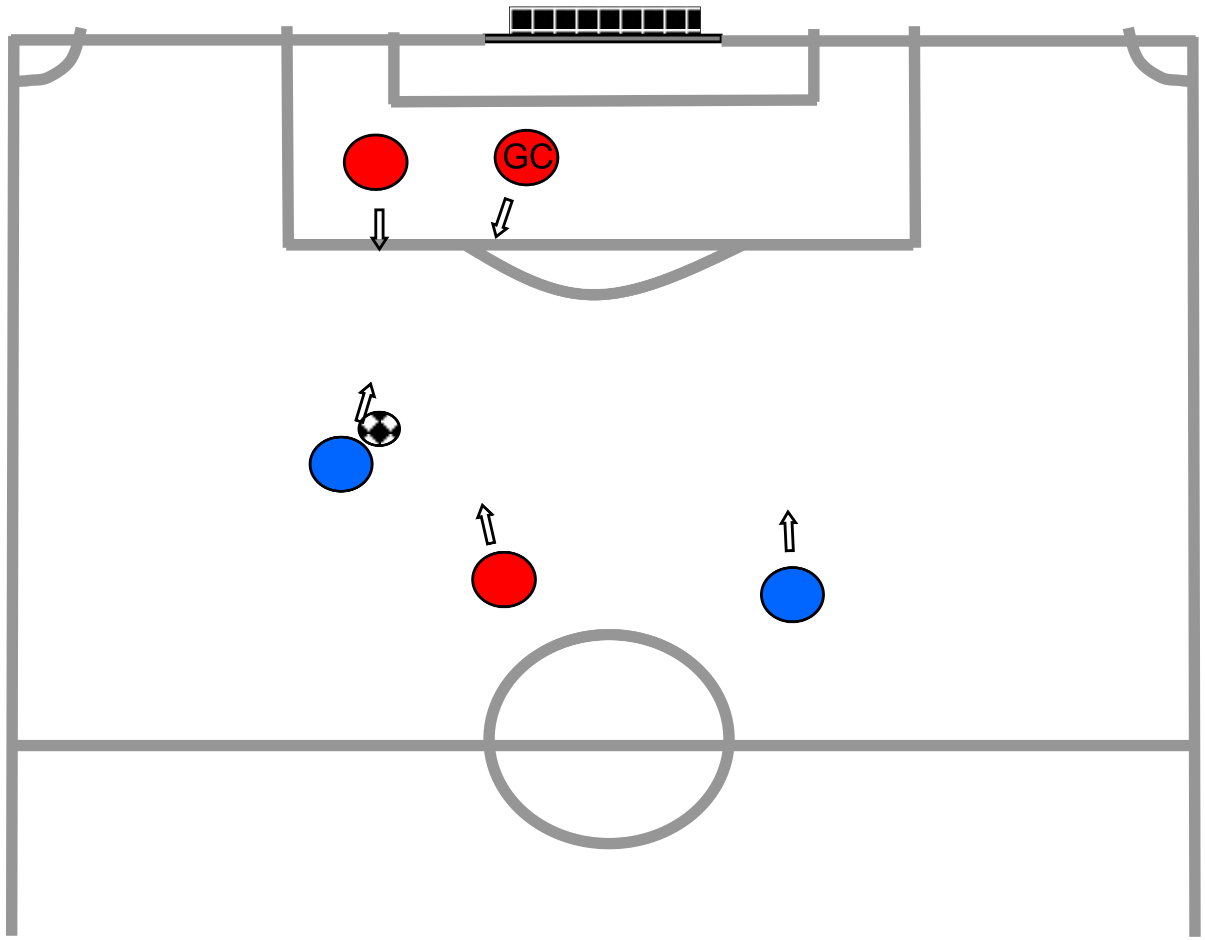
Source: http://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence

Problem Solving

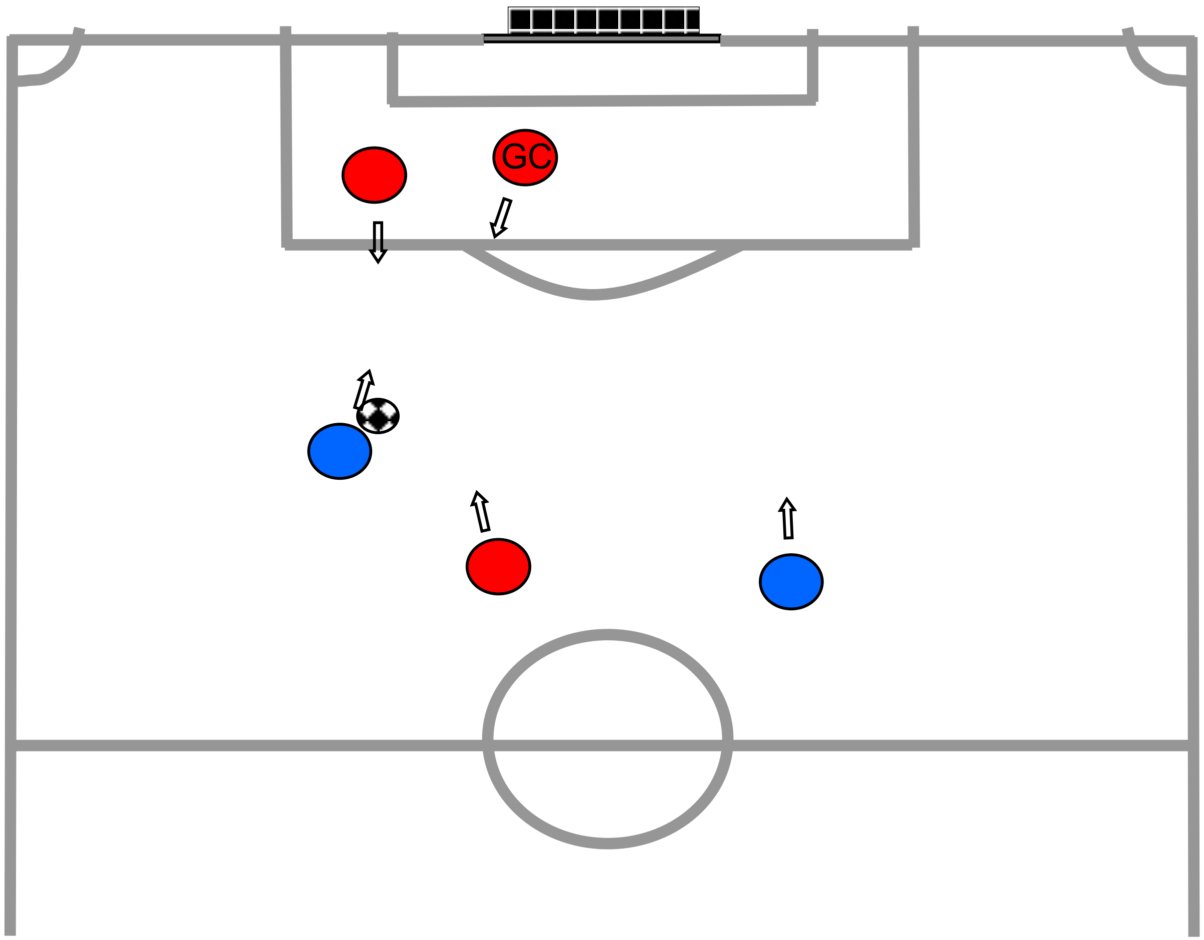
On a football field…



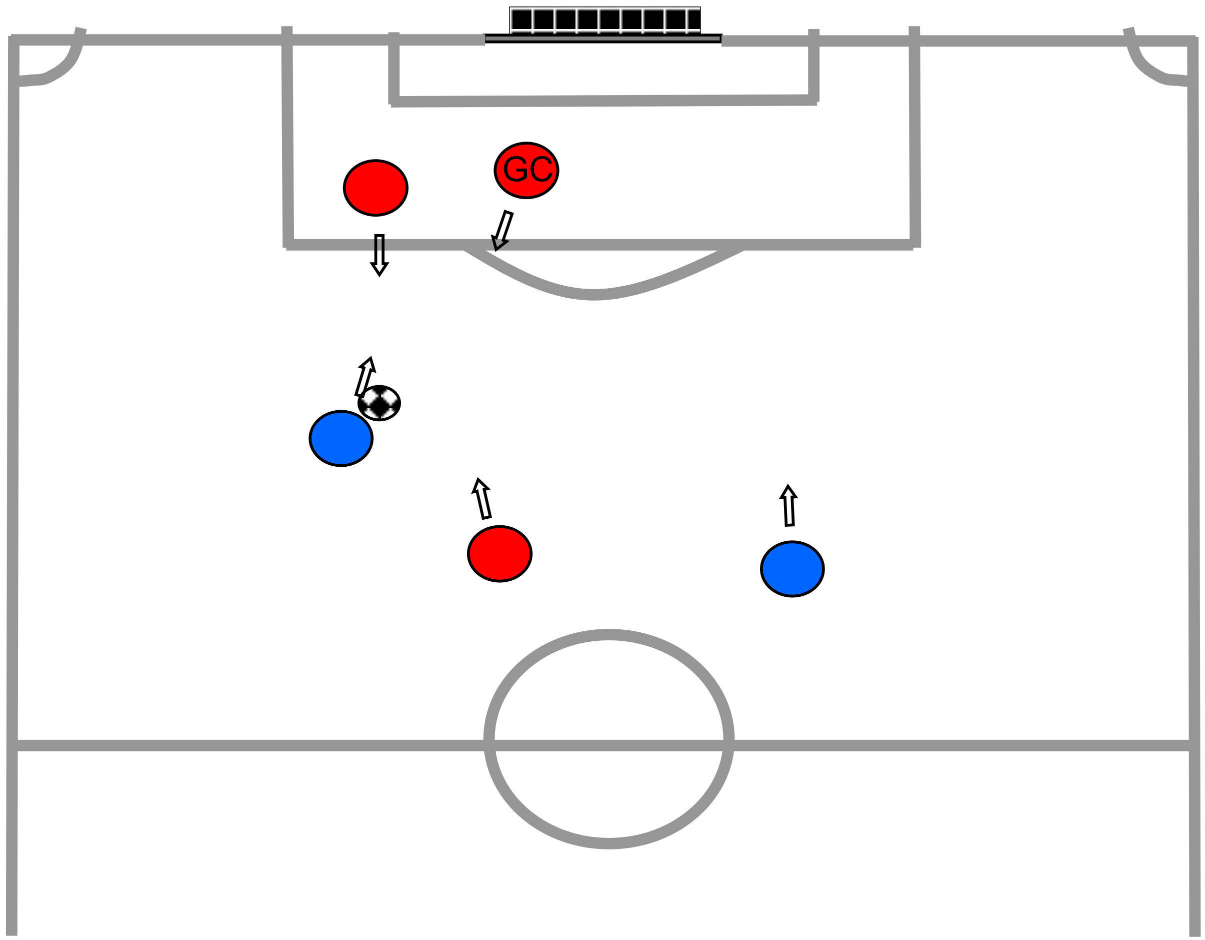
.. moving forward with the ball…



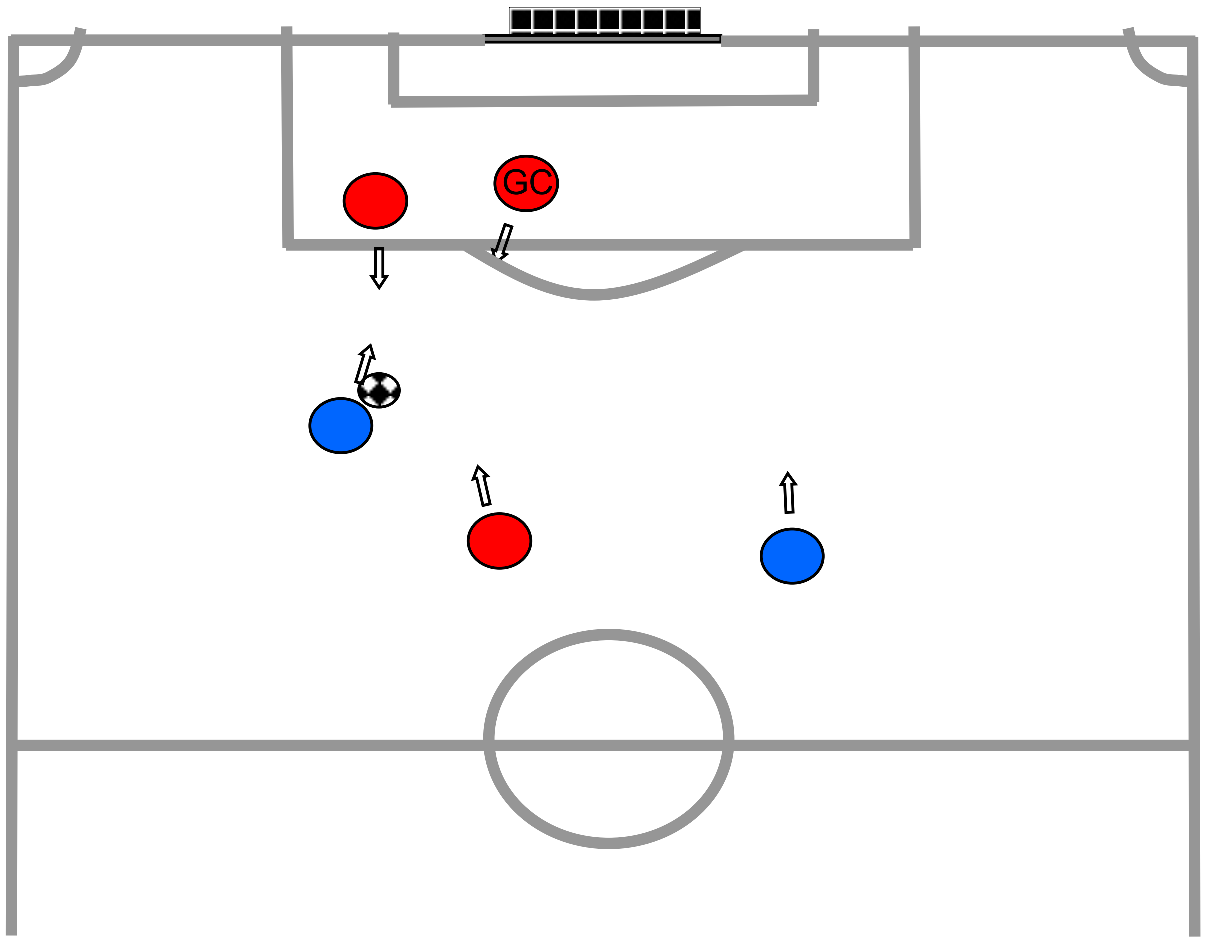
.. moving forward with the ball…



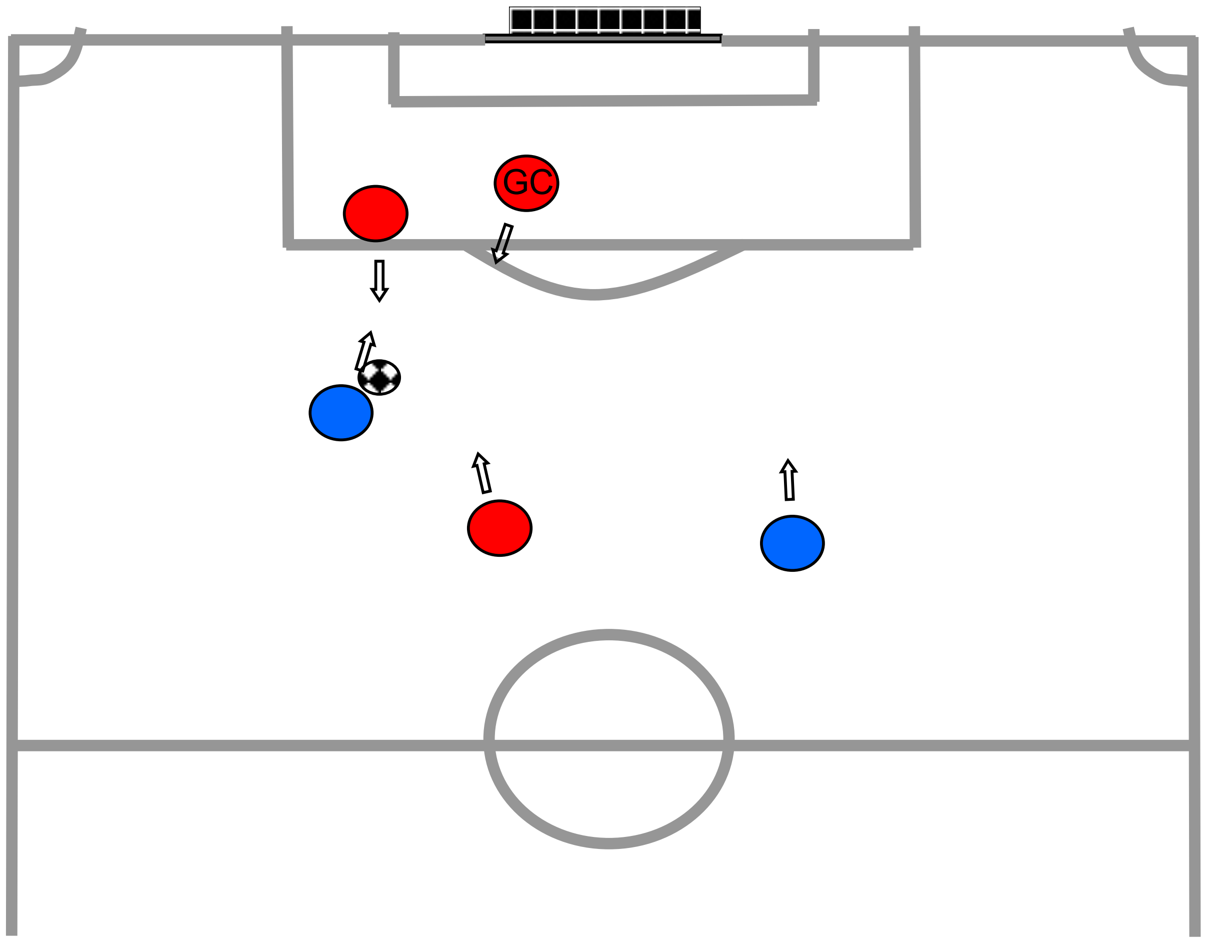
.. moving forward with the ball…



… the defenders are closing in …



What should you do?



Problem solving

An autonomous agent

in some world

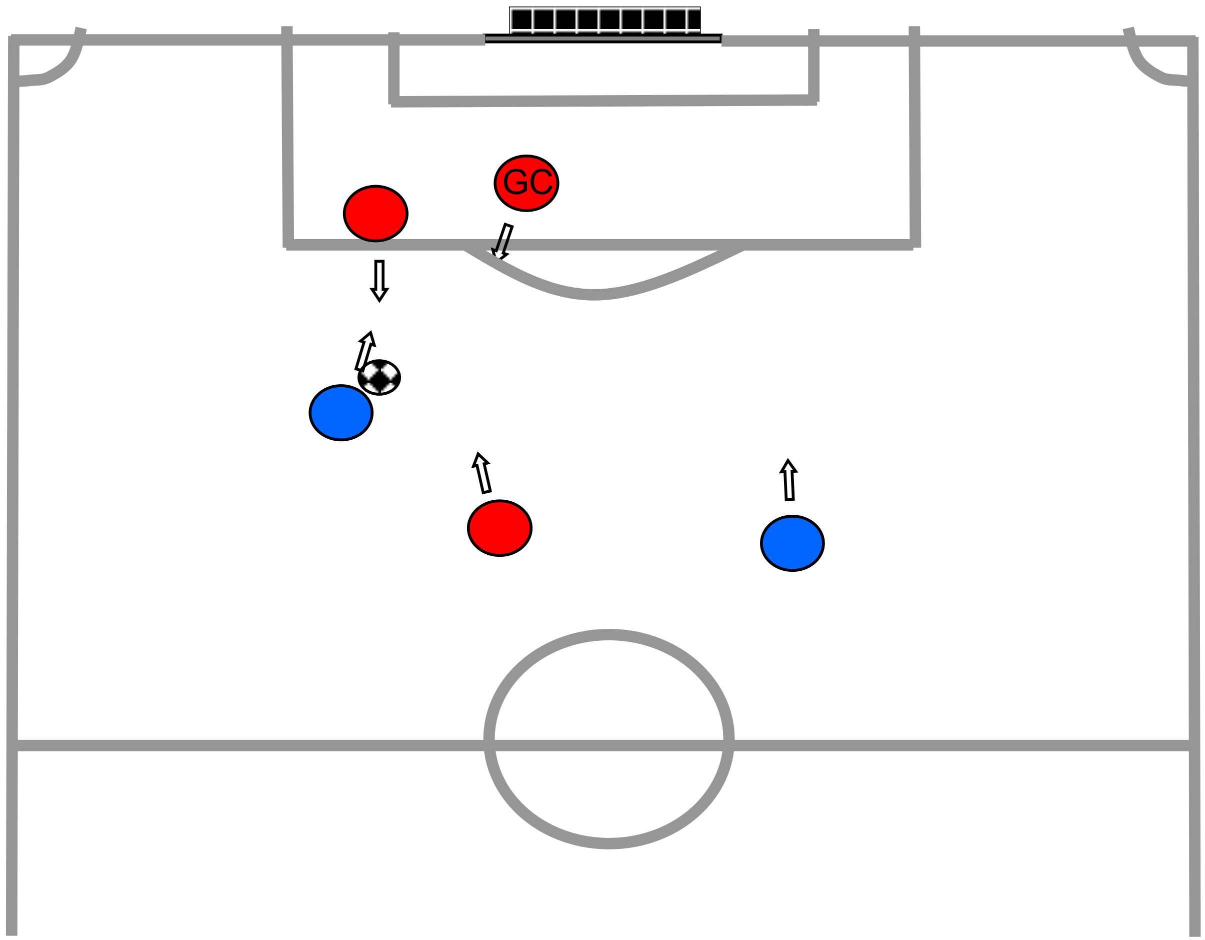
has a goal to achieve

and

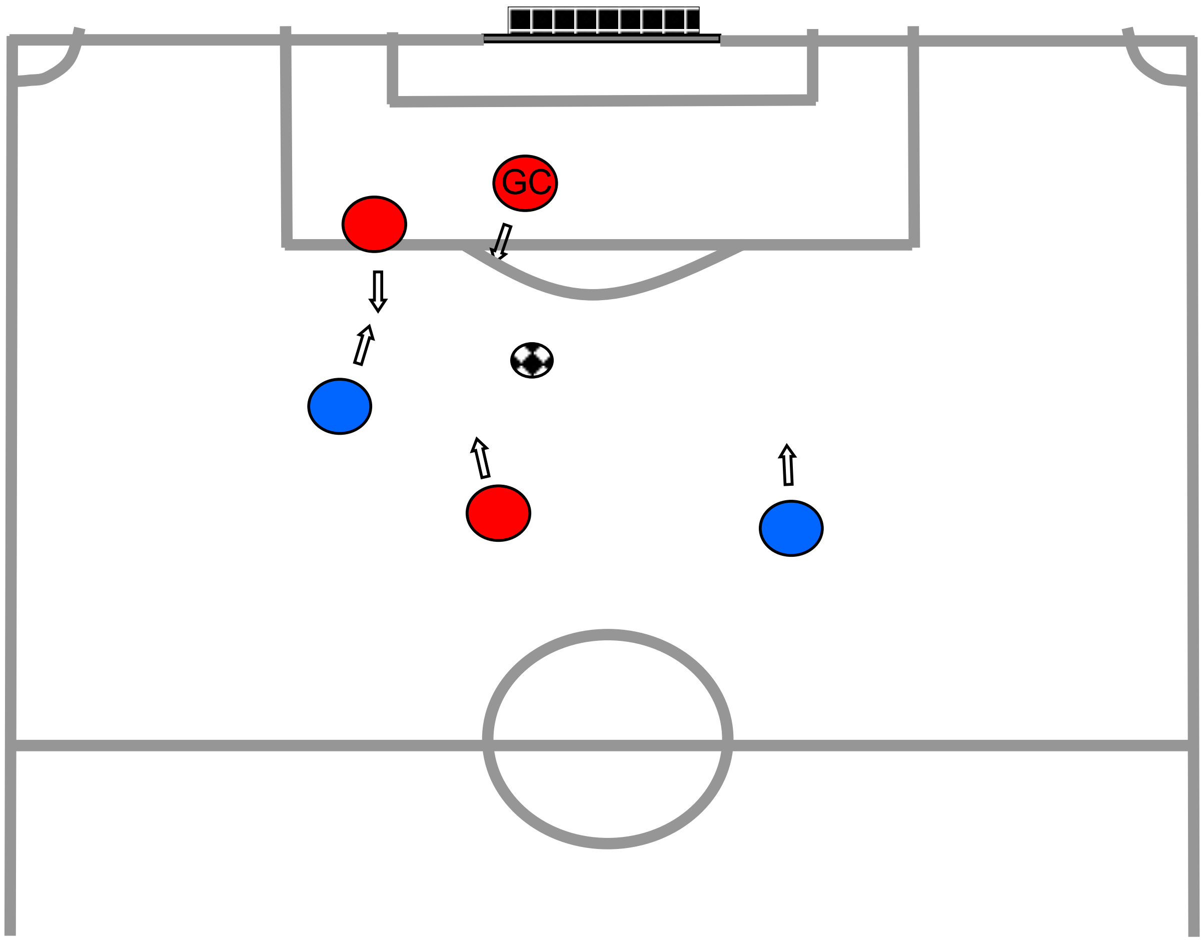
a set of actions to choose from

to strive for the goal

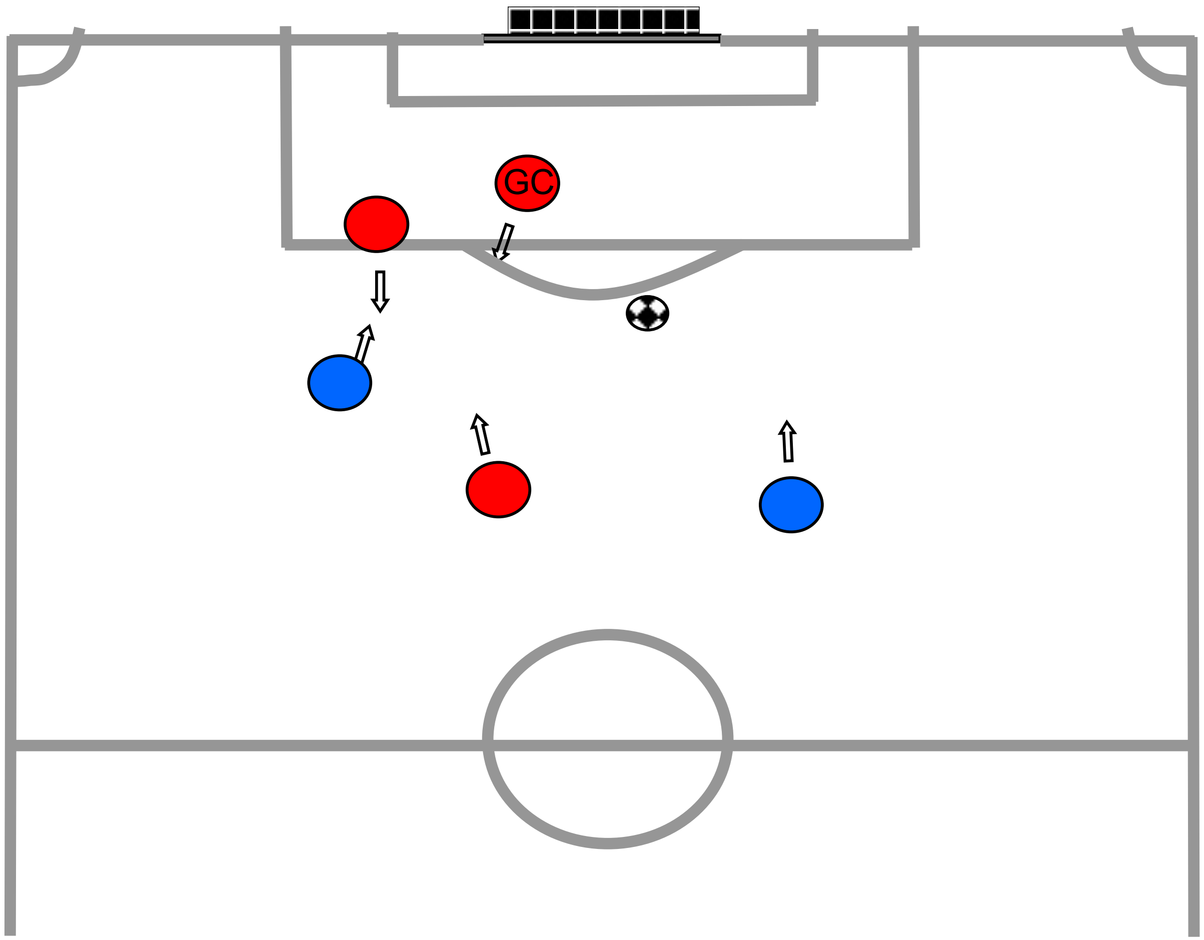
An intelligent agent would…



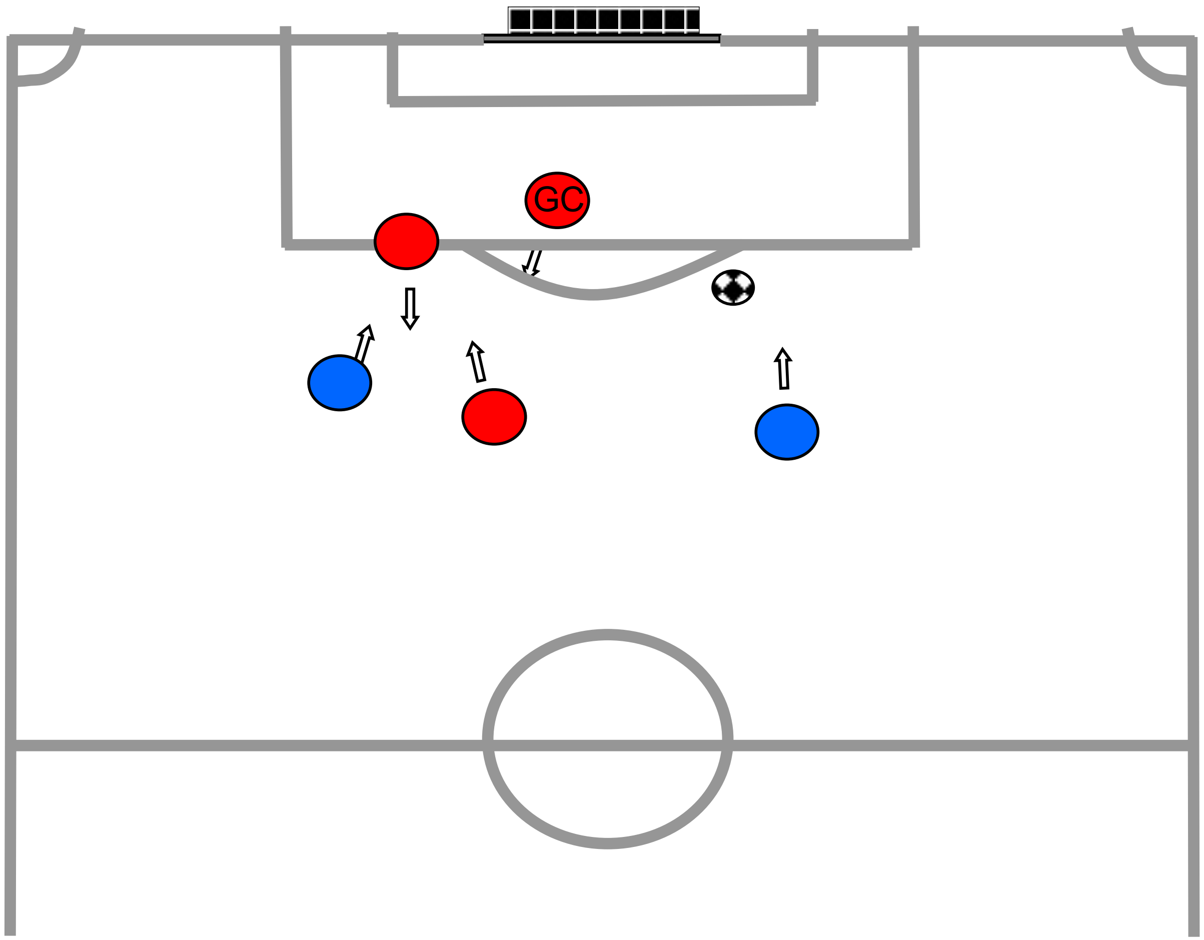
Pass the ball to a teammate who is free…



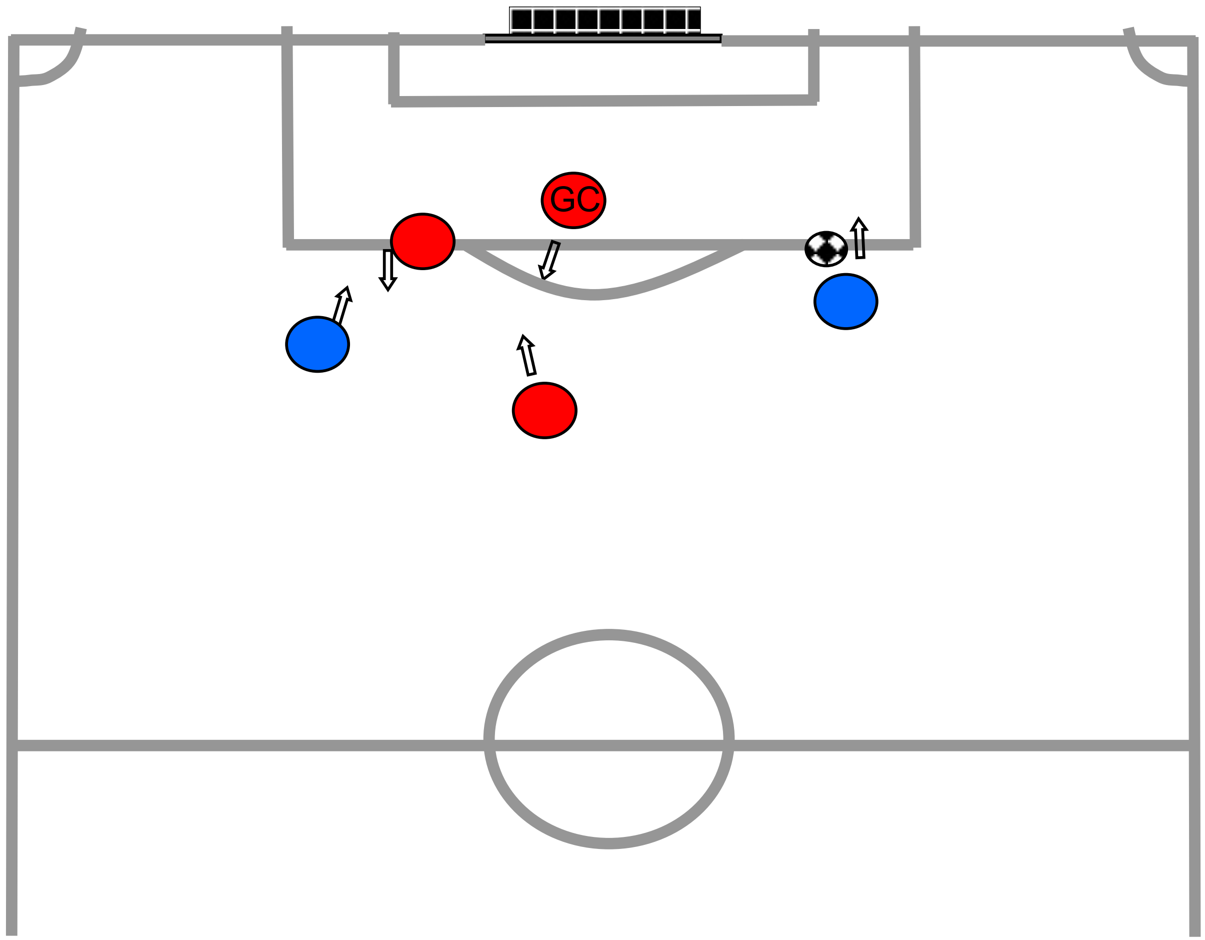
Pass the ball to a teammate who is free…



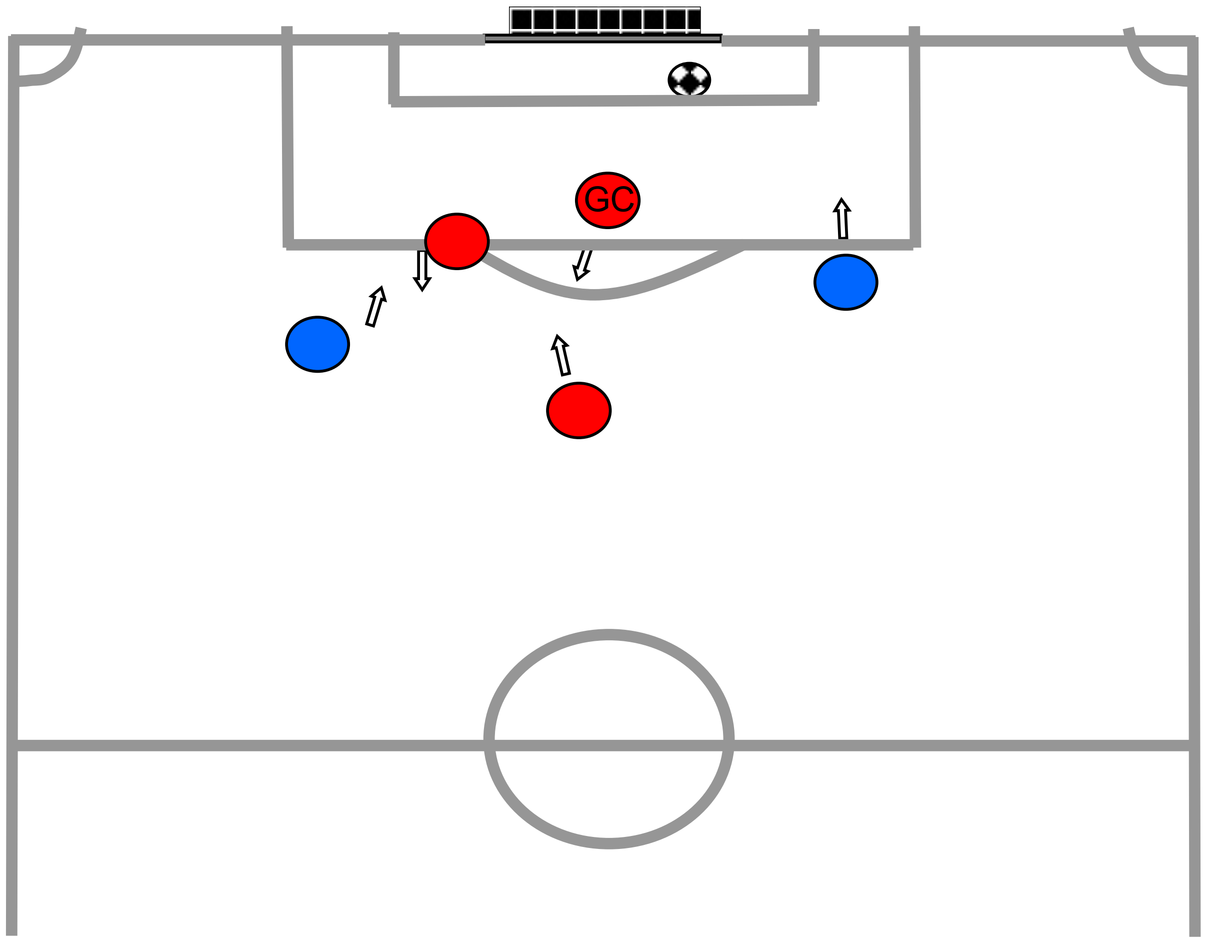
Pass the ball to a teammate who is free…



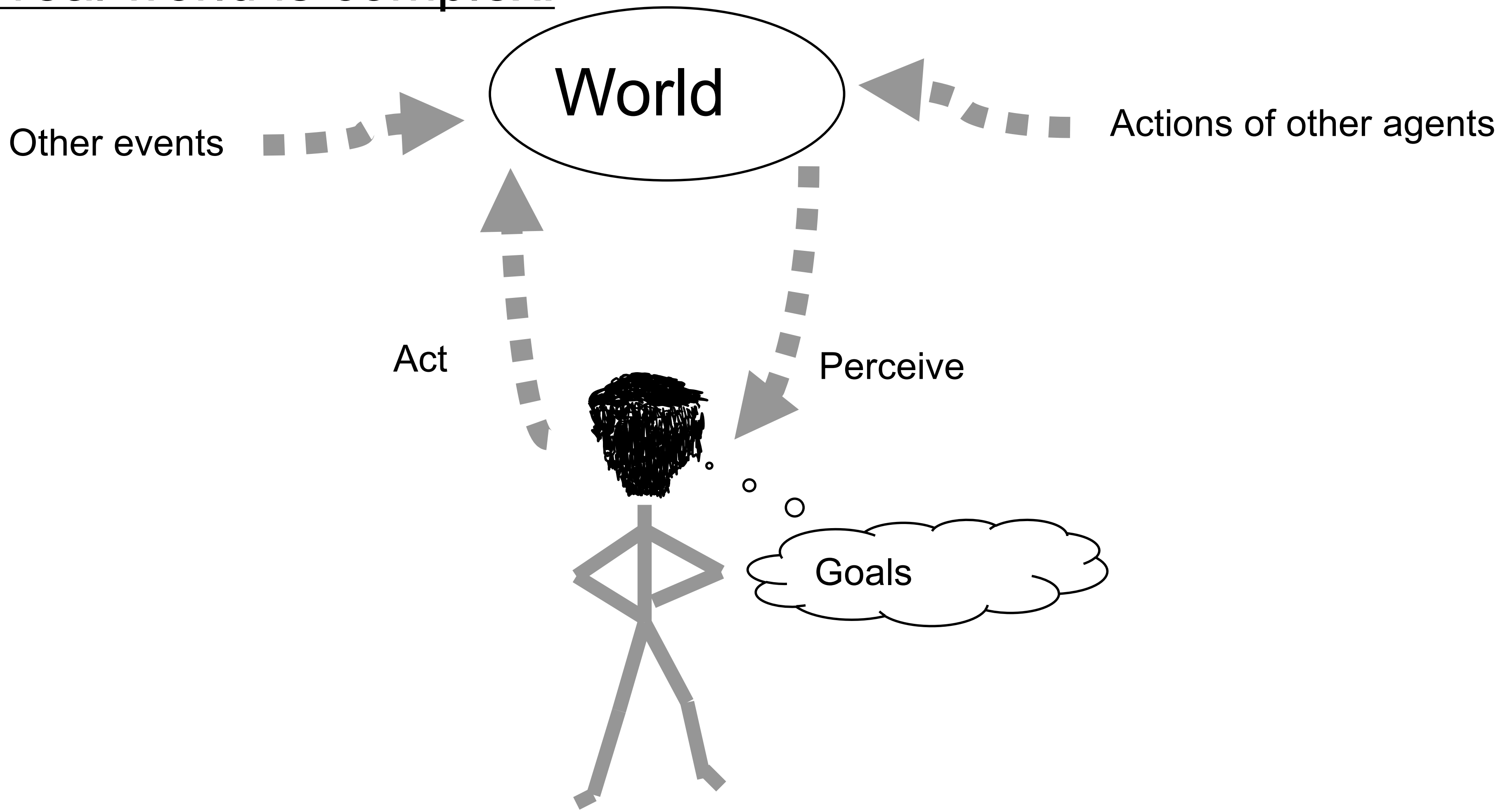
… and has a better chance to score



… and has a better chance to score



The real world is complex!



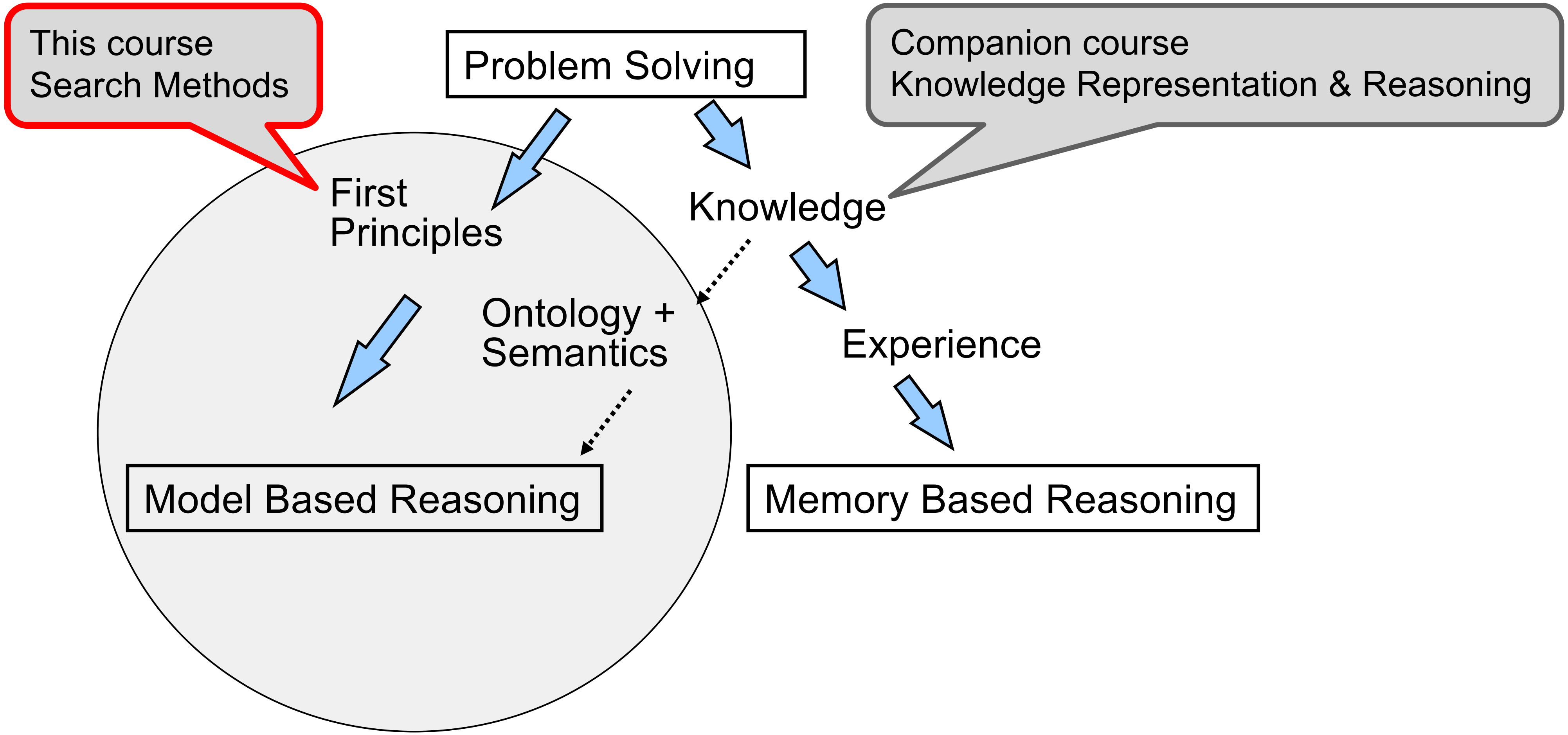
Must learn to walk before one can run

Deal with simple problems first

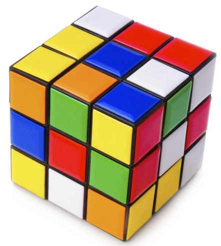
- The world is static
- The world is completely known
- Only one agent changes the world
- Actions never fail
- Representation of the world is taken care of
  (to start with at least)

Problem Solving

Humankind is a problem solving species.



Search vs. Knowledge: Solving the Rubik's Cube



Since the Hungarian architect Erno Rubik invented the Rubik's cube in 1974 millions of us have been engaged with solving the cube. Now everyone gets hold of a cube solving algorithm from somewhere, and even kids can solve it in a few minutes.

This illustrates the *knowledge based* approach in which we (now) already *know* how to solve it.

But without that knowledge we have to adopt a *first principles search method* to try and solve it. The link below points to an article which says that Rubik *took one month* to find the first algorithm to solve it.

More recently deep reinforcement learning was used to find efficient solutions without any human guidance. See this Nvidia blogpost.

https://www.hpcwire.com/2018/07/25/new-deep-learning-algorithm-solves-rubiks-cube/

Search vs. Reasoning: Solving the Sudoku

Reasoning

5 is already in this column

5 is already in this row

5 is already in this row

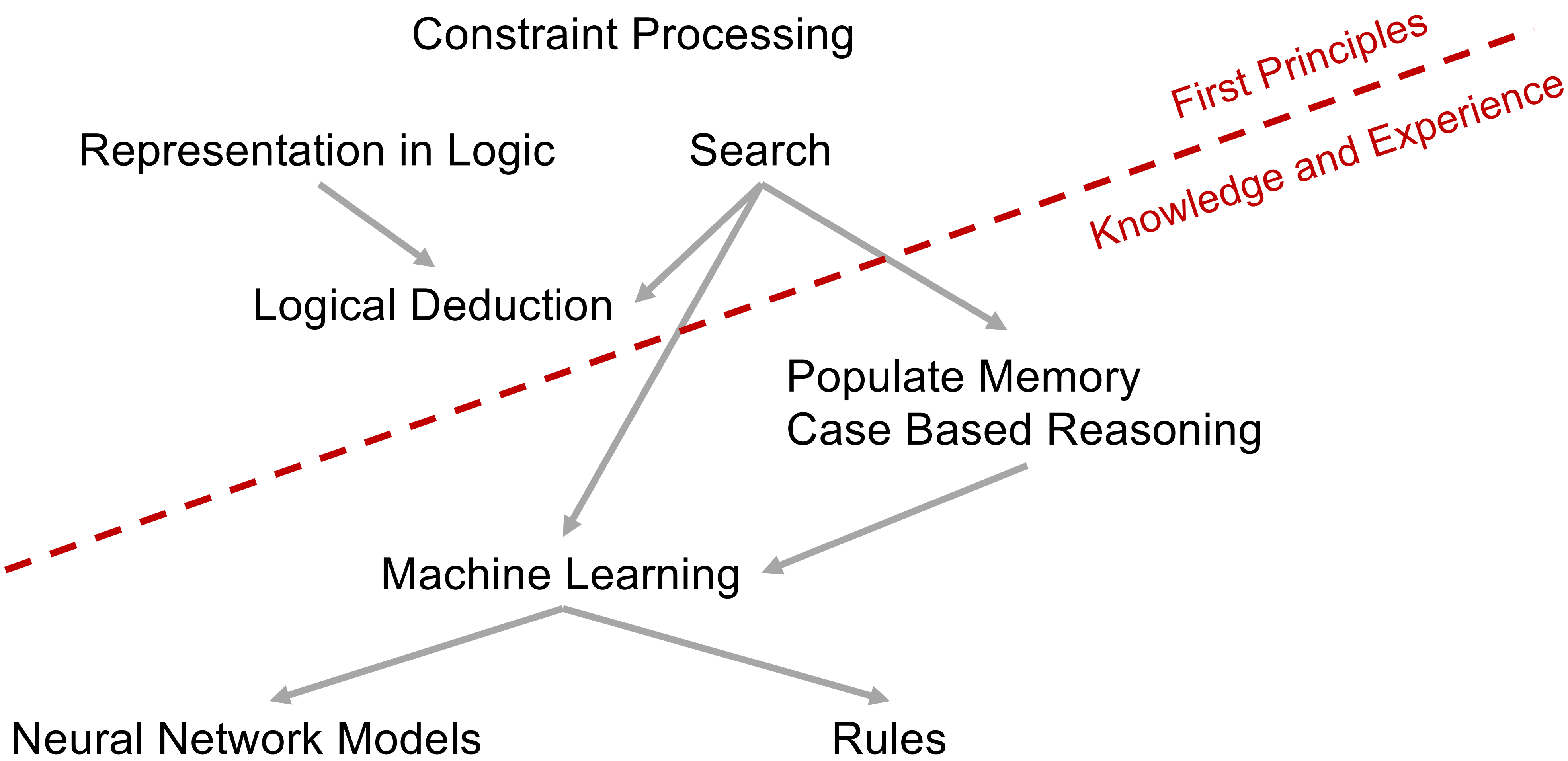
5 *must* be in this empty square

5	3			7		X	X	X
6			1	9	5	X	X	X
	9	8				5	6	X
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

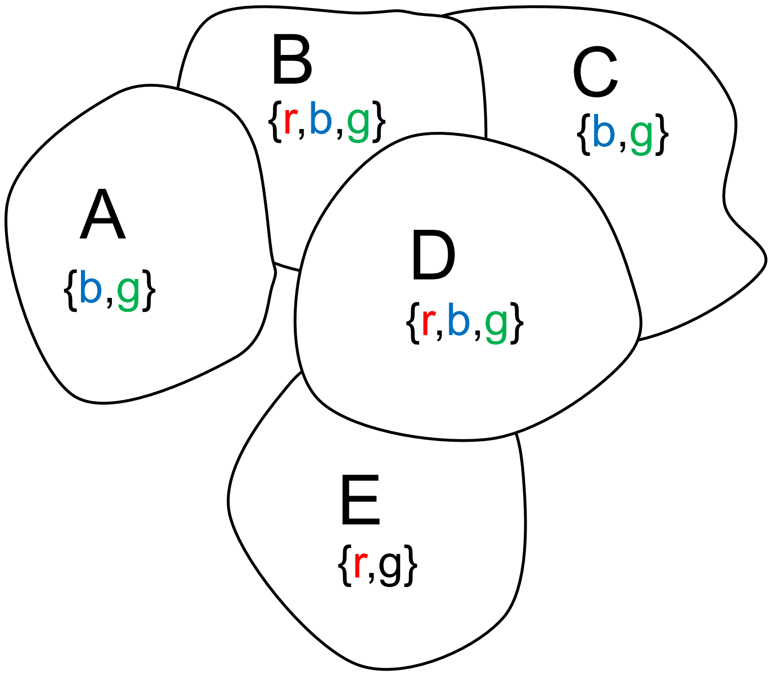
Both
reasoning and search
are subsumed by
Constraint Satisfaction
as we will see later

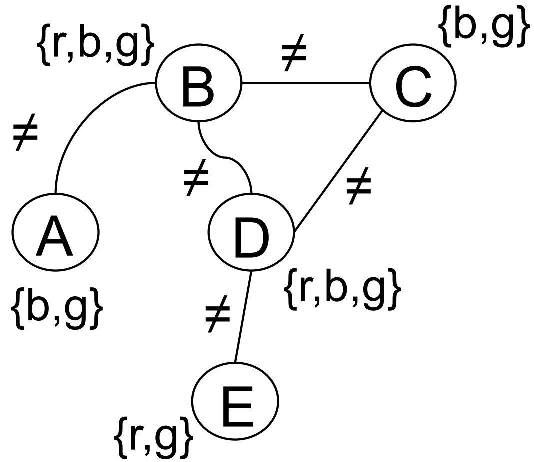
https://en.wikipedia.org/wiki/Sudoku

An Architecure for Problem Solving



A Map Colouring Problem





The constraint graph.
Choose a label for each node

Colour each region in the map with an allowed colour such that no two adjacent regions have the same colour.

End

Introduction