Evolutions in the Understanding of Intelligence

From Automata to Ambient Intelligence

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Evolutions in the Understanding of Intelligence
From Symbol Manipulation to Cognitive Systems

Outline

- The Scientific Study of Artificial Intelligence
- Epochs in Computing
- Epochs in Artificial Intelligence
  - Pre 1960: Automata and Recognition
  - 1960-1980: Planning and Problem Solving
  - 1970-1990: Expert Systems
  - 1980-2000: Logic, Neural Networks and Behavioral Robotics
  - 1990-2010: Cognitive Systems
  - 2000-2020: The Semantic Web
  - 2010-2030: Ambient Intelligence
- What do we mean by intelligence?

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Before we start….

The Scientific Study of Artificial Intelligence

This talk is about the scientific study of
Artificial Intelligence as a branch of Informatics.

Science: The elaboration of theories and models that predict and explain.
Science is a Social Activity. (T. Kuhn 1962, H. Simon 1996).

Informatics: The elaboration of theories and models that predict and explain the design and behaviour of Informatic Systems.

Postulate:

The theories and models of Artificial Intelligence are influenced by available computing power.

Some Definitions

Words mean what we want them to mean.

Intelligence: The ability to know and reason (American Heritage Dictionary),
Le faculté de Connaitre et Comprendre (Petit Robert).

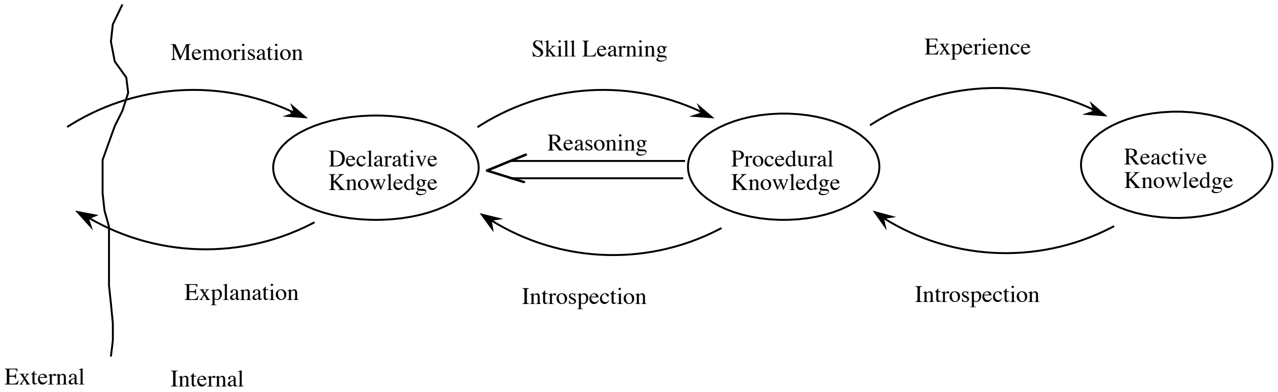
Knowledge: Expertise; Abilities acquired through experience or education (Oxford English Dictionary)

Reasoning: The act of drawing conclusions, actions, beliefs or feelings from facts or evidence.

Understanding: The ability to predict or explain phenomena.

The Problem of Artificial Intelligence is to provide computational theories for Intelligence, Knowledge, Reasoning and Understanding.

Some Definitions



Kinds of Knowledge:

Declarative: Symbolic expressions of knowledge
Used for Communication and abstract reasoning.

Procedural: Sequences of actions or desired states.
Methods for attaining goals (desired states of the universe).

Reactive: Condition-Action responses.
Reaction to Stimuli.

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Epochs in the Evolution of Computing

Moore's Law for Transistor Denisty:
Transistor Density on IC's (per m^2) doubles every 18 months.

Law for Digital Device Density:
Networked programmable digital devices (CPUs) per person doubles every 3 years

Epochs in computing:

Early Computing: (1950-1970):	1 CPU for 1000 to 10,000 persons
Main-Frame Computers: (1960 - 1980):	1 CPU for 100 to 1000 persons
Mini-Computers (1970 - 1990):	1 CPU for 10 to 100 persons
Desktop Computers (1980 - 2000):	1 CPU for 1 to 10 person
Mobile Computing (1990 – 2010):	1 to 10 CPUs per person
Internet Computing (2000 – 2020):	10 to 100 CPUs per person
Ambient Computing (2010 - 2030) :	100 to 1000 CPUs per person

Epochs in Artificial Intelligence

Early Computing (1950-1970)	⇒	Automata Theory
		Pattern Recognition
Main-Frame Computers (1960-1980)	⇒	Planning and Problem Solving
Mini-Computers (1970 - 1990)	⇒	Expert Systems
Personal Computing (1980 - 2000)	⇒	Logic Programming
		Neural Networks
		Behavioural Robotics
Mobile Computing (1990 – 2010)	⇒	Cognitive Systems,
		Bayesian Reasoning
Internet Computing (2000 – 2020)	⇒	The Semantic Web
Ambient computing (2010 - 2030)	⇒	Ambient Intelligence
		Intelligent Agents

Informatics view of Intelligence is strongly influenced by available computing

Early Computing: Automata and Pattern Recognition

1950: Turing - Intelligence is defined by behaviour

- A. Turing, (1950), "Computing Machinery and Intelligence", Mind LIX (236): 433–460, 1950.

1954: Markov: Finite State Machines.

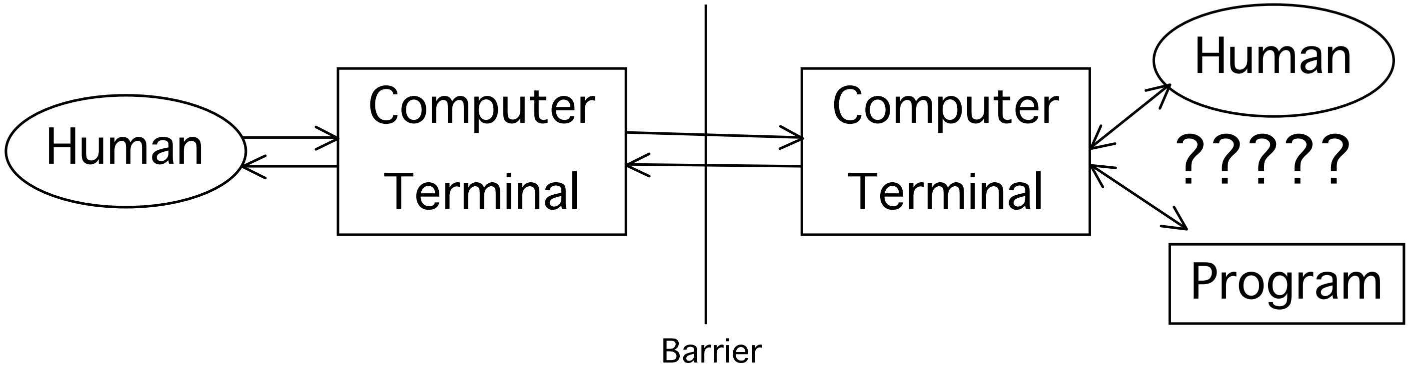
- Markov A. A Theory of Algorithms. Moscow: National Academy of Sciences, 1954.

1958: Rosenblatt: Perceptrons.

- Rosenblatt, Frank (1958), The Perceptron: A Probabilistic Model for Information Storage and Organization in the Brain, Cornell Aeronautical Laboratory, Psychological Review, v65, No. 6, pp. 386-408.

Early Computing:
Turing's View of Intelligence

The Turing Test: The imitation game



Alan Turing changed the question from "Can machines think?" to "Can machines do what we (as thinking entities) can do?"

He claimed that a machine would exhibit intelligence if it exhibited behaviour that could not be distinguished from a person.

Limits: 1) Assumes that only humans are intelligent
2) Reduced intelligence to human linguistic interaction

Grey Walter's Tortoise

BBC newsreel
aquired by
Owen Holland

Main Frame Computers : The Birth of AI

Planning and Problem Solving

Intelligence is the Ability to Solve Problems

The field of artificial intelligence research was named at a conference on the campus of Dartmouth College in the summer of 1956. Participants included Herb Simon, Alan Newell, Marvin Minsky, John McCarthy and Nils Nilsson.

Newell and Simon: Planning and problem solving

- Newell, A.; Shaw, J.C.; Simon, H.A. (1959). Report on a general problem-solving program. *Proceedings of the International Conference on Information Processing.* pp. 256-264.

Minsky: Finite State Machines

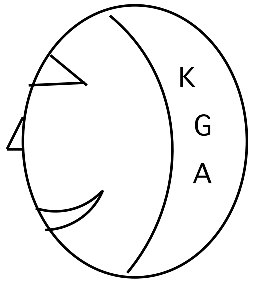
- Minsky, Marvin (1967). *Computation: Finite and Infinite Machines,* Prentice Hall, NJ, USA

Nilsson: STRIPS, A* GraphSearch

- R. Fikes and N. Nilsson (1971), "STRIPS: A new approach to the application of theorem proving to problem solving", Artificial Intelligence 2: 189–208

Planning and Problem Solving

Intelligence is the Ability to Solve Problems



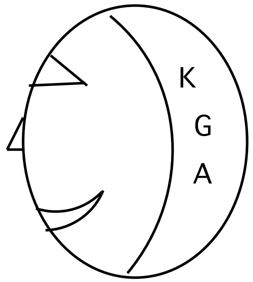
Formal Foundation: The Intelligence Agent (Nilsson).

The Intelligent agent is defined by {Actions, Goals, Knowledge}

(A) Actions:	A physical existence capable of actions
(G) Goals:	A desired state of the environment
(K) Knowledge:	The ability to choose actions to accomplish goals.

Main Frame Computers : The Birth of AI
Planning and Problem Solving

Intelligence is the Ability to Solve Problems



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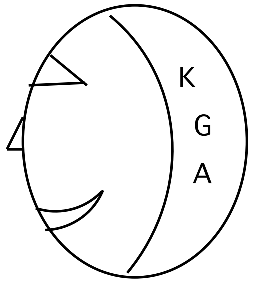


The principle of Rationality: An agent {A,G,K} is intelligent if it is able to choose Actions to accomplish Goals (Newell)

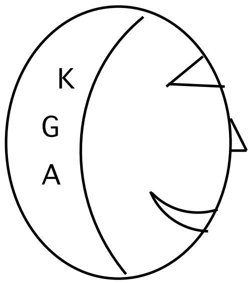
Knowledge: Anything the allows the agent to accomplish Goals (Newell).

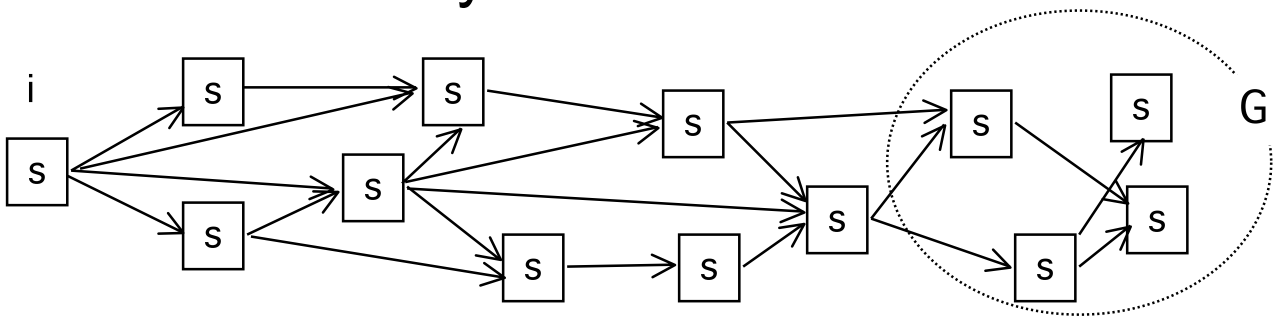
Formal Foundation: State Space definition of a problem domain.

Action, Goals and Knowledge are defined in a problem domain composed of States, Actions, and Goals.

Planning and Problem Solving

Intelligence is the Ability to Solve Problems





Problem Domain: U = ({S}, {A}, {G})

{S} : A set of states, defined as a conjunction of predicates (truth functions)
{A}: A set of transitions between states (actions)
{G}: A set of goal states; States to be reached.

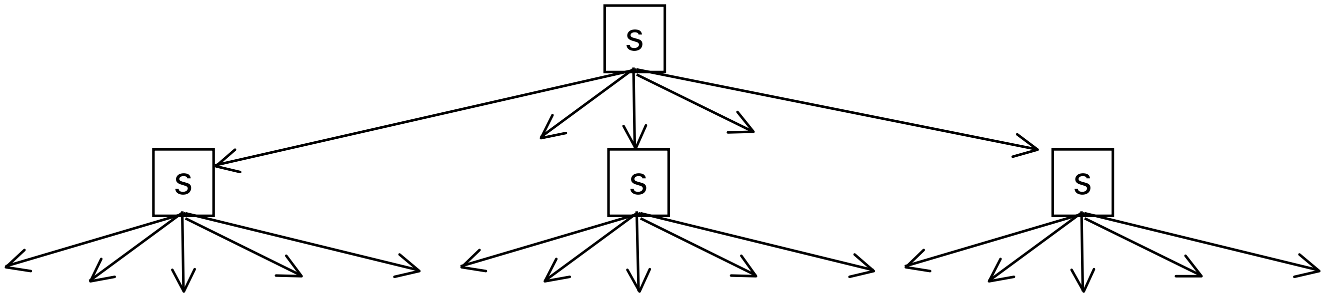
A Problem: i, U
i : An initial state, U: A problem domain.

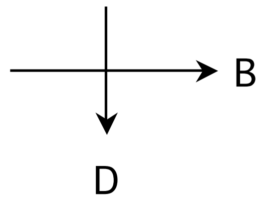
Planning: the search for a path of actions leading from s to g $\in$ {G}

Main Frame Computers : The Birth of AI

Planning and Problem Solving

Intelligence is the Ability to Solve Problems





Problem: Exponential Combinatorial Explosion.

Classes of Planning Algorithms:

B = Branching Factor, D = Depth, Number of Actions required

1) Exhaustive: Depth First, Breadth First: Time = $O(B^D)$
2) Heuristic Search: Time = $O(C^D)$ where $C \leq B$ (Prune the tree.)
3) Hierarchical Search (Subproblems) Time = $O(B^{D1}+B^{D2})$ where $D1+D2 \geq D$
4) Anytime Search : Bounded search time with suboptimal answer.

1980s : Mini-Computers and the The AI Bubble

Expert Systems

Intelligence = Knowledge + Inference

Feigenbaum: Rule Based Reasoning: Lots of Knowledge and a little bit of reasoning

- E. A. Feigenbaum : The Art of Artificial Intelligence: Themes and Case Studies of Knowledge Engineering , IJCAI , 1977

Newell: Symbol Manipulation using models from Cognitive Science

- A. Newell, (1980), Physical Symbol Systems, Cognitive Science, 4, pp 135-183.

Minsky : Frames and Schema Systems - Lots of Reasoning with a bit of knowledge

- Marvin Minsky, A Framework for Representing Knowledge, in: Patrick Henry Winston (ed.), The Psychology of Computer Vision. McGraw-Hill, New York (U.S.A.), 1975.

1980s : Mini-Computers and the The AI Bubble

Expert Systems

Intelligence = Knowledge + Inference

1970 to 1980 : The Stanford Heuristic Programming Project (A. Feigenbaum)

Hypothese : Intelligence = Lots of domain knowledge, aided by a little bit of reasoning.

Approach: Transcribe Expert Knowledge in computer code.

Dendral (1970-1973) - A system to identify molecules from spectrograms

Result: Hacked Code. Impossibly complex program of domain knowledge.

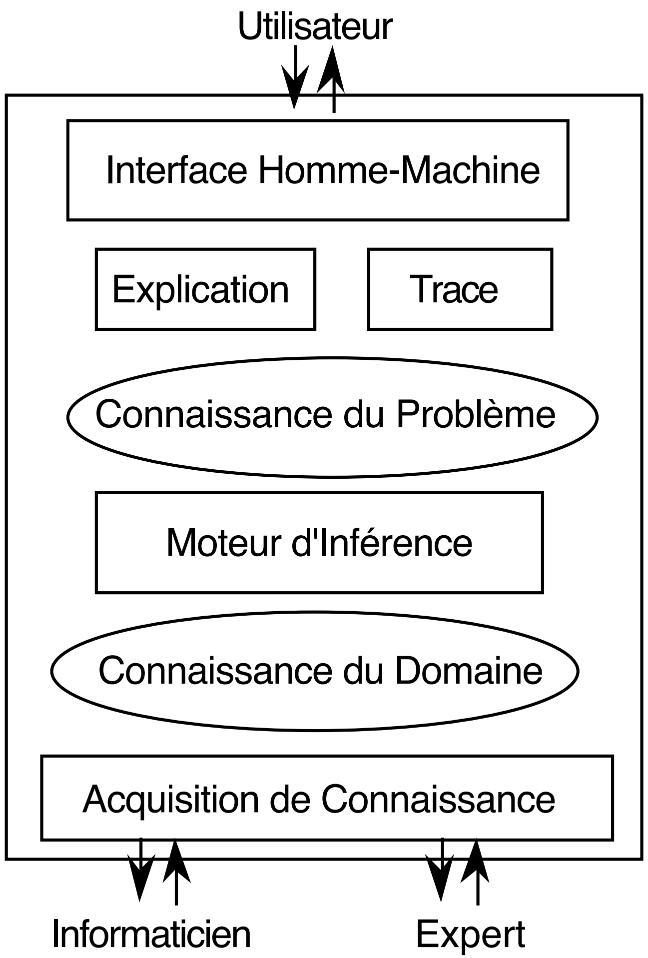
Lesson learned - Code domain knowledge as rules.

Mycin (1973 - 1980) - An Antibiotic therapy advisor.

The first TRUE expert System.

MYCIN: The first successful Expert System

Mycin: An Antibiotic Therapy advisor



Domain knowledge coded by a programmer working with a domain expert.

Inference Motor: Backward chaining rule based implementation of Abduction

Problem data: Obtained interactively from user.

Advise: Provided in natural language. User can always ask "Why" and "How".

Major Innovations:

1) Every fact labeled with a certainty factor.

2) Separation of inference and domain knowledge

MYCIN: The first successful Expert System

Mycin: An Antibiotic Therapy advisor

Domain Knowledge: Context tree

Facts: (context, parameter, Value, CF)

Reasoning: ABDUCTION coded with

Backward chaining rules. Abduction tree

Major Innovation: ALL FACTS labeled with certainty factor CF $-1 \leq CF \leq 1$

Abduction: If B and C then Maybe(A).

Reasoning: Backward Chaining Rules with

(A, CF_A) <-(CF)- (B, CF_B) AND (C, CF_C) with $CF_A = CF \times \mathrm{Min}\{CF_B, CF_C\}$

EMYCIN: General Expert System

EMycin: A General Expert System Shell.

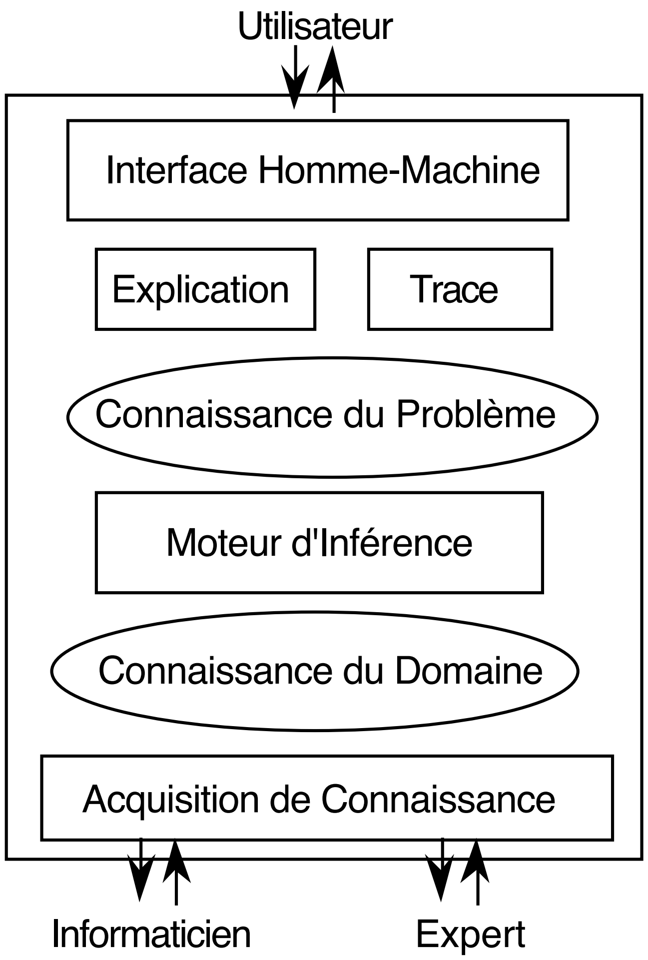
Feigenbaum removed the domain knowledge to create "EMYCIN", commercialised by a startup: Technowledge.

EMYCIN was used for prospecting and discovered a Major new source of ore worth several hundred million dollars.

Technowledge inc attracted enormous investments. The AI Bubble was launched.

Feigenbaum predicted that Expert Systems would revolutionize informatics.

AI Researchers were rich until around 1985.



1980s : Mini-Computers and the The AI Bubble

Expert Systems

Rule Based (production) systems.

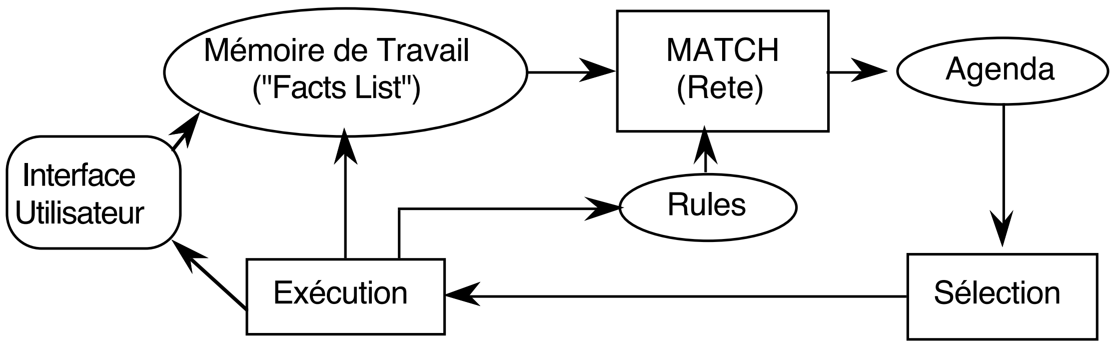
Productions are Forward Chaining Rules (proposed by Post in 1946).

A. Newell proposed create a general inference engine modeled after "conditioned responses" (Pavlov).

In 1978, A. Newell and L. Forgy proposed a programming system:

OPS - A Operational Problem Solver

The OPS Architecture (1978)



A forward chaining rule based inference engine.

Principle: Trigger Rule (reflexes) with Facts in short term memory

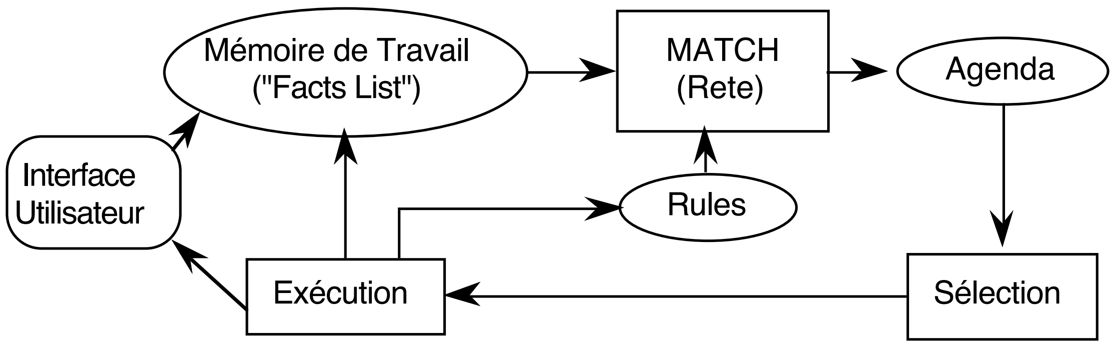
Operation: The Recognize - Act Cycle:

Match - Select - Execute.

Fundamental problem - Exponential Algorithmic Complexity of Matching facts to rules.

Solution: The RETE algorithm.

The OPS Architecture (1978)



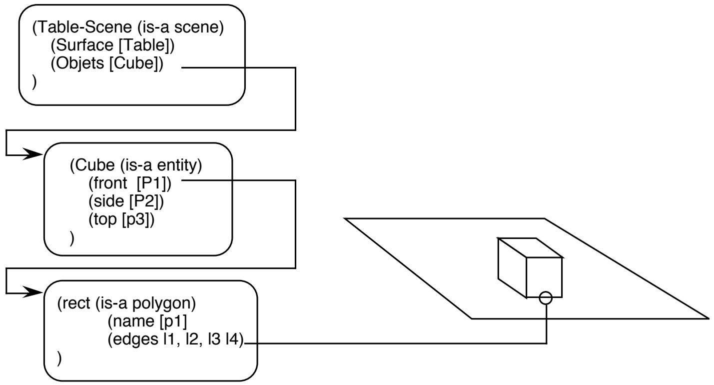
In 1980 J. McDermott applied OPS to solve the Compatible Configuration Problem for VAX computers sold by Digital Equipment.

From 1981 to 1984 DEC saved several hundred MILLION dollars.

AI Researchers were highly sought as consultants. (grad students made fortunes : -)

- 1981 OPS was commercialized by DEC
- 1982 OPS was commercialized as ART (by adopted as a standard by NASA.)
- In 1986 Nasa realized a C language public domain version CLIPS
- CLIPS (and RETE) are now widely used as on-board supervisors of spacecraft, and for logistics planning.

Structured Knowledge Representation



<u>Structure Knowledge Representations</u> (Schema) were explored as a general representation for declarative knowledge.

Computer Vision: FRAMES (Computer Vision:)

- Marvin Minsky, A Framework for Representing Knowledge, in: Patrick Henry Winston (ed.), The Psychology of Computer Vision. McGraw-Hill, New York (U.S.A.), 1975.

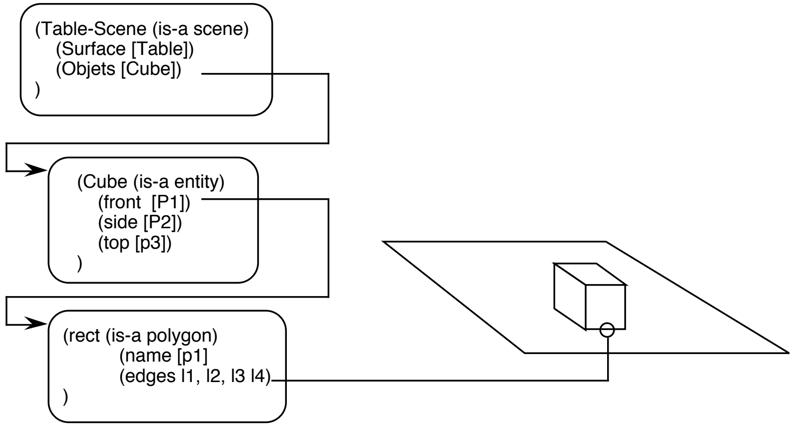
Language: Semantic Nets

- M.Quillian, (1968). Semantic Memory, in M. Minsky (ed.), Semantic Information Processing, pp 227-270, MIT Press

Story Understanding: Scripts

- Schank and Abelson Scripts, Plans, Goals and Understanding, Erlbaum, 1977.

Structured Knowledge Representation



FRAMES (Computer Vision:)

- Marvin Minsky, A Framework for Representing Knowledge, in: Patrick Henry Winston (ed.), The Psychology of Computer Vision. McGraw-Hill, New York (U.S.A.), 1975.

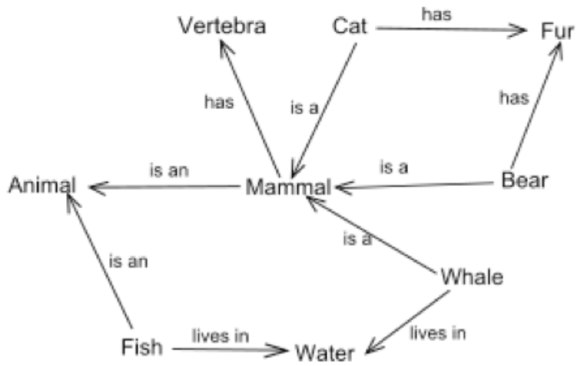
A Structured Representation to provide context for focussing visual interpretation of scenes.

A Frame tells the program what to look for and where to look for it.

Problems:

1) Frame acquisition is long, tedious, and ad hoc
2) Recognizing the proper frame to apply to a new scene.

Structured Knowledge Representation



Semantic Nets

- Network of semantic relations between concepts.
- Used as a form of knowledge representation for language understanding and translation

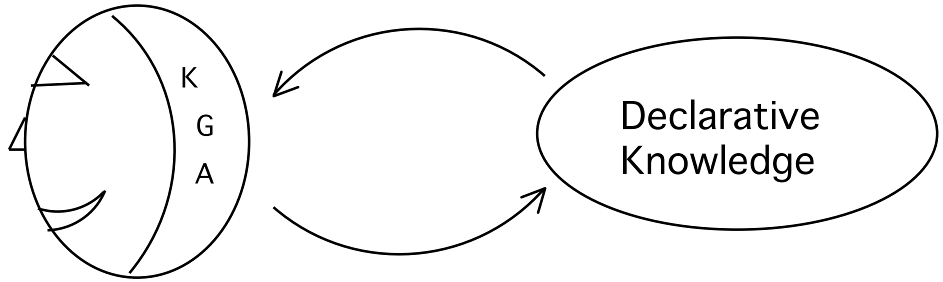
References

- M.Quillian, (1968). Semantic Memory, in M. Minsky (ed.), Semantic Information Processing, pp 227-270, MIT Press
- J. F. Sowa (1987). "Semantic Networks". in Stuart C Shapiro. Encyclopedia of Artificial Intelligence. Retrieved 2008-04-29.

1980s : Mini-Computers and the The AI Bubble

Expert Systems

Physical Symbol System Hypothesis (PSSH)



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

- Newell, Allen; Simon, H. A. (1976), "Computer Science as Empirical Inquiry: Symbols and Search", Communications of the ACM, 19

Origins: B. Russel, L Wittegenstein, AJ Ayer, E. Kant, G. Leibniz, T. Hobbes, and others

PSSH became dogma in the 1980's and was severely criticized in the 90's and rejected in the 2000's

Personal Computing - The 90's
Logical Foundations and the Behavioral Backlash

1990's Formal methods sterilized Artificial Intelligence

Logic Programming. Neats vs Scruffies

- Genesereth, Michael; Nilsson, Nils (1987), *The Logical Foundations of Artificial Intelligence*, Morgan Kaufmann

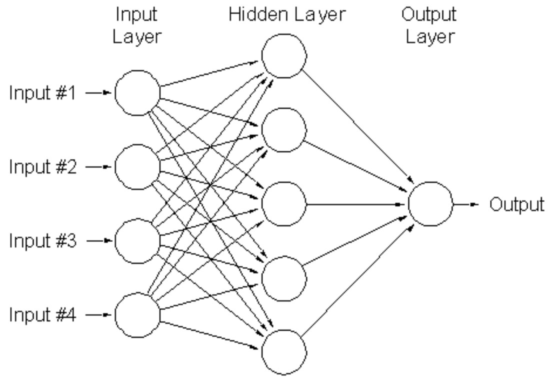
Behavioural robotics brought it back

RA Brooks: Behaviour Robotics

- Brooks, R. A., (1990), "Elephants Don't Play Chess", Robotics and Autonomous Systems (6), pp. 3–15.
- Brooks, R. A., (1991), "Intelligence Without Representation", Artificial Intelligence Journal (47), pp. 139–159.

Personal Computing - The 90's
Artificial Neural Networks

Artificial Neural Networks: A two Layer Perceptron.



Artificial Neural Networks were a "Loose analogy" of biological neural networks that became popular in the in '80s

- D.E. Rumelhardt, G.E. Hinton, and R. J. Williams, (1988), "Learning internal representations by error propagation", in Neurocomputing: Foundations of research, pp 673-695, MIT Press, Cambridge.

G. Hinton Showed that Artificial Neural Networks trained with "Back-propagation" were powerful recognition engines.

ANNs were learned "black boxes" that learned to solve classic hard problems in speech recognition and computer vision.

The result was a growth in learning in machines that learn.

Eventually Bayesian learning replaced Back-propagation as a learning mechanism.

Mobile Computing - 2000
Bayesian Reasoning and Machine Learning

Bayesian Reasoning as a foundation for Cognition

Baysian Reasoning: Probabilistic inference using Bayes Rule to combine statistical evidence and a-priori probabilities.

- Pearl, J. (1988) *Probabilistic Reasoning in Intelligent Systems,* San Mateo, CA: Morgan Kaufmann.

Bayes Rule can be implemented with statistics (histograms), or with Probabilty Densities (a-priori information).

Uses: Machine Learning, Classification, Estimation, Reasoning.

$$\text{Bayes Rule}: \; P(Hypothesis \mid Evidence) = \frac{P(Evidence \mid Hypothesis)P(Hypothesis)}{P(Evidence)}$$

Mobile Computing - 2000
Bayesian Reasoning and Machine Learning

Bayesian Machine Learning has produced dramatic results in

1) Speech Recognition
2) Face Detection and Recognition
3) Visual Category Learning
4) Machine Translation
5) Data Mining.

$$\text{Bayes Rule}: \ P(Hypothesis \mid Evidence) = \frac{P(Evidence \mid Hypothesis) P(Hypothesis)}{P(Evidence)}$$

Mobile Computing - 2000
Cognitive Systems

Intelligence as a Collection of Cognitive Abilities

Convergence of ideas from Artificial Intelligence, Computer Vision, Robotics, Cognitive Science, Machine Learning.

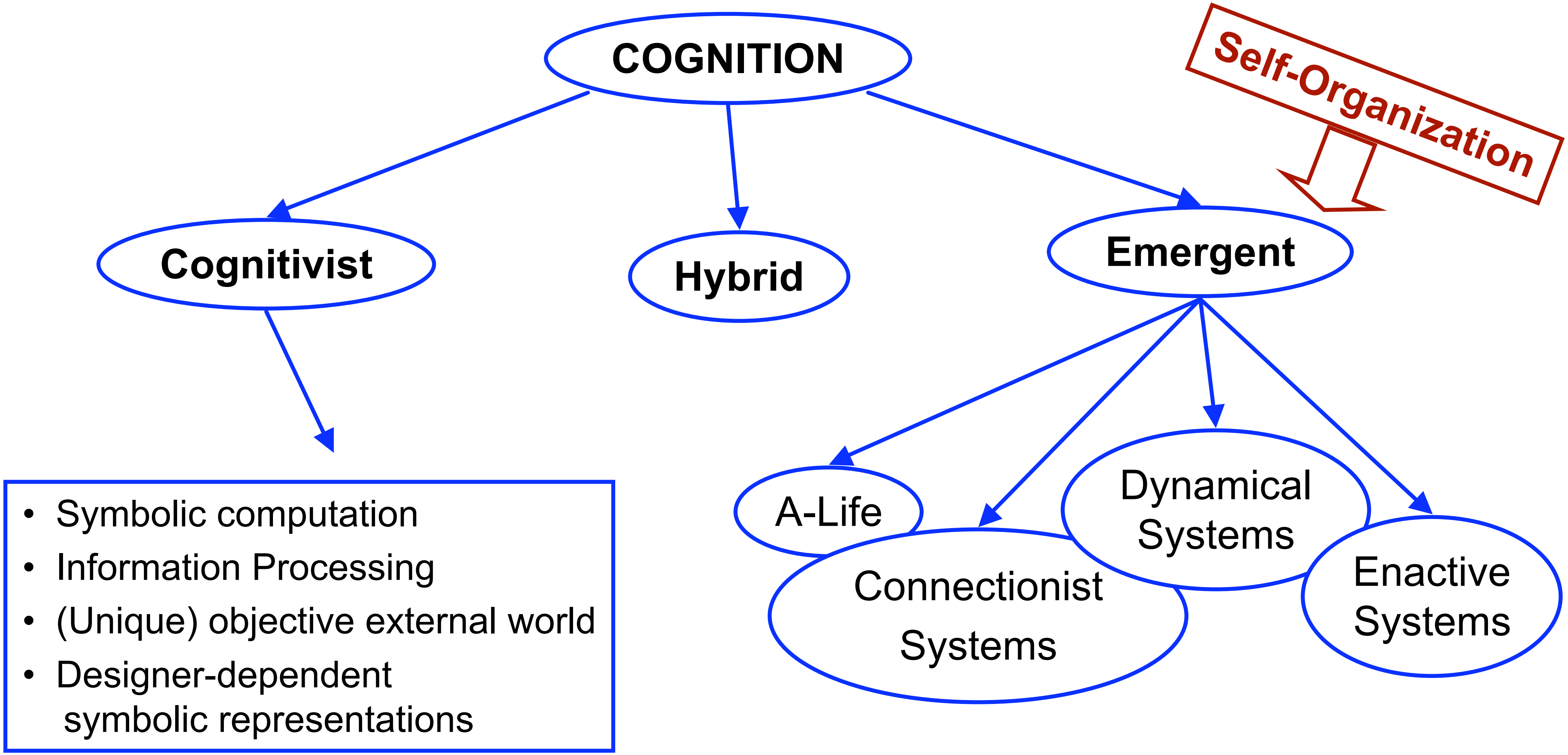
Cognitive Abilities: The ability to choose actions to accomplish goals.

Fundamental principles:

1. Cognitive Abilities can be reactive, procedural or symbolic
2. Cognitive Abilities are highly domain specific.

Paradigms of Cognitive Systems

(From EU Cognitive Systems Research Roadmap 2002)



Paradigms of Cognitive Systems

(From EU Cognitive Systems Research Roadmap 2002)

Cognitivist **Hybrid** **Connectionist** **Dynamical** **Enactive**

- Knowledge provided by human designers
- Possibly refined through learning
- Brittle

  Representations based axioms & assumptions of an external designer
- Fail when they stray far from the domain for which they were designed

Paradigms of Cognitive Systems

(From EU Cognitive Systems Research Roadmap 2002)

Cognitivist **Hybrid** **Connectionist** **Dynamical** **Enactive**

- Generic representational schemes
- Populated entirely by the agent
- Incremental unsupervised learning
- Deliberative behaviour designed in

(link between perceptual-motor skill and knowledge representation controlled by designer)

Paradigms of Cognitive Systems

(From EU Cognitive Systems Research Roadmap 2002)

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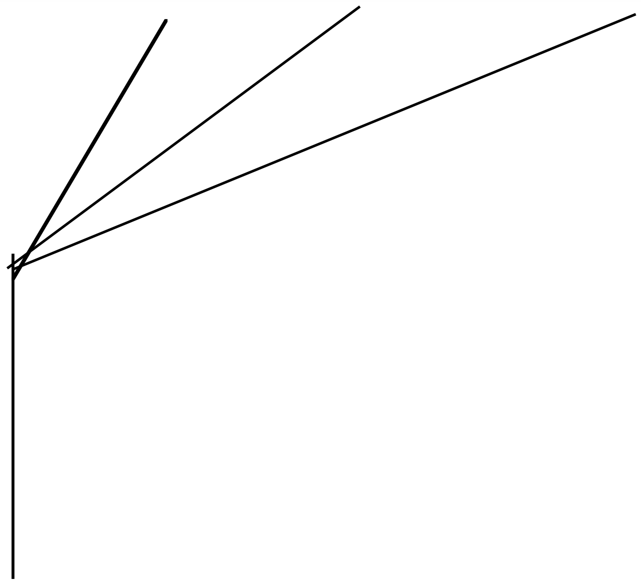


- No 'representations' – no symbols
- States encapsulate knowledge derived by the system
- Historical context of ontogenic development

Paradigms of Cognitive Systems

(From EU Cognitive Systems Research Roadmap 2002)

<u>Open Questions in the EU Research Roadmap</u>

Phylogeny vs. Ontogeny

- Hardwired function vs Learned Capabilities

The need for embodiment

- The argument for embodied cognition
- Impact of embodiment on perception and action

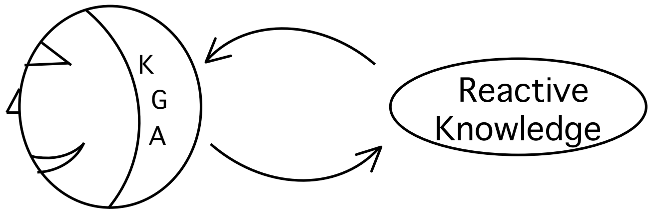
Scientific challenges

- Methods for continuous learning and development
- Minimal architectures
- Goal identification and achievement
- Generalization

Cognitive Systems
Intelligence as a Collection of Cognitive Abilities

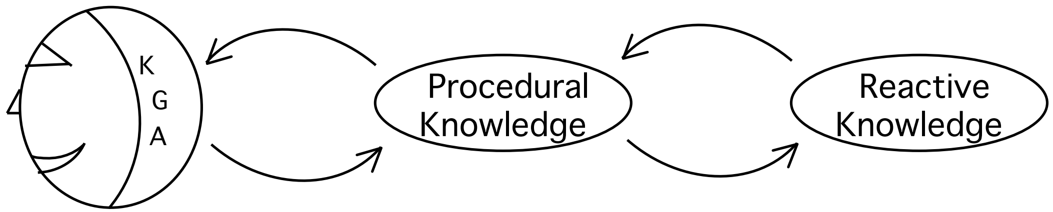
Core Cognitive Abilities (Mental Processes):

Object Constancy, Speech Recognition, Category Assignment, Visual Ego-motion,...



Composed Cognitive Abilities

Social Interaction, Writing, Navigation,..



Minsky proposes an architecture of core cognitive abilities for different forms of recognition, planning, and criticism and argues that Emotions selectively inhibit core cognitive processes.

- M. Minsky, (2006). *The Emotion Machine*. Simon & Schuster.

Internet Computing - 2010

The internet has grown exponentially for 40 years

Size doubles every1.5 years => 2^{26} = 64 Mega machines (2008)

Computer Applications are increasingly written as internet services:
Ad hoc composition of programs on machines distributed over the internet

Examples:

Google, Gmail, Google Maps, Skype, Cloud Computing, Web Commerce, …

The Semantic Web seeks to apply Artificial Intelligence tools to internet Services.

The Semantic Web

Semantic Web: The meaning of information and services on the web are defined, making it possible for services to understand and satisfy requests using the web as a resource.

- T. Berners-Lee, J. Hendler and O. Lassila (2001). "The Semantic Web". Scientific American, May 2001.

Fundamental Problems:

- Ontology Alignment (using structured knowledge Representation)
- Data Mining (Using Bayesian machine learning)
- Context aware Services (recognizing user interests from actions).
  (ex - Google advertising is based on search topic)

What is Next? Ambient Intelligence

The Vision:

- Large numbers (hundreds) of interconnected devices equipped with Sensing, Actuation, Networked Communications, and Man-Machine Interaction.
- Embedded in everyday human environment (furniture, buildings, appliances).
- Providing Context aware services

Convergence of:

- Embedded Systems
- Context aware computing
- Multi-modal human-computer Interaction
- Massively distributed computing.

Beyond Internet Computing - 2020

Ambient Intelligence -The Internet of Things

Technologies that are

- embedded: many networked devices integrated in the environment
- context aware: devices recognize individuals and situations
- personalized: Providing services for people
- adaptive: That respond and adapt to people
- anticipatory: anticipate desires without explicit command.

References

- Zelkha, Eli; Epstein, Brian (1998), "From Devices to "Ambient Intelligence"", Digital Living Room Conference, June 1998

- Aarts, Emile; Harwig, Rick; Schuurmans, Martin (2001), chapter "Ambient Intelligence" in The Invisible Future: The Seamless Integration Of Technology Into Everyday Life, McGraw-Hill Companies

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Intelligence <u>describes</u> the <u>interaction</u> of an <u>entity</u> with its <u>environment</u>.*

*Cognitive Systems Research Roadmap (2002), European Commission, ECVision Network (David Vernon, Editor).

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Intelligence describes the interaction of an entity with its environment.*

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Intelligence describes an entity that interacts.

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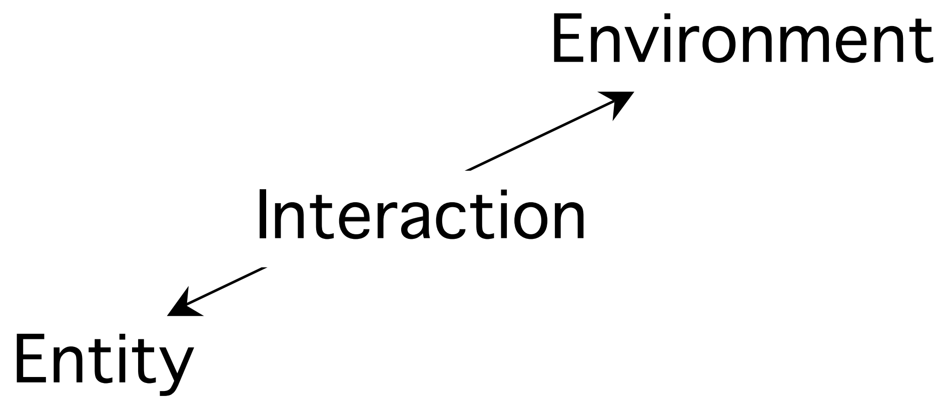
What do we mean by Intelligent?



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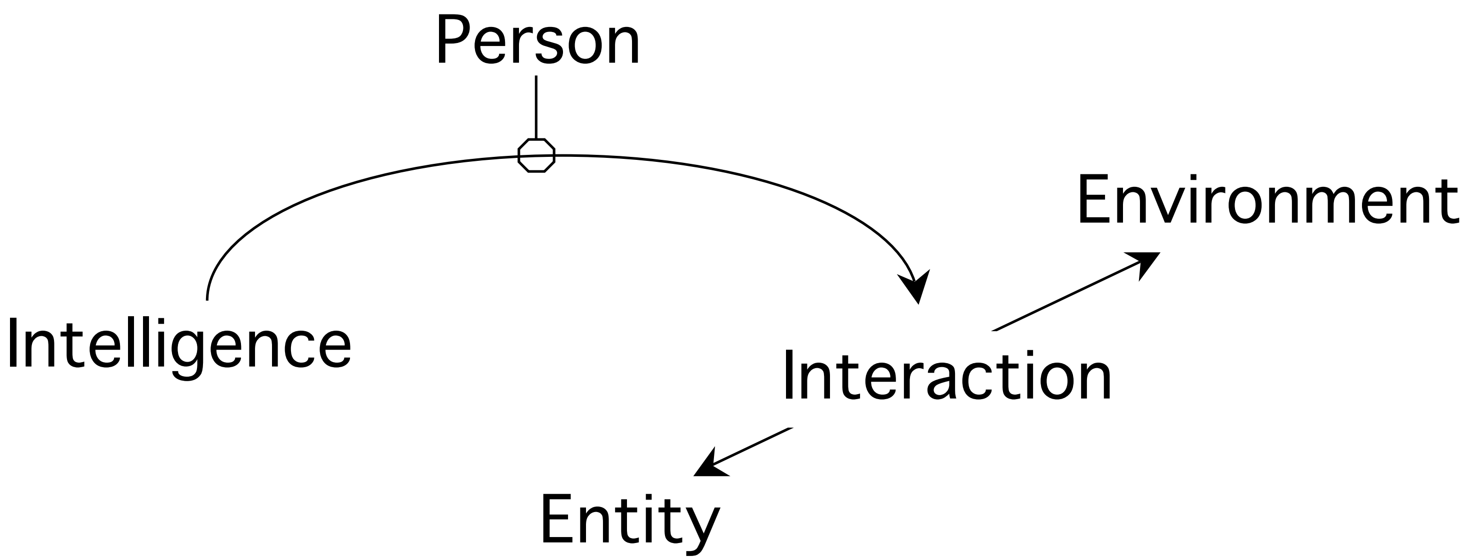

Intelligence describes the interaction of an entity with its environment.*

What do we mean by Intelligent?

To be considered as "intelligent" a system should be embodied, autonomous, and situated. *

Embodied:	Possessing a body
Autonomous:	Self-governing;
	Having independent existence
Situated:	Behaviour determined by the environment

- *C. Breazeal, Designing Sociable Robots, MIT Press, 2002.
- L. Steels, and R. Brooks, The artificial life route to artificial intelligence: Building Situated Embodied Agents. New Haven: Lawrence Erlbaum Ass., 1994.

Intelligent = Embodied, Autonomous and Situated

Embodied: Incarnated. Possessing a body.

Body: A sensori-motor system for tightly coupled interaction with an environment.

Examples of Bodies:

- Natural: Human, mammal, insects, bacteria, plants,
- Artificial: Humanoid Robot, AIBO, mobile robots, roomba?
- Abstract: none.

Intelligent = Embodied, Autonomous and Situated

Embodied: Incarnated. Possessing a body.

Body: A sensori-motor system for tightly coupled interaction with an environment.

Environment: A system composed of multiple interacting entities.

Examples of Environments:

- Natural: Jungle, desert, sea floor….
- Artificial: Office, home, family, social network, computer games…
- Abstract: Chess, mathematics, any academic discipline…

Embodied Systems

Body: A sensori-motor system for tightly coupled interaction with an environment.

Some debatable positions (exploring the limits):

Embodied Systems

Body: A sensori-motor system for tightly coupled interaction with an environment.

Some debatable positions (exploring the limits):

Can a body be distributed?

Yes, provided it acts as a single "entity", (ex: Ant colony)

Embodied Systems

Body: A sensori-motor system for tightly coupled interaction with an environment.

Some debatable positions (exploring the limits):

Can an animated "talking head" be a body?

Yes, if part of a larger entity engaged in tightly coupled interaction. (Þanimation is a kind of action)

Embodied Systems

Body: A sensori-motor system for <u>tightly coupled</u> interaction with an environment.

<u>Some debatable positions</u> (exploring the limits):

Can a computer simulation be a body?

No, because it can not act, hence is can not interact.

but…

Evolutions in the Understanding of Intelligence
From Symbol Manipulation to Cognitive Systems

Outline

- The Scientific Study of Artificial Intelligence
- Epochs in Computing
- Epochs in Artificial Intelligence
  - Pre 1960: Automata and Recognition
  - 1960-1980: Planning and Problem Solving
  - 1970-1990: Expert Systems
  - 1980-2000: Logic, Neural Networks and Behavioral Robotics
  - 1990-2010: Cognitive Systems
  - 2000-2020: The Semantic Web
  - 2010-2030: Ambient Intelligence
- What do we mean by intelligence?