
10 MINUTES
Average general attention span.
Continuous attention span is 8 secs.

Cognitive systems
– a systems engineering approach

Jan Larsen
Cognitive Systems Section
Dept. of Informatics and Mathematical Modelling
Technical University of Denmark
jl@imm.dtu.dk, www.imm.dtu.dk/~jl

Acknowledgments
-inspiration and aspiration

Lars Kai Hansen

Anders Meng

Ling Feng

Tobias Andersen

Søren Kyllingsbæk

Ingemar Cox

Michael Kai Petersen

Acknowledgments
-inspiration and aspiration

Simon Haykin

Sue Becker

Josh Bongard

Michael Wicks

Jeffrey Reed

Nikita Visnevski

What is it? - a vision for the future

An artificial cognitive system is the ***ultimate learning*** and thinking machine with ability to operate in ***open-ended environments*** with ***natural interaction*** with humans and other artificial cognitive systems and plays key role in the transformational society in order to achieve augmented *capabilities beyond* human and existing machines

Alan Turing 1950: *"We can only see a short distance ahead, but we can see that there is much to be done"*

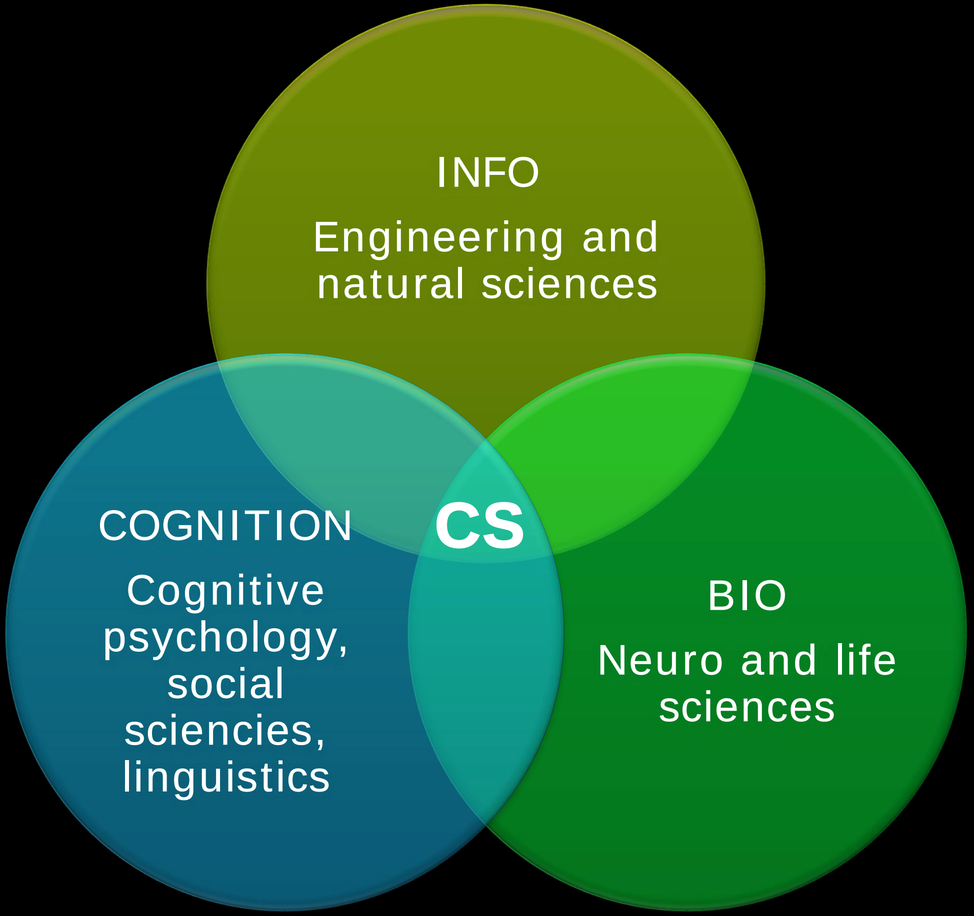
Jim Dator's definition of the transformational society: humans, and their technologies, and the environments of both, are all three merging into the same thing. Humans, as humans, are losing their monopoly on intelligence, while new forms of artificial life and artificial intelligence are emerging, eventually perhaps to supersede humanity, while the once-"natural" environments of Earth morph into entirely artificial environments that must be envisioned, designed, created and managed first by humans and then by our post-human successors.

A vision with great implications

Ubiquitous interaction between humans and artificial cognitive systems

- Ethical (maybe new regulatory bodies)
- Cultural (inclusiveness)
- Political (regulations and policies)
- Economical (digital economy and instability)
- Social (collaboration, globalization, conflicts)
- Anthropological (transformational society)

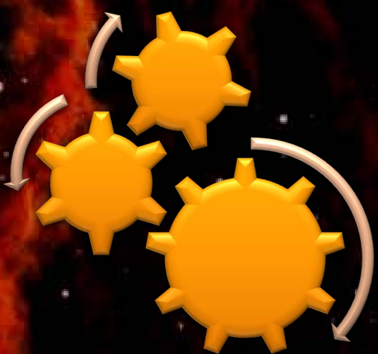
It takes cross-disciplinary effort to create a cognitive system



Ref: EC Cognitive System Unit http://cordis.europa.eu/ist/cognition/index.html

Scope

- The field of CS is to large to be covered in this tutorial
- The field of CS is still in its embryonic stage
  - Focus on a 360 degrees view of the concepts in cognitive systems
  - illustrated by specific examples



a systems engineering approach

Ref: Wikipedia: *Systems engineering is an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed*

A brief history

- Late 40's Allan Touring: theory of computation
- 1948 Claude Shannon: A Mathematical Theory of Communication
- 1948 Norbert Wiener: Cybernetics - *Control and Communication in the Animal and the Machine*
- 1950 The Touring test
- 1951 Marvin Minsky's analog neural networks
- 1956 Dartmouth conference: Artificial intelligence with aim of human like intelligence
- 1956-1974 Many small scale "toy" projects in robotics, control and game solving
- 1974 Failure of success and Minsky's criticism of perceptron, lack of computational power, combinatorial explosion, Moravec's paradox: simple tasks are not easy to solve

A brief history

- 1980's Expert systems useful in restricted domains
- 1980's Knowledge based systems – integration of diverse information sources
- 1980's The neural network revolution starts
- Late 1980's Robotics and the role of embodiment to achieve intelligence
- 1990's and onward AI research under new names such as machine learning, computational intelligence, evolutionary computing, neural networks, Bayesian networks, informatics, complex systems, game theory, **cognitive systems**

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

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

Revitalizing old ideas through cognitive systems by means of enabling technologies

Computation

distributed and ubiquitous computing

Connectivity

internet, communication technologies and social networks

Pervasive sensing

digital, accessible information on all levels

New theories of the human brain

Neuroinformatics, brain-computer interfaces, mind reading

New business models

Free tools paid by advertisement, 99+1 principle: 99% free, 1% buys, the revolution in digital economy

The unreasonable effectiveness of data

- E. Wigner 1960: The unreasonable efffectiveness of mathematics in the natural sciences.
- Simple linear classifiers ba… representations performs better than elaborate models.

There is often a threshold of sufficient data

- Unsupervised learning on unlabeled data which are abundant
- The power of linking many different sources
- Semantic interpretation
  - The same meaning can be expressed in many ways – and the same expression can convey many different meanings
  - Shared cognitive and cultural contexts helps the disambiguation of meaning
  - Ontologies: a social construction among people with a common shared motive
  - Classical handcrafted ontology building is infeasible – crowd computing / crowdsourcing are possible

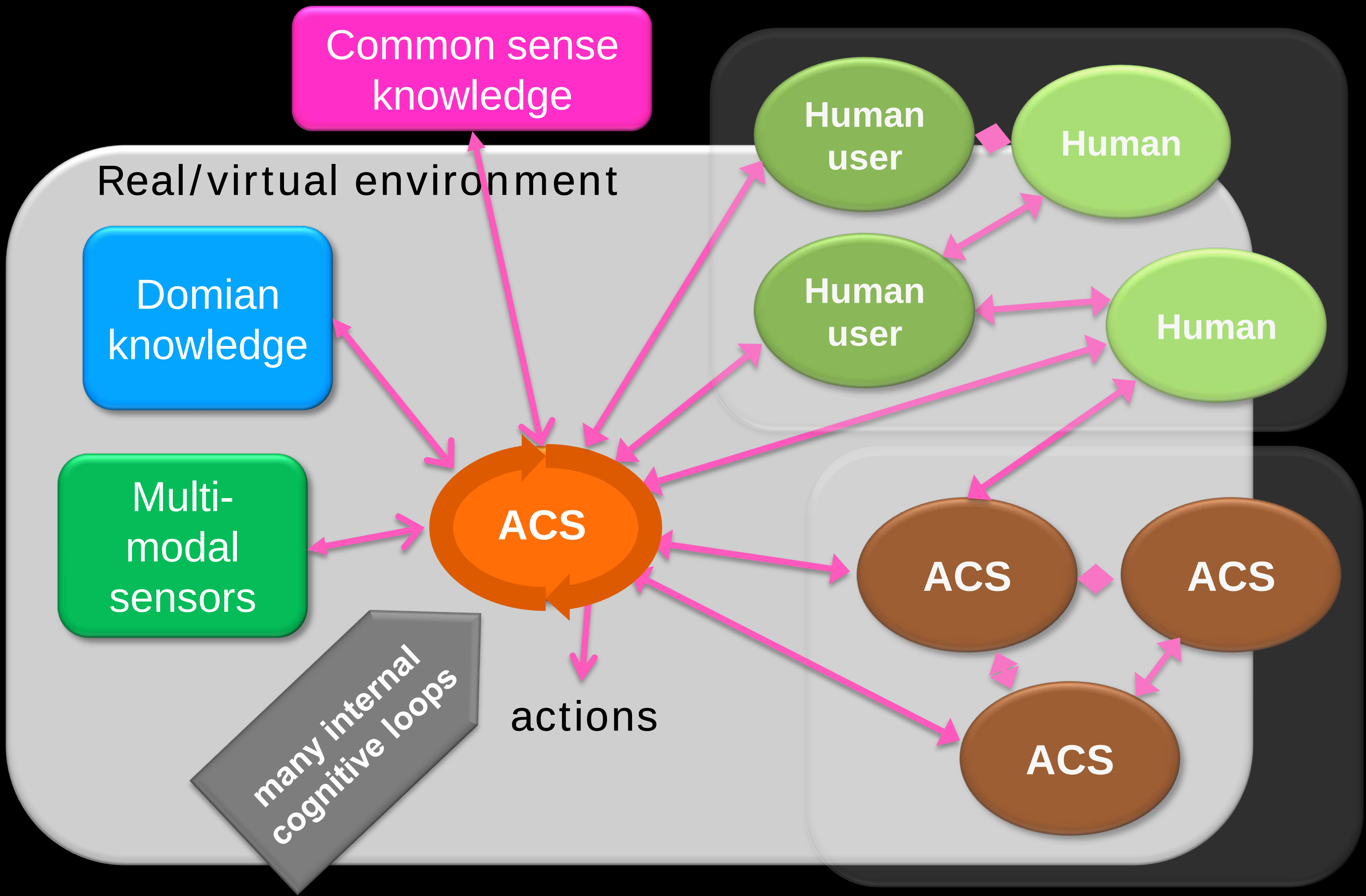
Ref: A. Halevy, P. Norvig, F. Pereira: The unreasonbale effectiveness of data,

IEEE Intelligen Systems, March/April, pp. 8-12, 2009.

Outline

- A 360 degrees view of the concepts in cognitive systems
  - How: data, processing
  - Why: goals
  - What: capabilities
- Examples of state of the art along diverse dimensions

The cognitive system and its world



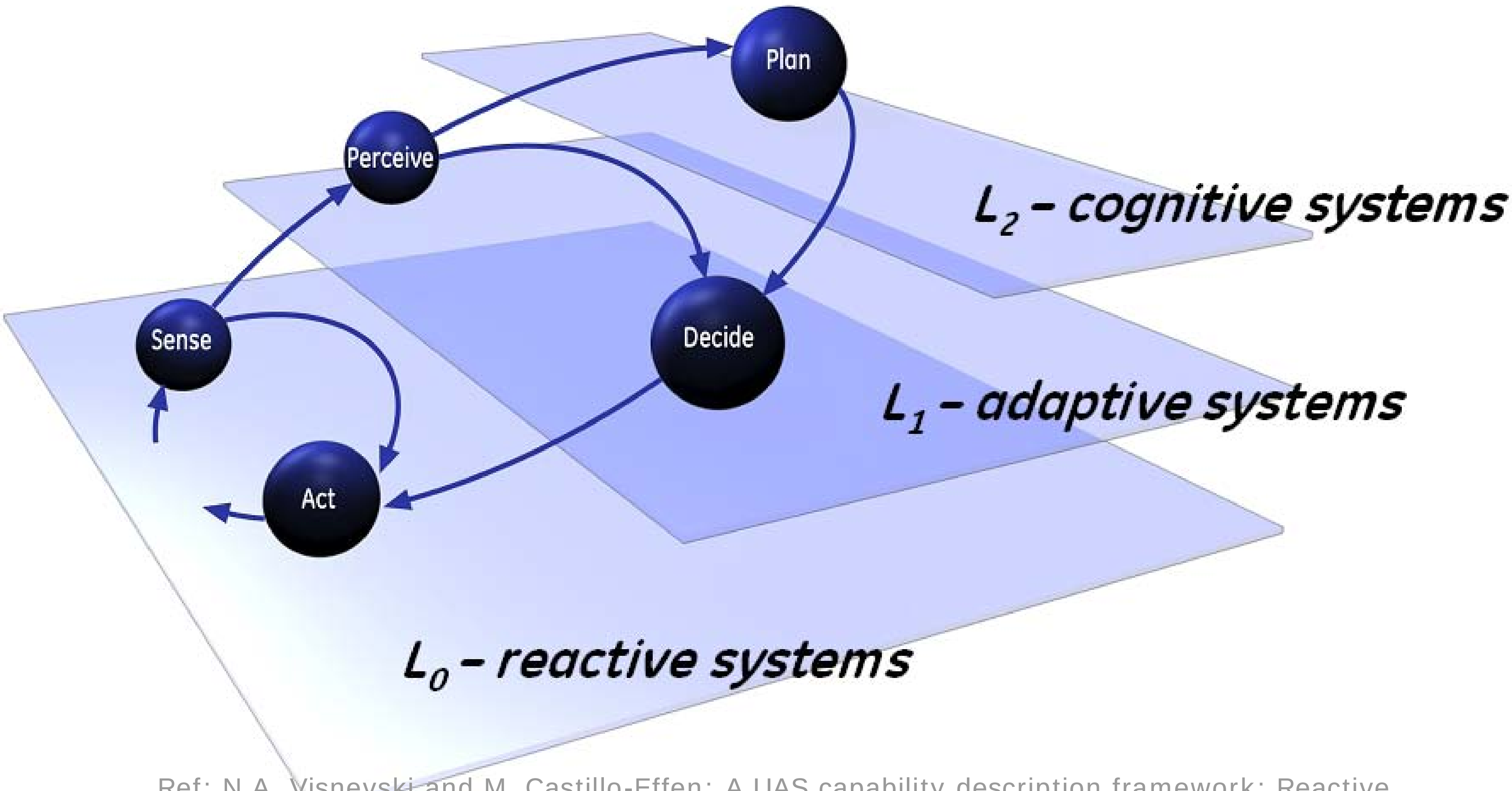
Cognitive systems

- Why: goals
- How: data, processing
- What: capabilities

How much is needed to qualify the system as being cognitive?

A tiered approach: from low to high-level capabilities

Visnevski / Castillo-Effen tiered approach



Ref: N.A. Visnevski and M. Castillo-Effen: A UAS capability description framework: Reactive, adaptive, and cognitive capabilities in robotics, 2009 IEEE Aerospace Conference, pp. 1-7, 2009.

Why - goals

Disentanglement of confusing, ambiguous, conflicting and vast amounts of multimodal, multi-level data and information

Perform specific tasks

- Exploration
- Retrieval
- Search
- Physical operation and manipulation
- Information enrichment
- Making information actionable
- Navigation and control
- Decision support
- Meaning extraction
- Knowledge discovery
- Creative process modeling
- Facilitating and enhancing communication
- Narration

How – data, processing and computing

Dynamical, multi-level, integration and learning of

– heterogeneous,
– multi-modal,
– multi-representation (structured/unstructured),
– multi-quality (resolution, noise, validity)
– data, information and interaction streams

with the purpose of

- achieving relevant specific goals for a set of users,
- and ability to evaluate achievement of goals

using

- new frameworks and architectures and
- computation (platforms, technology, swarm intelligence, grid computing, crowd computing)

What - capabilities

Robustness

- Perturbations and changes in the world (environment and other cognitive agents)
- Graceful degradation
- Ability to alert for incapable situations

Adaptivity

- Handling unexpected situations
- Attention
- Ability to adapt to changes at all levels: data, environment, goals
- Continuous evolution

What - capabilities

Effectiveness

- Level of autonomy
- Prediction
- Learning at all levels (interactive learning)
- Generalization
- Pro-activeness
- Multi-level planning (actions, goals)
- Simulation
- Exploration
- Self-evaluation
- Learning transfer
- Emergent behavior
- Handling of inaccuracy and deception

What - capabilities

Natural interaction

- Mediation and ontology alignment
- Handling of ambiguity, conflicts, uncertainties
- Communication
- Multi-goal achievement
- Locomotion and other physical actions

High-level emergent properties (strong AI)

- Consciousness
- Self-awareness
- Sentience (feeling)
- Empathy
- Emotion
- Intuition

Weak AI is preferred as it is easier to engineer and evaluate

Outline

- A 360 degrees view of the concepts in cognitive systems
  - How: data, processing
  - Why: goals
  - What: capabilities
- Examples of state of the art along diverse dimensions

Examples of state of the art along diverse dimensions

- The European dimension
- Cognitive system architectures
- Cognitive radio networks
- Cognitive sensing networks
- Cognitive robotics
- Cognitive knowledge discovery engines
- Cognitive modeling

Eropean level research

- Carried out under 6th and 7th Frame Programs
- 141 projects related to cognition under *cognitive systems* and *intelligent content and semantics* units
- Funding more than 300 M€

Ref: http://cordis.europa.eu/ist/cognition/index.html

http://cordis.europa.eu/fp7/ict/content-knowledge/home_en.html

Eropean level research

General

- Object / scene detection
- Cognitive architecture
- Neuro- and/or behavior modeling
- Probabilistic approaches
- Concept formation and proto-language
- Planning and reasoning
- Learning and adaptation

Robot specific

- Robot-Robot interaction and swarms
- Human-Robot interaction
- Service robotics
- Humanoid robotics
- Roving and navigation (2D & 3D)
- Manipulation and grasping
- Robot benchmarking

Eropean level research

Other

Agency in digital content and service spaces

Cognitive assistance

HW support of cognitive functions

Content and semantics

Creativity and content authoring

Content management and workflow

Content personalisation and consumption

Semantic foundations

Knowledge management

Information search and discovery

Community building, technology assessment, socio-economics

Cognitive system architectures

- A general computational framework which enables the implementation of one or several cognitive system capabilities
- General characteristics
  - Symbolic/cognitivist (mind-computer-analogy)
  - Emergent (no prior rules which emerge)
  - Hybrid
  - Centralized or distributed computing
  - Holistic vs. atomism (modular)
  - Bottom-up vs. top-down processing

References:

http://www.eucognition.org,

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

David Vernon, Giorgio Metta, Giulio Sandini: "A survey of Artificial Cognitive Systems: Implications for the Autonomous Development of Mental Capabilites in Computational Agents," IEEE Trans. Evolutionary Comp., 11(2), 2007

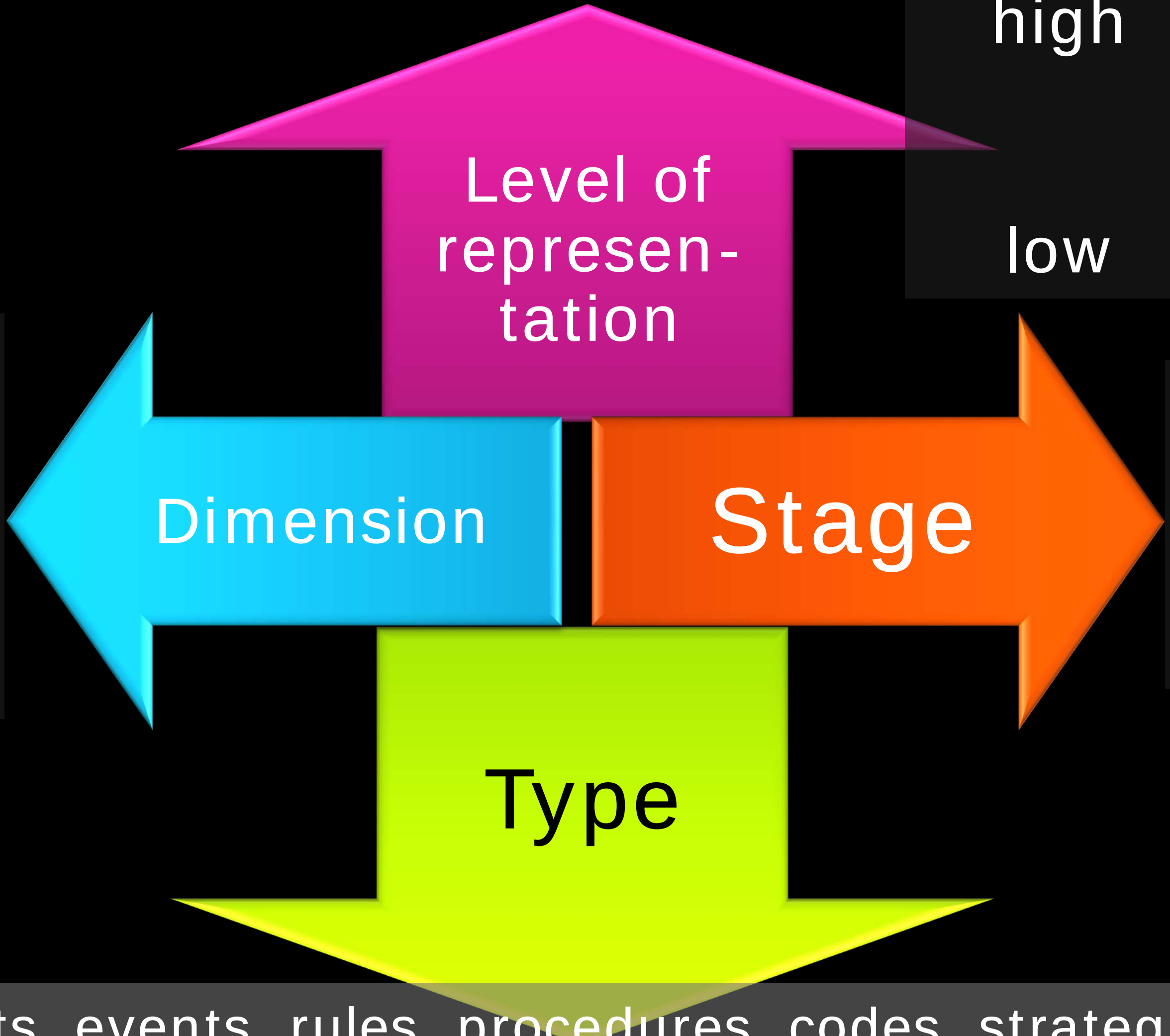
P. Langley, J. E. Laird & S. Rogers: "Cognitive architectures: Research issues and challenges," 2006

Symposium GC5: Architecture of Brain and Mind Integrating high level cognitive processes with brain mechanisms and functions in a working robot, April 2006

Memory system

high

low



visual, auditory, textual, haptic, olfactory, sensors

short
medium
long

Facts, events, rules, procedures, codes, strategies, categories, decisions, plans, theories, simulations

Human memory and learning

TABLE 54.1

Major categories of human learning and memory

System	Other terms	Subsystems	Retrieval
Procedural	Nondeclarative	Motor skills Cognitive skills Simple conditioning Simple associative learning	Implicit
PRS Perceptual representation system	Priming	Structural description Visual word form Auditory word form	Implicit
Semantic	Generic Factual Knowledge	Spatial Relational	Implicit
Primary	Working Short-term	Visual Auditory	Explicit
Episodic	Personal Autobiographical Event memory		Explicit

Ref: M.S. Gazzaniga *et al.:* The Cognitive Neurosciences, Ch. 54 by E. Tulving, 1994.

Cognitive system architectures

Ref: Vernon et al., 2007

The Cognitivist *vs.* Emergent Paradigms of Cognition		
Characteristic	**Cognitivist** /symbolic	**Emergent**
Computational Operation	Syntactic manipulation of symbols	Concurrent self-organization of a network
Representational Framework	Patterns of symbol tokens	Global system states
Semantic Grounding	Percept-symbol association	Skill construction
Temporal Constraints	Not entrained	Synchronous real-time entrainment
Inter-agent epistemology	Agent-independent	Agent-dependent
Embodiment	Not implied	Cognition implies embodiment
Perception	Abstract symbolic representations	Response to perturbation
Action	Causal consequence of symbol manipulation	Perturbation of the environment by the system
Anticipation	Procedural or probabilistic reasoning typically using *a priori* models	Self-effected traverse of perception-action state space
Adaptation	Learn new knowledge	Develop new dynamics
Motivation	Resolve impasse	Increase space of interaction
Relevance of Autonomy	Not necessarily implied	Cognition implies autonomy

Cognitive system architectures properties

Architecture	Paradigm	Embodiment	Perception	Action	Anticipation	Adaptation	Motivation	Autonomy
Soar	C				+	+		
Epic	C		+	+	+			
ACT-R	C		+	+	+	+		
ICARUS	C		+	+	+	+		
ADAPT	C	×	×	×	+	+		
AAR	E	×	×	×			+	×
Global Workspace	E	+	+	+	×		×	×
I-C SDAL	E	+	+	+	+	+	×	×
SASE	E	×	×	×	+	×	×	×
Darwin	E	×	×	+		×	×	×
HUMANOID	H	×	×	×	×	+	+	
Cerebus	H	×	×	×	+	+		
Cog: Theory of Mind	H	×	×	×	+			
Kismet	H	×	×	×			×	

x: strong

+: weak

C: cognitivist

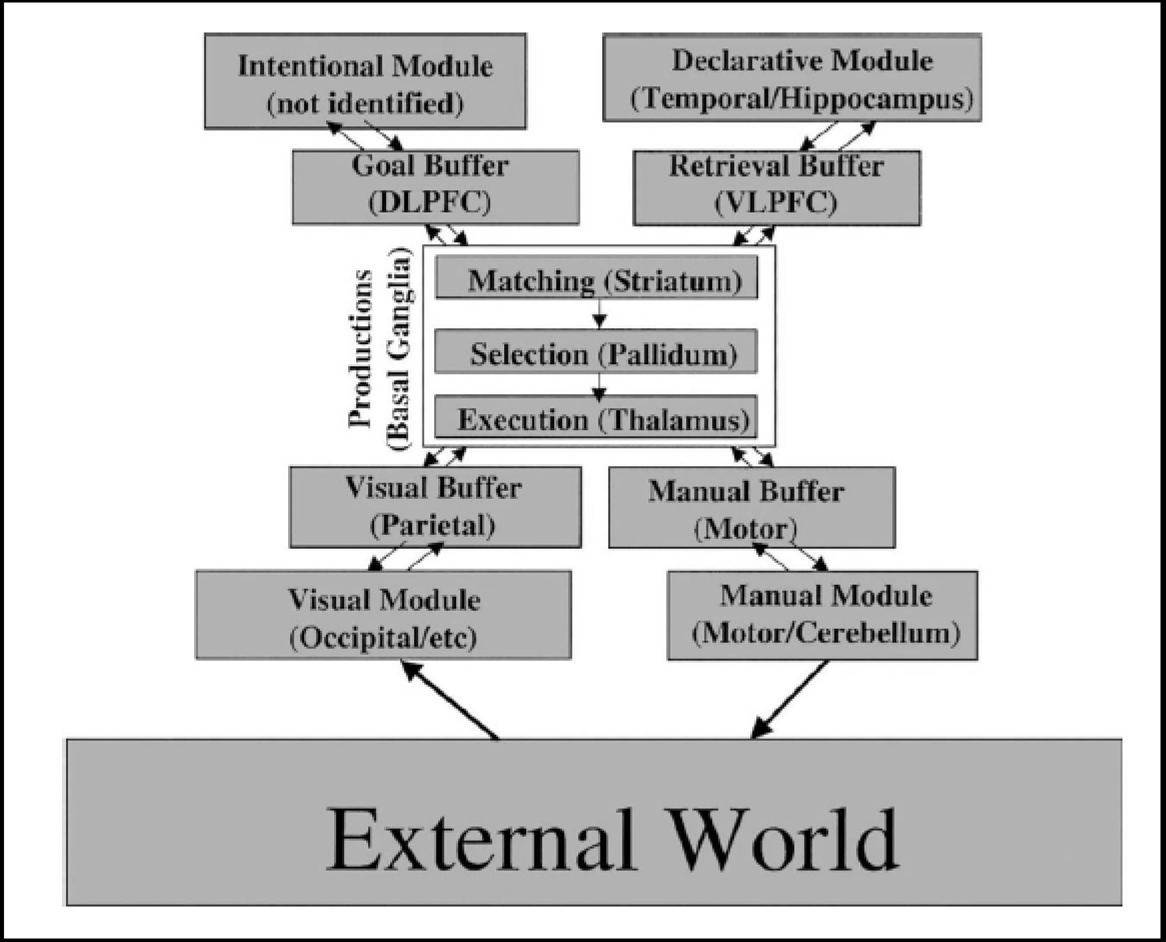
E: emergent

H: hybrid

Ref: Vernon et al., 2007

ACT-R architecture

- Five modules:
  - Vision module identifies objects
  - Manual module for control of hands
  - Declarative module for retrieving info from long term info
  - Goal module tracking internal states
  - Production module for coordination
- Inspired by human information processing



Ref: J.R. Anderson, D. Bothell, and M.D. Byrne

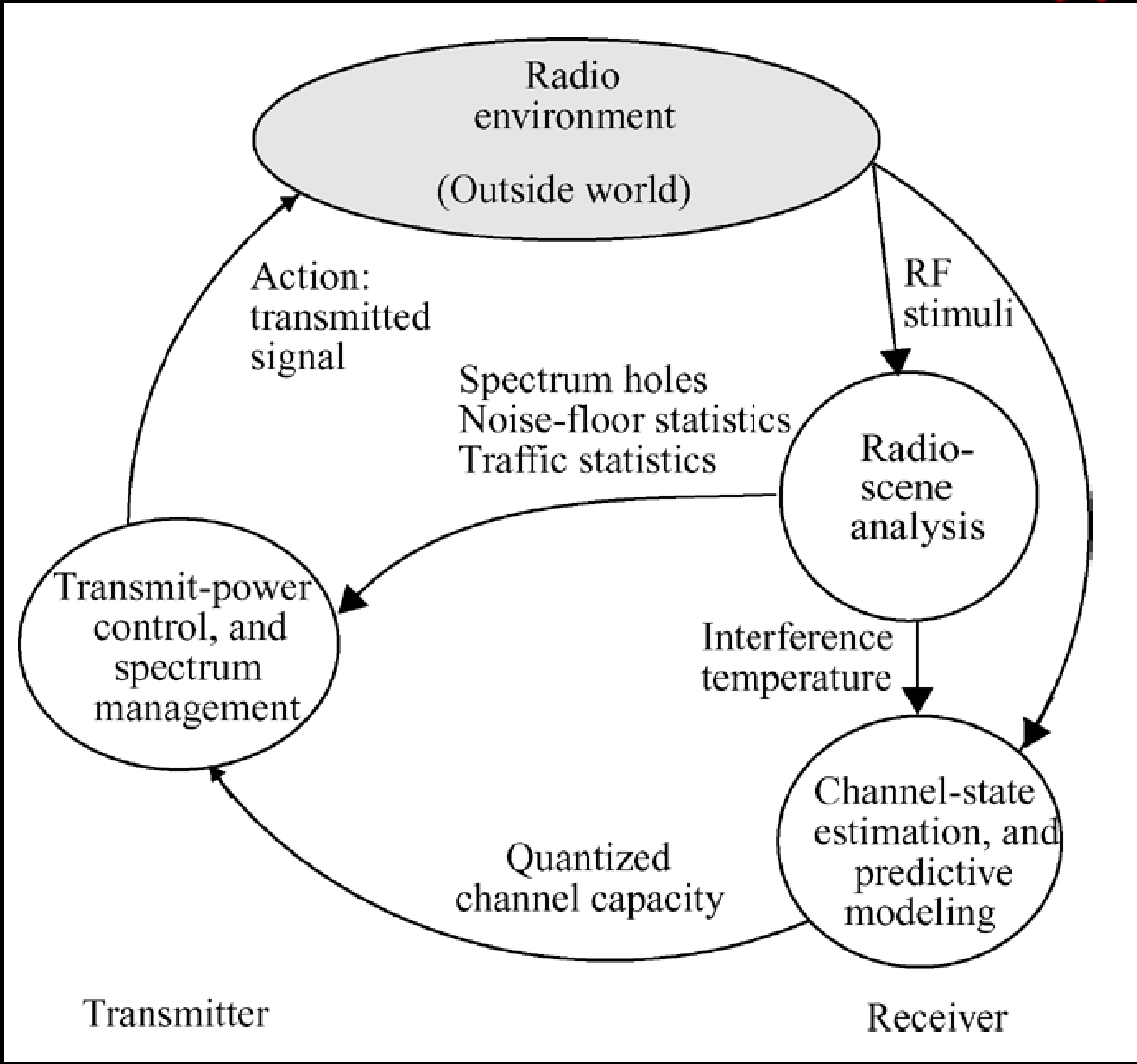
Psychological Review 2004, Vol. 111, No. 4, 1036–1060

Cognitive radio networks

Goals:

•High reliability

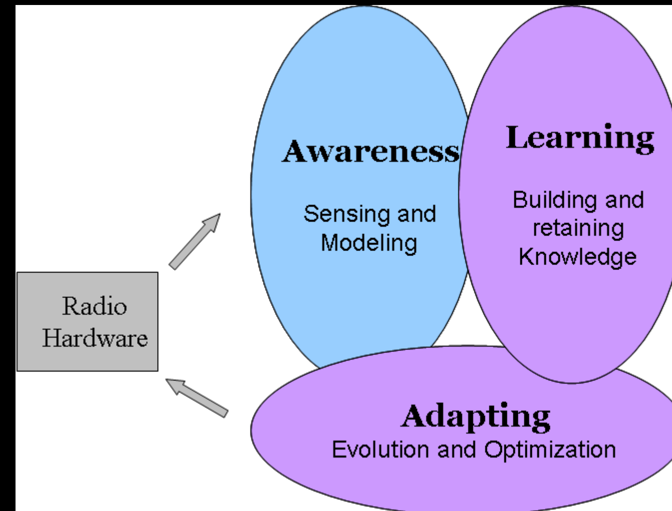
•Efficient utilization of spectrum

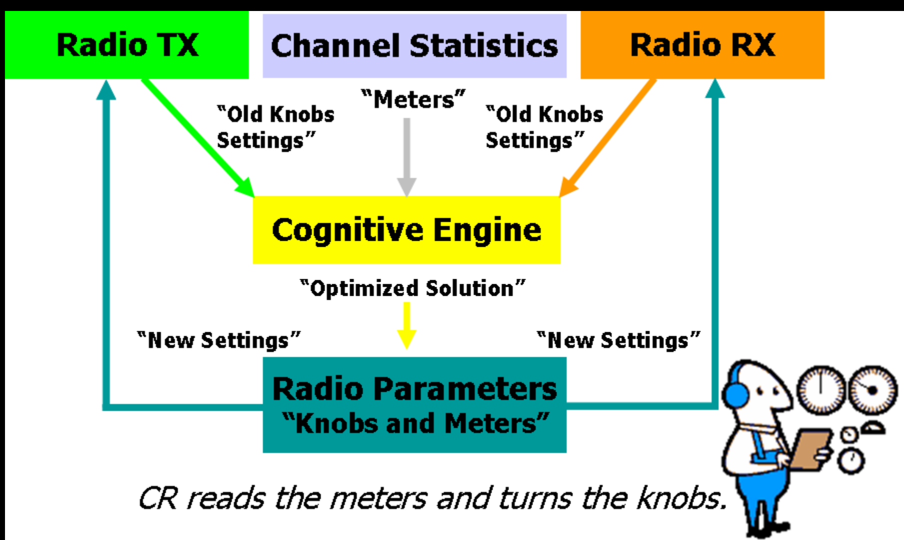


Ref: Simon Haykin: "Cognitive radio: brain-empowered wireless communications," IEEE Selected Areas in Communications, 23(2), 2005

Cognitive Radio Concept

Cognitive radios are flexible and intelligent radios that are capable of...





... and can be realized as a **cognitive engine** (intelligent software package) controlling a software defined **radio platform**.

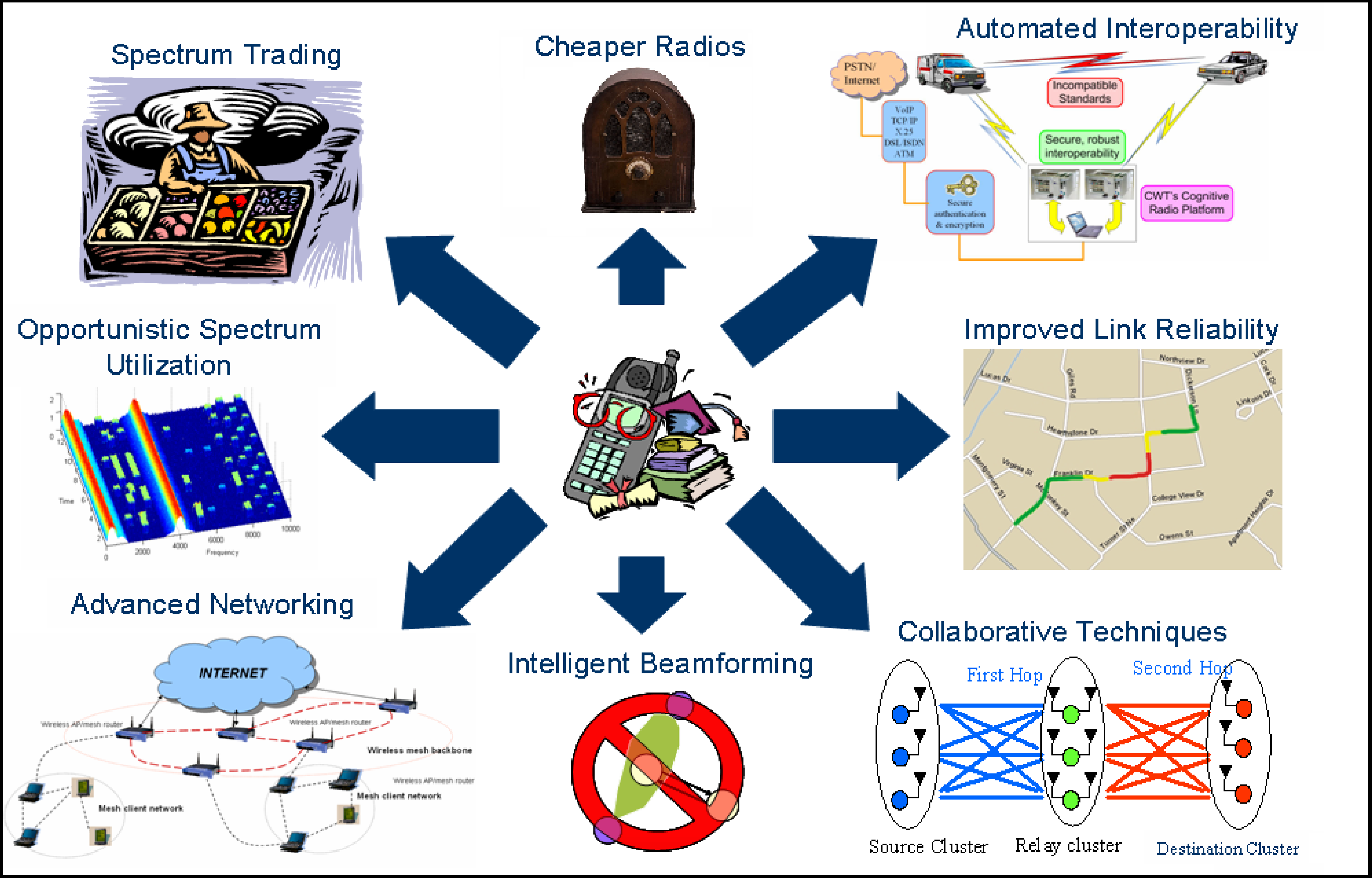
Courtesy of Jeffrey Reed, Virginia Tech

Revolutionary Applications in Cognitive Radio Networks

- Advanced Networking for QoS
- Power Consumption Reduction
- Collaborative Radio – Coverage and capacity extensions
- Femto cells and spectrum management
- Cognitive MIMO, e.g, learning the best spatial modes
- Cellular Radio Resource Management
- Maintenance and Fault Detection of Networks
- Multibanding, e.g., mixing licensed and unlicensed spectrum or protected and unprotected
- Public Safety Interoperability
- Cognitive Routing and prioritization
- Emergency Rapid Deployment and Plug-and-Play optimization
- Enhanced security
- Anticipating user needs – intersystem handoff and network resource allocation
- Smart Antenna management
- Location dependent regulations

Courtesy of Jeffrey Reed, Virginia Tech

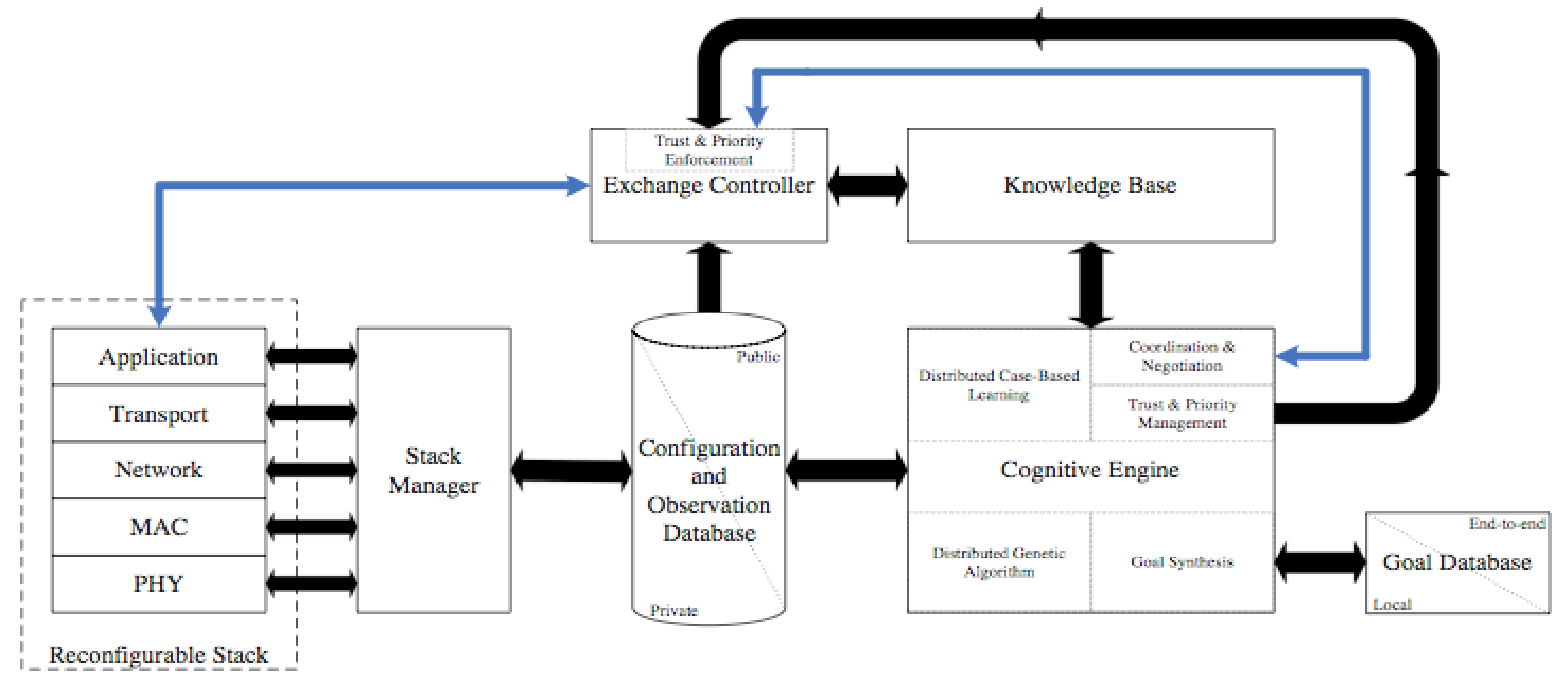
Cognitive Radio Applications



Courtesy of Jeffrey Reed, Virginia Tech

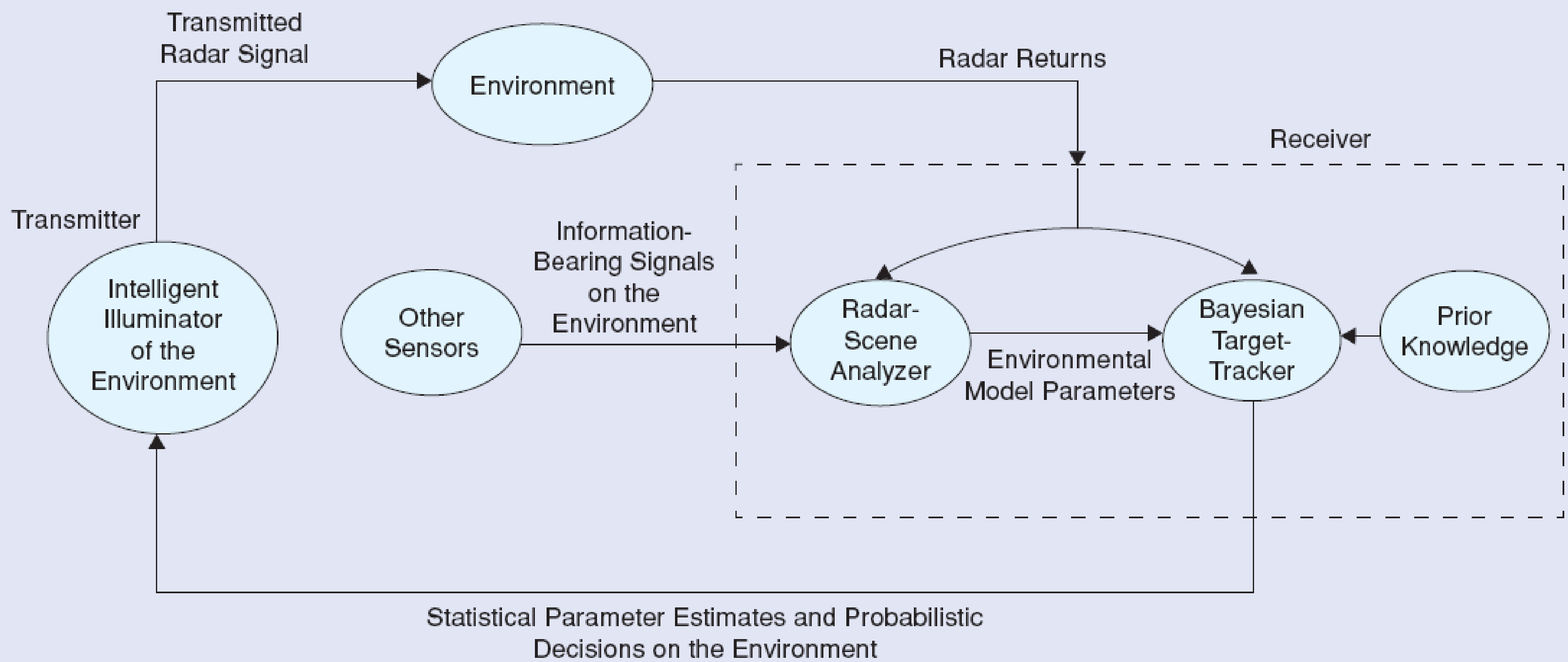
Cognitive Networks

- A single cognitive radio has limited utility.
- Radios must work together to achieve goals, and requires fundamental changes to
  - Routing -- QoS provisioning
  - Spectrum sensing -- Collaboration
- Intelligence is cheaper at the network level than the node level



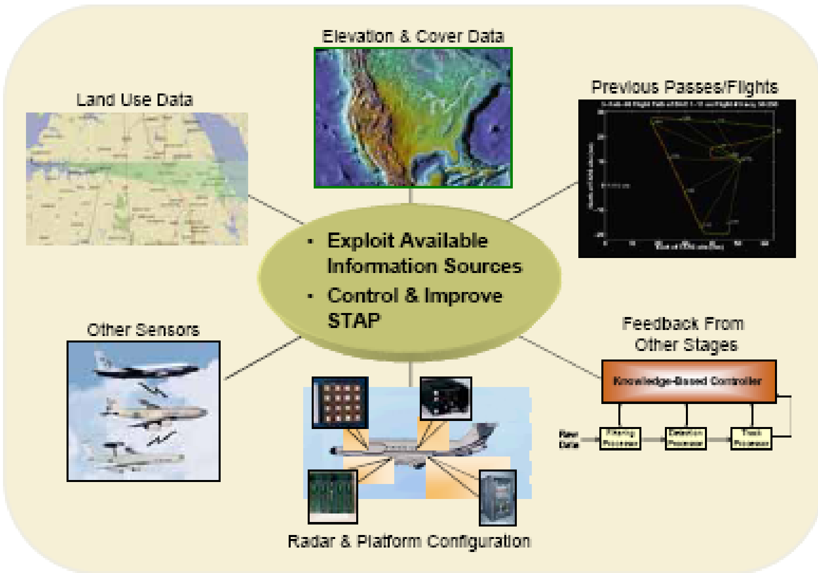
Courtesy of Jeffrey Reed, Virginia Tech

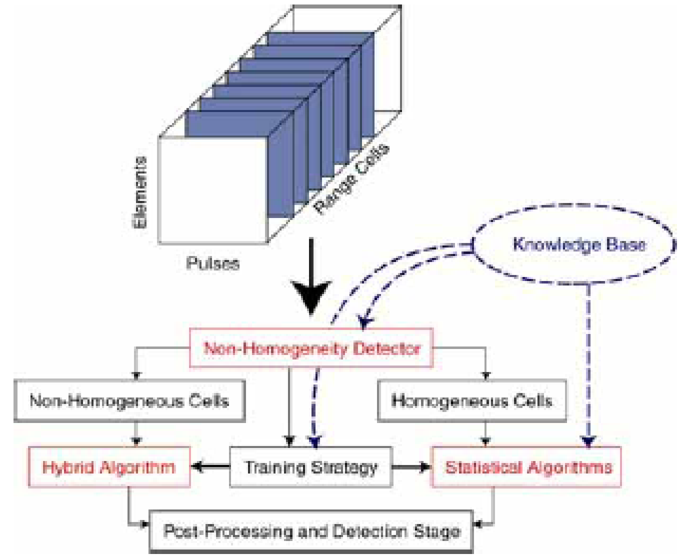
Cognitive sensing networks

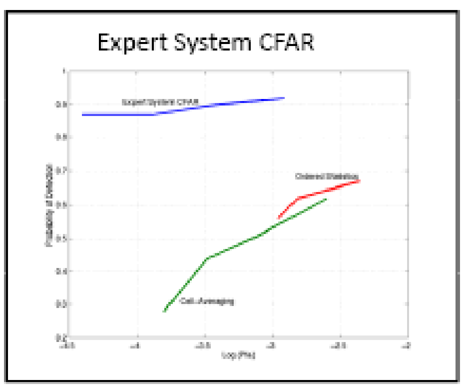


Ref: Simon Haykin: "Cognitive Radar," IEEE Signal Processing Magazine, Jan. 2006

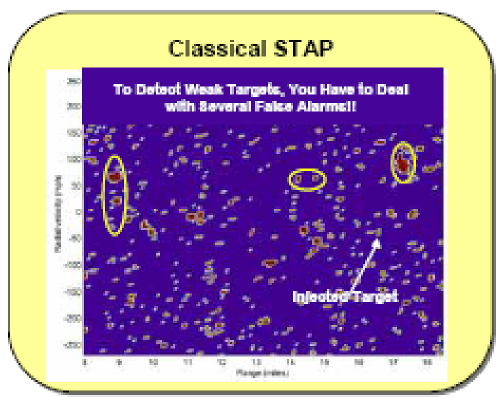
Knowledge Based Signal & Data Processing

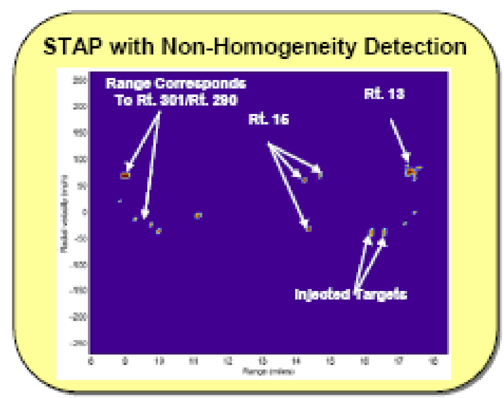






Measured E-3A Data Results



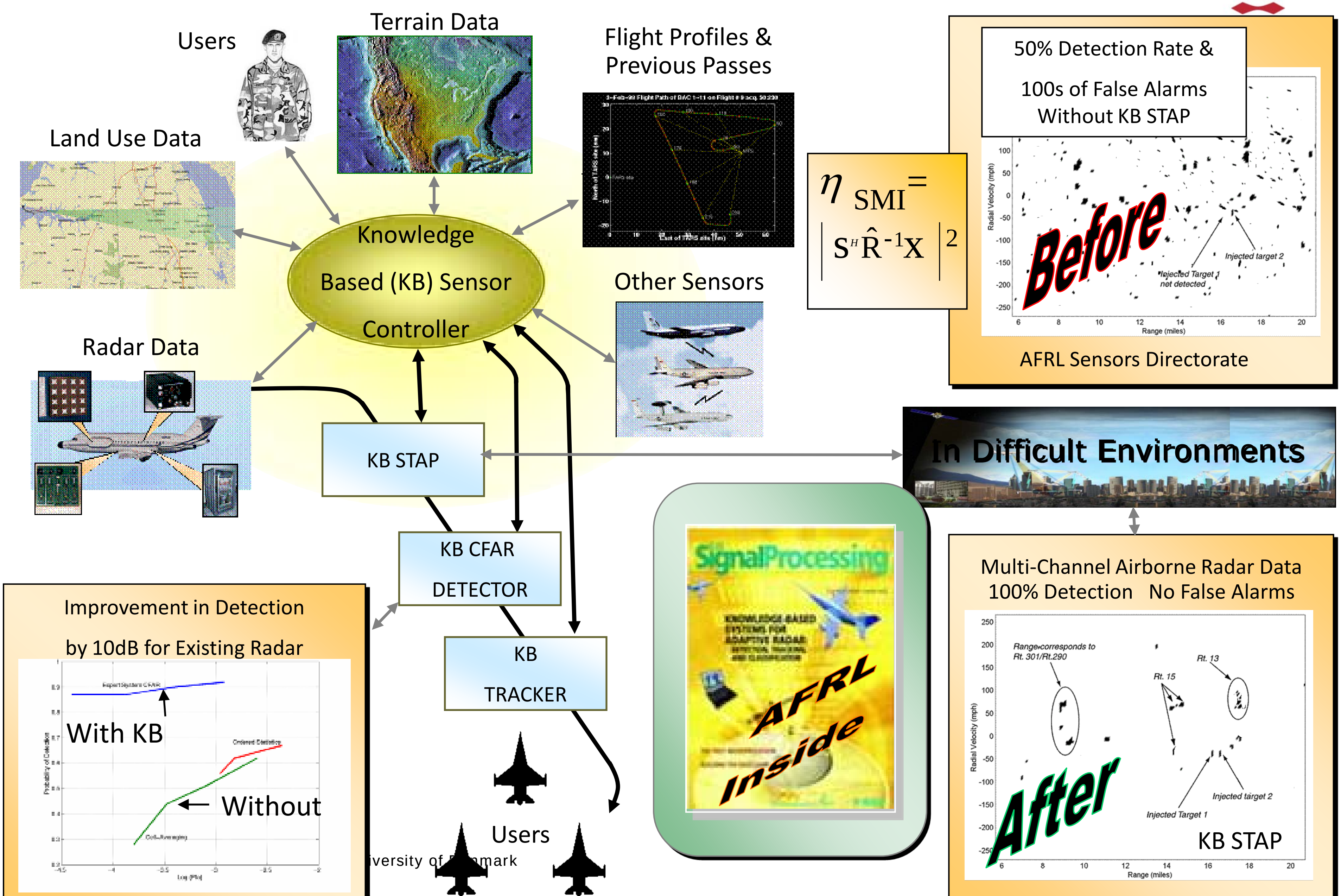


MCARM Data Analysis Results

Courtesy of Michael Wicks, Air Force Research Laboratory, Rome, N.Y.

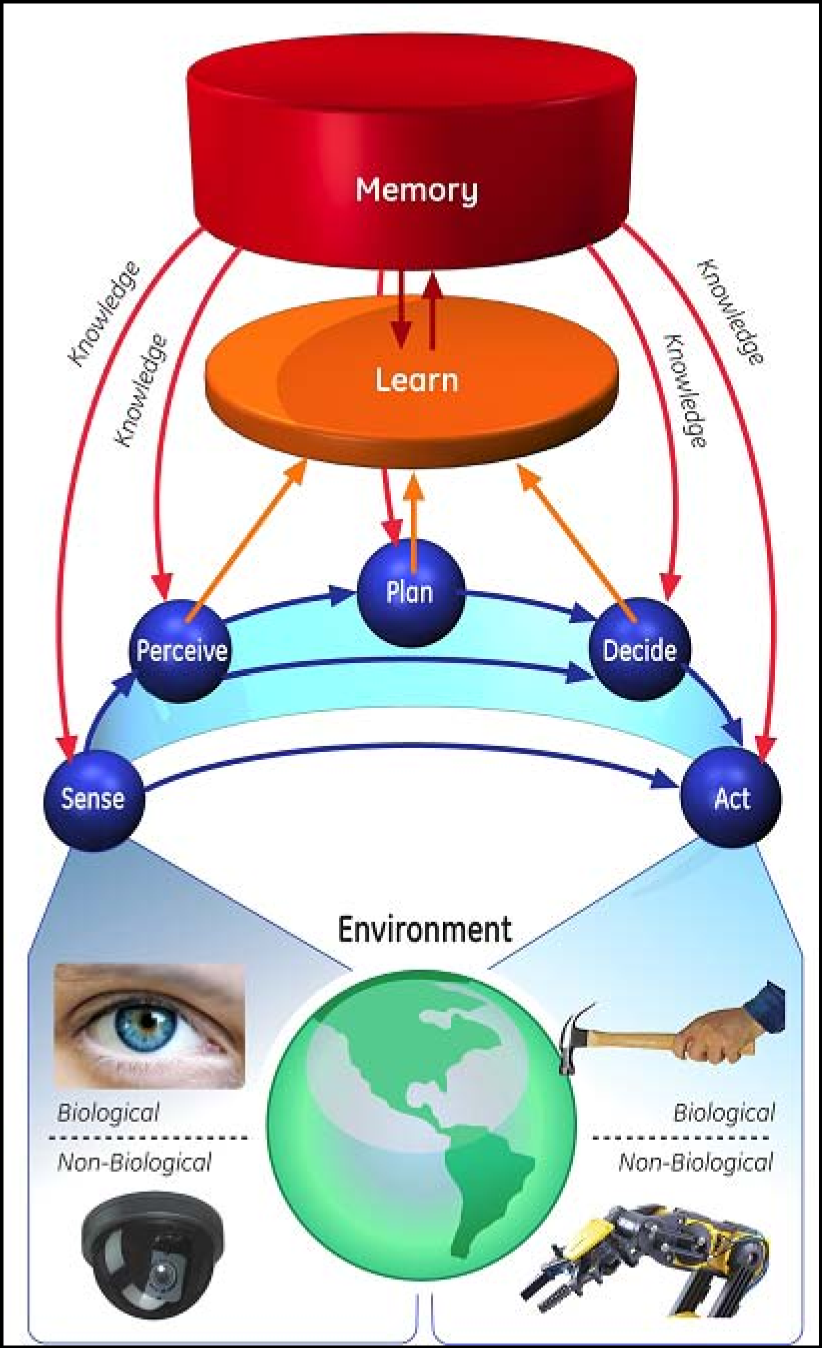
Cognitive sensor networks: advanced processing will help make this work!

Courtesy of Michael Wicks, Air Force Research Laboratory, Rome, N.Y.



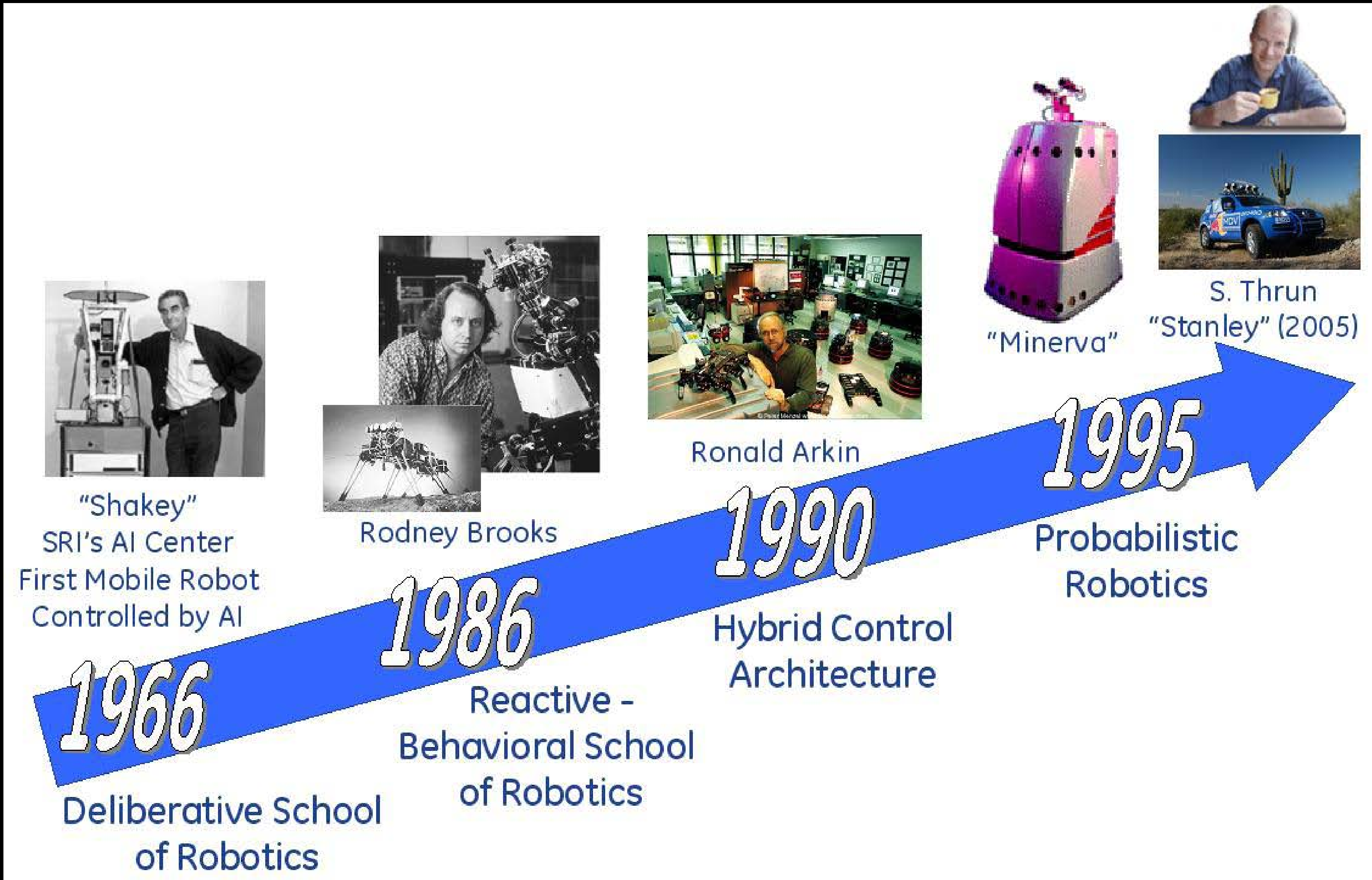
Unmanned autonomous systems – a new framework

- Sense
- Perceive (relevance and representation)
- Plan (predict and simulate future)
- Decide (choose actions)
- Act (influence the world)

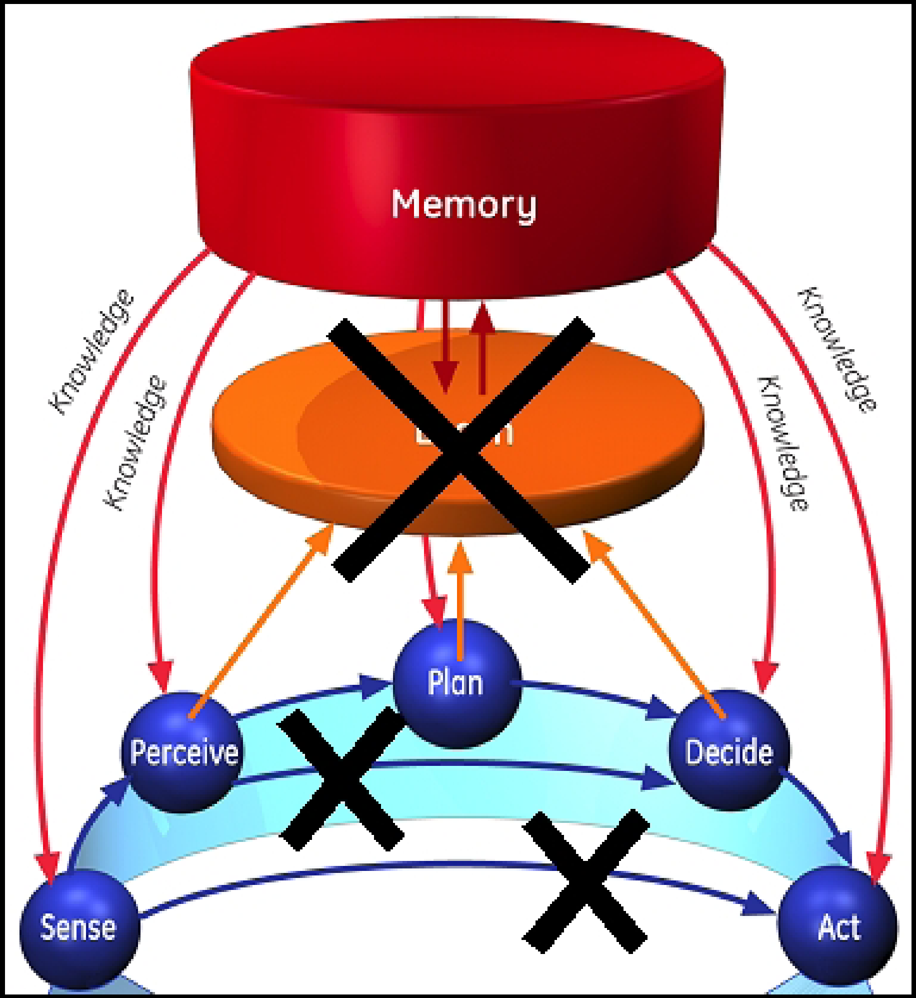


Ref: N.A. Visnevski and M. Castillo-Effen: A UAS capability description framework: Reactive, adaptive, and cognitive capabilities in robotics, 2009 IEEE Aerospace Conference, pp. 1-7, 2009.

Mobile robotics history

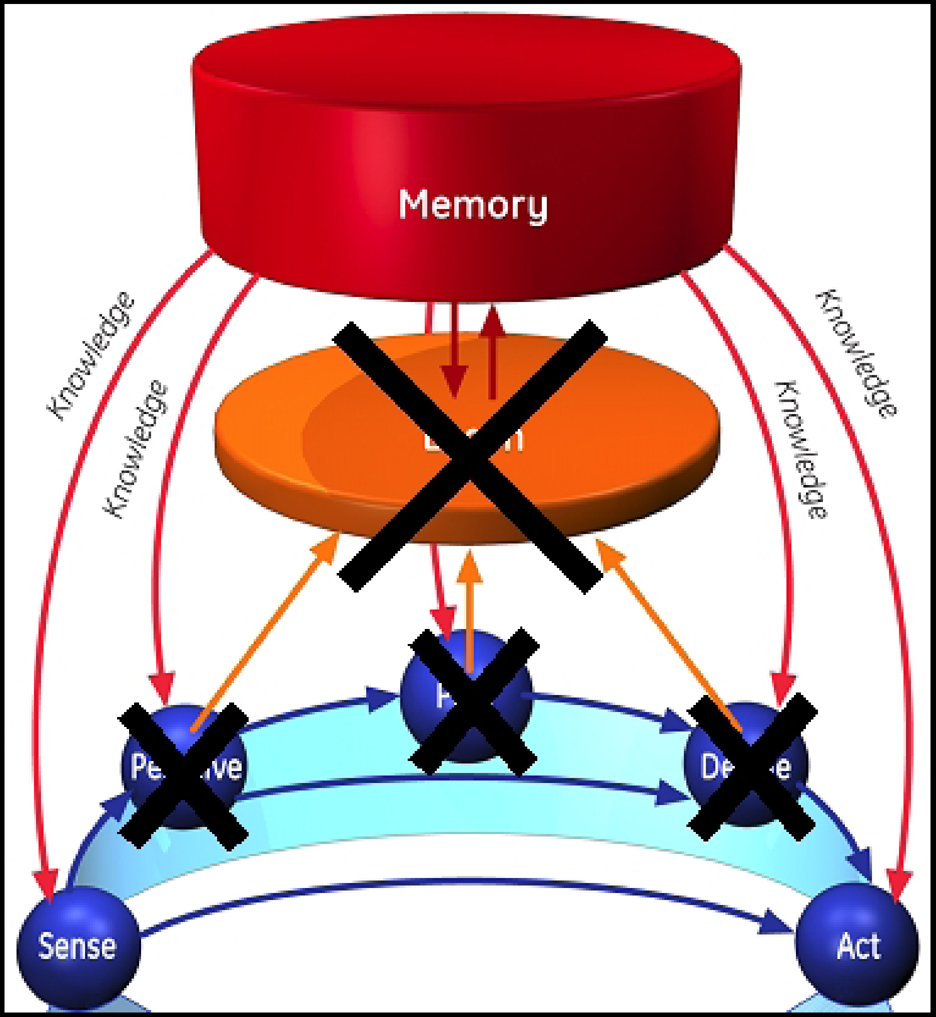


Deliberate school



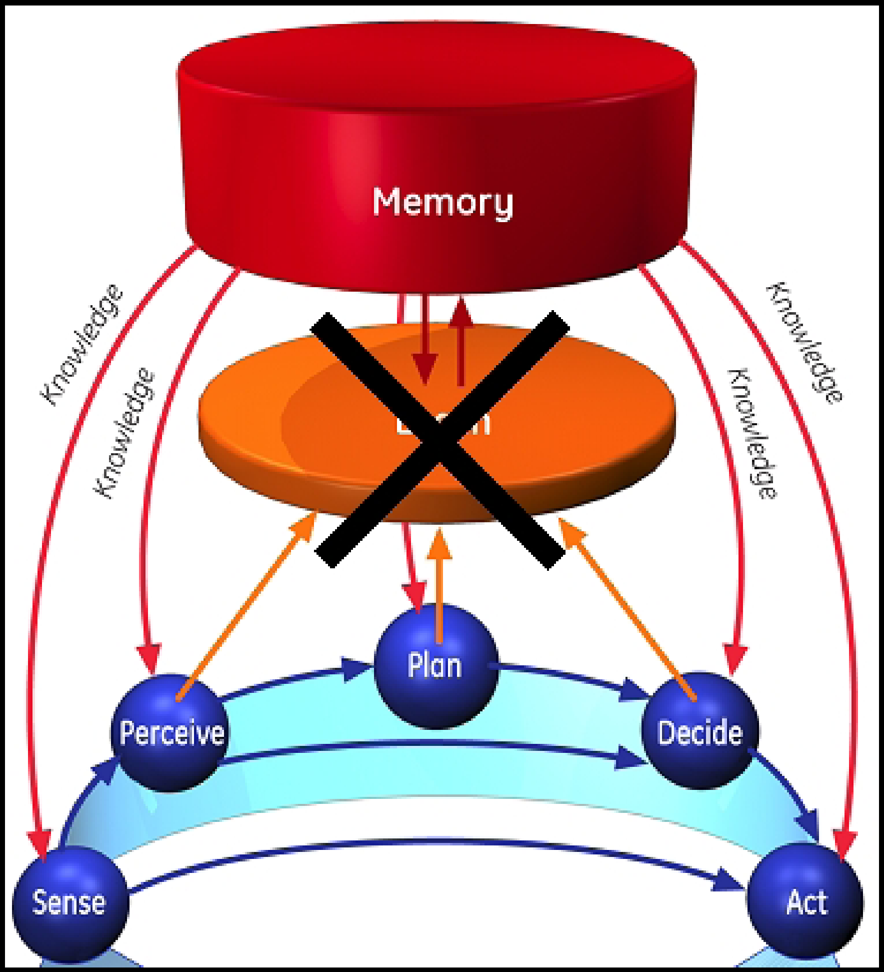
- Model of the world and environment
- Based on classical AI
- Fails to respond rapidly on new stimuli
- Learning is very limited

Reactive school



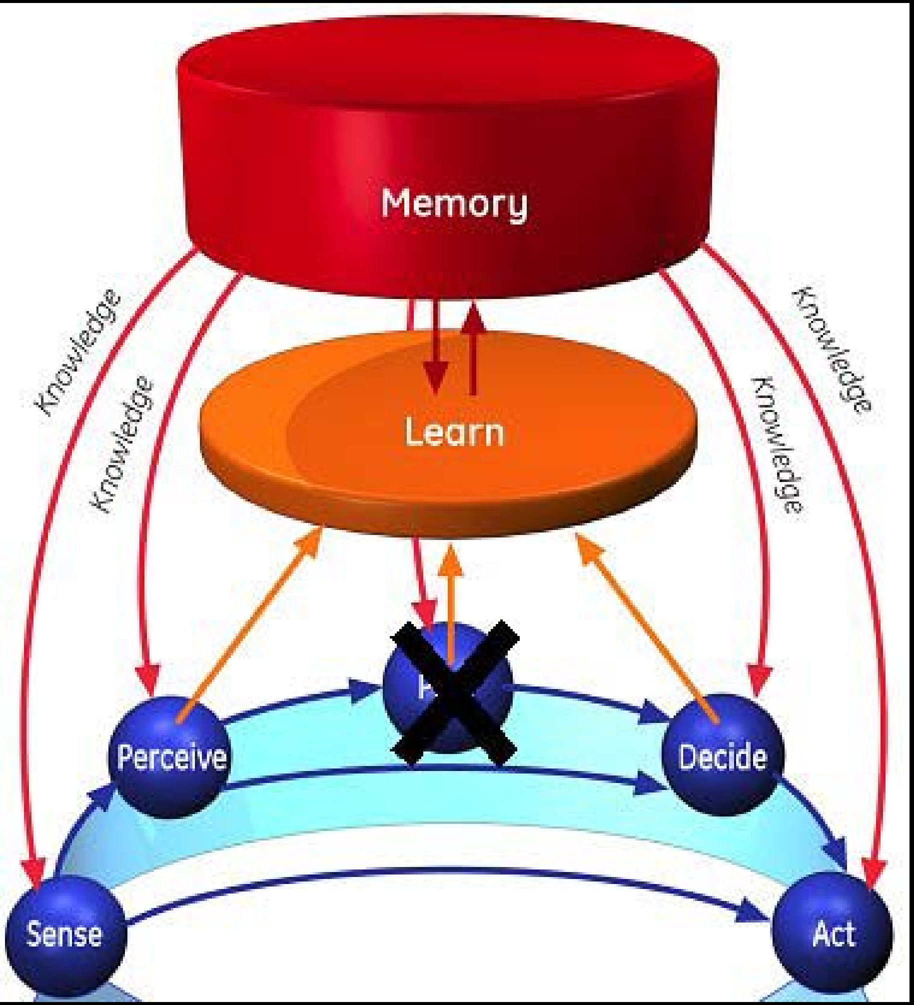
- Simple and easy
- Complex behavor from emergent properties
- Procedural knowledge
- Some reinforcement learning

Hybrid and probabilistic school



- Hybrid=merger of reactive and deliberative schools
- Probabilistic to handle uncertainties in the world and knowledge
- Learning is not really an integral part

Bongard direction



- Closest to reactive school
- Learning is an integral and core part

Starfish cognitive robotics

•Animals sustain the ability to operate after injury by creating qualitatively different compensatory behaviors.

•a robot that can recover from such change autonomously, through continuous self-modeling.

•A four-legged machine uses actuation-sensation relationships to indirectly infer its own structure, and it then uses this self-model to generate forward locomotion.

•When a leg part is removed, it adapts the self-models, leading to the generation of alternative gaits.

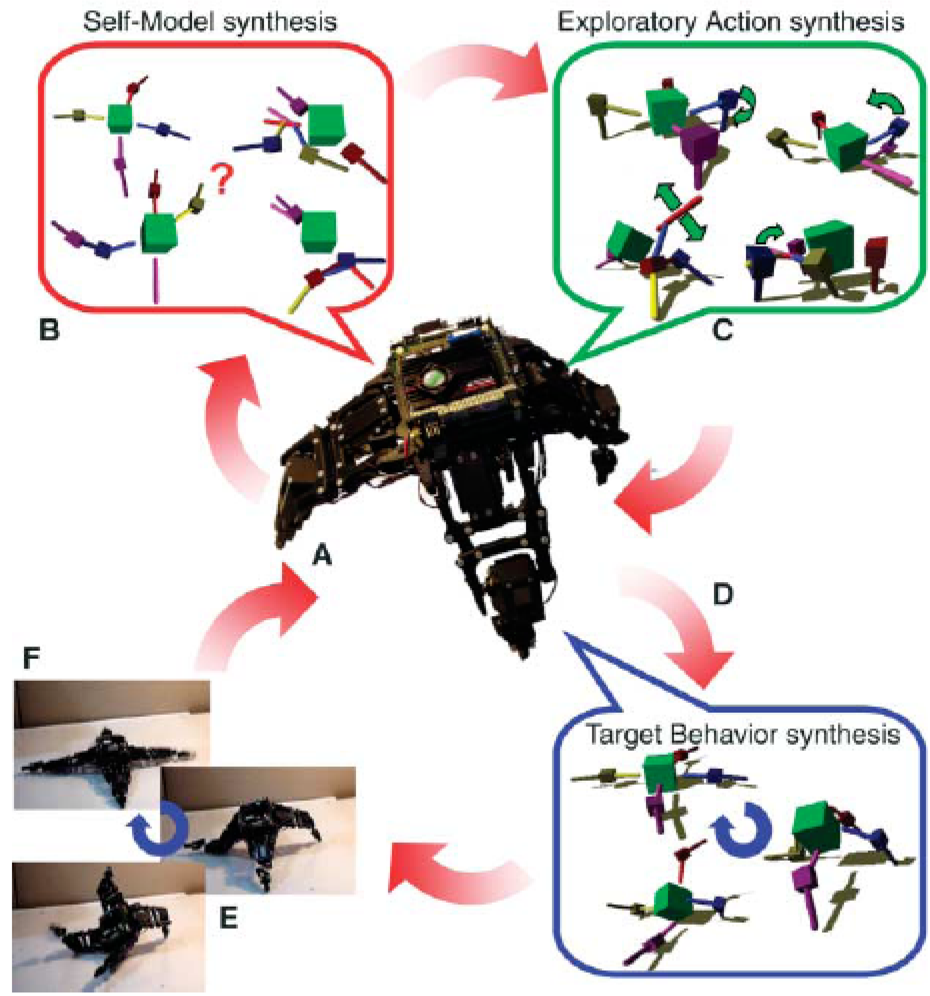
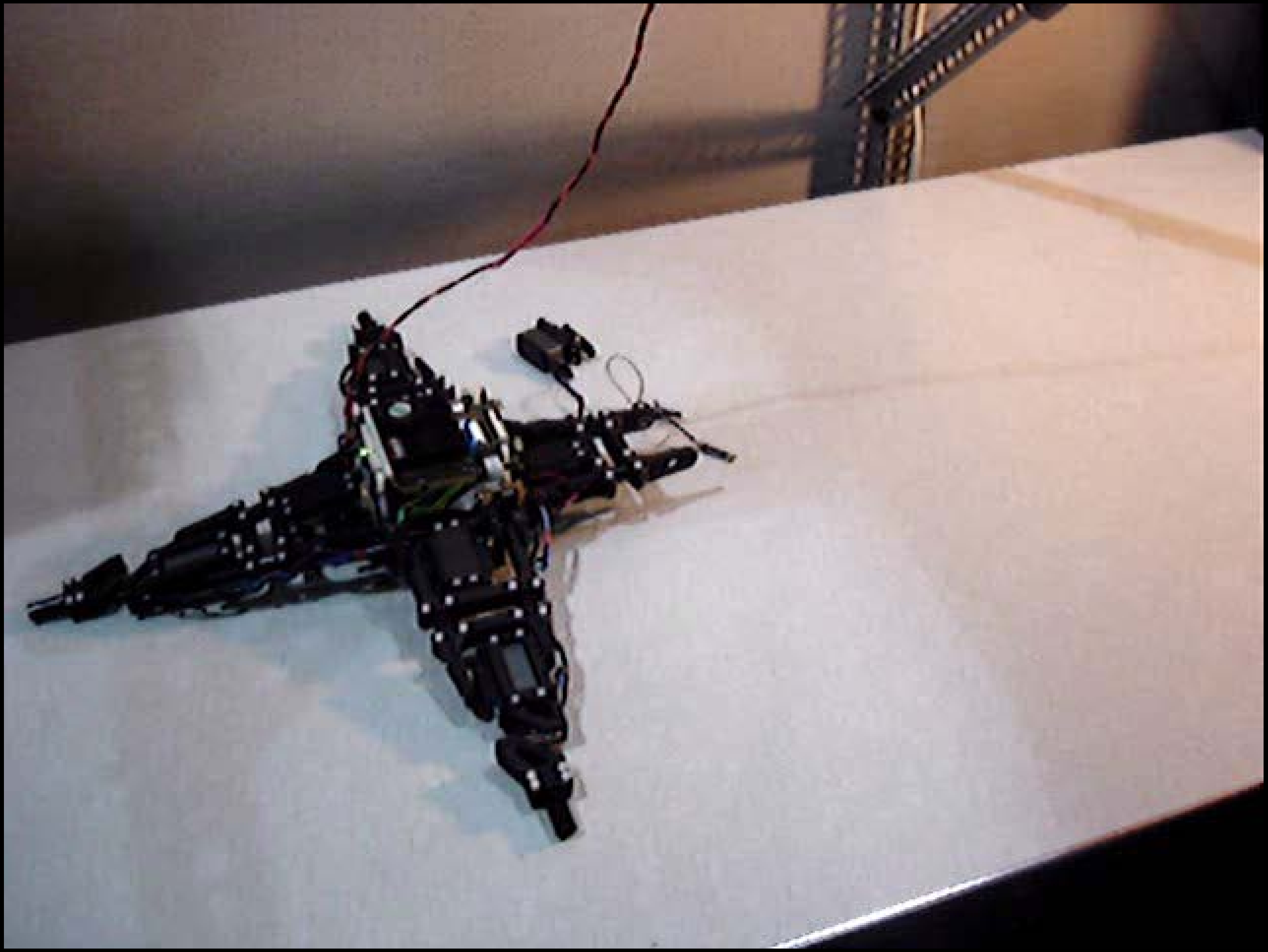


Fig. 1. Outline of the algorithm. The robot continuously cycles through action execution. (**A** and **B**) Self-model synthesis. The robot physically performs an action (A). Initially, this action is random; later, it is the best action found in (C). The robot then generates several self-models to match sensor data collected while performing previous actions (B). It does not know which model is correct. (**C**) Exploratory action synthesis. The robot generates several possible actions that disambiguate competing self-models. (**D**) Target behavior synthesis. After several cycles of (A) to (C), the currently best model is used to generate locomotion sequences through optimization. (**E**) The best locomotion sequence is executed by the physical device. (**F**) The cycle continues at step (B) to further refine models or at step (D) to create new behaviors.

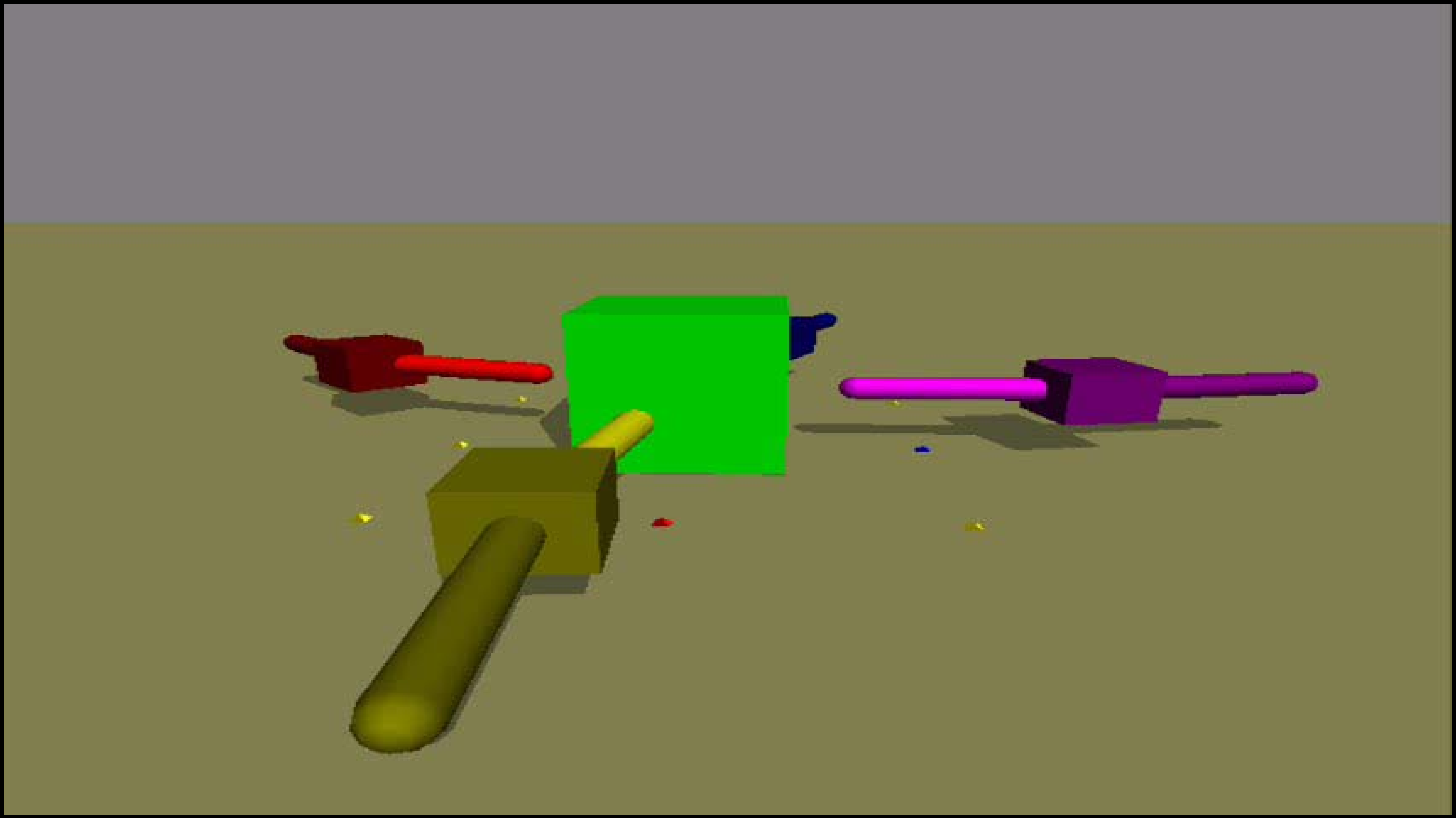
Ref: Josh Bongard et al.: "Resilient Machines Through Continuous Self-Modeling," Science 314, 2006

Resilient cognitive robotics gait after a leg has been damaged



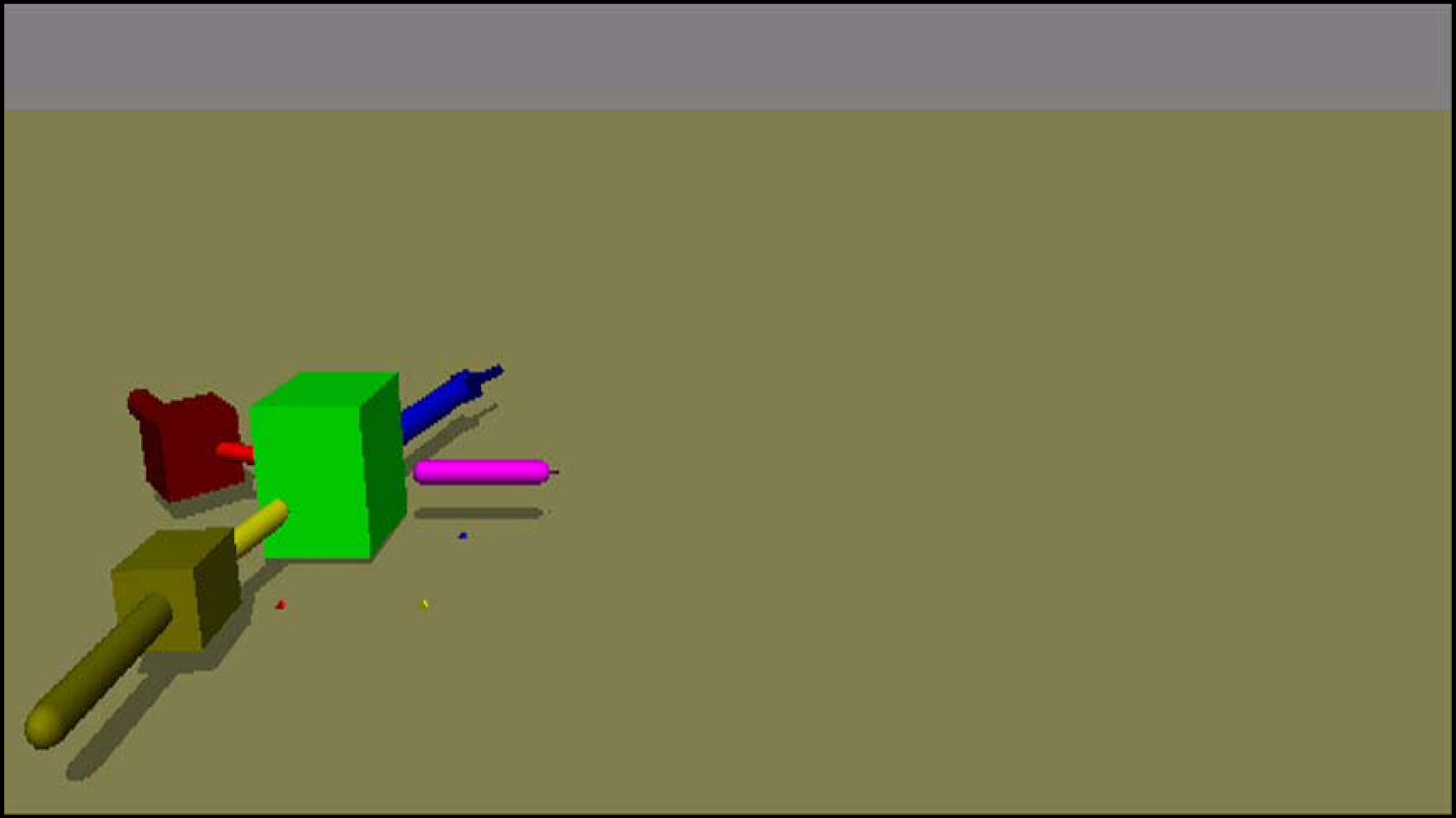
Courtesy of Josh Bongard , Univ. of Vermont, USA

Resilient cognitive robotics – damge models



Courtesy of Josh Bongard , Univ. of Vermont, USA

Resilient cognitive robotics – simulated gait model

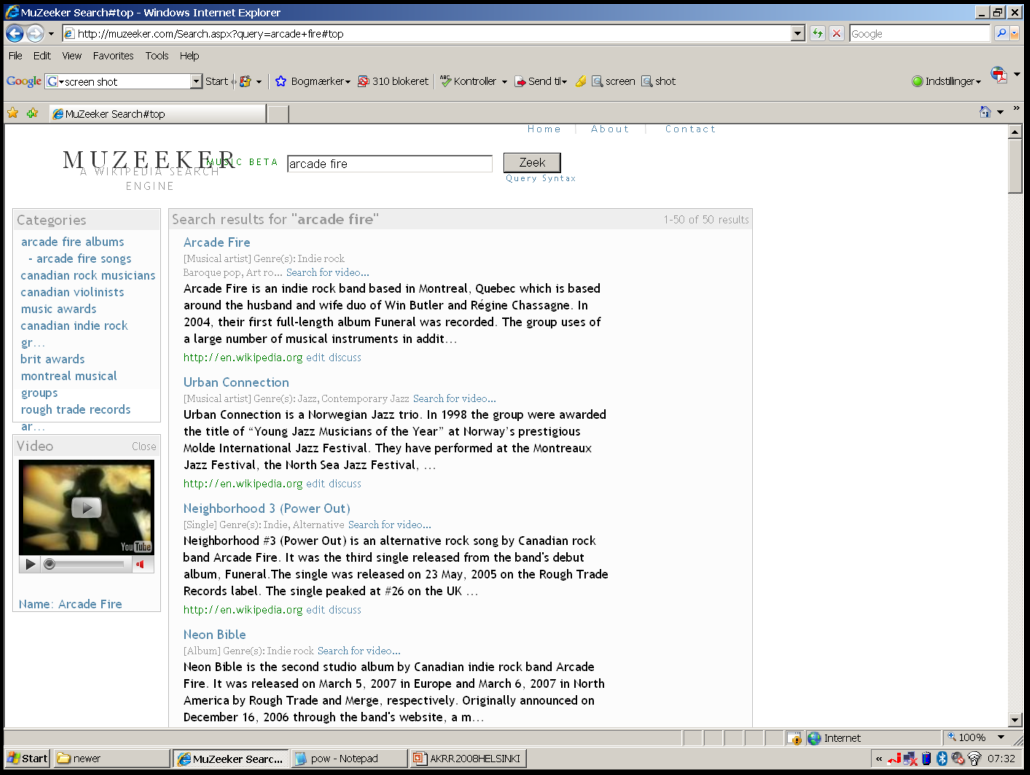


Courtesy of Josh Bongard , Univ. of Vermont, USA

A cognitive search engine - Muzeeker

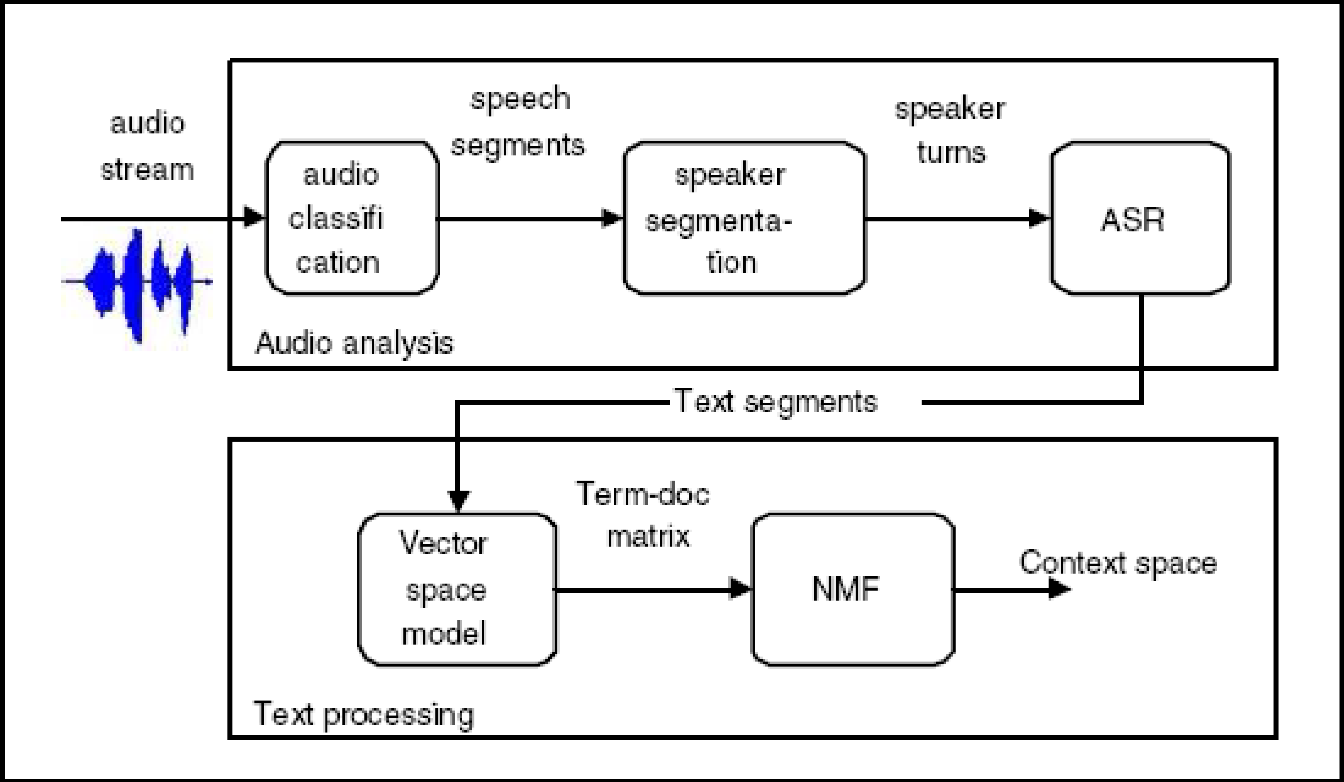
- Wikipedia based common sense
- Wikipedia used as a proxy for the music users mental model
- Implementation: Filter retrieval using Wikipedia's article/ categories

- Muzeeker.com

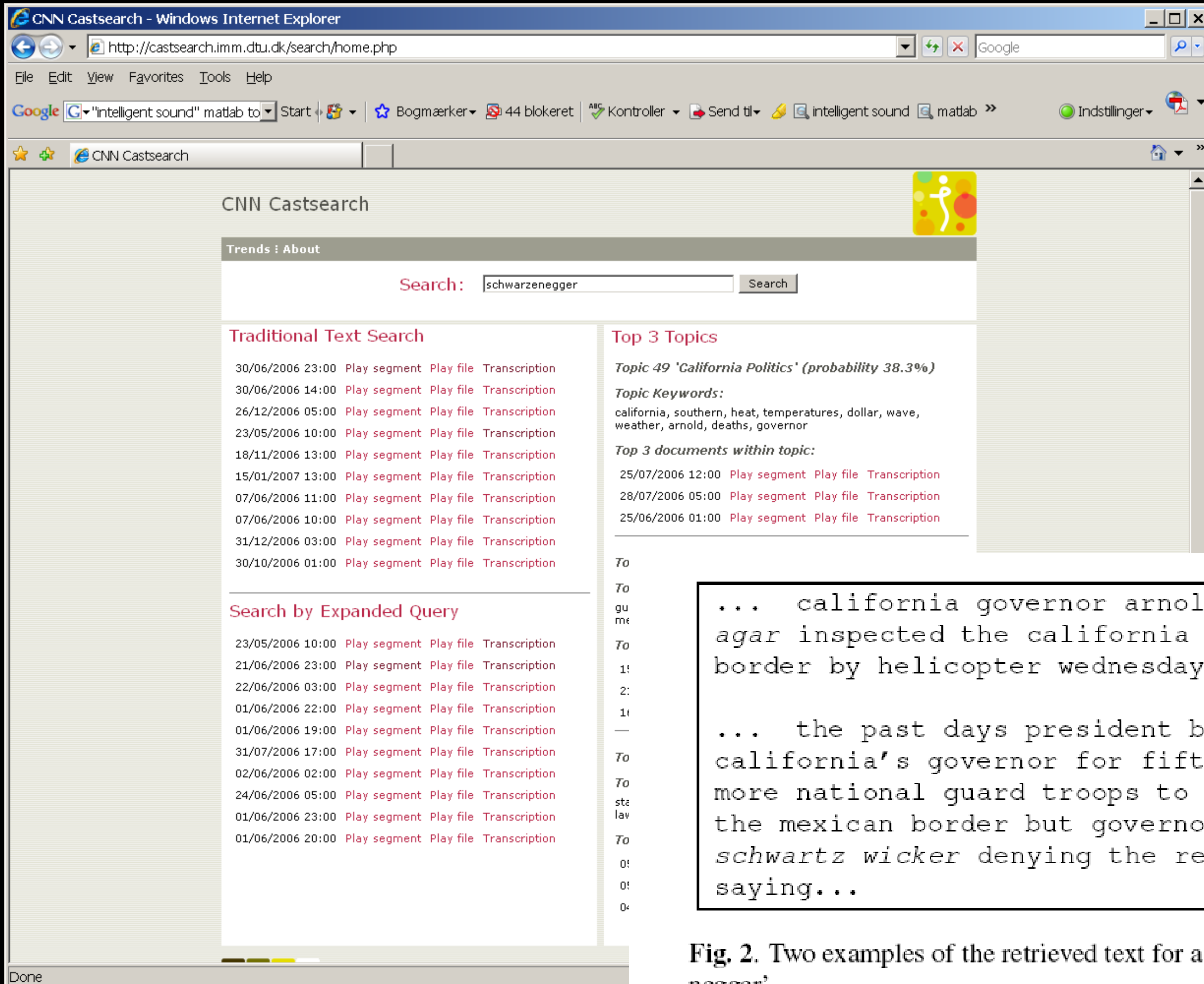


Courtesy of Lars Kai Hansen, DTU

A cognitive search engine – CASTSEARCH: Context based Spoken Document Retrieval



Ref: Lasse Mølgaard, Kasper Jørgensen, Lars Kai Hansen: ”CASTSEARCH: Context based Spoken Document Retrieval,” ICASSP2007



... california governor arnold's *fortson agar* inspected the california mexico border by helicopter wednesday to see ...

... the past days president bush asking california's governor for fifteen hundred more national guard troops to help patrol the mexican border but governor orville *schwartz wicker* denying the request saying...

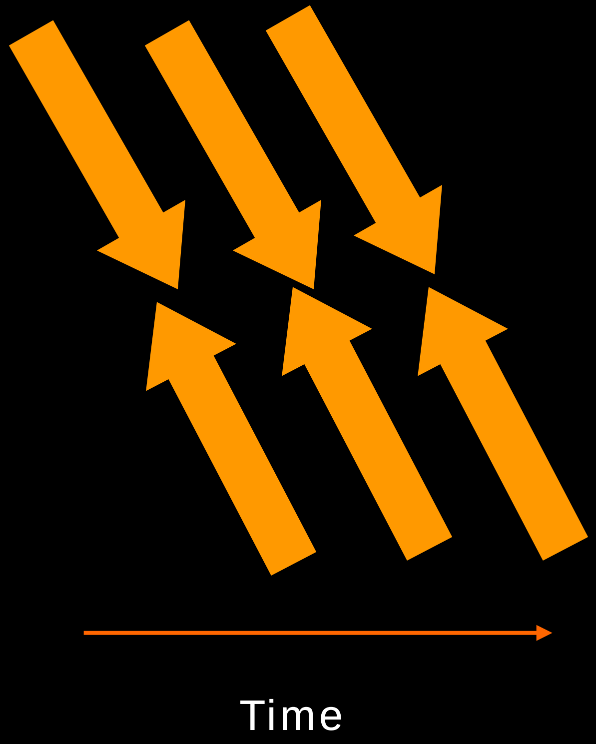
Fig. 2. Two examples of the retrieved text for a query on 'schwarzenegger'.

Ref: http://castsearch.imm.dtu.dk

A cognitive architecture for search

Combine bottom-up and top-down processing

- Top-down
  - High specificity
  - Time scales: long, slowly adapting
- Bottom-up
  - High sensitivity
  - Time scales: short, fast adaptation



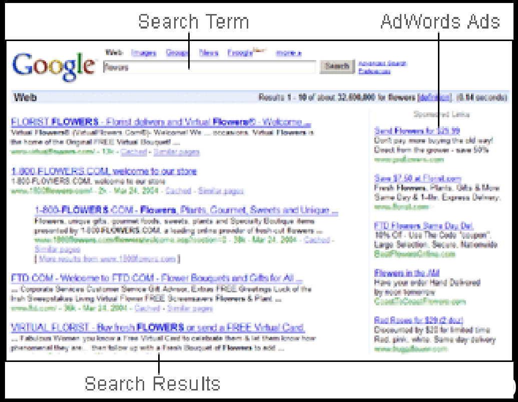
Courtesy of Lars Kai Hansen, DTU

Vertical search

- Deep web databases
  - Digital media
  - For profit: DMR issues
- Specialized search engines
  - Professional users
  - Modeling deep structure
- Key role in Web 2.0
  - User generated content
  - Bioinformatics
  - Neuroinformatics:
    - BrainMap, Brede search engine

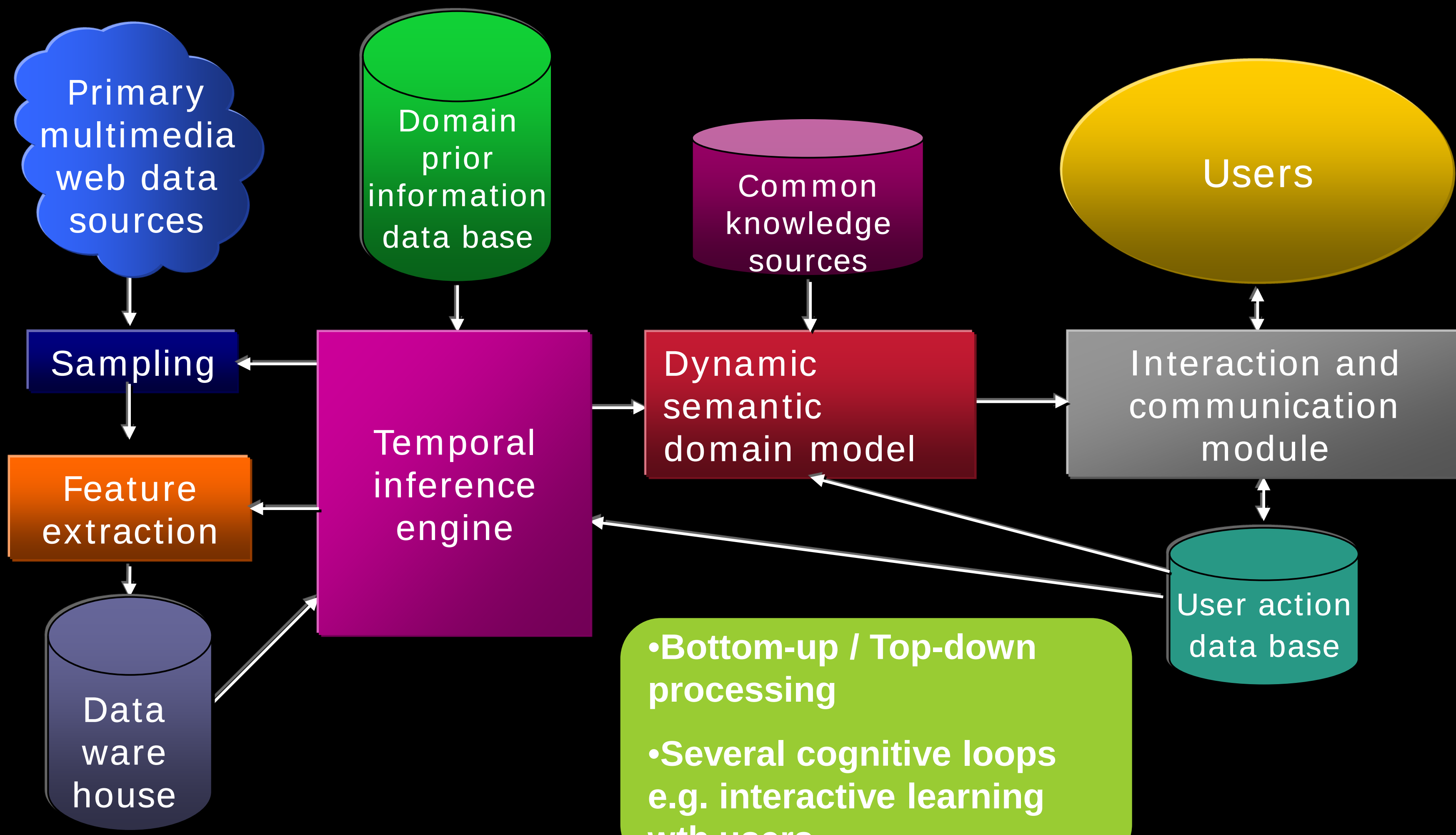
Horizontal search

- Google
  - Volume
  - Ranking
  - Explorative vs. retrieval
  - Adword business model
- Semantic web
  - Wikipedia
  - User generated content



Courtesy of Lars Kai Hansen, DTU

Conceptual diagram of a knowledge discovery multimedia engine



- **Bottom-up / Top-down processing**
- **Several cognitive loops e.g. interactive learning wth users**

Cognitive modeling by cognitive components

What is Cognitive Component Analysis (COCA)?

COCA is the process of unsupervised grouping of data such that the ensuing group structure is well-aligned with that resulting from human cognitive activity.

- Unsupervised learning discovers statistical regularities;

- Human cognition is a supervised on-going process;

Human Behavior

Cognition is hard to quantify – its direct consequence: human behavior is easy to access and model but direct modeling is also often required

L.K. Hansen, P. Ahrendt, and J. Larsen: *Towards Cognitive Component Analysis*. AKRR'05 - (2005).

L.K. Hansen, L. Feng: *Cogito Componentiter Ergo Sum*. ICA2006 (2006).

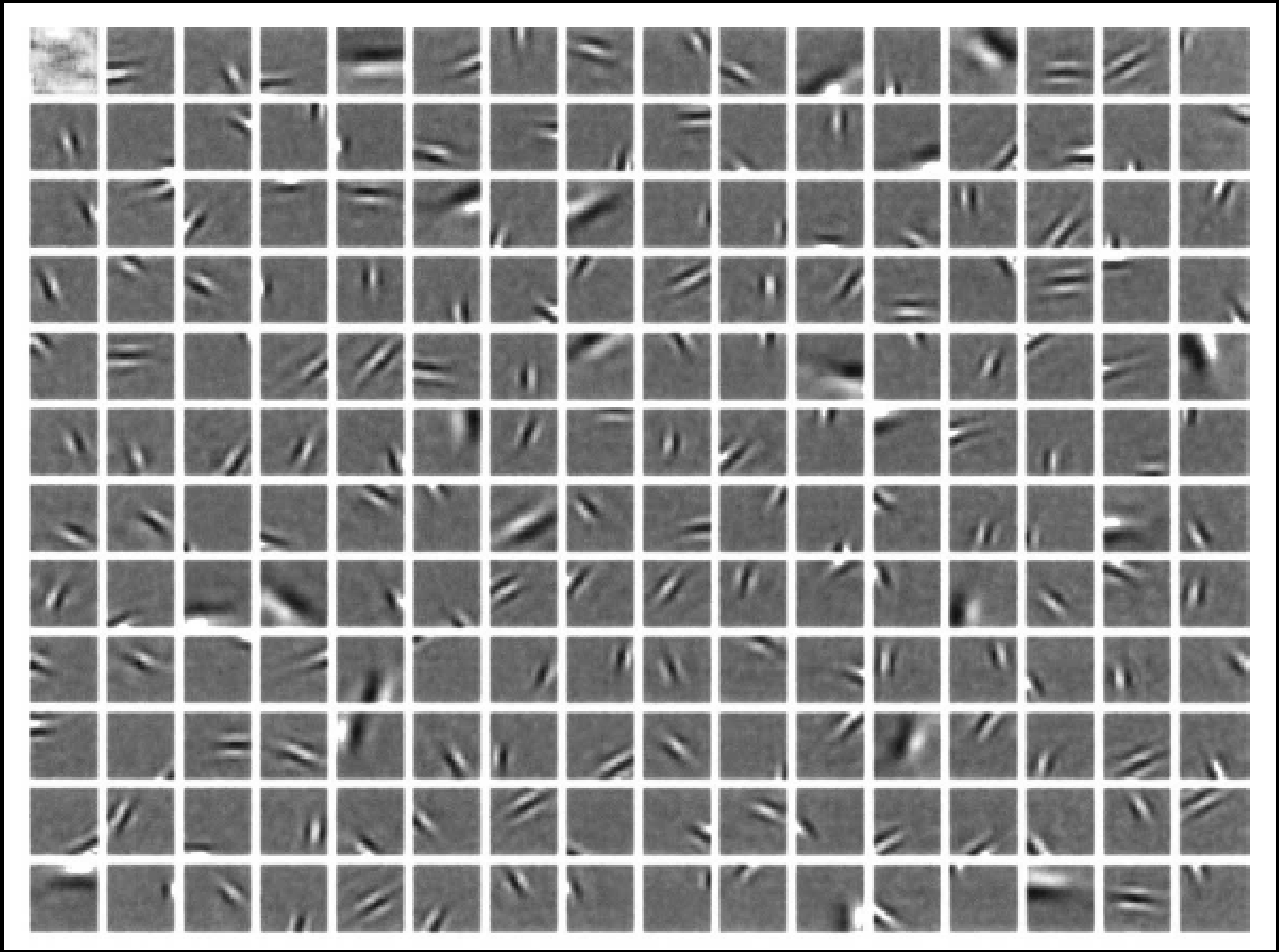
L. Feng, L.K. Hansen. *Phonemes as short time cognitive components*. ICASSP'06 (2006)

L. Feng, L.K. Hansen: *Cognitive components of speech at different time scales.* CogSci 2007 (2007).

L. Feng, L.K. Hansen: *Is Cognitive Activity of Speech Based on Statistical Independence*? CogSci 2008 (2008).

E.R. Kandel *et al.,* Principles of Neural Science, Chapter 64: Learning and Memory by I. Kupfermann, 1991.

Cognitive components in mammalian primary virtual cortex and natural images



Ref: Olshausen and Field, Nature, 1996. Hoyer and Hyvärinen, 2000.

Cognitive modeling: human visual and auditory cognition

- Relations between auditory and visual cognition
- Theory of visual attention

Ref:

Andersen, T.S., K. Tiippana, and M. Sams, Factors influencing audiovisual fission

and fusion illusions. Cognitive Brain Research, 2004. 21(3): p. 301-8.

Andersen, T.S. and P. Mamassian: Audiovisual Interactions in Signal Detection, Journal of Vision, 6(6):172, 2006.

Tiippana, K., T.S. Andersen, and M. Sams: Visual attention modulates audiovisual

speech perception. European Journal of Cognitive Psychology, 2004. 16(3): p. 457-472.

Andersen, T.S., et al.: The Role of Visual Spatial Attention in Audiovisual Speech Perception. Speech Communication, 2008. In Press.

Bundesen, C., Habekost, T., & Kyllingsbæk, S.: A neural theory of visual attention. Bridging cognition and neurophysiology. Psychological Review, 112, 291-328, 2005.

What is she saying – the McGurk effect

Courtesy: Tobias Andersen, DTU Informatics

Ref: H. McGurk and J. MacDonald: Hearing lips and seeing voices, Nature, Vol 264(5588), pp. 746–748, 1976.

Is speech special?

Auditory and visual integration is present only when the audio is perceived as speech

Courtesy: Tuomainen, Andersen, Tiippana, Sams, Cognition, 2005

Quo vadis?

Systems engineering apparoch

- 360 degrees modeling
- Use abdundancy of data
- Interative learning
- Crowd computing and sourcing
- Users' engagement through relevance, surprice and precision of results
- Create new frameworks with inspiration from existing paradigms and evaluatation of current systems

learning

Summary

- We addressed levels of cognition in cognitive systems by describing various *capabilities*
- We mentioned recent enabling technologies which likely will advance cognitive abilities
- State of the art was illustrated in diverse applications domains
- A cross-disciplinary effort is required to build realistic research platforms
- A systems engineering approach with careful evaluation measures is a possible road to advance state-of-art

Thank you for your *attention* –

hope to have created *cognitive arousal*