Cognitive systems

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Jeffrey Reed
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. It plays a key role in the transformational society in order to achieve 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"
A vision with great implications

Ubiquitous interaction between humans and artificial cognitive systems

- Ethical (maybe new regulatory bodies)
- Cultural (inclusiveness)
- Political (regulations and policies)
- Economic (digital economy and instability)
- Social (collaboration, globalization, conflicts)
- Anthropological (transformational society)
It takes cross-disciplinary effort to create a cognitive system

INFO
Engineering and natural sciences

COGNITIVE
Cognitive psychology, social sciences, linguistics

BIO
Neuro and life sciences

Scope

• The field of CS is too large to be covered in this tutorial
• The field of CS is still in its embryonic stage

  – Focus on a 360 view of the concepts in cognitive systems
  – Illustrated by specific examples;
  – And followed by a mini future workshop on the role of machine learning

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 network
- **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 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**

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
Outline

• A 360 view of the concepts in cognitive systems
  – How: data, processing
  – Why: goals
  – What: capabilities

• Examples of state of the art along diverse dimensions

• Mini future workshop on the role of machine learning
The cognitive system and its world

Common sense knowledge

Real/virtual environment

Domain knowledge

Multi-modal sensors

ACS

Human user

Human

many internal cognitive loops
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
Why - goals

Disentanglement of confusing, ambiguous, conflicting and vast amounts of multi-modal, 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 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)
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

- Autonomy
- Prediction
- Learning at all levels (interactive learning)
- Generalization
- Pro-activeness
- Multi-level planning (actions, goals)
- Simulation
- Exploration
- Self-evaluation
- Learning transfer
- Emergent behavior
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 view of the concepts in cognitive systems
  – How: data, processing
  – Why: goals
  – What: capabilities

• Examples of state of the art along diverse dimensions

• Mini future workshop on the role of machine learning
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
European 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€

http://cordis.europa.eu/fp7/ict/content-knowledge/home_en.html
European 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
European 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 rule which emerges)
  • Hybrid
  • Centralized or distributed computing
  • Holistic vs. atomism (modular)
  • Bottom-up vs. top-down processing

References:
http://www.eucognition.org,


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

Ref: Vernon et al., 2007

## The Cognitivist vs. Emergent Paradigms of Cognition

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

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Paradigm</th>
<th>Embodiment</th>
<th>Perception</th>
<th>Action</th>
<th>Anticipation</th>
<th>Adaptation</th>
<th>Motivation</th>
<th>Autonomy</th>
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<td>Global Workspace</td>
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<tr>
<td>Darwin</td>
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<td>HUMANOID</td>
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<td>Cerebus</td>
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<td>Cog: Theory of Mind</td>
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</tbody>
</table>

x: strong
+
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
Cognitive radio networks

Goals:
• High reliability
• Efficient utilization of spectrum

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
- Multiband, 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

Spectrum Trading

Opportunistic Spectrum Utilization

Advanced Networking

Cheaper Radios

Intelligent Beamforming

Collaborative Techniques

Automated Interoperability

Improved Link Reliability

Source Cluster  Relay cluster  Destination Cluster

Courtesy of Jeffrey Reed, Virginia Tech

31  DTU Informatics, Technical University of Denmark  Jan Larsen  18/10/2008
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

Knowledge Based Signal & Data Processing

- Exploit Available Information Sources
- Control & Improve STAP

Land Use Data
Elevation & Cover Data
Previous Passes/Flights
Feedback From Other Stages

Radar & Platform Configuration

Knowledge-Based Controls

Expert System CFAR

Classical STAP
To detect weak target, you have to deal with several false alarms!

MCARM Data Analysis Results

STAP with Non-Homogeneity Detection

Non-Homogeneity Detector

Non-Homogeneous Cells
Homogeneous Cells

Hybrid Algorithm
Training Strategy
Statistical Algorithms

Post-Processing and Detection Stage

Courtesey 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.
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.

Resilient cognitive robotics gait after a leg has been damaged

Courtesy of Josh Bongard, Univ. of Vermont, USA
Resilient cognitive robotics – damage models
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

Courtesey of Lars Kai Hansen, DTU
A cognitive search engine – CASTSEARCH: Context based Spoken Document Retrieval

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

... 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...
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

Courtesey of Lars Kai Hansen, DTU
Vertical search vs horizontal 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
- Google
  - Volume
  - Ranking
  - Explorative vs retrieval
  - Adword business model
- Semantic web
  - Wikipedia
  - User generated content

Courtesey of Lars Kai Hansen, DTU
Conceptual diagram of a knowledge discovery engine

Primary multimedia web data sources

Domain prior information database

Feature extraction

Temporal inference engine

Dynamic semantic domain model

Common knowledge sources

Sampling

User action data base

Interaction and communication module

Users

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

Data warehouse

Common knowledge sources
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.

Cognitive modeling: human visual and auditory cognition

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

Ref:
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
Outline

• A 360 view of the concepts in cognitive systems
  – How: data, processing
  – Why: goals
  – What: capabilities
• Examples of state of the art along diverse dimensions
• Mini future workshop on the role of machine learning
The future workshop

• A workshop held with the aim of cooperatively generating visions for the future
• A technique developed by Jungk & Müller as a way to create desirable futures’
• Consists of five phases – we will focus on three central
  – The critique phase
  – The fantasy phase
  – The implementation phase

The future workshop

Critique phase
- Problem is critically and thoroughly discussed
- Brainstorming in groups of 5 people (divergent process)
- Concentration in a few sub-themes (convergent process)

Fantasy phase
- Work out a utopia in groups of 5 people
- Avoid known solutions and don’t worry about resources constraints or feasibility
- Concentration and prioritizing 5 main challenges

Implementation phase
- SWOT analysis of each of the five ideas

Future workshop on the role of machine learning in cognitive systems

• What are the gaps to be bridged or filled?
• What can machine learning offer?
• Are there critical issues which needs to be addressed to use a learning approach?
• What are the challenges?
Challenges and gaps – a EC view

• Reinforcement learning as a middleground between supervised and unsupervised learning
• Learning to link sub-systems
• Adaptive sub-systems
• Cross-media and cross-sources data
• Social network of learning systems
• Multi-task learning

The future workshop

Critique phase

- Problem is critically and thoroughly discussed
- Brainstorming in groups of 5 people (divergent process) 15 min
- Concentration in a few sub-themes (convergent process) 10 min
Sub-themes of the critique phase

• 1: cognitive architecture for vision
• 2: multiple objectives
• 3: representation
• 4: data compression
• 5: active learning
• 6: on-line adaptivity
• 6a: structuring of temporal data
• 7: feature selection
• 8: architecture and learning algorithms
• 9: linking heterogeneous data
• 10: machine learning in cognitive sonar
The future workshop

Fantasy phase

• Work out a utopia in groups of 5 people 15 min
• Avoid known solutions and don’t worry about resources constraints or feasibility
• Concentration and prioritizing 5 main challenges 10 min
Five prioritized challenges of the fantasy phase

• 1: super smart active learning involving all aspects (data points, environment)
• 2: unsupervised learning finding any structure
• 3: copy/learn/generalize/mimic human cognition
• 4: optimal representations for any data stream
• 5: the divine feature selector
• 6: use trained ACS to simulate interaction and group behavior
• 7: learn the state of other ACS
• 8: perfect collaborative systems
The future workshop

Implementation phase

- SWOT analysis of each of the five ideas 15 min
Challenge 1:

- Strength
- Weaknesses
- Opportunities
- Threats
Challenge 2:

- Strength
- Weaknesses
- Opportunities
- Threats
Challenge 3:

- Strength
- Weaknesses
- Opportunities
- Threats
Challenge 4:

- Strength
- Weaknesses
- Opportunities
- Threats
Challenge 5:

- Strength
- Weaknesses
- Opportunities
- Threats