Cognitive Machines

Simon Haykin
McMaster University, Canada
email: haykin@mcmaster.ca
Website: http://soma.crl.mcmaster.ca

Outline of the Lecture

1. What is a Cognitive Machine?

2. Example Applications

3. Cognitive Radio

4. Cognitive Radar

5. Active Audition

6. What Do These Three Diverse Applications Have in Common?

7. Approximate Dynamic Programming

8. Concluding Remarks

References

1. What is a Cognitive Machine?

1.1 What is cognition?

1.2 Definition of cognitive machine

1.1 What is cognition?

- According to the Oxford English dictionary, *cognition* is "knowing, perceiving, or conceiving as an act..."

- According to the Encyclopedia of Computer Science [1], we have a three-point computational view of cognition:

(i) *Mental states and processes* intervene between input stimuli and output responses.

(ii) The mental states and processes are described by *algorithms*.

(iii) The mental states and processes lend themselves to *scientific investigations*.

- For another view of cognition, we infer the following from Pfeifer and Scheier [2]:

> The interdisciplinary study of cognition is concerned with general principles of *intelligence* through a synthetic methodology termed *learning by understanding*.

1.2 Definition of cognitive machine

Cognitive machine is an *intelligent system* that is aware of its surrounding environment (i.e., outside world) and uses understanding-by-building to learn through interactions with the environment and other means, and *adapt its internal states* to statistical variations in input stimuli by making corresponding changes in adjustable system parameters in *real-time* with specific objectives (e.g., reliability, efficiency, active sensing) as defined by the application of interest.

Key words that stand out from the definition:

- Awareness
- Intelligence
- Learning
- Adaptivity
- Action
- Real-time operation

2. Example Applications

2.1 Cognitive radio:

Efficient utilization of the electromagnetic radio spectrum

2.2 Cognitive radar

Improved surveillance of the environment using inexpensive radars

2.3 Active audition

Active sensing of the environment through (passive) listening

3. Cognitive Radio

- The electromagnetic radio spectrum is a natural resource, the use of which by transmitters and receivers is licensed by governments.

- Scanning the radio spectrum, including the revenue-rich urban areas, we find

  (i) some frequency bands are largely unoccupied most of the time

  (ii) other frequency bands are only partially occupied, and

  (iii) remaining frequency bands are heavily used.

- Under-utilization of the spectrum makes us think in terms of *spectrum holes*, access to which at the right location and time by unserviced users can result in a significantly more efficient utilization of the spectrum.

- *Cognitive radio* building on software-defined radio, offers a novel way of achieving this objective by

  (i) "sniffing" the radio environment,

  (ii) providing for dynamic spectrum management, and

  (iii) controlling the level of transmit power.

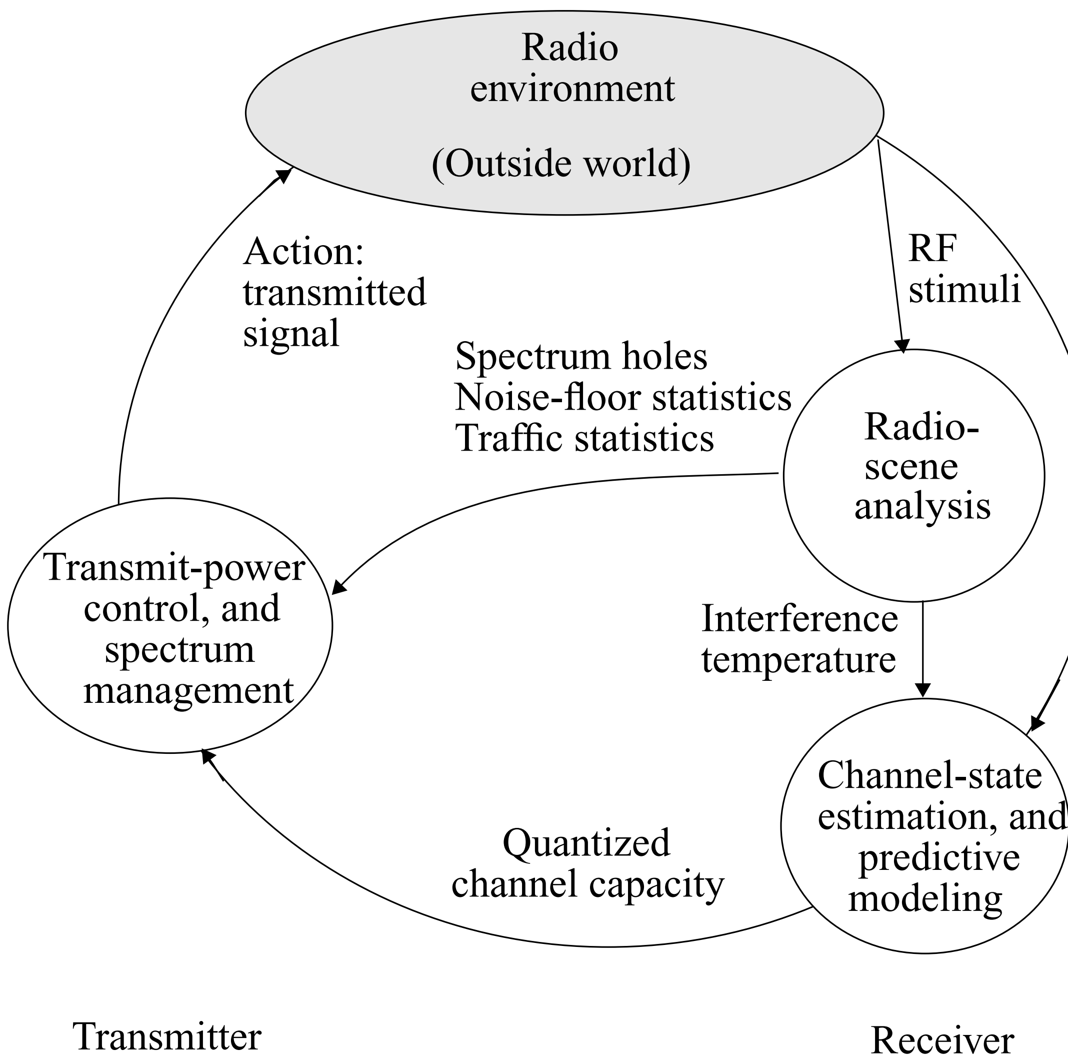

Figure 1: Basic cognitive cycle. (The figure focuses on three fundamental cognitive tasks.)
(Taken from Haykin [3])

4. Cognitive Radar

- Cognitive radar (motivated by the echo-location system of a bat) offers three basic ingredients:

  (i) *Intelligent signal processing*, which builds on real-time learning through continuous interactions of the radar with the surrounding environment.

  (ii) *Feedback from the receiver to the transmitter*, which is a facilitator of intelligence.

  (iii) *Preservation of the information content of radar returns*, which is realized by the Bayesian approach to target detection through tracking.

- A novel application includes a *Cognitive Radar network*, encompassing several (three or more) inexpensive marine radars whose resolution capability (limited to amplitude discrimination) is significantly enhanced through advanced signal-processing and software flexibility.

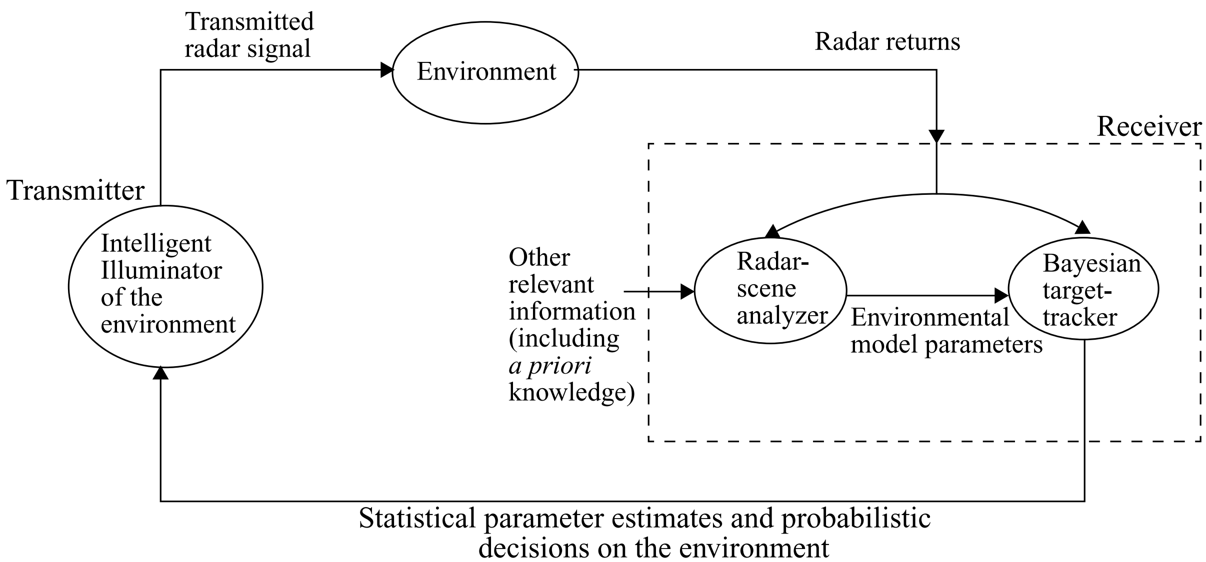

Figure 2: Block diagram of cognitive radar viewed as a closed-loop feedback system
(Taken from Haykin [4])

5. Active Audition

- *Embodied cognitive models*, relying on cognitive processes that emerge from interactions between neural, bodily and environmental factors, provide the framework for **active audition**.

- Active audition system embodies four factors:

  (i) *Sound localization*, which can be viewed as a form of binaural depth perception.

  (ii) *Segregation* of the target sound stream, which (combined with fusion) makes it possible to suppress sources of interference.

  (iii) *Tracking*, which exploits the streaming property of target sound.

  (iv) *Learning*, which empowers the system to take "action" whenever changes in a dynamic environment call for it.

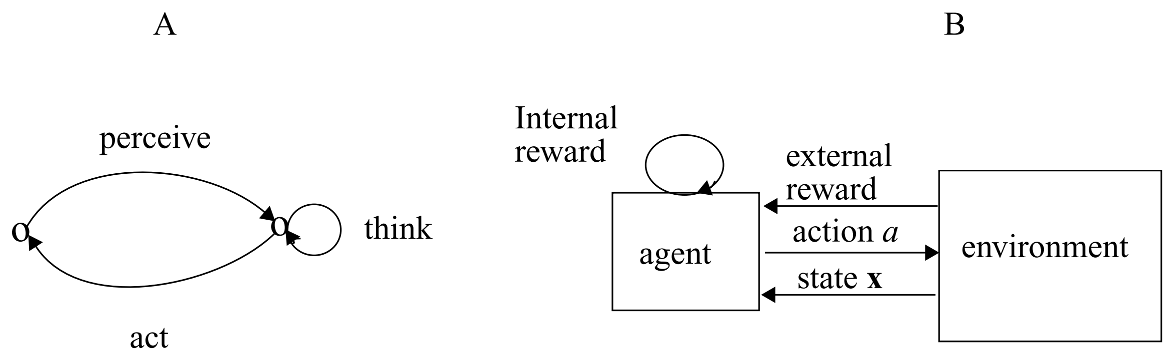

Figure 3: (a) Depiction of feedback loop consisting of three distinct functions: perceive, think and act. (b) The interaction between the agent and environment
(Taken from Haykin and Chen [5])

6. What Do These Three Diverse Applications Have in Common?

- They look to *embedded (i.e., software-defined) signal processing* for flexibility.

- They perform *learning* in real-time through continuous interactions with the outside environment.

- All three of them are examples of closed-loop feedback control systems.

Key question: How is the real-time learning process to be accomplished?

7. Approximate Dynamic Programming

First and foremost, we have to look to Bellman's classic work on Dynamic Programming for a principled approach for the formulation of an optimal *policy* to guide the interaction of the learning system with the outside world.

The difficulty with Bellman's dynamic programming is the likelihood of running into the curse of dimensionality problem, with dimensionality of the active audition system assuming such a large value that computational complexity becomes difficult if not impossible to realize.

Approximate dynamic programming provides an approximate (and therefore physically realizable) procedure for solving the task of dynamic programming in a principled manner.

Approximate Dynamic Programming (deFarias, 2003)

- To solve Bellman's dynamic programming in a computationally feasible manner, the algorithm is based on *linear programming for optimization of Markov decision processes* (MDPs).

- The algorithm approximates the differential cost function of a perturbed MDP via a *linear combination of basis functions*.

- The approximation minimizes a version of Bellman error in a computationally feasible manner.

- The cocktail party problem is a challenging problem that requires a deep understanding of human auditory scene analysis.

- Computational auditory scene analysis is motivated by one of two objectives:

  1. Design of an *active auditory system* that listens to its environment, but it is capable of active sensing through interaction with the environment.

  2. Design of an adaptive auditory system that is capable of helping a hearing-impaired person engage in conversations in a cocktail party environment with the same ease enjoyed by a normal hearing person.

8. Concluding Remarks

(i) Cognitive machines, exemplified by cognitive radio, cognitive radar, and active audition, provide novel applications where ideas from statistical signal processing and machine learning can be integrated to solve difficult engineering problems that are challenging in their own individual ways.

In so doing, we will have opened up a new landscape for exciting research projects.

(ii) All three of them are in their very early stages of development, and can therefore benefit from:

Creative Thinking Outside of the Box

(iii) All three applications look to

- approximate dynamic programming, and
- embedded signal processing

for their practical implementations.

References

[1] A. Ralston and E.D. Reilly, *Encyclopedia of Computer Science*, p.186, Van Nostrand Reinhold, 1993.

[2] R. Pfeifer and C. Scheier, *Understanding Intelligence*, pp. 5-6, MIT Press, 1999.

[3] S. Haykin, Cognitive Radio: Brain-empowered wireless communications", *IEEE. J. Selected Areas in Communications*, February, 2005 (invited).

[4] S. Haykin, Cognitive Radar, *IEEE Signal Processing Magazine*, 2006, under review (invited).

[5] S. Haykin and Z. Chen, *The Machine Cocktail Party Problem*. In Haykin, Principe, Sejnowski, and McWhirter, New Directions in Statistical Signal Processing, MIT Press, 2006.

[6] D.P. deFarias, The Linear Programming Approach to Approximate Dynamic Programming: Theory and Application, Dissertation for Doctor of Philosophy, Stanford University, 2002.