# Intelligent Signal Processing

# Cognitive Radio Networks

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# Introduction

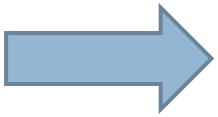
- Cognition
  - *mental action or process of acquiring knowledge and understanding through thought, experience, and the senses*

- Cognitive Radio
  - radio that is aware of its environment and the internal state and with knowledge of these elements and any stored predefined objectives can make and implement decisions about its behavior

# Why CR

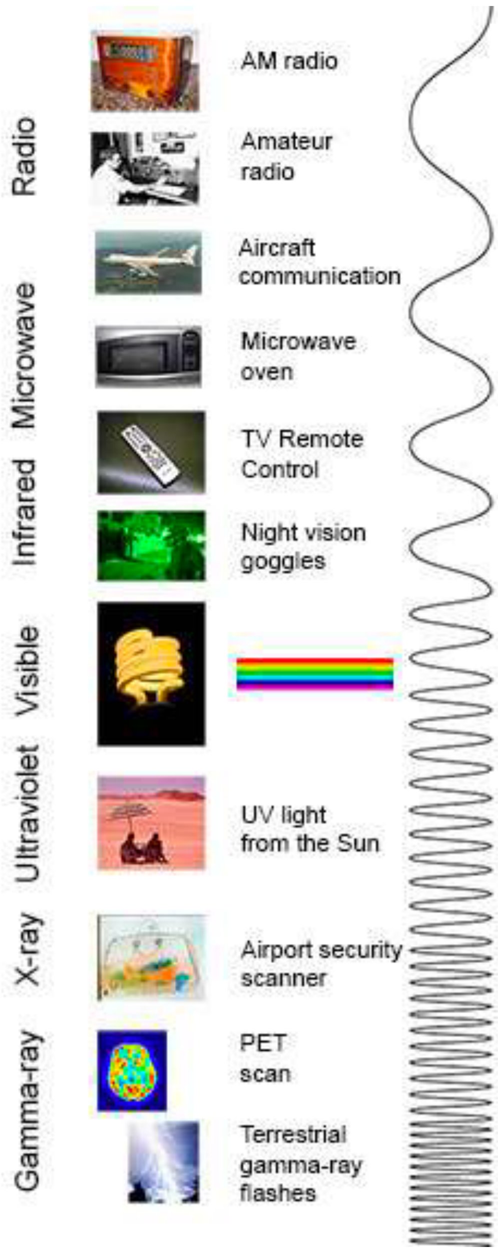


Natural resources

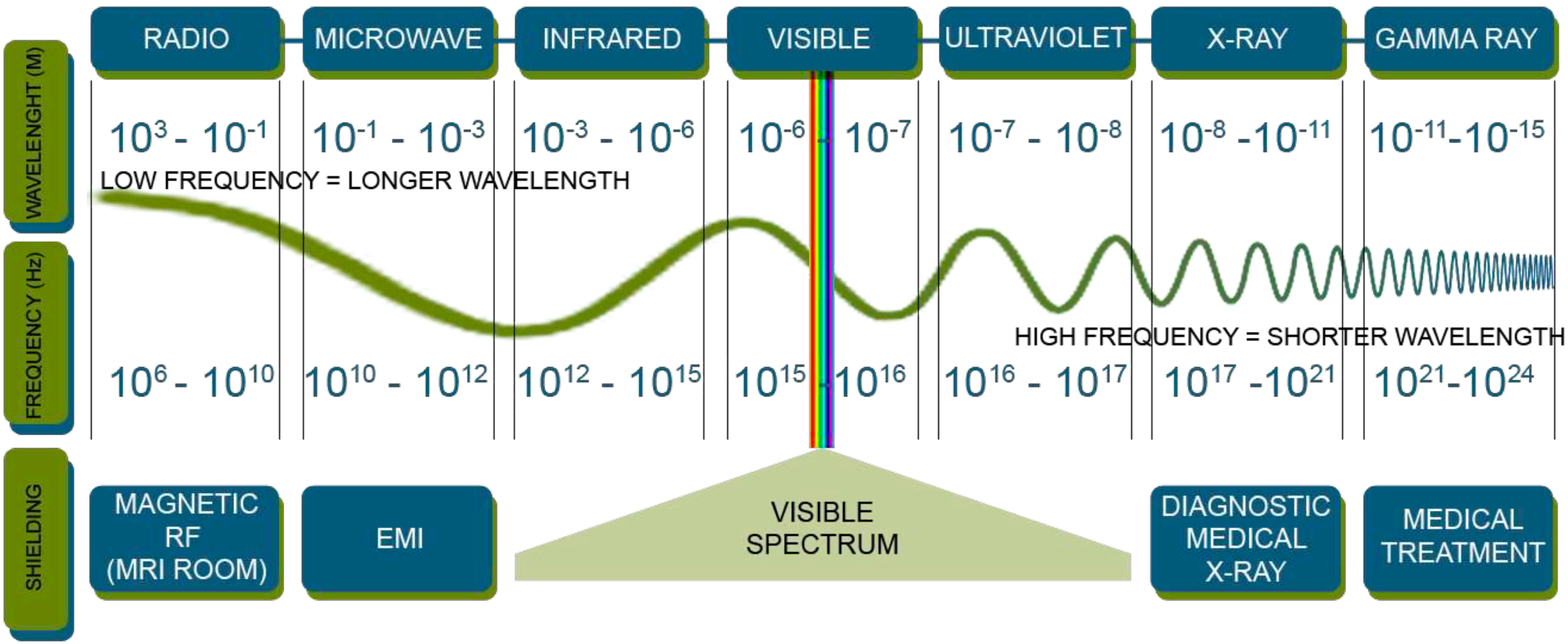


Scarsity

# Electro Magnetic Spectrum



# Electro Magnetic Spectrum



# Standards for Radio Frequency Allocation

- International Telecommunication Union (ITU)
- European Conference of Postal and Telecommunications Administrations (CEPT)
- Inter-American Telecommunication Commission (CITEL)

# Radio frequency bands

- Frequencies that are not usable for commercial purposes
  - are kept reserved for radio astronomy to avoid interference at radio telescopes
- Frequencies that are unlicensed and are open for personal or commercial use for free which
  - includes 2.4GHz and 5GHz WiFi, Bluetooth, cordless phones, etc.
- Frequencies that are licenced by the government
  - for purposes like telecommunication

# Radio Spectrum

- Radio spectrum
  - electromagnetic spectrum from 3 Hz to 3000 GHz
- Electromagnetic waves
  - called radio waves
  - used in modern technology
  - in telecommunication
- To prevent interference between different users
  - the generation and transmission of radio waves is strictly regulated by national laws
  - coordinated by an international body, the International Telecommunication Union (ITU)

# Band

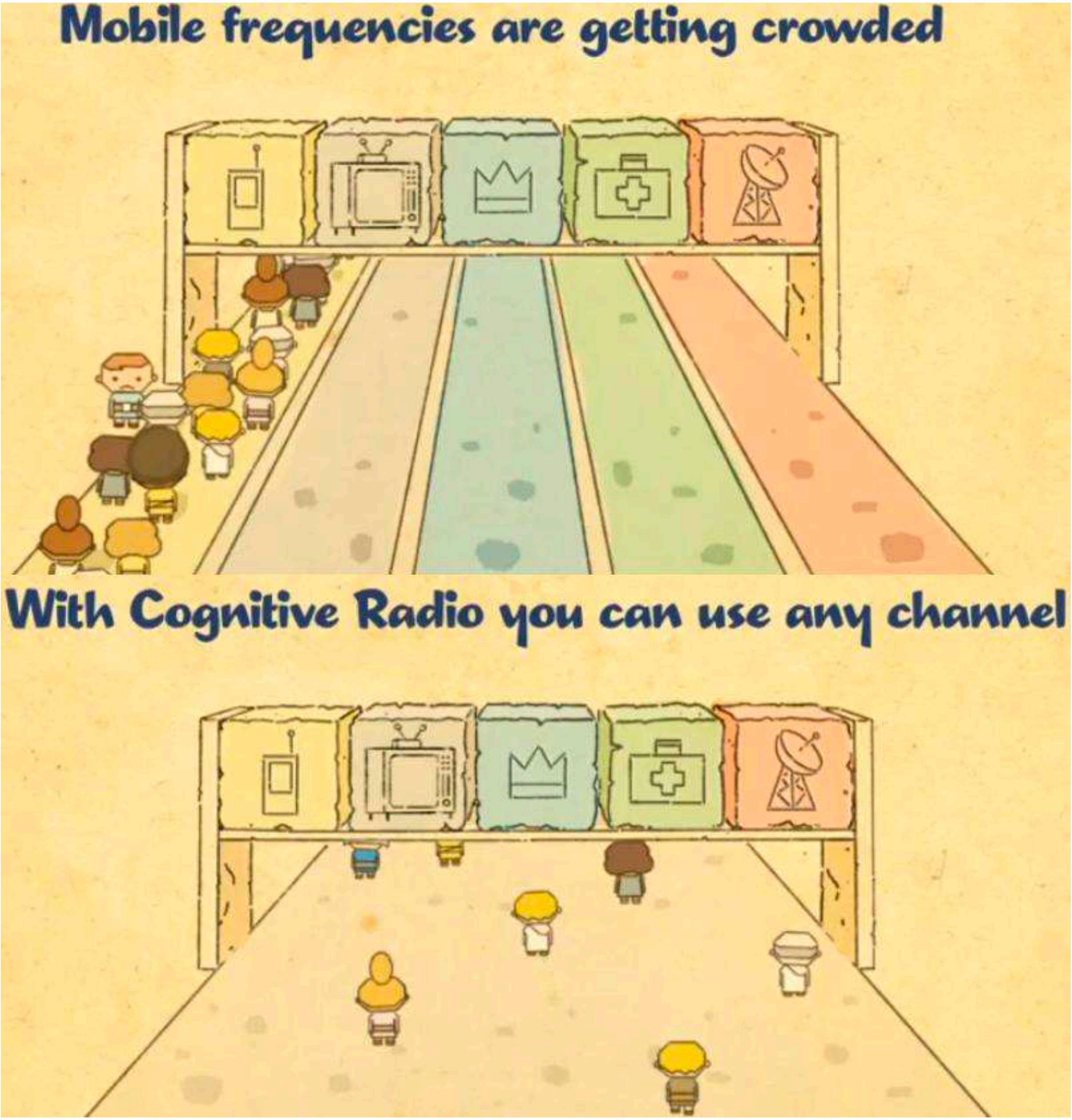
- Band
  - small section of the spectrum of radio communication frequencies
  - channels are used or set aside for the same purpose
- To prevent interference similar services are allocated in bands
  - e.g., broadcasting, mobile radio, or navigation devices, will be allocated in non-overlapping ranges of frequencies

# ITU's Band Allocation

| Band name | Abbreviation | ITU band | Frequency and wavelength in air | Example uses |
|---|---|---|---|---|
| Extremely low frequency | ELF | 1 | 3–30 Hz<br>100,000 km – 10,000 km | Communication with submarines |
| Super low frequency | SLF | 2 | 30–300 Hz<br>10,000 km – 1000 km | Communication with submarines |
| Ultra low frequency | ULF | 3 | 300–3000 Hz<br>1000 km – 100 km | Submarine communication, communication within mines |
| Very low frequency | VLF | 4 | 3–30 kHz<br>100 km – 10 km | Navigation, time signals, submarine communication, wireless heart rate monitors, geophysics |
| Low frequency | LF | 5 | 30–300 kHz<br>10 km – 1 km | Navigation, clock time signals, AM longwave broadcasting (Europe and parts of Asia), RFID, amateur radio |
| Medium frequency | MF | 6 | 300–3000 kHz<br>1 km – 100 m | AM (medium-wave) broadcasts, amateur radio, avalanche beacons |
| High frequency | HF | 7 | 3–30 MHz<br>100 m – 10 m | Shortwave broadcasts, citizens' band radio, amateur radio and over-the-horizon aviation communications, RFID, over-the-horizon radar, automatic link establishment (ALE) / near-vertical incidence skywave (NVIS) radio communications, marine and mobile radio telephony |
| Very high frequency | VHF | 8 | 30–300 MHz<br>10 m – 1 m | FM, television broadcasts and line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio |
| Ultra high frequency | UHF | 9 | 300–3000 MHz<br>1 m – 100 mm | Television broadcasts, microwave oven, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobile, FRS and GMRS radios, amateur radio |
| Super high frequency | SHF | 10 | 3–30 GHz<br>100 mm – 10 mm | Radio astronomy, microwave devices/communications, wireless LAN, most modern radars, communications satellites, cable and satellite television broadcasting, DBS, amateur radio |
| Extremely high frequency | EHF | 11 | 30–300 GHz<br>10 mm – 1 mm | Radio astronomy, high-frequency microwave radio relay, microwave remote sensing, amateur radio, directed-energy weapon, millimeter wave scanner |
| Terahertz or Tremendously high frequency | THz or THF | 12 | 300–3000 GHz<br>1 mm – 100 μm | Experimental medical imaging to replace X-rays, ultrafast molecular dynamics, condensed-matter physics, terahertz time-domain spectroscopy, terahertz computing/communications, remote sensing, amateur radio |

Spectrum Scarcity is the biggest problem …

# Cognitive Radio



# Making Radios Self Aware

- Three steps are important for making radio self aware
  - Aware radios
  - Adaptive radios
  - Learning Radios

# Aware Radios

- One motivation for an aware radio is providing information to the user
  - an aware radio may provide a pull-down menu of restaurants within a user-defined radius
  - code division multiple access (CDMA) based cellular system
    - aware of QoS metrics and makes reservations of bandwidth to improve overall QoS

# Adaptive Radios

- The various operating parameters that can be adapted are
  - frequency
  - instantaneous bandwidth
  - modulation scheme
  - error correction coding
  - channel mitigation strategies
    - equalizers or RAKE filters, system timing (e.g., a time division multiple access [TDMA] structure), data rate (baud timing), transmit power, and even filtering characteristics

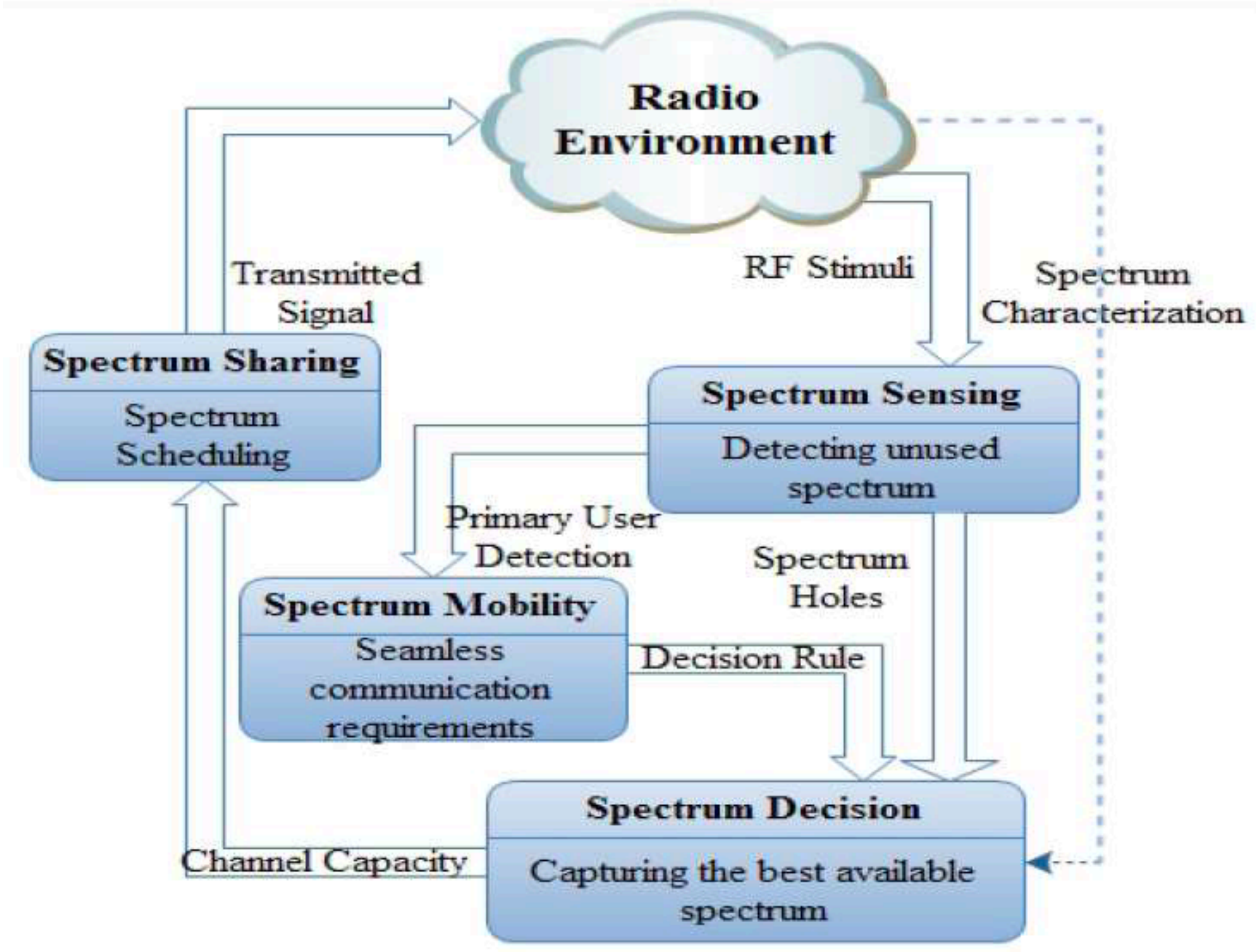
# Adaptive Radios

- Examples
  - frequency-hopping radio that changes hop pattern to reduce collisions
  - radio that changes instantaneous bandwidth and/or system timing parameters in response to offered network load

# Learning Radios

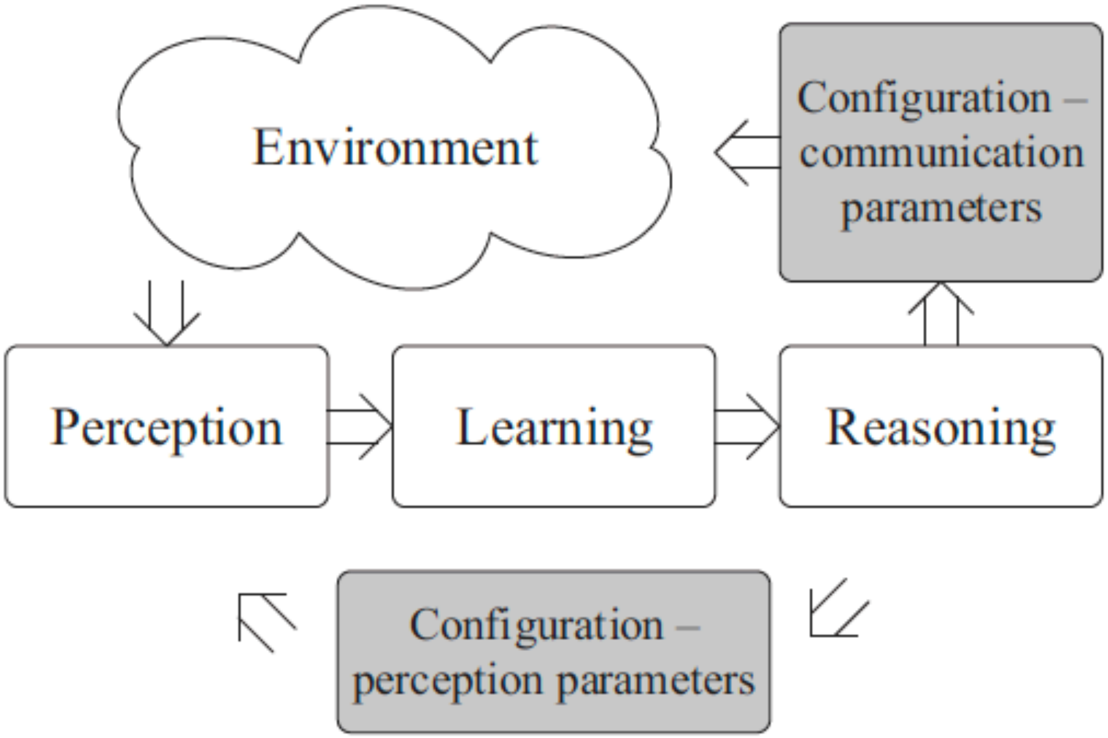
- A radio is said to be a learning radio or cognitive when they posses the following characteristics
  - Sensors creating awareness of the environment
  - Actuators to interact with the environment
  - A model of the environment that includes state or memory of observed events
  - A learning capability that helps to select specific actions or adaptations to reach a performance goal
  - Some degree of autonomy in action

# Radio Cycle



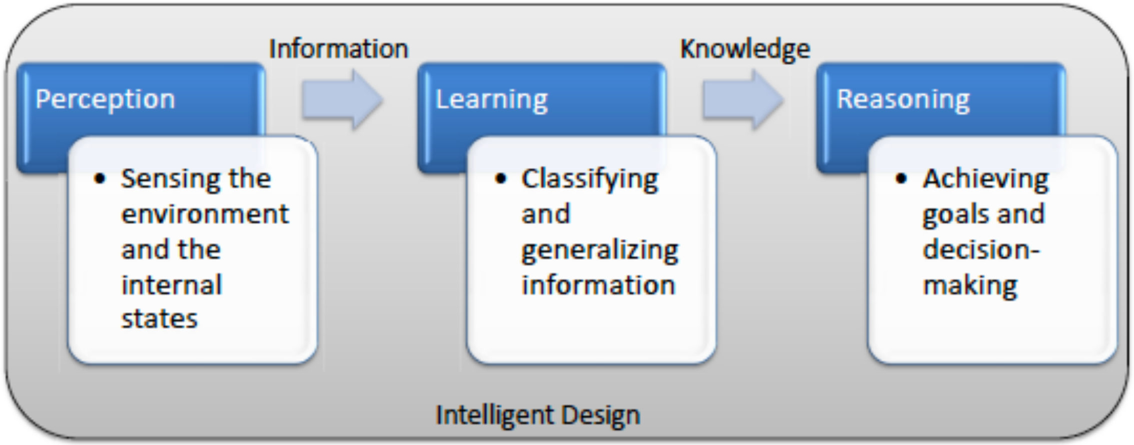
Radio Environment
Transmitted Signal
RF Stimuli
Spectrum Characterization
Spectrum Sharing
Spectrum Scheduling
Spectrum Sensing
Detecting unused spectrum
Primary User Detection
Spectrum Holes
Spectrum Mobility
Seamless communication requirements
Decision Rule
Spectrum Decision
Capturing the best available spectrum
Channel Capacity

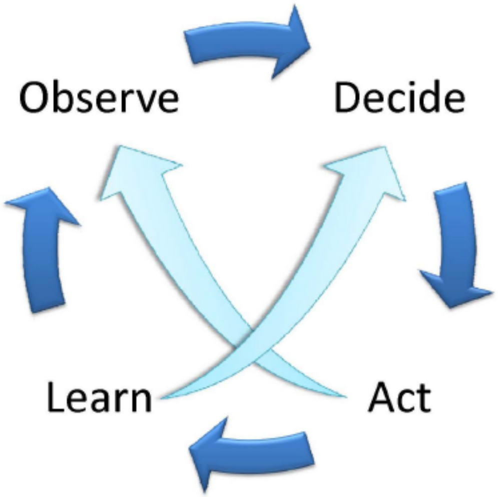
# CR and AI




Cognitive Radio and Machine Learning in Intelligent Wireless Communications

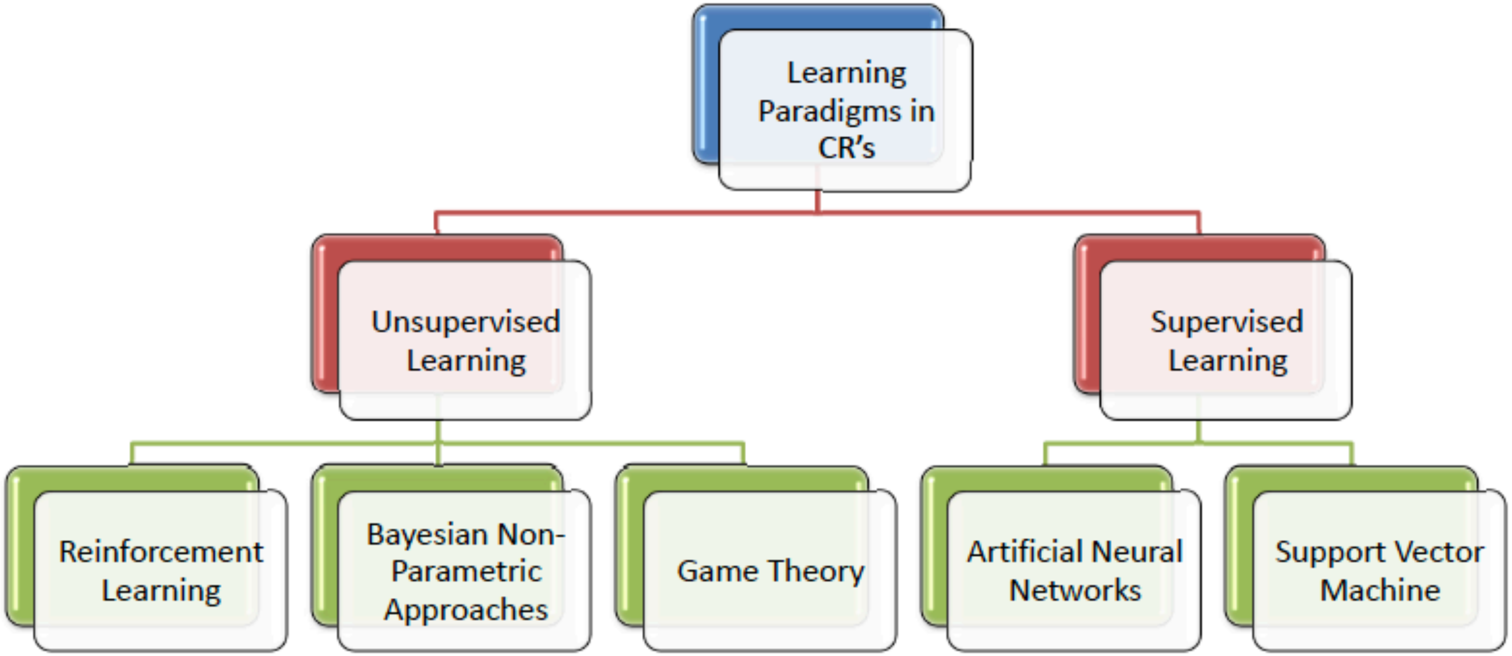
# CR and AI



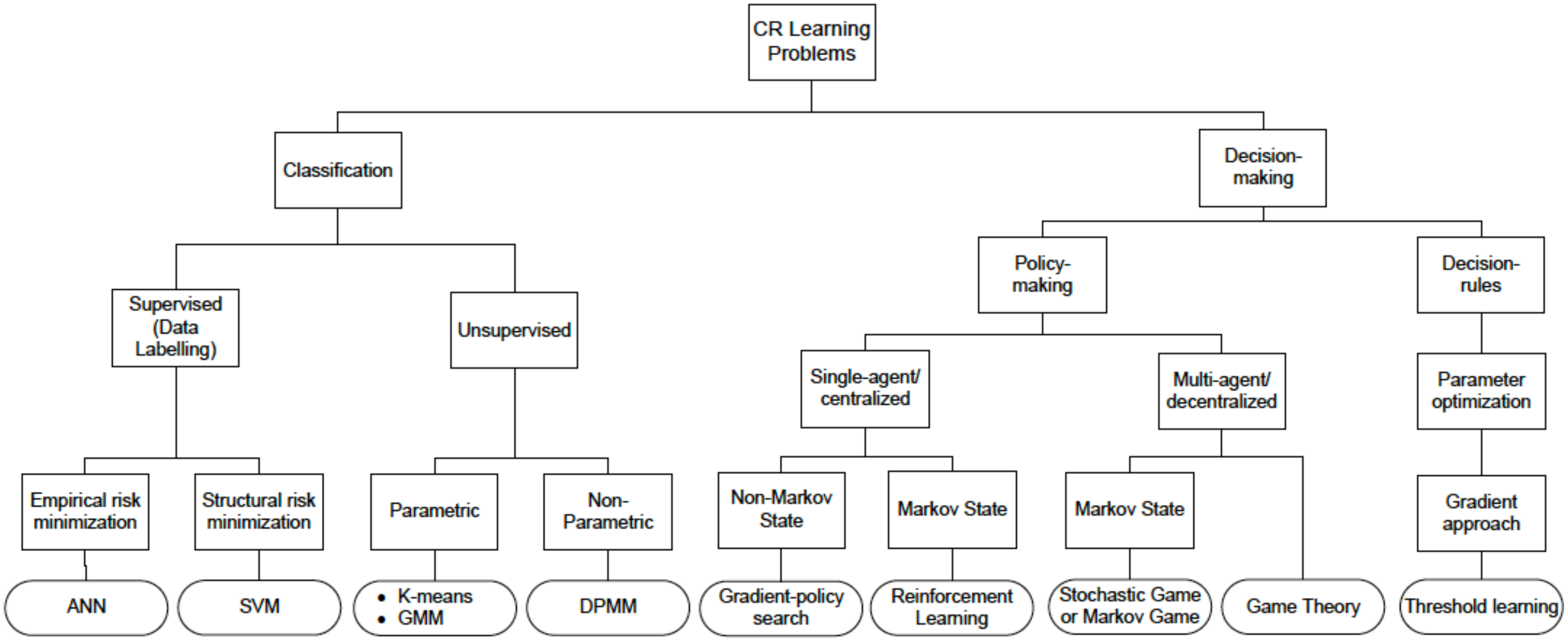

Cognition cycle of an autonomus Radio

# CR and AI



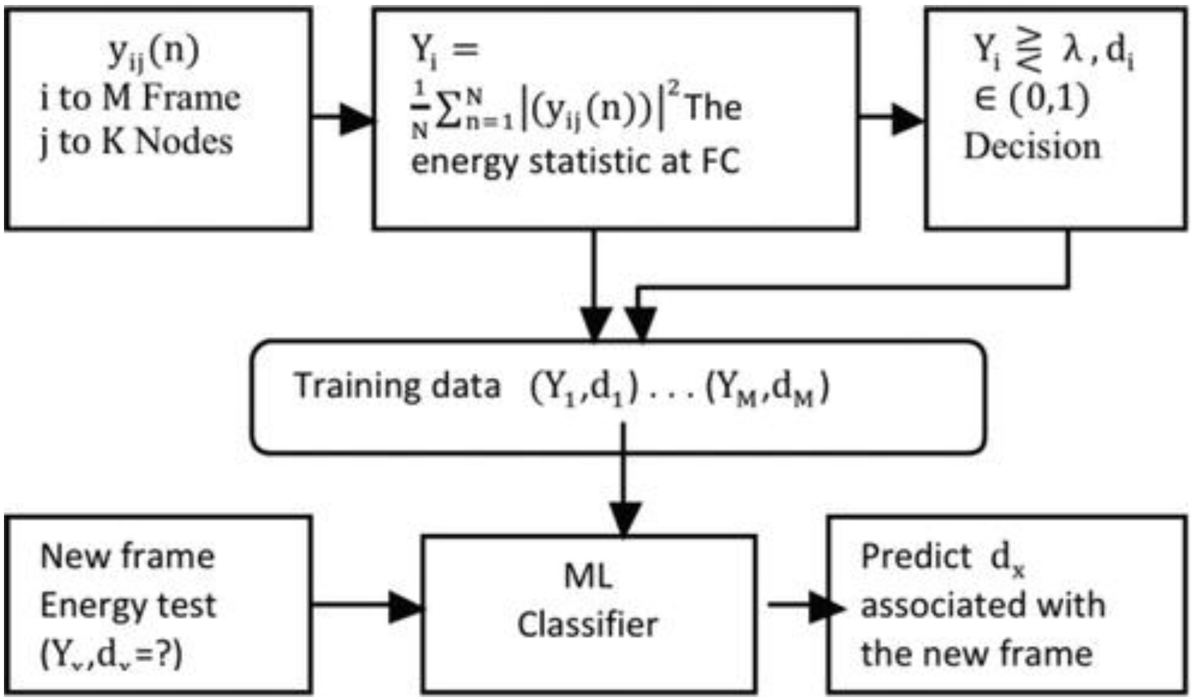

Supervised and unsupervised approaches for CR

# CR and AI



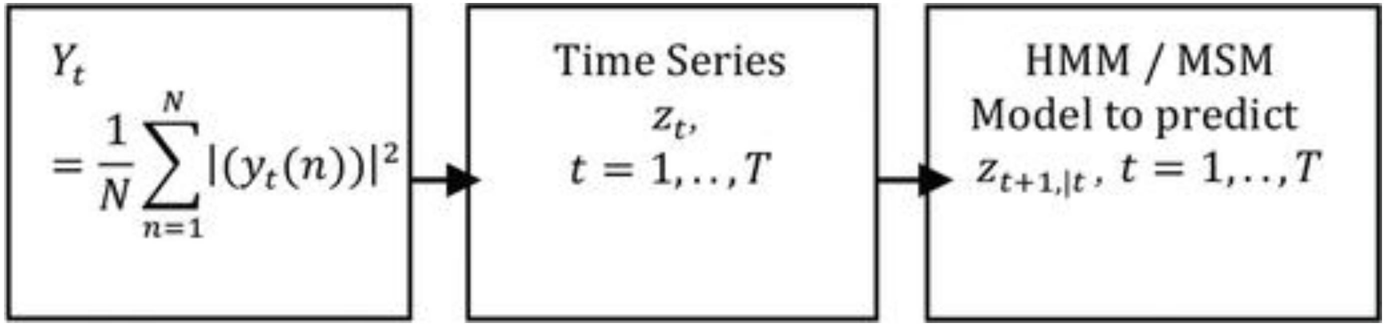

Typical CR problerms

# CR and AI




Block diagram of machine-learning-based fusion rule spectrum sensing

# CR and AI




Block diagram of PU channel state prediction model

# CR and AI



| | | Spectrum Sensing and MAC Protocols | Signal Classification and Feature Detection | Power Allocation and Rate adaptation | System Parameters Reconfiguration | Pros | Cons |
|---|---|---|---|---|---|---|---|
| Unsupervised learning techniques | Reinforcement learning (RL) | x | | | | Optimal solution for MDP's | In general, suboptimal for POMDP's, DEC-MDP's and DEC-POMDP's |
| | Non-parametric Learning: DPMM | | x | | | Does not require prior knowledge about the number of mixture components | Requires large number of iterations, compared to parametric methods |
| | Game theory-based Learning | x | | x | | Suitable for multi-player decision problems | Requires knowledge of different parameters (e.g. SINR, power, price from base stations, etc.) which is impractical in many situations |
| | Threshold Learning | | | | x | Suitable for controlling specific parameters under uncertainty conditions | Requires training data |
| Supervised learning techniques | Artificial Neural Network (ANN) | | x | | | Does not require prior knowledge of the distribution of the observed process | ▪ Suffers from *overfitting*<br>▪ Requires data labeling |
| | Support Vector Machine (SVM) | | x | | | Has better performance for small training examples, compared to ANN | ▪ Requires prior knowledge of the distribution of the observed process<br>▪ Requires data labeling |

Comparison of the learning algorithms