Cognitive RF Systems:

Why RF Demands a Different Kind of AI

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Notes based on the book
Cognitive EW: An AI Approach
by Haigh and Andrusenko [ArtechHouse, 2025]

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Who Am I – Dr. Karen Zita Haigh

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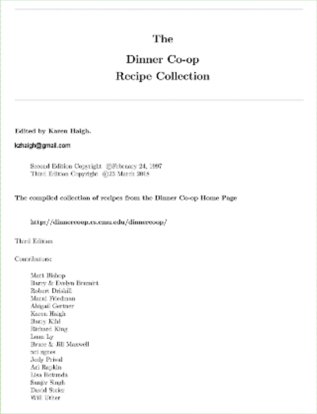
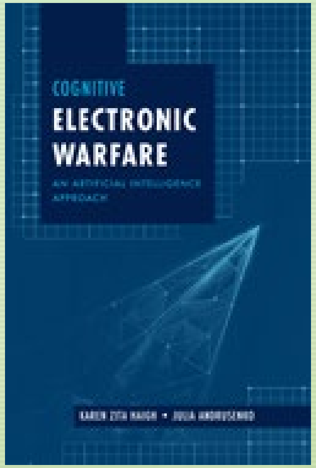
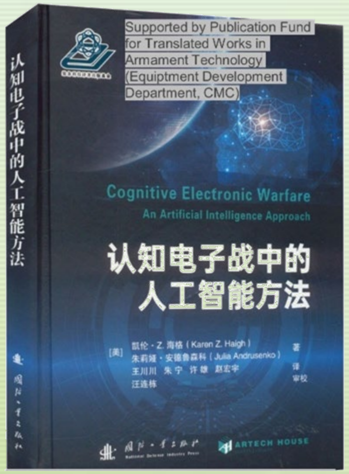
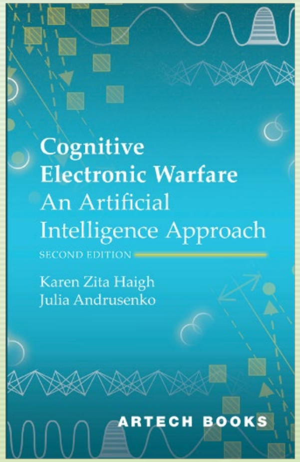
  - https://sites.google.com/site/kzhaigh
- PhD from Carnegie Mellon (AI and Robotics)
  BSc (Hon CompSci) from University of Ottawa *(summa cum laude)*
- 30+ years experience in embedded AI
  Pioneer in Cognitive EW
  - Mercury Systems, L3Harris, Raytheon BBN, Honeywell
- IEEE Fellow, AAIS Fellow, Life Member of AOC
- Published numerous articles in technical journals and conferences
- Published three books
  - The Dinner Co-op Cookbook (1997)
  - Scripting Your World (2008)
  - Cognitive EW (2021 and 2025)









US Book Orders: https://us.artechhouse.com/Cognitive-Electronic-Warfare-An-Artificial-Intelligence-Approach-Second-Edition-P2445.aspx

Brief Intro to Electromagnetic Spectrum Operations

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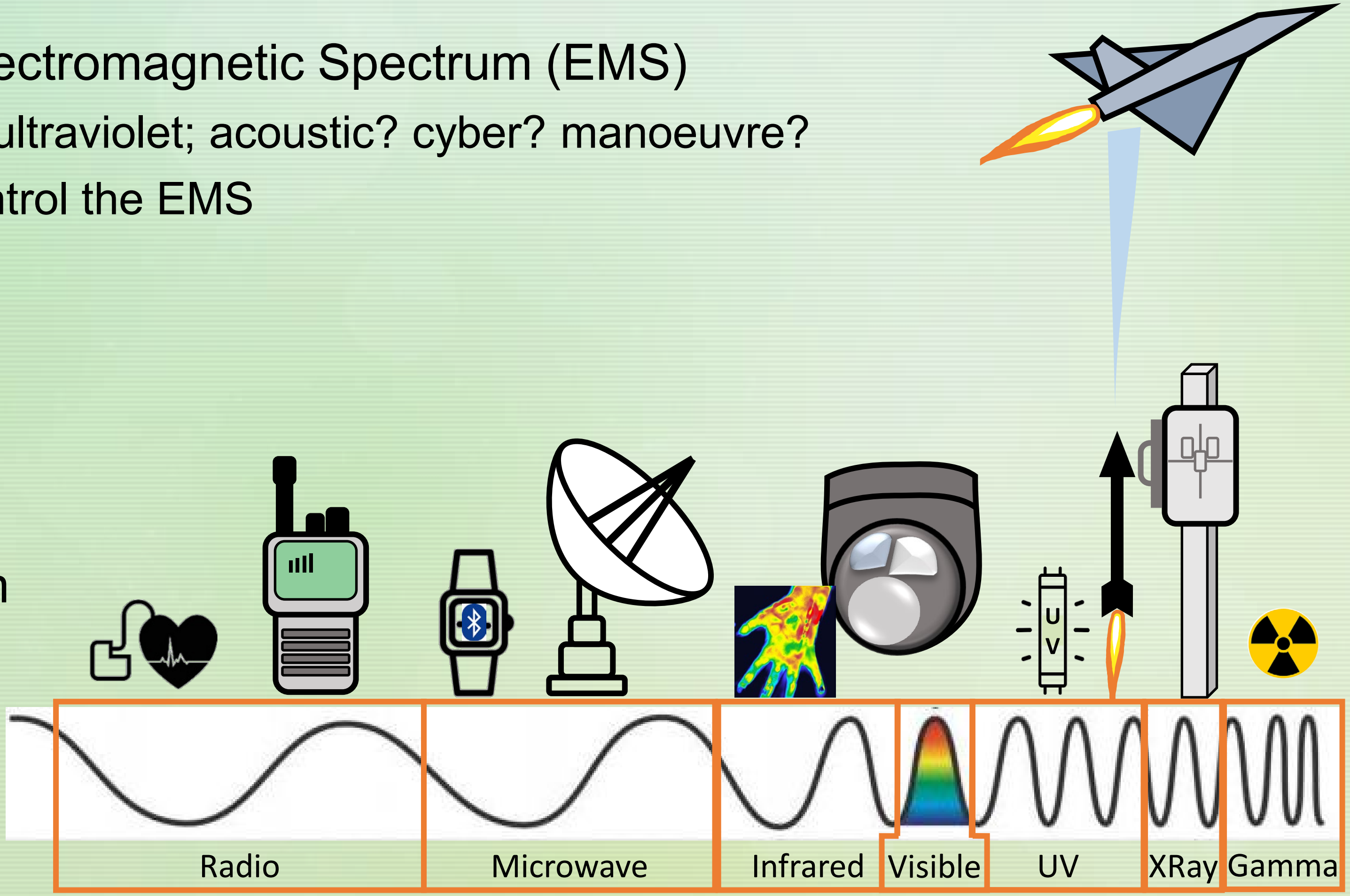
Electromagnetic Spectrum Operations (EMSO)

- Coordinated actions involving the Electromagnetic Spectrum (EMS)
  - Radio, radar, infrared, electro-optical, ultraviolet; acoustic? cyber? manoeuvre?
  - To leverage, protect, manage, and control the EMS
- Analogy: Cocktail party
- Multi-domain
  - Anywhere and everywhere
  - Multi-node, multi-task coordination
- Traditional approaches to RF system design are failing in modern engagements
  - Timeline is too fast
  - Complexity is too high
  - No methods handle novel emitters



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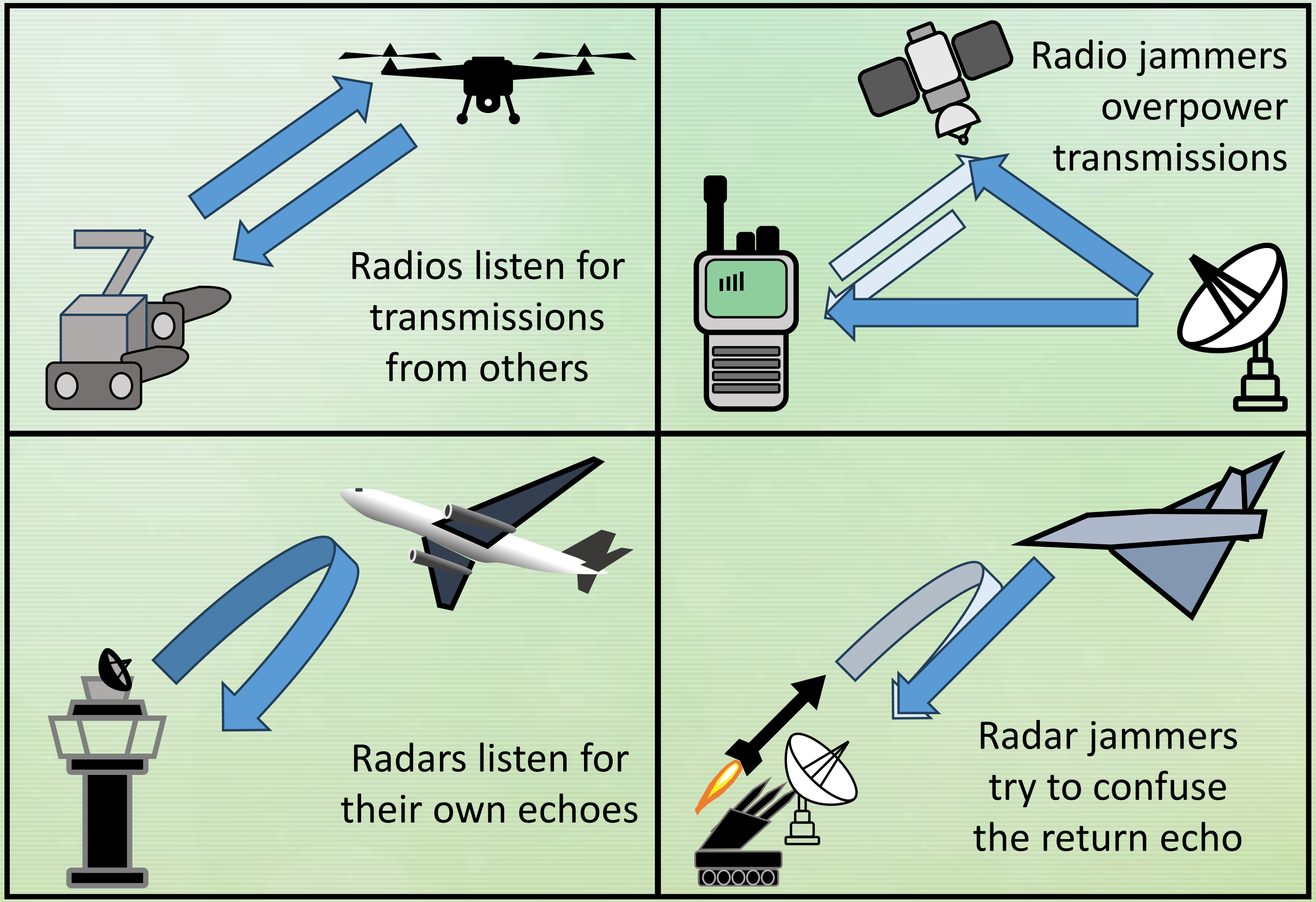
How does the EMS work?



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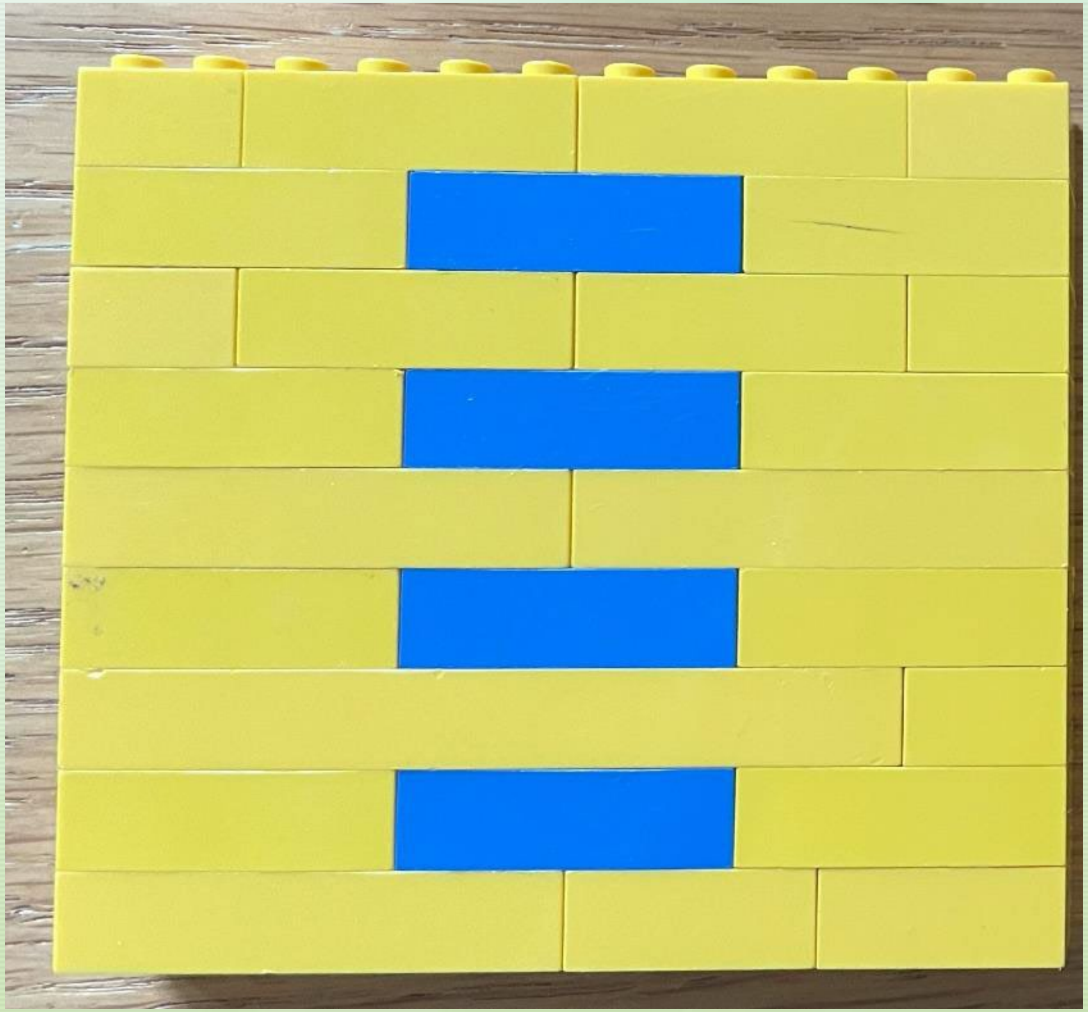
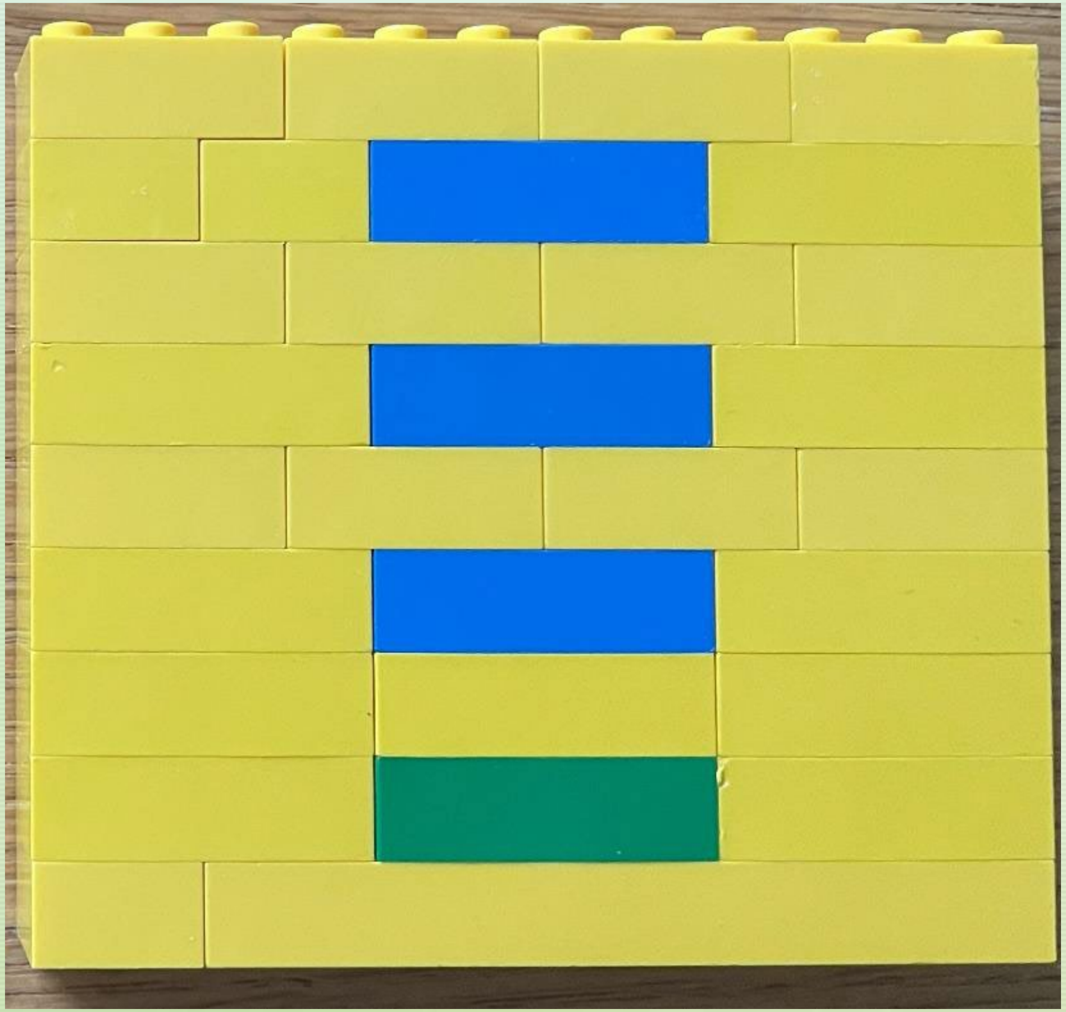
Are these waveforms the same?





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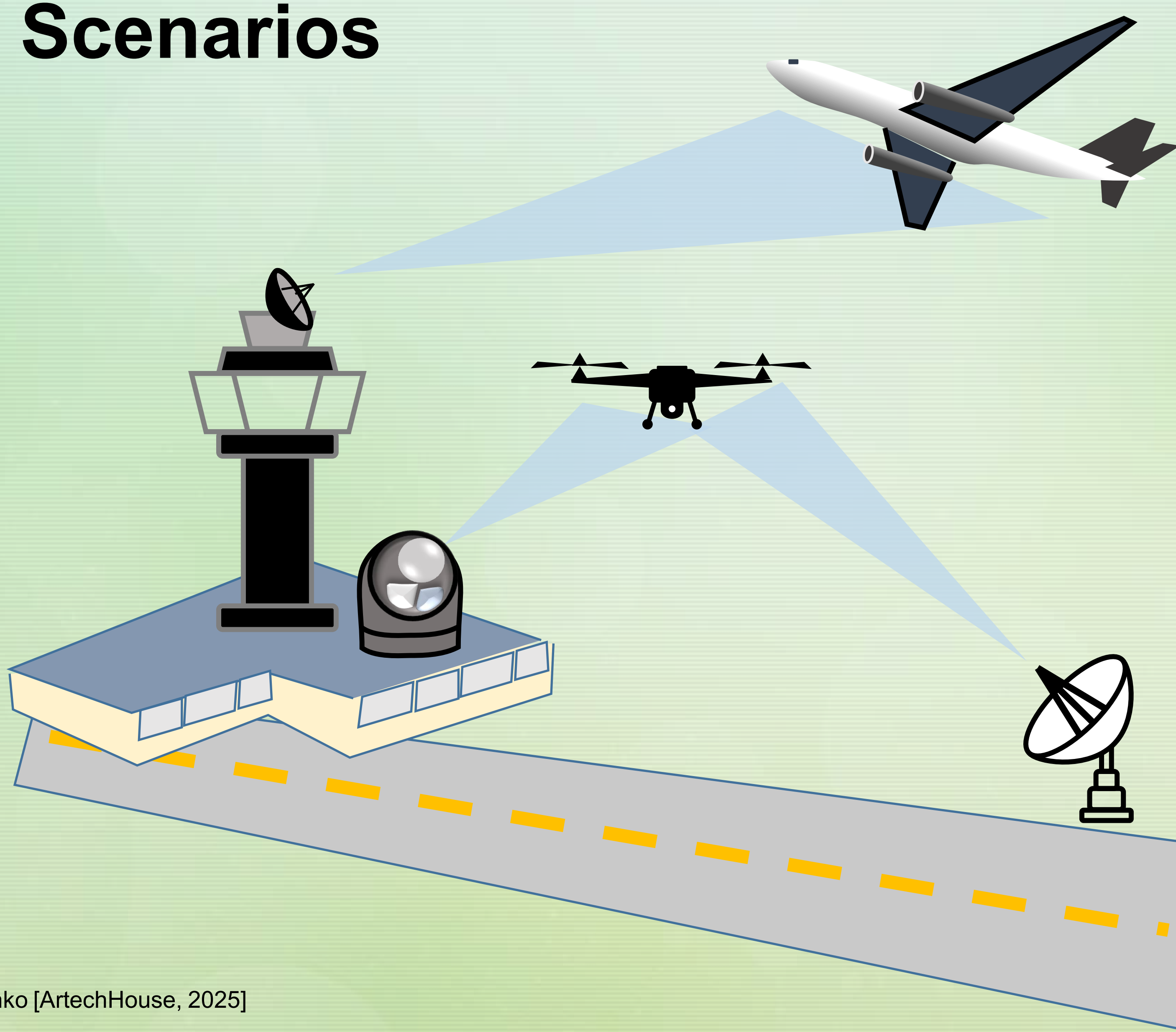
Civilian & Commercial Scenarios

- Emergency management
- Border security
- Anti-terrorism
- Anti-poaching
- Law enforcement
- EMSO in Medical Devices
- Aviation:
  - Airport Command & Control
  - Drone Incidents at Airports



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Three Sides to the Same Coin: Cognitive Radio, Cognitive Radar, Cognitive EW

- Rely on comprehensive understanding of the channel
  - Complex
  - Active probing
- Real-time environmental awareness to support decisions
  - Characterization, classification, data fusion, anomaly detection, intent recognition
- Dynamically adapt transmission and signal processing based on environmental feedback to maximize performance
  - Waveform design, resource allocation, spectrum sharing

Cognitive radio & radar handle *adversity*
Cognitive EW handles *adversaries*

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Vision of Cognitive RF Systems

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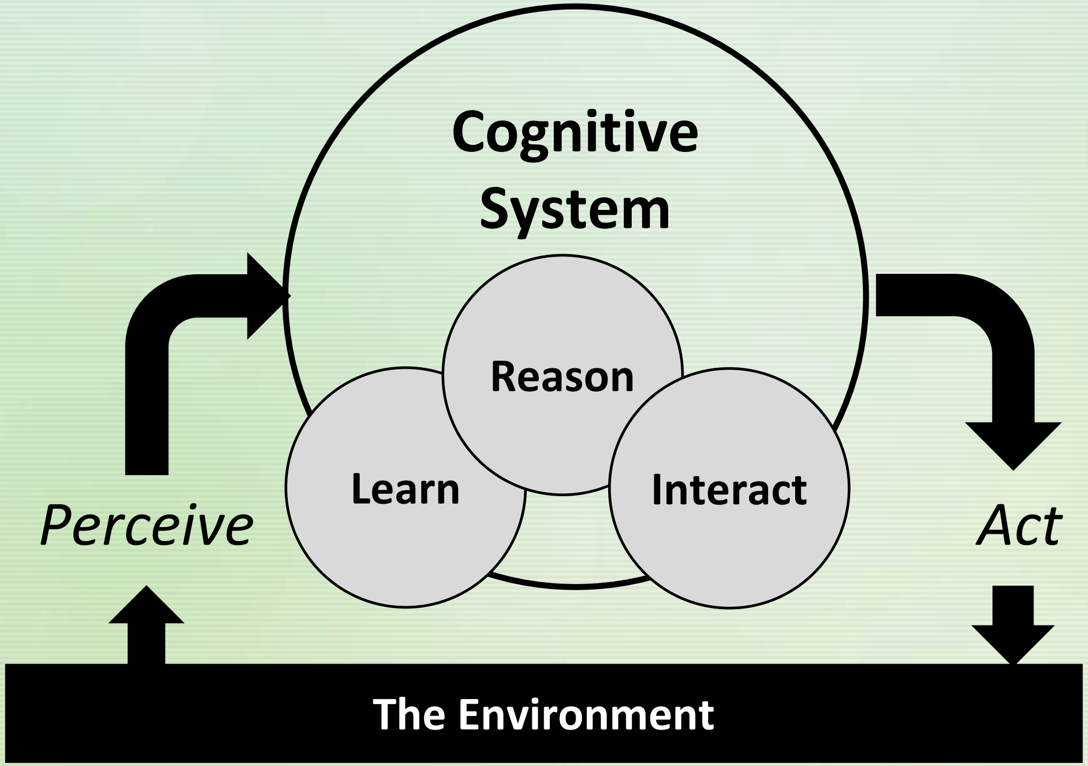
What is a Cognitive System?

- Cognitive systems perceive the environment and take actions to achieve goals.
  - **Iterative** (long-term behaviours)
  - **Interactive** (change the environment)
  - **Deliberative** (goal-directed)
  - **Transformative** (self-learning)

Cognitive systems
learn after deployment



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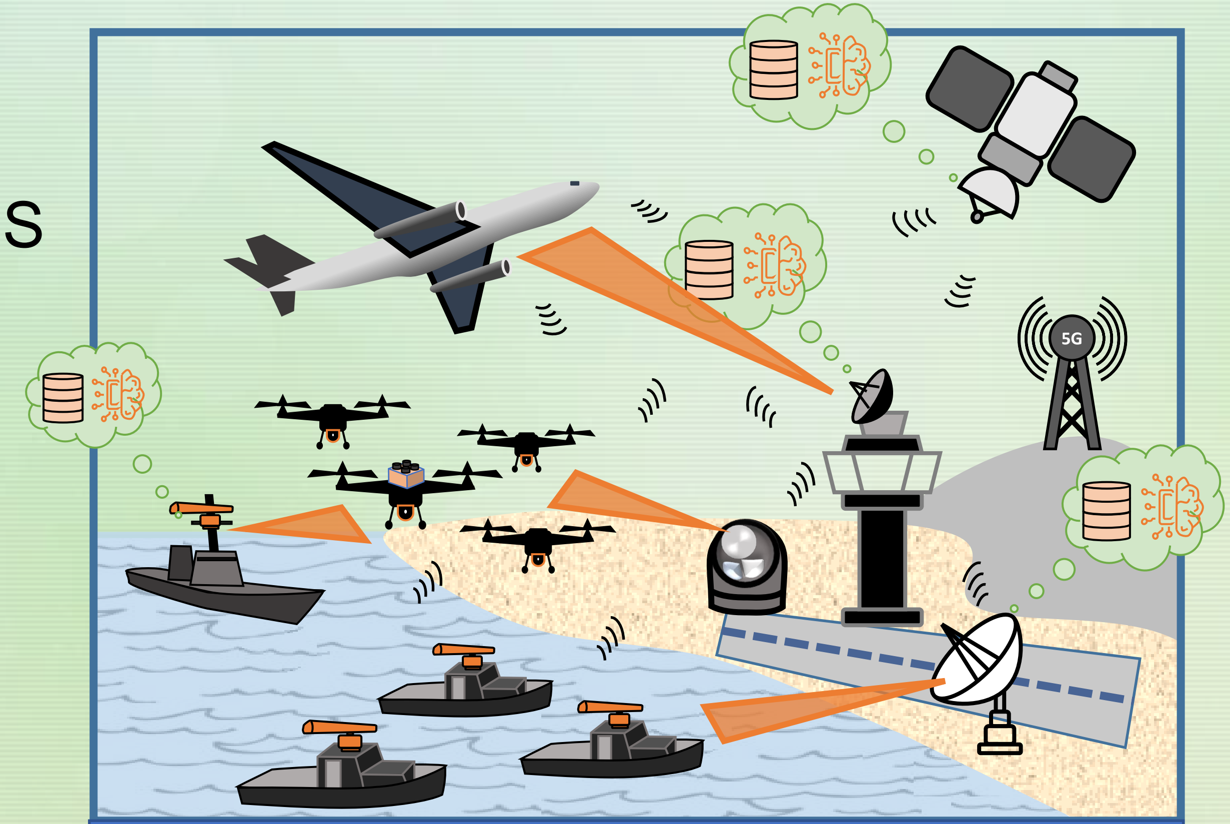
Vision of Cognitive EMSO

- A Cognitive RF system
  1. **Understands** and predicts the EMS environment,
  2. Makes goal-directed **decisions** to improve the performance of an RF system, and
  3. **Learns** from its own actions
- at mission-relevant timescales with minimal human supervision



See through the clutter
Respond to novel waveforms

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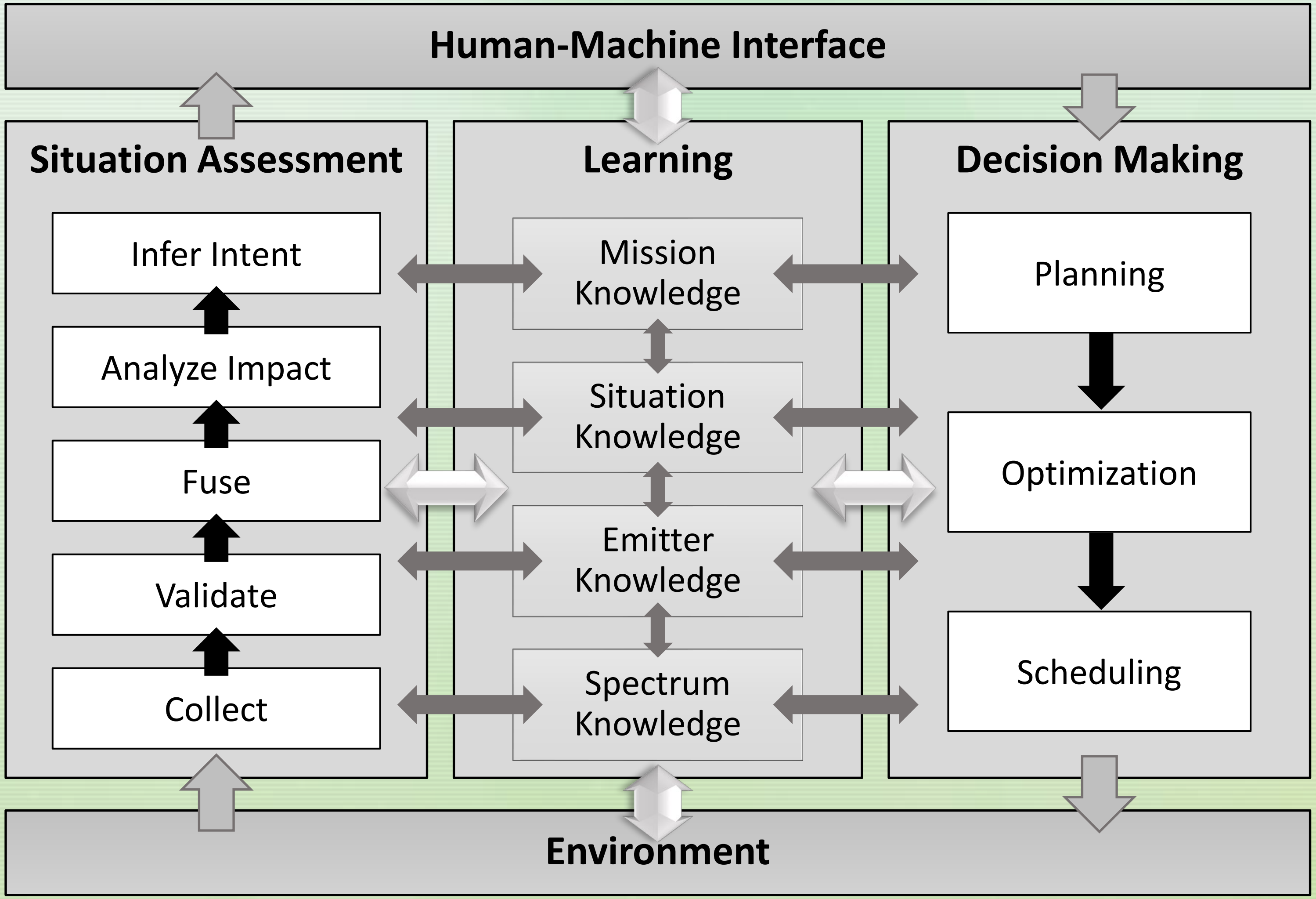
Information Flow in a Cognitive System



The framework applies to any Cognitive System

- **Iterative** (long-term behaviours)
- **Interactive** (change the environment)
- **Deliberative** (goal-directed)
- **Transformative** (self-learning)

It is the domain (and its data) that makes it a Cognitive **RF** System

…or cognitive hospital manager

…or cognitive training system

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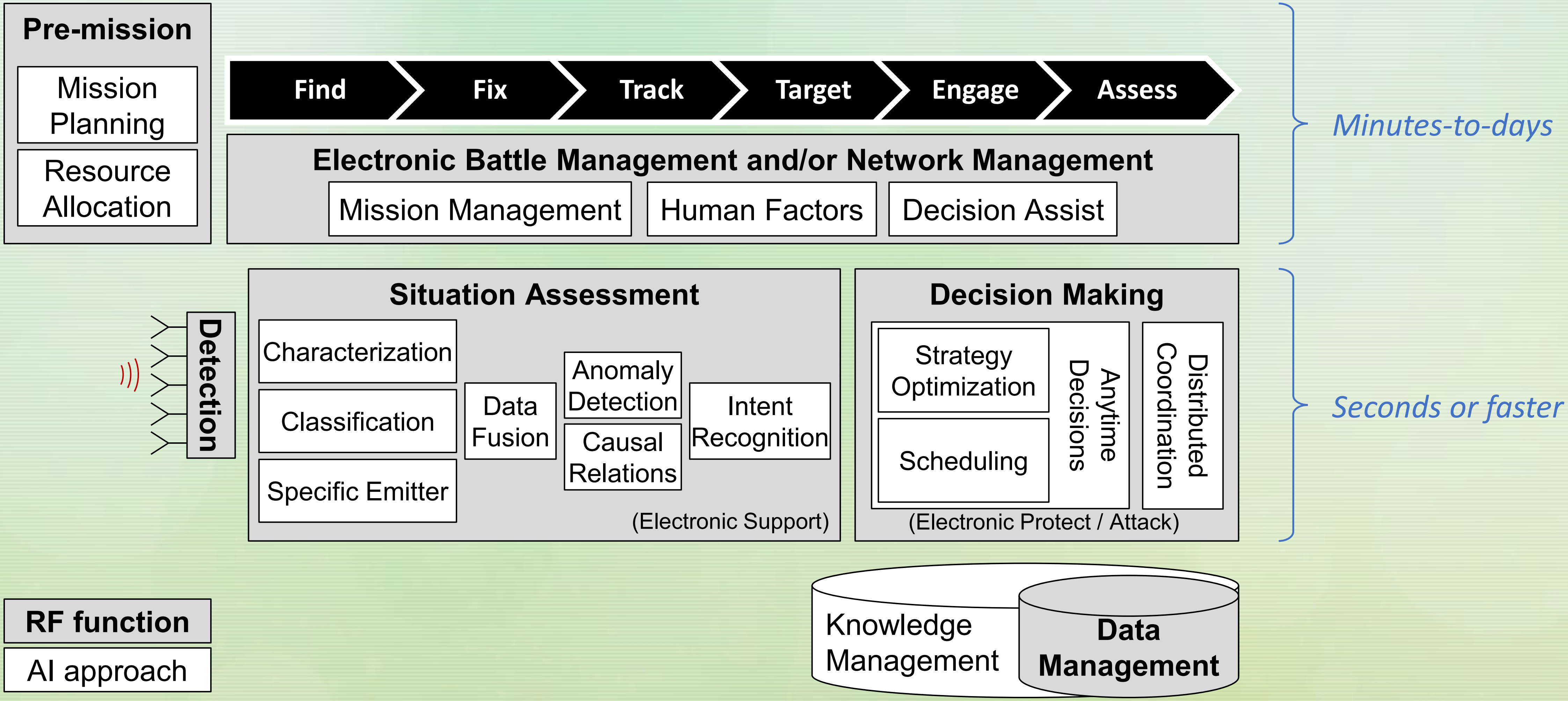
AI Capabilities in RF Systems



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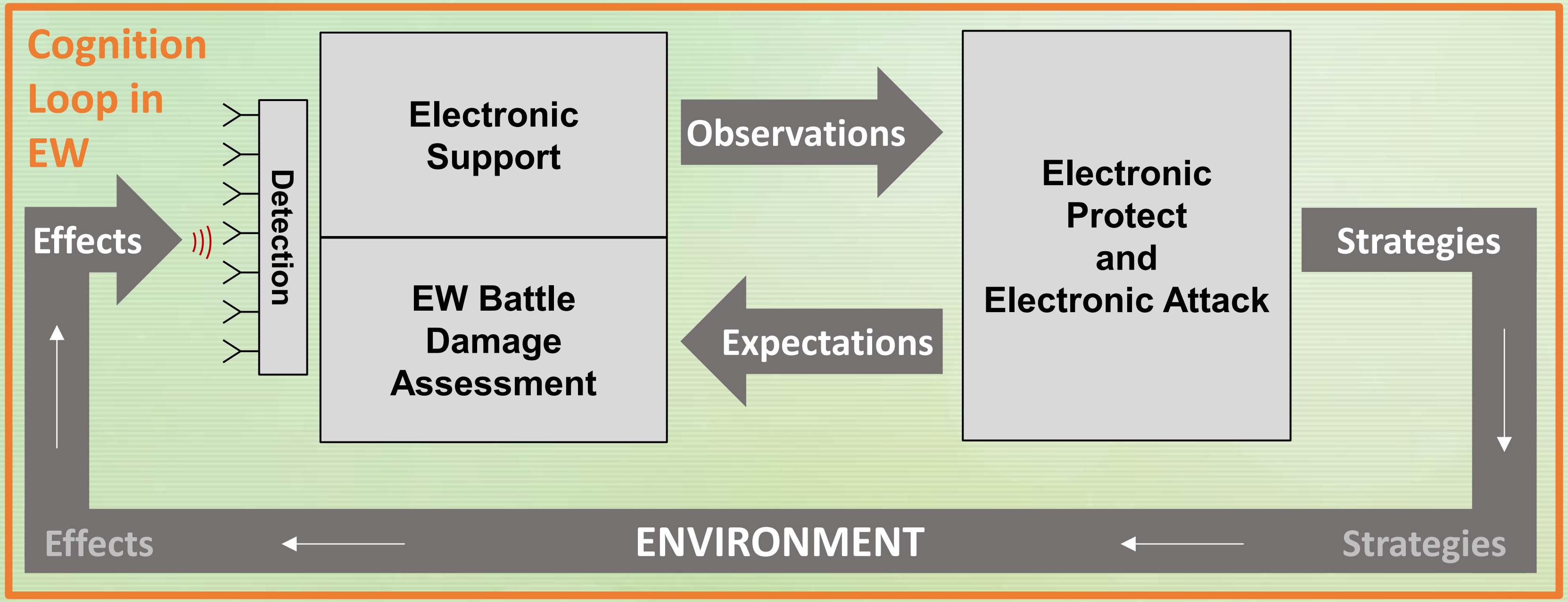
Real-Time In-Mission Cognition

- **Situation Assessment**
  - Update histories and probabilities based on task progress
  - Identify novel conditions
  - Predict the future
- **Effects Analysis**
  - Compare expected effects to observed effects
- **Decision Making:** Replanning
  - Update actions based on changing conditions
- **Decision Making:** Reinforcement Learning
  - Use experience to update expectations and choose actions based on expected reward



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What Makes Cognitive RF Unique

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Distributed Robotics vs Cognitive RF Systems

Dimension	Distributed Robotics	Cognitive RF Systems
Communication	Communication is pre-defined	Negotiate how to communicate
Observation timescale	Milliseconds or slower	Milliseconds or faster
Decision speed	Milliseconds or slower	Milliseconds or faster
Data characteristic	Moderate, often periodic or event-driven	Streaming, massive (e.g., 1PB/min)
Surprise Factor	Relatively well-modelled; exceptions are rare	Exceptions are the norm
Action space	Moderate (dozens of actuators per robot)	Extensive (1000+ controllable RF parameters per transceiver)

Predictable
Visible

Unpredictable
Invisible

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Cognition in Embedded Edge Environments

System Requirements

- Embedded systems must
  - autonomously process sensor data,
  - decide what actions to take, and
  - learn from their experiences
- without the benefit of Cloud infrastructure
- with limited data
- with limited human supervision

Operational Context

- Limited or no connectivity to other nodes
- Limited computation capabilities
- Limited power
- Enhanced security requirements
- Mission-critical reliability

Required Capabilities

1. Develop approaches that can learn from a ***single observation***
2. Assure the ***learning process***, rather than validating the static ***product*** (learned model)
3. Take ***small steps*** along the cognition spectrum

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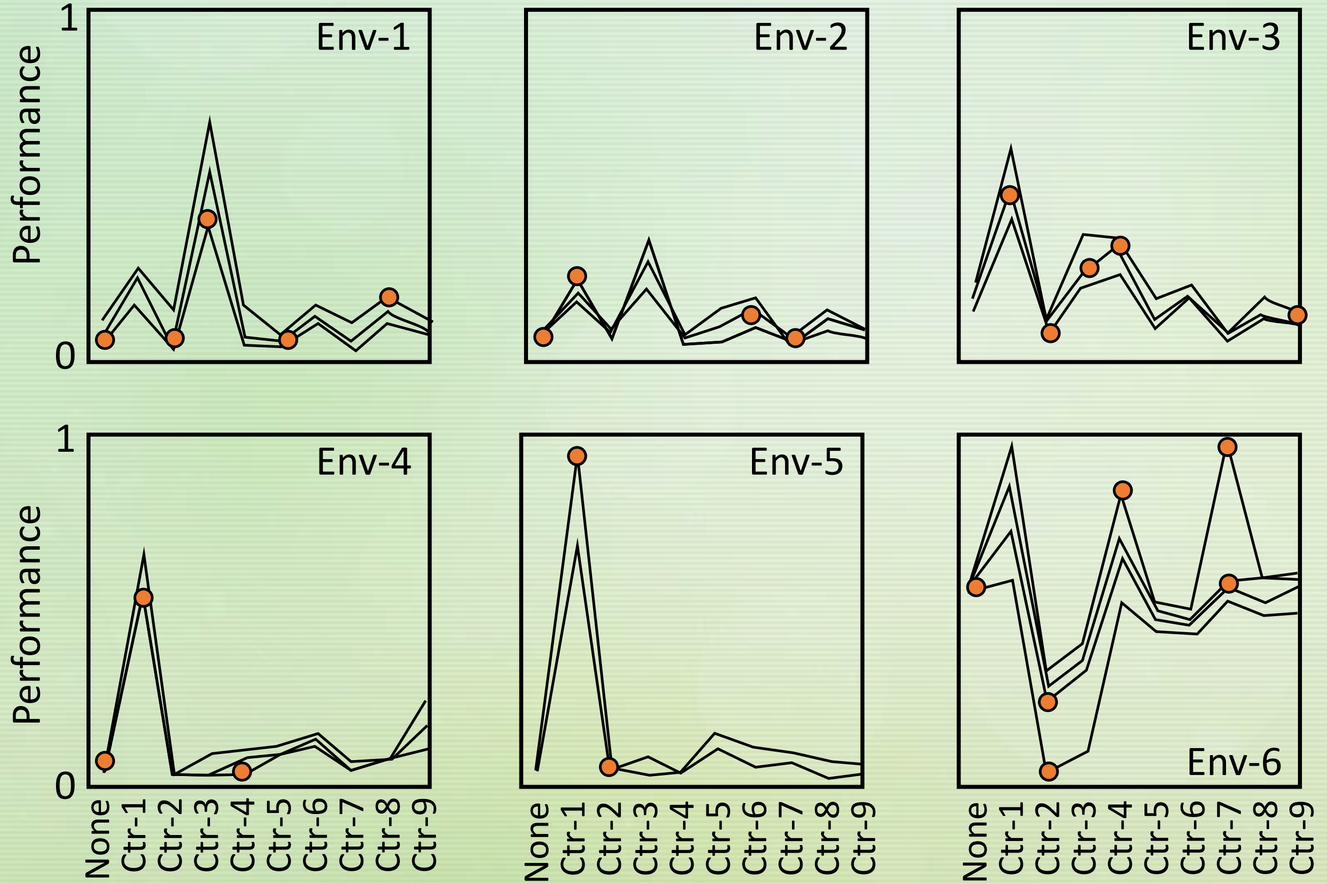
(1) Machine Learning in RF is About Surprise

- ML techniques use **empirical data** to learn a **model** of the environment
  - Similar to function approximation
- ML models generalize from examples
  - The model predicts values for all inputs, even if they were not present in the training data

In RF, surprise is normal, not the exception

Estimating Technique Effectiveness from Limited Data



Direct measurements represented by orange dots.
All other values estimated based on observables

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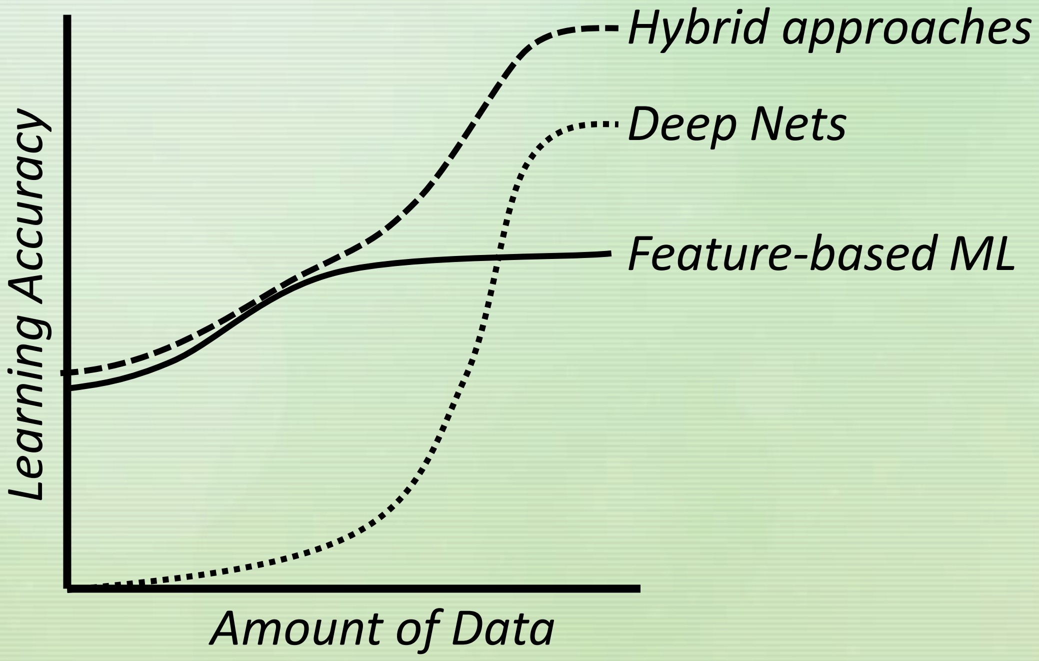
(1) Learning from a Single Observation

Rare modes may be lethal before we have multiple observations



- ***Hybrid learning*** leverages what we already know
  - …scientific principles, engineering expertise…

  to get better results, faster
- Hybrid ML out-performs purely empirical models
  - Especially when data is more limited
  - And the domain changes
- Known as
  - Knowledge-based ML
  - Neuro-Symbolic AI
  - Scientific ML

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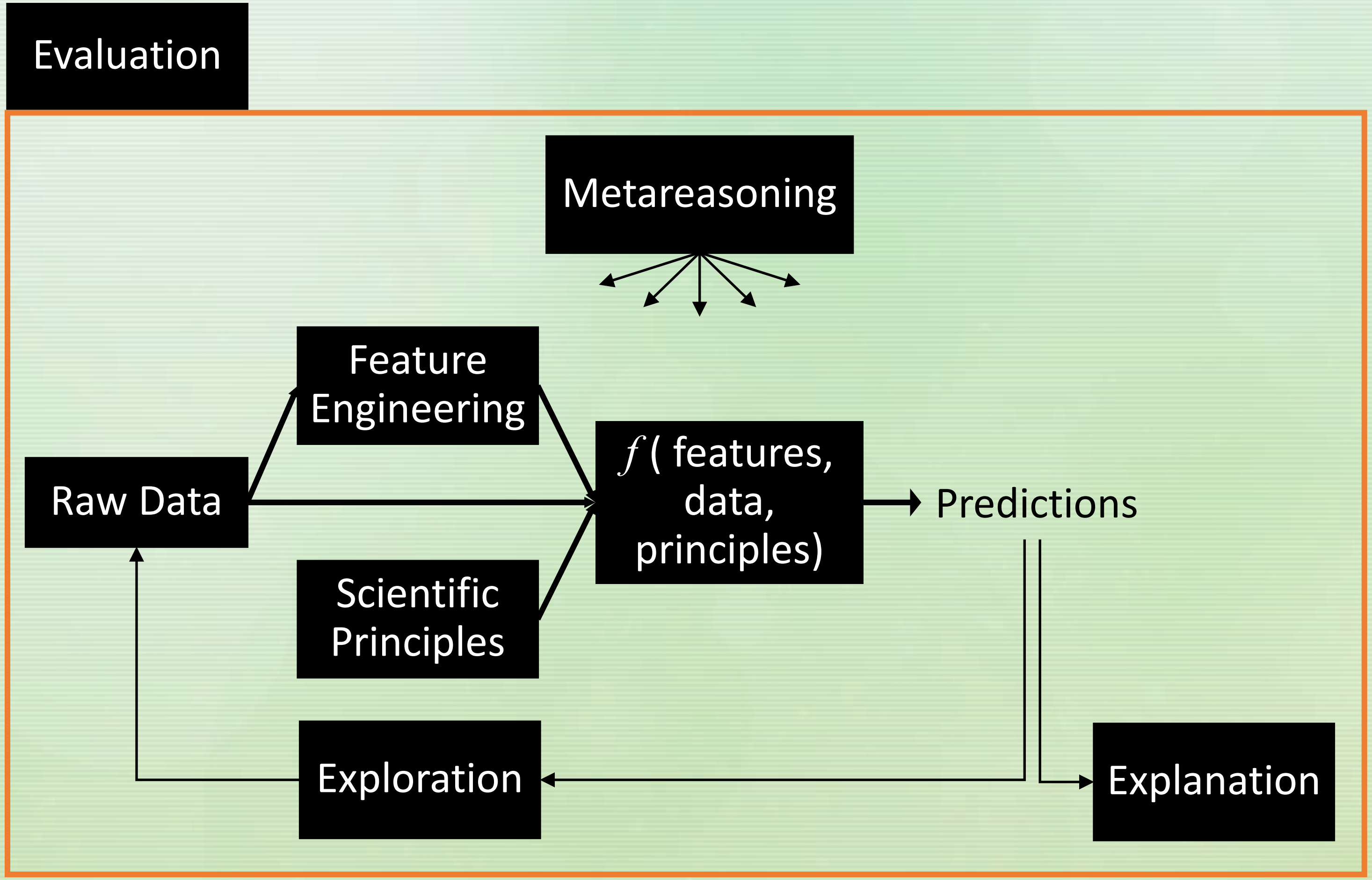
See https://arxiv.org/abs/2003.04919v5 for survey and taxonomy

(1) Domain-Specific Context in Action



- Survey and Taxonomy
  - Willard et al, *Integrating Scientific Knowledge with Machine Learning for Engineering and Environmental Systems*, 2022, https://arxiv.org/abs/2003.04919v6
- Design Patterns
  - Van Bekkum et al, "*Modular design patterns for hybrid learning and reasoning systems*," 2021, https://link.springer.com/article/10.1007/s10489-021-02394-3

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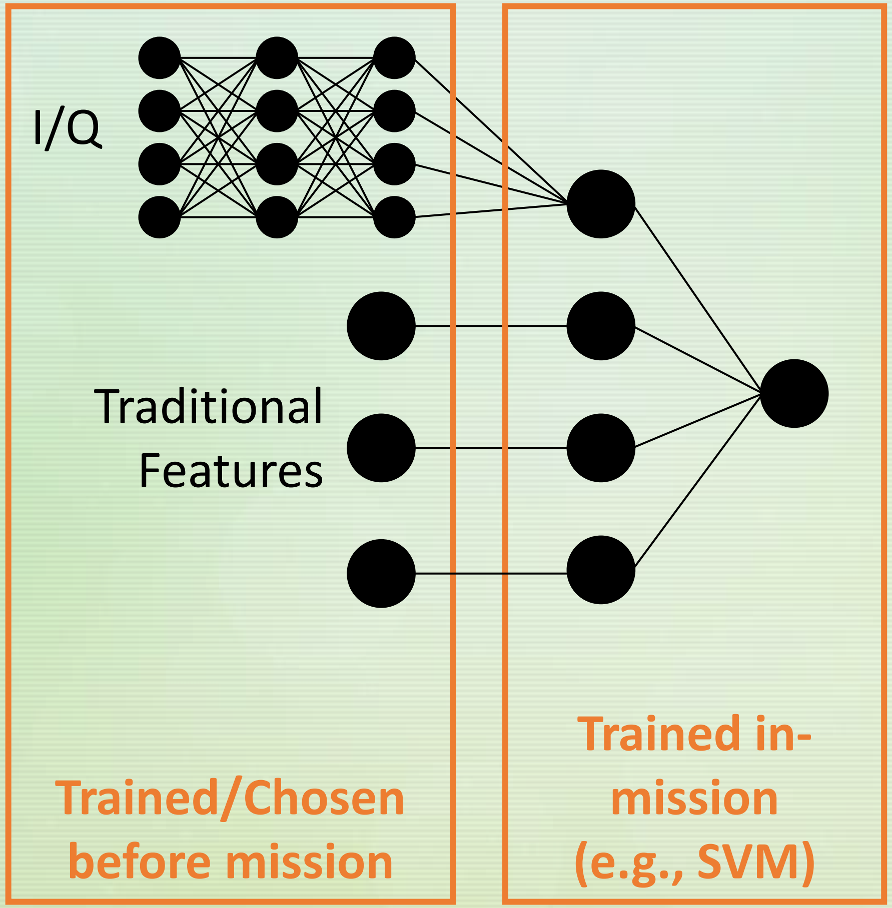
(1) Hybrid Models Enable Rapid In-Mission Learning

- **Barrier:** DeepNets can't learn from a single example online
- **But:** We'd like to leverage their ability to extract latent features
- **Therefore:** Train the DeepNet offline, and use a fast embedded ML technique that can be retrained quickly
  - e.g. Freeze all the weights, and only retrain the SoftMax layer



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(2) Assuring In-mission Learning

Cognitive systems
learn after deployment

- T&E must validate the learning ***process***, rather than the final learned ***model***
  - Because the model changes after deployment
- T&E must evaluate ***learning goals*** along with other performance metrics
  - The way a cognitive system learns impacts system suitability

Most tools focus on ***Development*** not ***Deployment*** considerations

Learning Goals
Accuracy of characterization and decisions
Data requirements (amount and quality)
Learning rate
Generalizability to surprise
Usability & Explainability
Complexity of mission
Computation effort of training and inference
Robustness to data variation
Ability to self-determine confidence
Performance over time
Scalability to new system capabilities
Portability to new hardware

T&E – Test & Evaluation
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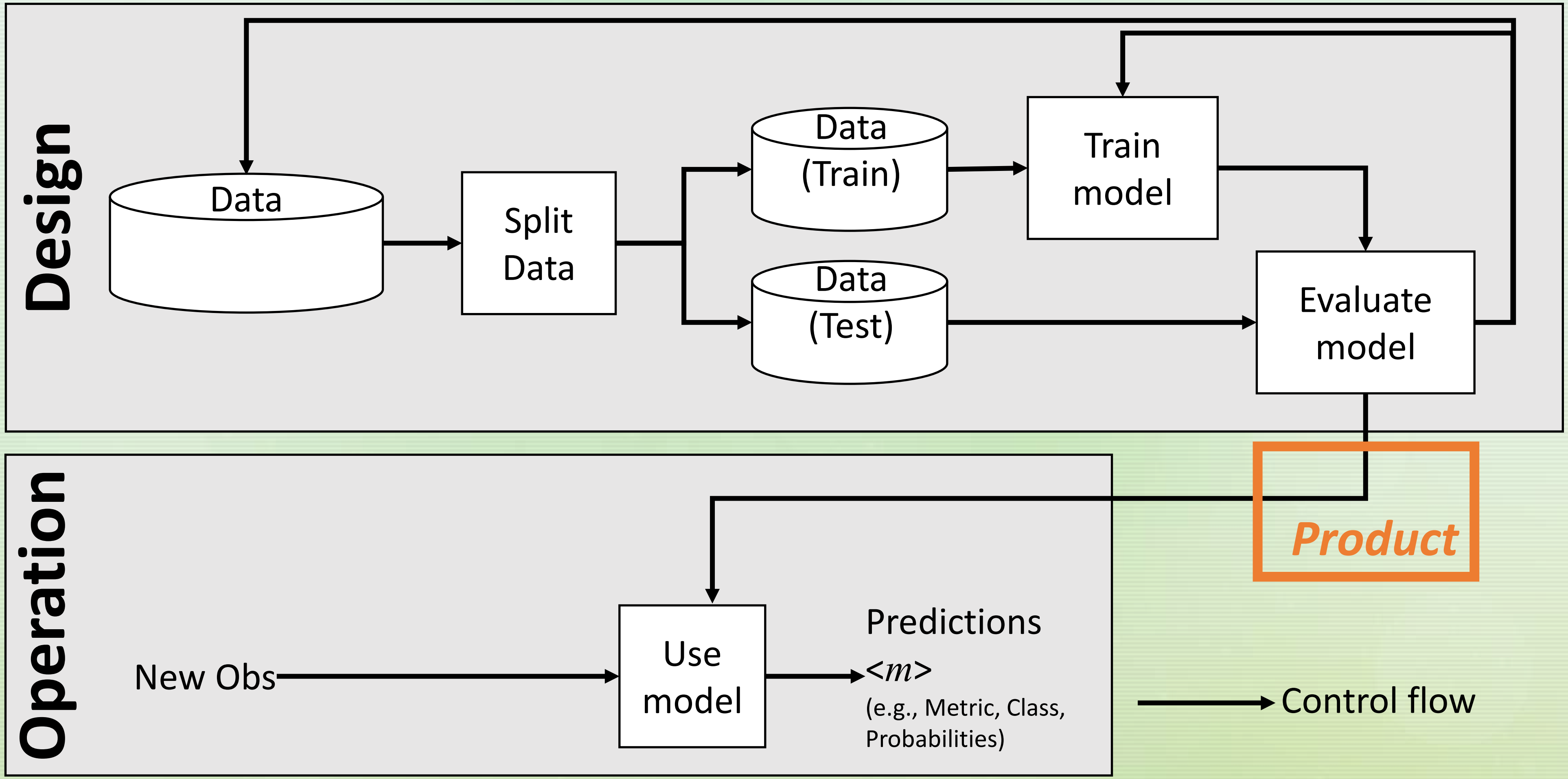
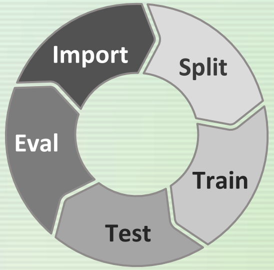
(2) Testing for AI-enabled Systems: Focus on *Product*





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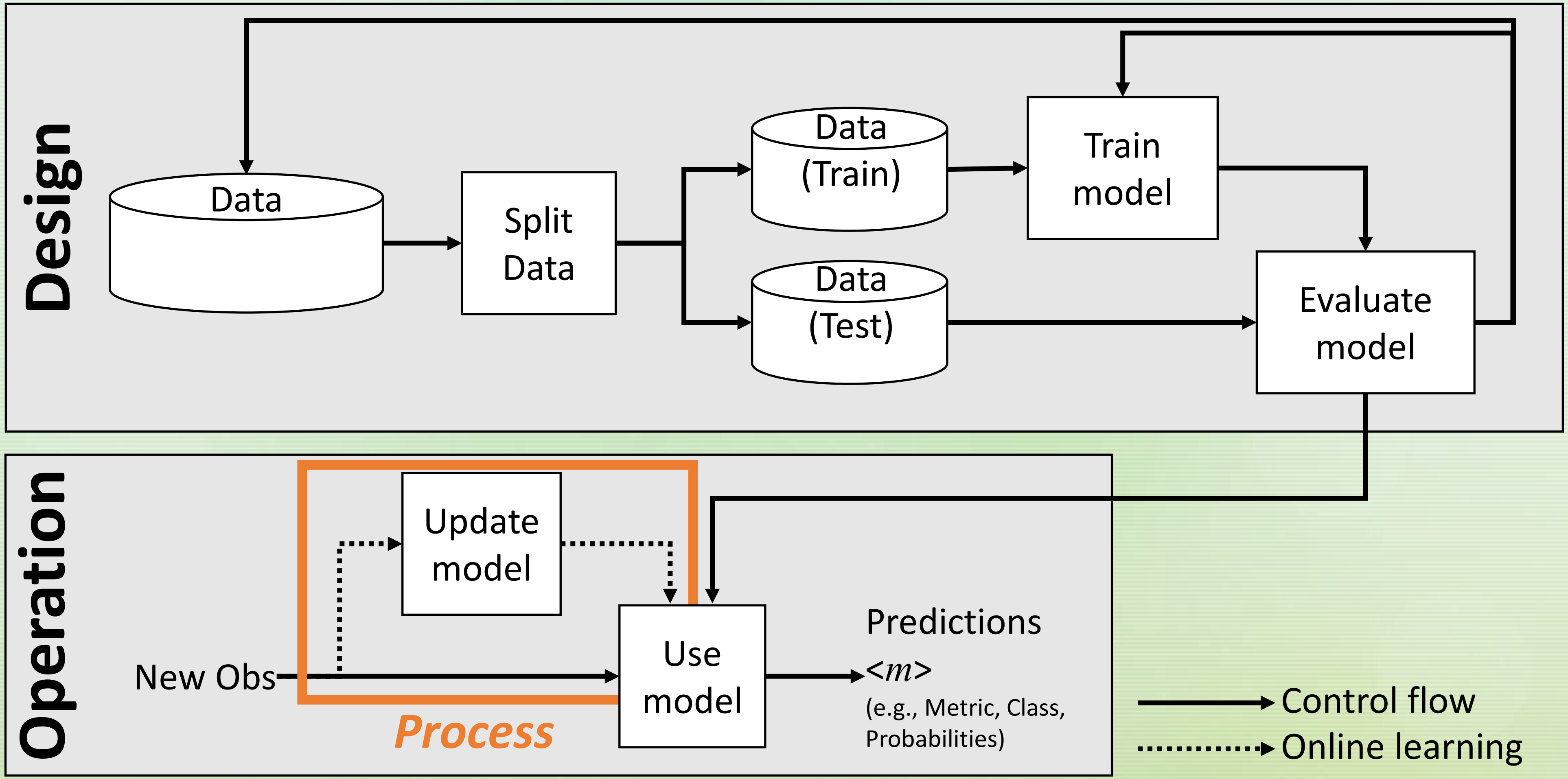
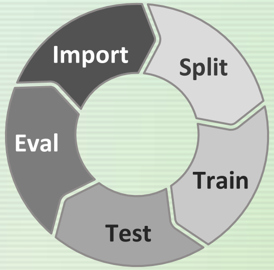
(2) Testing for Cognitive Systems: Focus on *Process*





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(2) Cognitive Models: Beyond the Textbook

Data Curation

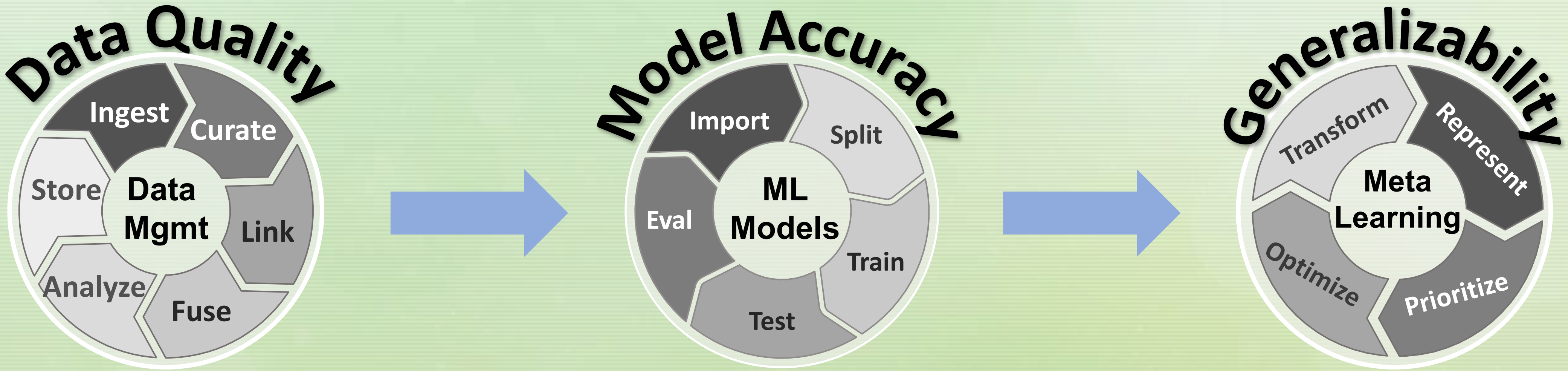
- Traditional
  - Accuracy, completeness
- Cognitive
  - Diversity, representativeness

Model Training

- Traditional
  - Predictive performance (accuracy)
- Cognitive
  - Real-time adaptability (computational effort, memory)

Handling Surprise

- Traditional
  - N/A (static)
- Cognitive
  - Learning rate for new examples, stability



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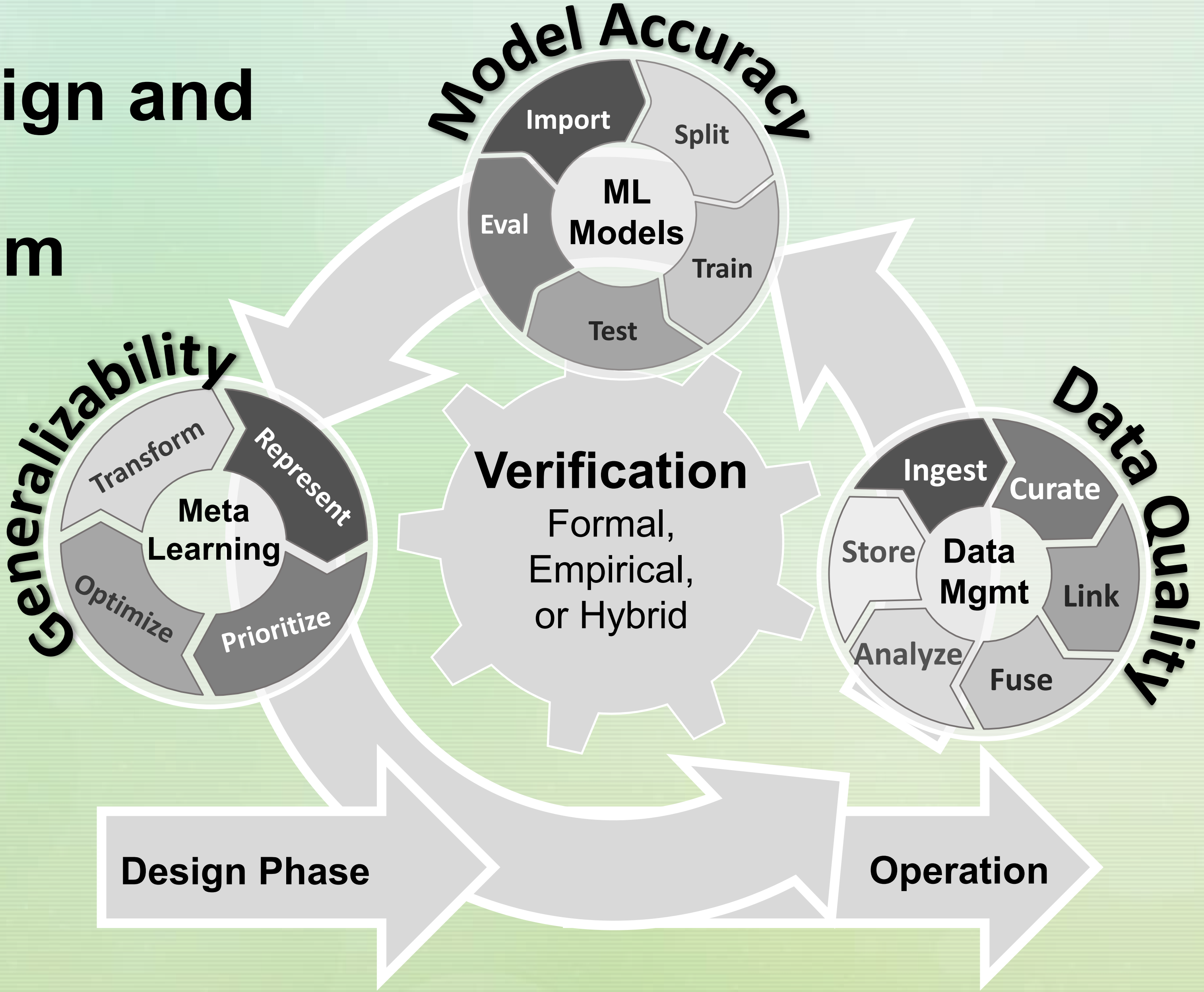
(2) Iterative Design and Verification of a Cognitive System



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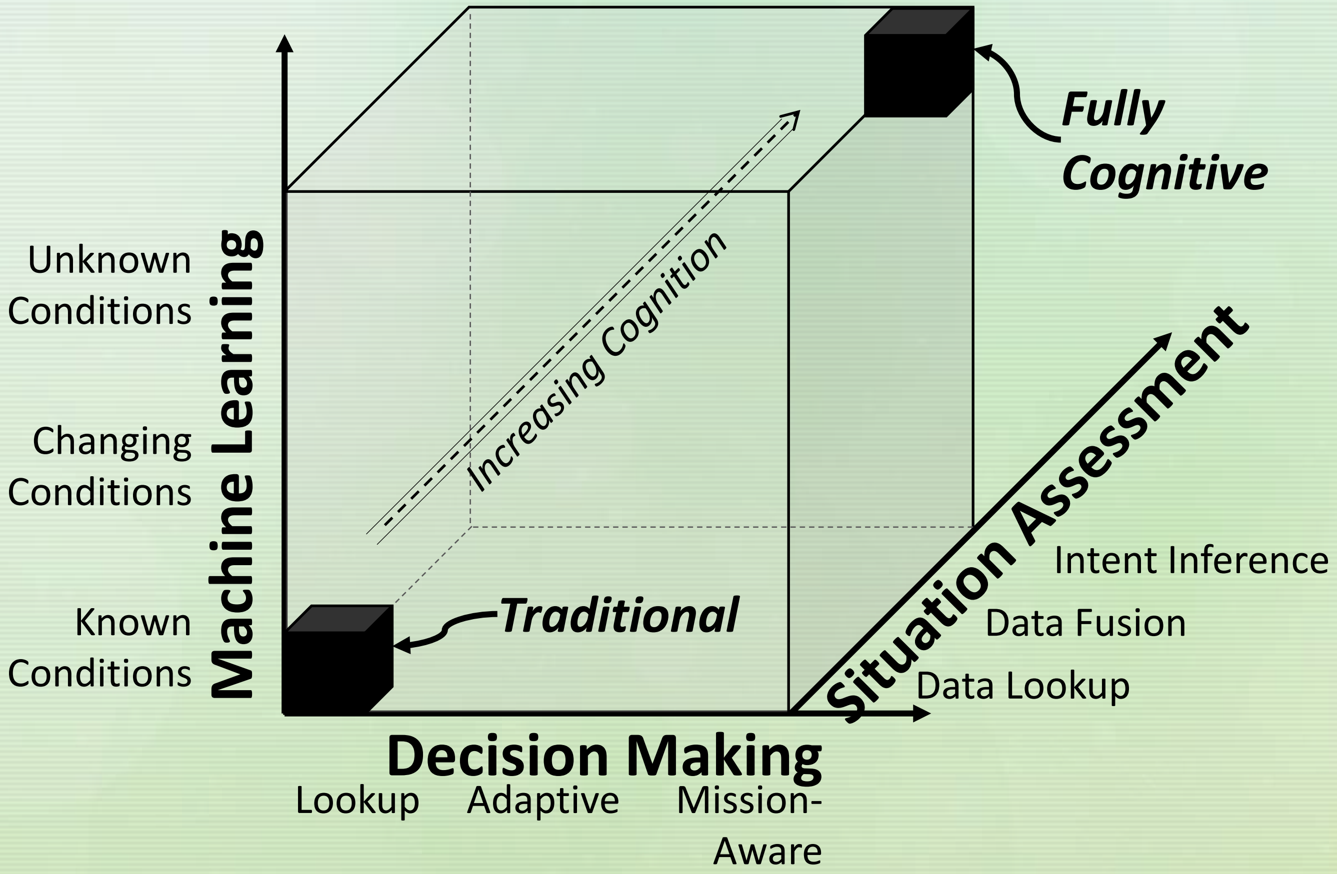
(3) Take Small Steps Along the Cognition Spectrum



- Does your system need better **situation assessment**? Deeper understanding of the RF environment, the anomalies, and the intent of the emitters?
- Does your system need better **decision making**? Something that can adapt to changing conditions and surprises?
- Does your system need to **learn** from its mistakes?

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Achieving the Cognitive RF Future

The Vision

- Cognitive RF systems operate in surprising, fast, and mission-critical environment
- Traditional ML pipelines are insufficient
  - Learning happens from minimal data after deployment
  - Evaluation must assure the process, not just the model
- Cognition is a spectrum
  - Progress comes in deliberate, incremental steps

In RF, surprise is normal

Online Resources

- https://sites.google.com/site/kzhaigh
  - Speaking events (in person & recorded)
    - Cognitive RF
    - Assuring Cognitive Systems
  - Papers
    - Cognitive EW
    - Trust in Autonomy
    - Insider Threat
    - Understanding Human Behaviour
    - Smart Homes / Elder Care
- IEEE (https://www.ieee.org/)
- AOC (https://crows.org/)

CogEW @ Artech

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