Cognitive Electronic Warfare:

Real-time Decision Making for Electromagnetic Warfare

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2023-04-12, Tokyo, Japan

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Japan Self-Defense Forces and the EW Community

Notes based on the book
Cognitive EW: An AI Approach
by Haigh and Andrusenko [ArtechHouse, 2021]

Who Am I – Dr. Karen Zita Haigh

- Consultant for Cognitive EW and Embedded AI
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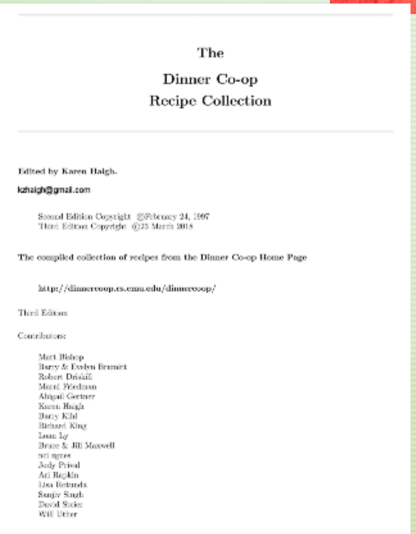
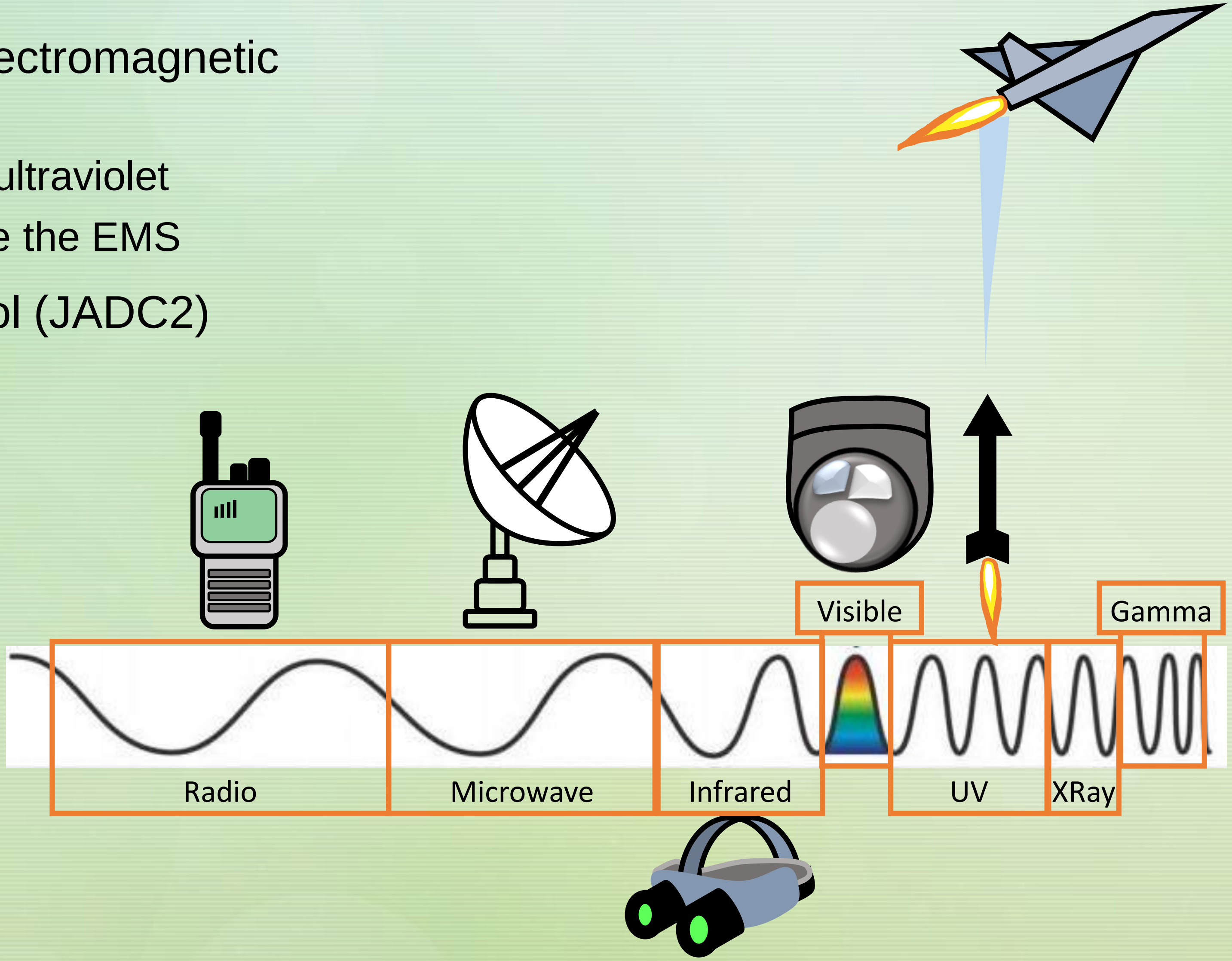
  - https://www.linkedin.com/in/karenhaigh/
  - https://sites.google.com/site/kzhaigh
- PhD in Computer Science from Carnegie Mellon University (AI and Robotics)
  BSc (Honours Computer Science) from University of Ottawa
- 30+ years experience in embedded AI
  Pioneer in Cognitive EW
  - Mercury Systems, L3Harris, Raytheon BBN, Honeywell
- IEEE Fellow, AAIA Fellow, Member of AAAI and 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)



US Book Orders: https://us.artechhouse.com/Cognitive-Electronic-Warfare-An-Artificial-Intelligence-Approach-P2208.aspx

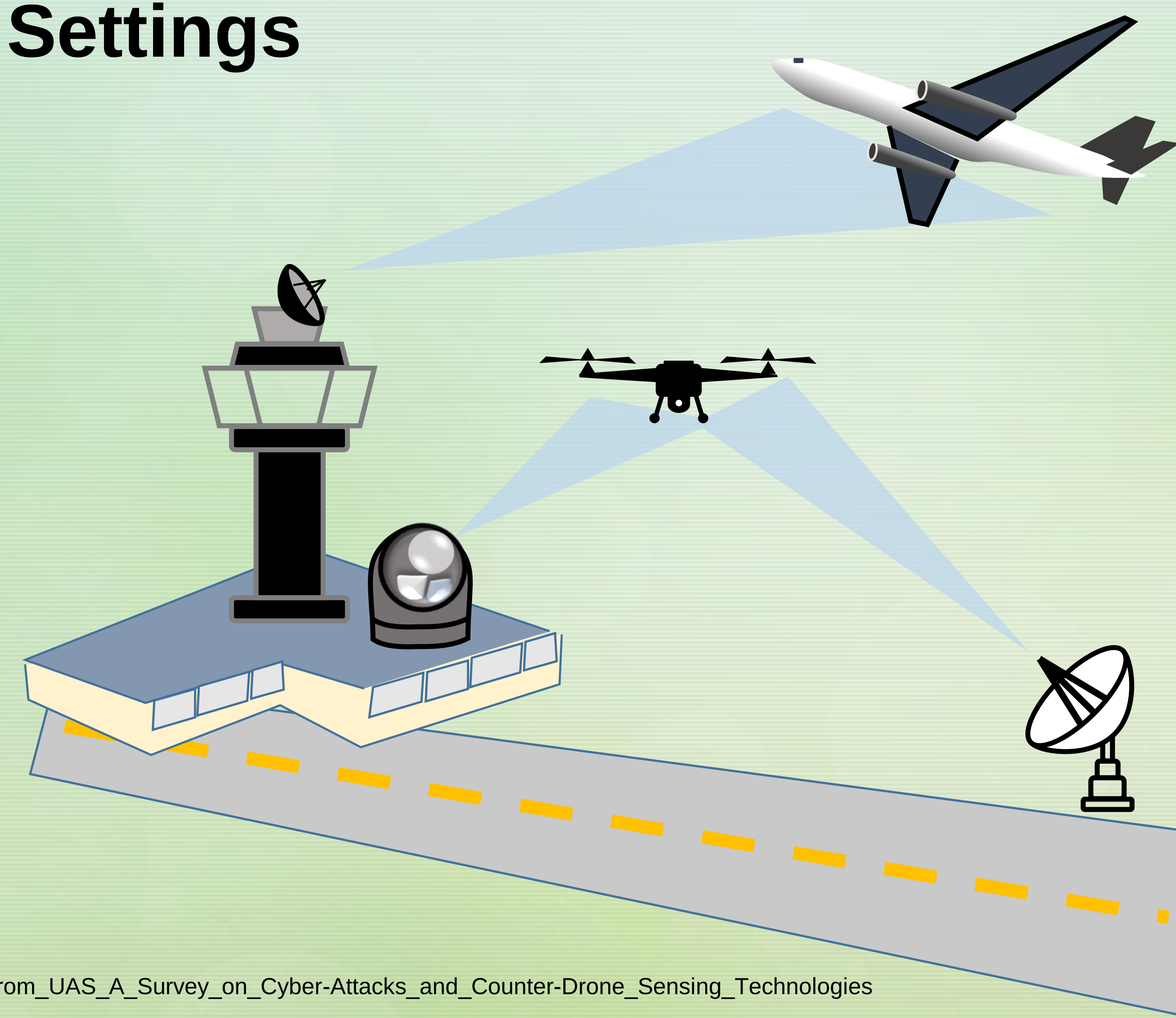
What is Electronic Warfare (EW)?

- Coordinated actions involving the Electromagnetic Spectrum (EMS)
  - Radio, radar, infrared, electro-optical, ultraviolet
  - To exploit, attack, protect, and manage the EMS
- Joint All-Domain Command & Control (JADC2)
  - Land, sea, air, space
  - EMS + acoustic + cyber + optic + …?
  - Multi-node, multi-task coordination
  - Military + Civilian



EW Events in Civilian Settings

- 9/11 “Mass Call Event”
- Emergency management
- Border security / Coast guard
- Law enforcement
  - Rioters jamming Police radios
  - Police tracking and jamming criminals
- Aviation:
  - Airport Command & Control
  - Drone Incidents at Airports
    - 2018: Gatwick
    - …
    - 2021: 70 global incidents
    - 2022: 2,554 global incidents
    - 2023: FAA currently reporting >100 events each month.



FAA – Federal Aviation Administration
https://www.researchgate.net/publication/342401654_Defending_Airports_from_UAS_A_Survey_on_Cyber-Attacks_and_Counter-Drone_Sensing_Technologies

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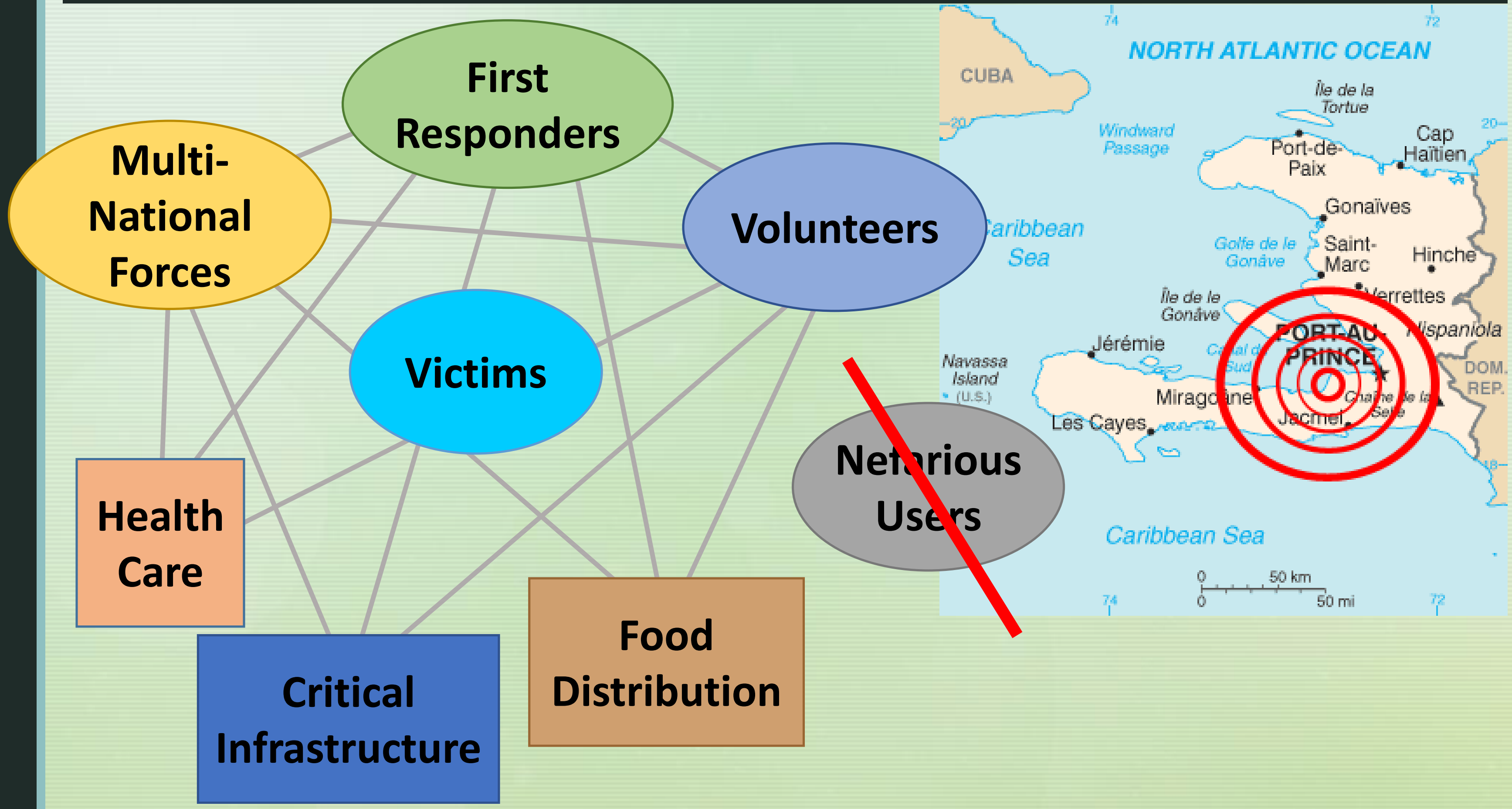
EW for Disaster Response

2010 Haiti Earthquake



Coordinate Aid

- Find victims
- Connect disparate networks
- Manage bandwidth
- Monitor evolving situation
- Coordinate and Prioritize Tasks
- Learn from experience
- Keep nefarious users out

Derived From: Haigh, *AI for the Perplexed: An L3 Perspective,* invited presentation to the *L3 WESCAM Drone Swarm Hackathon*, Ontario, 2019.

EW is No Longer a Static “Hardware” World

Software- and AI-defined Operations

- Software update cycles allow reconfiguration in hours
- Software-defined platforms support rapid reconfiguration
- AI allows the EW system to change everything at sub-second timescales
  - Decision-making can happen in milliseconds
  - Learning can happen in milliseconds, from a single training example
  - AI capabilities are exploding
- AI, Autonomy and Unmanned systems have redefined the speed of the kill-chain

Example: NASA Shuttle Columbia

- After the explosion, NASA wanted more sensors on remaining shuttles
  - 4 seismic sensors on each of the 22 wing leading-edge panels
- But the *existing* data on the Columbia showed that the wing had a problem
- ➢ It wasn’t a ***hardware*** problem, it was ***data analytics*** problem

https://picryl.com/media/a-left-front-view-of-the-columbia-space-shuttle-orbiter-landing-a1ceff

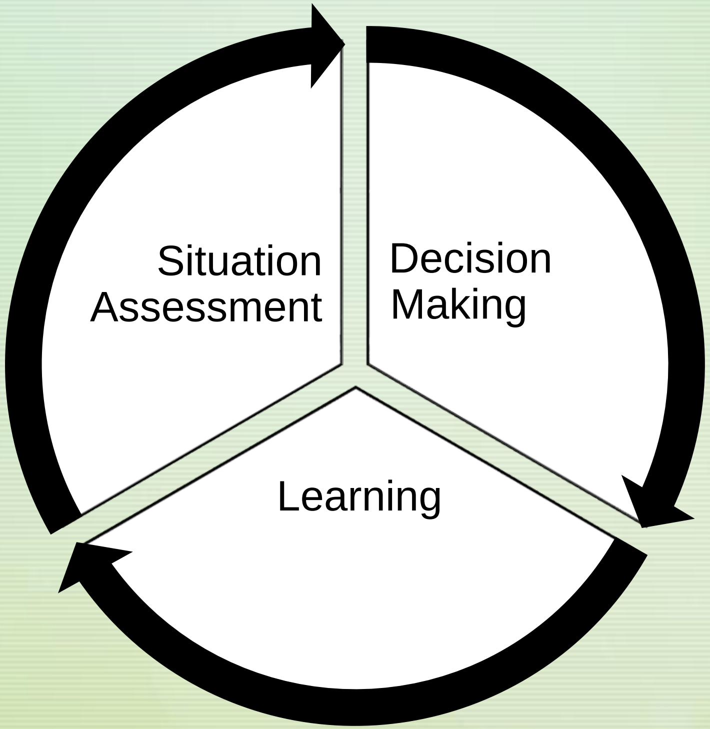
The Vision of Cognitive EW

- Imagine an AI that knows ***how***, ***when*** and ***where*** to act before an Electronic Warfare Officer can even understand what is happening
  - AI/ML can understand **patterns** in data that humans can't see
  - AI/ML can make decisions **faster** than humans
  - AI/ML can make decisions for more **complex** settings

EW → War at the speed of light

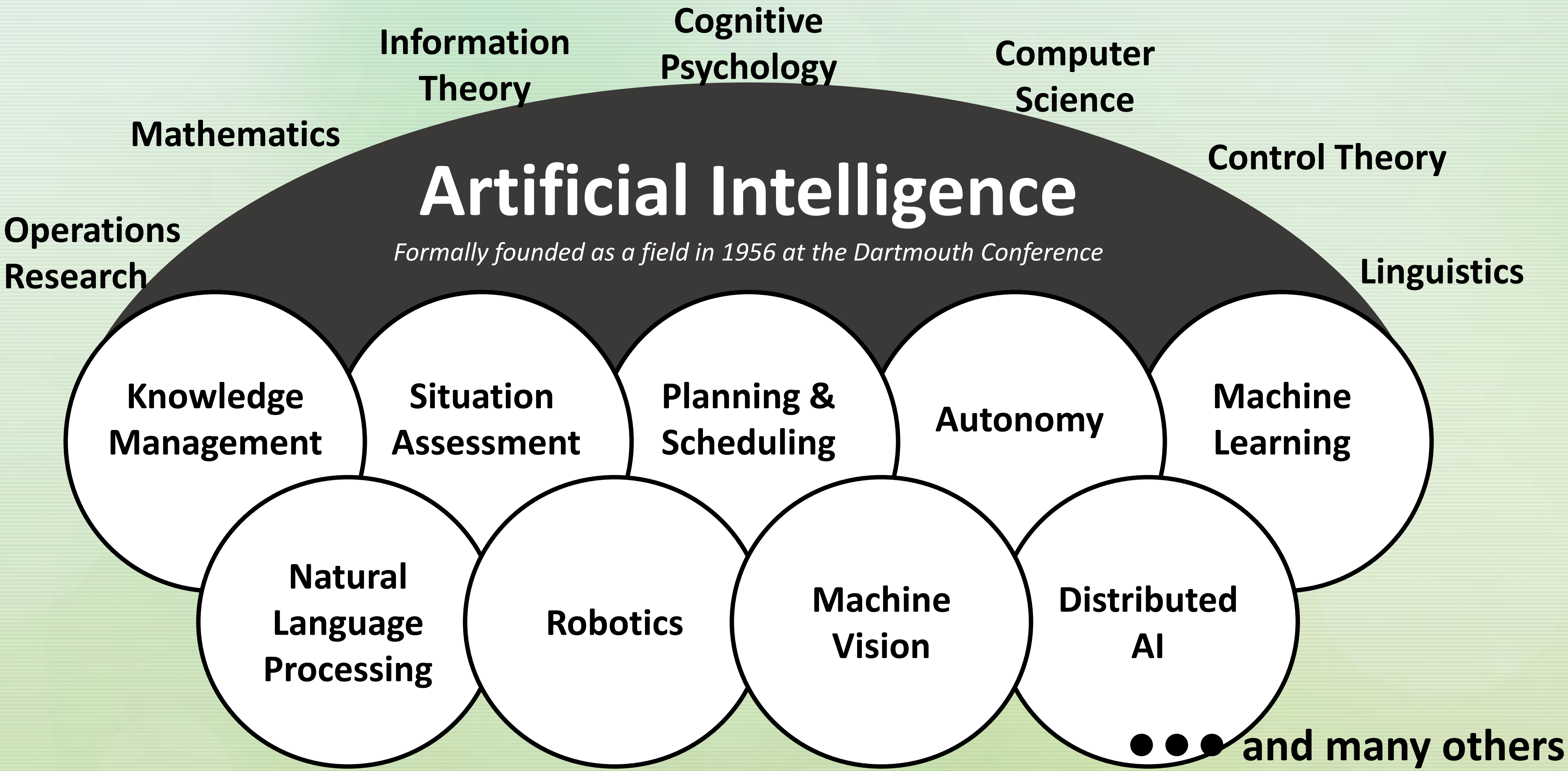
Cognitive Electronic Warfare: An AI Approach

- Traditional approaches to EW are failing in modern engagements
  - **Timeline** is too fast
  - **Complexity** is too high
  - No methods handle **novel** emitters
- Automatically learn to select actions that improve performance even in novel RF environments
  - **Characterize** the RF conditions
  - **Choose** the best strategy to improve mission performance
  - **Learn** performance of available strategies



From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

AI is not Just Machine Learning



Derived from Haigh, *AI for the perplexed: How does AI apply to you?*, Underwater Intervention, New Orleans, LA, Feb 2020.

AI Concepts in the EW World

AI Term	EW Term
Situation Assessment	Electronic Support (ES)
Decision Making	Electronic Protect and Attack (EP and EA) Electronic Battle Management (EBM)
Execution Monitoring	Electronic Battle Damage Assessment (EW BDA) Effects Analysis
Learning	EW Reprogramming (of data and software)

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Key AI Concepts

Situation Assessment

- Understand the environment
  - Time, space
  - Impact
- Steps:
  - Collect the data
  - Validate the observations
  - Fuse the data
  - Analyze the Impact
  - Infer the intent

Decision Making

- Set Goals and Priorities
- Analyze tradeoffs
- Resolve conflicts
- Determine plans
  - Feasible methods to achieve goals

Learning

- Extract information from prior experience
- Update models
- Evaluate effectiveness of previous decisions
  - Your own impact on the environment

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

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Modern EW Challenges Require AI Solutions

- Dynamic
  - Observations are fleeting
  - Decision timeline very fast
  - Novel conditions
  - Mission progression (e.g., team composition)
- Resource-constrained
  - Time
  - Size, Weight, Power, Compute, and Memory
  - Expendables
- Complex
  - Richness of RF environment
  - Disparate data sources
  - Heterogeneous platforms
  - Ambiguous observations
  - Interactions of control settings
  - Multiple temporal feedback loops
- Distributed
  - Unreliable communications
  - Heterogeneous sensors & platforms
  - Multiple objectives for multiple stakeholders

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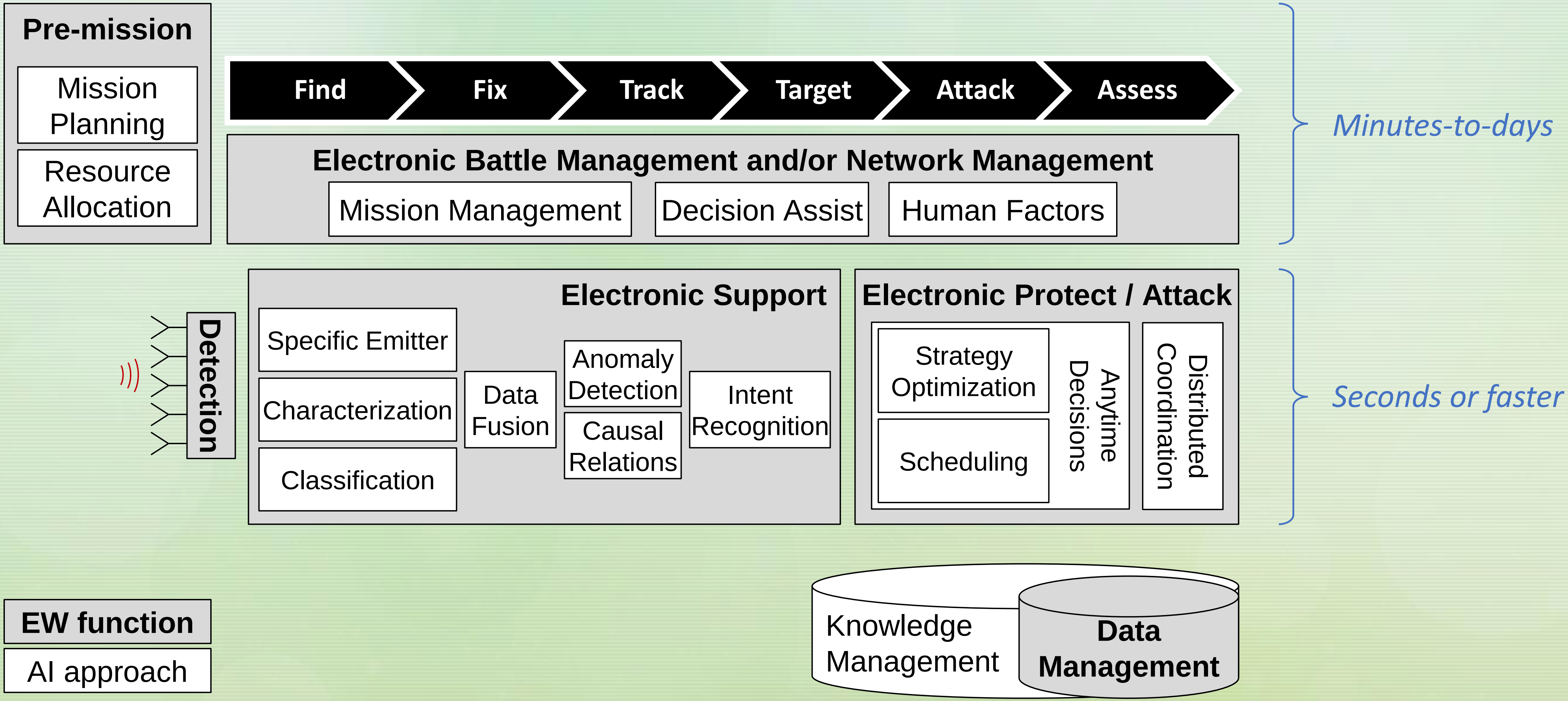
AI Capabilities in EW Systems

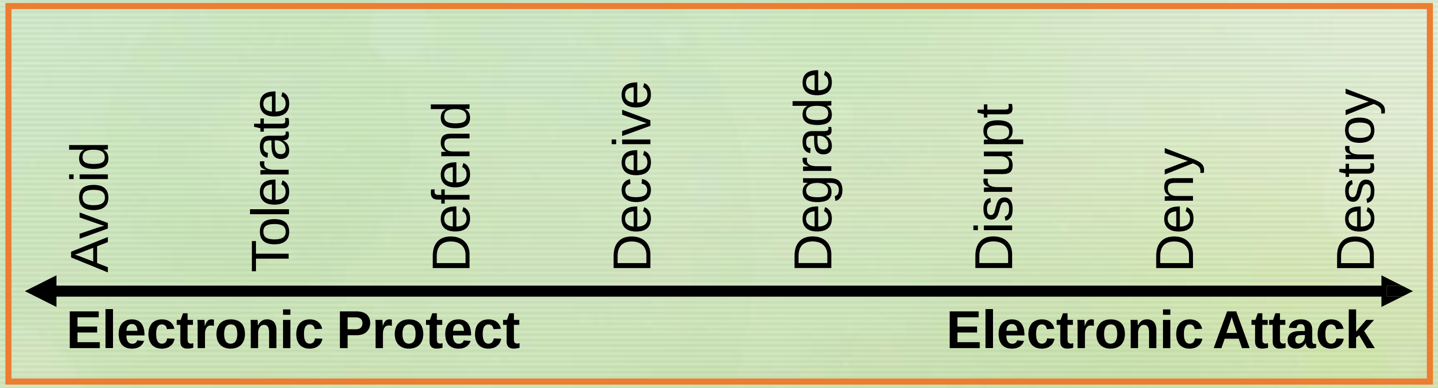


From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

AI Addresses Joint Optimization (JADC2)

- AI uses the same process to analyze the RF environment and make **multi-objective decisions** for unified multi-domain solutions
- Actions come from same toolset

- **EP vs EA:** the main difference is the mission objective
  - EP defines objectives with respect to **oneself**
  - EA defines objectives with respect to **others** (i.e., harder to measure)
- **Comms vs Radar:** the main difference is distributed decision making
  - Comms has more **latency**, more **coordination**, and more nuanced **utility** functions



From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Joint All-Domain Command & Control (JADC2)

Complex Decision-making to Manage Tradeoffs

- Planning & Scheduling is a branch of AI that concerns the realization of strategies or action sequences, typically for execution by intelligent agents, autonomous robots and unmanned vehicles. [Wikipedia]
  - Does the environment change?
  - Are observations ambiguous?
  - How many objectives must be satisfied?
  - How many actors participate?
  - How many actions are available?
  - Are actions deterministic?
  - Do actions have durations?
  - Can actions be taken simultaneously?

Stakeholders

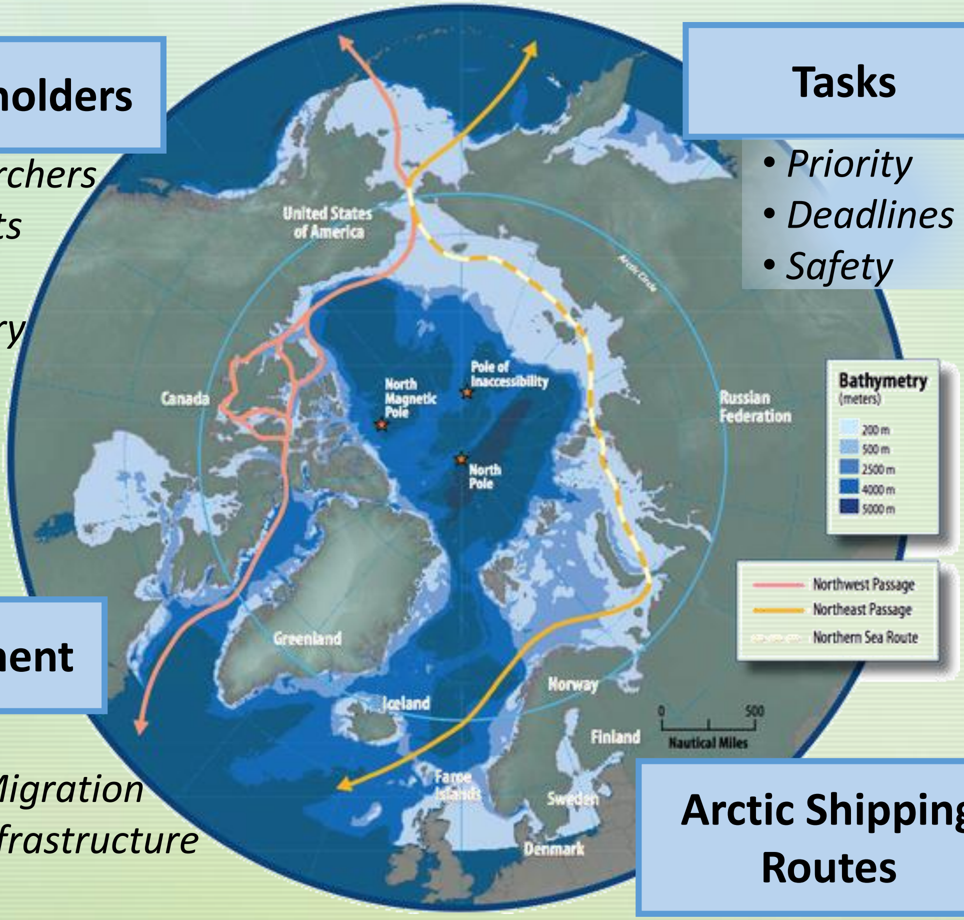
- *Researchers*
- *Tourists*
- *Trade*
- *Military*

Tasks

- *Priority*
- *Deadlines*
- *Safety*

Environment

- *Ice Floes*
- *Wildlife Migration*
- *Lack of infrastructure*



Arctic Shipping Routes

https://en.wikipedia.org/wiki/Arctic_shipping_routes

Derived from AI for the perplexed: How does AI apply to you?, *Underwater Intervention, Feb* 2020

Deliberative Decision Making

Decision Making chooses the best strategy to accomplish objectives

Define the Problem → Search for Alternatives → Evaluate Alternatives → Select Alternatives

Optimality is rarely critical;
usually "good" is good enough

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Deliberative Decision Making

- Protracted engagements must manage
  - Multiple Objectives (that may be conflicting)
  - Limited Resources
    - Ignoring resources creates plans that may not be achievable, and/or need to be updated based on execution monitoring
  - Multiple and/or extended timeframes
    - Temporal planning and resource planning are tightly coupled

➢ Do not be reactive
Be proactive and deliberate

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Decision Making Considerations

Inputs

- Rules of Engagement
- Environment
- Operating Constraints
- Available Assets
- Cooperation with other organizations
- Commander Intent
- Mission Model
- Expected Threats
- Attack Library
- Desired Effects

Outputs

- Asset Allocations
- Spectrum Sensing Plan
- EP and EA Planning
- Human Interactions
- Inter-operability

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Decision-Making Approaches in AI

Planning

- Planning synthesizes a sequence of actions that result in a desired goal state.
- Planning is **what** to do, and in what **order**, as a partially-ordered graph.
- Planning is more strategic, more global.
- An EBM system plans how many platforms to deploy, which resources each gets, and where they will go.

Optimization

- Optimization evaluates multiple plans to choose the “**best**" plan.
- Optimization is more tactical, more local.
- An EW system optimizes EP and EA metrics like power usage, probability of detection, and EW BDA.

Scheduling

- Scheduling maps a partially-ordered plan to specific resources and timeslots.
- Scheduling worries about **when** and **how** to do things.
- Scheduling drives down into the specifics of when to transmit and when to receive.

When these activities are fully automated, they are not clearly delineated

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Planning Approaches

- **CLASSICAL**
  - How many actions are available?
  - How many objectives must be satisfied?
- **PROBABILISTIC**
  - Are actions deterministic?
  - Are observations ambiguous?
- **TEMPORAL**
  - Do actions consume resources?
  - Do actions have durations?
  - Can actions be taken simultaneously?
- **MULTIAGENT**
  - How many actors participate?
- **CONDITIONAL**
  - Does the environment change (is it dynamic)?
  - How mission-critical are failures?

** Not mutually-exclusive*

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

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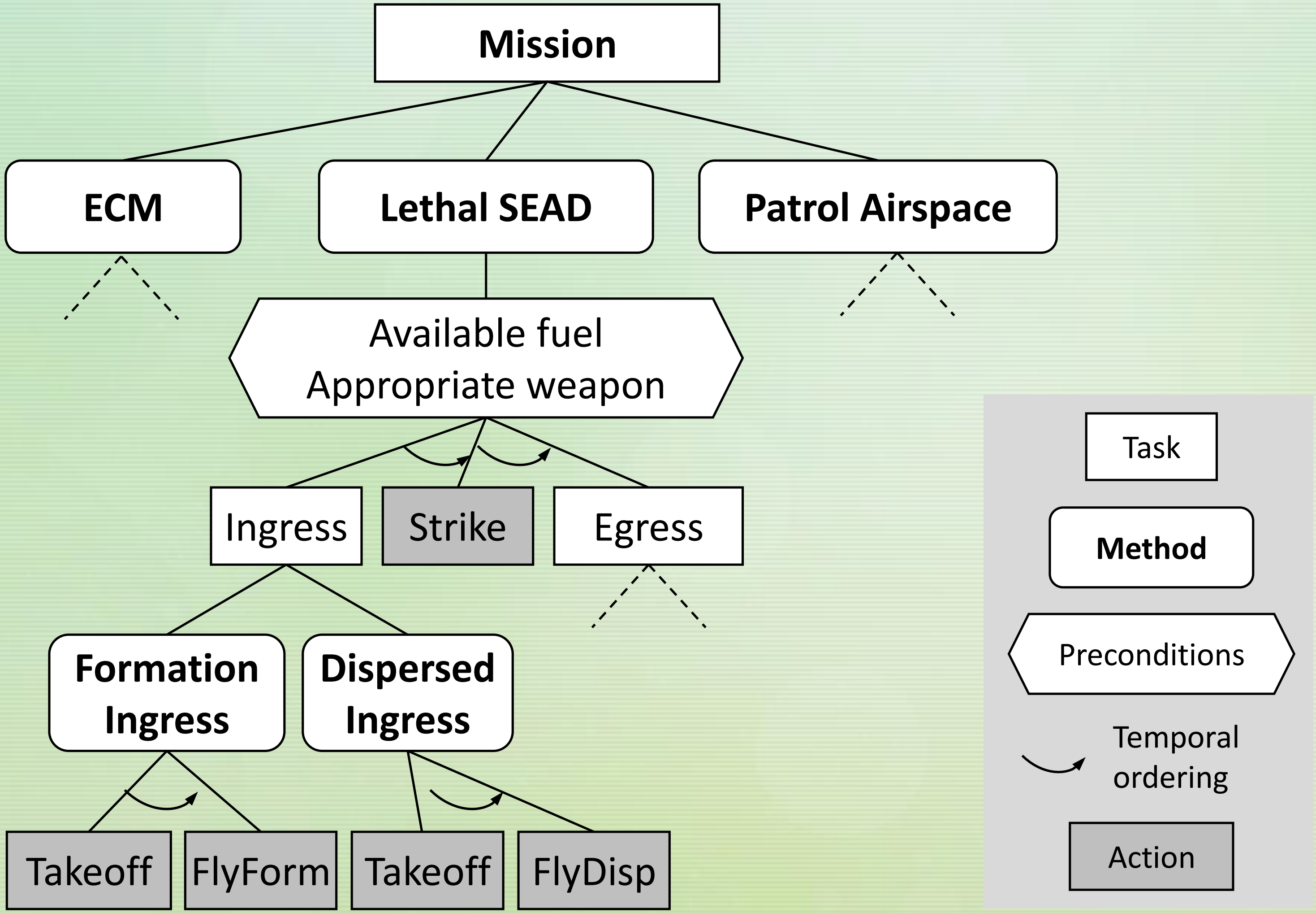
Example: Hierarchical Task Planning

HTNs are a set of abstract **tasks** to be done, and a set of **methods** for each task that represent different ways in which they can be carried out.

The dependency among actions is represented with hierarchically structured networks.



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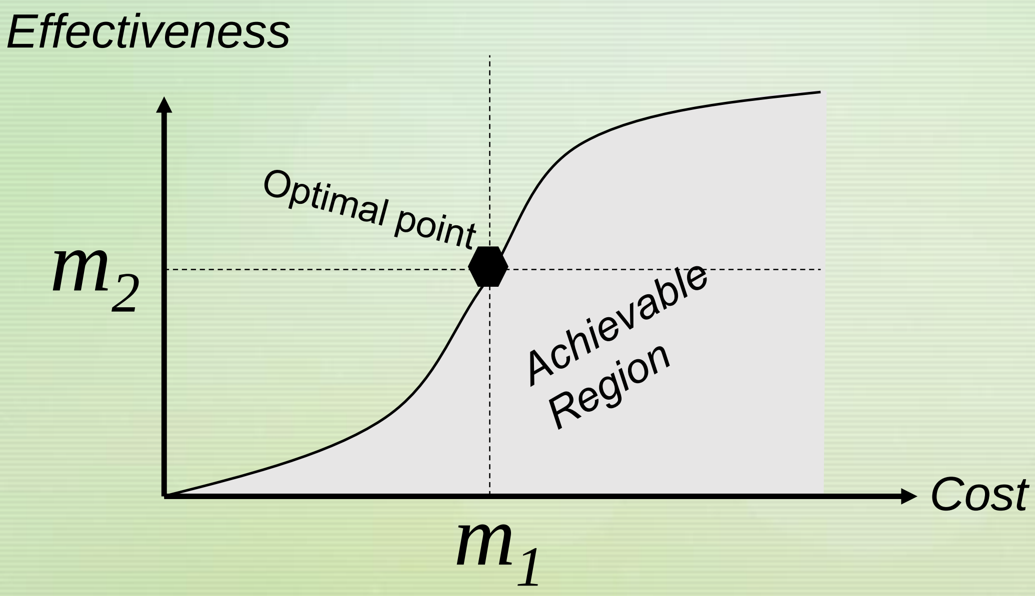
Multi-objective Optimization (Constraint Planning)

- Formulate the problem using one of two methods:
  - (a) Maximize Effectiveness subject to constraints on Cost, or
  - (b) Minimize Cost subject to constraints on Effectiveness.
- While mathematically equivalent, these two formulations lead to different practical issues.

- A goal of $Cost < m_1$ and $Effectiveness > m_2$ determines an optimal operating point.



From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Example: Navy Mission Planner

- Creates logistically supportable ship employment plans to maximize anticipated military mission accomplishment
- Assign ships and other assets each day to each region to complete missions on time
- Diverse missions, including logistics and unarmed combatants
  - Easily extensible to incorporate EW
- Complex dependencies + interactions between missions

- Linear Integer Directed Network Flow Optimization Model
  - > 1000 constraints, > 70000 variables
  - < 60 minutes for “clean sheet” plans
- Maximize the total value while satisfying constraints on **mobility**, simultaneous and conditional mission **completion**, **resource use**, and varying **effectiveness** of combatants and their assignments.
- Persistence over plan revisions

Kline & Brown, Optimizing the Navy Mission Planner, Military Operations Research, 2021, https://faculty.nps.edu/jekline/docs/Optimizing%20Navy%20Mission%20Planning.pdf

Scheduling

- Maps a partially-ordered plan to specific resources and timeslots
  - Generally, when to transmit and when to receive
- Requires
  - Sequence of actions and their resource requirements
  - Set of resources that can be used
  - Constraints
  - Objective function
- Approach must account for unexpected, unknown, or partially-observable states
  - Flexibility and (Re)prioritization are key

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Real-time Operations

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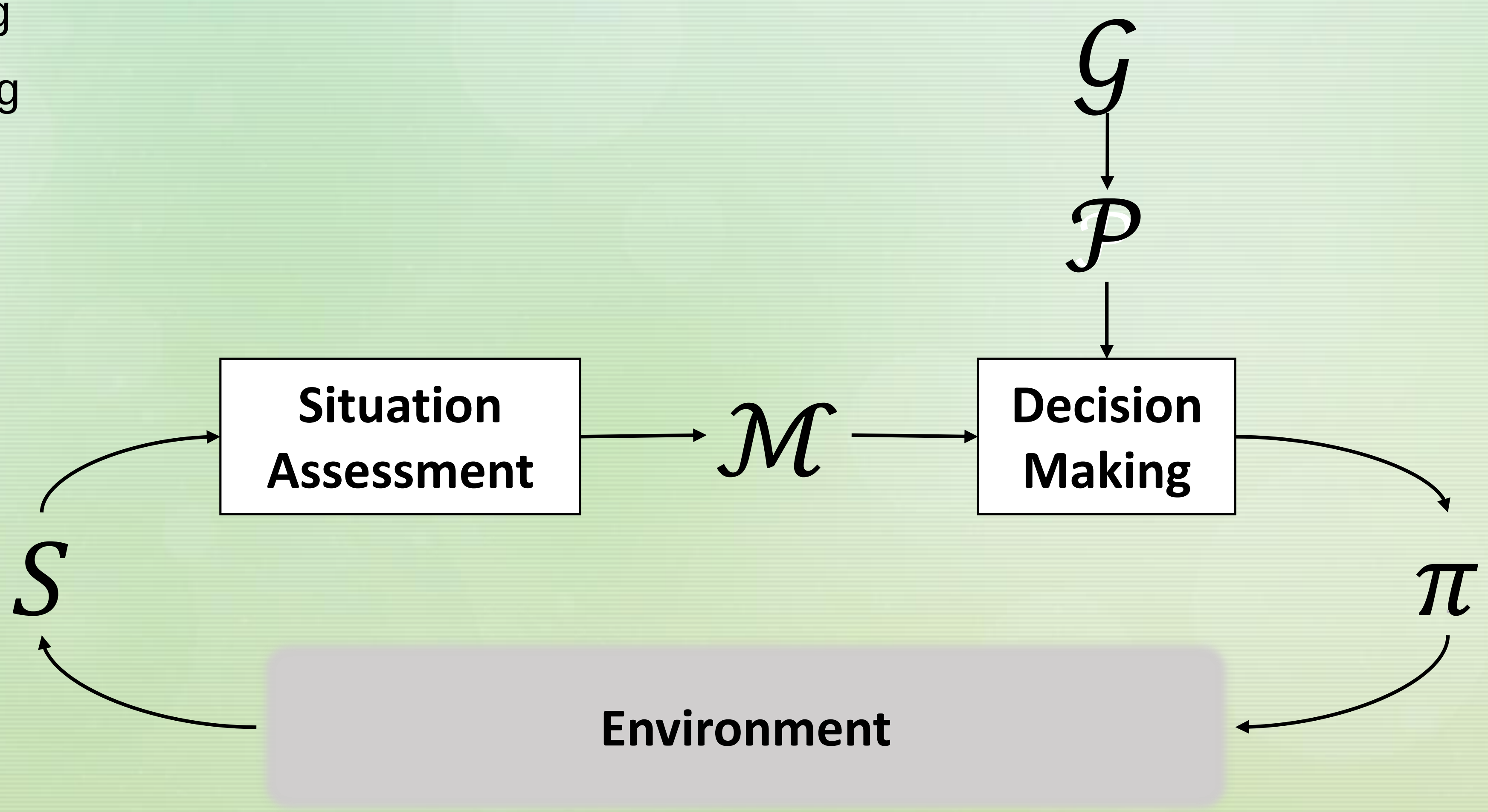
Execution Monitoring: Is everything going as expected?

- (S) Sensor monitoring
- ($\mathcal{M}$) Model monitoring
- (π) Action monitoring
- ($\mathcal{P}$) Plan monitoring
- ($\mathcal{G}$) Goal monitoring



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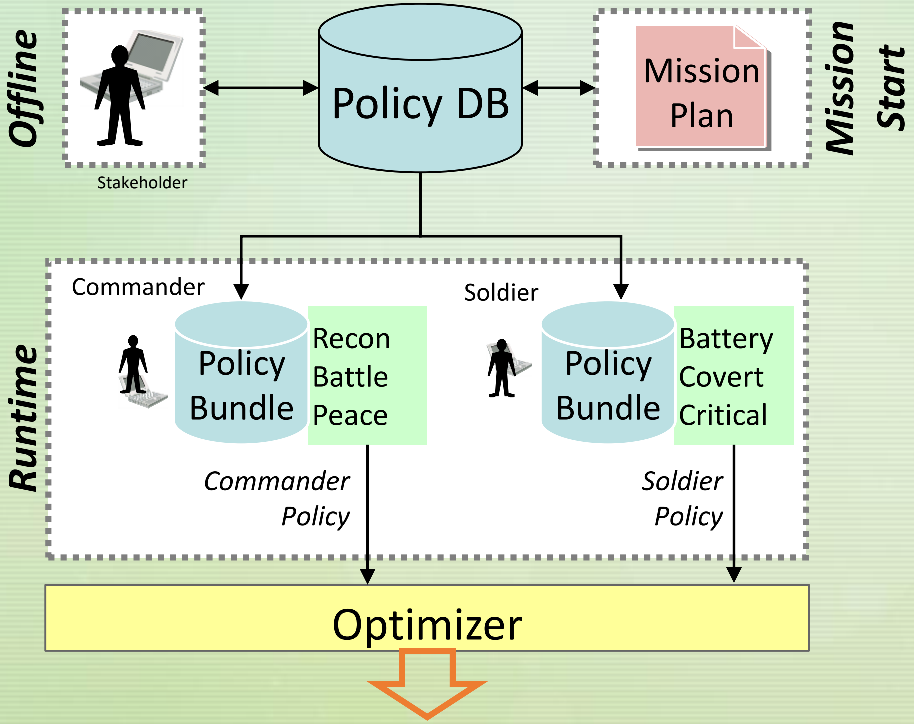
Changing Mission Priorities

Policy-Based Control

- A **policy** is a way to express statements about what to prefer or avoid in a domain
  - Capture stakeholder intent
  - Capture multiple stakeholder tradeoffs
  - Propagate high-level goals down to operational level
- **Policy statements** are heuristics with asserted, quantitative values
  - Can be rigorously mapped to a mathematical objective function
- **Policy Bundle**
  - Related policy statements for a given situation
  - Created offline or derived from mission plan
  - Invoked at run-time by user

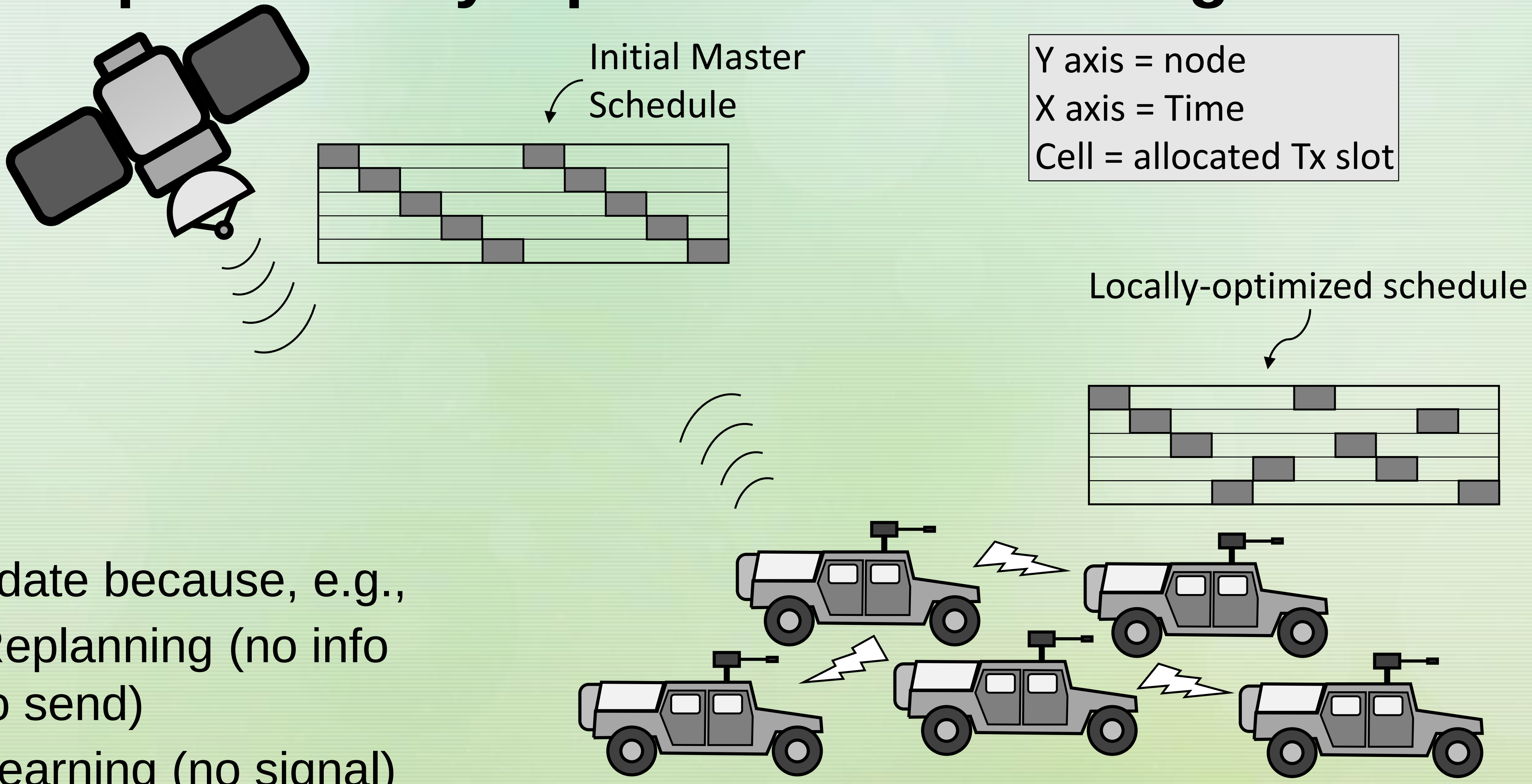
Policy-Bundles

- Commander: Recon, Battle, Peacekeeping
- Soldier: Covert, Battery, Critical Ops



From Haigh, Olofinboba, & Tang, "Designing an Implementable User-Oriented Objective Function for MANETs," in *IEEE International Conference On Networking, Sensing and Control*, April 2007. http://www.cs.cmu.edu/~khaigh/papers/Haigh07-ICNSC.pdf

Example: Locally Optimized Scheduling

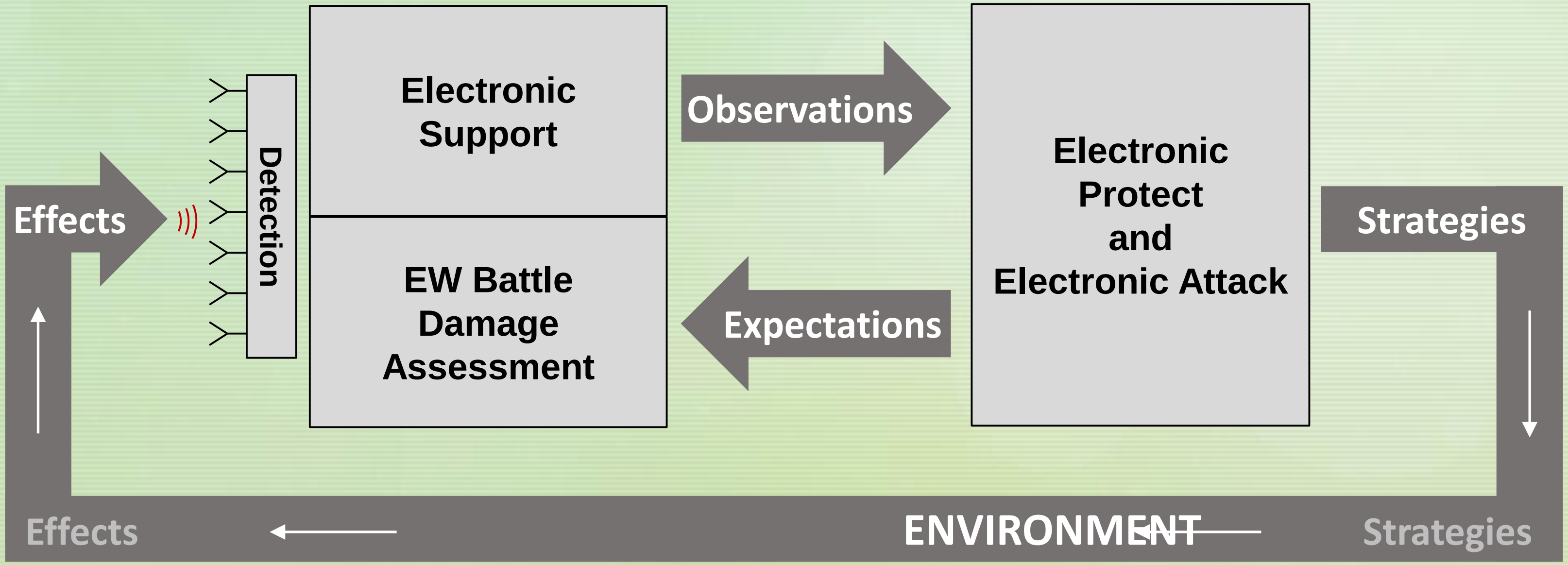


Update because, e.g.,

- Replanning (no info to send)
- Learning (no signal)

Closing the Loop: Real-Time In-Mission Cognition

- **Electronic Support**
  - Update histories and probabilities based on mission progress
  - Identify novel conditions
- **Battle Damage Assessment**
  - aka *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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In-mission Learning is *the* Decisive Element

- We can't afford to only learn post-mission
  - Novel emitters may be lethal in sub-minute timescales
  - We already ***have*** systems that learn in-mission
- Therefore
  - We must develop approaches that can learn from a ***single observation***
  - We must validate the ***learning process***, rather than validating the learned model
  - Automated, ***Closed-loop, multi-resolution*** testing is crucial
  - We need a CogEW ***Red Team*** to create threats

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Evaluation and Assurance

Developing trust

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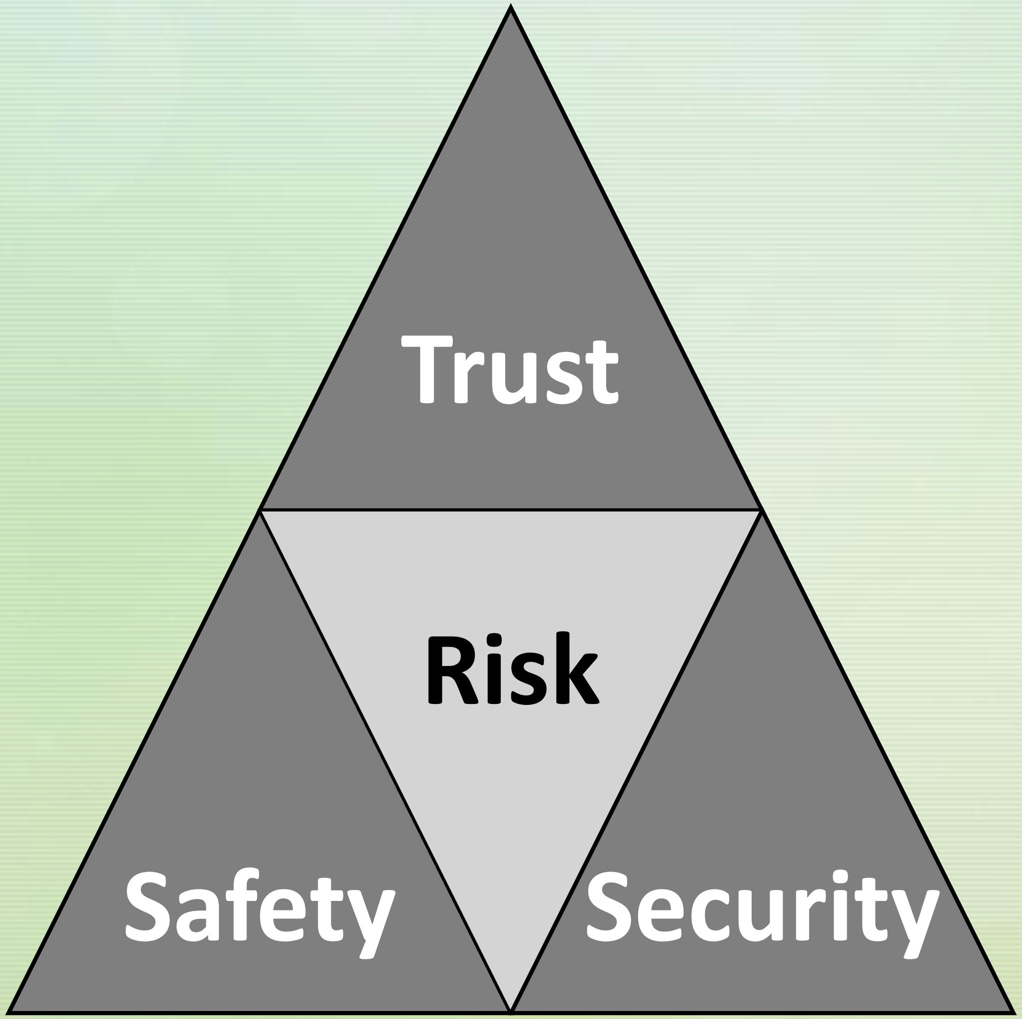
Trust depends on how much Risk the Trustor can Tolerate

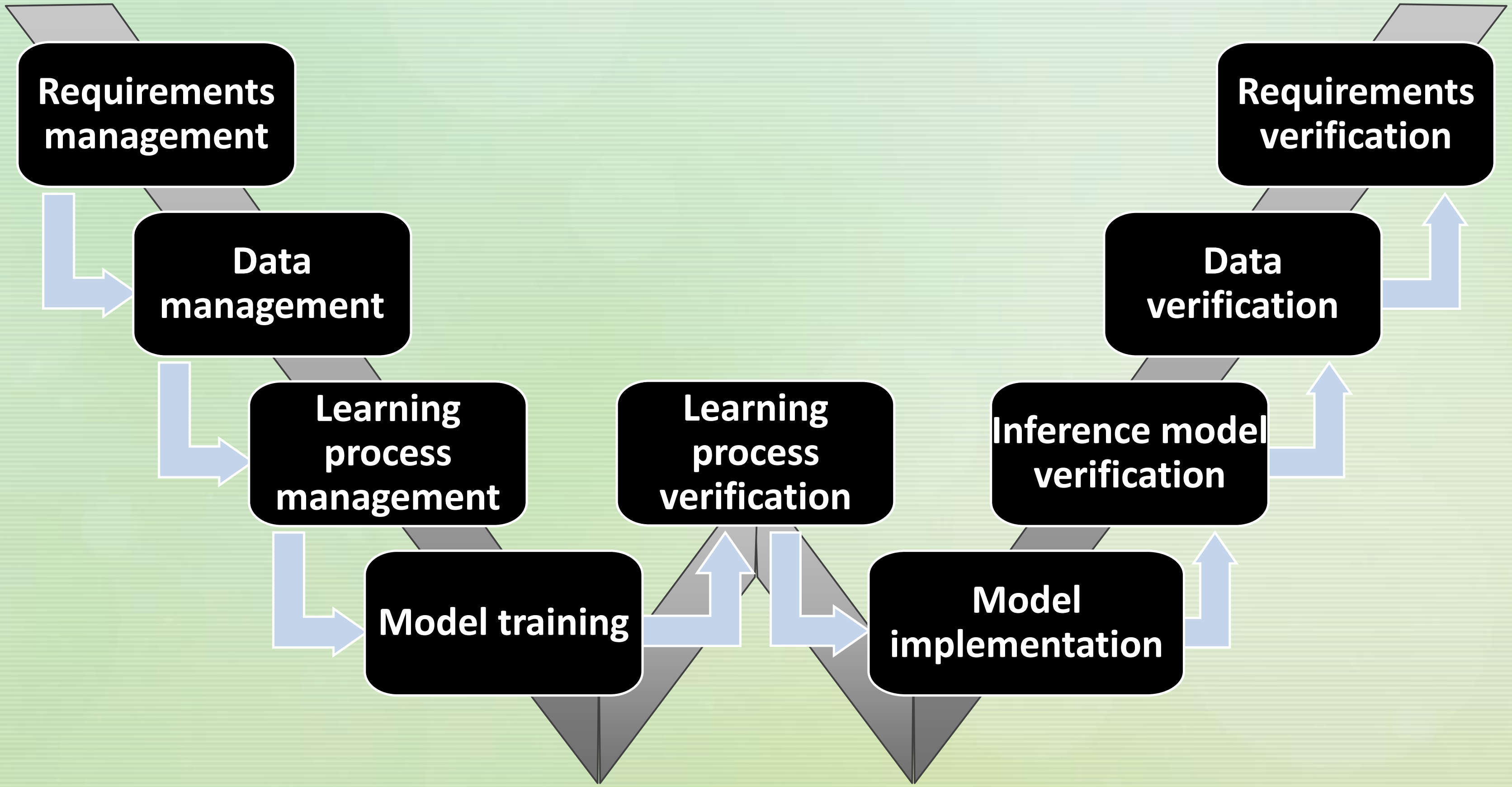
- Human-Machine Teaming develops trust
  - Complementary team-mates
- Framework must support
  - Accountability to humans
  - Cognizance of speculative risks and benefits
  - Respectfulness and security
  - Honesty and usability
- The more risk for trustor, and authority to AI, the greater the assurance requirements



From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Learning Assurance Design Requirements

- Use a **Learning Assurance** process to ensure comprehensive evaluation
- Validate the learning ***process***, not the learned ***model***



Used with permission from J. Cluzeau et al., [Concepts of design assurance for neural networks (CoDANN)](), European Union Aviation Safety Agency

Can we Certify In-Mission Learning?

Kalman Filters

- Predictive filtering ML technique
  - e.g., to compute the position and altitude of aircraft
- ML Characteristics
  - Statistical estimation process
  - Behaviour depends on empirical data and on hypotheses on the inputs
  - Outputs are associated with an estimation of the result quality
- Key characteristics
  - Input space is usually small
  - Uses an embedded model of the physical system
  - Errors are estimated based on physical models representing upper bounds of actual errors.

Certification Approach

- DO-229 Standard
  - “Minimum Operational Performance Standards for Global Positioning System/Satellite-Based Augmentation System Airborne Equipment”
  - US Radio Technical Commission for Aeronautics (RTCA)
    - Validation recommendations
    - Type and number of tests
    - Based on statistical knowledge of operating environment

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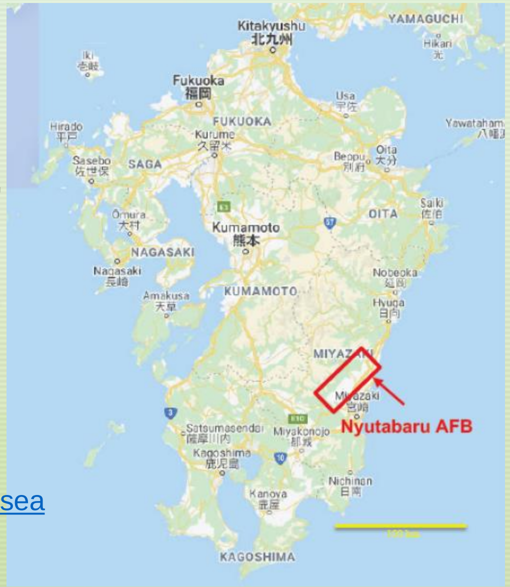
Vision: Attritable, Unmanned Fleets

Capability

- Large-scale (expensive; exquisite) operations are untenable
- Contested EMS battlespace; Cyber; Acoustic
- Multidomain: Air, Sea, Land, Space
- Civilian and Military applications
- Small, inexpensive, unmanned vehicles (UxVs) to perform a variety of functions, including ISR, PNT, communications, and strike.
- **The best counter to an expendable drone swarm is another expendable drone swarm**

Justification

- 96 drones form concentric patterns around the *Dewey* that continuously shift while individual drones make swooping passes on the destroyer's pilothouse, bow, and flight deck.
  - The *Dewey*'s commanding officer determines that the behavior of the drones and the PAFMM vessels constitute a **real, immediate, and direct threat** to the safety of the ship and crew
- RAND report outlines a possible deployment on Kyushu Island, near Japanese Defense Forces' Nyutabaru Airbase



PAFMM -- People's Armed Forces Maritime Militia
ISR – Intelligence, surveillance, and reconnaissance
PNT – Position, navigation & timing
Thornburg, Responding to Drone Swarms at Sea, 2022, https://www.usni.org/magazines/proceedings/2022/december/responding-drone-swarms-sea
Hamilton & Ochmanek, Operating LowCost, Reusable Unmanned Aerial Vehicles in Contested Environments, RAND report, 2020, https://www.rand.org/content/dam/rand/pubs/research_reports/RR4400/RR4407/RAND_RR4407.pdf

Next Steps

Embrace the change

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Cognitive Electronic Warfare

National Security Strategy Requires Both EW+AI

国家安全保障戦略について

- 新しい戦い方に対応するために必要な機能・能力としては以下のとおり
  - 我が国への侵攻そのものを抑止するために、遠距離から侵攻戦力を阻止・排除
    - ①スタンド・オフ防衛能力
    - ②統合防空ミサイル防衛能力
  - 抑止が破られた場合、①と②の能力に加え、領域を横断して優越を獲得し、非対称的な優勢を確保
    - ③無人アセット防衛能力
    - ④領域横断作戦能力
    - ⑤指揮統制・情報関連機能
  - 迅速かつ粘り強く活動し続けて、相手方の侵攻意図を断念
    - ⑥機動展開能力・国民保護
    - ⑦持続性・強靭性

速度
複雑
マルチドメイン

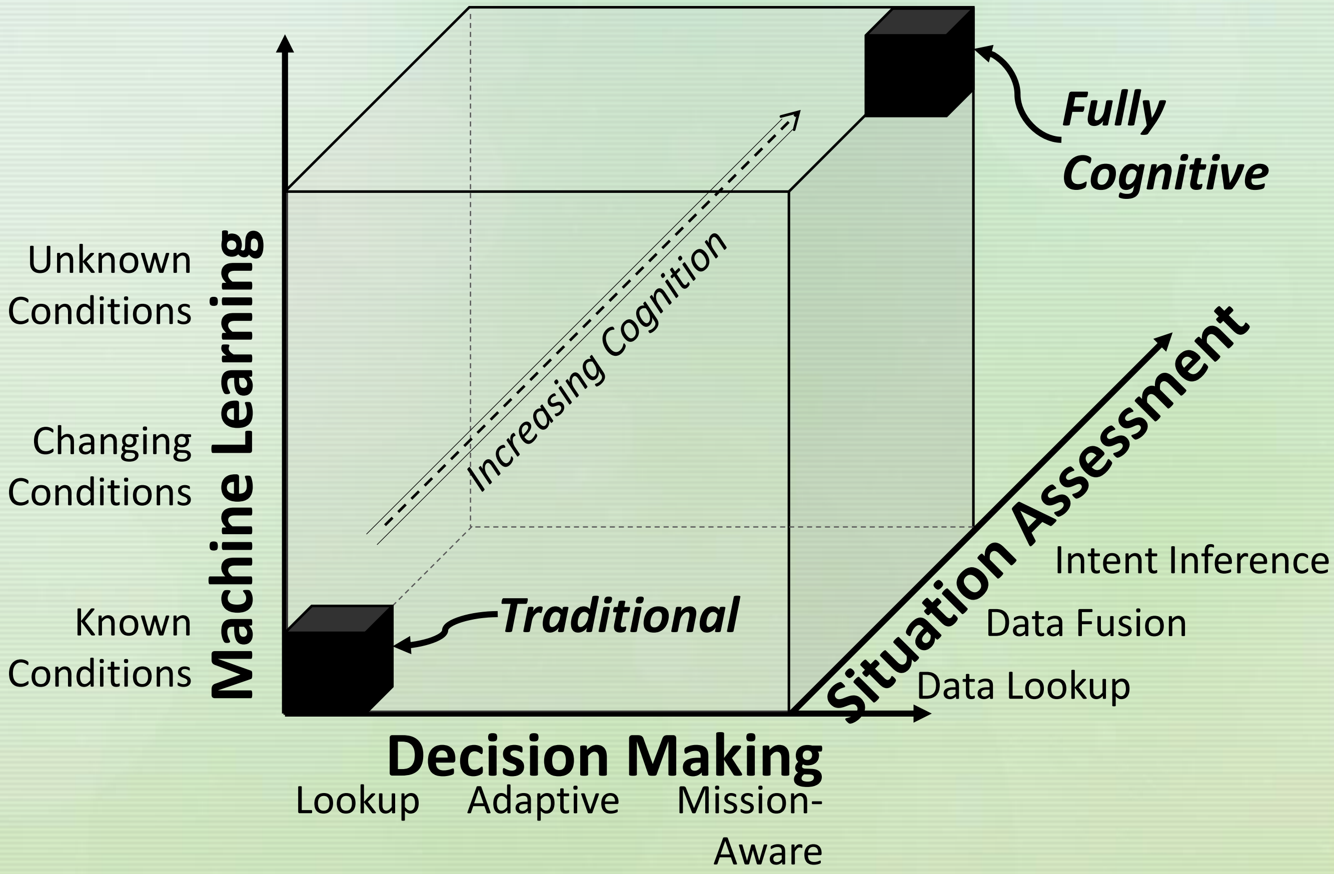
Speed
Complexity
Multi-Domain

Japan National Security Strategy

- To deter an invasion of Japan, we will intercept and eliminate the invasion force from a distance
  - (1) Stand-off defense capability
  - (2) Integrated Air and Missile Defense Capability
- If deterrence is breached, gain superiority across domains and create an asymmetric advantage
  - (3) Unmanned Asset Defense Capabilities
  - (4) Cross-domain operational capability
  - (5) C2 and information functions
- Continue to act swiftly and tenaciously to abandon the other party's intention to invade
  - (6) Rapid deployment and civil protection
  - (7) Sustainability and resilience

Apr 2023

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?

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

“Artificial intelligence could be the most transformative technology in the history of mankind”

Kai-Fu Lee (李開復), 14 September 2021

- BSc, Computer Science, Columbia
- PhD Computer Science (Speech), Carnegie Mellon University 1988
  - Advisor: Raj Reddy
- Chairman and CEO of Sinovation Ventures, the leading Chinese technology venture capital company
- In 2018, Sinovation Ventures' asset management reached US$2 billion and has invested over 300 portfolios primarily in China

“Artificial intelligence could be the most transformative technology in the history of mankind”

Kai-Fu Lee (李開復), 14 September 2021

- Disrupt or Die
- We cannot afford to be complacent
- Think ahead to discover new routes to innovation

Linker, 2014, *The Road to Reinvention: How to Drive Disruption and Accelerate Transformation*
Christensen, Raynor, 2013, *The Innovator's Solution: Creating and Sustaining Successful Growth*
Yueh, 2017, *Disrupt or Die*

Summary: Embrace the Future

Main Points

- Reasons for Cognitive EW
  - Speed of decision making
  - Complexity of control
  - Multi-domain coordination
- War at the speed of light
  - Software updates
  - AI updates
- Demographic Challenge
  - Unmanned systems

Resources

- Book
  - K. Z. Haigh and J. Andrusenko, *Cognitive EW: An AI Approach*, 2021. Artech House (USA and UK)
- AOC Webinar (1 hour, On-demand)
  - https://www.crows.org/page/CognitiveEW-AICourse
- AOC Course (6-sessions, 18 hours, On-demand)
  - https://www.crows.org/page/CognitiveEW-AICourse
- Regular upcoming speaking events
  - https://sites.google.com/site/kzhaigh

From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

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Backup

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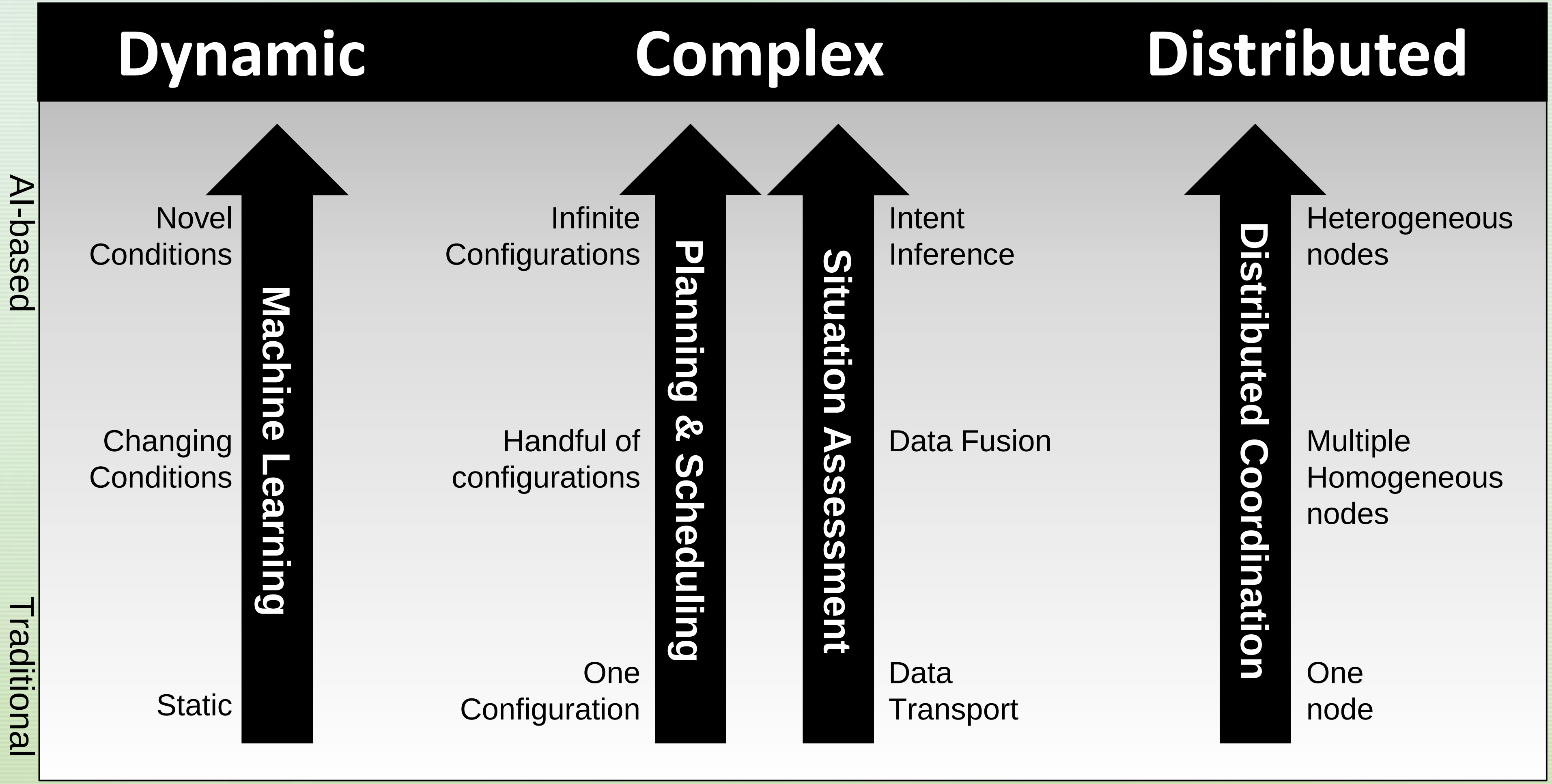
Assessing the Need for AI Capabilities



From *Cognitive EW: An AI Approach* by Haigh and Andrusenko [ArtechHouse, 2021]

Decision Making Advanced Concepts

Optimality

- "Good" is usually good enough
- Both mathematically and pragmatically

Anytime Decision Making

- Best decision for time available
- Better solutions the longer they run

Deliberate Sensing & Communication

- Actions to improve information quality
  - Reduce information uncertainty
  - Purpose is better ES (not better EP or EA)

Game Theory

- When outcomes depend on the reaction of others
  - Cooperative
  - Non-cooperative
- Introduce reasonable randomness

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Challenges to Fielding AI (not just in EW)

- Policies
  - Freedom to innovate
  - Speed of AI vs Acquisition cycle
  - Manned vs Unmanned force design
- Requirements must outline system goals
  - Novel threats
  - Capability tradeoffs and limitations
- Trust
  - Pragmatic action vs Provable performance
- Data Management
  - Data Portal, Data Formats
- Models
  - Threat-representative
- Continuous Test
  - DevTestSecML…Ops
- Vertical Test Frameworks
  - Automated, closed-loop, multi-resolution test frameworks

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