Performance Assessment of the C2ISR Enterprise

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The Problem

- Capability Gap
  - Stovepipes in the ISR community of interest (COI) prevent the timely delivery of the right data to the right recipients
- Solution
  - Use a service oriented architecture to eliminate the stovepipes
    - Distributed Common Ground System
      - Air Force, Army, Navy, Marines
- New Gap
  - No rigorous methodology for assessing the performance of Multi-INT ISR enterprises
- Proposed Solution
  - ONR funded study

Study Description

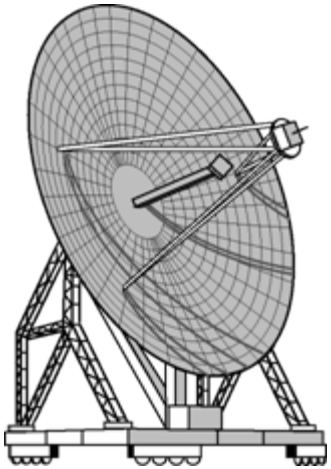
- Develop a rigorous methodology for characterizing the performance of Multi-INT ISR enterprises
  - Multi-disciplinary study of assessment methodologies for enterprise and related systems
  - Develop an assessment methodology for ISR enterprises
  - Apply the methodology to a simple demonstration
- Develop objective metrics for Multi-INT ISR enterprises
  - Figure of Merit
  - Measures of Effectiveness
  - Measures of Performance

Outline

- Motivation from other Figures of Merit
  - Radar Equation
  - Sonar Equation
- Review of other models and assessment methodologies
- Conceptual Model for the Multi-INT C2ISR Enterprise
- Mathematical foundations for the C2ISR Enterprise
- Distributed Multi-INT ISR Enterprise scenario
- Summary

Performance Archetypes

- **Radar equation**

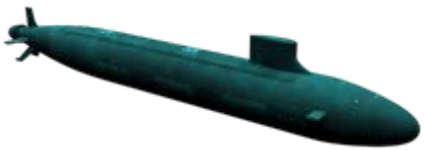


Log-Power received by Radar

$P_R = P_T + G_T + \sigma + A_E - 4\ln(R) - 2\ln(4\pi)$

P_R = Received Power
P_T = Peak Trans. Power
G_T = Transmit Gain
σ = Radar Cross Section
A_E = Effective Area of Receiving Antenna
(Above in dB)
R = Target Range

- **Sonar equations**



Active, Noise – background

$DT = SL + DI_T + TS - 2TL - (NL-DI_R)$

Active, Reverberation – background

$DT = SL + DI_T + TS - 2TL - RL$

Passive

$DT = SL + DI_S - TL - (NL-DI_R)$

DT = Detection Threshold
SL = Source Level
DI = Directivity Index
TL = Transmission Loss
RL = Reverberation Level
NL = Noise Level
TS = Target Strength
(All in dB)

Review of Relevant Literature

Documents	Good Conceptual Model	Can Model the ISR Enterprise	Contains Quantitative Measures	Strong Mathematical Foundation	Provides Single Figure of Merit
The OODA Loop Boyd	The Classic Model				
Situation Awareness Endsley	The Classic SA Model		Statistical Assessments		
Silent Hammer Limited Objective Experiment Pomianowski, et al	Hierarchical Taxonomy		FoM, MoE, MoP		
Network Centric Operations Conceptual Framework Office of Force Transformation	Complex Model		Disjoint Attributes		
Shared Awareness Perry, Signori, Boon			Probability		
Situation Assessment Mahoney, Laskey, Wright, Ng			Probability & Utility		
Complexity Theory; Network Centric Warfare Moffatt			Information Theory		
Distributed sensor networks Kadambe and Daniell			Information Theory		
Information Quality Business Research Community			~20 Information Quality Attributes		

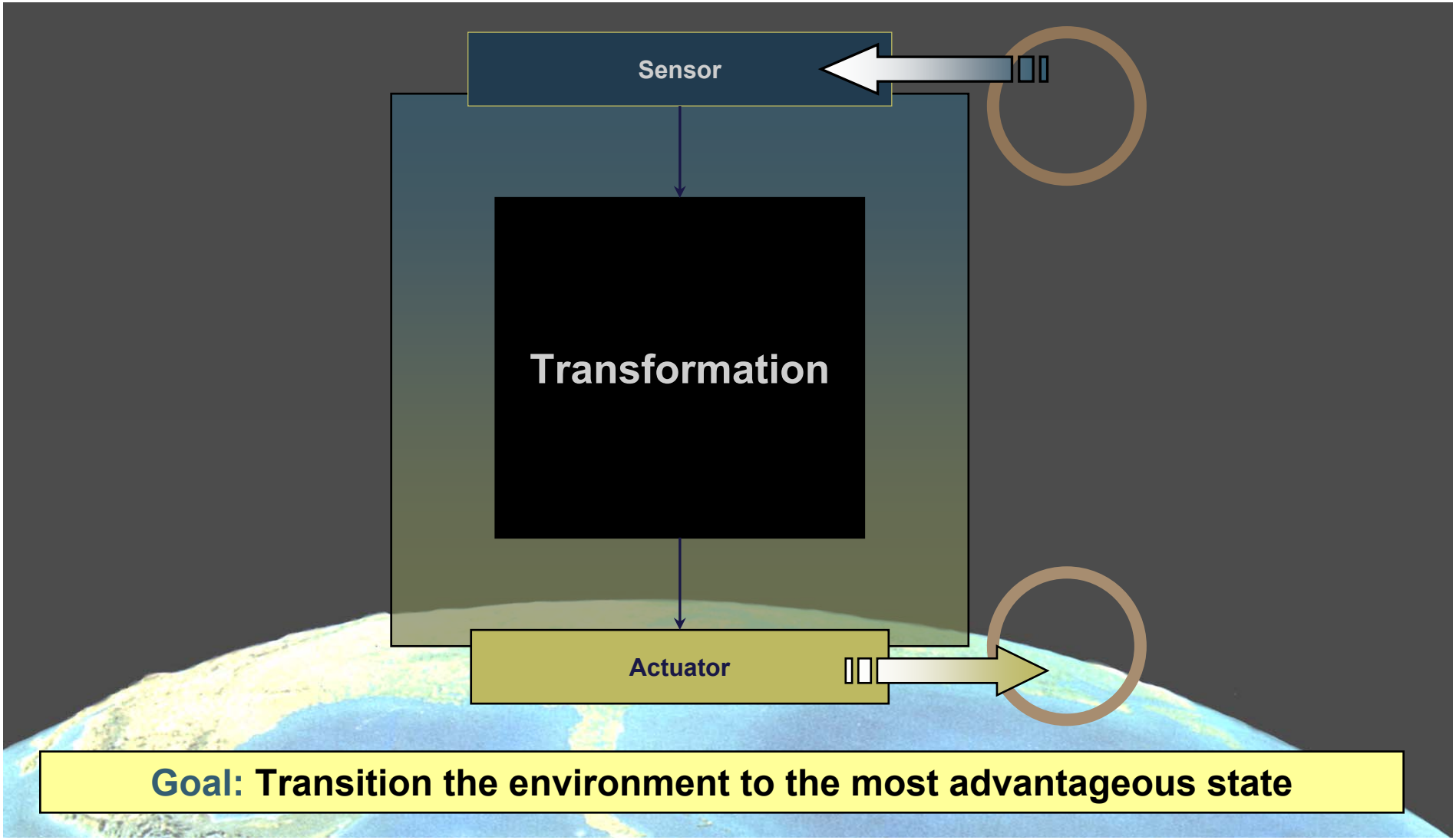
Survey found either good models with weak mathematical foundations or good mathematical foundations with weak models

Conceptual Model Construction

- Adopt Boyd's OODA loop and Endsley's SA loop as a template
  - The Multi-INT ISR enterprise is a decision system or is part of one
- Build in the mathematical foundations from the beginning
  - Probability theory
  - Information theory
  - Utility theory
- Model the enterprise as a state machine
  - Environmental states
  - Decision system states
- Assume that the true environmental state is unique
- Represent all other states by Probability Density Functions (PDFs)

Decision Process Model

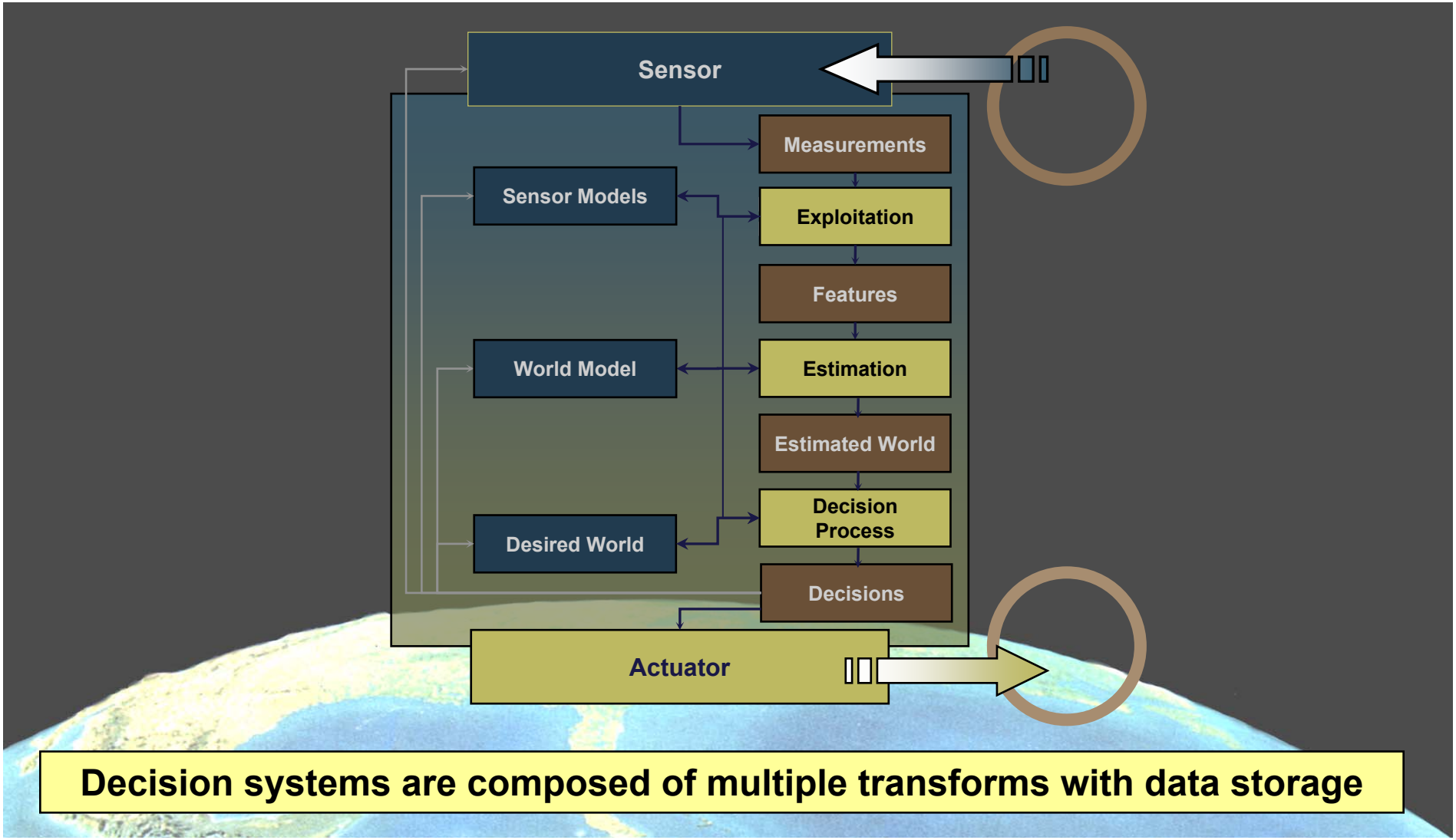
Level One



Goal: Transition the environment to the most advantageous state

Decision Process Model

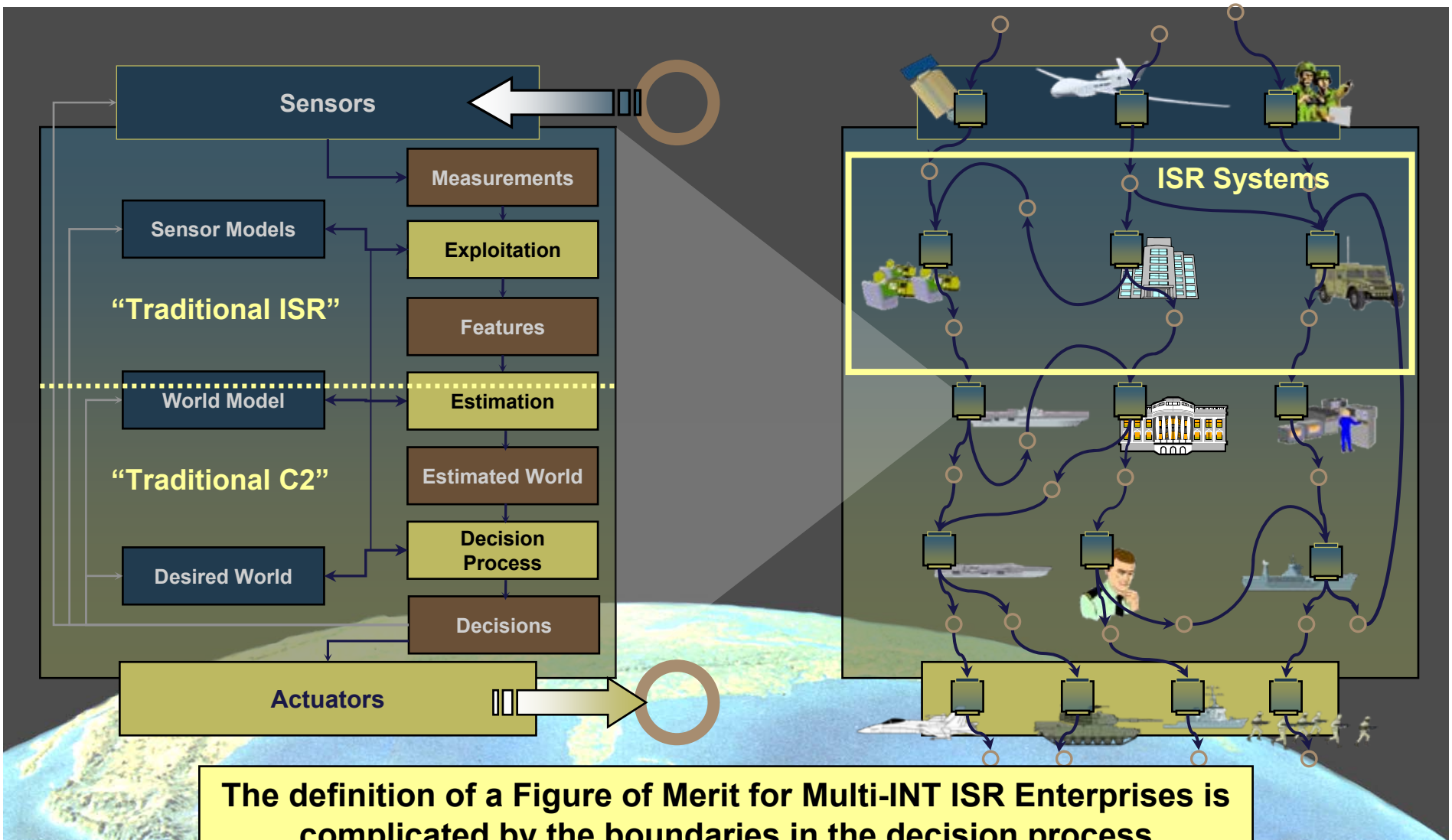
Level Two



Decision systems are composed of multiple transforms with data storage

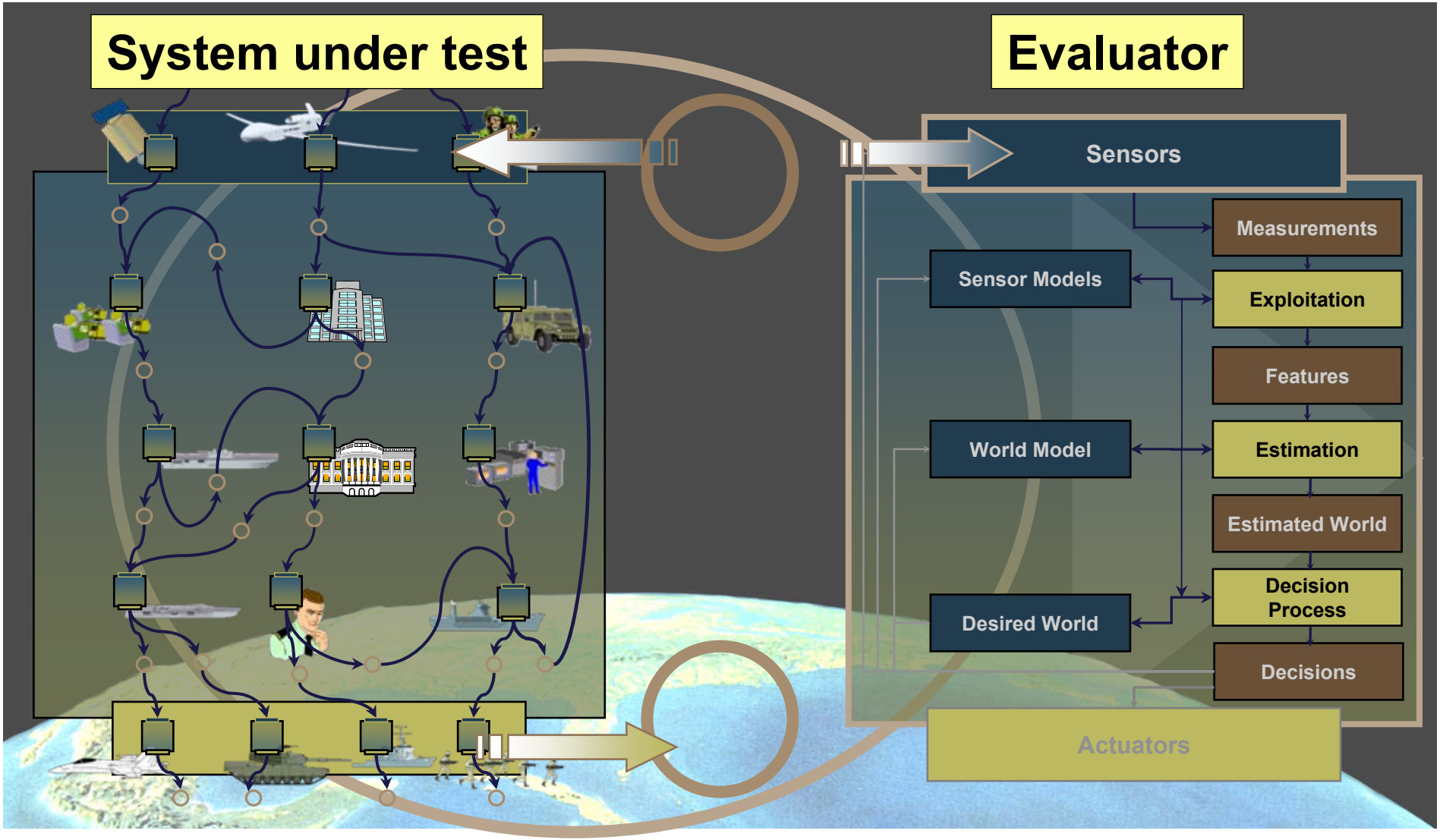
Distributed Decision Process Model

Level Three

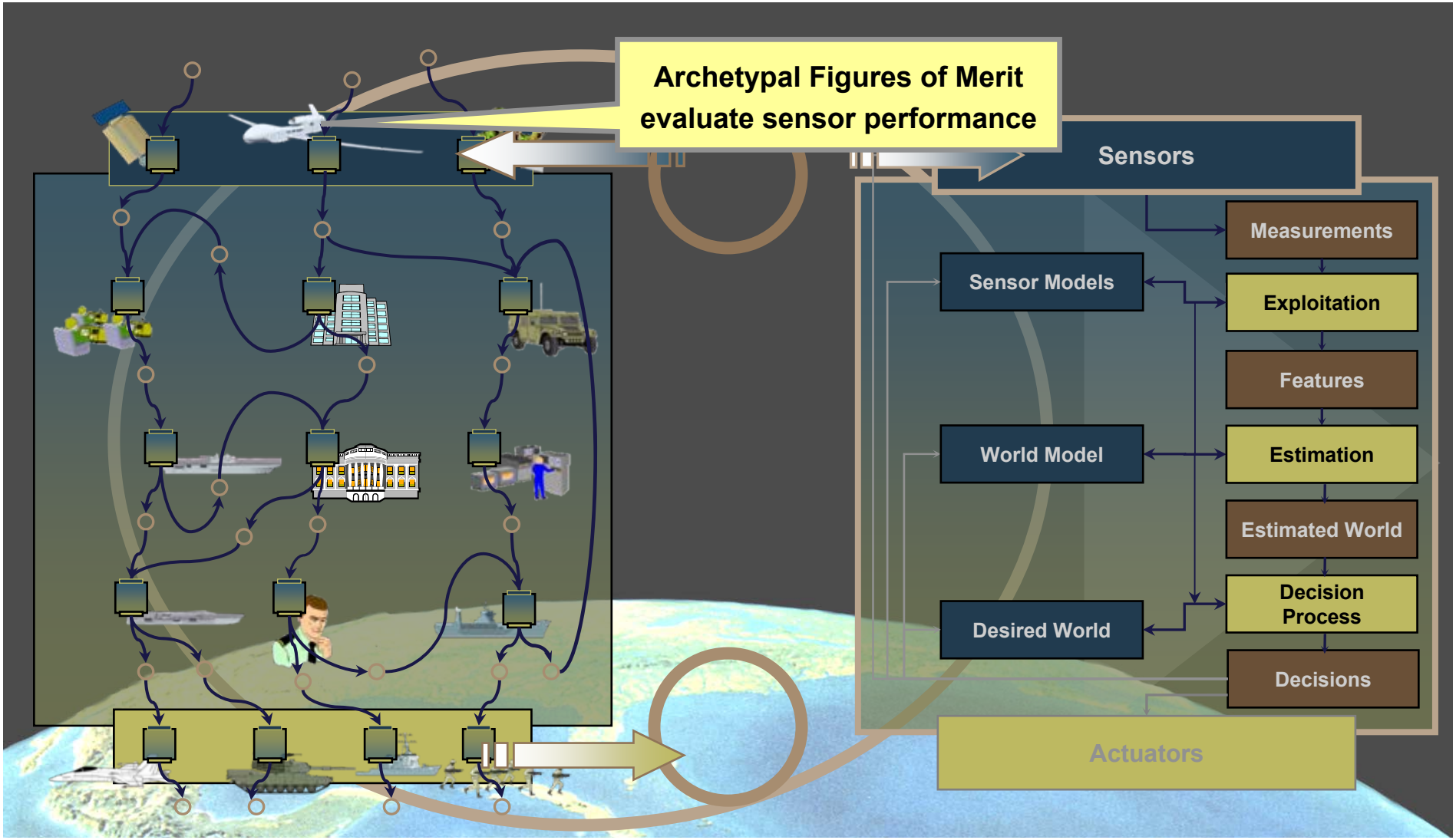


The definition of a Figure of Merit for Multi-INT ISR Enterprises is complicated by the boundaries in the decision process

Decision Process Evaluation

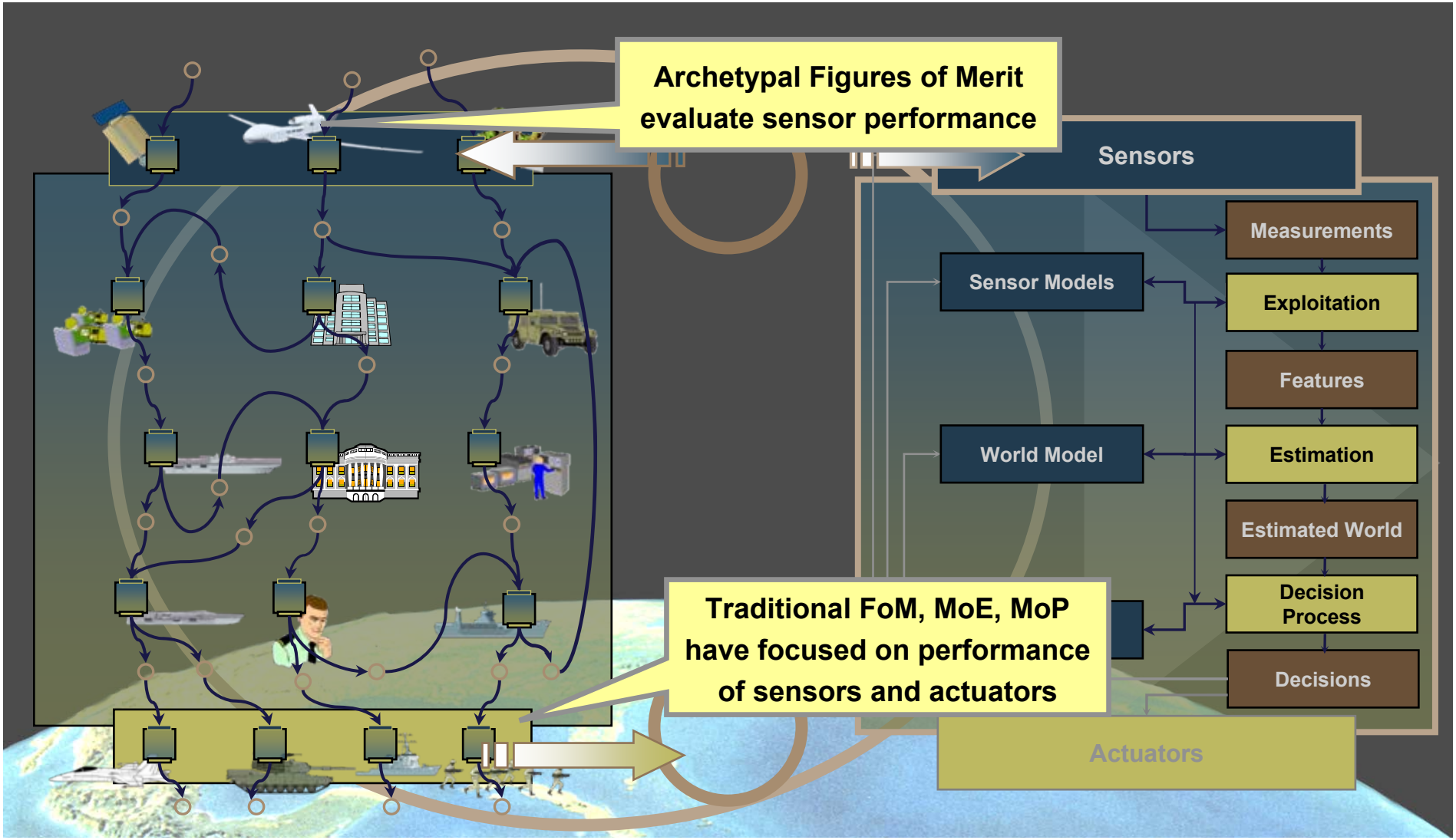


Figures Of Merit
Archetypes



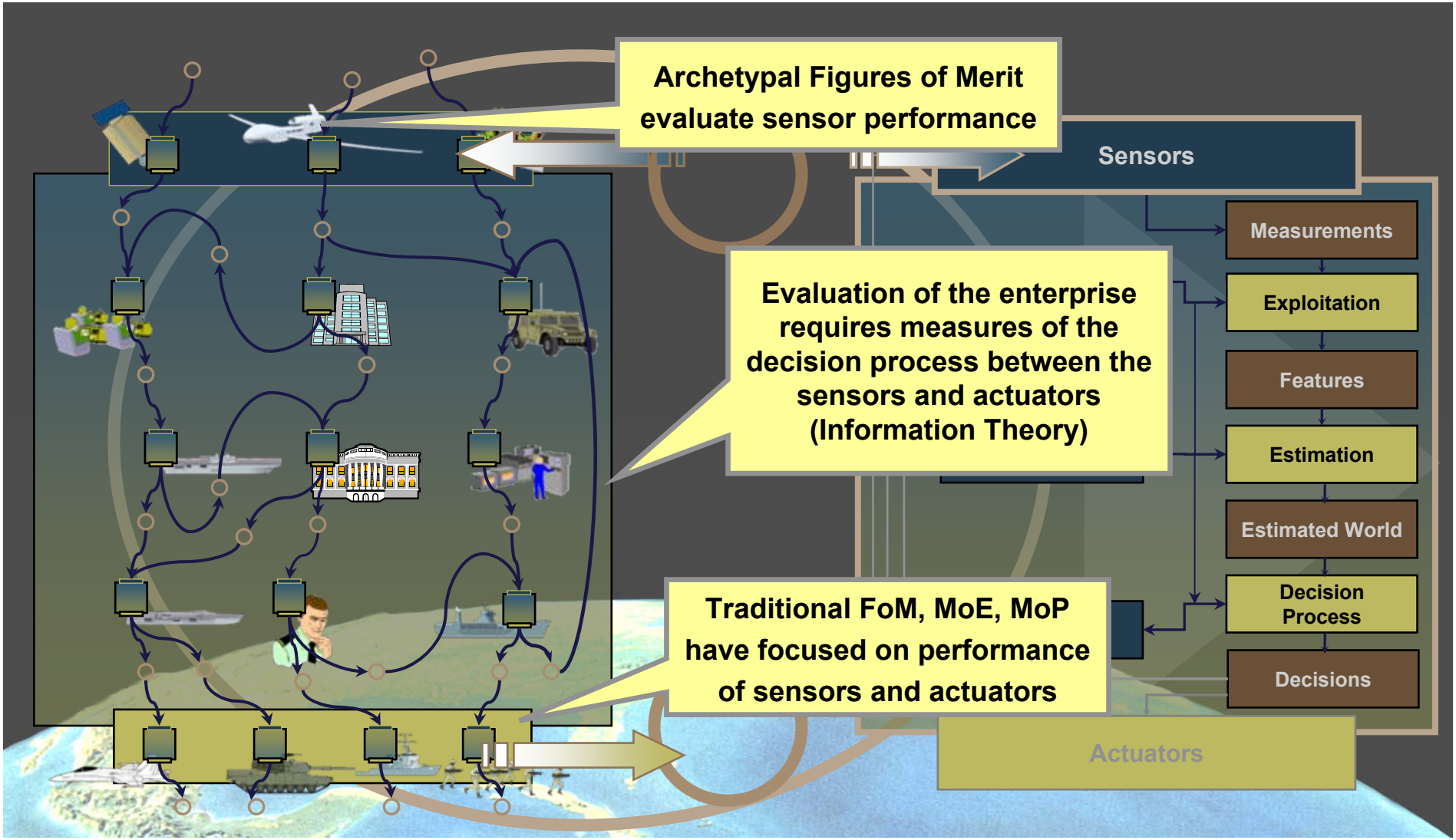
Figures of Merit

Traditional FoM, MoE, MoP



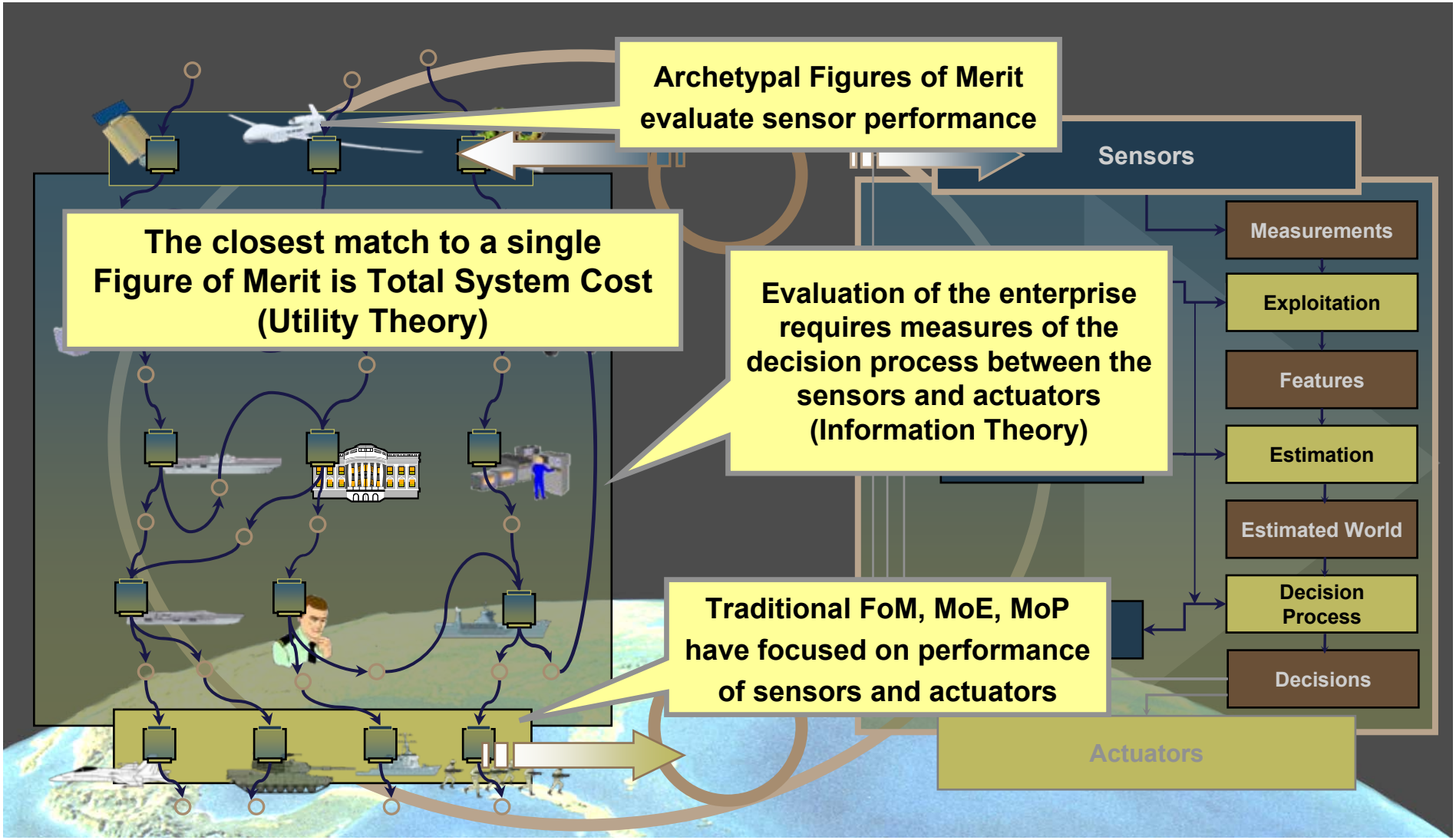
Figures Of Merit

Decision System Evaluation



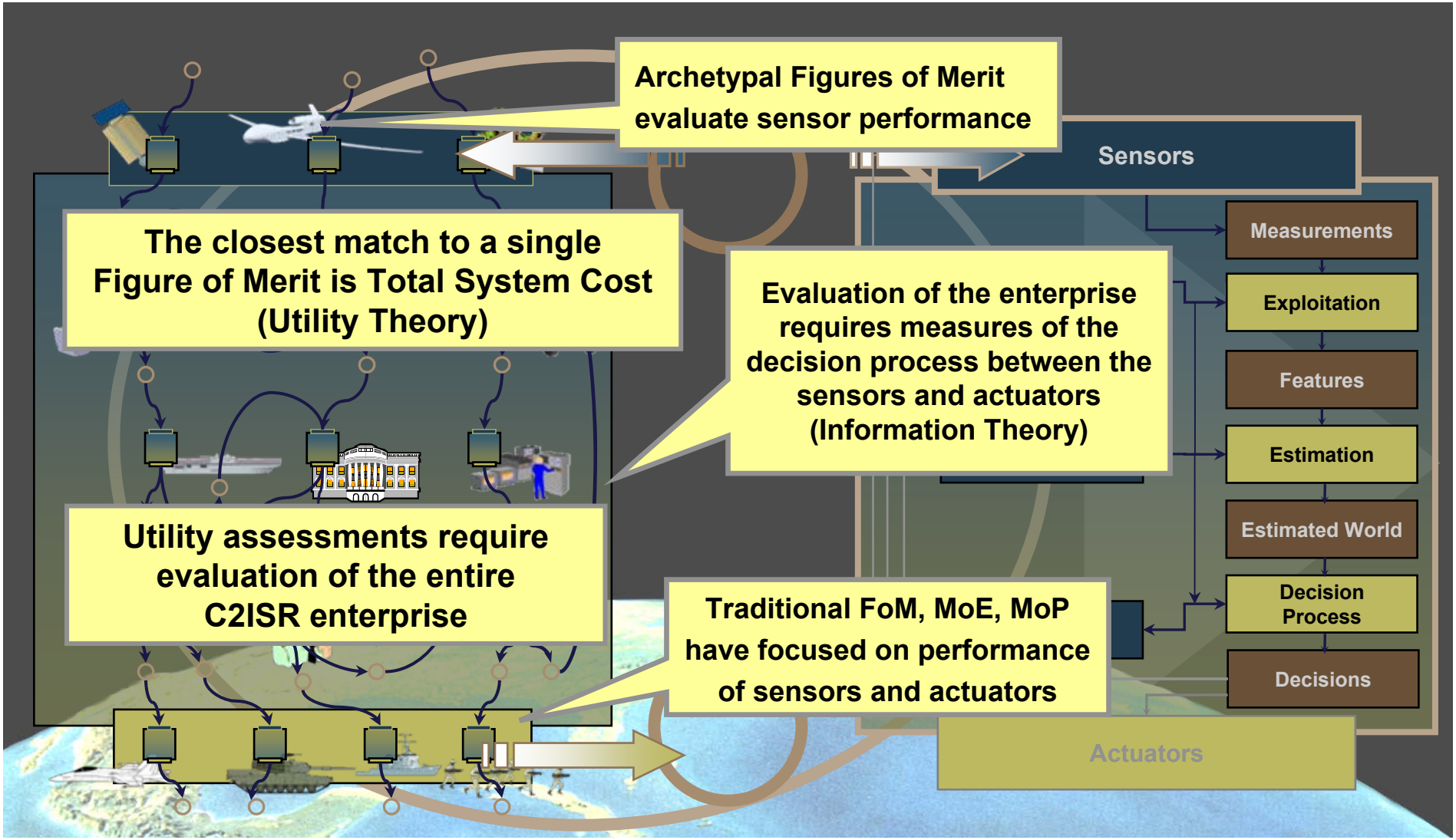
Figures Of Merit

Single FoM



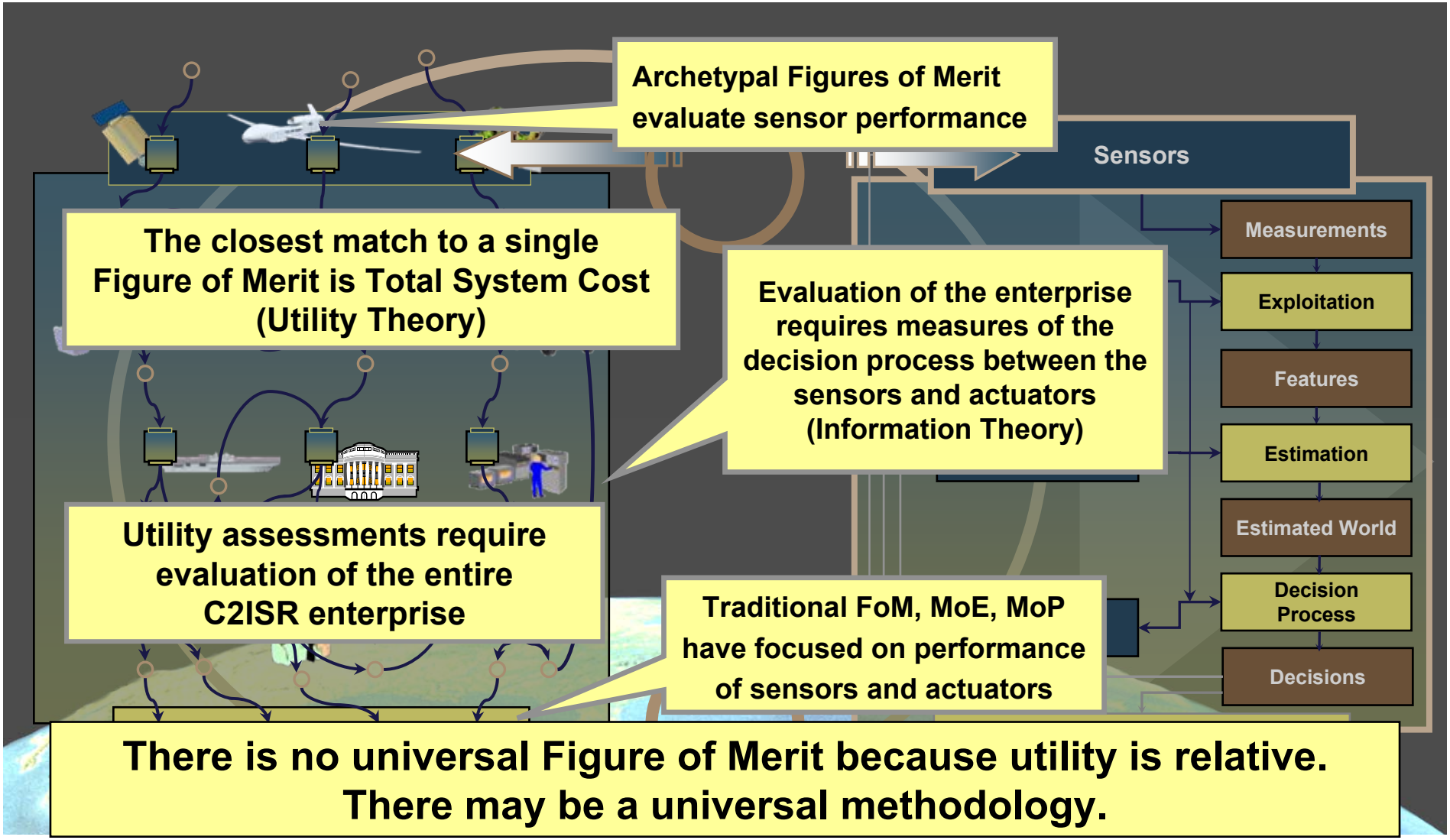
Figures Of Merit

Evaluation of Complete Systems



Figures Of Merit

Relativity



There is no universal Figure of Merit because utility is relative. There may be a universal methodology.

Probabilistic Measures of Performance

- **Correctness**
  - **Probability Integral**

$$D_B = \int_x P_S P_E \, dx \qquad \boxed{D_B = \int_x P_S \delta_E (T - x) dx}$$

- **Confidence (or Uncertainty)**
  - **Shannon information**

$$\boxed{D_{SI} = -\int_x P_S \ln(P_S) dx}$$

  - **Fisher information**

$$D_{FI} = -\int_x P_S \left[\frac{\partial \ln(P_S)}{\partial x} \right]^2 dx$$

- **Consistency**
  - **Kullback-Leibler (K-L) distance or symmetric K-L**

$$D_{KL} = \int_x P_{S1} \ln\left(\frac{P_{S2}}{P_{S1}} \right) dx \qquad \boxed{D_{SKL} = \int_x P_{S1} \ln\left(\frac{P_{S2}}{P_{S1}} \right) dx + \int_x P_{S2} \ln\left(\frac{P_{S1}}{P_{S2}} \right) dx}$$

  - **Mutual information**

$$D_{MI} = \int_x P(x, y) \ln(P(x \mid y)) dx dy - \int_x P(x) \ln(P(x)) dx$$

Enterprise Assessment Demonstration

- Demonstrate the evaluation of a C2ISR enterprise that is constructing a Common Operational Picture (COP)

- Build a conceptually simple simulation
  - Five sensors, each with a different sensory profile
  - Three target classes
  - 5x5 cellular grid representing Area of Interest
  - Sensors take cellular measurements and estimate Probability Density Functions (PDFs) for the content of each cell

- Evaluate the differences between different communications architectures

Simple Multi-INT Enterprise Model

- **Detection and Discrimination Task**
  - **5 sensors, 3 target types, 5x5 grid world**
- **Heterogeneous Sensor Mix**
  - **Synoptic detectors**
  - **Soda-straw discriminators**
- **Decision types**
  - **Movement**

    (North, South, East, West, Stay)
  - **Communication**

    (which metadata / data / queries to what node)

Sensor Modalities

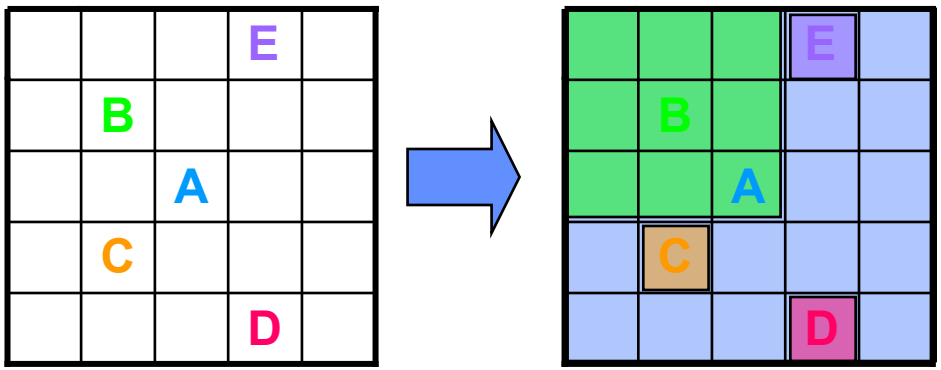
Strength	A	B	C	D	E
●	1	3	5	1	1
■	1	3	1	5	1
▲	1	3	1	1	5
	0	0	0	0	0
Extent	5	3	1	1	1

Sensor Equation

z = (strength) + (noise)

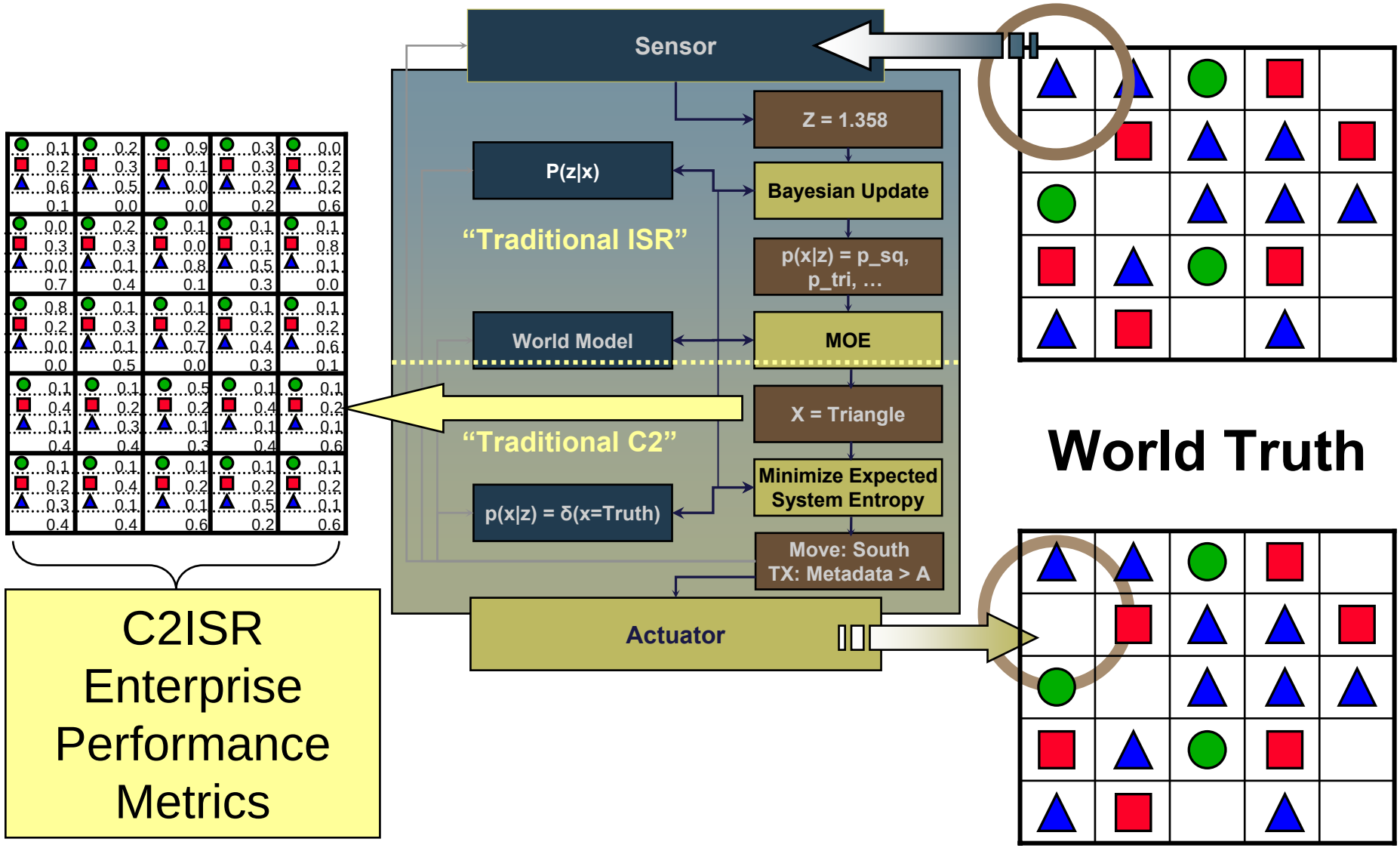
Extent Equation

E = NxN sub-grid



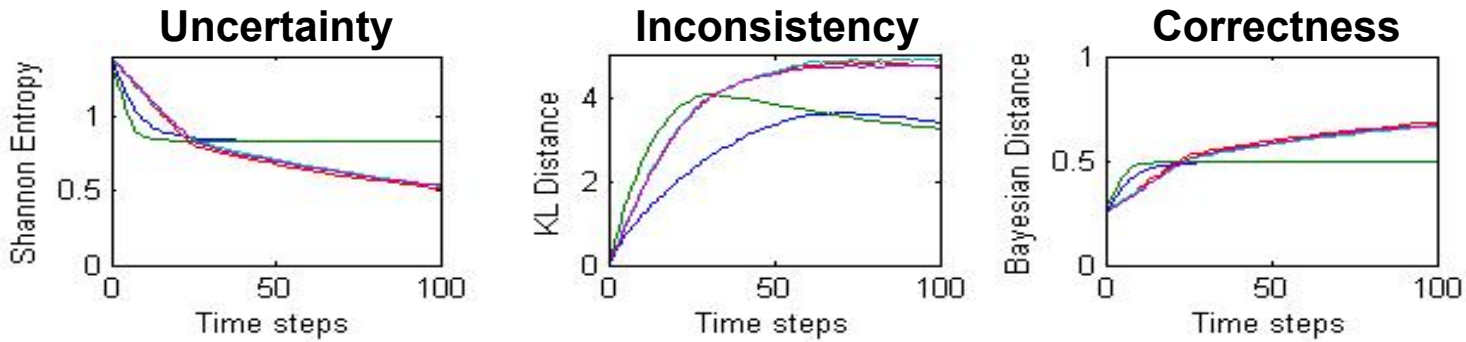
Placement **Coverage**

Decision Process in Action

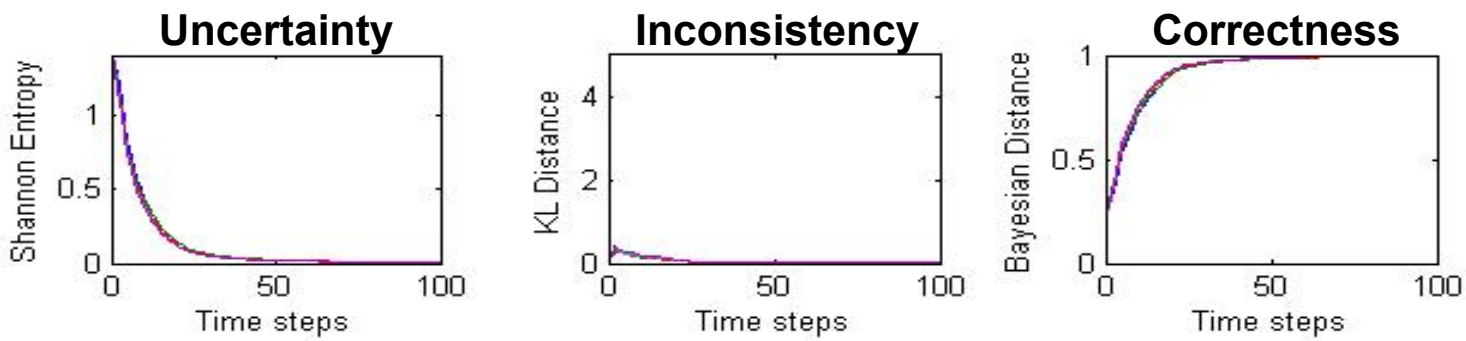


Baseline Communication Architectures

- **No inter-sensor communication (worst case)**
  - Sensor limitations preclude correct or certain estimation by any single sensor
  - Sensor heterogeneity precludes maintaining enterprise consensus

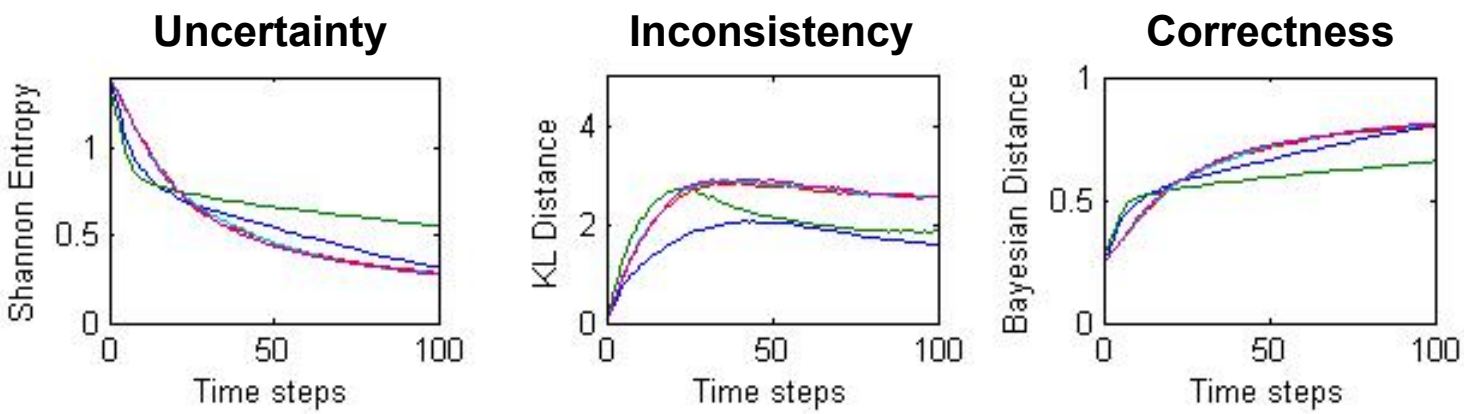


- **Unlimited inter-sensor communication (best case)**
  - Sharing non-mutual information leads to correct and confident world model
  - Sharing all information provides uniformity of consensus across the enterprise



Limited Communication:
Push Architecture

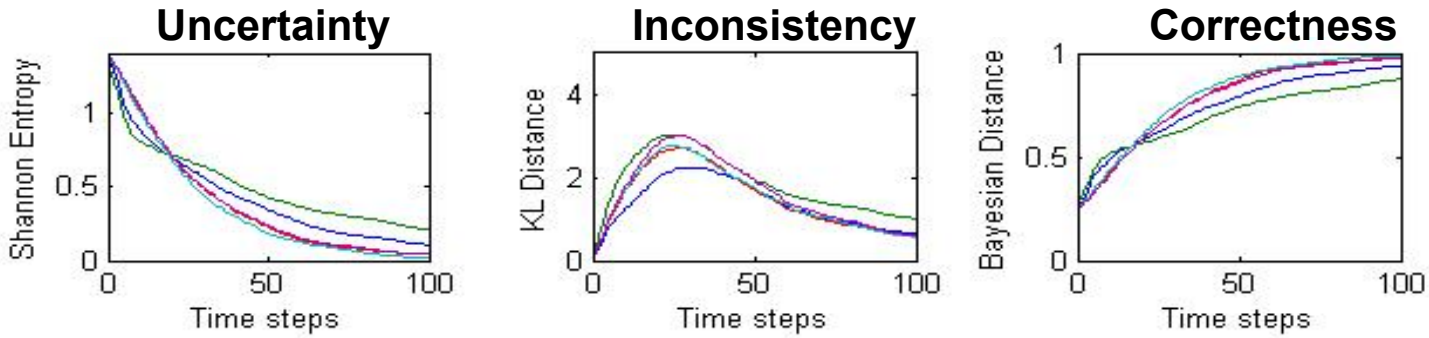
- **Limited inter-sensor communication**
  - **Bandwidth constraints prevent the sharing of all information**
  - **Communication bottlenecks result in long, un-prioritized queues**



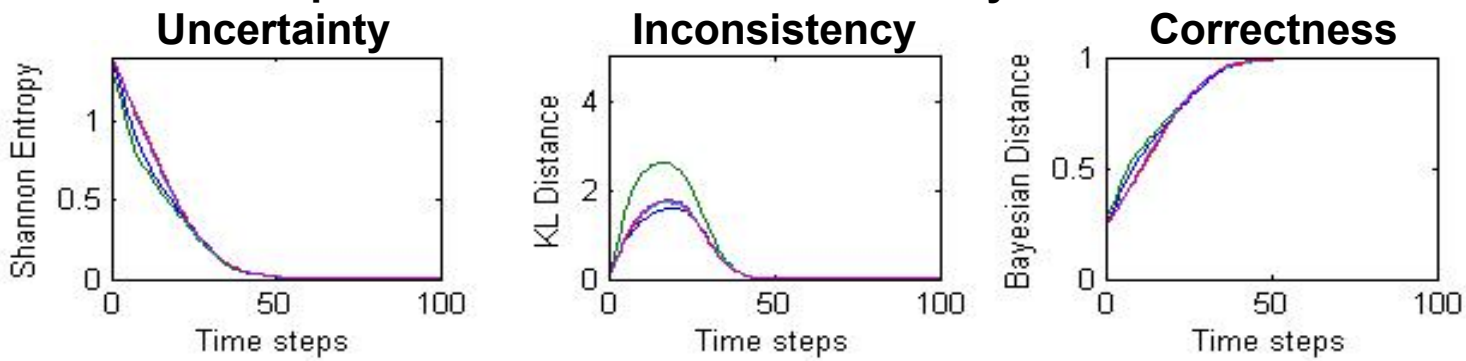
Information architectures that work well in unconstrained systems may not work well in constrained systems

Limited Communication:
Pull Architectures

- **Blind pull (requests/no metadata)**
  - Requests take up a small amount of bandwidth relative to data (1:10)
  - Without knowledge of available data requests may or may not be feasible



- **Informed pull (requests/published metadata)**
  - Metadata information pushed to all nodes, small relative to data (1:10)
  - Informed requests maximize information utility of transmitted data



Summary

- A conceptual model of the Multi-INT C2ISR enterprise has been constructed
- A mathematical foundation have been developed for the evaluation of the C2ISR enterprise
- Measures integrate disparate contributions to overall system performance
  - Information theory for partial systems and component analysis
  - Utility theory for complete decision systems
- The value of performance metrics has been demonstrated through a simulation of a simple scenario
  - Measurements confirm predictions of communications experts for the limited communications architectures