A Model for Situation and Threat Assessment

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A model is presented for situation and threat assessment, with a goal of advancing the state of the art in representing, recognizing and discovering situations and, in particular, threat situations.

The activity relates to levels 2 and 3 of the familiar JDL data fusion model. Level 2, "Situation Assessment", involves such applications as scene understanding, force structure analysis and many other types of situational analysis. Level 3, "Impact Assessment" includes, besides threat assessment (as level 3 was originally named), course of action analysis and outcome prediction.

Data fusion is the process of estimating or predicting some aspect of the world. Specifically, the data fusion process of Situation Assessment has the job of estimating or predicting situations. A *situation* can be defined very broadly as "any structure part of reality" (Devlin, 1991). In that structural analysis involves an assessment of the element of an entity in their relation to one another, Situation Assessment involves (a) inferring relationships, (b) inferring the states of elements on the basis of estimates of their relationships, and (c) recognizing or classifying situations on the basis of estimates of constituent elements and their relationships. In that the last of these is a recognition/classification problem, we should expect to have some similarity to target recognition and classification; i.e. the matching of data to prior models (a deductive process). As in target recognition/classification, this dependency on prior models presumes a process for generating, evaluating and selecting such models. These are characteristically abductive (i.e. explanatory) and inductive processes.

We take as our starting point the process involved in Scene Understanding as it occurs in machine vision, automatic target recognition (ATR) and remote sensing applications. ATR and machine vision have evolved from straight-forward template matching techniques, in which observed scenes are compared with stored images. Template techniques are obviously constrained by the number of target/context scenes that they can store. Various indexing schemes are used to reduce this burden, by extracting relatively invariant features, but the approach is ultimately restricted to situations in which target signatures are not much affected by contextual factors (occlusion, shadowing, illumination variability, etc.).

Far more robust (although more complex) are model-based techniques, in which candidate scene hypotheses are adaptively generated, evaluated, refined and modified. Such techniques can be augmented by adaptive data collection techniques that anticipate the utility of information in resolving present ambiguities and manage sensors or data mining processes to maximize the value of returned data.

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To extend model-based scene understanding processes for generalized Situation Assessment problem, the technique needs to be able to “think outside the frame”, as evidence can come from “anywhere”. Furthermore, the process must often deal with a wider range of evidence: understanding of many types of situations involves the use of a wide diversity of information types, relating, e.g. to political, social, informational and psychological aspects of the situation that are not inferable from direct physical signatures alone. Correspondingly, the recognition/classification process must often involve a wider range of entity and aggregate behavior models. This is certainly the case in the many situations of interest that involve estimating and predicting human individual and group behavior.

Therefore it will be necessary to have deductive, abductive and inductive tools that will characterize and recognize situations and constituent relationships. In various applications, relationships of interest can range from logical and semantic ones, to physical, functional, conventional and cognitive relationships. To be sure, most relationships of these types are not Directly Observable; rather, they must be inferred from the characteristics & activities of the related entities.

We are working on defining a formal scheme for representing and reasoning about relationships, situations, impacts, threat, etc. First, it should be noted that a relationships is not simply a multi-target state: a state of the sort of interest in Situation Assessment cannot in general be inferred from a set of single-target states. We will want to combine both direct measurements from “sensors” as all as inferred information – e.g. natural language reports by an analyst, or from HUMINT, document or communications. All such information can be represented in a second-order predicate calculus. We use the formalism of “Infons” introduced by Keith Devlin (1991), but there are equivalent formalisms. Situations *s* can be defined by means of minimal sets $\mu(s)$ of infons, often with fuzzy membership conditions. Infons and situations can be elements of other infons. This formulation supports Operational Net Assessment: reasoning from multiple perspectives.

Elements of state estimation relevant to threat assessment (and, indeed, to many other types of situation and impact assessment) extend beyond the physical state elements familiar in target tracking and target recognition. Ed Waltz, following Karl Popper, has identified physical, informational and perceptual aspects of state estimation problems. We have used this to develop a taxonomy of discrete and continuous state elements for physical, informational and perceptual aspects, both of entities and of their relationships. Reasoning about informational and perceptual (and, more broadly, psychological) aspects are at the heart of Operational Net Assessment.

We turn to the estimation and prediction *of threats*; or, more generally, of *intentional acts*. Little and Rogova, following the tradition of forensic analysis, have defined threats (i.e. the potential for harmful actions) as a product of the capability, opportunity and intent of agents to carry out such actions (We can generalize this to encompass any intentional act; we can further generalize this to include non-intentional events - harmful or otherwise - by ignoring intent).

The process defined for model-based scene understanding is extended to the general problem of situation and threat assessment. This is done in a very straight-forward manner, by expanding the types of modes for information sources, targets and situations. The functions of model management are also explicitly addressed. A consistent scheme for representing measurements, attributive and relational states and corresponding uncertainties is required throughout the deductive recognition/classification processes and the abductive/inductive model management processes.

The problem of characterizing information sources is present even in systems that have been designed and integrated as a package. Sensor noise statistics and biases can be characterized in calibration and registration;

either by using (a) internal calibration signal sources, (b) known “fiducial” targets in the environment, or (c) the ensemble of information available in a multi-sensor system.

The problem is made more difficult when the performance of information sources cannot be assumed. This is the case in network-centric operations, in which calibration and registration are not easily performed. It is even more the case when the cooperation of information sources cannot be assured; e.g. when sources are agents with varying degrees of autonomy, raising the possibility of private agendas. The same factors can affect the estimation and controllability of assets having some degree of autonomy. Cases extend to the use of non-cooperating agents; e.g. enemy radars that “report” to our ELINT systems who and where they are; generally with no attempt to deceive. Other cases include deception, in such Information Warfare techniques as decoys, deceptive jamming and propaganda. Then there are third-party agents – e.g. commercial news sources, reference texts, and the like – that may or may not be unbiased.

Given the general lack of useful calibration sources or fiducial targets in such cases, fusion system must characterize the reliability & performance of EACH source using the ensemble of information. In other words, the sources available to information systems (and control systems, too) can involve various degrees of noise and bias errors AND various degrees of performance characterization. To extend the network-centric concept, this implies that we can’t assume clear system boundaries: “us” vs “them”: Allegiance is a matter of estimation.

Technical issues in situation and threat assessment include: (a) Data Alignment: Exploiting heterogeneous information types and Normalizing confidence: source characterization, data evaluation; (b) Hypothesis Generation: determining relevant data, generating/selecting candidate scenario hypotheses and representing relationships , situations, etc.; (c) Hypothesis Evaluation: managing uncertainties in data association; (d) Hypothesis Selection: efficient schemes for representing and searching hypotheses.

Engineering issues include principles for partitioning the process into an information exploitation architecture. This includes issues of allocating tasks to humans and to automated processes and attendant presentation and control issues. Particularly difficult engineering issues involve managing models of situations, threats, sources and system resources. Such model management and exploitation will require an otology of situational, mission and system elements and their relationships. The ontology will need to provide criteria for recognizing relationships and situations. It must capture uncertainties in dependencies (e.g. in terms of fuzzy membership).

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November, 2005

Objectives

- **Advance the state-of-the art in**
  - **Representing**
  - **Recognizing**
  - **Discovering**

  situations of interest; particularly threat situations
- **Improve inferencing* across information levels:**

  Level 0. Measurements & Features

  Level 1. Entities

  Level 2. Relationships & Situations

  Level 3. Outcomes & Costs

  Level 4. Own System Characteristics

By people, machine or some combination

Characteristic Process Flow Across the Data Fusion “Levels”

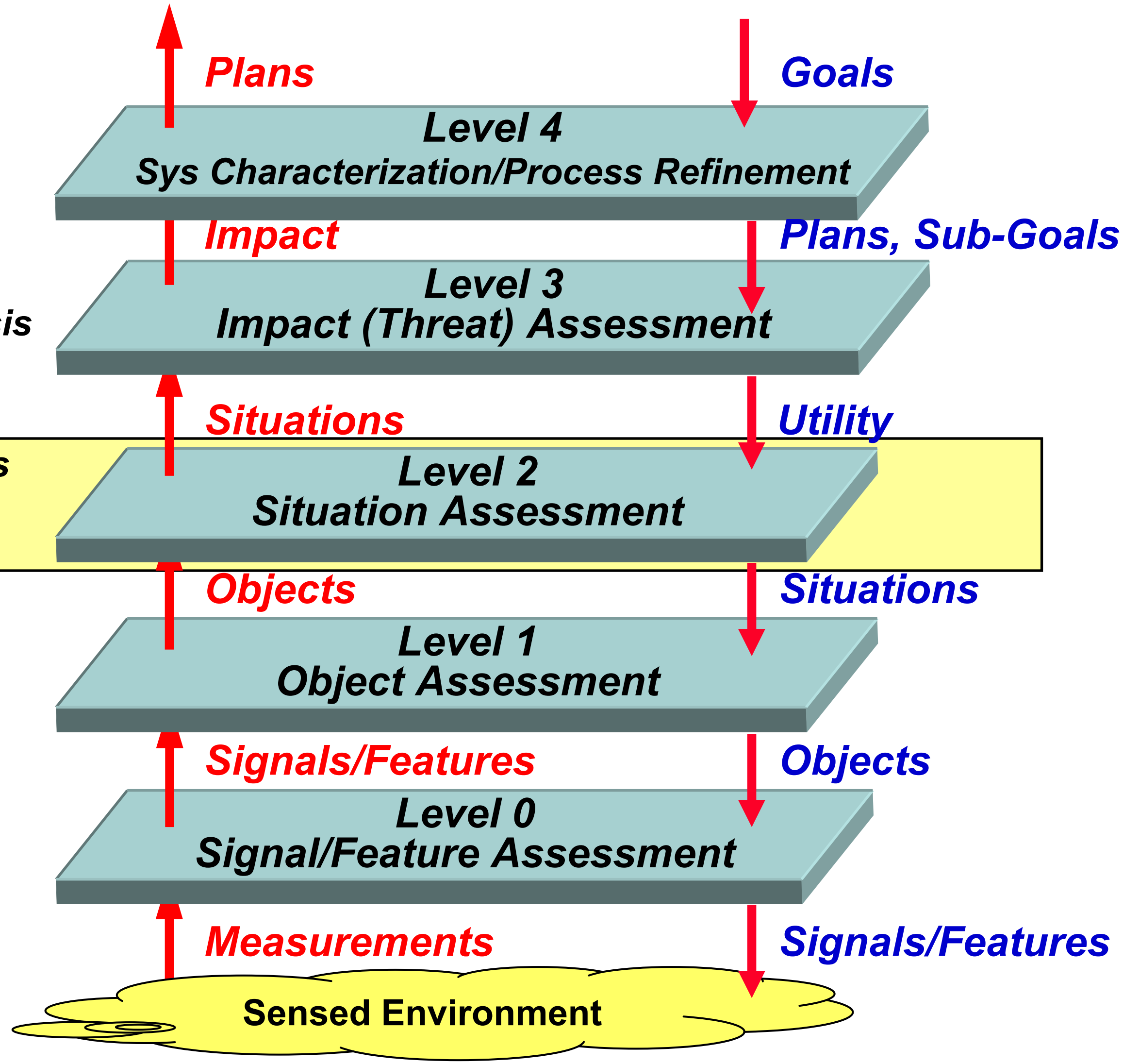
- *Collection Management*
- *Data Mining*
- *Fusion Process Control*

- *Threat Assessment*
- *Course of Action Analysis*
- *Outcome Prediction*

- *Force Structure Analysis*
- *Situation Analysis*
- *Scene Understanding*

- *Target Recognition*
- *Target Tracking*

- *Feature Extraction*
- *Signal Definition*



Definition of Terms

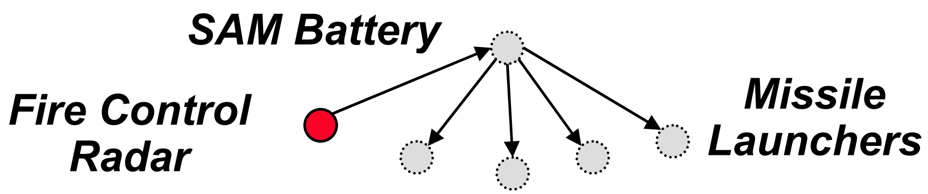
- **Data Fusion := estimation/prediction of the state of some aspect of the world on the basis of multiple data** (*JDL model, 1998 revision*)
- **Situation := any structured part of reality** (*K. Devlin, 1991*)
- **Structure := the aggregate of elements of an entity in their relationships to each other** *(Merriam-Webster Online Dictionary, 2005*)
- **Situation Assessment (Level 2 Data Fusion) := estimation/prediction of the state of some situation**
  a. Inferring relationships
  b. Inferring the states of elements on the basis of estimates of their relationships
  c. Recognizing/classifying situations on the basis of estimates of constituent elements and their relationships

Level 2/3 Inference Patterns

1. **Inferring relationships on the basis of entity states**

   $R_1(x), R_2(y) \rightarrow R_3(x,y)$,

2. **Inferring the presence and the states of entities on the basis of relations in which they participate**



3. **Inferring relationships on the basis of other relationships**

   Communicating (x,y) → Cooperating (x,y)

4. **Recognizing and characterizing extant situations**

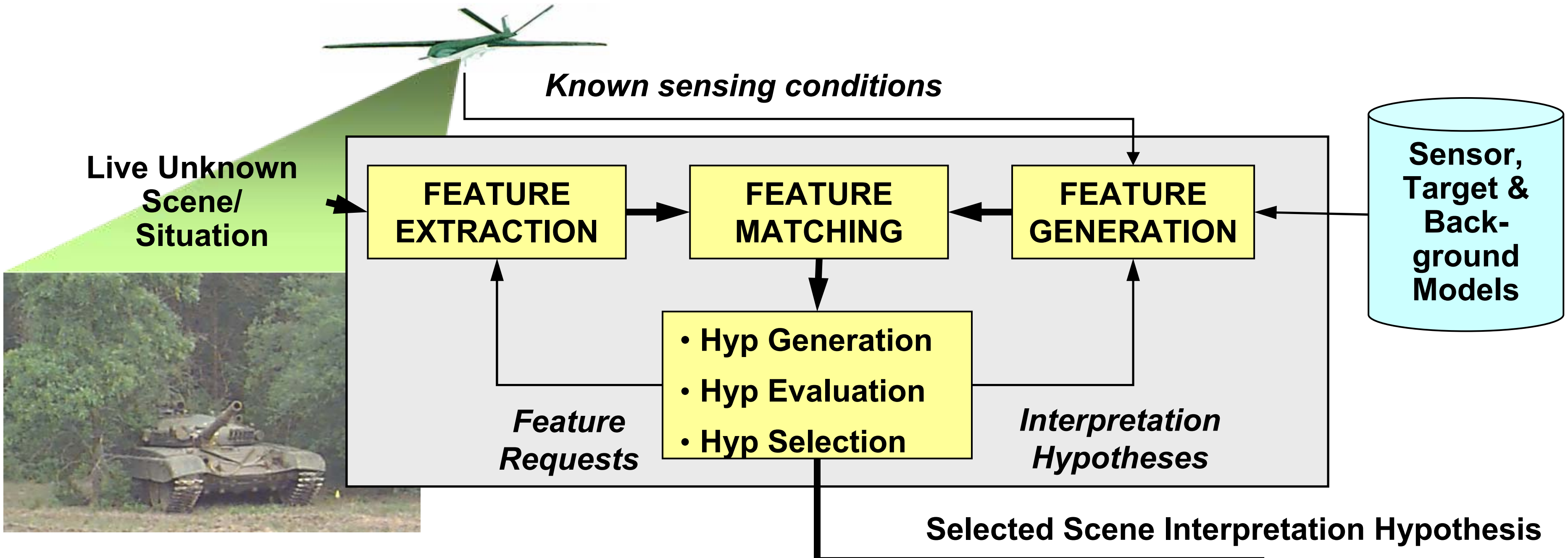
   $R_4(x,y,z), R_5(z), \ldots \rightarrow x,y,z$ *involved in situation S*

5. **Predicting undetected (e.g. future) situations**

   S_1 at time$_1$ → S_2 at time$_2$

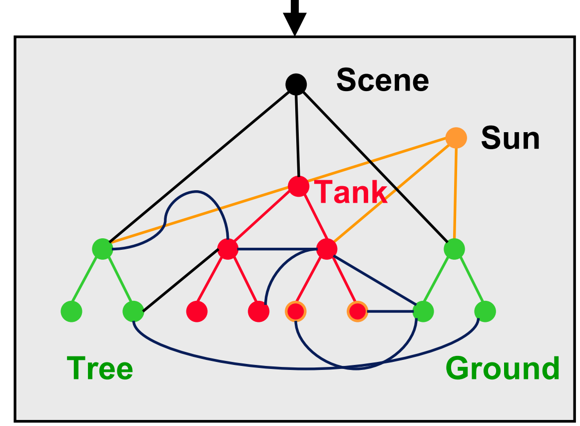
Such inferences may be conditional, counterfactual, or uncertain

Starting Point: Model-Based Evidential Accrual for Scene Understanding



For General Situation Assessment Problem, need to

- **Think outside the frame: evidence can come from "anywhere"**
- **Deal with wider range of evidence**
- **(Often) infer concerning human activity**



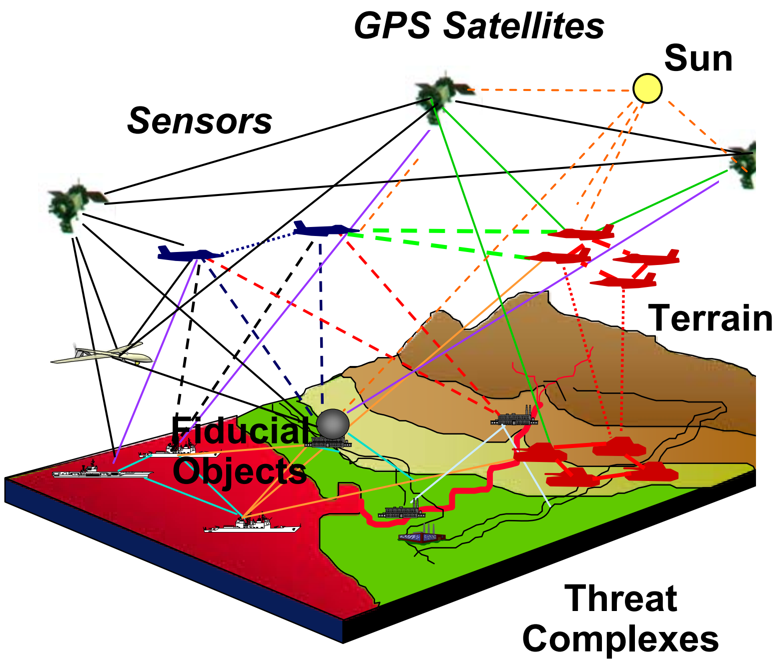
Taxonomy of Relationships Relevant to Situation Assessment

- **Logical/Semantic relationships** (e.g. definitional, analytic, taxonomic, mereologic)
- **Physical relationships** (e.g. spatio-temporal, causal)
- **Functional relationships** (e.g. structural or organizational role)
- **Conventional relationships** (e.g. ownerships, legal and other societal conventions)
- **Cognitive relationships** (e.g. sensing, perceiving, believing, fearing, imagining)

Most of these Relationships are not Directly Observable:

Must be Inferred From the Characteristics & Activities of the Related Entities

Relationships of Interest in Tactical Applications



- **Relationships among objects in threat complex** (deployment, kinetic interaction, organization role/subordination, comms, type similarity, etc.)
- **Relationships among blue sensor & weapon platforms** (spatio-temporal alignment, measurement calibration, confidence, communication/ coordination, etc.)
- **Relationships between sensors & sensed entities** (intervisibility, assignment/cueing, sensing, data association, countermeasures)
- **Relationships between red & blue tactical entities** (targeting, jamming, engaging, etc.)
- **Relationships between entities of interest & other entities** (terrain features; solar & atmospheric effects; weapon launch & impact points; etc.)

A Formulation for Situation Assessment

- **A relationships is not simply a multi-target state**
  - **A multi-target state of the sort of interest in Situation Assessment cannot in general be inferred from a set of single-target states** $X = \{x_1, \ldots, x_n\}$

E.g. from P = '*x* is healthy, wealthy and wise' can't infer Q = '*x* is married to y'

Formal Representation (1)

- **Want to combine both:**
  - Direct measurements - from “Sensors”
  - Inferred information – e.g. natural language reports by an analyst, or from HUMINT, documents or communications
- **All such information can be represented in a second-order predicate calculus**
  - H. Curry & R. Feys, *Combinatory Logic*, 1974
  - K. Devlin, *Logic & Information*, 1991: “Infon”

Formal Representation (2)

- **Infon: a unit of information $\eta = (r, x_1, \ldots, x_n, h, k, p)$**

  for some m-place relation r, $m \geq n$, entities $x_1, \ldots, x_n$, location h, time k and probability p
  - Replacing {0,1} polarities with probabilities allows us to reason with uncertain information
- **Situations s can be defined by means of minimal sets $\mu(s)$ of infons, often with fuzzy membership conditions**
- **Can classify real-world situations in the same way as we classify real-world objects**
  - Indeed, an object is – by definition – a kind of situation

Formal Representation (2a)

- **A Situation-type or Object-type s can be defined in terms of an equivalence class $R(s)$ of relationships;**

  i.e. as a *set of un-anchored infons:*

  'x is an s' can be defined as

  $$\text{`}\forall r[r^{(m)} \in R(s) \rightarrow \exists y_1,\ldots,y_{m-1}[(r,x, y_1,\ldots,y_{m-1},h,k,1)]]\text{'}$$

Formal Representation (3)

- **Infons and situations can be elements of other infons**
  - **E.g.** $s_1 = (r, x, s_2, h, k, p)$, **where** r **=** ***believes*** **(i.e., "with probability** p**, at place & time** h,k**,** x **believes that** s_2**")**
  - **Similarly with** r = ***perceives, hypothesizes, wonders whether, doubts that,*** **etc.**
  - **Also, can be nested recursively:** **"**x ***believes that*** y ***believes that … η"***
- **This formulation supports Operational Net Assessment: reasoning from multiple perspectives**
  - **Conditional, counterfactual, uncertain**

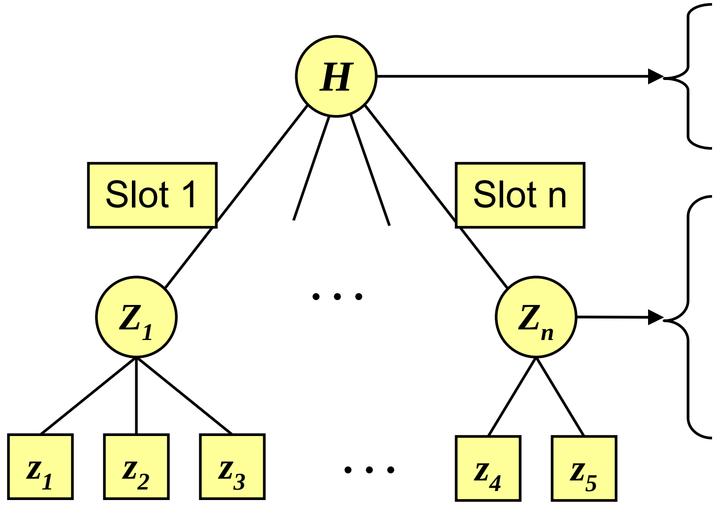
Level 2/3 Fusion Outputs: Relational & Situational State Elements

- **A Relationship Hypothesis has the form**

  $H = (r_1, Z_{1(1)}, \ldots, Z_{(m(1)}, p_1), \ldots, (r_n, Z_{1(n)}, \ldots, Z_{m(n)}, p_n)$, for Level 1 hypotheses Z_i, relation types r_j, and associated probabilities p_j

  i.e. "entities y_i, $i=1,\ldots,n$, inferred , respectively, from measurement sets Z_i are in relations r_j with probabilities p_j"

- **Level 2 Hypotheses ("Perceived Relationships")**
- **Level 1 Hypotheses ("Perceived Entities")**
- **Measurements**



Discrete Relational state probability vector

$< (r_j, Z_{j(1)}, \ldots, Z_{n(j)}, p_j), \ldots, >$

Discrete Attributive state probability vector

$< (Type\ 1, Z_n, p_1), \ldots, >$

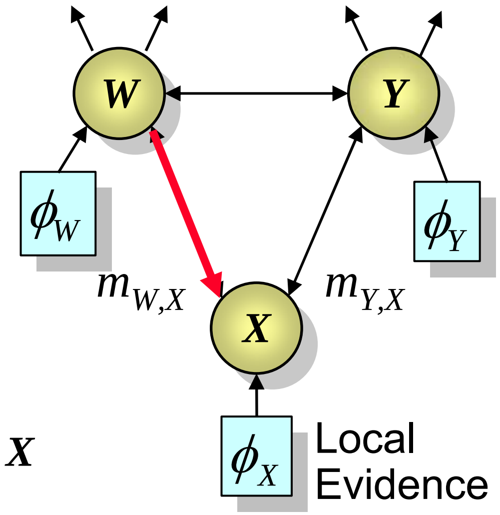
Continuous state est

$(\hat{x}_n, Z_n, S)$

(Infon notation with suppressed place & time indices)

- **Situation Hypothesis:**
  - **A Set of Relationship Hypotheses – often a fuzzy set**

Generalized Belief Propagation



- **Evidence accrual represented equivalently via Belief Propagation Nets, Markov Random Fields or Factor Graphs**
- **Belief in a state x_j of a node X is modeled as**

$$b_X(x_j) = k\phi_X(x_j) \prod_{W \in N(X)} m_{W,X}(x_j)$$

set of immediate neighbors of X

In terms of "local" evidence $\varphi_X(x_i)$ and "messages" $m_{W,X}$ from other nodes

$$m_{W,X}(x_j) = \sum_{w_i} \phi_W(w_i)\psi_{W,X}(w_i, x_j) \prod_{Y \in N(i)\backslash j} m_{Y,W}(w_i)$$

$$= \sum_{w_i} \phi_W(w_i) \sum_{r} f(w_i, x_j \mid r(W,X)) f(r(W,X)) \prod_{Y \in N(i)\backslash j} m_{Y,W}(w_i)$$

- **Joint belief is given as**

$$b_{W,X}(w_i, x_j) = k\psi_{W,X}(w_i, x_j)\phi_W(w_i)\phi_X(x_j) \prod_{Y \in N(W)\backslash X} m_{Y,W}(w_i) \prod_{Z \in N(X)\backslash W} m_{Z,X}(x_j)$$

Expanded from J.S. Yedida, W.T. Freeman & Y. Weiss, "Understanding belief propagation and ts generalization" (2002)

Characteristic Process Flow Across the Data Fusion “Levels”

- *Collection Management*
- *Data Mining*
- *Fusion Process Control*

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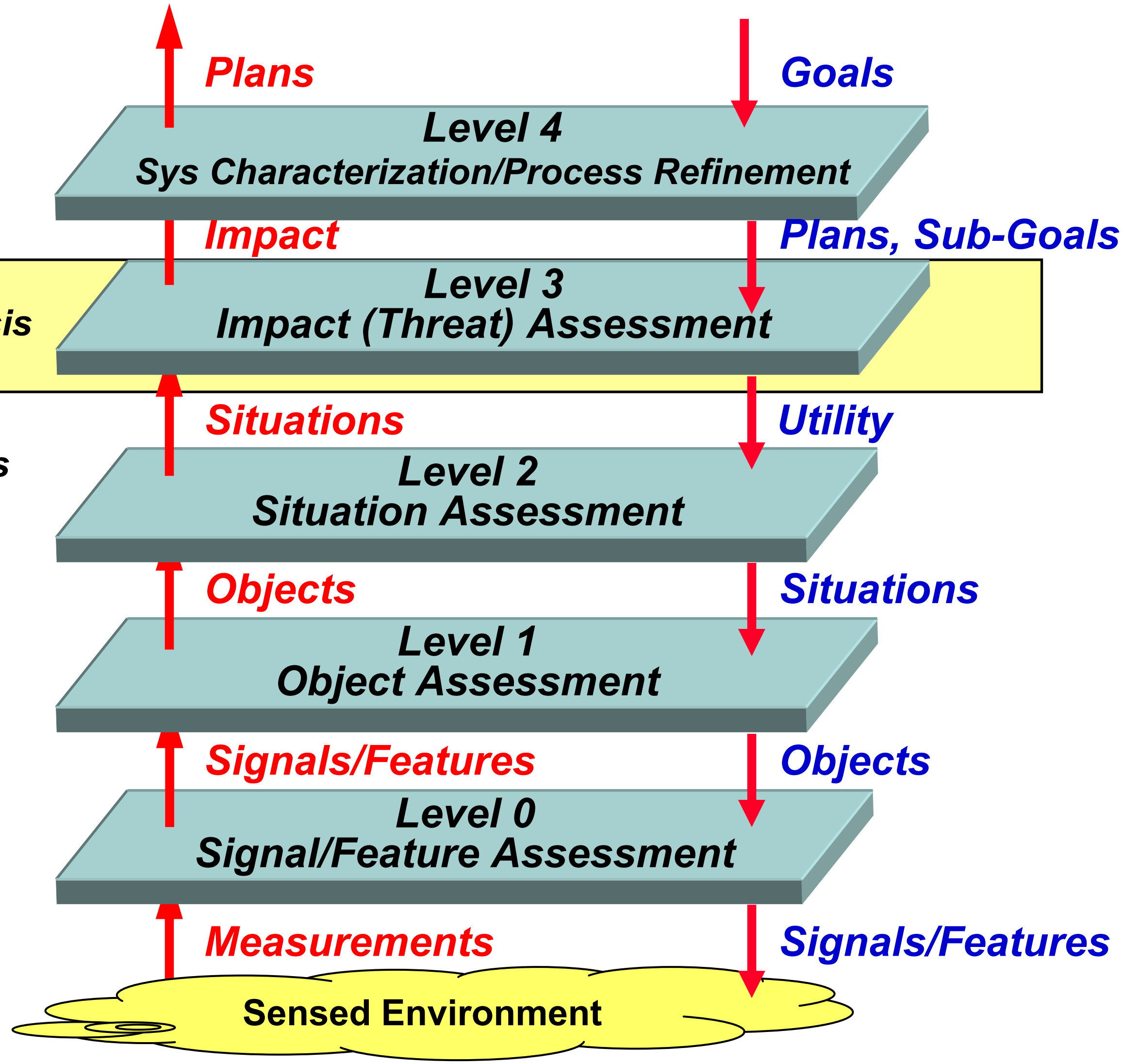
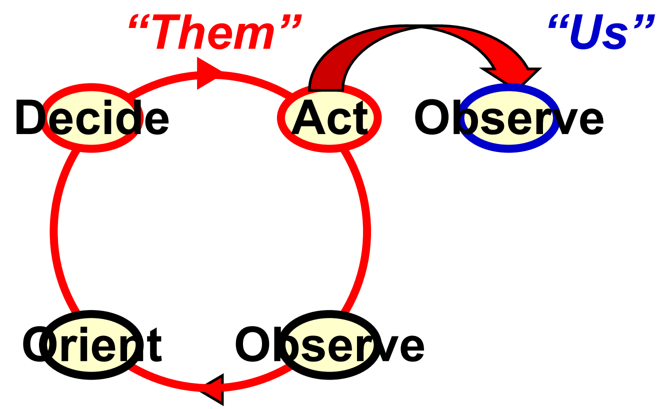


Data Fusion Functions in Threat Assessment

Pre-Attack	• **Threat prediction: Determining likely threats:** who, what, where, when, why, how
Imminent Attack	• **Indications & warning:** Recognition that attack is imminent or underway
Attack Under-way	• **Threat entity detection & characterization:** identification, attributes, composition, location/track, activity capability, intent • **Attack assessment:** – Responsible country/ organization – Intended target(s) – Intended effect (e.g. damage, mass murder, weaken will, economic disruption) – Threat capability (e.g. weapon characterization) – Raid size, coordination & tactics
Post-Attack	• **Consequence assessment**

Impact Assessment (JDL Level 3)

Estimation & prediction of effects on situations of planned or estimated/ predicted actions by the participants

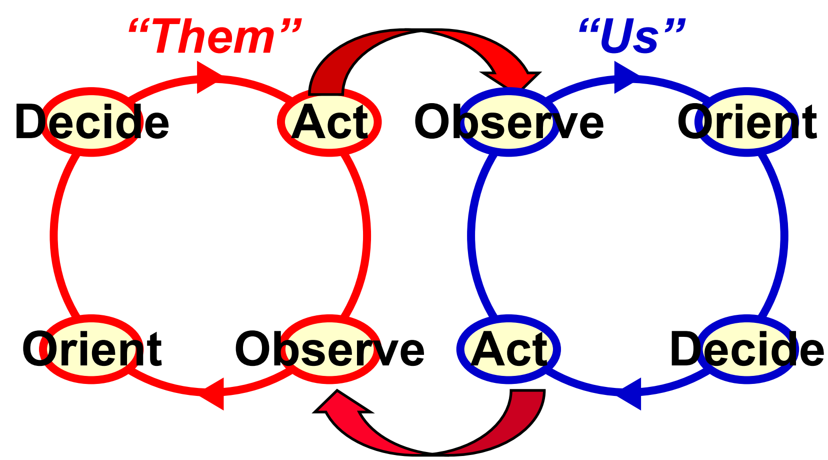


Estimate/predict threat knowledge, perception and planning

Including interactions between action plans of multiple players:

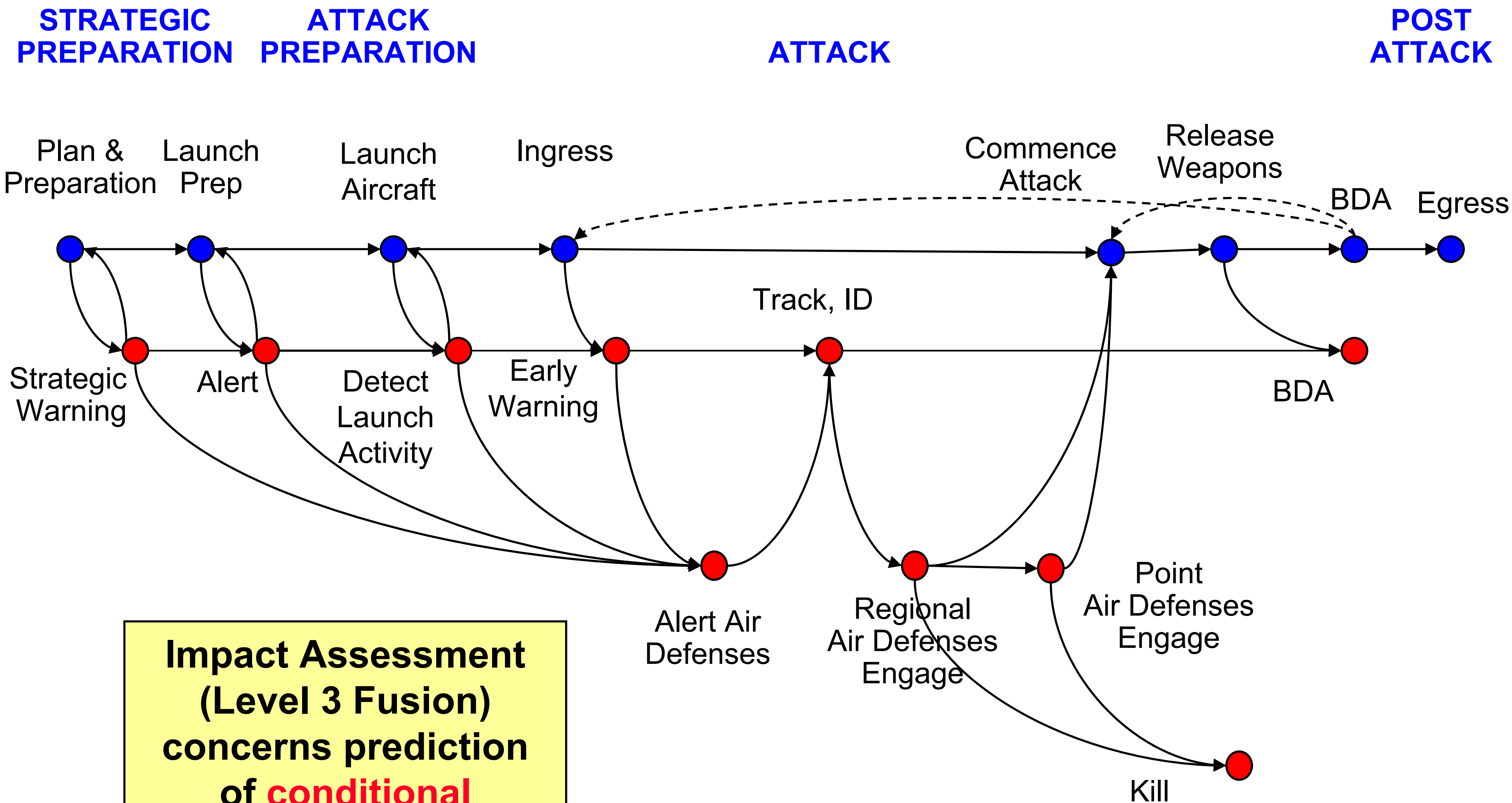
> Assessing susceptibilities & vulnerabilities to estimated/ predicted threat actions given one's own planned actions

> Effect on own forces and assets of Intended course of action



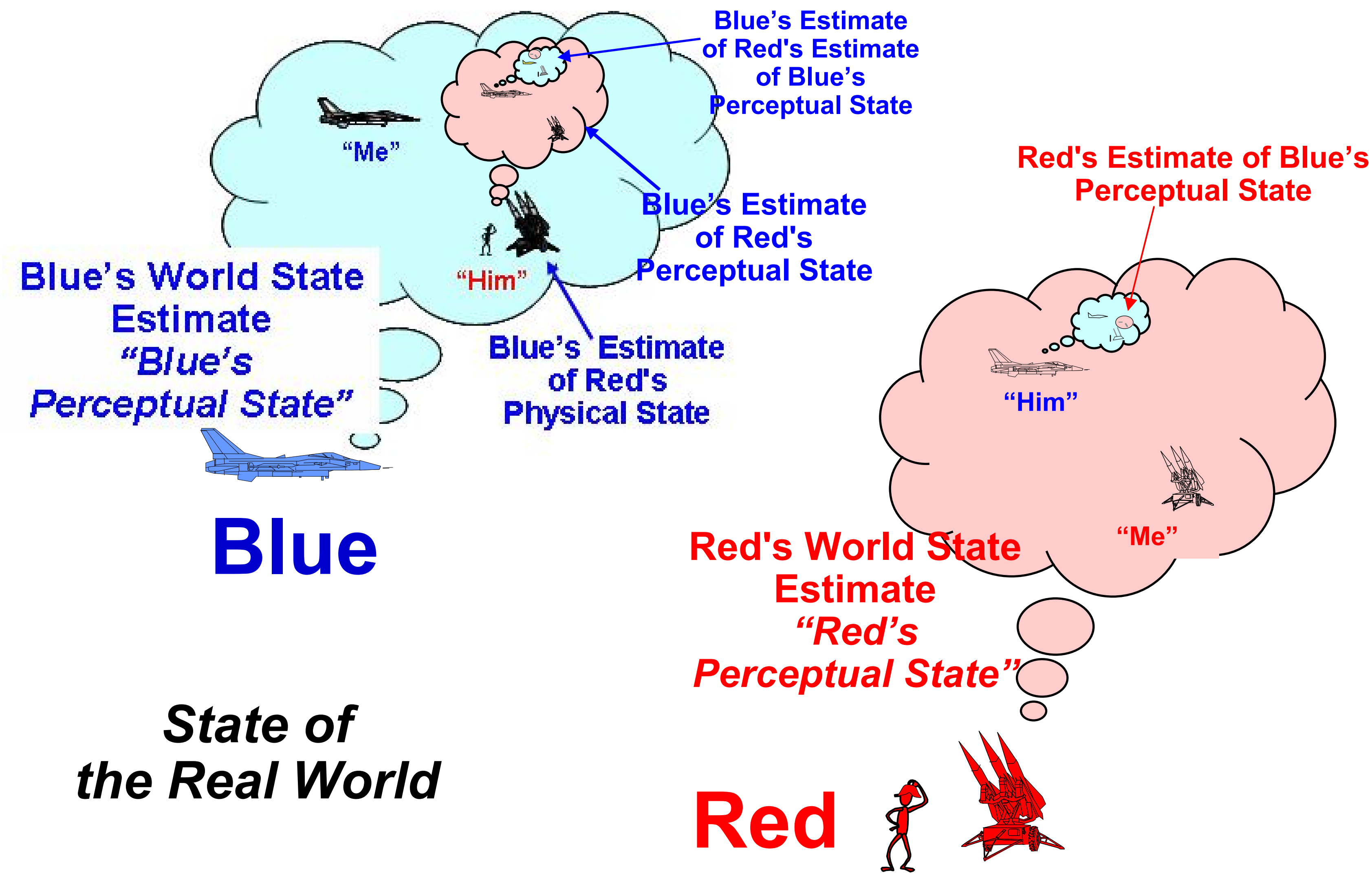
Estimate/predict effects of our planned actions on threat behavior

Example: Air Strike Scenario



Impact Assessment (Level 3 Fusion) concerns prediction of conditional situations and costs

Operational Net Assessment (ONA):
Reasoning from Multiple Perspectives



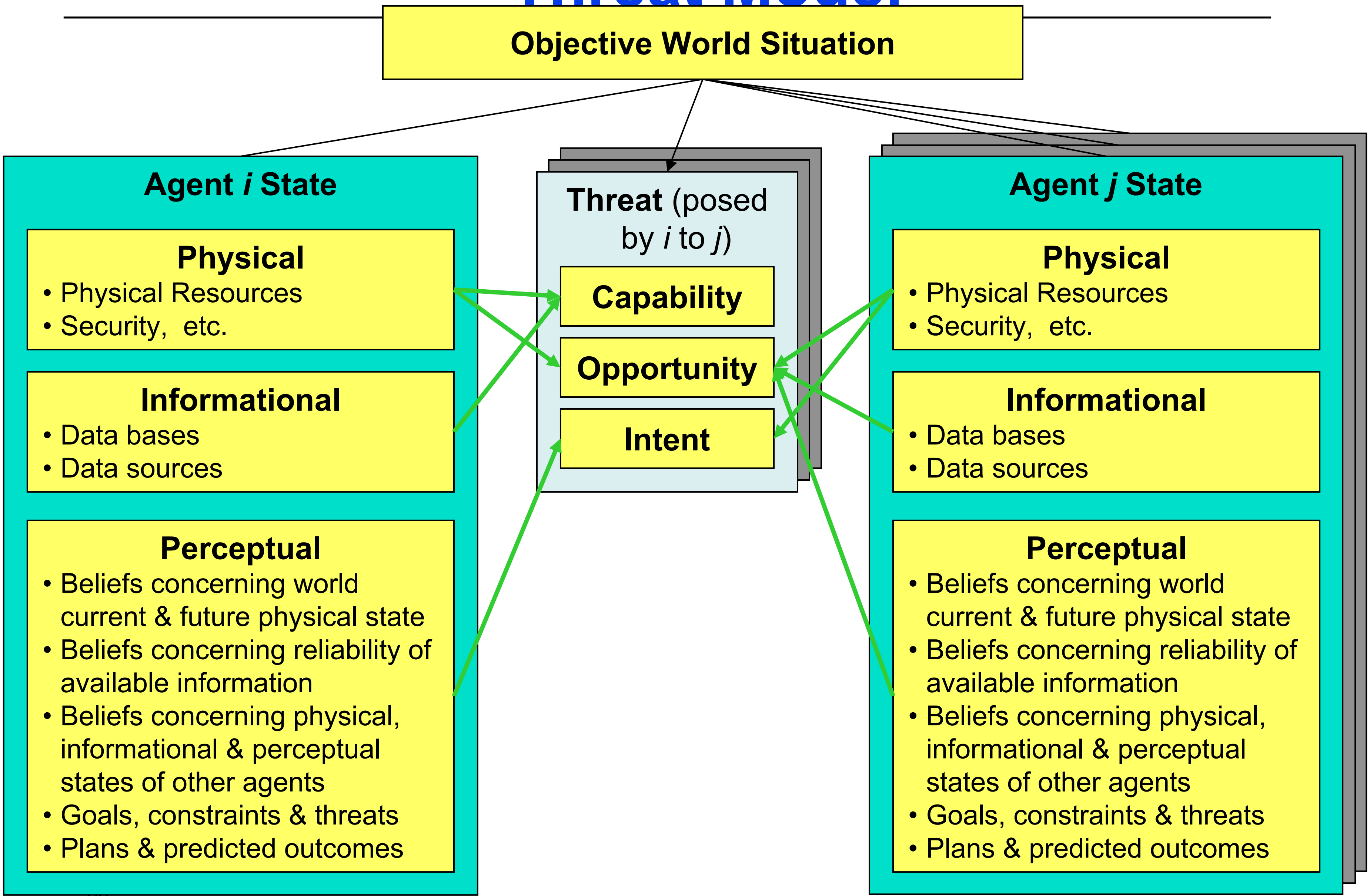
Elements of State Estimation

Table A

Object Aspect	Attributive State		Relational State	
	Discrete	Continuous	Discrete	Continuous
Physical	• Type, ID • Activity State	• Location/ Kinematics • Waveform Parameters	• Causal Relation Type • Role Allocation	• Spatio/ Temporal Relationships
Informational	• Available Data Types • Available Data Records and Quantities	• Available Data Values • Accuracies • Uncertainties	• Informational Relation Type • Info Source/ Recipient Role Allocation	• Source Data - Quality - Quantity - Timeliness • Output QQT
Perceptual	• Perceptions* • Goals • Priorities	• Perceptions* • Cost Assignments • Confidence • Plans/Schedule	• Perceptions* • Influence Relation Type • Influence Source/ Recipient Role	• Perceptions* • Source Confidence

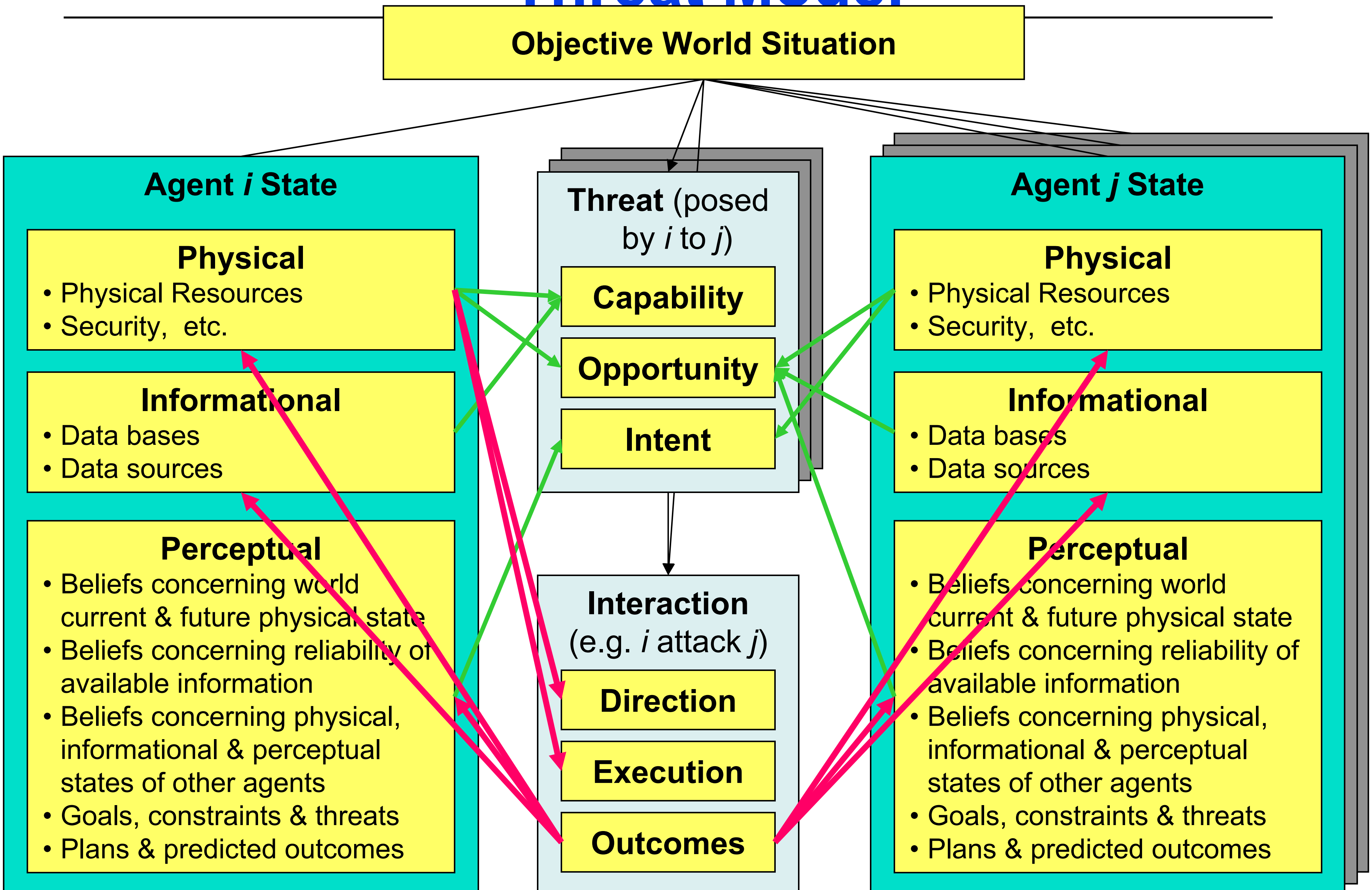
* Perceptions structured per Table A

Generic Intentional Threat Model

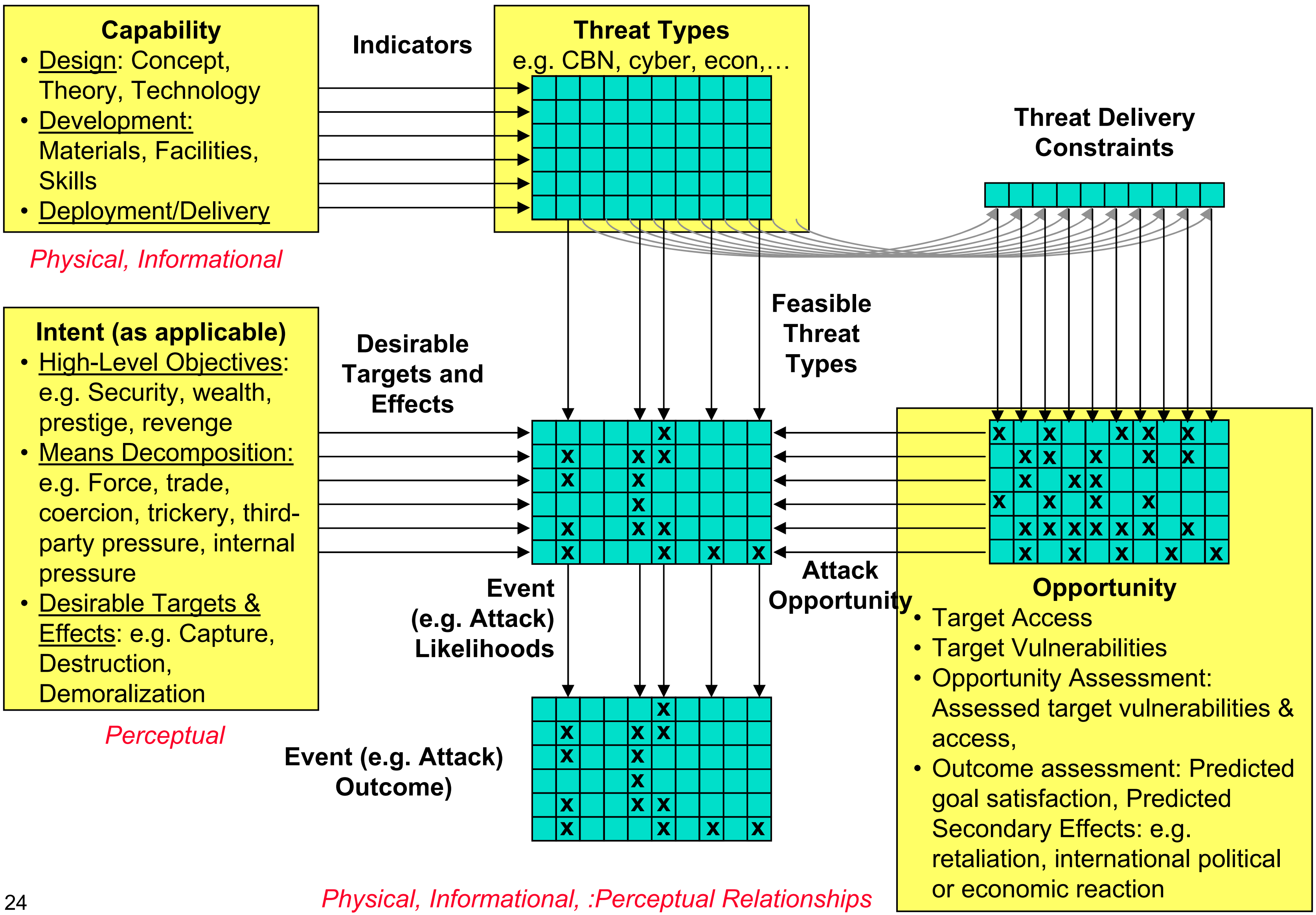


Expanded from G. Rogova and E. Little, *"Ontology for Threat Assessment" (2004)*

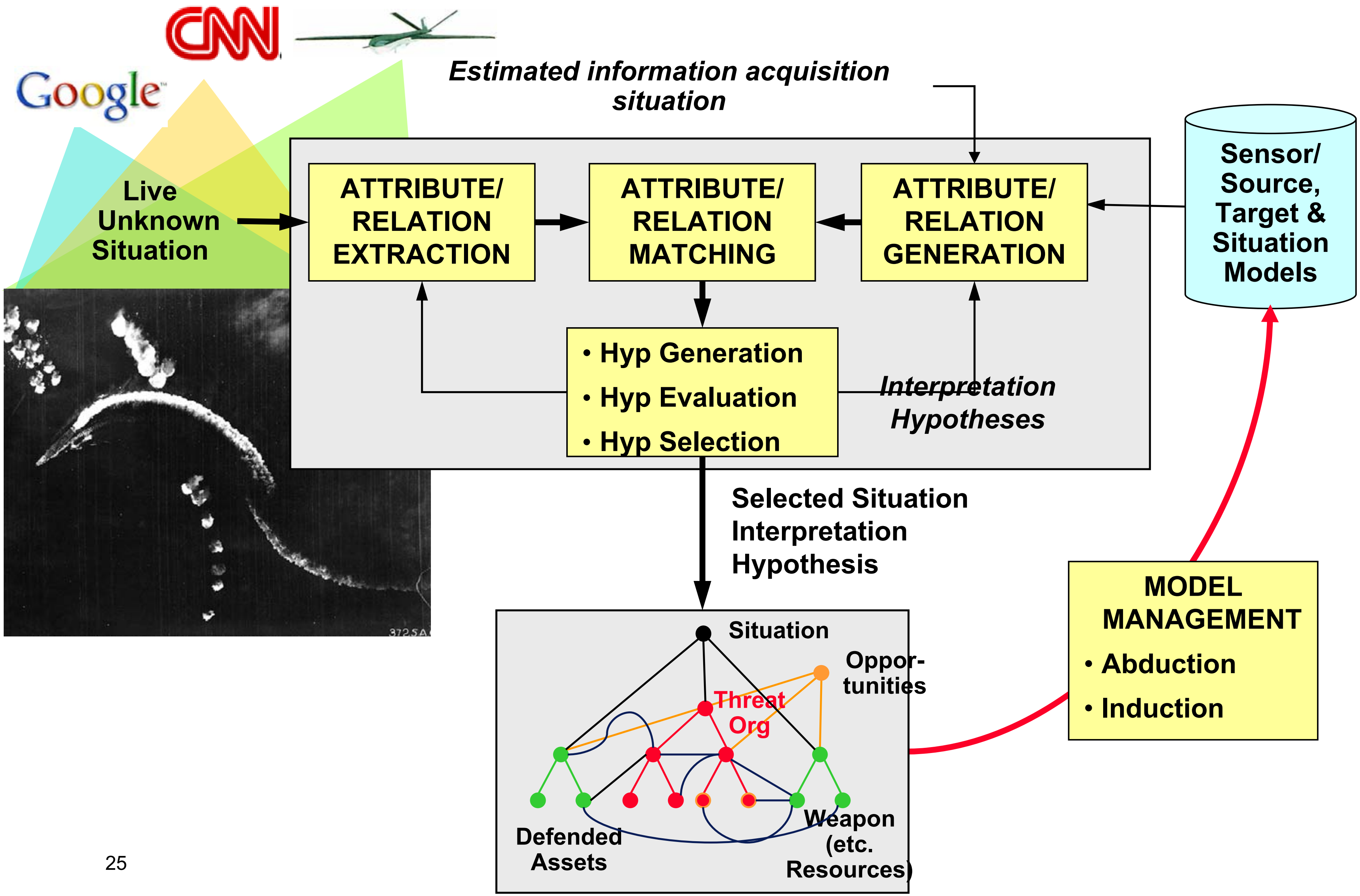
Generic Intentional Threat Model



Model of Potential Threat
(Potential for Intentional Actions)



Model-Based Evidential Accrual for Situation/Threat Assessment



Situation Assessment Technical Issues (1 of 2)

- Data Alignment
  - Exploiting heterogeneous information types (text, signals, numeric data, etc.)
  - Normalizing confidence: source characterization, data evaluation
- Hypothesis Generation
  - Determining relevant data (data batching)
  - Generating/selecting candidate scenario hypotheses (abduction)
  - Representing
    - Relationships (discrete & continuous)
    - Situations
    - “Threats”/”Impacts”
    - Situation dynamics
    - Capabilities, opportunities, intents, perceptions (etc.)
- Hypothesis Evaluation
  - Managing uncertainties in data association

Situation Assessment Technical Issues (2 of 2)

- **Hypothesis Selection**
  - Efficient schemes for representing and searching hypotheses (Managing hypothesis topologies)
  - Pruning schemes
- **State Estimation/Prediction**
  - Representation (Ontology)
  - Combining heterogeneous data and uncertainties
  - Belief propagation
    - In unconstrained graphs
    - With continuous attribute & relational variables

How achieve formal rigor to ensure consistency & predictable performance

Without high-confidence prior models?

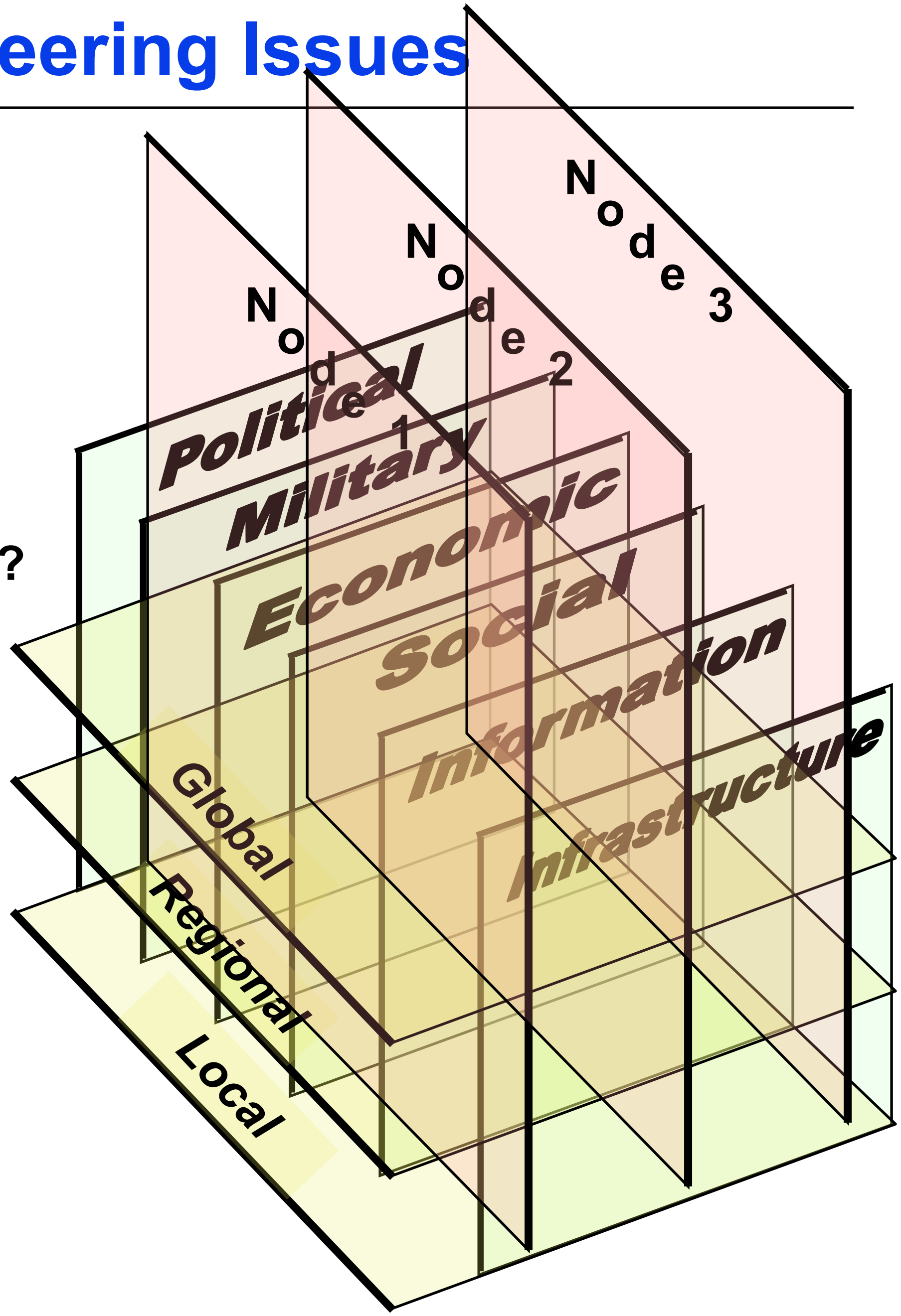
Ontology Requirements

- Criteria for recognizing relationships
  - Including logical, semantic, causal and conventional (e.g. moral, legal, cultural) expectations
  - Requires a validated, comprehensive ontology
  - Must capture uncertainties in dependencies (e.g. in terms of fuzzy membership)
- Criteria for recognizing situations
  - Some formal method of situation semantics and situation logic
- Criteria for contextually conditioned estimation of target states and relationships
  - Requires some form of inferential calculus, in which uncertainties
    - » In the ontology
    - » in sensor reports
    - » in the inference process

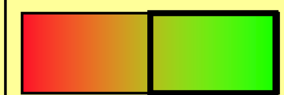
    are systematically represented and manipulated

Situation Assessment Engineering Issues

- **Architecture Partitioning**
  - By domain?
  - By resolution level?
  - Distributed processing?
  - Human/machine task allocation?
    - > Human vs. automated tasks & interfaces
    - > Information presentation
- **Model Management: Situations, Threats, Sources, System behavior & performance**
  - Ontology management
  - Empirical model refinement abduction, induction



Problem of Source Characterization

Cases of Biased Information or Biased Response	Examples	Trust-worthiness
Fully cooperative autonomous agents (unintentional reporting & response errors)	**Integrated, fully controlled system-of-systems**	
Semi-cooperative agents (possibly intentional reporting & response errors)	**Employees, Partners**	
Deceptive hostile agents (likely biased reporting & response)	**Enemy decoys, False-target jamming, Info ops**	
Non-deceptive hostile information sources (only unintentional reporting & response errors)	**Enemy radars, Combatant platforms**	
Non-cooperative third-parties sources (possibly biased reporting & responses)	**Commercial news sources, Websites**	

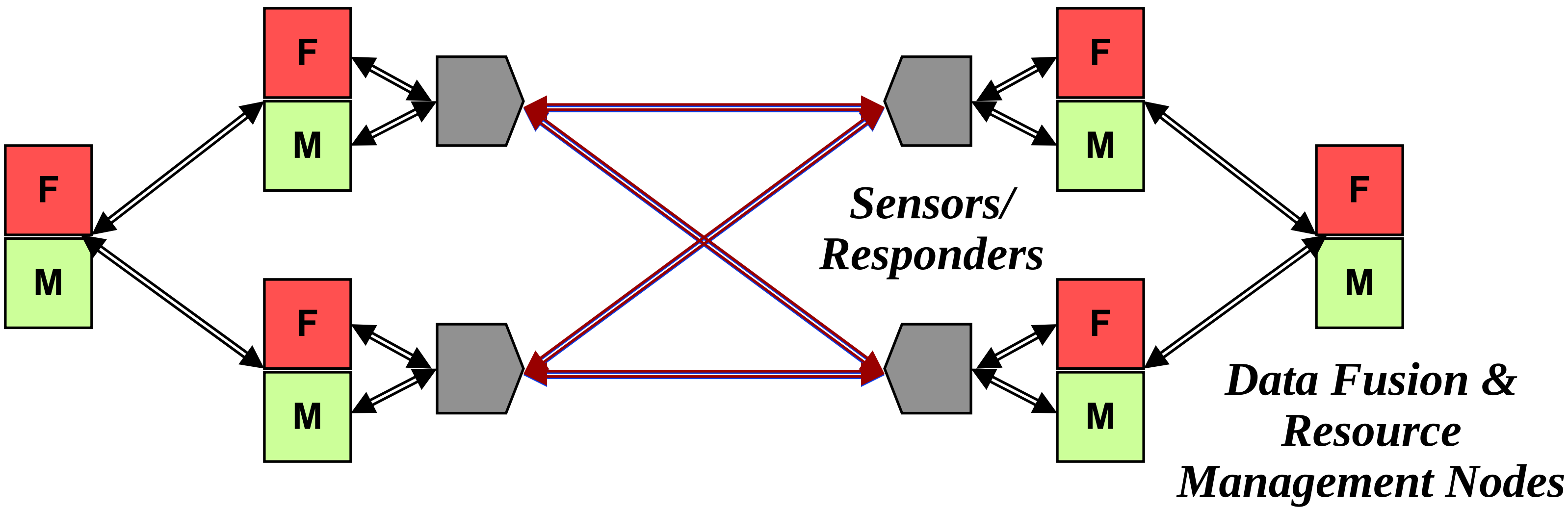
The fusion system must characterize the reliability & performance of EACH source using the ensemble of information

Open Net Concept

- <u>**COOPERATION/COLLABORATION (e.g. in NCW)**</u>
  - **Information Exchange**
  - **Physical Collaboration, Cooperation**
- <u>**COMPETITION/CONFLICT**</u>
  - **Information Interception or Disruption (e.g. Deceptive Information, Jamming)**
  - **Physical Disruption, Damage, Destruction**

"AGENT B"

"AGENT A"



Can't assume clear system boundaries: "us" vs "them": Trustworthiness is a matter of <u>Estimation</u>

Summary

- **Use the structure of situations for inferring prior and posterior statistics, both for "attributive" and "relational" states**
  - Second-order non-monotonic predicate calculus (e.g. probabilistic infon notation)
  - Supports Operational Net Assessment: Multi-Perspective, Conditional, Counterfactual Reasoning
- **Noisy, complex and poorly-modeled problems:**
  - Requires integration of Abductive, Inductive & Deductive methods
  - Requires Ontology of Relationships & Situations, recognizing Fuzziness: ***HUMAN BEHAVIOR IS COMPLEX , BUT IT'S NOT RANDOM***
- **Need sophisticated techniques to characterize info sources**
  - Trustworthiness is a matter of Estimation

Comparison of Level 1 and Level 2/3 Data Fusion Problems

Level 1 Fusion (Object Assessment; e.g. ATR, Target Tracking)	Level 2/3 Fusion (Situation/ Impact Assessment)
Strong constraints on relevant evidence Hypothesis Generation via Validation Gate	**Weak constraints on relevant evidence** Hypothesis Generation via Situation/Behavior Model
Strongly Constrained Ontology	**Weak Ontological Constraints**
Strong (i.e. high-confidence) Causal Models: Typically dominated by Physical Models: e.g. Signature, Kinematics models	**Weak Causal Models:** Typically dominated by Human/Group Behavior Models: e.g. Coordination/ Collaboration, Perception, Value, Influence models

Level 2/3 Problems are more

→ **Diverse**

→ **Complex**

→ **Uncertain**

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