High Level Fusion and Predictive Situational Awareness with Probabilistic Ontologies

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Uncertainty and Timelessness

"…The commander is compelled during the whole campaign to reach decisions on the basis of situations that cannot be predicted … The problem is to grasp, in innumerable special cases, the actual situation which is covered by the mist of uncertainty, to appraise the facts correctly and to guess the unknown elements, to reach a decision quickly and then to carry it out forcefully and relentlessly."

Helmuth von Moltke, 1800-1891

Paret, P.; Craig; A.G.; Gilbert, F. (1986) Makers of Modern Strategy: From Machiavelli to the Nuclear Age. London, UK: Oxford University Press (Page 289)

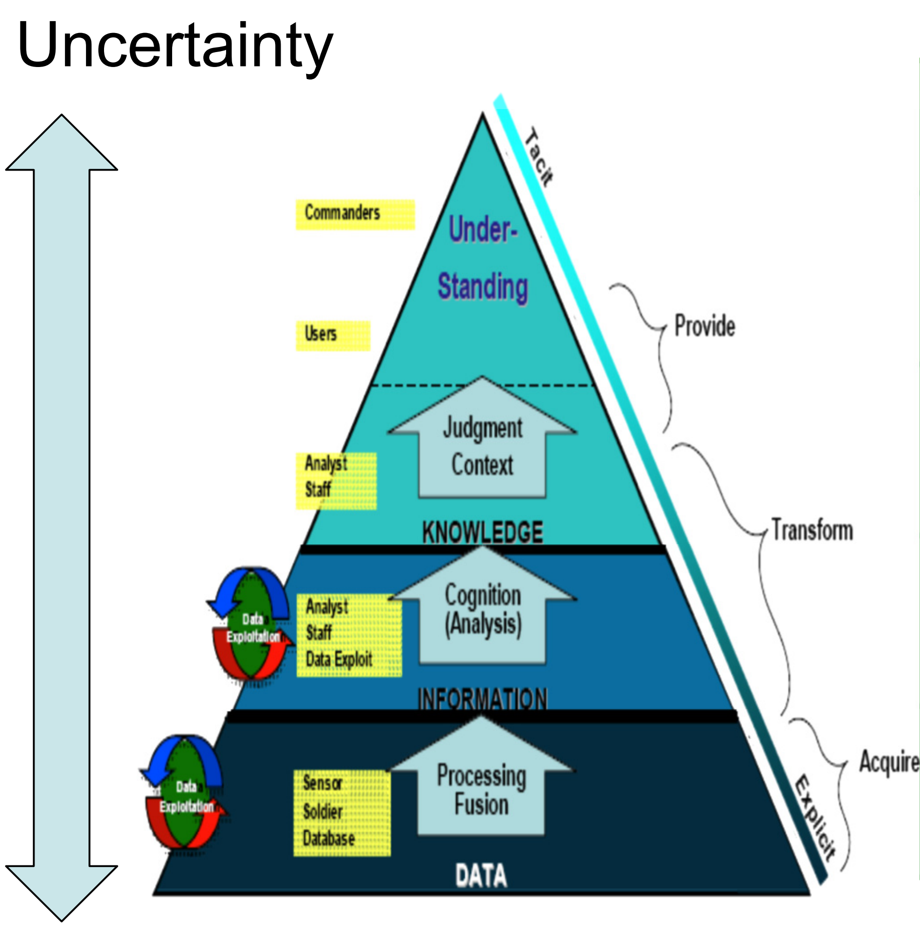
Agenda

- Knowledge Exchange in C^2
- Ontologies
- Probabilistic Ontologies
- Case Study: PROGNOS

What is Preventing True Netcentricity?

- Inability to produce a dynamic, comprehensive, and accurate battlespace picture for the warfighter that integrates tactical data from multiple intelligence sources.
- Lack of automated techniques to integrate data (geolocation, detection, and identification) from multiple intelligence sources, in a consistent and timely manner.
- Lack of accurate and timely information about battlespace objects and events to support warfighter decision making in an asymmetric warfare.

Knowledge and Data Fusion



Data Fusion Level	Association Process	Estimation Process	Product
L3 Impact Assessment	Evaluation (situation to actor's goals)	Game-Theoretic Interaction	Estimated Situation Utility
L2 Situation Assessment	Relationship (entity-to-entity)	Relation	Estimated Situation State
L1 Object Assessment	Assignment (observation-to-entity)	Attributive State	Estimated Entity State
L0 Signal Assessment	Assignment (observation-to-feature)	Detection	Estimated Signal State

Cognitive Hierarchy

JDL Data fusion levels

FM 6-0: Mission Command: Command and Control of Army Forces. Aug 2003.

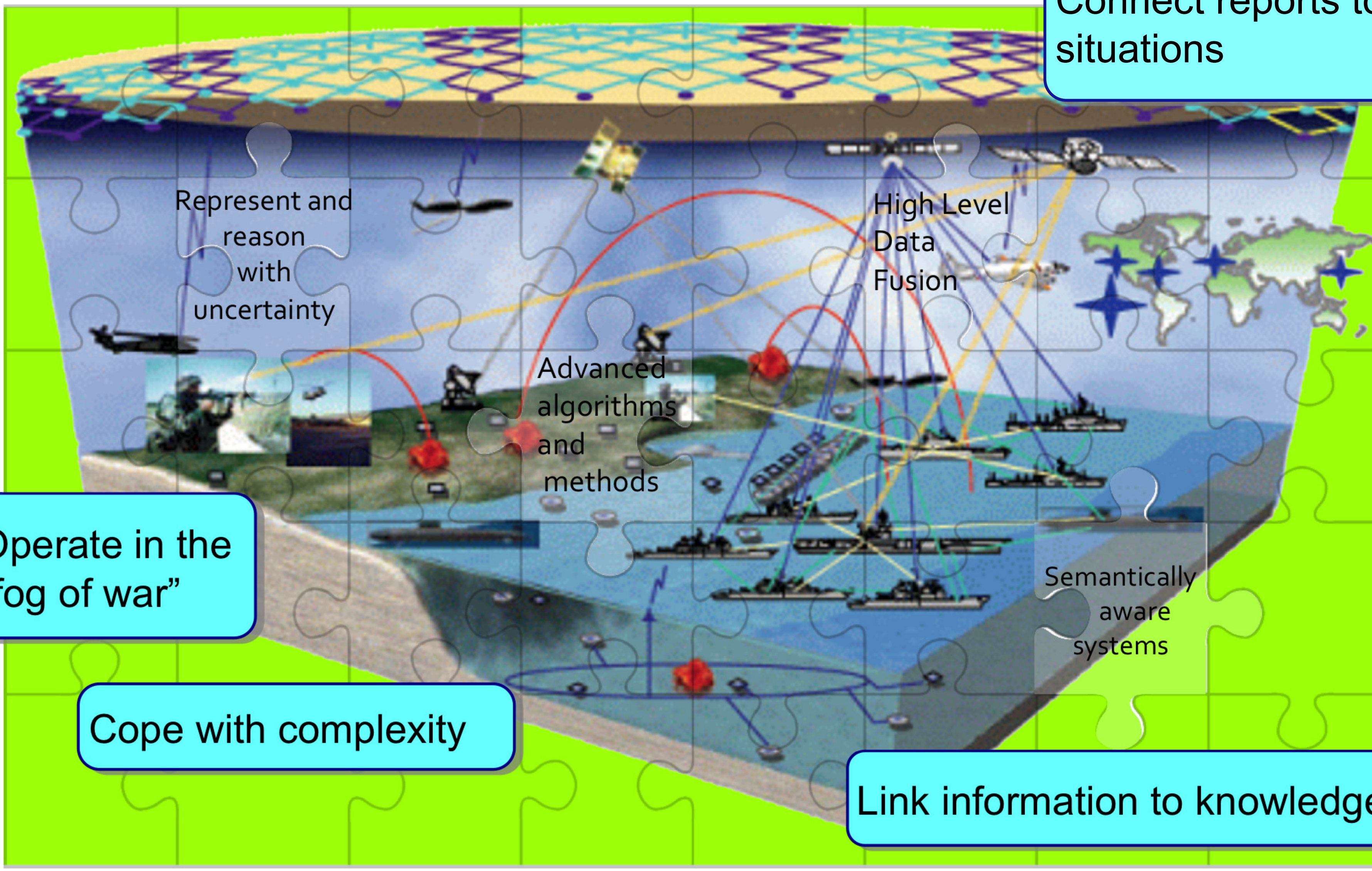
White, F.E., "A Model for Data Fusion", Proc. 1st National Symposium on Sensor Fusion, 1988

Shortfalls of Current Approaches

- Either cannot achieve fusion levels 2 and above (JDL model), or can do so only in controlled environments (limited scalability and expressivity).
- Limited ability to cope with uncertainty, typically ignoring or mishandling it.
- Can handle only standardized messages, special -case scenarios, and specific sensor types, leading to interoperability issues and less than optimal use of available information.

The Missing Pieces

Connect reports to situations



Operate in the "fog of war"

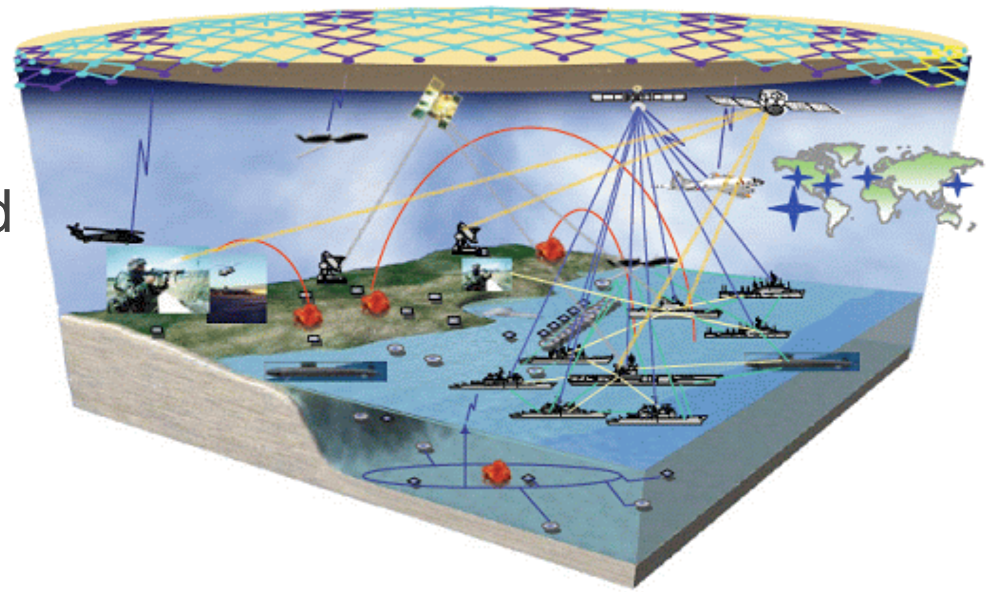
Cope with complexity

Link information to knowledge

The Way Forward

- Rigorous mathematical foundation and efficient algorithms to combine data from diverse sources for reliable predictive situation assessment
- Automated techniques to reduce warfighter's information processing load and provide timely actionable knowledge to decision makers
- Interoperable methodologies for propagating uncertainty through the integration process to characterize and distinguish situational conditions for predictive analysis and impact assessment under various behaviors and environments
- Semantically aware systems for interoperability in net-centric environment

C4I Center's Multi-Disciplinary Approach



- Developing interoperable enabling technologies based on Multi-entity Bayesian Networks, Probabilistic Ontologies, and pragmatic frames to support Net Centric operations
- Developing mathematically rigorous and computationally efficient algorithms based on Spatio-Temporal Hypothesis Management and Efficient Hybrid Inference to provide dependable predictive situational awareness Developing formal approaches and tools to represent command intent and to reduce ambiguity in operational communications.

Interoperation vs. Integration

Interoperation of systems	Integration of systems
• participants remain autonomous and independent • loosely coupled • interaction rules are soft coded and encapsulated • local data vocabularies and ontologies for interpretation persist • share information via mediation • asynchronous data transfer	• participants are assimilated into whole, losing autonomy and independence • tightly coupled • interaction rules are hard coded and co-dependent • global data vocabulary and ontology for interpretation adopted • share information conforming to strict standards • synchronous data transfer

reusability
composability
flexibility

Vs.

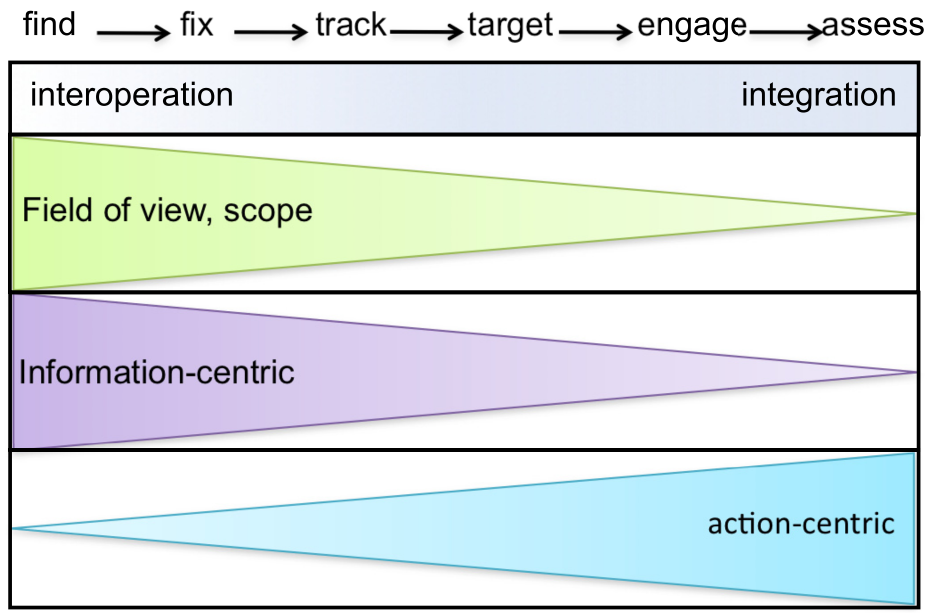
fit-to-purpose
responsiveness

NOT Polar Opposites!

SPECTRUM of INTERACTION MODES

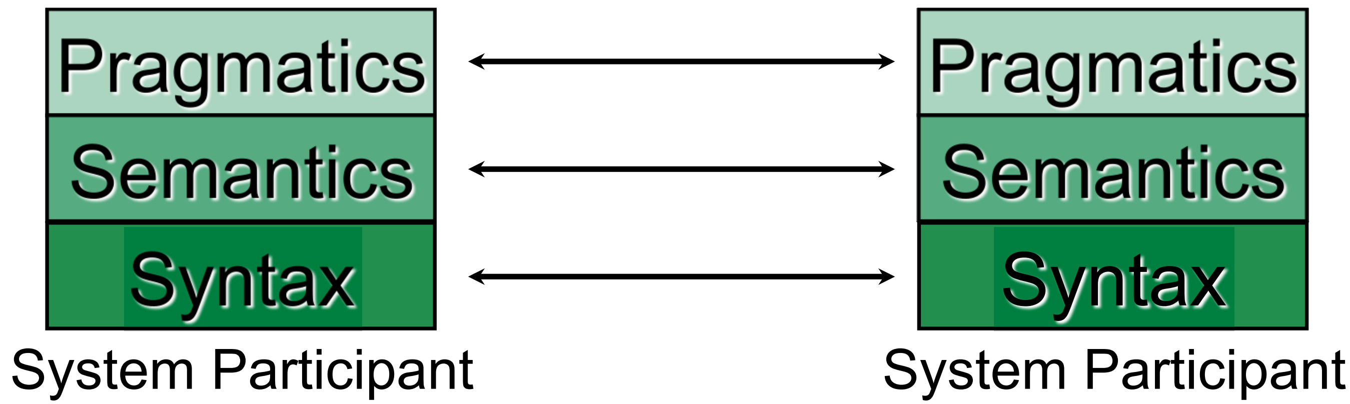
* adapted from: J.T. Pollock, R. Hodgson, "Adaptive Information", Wiley-Interscience, 2004

Example: Kill chain



- The kill chain illustrates the co-existence of interoperation and integration modes of component interaction.
- Early activities in the chain are characterized by larger field of view and have more information-centric functions than do later activities. They need the loose coupling and flexibility of interoperation.
- Later activities are more action-centric requiring the tight coupling and responsiveness of integrated components.

Linguistic Levels of Information Exchange and Interoperability



Linguistic Level of Information Exchange	A System of Systems interoperates at this level if :
Pragmatic – how information in messages is used	The receiver re-acts to the message in a manner that the sender intends (assuming non-hostility in the collaboration).
Semantic – shared understanding of meaning of messages	The receiver assigns the same meaning as the sender did to the message.
Syntactic –common rules governing composition and transmitting of messages	The consumer is able to receive and parse the sender's message

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Ontologies

- In Philosophy: the study of nature of being and knowing
- In Information Systems: many definitions

An Explicit formal specification on how to represent the objects, concepts, and other entities that are assumed to exist in some area of interest an the relationships among them. (dictionary.com)

In information science, an ontology is the product of an attempt to formulate an exhaustive and rigorous conceptual schema about a domain. An ontology is typically a hierarchical data structure containing all the relevant entities and their relationships and rules within that domain (Wikipedia.org).

an ontology is a set of concepts - such as things, events, and relations - that are specified in some way (such as specific natural language) in order to create an agreed-upon vocabulary for exchanging information. (whatis.com)

Is a formal specification of a conceptualization (Gruber)

An ontology models the vocabulary and meaning of domains of interest: the objects (things) in domains; the relationships among those things; the properties, functions, and processes involving those things; and constraints on and rules about those things (DaConta et al., 2003)

An Ontology formally defines a common set of terms that are used to describe and represent a domain. Ontologies can be used by automated tools to power advanced services such as more accurate Web search, intelligent software agents and knowledge management. (Owl Use Cases)

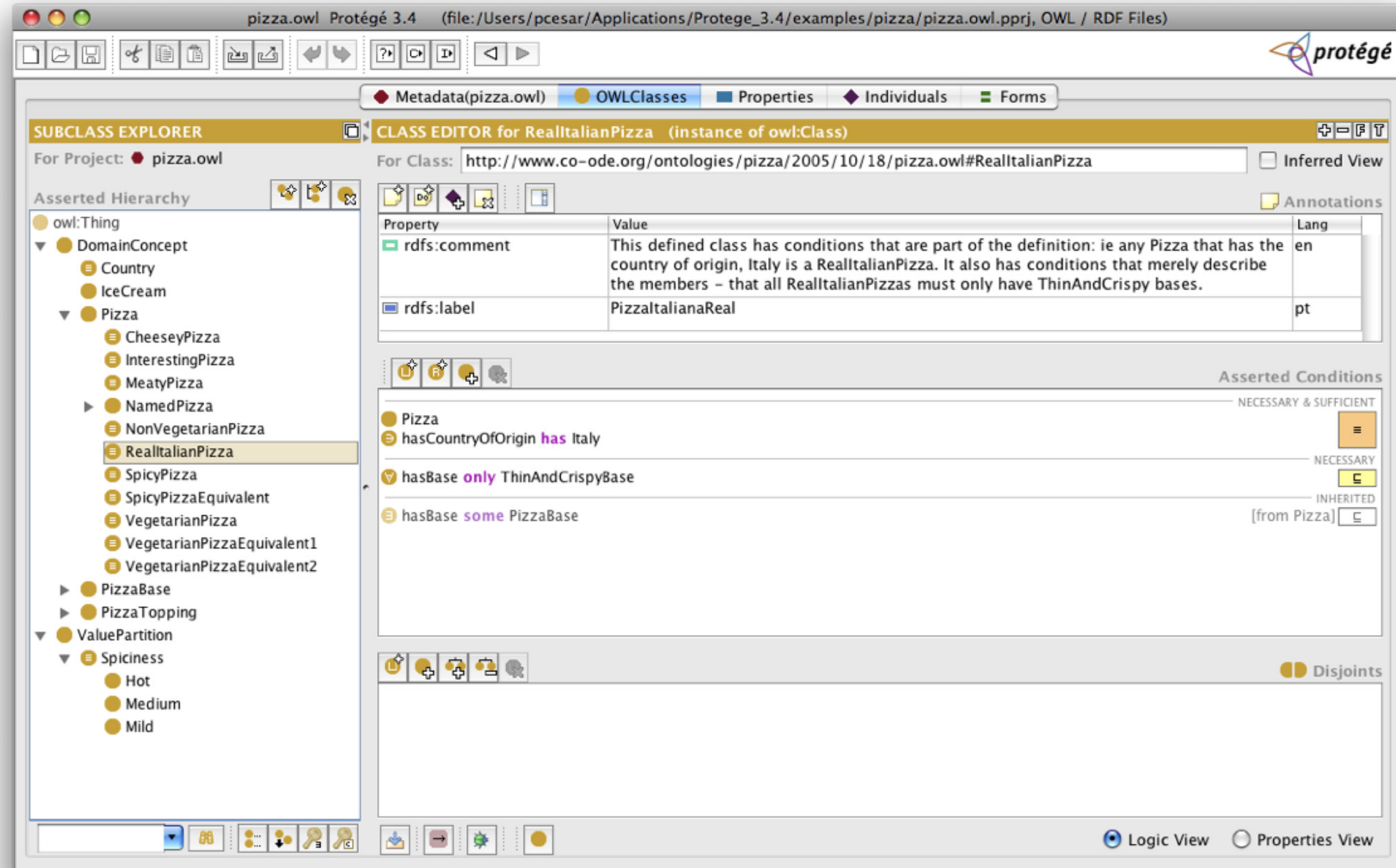
A partial specification of a conceptual vocabulary to be used for formulating knowledge-level theories about a domain of discourse. The fundamental role of an ontology is to support knowledge sharing and reuse. (The Internet Reasoning Services project - IRS)

What is really important?

Semantics in Data Fusion

- Information in the battlefield comes from reports from diverse sources, in distinct syntax, and with different meanings.
- Effective interoperability requires understanding the relationship between reports from different systems and the events reported upon
- Semantically aware systems are essential to distributed knowledge fusion.
- Ontologies are a means to semantic awareness

Asserted vs. Inferred



Ontologies vs. OO

Ontologies

- Rely on logical reasoners to infer class relationships and instance membership
- Flexible format that adapts its class structure as new information is learned
- Open World Assumption / Well suited for open systems

Databases / OO

- Rigidly defined classes that govern the system behavior
- All instances are created as members of some class.
- Changing a class affects all of its instances
- Closed World Assumption / Well suited for top down governance

Ontologies and Uncertainty

- There are many kinds of uncertainty, e.g.:
  - Noise in sensors
  - Incorrect, incomplete, deceptive human intelligence
  - Lack of understanding of cause and effect mechanisms in the world
- Representing and reasoning with uncertainty is essential
- But...

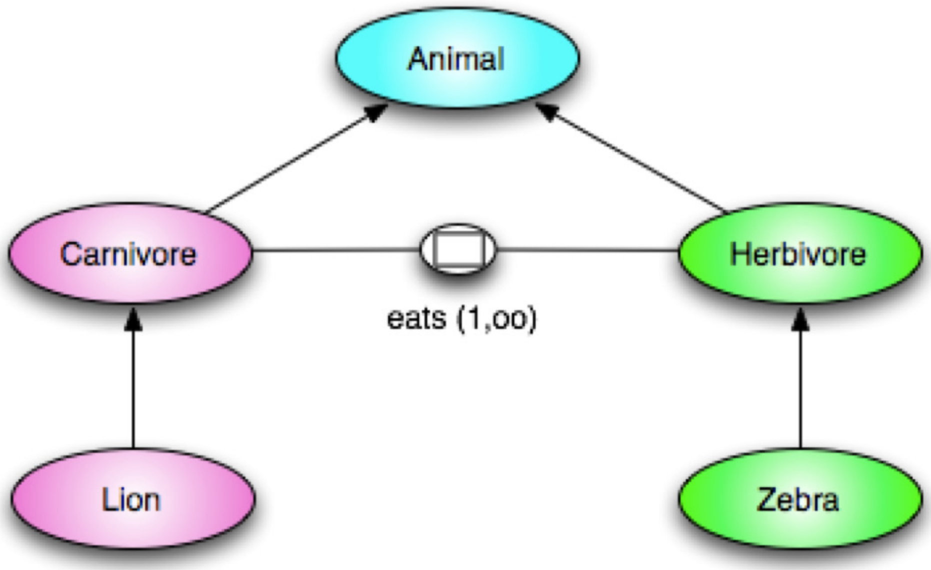
Traditional ontological Engineering methods provide no support for representing and reasoning with uncertainty in a principled way

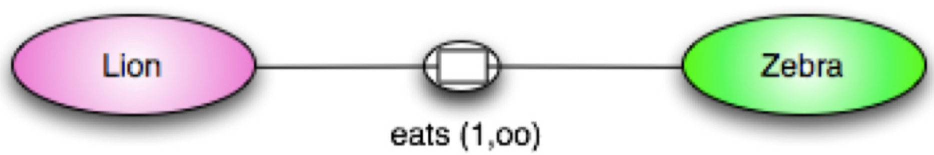
Deterministic Reasoning

Concepts
animal, carnivore, herbivore

Relationships
carnivore **is-a** animal
herbivore **is-a** animal
carnivore **eats** herbivore
lion **is-a** carnivore
zebra **is-a** herbivore

Reasoning
lion eats zebra





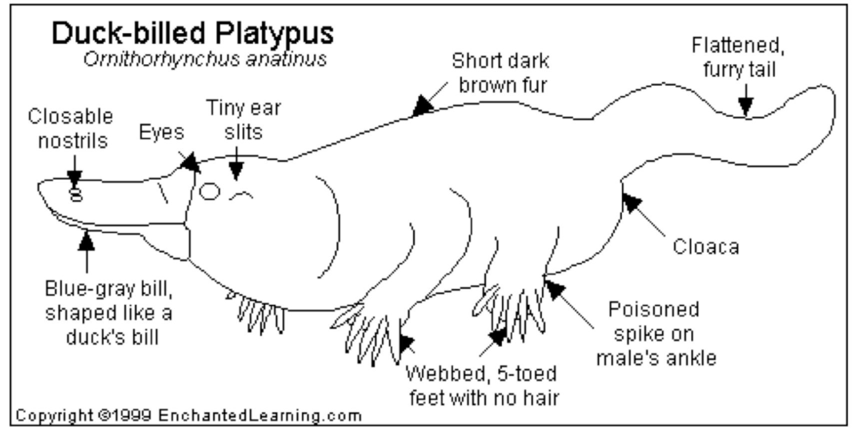
Deterministic Reasoning

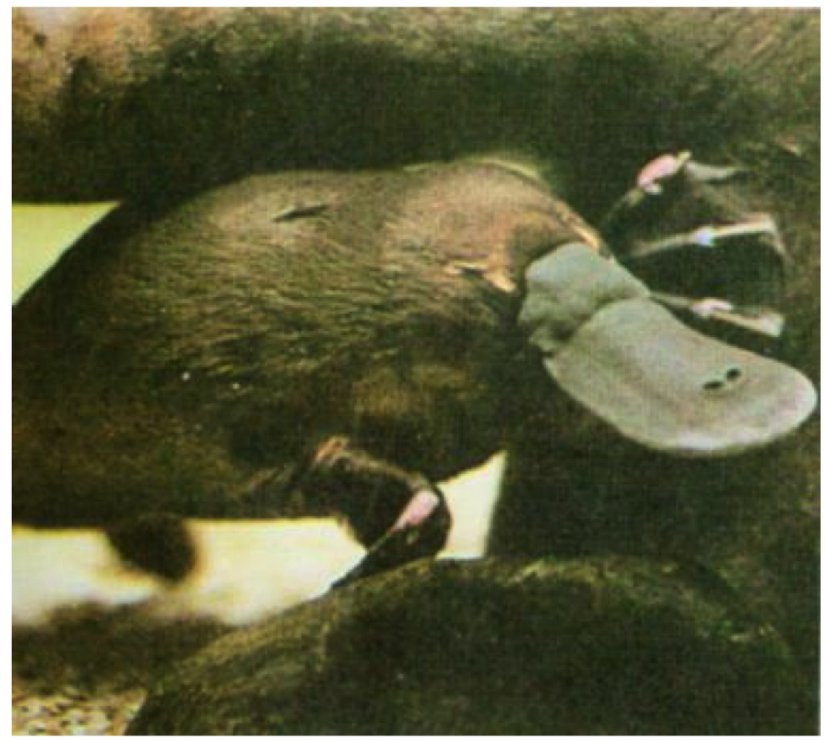
(... is not always suitable to the problem)

- All Birds lay eggs
- Many aquatic birds have Duck-like bills
- Many aquatic birds have webbed feet (like ducks)
- All aquatic birds swim very well and can hold breath for a long period
- Joe:
  - Is an egg-laying animal
  - Has a Duck-like bill
  - Has webbed feet
  - Swin very well and can hold breath for a long period
- Therefore: Joe is a…

Joe is a Duck-Billed Platypus (a mammal)

- It lays eggs like a bird or a reptile (this makes it a monotreme mammal)
- The males have poison like a snake in spurs on their hind legs. The poison can kill a dog and cause extreme pain in people.
- They have a bill like a duck.
- They have a tail like a beaver.
- They have webbed feet like a duck.
- The mother's milk comes out through glands on her skin and the babies lick it off of her fur.





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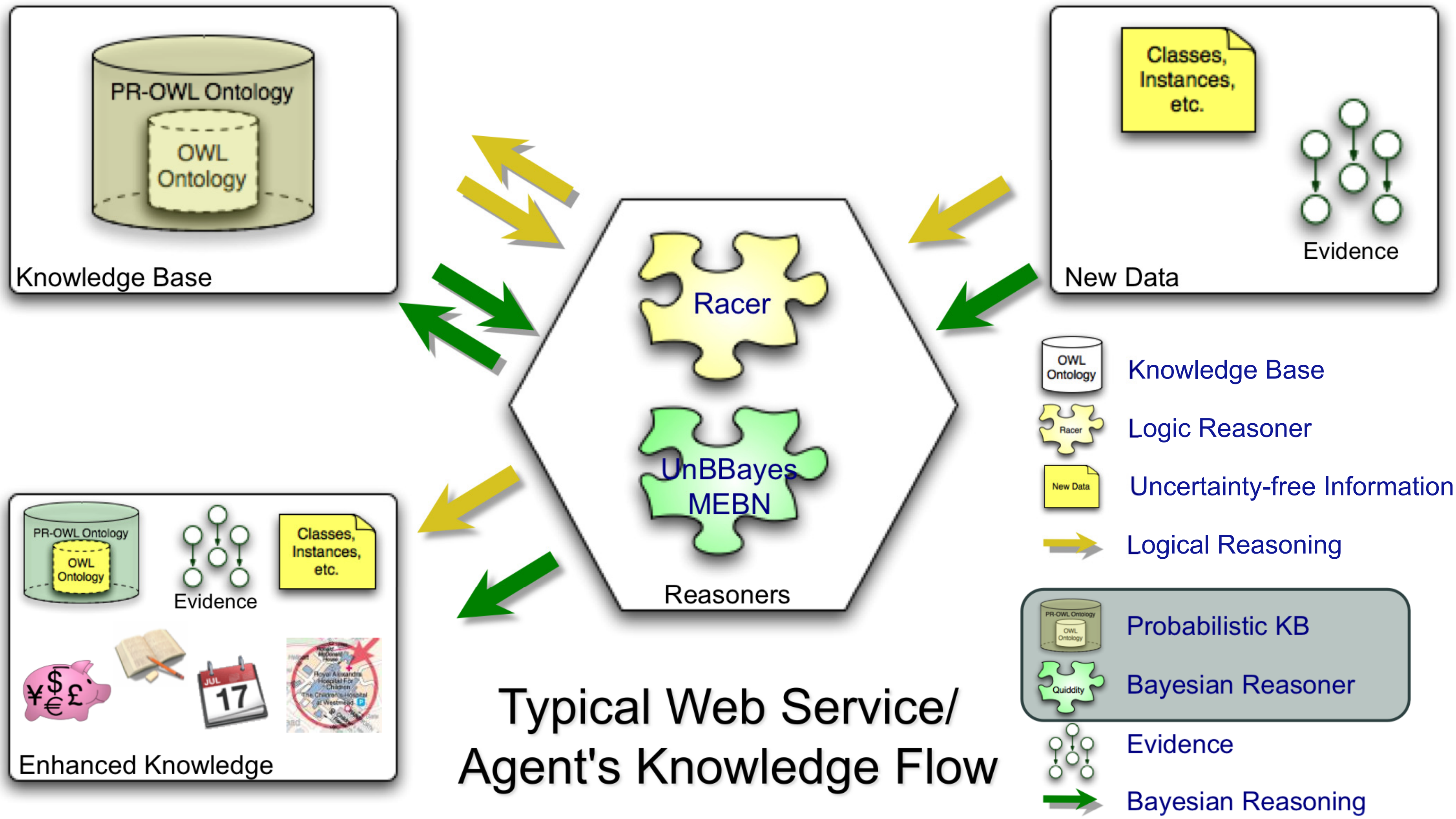
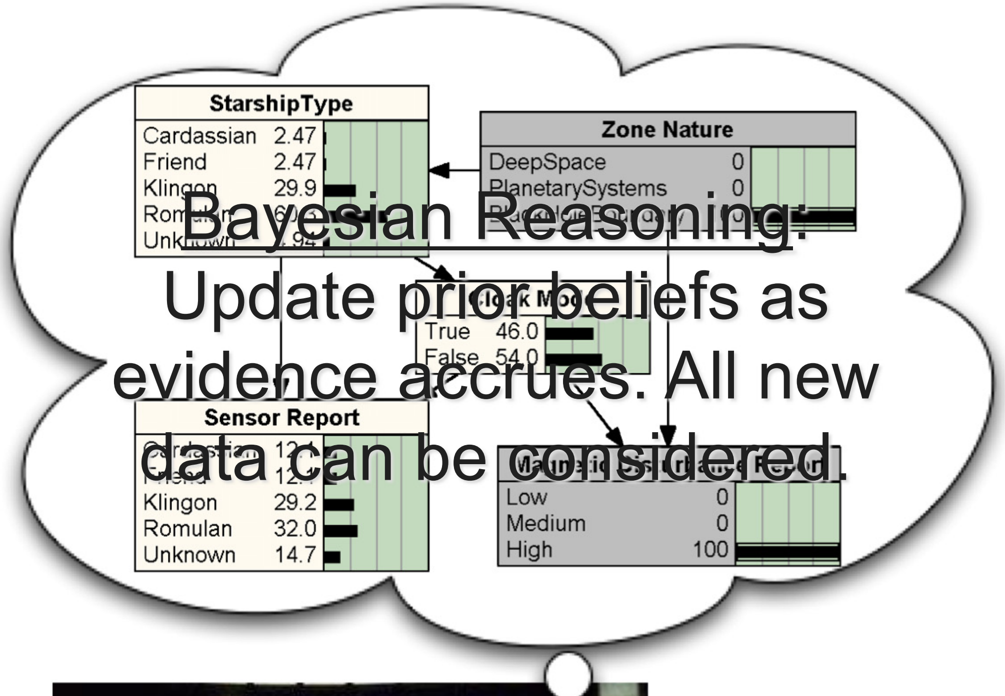
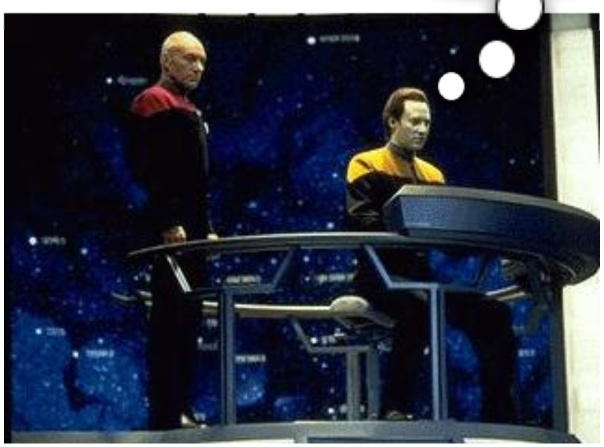
A Pragmatical View

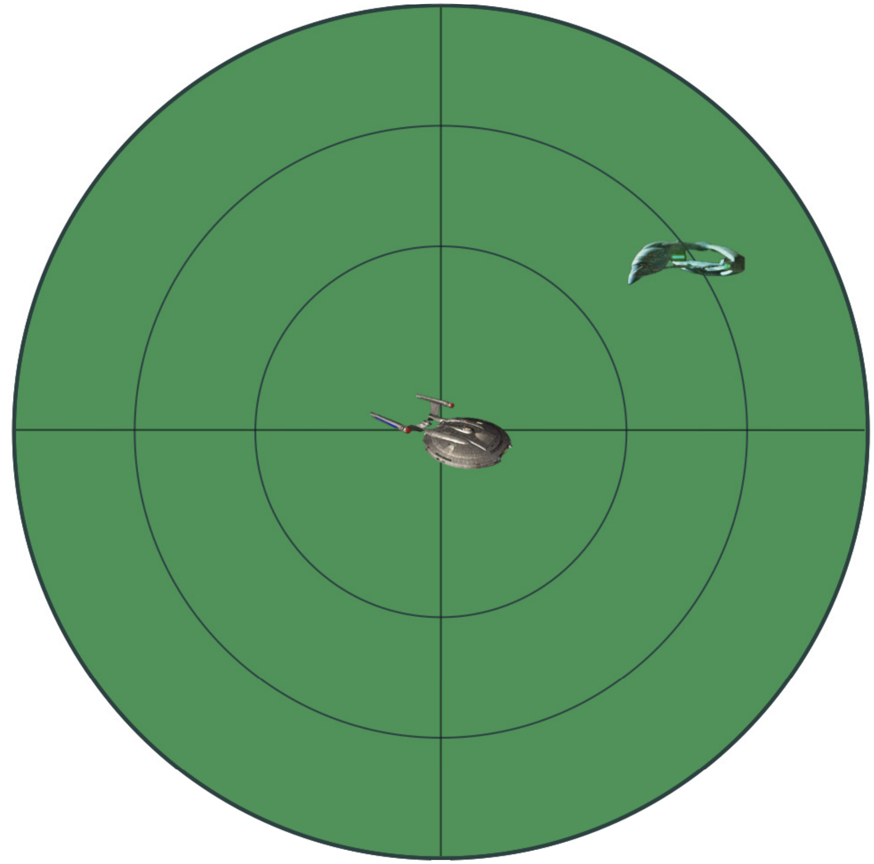


How about Bayesian Networks?



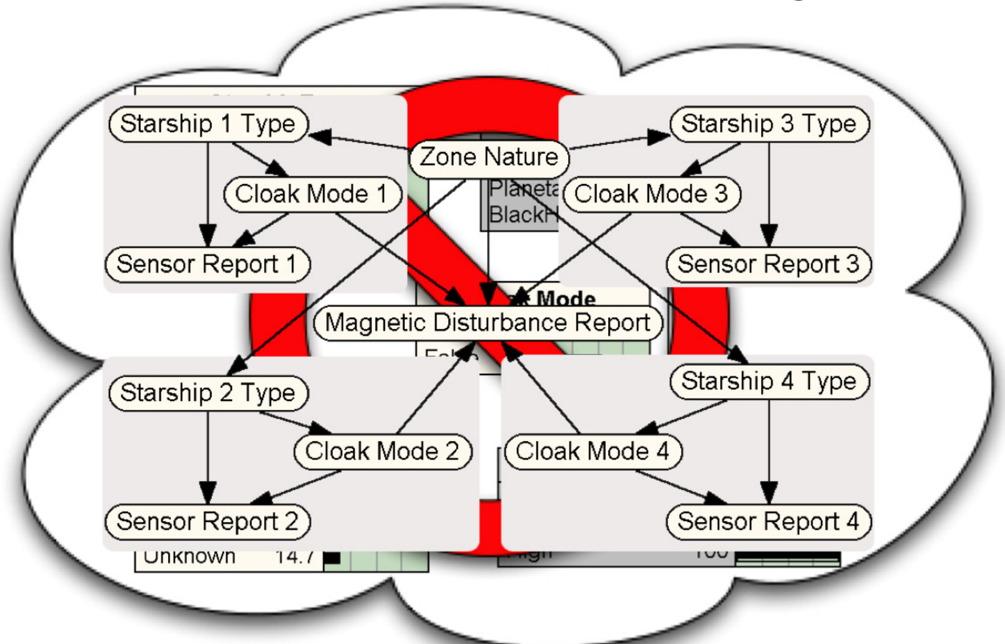
Bayesian Reasoning: Update prior beliefs as evidence accrues. All new data can be considered.

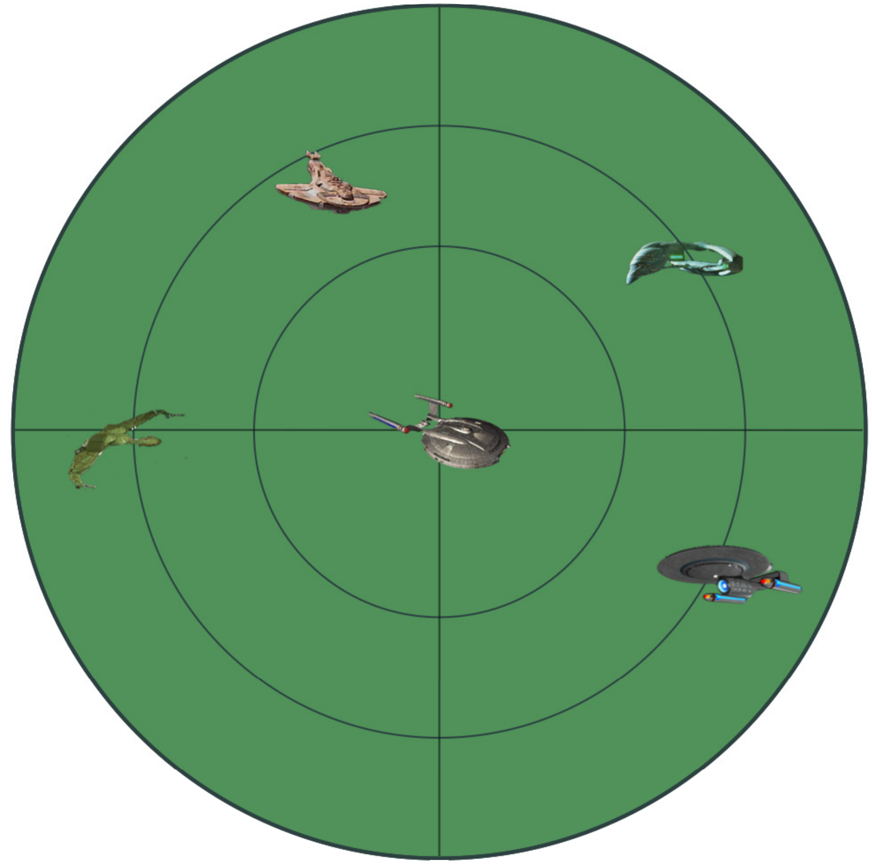




The Star Trek Problem: Discriminating Starships and making decisions with incomplete and uncertain knowledge

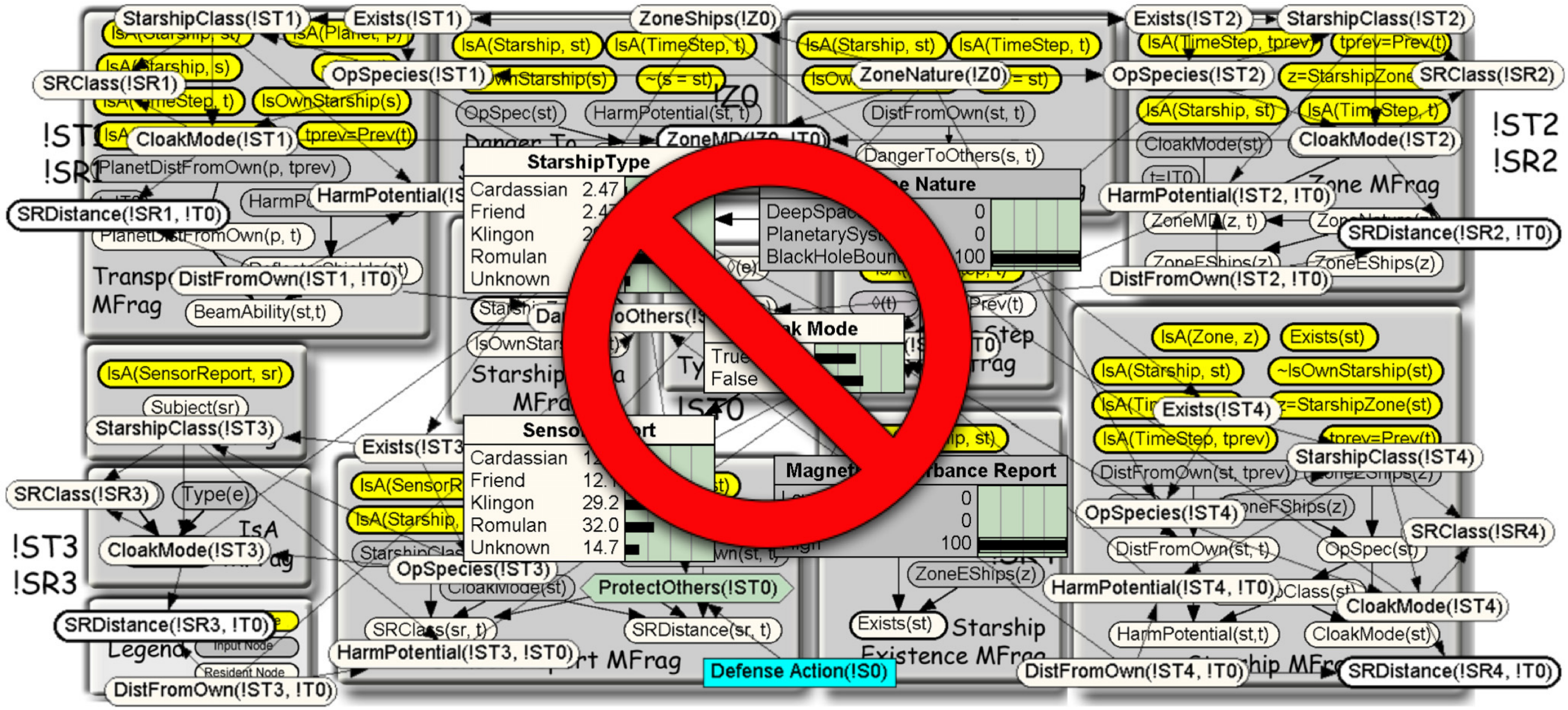
Why not BNs?



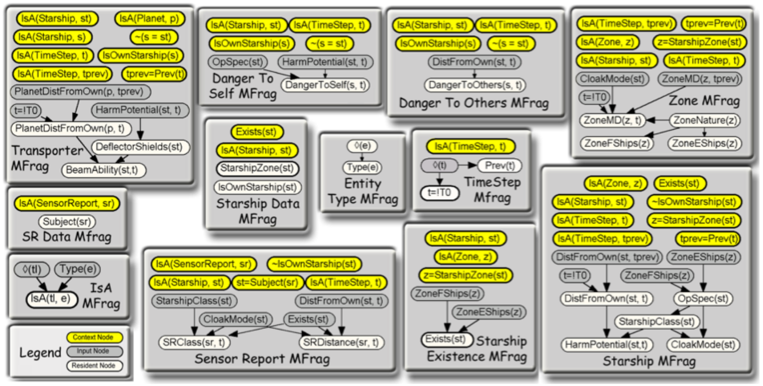


How about multiple starships showing up at the same time? One BN for each situation?

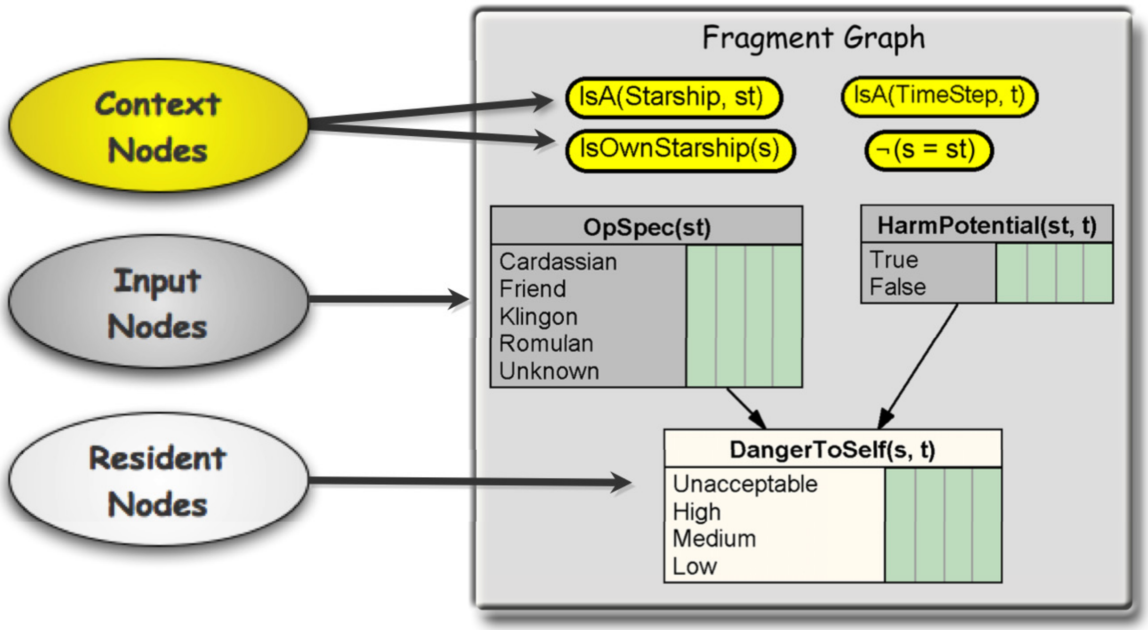
Multi-Entity Bayesian Networks



MEBN Fragments



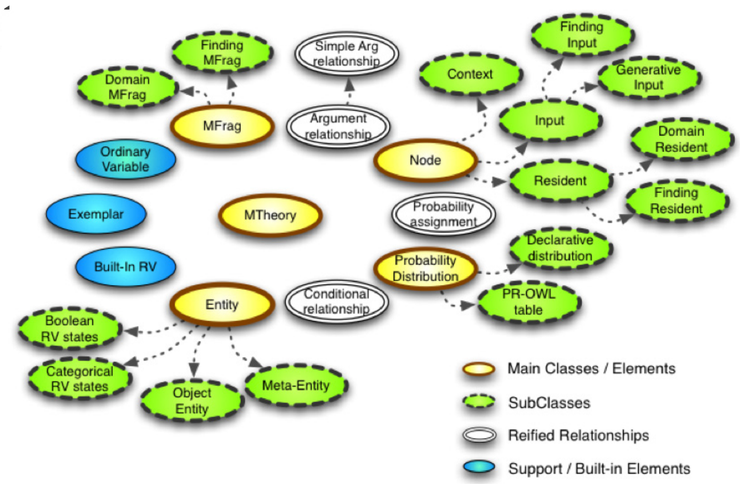
- Building blocks that collectively form a model (MTheory)
- Each one stores a specific "Chunk of knowledge"



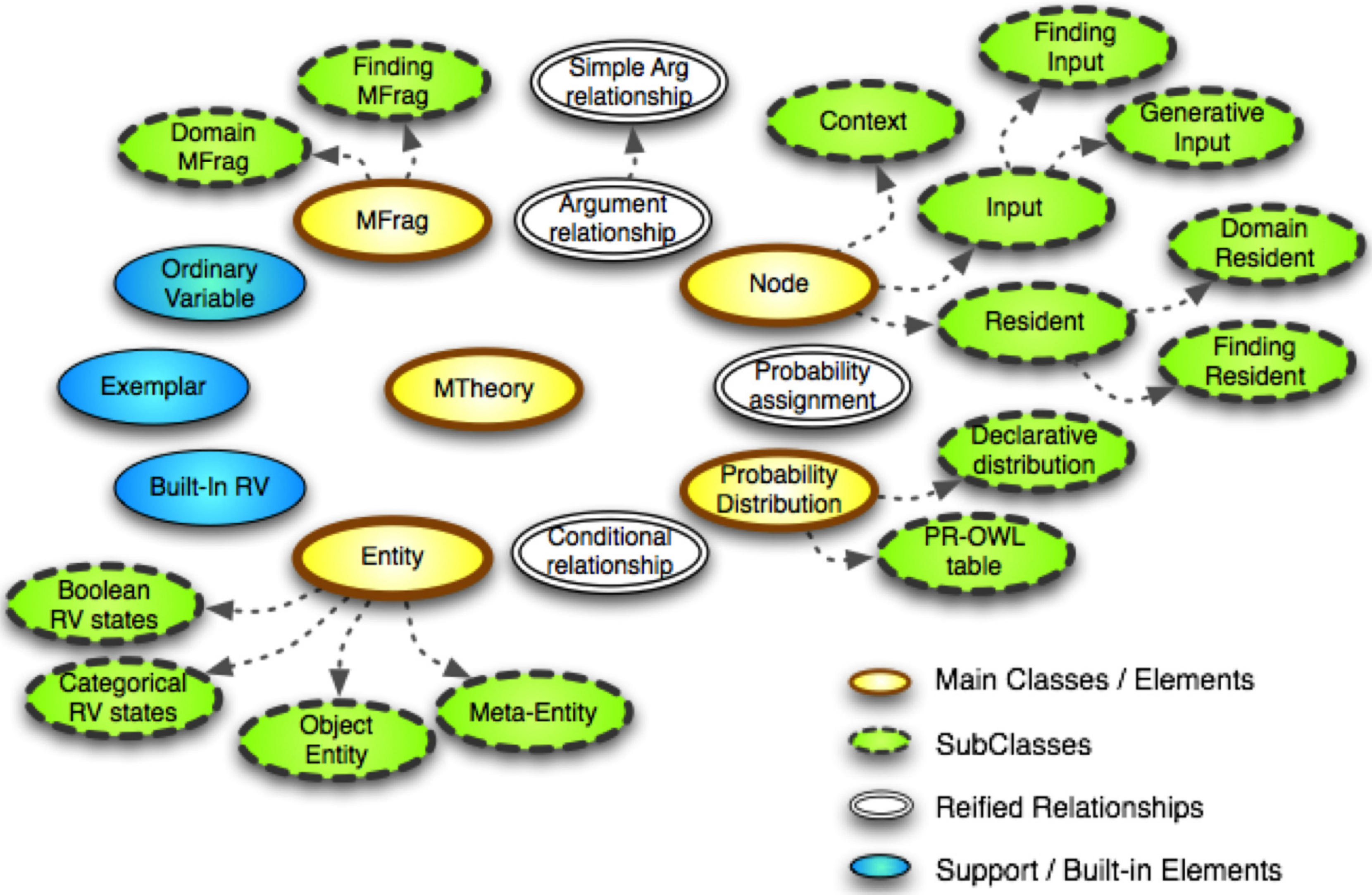
The danger to self MFrag

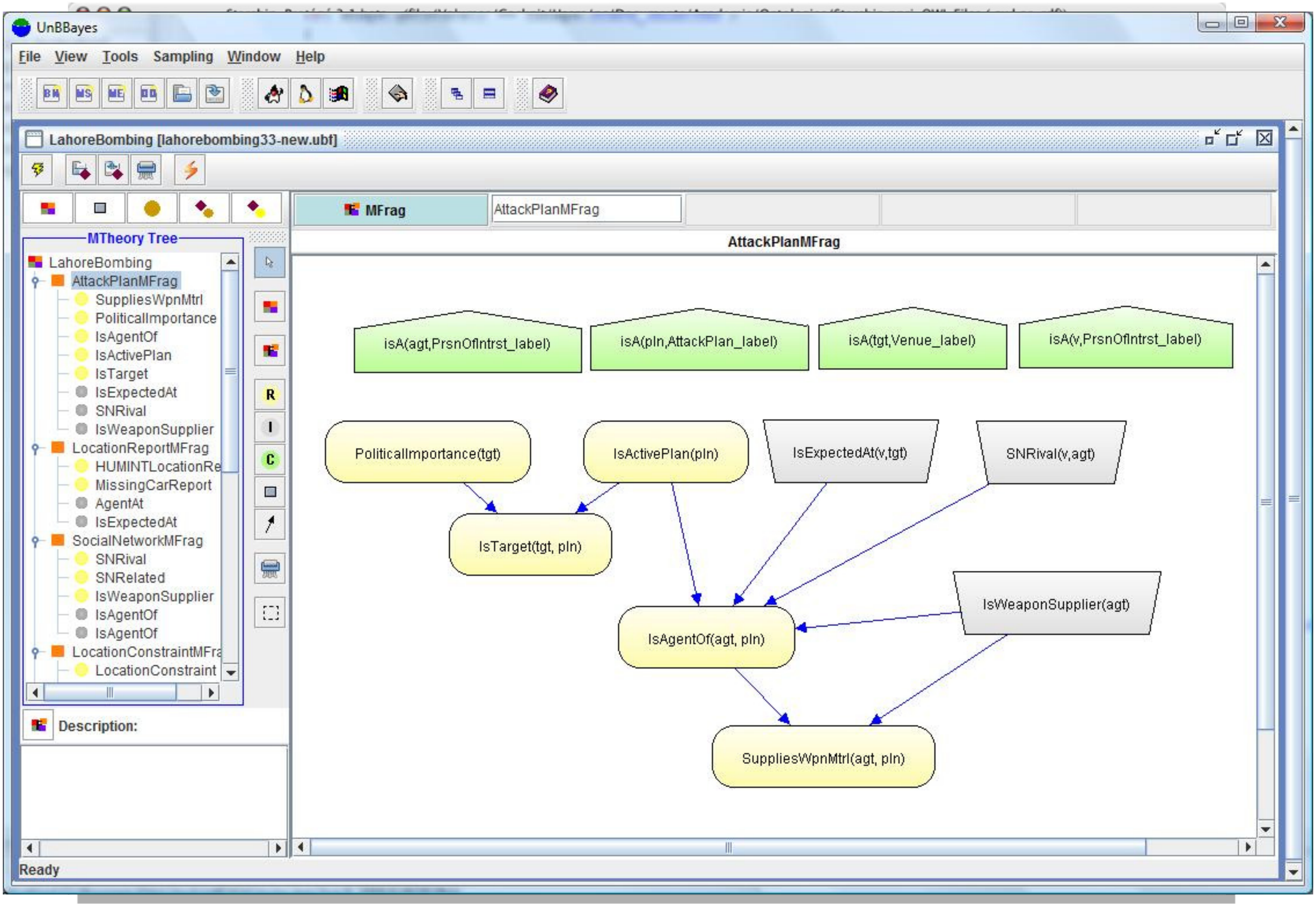
PR-OWL Probabilistic Ontology Language

- Upper ontology written in W3C-recommended OWL ontology language.
- Represents probabilistic knowledge in XML-compliant format.
- Based on MEBN, a probabilistic logic with first-order expressive power
- Open-source, freely available solution for representing knowledge and associated uncertain
- Reasoner under development in collaboration with University of Brasilia

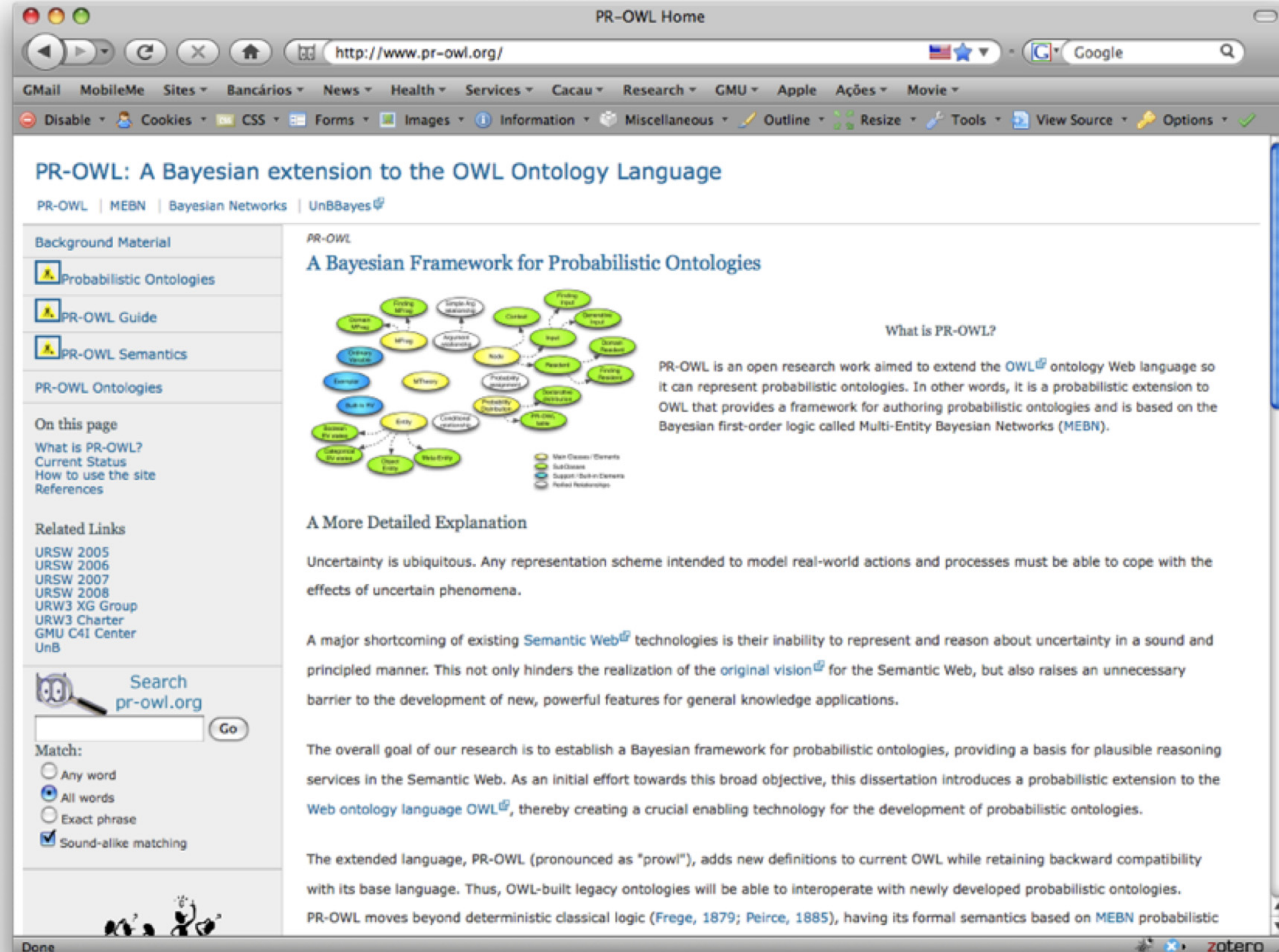


PR-OWL General Architecture




UnBBayes
File View Tools Sampling Window Help
LahoreBombing [lahorebombing33-new.ubf]
MFrag
AttackPlanMFrag
MTheory Tree
LahoreBombing
AttackPlanMFrag
SuppliesWpnMtrl
PoliticalImportance
IsAgentOf
IsActivePlan
IsTarget
IsExpectedAt
SNRival
IsWeaponSupplier
LocationReportMFrag
HUMINTLocationRe
MissingCarReport
AgentAt
IsExpectedAt
SocialNetworkMFrag
SNRival
SNRelated
IsWeaponSupplier
IsAgentOf
IsAgentOf
LocationConstraintMFra
LocationConstraint
Description:
Ready
AttackPlanMFrag
isA(agt,PrsnOfIntrst_label)
isA(pln,AttackPlan_label)
isA(tgt,Venue_label)
isA(v,PrsnOfIntrst_label)
PoliticalImportance(tgt)
IsActivePlan(pln)
IsExpectedAt(v,tgt)
SNRival(v,agt)
IsTarget(tgt, pln)
IsWeaponSupplier(agt)
IsAgentOf(agt, pln)
SuppliesWpnMtrl(agt, pln)

Resources - PR-OWL Website



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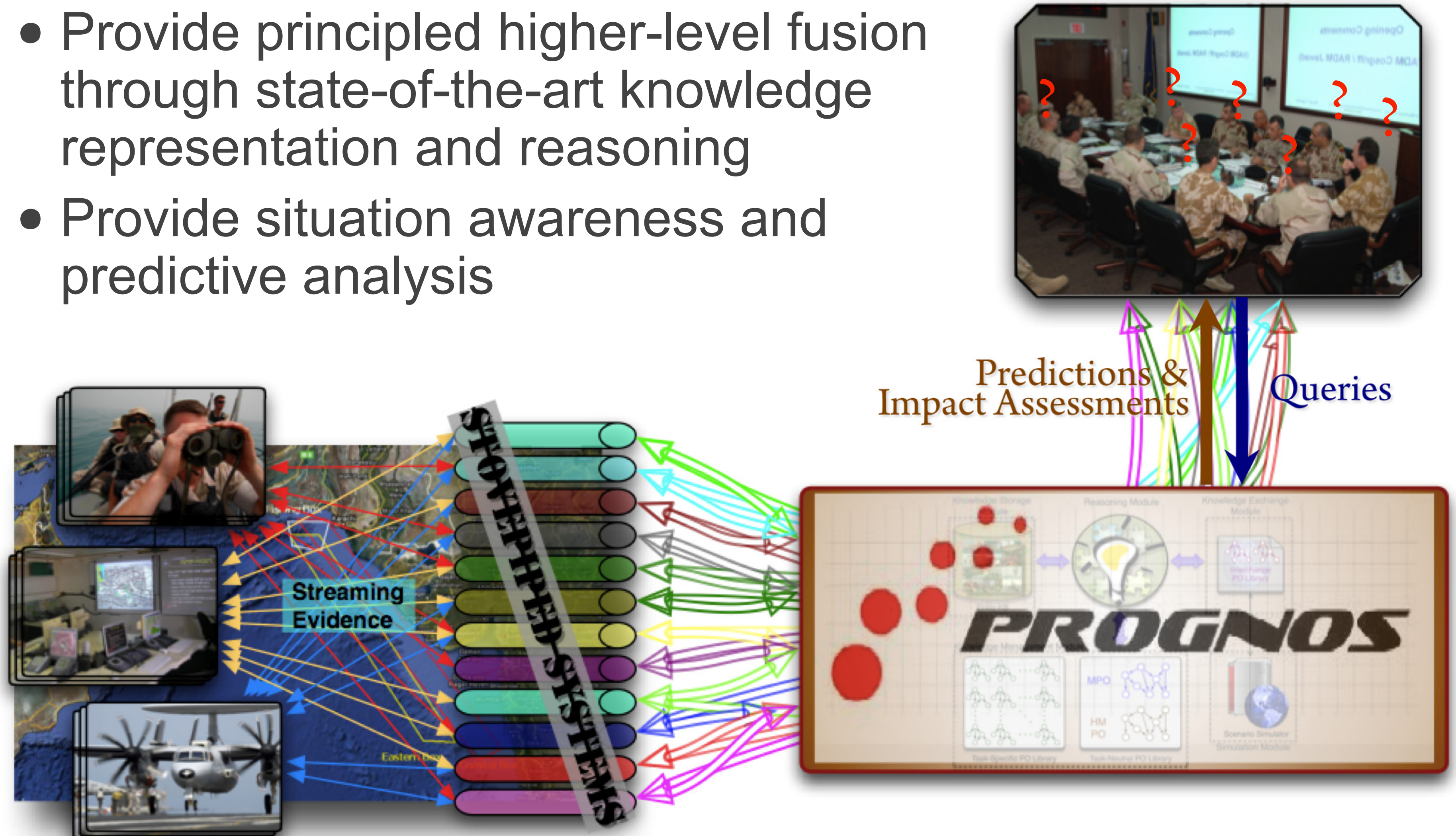
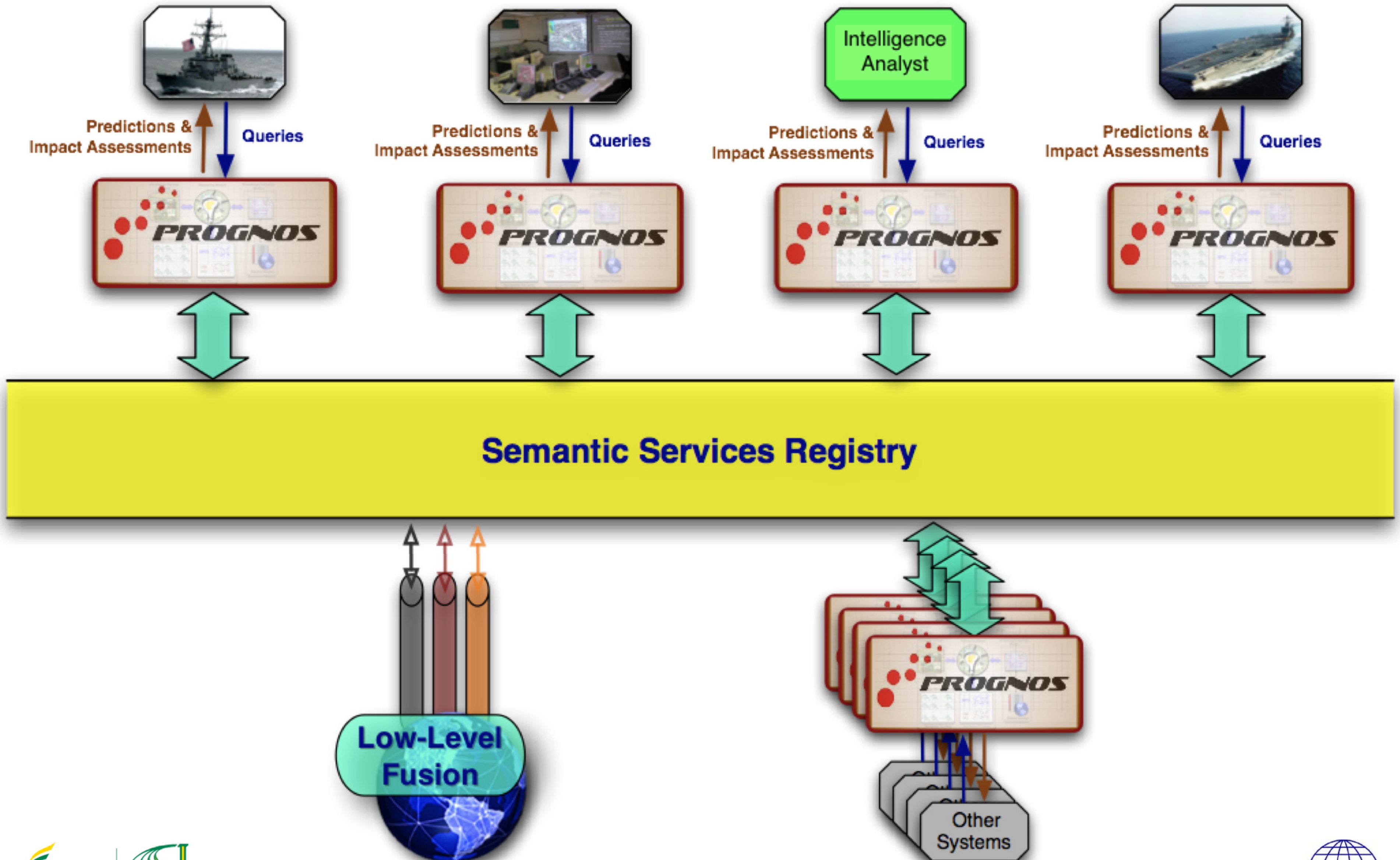
Prognos Vision

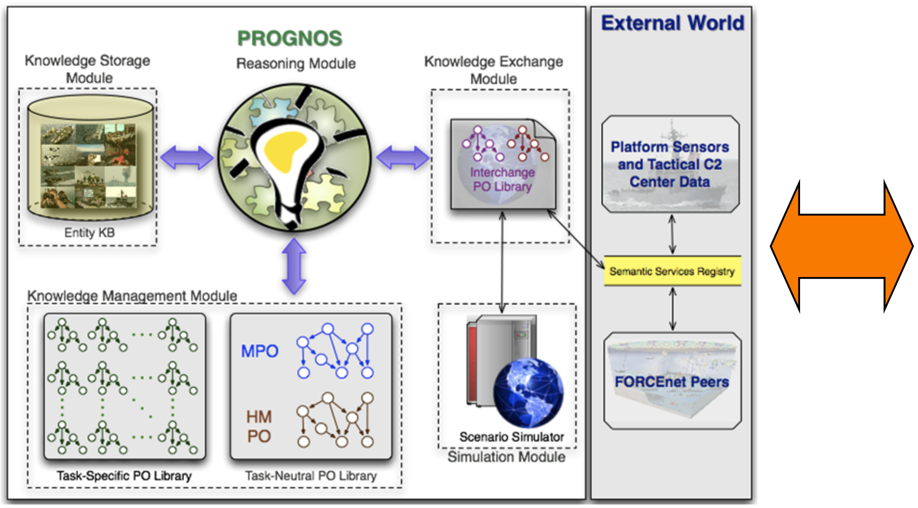
- Provide principled higher-level fusion through state-of-the-art knowledge representation and reasoning
- Provide situation awareness and predictive analysis

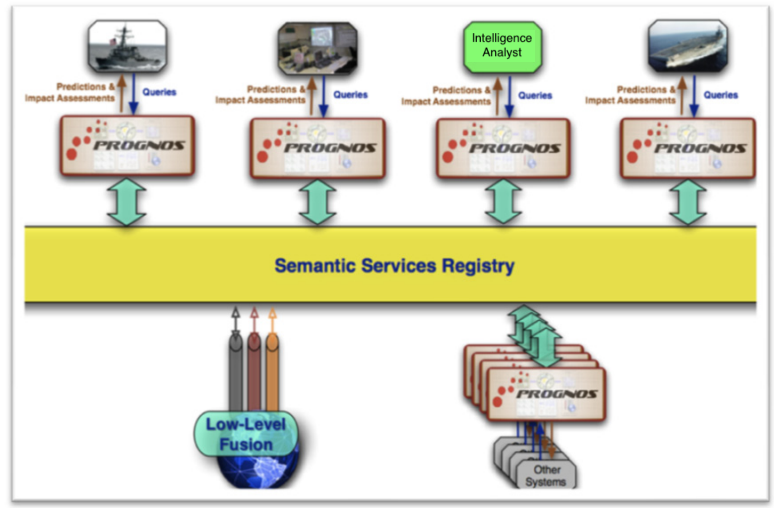


Operational Concept



High-Level Design Concept

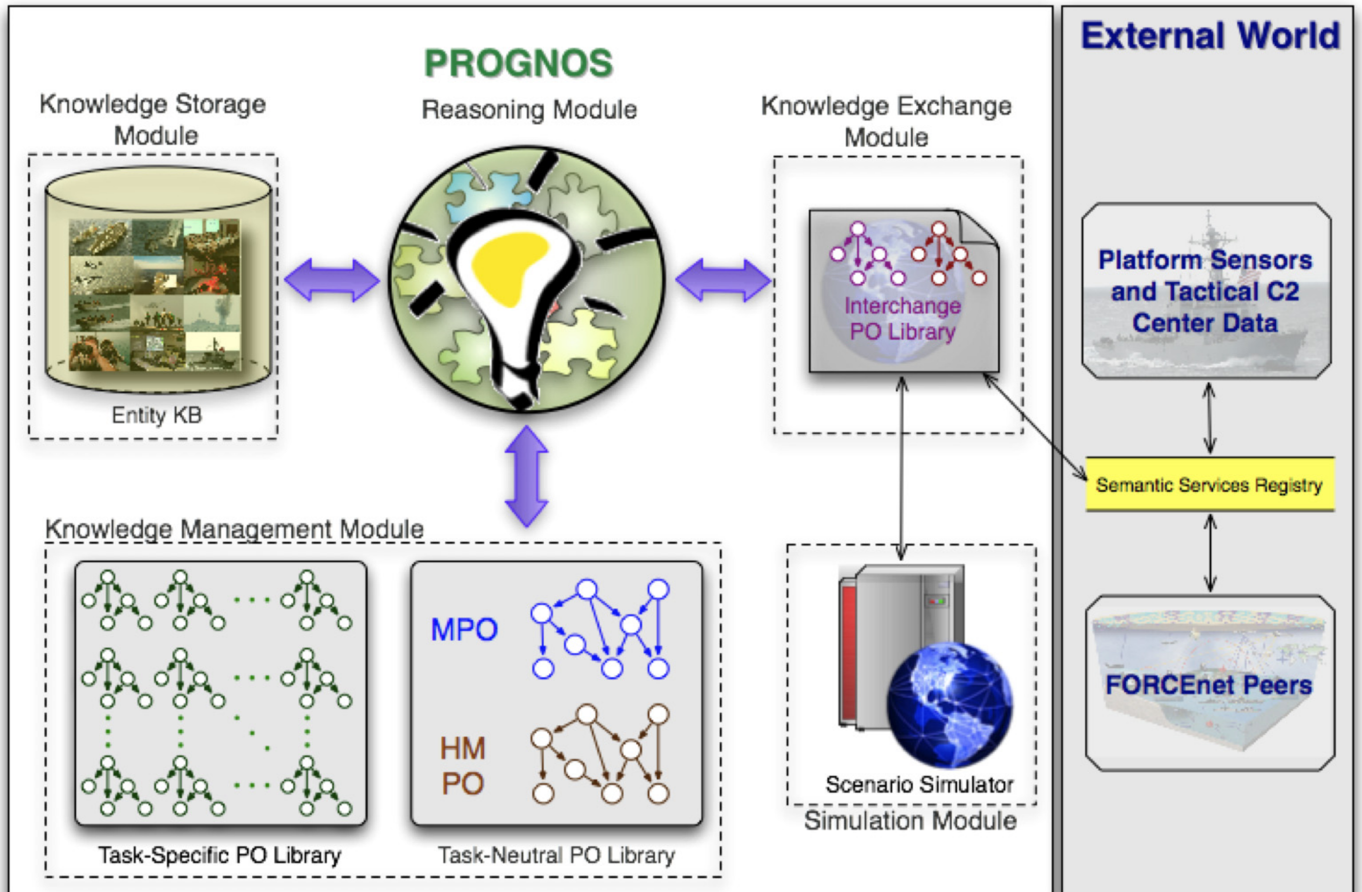




- Integrate the enabling technologies in a distributed system architecture
  - Represent domain knowledge as MEBN fragments that define situation variables
  - MFrags are small and model “small pieces” of knowledge for building complex model
- Perform hypothesis management for predictive situation and impact assessment
  - Match new evidence to existing hypotheses and/or nominate new hypotheses via MC2HM, generating an approximation to the posterior distribution of hypotheses given evidence
  - Pass results to the inference module, which builds a Bayesian network to predict future events
- Enable Distributed net-centric SOA
  - Probabilistic ontologies fill a key gap in semantic matching technology, facilitate wide-spread usage of Web Services for efficient resource sharing in distributed FORCENet. environments

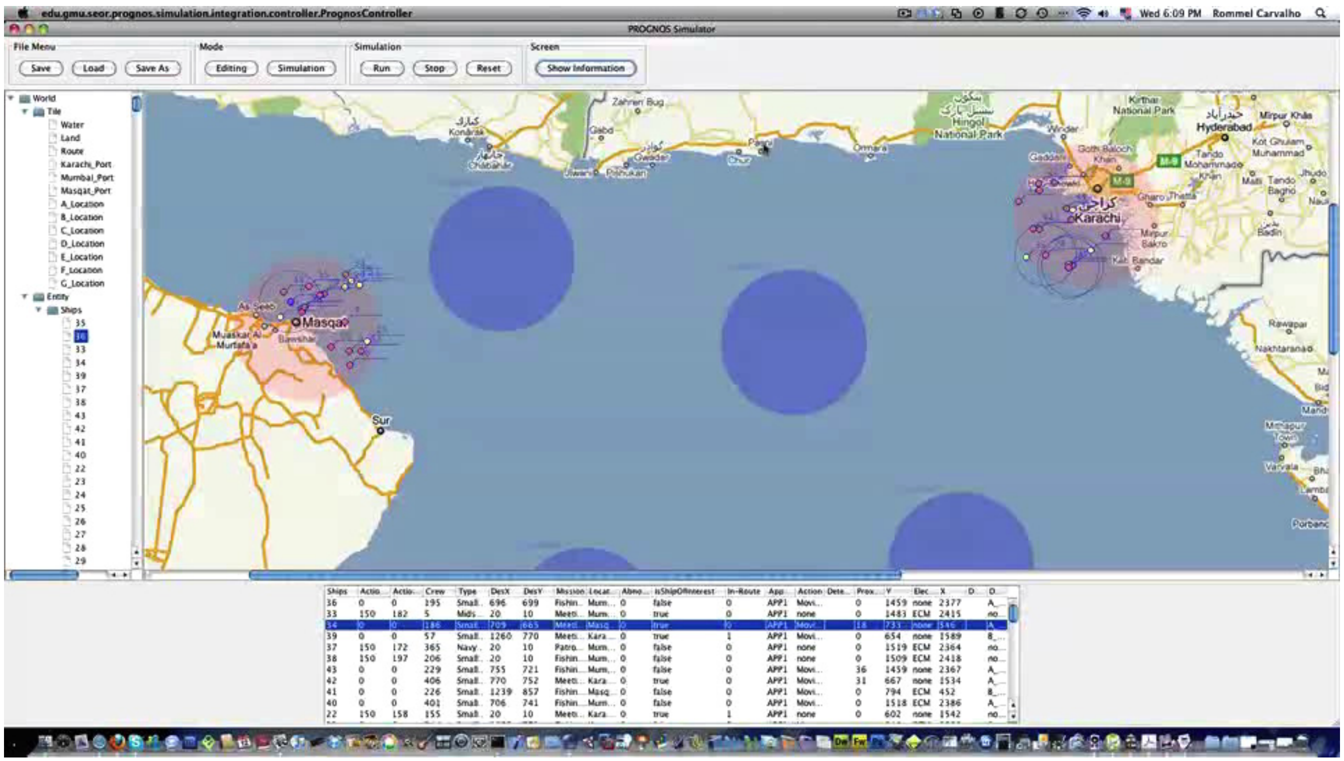
Architecture Components

- Interoperability with FORCENet and external systems via a set of interchange POs
- Hybrid reasoning in support for a Hypothesis Management engine
- Internal entity storage module in FORCENet formatting
- Task-specific POs for optimal mission-based inferences, ensuring modularity and helping scalability



- Domain-agnostic Prognos Core library in support to general reasoning and Hypothesis Management
- Simulation module for both system training and evaluation

Simulation


PROGNOS Simulator
File Menu
Save
Load
Save As
Mode
Editing
Simulation
Simulation
Run
Stop
Reset
Screen
Show Information

Links and Contact Data

- Contact:
  - http://c4i.gmu.edu/~pcosta
- C4I Center:
  - http://c4i.gmu.edu
- PR-OWL
  - http://www.pr-owl.org
- Uncertainty Reasoning for the Semantic Web
  - http://c4i.gmu.edu/ursw/2009
- Semantic Technologies for Intelligence, Defense, and Security (STIDS 2010)
  - http://c4i.gmu.edu/stids2010

Thanks for your Attention!!!