Information Fusion: the Concepts, the Technology, the Community, and Modern Research Challenges

Dr. James Llinas
Research Professor (Emeritus), Executive Director
Center for Multisource Information Fusion
State University of New York at Buffalo, USA
llinas@buffalo.edu

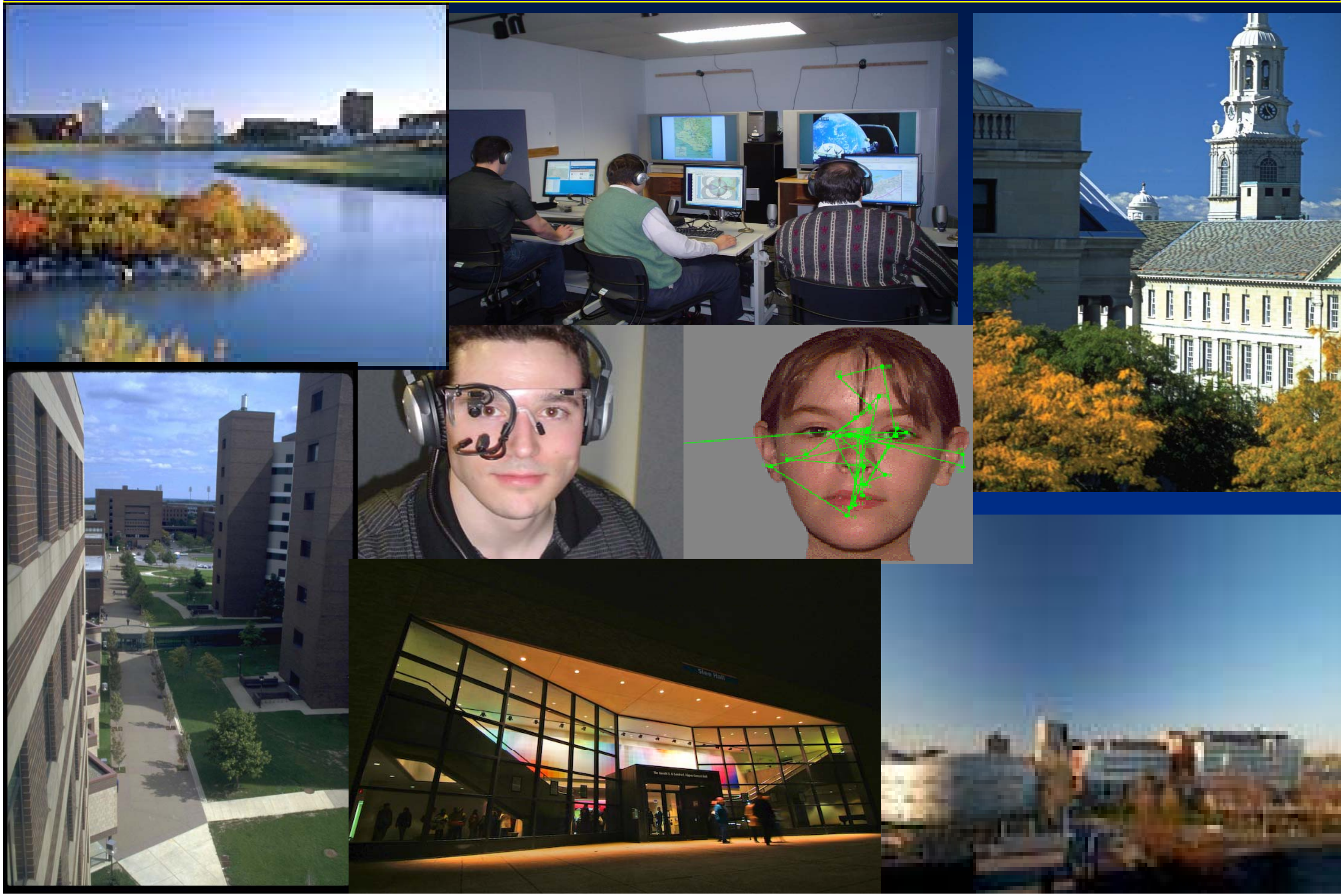
center for multisource informationfusion
A CUBRC and University at Buffalo Research Center

CMIF Location: Buffalo, New York, USA

About the "University at Buffalo"

- "University at Buffalo" aka State University of NY at Buffalo
- New York State's largest and most comprehensive public university
- Member of the Association of American Universities
- Funded research activity in the range of US$350M per year
- Selected Research Centers:
  - Center for Multisource Information Fusion
  - Natl Center for Geographic Information and Analysis
  - National Center for Ontological Research
  - Virtual Reality Laboratory
  - Center for Information Systems Assurance
  - Lab for Advanced Network Design, Evaluation and Research
  - Wireless and Networking Systems Lab
  - Semantic Network Processing Systems Research Group
  - The Center for Unified Biometrics and Sensors
  - Center for Computational Research (Supercomputing)
  - Center for Document Analysis and Recognition
- Current enrollment approx 30K+ students, 18K undergrad, 12K grad

Around the Campuses: Suburban-South-Downtown



CMIF OVERVIEW

- **Mission:** Information Fusion and related areas primarily but not exclusively for defense and homeland security applications
- **Basic and Applied Research in:**
  - Multiple-sensor and instrumented systems
  - Synergistic Human-Multisensor systems
  - Real-time Decision-making using Hierarchical Fusion
  - Graph Theory and Optimization for Level 2/3 Fusion
  - Multi-modal/spectral information environments (speech+text+imagery+RF sensor+human input)
- **Applications:**
  - Defense: Intelligence/Surveillance/Reconnaissance; Tactical Applications; Homeland Security
  - Non-Defense: Robotics; Conditioned-Based Maintenance; Medical; Transportation; Geology; Natural Disasters/Crisis Mgmt
- **History and Funding:**
  - Started in 1996 with Air Force Research Lab Contract
  - Typical funding activity ~US$4M/year
- **Scholarly:**
  - Long-standing member of "JDL" fusion group and First President of Intl Society for Info Fusion
  - Extensive publishing by CMIF PI Team including books, Jl papers, conference papers and review boards
  - "Critical Issues" Workshops—8 years
  - CMIF is unique in American Universities as a research activity focused on IF technology for DHS/DoD
  - Consortium development to include other universities (SU, RIT and PSU) and industrial partners and development of a Graduate-level pgm in Data Fusion

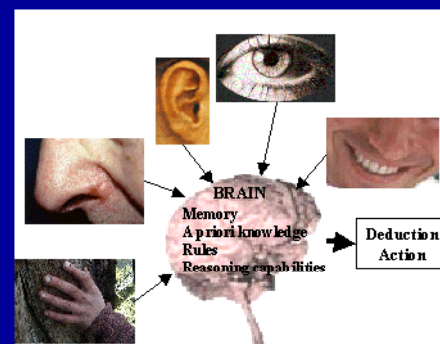
The Concepts

Everyday Data Fusion

- Sound
- Smell
- Taste
- Images
- Touch
- Pain
- Balance
- Temperature
- Body Awareness (Proprioception

Sensing Association

Multinodal Fusion



Robotic Multisensor Fusion

Augmented Sensing

History of Information Fusion

- **Dates to circa 1970's** —fairly young in the sense of technological history—a maturing technology/field of study
- **Driven by defense and intelligence needs**
  - Originally as a "data compression" device to digest huge amounts of sensed data as sensors advanced in capability (a "push" requirement)
  - Later as an important element for decision support (a "pull" requirement)
- **Matures to very broad range of application**
  - Robotics, medicine, imagery/remote sensing, intelligent transportation, conditioned-based maintenance, biometrics, etc

What is Information Fusion?

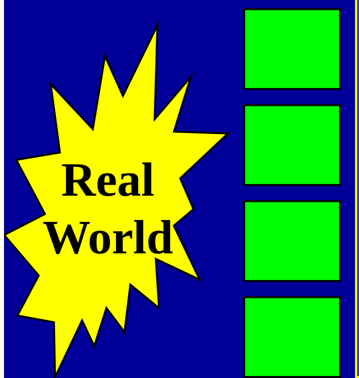
"Information fusion is an ***Information Process*** dealing with the:

- {***Association, correlation, and combination}*** of data and information from
- {***Single and multiple sensors or sources***} to achieve
- {***Refined estimates}*** of parameters, characteristics, events, and behaviors for observed entities in an observed field of view

•It is sometimes implemented as a Fully Automatic process or as a ***Human-Aiding process*** for Analysis and/or Decision Support

Most Simply--

Observation System



Multiple types of data

--various types of information

--redundant

--and complementary)

"Associated" or "Correlated" to :

--the same object

or event

or behavior

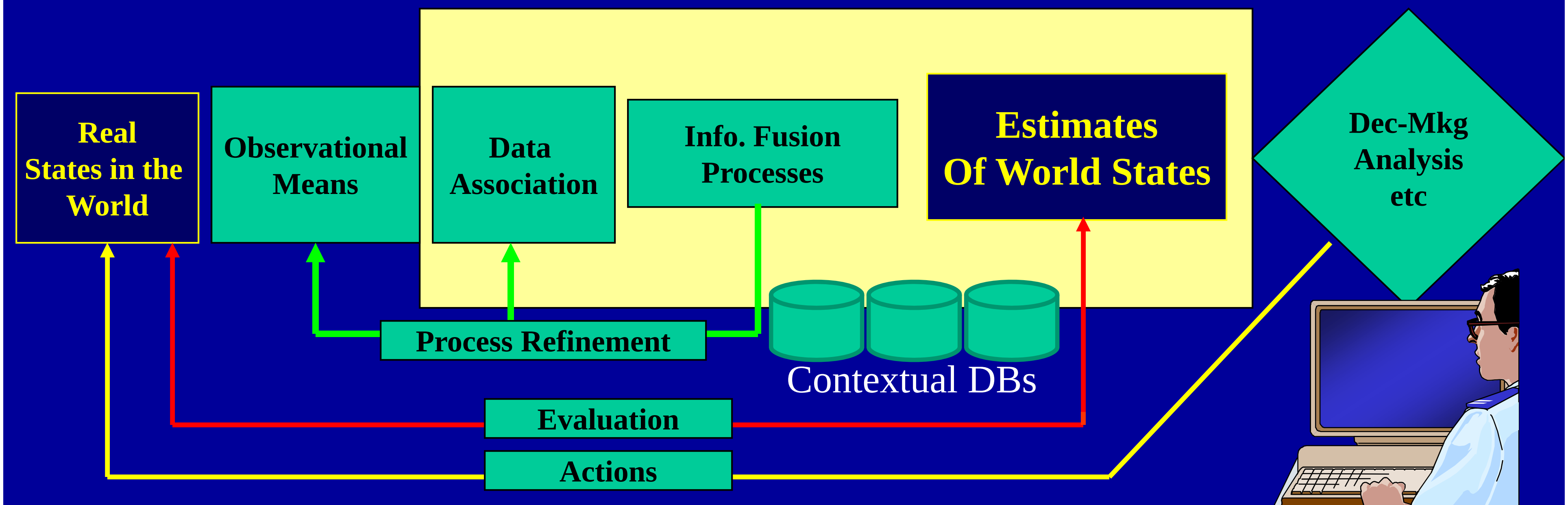
So that estimation algorithms (mathematical techniques)—or—automated reasoning methods (artificial intelligence techniques) can produce better estimates (than based on any single type of data)

Multiple types of data → Related to things of interest → To improve estimates about those things

Observations (Multiple) → Association of Observations → Estimation

These Basic Ideas are Transferable to Many Types of Problems

Basic Role of Fusion: Adaptive, Recursive Estimation

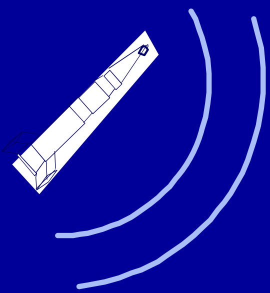


Six Informational / Knowledge Components:

- Observational Data
- A Priori Dynamic World Knowledge Model (Deductive)
- Contextual Information
- Runtime Learned Knowledge
- Tacit and Explicit Human Knowledge
- (Network) External Obsvns and Estimates

Information Fusion Exploits Sensor/Source Commonalities and Differences

Unknown Moving Object

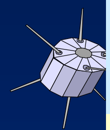


	DETECTION		KINEMATICS		CLASSIFICATION	
	CONFIDENCE	COVERT COVERAGE	RANGE	ANGLE	CLASS	TYPE
RADAR	FAIR	POOR	GOOD	FAIR	FAIR	POOR
EO/IR	FAIR	FAIR	POOR	GOOD	FAIR	FAIR
C3I	FAIR	GOOD	FAIR	FAIR	FAIR	FAIR

Data Preparation | Data Association | State Estimation

GOOD	GOOD	GOOD	GOOD	GOOD	GOOD

Data Fusion Functional Model



- Point and Standoff Sensors
- Data Sources
- Intel Sources
- Air Surveillance
- Surface Sensors
- Standoff Sensors
- Space Surveillance

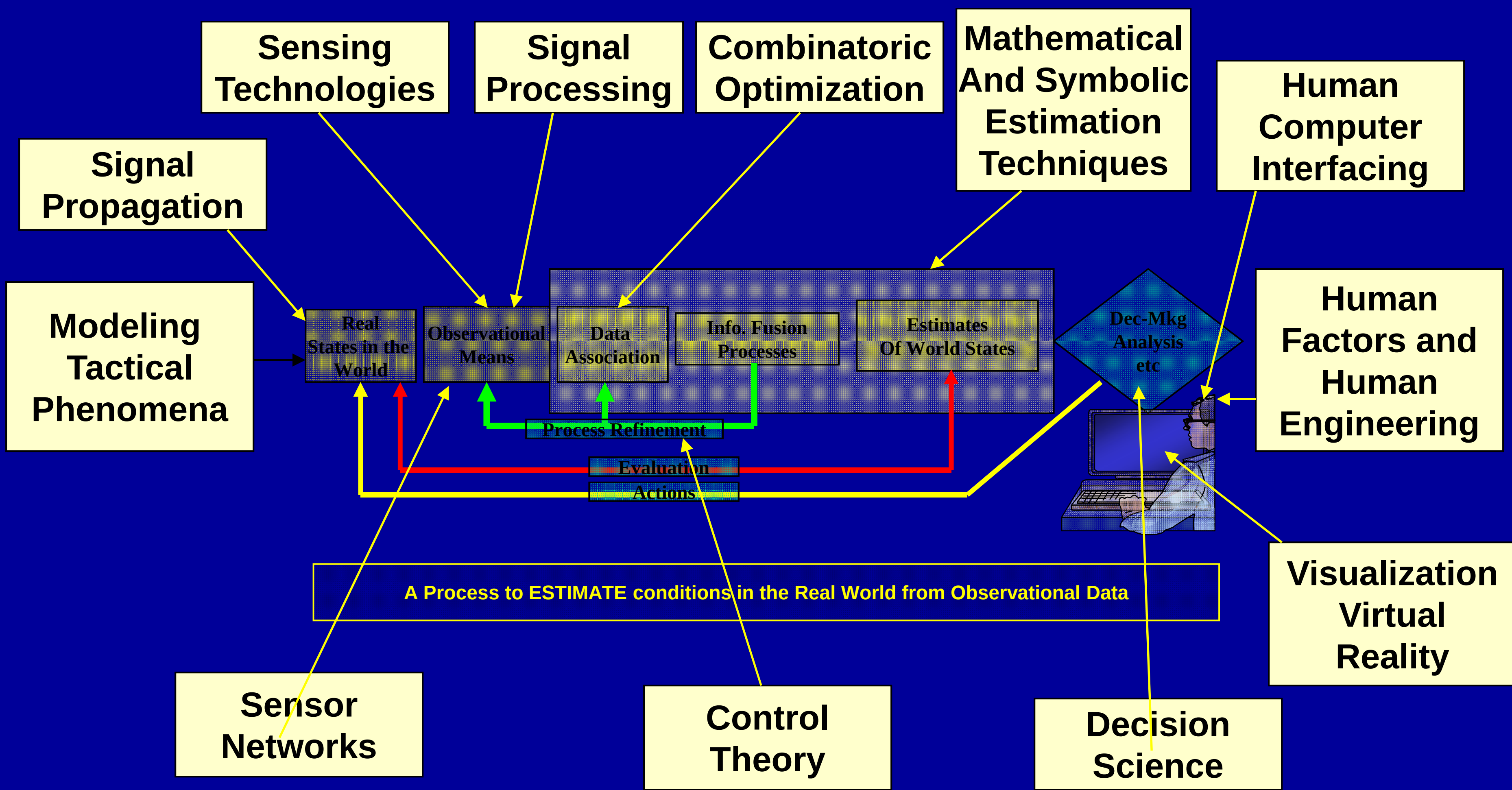
Operational Benefits of Multiple Sensor Data Fusion

- **Multiple Sensors** ➡
  - Reliability
  - Improved Detection
- **Multiple Platform Sensors** ➡
  - Extended Coverage (spatial and temporal)
  - Improved Spatial Resolution
- **Diverse Sensors** ➡
  - Robustness (Weather/visibility, Countermeasures)
  - Improved Detection

State Estimates of Reduced Uncertainty And Improved Accuracy

The Technology

The Technology:
Scientific Foundations of the Data Fusion Process



Broadly Multidisciplinary

Choices in Fusion Approaches

Fusion Approach	**Nature of Process**
* No Fusion	* Best single-source approach
* Non-fused but adaptive	* Phased application of single sources: --Multiresolutional --Cueing
“Real” Fusion	Synergistic; Adds Information, Reduces Uncertainty
--Limited Fusion	--Single Source + A Priori Info --Occasional in time,or --On demand
--Moderate-Level Fusion	--Few Sources
--Aggressive-Level Fusion	--”All Source”

Some Research Strategies

- **Estimation-process-centric**
  - Signal processing (eg detection fusion), intersource registration/alignment, estimation algorithms
  - Input: given; Output: mathematical estimate
- **System-centric**
  - Process architecture, standards, integration
  - Process mathematics
  - Process control, estimation/decision-making interdependencies, dynamic resource mgmt
  - Human-system design
  - Input: controllable; Output: usable by a human

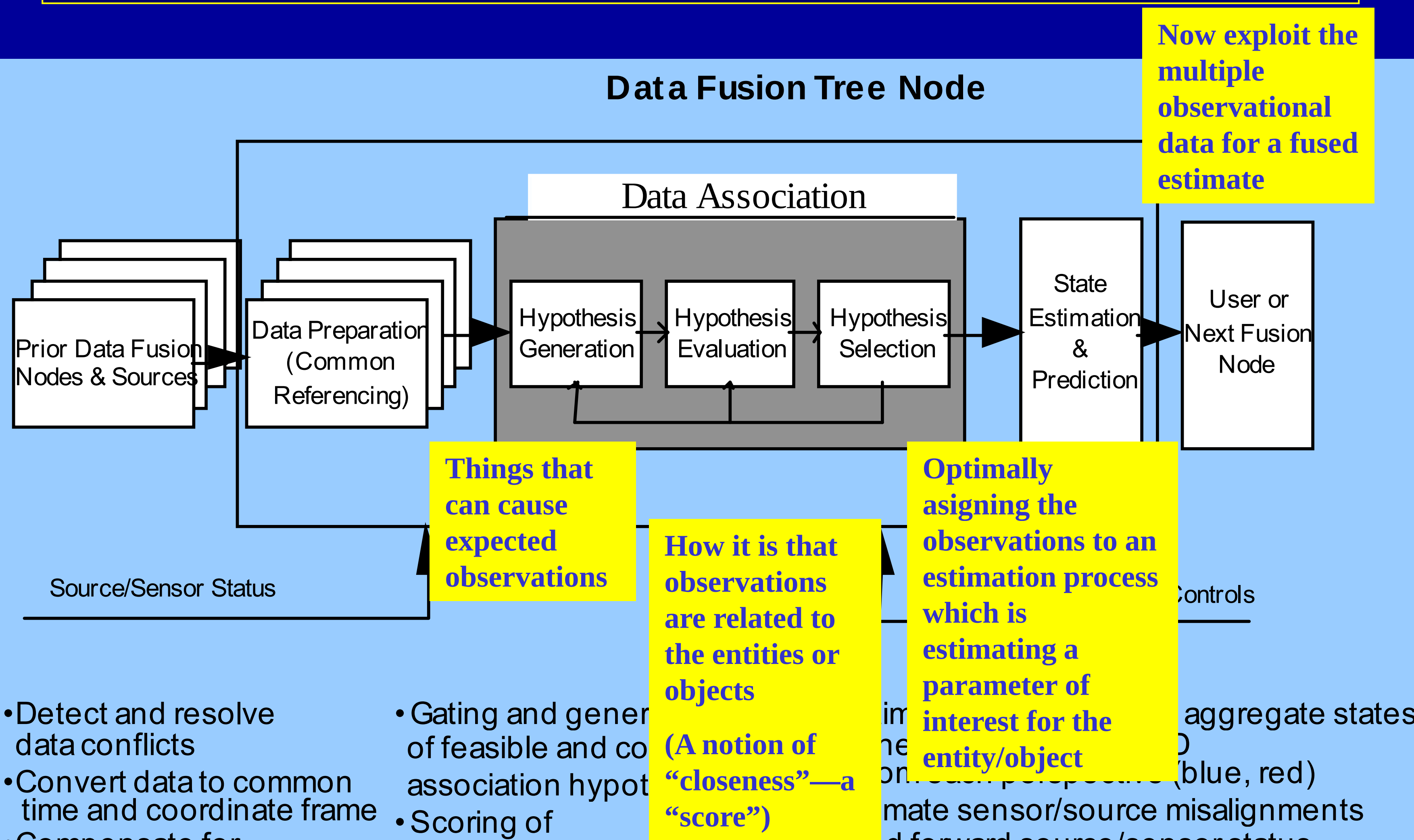
Architecting Systems

--Architectural Elements

--Dealing with Uncertainties

--Data Association, a core function

Data Fusion Tree Node



- Detect and resolve data conflicts
- Convert data to common time and coordinate frame
- Compensate for source misalignments

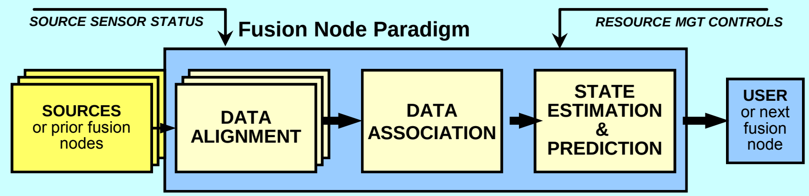
- Gating and gener… of feasible and co… association hypot…
- Scoring of data associations
- Select, delete, or feedback data associations

- …im… aggregate states
- …ne… …D
- …on… (blue, red)
- …mate sensor/source misalignments
- Feed forward source/sensor status

Architectural Elements

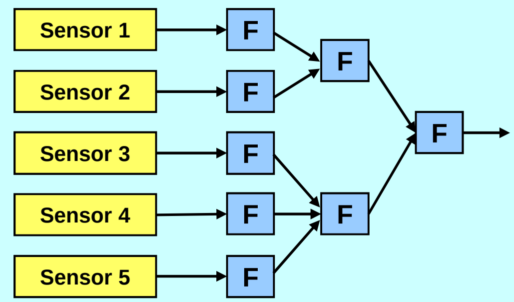
Data Fusion Node

Common Representation for all Data Fusion Processes



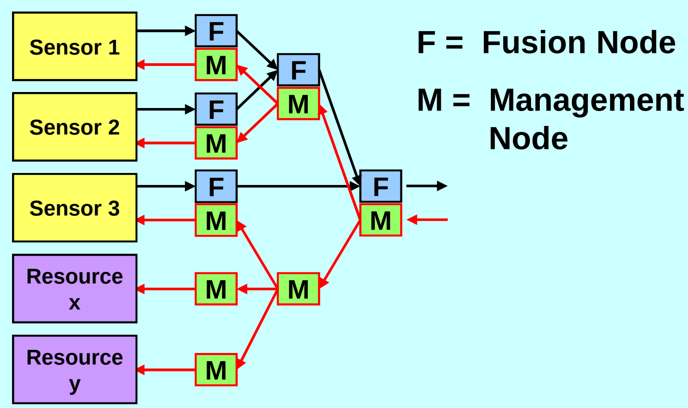
Data Fusion Network

Common Representation for all Data Fusion Architectures

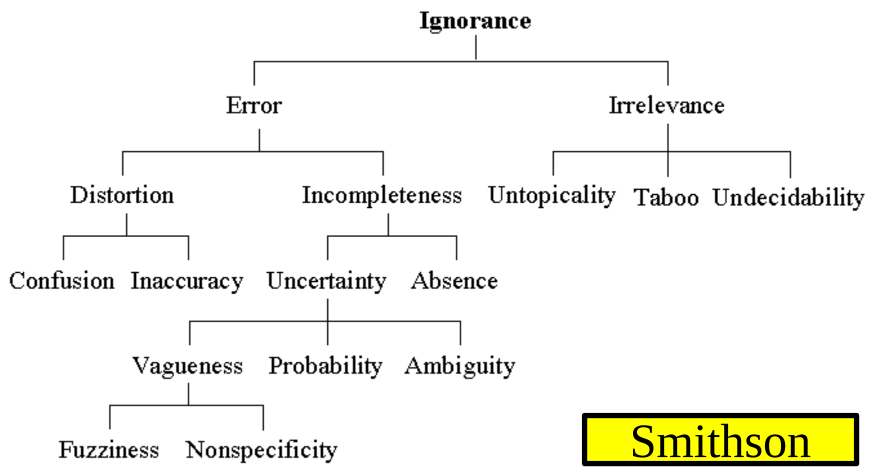


Integration of Data Fusion and Resource Management Networks

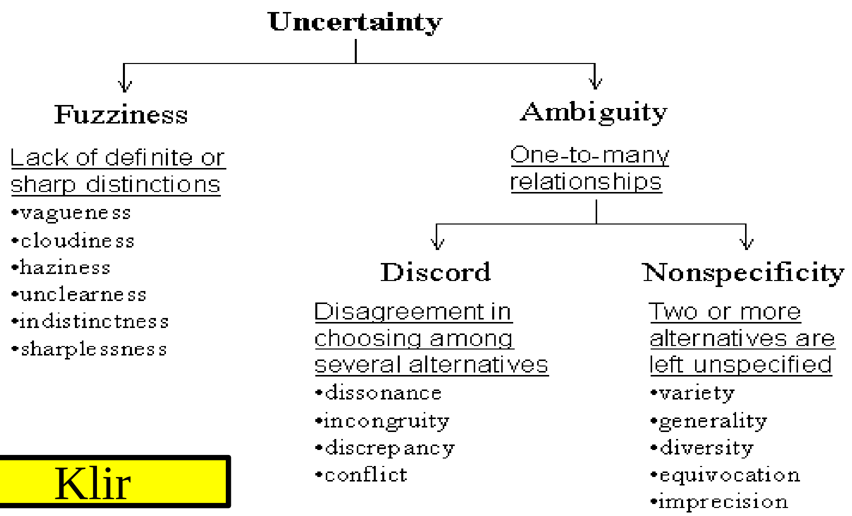
Common Representation for all Information System Architectures



Dealing with Uncertainty



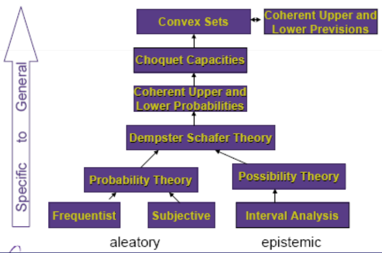
Smithson



Klir

Second Order Uncertainty and Imprecise Probability

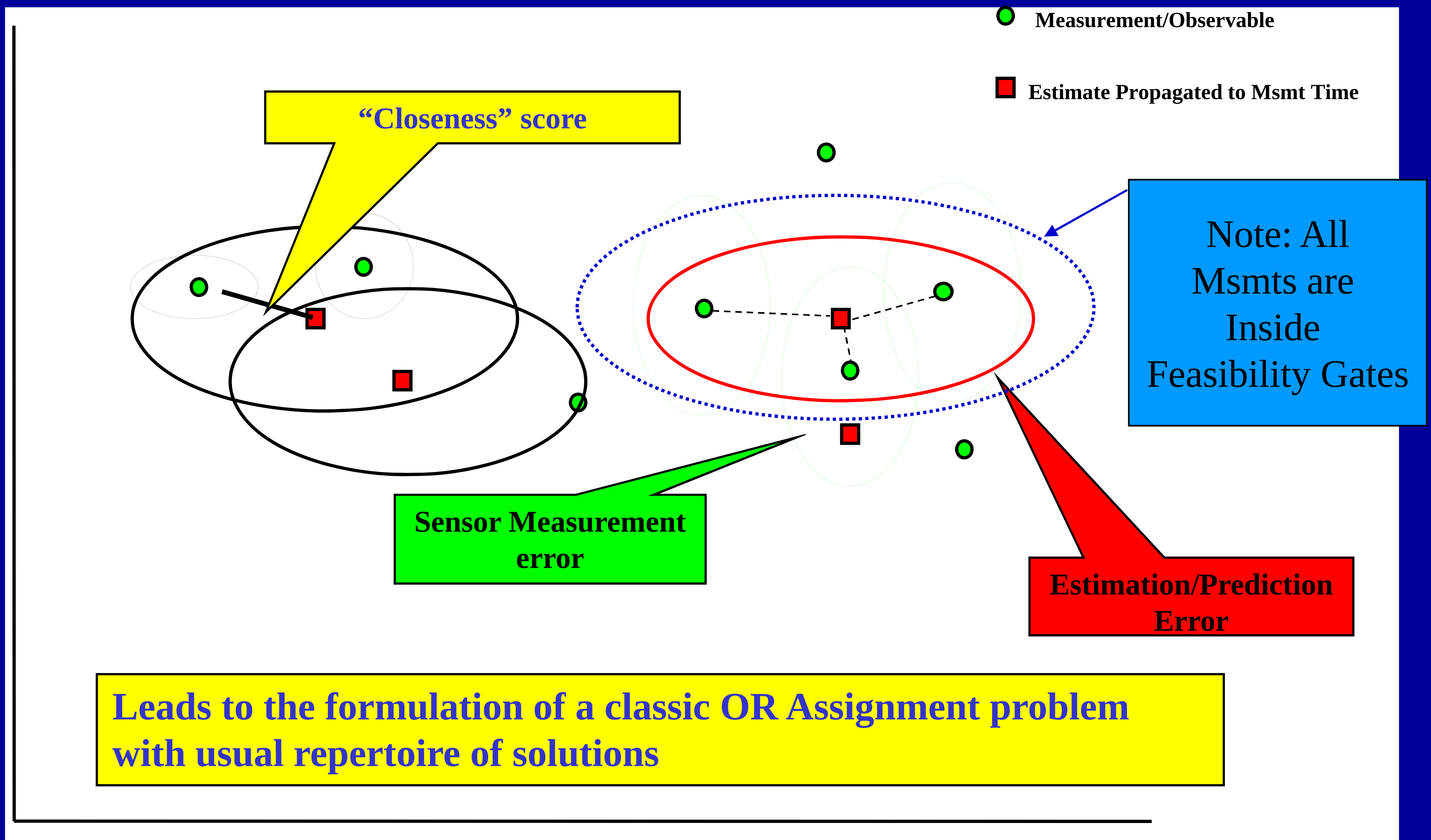
- Theoretical aspects of Second Order Uncertainty
  - Focus on Epistemic Uncertainty (limitations in knowledge)
  - Aspect of degrees of satisfaction of the Kolmogorov Axioms, especially the Additivity Axiom
  - Walley (1991) shows that imprecise probabilities satisfy the principles of coherence—relaxes need to satisfy Additivity
- Leads to range of alternatives, each of which satisfy "relaxed" Additivity Axioms



Most problems involve both Aleatory and Epistemic Uncertainties

Data Association Basics

--What measurement goes with what entity?

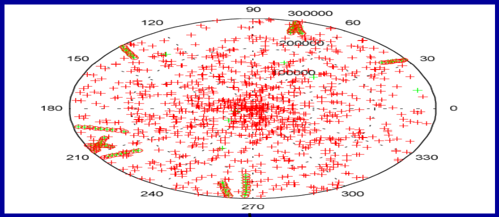


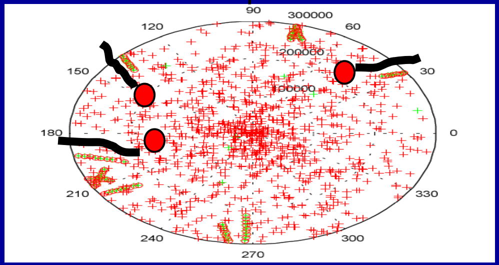
Association and Assignment Optimization

O	Ti	Tj	Tk	Tl	•	•	•
m_i							
m_j							
m_m							

Need some type of Mapping that determines a good way to allocate Obsvns To Tracks

M Observations From N Sensors





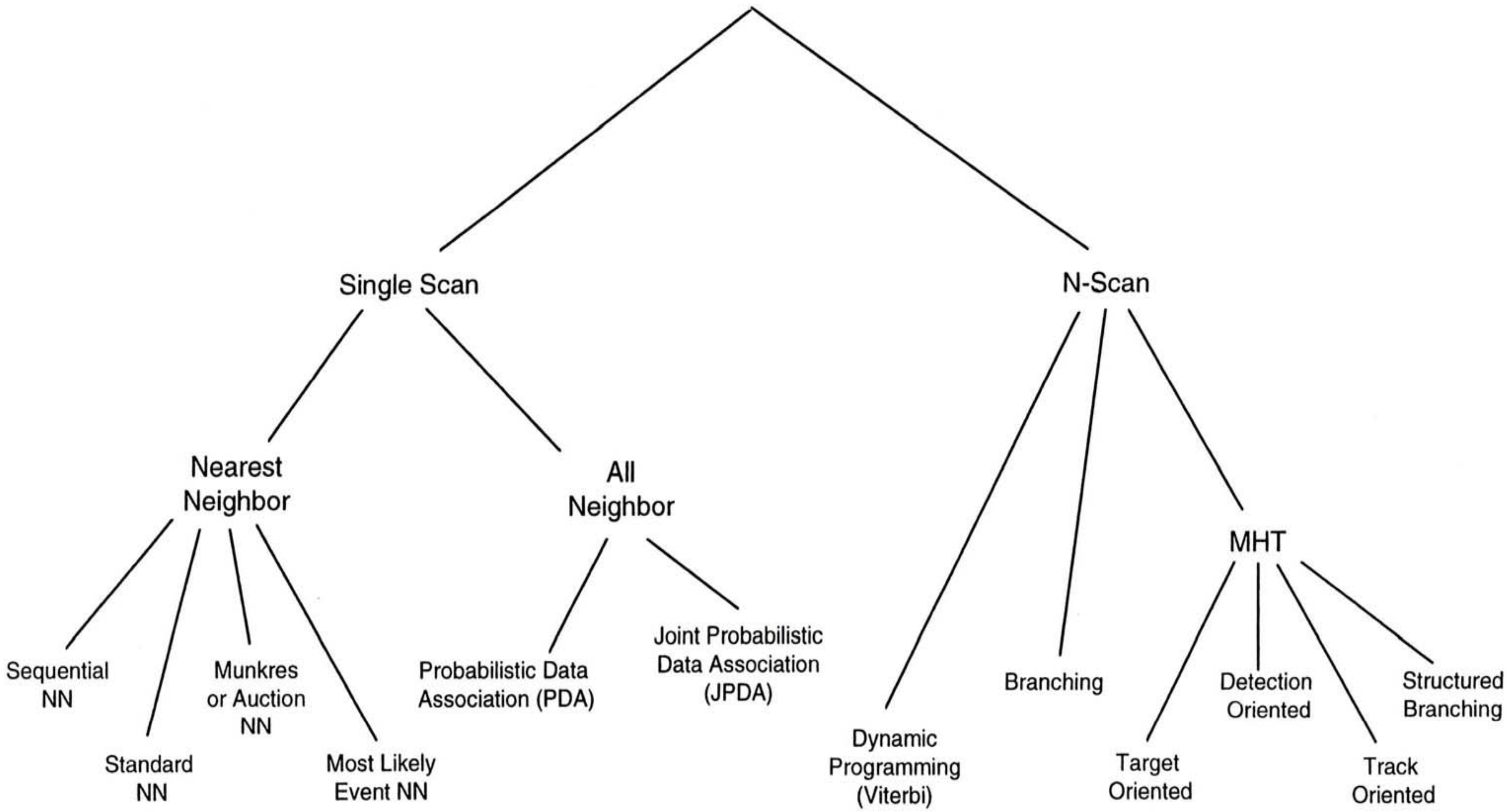
DATA ASSOCIATION

Tracks “T”

STATE ESTIMATION & PREDICTION

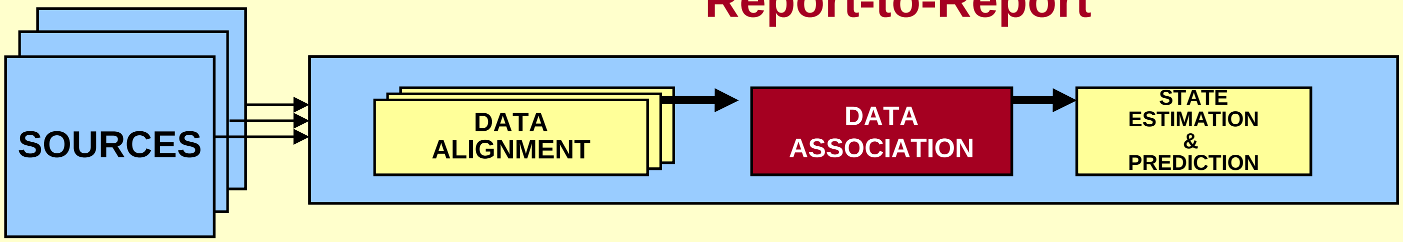
“Assigned” Observations Resulting from some “Best” way to decide which Observations should be “given” to each State Estimator

One Taxonomy of Assignment Problem Solutions



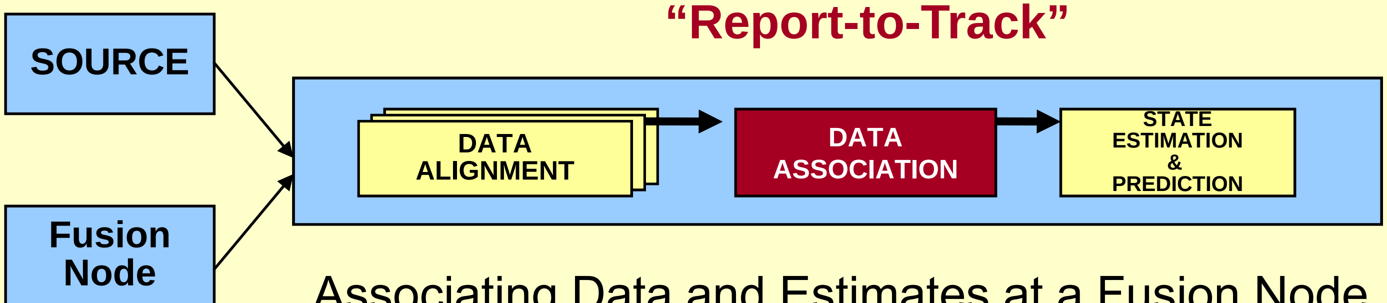
Categories of Data Association

"Report-to-Report"



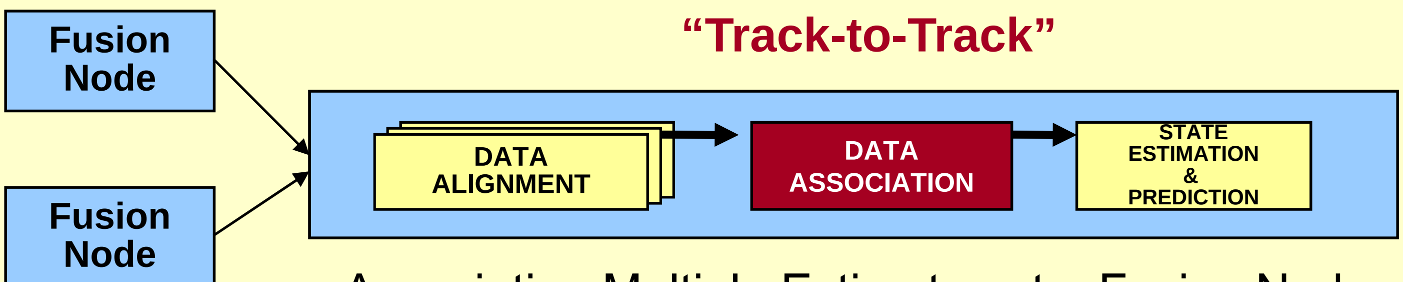
Associating Data from Multiple Sources at a Fusion Node
("Measurement-to-Measurement Association")

"Report-to-Track"



Associating Data and Estimates at a Fusion Node
("Measurement-to-Estimate Association")

"Track-to-Track"



Associating Multiple Estimates at a Fusion Node
("Estimate-to-Estimate Association")

The Community

The Early Community

- Early 1980's
  - Mostly US, UK, Australian, Canadian Defense related (in UK eg Royal Signals and Radar Establishment, DRA, etc before DERA)
  - 1985: First US "National Symposium on Sensor and Data Fusion", NSSDF
    - US only (attempts at NATO integration fail)
    - Classified
    - Ongoing today
  - US: Joint Directors of Laboratories
    - Aids in unifying terminology and concepts
  - 1990: First unified text published

Second Generation

- Early 1990’s to early 2000’s
  - Still rather ad hoc through early 90’s
  - Mid 90’s sees evolving structure
- Mid-late 90’s
  - IEEE Conference on Multisensor Fusion and Integration, from 1995 on
  - International Conference on Information Fusion, annually, from 1998 on
  - International Society of Information Fusion, established in 1999
- Early 2000’s
  - International Journal of Information Fusion, 2000
  - Journal of Advances in Information Fusion, 2003
  - Many other conferences (e.g., in SPIE)
  - Textbooks begin to flow

Current Status

- **Community**
  - Stable but needing a broader technological view as capability for L1 matures and challenges of L2, L3 are addressed
  - Structured outreach required
- **Operating Domain**
  - Too defense-oriented; multi-domain outreach also required
- **Fusion process and concepts**
  - Need structured extension eg to distributed, networked case and L2, L3 processes
  - Control-theoretic aspects to be addressed
  - Frameworks for cost-effective development

Modern Research Challenges

One List – No particular order

- **Achieving scalability and robustness**
  - Beyond one-algorithm/process solutions
- **Structured, standardized strategies for contextual exploitation**
  - Extends, as a basic research topic, to hybrid deductive/inductive systems
- **Holistic strategies for distributed fusion processes**
  - Eg linking Information-sharing strategies with network fusion operations
- **Dealing with weak knowledge problems (world dynamics poorly understood)**
  - Second-order uncertainty, response-based balanced designs
  - Extends to the case of Situation Management
- **Overall Hard and Soft Fusion process designs and methods**
- **Improved techniques for Test and Evaluation, Metrics**

A Taste of the Hard + Soft Data Fusion Problem

The Network Enterprise, Irregular Warfare, and Fused Situational Awareness

Net Enterprise Services

"Hard" Sensor Data

Calibrated, Precise

"Soft" Sensor/Contextual Data

Uncalibrated Human Observers/Uncalibrated Sources

Observations expressed in (inherently) ambiguous language

Extensive Data and Information-Sharing Enabled by Network Infrastructure Gives Rise to a New Challenge in Information Fusion:

"HARD" + "SOFT" INFORMATION FUSION

Some Distinctions in Hard and Soft Observational Data

Data Characteristic	Hard	Soft	Remarks
Observation sampling rate	High	Low	Imputes requirements for adaptive, retrodiction-type processing (i.e. "Out-of-Sequence Measurement" type processing), as well as agile Temporal Reasoning
Semantic Content	Limited to specific, usually singular Entities	Can be conceptually broader than single Entities	Imputes requirements to design an automated Semantic Labeling process, coupled to a rich Domain Ontology Requires ability to associate and infer at multiple levels of abstraction
	Limited to Entity Attributes	Can include Judged Relationships	
Accuracy, Precision	Relatively high, good repeatability (Precision)	Broadly low accuracy in attributes, high at the conceptual level	Imputes requirements for robust Common Referencing and Data Association

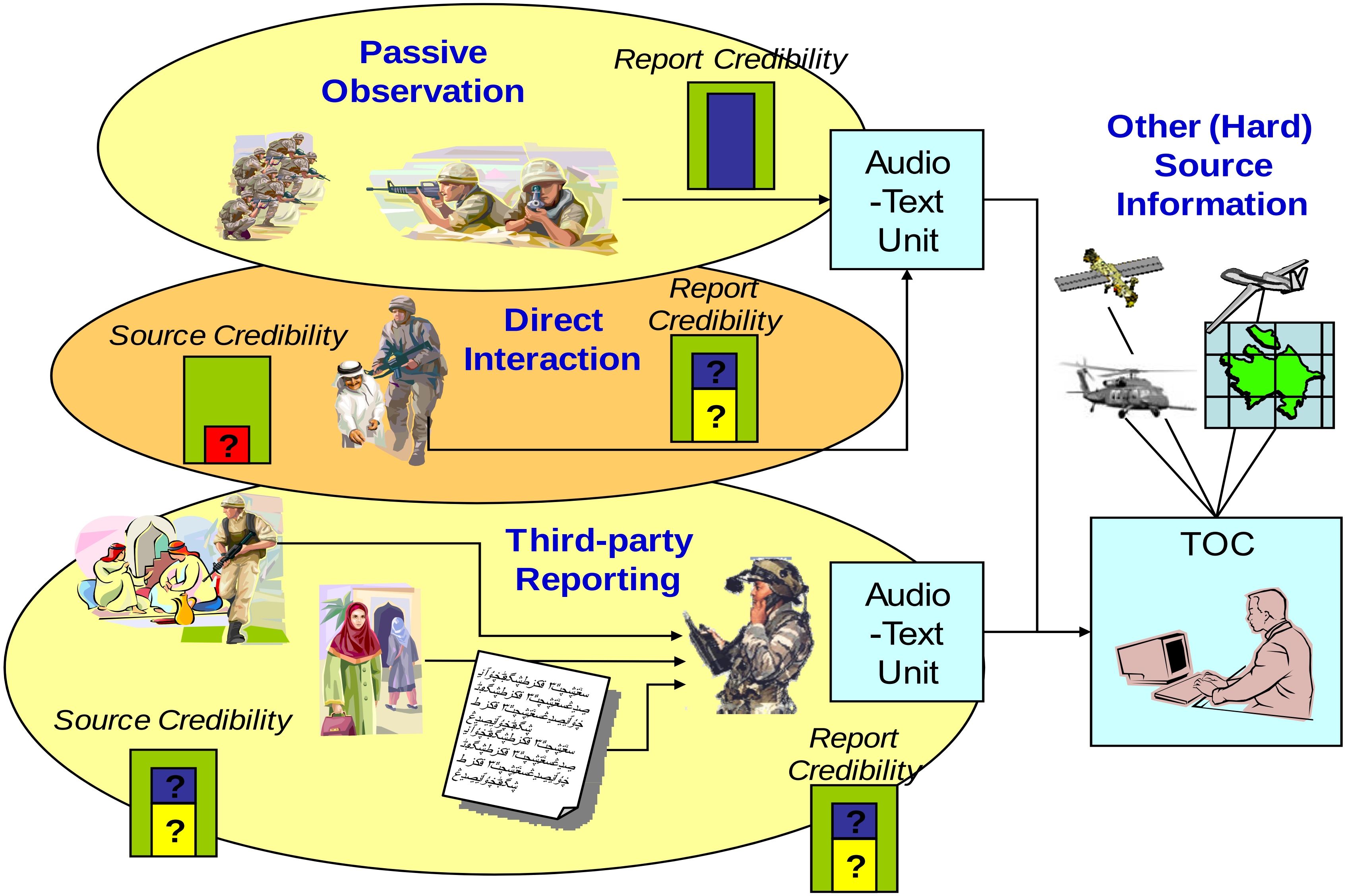
Humans can also judge intangibles --emotional state

Totally distinct from Hard Sensors Philosophy: Relations not directly observable—require reasoning over properties of entities

This line of thought suggests *that relations are the result of a process* of some type of comparison, ie [Brower, 2001], "an act of reasoning".

Brower, J., (2001) "Relations without Polyadic Properties: Albert the Great on the Nature and Ontological Status of Relations." Archiv für Geschichte der Philosophie 83: 225–57.

Categories of Human Input



Source Characterization—very difficult to generalize

Soft Data

Real World Truth

Average Human Soldier

Auto Text Extract & Semantics		
	Perceptual and Cognitive Errors in observation	є1
	Error in oral expression	є2
	Error in audio capture	є3
	Error in audio - to text Conversion	є4
	Error in text extraction	є5

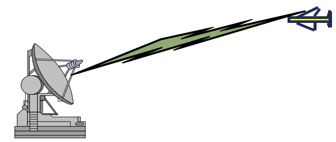
To Common Ref, Data Association

Some Obsvnl Data types qualified and Generalized

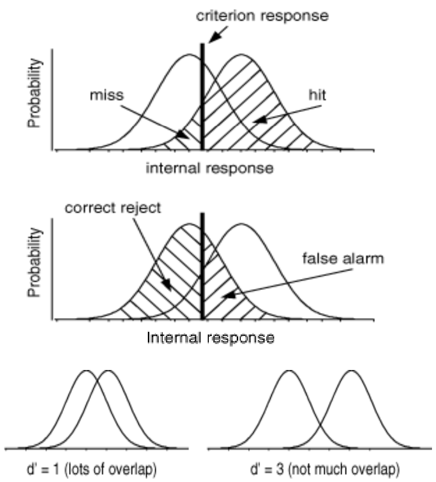
Some errors specific to obsvnl conds (need context)

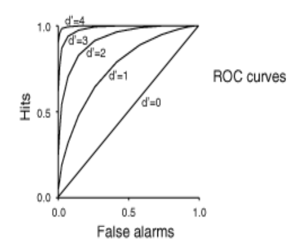
Some errors will go unlabeled, unknown

Hard Data



Calibration (Truth) Target





Pd (Obs Params)

To Common Ref, Data Association

Initial Prototype Approach