Scenario	Desc.	Year	Cycle	Malf. Order	Malfunction	TOE Order	TOE (training objective element)
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	1	TRIGGER step 1, Loss of Feedwater.
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	2	Acknowledges annunciators using directed communications t
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	3	Directs a manual reactor trip and entry into 0POP05-EO-EO00.
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	4	Perform Immediate 0POP05-EO-EO00 Immediate Actions from
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	5	Reports Lockout on E1C
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	6	Stops SDG 13
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	7	Takes SG C PORV, to manual.
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	2	Loss of All AFW Flow Rec	1	Transition to 0POP05-EO-ES01
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	2	Loss of All AFW Flow Rec	2	Crew begins monitoring Critical Safety Functions.
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	2	Loss of All AFW Flow Rec	3	At ES-0.1 step 3, crew recognizes that 'A' and 'C' MDFP are not
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	2	Loss of All AFW Flow Rec	4	(Prior to ES-0.1, step 8) Notices and reports NO AFW Flow mak
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RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	2	Loss of All AFW Flow Rec	11	ENTERS and Directs FRH1
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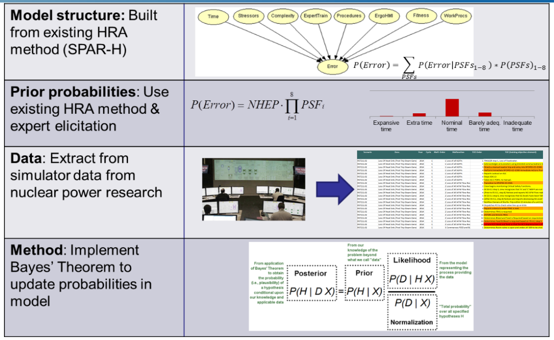
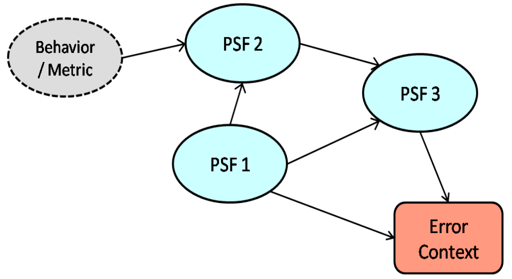
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	3	Commences FEED and BL	1	Determines Recirc valve is open and orders AF-009 to be shut





$$Pr(EC \cap PSF1 \cap PSF2 \cap PSF3 \cap BM)$$

A framework for using SACADA to enhance the qualitative and quantitative basis of HRA

Katrina M. Groth, Reuel Smith, Ramin Moradi

University of Maryland, Mechanical Engineering Department

Systems Risk and Reliability Analysis Lab

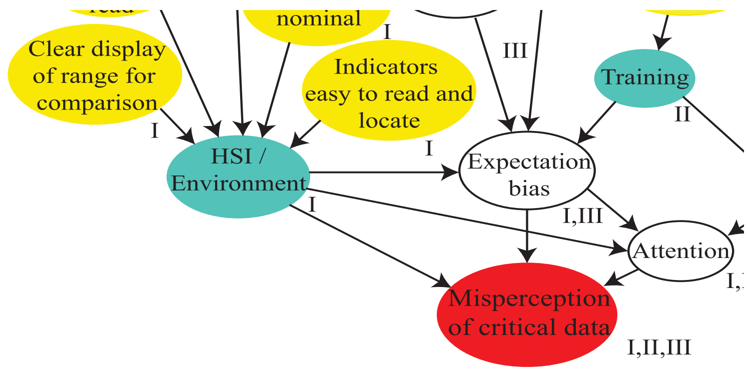
Center for Risk and Reliability

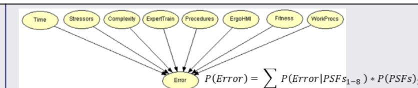
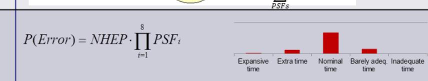
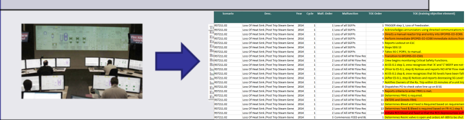
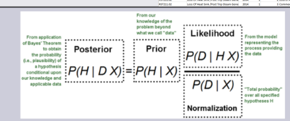
Motivation & Objective

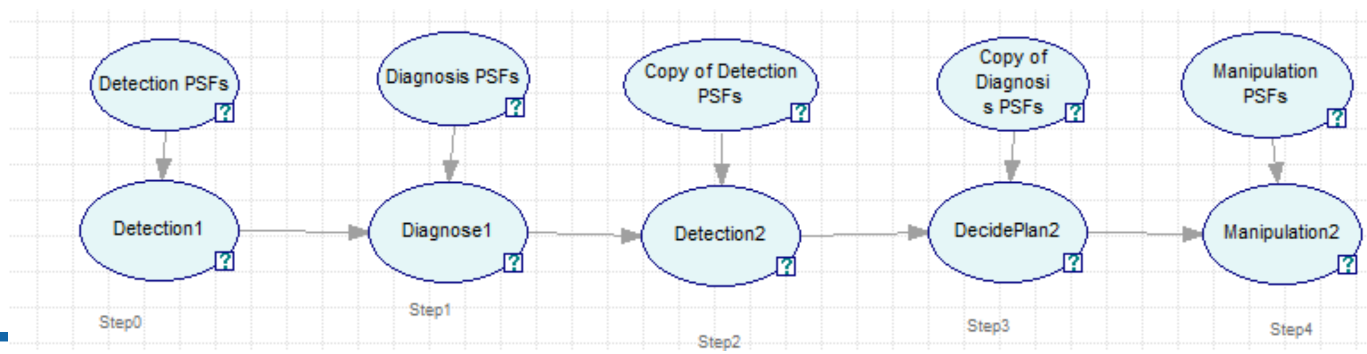
- Challenge: Existing HRA methods are heavily reliant on expert judgment
- International HRA data collection projects using control room simulator studies offer the opportunity to enhance HRA technical basis.
  - US NRC SACADA, OECD Halden Reactor Project, KAERI's HuREX/OPERA, etc.
- **Objective:** Develop a framework for using the SACADA data and Bayesian methods to improve HEP estimation & HRA technical basis.

Proposed algorithm

- **PIF hierarchy + HRA data + Cognitive Basis + DBNs**
- **Result: New paradigm for HRA.**
  - **Data-driven, science-based, dynamic, transparent, repeatable.**



Model structure: Built from existing HRA method (SPAR-H)	
Prior probabilities: Use existing HRA method & expert elicitation	
Data: Extract from simulator data from nuclear power research	
Method: Implement Bayes' Theorem to update probabilities in model	



Approach (& Presentation outline)

- Step 1: Understand the SACADA data & define desirable characteristics of data-informed HRA models
- Step 2: Define elements of the modeling framework
- Step 3: Develop detailed algorithm for modeling
- Step 4: Map SACADA data onto specific parts of the algorithm

Description of SACADA Data

- SACADA database developed by U. S. NRC (Chang et al)
- Data collection during operator simulator training (multiple participating organizations)

Scenario	Desc.	Year	Cycle	Malf. Order	Malfunction	TOE Order	TOE (training objective element)
RST211.02	Loss Of Heat Sink /Post Trip Steam Gene	2014	1	1	Loss of all SGFPs	1	TRIGGER step 1, Loss of Feedwater.
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Summary statistics (March 2018)	
# Scenarios	86
# Malfunctions	329
# TOEs (aka Steps)	2155
Avg # crews performing a step	12
# Crew-Steps (Total)	26153
# Unsat	209 (149 unique steps)
PIFs*	~50

*Situational Factors & Performance Factors

Description of SACADA Data: Situational Factors

SYRRA

	Situational Factors (Multistate)	Performance Factors (Multistate)
Detection	7	3
Diagnosis	6	4
Decision Making	4	2
Execution/Manipulation	5	3
Communication & Coordination	2	2
Overarching	5	7
Total	**29**	**21**

detecting the status change of an indicator.

tion

Detecting Mode:
- **Procedure directed check**: procedure directs crew to check a specific indicator or parameter.
- **Procedure directed monitoring**.
- **Knowledge driven monitoring**: knowledge of the situation or expectation of change in the parameter
- **Awareness/inspection**: non-procedurally directed monitoring or awareness of plant parameters.

Degree of change:
- **Slight change**: i.e., requires some effort to detect the change.
- **Distinct change**: i.e., prominent and readily detected if looked at.

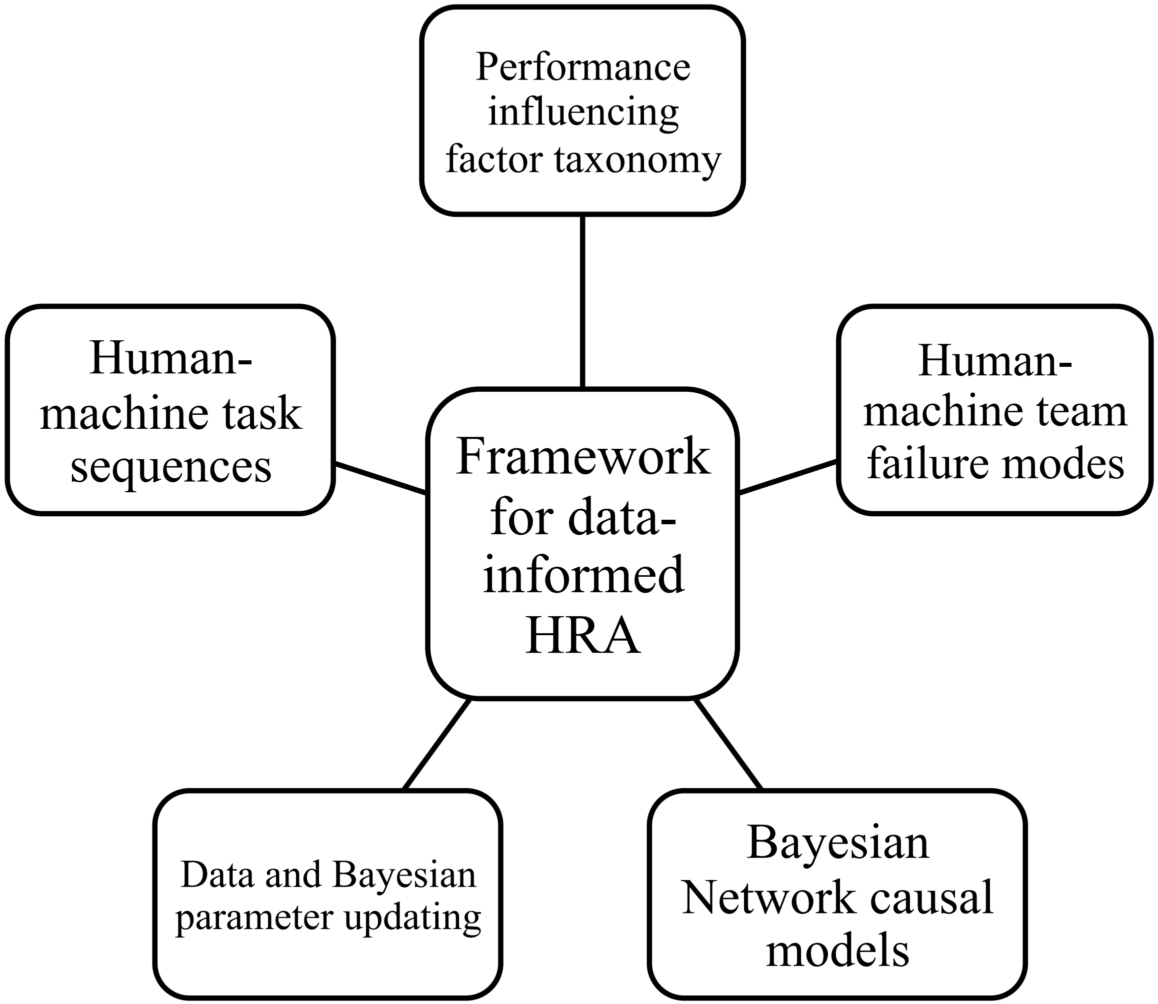
Miscellaneous:
- **No mimics**: requires operator to rely on memory.
- **Small indications**: can be read only from a close distance.
- **Similar displays**: multiple identical displays in the same bank of control panel.

Y. J. Chang *et al.*, "The SACADA database for human reliability and human performance," *Reliability Engineering & System Safety*, vol. 125, no. 0, pp. 117–133, 2014

Approach: Identified requirements for models

- **Using HRA data to improve HRA models requires new approaches**
- Desirable characteristics of advanced HRA models
  1. Using **underlying causal model rooted in strong technical basis** (combining psychological research, operating experience, simulator data)
  2. **Explicitly representing causal factors** that affect performance (& are collected in data)
  3. **Support qualitative & quantitative HRA**
  4. Framework should be **both data-informed and model-informed.**
  5. **Flexibility to accommodate changes** as our databases mature
  6. **Ability to fuse information from multiple sources of data & models**
  7. Generate detailed insights to improve human performance (beyond quantifying)

Elements of the framework



Taxonomy of PIFs

- Provides application neutral, clearly defined, non-overlapping set of factors for modeling use.

Organization

Organization-based

- Training Program
  - Availability
  - Quality
- Corrective Action Program
  - Availability
  - Quality
- Other Programs
  - Availability
  - Quality
- Safety Culture
- Management Activities
  - Staffing
    - Number
    - Qualifications
    - Team composition
  - Scheduling
    - Prioritization
    - Frequency
- Workplace adequacy
- Resources
  - Procedures
    - Availability
    - Quality
  - Tools
    - Availability
    - Quality
  - Necessary Information
    - Availability
    - Quality

Team

Team-based

- Communication
  - Availability
  - Quality
- Direct Supervision
  - Leadership
  - Team member
- Team Coordination
- Team Cohesion
- Role Awareness

Person

Person-based

- Attention
  - To Task
  - To Surroundings
- Physical & Psychological Abilities
  - Alertness
  - Fatigue
  - Impairment
  - Sensory Limits
  - Physical attributes
  - Other
- Bias
- Morale/Attitude
  - Problem Solving Style
  - Information Use
  - Prioritization
    - Conflicting Goals
    - Task Order
  - Compliance
- Knowledge/Experience
- Skills
- Familiarity with Situation

Machine

Machine-based

- HSI
  - Input
  - Output
- System Responses
  - Ambiguity

Situation

Situation-based

- External Environment
- Hardware & Software Conditions
- Task Load
- Time Load
- Other Loads
  - Non-task
  - Passive Information
- Task Complexity
  - Cognitive
  - Task Execution

Stressors

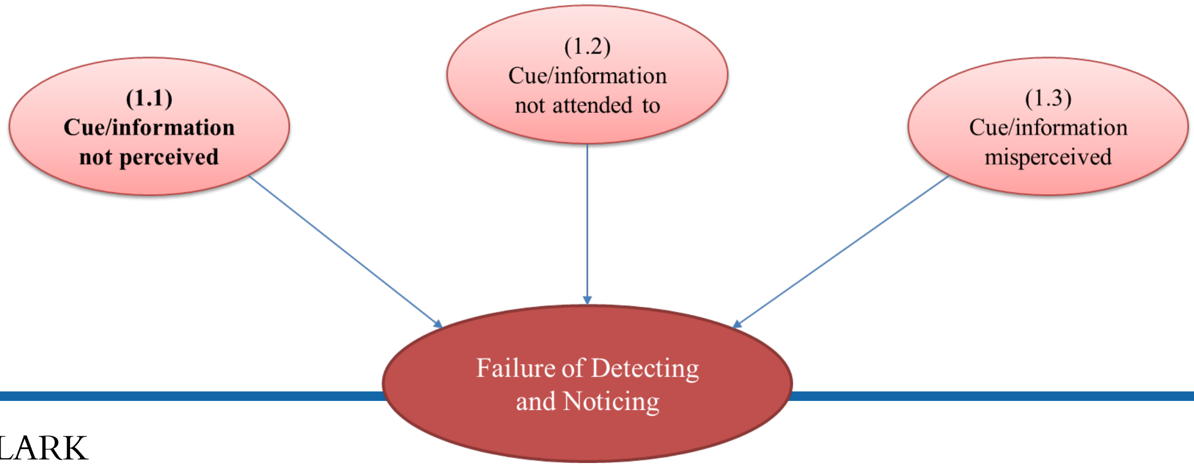
Stressor-based

- Perceived Situation:
  - Severity
  - Urgency
- Perceived Decision:
  - Responsibility
  - Impact
    - Personal
    - Plant
    - Society

Groth & Mosleh (2012). A data-informed PIF hierarchy for model-based Human Reliability Analysis. *Reliability Engineering and System Safety, 108*, 154-174.

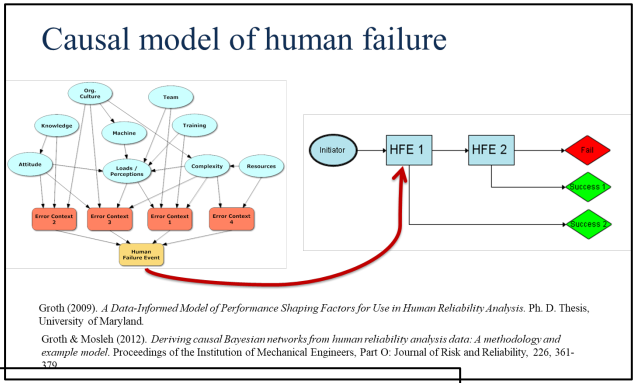
Human-machine team failure modes & mechanisms

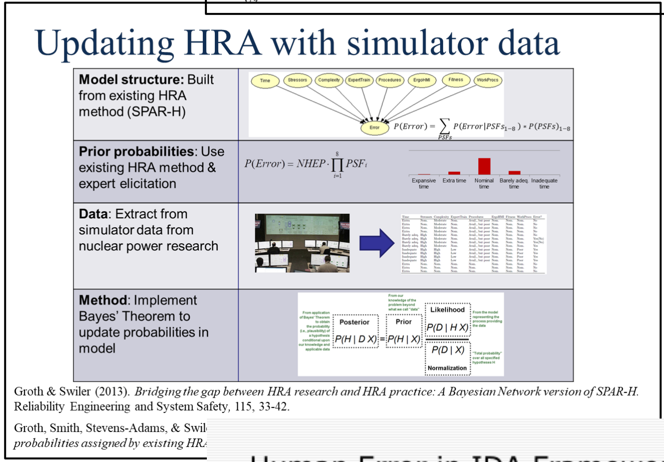
- **Current approach: Create one BN (one failure mode (FMs)) for each macro-cognitive function (MCF).**
  - Detection
  - Diagnosis
  - Decision Making
  - Execution
  - Teamwork/Communication
- NRC cognitive foundations report (Whaley et al) defined several failure modes, failure mechanisms & proximate causes;
  - Similar concepts used in IDHEAS and PHOENIX

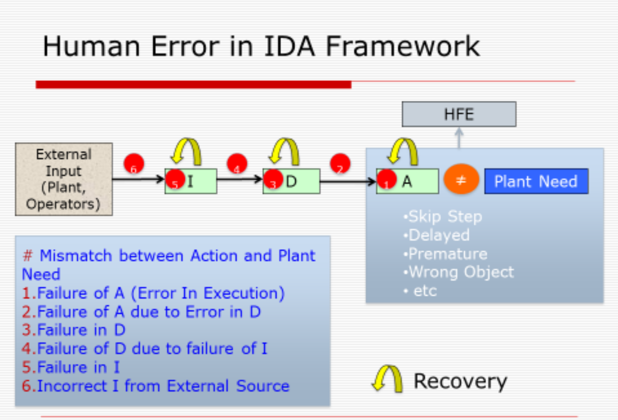


Three-pronged approach to modeling

- **Bayesian Networks causal models**
  - To capture causal relationships & uncertainty
- **Bayesian parameter updating**
  - To incorporate data into probability assignments
- **IDAC-like DBN model**
  - To capture scenario evolution & human-machine task sequences





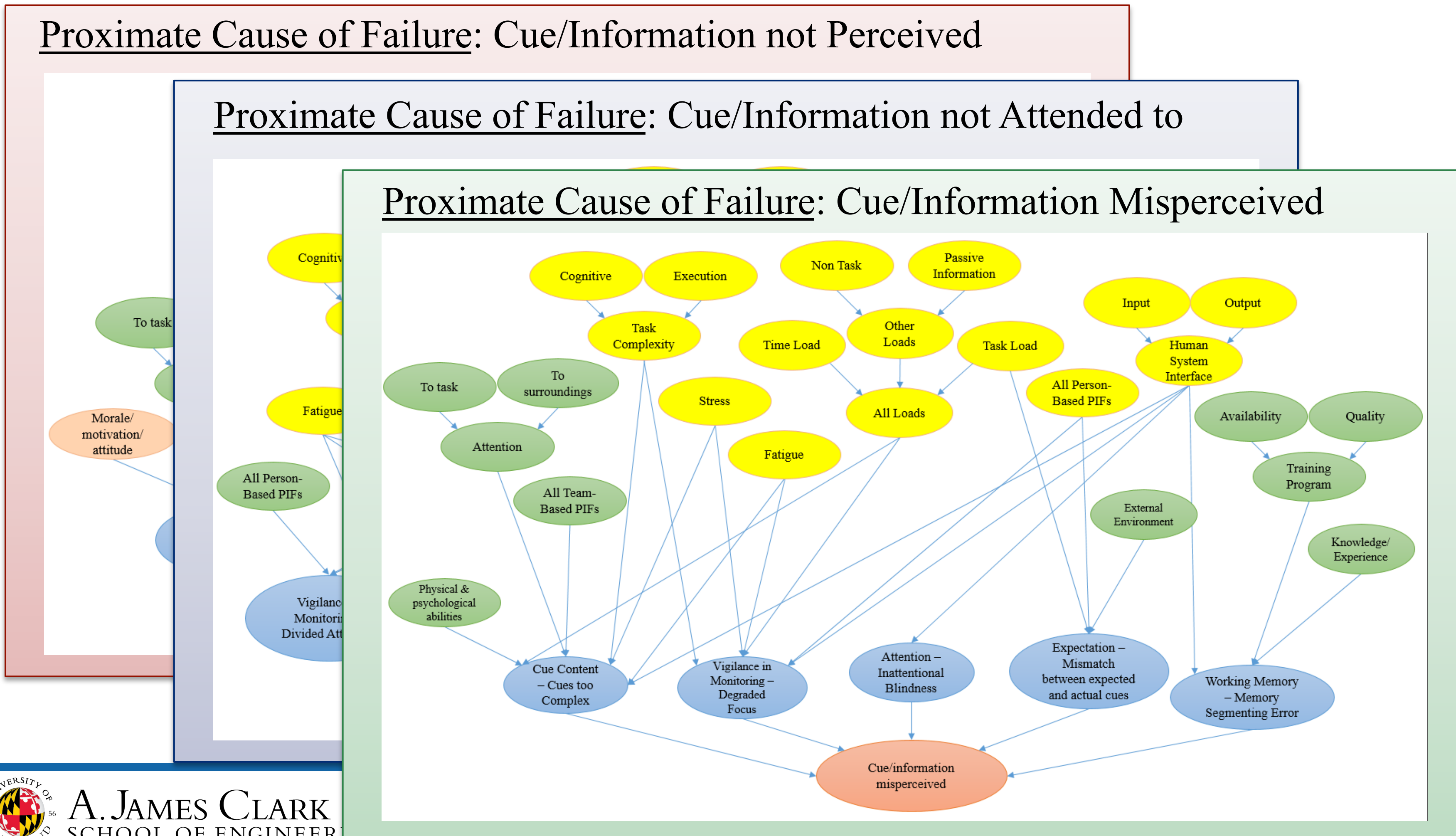


Summary: Proposed algorithm

- Build BN causal model for each macro-cognitive function.
  - Use PIF hierarchy from Groth 2012 to provide neutral terminology
  - Build causal structure for each BN based on published NRC "Cognitive Basis for HRA" (Whaley et al 2016) & mapping method in (Zwirglmaier, Straub, Groth 2017)
  - Use node reduction to simplify BBN structure for quantification (Zwirglmaier, Straub, Groth 2017)
- Quantify priors
  - Using IDHEAS & expert elicitation as done in Groth, Swiler, Smith.
- Update model using SACADA data (repeat for each data source)
  - Develop mapping of SACADA data onto nodes of BN model
  - Conduct Bayesian updating on the conditional probability tables using method from Groth, Swiler, Smith.
- Extend into dynamic space using DBNs + IDAC

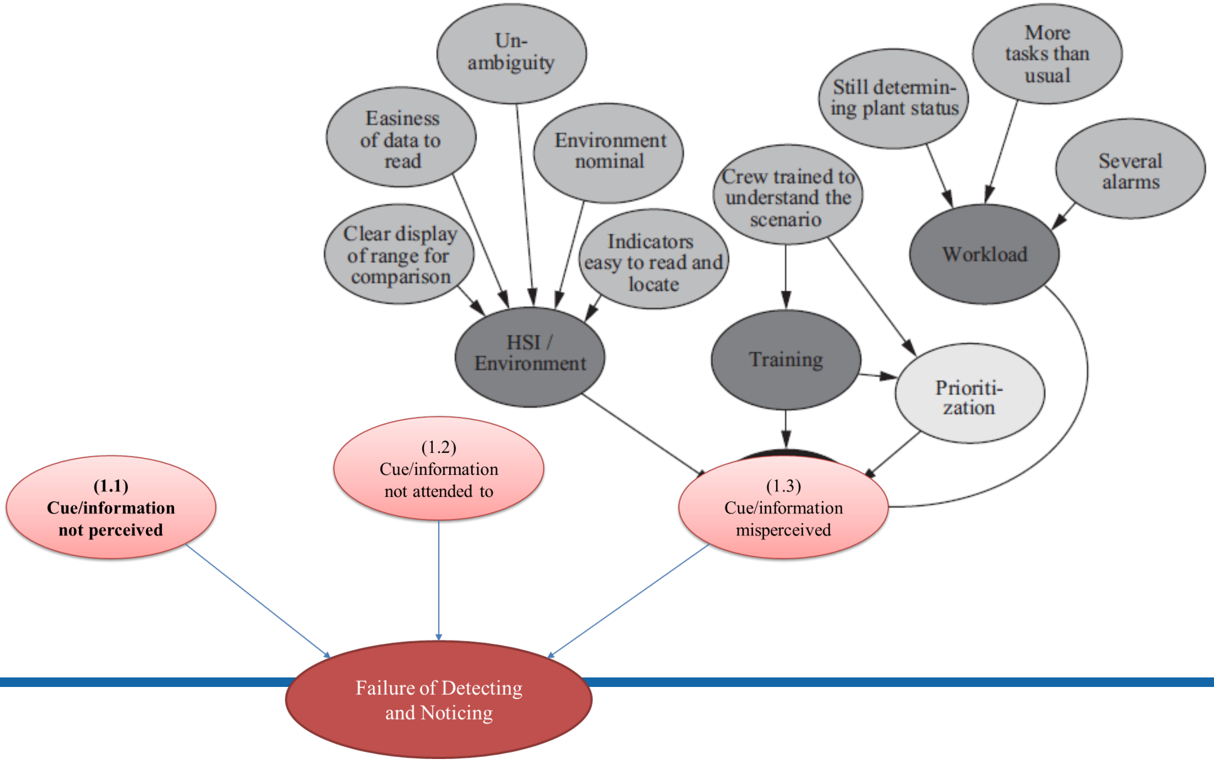
Full BNs for Detection (3 prox. Causes)

- **Create model structure explicitly links PIFs to crew failure mechanisms & modes** for each macrocognitive failure



Node reduction & data linking

- Follow approach from Zwirglmaier et al (2017) to formally eliminate nodes;
  - Goal: eliminate mathematically/structurally irrelevant nodes; enabling direct link between PIFs and FMs
- Then link renaming PIFs to specific data collection elements



Example mapping of SACADA elements to PIFs & FMs

SYRRA

- SACADA can be used for quantifying Pr(failure mode|PIFs)
- Unlikely to be used for Pr(PIFs)
- …Also for Pr(HFE|HFE) and Pr(PIFs|PIFs)

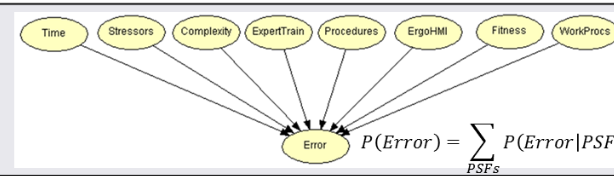
(I) Information Pre-processing
(D) Diagnosis and Decision Making
(A) Action Execution

SACADA State Name		SACADA States	IDA State			Variable Type			
			I	D	A	Indicator	PSF (Groth, 2012)	Characteristics	Using?
'Cognitive Type'		2:Diagnosis & Response Planning		X		X			Yes
		3:Manipulation			X	X			Yes
		4:External Communication			X	X			Yes
'Monitoring/Detection'	'Detection Type'	1:Alarm	X				HSI Output	Good	Yes
		2:Status Tile	X				HSI Output	Good	Yes
		3:Meter	X				HSI Output	Good	Yes
		4:Indication Light	X				HSI Output	Good	Yes
		5:Flag	X				HSI Output	Good	Yes
		6:Computer	X				HSI Output	Good	Yes
		7:Other	X				HSI Output	Good	Yes
'Alarms/Status Tile'	'Detection Mode'	1:Self-Revealing	X				HSI Output	Good	Yes
		2:Procedure Directed Check	X				Resources Procedures Availability Resources Procedures Quality	Good Good	Yes
		3:Procedure Directed Monitoring	X				Resources Procedures Availability Resources Procedures Quality	Good Good	Yes
		4:Awareness/Inspection	X				Attention to Surroundings	Good	Yes
	'Status of Alarm Board'	1:Dark	X				Other Loads Passive information	Normal	Yes
		2:Busy	X				Other Loads Passive information	Normal	Yes
		3:Overloaded	X				Other Loads Passive information Task Complexity	Bad Bad	Yes
	'Expectation of Alarm/Indication Change'	1:Expected	X				System Response	Good	Yes
		2:Not Expected	X				System Response	Bad	Yes
		3:Not Applicable	X					N/A	No

Method for Bayesian updating Pr(HEP|PIFs)

- Method developed by Groth & Swiler 2013, 2014 applied to SPAR- case study updated w/ Halden data
- Method is applicable to the new BNs + SACADA: would use IDHEAS or PHOENIX as a prior instead of SPAR-H.

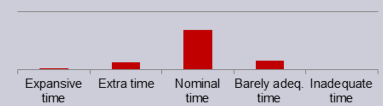
Model structure: Built from existing HRA method (SPAR-H)



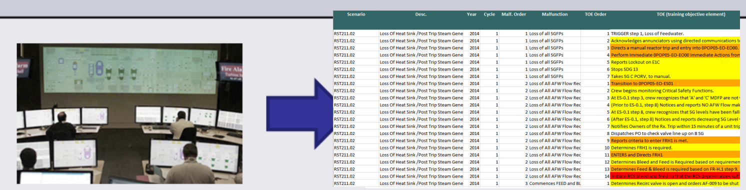
$$P(Error) = \sum_{PSFs} P(Error|PSFs_{1-8}) * P(PSFs)_{1-8}$$

Prior probabilities: Use existing HRA method & expert elicitation

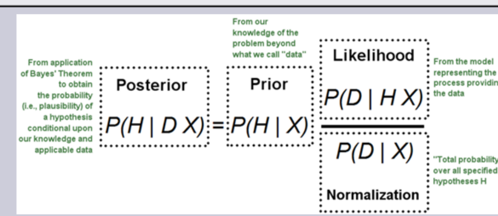
$$P(Error) = NHEP \cdot \prod_{i=1}^{8} PSF_i$$



Data: Extract from simulator data from nuclear power research



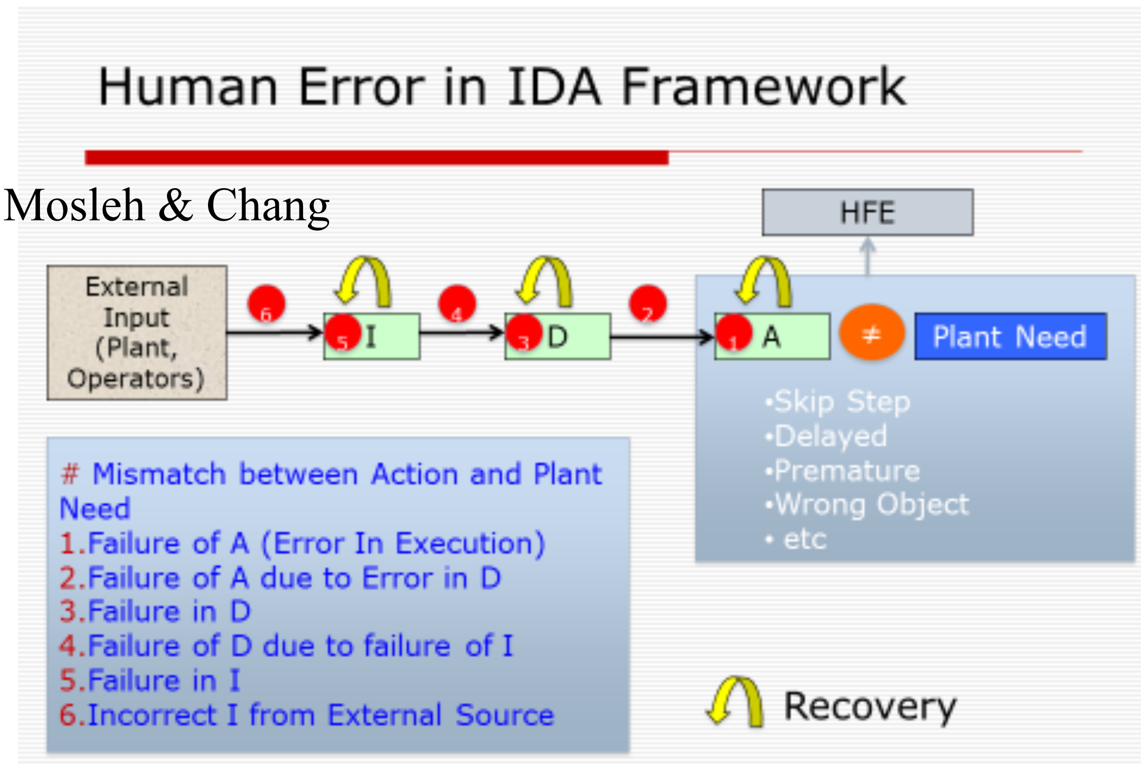
Method: Implement Bayes' Theorem to update probabilities in model



Next steps: Can we use SACADA to quantify (inter)dependency among HFEs & PIFs?

SACADA also shows first-of-kind potential for quantifying Pr(HFE|HFE) and Pr(PIFs|PIFs)

Mosleh & Chang



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1	1	Loss of all SGFPs	5	Reports Lockout on E1C
1	1	Loss of all SGFPs	6	Stops SDG 13
1	1	Loss of all SGFPs	7	Takes SG C PORV, to manual.
1	2	Loss of All AFW Flow Rec	1	Transition to 0POP05-EO-ES01
1	2	Loss of All AFW Flow Rec	2	Crew begins monitoring Critical Safety Functions.
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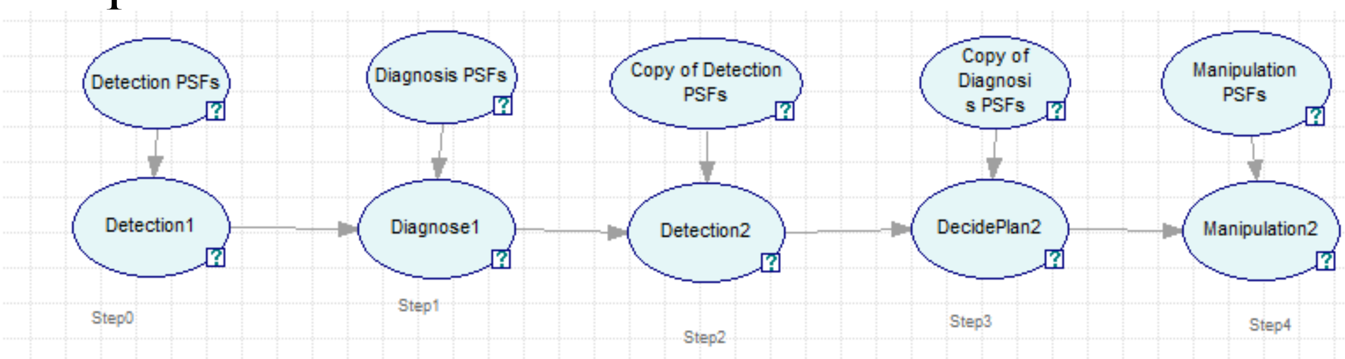
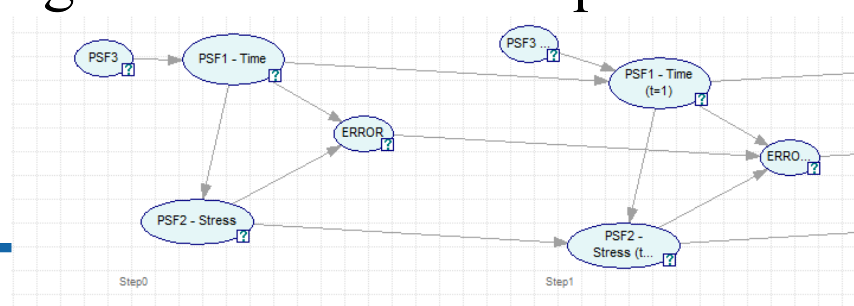
1	3	Commences FEED and BL	1	Determines Recirc valve is open and orders AF-009 to be shut

Next steps: DBNs for HFE dependency

- Dynamic Belief Networks (DBNs) to model dependency between sequential activities (human failure events)
  - First proposed in Groth (2009), Mosleh (2012); Expanded in PHOENIX (Ekanem & Mosleh 2013) and HUNTER (Boring et al 2015)
- Repeated BNs for each MCF:

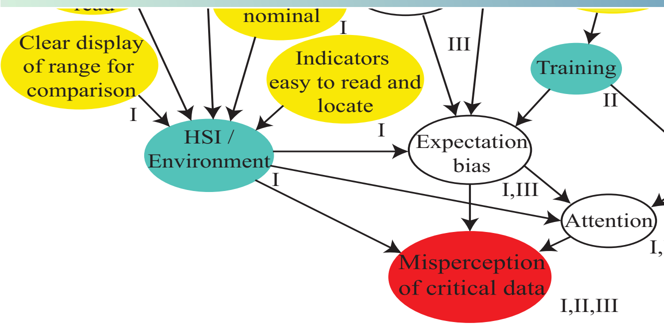


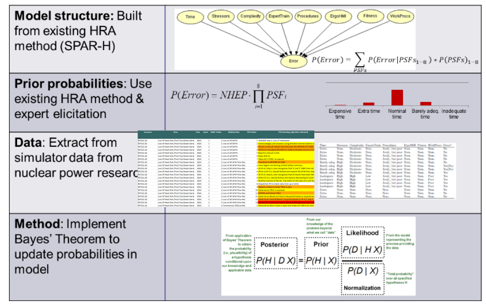
- With PIF lag/linger & HFE-to-subsequent-HFE dependency

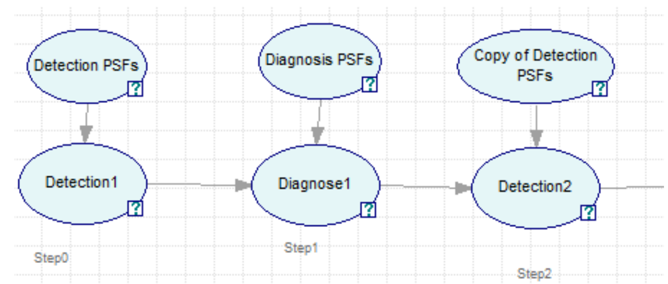


Conclusions

1. Using HRA data to improve HRA models adds credibility, traceability – but requires new approaches.
2. HRA data needs to be combined with causal understanding of failure (cognitive “physics of failure” for human-machine teams) to deal with inherent data limitations – requires BNs & data fusion.
3. Each data source can quantify a portion of the models - SACADA readily enables quantification of Pr(failure mode|PIFs)
4. New potential of SACADA: enabling first look into temporal evolution of human error & PIFs







Thank you!

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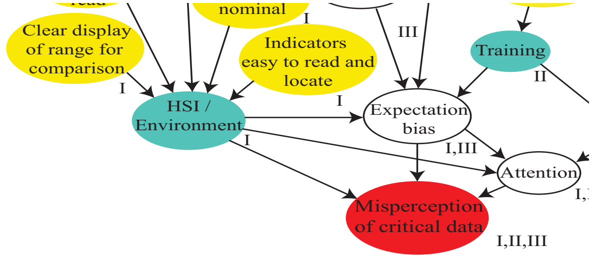
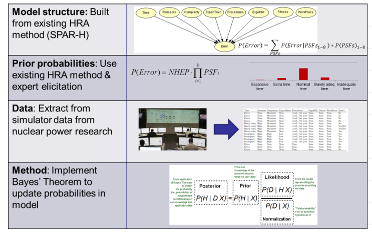
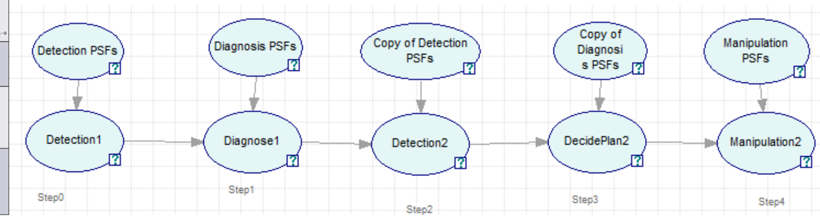
Draft Algorithm







1. For each MCF: Create a causal map (BN) of the relationship between the failure modes, proximate causes of failure, failure mechanisms, and PIFs (Zwirglmaier, Straub, Groth 2017)
2. Use node reduction to simplify BBN structure for quantification (Zwirglmaier, Straub, Groth 2017)
3. Identify which arcs & probability tables can be quantified using each type of data
    1. Pr(PIFs)) and Pr(PIFs|PIFs)
    2. Pr(Failure modes | PIFs)
    3. If needed: Pr(failure modes|failure mechanisms) and Pr(Failure mechanisms | PIFs)
4. For each data source: map data source variables to BN nodes
5. For each additional data source: Bayesian update probability of relevant arcs (See: Groth, Swiler, Smith 2014)
6. Extend BN to DBN to capture temporal dependencies.
7. End. (Now use the BBN for HRA)

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Matlab Algorithm

- Implemented algorithm MATLAB and GeNie that performs the following tasks:
  - Read and process SACADA data into data analysis elements:
    - State Names, States, and State Assignments for SACADA Data
    - Conditional probability for PIFs with respect to SACADA States
    - State Assignments and PIF's of all data under SACADA States
  - Generate BBN conditional probability tables from the state and PIF data
  - Elicit prior data into prior distribution for (HEP|PIFs), Pr(PSFs)
  - OR (or Noisy OR) gate for Pr(failure mode|failure mechanisms) and Pr(error|failure mode)
  - Perform Bayesian updating and produce the posterior HEP distribution

Summary of proposed model development approach

- Use clearly defined taxonomy of PIFs as basis for modeling
  - Provides application neutral, clearly defined, non-overlapping set of factors for modeling use
- Build BN causal model for each failure mode (based on macro-cognitive functions & human failure mechanisms)
  - Build causal structure for each BN based on published NRC Cognitive Basis for HRA (Whaley et al 2016).
- Apply node reduction to simplify model structure to critical variables
- Quantify prior model(expert elicitation + existing HRA + other data)
  - Using existing HRA methods and published data sources as done in previous work.
- Bayesian Update model using SACADA data
  - Develop mapping of SACADA data onto nodes of BN model
  - Conduct Bayesian updating on the conditional probability tables using method from Groth, Swiler, Smith.
- Extend into dynamic space using DBNs + IDAC

Taxonomy of PIFs

- Provides application neutral, clearly defined, non-overlapping set of causal factors for modeling use.

Organization

- Training Program
  - Availability
  - Quality
- Corrective Action Program
  - Availability
  - Quality
- Other Programs
  - Availability
  - Quality
- Safety Culture
- Management Activities
  - Staffing
    - Number
    - Qualification
    - Team Composition
  - Scheduling
    - Prioritization
    - Frequency
- Workplace Adequacy
- Resources
  - Procedures
    - Availability
    - Quality
  - Tools
    - Availability
    - Quality
  - Necessary Information
    - Availability
    - Quality

Team

- Communication
  - Availability
  - Quality
- Direct Supervision
  - Leadership
  - Team Member
- Team Coordination
- Team Cohesion
- Role Awareness

Person

- Attention
  - To Task
  - To Surroundings
- Physical & Psychological Abilities
  - Alertness
  - Fatigue
  - Impairment
  - Sensory Limits
  - Physical Attributes
  - Other
- Knowledge/Experience
- Skills
- Bias
- Familiarity with Situation
- Morale/Motivation/Attitude
  - Problem Solving Style
  - Information Use
  - Prioritization
    - Conflicting Goals
    - Task Order
  - Compliance

Machine

- HSI
  - Input
  - Output
- System Response
  - Ambiguity

Situation

- External Environment
- Hardware & Software Conditions
- Task Load
- Time Load
- Other Loads
  - Non-task
  - Passive Information
- Task Complexity
  - Cognitive
  - Execution

Stressors

- Severity
- Urgency
- Perceived Decision
- Responsibility
- Impact
  - Personal
  - Plant
  - Society

Groth & Mosleh (2012). A data-informed PIF hierarchy for model-based Human Reliability Analysis. *Reliability Engineering and System Safety, 108*, 154-174.

Example BN built directly from SACADA "Diagnosis" SFs