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July 18 - 21, 2016

Towards a Quantitative Framework for Evaluating the Expressive Power of Conceptual System Models

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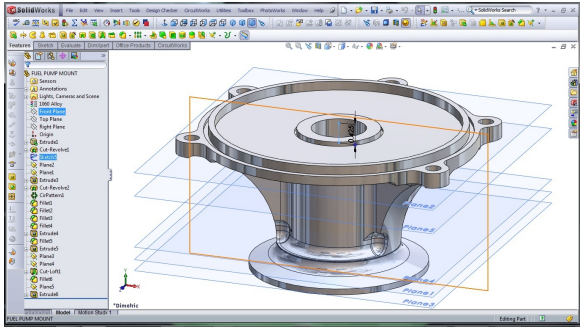
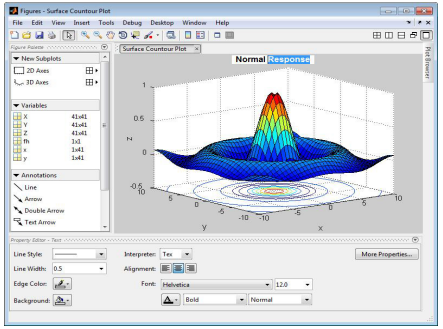
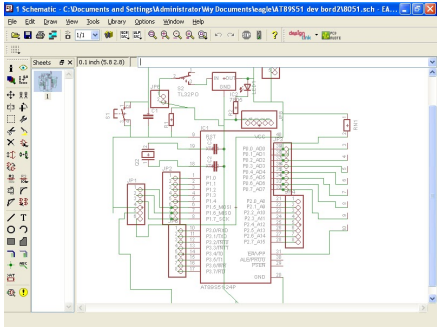
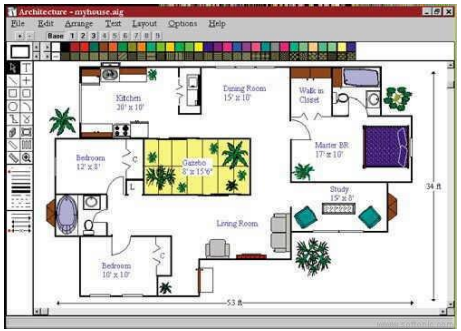
Technion – Israel Institute of Technology

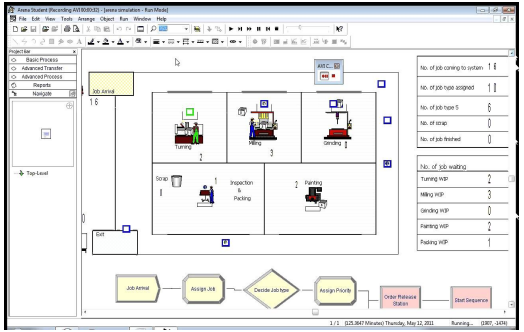
Engineering is founded on modeling

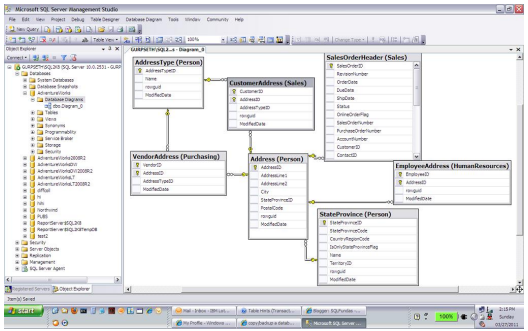












Why model? What are models for?

- **Understanding:** clarifying, explaining a concept, rationalizing "how things look and work"
- **Communicating:** Sharing and ideas, brainstorming, experimenting with new ideas
- **Early Lifecycle:** Architecting, analysis, conceptual design, concept evaluating & selecting, optimizing, what-if, operational concepts and problems, formal validating and verifying design, consistency, potential scenarios and results
- **Late Lifecycle:** Design, development, testing, demonstration, simulation, manufacturing, assembly, installation
- **Documentation:** Current, intended, expected system
- **Control:** Monitoring, tracking, evaluating, behavior regulating

Why should we care about model value?

- How many times have you heard systems engineers, architects, or designers ask questions like:
  - "How **informative** is a given model?“
  - "How much **information** does (or can) a model convey?“
  - "Which of two models of the same problem is more **informative**?"
- Too difficult to answer?
- Yet needs to be pursued!

Can we define model value?

- Assessing models for faithfully specifying systems is intuitive, if at all pursued.
- Model formality is critical for encoding, verification, validation, consistency checking, reproduction, and comparison with other models.
- The value of a model is affected by the amount and quality of information that the model expresses.
- **Yet, research on conceptual model evaluation has been surprisingly scarce!**

Problem: System model utility is not being measured

- **No clear definition** of the informative value of a model
- **No finite reference** for relative information contribution
- **Lack of objectivity** of the value of information
- **No convention of quantitative measuring** and analysis of model utility
- **Decision-theoretic information value** is difficult to attribute to model facts
- **Lack of support** by modeling and architecting frameworks, processes, tools

Model Informativity

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- A measure of the value of information that a model conveys.
- A highly useful index for evaluation and comparison of models and versions.
- Informativity can be perceived as a form of utility (Azrieli & Lehrer, 2008).
- Information utility of is difficult to quantify (Bernardo, 1979).
- Utility is subjective.
- Model informativity is subjective – in the eyes of the model user.
- Viable as utility in its own right

Previous Research

- Akaike's Information Criterion (AIC) for predictive model efficiency.

$$AIC = -2 \cdot \log L(\theta) + 2k$$ (Akaike, 1974)

- Variations of AIC for information complexity in statistical models (Bozdogan, 2000)
- Studies of the informativity of knowledge representations (Bowdle & Gentner, 1997), (Frankel, Kothari, & Weber, 2006), (Trentelman, 2009)
- Variability among several models of the same problem (Goldstein et al. 2008)
- Structural/functional qualitative/quantitative measures of informativity (Reich, 2002)

Model Informativity Analysis – MIA

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- A quantitative, utility-based approach for measuring the value of the information in conceptual models
- A prescriptive approach for boosting the model's expressive power
- Based on analyzing the knowledge represented by the model.

Model Informativity Index

- EP(M) = f(I(M),*other things*) // EP: Expressive Power, M = Model, I = Informativity
- $I(M) = \Sigma_{specs}(INF(spec))$ // INF = Information figure in [0..1] of specs (statement, model facts) in M.
- $INF(spec) = \Sigma_{IEFs}(INF_{IEF}(spec))$ // IEF = Informativity Enhancing Factor: an attribute of a statement that determines how to glean information about the system from that statement
- $INF_{IEF}(M) = \Sigma_{IEFs}(INF_{IEF}(spec))$ // Total IEF contribution

Informativity Delta

- I(M), INF_{IEF}(M) are unbounded measures.
- The value of interest is the ***change in informativity as the model evolves*** (like a stock exchange or price index):

$$\Delta I(I(M{\downarrow}1),I(M{\downarrow}0))=I(M{\downarrow}1)/I(M{\downarrow}0)-1$$

  - $M{\downarrow}1$ is the relevant version of the model.
  - $M{\downarrow}0$ is the reference version of the model.

Informativity Enhancing Factors

Specification Pattern	**Uncertainty**
Meta-Specification	**Model Management**

Specification Patterns and Graphical Constructs

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- A model consist of facts
  - expressed graphically as constructs that follow specification patterns
- Spec. patterns enhance formality and uniformity
- A modeling language is evaluated by its capability to support spec. patterns
  - In OPM each construct is translated into a textual statements – easy to analyze.

Optimizing number of spec patterns to increase informativity

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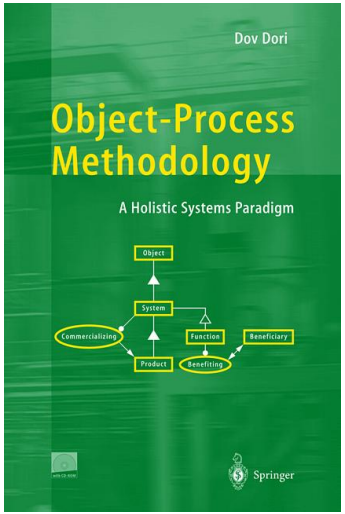
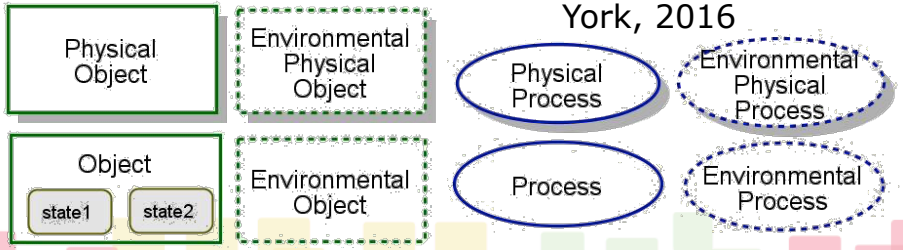
- Spec patterns are where syntax meets semantics.
- If there are not enough spec patterns – no differentiation.
- If there are too many spec patterns – over-discriminative, difficult to maintain.
- The challenge: minimize the number of spec patterns while maximizing semantic richness.

Object-Process Methodology



Dov Dori, [Object-Process Methodology - A Holistic Systems Paradigm](), Springer Verlag, Berlin, Heidelberg, New York, 2002

Dov Dori, [Model-Based Systems Engineering with OPM and SysML](), Springer, New York, 2016



Object Process Methodology - OPM

Conceptual modeling language and methodology

Based on the minimal universal ontology

A single diagram kind expresses system structure, behavior, and function

Diagrams are organized hierarchically

Bimodal: the model is both graphical (OPD) and textual (OPL).

Standard: OPM is ISO 19450

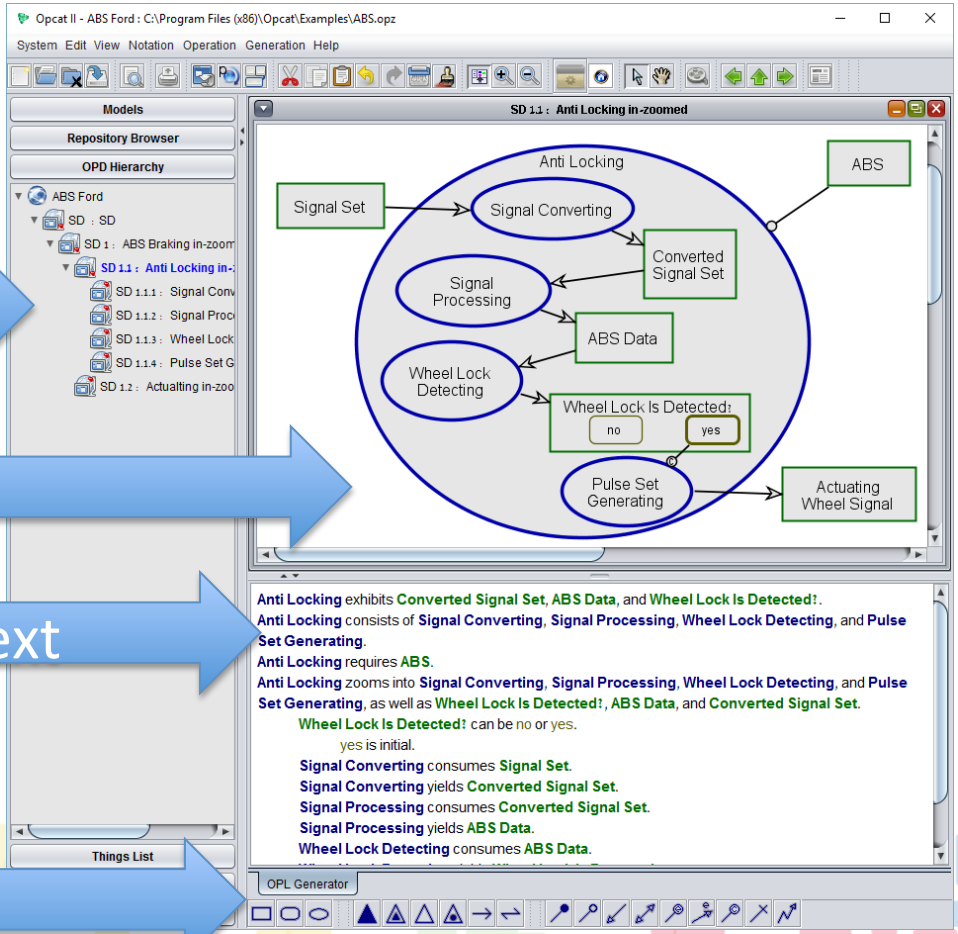
Constructing OPM models with OPCAT

OPD Hierarchy

Current OPD

Current OPD's OPL Text

OPM Notation



Spec Patterns in OPM

OPM consists of 22 Specification Patterns.

Specification Pattern exhibits Graphical Pattern, Textual Pattern, Execution Semantics, Informativity Score, and at least one Specification Refinement.

Informativity Score consists of Execution Semantics, Informativity Factor, and Subjective Importance.

Specification Refinement exhibits Informativity Factor.

OPM Model is instance of an OPM.

OPM Model consists of many OPDs.

OPD consists of Model Fact.

Model Fact is instance of a Specification Pattern.

Model Fact exhibits OPL Sentence, OPD Construct, and Informativity Figure.

OPL Sentence is instance of a Textual Pattern.

OPD Construct is instance of a Graphical Pattern.

Informativity Figure is instance of an Informativity Score.

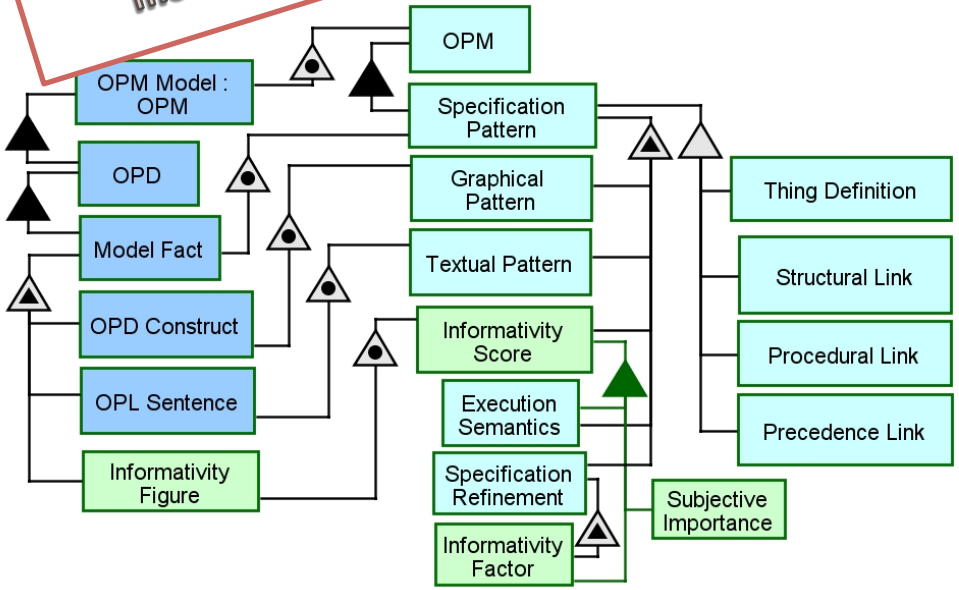
Thing Definition is a Specification Pattern.

Structural Link is a Specification Pattern.

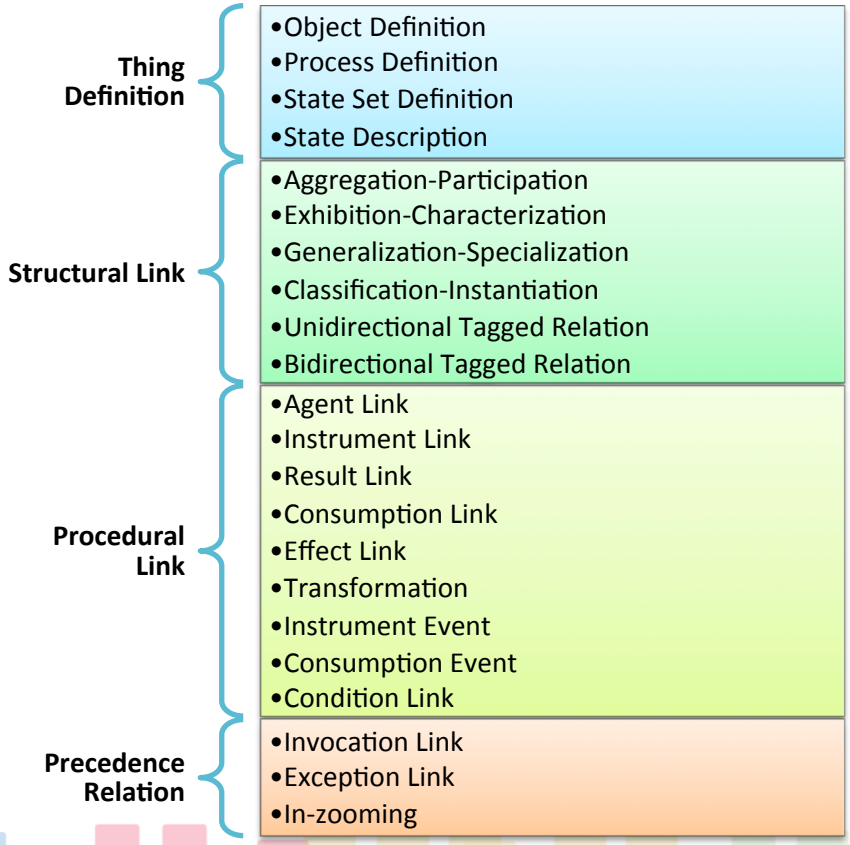
Procedural Link is a Specification Pattern.

Precedence Link is a Specification Pattern.

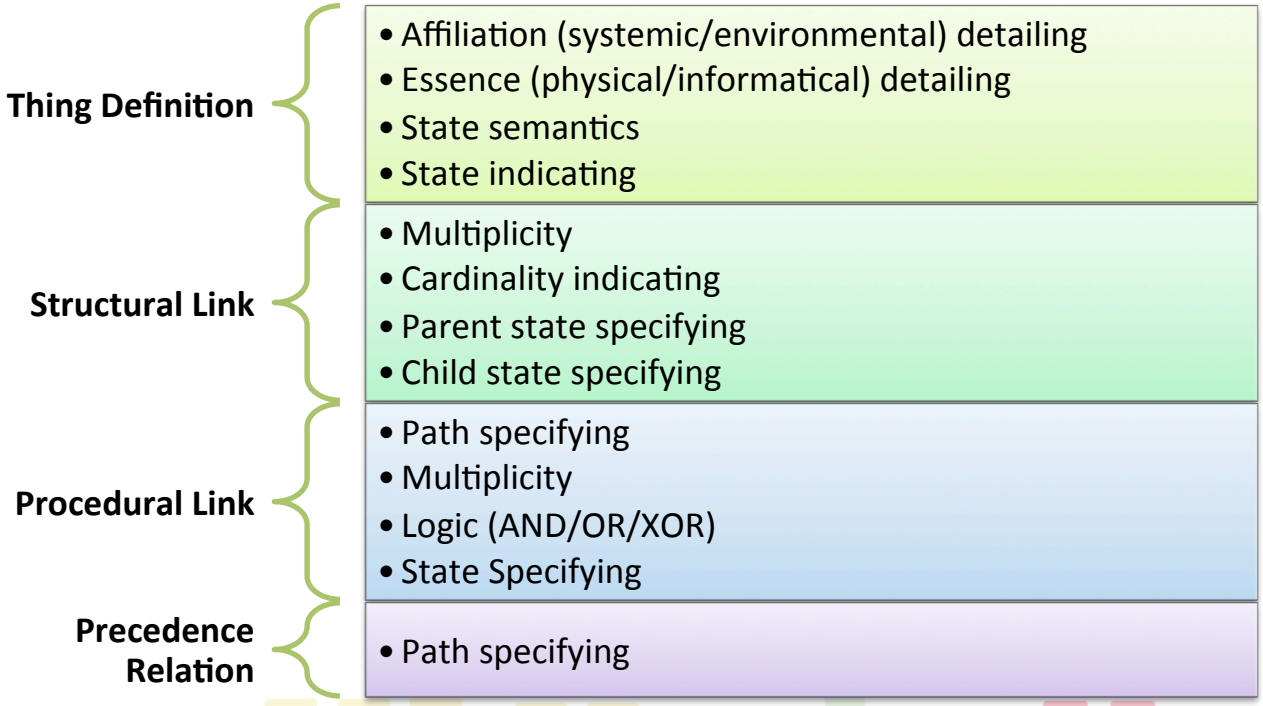
A conceptual model of informativity analysis in OPM models, using OPM!



OPM has 22 specification patterns



Specification Pattern Refinements



Spec Pattern Informativity Figure

Spec Pattern Group	Spec Pattern	Distinctive OPL Phrase	INF
Thing Definition	Object Definition	object	0.0
	Process Definition	process	0.0
	State Set Definition	can be	0.25
	State Description	initial, final	0.50
Structural Link	Aggregation-Participation	consists of	0.50
	Exhibition-Characterization	exhibits	0.50
	Generalization-Specification	is a, is an	0.25
	Classification-Instantiation	instance	0.25
	Unidirectional Tagged Relation	relates to	0.50
	Bidirectional Tagged Relation	are	0.50
Procedural Link	Agent Link	handles	0.50
	Resource Link	requires	0.75
	Result Link	yields	1.00
	Consumption Link	consumes	0.75
	Effect Link	affects	0.50
	Transformation	changes	1.00
	Instrument Event	triggers	0.75
	Condition Link	occurs if	1.00
Precedence Link	Invocation Link	invokes	1.00
	Exception Link	when it lasts	0.50
	In-zooming	zooms into	1.00

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$INF_{Spec\_Pattern}$ is subjective and depends on:

1. Model orientation.
2. Subjective preference.
3. Execution semantics.

Specification Uncertainty

- So far we have assumed that any statement's informativity is deterministic and time/timing-insensitive.
- We should also take into consideration stochastic factors such as:
  - The reliability of the statement
  - The possibility that the information is already known
  - The ambiguity vs simplification potential of the information

Informativity and Uncertainty: reliability

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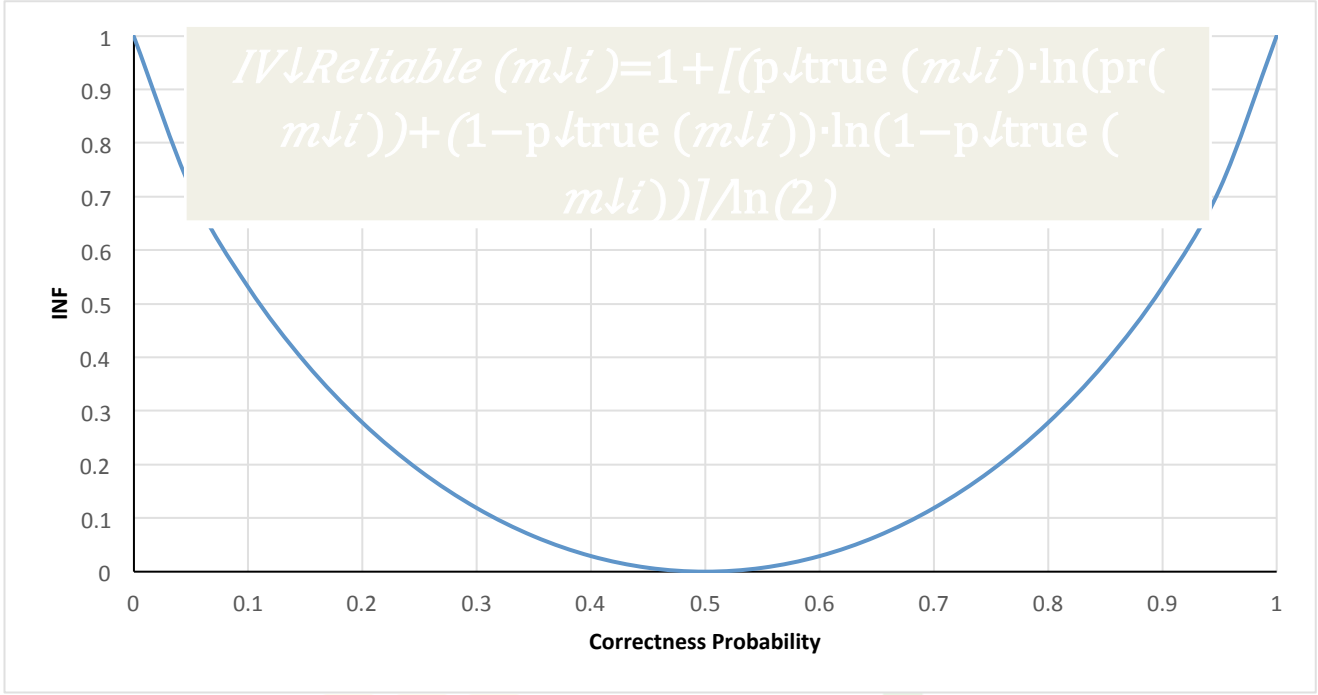
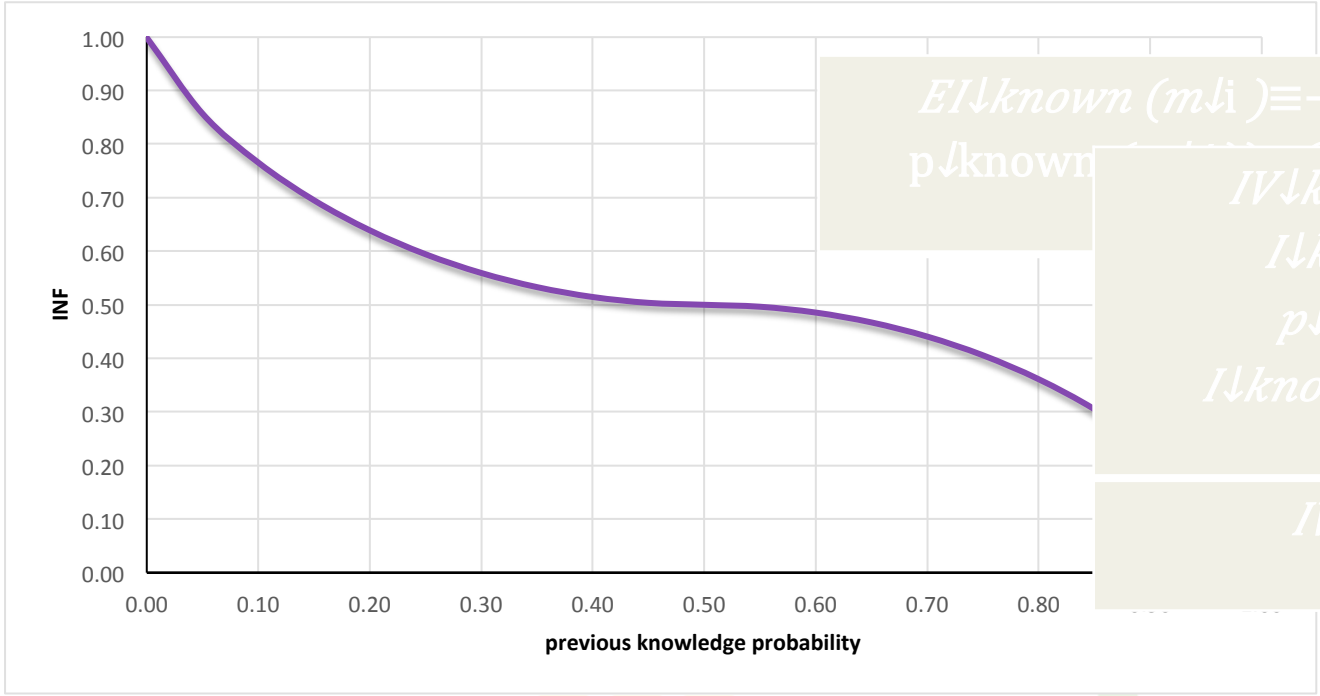
$$IV{\downarrow}Reliable\ (m{\downarrow}i) = 1 + [(p{\downarrow}true\ (m{\downarrow}i) \cdot \ln(pr(m{\downarrow}i)) + (1 - p{\downarrow}true\ (m{\downarrow}i)) \cdot \ln(1 - p{\downarrow}true\ (m{\downarrow}i))] / \ln(2)$$



Informativity and Uncertainty: discovery

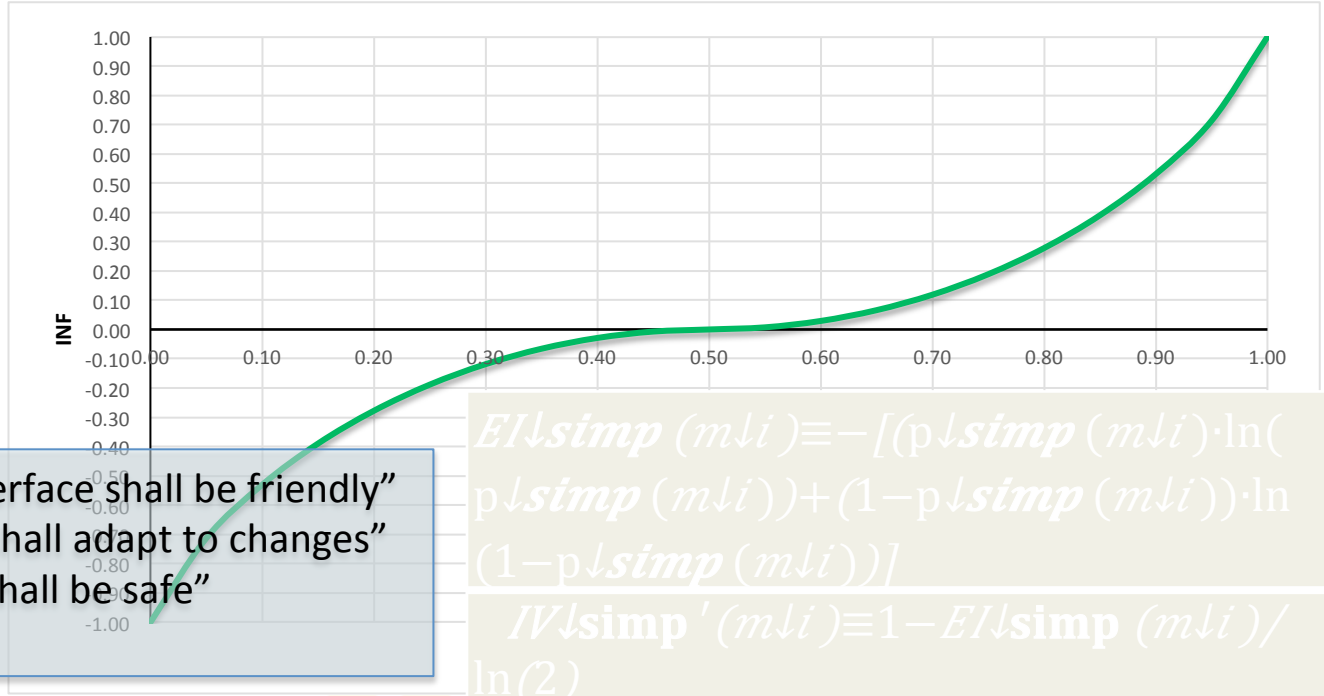


$$EI{\downarrow}known\ (m{\downarrow}i\ )\equiv-[(\mathrm{p}{\downarrow}\mathrm{known}\ (m{\downarrow}i\ )\cdot\ln($$
$$\mathrm{p}{\downarrow}\mathrm{known}$$

$$IV{\downarrow}known'(m{\downarrow}i)\equiv\{\blacksquare 1+E$$
$$I{\downarrow}known\ (m{\downarrow}i\ )/\ln(2)\ ,\&$$
$$p{\downarrow}known\ (m{\downarrow}i\ )\leq 0.5@E$$
$$I{\downarrow}known\ (m{\downarrow}i\ )/\ln(2)\ -1,\&$$
$$p{\downarrow}known\ (m{\downarrow}i\ )>0.5$$

$$IV{\downarrow}known\ (m{\downarrow}i\ )=0.5(I$$
$$V{\downarrow}known'(m{\downarrow}i\ )+1)$$

Informativity and Uncertainty: simplification



"The User Interface shall be friendly"
"The System shall adapt to changes"
"The vehicle shall be safe"

$$EI{\downarrow}\textbf{simp}\,(m{\downarrow}i)\equiv-[(\mathrm{p}{\downarrow}\textbf{simp}\,(m{\downarrow}i)\cdot\ln(\mathrm{p}{\downarrow}\textbf{simp}\,(m{\downarrow}i))+(1-\mathrm{p}{\downarrow}\textbf{simp}\,(m{\downarrow}i))\cdot\ln(1-\mathrm{p}{\downarrow}\textbf{simp}\,(m{\downarrow}i))]$$

$$IV{\downarrow}\textbf{simp}'(m{\downarrow}i)\equiv 1-EI{\downarrow}\textbf{simp}\,(m{\downarrow}i)/\ln(2)$$

$$IV{\downarrow}\textbf{simp}\,(m{\downarrow}i)\equiv\{\blacksquare\blacksquare-IV{\downarrow}\textbf{simp}'(m{\downarrow}i),@ IV{\downarrow}\textbf{simp}'(m{\downarrow}i)\ \&\blacksquare\mathrm{p}{\downarrow}\textbf{simp}\,(m{\downarrow}i)\leq 0.5@$$

Meta Specification

- Details about specification statements:
  - Maturity
  - Category
  - Rationale
  - Priority
  - Ownership

Maturity Levels

Precedence	Maturity Level	Explanation	INF
1	Initiation	Coming of idea into existence	0.6
2	Conception	Creating a systems concept	0.7
3	Elaboration	Detailing the design	0.9
4	Allocation	Assigning or posting for implementation	1.0
5	Implementation	Developing or prototyping	0.8
5	Verification	Testing and evaluation	0.7
6	Production	Manufacturing or integrating	0.6
7	Introduction	Marketing deploying, or driving adoption	0.5
8	Operation & Maintenance	Using and maintaining	0.4
9	Retirement	Phasing the system out	0.1
99	Not specified		0.0

Category

Precedence	Category	INF
1	Contractual Commitment	1.0
2	Requirement	0.9
3	Engineering Design	0.8
4	Implementation	0.7
5	Risk Effect / Response	0.6
6	Physical Fact / Constraint	0.5
99	Not specified	0.0

Specification Management

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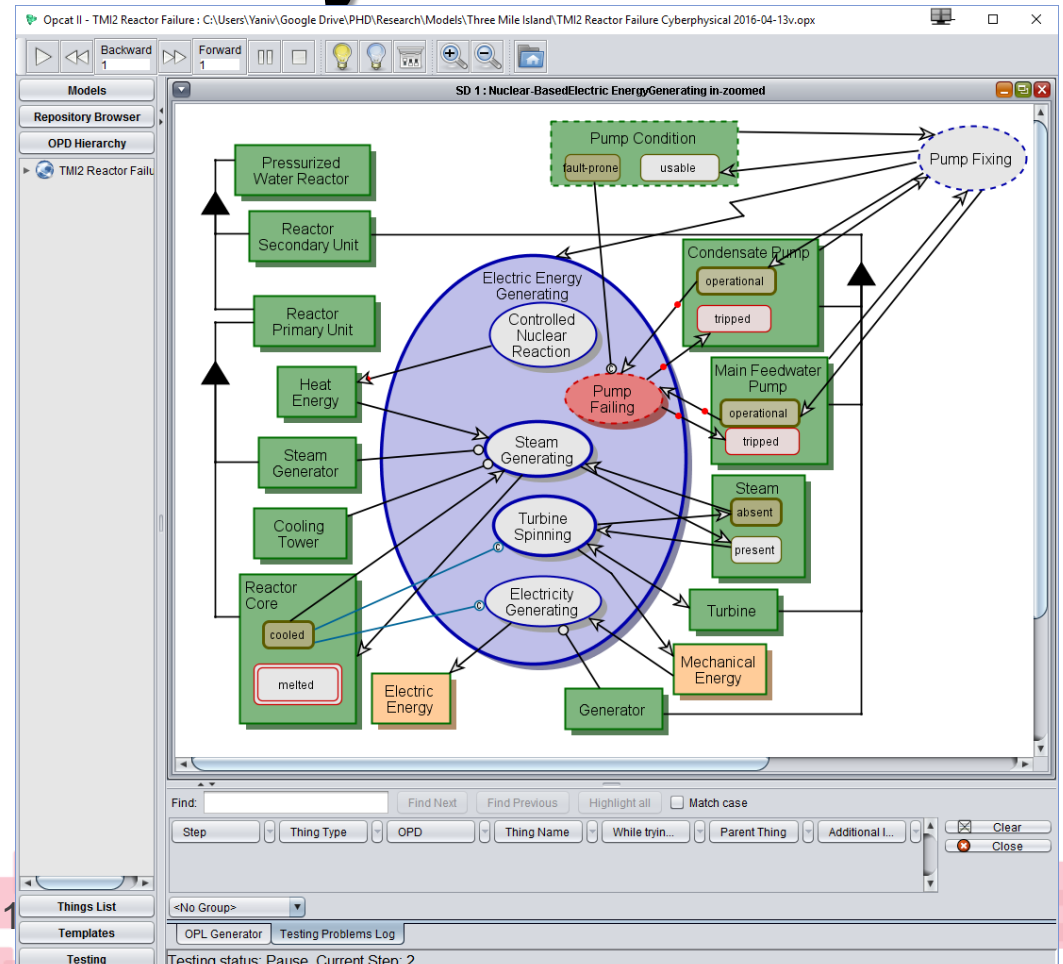
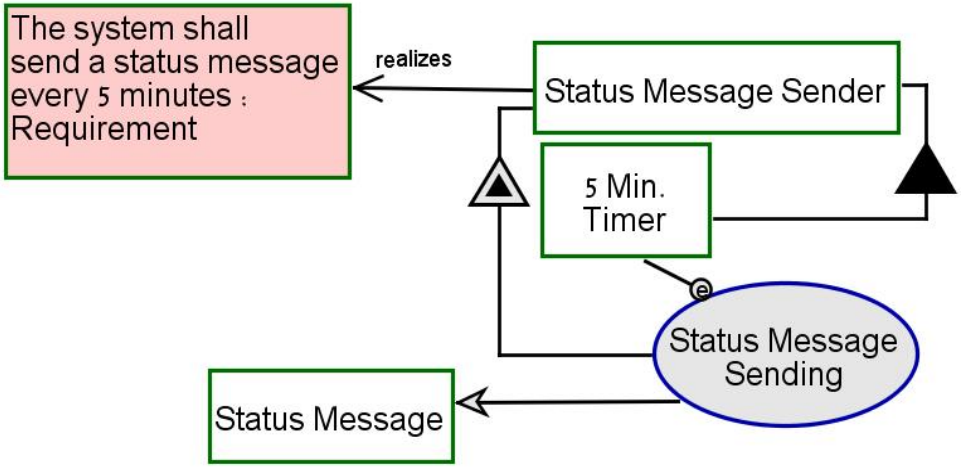
- **Demonstrability**
  - In action
  - In experiment
  - By simulation
  - By analysis
- **Traceability**
  - Operational requirements ⇔ Functional analysis ⇔ architecture & design ⇔ implementation ⇔ test cases ⇔ failures

Demonstration by Simulation



Traceability: Integrating Requirements into the Model



1. The system shall send a status message every 5 minutes is of type Requirement.
2. Status Message Sender exhibits Status Message Sending.
2.1. Status Message Sending requires 5 Min. Timer.
2.2. Status Message Sending yields Status Message.
3. Status Message Sender consists of 5 Min. Timer.
3.1. 5 Min. Timer triggers Status Message Sending.

Status Message Sender realizes The system shall send a status message every 5 minutes.

The Integrated Informativity Index

IEF Cluster	IEF name	Weight
Specification (e.g., 40%)	Specification Pattern	40
Uncertainty (e.g., 30%)	Reliability	12
	Discovery	12
	Simplification	6
Meta-Specification (e.g., 20%)	Rationale	5
	Initiator	5
	Category	5
	Priority	5
	Maturity	5
Model Management (e.g., 10%)	Traceability	3
	Demonstrability	7

The weighting scheme is <u>subjective to the stakeholder</u>

The Integrated Informativty Index

= Weighted Informativity Figure of statement (i)

$FINF\downarrow j$ = Aggregate Informativity Figure of factor (j)

I^3 = Integrated Informativity Index = Aggregate WINF over all model statements.

$\Delta I\uparrow 3$ = difference in I^3 between two versions of the model

MIA for UML / SysML

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- Can we implement MIA on UML or SysML models?
  - **YES!**
- What would it require?
  - The ability to export a formal schematic description of the model
  - The ability to identify each statement
  - A quantitative mapping of each statement and its refinements
- Once we have a set of identifiable and quantifiable statements, we can draw informativity values for a model in any language.

SysML vs OPM

Feature	SysML	OPM
Theoretical foundation	Rational Unified Process	Minimal Universal Ontology
Standardization	OMG	ISO (19450)
# of spec pages	~1600 (inc. UML)	~130
# diagram kinds	9	1
# symbols	~120	~20
# spec patterns	~10-15 per diagram kind	21
# Google Scholar Citations	~9000	~1000
Complexity management	Aspect-based	Detail-based
Hierarchical decomposition	Partial, limited	Full, unlimited
Graphic modality	Yes	Yes
Textual modality	No	Yes
Physical-informatical distinction	No	Yes
System-Environment distinction	Partial	Yes
Probability modeling	No	Yes
System of Systems compatibility	Limited	Extended
CASE tools	Multiple, licensed, commercial	Single, free to use, academic

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Informativity Analysis in Action

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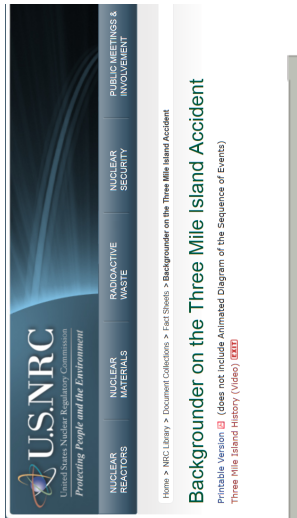
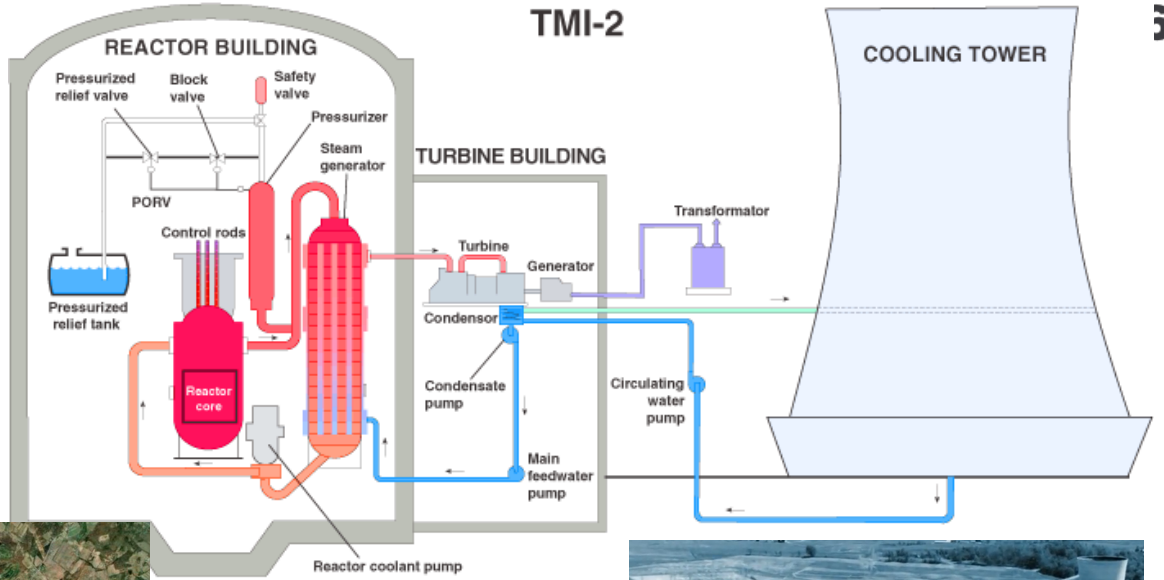
- Comparing nominal vs risk-informed models of the Three Mile Island nuclear reactor.
- The nominal model did not cover the possibility of the failure that led to the TMI 2 meltdown accident of 1979.
- Enhancing the nominal model with failure information led to a significant (order of magnitude) improvement in the model's informativity.

Three Mile Island 2 Accident

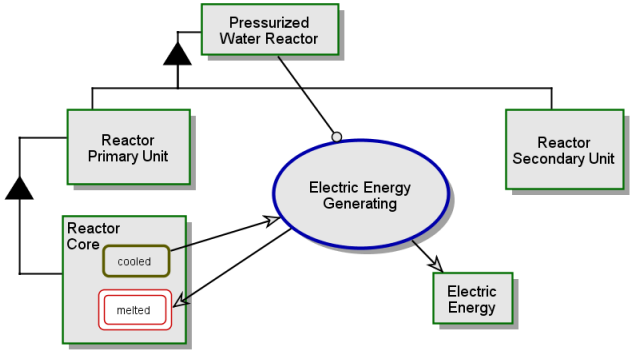
March 28, 1979

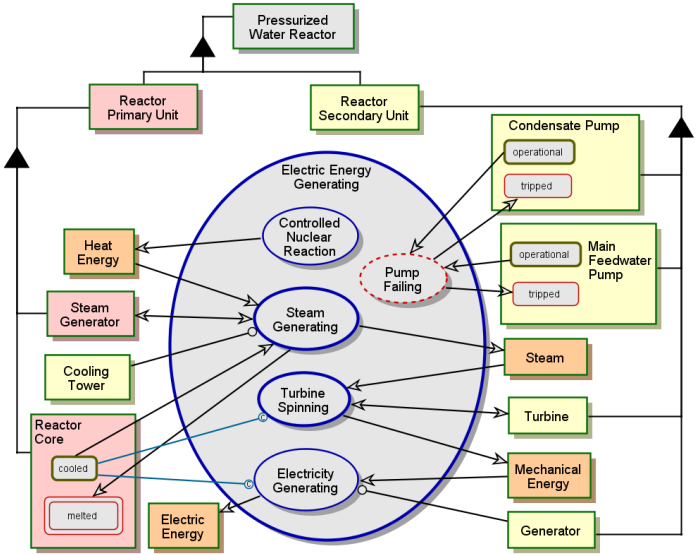
http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html



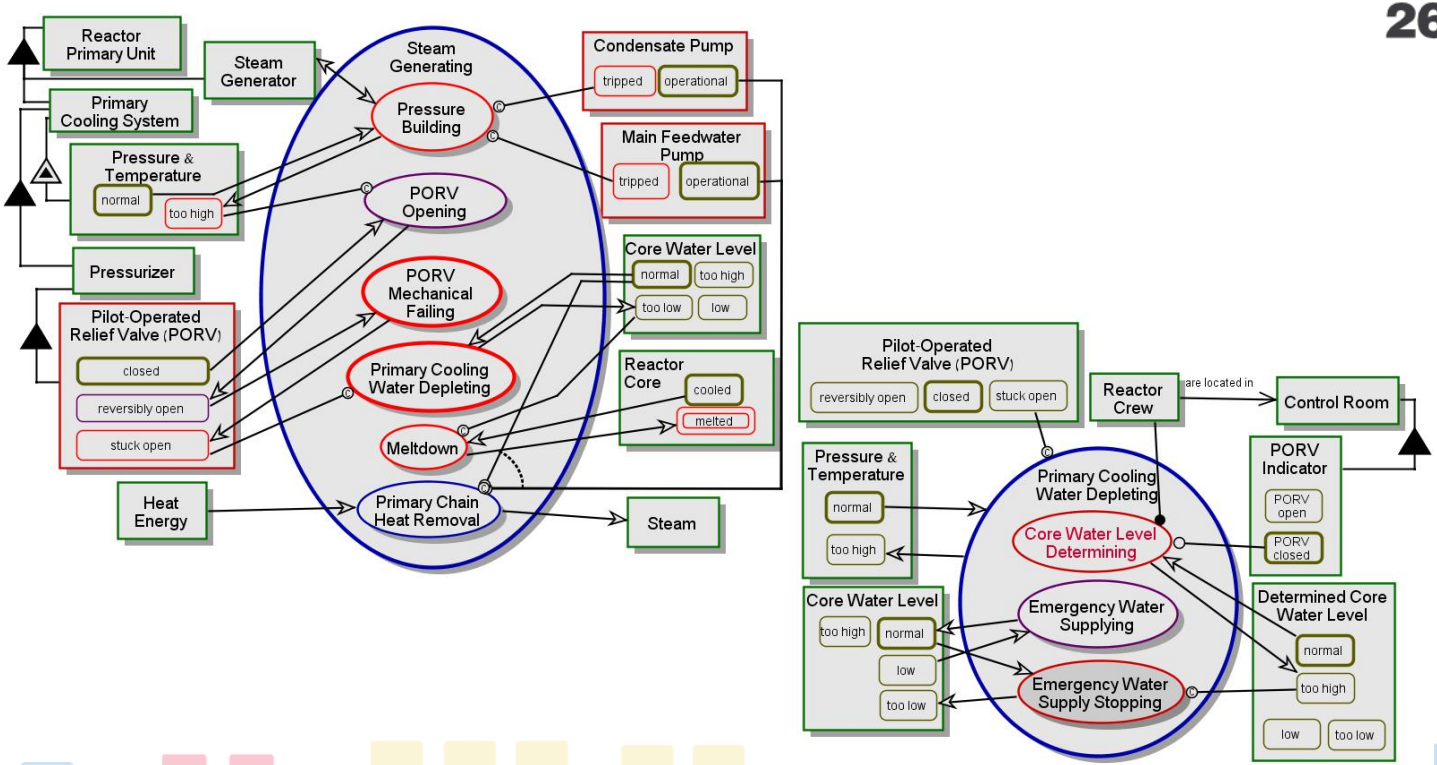


Nominal Model





Risk-Informed Model



Informative Value Comparative Analysis: Nominal vs Risk-Informed

Measure	Nominal Version	Risk-Informed Version
Number of MFs	61	141
Removed MFs	9	
New MFs		89
Structural MFs	27	56 (+33,-4)
Behavioral MFs	34	86 (+56,-4)
Model Informativity (I^3)	18.526	38.539 **(+108%)**
Spec Pattern INF (unweighted)	24	63.25 **(+164%)**
Reliability INF (unweighted)	20	17.33 **(-13%)**
Discovery INF (unweighted)	30.7	70.5 **(+130%)**
Complexity Reduction INF (unweighted)	-0.56	3.1 **(+548%)**

Summary

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- Model informativity is a prime indicator of model usefulness.
- MIA is a framework for **M**odel **I**nformativity **A**nalysis.
- MIA is subjective and heuristic BUT:
  - the analytical foundations of subjective judgement, utility, information, and probability are well-defined (Pratt, Raiffa, & Schlaifer, 1964; Savage, 1972).
- Future research:
  - Informativity analysis of model-based protocol specifications
  - Informativity analysis of knowledge-based engineering (KBE) models for design automation.
  - Integration of MIA into OPCloud – the new cloud-based OPM modeling tool

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Thanks!
Questions?

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