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Applying Bayesian Networks to TRL Assessments - Innovation in Systems Engineering

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Agenda

1. Introduction
2. Why Use Bayesian Networks for TRLs?
3. Constructing the TRL Bayesian Network Model
4. Case Studies
5. Next Steps

Bayes Theorem

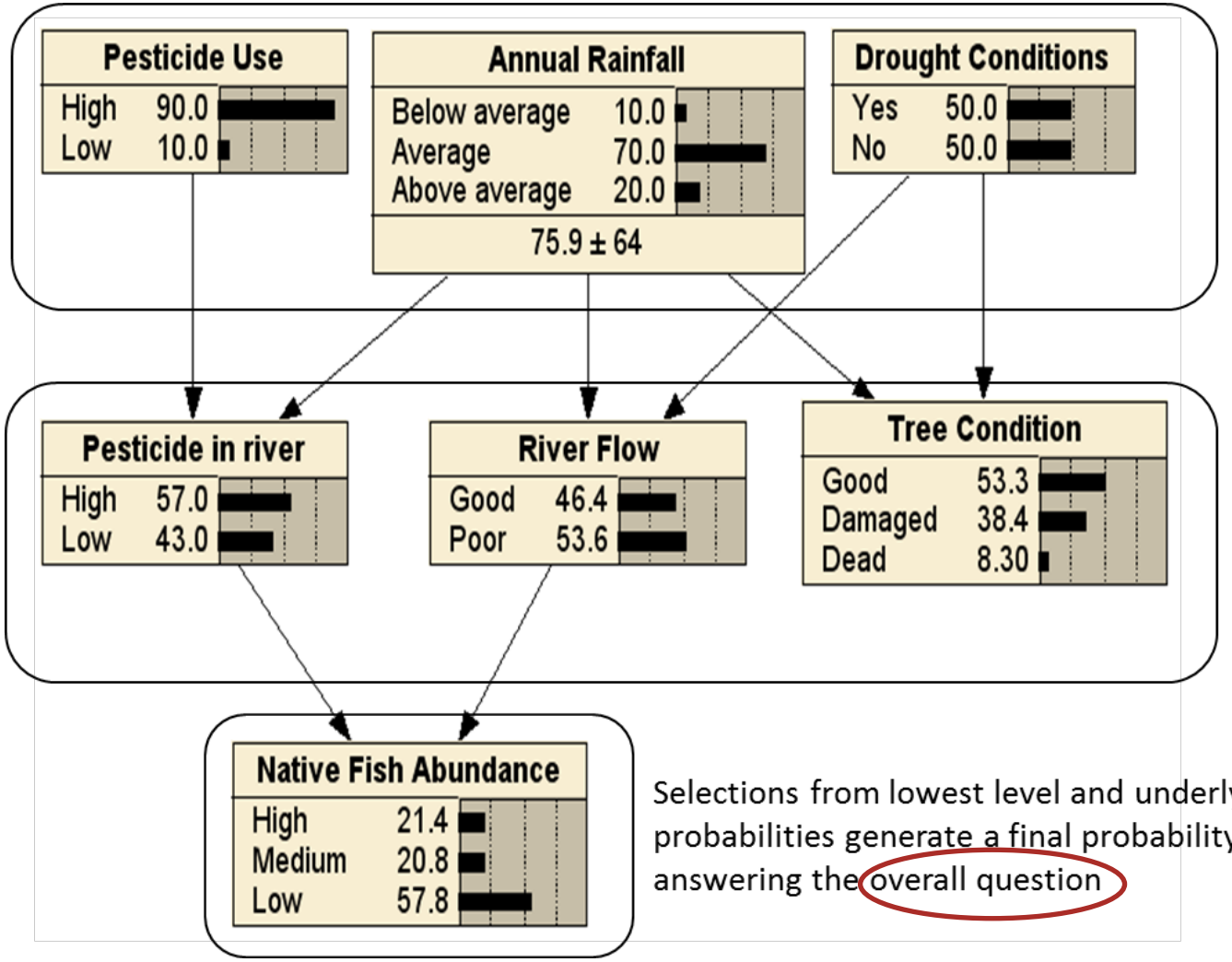
Thomas Bayes (1701 – 1761)

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)}$$

Bayesian Networks

- A graphical probabilistic model representing a set of random variables and their conditional dependencies
- Represents a multi-dimensional probability distribution
- Each node in the model represents an individual indicator and each link represents a dependency
- Suitable for translating complex relationships of dependencies into intuitive and mathematical models
- The model gathers evidence and elicits expert opinion incorporating uncertainty
- Performs in the face of missing or inconsistent data

Bayesian Belief Network – An Example



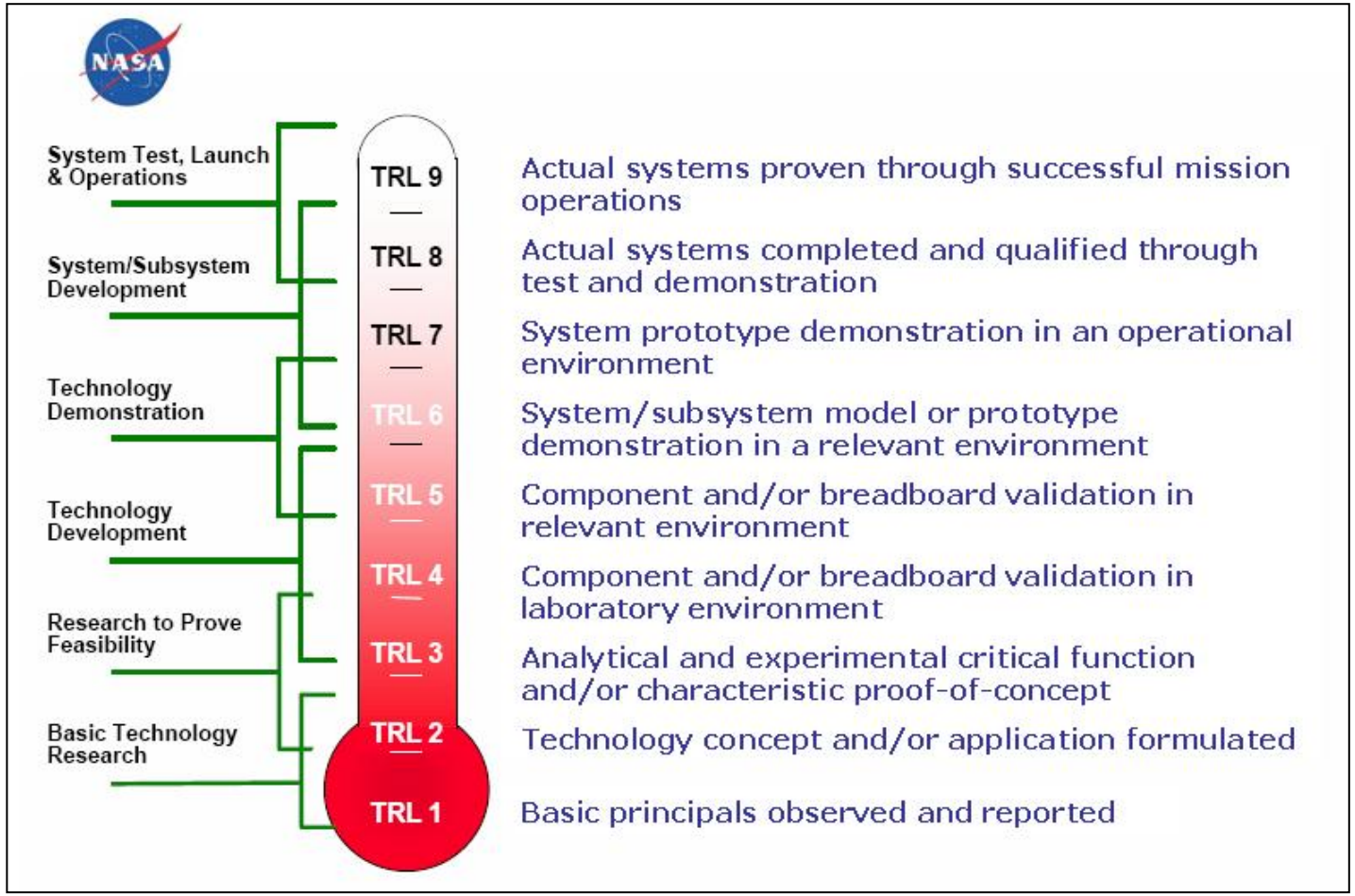
We enter a "finding" (select an option)

Results from previous level update the probabilities of intermediate categories

Selections from lowest level and underlying probabilities generate a final probability of each level answering the overall question

What are Technology Readiness Levels (TRLs)?

- Describes the maturity level of a technology (9 levels)
- Introduced by NASA for their space programs
- Later adapted for use by other agencies (DoD)
- Supports the maturity assessment of individual technologies



TRL Decision Criteria

TRL	Definition	Description	Supporting Information
6	System/subsystem model or prototype demonstration in a relevant environment.	• Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. • Represents a major step up in a technology's demonstrated readiness. • Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	✓ Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. ✓ How did the test environment differ from the operational environment? ✓ Who performed the tests? ✓ How did the test compare with expectations? ✓ What problems, if any, were encountered? ✓ What are/were the plans, options, or actions to resolve problems before moving to the next level?

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Why use Bayesian Networks for TRLs?

- The decision making process that assigns TRL values to the system's technology elements involves multiple attributes that are often subjective
- Captures and normalizes the judgments of expert evaluators who may often differ in their conclusions
- Combines both subjective expert opinions with available quantitative information/data providing informed decision making without requiring complete knowledge of the problem
- Incorporates a set of complex and highly interrelated attributes and through the laws of probability produces a consistent and mathematically rigorous TRL recommendation
- Validates the judgment of experts using the Bayesian network and resulting probability distributions

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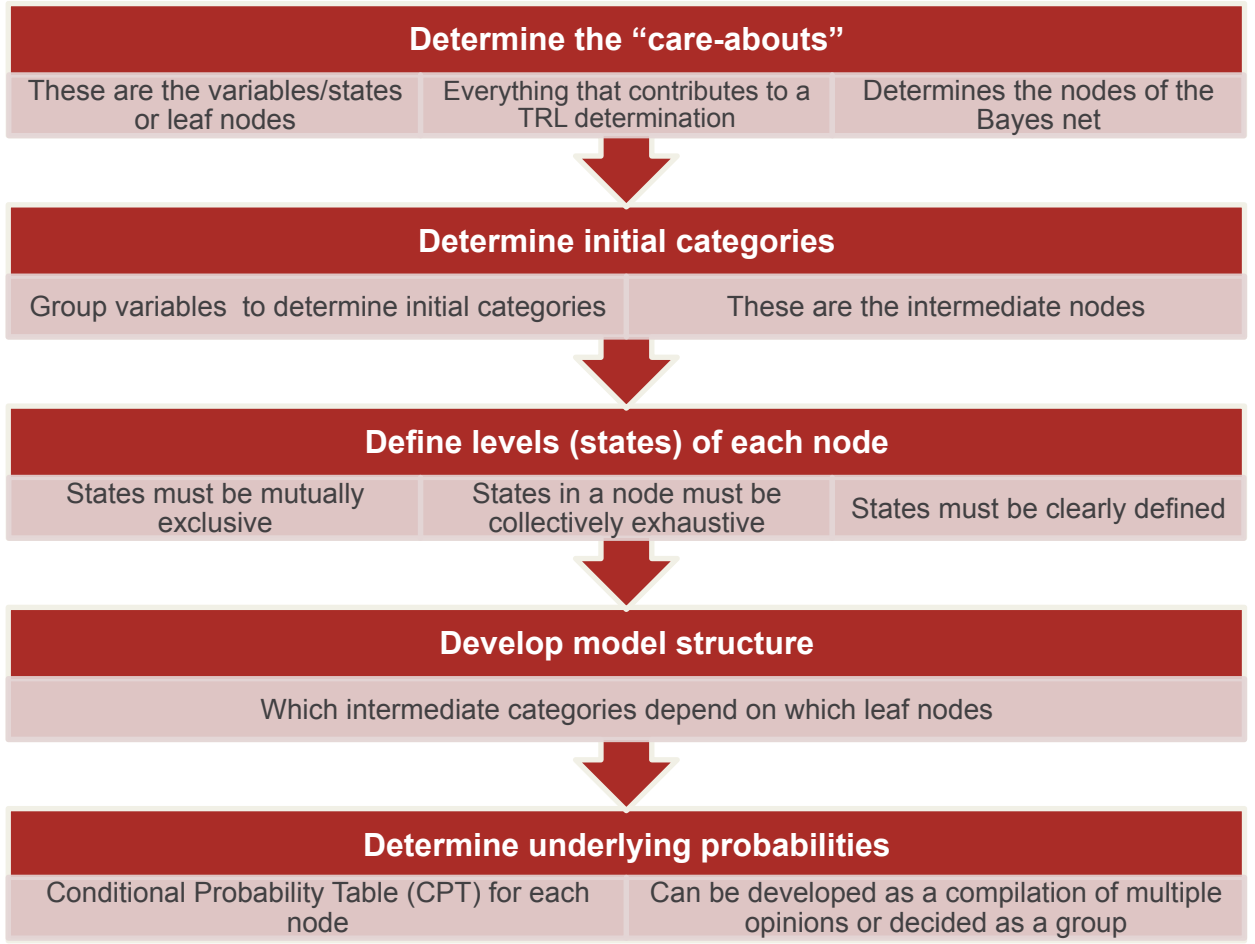
Constructing the Bayesian Network



TRL Care Abouts (Leaf Nodes)

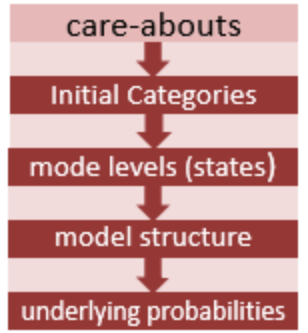
- SW vs. HW
- SW/HW/Firmware
- Independent view, bias in testing
- Source/confidence in "proof"
- Scope/boundary of program being investigated
- What requirements have been verified by testing? How do you know?
- Requirements set, stable/complete or unstable/incomplete
- Hard science based evidence
- Demonstration

- A prototype has been developed
- Existence
- Demonstrated Use
- Used in Mission
- Reliability (High, Med, Low)
- Has reliability for element been defined or demonstrated?
- Well described (documentation of how it works and why)
- Has the element been described well
- Documentation
- How likely are other factors to influence outcome or TRL #?
- Politics

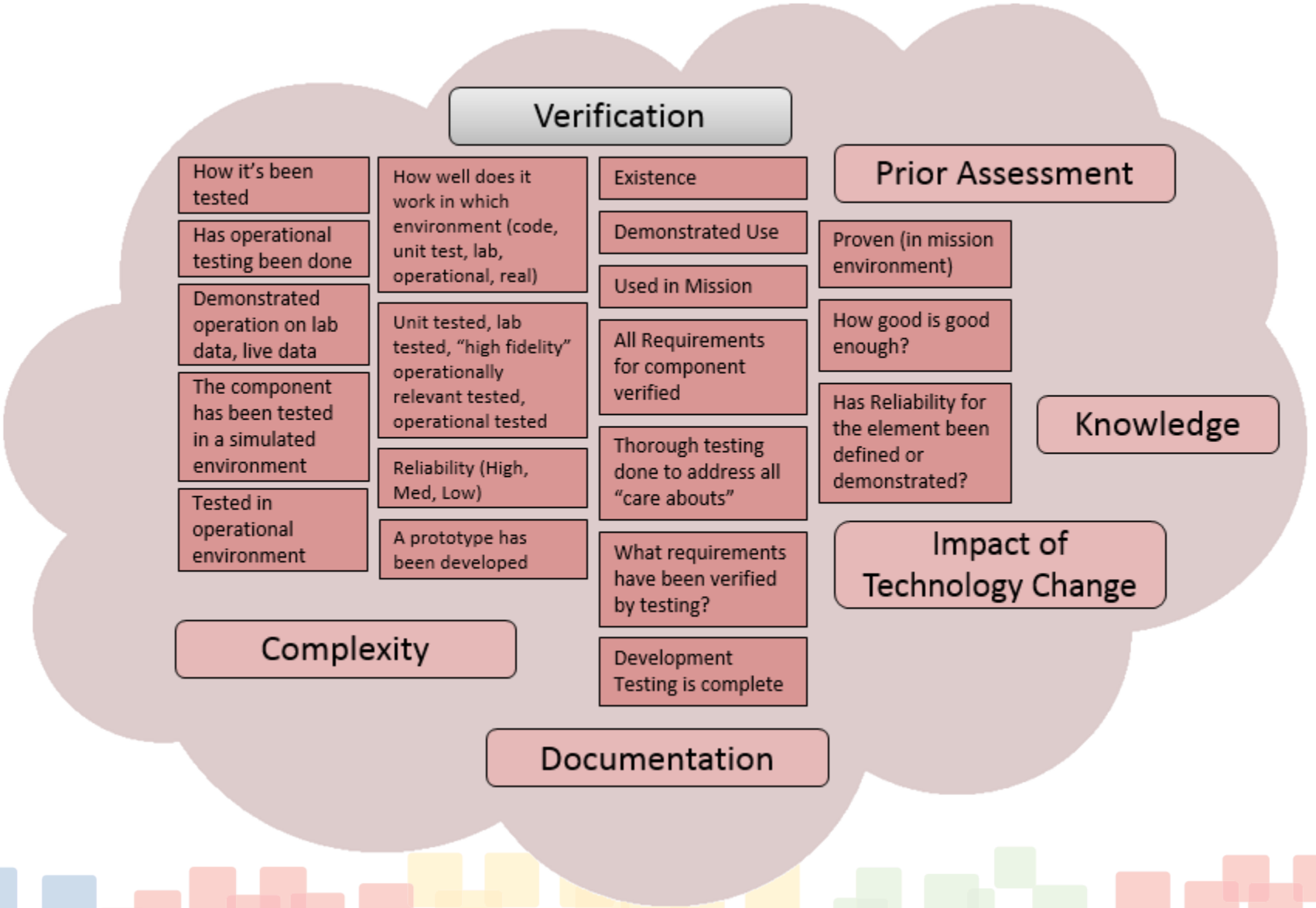
- Integration
- Dependencies on other technologies
- Change in context, different usage
- System environment
- Interfaces, stable v. unstable
- Has the "resting place" for the element been identified?
- All the requirements for the component have been verified
- Has the testing been done thoroughly to address all the "care abouts"?

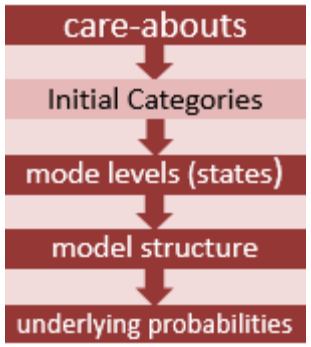
- How often it changes
- Changes, managed or unmanaged?
- Passage of time
- How it's been tested
- Has operational testing been done
- Demonstrated operation on lab data, live data
- The component has been tested in a simulated environment
- Tested in operational environment
- How well does it work in which environment (code, unit test, lab, operational, real)
- Unit tested, lab tested, "high fidelity" operationally relevant tested, operational tested

- Evaluation Point (milestone, FOC, etc)
- What level of development has been done to date?
- Development testing is complete
- Sustainability
- Level of investment/ ownership
- Prior art provides doesn't provide proof
- What research needs to be done yet?
- Already identified TRL
- Scale of the tech
- Maintainability
- Availability
- How good is good enough?
- Proven (in mission environment)



Determine Initial Categories





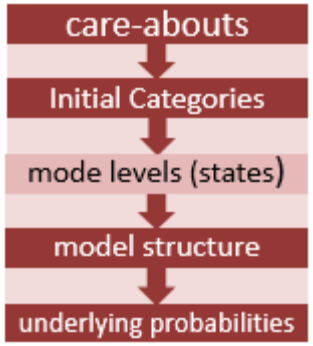
Knowledge Category (defining the node states)

What is the status of the underlying research?
Completed/Not needed
Not completed

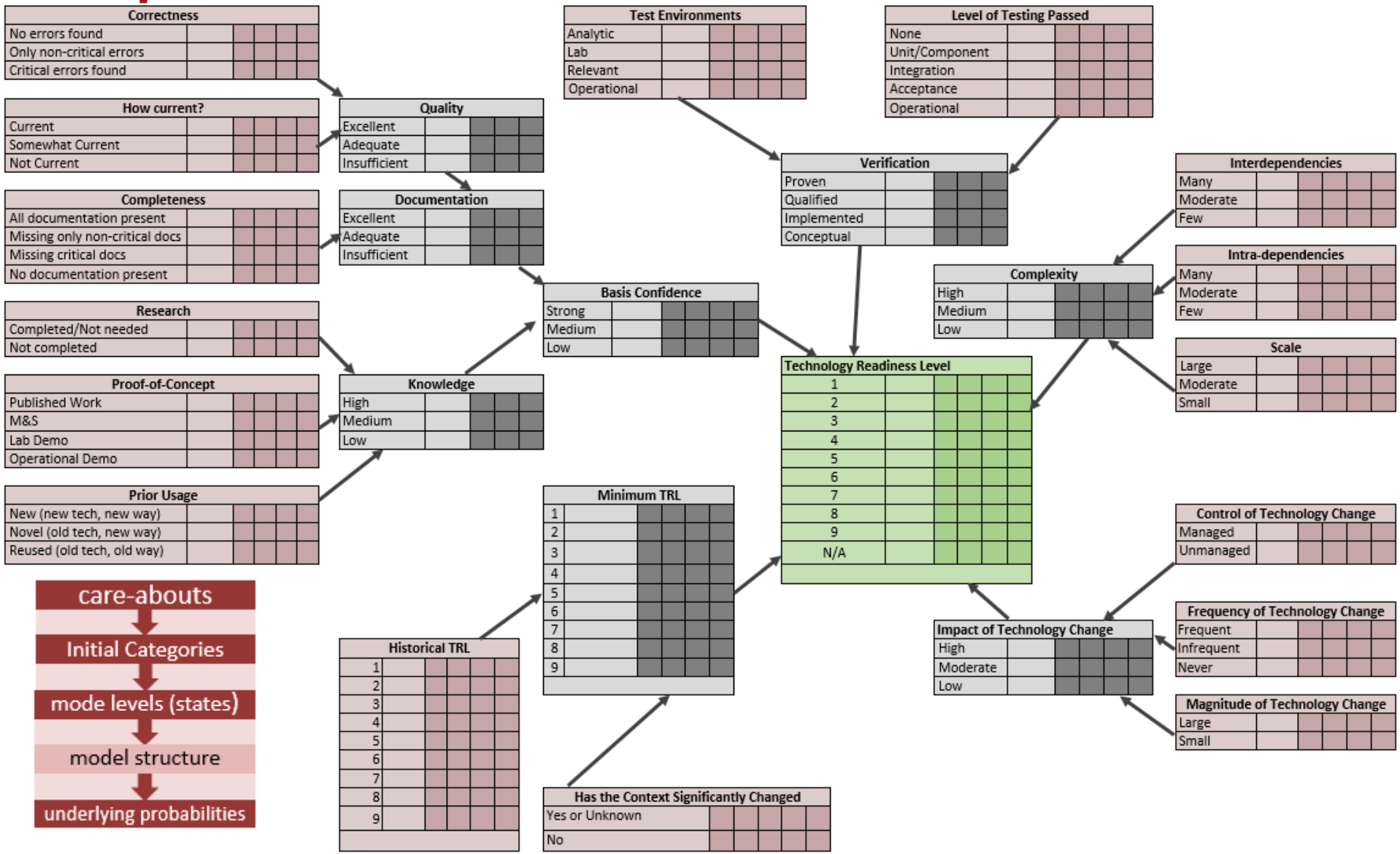
To what level has the concept been demonstrated?
Published work
M&S (Modeling & Simulation)
Lab Demo
Operational Demo

How has it been used in the past?
New (new technology being used in a new way)
Novel (old technology being used in a new way)
Reused (old technology being used in an old way)

Knowledge

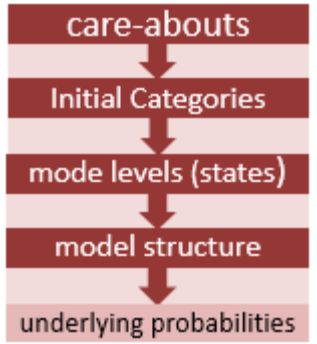


Develop Model Structure



Sample Conditional Probability Table

Control of Technology Change	Frequency of Technology Change	Magnitude of Technology Change	Explanation	High	Moderate	Low
Managed	Frequent	Large	If managed technology change frequently occurs and the magnitude of that change is large how likely is the impact of that technology change to be: High? Moderate? Low?	33	34	33
Managed	Never	Small	If managed technology change never occurs and the magnitude of that change is small how likely is the impact of that technology change to be: High? Moderate? Low?	0	0	100
Unmanaged	Infrequent/ Seldom	Small	If unmanaged technology change infrequently/seldom occurs and the magnitude of that change is small how likely is the impact of that technology change to be: High? Moderate? Low?	60	30	10



TRL Bayesian Network

Technology Readiness Assessment (TRA) Questionnaire

Category	Subcategory	Question	Possible Answers (Select/ highlight one)
Documentation	Quality	Correctness: How accurate is the documentation?	■ No Errors Found □ Only non-critical errors found □ Critical Errors Found
		How current: How current is the documentation?	□ Current ■ Somewhat current □ Not current
	Completeness	How complete is the documentation?	□ All Documentation Present ■ Missing only non-critical documents □ Missing critical documents □ No documentation present
Documentation includes e.g., acquisition documents, architecture products, engineering specs, test plans, and general references. **Critical errors are those which cause a misunderstanding of the facts and significantly impact the outcome.** **A critical document is any document that contains data elements essential to understanding the technology under evaluation.**			

Questionnaire, cont'd

Knowledge	Research	What is the status of the underlying research?	□ Completed/Not needed ■ Not completed
	Proof-of-Concept	To what level has the concept been demonstrated?	□ Published work ■ M&S (Modeling and Simulation) □ Lab Demo □ Operational Demo
	Prior Usage	How has it been used in the past?	■ New (new technology being used in a new way) □ Novel (old technology being used in a new way) □ Reused (old technology being used in an old way)
Prior Assessment	Historical TRL	Was it previously assessed at a certain TRL level? If so, what level?	■ _2_ (Insert previous TRL 1-9 here, or leave blank if not previously assessed)
	Context Change	Has the context significantly changed (from prior assessment)?	■ Yes or Unknown (or, not previously assessed) □ No

Questionnaire, cont'd

Impact of Technology Change	**Magnitude**	**What is the magnitude of technology change?**	■ **Large** □ **Small**
	Frequency	What is the frequency of technology change?	□ Frequent ■ Infrequent/Seldom □ Never
	Control	What is the control of technology change? (How well is change controlled?)	■ Managed □ Unmanaged
Complexity	Scale	What is the scale?	■ Large □ Moderate □ Small
	Intra-dependencies	How many intra-dependencies?	■ Many □ Moderate □ Few
	Interdependencies	How many interdependencies?	■ Many □ Moderate □ Few

Scale refers to, for example, the scope, magnitude, quantity, or breadth of the technology within the system.

Intra-dependencies are within the technology.

Interdependencies are between the technologies.

Questionnaire, cont'd

Verification	Test Environments	What is the environment in which the testing was conducted?	□ Analytic □ Lab ■ Relevant □ Operational
	Level of Testing Passed	What level of testing has been passed?	■ None □ Unit/Component Testing □ Integration testing □ Acceptance testing □ Operational testing

Level of testing refers to the highest level of testing that has been fully completed and successfully passed, with accompanying evidence.

Testing need not be comprehensive to be completed.

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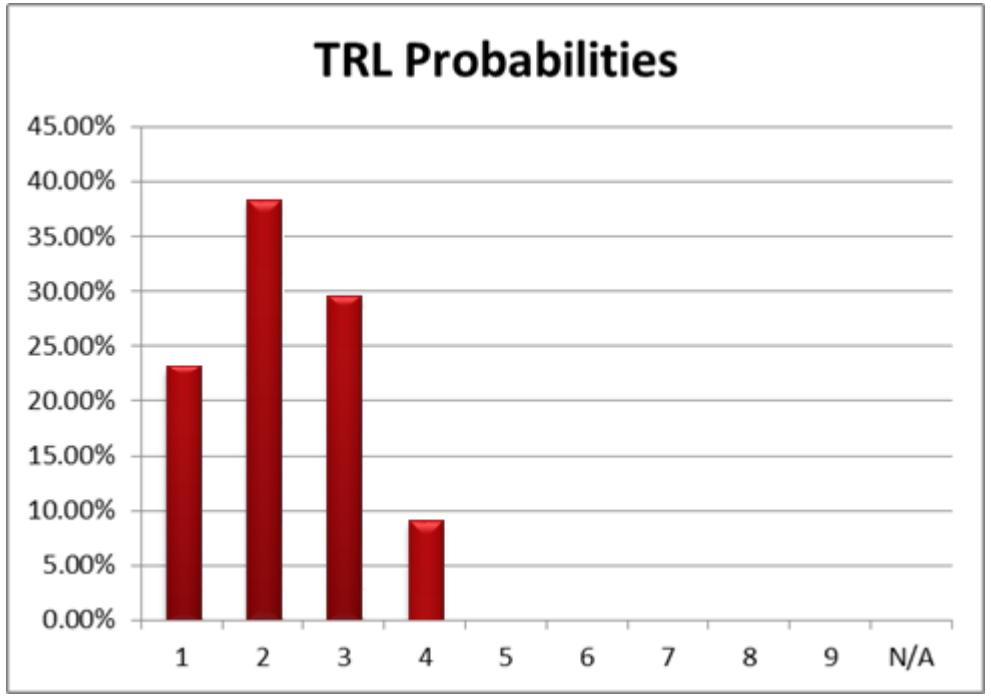
Case Study I

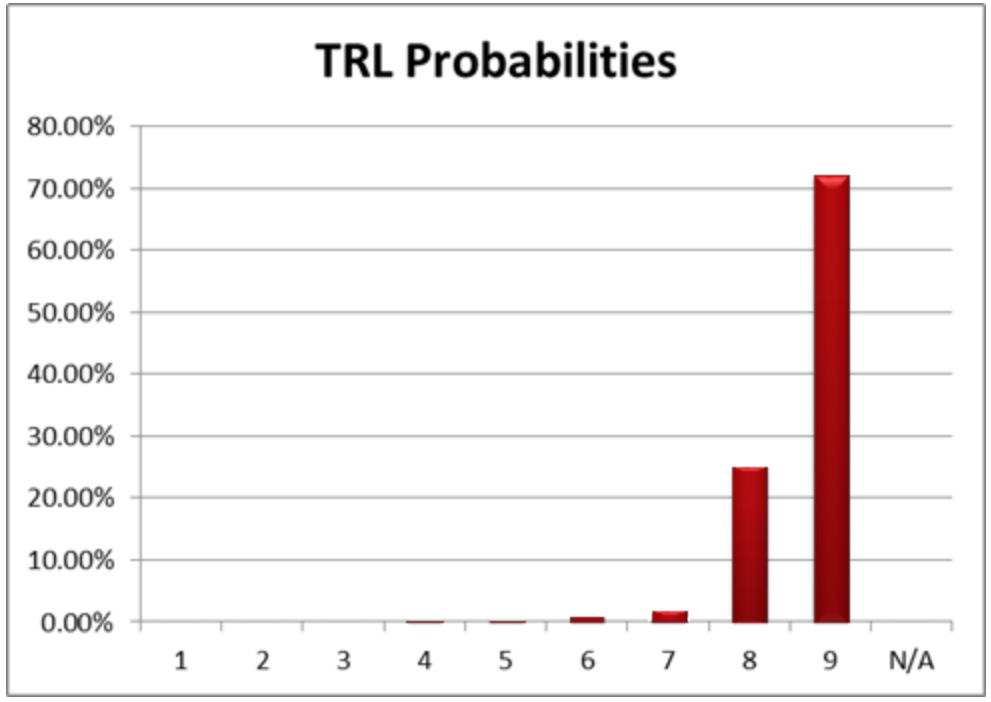
- Assessed TRL = 3



- Model prediction aligns closely with expert judgment

Case Study II

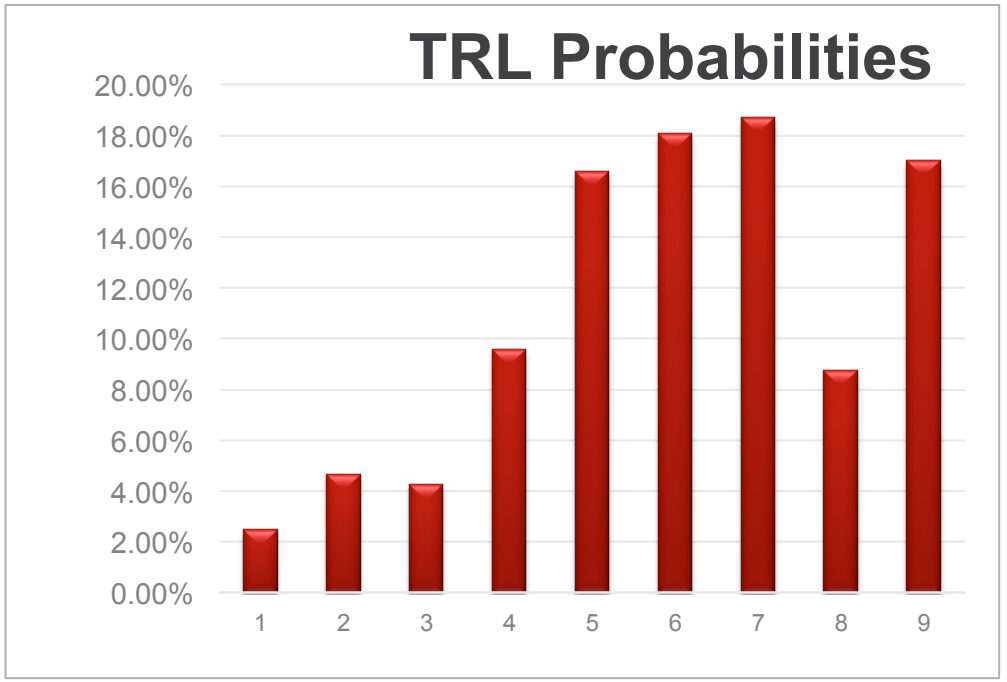
- Assessed TRL = 7



- Expert judgment more conservative than model prediction

Case Study III

- Assessed TRL = 6



- In the case of inconsistent data the model conservatively predicts a distribution of TRL values around the assessed TRL

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Summary and Future Work

- The Bayesian network model mitigates system development risk by providing a level of confidence in the judgments made by experts in assigning TRLs
- A Bayesian network model for Integration Readiness Levels (IRLs) of system components has also been developed
- The TRL and IRL Bayesian network models are part of a larger ongoing effort to develop system-level metrics

Backup Slides

Typical Product Development Process