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Mitigating Integration Risks in Complex Systems

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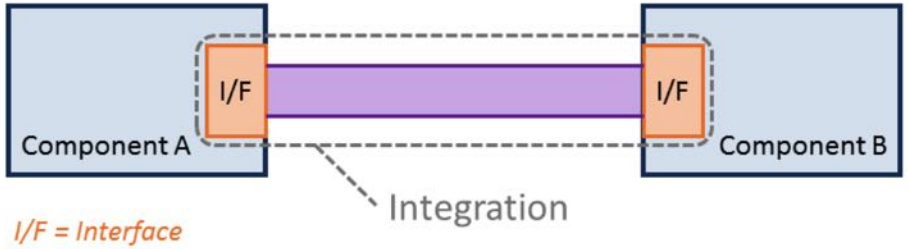
Introduction

- System design problems are reaching challenging levels of complexity
- Transformation in Systems Engineering will be required to increase its effectiveness in this environment
- New system-level metrics necessary with emphasis on integration to produce capable, interoperable, and supportable systems for the end user

Integration

The Importance of Integration

- "*The purpose of the Integration Process is to assemble a system that is consistent with the architectural design. This process combines system elements to form complete or partial system configurations in order to create a product specified in the system requirements.*" (ISO/IEC 15288:2008)

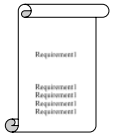
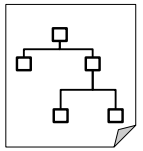
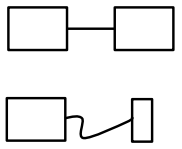
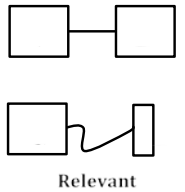
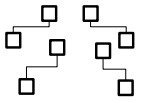
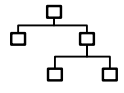
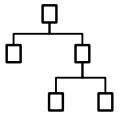
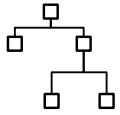


- Integration issues continue to be a common cause of delayed and unsuccessful system deployment (GAO-18-23)

Integration Readiness

- A system metric designed to measure the integration maturity between two components
- An evidence-based scale
  - Consistent with the foundation of NASA's TRL scale
    - The Technology Readiness Level (TRL) assesses the risk associated with development technologies
    - The Integration Readiness Level (IRL) assess the risk of integrating these technologies
  - Closely reflects the system development life cycle
- Integration Readiness Levels characterize the systematic analysis of the interactions between various components and provide a consistent comparison of the maturity between integration points.

Decision Criteria for Assessing Integration Readiness

IRL	Definition	Depiction	Evidence Description
0	No Integration		**No integration between specified components has been planned or intended**
1	A high-level concept for integration has been identified.	 Concept	**Principal integration technologies have been identified** Top-level functional architecture and interface points have been defined High-level concept of operations and principal use cased has been started
2	There is some level of specificity of requirements to characterize the interaction between components	 Requirements	**Inputs/outputs for principal integration technologies/mediums are known, characterized and documented** Principal interface requirements and/or specifications for integration technologies have been defined/drafted
3	The detailed integration design has been defined to include all interface details	 Design	**Detailed interface design has been documented** System interface diagrams have been completed Inventory of external interfaces is completed and data engineering units are identified and documented
4	Validation of interrelated functions between integrating components in a laboratory environment	 Lab	**Functionality of integrating technologies (modules/functions/assemblies) has been successfully demonstrated in a laboratory/synthetic environment** Data transport method(s) and specifications have been defined
5	Validation of interrelated functions between integrating components in a relevant environment	 Relevant	**Individual modules tested to verify that the module components (functions) work together** External interfaces are well defined (e.g., source, data formats, structure, content, method of support, etc.)
6	Validation of interrelated functions between integrating components in a relevant end-to-end environment	 End-to-end	**End-to-end Functionality of Systems Integration has been validated** Data transmission tests completed successfully
7	System prototype integration demonstration in an operational high-fidelity environment	 Demonstrated	**Fully integrated prototype has been successfully demonstrated in actual or simulated operational environment** Each system/software interface tested individually under stressed and anomalous conditions Interface, Data, and Functional Verification complete
8	System integration completed and mission qualified through test and demonstration in an operational environment	 Qualified	**Fully integrated system able to meet overall mission requirements in an operational environment** System interfaces qualified and functioning correctly in an operational environment
9	System Integration is proven through successful mission-proven operations capabilities	 Proven	**Fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operational environment** Integration performance has been fully characterized and is consistent with user requirement

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

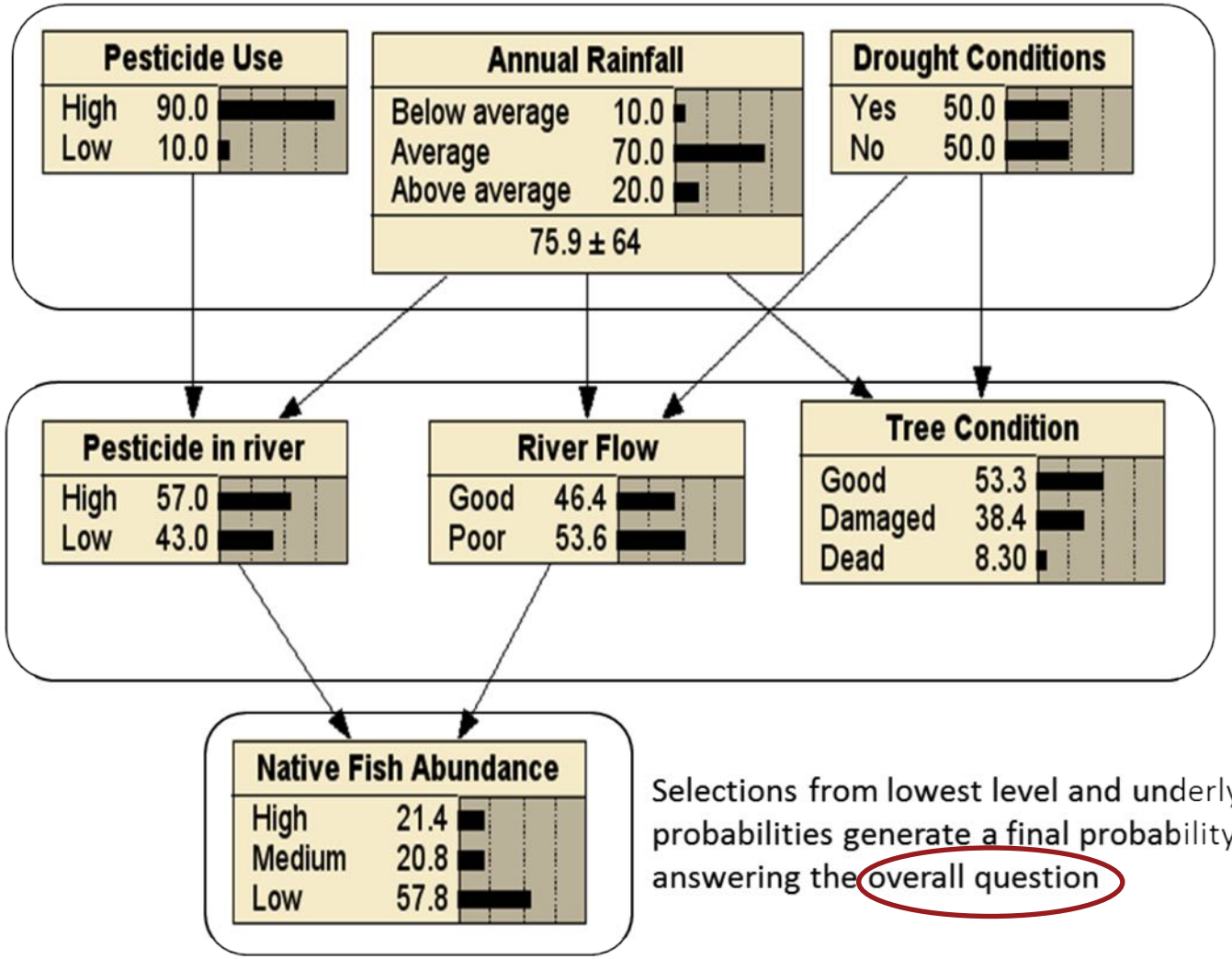
Thomas Bayes (1701 – 1761)

A Bayesian Network Model for Integration Readiness

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)

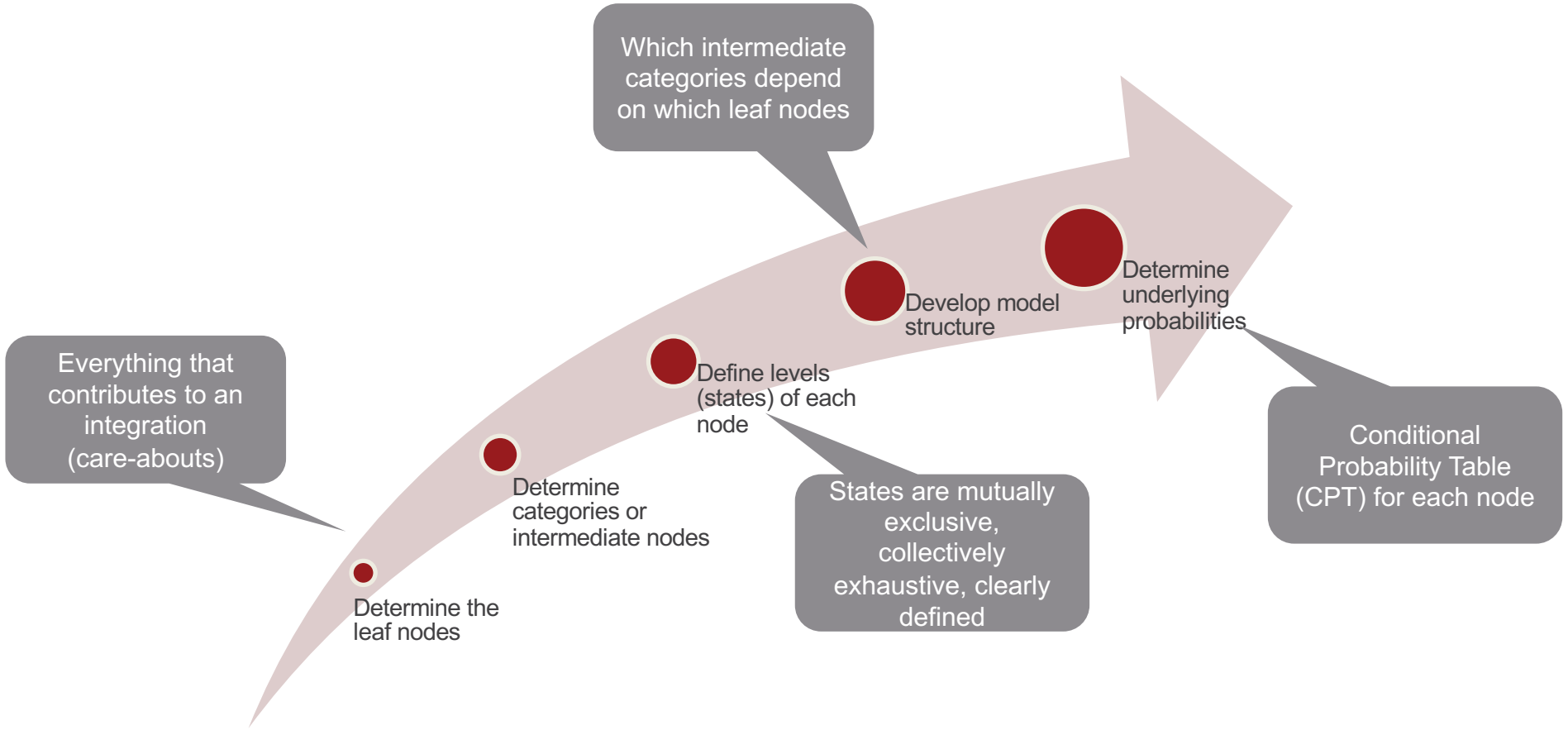
Results from previous level update the probabilities of intermediate categories

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

Why use Bayesian Networks for IRLs?

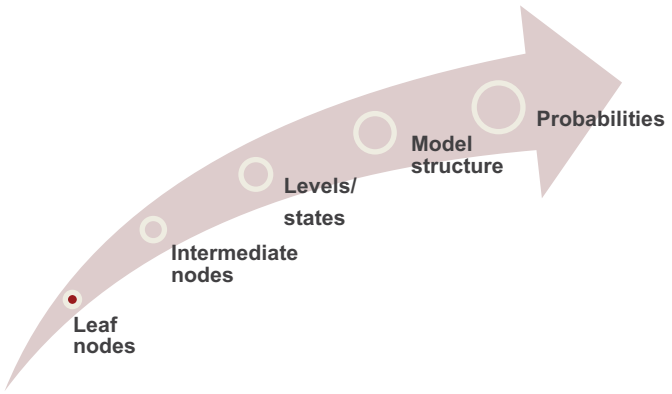
- The decision making process that assigns IRL values to the system's integrations involves multiple attributes that are often subjective
- Captures and normalizes the judgments of expert evaluators who may often differ in their conclusions
- Combines both subjective expert opinions with available quantitative 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 IRL recommendation
- Validates the judgment of experts using the Bayesian network and resulting probability distributions

Constructing the IRL Bayesian Network



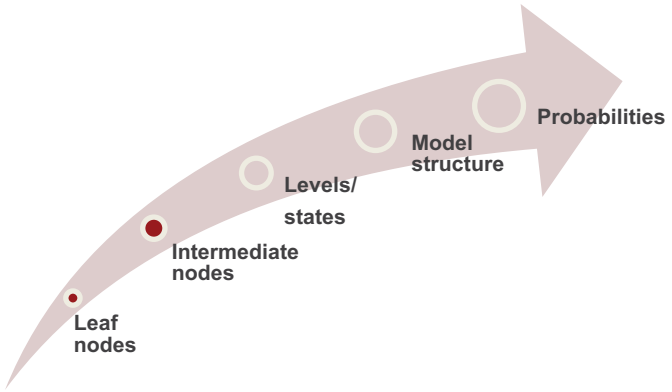
Integration Factors

- Brainstormed care-abouts impacting the integration between two components
- Reduce to the leaf nodes in the model
- Relationships between connected nodes are governed by Bayes Theorem



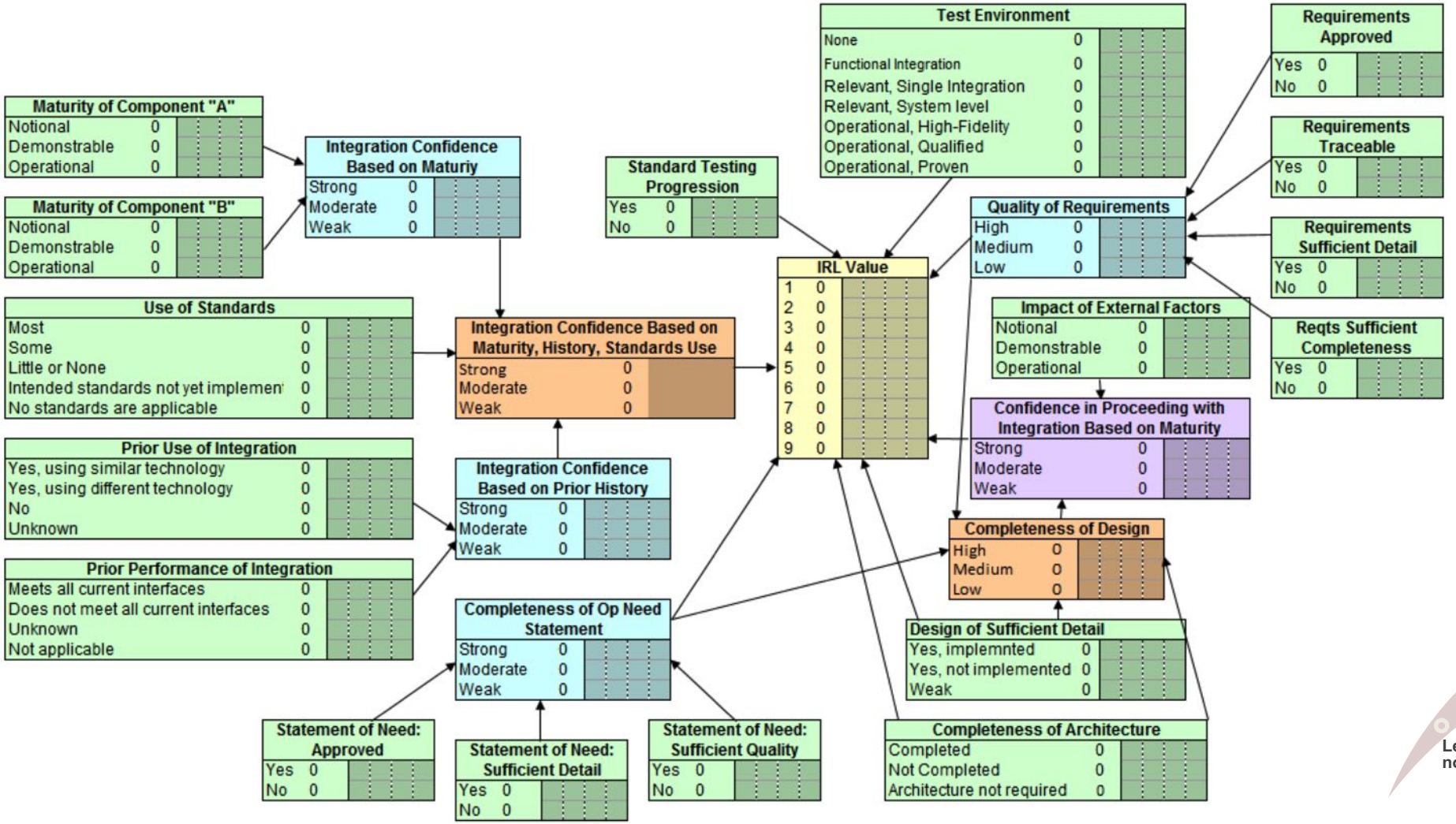
Performance
Stability of interface
Risk (complexity, new/novel)
Scalability
TRLs of components?
What is being exchanged
Interpretability /Understandability
Purpose (what is integration trying to accomplish)
Consequence of failure/ criticality
Operational Functionality
Why interface is needed
Testing
Characterizing information transfer
Operational Metrics (how will you measure performance?)
Interoperability
Receiving processing
Feedback/ Confirmation
Standards - based
How you generate information
Does it meet requirements?
Prior performance of integration type
Manufacturing processes
Combined functionality
New/Novel?
Completeness of Function
Functional requirements
Lifecycle status (/maturity/what already exists)
Test environment
Quality of Function
Enablement
Verification /Validation
Level of integration (scope)
Pass/Fail Criteria
Documentation
Pathway for integration(how well do you understand it)
Interface Hardware /Software (prior use, new/novel)
Complexity of Integration (overall; subintegrations)
Initial conditions /external factors
Security
Multiple test authorities/ specialties
Nonfunctional criteria
Commercial vs. Custom Components
Rollup Factor
Error handling

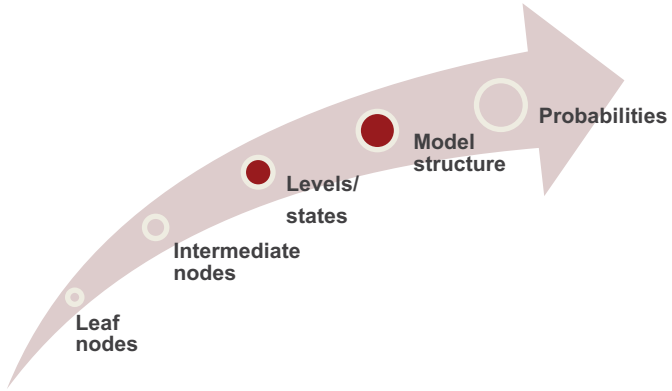
The IRL Bayesian Network



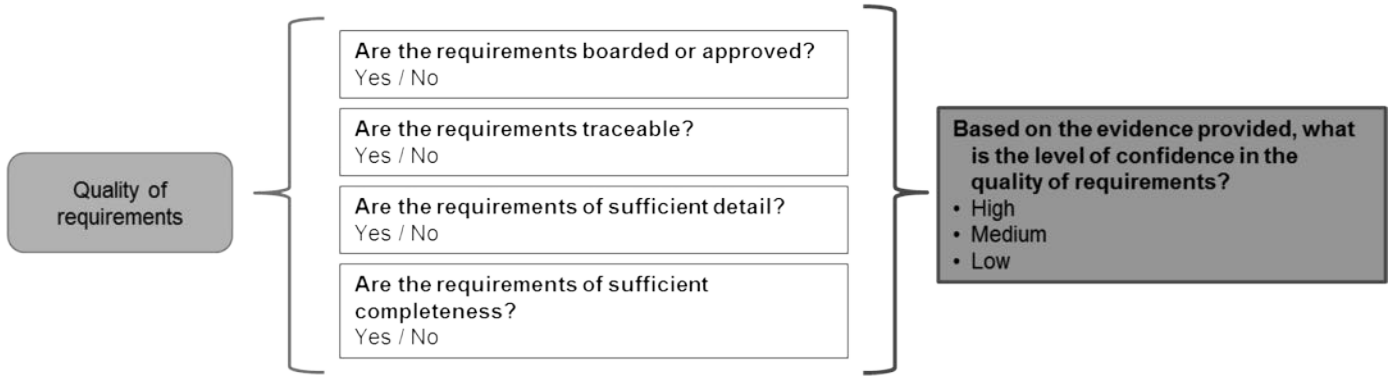
Maturity of component "A"
Maturity of component "B"
Based on the maturity of the components, what is our level of confidence in the integration?
Passed Test Environment
Use of Standards
Basis
Standard Progression
Testing and Evaluation
Prior use of integration
Prior performance of integration
Based on the relevant prior history, what is our level of confidence in the integration?
Based on the Component History, Maturity, Standards, What is our level of confidence in the foundation of the integration?
Impact of (dependent) external factors
Output: Probability of IRL values 1-9
Based on the integration development evidence provided, what is the level of confidence in proceeding with integration?
Based on the evidence provided, what is the level of confidence in the completeness of the statement of operational need?
Completeness of Design Based on the evidence provided, what is our level of confidence in the completeness of the design?
Based on the evidence provided, what is the level of confidence in the quality of requirements?
Requirements – completeness
Operational Need Statement – Approved?
Integration Development
Operational Need Statement – Quality
Requirements – detail
Requirements – traceable?
Operational Need Statement – Detail
Quality of Design
Completeness of architecture
Requirements – approved?

The IRL Bayesian Network Model

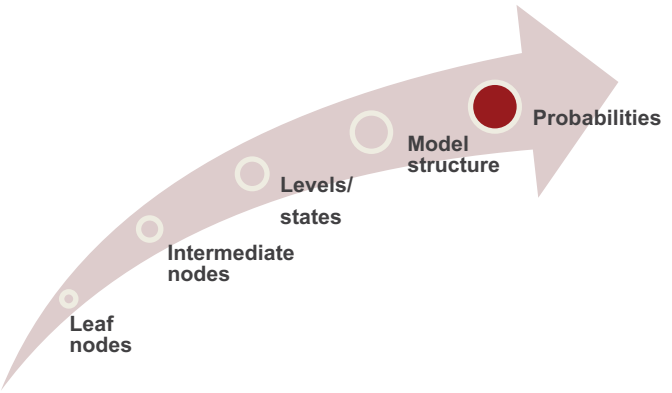




Sample Conditional Probability Table



Boarded/ Approved	Traceable	Of Sufficient Detail	Of Sufficient Completeness	High	Medium	Low
Yes	–	–	–	100	0	0
No	Yes	Yes	Yes	70	20	10
No	Yes	Yes	No	40	30	30
No	Yes	No	Yes	40	30	30
No	Yes	No	No	20	20	60
No	No	Yes	Yes	30	30	40
No	No	Yes	No	10	20	70
No	No	No	Yes	10	20	70
No	No	No	No	0	0	100



Model Case Studies

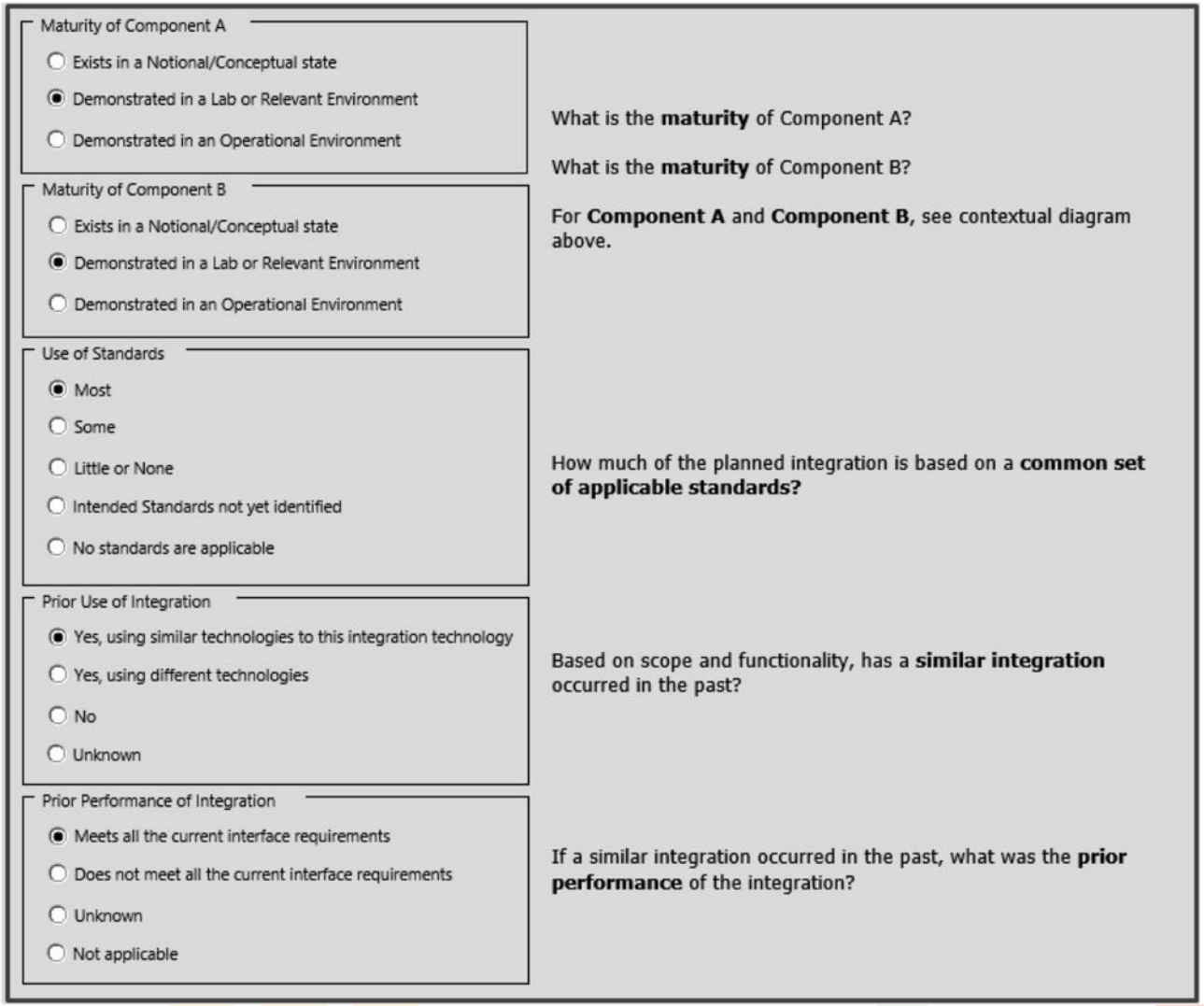
IRL Questionnaire

Questionnaire Instructions: *This tool utilizes a Bayesian Network approach to evaluate Integration Readiness Levels (IRLs). This approach is intended to determine the IRL for a single integration between two components, which we refer to as Component A and Component B (order does not matter). The term 'integration' refers to both the connection (or link or bridge) between Components A and B and the interface (I/F) to each component. The diagram below provides additional context.* [Diagram is that shown in Figure 2]

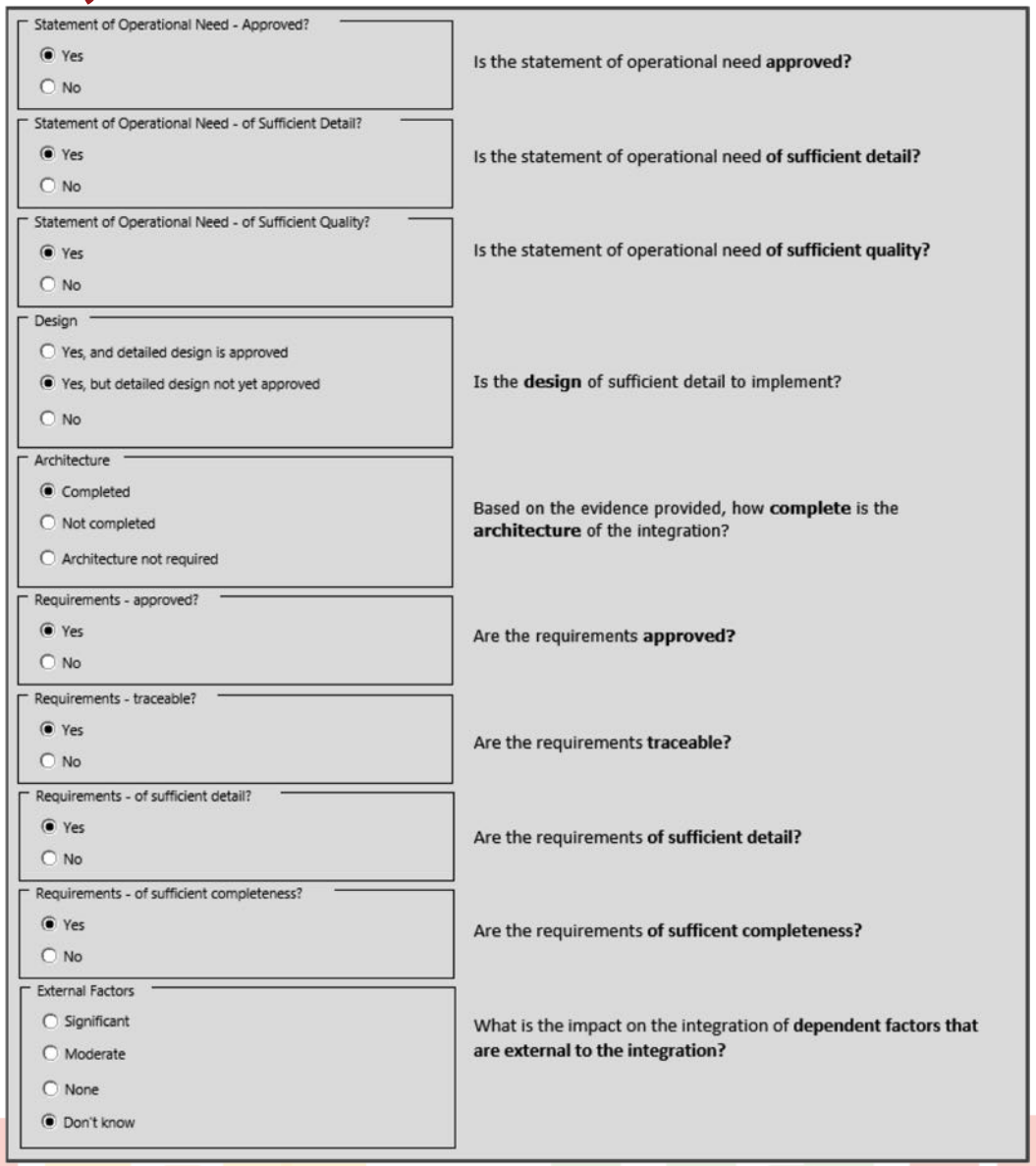
The model uses the responses to the series of questions shown in the tables below to generate a probability distribution of the IRL levels. Please note: This tool does not provide a single IRL value, but rather a distribution on the most likely IRL values. The final assessment is up to the user.

To evaluate the IRL of a single integration using this tool: Please make a selection for each multiple choice question below.

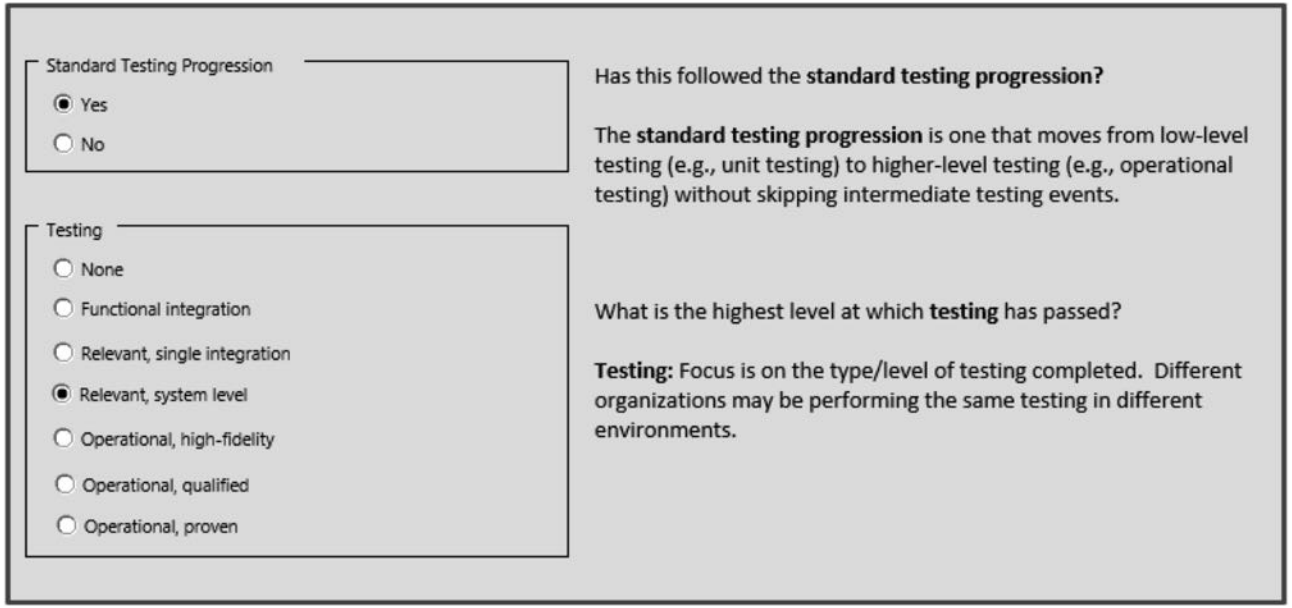
Questionnaire, cont'd



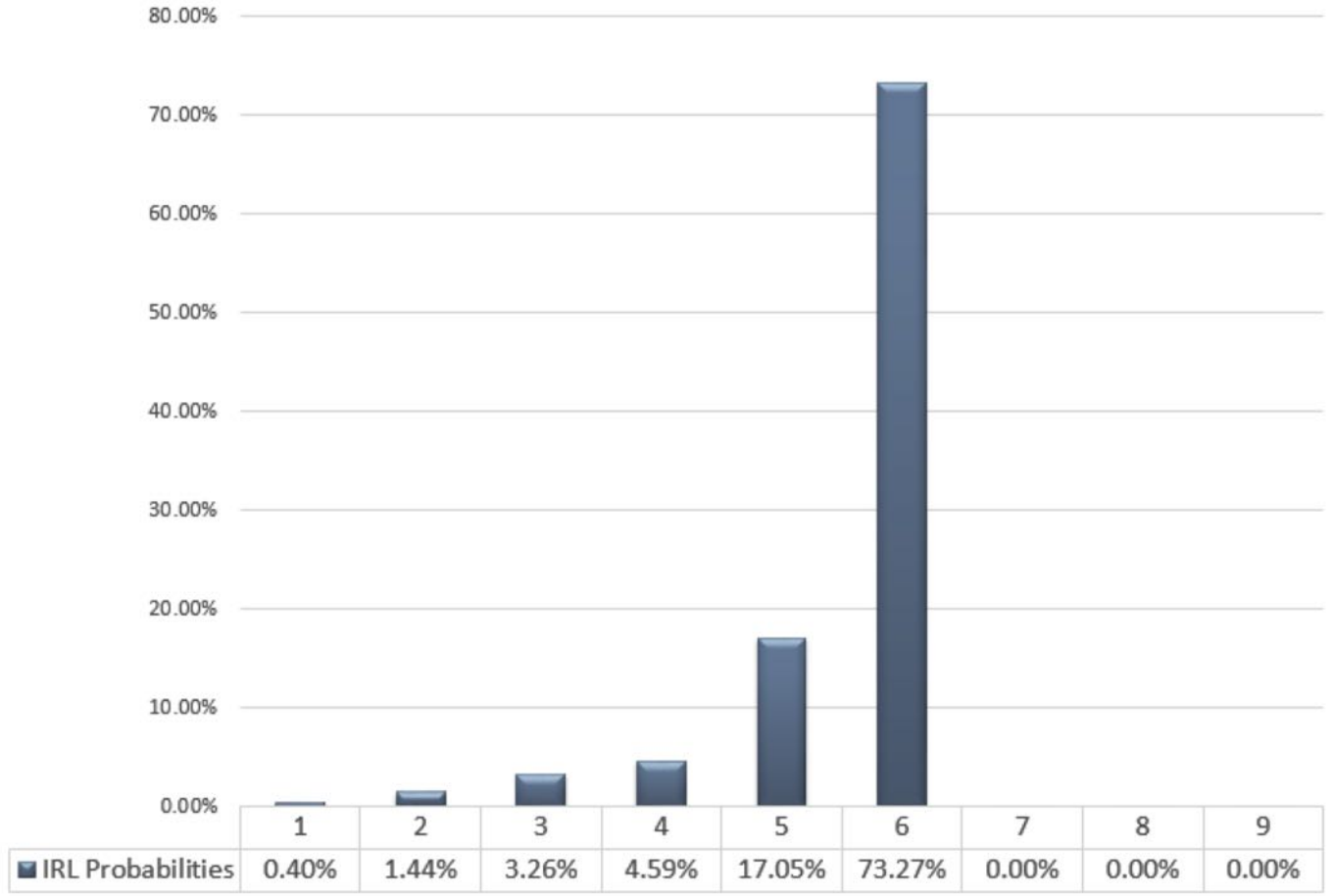
Questionnaire, cont'd



Questionnaire, cont'd



IRL Bayesian network model results (an example)



	1	2	3	4	5	6	7	8	9
IRL Probabilities	0.40%	1.44%	3.26%	4.59%	17.05%	73.27%	0.00%	0.00%	0.00%

Case Study Results

Case	Actual IRL (Assessed)	Model Prediction
Example 1	7	IRL 1 = 0.25% IRL 2 = 1.08% IRL 3 = 2.85% IRL 4 = 4.78% IRL 5 = 17.0% IRL 6 = 74.1%
Example 2	8	IRL 1-5 = 5.17% total IRL 6 = 2.76% IRL 7 = 12.0% IRL 8 = 80.0%
Example 3	3	IRL 1 = 8.42% IRL 2 = 20.1% IRL 3 = 71.5%
Example 4	3	IRL 1 = 21.6% IRL 2 = 49.1% IRL 3 = 29.3%
Example 5	6	IRL 1 = 0.75% IRL 2 = 2.11% IRL 3 = 4.15% IRL 4 = 4.60% IRL 5 = 14.9% IRL 6 = 73.5 %

Learning from the Case Study Validation

Standard Testing Progression*	Has this followed the standard testing progression?	Yes No
Test Environment**	What is the highest-level ~~environment~~ at which testing has passed?	None ~~Lab~~ **Functional Integration** Relevant, single integration Relevant, system level Operational, high-fidelity Operational, qualified Operational, proven
*The standard testing progression is one that moves from low-level testing (e.g., unit testing) to higher-level testing (e.g., operational testing) without skipping intermediate testing events.		
**Testing: Focus is on the type/level of testing completed. Different organizations may be performing the same testing in different environments.		

Conclusion

- The Integration Readiness Level provides a new system metric that enables systems engineers to more effectively manage risk during system development in today's complex environments.
- Our IRL Bayesian network model mathematically validates the assessment of integration readiness mitigating system development risk and helping systems engineers produce more capable, interoperable and supportable systems for the end user.
- The model has been implemented in an MS Excel environment and has been open-sourced for use by the international Systems Engineering community.

There will be a meeting of the International System Readiness Assessment Community of Interest (ISRACOI)

Wednesday, July 11th

1330 – 1500

Burnham Room

www.ISRACOI.org

Contact Don York (donald.york@engility.com)

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Backup

Learning from the Case Study Validation

- In the *Testing* section of the original survey ("*What is the highest-level environment at which testing has passed*?"), we initially listed some states using the test environment's physical instantiation – specifically, "*Lab*" – and others by listing both the state and the purpose of the test – e.g., "*Relevant* (state), *system level* (purpose)."
- This caused some confusion. It is possible to do Operational Testing in a physical Lab, especially in cases where true replication of the operational environment would be impossible, e.g., launching rockets in space. In the original version of the model, checking "Lab" was meant to imply no Relevant or Operational testing had necessarily been done. However, as just described, for certain types of systems in specific domains, Operational and Integration Testing may be done in a Lab.
- In external Example #1 this would explain the difference between the Actual (Assessed) IRL = 7 vs. the model predicted IRL = 6. In addition, examining the IRL detailed criteria used by the respondents in the external case studies, we see that for IRL = 7, they specify "*Platform or Lab / DT/ OT*".
- As a result, the decision was made to change the description/state title of "*Lab*" to "*Functional Integration*" and remove the word "*environment*" from the question resulting in the revised question, "*What is the highest level at which testing has passed*?"
- This was an important clarification to make, as the response in Example #1 had demonstrated evidence of system-level testing occurring, but in a "*Lab*", and selecting "*Lab*" skewed the results. Correcting for this potential difference in interpretation of environments of testing levels by other domains, the model provided consistent results compared to the actual assessments.