Software Quality Research Laboratory

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Software Production Essentials

Beyond the Buzz Words

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Why Process?

- Quality
  - Maximize Customer Satisfaction
  - Minimize Rework and Repair
- Productivity
  - Optimize Production Cost
  - Shorten Time to Market

This is not a tradeoff. Quality is Free.

Post ~2000 Scientific Computation
What's Different?

- Collaboration, Collaboration, Collaboration
- Results affect national policy NOW (*e.g.*, climate models)
- Results can have major economic impact SOON (e.g., materials, energy, and IT infrastructure)

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Process Objectives in a Scientific HPC Environment

- Produce reliable software for community use
- Implement functionality tailored to user needs and expectations
- Maximize resource commitment to scientific innovation and productivity
- Minimize resources required for rework and maintenance
- Meet regulatory SQA requirements, where applicable

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Basic Process Elements

- Requirements Definition
- Coding
- Release

Everybody does it, but the order may vary.

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How Do We Fill the Gaps?

- Requirements Definition
- Specification?/Design?/Verification?/?
- Coding
- Test?/ Inspection?/?
- Release

No shortage of lifecycle/process candidates.

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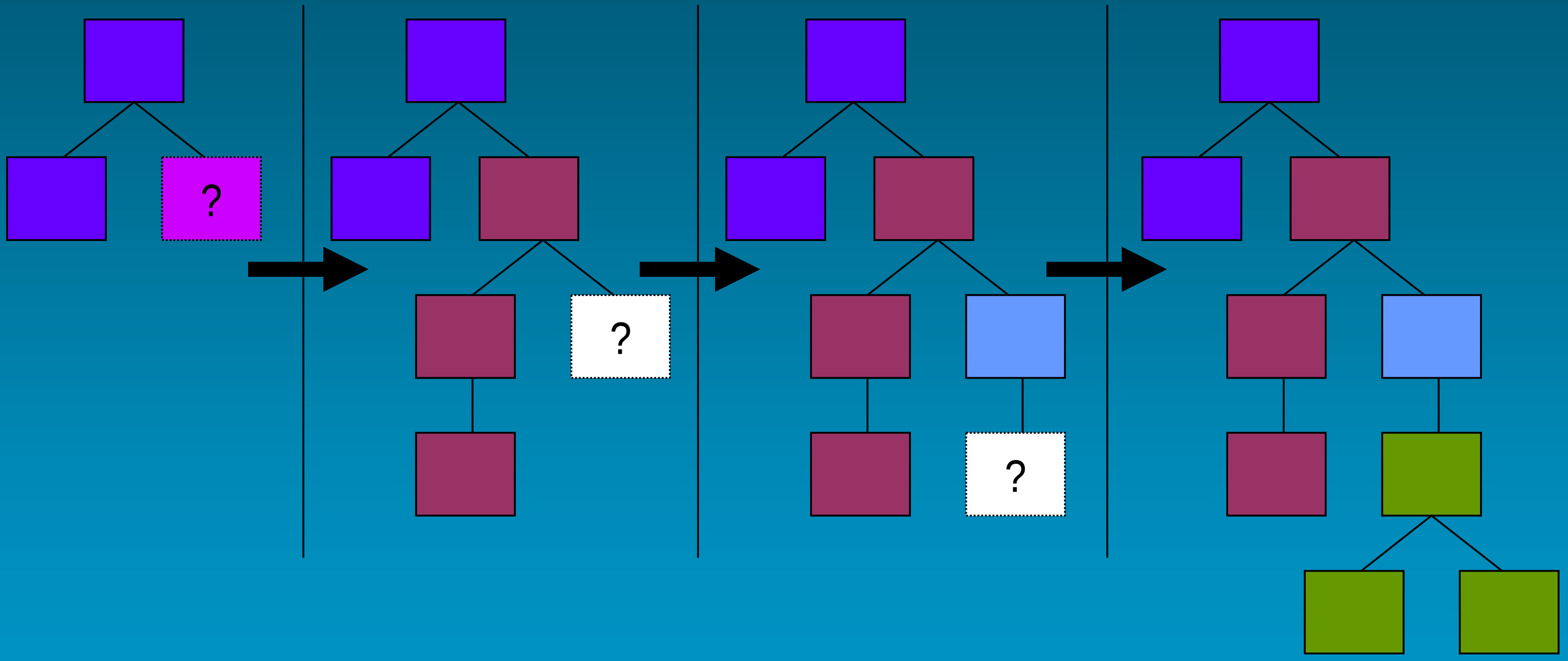
Software Production is Incremental



An efficient, repeatable process is necessary for expanding, changing requirements.

Software Production Keys

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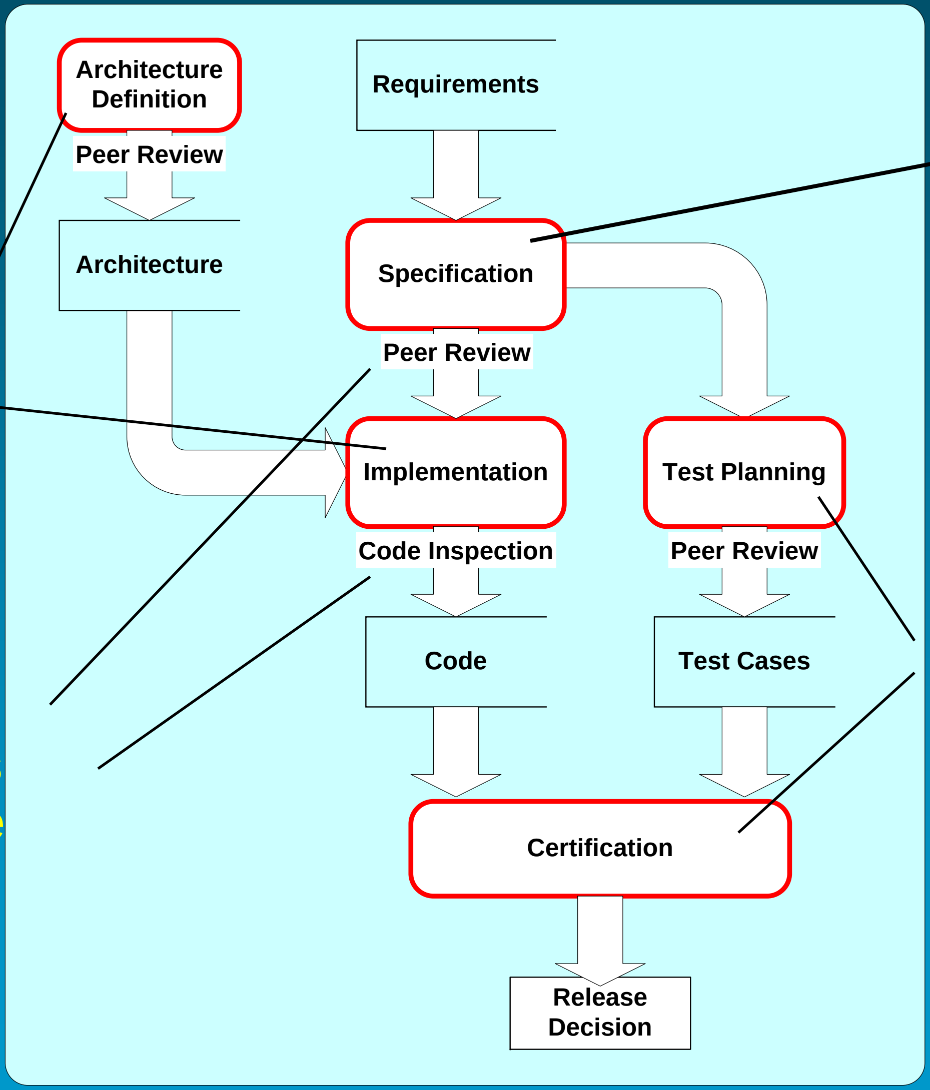
(2) Mapping specified code to a robust, maintainable architecture.

(3) Peer review of key work products including code inspection.



(1) A seamless, traceable transformation from requirements to behavior specification.

(4) Certification via quantitative testing.

Behavior Specification Objectives

- **Completeness**
  - a response is defined for every stimulus history
- **Consistency**
  - each stimulus history maps to only one response
- **Correctness**
  - the specification is explicitly traceable to the requirements

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Requirements

- Individual requirements tagged for traceability.
- Initial requirements assumed to be incomplete, inconsistent, and possibly incorrect.

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The Simple Case: Static Calculations

(Things that run to completion without user interaction)

1. Partition input space into domains bounded by discontinuities
2. Specify response function for EVERY domain

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Function Specifications

- Describe function mathematically for each distinct region of input space
- Specify correspondence between program variables and math symbols used
- Include responses to invalid inputs
- Specify all function results - returned values, state variable modification, modified globals

Practical Consideration: Embed Static Specs in Code Using Doxygen, JavaDoc, or equivalent

Function Specifications: Arguments and Return Values

- Scalars and arrays of fundamental types
  - Specify type, definition, units, valid range, and default value
- Pointers to fundamental types
  - Same as above for dereferenced values
- Compound types – classes, templates, etc.
  - Specify recursively by providing above info wherever data members of fundamental types are declared

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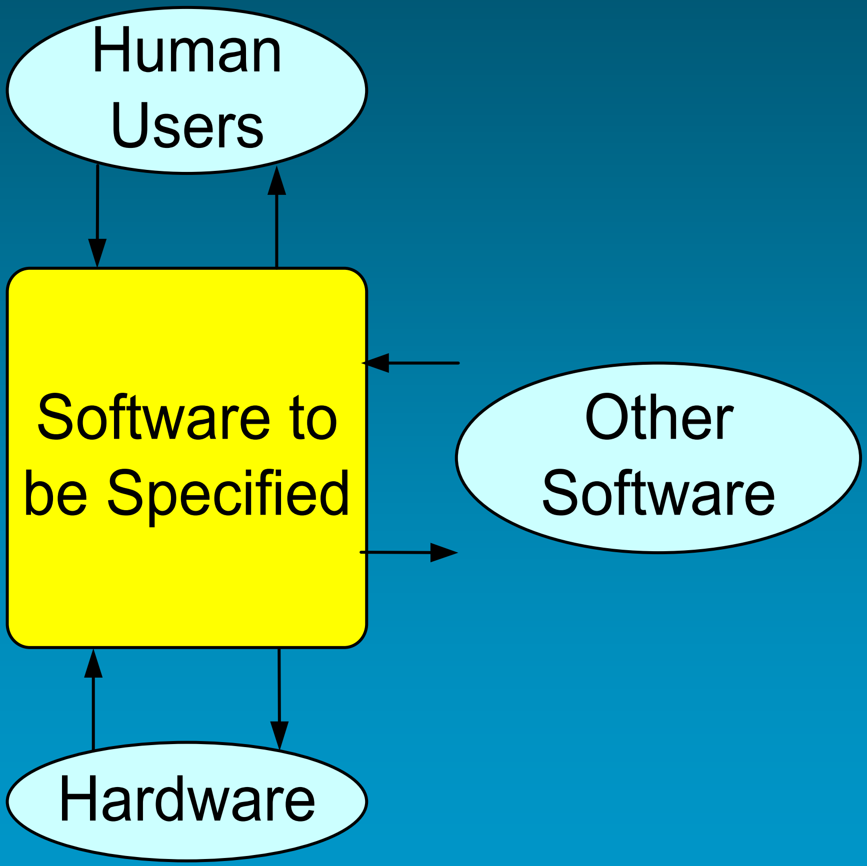
The General Case: Stateful Systems (GUIs, datacom, control, etc.)

- Establish system boundary in terms of human/software/hardware interfaces.
- Itemize stimuli.
- Itemize responses.
- Perform enumeration of stimulus sequences.
- Perform canonical sequence analysis.
- Generate state machine specification.

System Boundary and Interfaces



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Important Definitions

- Stimulus - an event resulting in information flow from the outside to the inside of the system boundary
- Output – externally observable item of information flow from inside to outside the system boundary
- Response – occurrence of one or more outputs caused by a stimulus

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Enumeration Mechanics

- For each stimulus sequence of length n:
  - If illegal, mark it illegal and do not extend further.
  - Document correct response based on requirements.
  - If no requirement found, create derived requirement.
  - Record requirements trace.
  - Check for equivalence with previous sequences.
- Extend only those sequences that are not illegal or equivalent.
- Continue until all sequences of a given length are illegal or equivalent to previous sequences.

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Canonical Sequence Analysis

- Identify canonical sequences – all legal sequences not equivalent to earlier sequences.
- List the canonical sequences in the order enumerated.
- Define state variables such that each canonical sequence corresponds to a unique state vector.

Canonical sequences define all system states

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State Machine Generation

- For each stimulus
  - For each canonical sequence (CS)
    - Get state variable values
    - Find sequence (CS+stimulus) in enumeration
    - Get response
    - Get new CS (CS+stimulus or its equivalence)
    - Get new state variable values

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Map Code Specified in Behavior Specification to Architecture

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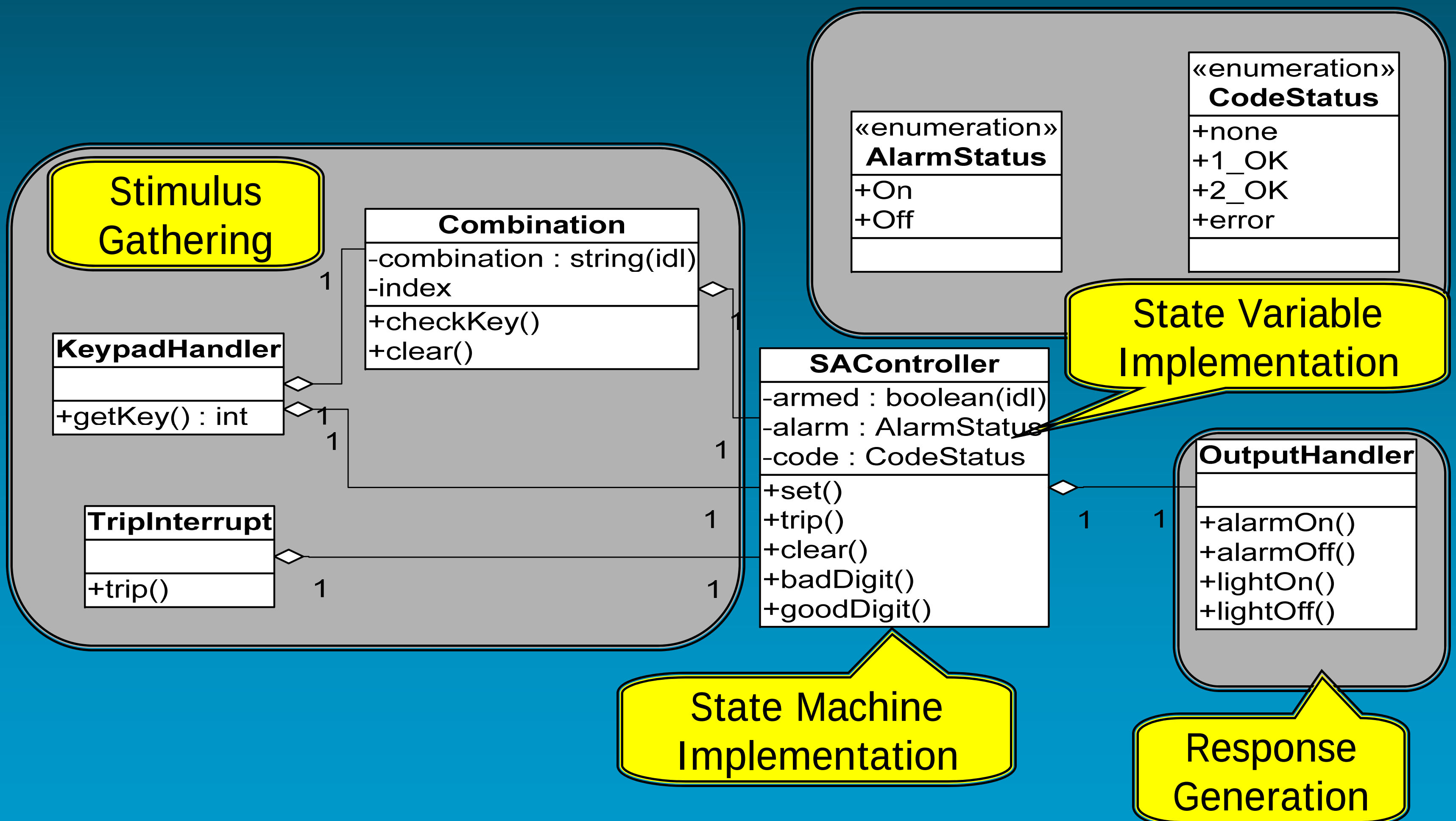

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Specification Procedure Summary

- Specification must be complete, consistent, and traceably correct
- Partition system into manageable components for scalability
- Use enumeration to discover and correct ambiguity and omissions in requirements
- Completed enumeration converts to state machine specification
- Map stimulus gathering, response generation, and state machine spec to architecture for code generation

High Level Architecture Examples

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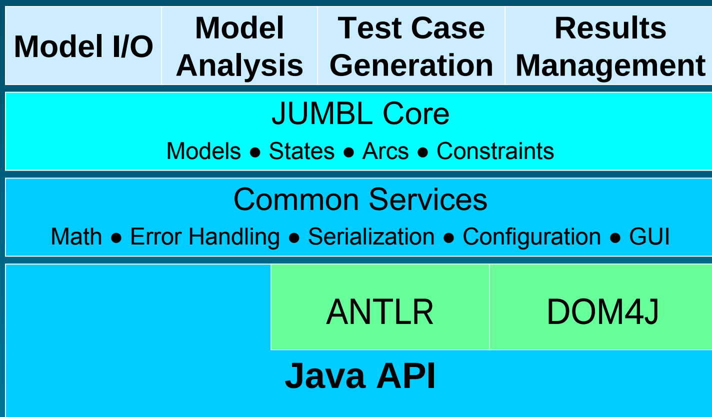
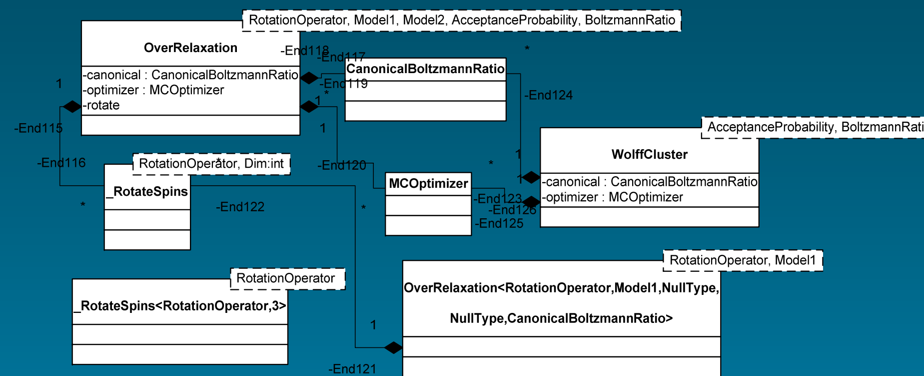
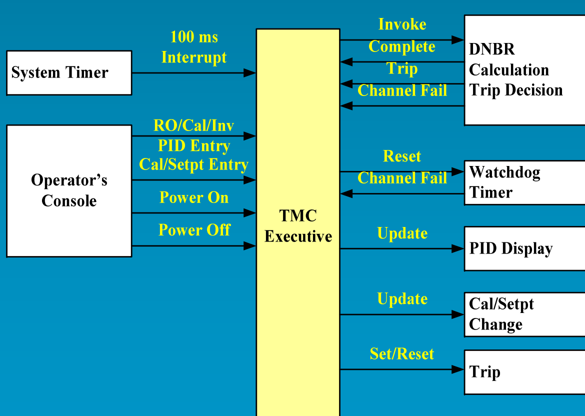


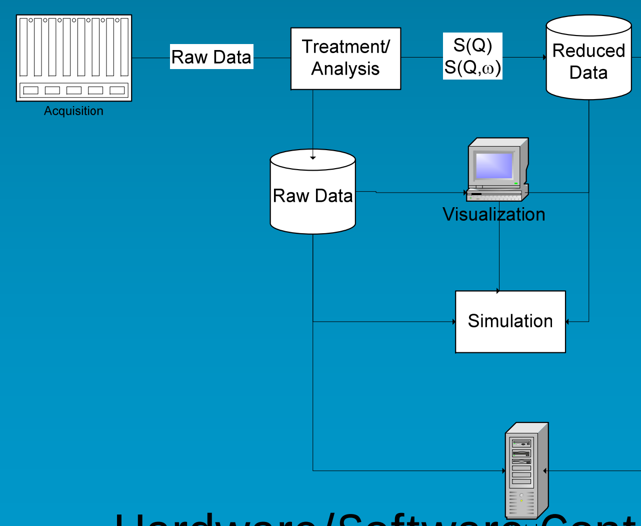
Library



Computational Component



System Abstractions



Hardware/Software Context

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Architecture Specification Contents

- Define components and their responsibilities
- Specify relationships among components
- Specify intra-element and external interfaces
- Ensure unidirectional use hierarchy
- Specify assumptions regarding platform/environment

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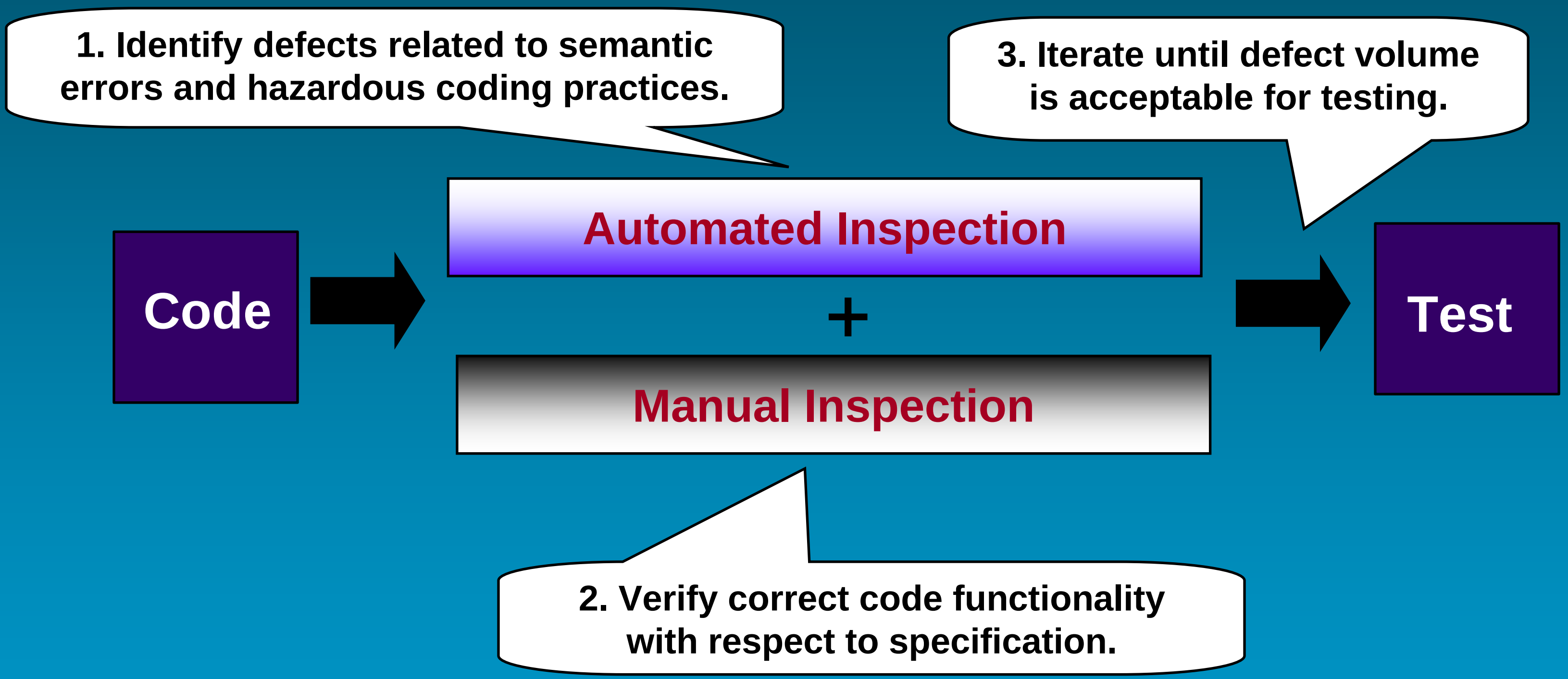
Independent Peer Review

- Domain Expert Review
  - Initial Requirements
  - Derived Requirements from Specification
- Development Team Peer Review
  - Architecture Specification
  - Test Plan
- Code Inspection
  - Automated Enforcement of Coding Standards
  - Manual Verification of Functional Correctness

Manual and Automated Code Inspection



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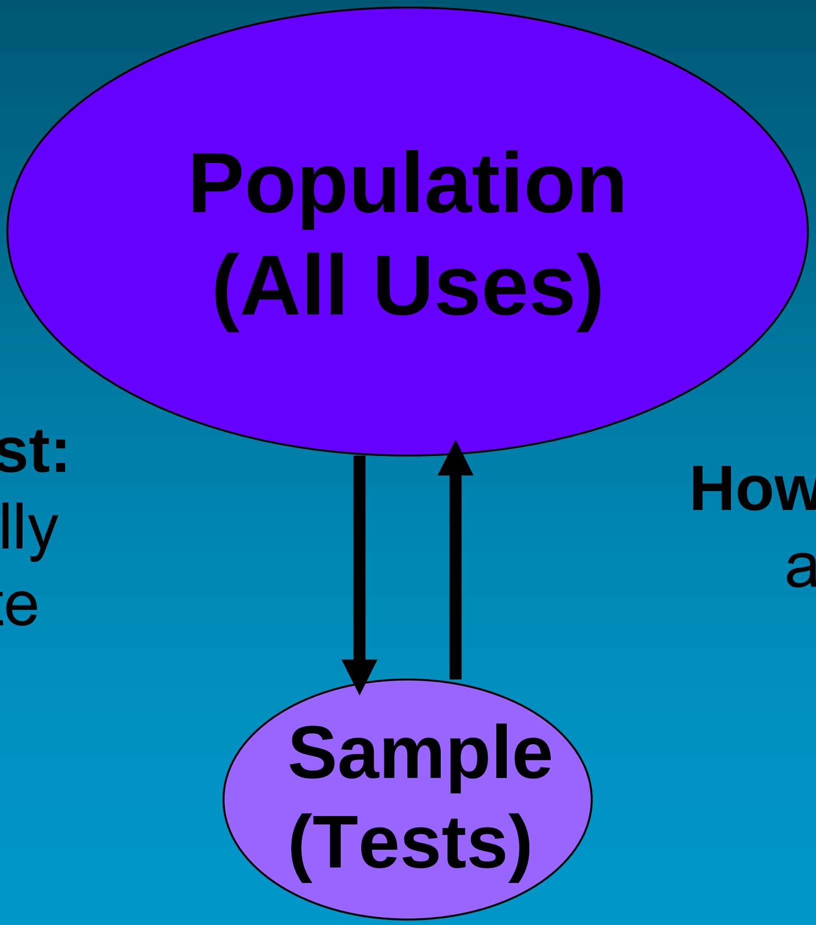
Software Certification

- Certification establishes product conformance with well-defined standards.
- Product certification requires a process that is independently repeatable within statistical variation.
- Statistical testing supports quantitative certification through statistical characterization of system use and reliability.

Testing is Always Sampling



What to test:
a statistically appropriate sample

How much to test:
a risk/benefit tradeoff

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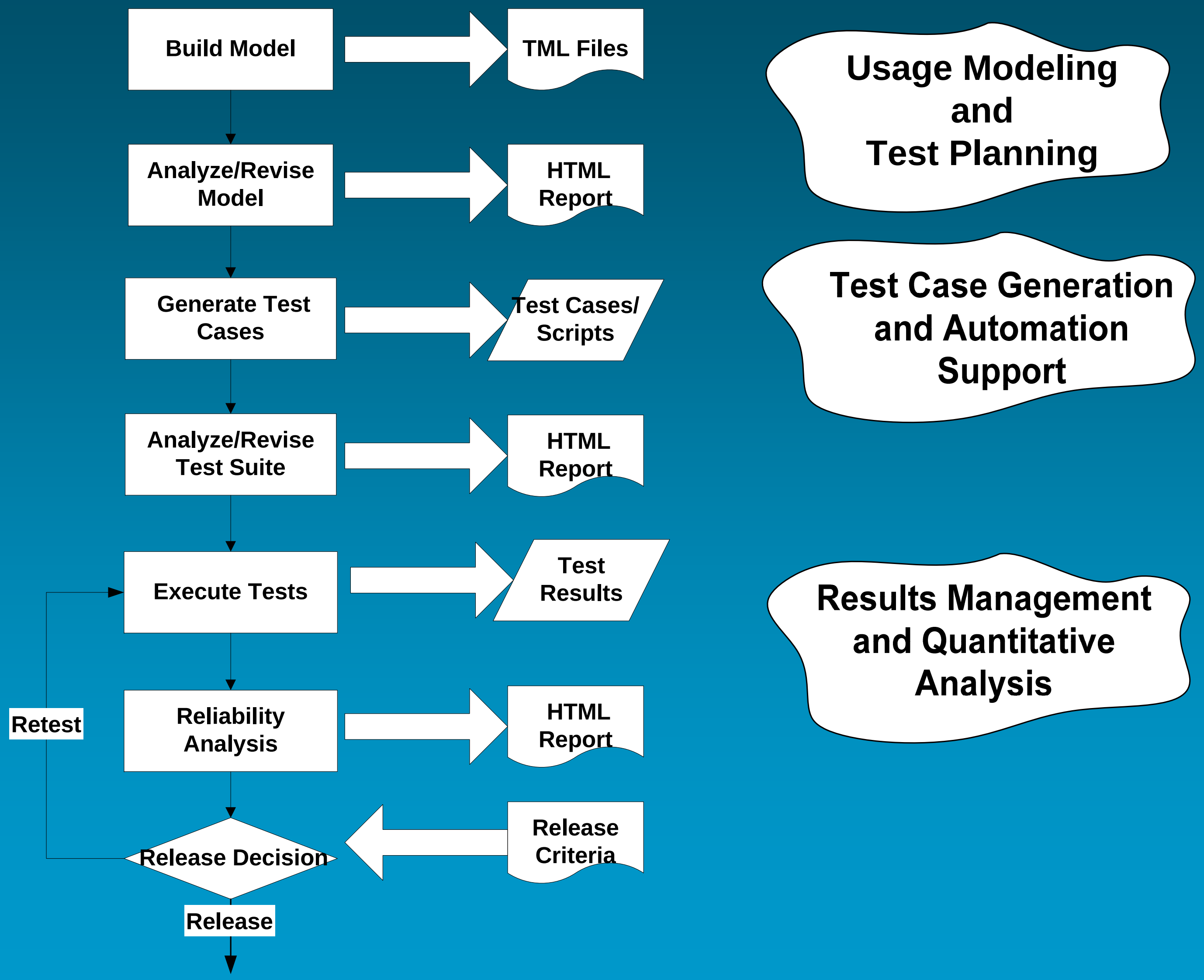
Model-Based Statistical Testing (MBST)



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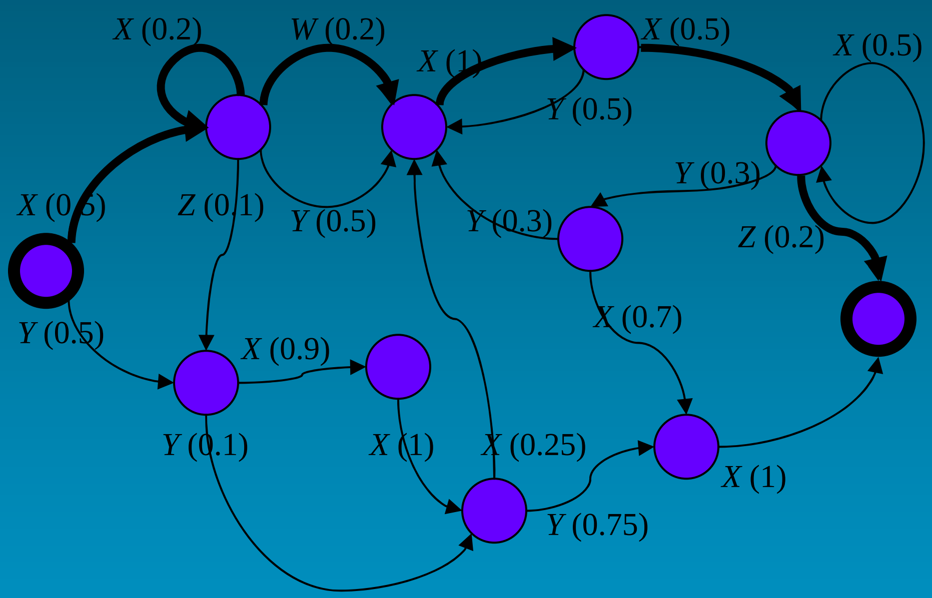
The Population of All Uses Is Represented by a Markov Chain Usage Model



$\Pr[\,x \quad x \quad w \quad x \quad x \quad z\,] = 0.0002$

- Nodes represent “states of use”
- Arcs represent stimuli/events
- Probabilities represent likelihood of a stimulus, given the current state.

A “use” (or test) is any path from the source to the sink.

Special Case: Static Computation with Large Input Space

- Partition input space via abstractions
- Model input selection
- Provide specific parametric input at run time
- Probability weighted generation can give all possible input combinations after partitioning
- Test oracles
  - diverse implementations
  - constraints based on science
  - interpolate between benchmark points
  - favor clarity over performance
  - incentive for good specifications

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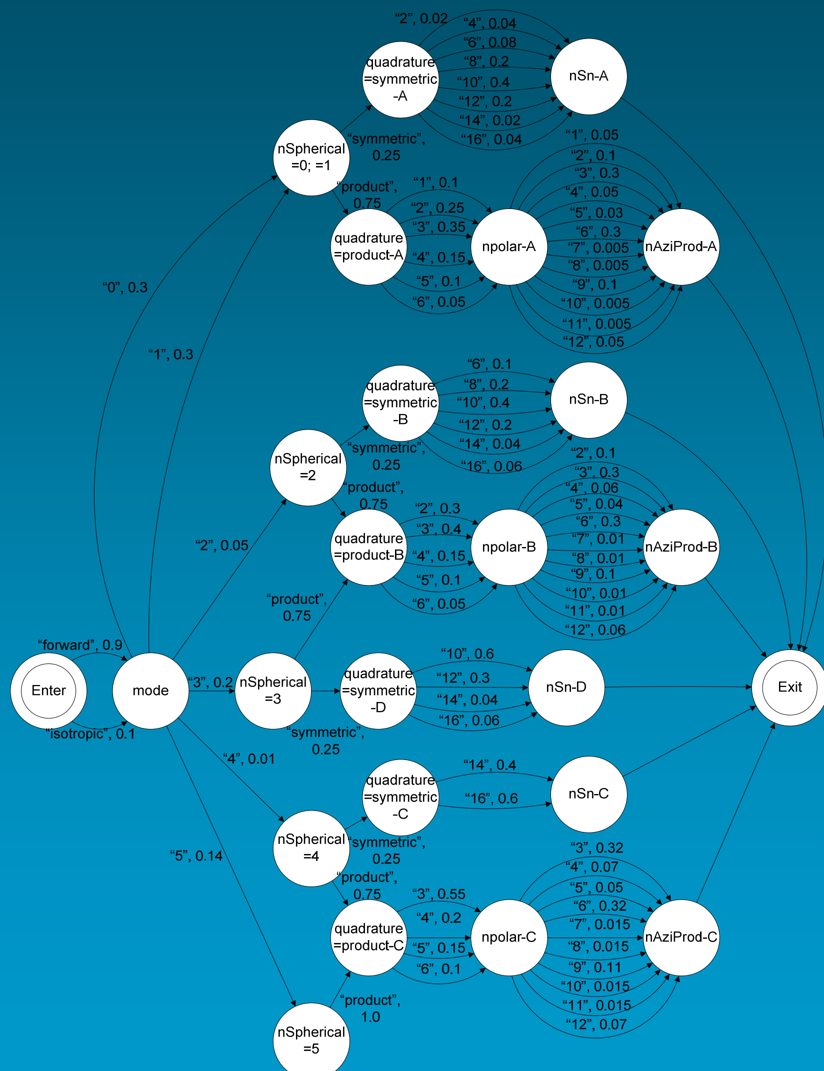
For Static Computation Model Input Selection



A Usage Model is a Finite-State *Markov Chain*

- Well-understood formalism
- Rich body of analytical results
- Engineering basis for testing
- Objectivity in test planning and management
- Describes "use" of product and not the product itself

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Useful Properties Available via Markov Analysis

- Expected Test Case Length: average number of stimulus events from start to end
- Arc/Stimulus Occupancy: fraction of all transitions performed by each Arc/Stimulus
- State/Arc Probability of Occurrence: probability a State/Arc will be visited during a single use
- State/Arc Visits per Test Case: Average number of visits to each State/Arc per use
- Mean First Passage: average number of test cases required to exercise a particular state/function

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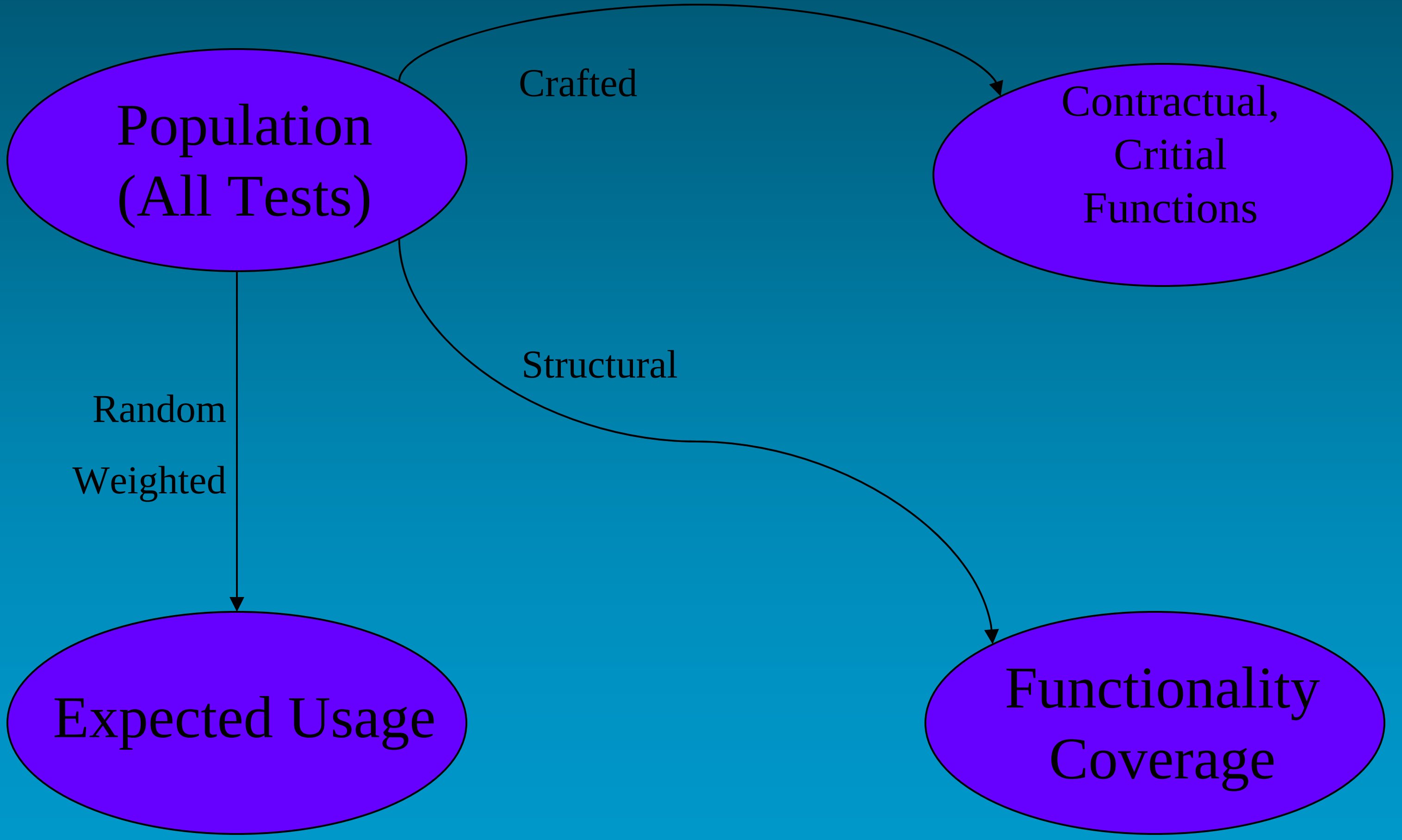
Model Revision and Validation

- Analytical results are inescapable, given the model.
- If results do not square with what is known of the real-world application, the model must be revised.
- Continue the analyze-revise cycle until the model is an acceptable description of use of the system.

Sampling Options (Test Case Generation)



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Nonrandom Testing

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- Coverage tests
  (cover all arcs at the least cost of testing)
- Importance tests
  (generate tests in order of probability or cost)
- Crafted tests
  (contractual, safety issues, critical functions)

Random sample testing

- Test cases are generated by random walks through the usage model.
- Permits statistical analysis of the sample and generalization to the population of uses.
- Each test case is a sequence of stimuli and random test sets may be reused.

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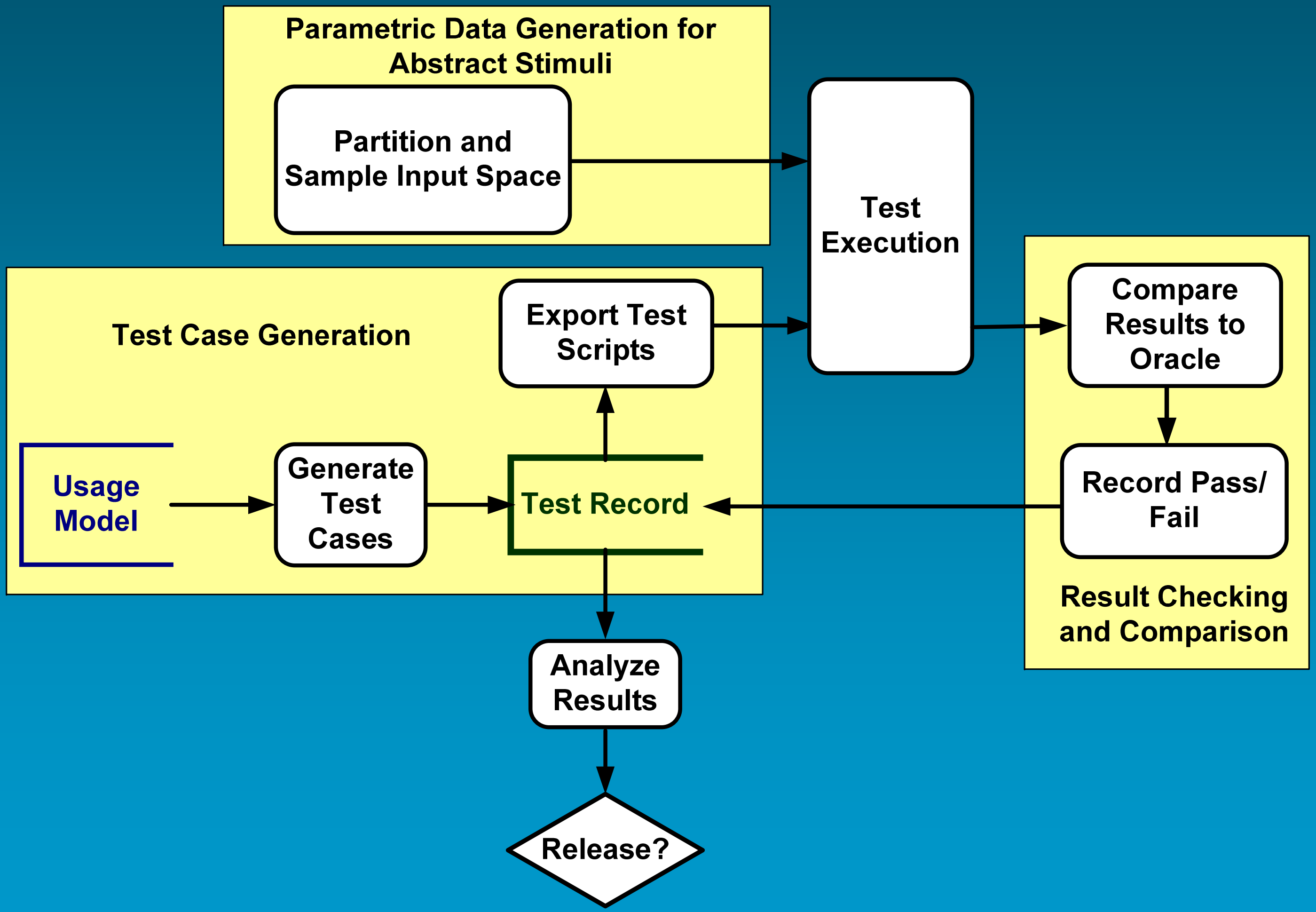
Testing Scripts

Script commands are attached to arcs and give the instructions for testing the transition:

- Manual testing
  - written instructions
  - data to use
  - items to check
- Automated testing
  - signals for testing equipment
  - commands for driver software (*e.g.*, X-runner)
  - statements in a programmed test driver

Test Automation



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Test Automation

- Application-Specific Tools
  - Generate parametric data for abstract stimuli
  - Compute expected results
  - Make pass/fail determination
- Generic Tools
  - Generate test cases as test scripts
  - Associate test instructions with arcs and states in a model
  - Perform statistical analysis of test results

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Test Results

- Record failures by test case and transition
- Estimate reliability based on testing experience
- Evaluate stopping criteria

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Reliability Estimation

- Test case pass/fail statistics give reliability and confidence based on binomial distribution.
- Bayesian models
  - provide reliability estimates regardless of whether failures are observed
  - allow use of prior reliability information

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MBST Benefits

- Better Product
  - Clearer requirements, improved specification
- Better Use of Resources
  - Optimization of testing strategy
  - Reusable assets: models, test plans, scripts, test cases
- Shorter Life Cycle
  - Test planning done in parallel with development
  - Easier test automation
- Better Management
  - Quantitative support for release decisions
  - Quantification of expected reliability
  - Measurement tool for continuous process improvement

Essential Process Elements

- Requirements Definition
- Robust Architecture Definition
- Rigorous Specification
- Domain Expert and Peer Review
- Coding
- Code Inspection
- Statistical Testing/Certification
- Release

Fill the gaps with rigorous engineering practices.