Model-based testing

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- Concepts of model-based testing
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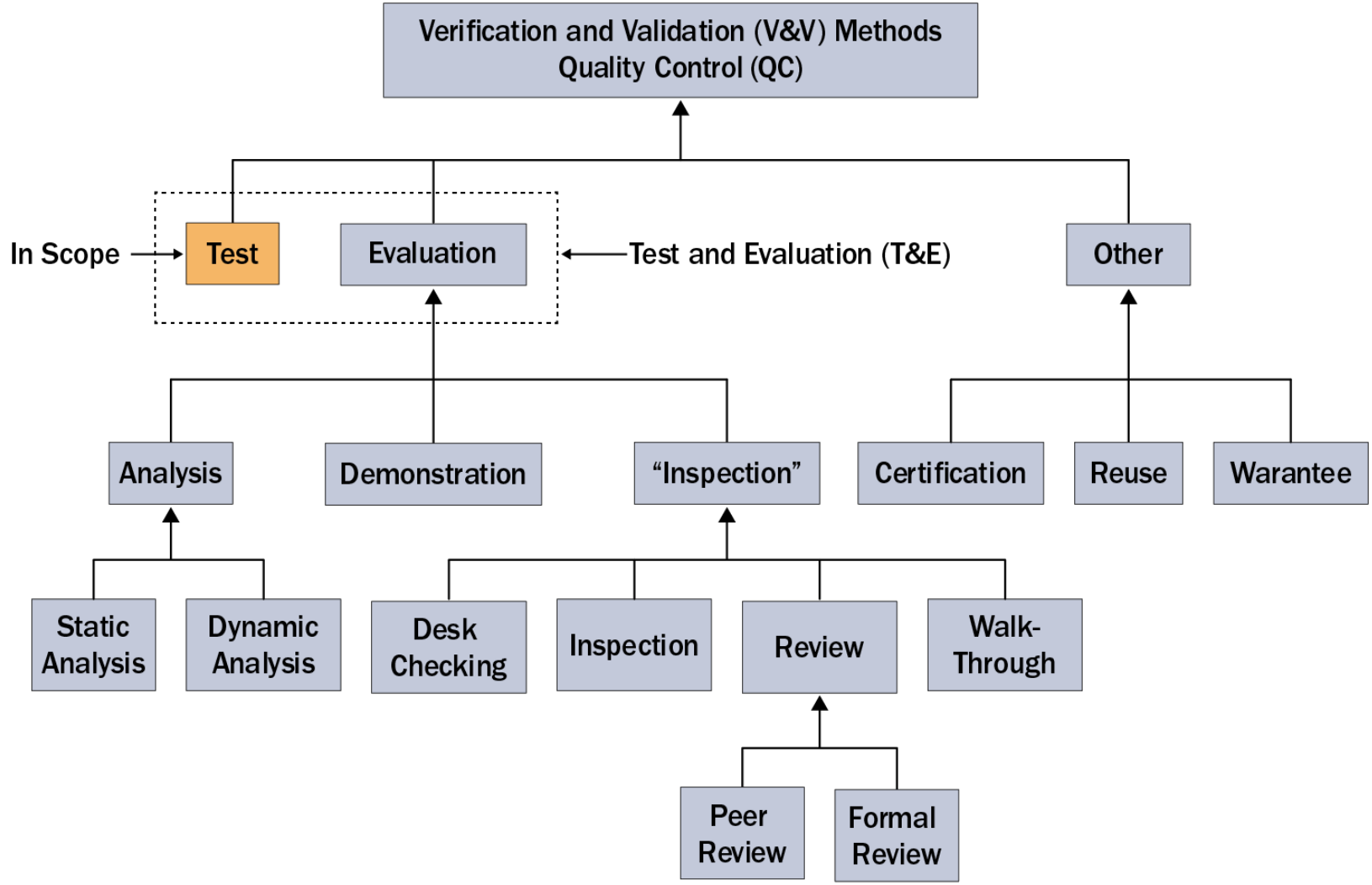
- Automated test generation using model checking
- AutoCheck^{FP}

Overview

Taxonomy of testing (Donald Firesmith, CMU SEI, 2015)



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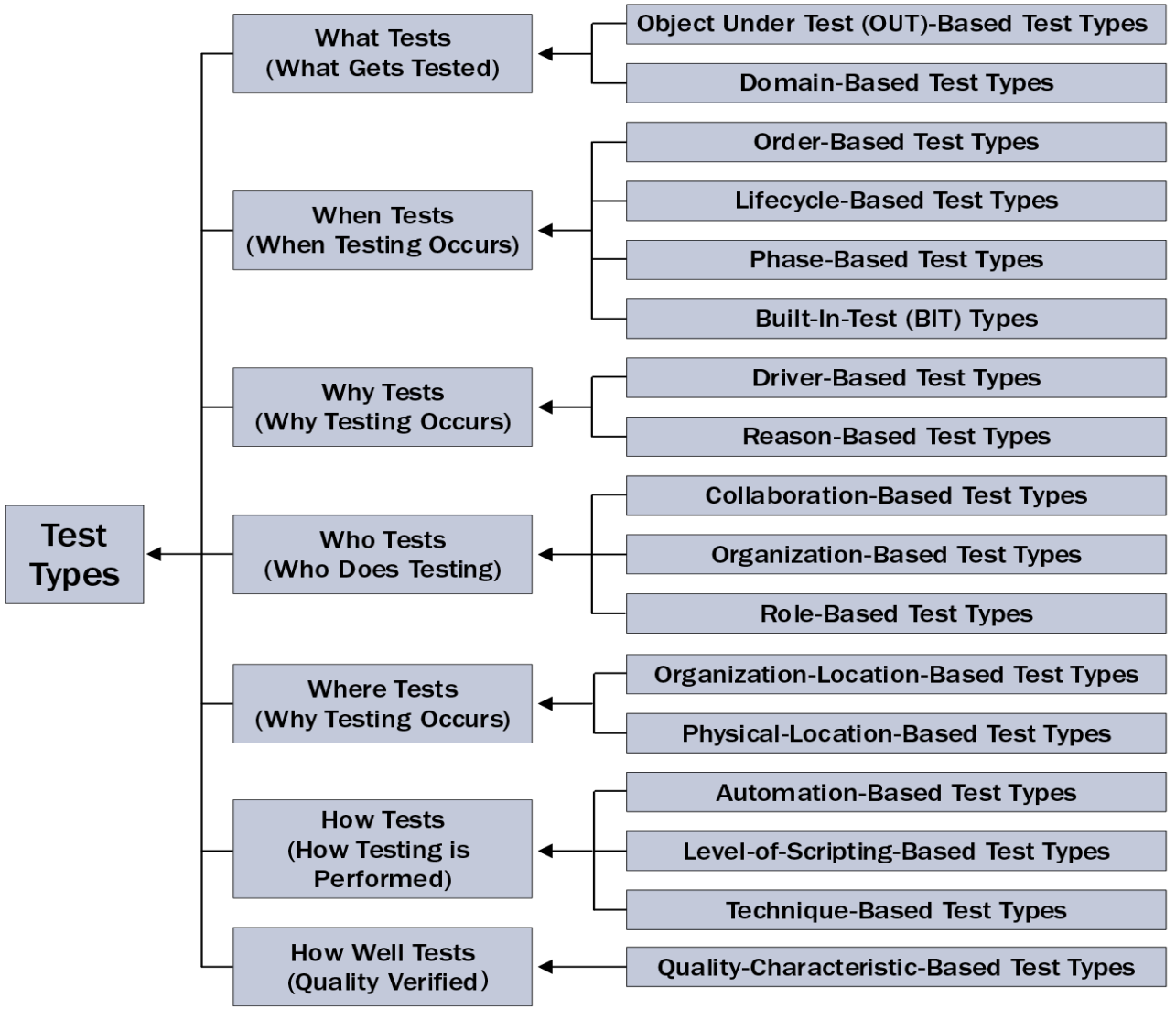

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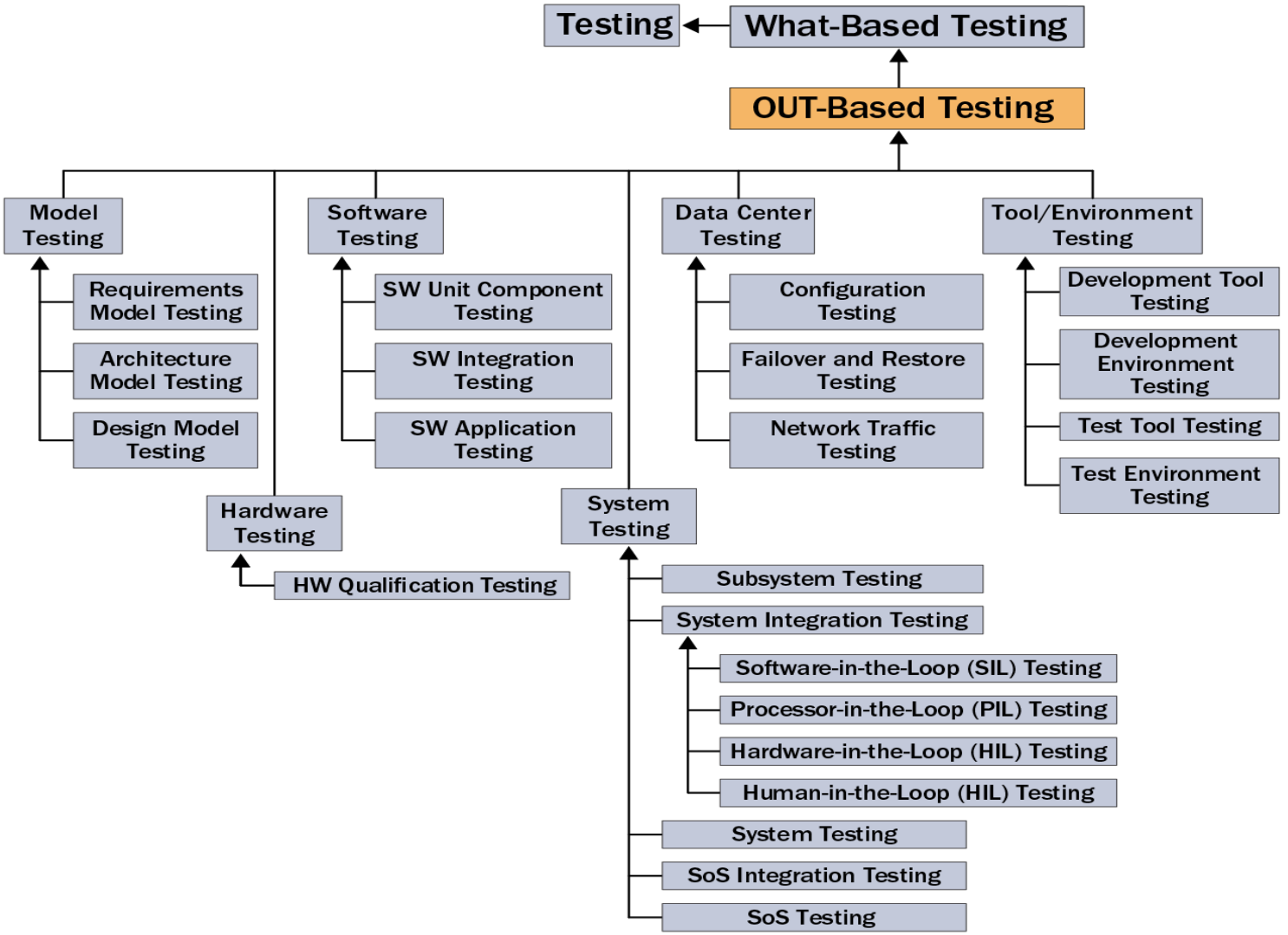

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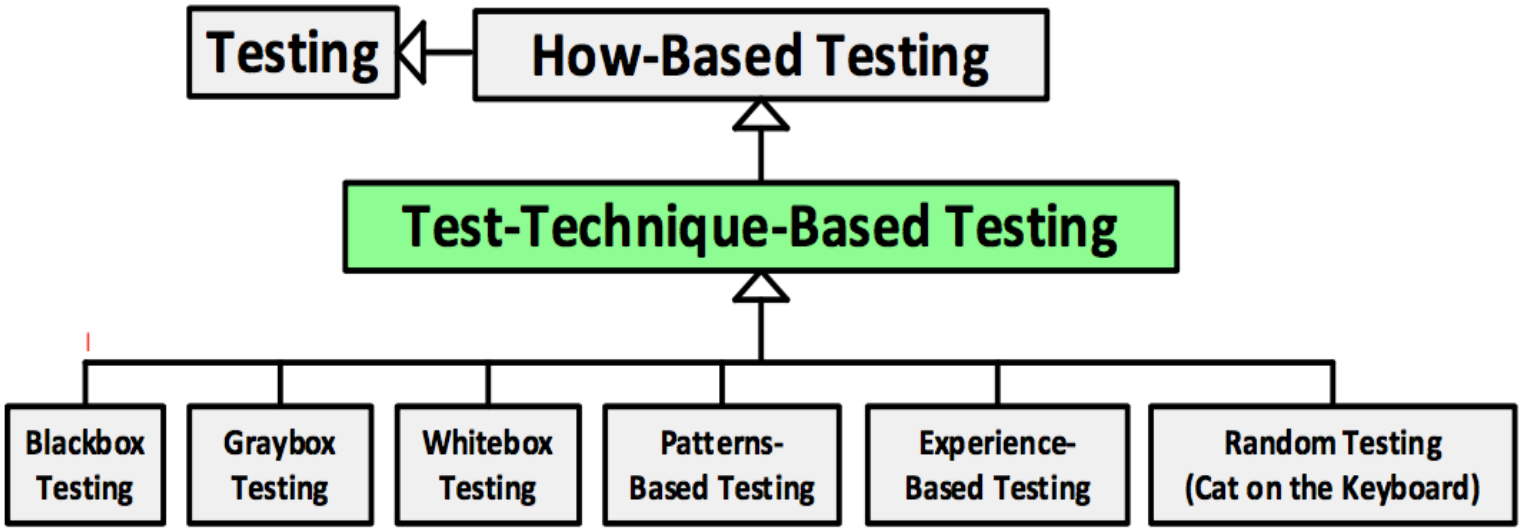

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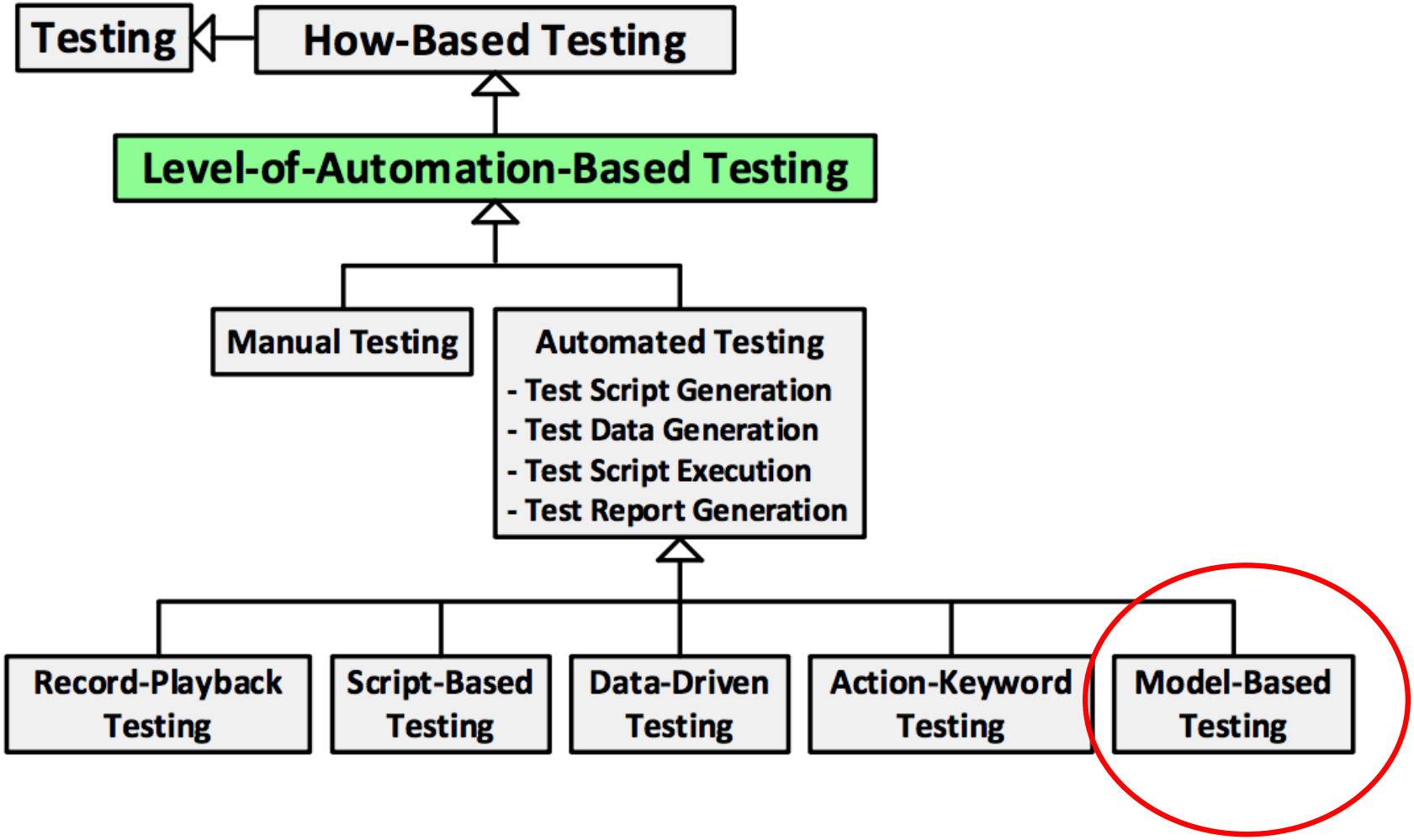
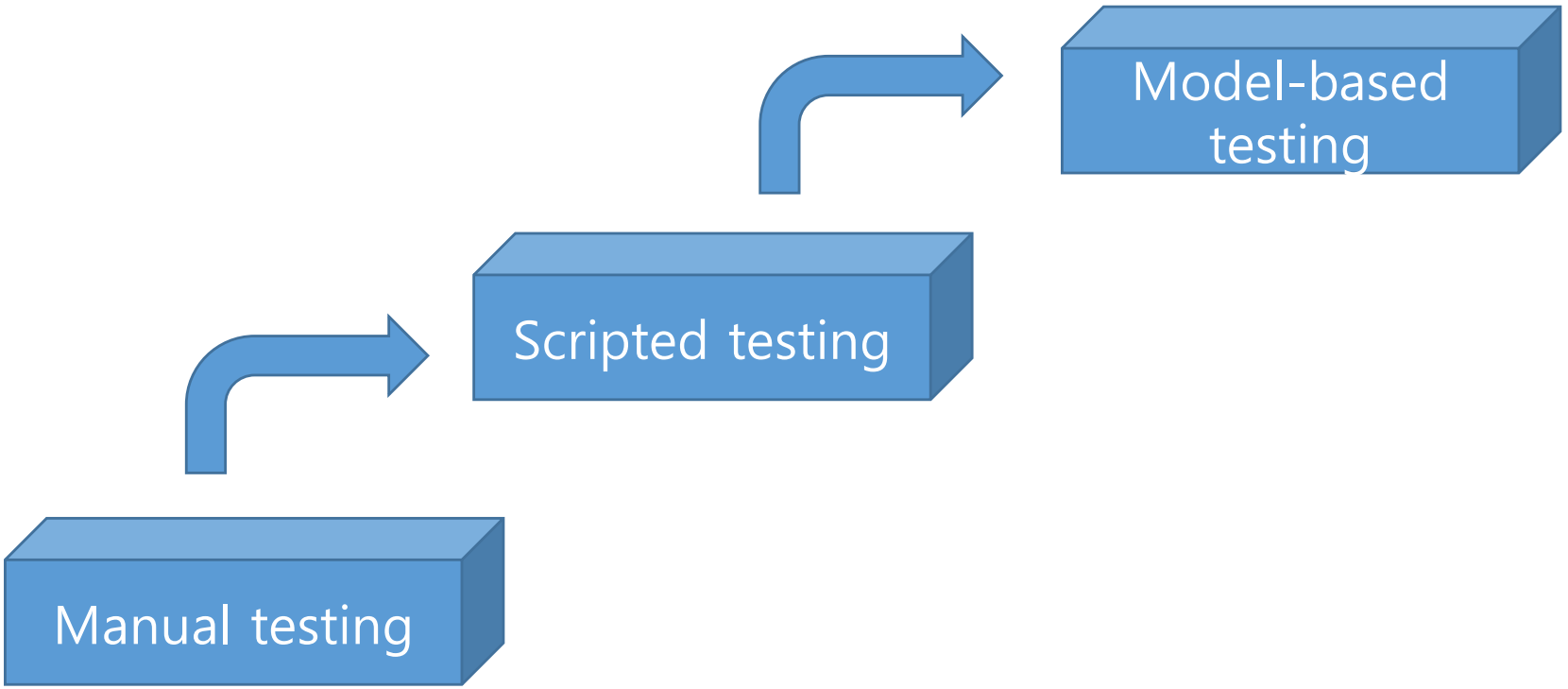


Software testing evolution



What is a model?

- A representation of a system using general rules and concepts
- A model can come in many shapes, sizes, and styles.
- A model is not the real world, but a human construct to help us better understand the real world.
- All models have an information input, an information processor, and an output of expected results

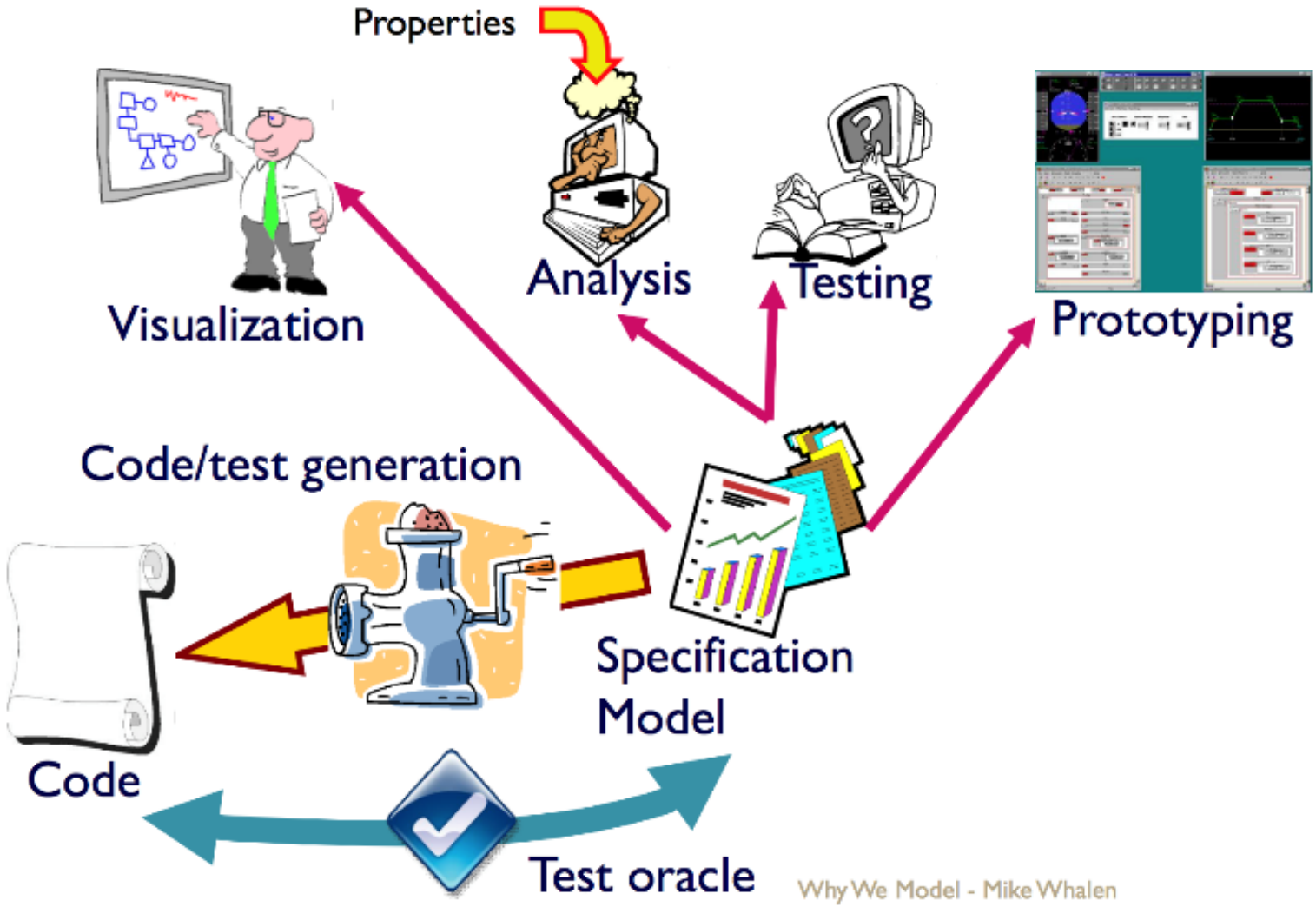
Why model-based? (development perspective)

1. To make sure that we understand what we want to develop
2. To make sure that what we develop is what we wan ted to develop in the first place (validation)
3. Models are easier to understand than natural langu age documents
   - Validation through simulation is possible
   - Completeness and consistency of the model can be checked automatically

Why model-based? (development perspective)

5. Development can be entirely model-based through step-by-step refinements
   - ➢ Entire development process can be automated using model -based code generation

Model-based development
(Mike Whalen, ICSE2013 Tutorial)



Model-based development examples

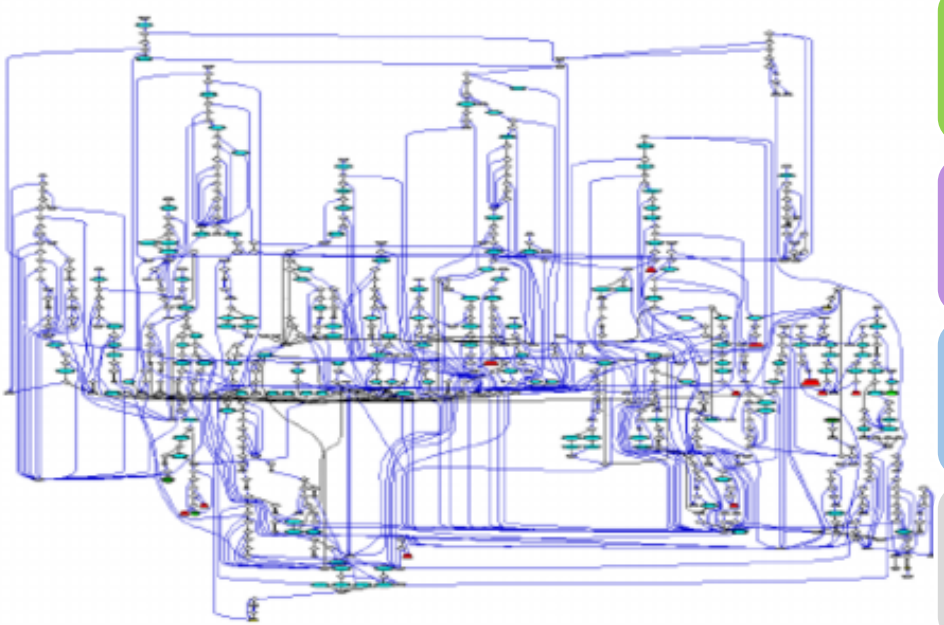
Company	Product	Tools	Specified & Autocoded	Benefits Claimed
Airbus	A340	SCADE With Code Generator	• 70% Fly-by-wire Controls • 70% Automatic Flight Controls • 50% Display Computer • 40% Warning & Maint Computer	• 20X Reduction in Errors • Reduced Time to Market
Eurocopter	EC-155/135 Autopilot	SCADE With Code Generator	• 90 % of Autopilot	• 50% Reduction in Cycle Time
GE & Lockheed Martin	FADEDC Engine Controls	ADI Beacon	• Not Stated	• Reduction in Errors • 50% Reduction in Cycle Time • Decreased Cost
Schneider Electric	Nuclear Power Plant Safety Control	SCADE With Code Generator	• 200,000 SLOC Auto Generated from 1,200 Design Views	• 8X Reduction in Errors while Complexity Increased 4x
US Spaceware	DCX Rocket	MATRIXx	• Not Stated	• 50-75% Reduction in Cost • Reduced Schedule & Risk
PSA	Electrical Management System	SCADE With Code Generator	• 50% SLOC Auto Generated	• 60% Reduction in Cycle Time • 5X Reduction in Errors
CSEE Transport	Subway Signaling System	SCADE With Code Generator	• 80,000 C SLOC Auto Generated	• Improved Productivity from 20 to 300 SLOC/day
Honeywell Commercial Aviation Systems	Primus Epic Flight Control System	MATLAB Simulink	• 60% Automatic Flight Controls	• 5X Increase in Productivity • No Coding Errors • Received FAA Certification

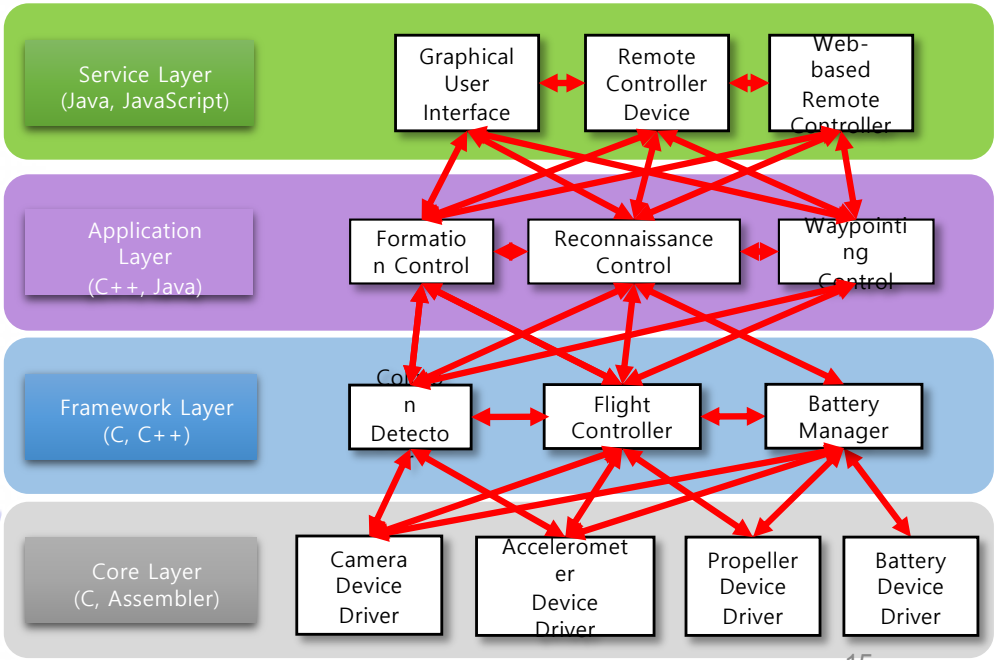
Slide from “Proving the Shalls” by Steve Miller, 2006 Rockwell Collins, Inc. All rights reserved

Why model-based? (testing perspective)

- Manual testing cannot cope with the increasing complexity of software itself
  - Exponential complexity due to
    - The size of software
    - Interactions with users, external systems, and HW
    - The size of inputs

Automation!

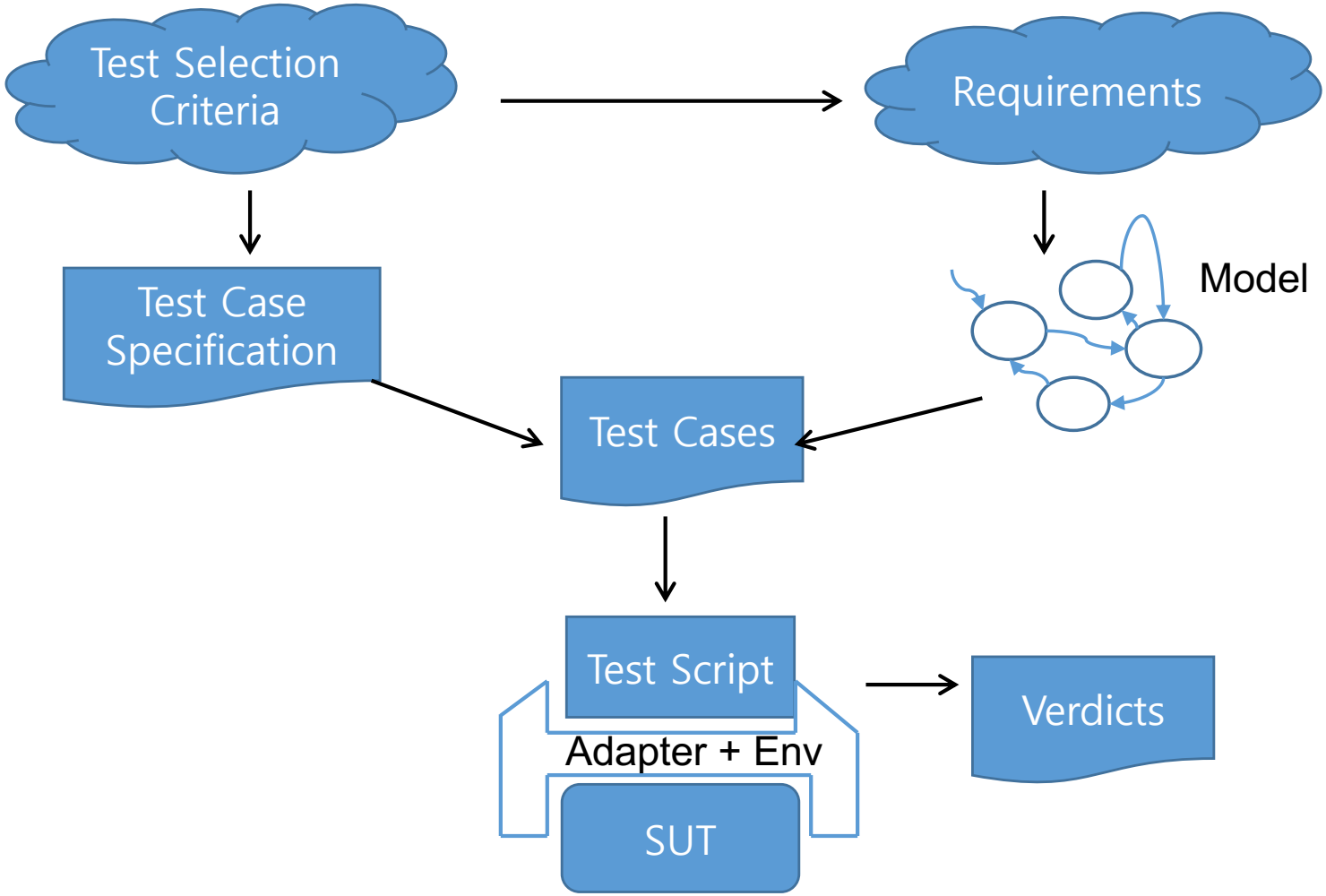




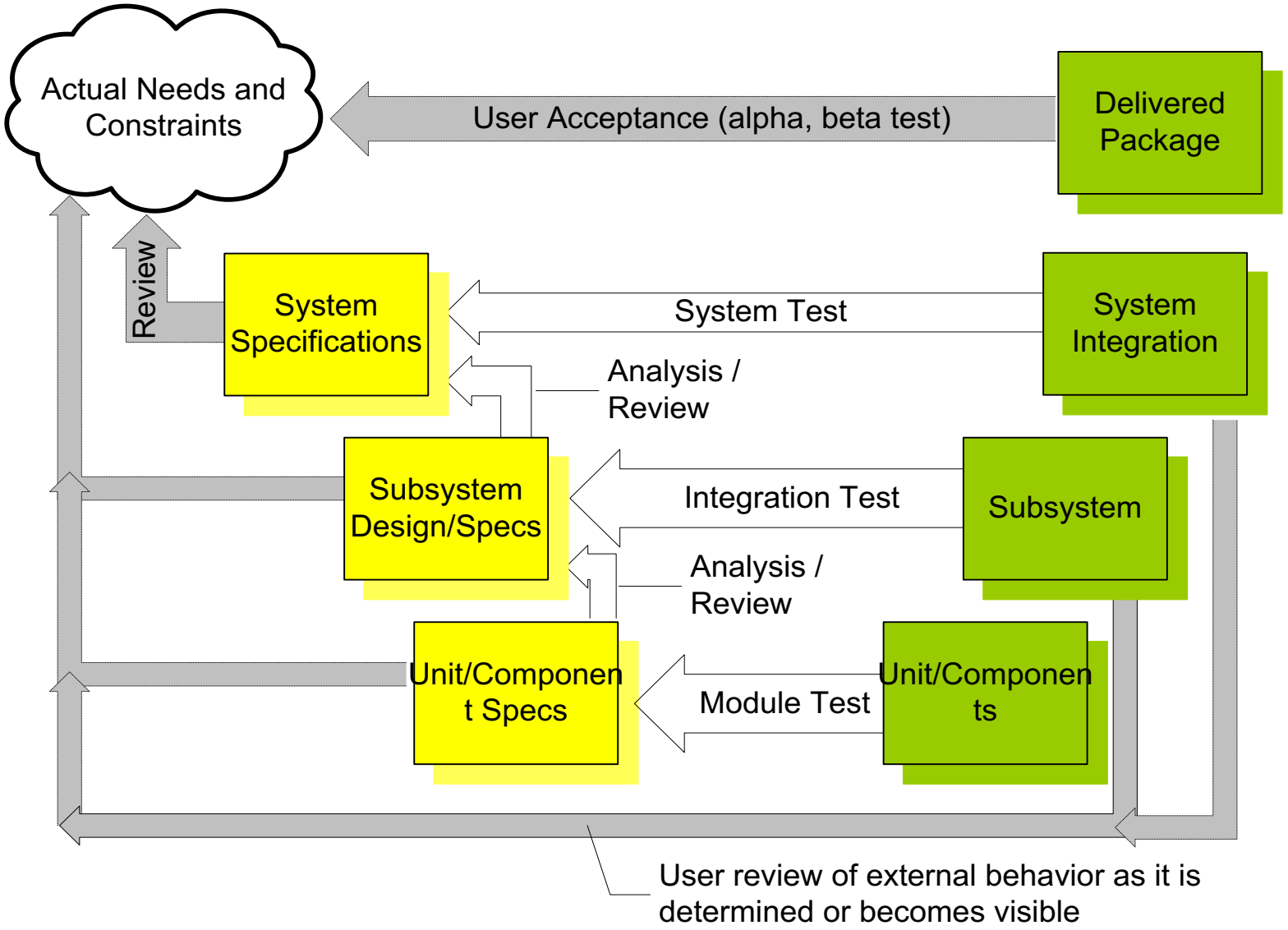
Why model-based? (testing perspective)

- We need a systematic testin g approach to cope with the growing complexity
- We can measure the quality of testing using coverage cri teria, but how to ensure the best coverage?

Model-based testing



Determining what to test: V-model



Model-based testing in industry

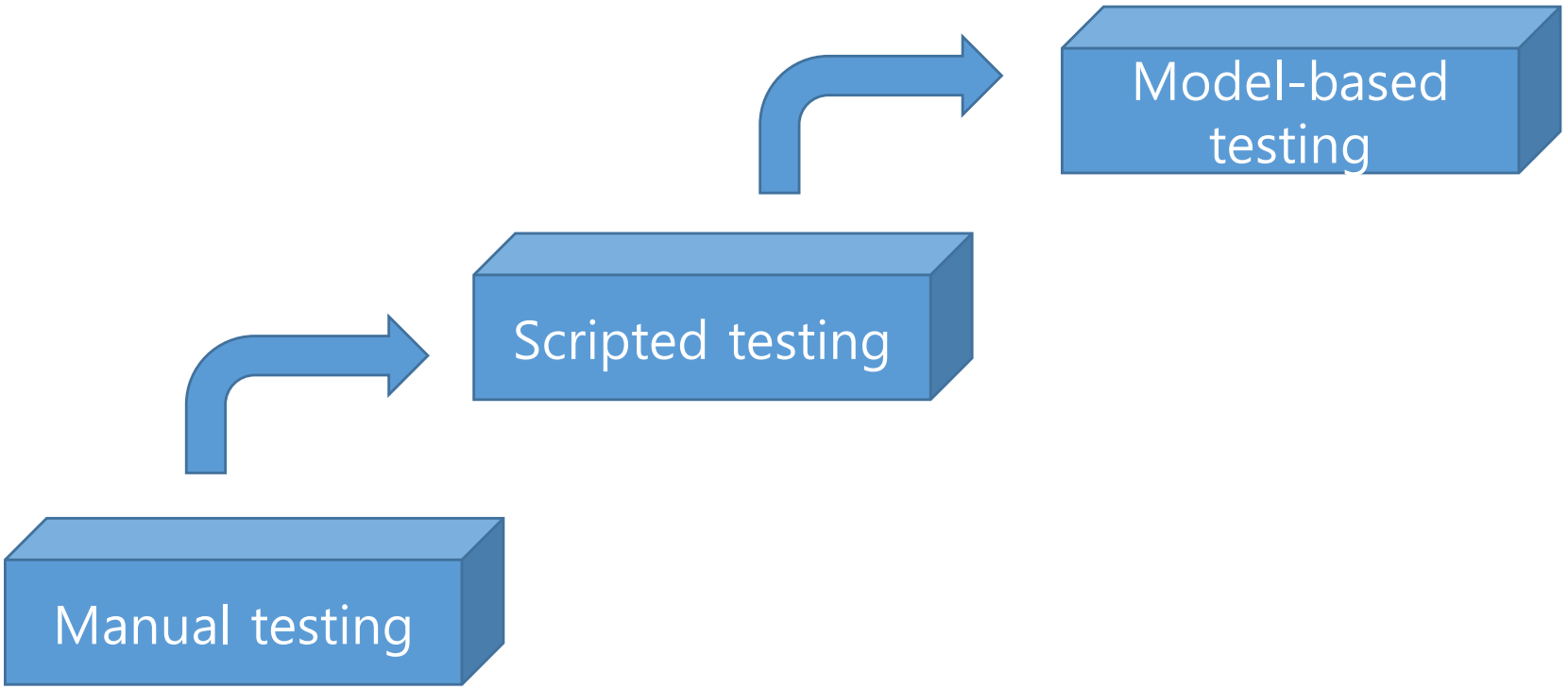
Summary of overview

- Models are useful abstractions
  - In specification and design, they help us think and communicate about complex artifacts by emphasizing key features and suppressing details
  - Models convey structure and help us focus on one thing at a time
- We can use models in systematic testing
- Model-based testing automates testing process at an y level of software development
  - Automation requires the use of formal models

Model-based testing

Concepts

Software testing evolution



Remind: software testing activities

- Test Engineer: An IT professional who is in charge of one or more technical test activities
  - Designing test inputs
  - Producing test values
  - Running test scripts
  - Analyzing results
  - Reporting results to developers and managers
- Test Manager: In charge of one or more test engineers
  - Sets test policies and processes
  - Interacts with other managers on the project
  - Supports the engineers

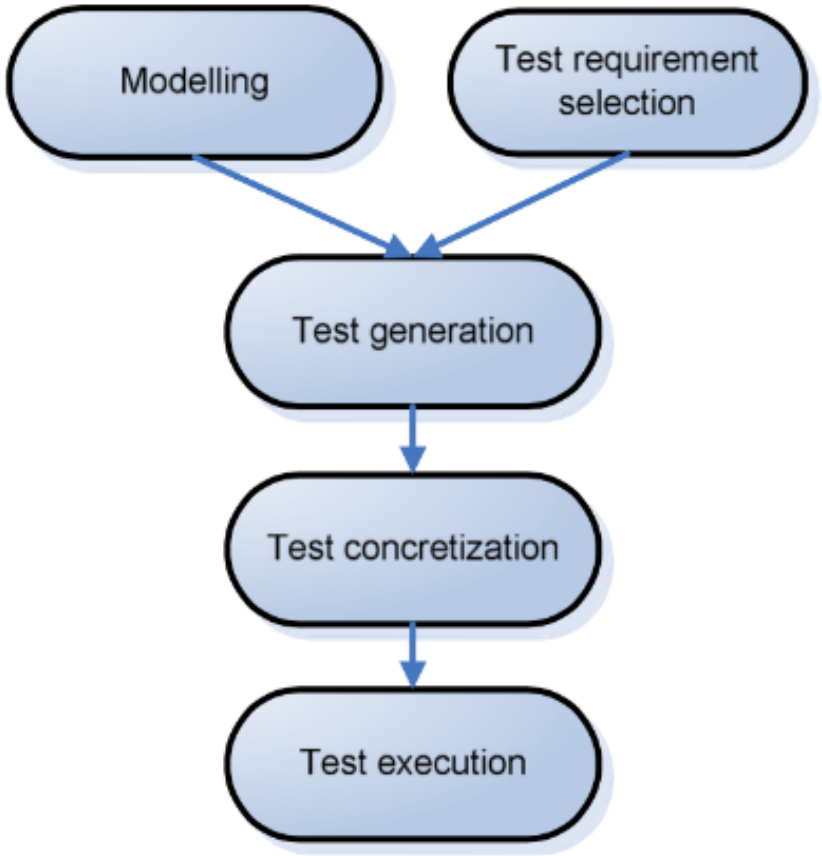
Remind: types of test activities

- Testing can be broken up into four general types of activities
  - Test design
  - Test automation
  - Test execution
  - Test evaluation
- Each type of activity requires different skills, background knowledge, education and training

Remind: Other test activities

- Test management
  - Sets policy, organizes team, interfaces with development, chooses criteria, decides how much automation is needed
- Test maintenance
  - Save tests for reuse as software evolves
- Test documentation
  - Each test must document “why” – criteria and test requirement
  - Ensure traceability throughout the process
  - Keep documentation in the automated tests

Model-based testing

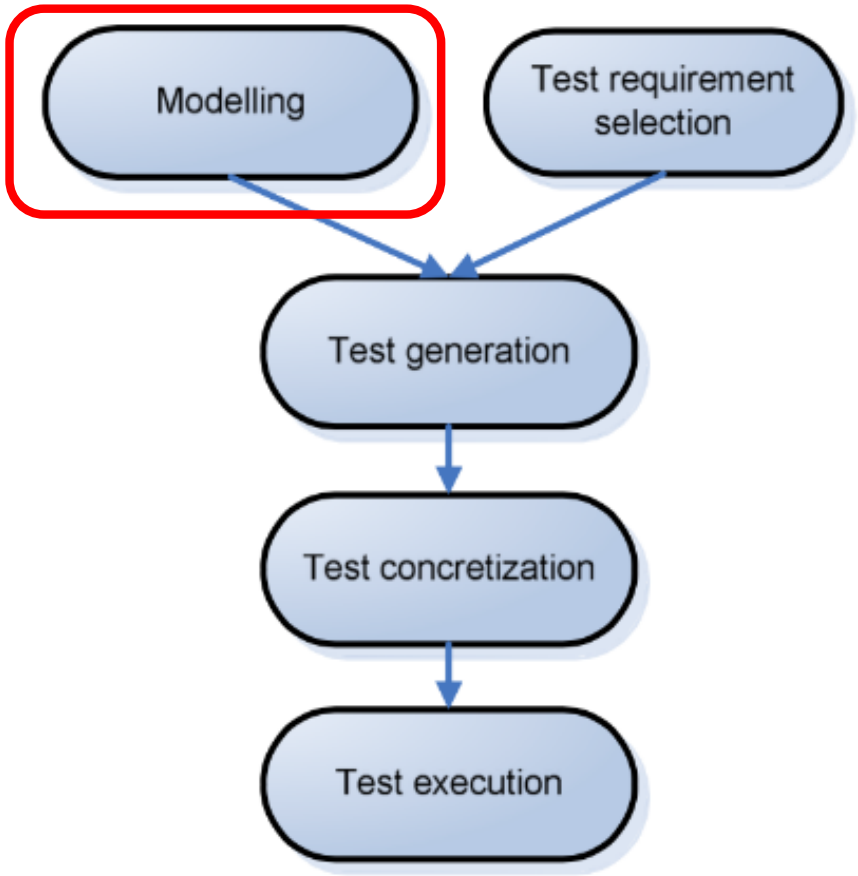


- Model-based testing is software testing in which test cases are generated in whole or in part from a model that describes some (functional, non-functional) aspects of the system under test (SUT)
- Almost synonyms
  - Model-driven testing
  - Test generation

Model-based vs. model-driven

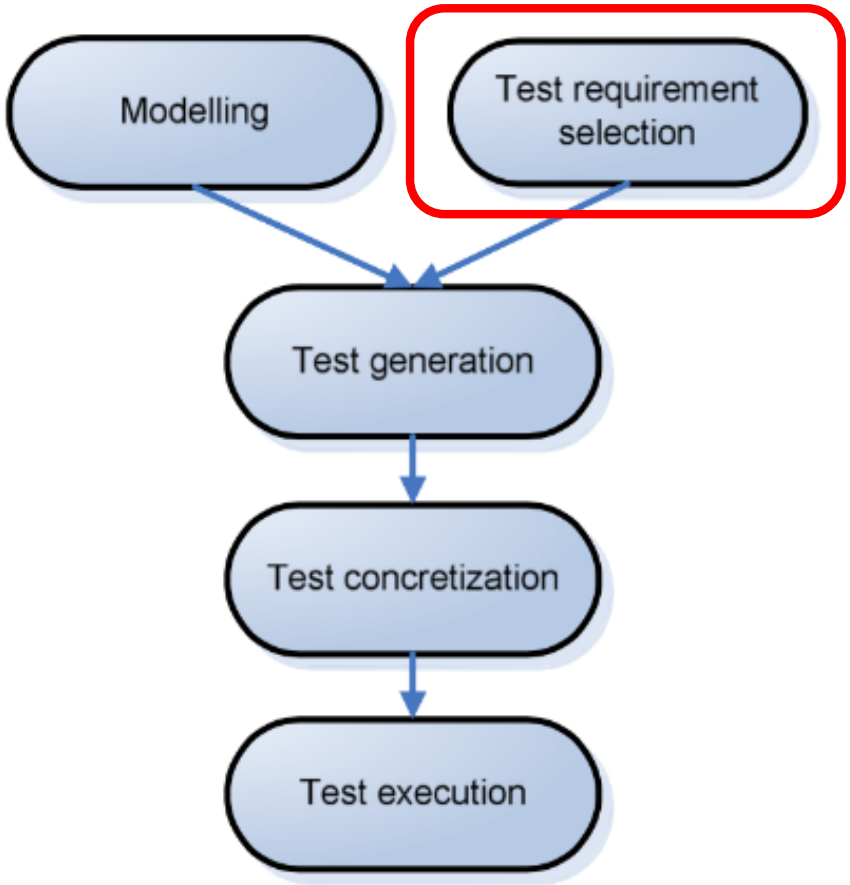
- Model-based
  - Starts from models
- Model-driven
  - Anything can be a model (through abstraction & extraction)

Model-based testing: modeling



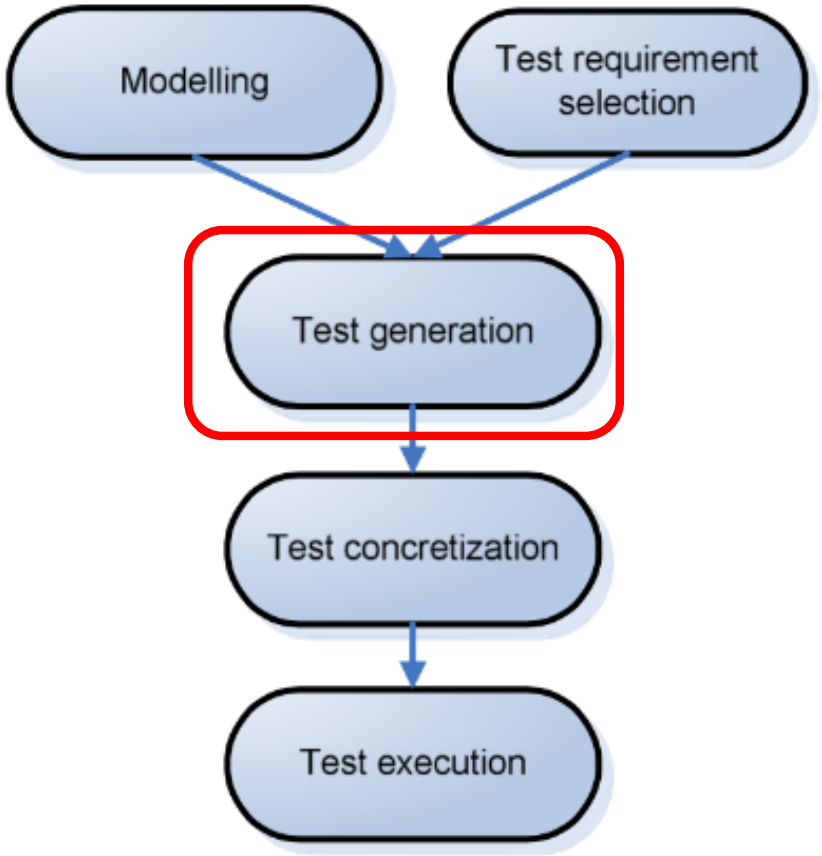
- Purpose: To describe the system requirements for test generator
- Choice of modeling notations
  - General vs. domain-specific
  - Control-oriented vs. data flow oriented

Model-based testing: Test requirements selection



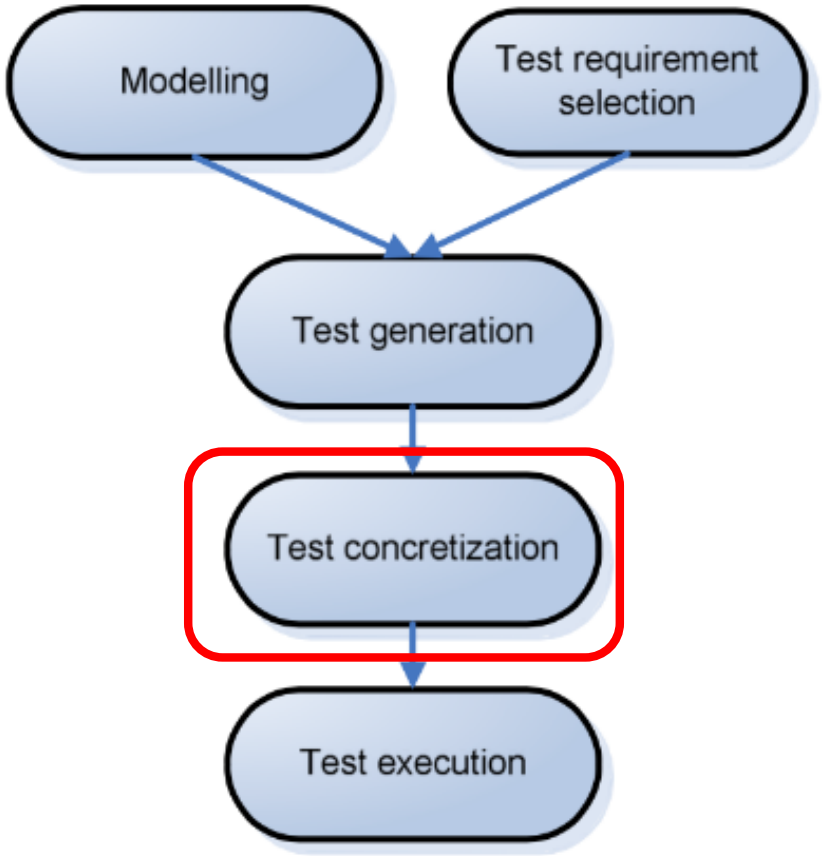
- Purpose: To guide test generation
- Categories:
  - Coverage criteria
    - State coverage
    - Transition coverage
    - Path coverage
    - Etc.
  - Walking algorithms
    - Random walking
    - Coverage guided

Model-based testing: Test generation



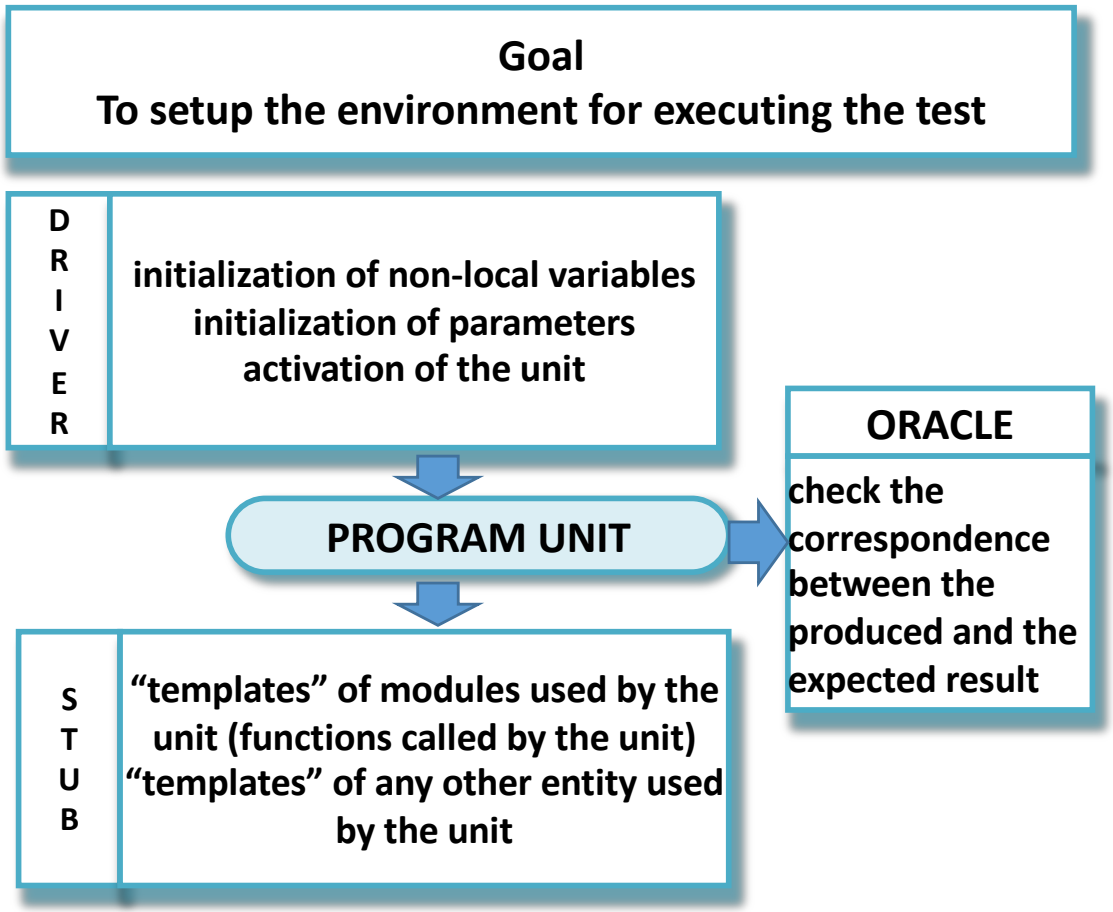
- Purpose: To design the tests
- Use search algorithms
- Tests are written in determined format

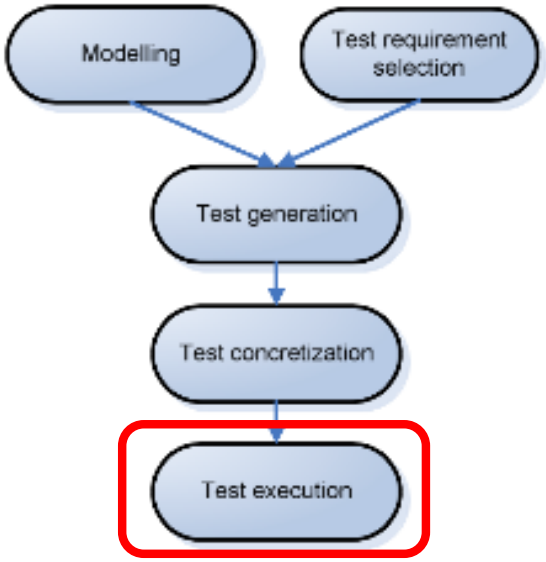
Model-based testing: Test concretization



- Purpose: Concretize abstract t est suite to executable level
- Tools are provided
  - Various test exporting formats
  - Do-it-yourself plug-ins

Test execution environment

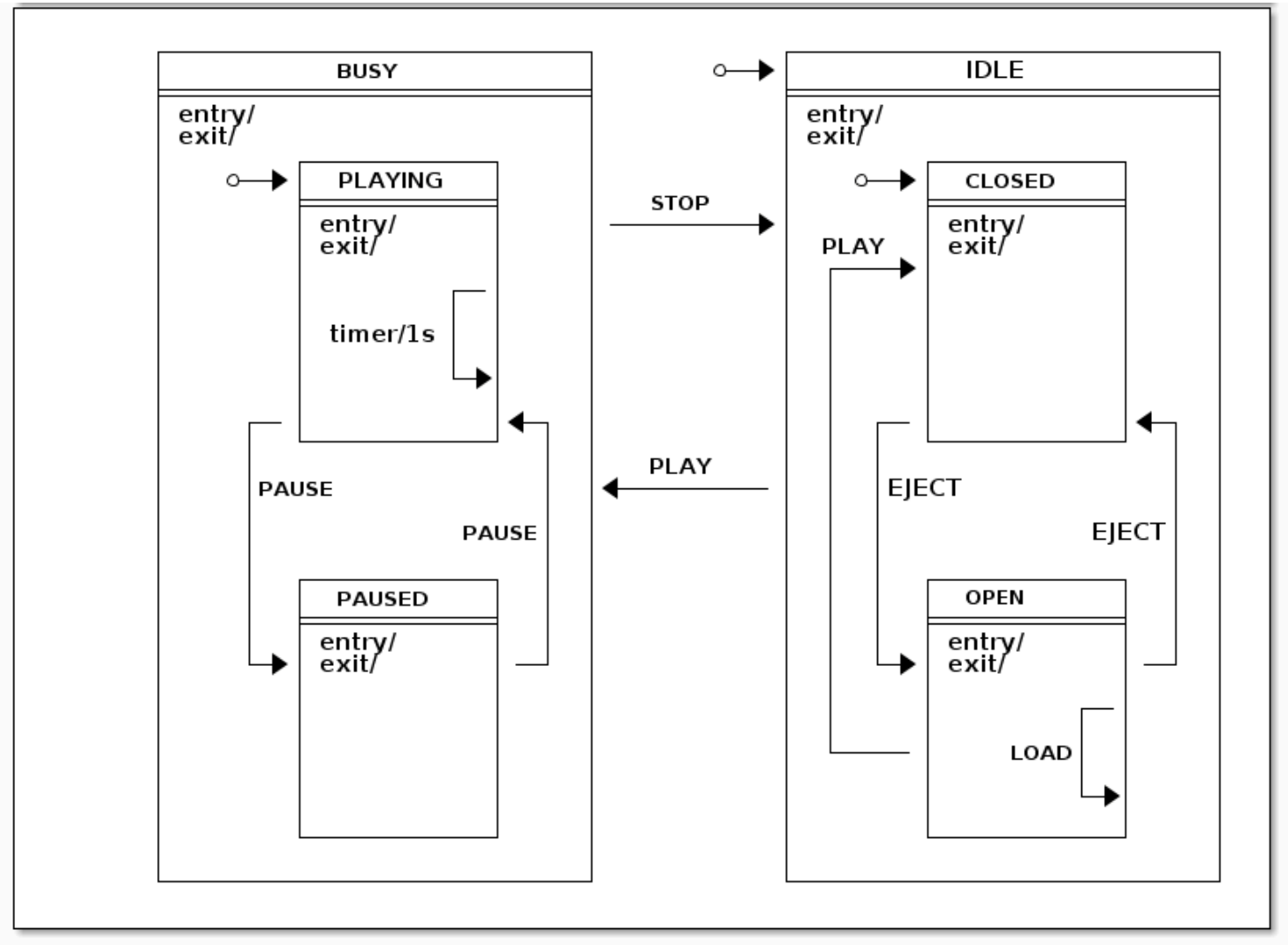




Main benefits of model-based testing

- Easier test suite maintenance
- Automated test design
  - Save effort
- Better test quality
  - No human mistakes
- Tool support for the validation of requirements
- Early detection of design errors
  - If extended by formal methods

Example (1): Test generation from State machine (CD player)



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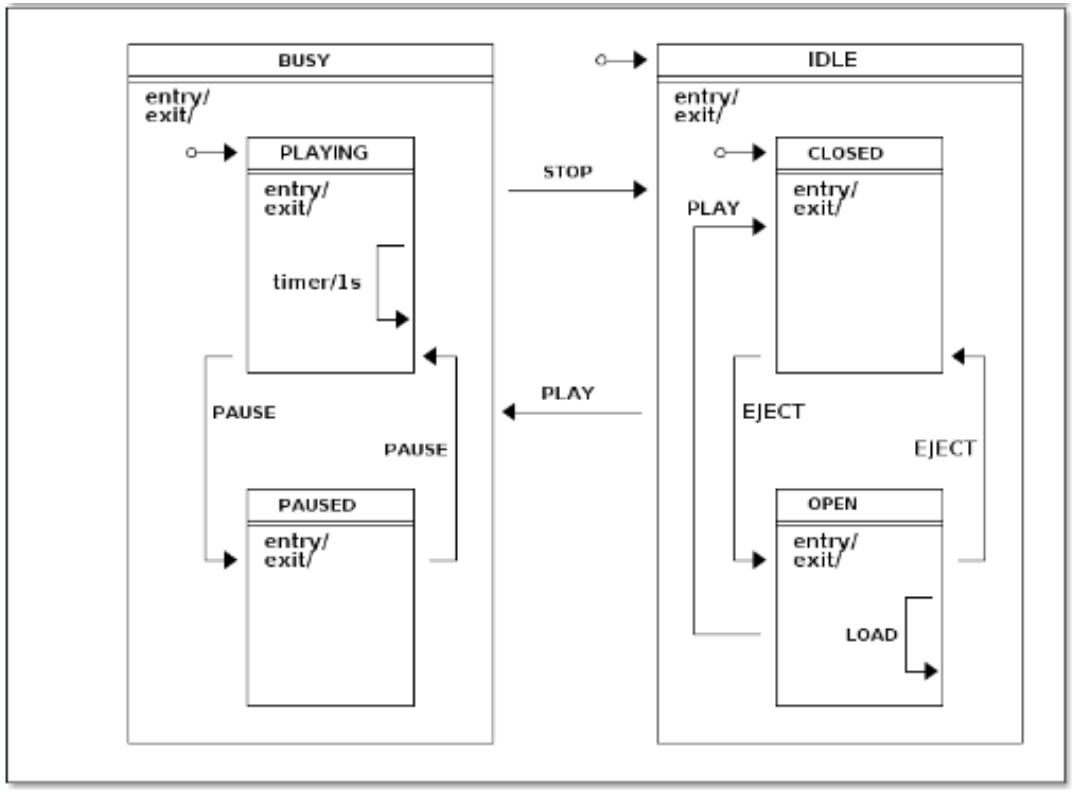
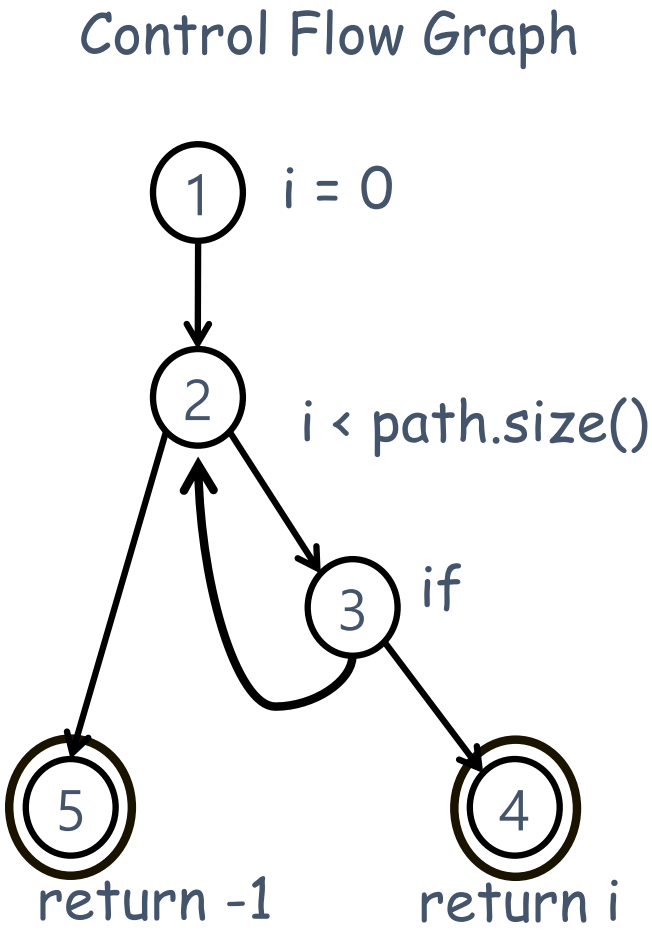


- State coverage
  - Test1: EJECT, OPEN
    PLAY, PLAYING
    PAUSE, PAUSED
- Transition coverage?

Example (2): Test generation from CFG

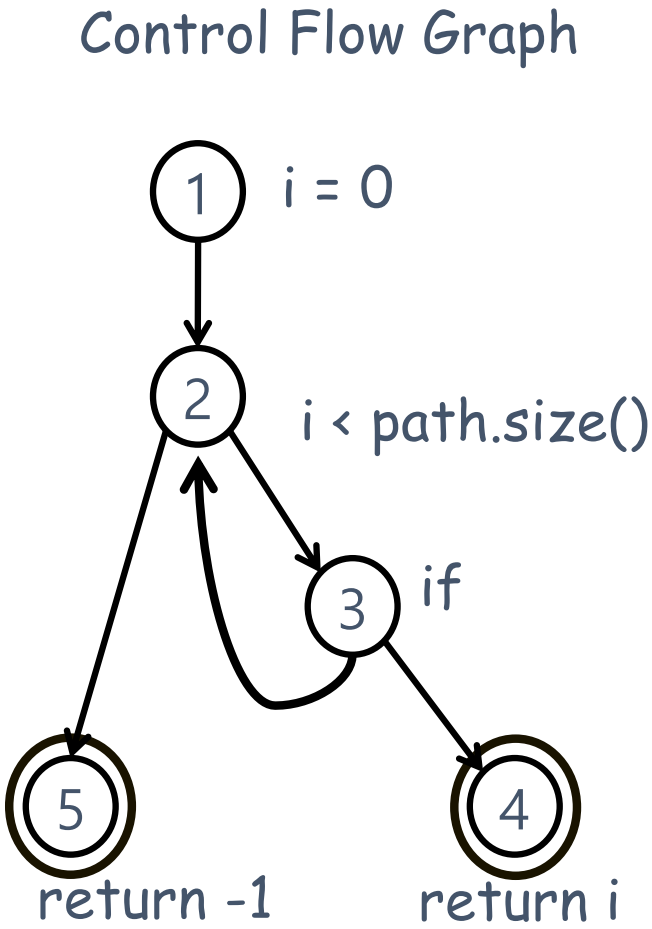
Software Artifact : Java Method

```
/**
 * Return index of node n at the
 * first position it appears,
 * -1 if it is not present
*/
public int indexOf (Node n)
{
  for (int i=0; i < path.size(); i++)
    if (path.get(i).equals(n))
      return i;
  return -1;
}
```



Example (2): Test generation from CFG

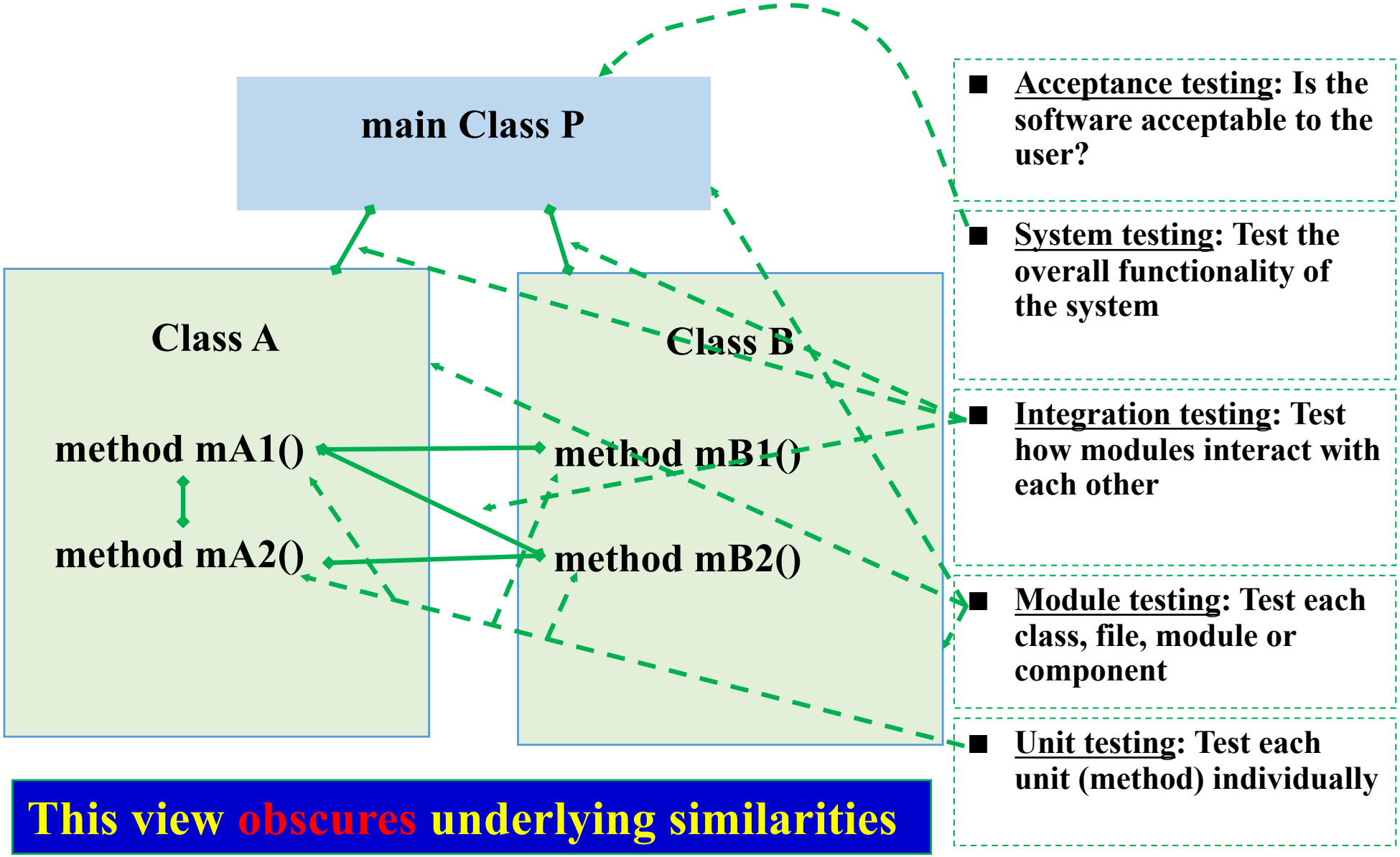
- State coverage
  - Test input (path, n): ({1}, 1)
- Transition coverage?



Changing Notions of Testing

- Old view considered testing at each software development phase to be very different from other phases
  - Unit, module, integration, system …
- New view is in terms of structures and criteria
  - Graphs, logical expressions, syntax, input space
- Test design is largely the same at each phase
  - Creating the model is different
  - Choosing values and automating the tests is different

Old : Testing at Different Levels



New : Test Coverage Criteria

A tester's job is simple :

Define a model of the software, then find ways to cover it

- Test Requirements : Specific things that must be satisfied or covered during testing

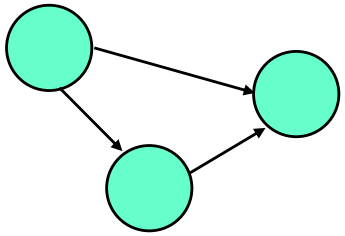
- Test Criterion : A collection of rules and a process that define test requirements

Testing researchers have defined dozens of criteria, but they are all really just a few criteria on four types of structures …

Criteria Based on Structures

Structures : Four ways to model software

1. Graphs



2. Logical Expressions

(not X or not Y) and A and B

3. Input Domain Characterization

A: {0, 1, >1}
B: {600, 700, 800}
C: {swe, cs, isa, infs}

4. Syntactic Structures

```
if (x > y)
    z = x - y;
else
   z = 2 * x;
```

Source of Structures

- These structures can be extracted from lots of software artifacts
  - Graphs can be extracted from UML use cases, finite state machines, source code, …
  - Logical expressions can be extracted from decisions in program source, guards on transitions, conditionals in use cases, …

- "*model-based testing*" and "model-driven testing" are different (Jeff Offutt)
  - Model-based testing derives tests from a model that describes some aspects of the system under test
  - The source is usually *not* considered a model

Summary

- Test design is the most important but difficult task among testing activities. It requires knowledge in mathematics and computer science.
- Test design is largely the same at each phase
- Tester designer's job is to define a model of the software, then find ways to cover it
- There are four ways to model software
  - Using graphs, logical expression, input domain characterization, and syntactic structures

Model-based testing techniques

Deriving test cases from finite state machines

From informal specifications..

Maintenance: The Maintenance function records the history of items undergoing maintenance.

If the product is covered by warranty or maintenance contract, maintenance can be requested either by calling the maintenance toll free number, or through the web site, or by bringing the item to a designated maintenance station.

If the maintenance is requested by phone or web site and the customer is a US or EU resident, the item is picked up at the customer site, otherwise, the customer shall ship the item with an express courier.

If the maintenance contract number provided by the customer is not valid, the item follows the procedure for items not covered by warranty.

If the product is not covered by warranty or maintenance contract, maintenance can be requested only by bringing the item to a maintenance station. The maintenance station informs the customer of the estimated costs for repair. Maintenance starts only when the customer accepts the estimate.

If the customer does not accept the estimate, the product is returned to the customer.

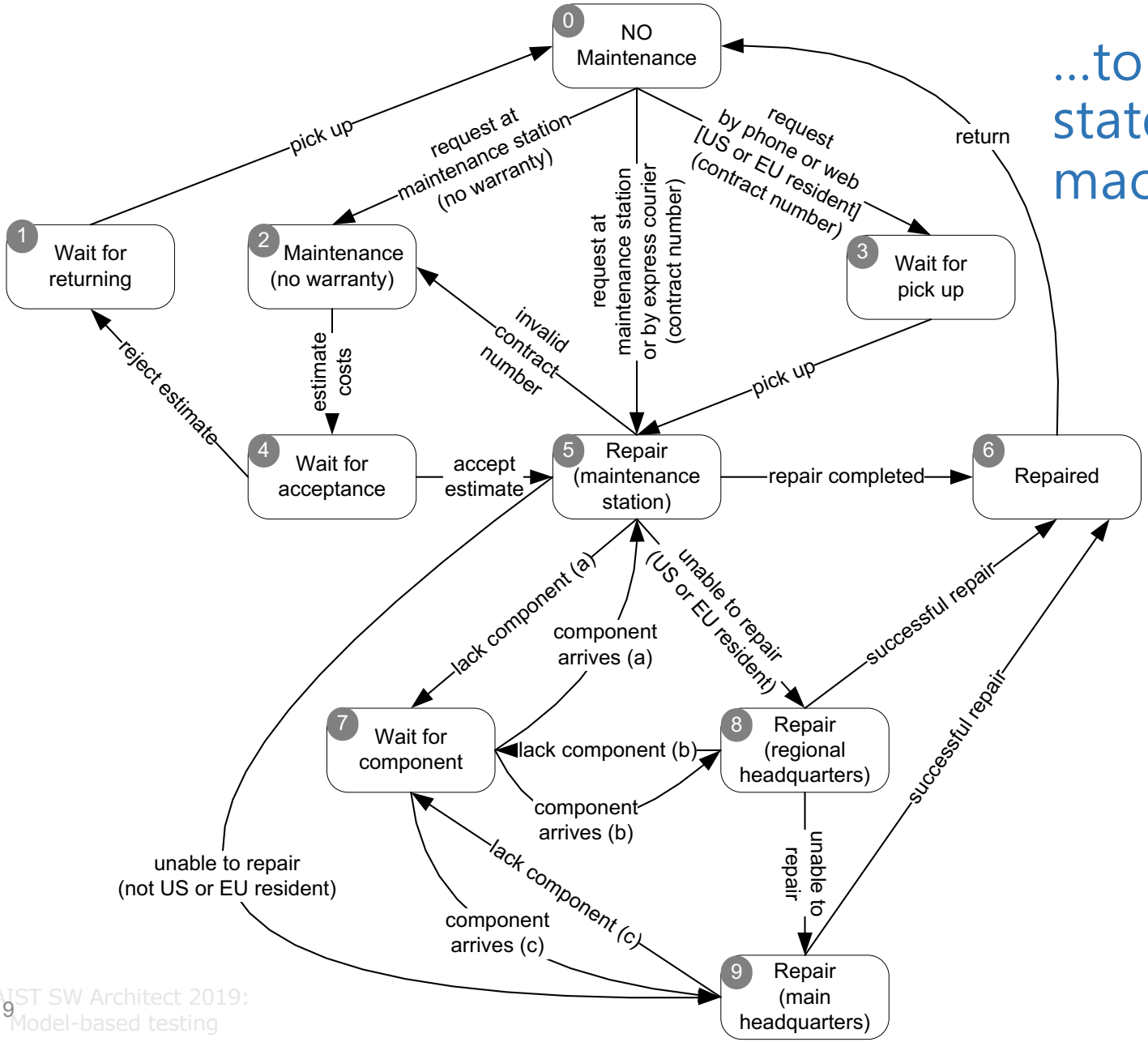
Small problems can be repaired directly at the maintenance station. If the maintenance station cannot solve the problem, the product is sent to the maintenance regional headquarters (if in US or EU) or to the maintenance main headquarters (otherwise).

If the maintenance regional headquarters cannot solve the problem, the product is sent to the maintenance main headquarters.

Maintenance is suspended if some components are not available.

Once repaired, the product is returned to the customer.

Deriving test cases from finite state machines



...to a finite state machine...

Deriving test cases from finite state machines

...to a test suite

TC1	0	2	4	1	0						
TC2	0	5	2	4	5	6	0				
TC3	0	3	5	9	6	0					
TC4	0	3	5	7	5	8	7	8	9	6	0

Meaning: From state 0 to state 2 to state 4 to state 1 to state 0

Is this a thorough test suite?
How can we judge?

Deriving test cases from finite state machines

"Covering" finite state machines

- State coverage:
  - Every state in the model should be visited by at least one test case
- Transition coverage
  - Every transition between states should be traversed by at least one test case.
  - *This is the most commonly used criterion*
    - A transition can be thought of as a (precondition, postcondition) pair

Deriving test cases from finite state machines

Path sensitive criteria?

- Basic assumption: States fully summarize history
  - No distinction based on how we reached a state; this should be true of well-designed state machine models
- If the assumption is violated, we may distinguish paths and devise criteria to cover them
  - Single state path coverage:
    - Traverse each subpath that reaches each state at most once
  - Single transition path coverage:
    - Traverse each transition at most once
  - Boundary interior loop coverage:
    - Each distinct loop of the state machine must be exercised the minimum, an intermediate, and the maximum or a large number of times

Deriving test cases from finite state machines

Remind: Statemachines

- Objects may change state in response to an event
- Different states are captured in a statemachine model
  - which a single object passes during its life
  - May include the object's responses and actions
- Components of statemachines
  - State: values of the object state at a point in time
  - Events: the cause of the change in values of the state
  - Transitions: movement of the object from one state to another
    - May include a guard condition and transition action

Remind: Guidelines for creating statemachines

- Draw the initial state in the upper left corner
- Draw the final state in the bottom right corner
- Use simple, but descriptive names for states
- Look out for “black holes” and “miracles”
- Ensure guard conditions are mutually exclusive
- Ensure transitions are associated with messages and operations

Remind: building a behavioral statemac hine

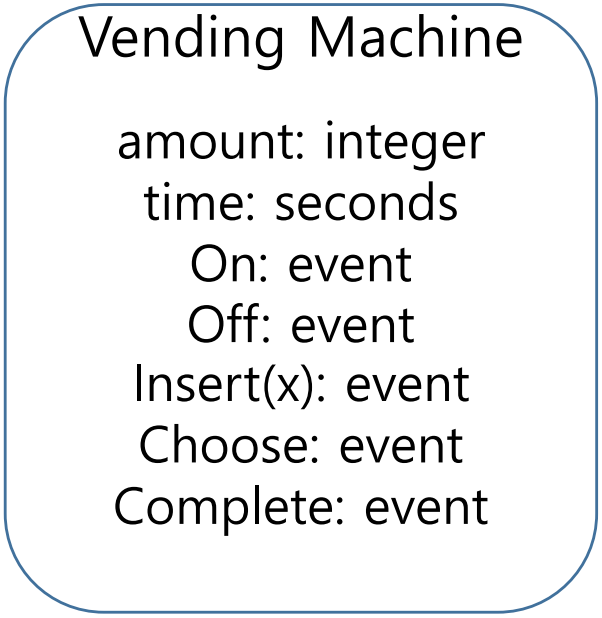
- Set the context
- Identify the states of the object
  - Initial
  - Final
  - Stable states during its lifetime
- Lay out the diagram—use a left to right sequence
- Add the transitions
  - Identify the triggers (events that cause the transition)
  - Identify the actions which execute
  - Identify the guard conditions
- Validate the model—ensure all states are reachable

Exercise: Chocolate Vending machine

- The vending machine sells chocolates
- The price of a chocolate is 500 Won
- When the machine is turned on, it waits for a customer to insert coins or paper money
- If 500 Won or more is inserted, the button for choosing chocolate is illuminated
- If there is no more actions after inserting money for more than 10 seconds, it returns the money already inserted
- If the customer presses the illuminated button, it moves the chocolate to the exit and returns the remaining money

Exercise: Chocolate Vending machine

- Identifying data and operations



Exercise: Chocolate Vending machine

- Identifying states

Exercise: Chocolate Vending machine

- Deciding transitions

Exercise: Chocolate Vending machine

- Deriving test cases

Testing decision structures

- Some specifications are structured as decision tables, decision trees, or flow charts.
- We can exercise these as if they were program source code.

Testing decision structures

from an informal specification..

Pricing: The pricing function determines the adjusted price of a configuration for a particular customer.

The scheduled price of a configuration is the sum of the scheduled price of the model and the scheduled price of each component in the configuration. The adjusted price is either the scheduled price, if no discounts are applicable, or the scheduled price less any applicable discounts.

There are three price schedules and three corresponding discount schedules, Business, Educational, and Individual.

….

- Educational prices: The adjusted price for a purchase charged to an educational account in good standing is the scheduled price from the educational price schedule. No further discounts apply.

…

- Special-price non-discountable offers: Sometimes a complete configuration is offered at a special, non-discountable price. When a special, non-discountable price is available for a configuration, the adjusted price is the non-discountable price or the regular price after any applicable discounts, whichever is less

Testing decision structures

…to a decision table …

	edu		individual					
EduAc	T	T	F	F	F	F	F	F
BusAc	-	-	F	F	F	F	F	F
CP > CT1	-	-	F	F	T	T	-	-
YP > YT1	-	-	-	-	-	-	-	-
CP > CT2	-	-	-	-	F	F	T	T
YP > YT2	-	-	-	-	-	-	-	-
SP < Sc	F	T	F	T	-	-	-	-
SP < T1	-	-	-	-	F	T	-	-
SP < T2	-	-	-	-	-	-	F	T
out	Edu	SP	ND	SP	T1	SP	T2	SP

Testing decision structures

…with constraints…

at-most-one (EduAc, BusAc)

at-most-one (YP < YT1, YP > YT2)

YP > YT2 -> YP > YT1

at-most-one (CP < CT1, CP > CT2)

CP > CT2 -> CP > CT1

at-most-one (SP < T1, SP > T2)

SP > T2 -> SP > T1

Testing decision structures

…to test cases

- Basic condition coverage
  - a test case specification for each column in the table
- Compound condition adequacy criterion
  - a test case specification for each combination of truth values of basic conditions
- Modified condition/decision adequacy criterion (MC/DC)
  - each column in the table represents a test case specification.
  - we add columns that differ in one input row and in outcome, then merge compatible columns
    - Each condition should effect the decision outcome independently
  - Test important combinations of conditions and limit testing costs

Testing decision structures : MC/DC

	C.1	C.1a	C.1b	C.10
EduAc	T	F	T	-
BusAc	-	-	-	T
CP > CT1	-	-	-	F
YP > YT1	-	-	-	F
CP > CT2	-	-	-	-
YP > YT2	-	-	-	-
SP > Sc	F	F	T	T
SP > T1	-	-	-	-
SP > T2	-	-	-	-
out	Edu	*	*	SP

Generate C.1a and C.1b by flipping one element of C.1

C.1b can be merged with an existing column (C.10) in the spec

Outcome of generated columns must differ from source column

Exercise:

Flowgraph based testing

- If the specification or model has both decisions and sequential logic, we can cover it like program source code.

Flowgraph based testing

from an informal spec (i/iii)...

- Process shipping order: The Process shipping order function checks the validity of orders and prepares the receipt
  A valid order contains the following data:
  - cost of goods: If the cost of goods is less than the minimum processable order (MinOrder) then the order is invalid.
  - shipping address: The address includes name, address, city, postal code, and country.
  - preferred shipping method: If the address is domestic, the shipping method must be either land freight, expedited land freight, or overnight air; If the address is international, the shipping method must be either air freight, or expedited air freight.

Flowgraph based testing

...(ii/iii)...

- a shipping cost is computed based on
  - address and shipping method.
  - type of customer which can be individual, business, educational
- preferred method of payment. Individual customers can use only credit cards, business and educational customers can choose between credit card and invoice
- card information: if the method of payment is credit card, fields credit card number, name on card, expiration date, and billing address, if different than shipping address, must be provided. If credit card information is not valid the user can either provide new data or abort the order

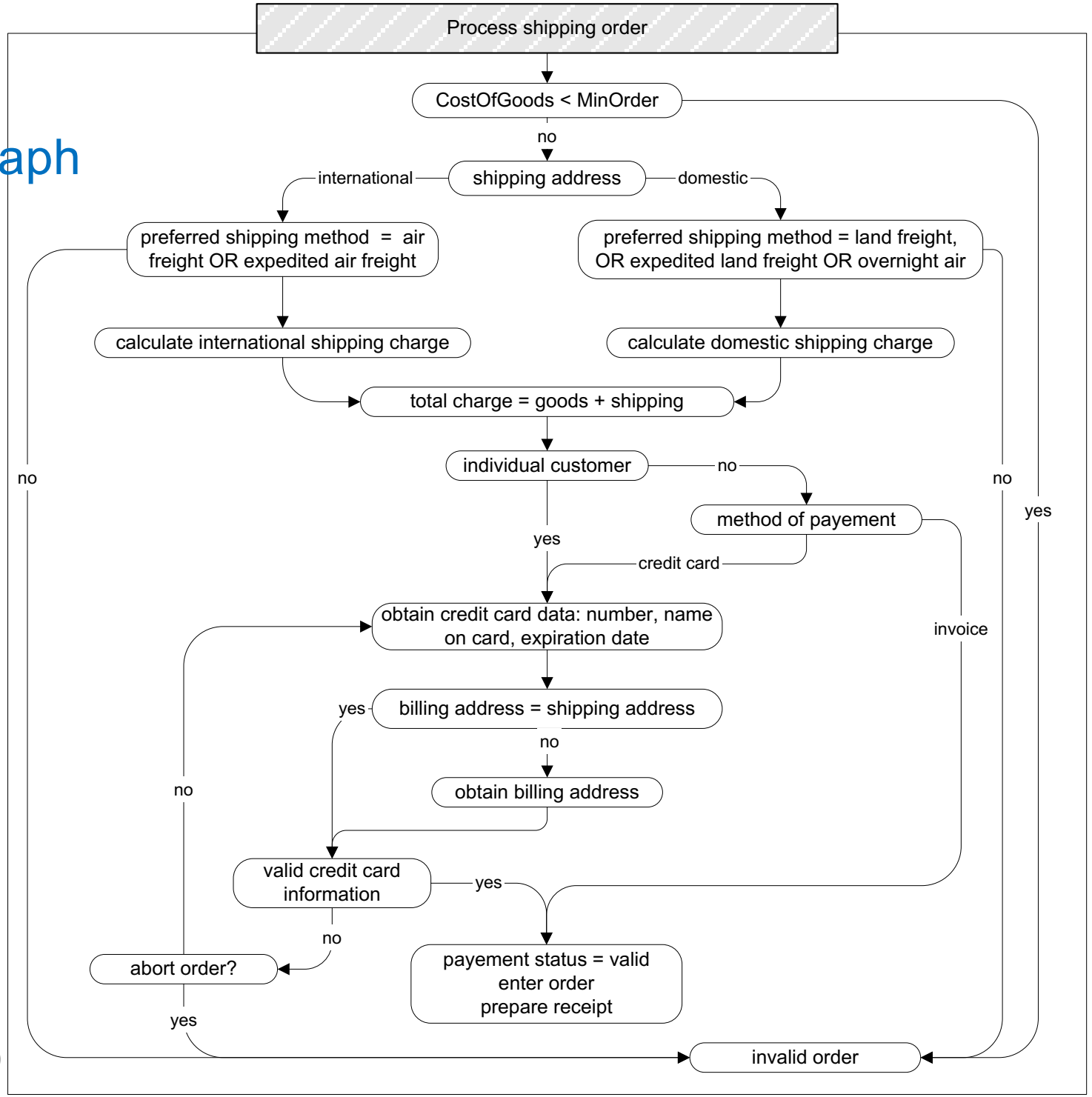
Flowgraph based testing

…(iii/iii)

- The outputs of Process shipping order are
- validity: Validity is a Boolean output which indicates whether the order can be processed.
- total charge: The total charge is the sum of the value of goods and the computed shipping costs (only if validity = true).
- payment status: if all data are processed correctly and the credit card information is valid or the payment is invoice, payment status is set to valid, the order is entered and a receipt is prepared; otherwise validity = false.

Flow graph based testing

…to a flowgraph



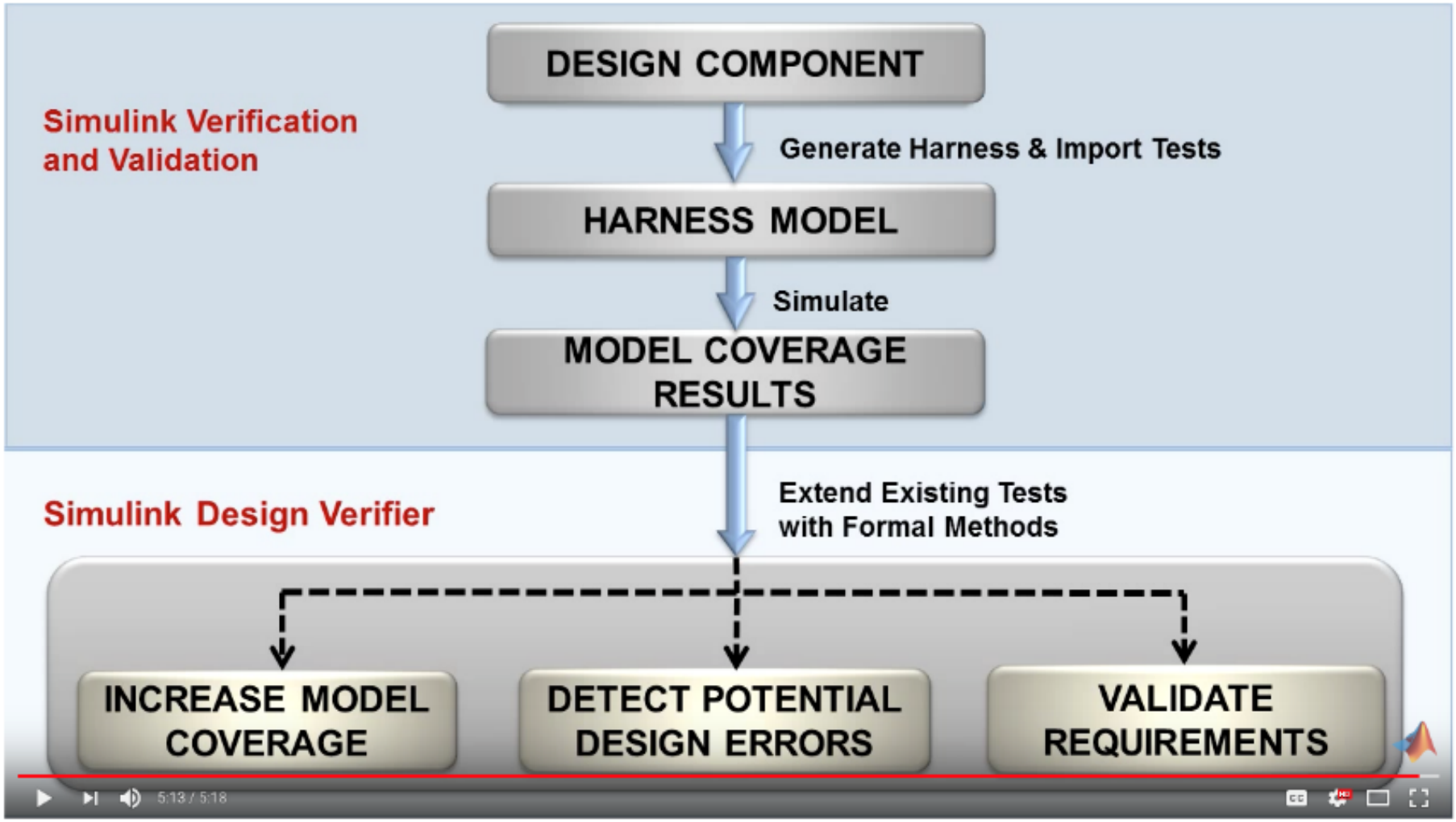
...from the flow graph to test cases

Branch testing: cover all branches

Case	Too Small	Ship Where	Ship Method	Cust Type	Pay Method	Same Address	CC valid
TC-1	No	Int	Air	Bus	CC	No	Yes
TC-2	No	Dom	Land	-	-	-	-
TC-3	Yes	-	-	-	-	-	-
TC-4	No	Dom	Air	-	-	-	-
TC-5	No	Int	Land	-	-	-	-
TC-6	No	-	-	Edu	Inv	-	-
TC-7	No	-	-	-	CC	Yes	-
TC-8	No	-	-	-	CC	-	No (abort)
TC-9	No	-	-	-	CC	-	No (no abort)

Model-based testing in Simulink

https://www.youtube.com/watch?v=2bO72KEWLNY



Summary

- Models are useful abstractions
  - In specification and design, they help us think and communicate about complex artifacts by emphasizing key features and suppressing details
  - Models convey structure and help us focus on one thing at a time
- We can use them in systematic testing
  - If a model divides behavior into classes, we probably want to exercise each of those classes!
  - Common model-based testing techniques are based on state machines, decision structures, and grammars
    - but we can apply the same approach to other models

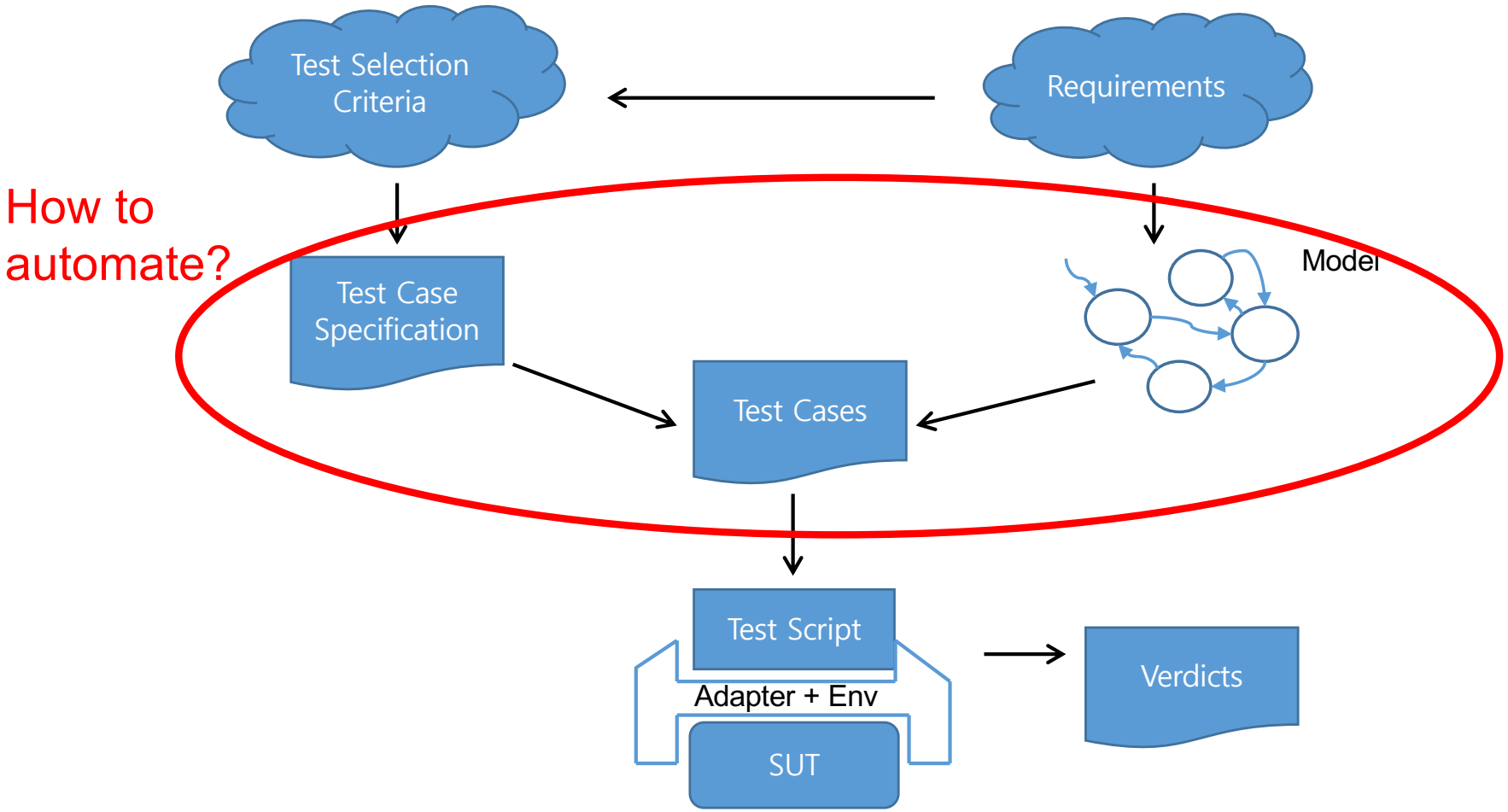
Automated Test Generation

Using model checking

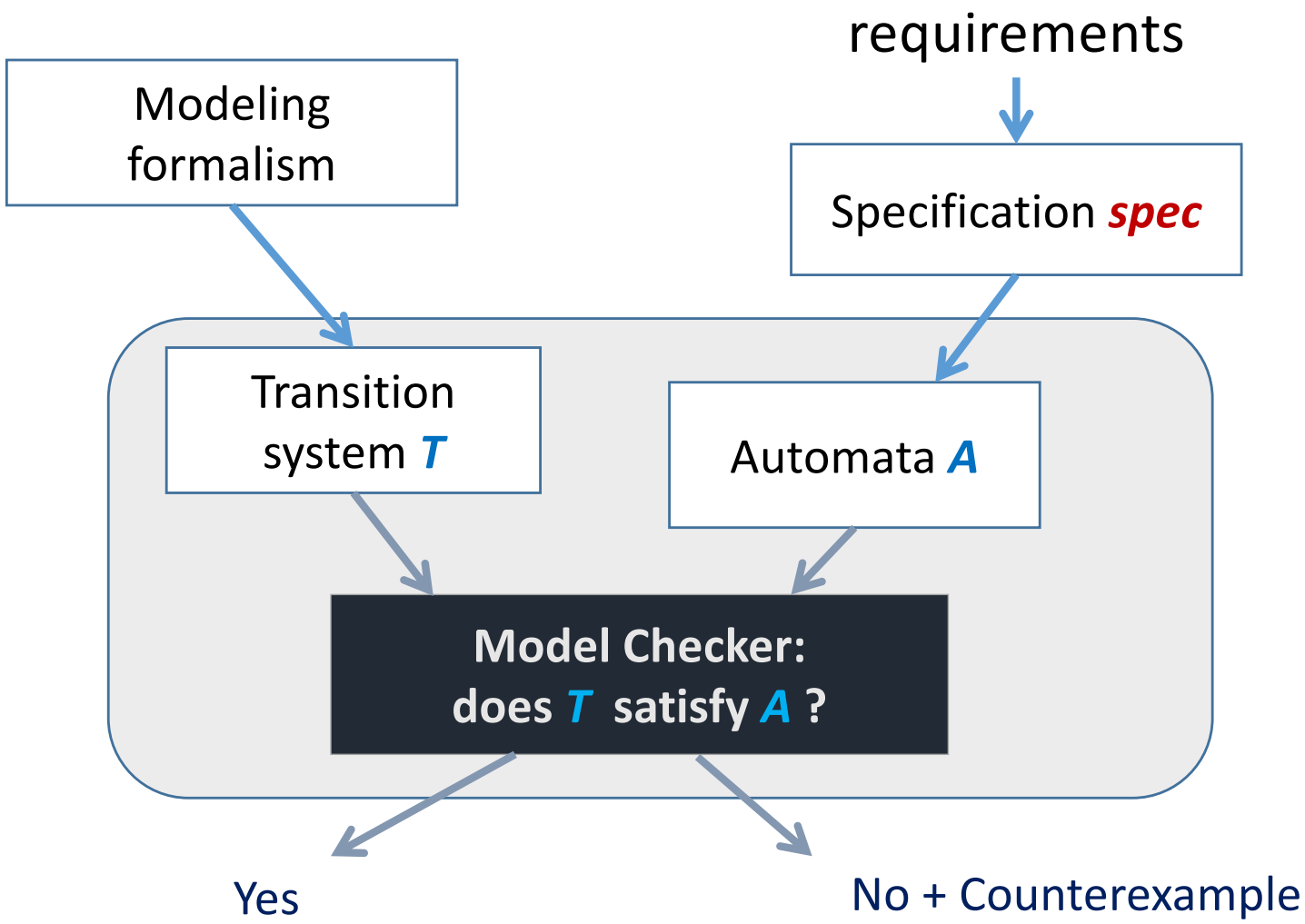
Model-based testing is for automated testing

- But, how to automate the test process?
  - Creation of models is still manual, though domain-specific automation is possible
  - Test specification is also manually determined
- Automation is mainly for the test case generation, test environment generation, and test execution
- Then, how to automate test case generation?
  - Random walk
  - Formal verification

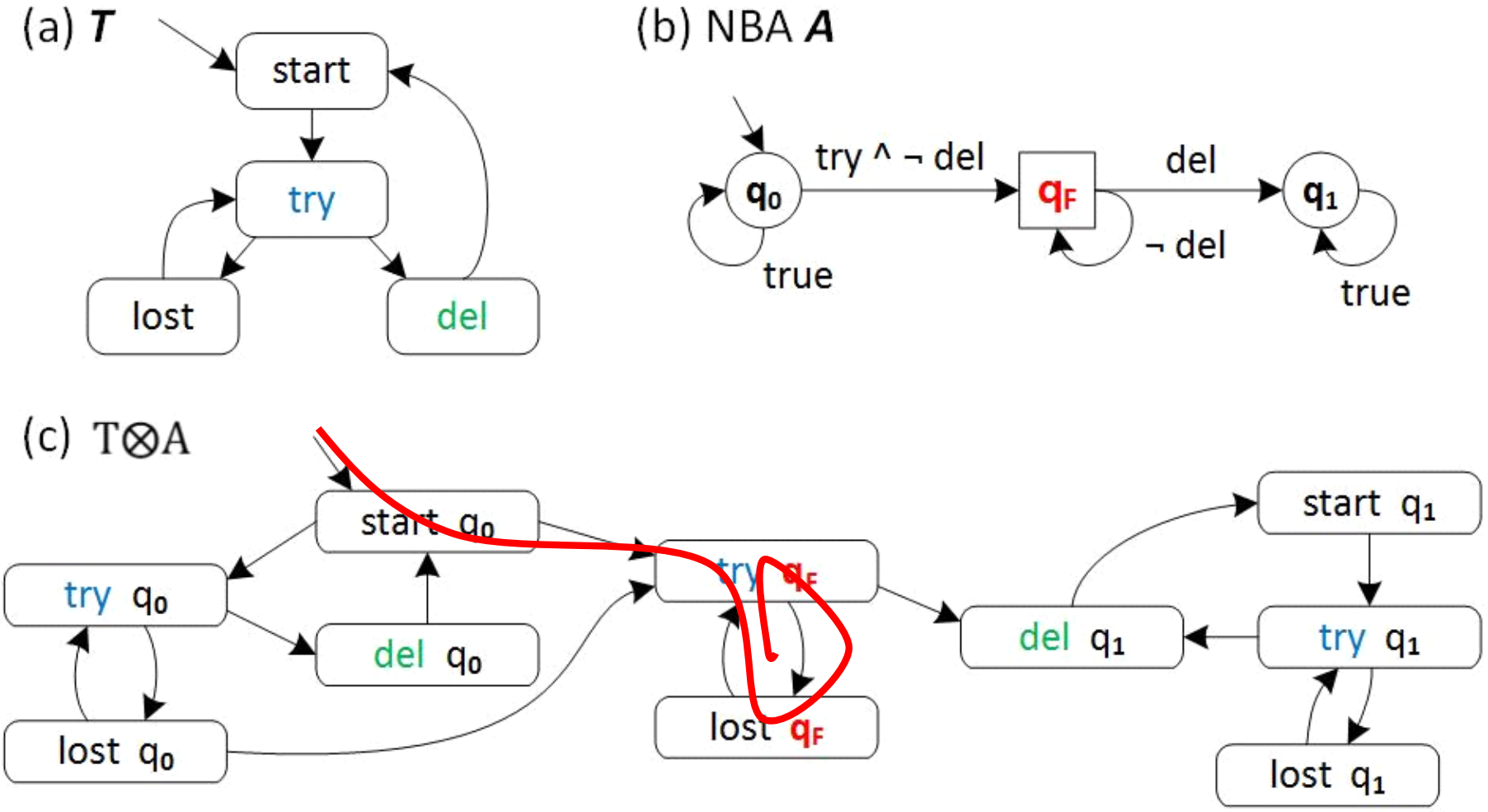
Model-based testing



Techniques used: Model Checking



An example: LTL model checking

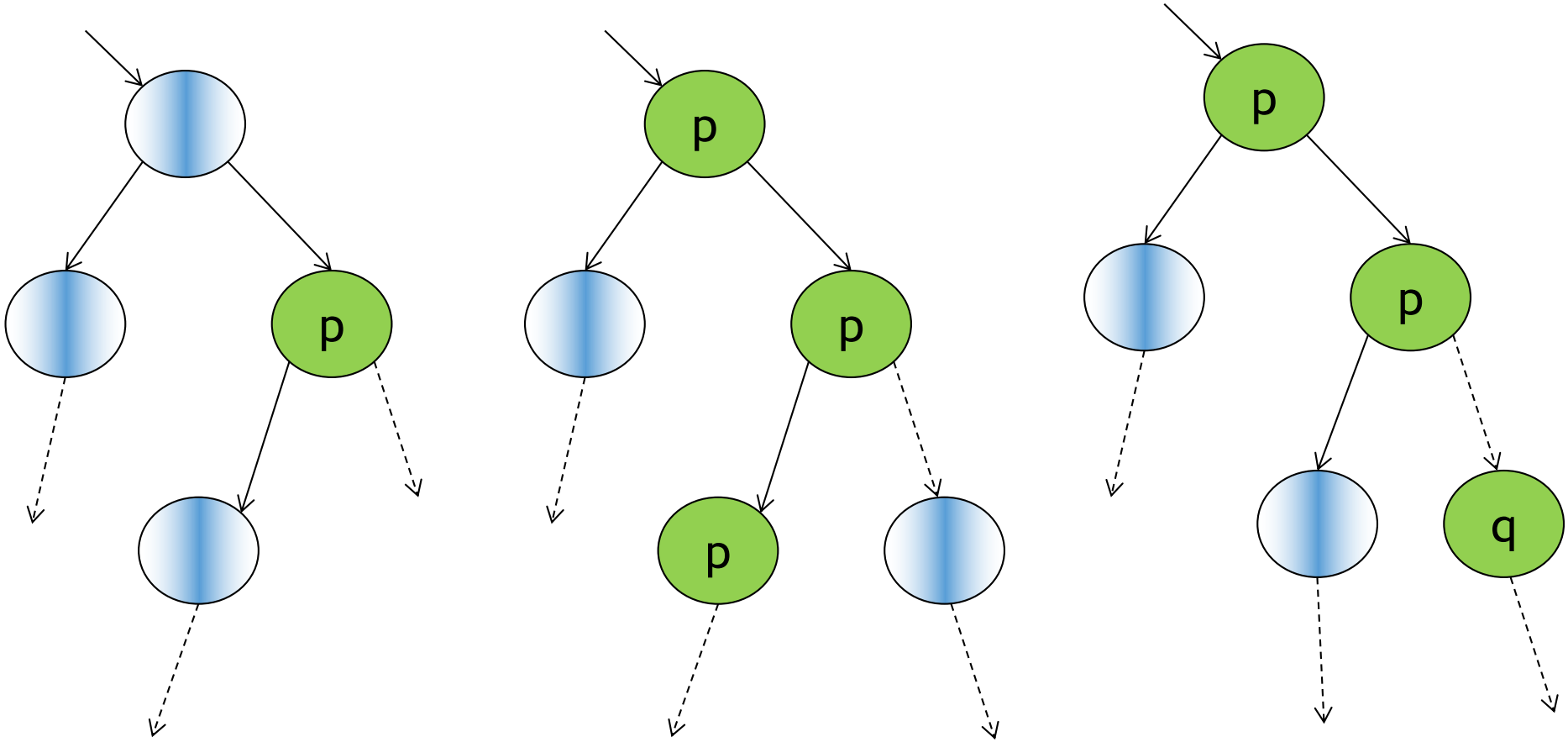


Model checking : theoretical work

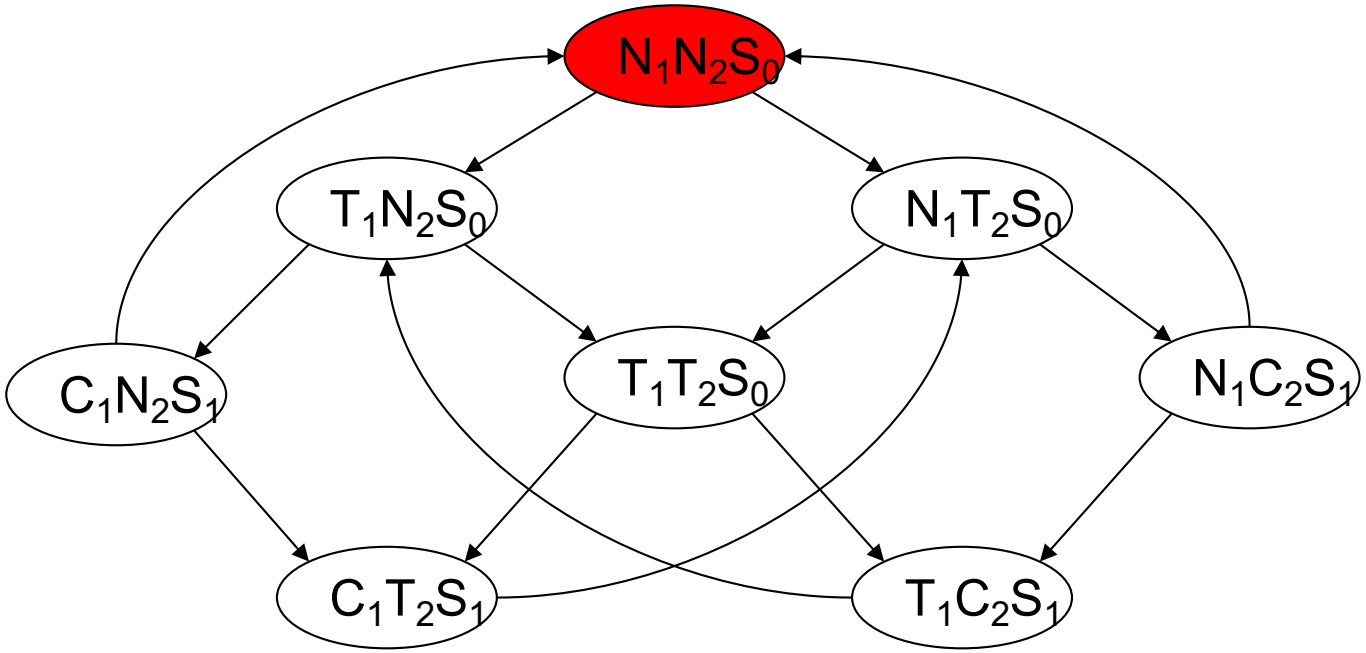
- Temporal logic specifications: Amir Pnueli (Turing award, 1996)
- Founding and developing model checking: E. M. Clarke, E. A. Emerson, and J. Sifakis (Turing award, 2007)

G (p → q)	AG (p → q)	EG (p → q)
F (p && q)	AF (p && q)	EF (p && q)
p U q	A (p U q)	E (p U q)
X p	AX p	EX p

EX p, EG p, E pUq



Mutual Exclusion Example



$K \models AG\ EF\ (N_1 \wedge N_2 \wedge S_0)$

Model checking : tools and applications

- 47+ tools can be found in Wikipidia
- Explicit model checking
  - SPIN
  - Java Path Finder
- Symbolic model checking
  - SMV, NuSMV, SAL, UPPAAL
- Probabilistic model checking
  - CADP
  - PRISM
- Rewriting-based model checking
  - Maude
- Source-code model checking
  - Bandera
  - BLAST
  - CBMC
  - LLBMC
  - DIVINE
- etc

- ~30 years of application history
- Hardware circuit designs
- Verification of software specifications
  - Aircraft control software
  - Nuclear power plant reactor control software
  - Train control software
  - Medical device control software
- Verification of software models
  - UML diagrams
- Verification of source code
  - Java applications
  - C, C++ source code
- Model-based test generation
  - Aircraft control software
  - Automotive operating systems
- etc

Goal of model checking

- Pushing acceleration pedal increases speed
- Rotating the handle x degree changes wheels y degree
- Never opens the doors while driving
- Etc.

p

Formal checking

M ⊨ p

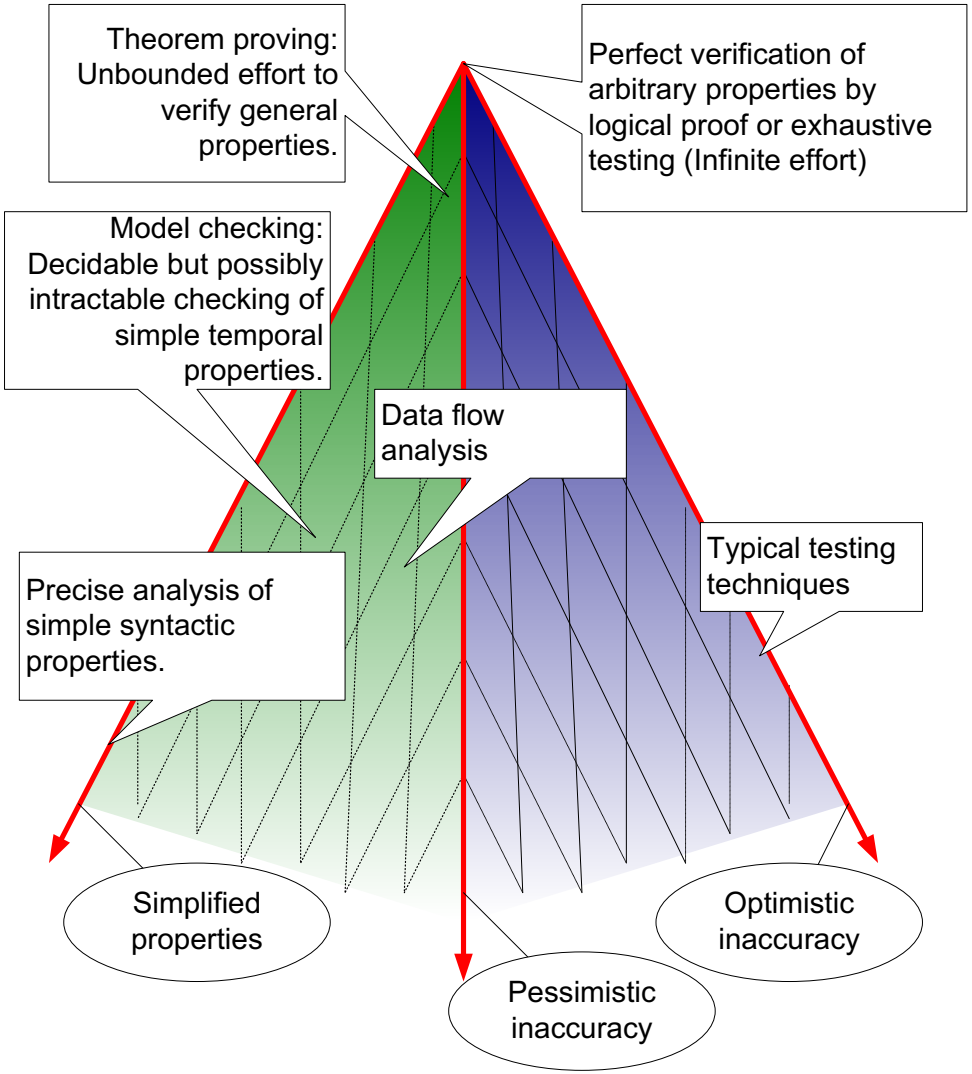
!(M ⊨ p)

Fix this and that ..

Test generation using model checking

- State coverage
  - For each state s in the model, define a property p as "s is not reachable in the model"
  - Model check M ⊭ p
  - If p is not true, the model checker generates a counterexample which is a execution trace that leads to the state s
- Transition coverage
  - For each transition from s to s', define a property p as "s' cannot be the next state of s"
- Condition coverage
- MC/DC coverage
- It is a matter of how to specify a property for a given test criterion

Accuracy & Efficiency



Hands-on example: NuSMV

- A representative symbolic model checker
  - An extension of SMV from CMU
  - http://nusmv.fbk.eu

Hands on exercise

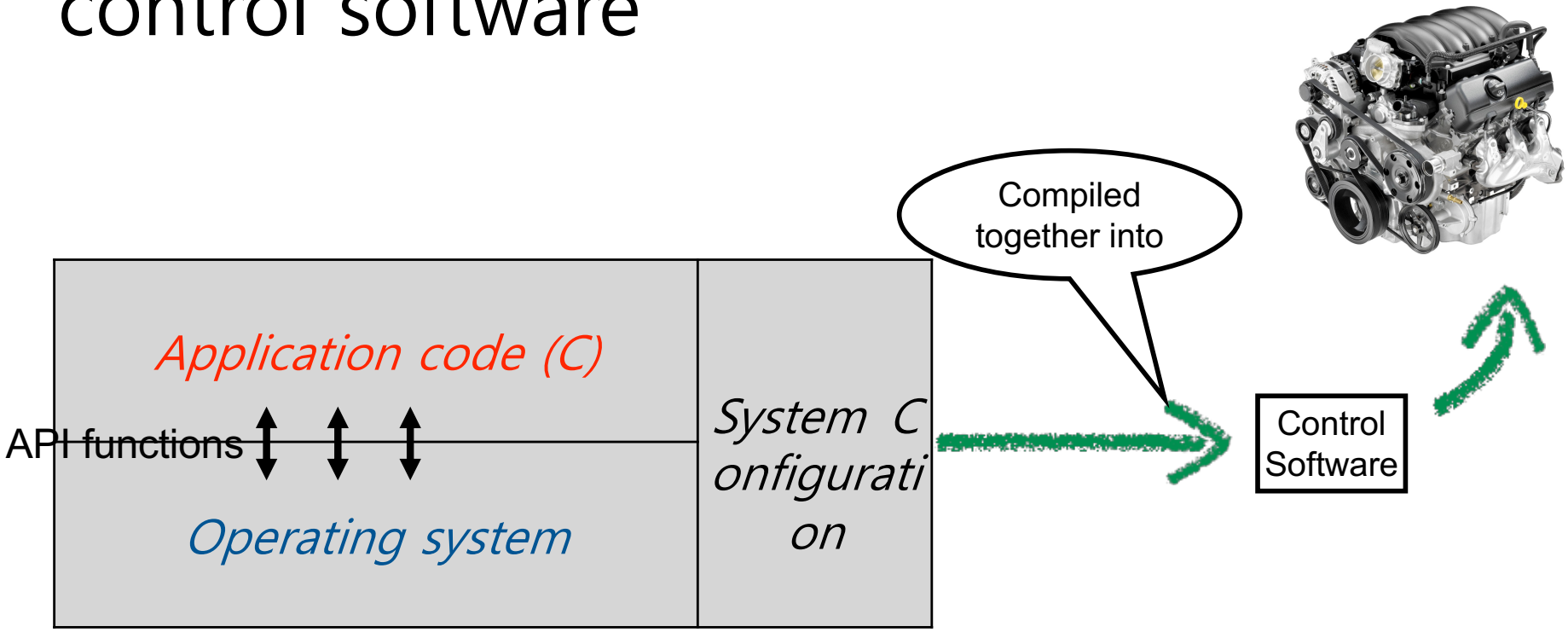
Summary

- When a model is available, automated test generation is not difficult
  - Simplest solution is to use random walk
- The problem is the level of comprehensiveness we would like to achieve
- Formal method is necessary for a comprehensive/guided/focused test generation

Case example: AutoCheck^{FP}

Real world application

Background: Development of device control software



- The application code is inseparable from operating system kernel

Problem

- A task shall not terminate while occupying resources
- A task that does not own events shall not set events
- A task shall not terminate without calling TerminateTask

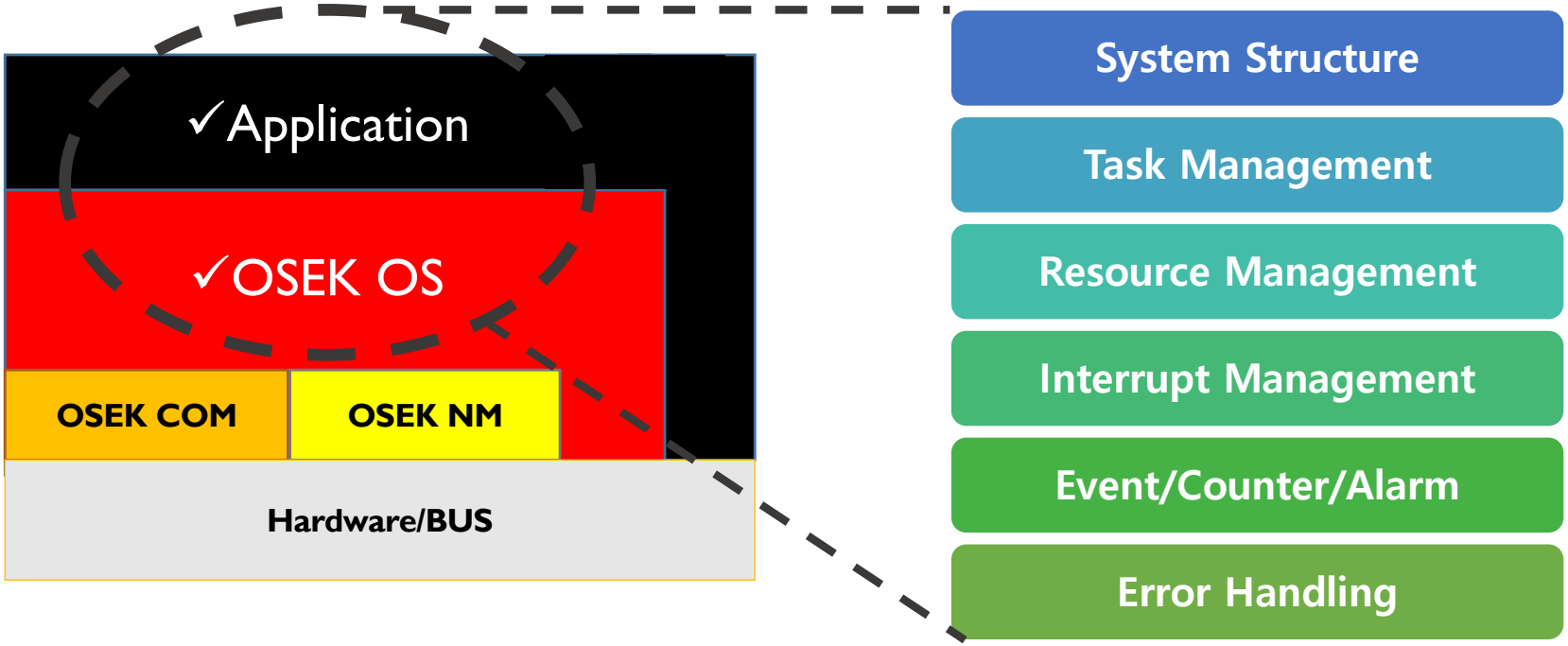
```
01: Task(t1) {
02:   ActivateTask(t2);
03:   SetEvent(t2,e1);
04:   if(condition)
05:     GetResource(r1);
06:   TerminateTask();
07: }
```

Violation of API call constraints may result in system failure

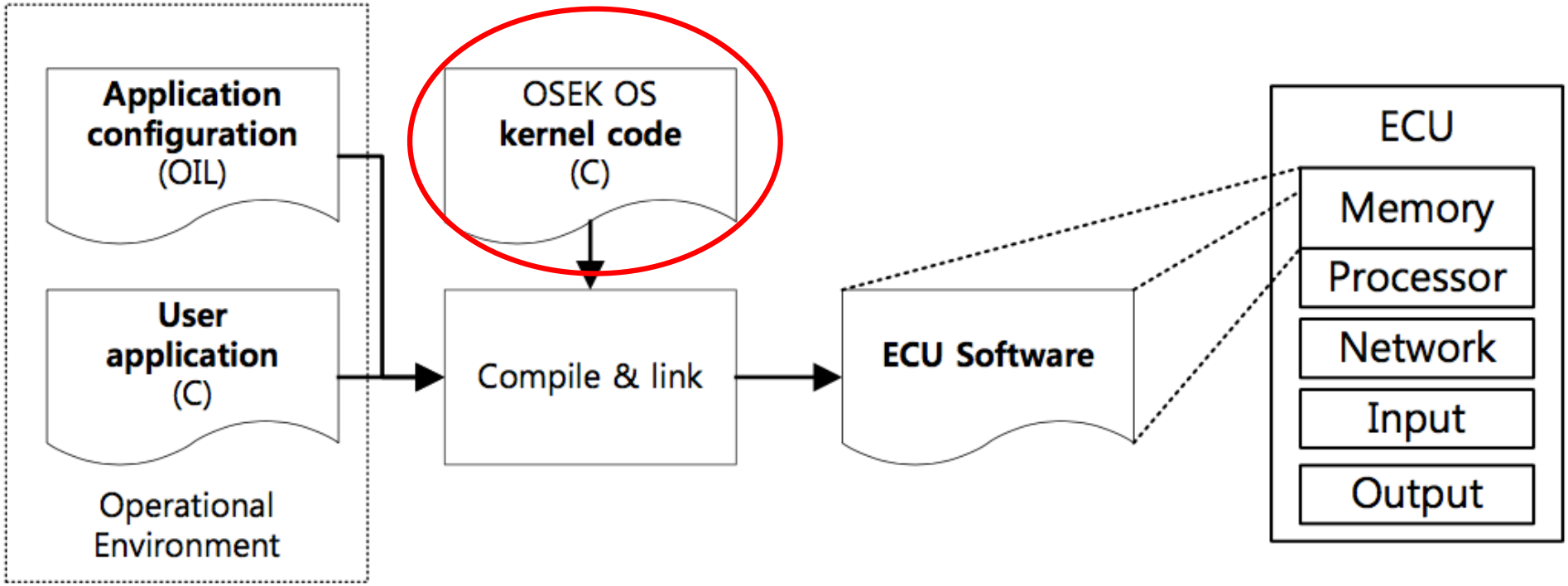
We need to make sure that the OS works safely under unexpected use of API function calls

Target: OSEK/VDX OS

- An international **standard** for distributed control units in vehicles.
- It comprises Communication, Operating System, and Network Management



Issues: Complexity



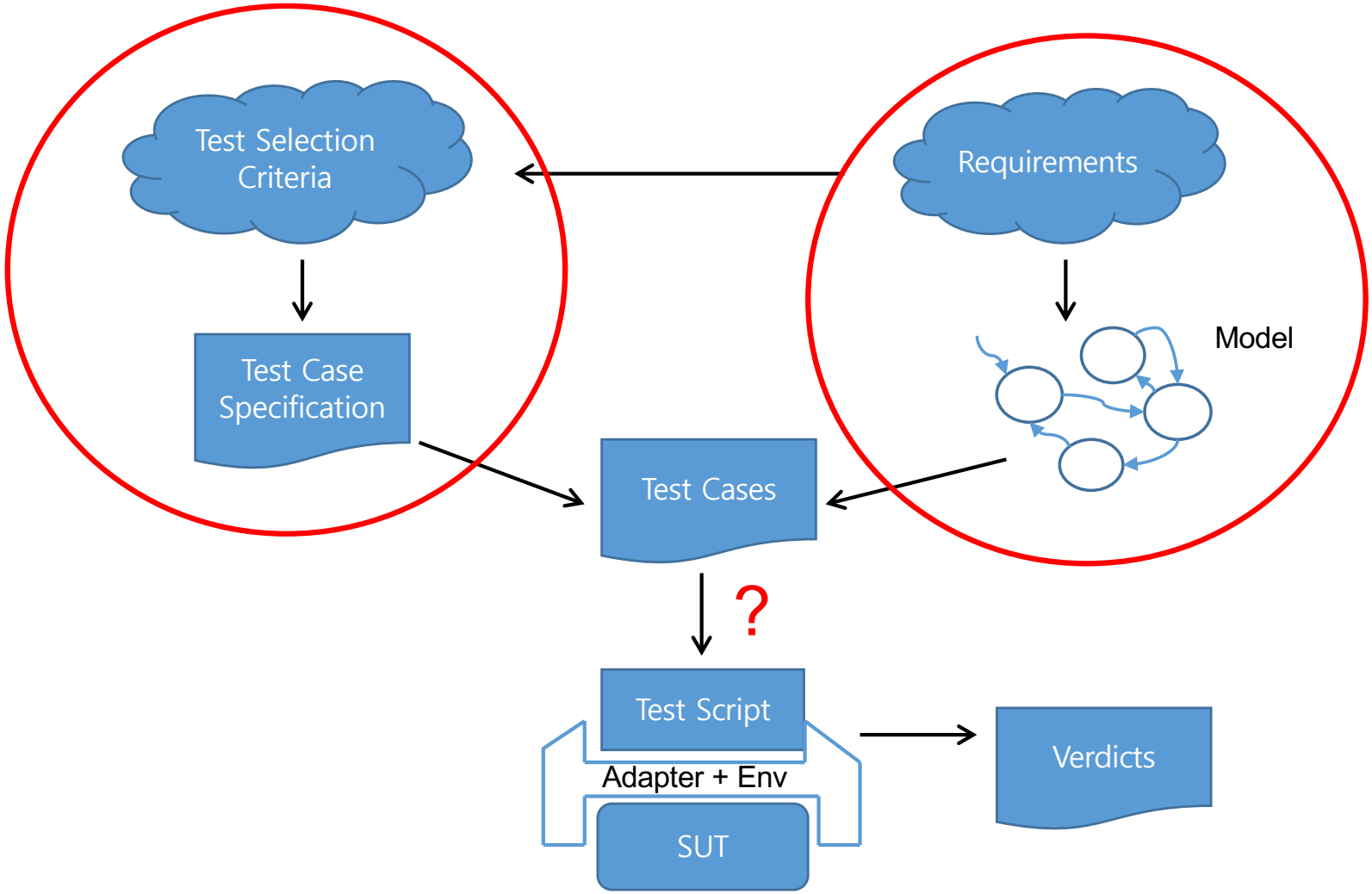
A systematic and efficient verification method is desirable

We solve this problem using

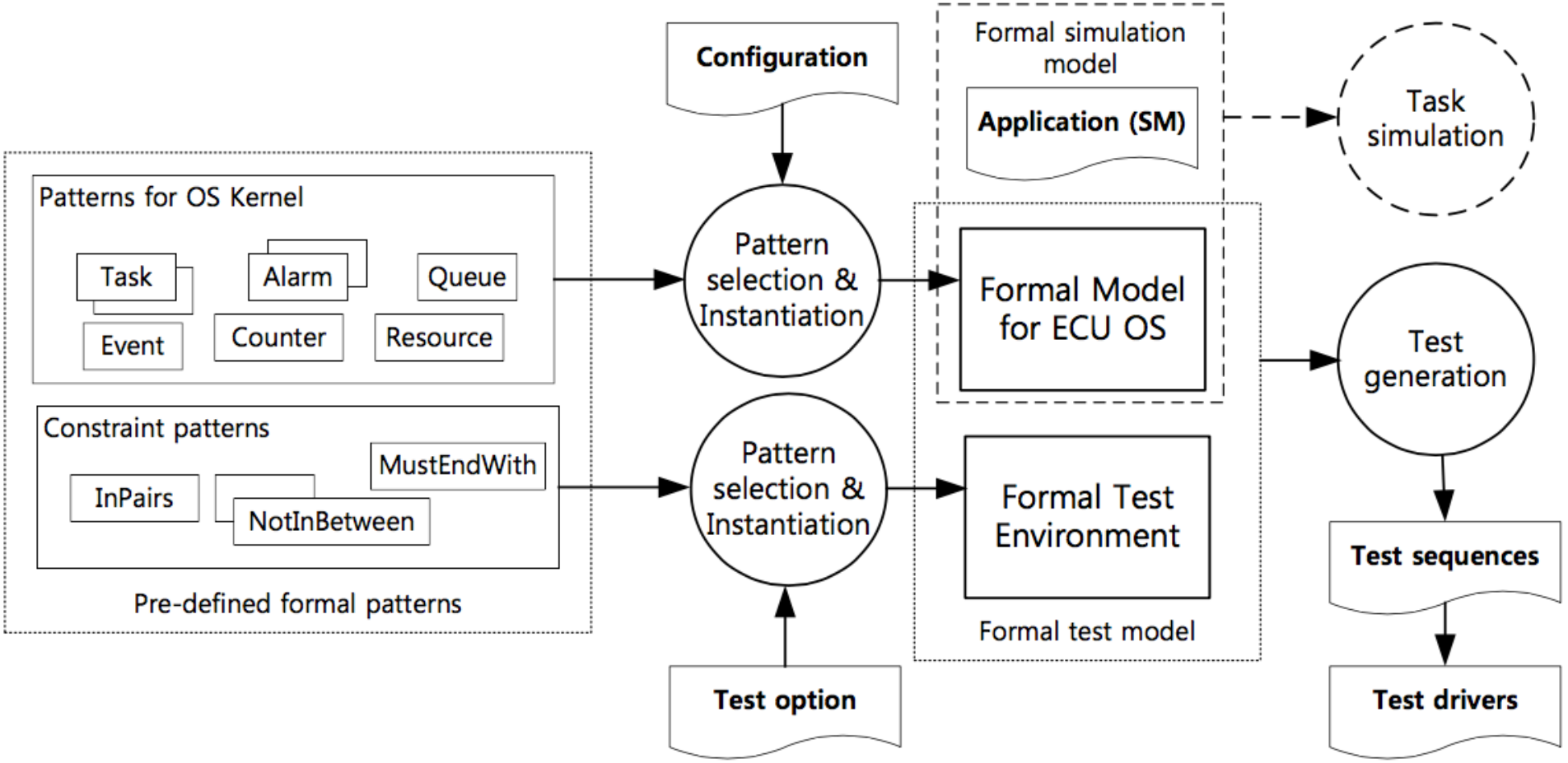
- Domain-specific modeling
- Constraint-based environment modeling
- Modular & pattern-based approach
- Configurable generation of formal models
- Model checking as backend verification engine

- Automate test process as much as possible from model construction
- Reuse models as well as tests

Automating model construction process



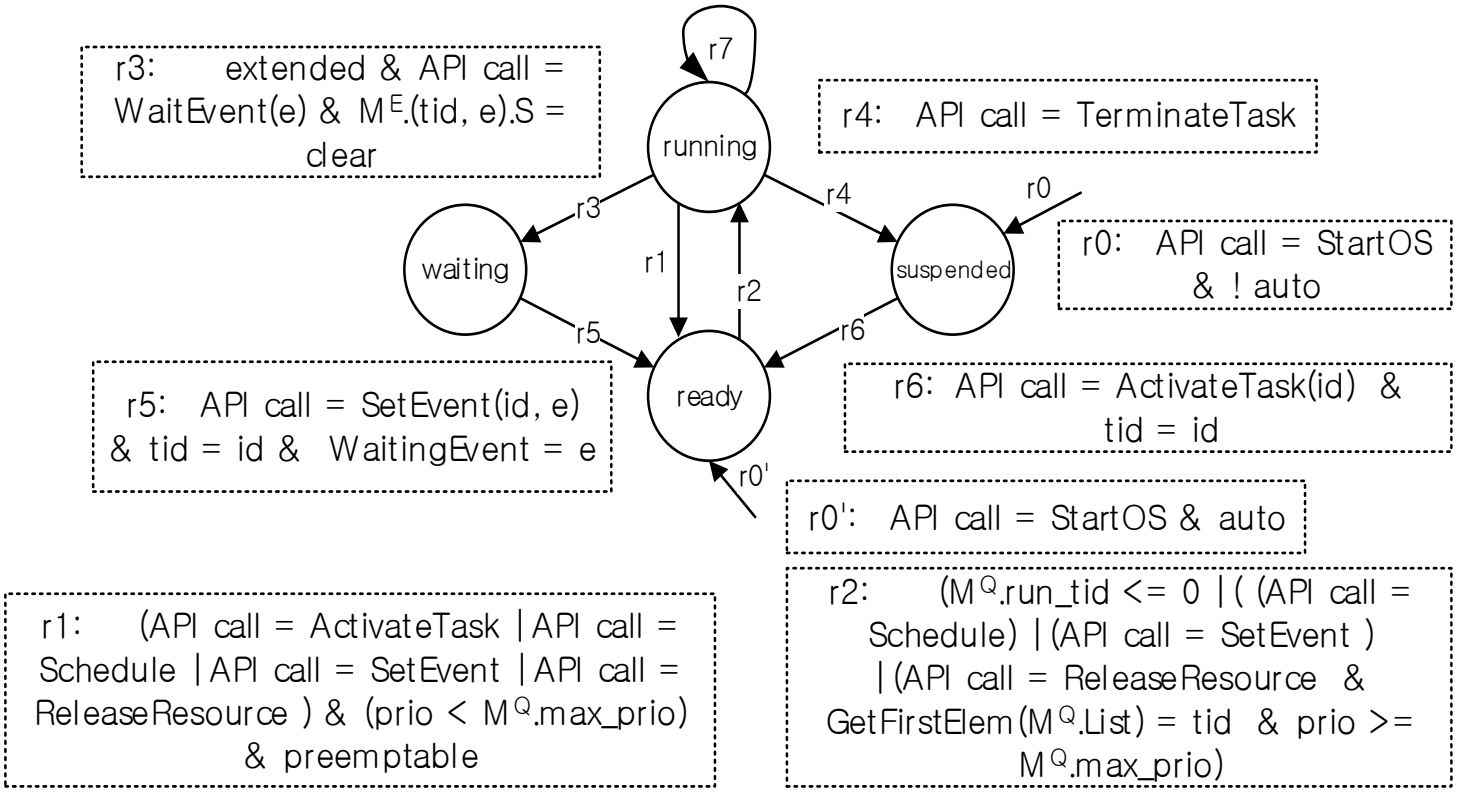
Automating model construction process:
A pattern-based V&V framework



A pattern-based V&V framework

- A set of functional models are pre-defined as parameterized statemachines
  - which is used to auto-generate a formal OS model for each configuration
- A set of constraint patterns are pre-defined as parameterized statemachines
  - They represent operational constraints of underlying operating systems
  - Test engineers can choose a subset of the constraints to impose constraint on the operational environment and generate test sequences
- It supports
  - automated safety checking for operating systems
  - automated API-call constraint checking for control software
  - simulation of task sequences and validation of task design

Formal specifications: Tasks



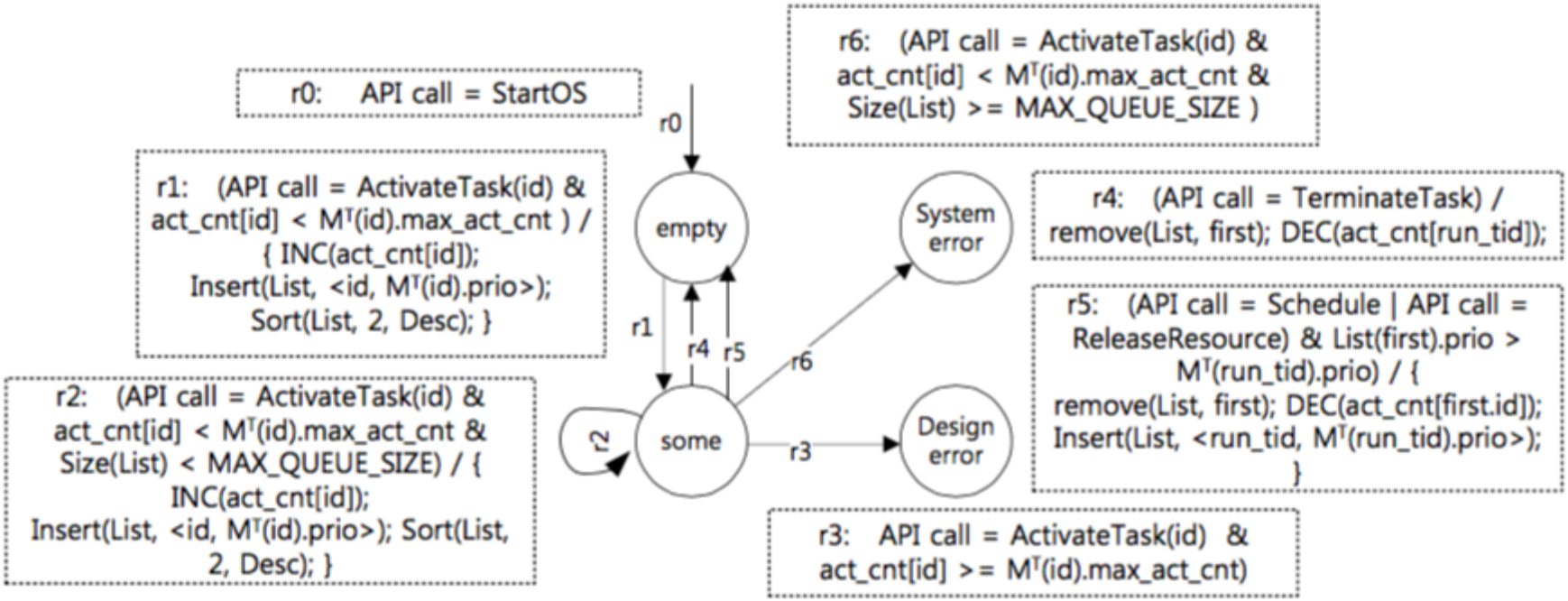

```
MODULE Task(env, tid, ptiv, pri, autostrt, extended, rq, e_run, res, evt)
```

Formal specifications: Tasks

```
MODULE Task(env, tid, ptiv, pri, autostrt, extended, rq, e_run, res, evt)
  MODULE Task(env, tid, ptiv, pri, autostrt, extended, rq, e_run, res, evt)
          VAR
          state : {SUS, RDY, WIT, RUN};
          prio : 1..5;
          go_rdy : boolean;
          wait_e : 1..2;
          c2 : NotInBetween(env,
          c3 : MustEndWith(env,

          FROZENVAR
          id : 1..5;
          autostart : boolean;

          DEFINE
          exc_set2 := {TT, WE};
          end_set3 := {TT};
          ext := extended;

          ASSIGN
          init(autostart) := aut
          init(id)        := tid
          init(state)     := cas
                  autostrt : RDY
                  TRUE : SUS;
          esac;
          init(wait_e)    := 1;
          next(wait_e)    := case
                  env.nWE & state = RUN & nex   tate) = WIT : next(env.p_e);
                  TRUE : wait_e;
          esac;
          next(state)     := case
                  state = RDY : case
                  !e_run & prio >= rq.max_prio : RUN;
                  (env.nSC | env.nRR | env.nSE) & rq.pq[prio][0] = 1 & prio > rq.max_prio : RUN;
                  TRUE : state;
          esac;
                  state = RUN : case
                  next(env.api) = None & ptiv = TRUE & prio < rq.max_prio : RDY;
                  env.nAT & ptiv = TRUE & prio < (rq.max_prio) : RDY;
                  (env.nSC | env.nSE | env.nRR) & prio < rq.max_prio & ptiv = TRUE : RDY;
                  env.nCT : SUS;
                  env.nTT : SUS;
                  ext & env.nWE & next(evt.valid) & evt.state[tid][next(env.p_e)] = clear : WIT;
                  TRUE : state;
          esac;
                  state = SUS & (env.nAT | env.nCT) & next(env.p_t) = id : {state, RDY};
                  state = WIT & env.nSE & next(env.p_t) = tid & evt.valid & wait_e = next(env.p_e) : RDY;
                  TRUE : state;
          esac;
          init(go_rdy)    := (state = RDY);
          next(go_rdy)    := case
                  state = SUS & next(state) = RDY : TRUE;
                  TRUE : FALSE;
          esac;
          init(prio)      := pri;
          next(prio)      := case
                  env.nGR & state = RUN & next(res.ceil_prio) > prio : next(res.ceil_prio);
                  env.nRR : pri;
                  TRUE : prio;
          esac;
```

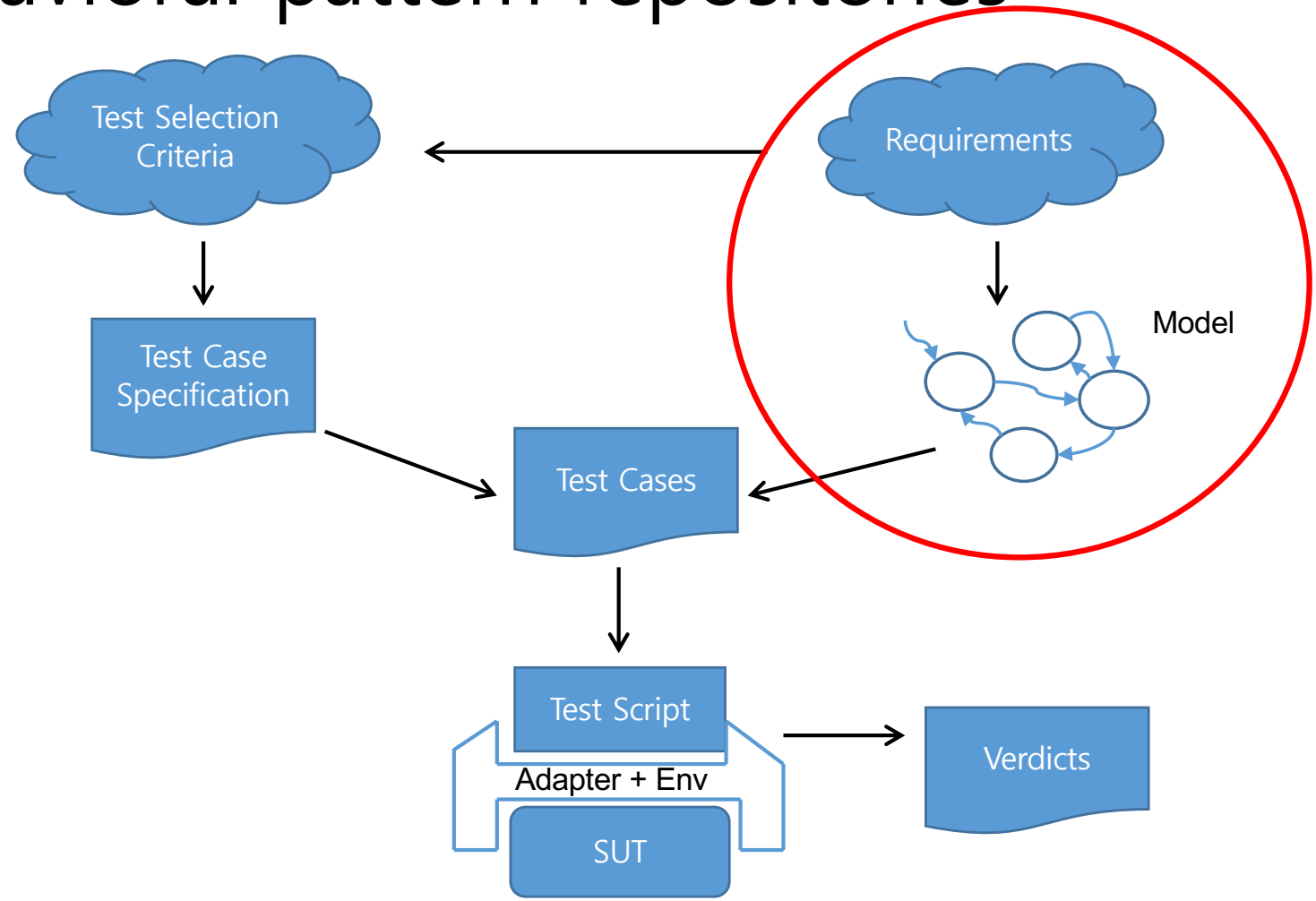
```
next(state) := case
    state = RDY :
      case
        !e_run & prio >= rq.max_prio : RUN;
        (env.nSC | env.nRR | env.nSE) & rq.pq[prio][0] = 1 & prio > rq.max_prio : RUN;
        TRUE : state;
      esac;
    ....
```

Formal specifications: Scheduler

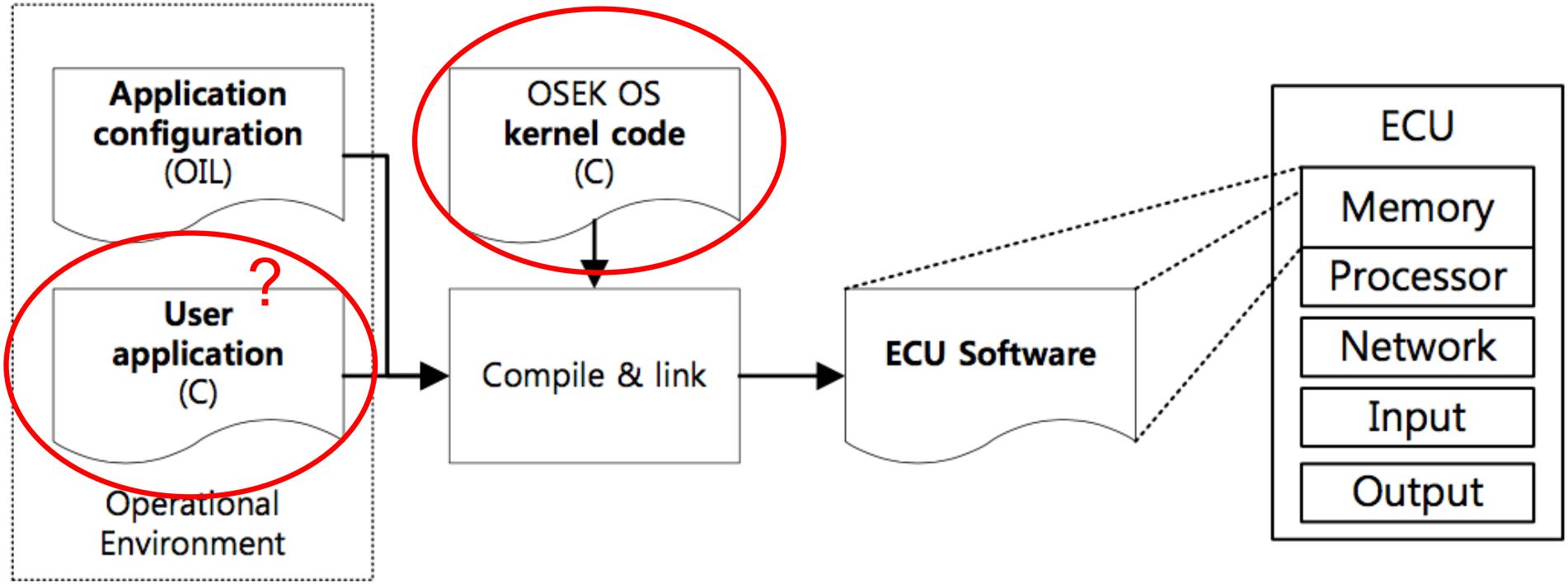



```
MODULE Scheduler(tasks)
```

Configurable model generation using behavioral pattern repositories



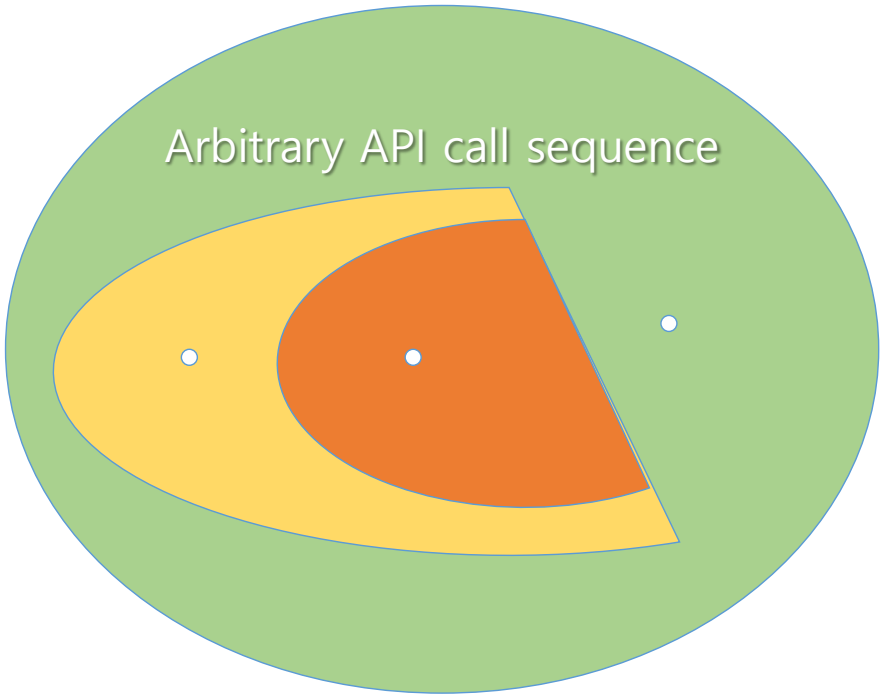
Modeling operational environment using constraint patterns



A systematic and efficient verification method is desirable

Constraint-based Environment Modeling

- Systematically apply constraints to the universal environment



Examples of Constraints

1. Ending a task without a call to TerminateTask or ChainTask is strictly forbidden and causes undefined behavior
2. TerminateTask, ChainTask, Schedule, WaitEvent shall not be called while a resource is occupied
3. A task calling WaitEvent shall go to the waiting state and shall not be called while a resource is occupied
4. OSEK strictly forbids nested access to the same resource
5. A task shall not terminate without releasing resources

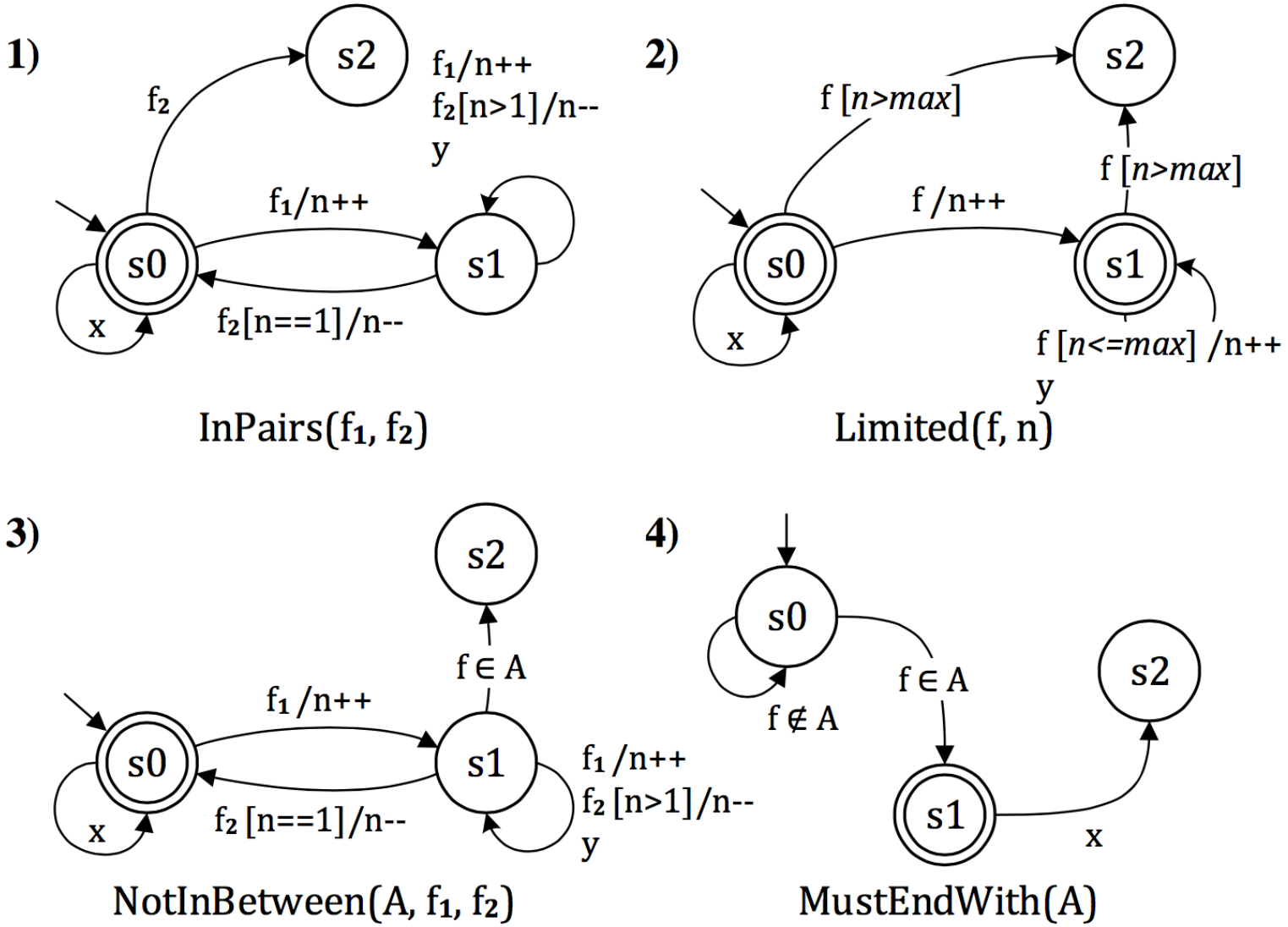
Formal Constraint Specification

< OSEK_CSL>

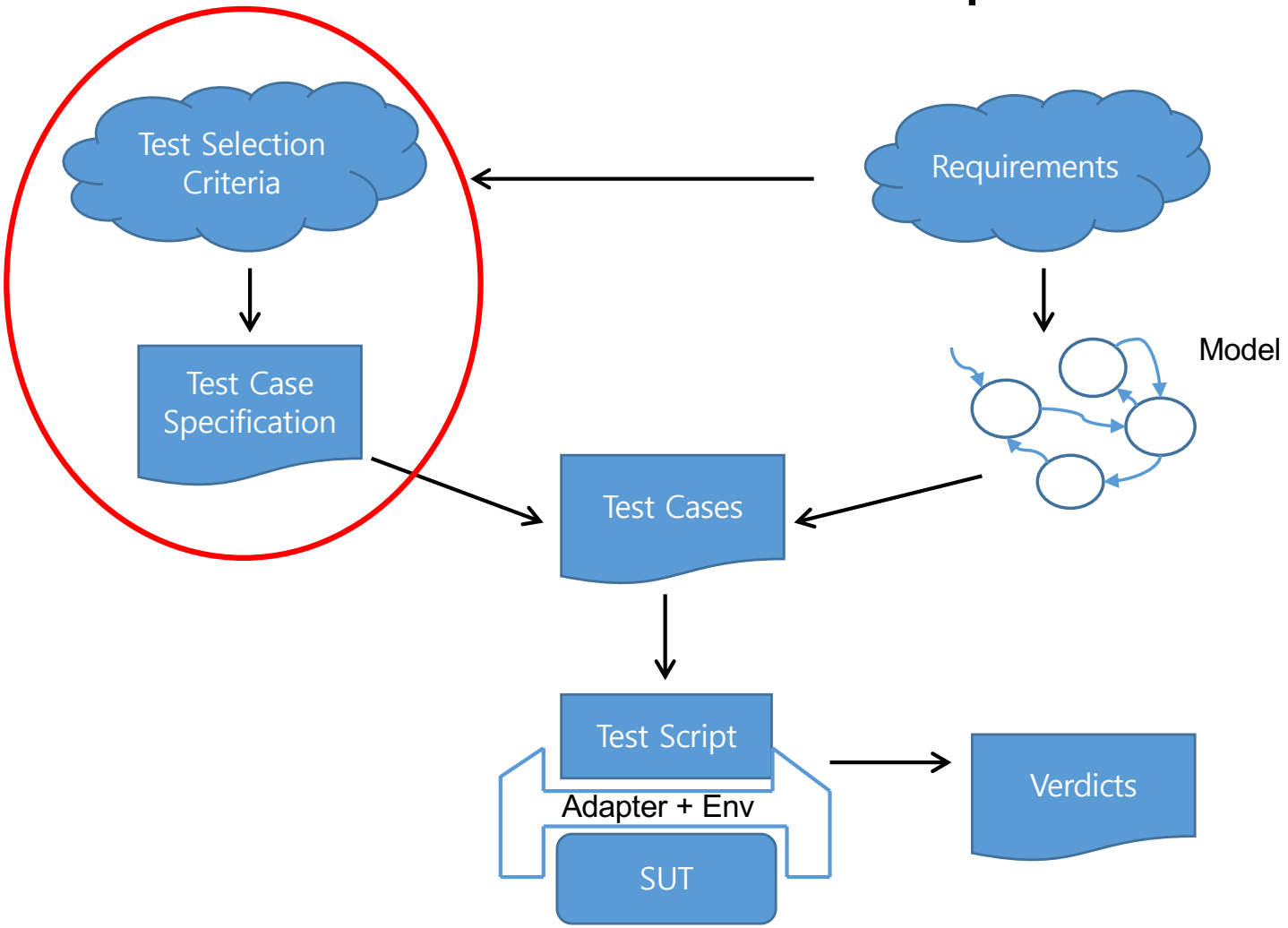
1. **InPairs(f1, f2) :** A system call f1 shall be followed by f2
2. **Limited(f, n)/ SetLimited(A, n) :** The number of calls to f is limited by n
3. **NotInBetween(f, f1, f2) :** A system call f shall not be called in between two system calls f1 and f2
4. **MustEndWith(f) :** No system call shall be made after a call to f

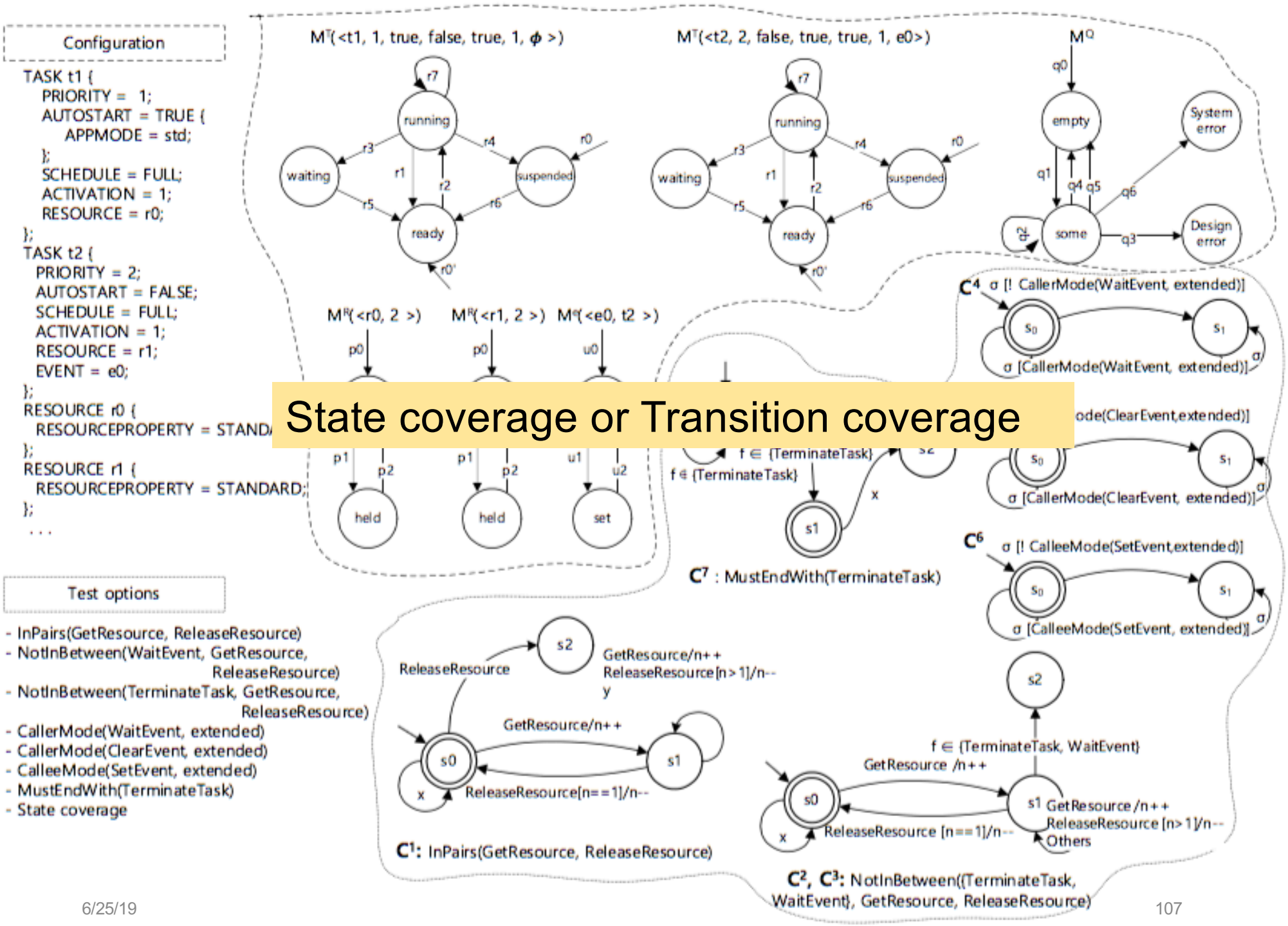
$$Limited(f,n) = \{w \mid w \in \Sigma^*,\ n_f(w) \leq n\}$$
$$SetLimited(A,n) = \{w \mid w \in \Sigma^*,\ SUM_{f_i \in A}(n_{f_i}(w)) \leq n\}$$
$$MustEndWith(A) = \{wf \mid w \in (\Sigma - A)^*,\ f \in A\}$$

Constraint Patterns



Constraint-based test case specification



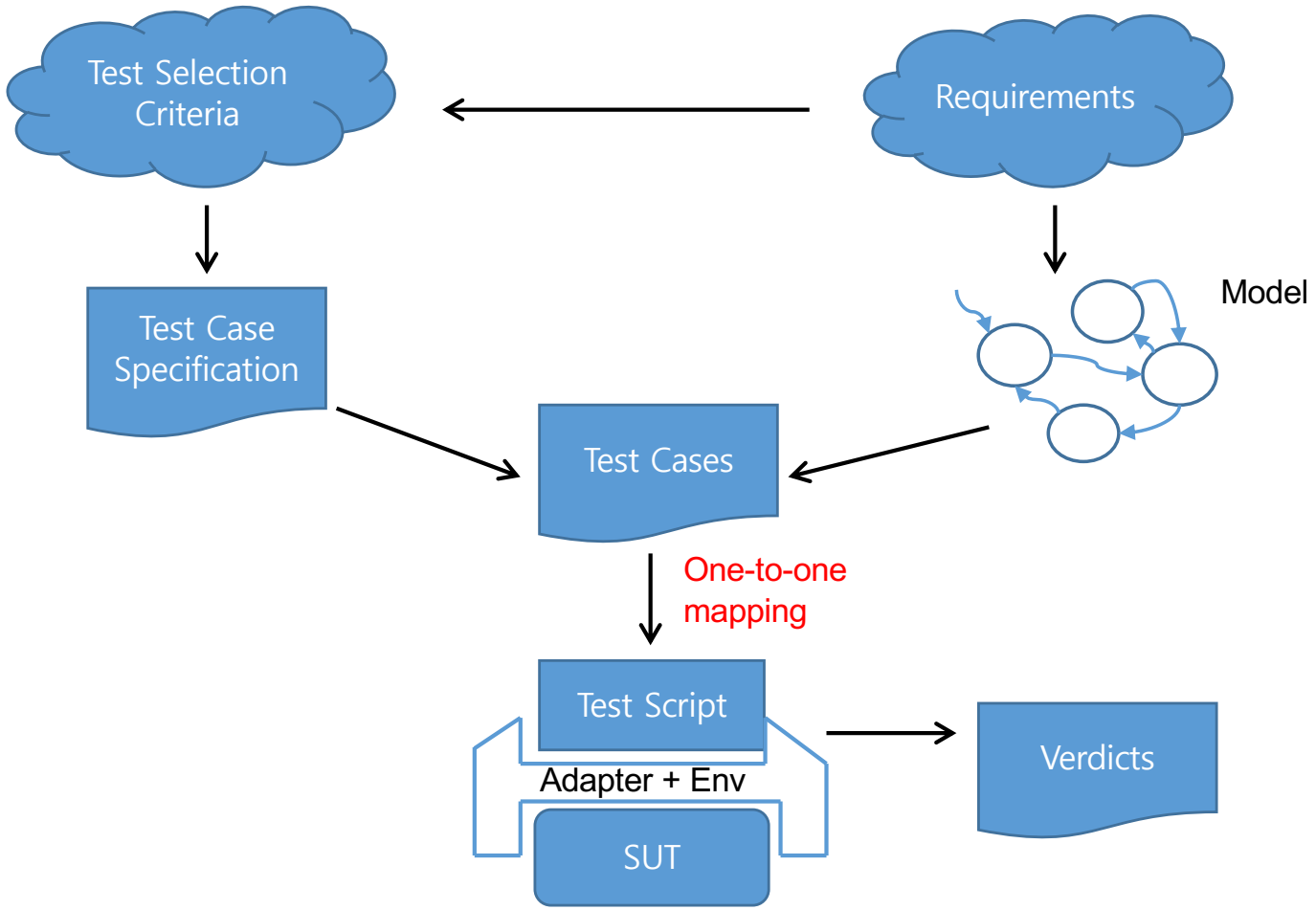

Configuration
TASK t1 {
PRIORITY = 1;
AUTOSTART = TRUE {
APPMODE = std;
};
SCHEDULE = FULL;
ACTIVATION = 1;
RESOURCE = r0;
};
TASK t2 {
PRIORITY = 2;
AUTOSTART = FALSE;
SCHEDULE = FULL;
ACTIVATION = 1;
RESOURCE = r1;
EVENT = e0;
};
RESOURCE r0 {
RESOURCEPROPERTY = STANDA
};
RESOURCE r1 {
RESOURCEPROPERTY = STANDARD;
};
...
Test options
- InPairs(GetResource, ReleaseResource)
- NotInBetween(WaitEvent, GetResource, ReleaseResource)
- NotInBetween(TerminateTask, GetResource, ReleaseResource)
- CallerMode(WaitEvent, extended)
- CallerMode(ClearEvent, extended)
- CalleeMode(SetEvent, extended)
- MustEndWith(TerminateTask)
- State coverage
M^T(<t1, 1, true, false, true, 1, ϕ >)
M^T(<t2, 2, false, true, true, 1, e0>)
M^Q
running
waiting
ready
suspended
empty
some
System error
Design error
M^R(<r0, 2 >)
M^R(<r1, 2 >)
M^e(<e0, t2 >)
held
held
set
State coverage or Transition coverage
C4 σ [! CallerMode(WaitEvent, extended)]
σ [CallerMode(WaitEvent, extended)]
ode(ClearEvent,extended)]
σ [CallerMode(ClearEvent, extended)]
f ∈ {TerminateTask}
C7 : MustEndWith(TerminateTask)
C6
σ [! CalleeMode(SetEvent,extended)]
σ [CalleeMode(SetEvent, extended)]
ReleaseResource
GetResource/n++
ReleaseResource[n>1]/n--
y
GetResource/n++
ReleaseResource[n==1]/n--
C1: InPairs(GetResource, ReleaseResource)
f ∈ {TerminateTask, WaitEvent}
GetResource /n++
ReleaseResource [n==1]/n--
GetResource /n++
ReleaseResource [n>1]/n--
Others
C2, C3: NotInBetween({TerminateTask, WaitEvent}, GetResource, ReleaseResource)

Trap properties

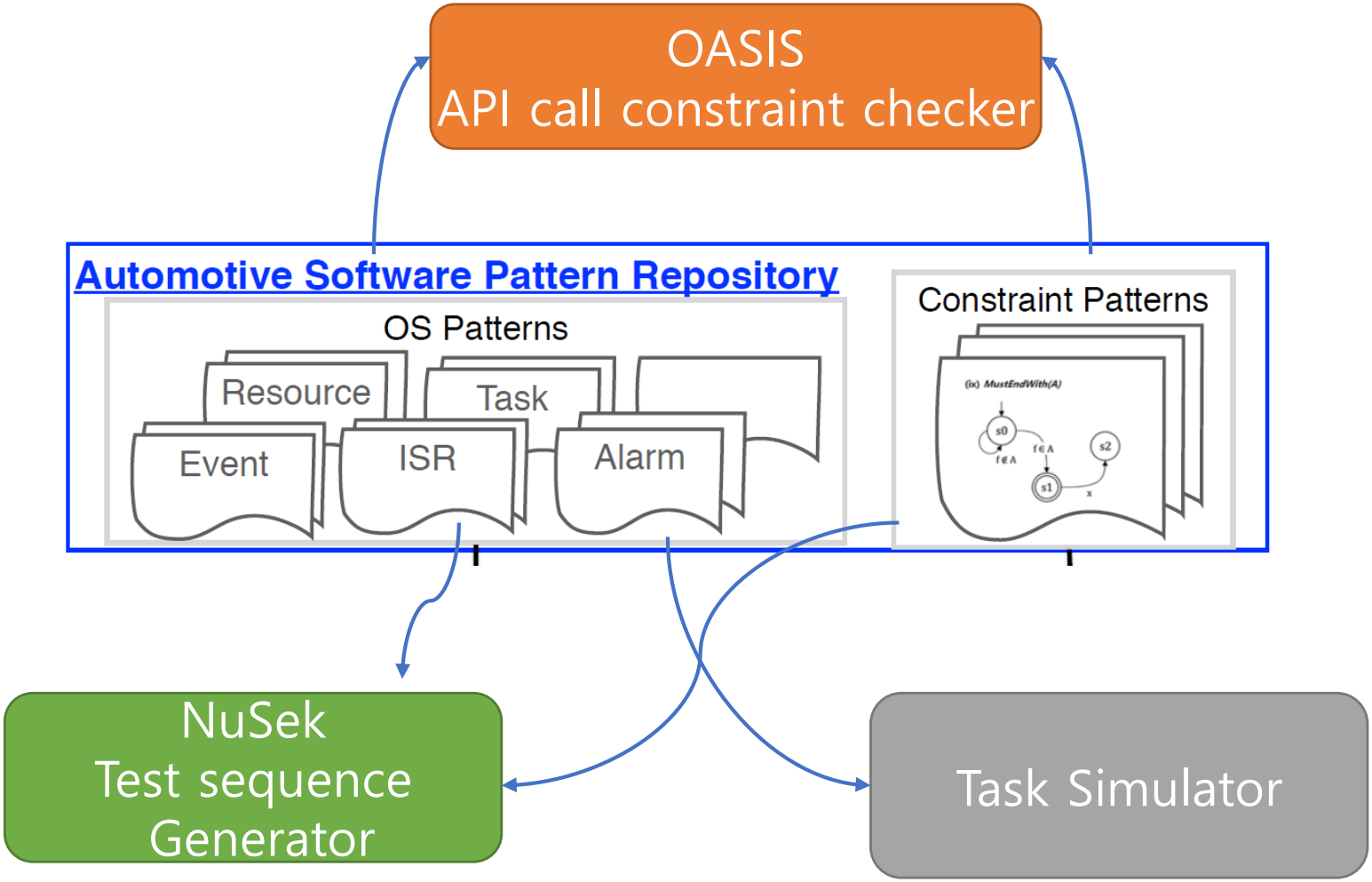
- A trap property is for generating counterexamples
  - e.g., a certain state cannot be reached from the initial state
- Typically a false property
- Model checker can generate an execution trace showing how the property can be violated
  - The counterexample trace becomes a test sequence

To generate a test sequence from an initial state s_0 to a state s_i, then define a trap property as
$G(s_0 \rightarrow ! F\ s_i)$

Test driver generation



Prototype tools: AutoCheck^{FP}



Tool demo available at https://youtu.be/ajhV9N2jCb8

User's perspective

Configuration

```
OIL_VERSION = "2.5";

CPU default_cpu {
	OS myOS {
		STATUS = EXTENDED;
		APP_SRC = "gen_model_test.c";
		LDFLAGS = "-g -lpthread";
		CFLAGS = "-DWITH_DEBUG";
	};
	APPMODE std { };
	TASK t1 {
		PRIORITY = 1;
		AUTOSTART = TRUE {
			APPMODE = std;
		};
		SCHEDULE = FULL;
		ACTIVATION = 1;
		RESOURCE = r0;
	};
	TASK t2 {
		PRIORITY = 2;
		AUTOSTART = FALSE;
		SCHEDULE = FULL;
		ACTIVATION = 1;
		RESOURCE = r1;
		EVENT = e0;
	};
```

```
int main(void)
{
	StartOS(OSDEFAULTAPPMODE);
	return 0;
}

TASK(t1)
{
	printf("Task t1 activated.\n");
	printState();
	printf("		ActivateTask(t2)\n");
	ActivateTask(t2);
	printState();
	printf("		SetEvent(t1, e0)\n");
	SetEvent(t1, e0);
	printState();
	printf("		TerminateTask()\n");
	TerminateTask();
}


TASK(t2)
{
	printf("Task t2 activated.\n");
	printState();
	printf("		WaitEvent(e0)\n");
	WaitEvent(e0);
}
```

Efficiency of NuSek

- Construction of formal models does not take time
- Test generation from those models is quite efficient
  - No manual effort required
  - Finds more subtle errors than manually constructed test cases by experts
    - 64 test cases finding 4 causes of failures vs. 164 test cases finding only one of the 4 causes

Table 3: Performance of test generation

Config.	CS		CS_{all}		CS × TS		$CS \times TS_{all}$	
(T, C)	Time	#P (#S)	Time	#P(#S)	Time	#P(#S)	Time	#P(#S)
(2, 2)	0.073	8 (6)	0.577	18(17)	4.630	64(24)	16.244	128(45)
(2, 3)	0.104	11(7)	147.73	54 (38)	39.461	88 (31)	28.322	176(53)
(2, 4)	0.211	13(7)	209.66	72 (41)	40.480	104(34)	32.152	208(58)
(3, 2)	0.159	11(7)	0.604	18(13)	21.239	132(50)	226.244	704(218)
(3, 3)	0.198	14(10)	23.664	54(33)	56.275	144(59)	370.709	896(253)
(3, 4)	0.186	16(10)	142.475	108(69)	33.629	192(65)	412.688	1024(265)
(4, 2)	0.233	14(10)	1.043	21(15)	64.415	224(92)	6289.913	3584(817)
(4, 3)	0.258	17(12)	93.207	72(42)	103.966	272(109)	3766.217	4352(1102)
(4, 4)	0.271	19(12)	200.365	144(95)	105.308	304(116)	4266.778	4864(1152)

Experiments on Trampoline OS

- Five constraint patterns are applied including
  1. InPairs(WaitEvent, SetEvent),
  2. InPairs(GetResource, ReleaseResource),
  3. NotInBetween({TerminateTask, ChainTask, WaitEvent, Schedule}, GetResource, ReleaseResource),
  4. MustEndWith(TerminateTask, ChainTask)

No.	Constraint Input	Time	Mem	#TS	#Err	#type	Coverage
1	InPairs(WaitEvent, SetEvent)	2' 22"	248.8MB	4	2	1	22.3%
2	InPairs(WaitEvent, SetEvent) NotInBetween(GetResource, ReleaseResource, ...)	1' 31"	270.0MB	40	20	1	27.7%
3	InPairs(WaitEvent, SetEvent) NotInBetween(GetResource, ReleaseResource, ...) RestrictedCaller(extended, WaitEvent)	51' 05"	623.8MB	129	90	2	34.0%
4	InPairs(WaitEvent, SetEvent) NotInBetween(GetResource, ReleaseResource, ...) RestrictedCaller(extended, WaitEvent) MustEndWith(TerminateTask, ChainTask)	306' 34"	986.2MB	142	69	2	35.0%

Experiments on Trampoline OS

- More efficient in finding errors compared to typical specification-based test generation

No.	Constraint Input	Method	Time	Memory	#Tests	#Failures	Error types	Branch Coverage
1	InPairs(*WaitEvent, SetEvent*) NotInBetween(*{TerminateTask, ChainTask, WaitEvent, Schedule}, GetResource, ReleaseResource*) CallerMode(*extended, WaitEvent*)	CB	7' 39"	881MB	168	101	W,S,R	34.5%
2		SB1	19"	212MB	39	0	_	27.7%
3		SB2	4' 07"	293MB	39	2	S	32.0%
4	InPairs(*WaitEvent, SetEvent*) NotInBetween(*{TerminateTask, ChainTask, WaitEvent, Schedule}, GetResource, ReleaseResource*) CallerMode(*extended, WaitEvent*) CallerMode(*extended, ClearEvent*)	CB	21' 22"	1594MB	444	355	C,W,S,R	35.3%
5		SB1	16"	210MB	39	0	_	29.7%
6		SB2	5' 57"	284MB	39	5	S	34.5%
7	Constraint input for 1~3 + MustEndWith(*ChainTask, TerminateTask*)	CB	68' 15"	4725MB	398	288	W,S,R	33.2%
8	Constraint input for 7 + CallerMode(*extended, ClearEvent*)	CB	187' 42"	7353MB	1094	940	C,W,S,R	35.5%
9	Constraint input for 1~3 + 4 tasks	CB	603' 18"	8355MB	225	69	W,S,R	32.5%

<Comparison with typical specification-based testing approaches>

Summary of AutoCheck^{FP}

- A **formal specification** can be used
  - ✓ to **define functional patterns** as well as **constraint patterns**
  - ✓ to **generate** smaller number of **test sequences** that **covers both expected and unexpected system behaviors**
- A configuration-dependent formal model generation can be automated
- Test generation using constraint patterns is efficient and effective
  - ✓ No redundant test sequences
- The use of OS models in test generation reduces the number of infeasible test sequences
  - ✓ No false alarms

References

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