Model based testing

Automated testing and verification

J.P. Galeotti - Alessandra Gorla

Model based testing

- We already know how it works... right?
- At least partially...

Model based testing

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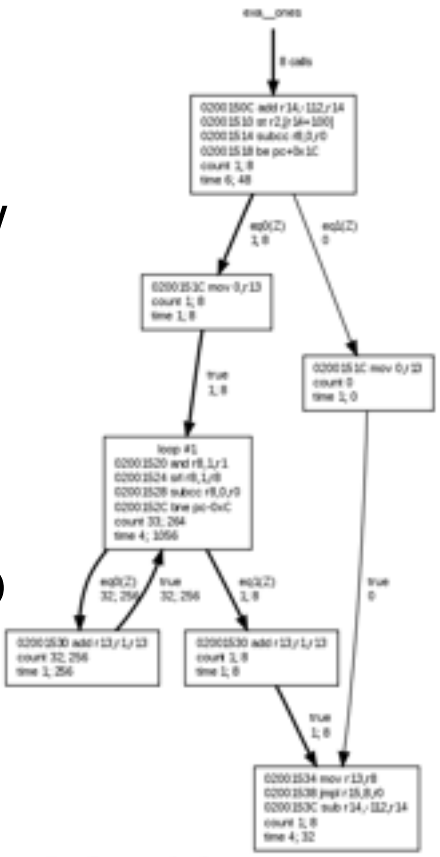
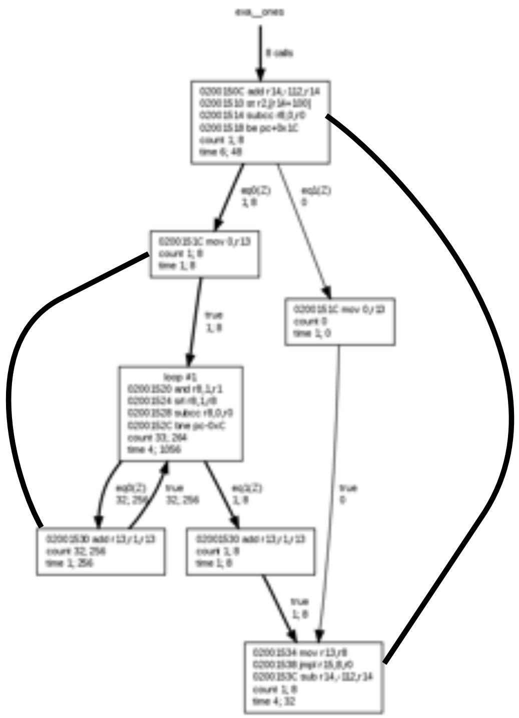
- At least partially.

Control flow
and
data flow
graphs are
models, too



One flow-graph of exa__ones
totals (after ';') for 8 calls from one path
time 1408 = 8 * 176



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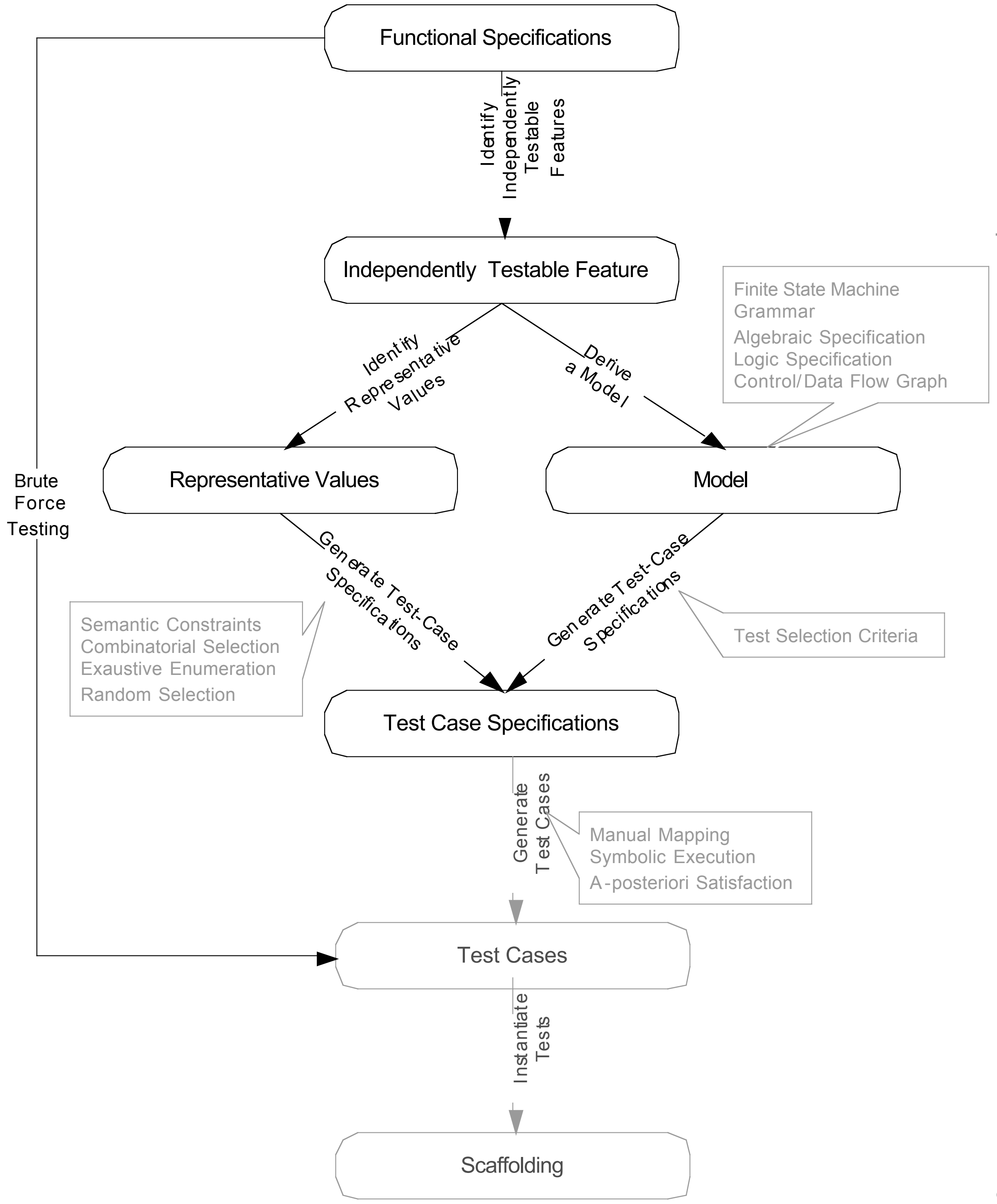
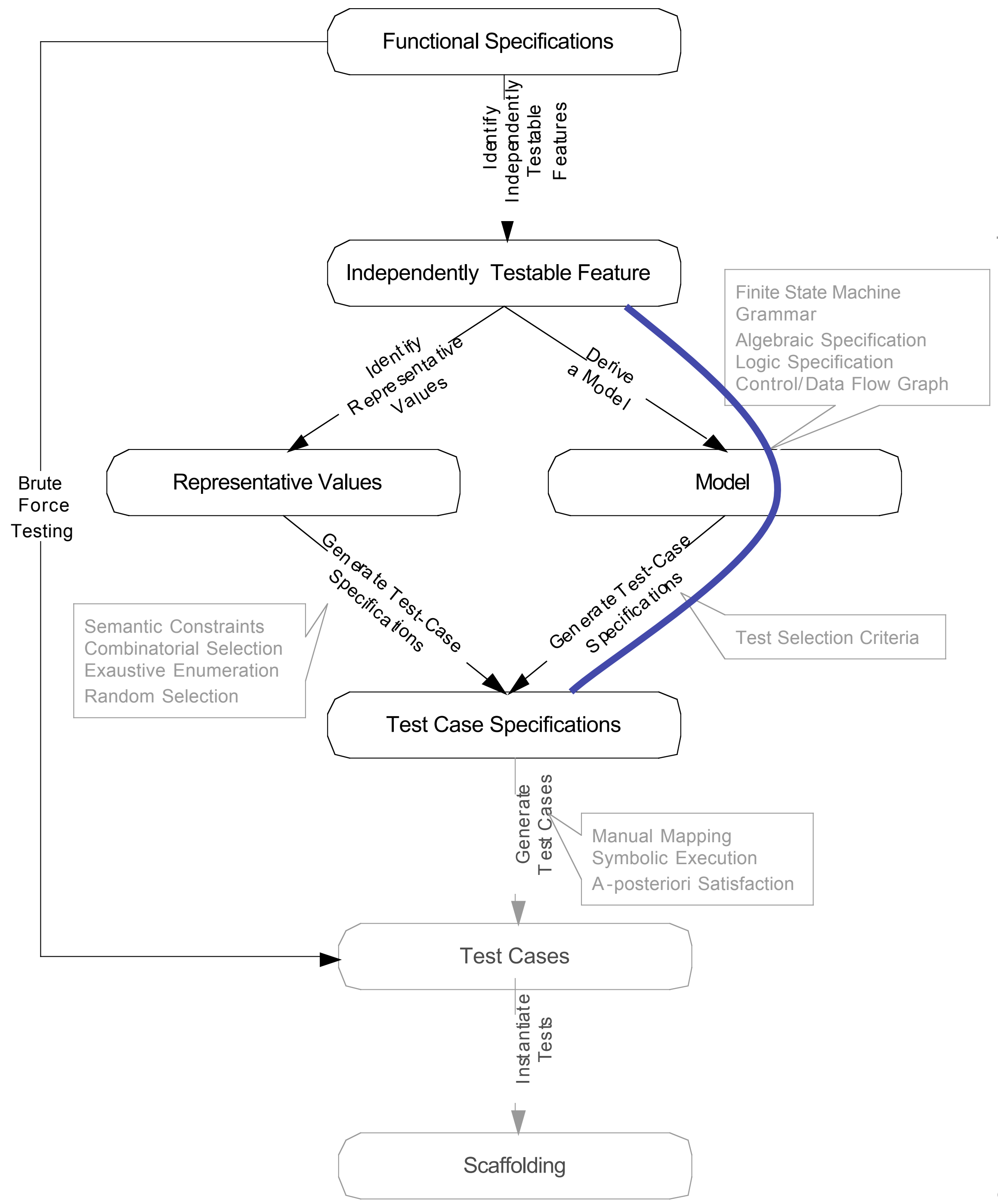


ezzè & Michal Young



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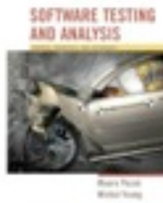
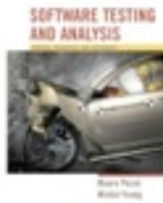
Why model-based testing?

- Models used in specification or design have structure
    - Useful information for selecting representative classes of behavior;
    - Difficult to capture that structure clearly and correctly in constraints in combinatorial testing.
- We can devise test cases to check actual behavior against behavior specified by the model
    - "Coverage" similar to structural testing, but applied to specification and design models



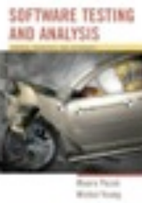
Deriving test cases from finite state machines

A common kind of model for describing behavior that depends on sequences of events



Finite State Machines

- Good at describing interactions in systems with a small number of modes.
- Good at describing transducers (via finite state machines).
- Widely used in industry (Statecharts).
- Most systems are “infinite state” (or effectively so), but many systems are finite state + parameters – there are a finite set of states that control the way data is moved around.
- Good examples are systems like communication protocols or many classes of control systems (e.g. automated braking, flight control systems).
- Good for describing interactive systems that rarely reach a final state



From an informal specification…

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.

From an informal specification…

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

If the product is covered by warranty or mainten
calling the maintenance toll free number, or through the ed
maintenance station.

Multiple choices in the first step ...

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 custome

... determine the possibilities for the next step ...

If the maintenance contract number provided by the cu ure
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 sta The maintenance station informs the customer of the estimated costs for repair. Maintenance starts only whe

If the customer does not accept the estimate, the prod

... and so on ...

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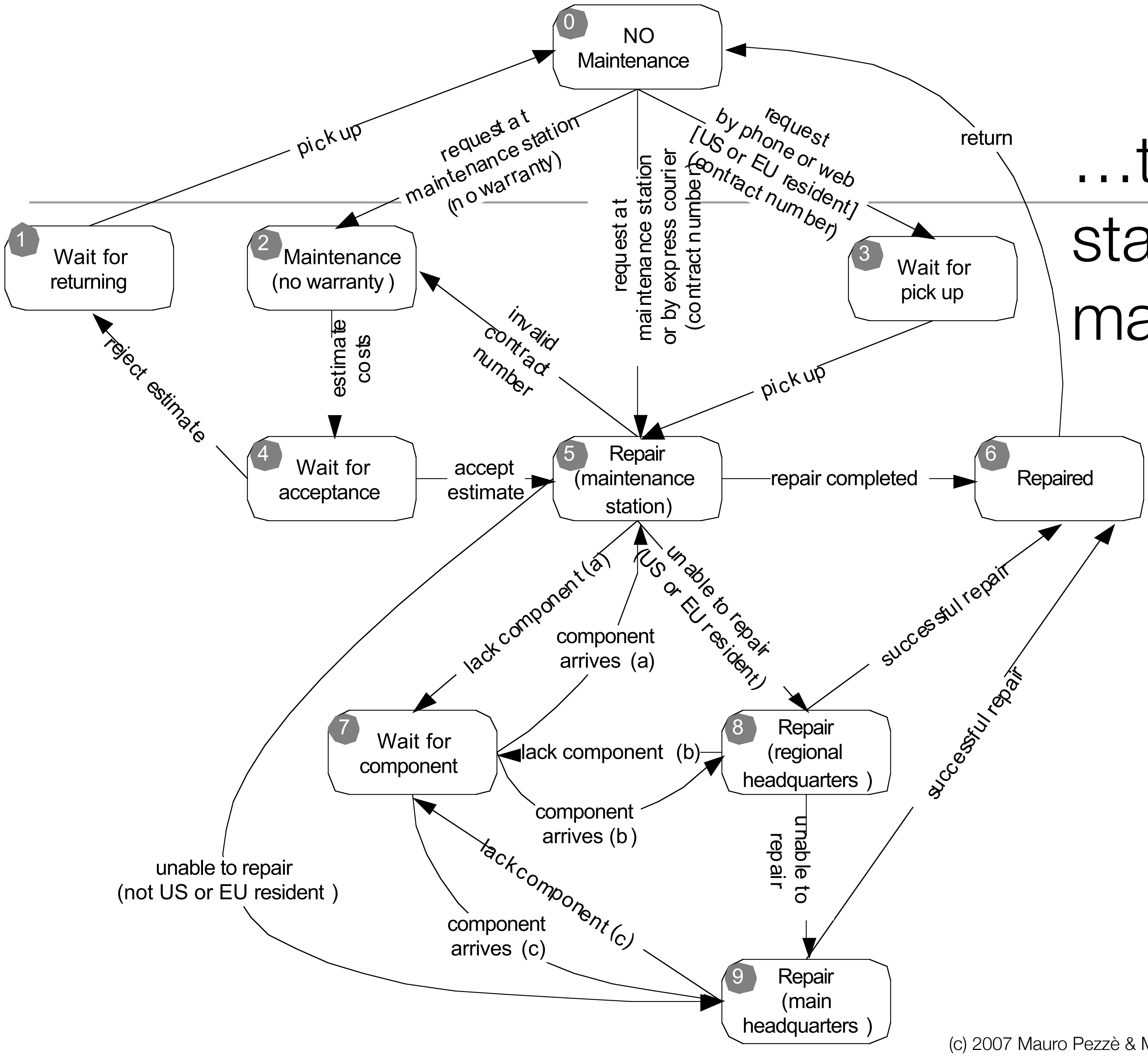
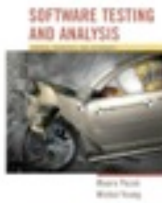


…to a finite state machine…

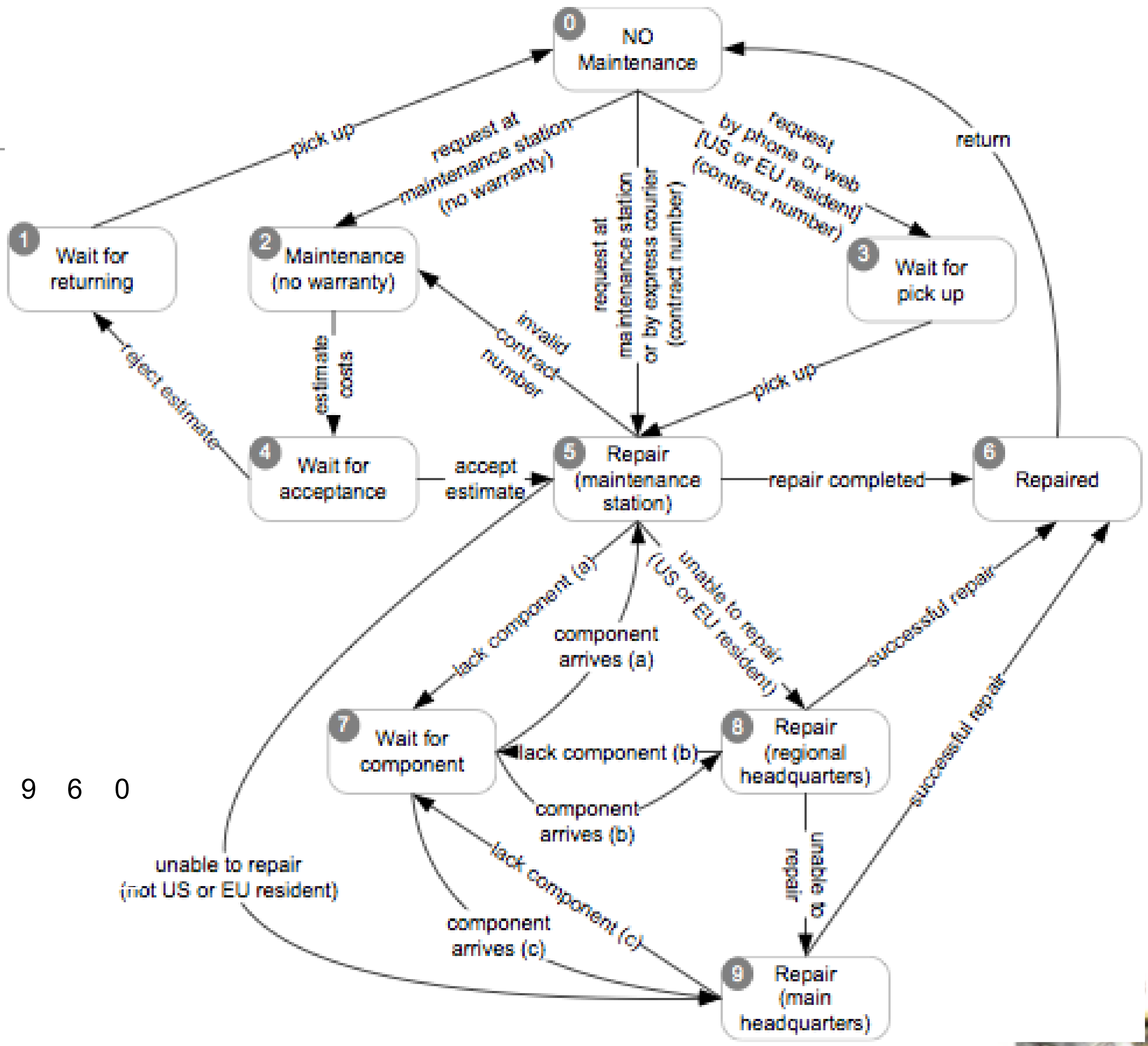


…to a test suite

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?



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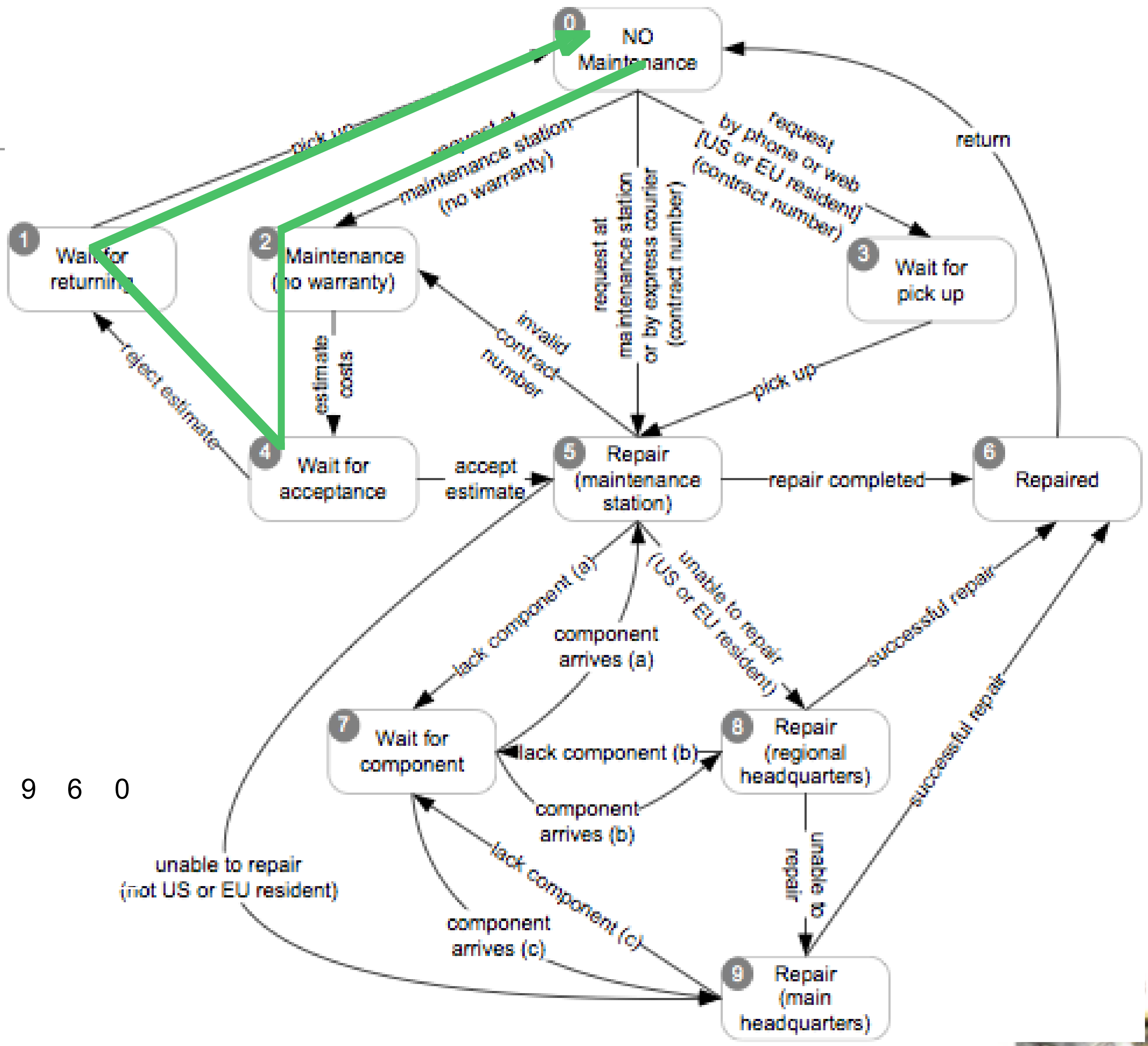
TC4	0	3	5	7	5	8	7	8	9	6	0

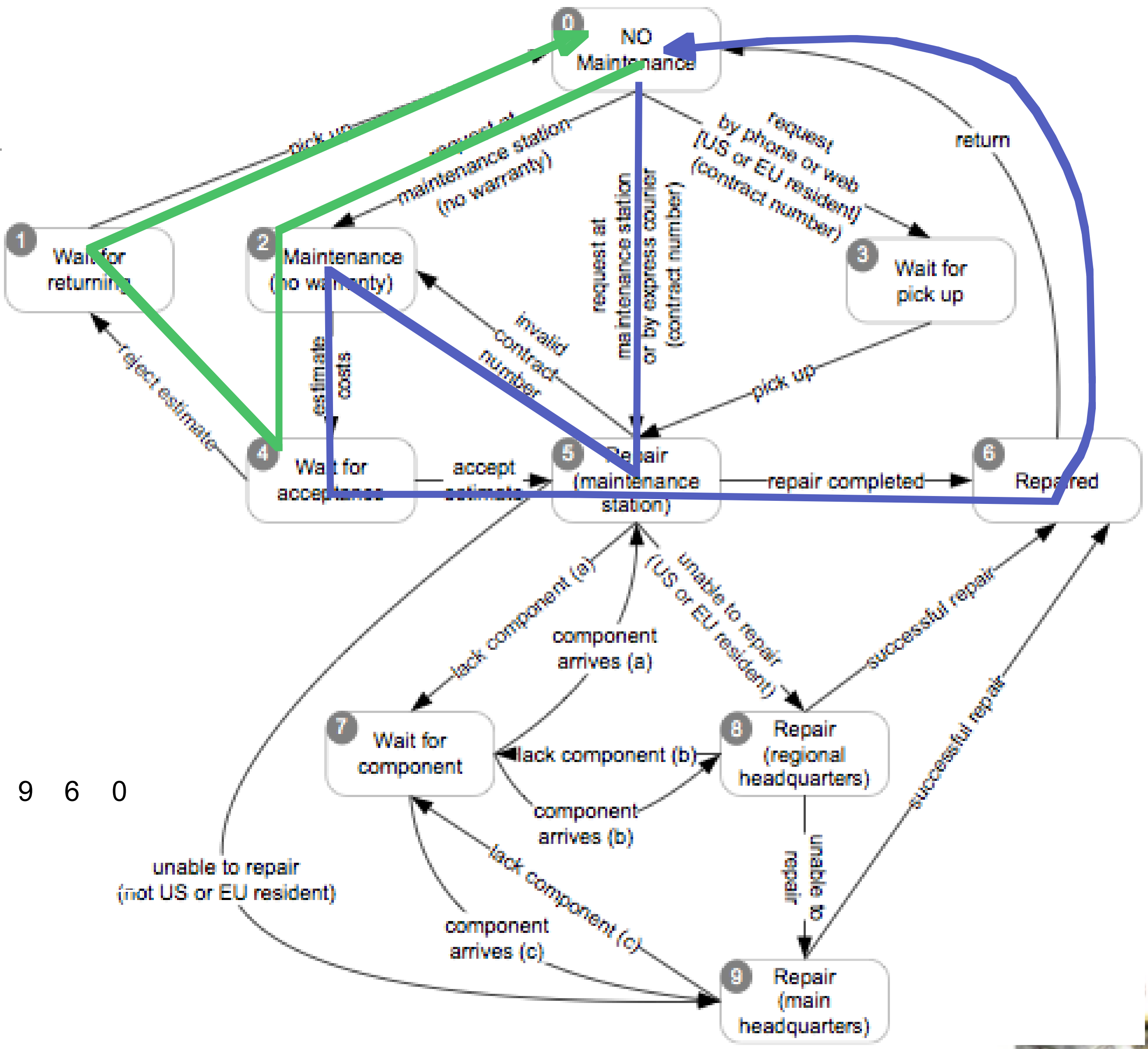


TC1 0 2 4 1 0

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



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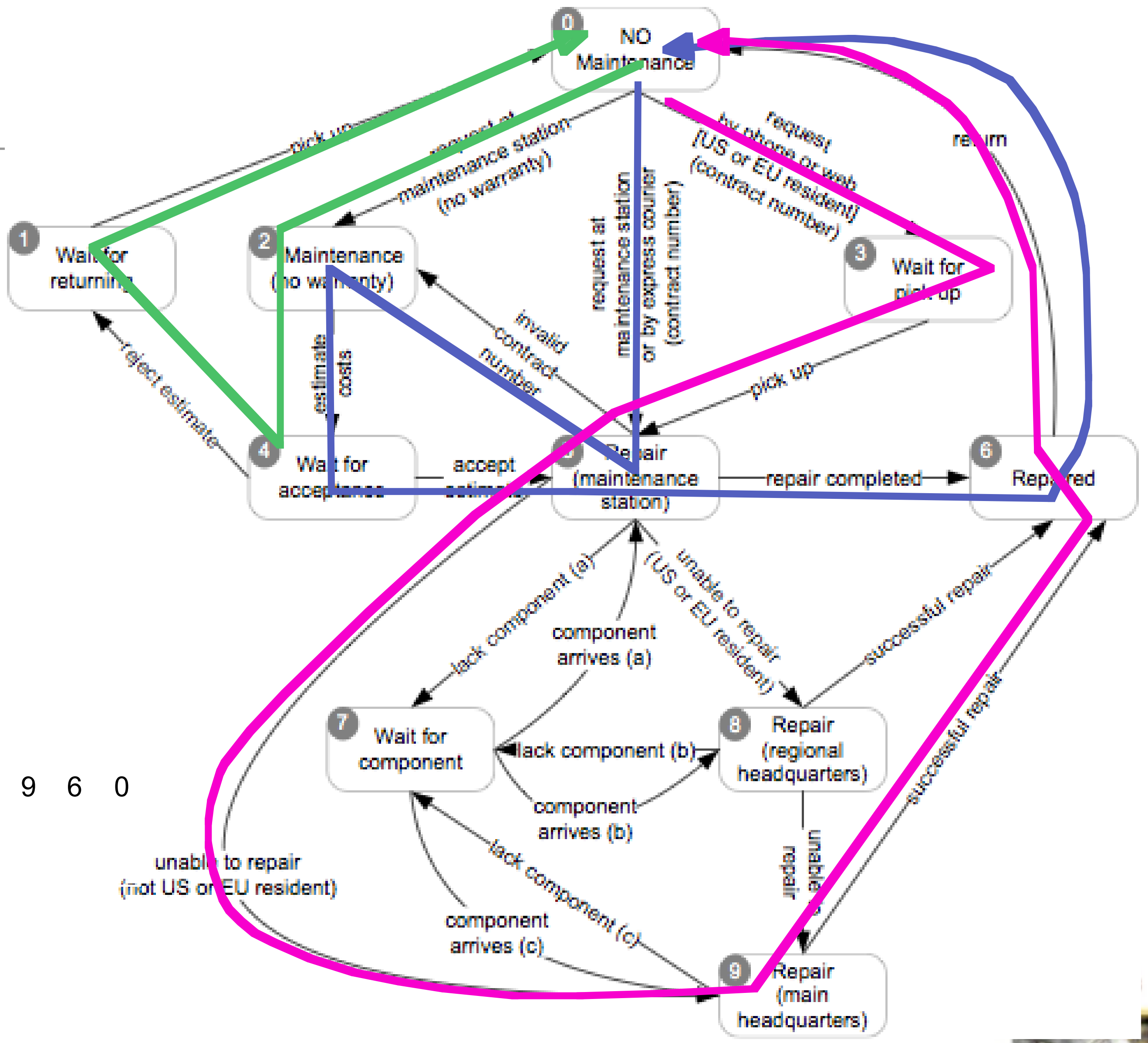

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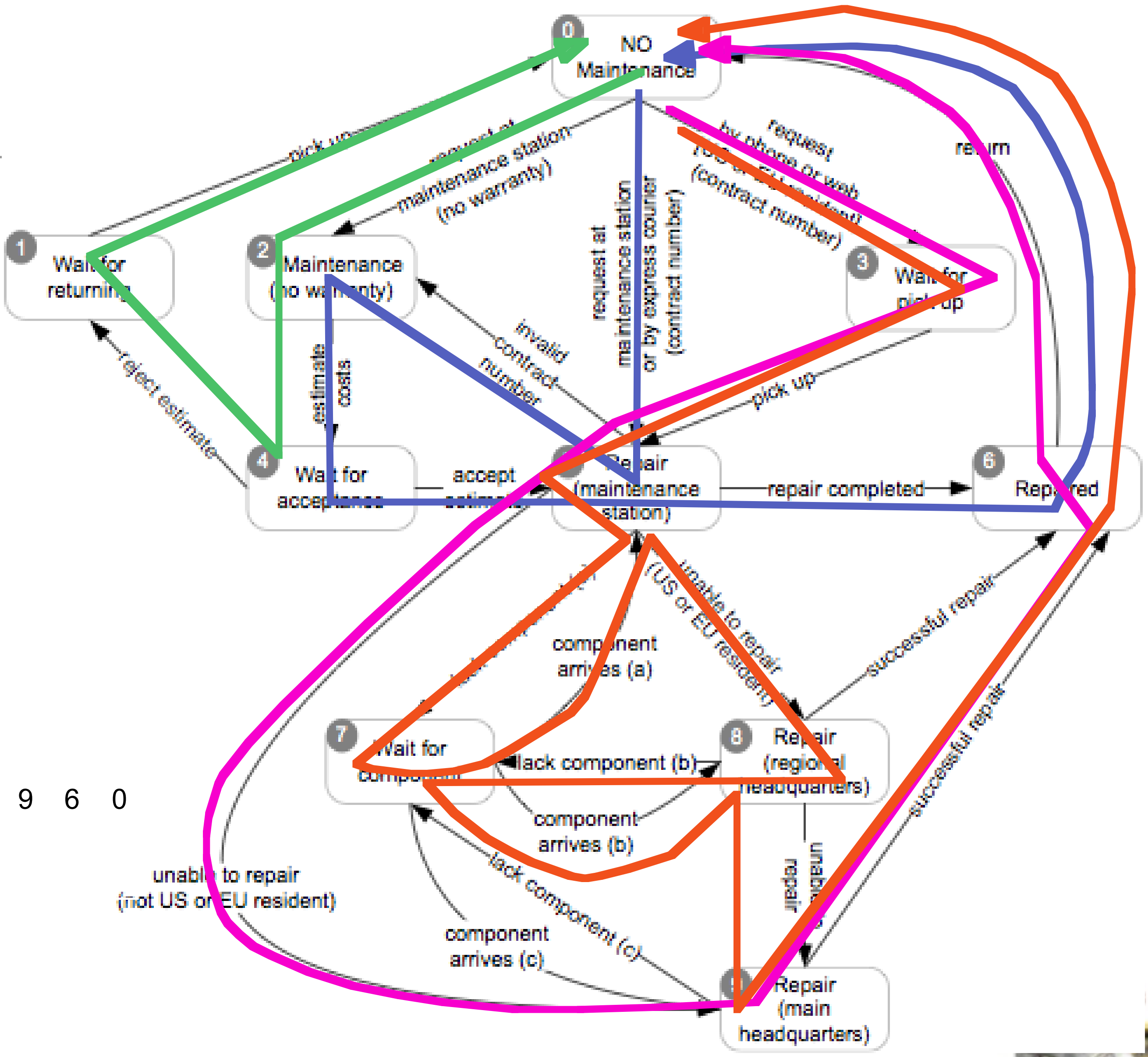
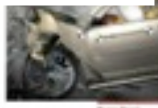
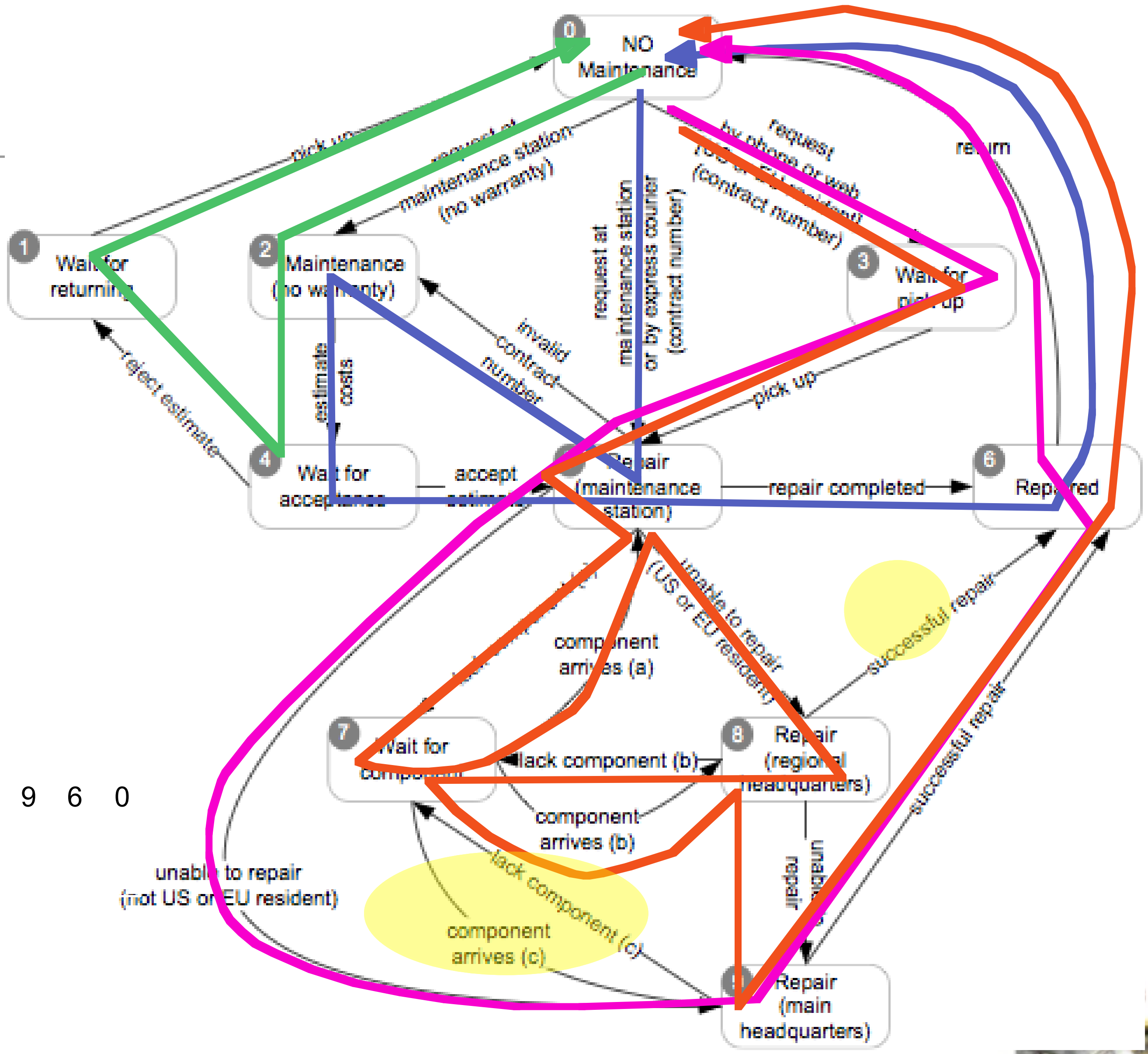

0 NO Maintenance
1 Wait for returning
2 Maintenance (no warranty)
3 Wait for pick up
4 Wait for acceptance
5 Repair (maintenance station)
6 Repaired
7 Wait for component
8 Repair (regional headquarters)
9 Repair (main headquarters)
pick up
request at maintenance station (no warranty)
request at maintenance station or by express courier (contract number)
request by phone or web (US or EU resident) (contract number)
return
invalid contract number
estimate costs
reject estimate
accept estimate
pick up
repair completed
component arrives (a)
unable to repair (US or EU resident)
successful repair
lack component (b)
component arrives (b)
lack component (c)
component arrives (c)
unable to repair
unable to repair (not US or EU resident)
successful repair

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





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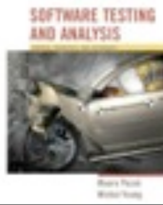
“Covering” finite state machines

- **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

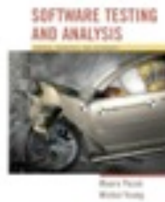
Path sensitive criteria?

- 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 subpath that reaches 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
    - *Of the path sensitive criteria, only boundary-interior is common*



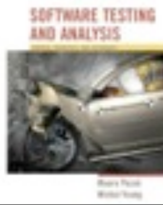
Completeness of the model

- Finite State Machines are usually incomplete
  - *don't care* transitions (do anything or nothing)
  - *error* transitions (trigger error-handling procedure)
  - *self* transitions (remain in the same state)
- Implicit transitions usually represent impossible or irrelevant transitions.
- Not necessary to test them



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.



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

Boolean expressions as outputs

(individual account

AND NOT current purchase > tier1 individual threshold

AND NOT special offer price < individual scheduled price)

OR (business account

AND NOT current purchase > tier1 business threshold

AND NOT current purchase > tier1 business yearly threshold

AND NOT special offer price < business scheduled price)

-> no discounts

…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

	business											
EduAc	-	-	-	-	-	-	-	-	-	-	-	-
BusAc	T	T	T	T	T	T	T	T	T	T	T	T
CP > CT1	F	F	T	T	F	F	T	T	-	-	-	-
YP > YT1	F	F	F	F	T	T	T	T	-	-	-	-
CP > CT2	-	-	F	F	-	-	-	-	T	T	-	-
YP > YT2	-	-	-	-	F	F	-	-	-	-	T	T
SP > Sc	F	T	-	-	-	-	-	-	-	-	-	-
SP > T1	-	-	F	T	F	T	-	-	-	-	-	-
SP > T2	-	-	-	-	-	-	F	T	F	T	F	T
out	ND	SP	T1	SP	T1	SP	T2	SP	T2	SP	T2	SP

…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

…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

Example 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

Example MC/DC

	C.1	C.1a	C.1b	
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	-	-	-	[illegible]
out	Edu	*	*	SP

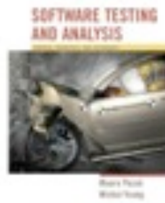
Generate C.1a and C.1b by flipping one element of C.1

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

Outcome of generated columns must differ from source column

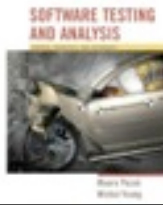
Flowgraph based testing

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



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.

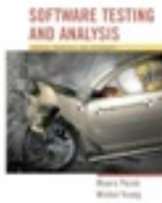


…(ii/iii)…

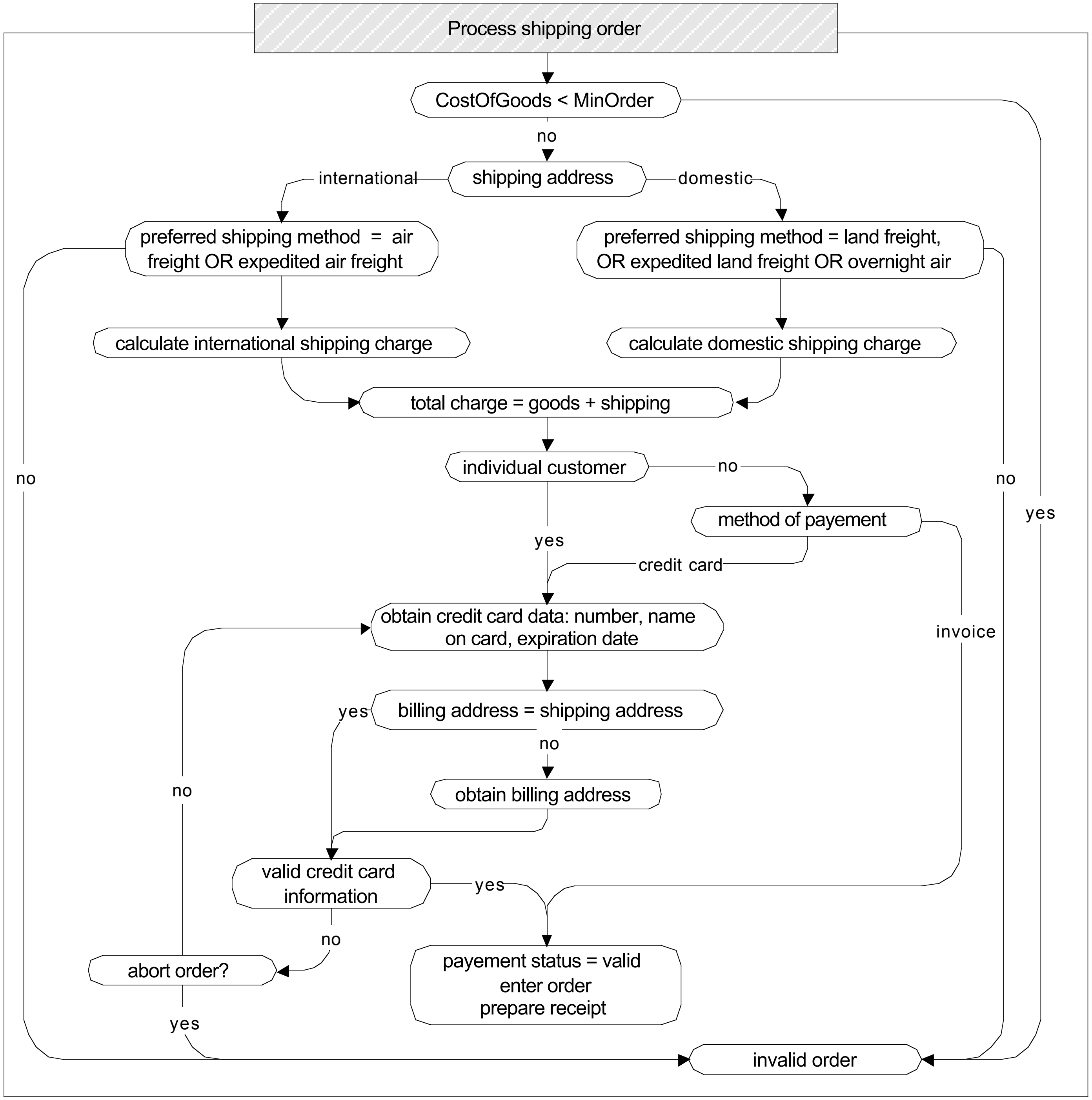
- a shipping cost is computed based on
    - address and shipping method.
    - type of customer which can be individual, business, educational
- preferred method of payment. Individual customers can use only credit cards, business and educational customers can choose between credit card and invoice
- 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

…(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.



…to a flowgraph

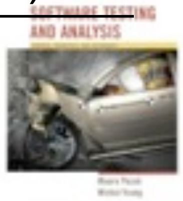


Process shipping order
CostOfGoods < MinOrder
no
yes
shipping address
international
domestic
preferred shipping method = air freight OR expedited air freight
preferred shipping method = land freight, OR expedited land freight OR overnight air
no
no
calculate international shipping charge
calculate domestic shipping charge
total charge = goods + shipping
individual customer
no
method of payement
yes
credit card
invoice
obtain credit card data: number, name on card, expiration date
billing address = shipping address
yes
no
obtain billing address
valid credit card information
yes
no
abort order?
no
yes
payement status = valid
enter order
prepare receipt
invalid order

...from the flow graph to test cases

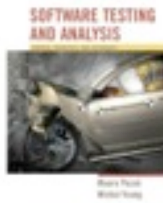
Branch testing: cover all branches

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)



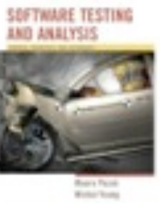
Grammar-based testing

Complex input is (or can) often be described by a context-free grammar



Grammars in specifications

- Grammars are good at:
    - Representing inputs of varying and unbounded size
    - With recursive structure
    - And boundary conditions
- Examples:
    - Complex textual inputs
    - Trees (search trees, parse trees, ...)
        - Note XML and HTML are trees in textual form
    - Program structures
        - Which are also tree structures in textual format!

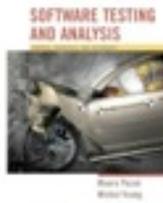


Grammar-based testing

- Test cases are strings *generated* from the grammar
- Coverage criteria:
  - **Production coverage**: each production must be used to generate at least one (section of) test case
  - **Boundary condition**: annotate each recursive production with minimum and maximum number of application, then generate:
    - Minimum
    - Minimum + 1
    - Maximum - 1
    - Maximum

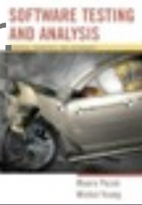
from an informal specification (i/iii)...

- The Check-configuration function checks the validity of a computer configuration.
- The parameters of check-configuration are:
    - Model
    - Set of components



… (ii/iii)…

- **Model**: A model identifies a specific product and determines a set of constraints on available components. Models are characterized by logical slots for components, which may or may not be implemented by physical slots on a bus. Slots may be required or optional. Required slots must be assigned with a suitable component to obtain a legal configuration, while optional slots may be left empty or filled depending on the customers' needs
  - Example: The required ``slots'' of the C20 laptop computer include a screen, a processor, a hard disk, memory, and an operating system. (Of these, only the hard disk and memory are implemented using actual hardware slots on a bus.) The optional slots include external storage devices such as a CD/DVD writer.

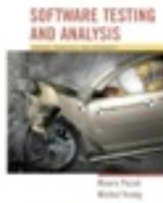


… (iii/iii)

- Set of Components: A set of [slot,component] pairs, which must correspond to the required and optional slots associated with the model. A component is a choice that can be varied within a model, and which is not designed to be replaced by the end user. Available components and a default for each slot is determined by the model. The special value empty is allowed (and may be the default selection) for optional slots. In addition to being compatible or incompatible with a particular model and slot, individual components may be compatible or incompatible with each other.
    - Example: The default configuration of the C20 includes 20 gigabytes of hard disk; 30 and 40 gigabyte disks are also available. (Since the hard disk is a required slot, empty is not an allowed choice.) The default operating system is Ubuntu 12, personal edition, Ubuntu 10 edition may also be selected. The 12 edition requires at least 30 gigabytes of hard disk.

…to a grammar

<Model>	::= <modelNumber> <compSequence> <optCompSequence>
<compSequence>	::= <Component> <compSequence> | empty
<optCompSequence>	::= <OptionalComponent> <optCompSequence> | empty
<Component>	::= <ComponentType> <ComponentValue>
<OptionalComponent>	::= <ComponentType>
<modelNumber>	::= string
<ComponentType>	::= string
<ComponentValue>	::= string



…to a grammar with limits

Model	<Model>	::= <modelNumber> <compSequence> <optCompSequence>
compSeq1 [0, 16]	<compSequence>	::= <Component> <compSequence>
compSeq2	<compSequence>	::= empty
optCompSeq1 [0, 16]	<optCompSequence>	::= <OptionalComponent> <optCompSequence>
optCompSeq2	<optCompSequence>	::= empty
Comp	<Component>	::= <ComponentType> <ComponentValue>
OptComp	<OptionalComponent>	::= <ComponentType>
modNum	<modelNumber>	::= string
CompTyp	<ComponentType>	::= string
CompVal	<ComponentValue>	::= string

…to test cases

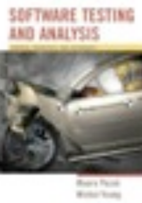
- "Mod000"
  - Covers Model, compSeq1[0], compSeq2, optCompSeq1[0], optCompSeq2, modNum
- "Mod000 (Comp000, Val000) (OptComp000)"
  - Covers Model, compSeq1[1], compSeq2, optCompSeq2[0], optCompSeq2, Comp, OptComp, modNum, CompTyp, CompVal

Boundary condition grammar-based criterion

- compSeq1[0] (0 times)
- compSeq1[1] (1 time)
- compSeq1[15] (n-1 times)
- compSeq1[16] (n times)
- compSeq1[17] (n+1 times)

Grammar vs. Combinatorial Testing

- Combinatorial specification-based testing is good for "mostly independent" parameters
  - We can incorporate a few constraints, but complex constraints are hard to represent and use
  - We must often "factor and flatten"
    - E.g., separate "set of slots" into characteristics "number of slots" and predicates about what is in the slots (all together)
- Grammar describes sequences and nested structure naturally
  - But some relations among different parts may be difficult to describe and exercise systematically, e.g., compatibility of components with slots



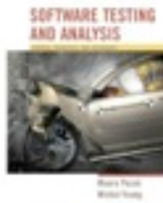
Probabilistic grammar-based criteria

- Assign probabilities to productions, indicating which production to select at each step to generate test cases.
- Probabilities as interpreted as weights that determine how frequent each production is used to generate a test case.

Summary: The big picture

- 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

Model based testing for Object Oriented Software



Characteristics of OO Software

Typical OO software characteristics that impact testing

- State dependent behavior
- Encapsulation
- Inheritance
- Polymorphism and dynamic binding
- Abstract and generic classes
- Exception handling

Intraclass State Machine Testing

- Basic idea:
  - The state of an object is modified by operations
  - Methods can be modeled as state transitions
  - Test cases are sequences of method calls that traverse the state machine model
- State machine model can be derived from specification (functional testing), code (structural testing), or both

Informal state-full specifications

Slot: represents a slot of a computer model.

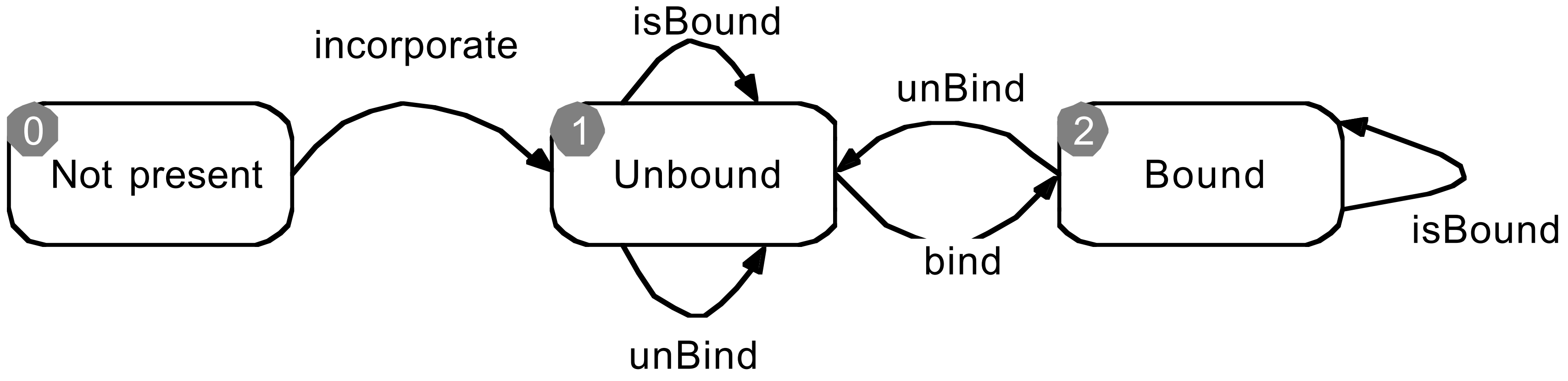
.... slots can be bound or unbound. Bound slots are assigned a compatible component, unbound slots are empty. Class slot offers the following services:

- **Incorporate**: slots can be installed on a model as *required* or *optional*.
  ...
- **Bind**: slots can be bound to a compatible component.
  ...
- **Unbind**: bound slots can be unbound by removing the bound component.
- **IsBound**: returns the current binding, if bound; otherwise returns the special value *empty*.

Identifying states and transitions

- From the informal specification we can identify three states:
  - Not_present
  - Unbound
  - Bound
- and four transitions
  - incorporate: from Not_present to Unbound
  - bind: from Unbound to Bound
  - unbind: ...to Unbound
  - isBound: does not change state

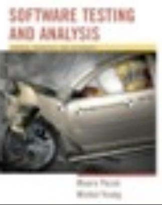
Deriving an FSM and test cases



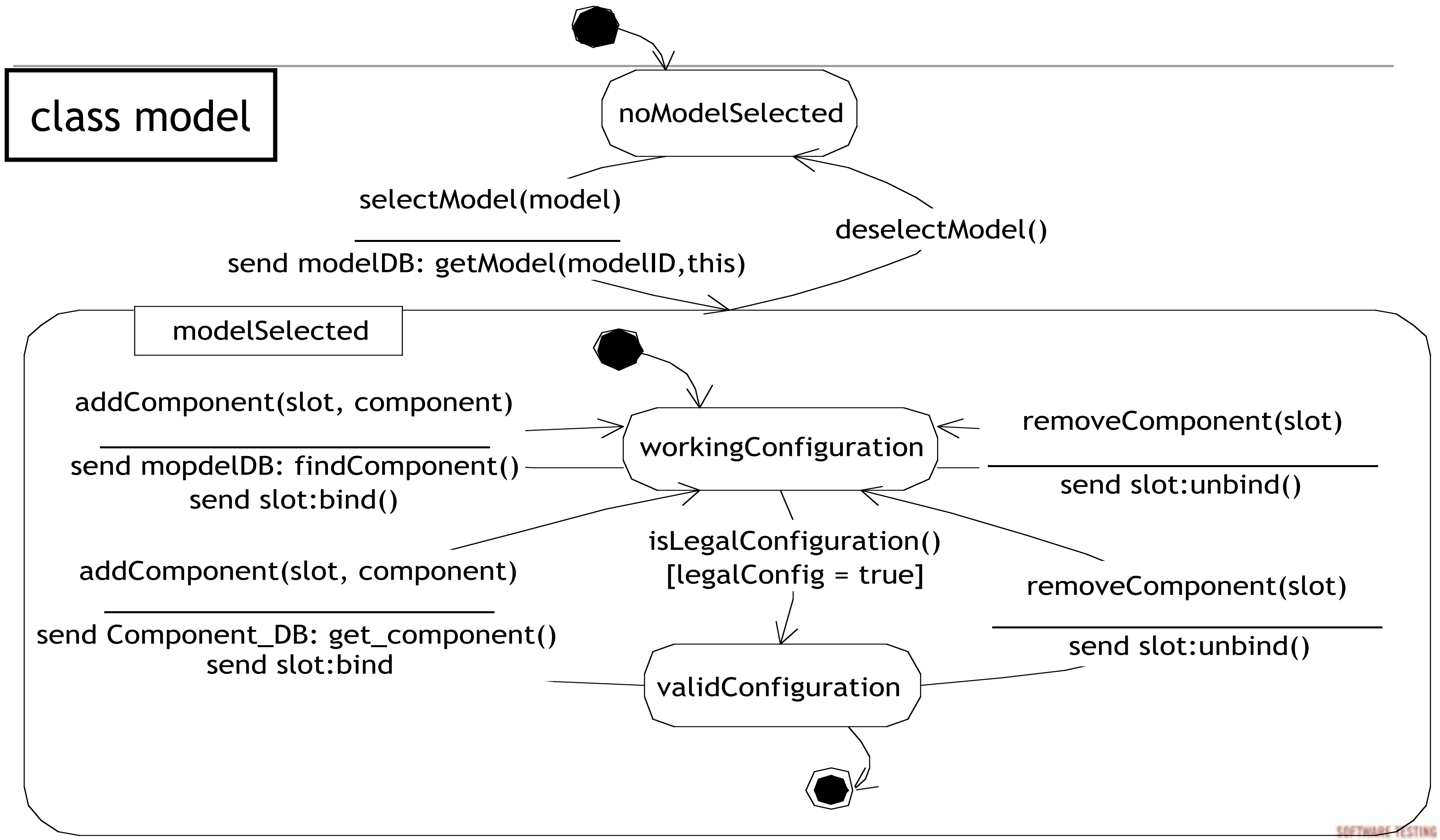
- TC-1: incorporate, isBound, bind, isBound
- TC-2: incorporate, unBind, bind, unBind, isBound

Testing with State Diagrams

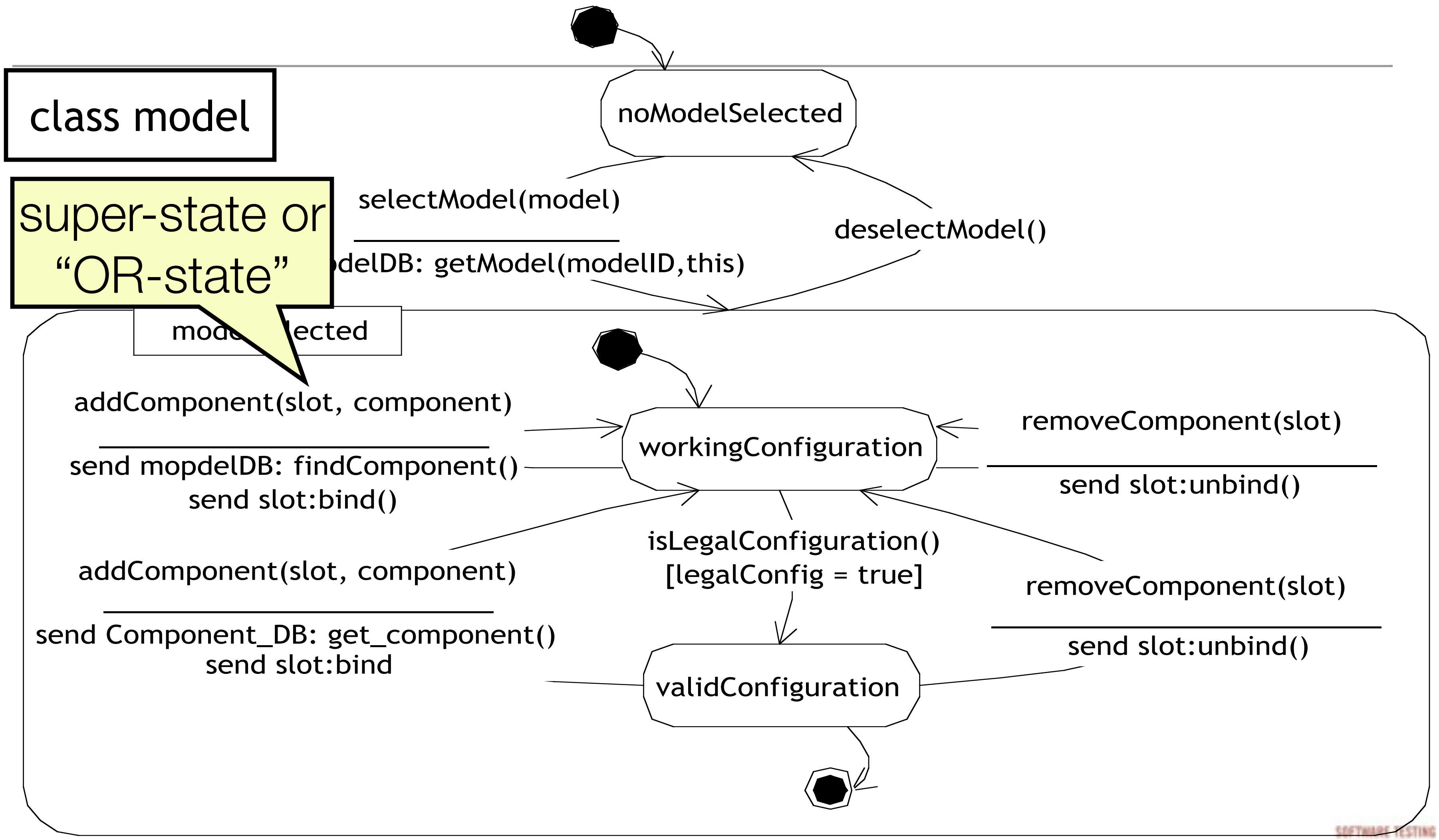
- A statechart (called a “state diagram” in UML) may be produced as part of a specification or design
    - May also be implied by a set of message sequence charts (interaction diagrams), or other modeling formalisms
- Two options:
    - Convert (“flatten”) into standard finite-state machine, then derive test cases
    - Use state diagram model directly

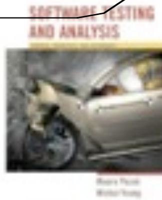


Statecharts specification

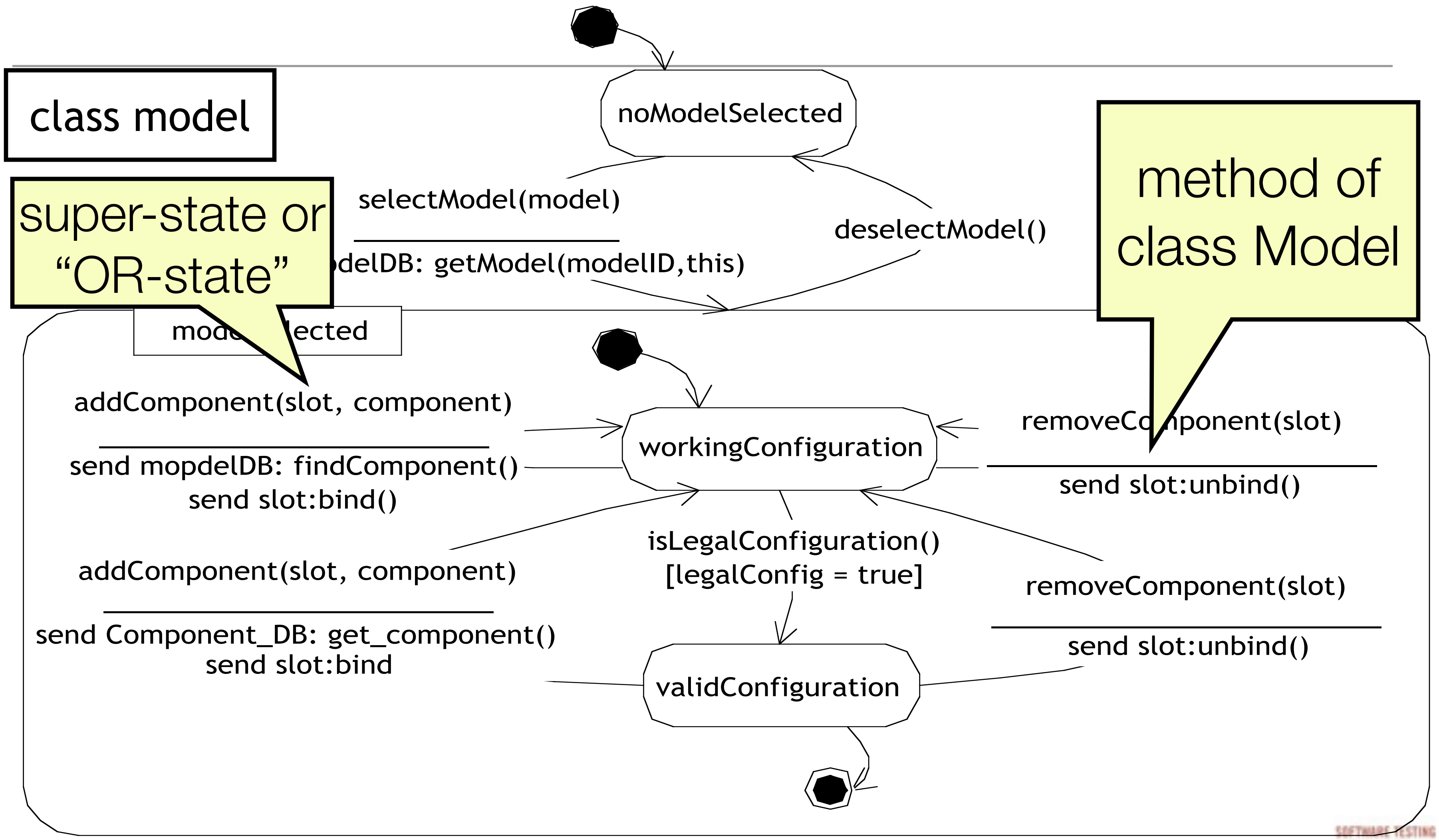


Statecharts specification

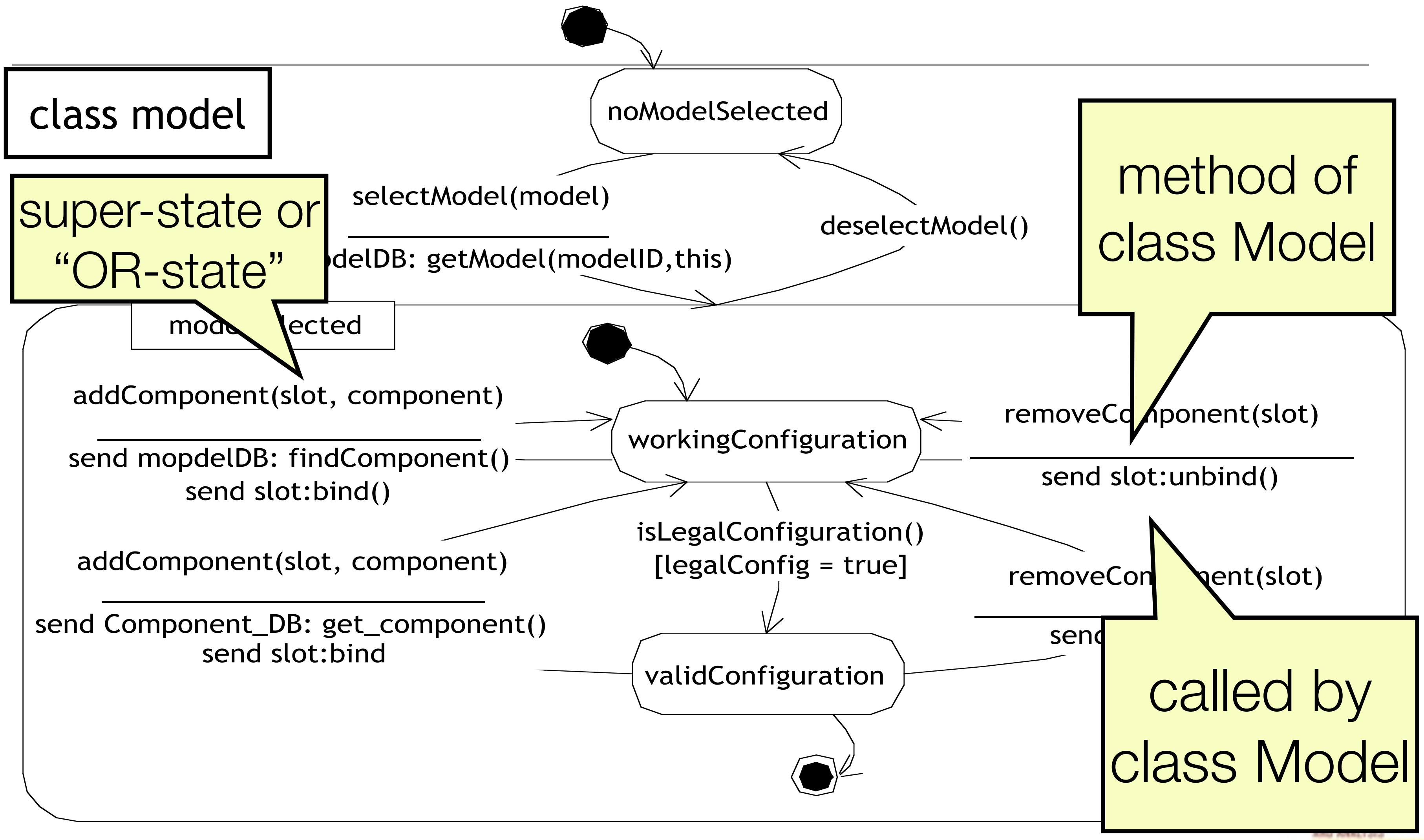




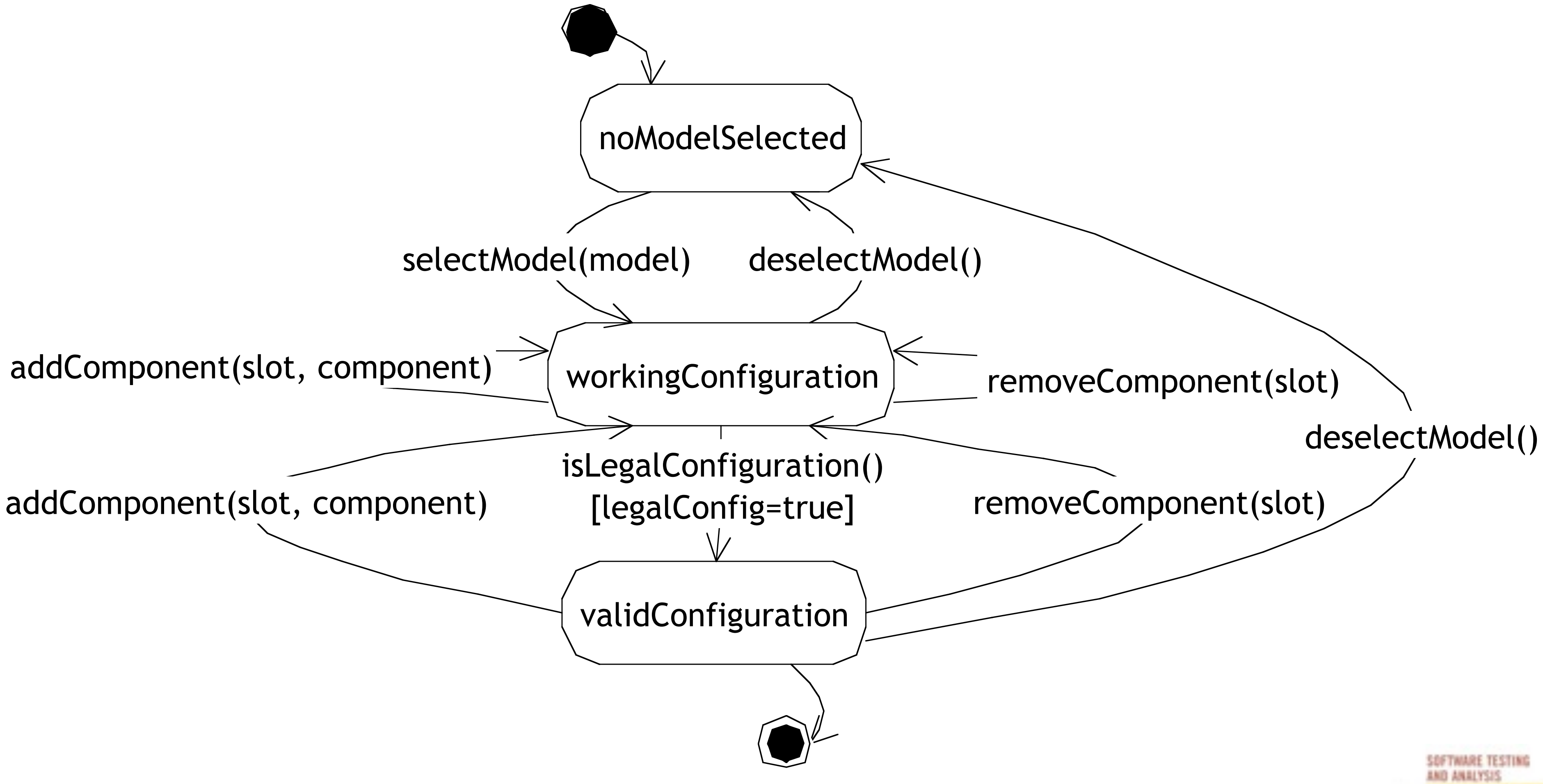
Statecharts specification

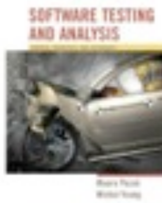


Statecharts specification



From Statecharts to FSMs





Statechart based criteria

- In some cases, “flattening” a Statechart to a finite-state machine may cause “state explosion”
    - Particularly for super-states with “history”
- Alternative: Use the statechart directly
- Simple transition coverage:
  execute all transitions of the original Statechart
    - incomplete transition coverage of corresponding FSM
    - useful for complex statecharts and strong time constraints (combinatorial number of transitions)