Temporal Properties for Testing

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Master 2 Informatique

UE Spécification et Vérification Automatique de Modèles

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Syllabus

Goal of this lecture:

- Provide an overview of how to use temporal properties in a software validation process involving models.

At the end of this lecture, you will be able:

- to explain the possible usages of temporal properties in the software validation process
- to express properties using temporal patterns
- to translate temporal pattern properties into automata
- to implement monitors that detect the violation of a property or evaluate its coverage

Prerequisites

You should already be able to:

- write a temporal property using LTL (using appropriate symbols)
- transform an LTL property into a Büchi automaton
- explain how to model-check a temporal property
- give an example of an indecidable problem ☺

- explain what is all of this used for...

Agenda

1. Dwyer's temporal property patterns
2. Principles of Model-Based Testing
3. Use of properties for testing
4. Your assignment for the next two weeks

Agenda

1. Dwyer's temporal property patterns
   - what is it?
   - how does it work?
   - examples
2. Principles of Model-Based Testing
3. Use of properties for testing
4. Your assignment for the next two weeks

Temporal Property Patterns - what is it?

- 20 years ago, Matt Dwyer, Georges Avrurnin and James Corbett defined a set of temporal patterns, aiming to simplify the writing of temporal properties [DAC99].

- Property = Pattern + Scope
  - Pattern: describes occurrences or orderings of events
  - Scope: describes the observation window on which the pattern is supposed to hold

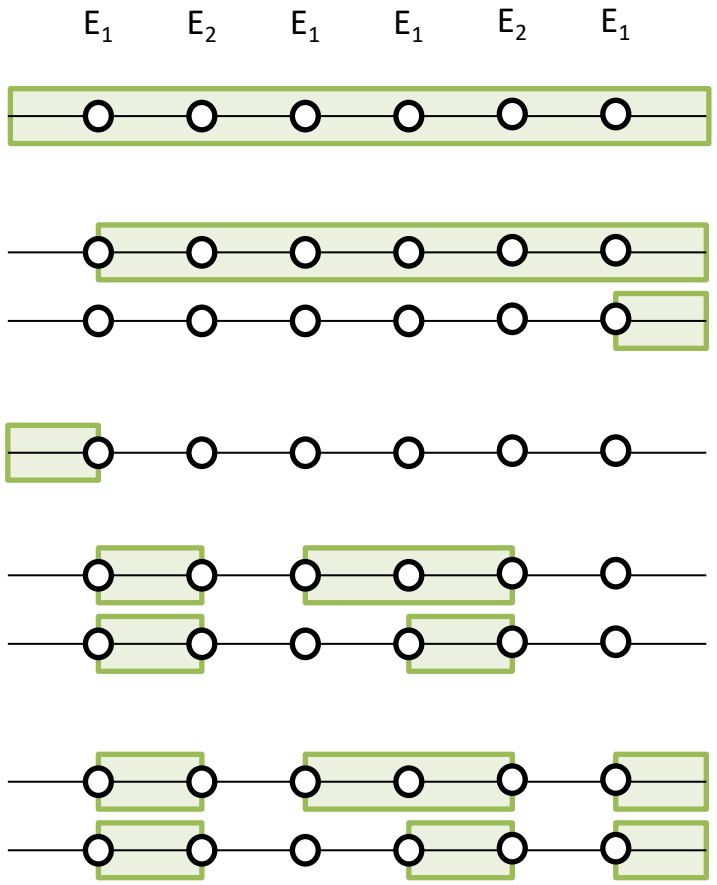
- 5 scopes + 8 patterns → 88% of temporal properties in various case studies.

- Easier to understand and practice by industrials…

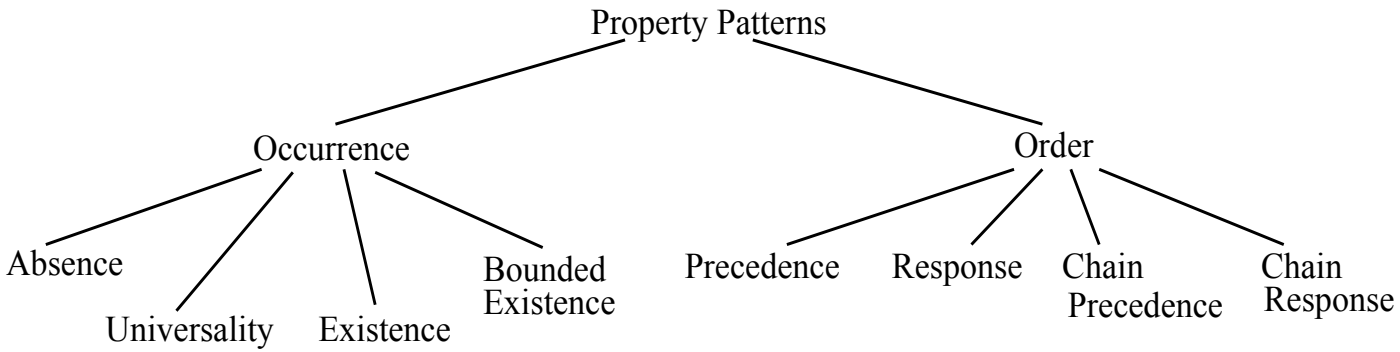
[DAC99] **Patterns in Property Specifications for Finite-state Verification**, *Matthew B. Dwyer, George S. Avrunin and James C. Corbett*. Proceedings of the 21st International Conference on Software Engineering, May, 1999.

Temporal Property Patterns - Scope

- globally
- after E_1
  - after last E_1
- before E_1
- between E_1 and E_2
  - between last E_1 and E_2
- after E_1 until E_2
  - after last E_1 until E_2



Temporal Property Patterns - Patterns



Usually defined using keywords

- always P
- never E
- eventually E at least/at most/exactly k times
- E_1 [directly] precedes E_2
- E_1 [directly] follows E_2

Temporal Property Patterns - Events

Events: left unspecified in the original paper

- Basic idea: what ever you want/can observe
- Can be (a combination of):
  - operation invocation (name, possibly with parameters and return values)
  - guard/precondition
  - postcondition
- At least you can use “keywords” representing abstract actions

Temporal Property Patterns - Examples

Requirement: « In order to buy tickets, I need to be authenticated. »

- Property 1

  never BUY_TICKET_OK
  before LOGIN_OK

- Property 2

  never BUY_TICKEY_OK
  after LOGOUT_OK
  until LOGIN_OK

- Property 3

  eventually BUY_TICKET_OK at least 0 times
  between LOGIN_OK
  and LOGOUT_OK

Syntax makes temporal pattern look like they're easy. However, usage needs some serious thinking... Nevertheless, it is still easier than using LTL or CTL... No?

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Model-Based Testing – what is it?

Model-Based Testing (MBT) aims to automate conformance testing by using a formal model of the system which:

- → describes the inputs and/or
- → characterizes the outputs

Unlike other approaches (e.g. white-box testing using code coverage criteria), it especially targets (business) logics faults in the application.

- ➔ 15% of total faults in an application[1]

And sometimes, it is the only applicable technique…

- No access to the code,
- Other V&V tools/approaches can not be applied

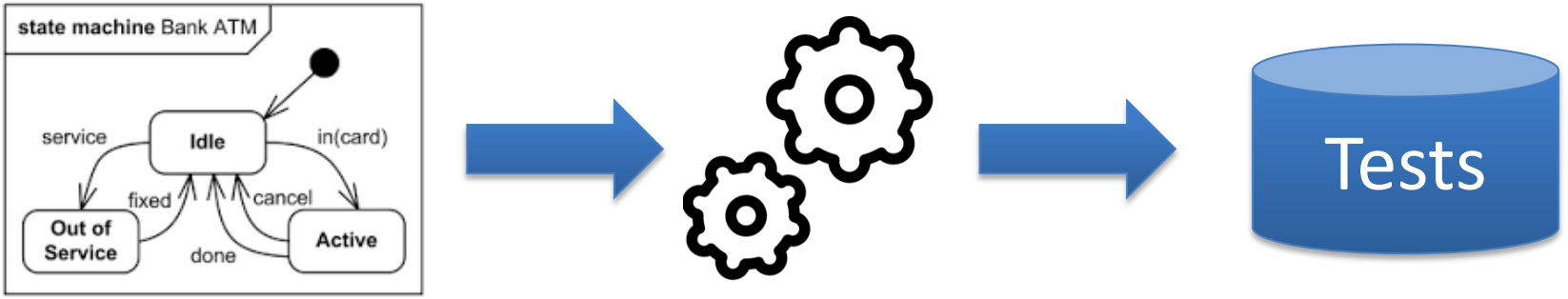
[1]Source: H. Hemmati. *How effective are code coverage criteria?* Int. Conf. on Quality Reliability and Security, 2015

Model-Based Testing – what is it?

```
/**
 * @requires s != null;
 * {|
 *    @requires (\exists int i; 0 <= i < s.length(); s.charAt(i) == c);
 *    @ensures \result >= 0 && \result < s.length() &&
 *      (\forall int i; 0 <= i < s.length(); s.chatAt(i) == c ==> \result <= i);
 *  also
 *    @requires (\forall int i; 0 <= i < s.length(); s.charAt(i) != c);
 *    @ensures \result < 0;
 * |}
 */
int findIndex(char c, String s) {
   int r = -42;
   for (int i=0; i <= s.length(); i++) {
      if (s.charAt(i) == c) {
         r = i;
      }
   }
   return r;
}
```

Is there any fault in this Java function?

Model-Based Testing – what is it?

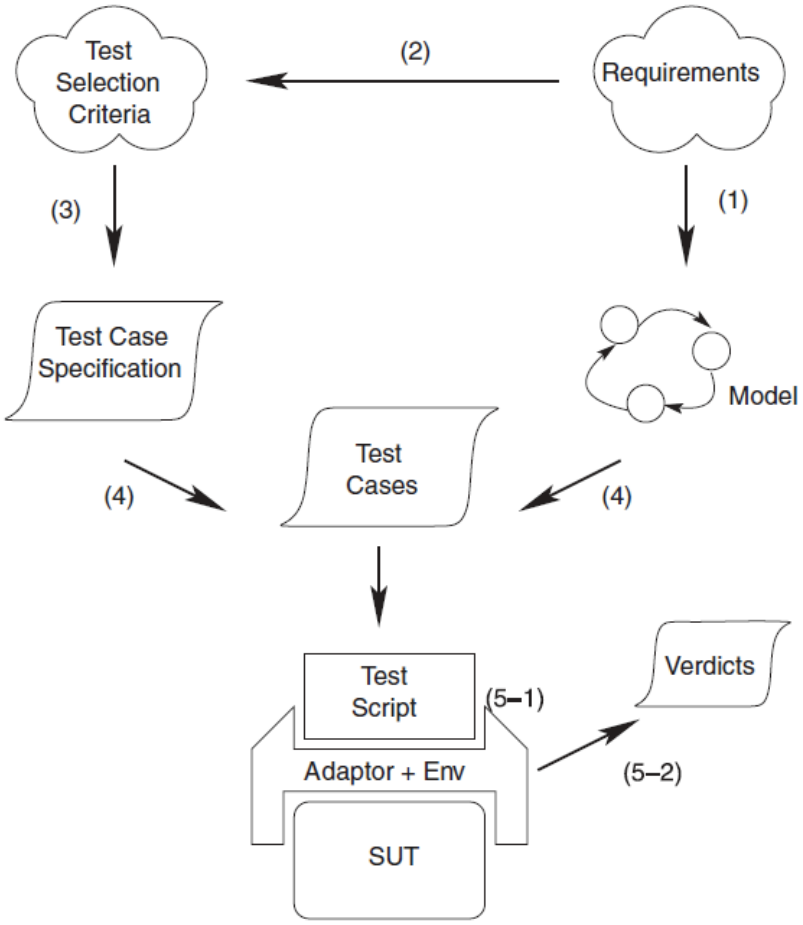


Model-Based Testing: testing based on or involving models

Test case: *A set of input values, execution preconditions, expected results and execution postconditions, developed for a particular objective or test condition, such as to exercise a particular program path or to verify compliance with a specific requirement.*

ISTQB Glossary 2015 – International Software Testing Qualifications Board - http://www.istqb.org – MBT extension

Model-Based Testing – what is it?



(1) Model design

(2) Choice of the appropriate test selection criteria

(3) Transformation of TS criteria into an « operational form » (algorithms)

(4) Test cases generation

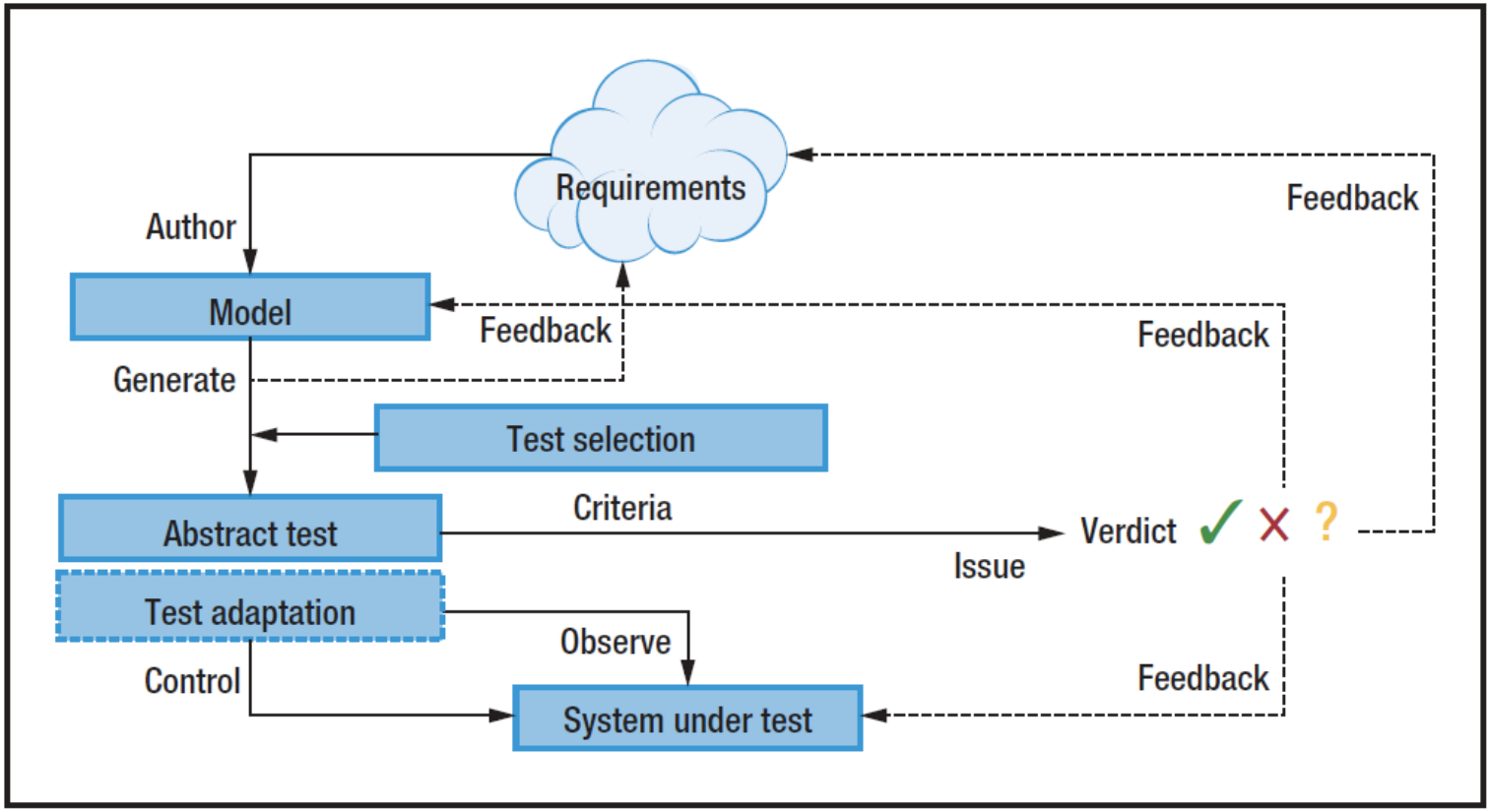
(5) Test execution

(5-1) Concretization of test cases

(5-2) Establishment of the test verdict

Source: M. Utting, A. Pretschner, B. Legeard
Taxonomy of MBT approaches. STVR, 22-5, 2012

Model-Based Testing – what is it?



Source: Methods for Testing & Specification (MTS); Model-Based Testing (MBT); Requirements for Modelling Notations, ES 202 951 v.1.1.1 European Telecommunications Standards Institute, 2011

Model-Based Testing – what is it?

In MBT approaches, models are used to:

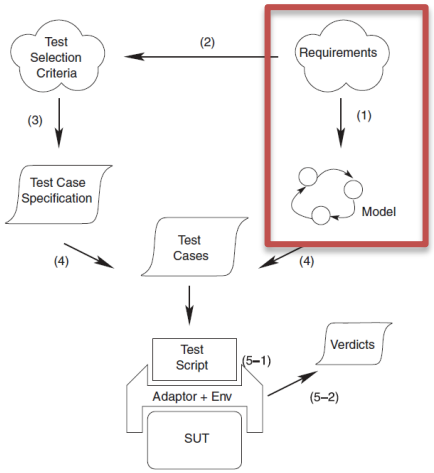
- compute test cases: test data and/or operation sequences
- predict the test oracle, and thus establish the test verdict

→ automate test generation & execution

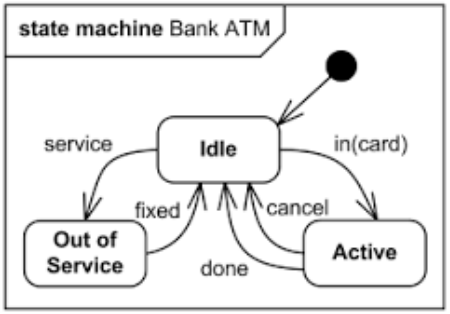
Scientific challenges:

- how to model the SUT?
- how to exploit the model to derive the tests?
- how to bridge the gap between the (abstract) model and the (concrete) SUT?
- how to establish the conformance between the model and the SUT?

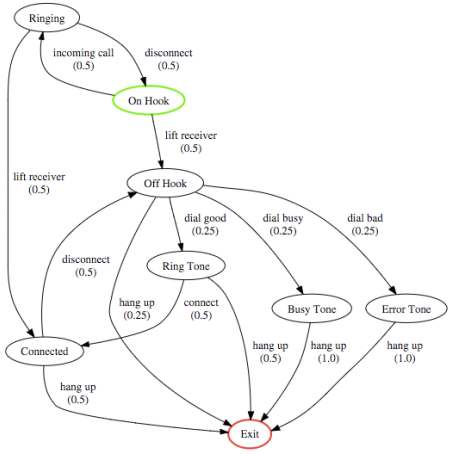
MBT challenges – Model Design



- Transition-based notations: (Extended-)Finite State Machines, Mealy Machines, statecharts, (Input-Output) Labelled Transitions Systems
- Pre-Post or Input Domains (a.k.a. State-based) notations: B (generalized substitutions), Z, JML (contracts), OCL (pre/post), SpecExplorer
- Operational notation: process algebra such as CSP, VHDL, Petri Nets, HLPSL
- Stochastic notation: markov chains



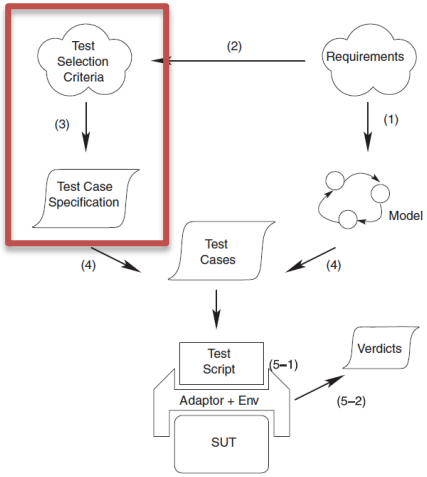

```
if (p_Code=CODE::FAUX)then
    ---@REQ:COUNTER_DECREASED
    carte.nbEssaisCode = carte.nbEssaisCode-1 and
    afficherMessage(MESSAGE::CODE_ERRONE) and
    if (carte.nbEssaisCode <= 0) then
        ---@REQ:CARD_BLOCKED
        afficherMessage(MESSAGE::CARTE_BLOQUEE) and
        restituerCarte()
    else
        ---@REQ:CARD_NOT_BLOCKED
        afficherMessage(MESSAGE::ENTRER_CODE)
    endif
else
    ---@REQ:OK
    statut = STATUTDAB::ATTENTE_SAISIE_MONTANT and
```




```
role alice(
  A,B     : agent,
  K       : symmetric_key,
  Hash    : hash_func,
  SND,RCV : channel(dy))
played_by A def=

  local
    State   : nat,
    Na,Nb   : text,
    K1      : message

  init
    State := 0

  transition

  1. State  = 0 /\ RCV(start) =|>
     State':= 2 /\ Na' := new()
                /\ SND({Na'}_K)

  2. State  = 2 /\ RCV({Nb'}_K) =|>
     State':= 4 /\ K1' := Hash(Na.Nb')
                /\ SND({Nb'}_K1')
                /\ witness(A,B,bob_alice_nb,Nb')

end role
```

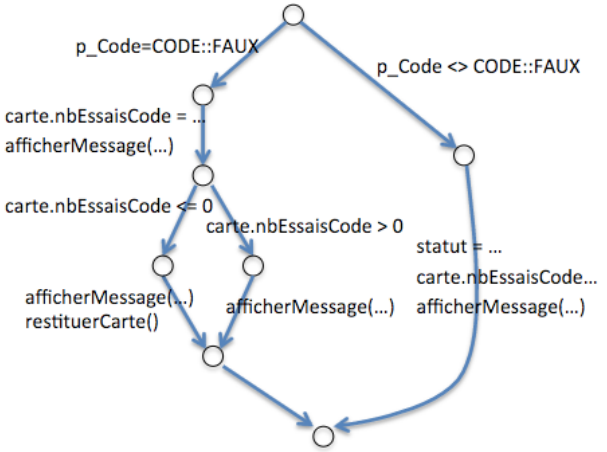
```
role bob (A,B: agent,
          Ka: public_key,
          Kb: public_key,
          Snd,Rcv: channel(dy))
played_by B
def=

  local State   : nat,
        Na,Nb : text
  const sec_k2 : protocol_id
  init  State := 0

  transition
   1. State = 0 /\ Rcv({Na'.A}_Kb)
      =|>
      State' := 1
      /\ Nb' := new()
      /\ Snd({Na'.Nb'}_Ka)
      /\ witness(B,A,nb,Nb')
      /\ secret(Nb',sec_k2,{A,B})
   2. State = 1 /\ Rcv({Nb}_Kb)
      =|>
      State' := 2
      /\ request(A,B,na,Na)
end role
```

MBT challenges – Model exploitation



Test generation criteria:

- structural coverage: nodes, arcs, etc.
- data coverage: boundary values, pairwise, etc.
- requirement coverage
- test case specification: test purpose, scenario
- stochastic coverage: usage model
- fault-based




```
1if (p_Code=CODE::FAUX)then
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4    afficherMessage(MESSAGE::CODE_ERRONE) and
5    if (carte.nbEssaisCode <= 0) then
6        ---@REQ:CARD_BLOCKED
7        afficherMessage(MESSAGE::CARTE_BLOQUEE) and
8        restituerCarte()
9    else
0        ---@REQ:CARD_NOT_BLOCKED
1        afficherMessage(MESSAGE::ENTRER_CODE)
2    endif
3else
4    ---@REQ:OK
5    statut = STATUTDAB::ATTENTE_SAISIE_MONTANT and
```
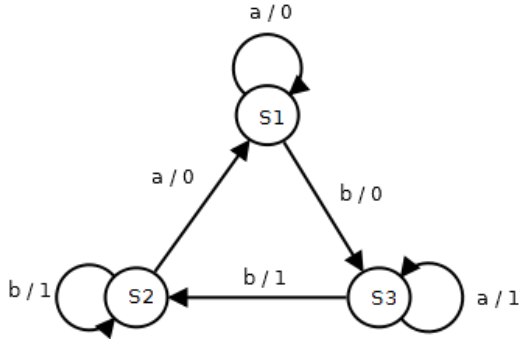

Test generation technologies :

- model-checking
- theorem proving
- symbolic execution
- random
- machine learning/AI



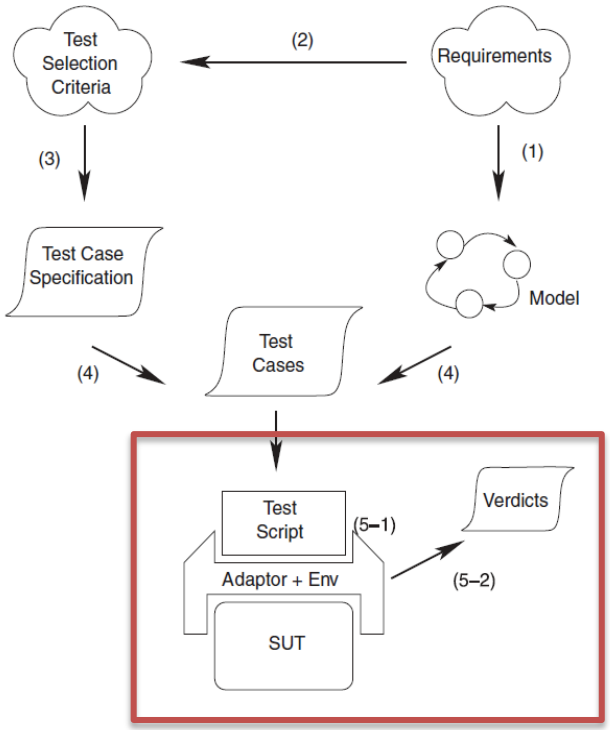
MBT challenges – Establishing conformance (oracle problem)

More or less intrusive techniques:

- analyze execution traces (logs)
- assertions in the tests cases (on public/observable data/artifacts) on expected results
- instrumentation of the code, notably with runtime assertion checking (e.g. JML-RAC)

Conformance relationships:

- simulation, bi-simulation (trace equivalence), ioco (trace inclusion), etc.



MBT challenges - Conformance relationship

Reasonable compromise: **ioco** defined on IOLTS

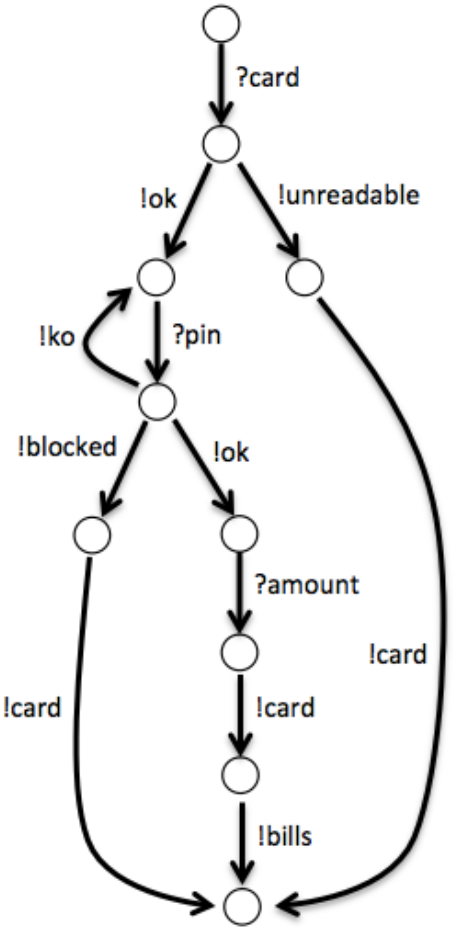
IOLTS = < Q, A, →, q0 >

- Q = set of states
- A = $A_i \cup A_o \cup \{\tau\}$ with
  - A_i = input actions (prefixed by ?)
  - A_o = output actions (prefixed by !)
  - τ = internal action
- → ⊆ Q × A × Q
- q0 = initial state

δ : quiescence (observation of no output) : deadlock/livelock

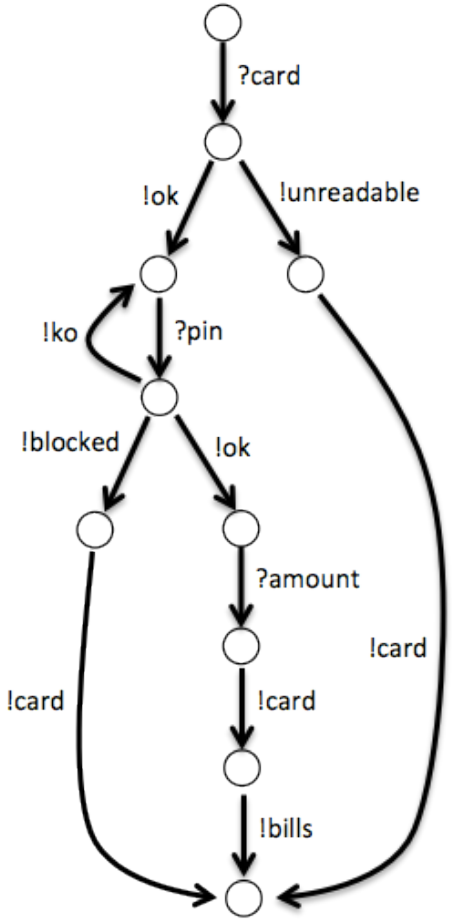
IUT ioco S: ∀σ : Straces(S) : out(IUT after σ) ⊆ out(S after σ)

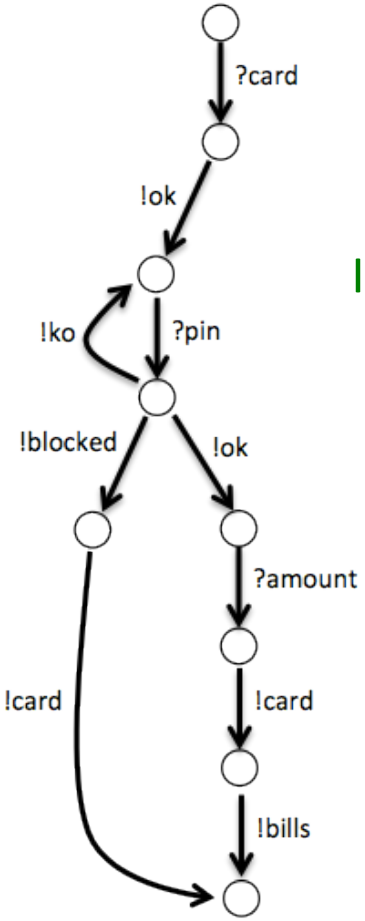
After each suspended trace (ie. an execution up to a quiescence), IUT exhibits only outputs and quiescences present in S.



- J Tretmans. *Test generation with inputs, outputs and repetitive quiescence.* Software---Concepts and Tools, 1996

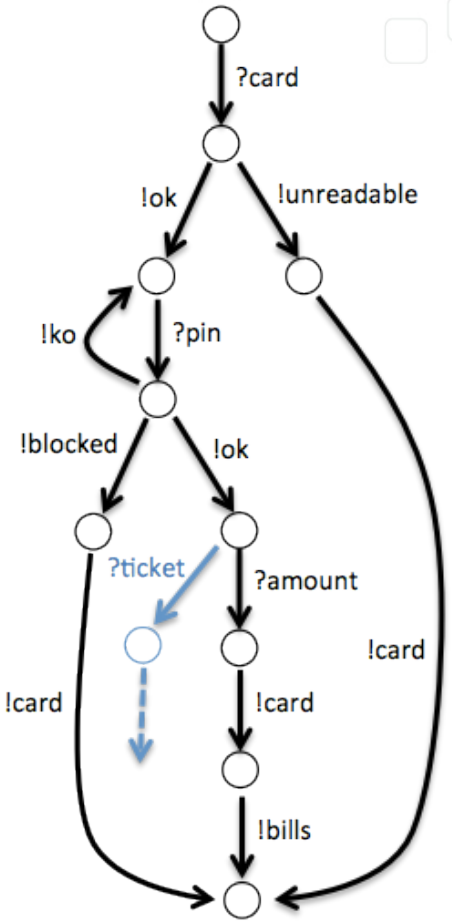
MBT challenges - Conformance relationship





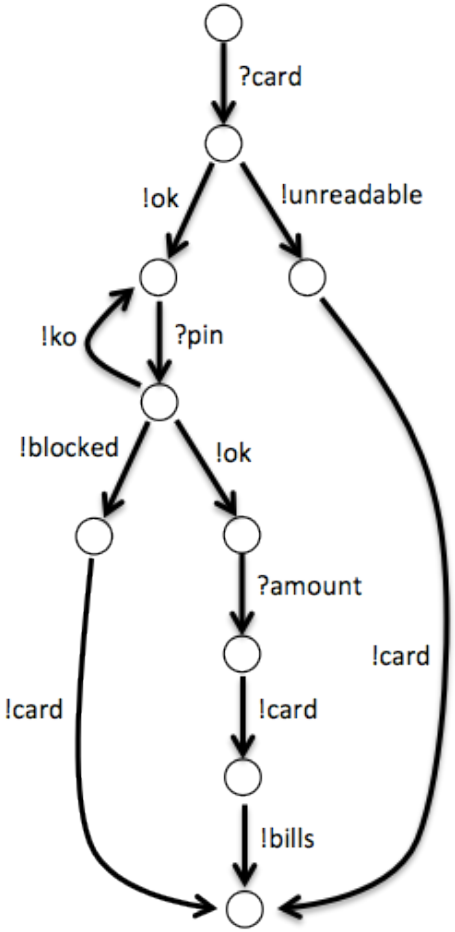
Implementation choice

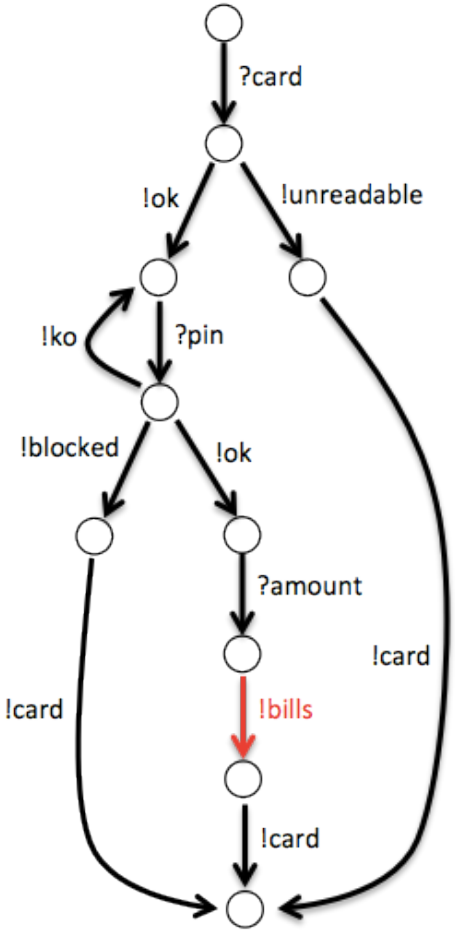
IOCO



Implementation of partial specification

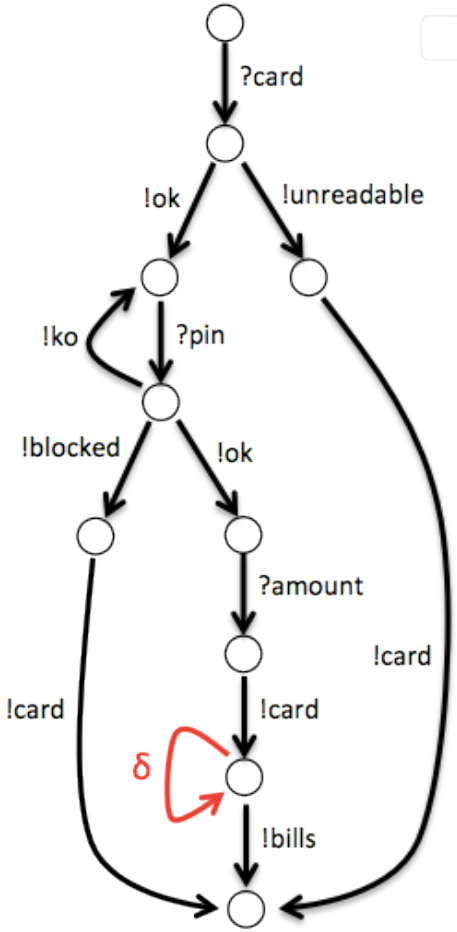
MBT challenges - Conformance relationship





Unexpected output

~~IOCO~~



Unexpected quiescence

Summary on Model-Based Testing

The fine art of modelling for testing…

Models are strongly related to the test objectives!

MBT **test models** should be:

- abstract:
  - to cover what is intended to be tested
- detailed and precise enough:
  - to compute the expected result (oracle) → test verdict assignment
- validated and verified[1]:
  - if the test « fails » what is wrong? the model or the SUT?
    (keep in mind that MBT is « back-to-back testing » - MBT model vs. SUT)

…a difficult trade-off!

[1]a must-read: M.-C. Gaudel. *Checking models, proving programs, testing systems*. Tests & Proofs'2011. LNCS.

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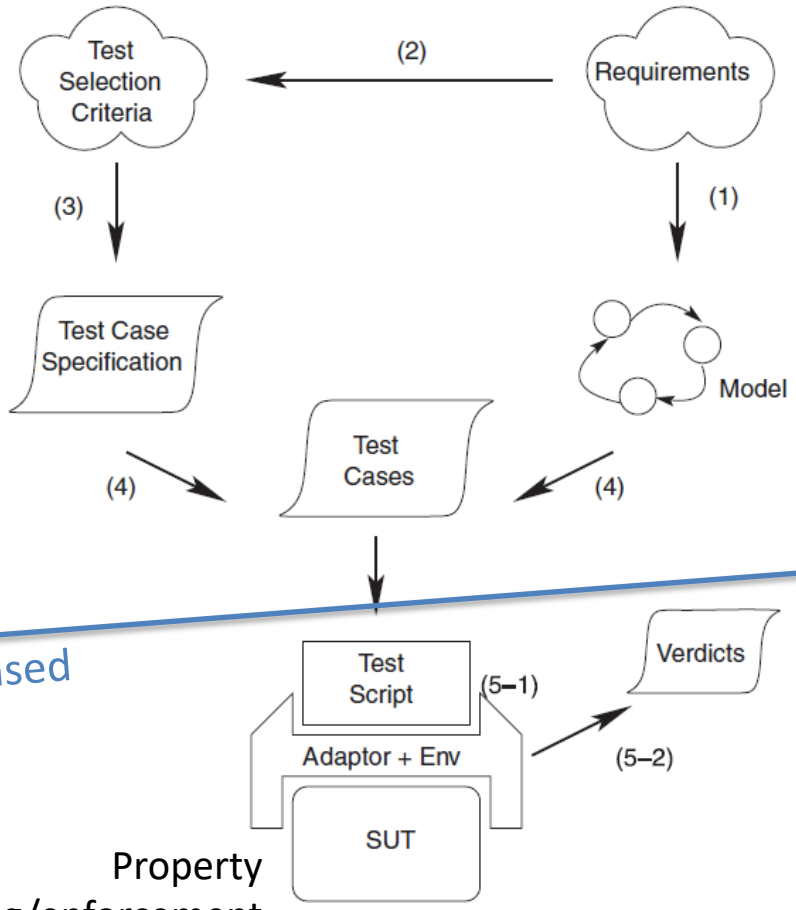
Property-based testing – where?

Property coverage (automaton)

Express a temporal (dynamic) requirement

Exploit property to drive the test gen. process

Verification & validation of the model



Model-based

Not necessarily model-based

Detect property violation → test failure

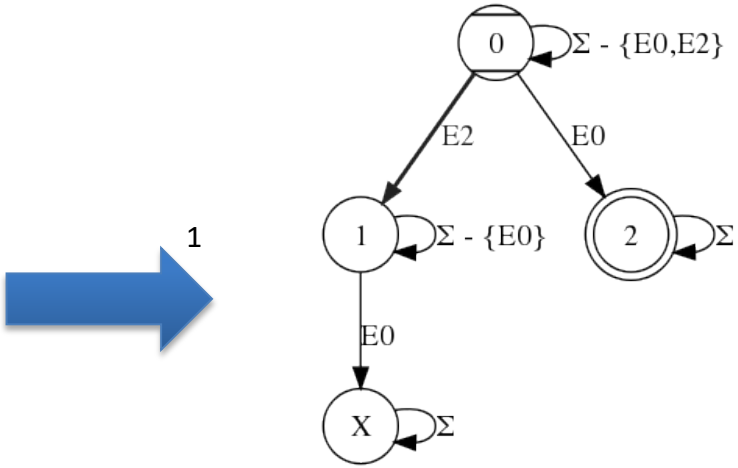
Property monitoring/enforcement

Property-based testing – How-to

Properties have to be written in a format that allows processing:

- measuring property coverage
- guide the test generation process
- monitoring the property to detect violation
- enforcing its satisfation

never BUY_TICKET_OK
before LOGIN_OK



[1]

Property automata have to be complete and (preferably) deterministic.

[1]Kalou Cabrera Castillos. **Génération automatique de tests à partir de propriétés temporelles et de modèles comportementaux.** Thèse de doctorat. Novembre 2013.

Property-based testing – Use of automata

Monitoring of the property on the model/system :

- composition of the model/system and the property automata
  - if both are expressed as automata
  - rarely the case in practice
- exploration of the property automaton
  - in parallel while the model/system is running, or
  - after the execution, on recorded logs/traces

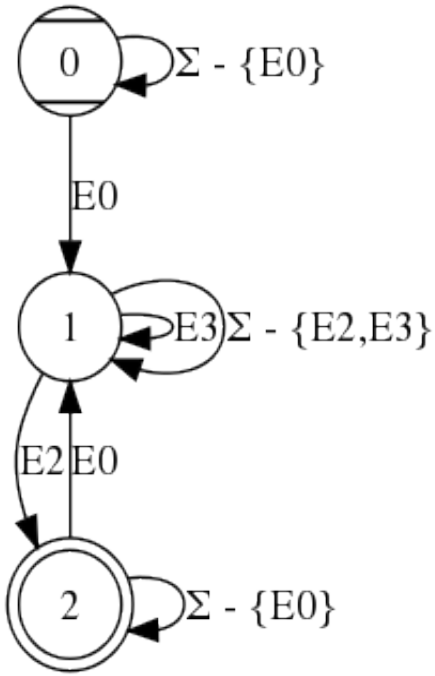
Monitoring vs. enforcing:

- monitoring consists in observing the execution of the system/model and reporting the violations of the property
- enforcing consists in preventing the violation of the property to happen (and also report violation attempts)

PBT – K. Cabrera PhD Thesis

- Existing automata coverage criteria are not appropriate

➔ all transitions are considered equally!



E0 = LOGIN_OK

E2 = LOGOUT_OK

E3 = BUY_TICKET_OK

Need to distinguish two different kinds of transition

⇒ α-transitions, labelled by events expressed in the property

⇒ Σ-transitions, the others

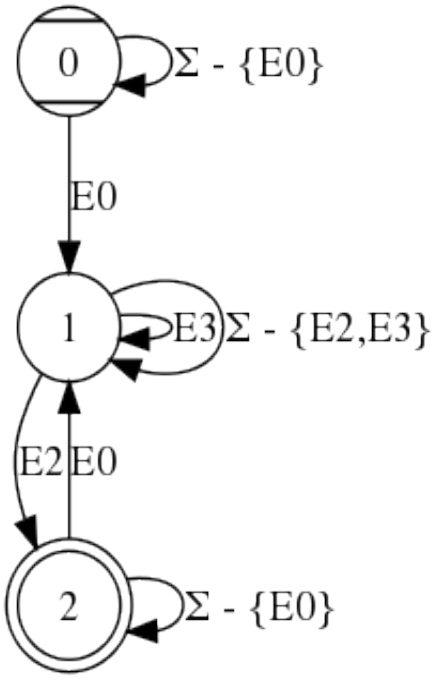
Also, the origin of all the transitions (scope/pattern) is known.

PBT – K. Cabrera PhD Thesis

- New coverage criteria for the property automata
  - alpha-transition coverage: coverage of the transitions labelled by events expressed in the property

Transitions to cover:

(0, E0, 1)
(1, E3, 1)
(1, E2, 2)
(2, E0, 1)



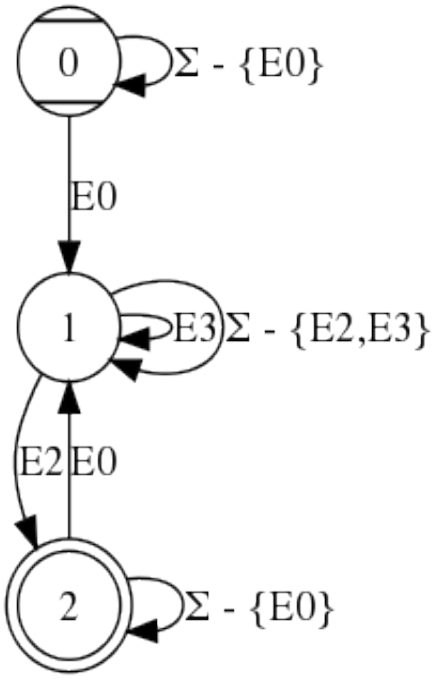
PBT – K. Cabrera PhD Thesis

- New coverage criteria for the property automata
  - alpha-transition-pairs coverage: coverage of the pairs of transitions labelled by events expressed in the property

Pairs of transitions to cover:

< (0, E0, 1) ; (1, E3, 1) >
< (1, E3, 1) ; (1, E2, 2) >
< (1, E2, 2) ; (2, E0, 1) >
< (2, E0, 1) ; (1, E3, 1) >
< (2, E0, 1) ; (1, E2, 2) >

Important: strict successions of α-transitions are not required (intermediate Σ-transitions are allowed)



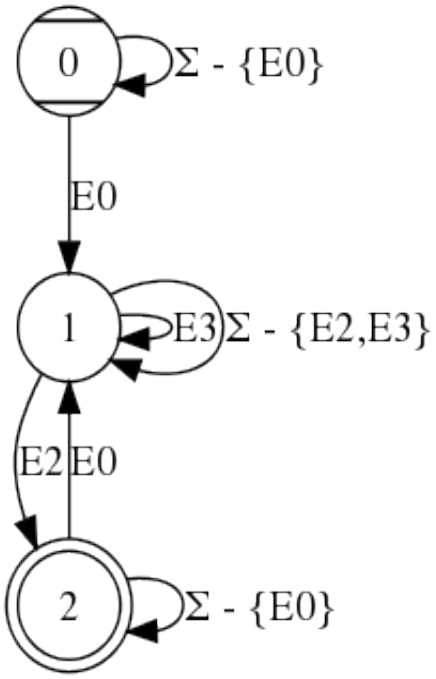
PBT – K. Cabrera PhD Thesis

- New coverage criteria for the property automata
  - k-pattern coverage: coverage of the iterations of the pattern

All pattern-loops have to iterated between 0 and k times.

Applicable to « repeatable » patterns:

- precedes
- follows
- eventually at least n times (if n >= k)



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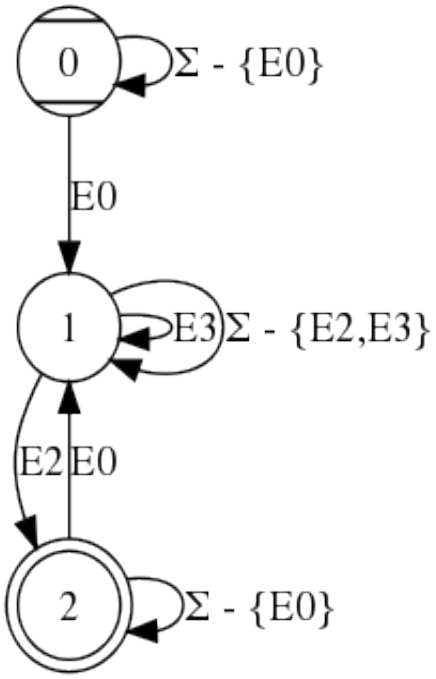
- New coverage criteria for the property automata
  - k-scope coverage: coverage of the iterations of the scope

All scope-loops have to iterated between 1 and k times.

Applicable to « repeatable » scopes:

- between
- after… until…



Notice: interesting paths end on a final state of the automaton

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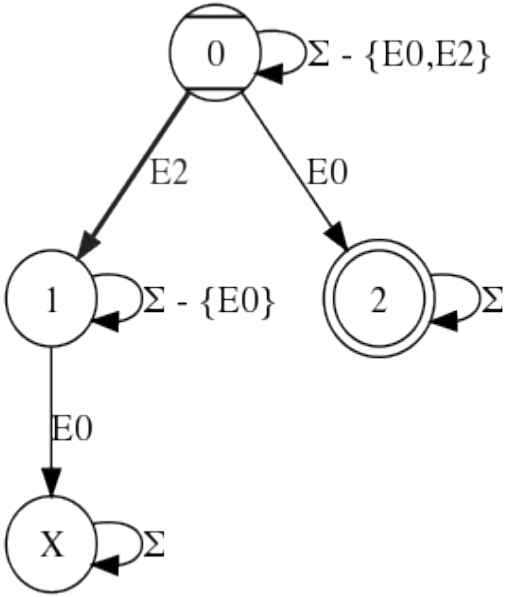
Case of transitions leading to the error state



never BUY_TICKET_OK
before LOGIN_OK

Can not be activated if we assume that the model satisfies the property (which is supposed to be the case)

New coverage criteria are inefficient…

➔ Specific criterion to test the robustness of the system w.r.t. the property

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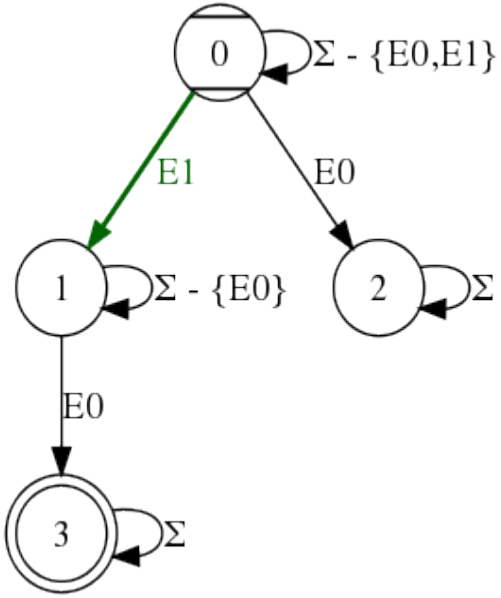
Coverage criterion: robustness



Modification of the automaton:
- the error state becomes the final state
- the event labelling the faulty transition is mutated/weakened to be made activable

Possible mutations:
- deletion/negation of predicates (pre/post)
- deletion/change of activated behavior

E1: BUY_TICKET_OK ➔ BUY_TICKET

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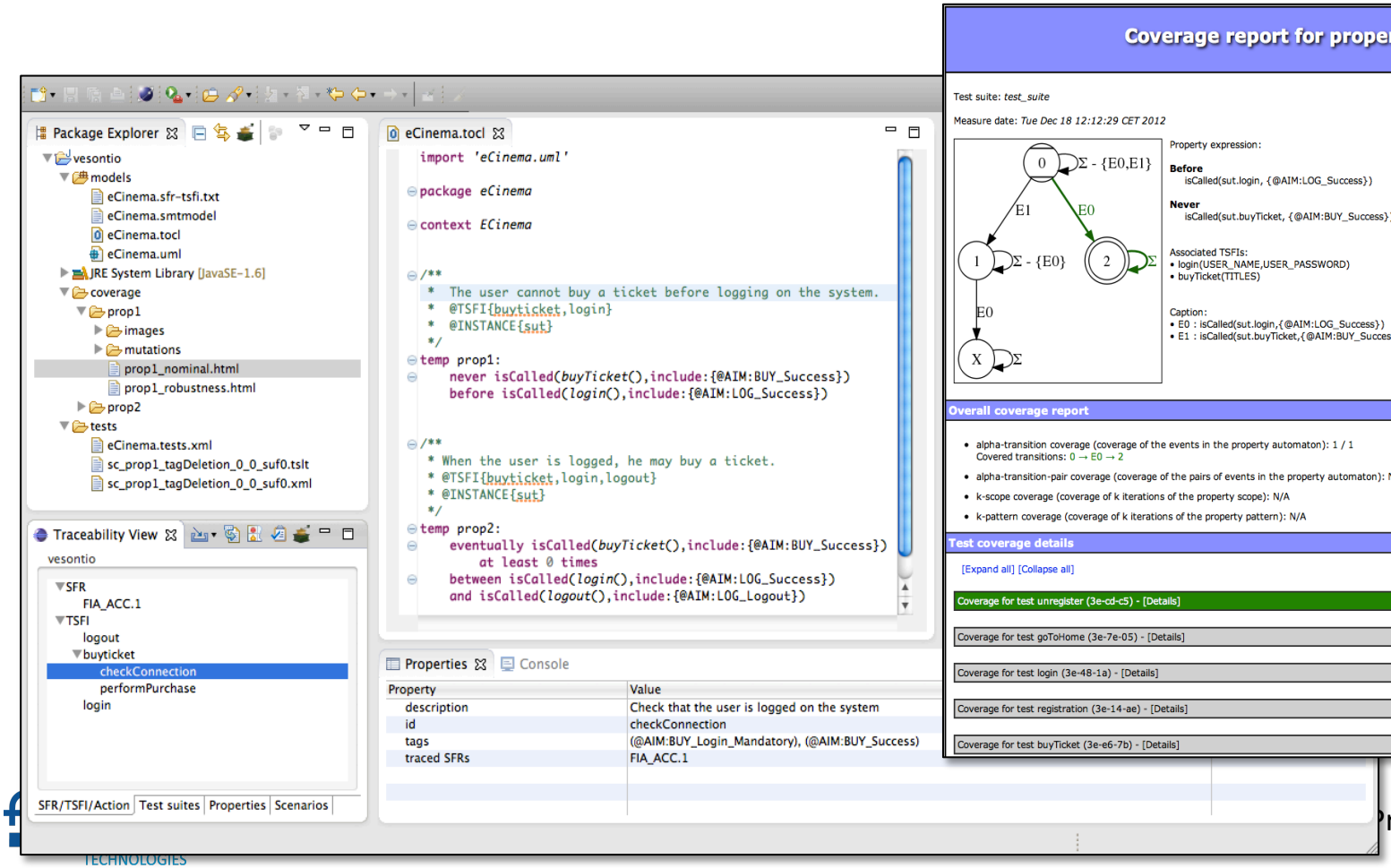
- Development of an Eclipse plug-in to support the approach



Agenda

1. Dwyer's temporal property patterns
2. Principles of Model-Based Testing
3. Use of properties for testing
1. Your assignment for the next two weeks
   - tutorial: write a model of an example application + property patterns
   - practical sessions: implement a monitor for property patterns, use it for model testing and model-based testing

Your assignment for the next two weeks – case study

Automated Teller Machine (ATM) - withdraw cash with a credit card

- System Under Test (SUT) = cash machine
- Test data = credit cards with associated bank accounts
- Control points = reader, pad (0-9 + cancel, delete, validate)
  → abstracted into « actions » (insert card, type PIN, etc.)
- Observation points = messages on the screen, card/bills ejected

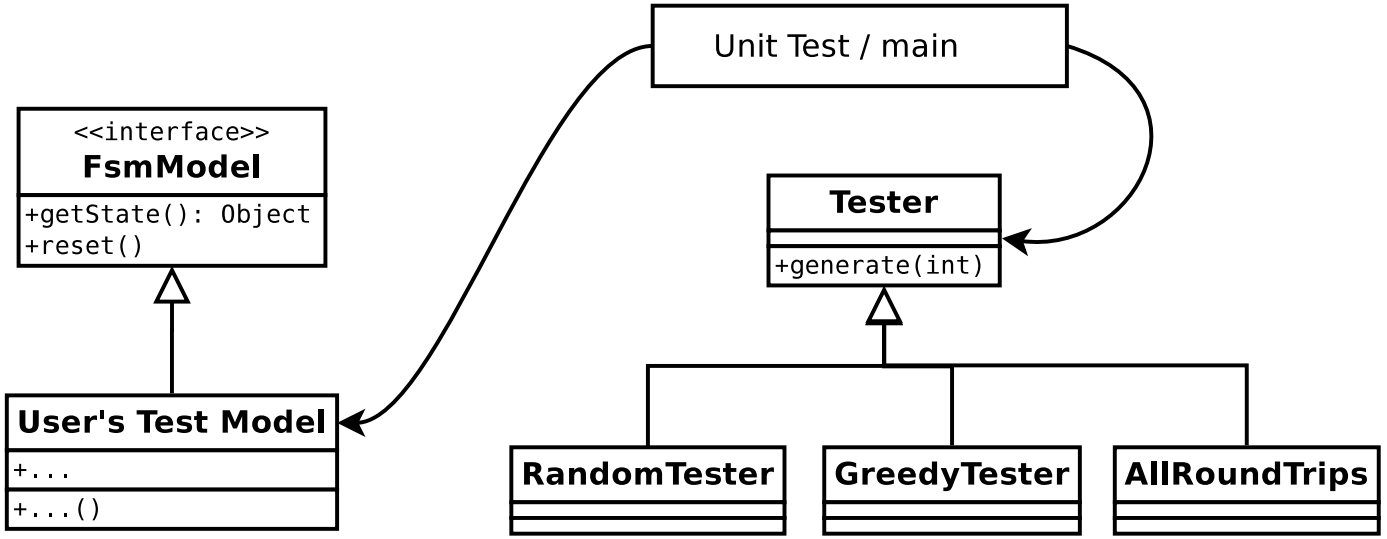
- Behaviours = « usual » behaviour of an ATM (functional testing)

A specification of the ATM will be given, along with Java binaries of the application.

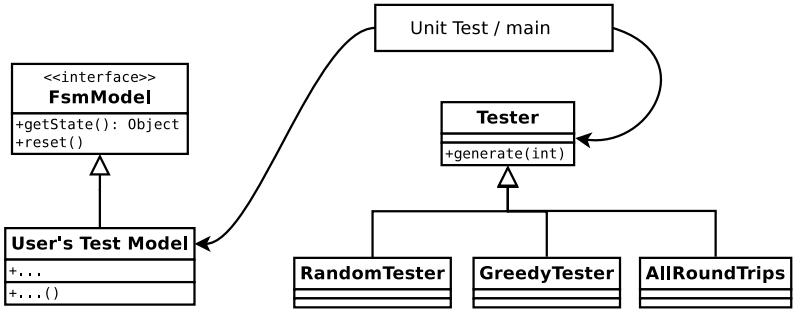
Your assignment for the next two weeks – supporting tools

Use of ModelJUnit - https://sourceforge.net/projects/modeljunit/

Library to perform model-based tests, by defining a Java class of a user model.



Your assignment for the next two weeks – supporting tools



Abstract !

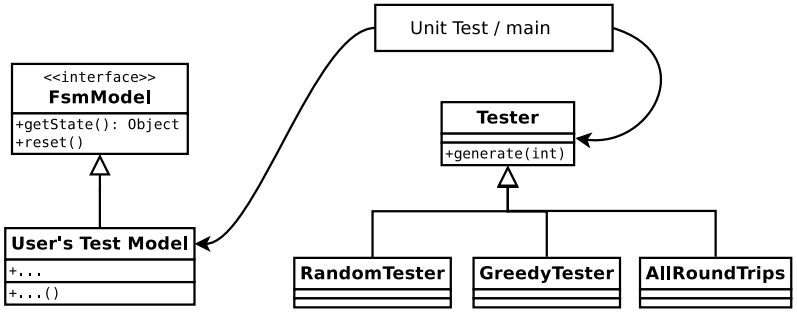
Write a model as a Java class that implements the two methods:

- getState() : Object → a method used to identify the current state of the FSM
- reset() → a method that (re-)initializes the automaton's variables (if any)

and, of course,

- additional methods that represent the transitions of the automaton, which have to be annotated by @Action (used by the tool to identify the FSM's transitions)
- possibly supporting methods if necessary

Your assignment for the next two weeks – supporting tools



It is possible to ask the tool to compute test cases and measure the states/transitions of the FSM covered by the tests

Apply the testers:

- RandomTester: tests a system by making random walks through the EFSM model.
- GreedyTester: improves the RandomTester by prioritizing, during the exploration, the transitions that have not been considered before
- AllRoundTrips: GreedyTester that stops after having visited N (parameter) times a state

Don’t worry: a code skeleton will be provided next week.

Finally, it is possible to link the test generator to the system under test → online testing

Your assignment for the next two weeks

What is expected of you today:

- work in groups of 3, with collaborative design/development tools

1. write a (Extended) Finite State Machine of the case study
2. write a set of temporal properties to express the requirements using temporal patterns (max. 3 properties/group – each group gets different properties)
3. translate these properties into their corresponding automata

For the next week (next Wednesday):

- develop or get a small automata library in Java (manage states, transitions, explore)

Your assignment for the next two weeks

What will be expected of you next week:

- use a simple Model-Based Testing tool (ModelJUnit)
  - implement your FSM (realized last week) in the tool
  - generate tests
  - execute tests on the implementation
- monitor the properties on the model by running the automaton in parallel and measure the property automata coverage
- monitor the properties on the implementation (e.g. using a proxy design pattern)

→ To be returned by the end of January.

Your assignment for the next two weeks

Summary: you have to test this ATM application regarding these properties

- formalize the properties
- generate and run tests and measure the coverage of the property (you are not expected to write a dedicated test generation algorithm – use the existing ones)
- make sure that your properties have been correctly formalized by monitoring their satisfaction at the model level.
- Produce some Java code and a small report that provides the considered properties and their expression as an automaton

Before we start...

Questions?