Model-based Mutation Testing

The Science of Killing Bugs in a Black Box

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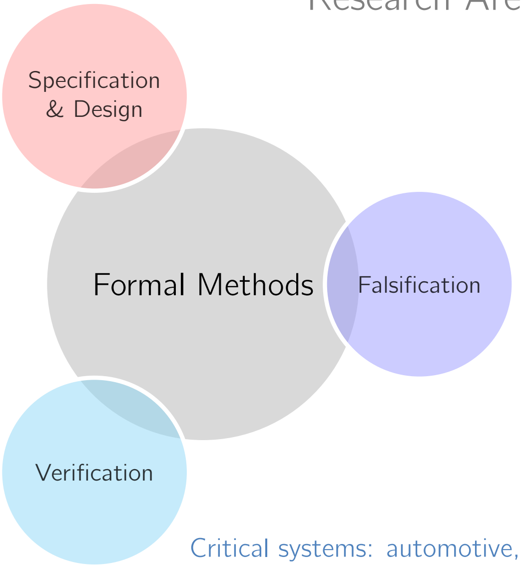
Halmstad University, 11 June 2018

Research Areas



- Precise abstraction
- Refinement
- Compositionality

- Model-based testing
- Model learning

- Proof-based development
- Statistical model checking

Critical systems: automotive, railways, IoT

FM Group Characteristics

- Size: key researcher + 3 research assistants (PhDs)
- EU projects: 4 in last 10 years
- LEAD project: Dependable Things
- Funding: EUR 192K per year (3 years avg.)
- Expertise: falsification + verification + languages
- Domains: automotive, railways, Internet of Things

DEPENDABLE INTERNET OF THINGS

TruConf

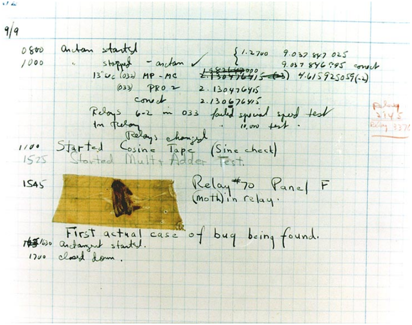
Agenda

- Mutation Testing
- Model-based Testing
- Model-based Mutation Testing
- Transformational Systems
  - Semantics
  - Test Case Generation
- Reactive Systems
  - Semantics
  - Test Case Generation
- Model- and Test-Driven Development
- MoMuT Tools
- Tool Demo and Examples

Bugs?

Part of engineering jargon for many decades:

- Moth trapped in relay of Mark II (Hopper 1946)
- Little faults and difficulties (Edison 1878):
- Software bugs



Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.

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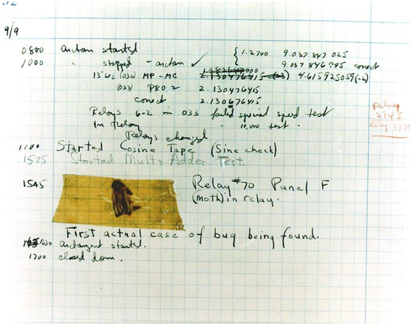

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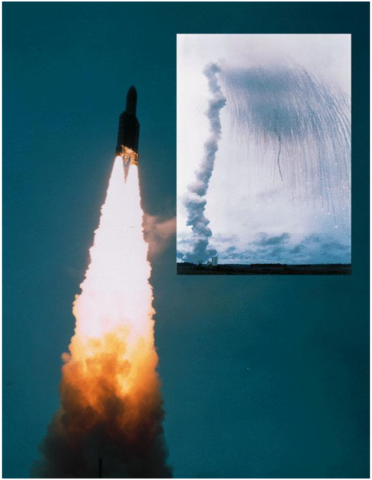
Definition

A software bug is the common term used to describe an

- error, flaw, mistake, failure, or fault in a computer program or system
- that produces an incorrect or unexpected result,
- or causes it to behave in unintended ways. (Wikipedia 2012)

Some Bugs Become Famous!

- Ariane 5 test flight (1996)
  - out of control due to software failure
  - controlled destruction!
- Loss of
  - money and time
  - satellites
  - research (TU Graz)
- Dijkstra (EWD 1036):
  - call it error, not bug
  - a programmer created it



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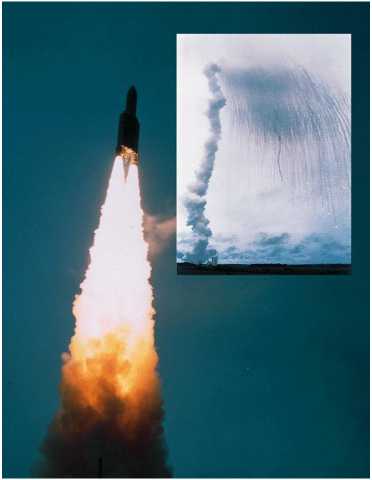

Some Bugs Hide for a Long Time!

Binary search bug in Java

- JDK 1.5 library (2006)
- out of boundary access of large arrays
- due to integer overflow
- 9 years undetected

```java
public static
int binarySearch(int[] a,int key)
{
  int low = 0;
  int high = a.length - 1;

  while (low <= high) {
    int mid = (low + high) / 2;
    int midVal = a[mid];

    if (midVal < key)
      low = mid + 1;
    else if (midVal > key)
      high = mid - 1;
    else
      return mid; // key found
  }
  return -(low + 1); // key not found
}
```

"Beware of bugs in the above code;
I have only proved it correct, not tried it."
[Knuth77]

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Observations

- Verification failed (wrong assumption)
- Established testing strategies failed:
  - statement coverage
  - branch coverage fails
  - multiple condition coverage
  - MC/DC: standard in avionics [DO-178B/ED109]
- Long array needed: `int[] a = new int[Integer.MAX_VALUE/2+2]`

Lesson

- Concentrate on possible faults, not on structure.
- Generate test cases covering these faults
- Mutation Testing [Lipton71, Hamlet77, DeMillo et al.78]

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What Is Mutation Testing?

Originally: Technique to verify the quality of test cases

"There is a pressing need to address the, currently unresolved, problem of test case generation." [Jia&Harman11]

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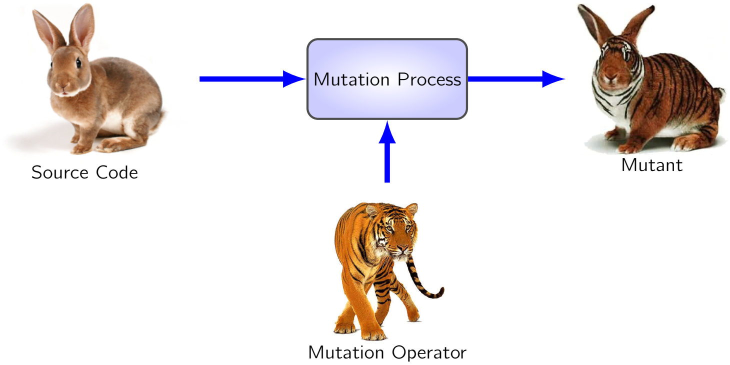
How Does It Work?

Step 1: Create mutants



Example: Transformational System

- Kind of triangles:
  - equilateral
  - isosceles
  - scalene
- Create mutants
  - mutation operator
    == ⇒ >=
  - creates 5 mutants

```scala
object triangle {

 def tritype(a : Int, b : Int, c: Int) =
  (a,b,c) match {
  case _ if (a <= c-b) => "no triangle"
  case _ if (a <= b-c) => "no triangle"
  case _ if (b <= a-c) => "no triangle"
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                          "equilateral"
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  case _  =>              "scalene"
  }
}
```

Source code in Scala

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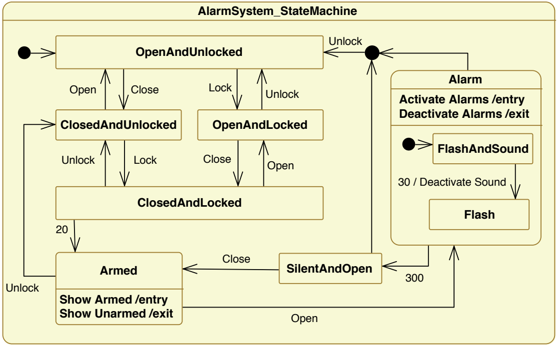
Mutant

Example: Reactive System

- Car Alarm System
  - event-based
  - controllable events
  - observable events
- Mutate the model
  - mutation operator
  - → ⇒ ↻
  - 17 mutants



State machine model in UML

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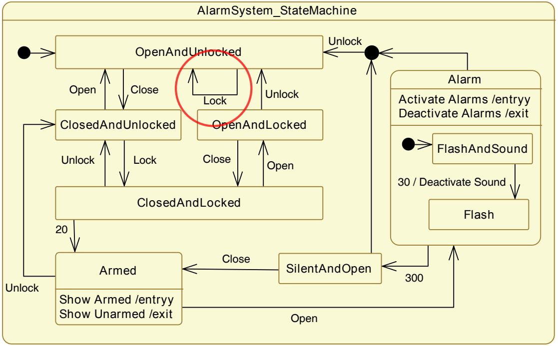

Mutated UML model

How Does It Work?

Step 2: Try to kill mutants

A test case kills a mutant if its run shows different behaviour.

Example: Transformational System

- Mutant survives path coverage (MC/DC):
  tritype(0,1,1)
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  tritype(1,1,0)
  tritype(1,1,1)
  tritype(2,3,3)
  tritype(3,2,3)
  tritype(3,3,2)
  tritype(2,3,4)
- Mutant killed by
  tritype(3,2,2)

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object triangle {

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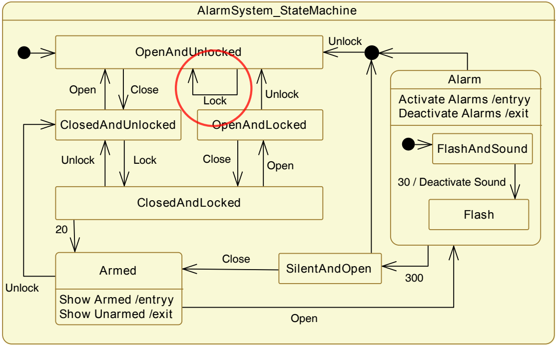
Mutant

Example: Reactive System

- Mutant survives
  - function coverage
  - state coverage
  - transition coverage
- Killed by
  Lock();
  Close();
  After(20);



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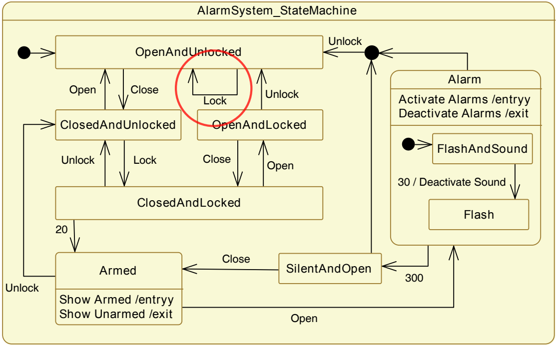
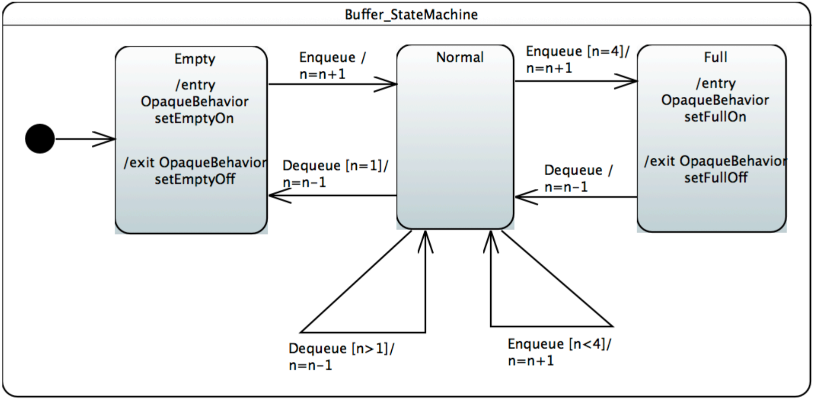


Mutated UML model

Fault-Propagation in Models

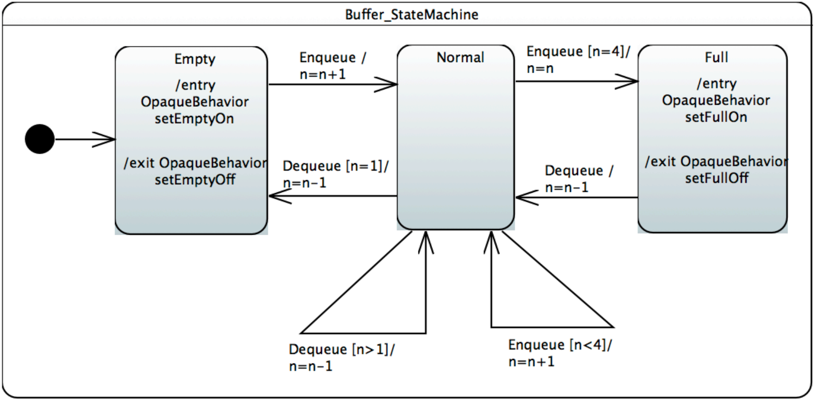
Abstract 5-place buffer model:



Counter variable n is internal!

Fault-Propagation in Models

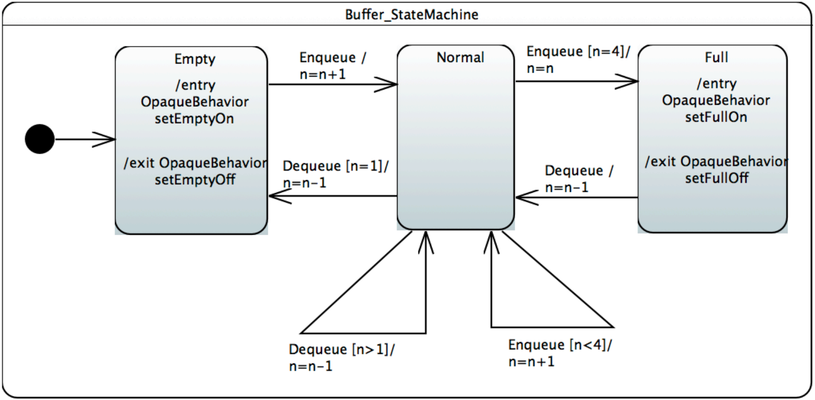
Let's inject a fault:



How does this fault propagate?

A Good Test Case

... triggers this fault and propagates it to a (visible) failure:



⟨!setEmptyOn, ?Enqueue, !setEmptyOff, ?Enqueue, ?Enqueue, ?Enqueue, ?Enqueue, !setFullOn, ?Dequeue, !setFullOff, ?Enqueue, !setFullOn⟩

From Analysis to Synthesis

State of art:

Analysis of test cases

How many mutants killed by test cases?

$$mutation\ score = \frac{\#killed\ mutants}{\#mutants}$$

Problem: equivalent mutants

Solution: review of surviving mutants

Research:

Synthesis of test cases

Find test cases that maximise mutation score.

Idea:

- Check equivalence between original and mutant
- Use counter-example as test case.

Problem: equivalence checking is hard (undecidable in general)

Solution: generate from models (abstraction)

→ model-based mutation testing

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Model-based Testing

Model-based testing (MBT) is

- the automatic generation of software test procedures,
- using models of system requirements and behavior
- in combination with automated test execution.

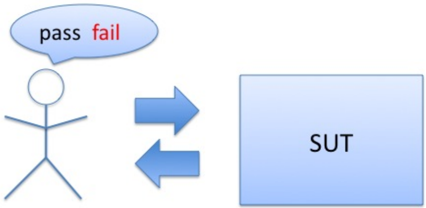
Objective

"Don't write test cases,

generate them!"

(John Hughes)

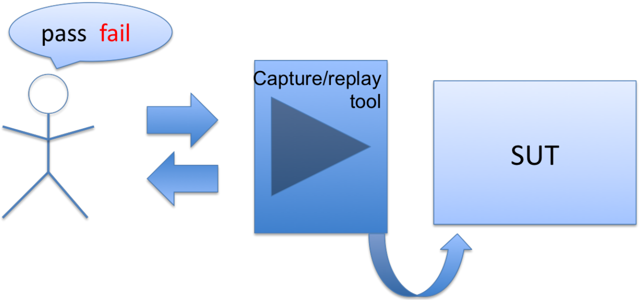
Levels of Testing: Manual



Levels of Testing: Manual

- \+ easy & cheap to start
- \+ flexible testing
- – expensive every execution
- – no auto regression testing
- – ad-hoc coverage
- – no coverage measurement

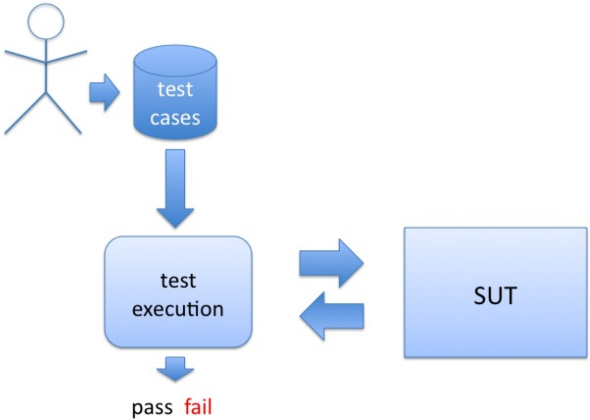
Levels of Testing: Capture & Replay



Levels of Testing: Capture & Replay

+ auto regression testing
+ flexible testing
– expensive first execution
– fragile tests break easily
– ad-hoc coverage
– no coverage measurement

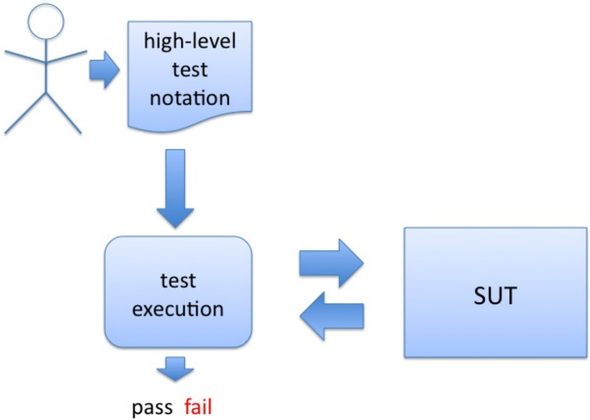
Levels of Testing: Scripts



Levels of Testing: Scripts

- + auto regression testing
- + automatic execution
- +/− test impl. = programming
- − fragile tests break easily? (depends on abstraction)
- − ad-hoc coverage
- − no coverage measurement

Levels of Testing: Test Scenarios



Levels of Testing: Test Scenarios

+ abstract tests
+ automatic execution
+ auto regression testing
+ robust tests
− ad-hoc coverage
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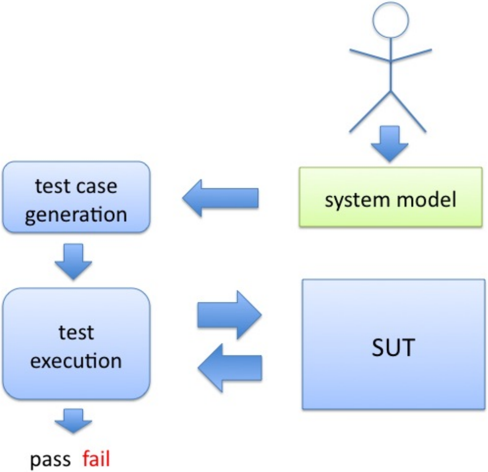
Levels of Testing: Model-Based Testing



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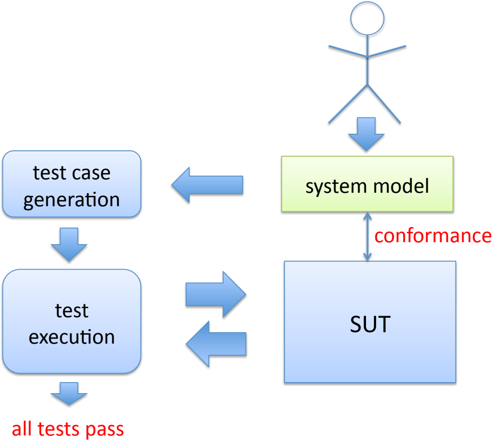
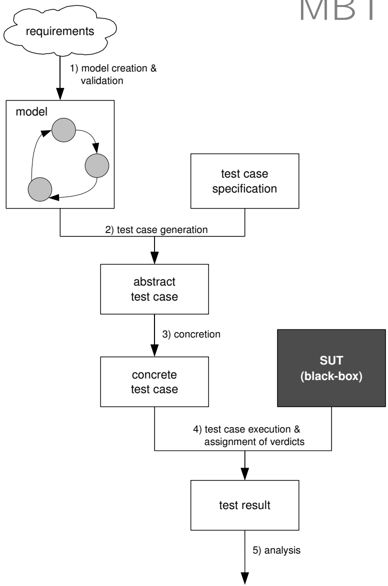


Levels of Testing: Model-Based Testing

+ abstract tests
+ automatic execution
+ auto regression testing
+ auto design of tests
+ systematic coverage
+ measure coverage of model and requirements
– modelling efforts

MBT Workflow



Manual tasks:

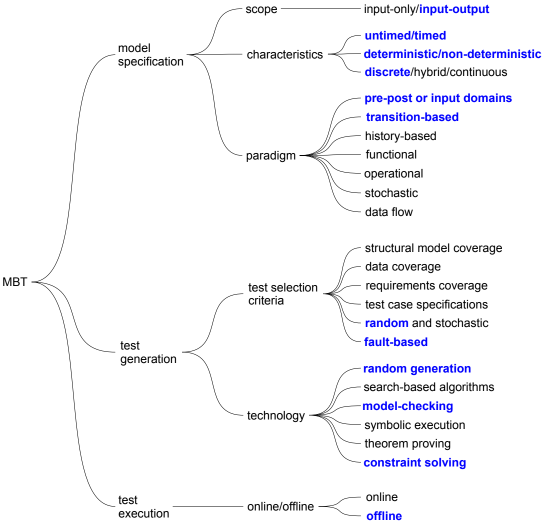
- (requirements analysis)
- model creation
- model validation
- concretion implementation

Automated tasks:

- model verification
- test-case generation
- test-case concretion
- test-case execution
- assignement of verdicts

Taxonomy

M. Utting, A. Pretschner, B. Legeard: *A taxonomy of model-based testing approaches.* Software Testing, Verification and Reliability, 22(5), 2012.



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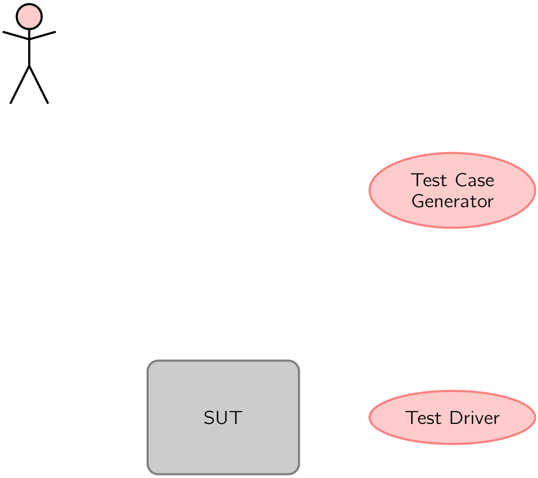

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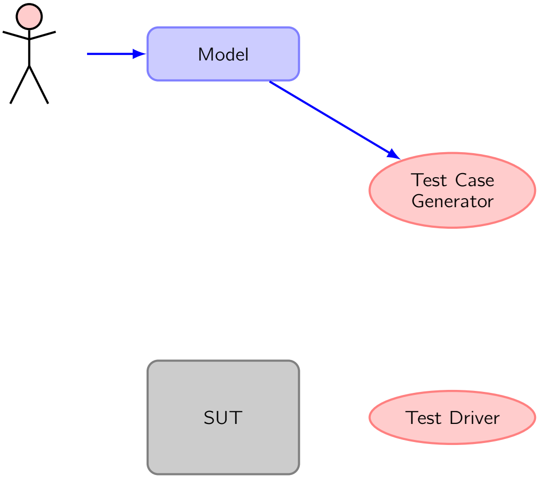

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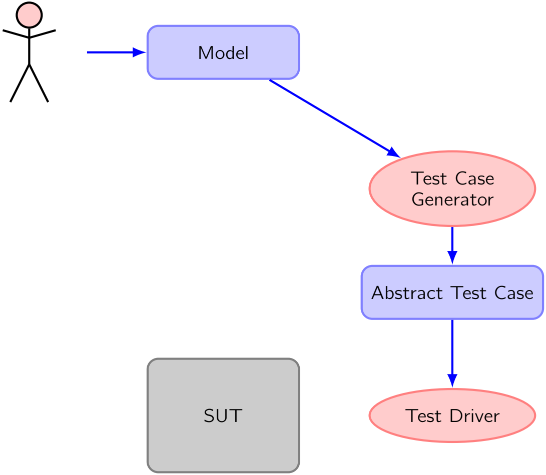

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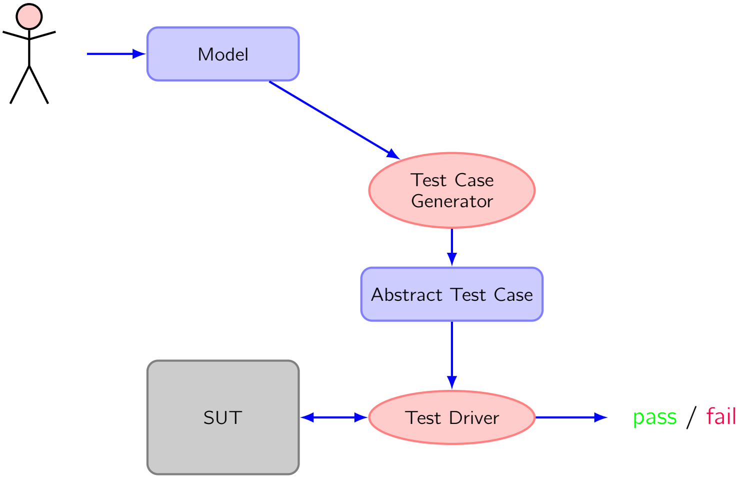

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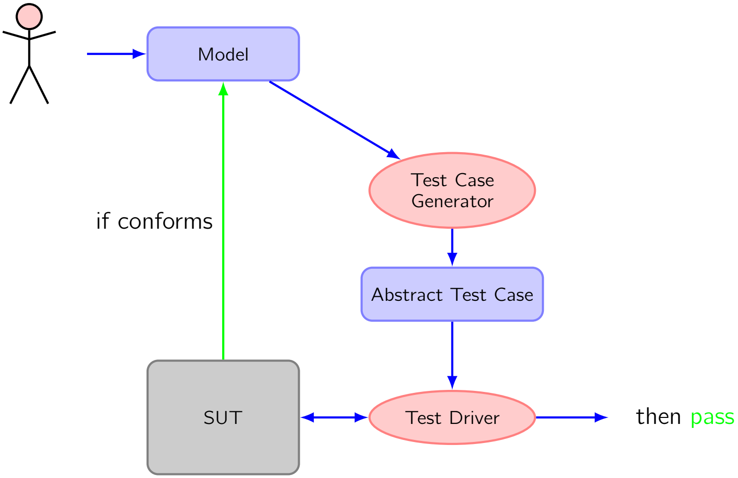

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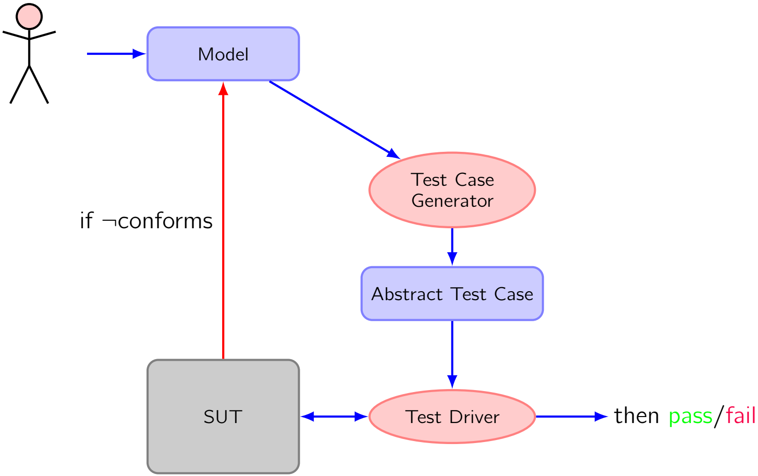
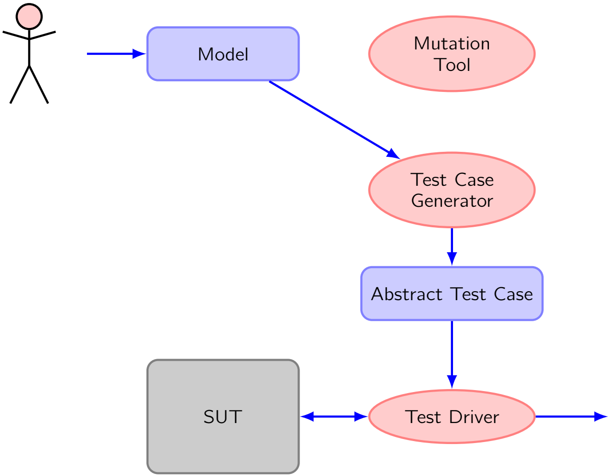
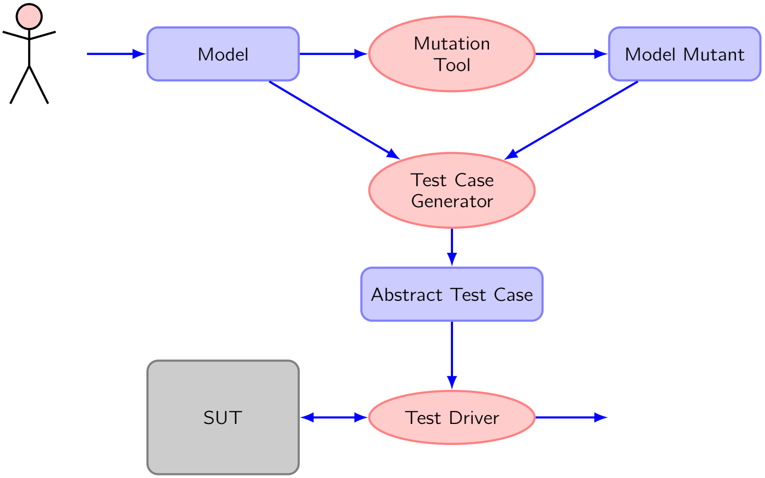


Model-Based Mutation Testing



Model-Based Mutation Testing



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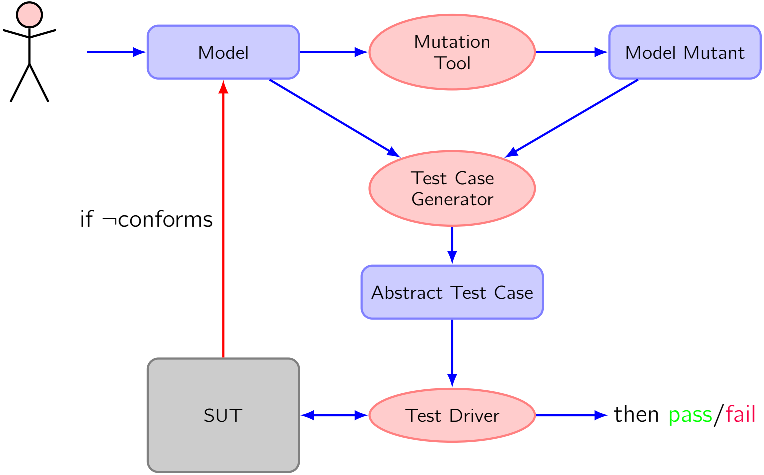

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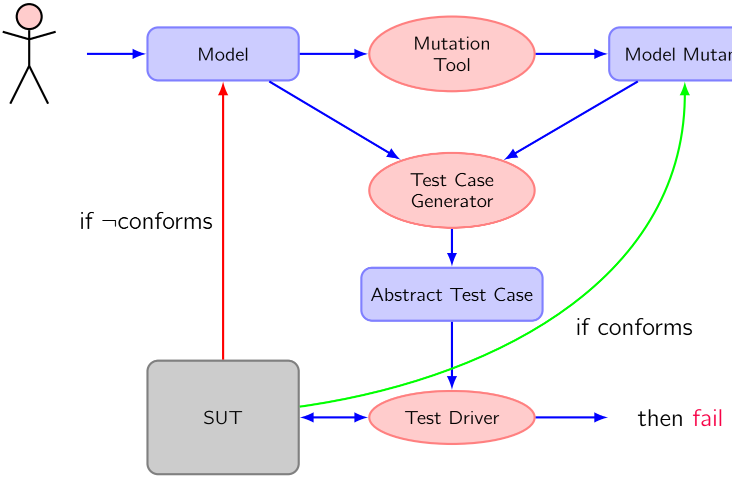

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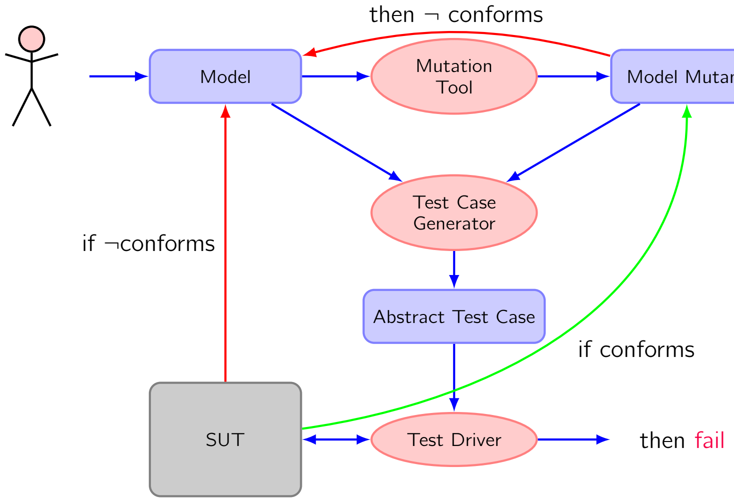

Non-Conformance & Test Cases

Theorem

Given a transitive conformance relation $\sqsubseteq$, then

$$(Model \not\sqsubseteq SUT) \land (Mutant \sqsubseteq SUT) \Rightarrow (Model \not\sqsubseteq Mutant)$$

- What are the cases of non-conformance?
- Test these cases on the SUT!
- These test cases will detect if mutant has been implemented.

Test Cases as Partial Specifications

- A test case can be interpreted as a partial specification (model)
  - defines output for one input case, rest undefined.
- If a SUT (always) passes a test case, we have conformance:

$$Test\ case \sqsubseteq SUT$$

- If we generate a test case from a model, we have selected a partial behaviour such that

$$Test\ case \sqsubseteq Model$$

- If SUT conforms to the model:

$$Test\ case \sqsubseteq Model \sqsubseteq SUT$$

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Fault-Detecting Test Case

- Generated from the model
- Kills the mutant

$$\textit{Test case} \sqsubseteq \textit{Model}$$

- It is a counter-example to conformance, hence

$$\textit{Model} \not\sqsubseteq \textit{Mutant}$$

iff

$$\exists\, \textit{Test case} : (\textit{Test case} \sqsubseteq \textit{Model} \wedge \textit{Test case} \not\sqsubseteq \textit{Mutant})$$

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- Model-based Testing
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- Transformational Systems
  - Semantics
  - Test Case Generation
- Reactive Systems
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- Model- and Test-Driven Development
- MoMuT Tools
- Tool Demo and Examples

Transformational Systems: Semantics

- Model and Mutant interpreted as predicates $Model(s, s')$ and $Mutant(s, s')$ describing state transformations $(s \rightarrow s')$
- Conformance:

$$Model \sqsubseteq Mutant =_{df} \forall s, s' : Mutant(s, s') \Rightarrow Model(s, s')$$

- Non-conformance:

$$Model \not\sqsubseteq Mutant \;=\; \exists s, s' : Mutant(s, s') \wedge \neg Model(s, s')$$

- Read: a behaviour allowed by mutant but not by original model?
- This is a constraint satisfaction problem!

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Transformational Systems: Example

Triangle semantics:

$$Mutant(a, b, c, res') \wedge \neg Model(a, b, c, res') =_{df}$$
$$(\ldots$$
$$\neg(a \leq c - b \vee a \leq b - c \vee b \leq a - c) \wedge (a \geq b \wedge b = c \wedge res' = \text{equilateral})$$
$$\ldots) \wedge$$
$$\neg(\ldots$$
$$\neg(a \leq c - b \vee a \leq b - c \vee b \leq a - c) \wedge (a = b \wedge b = c \wedge res' = \text{equilateral})$$
$$\ldots)$$

- Simplifies to $a > b \wedge b = c \wedge res' = \text{equilateral}$
- Solver produces solution: $a = 3, b = 2, c = 2, res' = \text{equilateral}$
- Test case with expected result: $a = 3, b = 2, c = 2, res' = \text{isosceles}$

Transformational Systems: Tools

Implemented with different solvers:

- OCL contracts (Constraint Handling Rules)
- Spec# contracts (Boogie, Z3)
- Reo connector language (rewriting in JTom)

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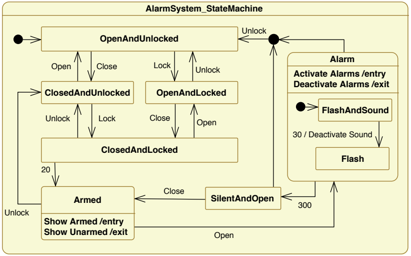
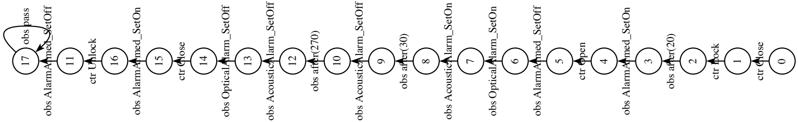
Reactive Systems

- React to the environment
- Do not terminate
- Servers and Controllers
- Events: controllable and observable communication events
- Test cases: sequences of events





Adaptive test cases: trees branching at non-deterministic observations

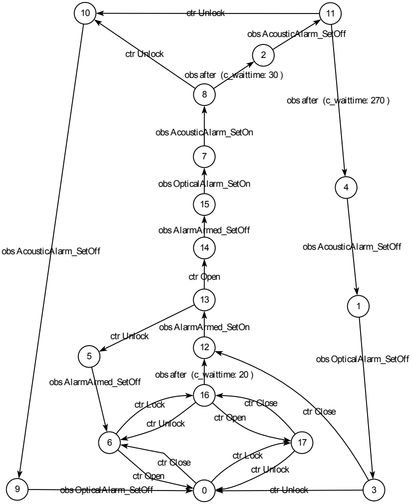
Semantics

- Operational semantics
  e.g. Labelled Transition Systems
- Input-output conformance (ioco)
  [Tretmans96]

SUT ioco $Model =_{df}$

$\forall \sigma \in traces(Model)$:
$out(SUT \text{ after } \sigma) \subseteq out(Model \text{ after } \sigma)$

out ... outputs + quiescence
after ... reachable states after trace



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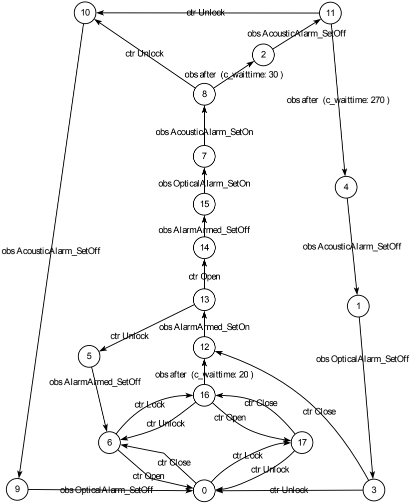

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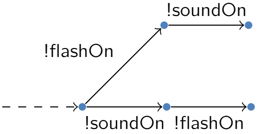
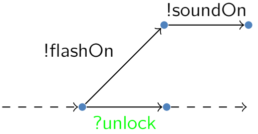


SUT:



SUT ioco Model ✓

Explicit Conformance Checking

- Model and Mutant → LTS
- Determinisation

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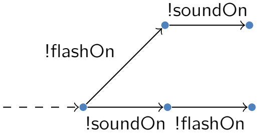
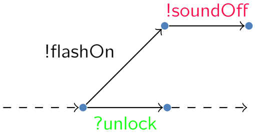


Mutant:



- Build synchronous product modulo ioco
- If mutant has additional
  - !output: → fail sink state
  - ?input: → pass sink state

Model $\times_{ioco}$ Mutant:

- Extract test case covering fail state

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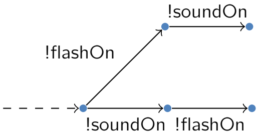

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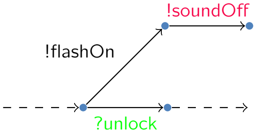

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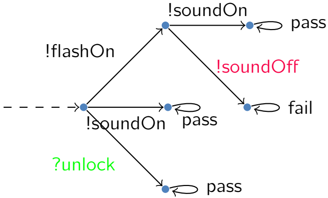

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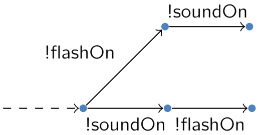

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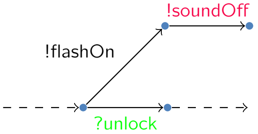

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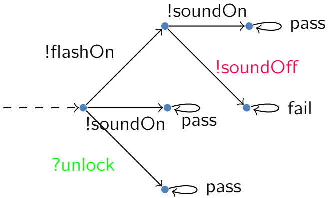

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Applications of Explicit Conformance Checking

- HTTP Server (LOTOS)
- SIP Server (LOTOS)
- Controllers (UML)
- Hybrid Systems (Action System)

Scalability: abstractions for data-intensive models

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Action Systems

- Action Systems [Back83]
- Non-deterministic choice of actions
- Actions are guarded commands
- Loop over Actions
- Terminates if all guards disabled
- Actions are labelled and represent events
- Two semantics:
  - Labelled Transition Systems
  - Predicative semantics

var $closed : Bool := false;$
$locked : Bool := false;$
$armed : Bool := false;$
$sound : Bool := false;$
$flash : Bool := false;$
actions
$Close :: \neg closed \rightarrow closed := true;$

$Open :: closed \rightarrow closed := false;$

$SoundOn :: armed \wedge \neg closed \wedge \neg sound \rightarrow$
$sound := true;$

$FlashOn :: armed \wedge \neg closed \wedge \neg flash \rightarrow$
$flash := true$

...

do $Close$
$\square$
$Open$
$\square$
$SoundOn; FlashOn$
$\square$
$FlashOn; SoundOn$
...
od

Predicative Semantics of Action Systems

The transition relation (one step) is

- translated to a constraint over state variables s and event-traces tr:

$$
\begin{aligned}
l :: g \rightarrow B &=_{df} g \ \wedge \ B \ \wedge \ tr' = tr ^\frown [l] \\
l(\overline{x}) :: g \rightarrow B &=_{df} \exists \ \overline{x} : g \ \wedge \ B \ \wedge \ tr' = tr ^\frown [l(\overline{x})] \\
x := e &=_{df} x' = e \ \wedge \ y' = y \ \wedge \ldots \wedge \ z' = z \\
g \rightarrow B &=_{df} g \ \wedge \ B \\
B(s, s'); B(s, s') &=_{df} \exists \ s_0 : B(s, s_0) \ \wedge \ B(s_0, s') \\
B_1 \ \Box \ B_2 &=_{df} B_1 \ \vee \ B_2
\end{aligned}
$$

- then simplified (DNF + quantifier elimination)

Symbolic Conformance Checking

$$\exists\ s, s', tr, tr' : reachable(s, tr) \ \wedge\ Mutant(s, s', tr, tr') \ \wedge\ \neg Model(s, s', tr, tr')$$

- Is non-conformance reachable?
- Fast, but stronger than ioco.
- Ioco for complete models:

$$\exists\ s_1, s_1', s_2, s_2', tr, !a : reachable(Mutant, tr, s_1) \ \wedge\ reachable(Model, tr, s_2)$$

$$\wedge$$

$$Mutant(s1, s1', tr, tr \frown !a) \ \wedge\ \neg Model(s2, s2', tr, tr \frown !a)$$

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Symbolic Conformance Checkers

- Two implementations for Action Systems
  - Constraint Logic Programming: Sicstus Prolog
  - SMT solving: Scala + Z3
- Timed Automata: Scala + Z3 (tioco)
- After optimisations:

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Symbolic Conformance Checkers

- Two implementations for Action Systems
  - Constraint Logic Programming: Sicstus Prolog
  - SMT solving: Scala + Z3
- Timed Automata: Scala + Z3 (tioco)
- After optimisations:

Prolog and SMT equally fast!

Bernhard K. Aichernig and Elisabeth Jöbstl. *Towards symbolic model-based mutation testing: Combining reachability and refinement checking*, MBT 2012.

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Optimisations

Performance gains for checking 207 mutants of the Car Alarm System.

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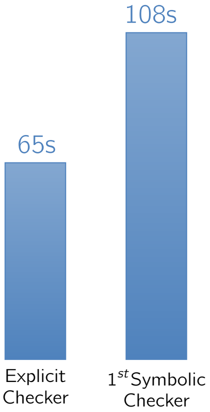

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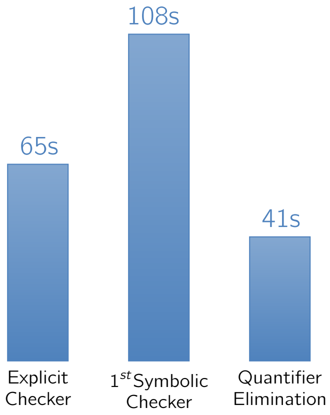

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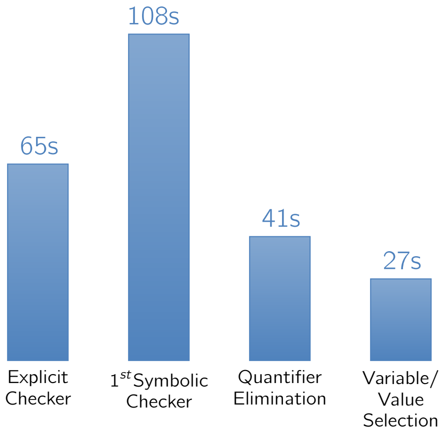

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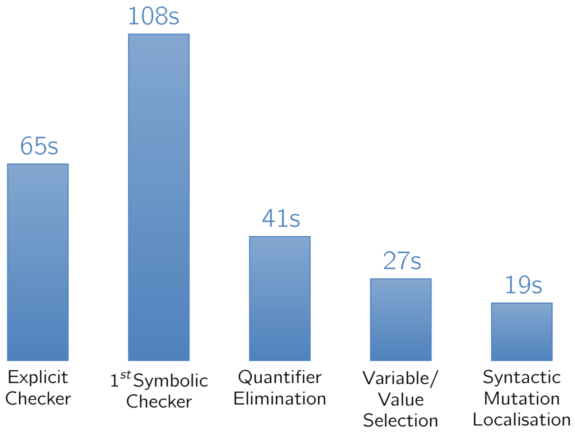

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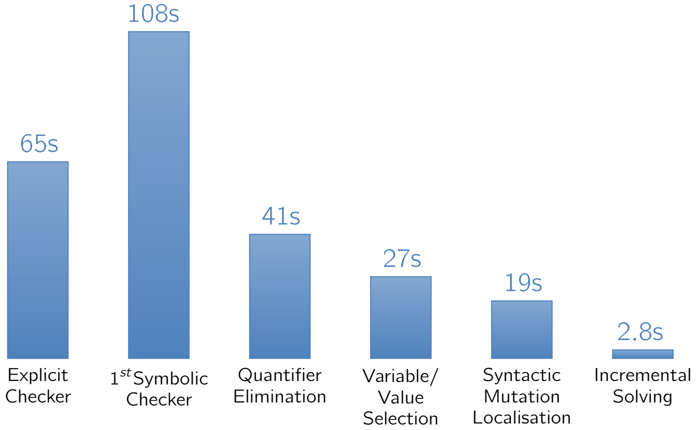

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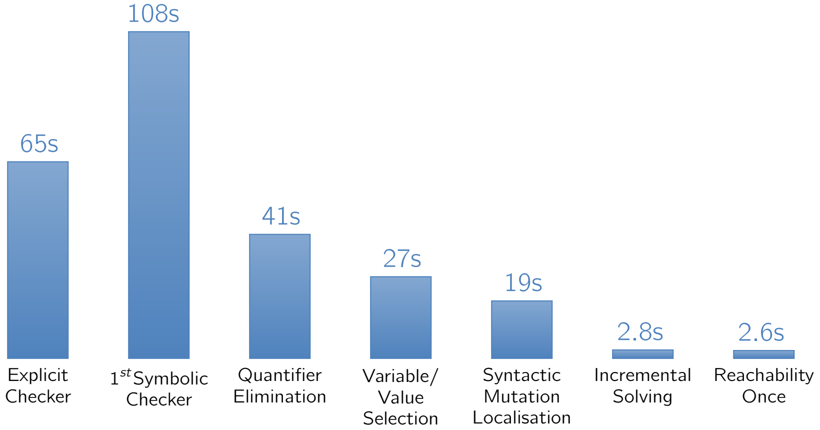
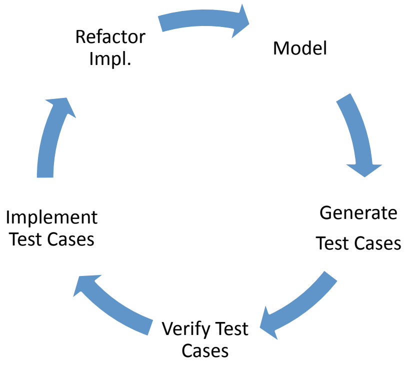


Agenda

- Mutation Testing
- Model-based Testing
- Model-based Mutation Testing
- Transformational Systems
  - Semantics
  - Test Case Generation
- Reactive Systems
  - Semantics
  - Test Case Generation
- Model- and Test-Driven Development
- MoMuT Tools
- Tool Demo and Examples

Agile Development



- Model-driven development
- Model-based test case generation
- Formal verification
- Test-driven development

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MoMuT Tools

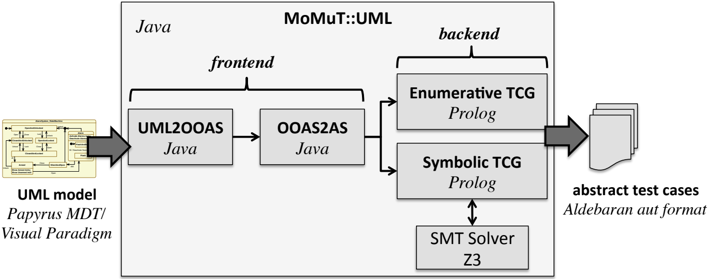
MoMuT

- is a family of tools implementing Model-based Mutation Testing.
- is jointly developed and maintained by AIT and TU Graz
- supports different modelling styles:
  - MoMuT::UML
  - MoMuT::OOAS
  - MoMuT::TA
  - MoMuT::Reqs

www.momut.org

MoMuT::UML

- Test-case generator of AIT and TU Graz
- Implementing model-based mutation testing for UML state machines

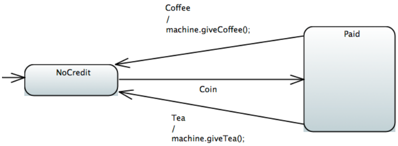


Architecture of the *MoMuT::UML* tool chain

AS ... Action Systems [Back83]

OOAS ... Object-Oriented Action Systems

MoMuT::UML



- Enumerative back-end: ioco
- Symbolic back-end supports two conformance relations:
  - State-based Refinement
  - Event-based ioco

Bernhard Aichernig, Harald Brandl, Elisabeth Jobstl, Willibald Krenn, Rupert Schlick and Stefan Tiran. *MoMuT::UML Model-Based Mutation Testing for UML*, ICST 2015.

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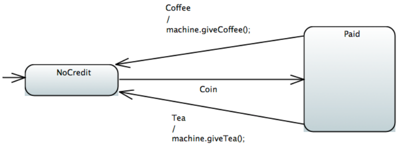
Combined conformance checking:

- Refinement checker searches for faulty state (fast)
- Ioco checker looks if faulty state propagates to different observations

MoMuT::UML



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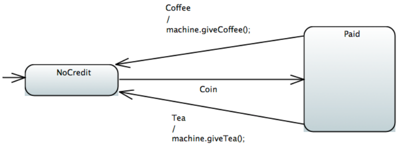

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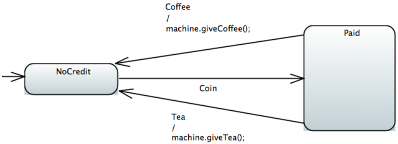

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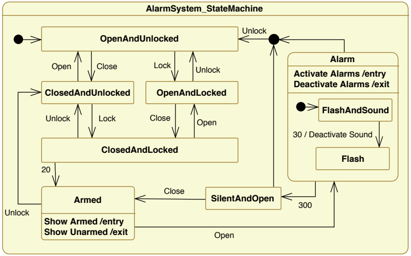
Case Study 1: Car Alarm System

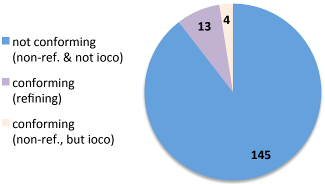


State machine model in UML

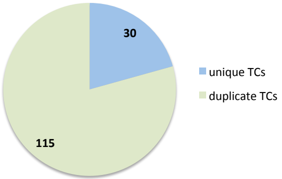
	CAS_UML
actions [#]	51
state variables [#]	35
possible states [#]	$1.7 \cdot 10^{18}$
reachable states [#]	229
required exploration depth	17

Metrics of Generated Action System

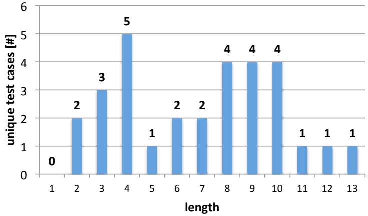
Case Study 1: TCG



(a) Breakup into conforming and not conforming model mutants.



(b) Breakup into unique and duplicate test cases.



(c) Lengths of the unique test cases.

Case Study 1: Fault Propagation

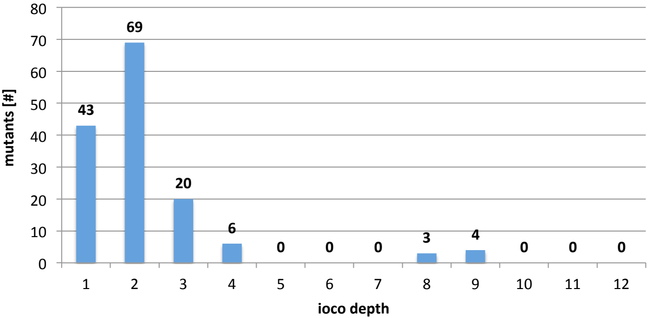


Figure: Number of steps from fault to failure (ioco depths)

Case Study 1: Run-times

... for combined conformance checking (in sec., max. depth 20+20) :

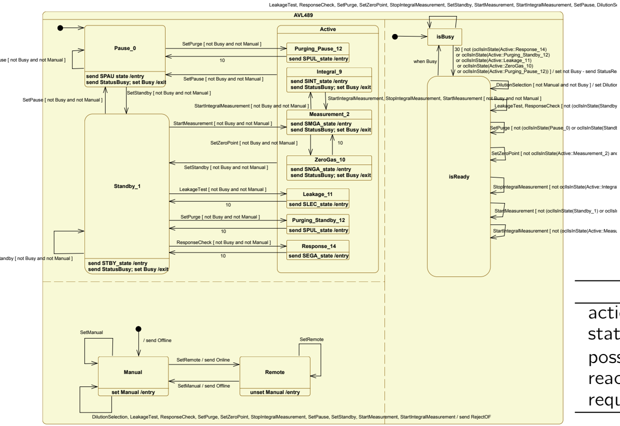
		conforming (refining)	conforming (non-ref., but ioco)	not conforming (non-ref. & not ioco)	total
mutants [#]		13	4	145	162
ref. check	Σ	4.03	1.63	56.41	62.07
	ϕ	0.31	0.41	0.39	0.38
	max	0.41	0.44	0.53	0.53
ioco check	Σ	-	17.71	1.9 min	2.2 min
	ϕ	-	4.43	0.79	0.81
	max	-	4.48	2.01	4.48
tc constr.	Σ	-	-	1.3 min	1.3 min
	ϕ	-	-	0.55	0.49
	max	-	-	1.48	1.48
total without logging	Σ	4.25	19.4	4.2 min	**4.6 min**
	ϕ	0.33	4.85	1.74	1.7
	max	0.43	4.89	2.77	4.89

Comparison to stand-alone ioco-check with depth 20: 5.1 min

Case Study 2: AVL489 Particle Counter

- One of AVL's automotive measurement devices
- Measures particle number concentrations in exhaust gas
- Focus: testing of the control logic

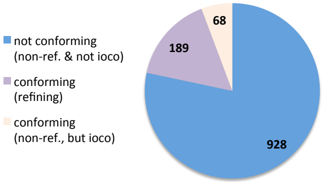
Case Study 2: Test Model of AVL489



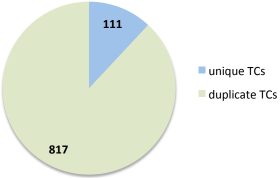
	PC_UML
actions [#]	109
state variables [#]	74
possible states [#]	$1.2 \cdot 10^{31}$
reachable states [#]	$> 850\,700$
required exploration depth	> 25

Metrics of Generated Action System

Case Study 2: TCG



(a) Breakup into conforming and not conforming model mutants.



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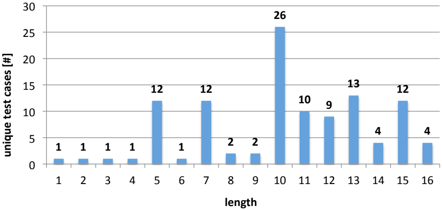

(c) Lengths of the unique test cases.

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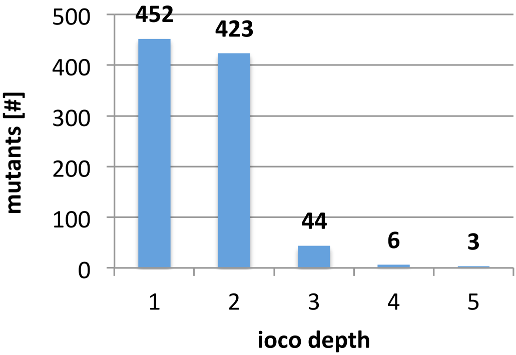


Figure: Number of steps from fault to failure (ioco depths)

Case Study 2: Run-times

... for combined conformance checking (in min., max. depth 15+5) :

		conforming (refining)	conforming (non-ref., but ioco)	not conforming (non-ref. & not ioco)	total
mutants [#]		189	68	928	1185
ref. check	Σ	6.1 h	7.7	7.1 h	13.3 h
	ϕ	1.9	6.8 sec	27 sec	40 sec
	max	4.3	1.8	3.9	4.3
ioco check	Σ	-	0.7 h	1.7 h	2.4 h
	ϕ	-	38 sec	7 sec	7.4 sec
	max	-	2	27 sec	2
tc constr.	Σ	-	-	22.9	22.9
	ϕ	-	-	1.5 sec	1.2 sec
	max	-	-	3.7 sec	3.7 sec
total without logging	Σ	6.1 h	0.9 h	9.2 h	**16.2 h**
	ϕ	1.9	0.8	0.6	0.8
	max	4.3	2.2	4.1	4.3

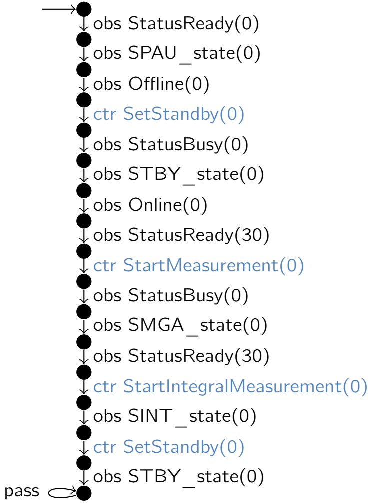
Case Study 2: Run-times

... comparison to stand-alone ioco check (in min., max. depth 10):

		not ioco	ioco	total
mutants [#]		719	466	1185
time – ioco check	Σ	9.8 h	22.8 h	32.6 h
	ϕ	0.8	2.9	1.7
	max	3.9	5.2	5.2
time – tc constr.	Σ	19	-	19
	ϕ	1.6 sec	-	1 sec
	max	5.8 sec	-	5.8 sec
total without logging	Σ	10.1 h	22.8 h	**32.9 h**
	ϕ	0.8	2.9	1.7
	max	3.9	5.2	5.2

appr. 16h vs. 33h

Abstract Test Case of AVL489



Abstract test cases → concrete C# NUnit test cases.

ctr … controllable event (input)

obs … observable event (output)

Test Execution on Particle Counter

We found several bugs in the SUT:

- Forbidden changes of operating state while busy
  - Pause → Standby
  - Normal Measurement → Integral Measurement
- Ignoring high-frequent input without error-messages
- Loss of error messages in client for remote control of the device

MoMuT::UML Reimplementation

Motivation: Railway Interlocking System (Thales)

- Reimplementation of enumerative TCG in C by AIT
- Assuming deterministic systems
- ioco checking $\Rightarrow$ ioco testing (random)
- Short lived mutants: create mutants while exploring

MoMuT::OOAS

Object-Oriented Action Systems:

- Textual model programs
- Guarded Actions in do-od loop
- Modularization via objects
- Communication via methods
- Mutation directly on OOAS

Willibald Krenn, Rupert Schlick, and Bernhard K. Aichernig. *Mapping UML to labeled transition systems for test-case generation - a translation via object-oriented action systems*. FMCO, 2009

```
types
    CoffeeMachine = autocons system
|[  var
        paid : Boolean = false ;
        coffee_sel : Boolean = false
    actions
        ctr coin =
            requires true :
                paid := true
        end;
        ctr coffeebutton =
            requires paid :
                coffee_sel := true;
                paid := false ;
        end ;
        obs coffee =
            requires coffee_sel :
                skip
        end ;
do
    coin () [] coffeebutton () [] coffee ()
od
]| system CoffeeMachine
```

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    CoffeeMachine = autocons system
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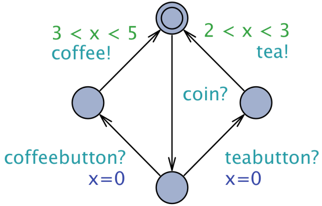
        end;
        ctr  coffeebutton  =
            requires  paid  :
                coffee_sel  :=  true ;
                paid  :=  false ;
        end  ;
        obs  coffee  =
            requires  coffee_sel  :
                skip
        end  ;
do
    coin ()  []  coffeebutton ()  []  coffee ()
od
]|  system  CoffeeMachine
```

MoMuT::TA

Timed Automata:

- Modelling in UPPAAL model checker
- Finite-state machines with real-valued clock variables
- Time passage in locations
- Time restrictions on locations and guards



MoMuT::TA (cont.)

- tioco-conformance: *M tioco S*
  - $out(M) \subseteq out(S)$
  - time delay is an output
- Conformance check via language inclusion
  - Requires deterministic automata
  - SMT-Solver Z3
- Determinization

Application: Crystal Usecase (Volvo)

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MoMuT::REQs

Contract-based Requirement Interfaces:

- Synchronous assume-guarantee pairs
- Combined via conjunction
- No model-based mutation testing yet

Application: Airbag Chip (Infineon)

```
Inputs  coin, teabutton, coffeebutton;
Outputs coffee, tea;
 Internals  paid;

{I}  not paid and not coffee and not tea
{R1} assume coin'
     guarantee paid'
{R2} assume paid and teabutton' and not coffeebutton'
     guarantee tea' and not paid'
{R3} assume paid and coffeebutton' and not teabutton'
     guarantee coffee' and not paid'

{R4} assume teabutton' and coffeebutton'
     guarantee skip
```

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     guarantee coffee' and not paid'

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Tool Demo

Conclusions

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- Formal semantics $\rightarrow$ test case generators $\rightarrow$ industry
- Novelty: general theory + tools for non-deterministic models + different modelling styles
- Future:
  - domain-specific models
  - non-functional fault models (resource limitations)

Testing cannot show the absence of bugs [Dijkstra72].

Testing can show the absence of specific bugs [Aichernig15].

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