Test Case Generation for Concurrent Systems Using Event Structures

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Motivation

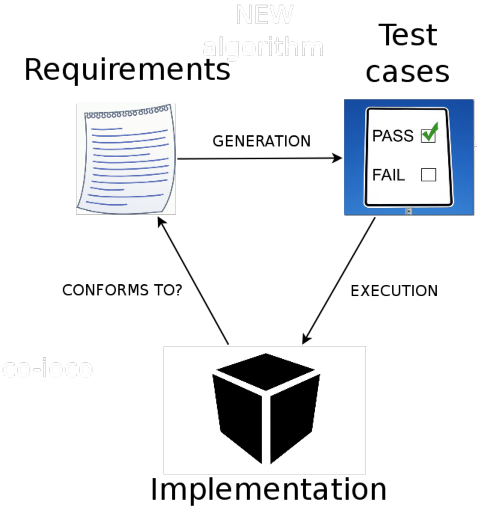
Concurrent and distributed systems are everywhere.

Testing is the most used technique to gain confidence in the correctness of the system.

- ✔ finds actual errors
- ✘ expensive, usually manual

Outline

Formal Black-box Testing



Requirements = *Formal specification*

⇒ *formal notion of conformance, test cases*

⇒ *automation of test case generation*

How to model and test requirement?

Sequential models

- *Formal model: Labeled Transition System*
- *Conformance:* **ioco** *(input-output conformance)*

Problem: State space explosion in concurrent systems

True concurrency models

- *Formal model: Petri nets, network of automata, event structures*
- *Conformance:* **co-ioco** *(concurrent* **ioco***)*

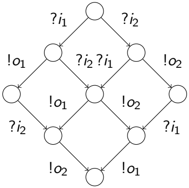
Test Cases

Sequential models

- *Complete test graph $\mathcal{G}$: all the tests for a purpose/criteria*
- *Test cases: partition (subgraphs) of $\mathcal{G}$*
- *Termination: finiteness of purpose/criteria*

$$\mathcal{S} = (i_1; o_1 \parallel i_2; o_2)$$

$$\mathcal{T} = \left\{ \begin{array}{c} ?i_1; !o_1; ?i_2; !o_2 \\ ?i_2; !o_2; ?i_1; !o_1 \\ ?i_1; ?i_2; (!o_1; !o_2 + !o_2; !o_1) \\ ?i_2; ?i_1; (!o_1; !o_2 + !o_2; !o_1) \end{array} \right\}$$

$\mathcal{G} =$ 

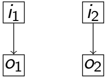
Test Cases

True concurrency models

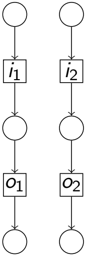
- *Complete test graph $\mathcal{U}$: finite unfolding of the specification*
- *Test cases: partition of $\mathcal{U}$*
- *Termination: cut-off events*

$$\mathcal{S} = (i_1; o_1 \parallel i_2; o_2)$$

$\mathcal{T} =$



$\mathcal{U} =$



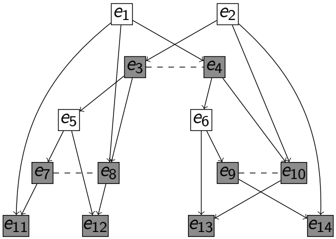
No choices between inputs due to concurrency: fewer test cases
No choice between outputs due to concurrency: smaller test cases

Outline

Definition (Input/Output Event Structure)

An IOES is 4-tuple $\mathcal{E} = (E, \leq, \#, \lambda)$ such that

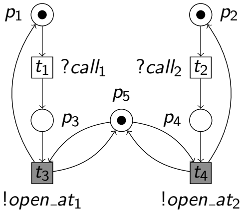
- E is a set of events,
- $\leq \subseteq E \times E$ is a partial order,
- $\# \subseteq E \times E$ is an irreflexive symmetric relation satisfying the property of *conflict heredity*, i.e. $\forall e, e', e'' \in E$: $e \# e' \wedge e' \leq e'' \Rightarrow e \# e''$,
- $\lambda : E \to (\mathcal{I}n \uplus \mathcal{O}ut)$ is a labeling mapping.

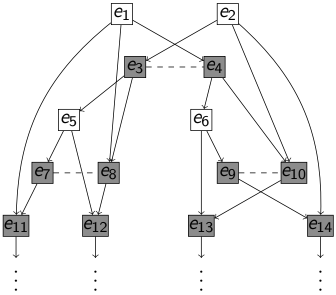


- e_1, e_2 can happen concurrently;
- e_8 needs e_1 and e_3;
- if e_3 happens, e_4 cannot;
- if e_8 happens, e_4 cannot.

Unfoldings

Complete behavior of a system $\approx$ (infinite) unfolding event structure.

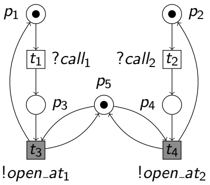




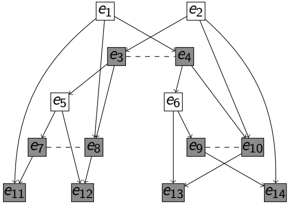
Testing should finish:

- all-states coverage
- all-transitions coverage
- all-loops coverage

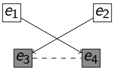
Coverage ≈ finite prefix of the unfolding **[PHL15]**. Detect cut-off events and stop unravelling there.



Specification



All-states

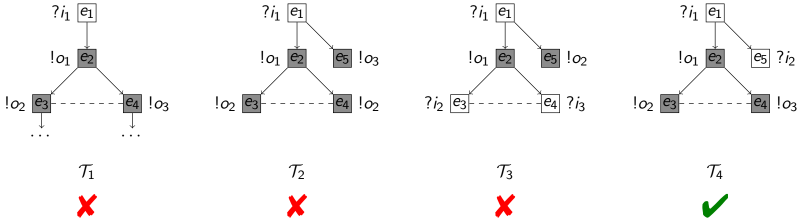


All-transitions

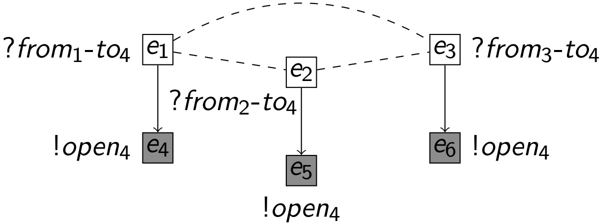
A tester should know the next input to propose and should finish.

Definition

A *global test case* is a finite, deterministic event structure $\mathcal{T} = (E, \leq, \#, \lambda)$ such that $(E^{\mathcal{I}n} \times E) \cap \#^i = \emptyset$.



Add events in order as far as they do not introduce conflicts between inputs:



If e_1 is added then e_2 and e_5 cannot be added (similar to e_3, e_6).

Once e_1 is added, the order of e_2, e_3 is irrelevant!

Preserve causality:

$$\forall e, f \in E : \bigwedge_{f \leq^i e} \varphi_e \Rightarrow \varphi_f$$

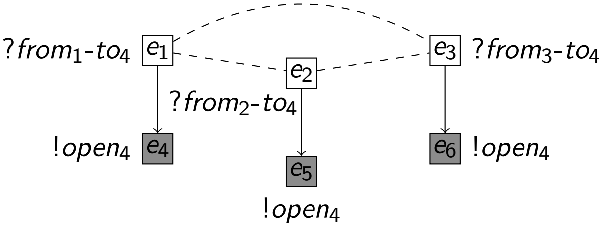
No direct conflicts for inputs:

$$\forall e \in E, f \in E^{\mathcal{I}n} : \bigwedge_{f \#^i e} \neg\varphi_e \vee \neg\varphi_f$$

All events are covered:

$$\forall e, f \in E, g \in E^{\mathcal{I}n} : \neg\varphi_e \Rightarrow \left(\bigvee_{f \leq^i e} \neg\varphi_f \vee \bigvee_{g \#^i e} \varphi_g \right)$$

Example



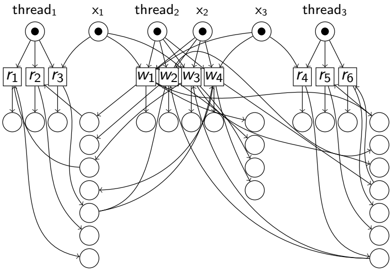
$$\mathrm{AMO}(\varphi_{e_1}, \varphi_{e_2}, \varphi_{e_3}) \wedge (\varphi_{e_1} \vee \varphi_{e_2} \vee \varphi_{e_3}) \wedge (\varphi_{e_1} \Leftrightarrow \varphi_{e_4})$$

$$\wedge(\varphi_{e_2} \Leftrightarrow \varphi_{e_5}) \wedge (\varphi_{e_3} \Leftrightarrow \varphi_{e_6})$$

Solutions: $\{e_1, e_4\}, \{e_2, e_5\}, \{e_3, e_6\}$

From multithreaded programs to unfoldings **[KSH12, KH14]**

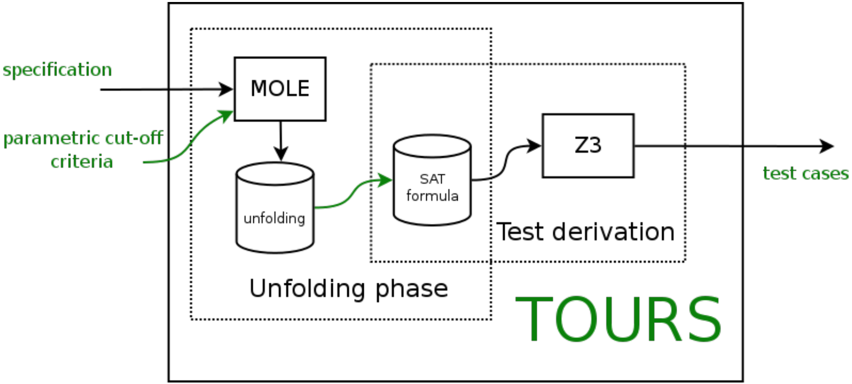
```
Global variable:
int x;

Thread 1:          Thread 2:       Thread 3:
local b = x;       x = 5           local c = x;
```

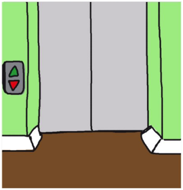


Minimal test suites for multithreaded programs **[PSK+15]** based on an SMT encoding.

Outline

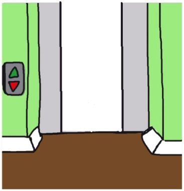
TOURS


specification
parametric cut-off
criteria
MOLE
unfolding
Unfolding phase
SAT
formula
Z3
Test derivation
test cases
TOURS



⇐ concurrent ?calls

concurrent or sequential !opens ⇒



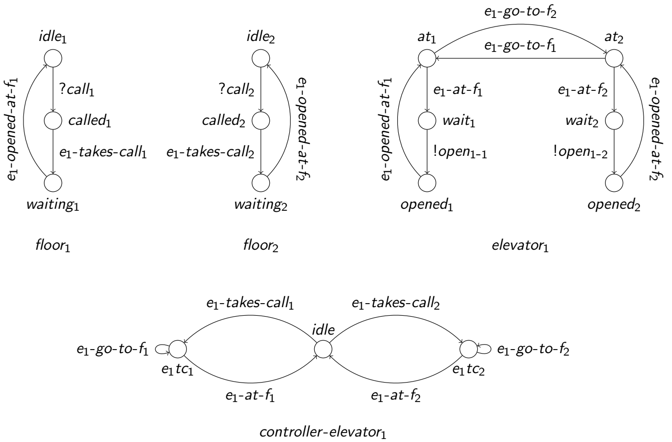
The set up:

- MOLE original cut-off criterion
- interleaving semantics: reachability graph as the input

Compare:

- size of the prefix vs size of the test graph
- number of test cases

Example (2)



Network of automata $\approx$ Petri net

Some Results

Floors	Elevators	Prefix	co-ioco tests	Test graph	ioco tests
2	1	11	1	95	14
2	2	29	1	3929	✗$_{SAT}$
3	1	43	1	2299	✗$_{SAT}$
3	2	220	1	3911179	✗$_{SAT}$
3	3	1231	1	✗$_{unf}$	
4	1	219	1	✗$_{unf}$	
4	2	1853	1	✗$_{unf}$	
4	3	17033	1	✗$_{unf}$	
4	4	140873	✗$_{SAT}$	✗$_{unf}$	

✗$_{unf}$: no solution from the unfolding after 24hs

✗$_{SAT}$: no solution from the SAT solver after 24hs

Smaller and fewer test cases with partial order semantics

Conclusions

- Event structures produce less and smaller test cases than sequential models.
- Automatic test case generation with unfoldings and SAT.
- Minimality can be encode in SMT.

Future work:

- From event structures to executable test cases.
- Validation of the approach on real-life examples.

Thanks!