Advanced Test Coverage Criteria: Specify and Measure, Cover and Unmask

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joint work with Omar Chebaro, Mickaël Delahaye, Michaël Marcozzi, Mike Papadakis, Virgile Prevosto...

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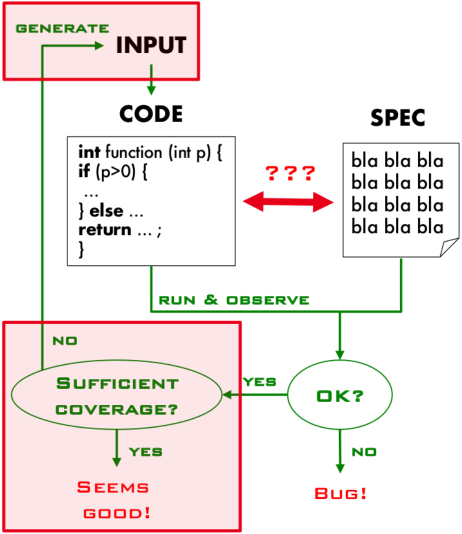
Context: White-Box Testing

Testing process

- Generate a test input
- Run it and check for errors
- Estimate coverage: if enough stop, else loop



CORE TESTING PROCESS

Context: White-Box Testing

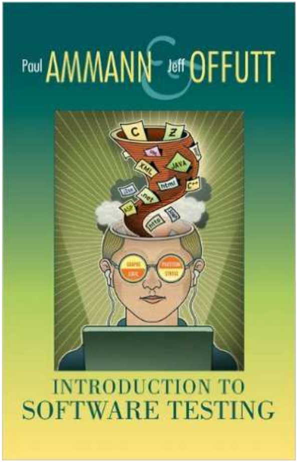
- Framework: white-box software testing process
- Automate test suite generation & coverage measure
- Coverage criterion = objectives to be fulfilled by the test suite
- Criterion guides automation
- Can be part of industrial normative requirements

Coverage criteria in white-box testing

Variety and sophistication gap between literature and testing tools

Literature:

- 28 various white-box criteria in the Ammann & Offutt book



Coverage criteria in white-box testing

Tools:

- Criteria seen as very dissimilar bases for automation
- Restricted to small subsets of criteria
- Extension is complex and costly

Tool name	BBC	FC	DC	CC	DCC	GACC	MCDC	MCC	BP	Other
Gcov	✓	✓	✓							0/19
Bullseye		✓			✓					0/19
Parasoft	✓	✓	✓	✓			✓		✓	0/19
Semantic Designs		✓	✓							0/19
Testwell CTC++	✓	✓			✓		✓			0/19

Global goal: bridge the gap between criteria and testing tools

Main ingredients of the talk:

Labels: a generic specification mechanism for coverage criteria

- can easily encode a large class of criteria
- a semantic view, with a formal treatment

DSE*: an efficient test generation technique for labels

- an optimized version of DSE (Dynamic Symbolic Execution)
- no exponential blowup of the search space

LUncov: an efficient technique for detection of infeasible objectives

- based on existing static analysis techniques

LTest: an all-in-one testing toolset

- on top of Frama-C and PathCrawler

HTOL: Hyperlabel Specification Language, extension of labels

- capable to encode almost all common criteria including MCDC

[Bardin et al., ICST 2014, TAP 2014, ICST 2015]
[Marcozzi et al., ICST 2017 (research), ICST 2017 (tool)]

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Outline

1. Labels
2. LTest: an all-in-one testing toolset
3. Efficient test generation for labels
   - Dynamic Symbolic Execution (DSE)
   - DSE*: optimized test generation for labels
4. Detection of infeasible test objectives
5. Hyperlabel Specification Language (HTOL)
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Labels and the notion of simulation (1/2)

Basic definitions

Given a program P, a label l is a pair (loc, φ), where:

- φ is a well-defined predicate at location loc in P
- φ contains no side-effects

Example:

```
statement_1;
// l1:  x==y
// l2:  !(x==y)
if (x==y && a<b)
   {...};
statement_3;
```

Labels and the notion of simulation (2/2)

Basic definitions

- a test datum t covers l if $P(t)$ reaches loc and satisfies φ
- new criterion **LC** label coverage: requires to cover the labels

Example:

```
statement_1;
// l1:  x==y
// l2:  !(x==y)
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```

- a criterion **C** can be simulated by **LC** if for any P, after adding "appropriate" labels in P, TS covers **C** $\Leftrightarrow$ TS covers **LC**.

Simulation of coverage criteria by labels: CC

```
statement_1;
if (x==y && a<b)
   {...};
statement_3;
```

→

```
statement_1;
// l1:  x==y
// l2:  !(x==y)
// l3:  a<b
// l4:  !(a<b)
if (x==y && a<b)
   {...};
statement_3;
```

Condition Coverage (**CC**)

Simulation of coverage criteria by labels: DC

```
statement_1;
if (x==y && a<b)
   {...};
statement_3;
```

→

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statement_1;
//l1:  x==y && a<b
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if (x==y && a<b)
   {...};
statement_3;
```

Decision Coverage (**DC**)

Simulation of coverage criteria by labels: MCC

```
statement_1;
if (x==y && a<b)
   {...};
statement_3;
```

→

```
statement_1;
// l1:  x==y && a<b
// l2:  x==y && a>=b
// l3:  x!=y && a<b
// l4:  x!=y && a>=b
if (x==y && a<b)
   {...};
statement_3;
```

Multiple-Condition Coverage (**MCC**)

Simulation of coverage criteria by labels: FC

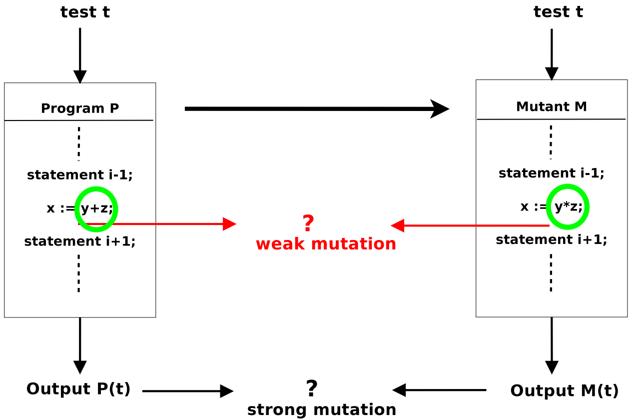
```
int f1() {
  code1;
}
int f2() {
  code2;
}
```

⟶

```
int f1() {
 // l1: true
  code1;
}
int f2() {
 // l2: true
  code2;
}
```

Function Coverage (**FC**)

Weak Mutation (WM) testing in a nutshell

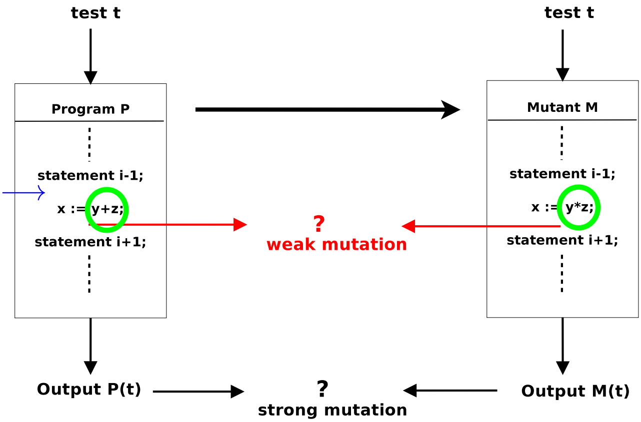


- mutant M = syntactic modification of program P
- weakly covering M = finding t such that $\mathrm{P}(t) \neq \mathrm{M}(t)$ just after the mutation

Weak Mutation (WM) testing in a nutshell

To simulate by labels, insert before the mutated instruction:

```
// l1:  y+z != y*z
```



- mutant M = syntactic modification of program P
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Simulation of coverage criteria by labels: WM

Insert one label per mutant before the mutated instruction

Mutation inside a statement

- `lhs := e` $\mapsto$ `lhs := e'`
  - insert label: $e \neq e'$
- `lhs := e` $\mapsto$ `lhs' := e`
  - insert label: $\&lhs \neq \&lhs' \wedge (lhs \neq e \vee lhs' \neq e)$

Mutation inside a decision

- `if (cond)` $\mapsto$ `if (cond')`
  - insert label: $cond \oplus cond'$

Beware: no side-effect inside labels

Simulation results

Theorem

The following coverage criteria can be simulated by **LC***:* **IC**, **DC**, **FC**, **CC**, **MCC**, *Input Domain Partition, Run-Time Errors.*

Theorem

For any finite set O of side-effect free mutation operators, $\mathbf{WM}_O$ *can be simulated by* **LC**.

Measuring the coverage of a test suite

- Labels already enjoy a simple and efficient algorithm for coverage measurement
- Given a test suite TS and a program P
  - instrument P with checks for labels (P')
  - run every $t \in TS$ on P', record covered labels
  - time cost: $\leq |TS| \cdot \max_{t \in TS}(P'(t))$
- **Works also for weak mutations**, whereas the standard algorithm for strong mutations is more costly:
  - create the set of mutants M
  - time cost: $\leq |TS| \cdot |M| \cdot \max_{m \in M, t \in TS}(m(t))$

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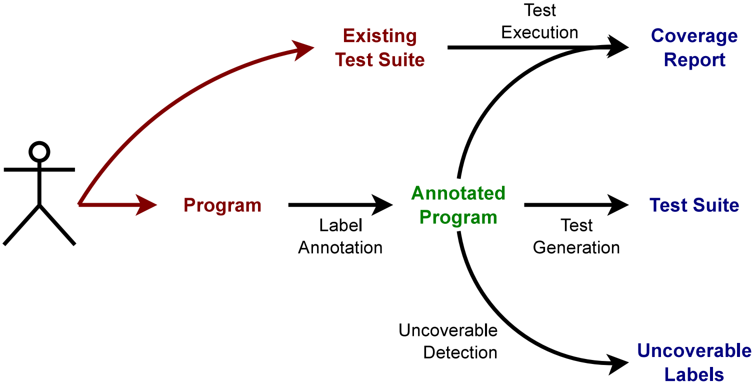
The LTest toolset for labels

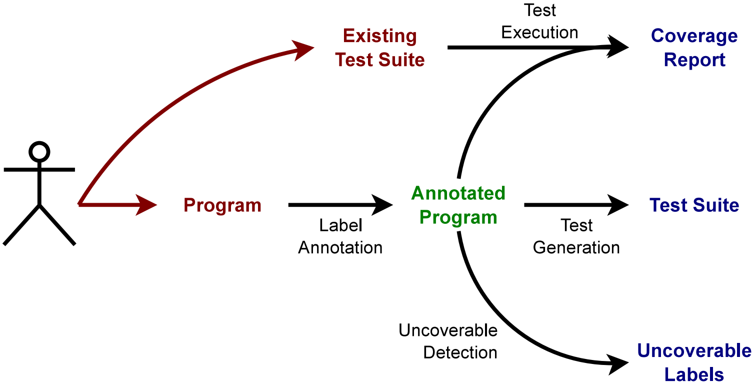
LTest is implemented on top of Frama-C

- Frama-C is a toolset for analysis of C programs
  - an extensible, open-source, plugin-oriented platform
  - offers value analysis (VA), weakest precondition (WP), specification language ACSL,...
- LTest is open-source except test generation
  - based on the PathCrawler test generation tool

The LTEST toolset for labels



The LTest toolset for labels



A large set of supported criteria

- all treated in a unified way
- rather easy to add new ones

A typical use case

```
// Checks if input points (x1,y1) and (x2,y2) lie
// in the same quadrant of the plane. Returns the
// quadrant number if so, otherwise returns 0.

int quadrant (int x1, int y1, int x2, int y2){
  if(x1 >= 0 && x2 >= 0 && y1 >= 0 && y2 >= 0)
    return 1;  // (+,+): quadrant 1
  if(x1 <= 0 && x2 <= 0 && y1 >= 0 && y2 >= 0)
    return 2;  // (-,+): quadrant 2
  if(x1 <= 0 && x2 <= 0 && y1 <= 0 && y2 <= 0)
    return 3;  // (-,-): quadrant 3
  if(x1 >= 0 && x2 >= 0 && y1 <= 0 && y2 <= 0)
    return 4;  // (+,-): quadrant 4
  return 0;    // not in the same quadrant
}
```

Step 1: Specify test objectives for MCC

LTest automatically encodes test objectives by labels

Example. For the 3nd conditional (quadrant 3), 16 labels are inserted:

$$
\begin{array}{ccccccc}
x1 \leq 0 & \wedge & x2 \leq 0 & \wedge & y1 \leq 0 & \wedge & y2 \leq 0 \\
x1 \leq 0 & \wedge & x2 \leq 0 & \wedge & y1 \leq 0 & \wedge & y2 > 0 \\
x1 \leq 0 & \wedge & x2 \leq 0 & \wedge & y1 > 0 & \wedge & y2 \leq 0 \\
 & & & \dots & & & \\
x1 > 0 & \wedge & x2 > 0 & \wedge & y1 > 0 & \wedge & y2 \leq 0 \\
x1 > 0 & \wedge & x2 > 0 & \wedge & y1 > 0 & \wedge & y2 > 0
\end{array}
$$

Result: Number of generated labels

16 labels generated for each conditional = 64 labels in total

Reminder: Goals

Specify [✓] and Measure [ ], Cover [ ] and Unmask [ ]

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Step 2: Measure the coverage of a test suite

LTest automatically measures test coverage

Example. For the test suite:

$$\begin{array}{lllll} Test\,1: & x1 = 5, & y1 = 8, & x2 = 10, & y2 = -15 \\ Test\,2: & x1 = 40, & y1 = 15, & x2 = -20, & y2 = 26 \end{array}$$

Result: Coverage ratio computed

8 labels are covered out of 64, thus MCC coverage ratio is 25%

Each test case is executed only once, and all covered test objectives are recorded

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Step 3: Generate test inputs to Cover MCC criterion

LTest automatically generates test inputs (using DSE*)

Results of DSE* test generation

- Explores 409 program program paths
- Generates a test suite that covers 58 labels out of 64

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What about the remaining 6 labels?

Are they really uncoverable?
If so, could they be detected before test generation?

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Step 4: Unmask uncoverable labels

LTest automatically detects uncoverable labels (using LUncov)

Example of uncoverable label (2nd conditional)

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  return 1; // (+,+): quadrant 1
// 128:  x1 > 0  ∧  x2 > 0  ∧  y1 ≥ 0  ∧  y2 ≥ 0
if ( x1 <= 0 && x2 <= 0 && y1 >= 0 && y2 >= 0)
  return 2; // (-,+): quadrant 2
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Results of detection with LUncov

6 labels are detected as **uncoverable** through static analysis

Benefits for test generation

- less paths to consider: here 284 paths instead of 409

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Dynamic Symbolic Execution

Dynamic Symbolic Execution [dart,cute,pathcrawler,exe,sage,pex,klee,. . .]

- ✓ very powerful approach to white-box test generation
- ✓ many tools and many successful case-studies since mid 2000's
- ✓ arguably one of the most wide-spread use of formal methods in "common software" [SAGE at Microsoft]

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Symbolic Execution [King 70's]

- consider a program P on input v, and a given path σ
- a path predicate φ_σ for σ is a formula s.t. for any input v

  $$\texttt{v} \text{ satisfies } \varphi_\sigma \Leftrightarrow \texttt{P(v)} \text{ follows } \sigma$$

- old idea, recently renewed interest [requires powerful solvers]

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Dynamic Symbolic Execution [Korel+, Williams+, Godefroid+]

- interleaves dynamic and symbolic executions
- drives the search towards feasible paths for free
- gives hints for relevant under-approximations

Dynamic Symbolic Execution (2)

input: a program P
output: a test suite *TS* covering all feasible paths of $Paths^{\leq k}(\mathtt{P})$

- pick an uncovered path $\sigma \in Paths^{\leq k}(\mathtt{P})$
- is the path predicate φ_σ satisfiable? [smt solver]
- if SAT(s) then add a new pair $< s, \sigma >$ into *TS*
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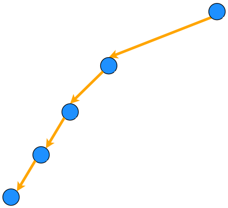

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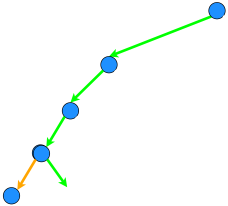

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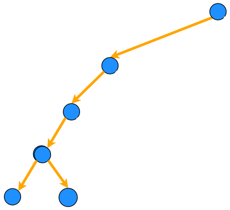

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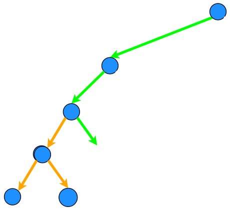

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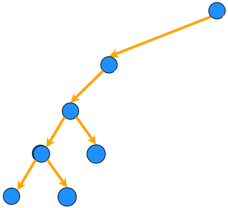

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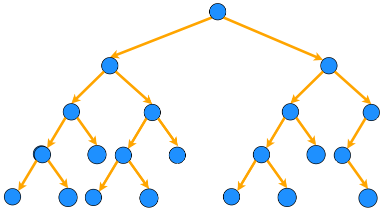

The problem

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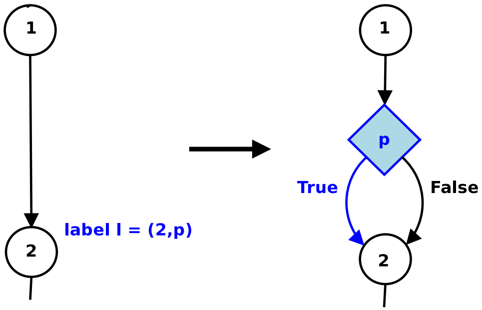
Challenge: extend DSE to a large class of coverage criteria

- well-known problem
- recent efforts in this direction through instrumentation [Active Testing, Mutation DSE, Augmented DSE]
- limitations:
  - exponential explosion of the search space [APEX: 272x avg]
  - very implementation-centric mechanisms
  - unclear expressiveness

Direct instrumentation P' [APEX, Mutation DSE]



Covering label l $\Leftrightarrow$ Covering branch `True`

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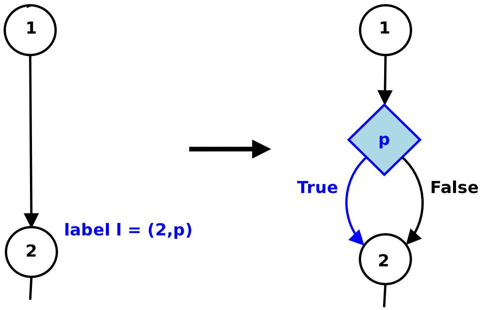

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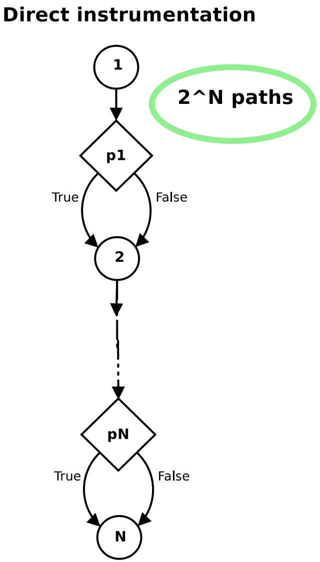
✓ sound & complete instrumentation w.r.t. **LC**

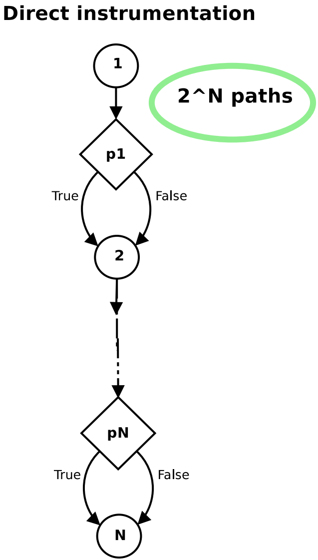
Direct instrumentation P' is not good enough



Direct instrumentation P' is not good enough

Non-tightness 1

- ✗ P' has exponentially more paths than P



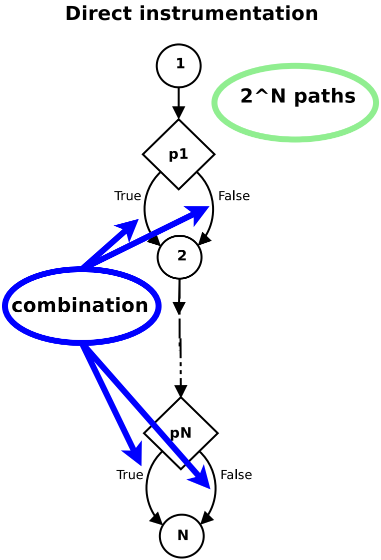
Direct instrumentation P' is not good enough

Non-tightness 1

- ✗ P' has exponentially more paths than P

Non-tightness 2

- ✗ Paths in P' too complex
  - at each label, require to cover p or to cover $\neg p$
  - π' covers up to N labels



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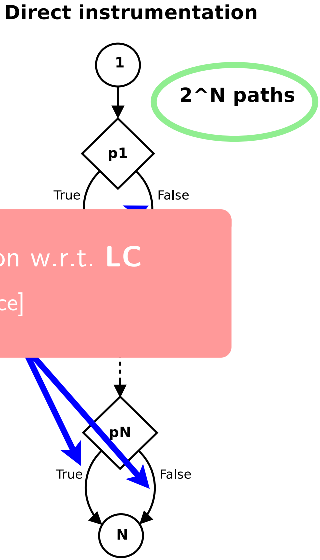


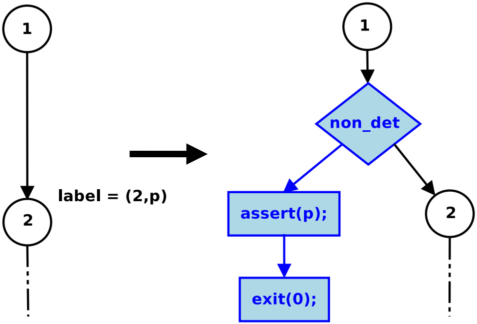
- ✓ sound & complete instrumentation w.r.t. **LC**
- ✗ dramatic overhead [theory & practice]

Our approach

The DSE* algorithm

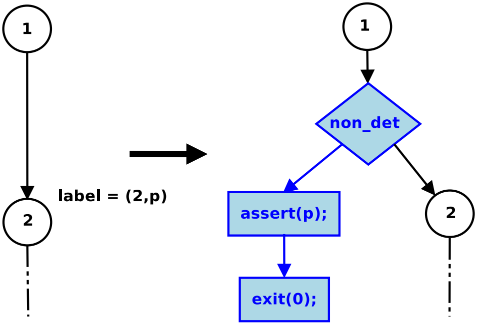
- Tight instrumentation $P^\star$: totally prevents "complexification"
- Iterative Label Deletion: discards some redundant paths
- Both techniques can be implemented in a black-box manner

DSE*: Tight Instrumentation $P^\star$



Covering label l $\Leftrightarrow$ Covering `exit(0)`

DSE*: Tight Instrumentation $P^\star$

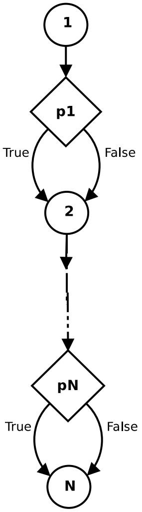


Covering label l $\Leftrightarrow$ Covering `exit(0)`

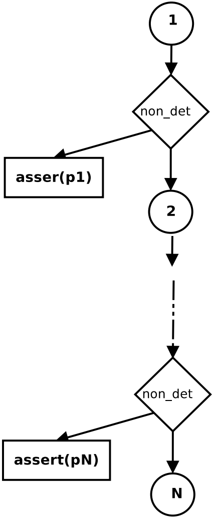
✓ sound & complete instrumentation w.r.t. **LC**

DSE*: Direct vs tight instrumentation, P' vs $P^\star$

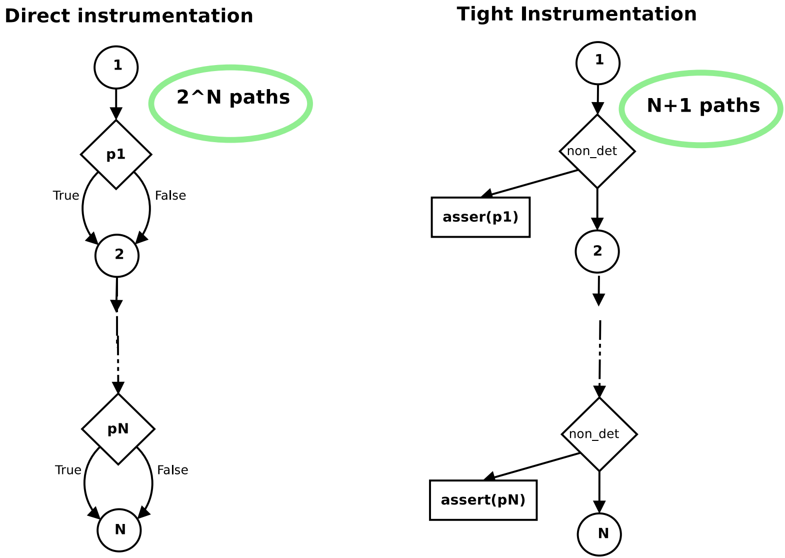
Direct instrumentation



Tight Instrumentation



DSE*: Direct vs tight instrumentation, P' vs $P^\star$



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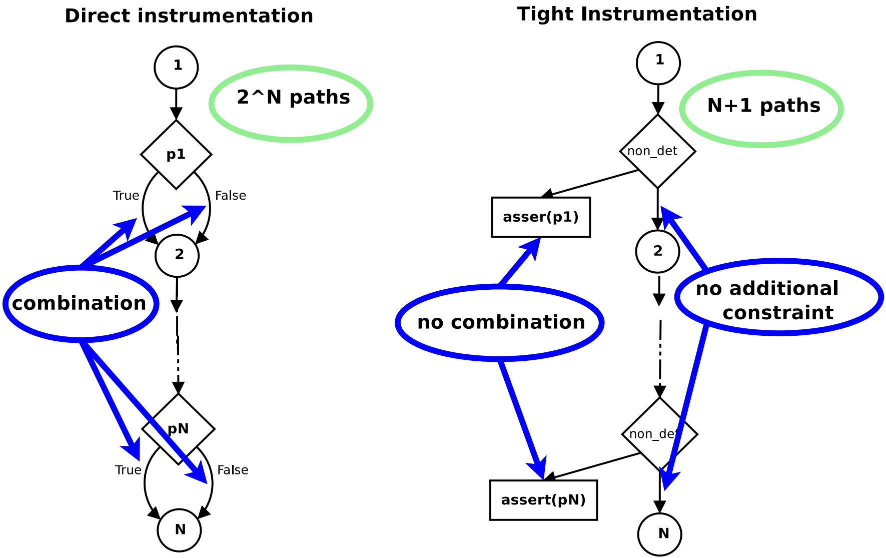
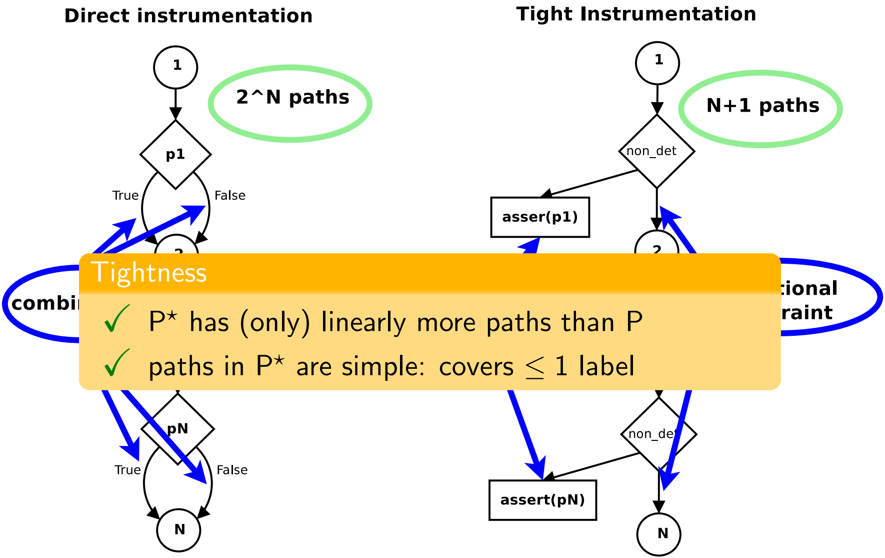
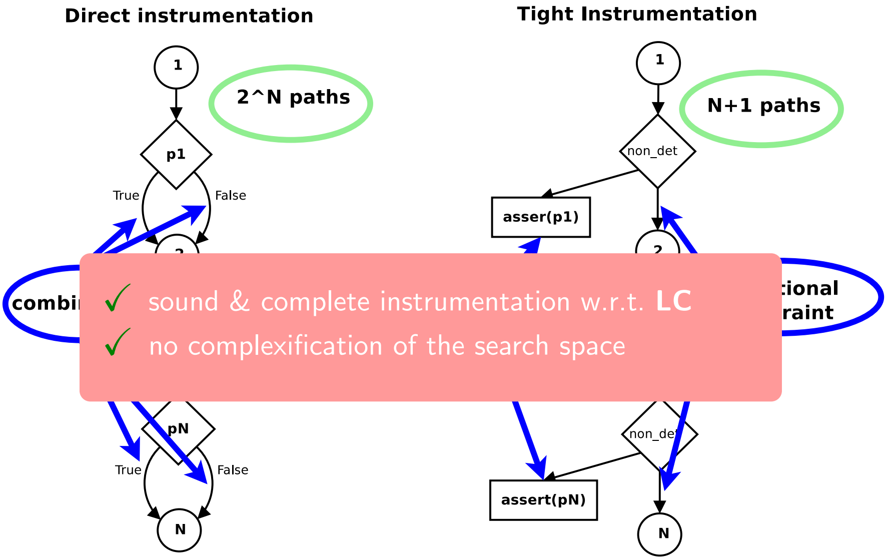


DSE*: Direct vs tight instrumentation, P' vs $P^\star$



Tightness

- ✓ $\mathrm{P}^\star$ has (only) linearly more paths than P
- ✓ paths in $\mathrm{P}^\star$ are simple: covers ≤ 1 label



✓ sound & complete instrumentation w.r.t. **LC**

✓ no complexification of the search space

DSE*: Iterative Label Deletion

Observations

- we need to cover each label only once
- yet, DSE explores paths of $P^\star$ ending in already-covered labels
- we burden DSE with "useless" paths w.r.t. **LC**

DSE*: Iterative Label Deletion

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- we burden DSE with "useless" paths w.r.t. **LC**

Solution: Iterative Label Deletion

- keep a *covered/uncovered* status for each label
- symbolic execution ignores paths ending in a covered label
- dynamic execution updates the status [truly requires DSE]

Implementation

- symbolic part: a slight modification of $P^\star$
- dynamic part: a slight modification of P'

DSE*: Iterative Label Deletion

Observations

- we need to cover each label only once
- yet, DSE explores paths of P* ending in already-covered labels
- we burden DSE with "useless" paths w.r.t. **LC**

Solution: Iterative Label Deletion

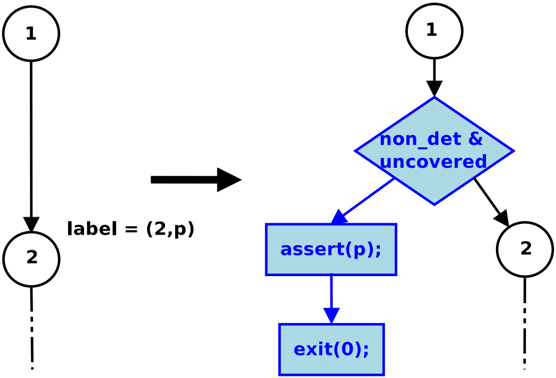
- keep a *covered/uncovered* status for each label
- symbolic execution ignores paths ending in a covered label
- dynamic execution updates the status [truly requires DSE]

Implementation

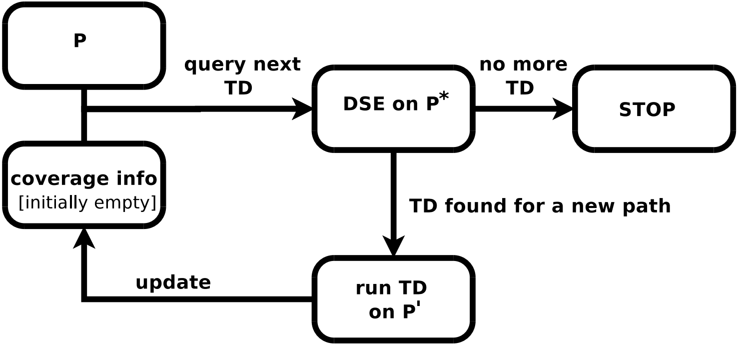
- symbolic part: a slight modification of $P^\star$
- dynamic part: a slight modification of P'

Iterative Label Deletion is relatively complete w.r.t. **LC**

DSE*: Iterative Label Deletion (2)



DSE*: Iterative Label Deletion (3)



Summary

The DSE* algorithm

- Tight instrumentation $P^\star$: totally prevents "complexification"
- Iterative Label Deletion: discards some redundant paths
- Both techniques can be implemented in black-box

Experiments

Implementation

- inside PathCrawler
- follows DSE*
- search heuristics: "label-first DFS"
- run in deterministic mode

Goal of experiments

- evaluate DSE* versus DSE'
- evaluate overhead of handling labels

Benchmark programs

- SQLite, OpenSSL
- 12 programs taken from standard DSE benchmarks (Siemens, Verisec, MediaBench)
- 3 coverage criteria: **CC**, **MCC**, **WM**

Experiments (2)

Results

- DSE': 4 timeouts (TO), max overhead 122x [excluding TO]
- DSE*: no TO, max overhead 7x (average: 2.4x)
- on one example, 94s instead of a TO [1h30]
- DSE* achieves very high **LC**-coverage [$>$ 90% on 28/36]
- after a static analysis step for detection of uncoverable labels, it becomes even higher [$>$ 99%]

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Conclusion

- DSE* performs significantly better than DSE'
- The overhead of handling labels is kept reasonable
- still room for improvement

Outline

1. Labels
2. LTest: an all-in-one testing toolset
3. Efficient test generation for labels
   - Dynamic Symbolic Execution (DSE)
   - DSE*: optimized test generation for labels
4. Detection of infeasible test objectives
5. Hyperlabel Specification Language (HTOL)
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The enemy: Uncoverable test objectives

- waste generation effort, imprecise coverage ratios
- reason: structural coverage criteria are ... structural
- detecting uncoverable test objectives is undecidable

Recognized as a hard and important issue in testing

- no practical solution
- not so much work (compared to test gen.)
- **real pain** (e.g. aeronautics, mutation testing)

Detection goals

Automatic detection of uncoverable test objectives

- a *sound* method
- applicable to a large class of coverage criteria
- strong detection power, reasonable speed
- rely as much as possible on existing verification methods:

Observation:

Label (loc, p) is uncoverable $\Leftrightarrow$ Assertion `assert` $(\neg p)$; at location *loc* is valid

Focus: checking assertion validity

- **Forward abstract interpretation, or Value Analysis (VA)** [state approximation]
  - compute an invariant of the program
  - then, analyze all assertions (labels) in one run
  - global but limited reasoning
- **Weakest precondition calculus (WP)** [goal-oriented]
  - perform a dedicated check for each assertion
  - a single check usually easier, but many of them
  - local but precise reasoning

Example: program with two uncoverable labels

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 // l1:  res == 0
 // l2:  res == 2
  return res;
}
```

Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;    // the only possible outcome
  else
    res = 0;
 //@ assert res != 0
 //@ assert res != 2
  return res;
}
```

Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0      // both VA and WP fail
 //@ assert res != 2      // detected as valid
  return res;
}
```

LUncov Methodology: Combine VA $\oplus$ WP

Goal: get the best of the two worlds

- Idea: VA passes to WP the global information that WP needs

Which information, and how to transfer it?

- VA computes variable domains
- WP naturally takes into account assumptions (`assume`)

Proposed solution:

- **VA exports computed variable domains in the form of WP-assumptions**

Example: alone, both VA and WP fail

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {



  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0     // both VA and WP fail

  return res;
}
```

Example: combination VA⊕WP succeeds

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VA inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0

  return res;
}
```

Example: combination VA⊕WP succeeds

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VA inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0        // ...  and WP succeeds!

  return res;
}
```

Detection power

Reuse the same benchmarks [Siemens, Verisec, Mediabench]

- 1,270 test requirements, 121 infeasible ones

	#Lab	#Inf	VA		WP		VA ⊕ WP	
			#d	%d	#d	%d	#d	%d
Total	1,270	121	84	69%	73	**60%**	118	**98%**
Min		0	0	0%	0	0%	2	**67%**
Max		29	29	100%	15	100%	29	100%
Mean		4.7	3.2	63%	2.8	**82%**	4.5	**95%**

#d: number of detected infeasible labels

%d: ratio of detected infeasible labels

Detection power

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- VA ⊕ WP achieves almost perfect detection
- detection speed is reasonable [$\leq$ 1s/obj.]

Impact on test generation

report more accurate coverage ratio

	Coverage ratio reported by DSE*		
Detection method	**None**	**VA ⊕WP**	**Perfect***
Total	**90.5%**	**99.2%**	100.0%
Min	**61.54%**	**91.7%**	100.0%
Max	100.00%	100.0%	100.0%
Mean	**91.10%**	**99.2%**	100.0%

* preliminary, manual detection of infeasible labels

LUncov: Results and Experiments

- automatic, sound and generic method
- new combination of existing verification techniques
- experiments for 12 programs and 3 criteria (CC, MCC, WM):
  - strong detection power (95%),
  - reasonable detection speed ($\leq$ 1s/obj.),
  - test generation speedup (3.8x in average),
  - more accurate coverage ratios (99.2% instead of 91.1% in average, 91.6% instead of 61.5% minimum)

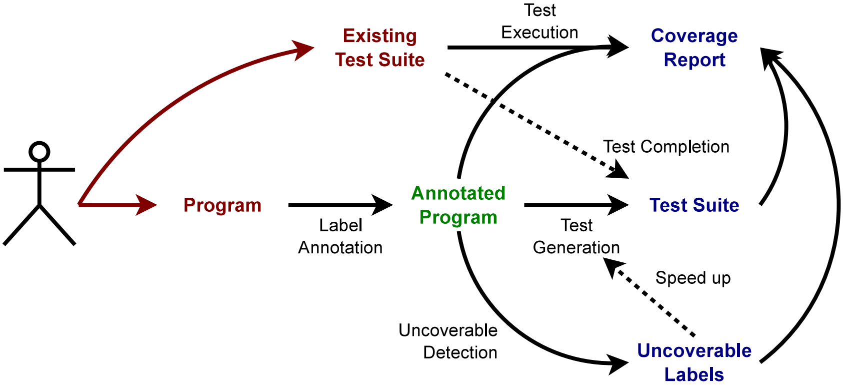
[Bardin et al. ICST 2014, TAP 2014, ICST 2015]

Breaking news: detect polluting objectives

Most recent work [Marcozzi et al. ICSE 2017, submitted]

- other sources of "pollution":
  - duplicate and/or subsumed test objectives
  - harmful effect [Papadakis et al., ISSTA 2016]
- detection technique:
  - WP-based dedicated algorithms
  - enhanced with multi-core and fine tuning
- achievements:
  - detecting a large number of polluting test objectives (up to 27% of the total number of objectives)
  - scales: OpenSSL, gzip, SQLite

LUncov in the LTEST toolset for labels



Uses static analyzers from FRAMA-C

- sound detection of uncoverable labels

Service cooperation

- share label statuses
- `Covered`, `Infeasible`, `?`

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Focus: GACC vs. MCDC criteria

MCDC:

- coverage criterion used in aeronautics
- demanding, industrially relevant
- requires to show that any atomic condition c_i in decision $D = D(c_1, ..., c_n)$ can independently influence the decision D
  - there exist two tests t_1 and t_2 such that:
  - $\forall j \neq i$, values of c_j on t_1 and t_2 are the same
  - values of c_i on t_1 and t_2 are different
  - values of D on t_1 and t_2 are different

Example: show that a alone can influence $D = a \wedge (b \vee c)$

- t_1: $(a = 1, b = 1, c = 0)$, $D = 1$
- t_2: $(a = 0, b = 1, c = 0)$, $D = 0$

Focus: GACC vs. MCDC criteria

GACC (global active clause coverage, a.k.a. shortcut MCDC)

- a weaker interpretation of MCDC, still demanding and industrially relevant
- the notion of "influences alone" is different
  - there exist two tests t_1 and t_2 such that:
  - $c_i =$ **False** on t_1
  - $c_i =$ **True** on t_2
  - for both t_1 and t_2, modifying c_i alone switches D
  - [no explicit link between t_1 and t_2 for the values of c_j or D]

Example: show that a alone can influence decision $D = a \wedge (b \vee c)$

- t_1: $(a = 1, b = 1, c = 0)$, $D = 1$
- t_2: $(a = 0, b = 1, c = 1)$, $D = 1$
- OK for GACC, not for MCDC

Focus: GACC vs. MCDC criteria

GACC can be encoded into labels [Tillmann et al. 2010]

- [no exact encoding is known for MCDC]

$$\begin{aligned}
\varphi_i \triangleq \quad & c_i = \mathbf{F} \ \wedge \ D(c_1, \ldots, c_{i-1}, \mathbf{T}, c_{i+1}, \ldots, c_n) \neq \\
& C(c_1, \ldots, c_{i-1}, \mathbf{F}, c_{i+1}, \ldots, c_n) \\
\varphi_i' \triangleq \quad & c_i = \mathbf{T} \ \wedge \ D(c_1, \ldots, c_{i-1}, \mathbf{T}, c_{i+1}, \ldots, c_n) \neq \\
& C(c_1, \ldots, c_{i-1}, \mathbf{F}, c_{i+1}, \ldots, c_n)
\end{aligned}$$

where $\mathbf{F} = \textbf{False}$, $\mathbf{T} = \textbf{True}$

Limitations of labels

- Labels encode only criteria whose objectives are reachability constraints
- Typical examples of criteria above labels:

Call Coverage

```
int f() {
if (...) { /* loc_1 */ g(); }
if (...) { /* loc_2 */ g(); }}
```

→ cover loc_1 or loc_2

All-defs

```
/* loc_1 */ a := x;
if (...) /* loc_2 */ res := x+1;
else /* loc_3 */ res := x-1;
```

→ Cover path loc_1 to loc_2
or path loc_1 to loc_3

MCDC

```
statement_0;
// loc_1
if (x==y && a<b) {...};
statement_2;
```

→ Cover if condition twice in a correlated way:
- a<b stays identical
- x==y and (x==y && a<b) change

DISJUNCTION

SAFETY

HYPERPROPERTIES

Hyperlabel Specification Language (HTOL)

- **A formal extension adding 5 operators to combine labels together (hyperlabels):**

l	::=	$\ell \triangleright B$	atomic label with bindings
B	::=	$\{v_1 \leftarrow e_1; \ldots\}$	bindings
h	::=	l	label
	|	$[l_1 \xrightarrow{\phi_1} \{l_i \xrightarrow{\phi_i} \}^* \; l_n]$	sequence of labels
	|	$\langle h \mid \psi \rangle$	guarded hyperlabel
	|	$h_1 \cdot h_2$	conjunction of hyperlabels
	|	$h_1 + h_2$	disjunction of hyperlabels

Formal Semantics:

LABEL

$$\frac{t \in TS \qquad t \rightsquigarrow_P^k \langle loc, s\rangle \qquad s \models \varphi \qquad \mathcal{E} \supseteq [\![B]\!]_s}{t \rightsquigarrow_{\mathcal{E}}^k \langle loc, \varphi\rangle \triangleright B \qquad \langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P \langle loc, \varphi\rangle \triangleright B}$$

GUARD

$$\frac{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h \qquad \mathcal{E} \models \psi}{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P \langle h \mid \psi\rangle}$$

CONJUNCTION

$$\frac{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_1 \qquad \langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_2}{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_1 \cdot h_2}$$

DISJUNCTION LEFT

$$\frac{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_1}{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_1 + h_2}$$

DISJUNCTION RIGHT

$$\frac{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_2}{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P h_1 + h_2}$$

SEQUENCE

$$\frac{\begin{array}{c} t \in TS \qquad \forall i \in [1,n],\ t \rightsquigarrow_{\mathcal{E}}^{k_i} l_i \qquad \forall i \in [1, n-1],\ k_i < k_{i+1} \\ \forall i \in [1, n-1],\ \forall j \in]k_i, k_{i+1}[,\ (loc_j, s_j) = P(t)_j \wedge \phi_i(\mathcal{E}, loc_j, s_j) \end{array}}{\langle TS, \mathcal{E}\rangle \overset{\text{H}}{\rightsquigarrow}_P [l_1 \xrightarrow{\phi_1} \{l_i \xrightarrow{\phi_i} \}^{*}\ l_n]}$$

Naming convention: TS test suite; $\mathcal{E}$ hyperlabel environment; h, h_1, h_2 hyperlabels; ψ hyperlabel guard predicate; n positive integer; $l_1, \ldots, l_n$ atomic labels with bindings; t test datum; $k, k_1, \ldots, k_n$ execution step numbers; loc_j, loc program locations; s_j, s execution states; $P(t)_j$ the j-th step of the program run $P(t)$ of P on t; $\phi_1, \ldots, \phi_n$ predicates over sequences of labels; φ label predicate; B hyperlabel bindings.

HTOL: Examples

- Hyperlabels add operators to combine labels together!

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int f() {
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if (...) { /* loc_2 */ g(); }}
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→ cover loc_1 or loc_2

$$(loc_1, true) + (loc_2, true)$$

All-defs

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/* loc_1 */ a := x;
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→ Cover path loc_1 to loc_2
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$$((loc_1, true) \rightarrow (loc_2, true)) + ((loc_1, true) \rightarrow (loc_3, true))$$

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→ Cover if condition twice in a correlated way:
- a<b stays identical
- x==y and d=(x==y && a<b) change

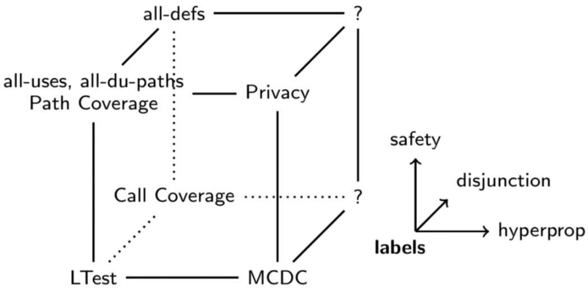
$$l \triangleq (loc_1, d) \triangleright \{c_1 \hookleftarrow \texttt{x==y};\ c_2 \hookleftarrow \texttt{a<b}\}$$

$$l' \triangleq (loc_1, \neg d) \triangleright \{c'_1 \hookleftarrow \texttt{x==y};\ c'_2 \hookleftarrow \texttt{a<b}\}$$

$$h_1 \triangleq \langle l \cdot l' \mid c_1 \neq c'_1 \land c_2 = c'_2 \rangle$$

HTOL: Taxonomy of coverage criteria

- Labels can encode test objectives that are **reachability constraints**
- **RESULT 1:** labels must be extended along **three orthogonal directions** to handle other criteria:



HTOL: Expressiveness and support

- **RESULT 2: Formal definition of the hyperlabel language (HTOL)**
  - Extends labels into the three directions
  - Adds support for **all criteria** including MCDC (except from full mutations)
  - Offers nice other testing perspectives (e.g. security hyperproperties, like non-interference)

Tool name	BBC	FC	DC	CC	DCC	GACC	MCDC	MCC	BP	Other
Gcov	✓	✓	✓							0/19
Bullseye		✓			✓					0/19
Parasoft	✓	✓	✓	✓			✓		✓	0/19
Semantic Designs		✓	✓							0/19
Testwell CTC++	✓	✓			✓		✓			0/19
LTest	✓	✓	✓	✓	✓	✓		✓		4/19
Hyper-LTest	✓	✓	✓	✓	✓	✓	✓	✓	✓	18/19

- **RESULT 3: Extension of Ltest to hyperlabels (in progress, essentially coverage)**

→ Current work provides a full-featured testing tool for all criteria

(yet, test generation is suboptimal, since hyperlabels not considered)

Outline

1. Labels
2. LTest: an all-in-one testing toolset
3. Efficient test generation for labels
   - Dynamic Symbolic Execution (DSE)
   - DSE*: optimized test generation for labels
4. Detection of infeasible test objectives
5. Hyperlabel Specification Language (HTOL)
6. Conclusion

Summary

Labels: a generic specification mechanism for coverage criteria

- can easily encode a large class of criteria
- a semantic view, with a formal treatment

DSE*: an efficient test generation technique for labels

- an optimized version of DSE (Dynamic Symbolic Execution)
- no exponential blowup of the search space

LUncov: an efficient technique for detection of infeasible objectives

- based on existing static analysis techniques

LTest: an all-in-one testing toolset

- on top of FRAMA-C and PATHCRAWLER

HTOL: Hyperlabel Specification Language, extension of labels

- capable to encode almost all common criteria including MCDC

Reminder: Goals

Specify [✓] and Measure, [✓], Cover [✓] and Unmask [✓]

Future work

- An efficient dedicated support of hyperlabels in test generation (DSE)
- Further optimizations of LTest (e.g. detection of uncoverable hyperlabels)
- Developing the emerging interest for LTool in industry