Design of a Modified Concolic Testing Algorithm with Smaller Constraints

Yavuz Koroglu   Alper Sen

Department of Computer Engineering
Bogazici University, Turkey
yavuz.koroglu@boun.edu.tr
depend.cmpe.boun.edu.tr

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Constraint-Based Testing (CBT)

Definition

If a testing technique uses a **constraint solver** to generate test cases, it is called **Constraint-Based Testing (CBT)**.

- Automated Unit Test Generation
  - Black-Box Testing
    - Random Testing (RT)
      - Adaptive Random Testing (ART)
    - Model-Based Testing (MBT)
  - White-Box (Structural) Testing
    - Search-Based Testing (SBT)
    - Constraint-Based Testing (CBT)
      - Symbolic Execution
      - Concolic Testing

Constraint-Based Testing (Overview)

- The term coined in 1991 by Offut and DeMillo.
- **Symbolic Execution** (dates back to 1975),
  - Considered **impractical**, lack of powerful constraint solvers.
- **Revival** in the last two decades,
  - Availablity of powerful constraint solvers (Yices, Z3 etc.),
  - **Concolic testing** is proposed.
- **Constraint solving bottleneck**,
  - **Scalability** issues.
  - Constraint solving optimizations (Concolic Unit Testing Engine (CUTE) offers **three** optimizations).
    - Did not completely solve the issue.

Our Motivation

What did we aim?

Design a modification on the current constraint solving methodology which

- **Decreases the burden** on the constraint solver,
- Still gets the **same coverage** as the previous CBT approaches and
- Allows **new heuristics and optimizations** to be implemented.

Our Motivation

What did we see?

CBT approaches make **few large queries** to the constraint solver.

- Instead, make **thousands of small queries**.
- In model checking domain, IC3 uses this strategy.
  (SAT-Based Model Checking Without Unrolling, Aaron R. Bradley, VMCAI2011)
- Can we better utilize constraint solvers in CBT?

Concolic Testing

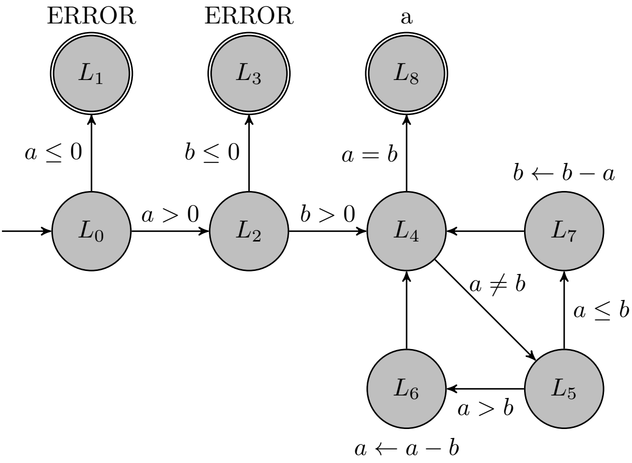
- Also called **Dynamic Symbolic Execution (DSE)**.
- Combines **conc**rete and symb**olic** execution.
- The idea dates back to **2005** (CUTE and DART).
- We implement our approach on top of Concolic Testing.

Example: Greatest Common Divisor (GCD)

```
int gcd(int a, int b) {
    if (a <= 0) {          // L0
        return ERROR;      // L1
    }
    if (b <= 0) {          // L2
        return ERROR;      // L3
    }
    while (a != b) {       // L4
        if (a > b) {       // L5
            a = a - b;     // L6
        } else {
            b = b - a;     // L7
        }
    }
    return a;              // L8
}
```

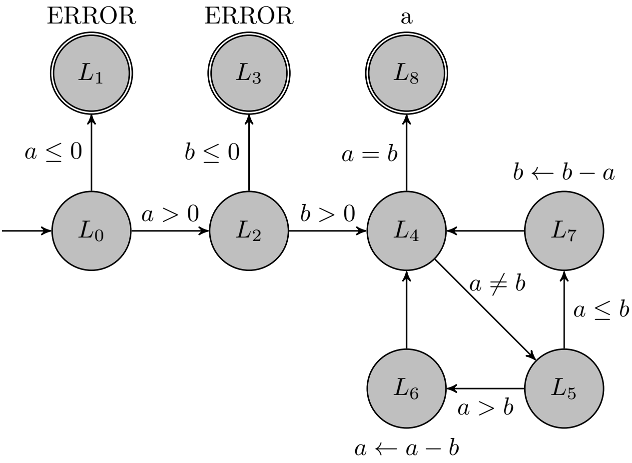
Test GCD using Concolic Testing

1) Generate random inputs: let $a = 4$, $b = 0$.



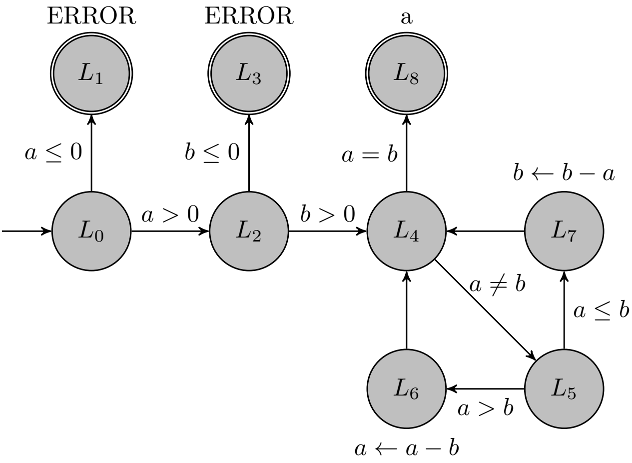
Test GCD using Concolic Testing

2) gcd(4,0) traverses the following execution path: $L_0 \rightarrow L_2 \rightarrow L_3$.



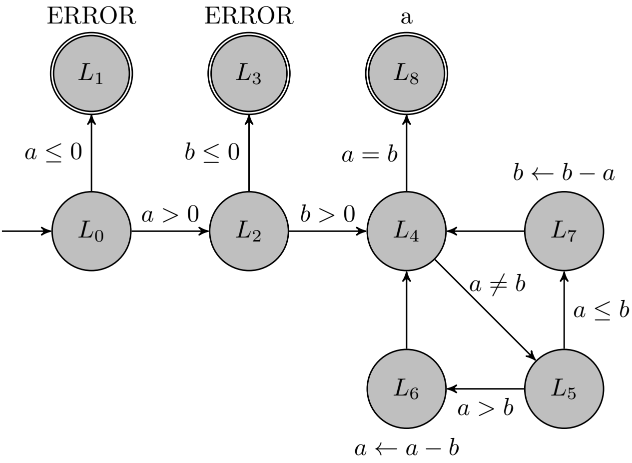
Test GCD using Concolic Testing

3) Gather $\pi_0 = (a > 0) \wedge (b \leq 0)$ during execution.



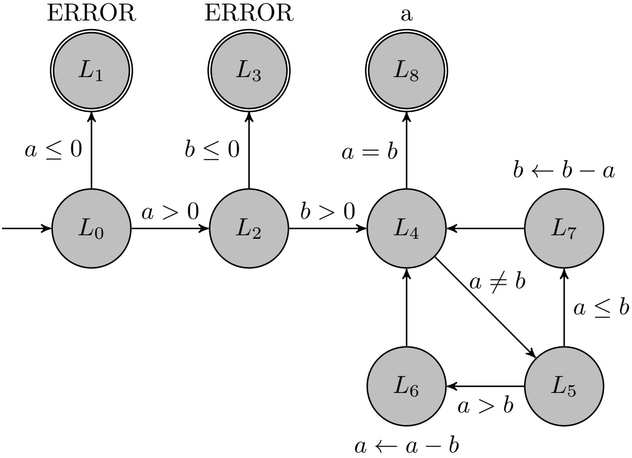
Test GCD using Concolic Testing

4) π_0 is a **full path constraint**.



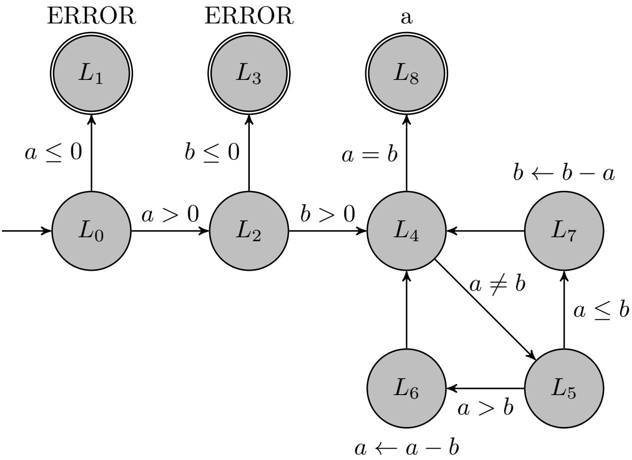
Test GCD using Concolic Testing

5) Full path constraint is the conjunction of all path conditions on an execution path.



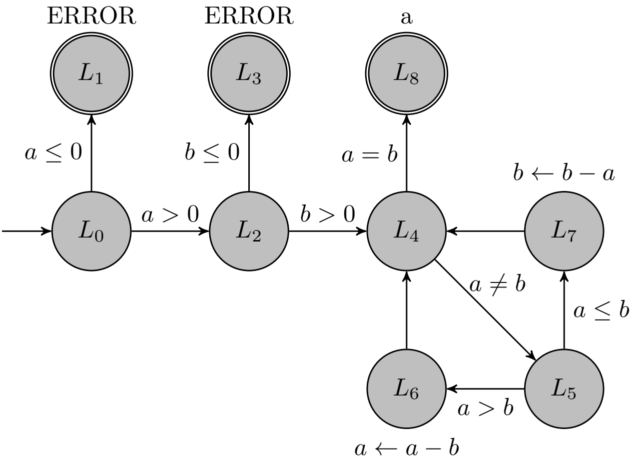
Test GCD using Concolic Testing

6) Generate $\phi_1 = (a > 0) \wedge (b > 0)$.



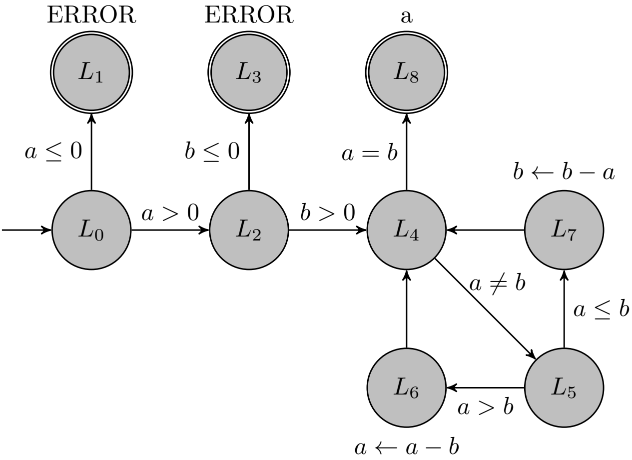
Test GCD using Concolic Testing

7) Let CS(ϕ_1) be $a = 4$ and $b = 6$.



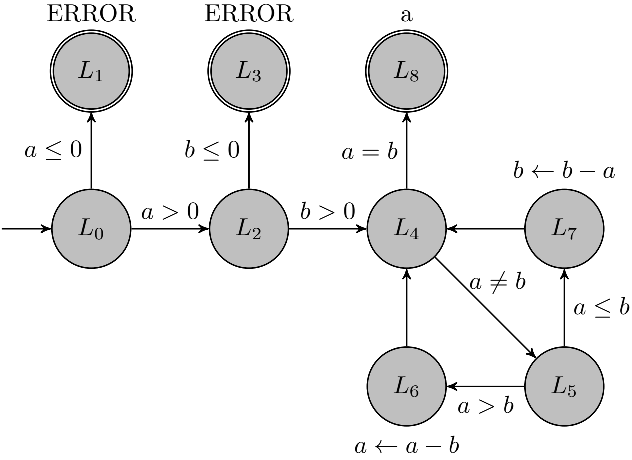
Test GCD using Concolic Testing

8) gcd(4,6) traverses
$L_0 \to L_2 \to L_4 \to L_5 \to L_7 \to L_4 \to L_5 \to L_6 \to L_4 \to L_8$.



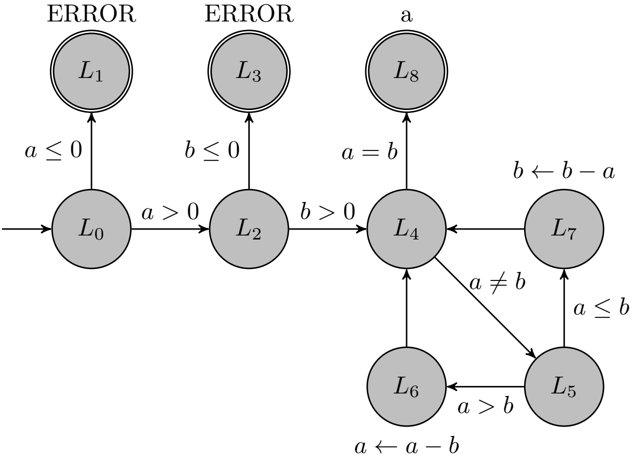
Test GCD using Concolic Testing

9) Gather $\pi_1 = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] = b - a)$.



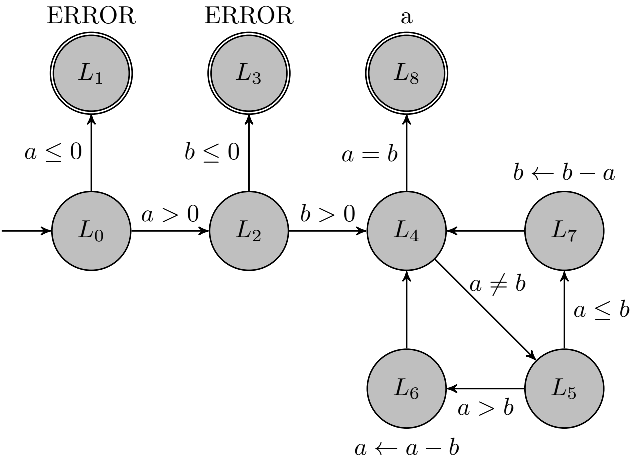
Test GCD using Concolic Testing

10) Solved only a small constraint (ϕ_1) to get an input which satisfies a large constraint (π_1).



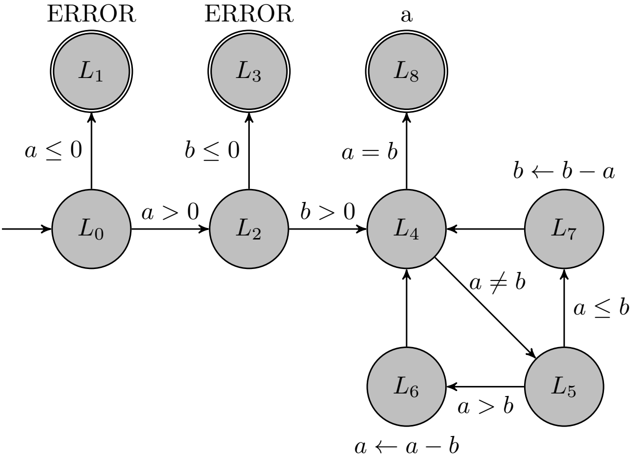
Test GCD using Concolic Testing

11) After a few iterations constraints get **very large**.



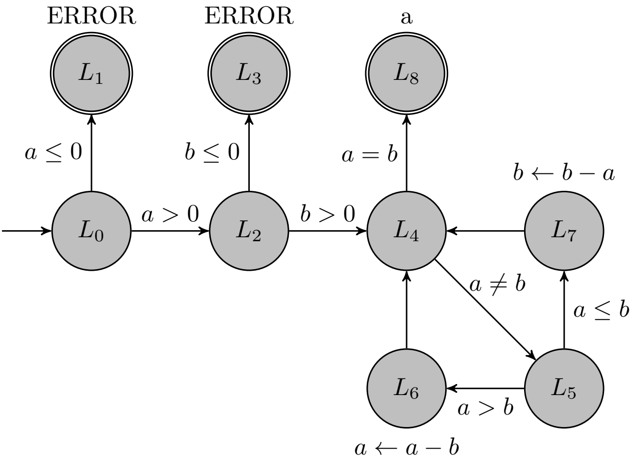
Test GCD using Concolic Testing

12) Generate $\phi_2 = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$.



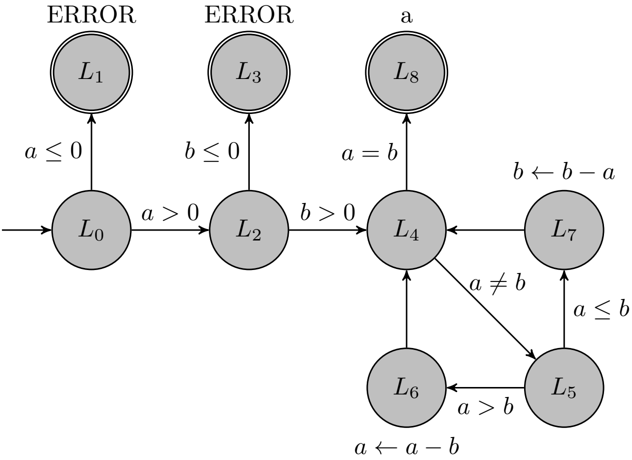
Test GCD using Concolic Testing

13) Let $\mathsf{CS}(\phi_2) = a = 5,\ b = 6.$



Test GCD using Concolic Testing

14) gcd(5,6) traverses $L_0 \to L_2 \to L_4 \to L_5 \to L_7 \to L_4 \to L_5 \to L_6 \to L_4 \to L_5 \to L_6 \to L_4 \to \ldots$



Previous Constraint Solving Optimizations

- One of the first concolic testers, CUTE,
  - Proposes **three** optimizations for **constraint solving**:

1) Fast Unsatisfiability Check.
2) Common Sub-Constraints Elimination.
3) Incremental Solving.

(OPT1) Fast Unsatisfiability Check

Main Idea

- Check if a path condition is **syntactically the negation** of any preceding ones in the full path constraint.
  e.g. $\pi = \ldots \wedge (a = b) \wedge \ldots \wedge (a \neq b) \wedge \ldots$
- If it is, the full path constraint is decided to be **infeasible** without solving.

OPT1,

- Reduces the number of constraint solver queries by 60-95% in general.
- Reduction in the GCD example: 0%.

(OPT2) Common Sub-Constraints Elimination

Main Idea

- Identify and eliminate common sub-constraints.

OPT2,

- Reduces common sub-constraints by 64-90% in general.
- Reduction in the GCD example: 0%.

(OPT3) Incremental Solving

Main Idea

- Remember that $\pi_0 = (a > 0) \wedge (b \leq 0)$ and $\phi_1 = (a > 0) \wedge (b > 0)$ from the GCD example.
- π_0 and ϕ_1 only differ by one condition.
- Let the conjunction of all conditions on ϕ_1 that depend on $(b > 0)$ be ${\phi_1}' = (b > 0)$.
- Let the solver fix a to its previous value and find a solution for ${\phi_1}'$ instead of ϕ_1.

OPT3,

- On average, $|\phi'| \approx |\phi|/8$ in general.
- On the GCD example: No significant improvement.

Partial Path Constraints (ϕ)

Definition

Any **overapproximation** of the Full Path Constraint π is called a Partial Path Constraint (ϕ).

Example

- Let $\pi = (a > 0) \wedge (b \leq 0)$.
- Then, the possible partial path constraints are
  - $\phi_0 = T$,
  - $\phi_1 = (a > 0)$,
  - $\phi_2 = (b \leq 0)$ and
  - $\phi_3 = (a > 0) \wedge (b \leq 0)$.

Motivation of Partial Path Constraints

- There are **subsumed** path conditions.

1. In the GCD example, ϕ_2 contains both $p = (a \neq b - a)$ and $q = (a > b - a)$.
2. Trivially, $q \to p$.
3. So, p is **redundant**.
4. We should **eliminate** redundant path conditions.

Partial Path Constraints Cont'd

- Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a = b)$.
- Let $\phi = (a = b)$.
- Probability of CS(ϕ) also satisfies π is 0.25.
- For $\phi' = (b > 0) \wedge (a = b)$, probability becomes 0.50.

Danger!

- Usage of partial path constraints may cause **path divergence**.
- Therefore, some feasible execution paths may not get executed (**incompleteness**).

Incremental Partial Path Constraints (IPPC)

Main Idea

- **Same** as concolic testing.
- We **replace** the constraint solver call with IPPC.
- IPPC tries a **small** partial path constraint.
- Learns **larger** ϕ and tries again until the answer is found.

Incremental Partial Path Constraints (IPPC)

Algorithm

1. Start from a partial path constraint ϕ where $\pi \rightarrow \phi$.
2. Generate test input i that satisfy ϕ.
3. If ϕ is infeasible, then π must be infeasible.
4. Else if i satisfies π, return i.
5. Find out the first path condition c_d which i does not satisfy.
6. Let $\phi \leftarrow \phi \wedge c_d$.
7. Goto 2.

- c_d is called the **Cause of Divergence**.
- Steps 5-6-7 occurs only if generated i causes a **path divergence**.

Determining Initial ϕ: Most Basic Strategy

Motivation

We negate **only one condition** on the previously satisfied full path constraint.

Approach

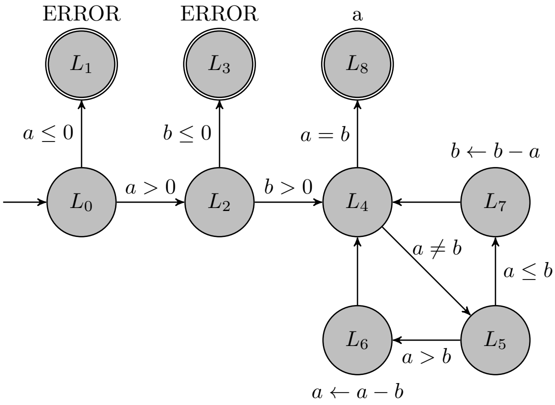
Take the **negated condition** as the initial ϕ.

Advantage

Incremental Solving optimization (OPT3) has more chance to satisfy π by fixing some of the inputs.

Example Returned: GCD

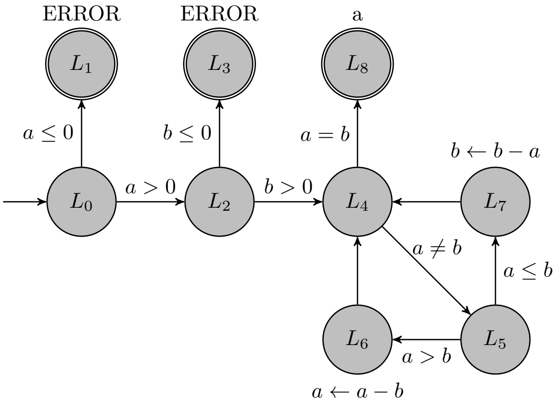
1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

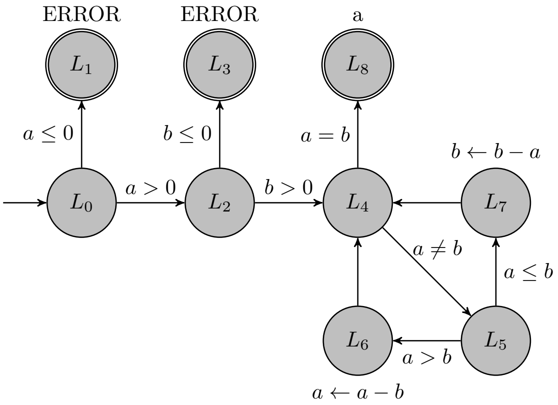
2) Let us solve this constraint using IPPC instead of a CS call.



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

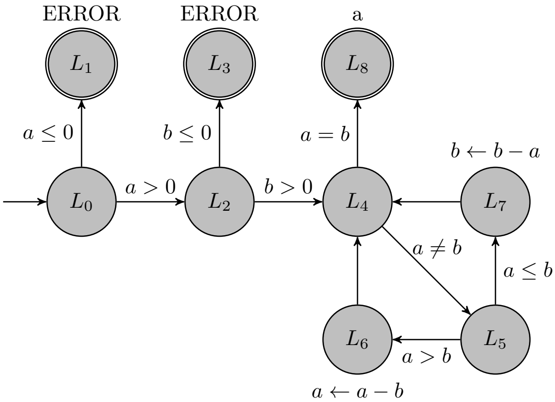
3) $\phi^1 = (a - [b - a] \neq b - a)$.



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

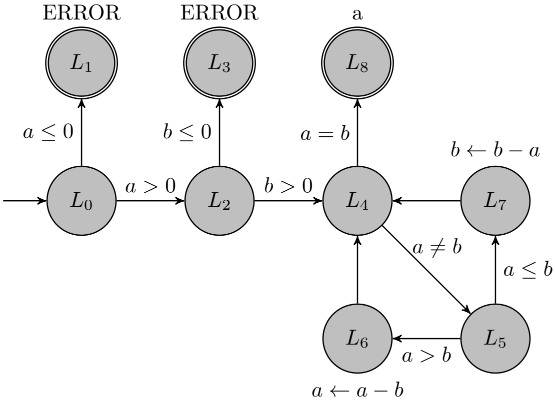
4) Yices in incremental mode generates $a = 2, b = 3$ for CS(ϕ^1).



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

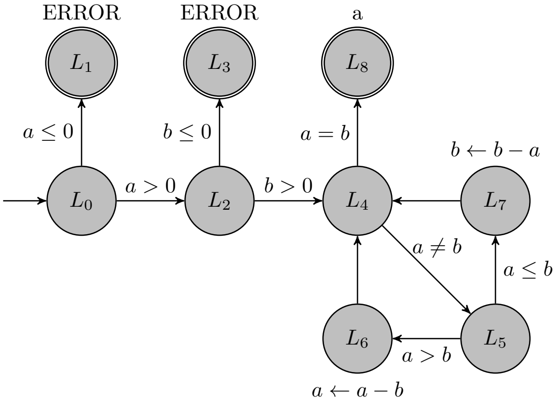
5) $(a, b) = (2, 3)$ does **NOT** satisfy π due to $c_d^1 = (a \neq b - a)$.



Example Returned: GCD

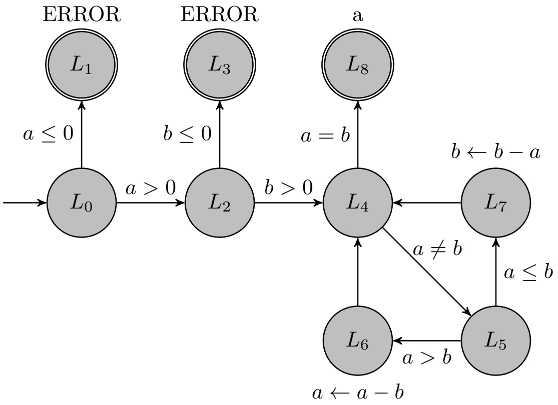
1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

6) $\phi^2 = \phi^1 \wedge c_d^1 = (a - [b - a] \neq b - a) \wedge (a \neq b - a)$.



Example Returned: GCD

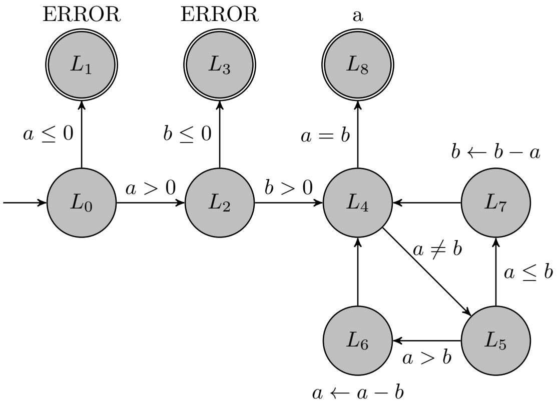
1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).
7) Yices generates $a = 4, b = 6$ for CS(ϕ^2) which satisfies the π.



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

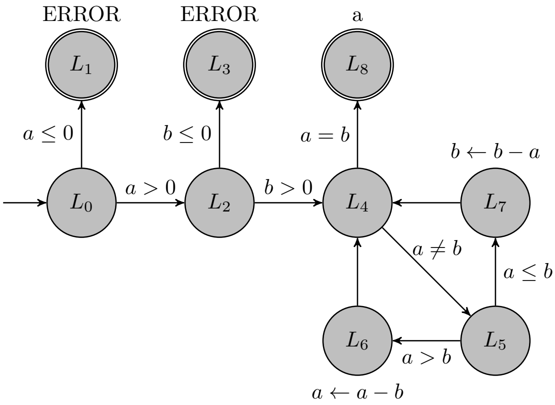
8) Standard concolic tester solves 1 path constraint of size 7.



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

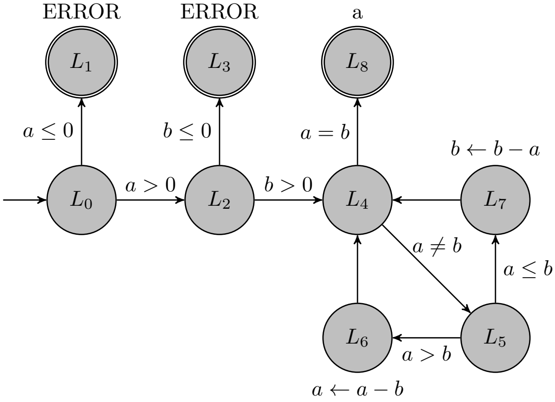
9) IPPC solves 2 path constraints of sizes 1 and 2.



Example Returned: GCD

1) Consider $\pi = (a > 0) \wedge (b > 0) \wedge (a \neq b) \wedge (a \leq b) \wedge (a \neq b - a) \wedge (a > b - a) \wedge (a - [b - a] \neq b - a)$ (ϕ_2 of the previous example).

10) More smaller queries vs. Few larger queries



Experimental Environment

The Environment

- Virtual Linux guest with 1024MB memory and one CPU,
- MacBook Pro host with an Intel Core i7 2.9 GHz GPU and 8GB Memory.

The Framework

CREST, is a known concolic testing framework developed by J. Burnim.

- **Source code** available.
- It uses **Yices**.
- It implements **different** concolic testing **strategies**.

Benchmarks

List of benchmarks used in the experiments are as follows:

UUT	**KLOC**	**#vars**
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

Benchmarks

All conditions are guaranteed to be correctly solvable by Yices.

UUT	KLOC	#vars
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

Benchmarks

Benchmarks are in different sizes.

UUT	KLOC	#vars
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

Benchmarks

We made 10 executions for each configuration.

UUT	**KLOC**	**#vars**
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

Benchmarks

We measured branch coverage via a script which uses `gcov`.

UUT	KLOC	#vars
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

Benchmarks

Standard Concolic Testing and IPPC achieves the same coverage in N iterations.

UUT	**KLOC**	**#vars**
gcd	0.05	2
bsort	0.05	30
sqrt	0.06	1
prime	0.1	1
factor	0.2	1
replace	0.5	20
ptokens	0.6	40
grep	15	10

IPPC Speedup over Standard Concolic Testing (DFS)

IPPC has smaller constraints by a factor of 60.

UUT	Avg Const. Size Ratio (DFS / IPPC)	Speedup (t_{DFS}/t_{IPPC})
replace	4.4	0.6x
bsort	20.8	0.79x
sqrt	21.3	1.25x
grep	31.8	0.83x
ptokens	48.4	1.7x
gcd	97.5	2.77x
prime	115.6	9.1x
factor	137.3	9.8x
avg	**59.6**	**3.35x**

IPPC Speedup over Standard Concolic Testing (DFS)

IPPC has a speedup of 3.35 on average.

UUT	Avg Const. Size Ratio (DFS / IPPC)	Speedup ($t_{\mathrm{DFS}}/t_{\mathrm{IPPC}}$)
replace	4.4	0.6x
bsort	20.8	0.79x
sqrt	21.3	1.25x
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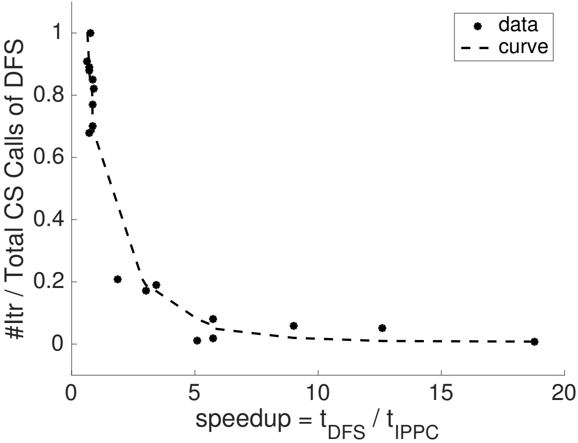
prime	115.6	9.1x
factor	137.3	9.8x
avg	**59.6**	**3.35x**

Relationship btw. Infeasible Constraints and Speedup

IPPC has better speedup when the UUT has more infeasibilities.



Conclusion

In this work, we desgined a modification which,

- Eliminates the need for solving large constraints,
  - Largest path constraint sizes found during the experiments:
    1. IPPC: 157
    2. DFS: 2922
- Works better if the UUT has many infeasible paths and
- Is **flexible**.

We also,

- Gave motivational examples and background for our work.
- Strongly suggested a relationship between speedup and infeasibility.
- Did experiments on the benchmarks.

Future Work

Caching

- KLEE utilizes caching as a performance improving optimization.
- We use partial path constraints,
  - Therefore we can have **both-way** caching:
  - Inputs have a corresponding full path constraint (input $\rightarrow$ path constraint, reduces UUT execution)
  - Full path constraints are mapped to inputs. (path constraint $\rightarrow$ input, reduces CS execution)

Future Work

Independent Path Conditions as the Initial ϕ

- Using a greedy algorithm, find a set of independent path conditions.
- Conjunct all the independent conditions to get the Initial ϕ.
- Maybe we can decrease the total CS calls if we use this initial ϕ.

Future Work

Implementation on Different Frameworks and More Benchmarks

- We should find more benchmarks (currently there are 8 benchmarks),
- We should implement IPPC on top of different CBT approaches,

Thank You. Any Questions?