Tamarin: Concolic Disequivalence for MIPS

Abel Nieto

A Tale of Two Boxes

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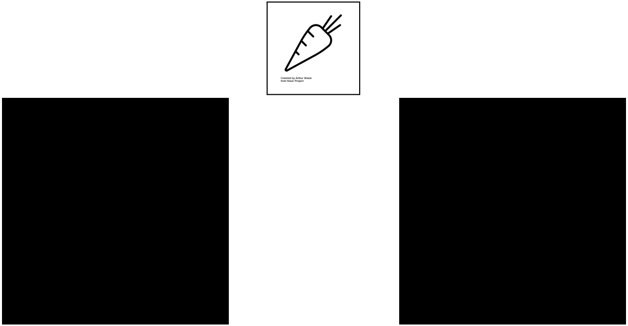

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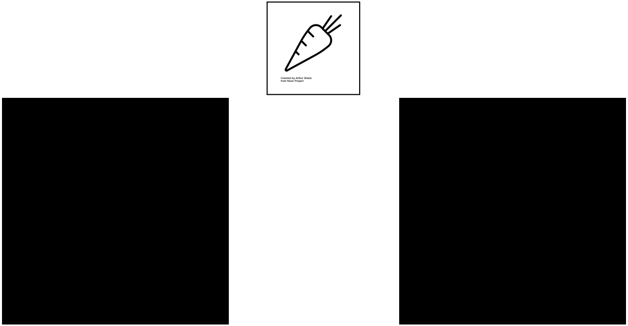

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A Tale of Two Boxes

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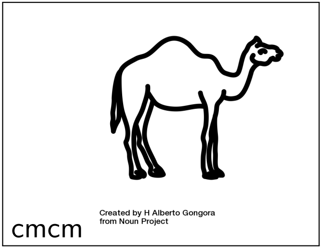

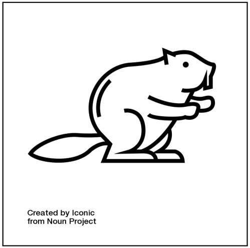

$$\neq$$

The Problem

Given MIPS program P_1 and P_2, when are they equivalent?

The Problem

Attempt 1: two programs are equivalent if they give the same output (resp.) for all inputs.

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What's an output?

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What's an input? Register \$1 and \$2.
What's an output? Register \$3.

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Attempt 1: two programs are equivalent if they give the same output (resp.) for all inputs.

What's an input? Register \$1 and \$2.
What's an output? Register \$3.

Don't care about (most) CPU interrupts/IO.

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Problem: undecidable via Rice's theorem.

The Problem

Attempt 2: two programs are S-equivalent if they cannot be told apart after S steps.

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Attempt 2: two programs are S-equivalent if they cannot be told apart after S steps.

S-equivalent (e.g. for $S = 10$), but not equivalent:

```
# P_1
add $3, $1, $2
```

```
# P_2
  add $4, $0, 1   # counter
  add $5, $0, 42  # upper bound
loop:
  slt $6, $4, $5
  beq $6, $0, end
  add $4, $4, 1
  beq $0, $0, loop
end:
  add $3, $1, $1
```

The Problem

Attempt 2: two programs are S-equivalent if they **cannot be told apart** after S steps.

R_1	R_2	S-equiv

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R_1	R_2	S-equiv
v	v	yes

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R_1	R_2	S-equiv
v	v	yes
v	$w \neq v$	no

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R_1	R_2	S-equiv
v	v	yes
v	$w \neq v$	no
v	error	no

The Problem

Attempt 2: two programs are S-equivalent if they **cannot be told apart** after S steps.

R_1	R_2	S-equiv
v	v	yes
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v	error	no
error	error	yes

The Problem

Attempt 2: two programs are S-equivalent if they **cannot be told apart** after S steps.

R_1	R_2	S-equiv
v	v	yes
v	$w \neq v$	no
v	error	no
error	error	yes
non-termination	???	yes
$\ldots$		

The Problem

Lemma

Equivalence implies S-equivalence.

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Lemma

Equivalence implies S-equivalence.

Corollary (Soundness)

If two programs are not S-equivalent (for any S), then they are not equivalent.

The Problem

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Which inputs?

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Try some inputs by hand: low coverage, fast (unit tests)

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Try all 2^{64}values of $1 and $2: high coverage, slow (but decidable)

The Problem

Attempt 2: two programs are S-equivalent if they **cannot be told apart** after S steps.

Which inputs?

Try some inputs by hand: low coverage, fast (unit tests)

Try all 2^{64}values of $1 and $2: high coverage, slow (but decidable)

Tamarin: use concolic execution: higher coverage(?), not too slow(?)

Idea

Alternating concolic execution

```
# P_1
  bne $1, 42, end
  add $3, $3, $0
end:
  add $3, $1, $2
```

```
# P_2
  add $3, $1, $2
  bne $2, 100, end
  add $3, $3, $2
end:
```

Idea

Alternating concolic execution

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# P_1
  bne $1, 42, end
  add $3, $3, $0
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# P_2
  add $3, $1, $2
  bne $2, 100, end
  add $3, $3, $2
end:
```

Run	Driver	Verifier	\$1	\$2	Path	R_D	R_V

Idea

Alternating concolic execution

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# P_1
  bne $1, 42, end
  add $3, $3, $0
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  add $3, $1, $2
```

```
# P_2
  add $3, $1, $2
  bne $2, 100, end
  add $3, $3, $2
end:
```

Run	Driver	Verifier	\$1	\$2	Path	R_D	R_V
1	P_1	P_2	1	1	$\$1 \neq 42$	2	2

Idea

Alternating concolic execution

```
# P_1
  bne $1, 42, end
  add $3, $3, $0
end:
  add $3, $1, $2
```

```
# P_2
  add $3, $1, $2
  bne $2, 100, end
  add $3, $3, $2
end:
```

Run	Driver	Verifier	\$1	\$2	Path	R_D	R_V
1	P_1	P_2	1	1	$\$1 \neq 42$	2	2
2	P_2	P_1	1	1	$\$2 \neq 100$	2	2

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  add $3, $1, $2
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end:
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Run	Driver	Verifier	\$1	\$2	Path	R_D	R_V
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3	P_1	P_2	42	1	$\$1 = 42$	2	2

Idea

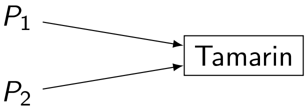
Alternating concolic execution

```
# P_1
  bne $1, 42, end
  add $3, $3, $0
end:
  add $3, $1, $2
```

```
# P_2
  add $3, $1, $2
  bne $2, 100, end
  add $3, $3, $2
end:
```

Run	Driver	Verifier	\$1	\$2	Path	R_D	R_V
1	P_1	P_2	1	1	$\$1 \neq 42$	2	2
2	P_2	P_1	1	1	$\$2 \neq 100$	2	2
3	P_1	P_2	42	1	$\$1 = 42$	2	2
4	P_2	P_1	1	100	$\$2 = 100$	201	2

Tamarin (Overview)



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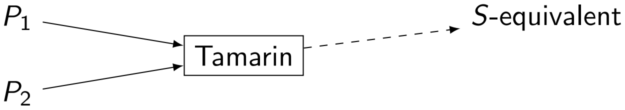

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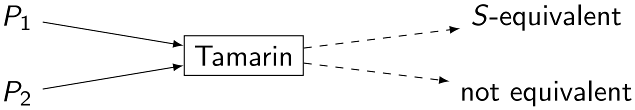

Tamarin (Overview)

Concolic

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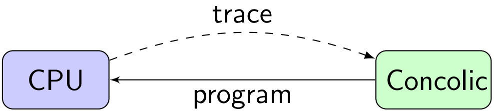

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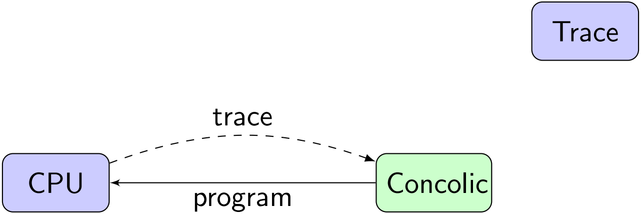

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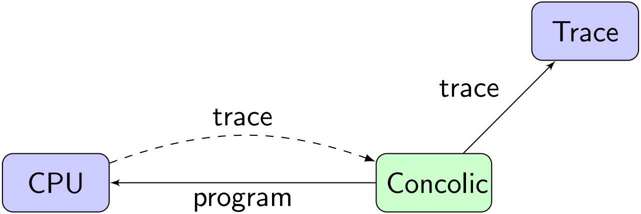

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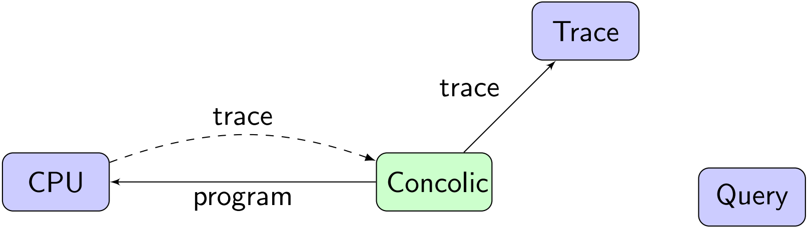

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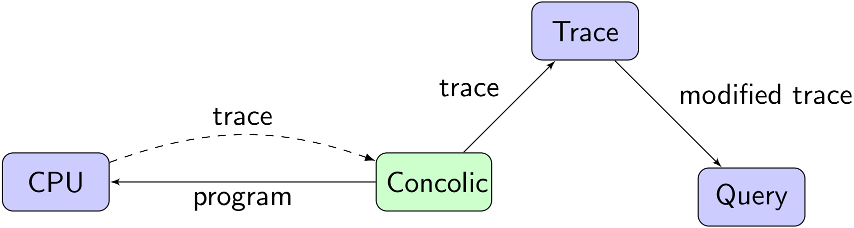

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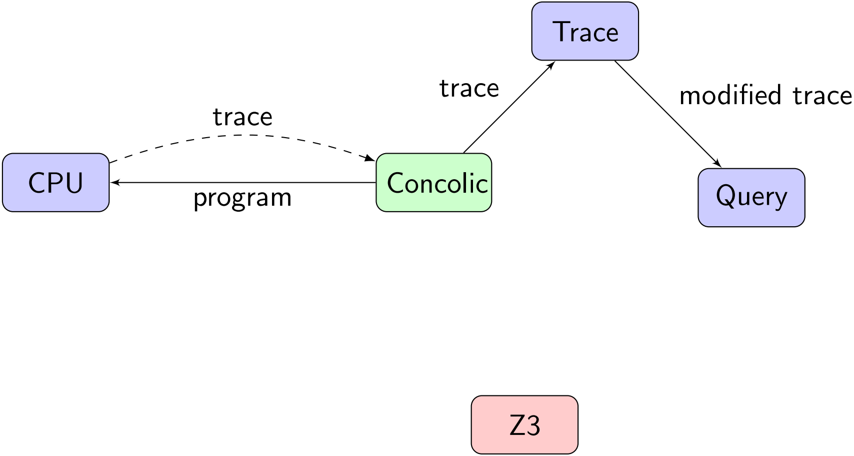

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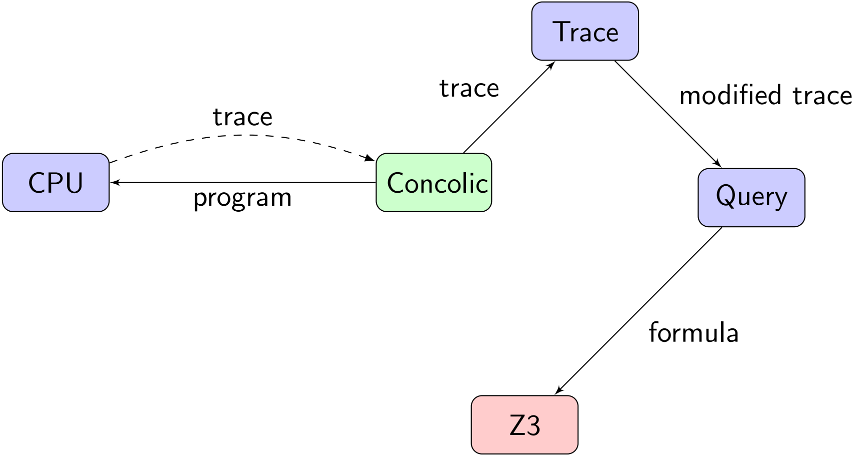

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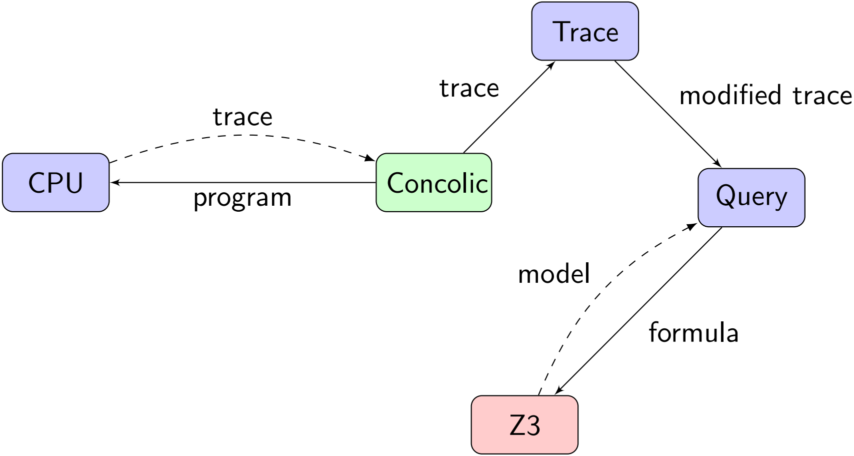

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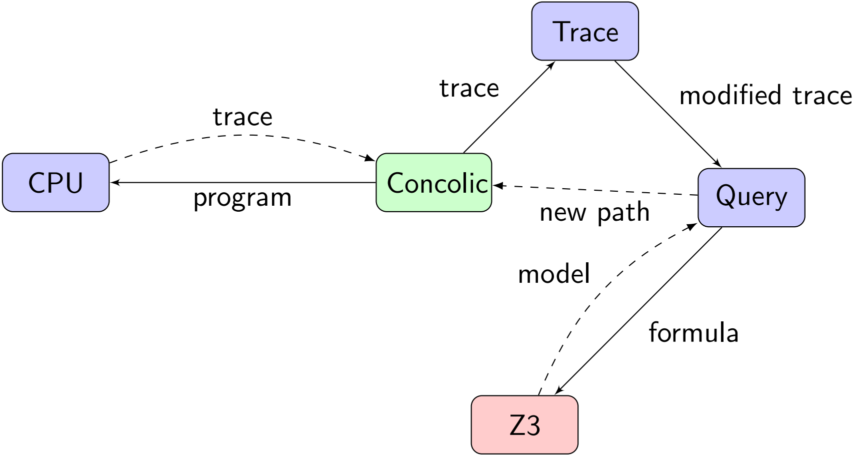

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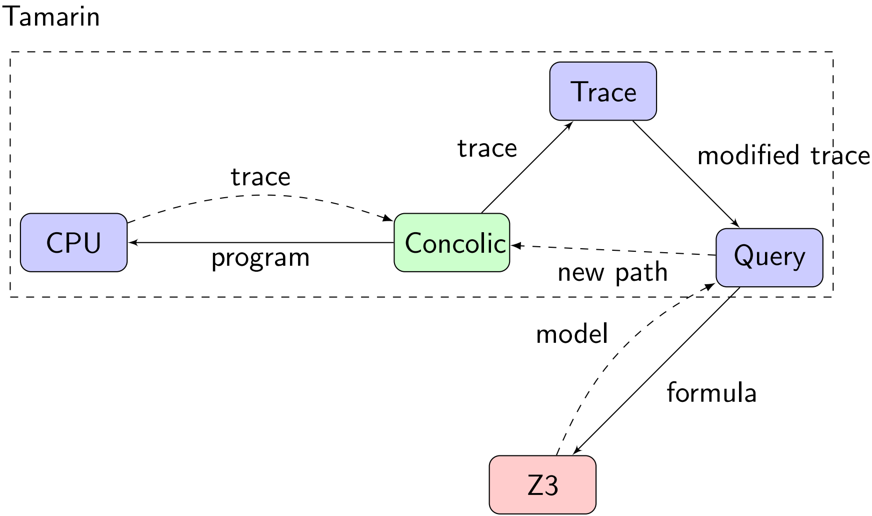
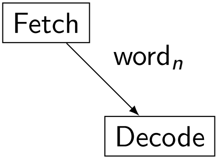


CPU

$\boxed{\text{Fetch}}$

CPU



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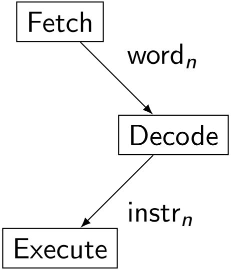

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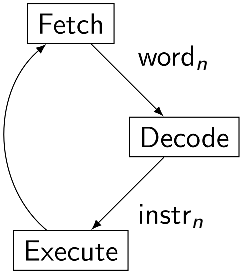

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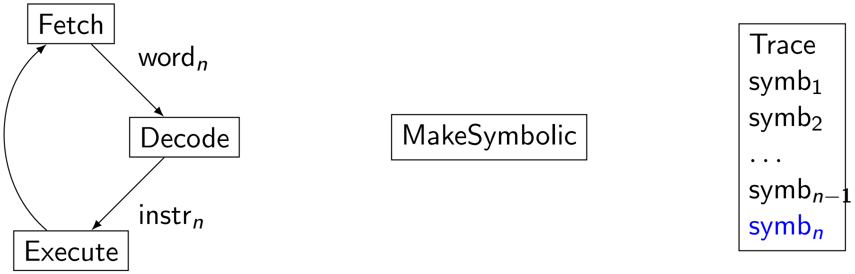
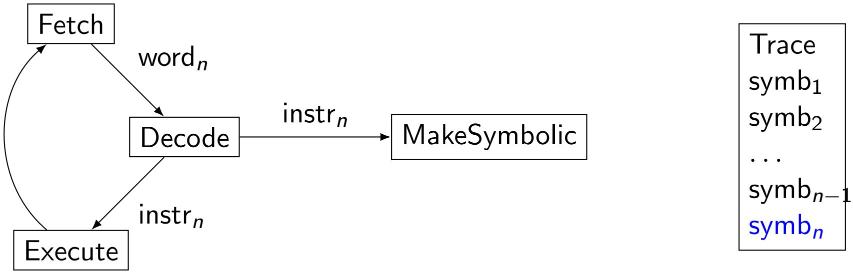

Fetch
word$_n$
Decode
instr$_n$
Execute
MakeSymbolic
Trace
symb$_1$
symb$_2$
...
symb$_{n-1}$
symb$_n$

CPU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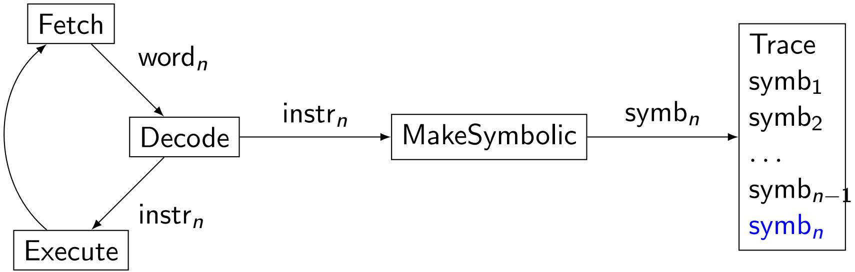
Fetch
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Decode
instr$_n$
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symb$_n$
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instr$_n$
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symb$_1$
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...
symb$_{n-1}$
symb$_n$

CPU (MakeSymbolic)

Instruction	Symbolic

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`add $3, $1, $2`	$r_3 \leftarrow r_1 + r_2$

CPU (MakeSymbolic)

Instruction	Symbolic
`add $3, $1, $2`	$r_3 \leftarrow r_1 + r_2$
`beq $1, $2, label`	$r_1 = r_2$ or $r_1 \neq r_2$
`add $3, $pc, $0`	$r_3 \leftarrow$ 0x8BADF00D
`lis $3; 42`	$r_3 \leftarrow 42$

Trace

$$T \longrightarrow \boxed{\text{Trace}} \longrightarrow T'$$

Trace

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```
Seq[Trace => Trace]
```

Trace

$$T \longrightarrow \boxed{\text{Trace}} \longrightarrow T'$$

`Seq[Trace => Trace]`

- Desugar

Trace

$$T \longrightarrow \boxed{\text{Trace}} \longrightarrow T'$$

`Seq[Trace => Trace]`

- Desugar
- Simplify

Trace

$$T \longrightarrow \boxed{\text{Trace}} \longrightarrow T'$$

`Seq[Trace => Trace]`

- Desugar
- Simplify
- Trim

Trace

$$T \longrightarrow \boxed{\text{Trace}} \longrightarrow T'$$

`Seq[Trace => Trace]`

- Desugar
- Simplify
- Trim
- SSA convert

Trace

Desugar

Trace

Desugar

`Mult(s, t)` $\longrightarrow$ `Mult64(tmp, s, t); Low32(lo, tmp); High32(hi, tmp)`

Trace

Desugar

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Simplify

Trace

Desugar

`Mult(s, t)` $\longrightarrow$ `Mult64(tmp, s, t); Low32(lo, tmp); High32(hi, tmp)`

Simplify

`beq $0, $0, label` $\longrightarrow \emptyset$

Trace

Desugar

`Mult(s, t)` $\longrightarrow$ `Mult64(tmp, s, t); Low32(lo, tmp); High32(hi, tmp)`

Simplify

`beq $0, $0, label` $\longrightarrow \emptyset$

Trim

Trace

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`Mult(s, t)` $\longrightarrow$ `Mult64(tmp, s, t); Low32(lo, tmp); High32(hi, tmp)`

Simplify

`beq $0, $0, label` $\longrightarrow \emptyset$

Trim

limit trace to D path conditions

Trace

Desugar

`Mult(s, t)` $\longrightarrow$ `Mult64(tmp, s, t); Low32(lo, tmp); High32(hi, tmp)`

Simplify

`beq $0, $0, label` $\longrightarrow \emptyset$

Trim

limit trace to D path conditions

SSA convert

Trace (SSA convert)

Trace	Incorrect	Correct

Trace (SSA convert)

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`Add($3, $1, $2)`		

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`		

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$
`Add($2, $1, $2)`		

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$
`Add($2, $1, $2)`	$y = x + y$	

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$
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‘

$$\$3 = 9 \land \$1 = 3$$

Trace (SSA convert)

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‘

$$\$3 = 9 \wedge \$1 = 3$$

$$z = 9 \wedge x = 3$$

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
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'

$\$3 = 9 \wedge \$1 = 3$

$z = 9 \wedge x = 3$ (no sol)

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$
`Add($2, $1, $2)`	$y = x + y$	$y_2 = x_2 + y_1$

‘

$$\$3 = 9 \wedge \$1 = 3$$

$$z = 9 \wedge x = 3 \text{ (no sol)}$$

$$z_1 = 9 \wedge x_2 = 3$$

Trace (SSA convert)

Trace	Incorrect	Correct
`Add($3, $1, $2)`	$z = x + y$	$z_1 = x_1 + y_1$
`Sub($1, $1, $2)`	$x = x - y$	$x_2 = x_1 - y_1$
`Add($2, $1, $2)`	$y = x + y$	$y_2 = x_2 + y_1$

‘

$\$3 = 9 \wedge \$1 = 3$

$z = 9 \wedge x = 3$ (no sol)

$z_1 = 9 \wedge x_2 = 3$ ($x_1 = 6 \wedge y_1 = 3$)

Query

$$\text{trace} \longrightarrow \boxed{\text{Query}} \longrightarrow \text{formula}$$

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
add $5, $1, $0
$4 != $5
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
add $5, $1, $0
$4 != $5
```

formula (SMT-LIB):

```
(declare-const r0 (_ BitVec 32))
(declare-const r1 (_ BitVec 32))
...
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
add $5, $1, $0
$4 != $5
```

formula (SMT-LIB):

```
(declare-const r0 (_ BitVec 32))
(declare-const r1 (_ BitVec 32))
...
(assert (= r0 (_ bv0 32)))
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
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formula (SMT-LIB):

```
(declare-const r0 (_ BitVec 32))
(declare-const r1 (_ BitVec 32))
...
(assert (= r0 (_ bv0 32)))
(assert (= r3 (bvadd r1 r2)))
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
add $5, $1, $0
$4 != $5
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formula (SMT-LIB):

```
(declare-const r0 (_ BitVec 32))
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...
(assert (= r0 (_ bv0 32)))
(assert (= r3 (bvadd r1 r2)))
(assert
  (= r4 (ite (bvslt r1 r2)
    (_ bv1 32)
    (_ bv0 32))))
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
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$4 != $5
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formula (SMT-LIB):

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(assert (= r0 (_ bv0 32)))
(assert (= r3 (bvadd r1 r2)))
(assert
  (= r4 (ite (bvslt r1 r2)
    (_ bv1 32)
    (_ bv0 32))))
(assert (= r5 (_ bv1 32)))
```

Query

trace:

```
add $3, $1, $2
slt $4, $1, $2
add $5, $1, $0
$4 != $5
```

formula (SMT-LIB):

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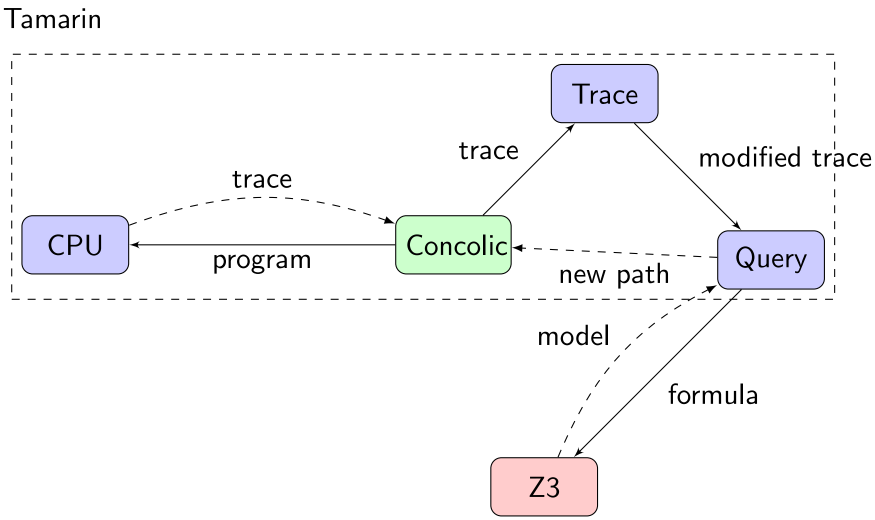
(check-sat) (get-model)
```

Tamarin (Recap)



Demo time

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The whole field is not just theory. Z3 actually works! (and it's not hard to integrate with)