Synthesis in Uclid5

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- This work includes
  - strengthening invariants,
  - annotating functions with pre- and post-conditions, and
  - modelling system calls and the environment.
- Tasks like these can be automated using SyGuS!

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We use SyGuS solvers to unify synthesis-for-verification tasks in a clean way inside of Uclid5.

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2. Generate a new set of SyGuS benchmarks.

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   - Uclid5 solves the queries using existing SyGuS engines.
2. Generate a new set of SyGuS benchmarks.

Related Work

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- Strengthening invariants (e.g. [2])
- Annotating functions with pre/post-conditions (e.g. [3])
- Modelling the environment and system calls (e.g. [4])

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- Program sketching (e.g. [5])
- Program repair (e.g. [6])
- Verification engines with synthesis capabilities (e.g. [7])

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[7] Torlak, Emina, and Rastislav Bodik. "A lightweight symbolic virtual machine for solver-aided host languages." PLDI ‘14.

Running Example

Strengthening an Invariant

Uclid5 Fibonacci Module

```
module main {

    // Part 1: System description.
    var a, b : integer;
    init {
        a = 0;
        b = 1;
    }
    next {
        a', b' = b, a + b;
    }

    // Part 2: System specification.
    invariant a_le_b: a <= b;

    // Part 3: Proof script.
    control {
        induction;
        check;
        print_results;
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Fibonacci Induction Attempt

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The induction algorithm checks

- P_1: a_le_b holds at init

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- P_1: a_le_b holds at init
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- P_2: if a_le_b holds on entry to next, then it will hold on exit

a_le_b actually does hold, but it is not inductive (P_2 is not valid)

Fibonacci With Synthesis

```
module main {
    synthesis function h(x : integer, y : integer) : boolean;
    var a, b : integer;

    init {
        a = 0;
        b = 1;
    }
    next {
        a', b' = b, a + b;
    }

    invariant a_le_b: a <= b && h(a, b);

    control {
        induction;
        check;
        print_results;
    }
}
```

Fibonacci With Synthesis

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module main {
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    next {
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    }

    invariant a_le_b: a <= b && h(a, b); // h(a, b) := a >= 0

    control {
        induction;
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}
```
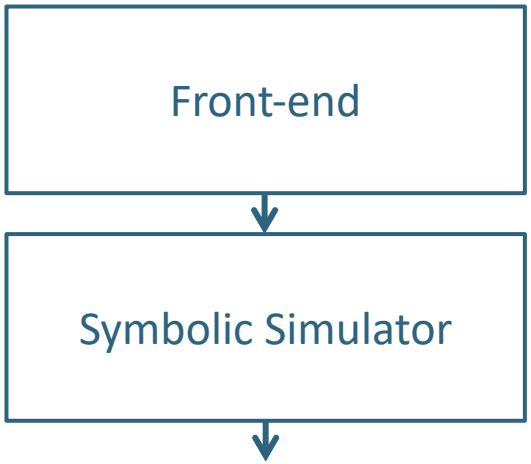

Under the Hood

Synth-Lib Intermediate Representation

Architecture of Synthesis in Uclid5



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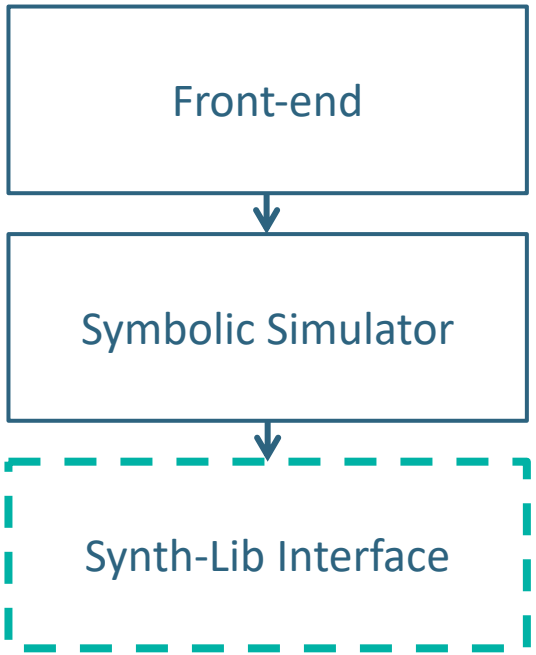

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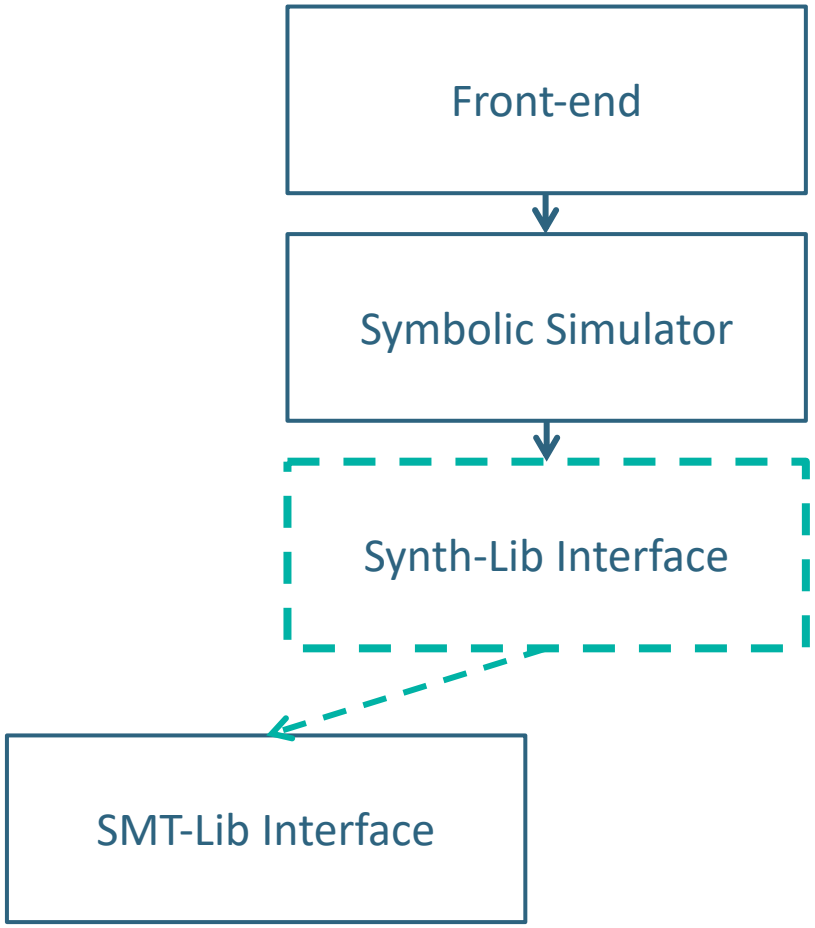

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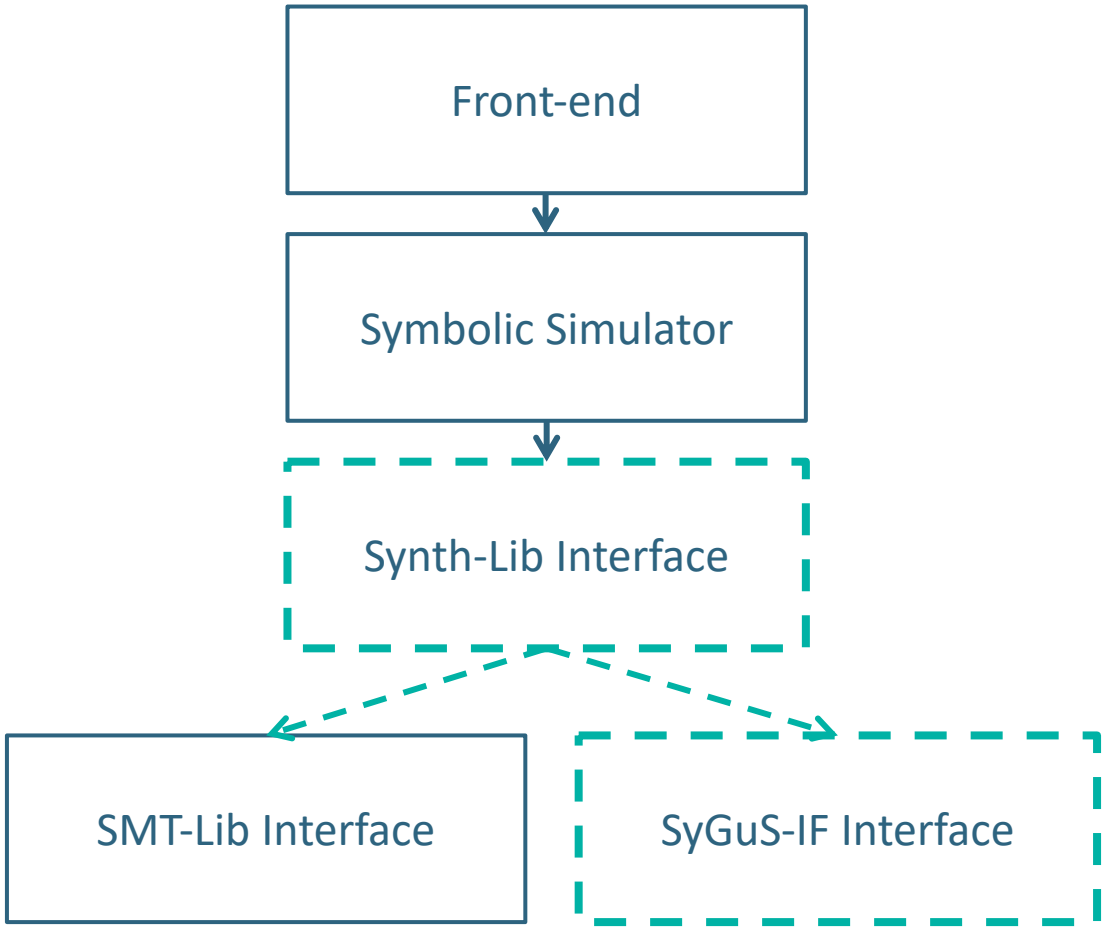

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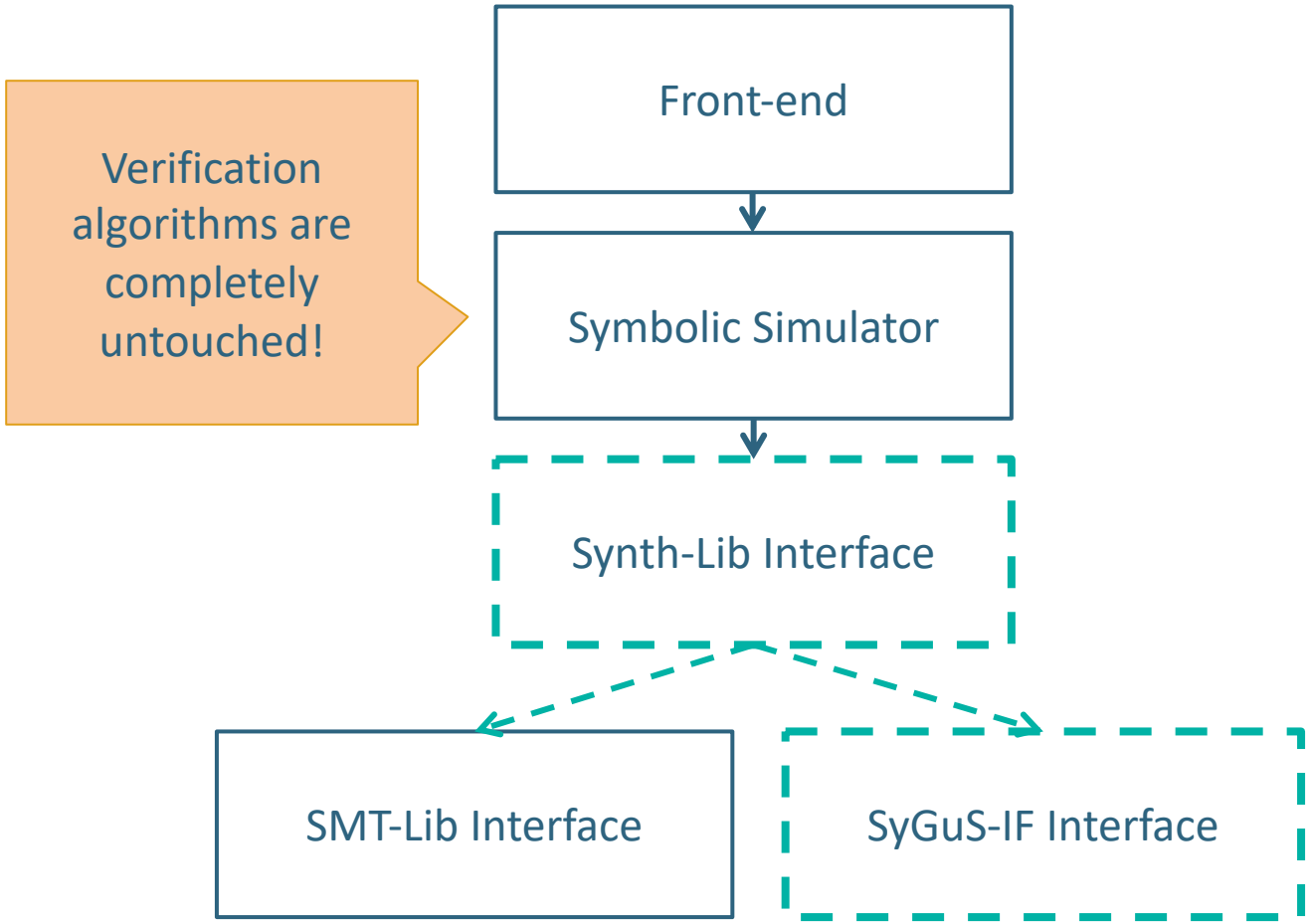

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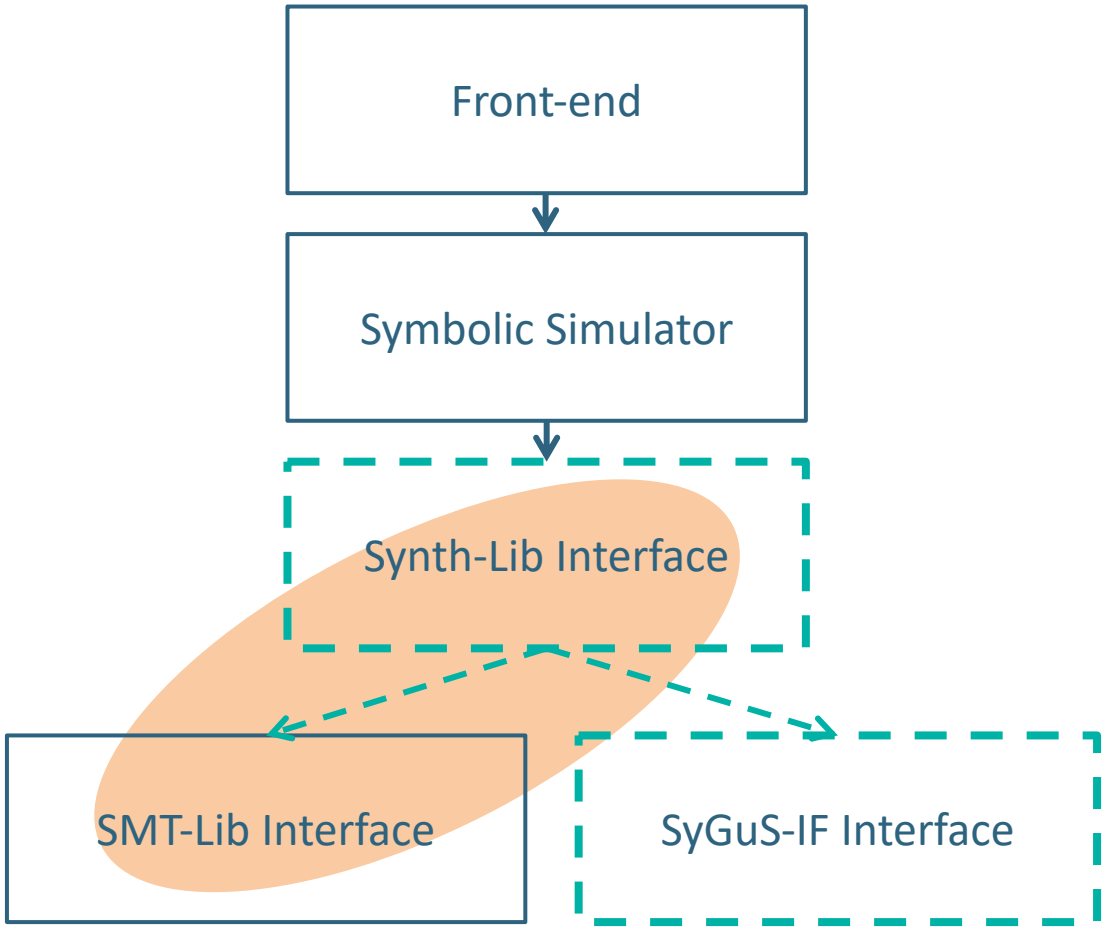

Synth-Lib Encoding

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The induction algorithm checks

- P_1: a_le_b holds at init
- P_2: if a_le_b holds on entry to next, then it will hold on exit

Synth-Lib Encoding

```
(synth-blocking-fun h ((x Int) (y Int)) Bool)

(declare-fun initial_b () Int)
(declare-fun initial_a () Int)
(declare-fun new_a () Int)
(declare-fun new_b () Int)

(assert (or
    (not (and (<= initial_a initial_b) (h 0 1))) ;(not P1)
    (and (and (<= initial_a initial_b) (h initial_a initial_b))
        (= new_a initial_b)
        (= new_b (+ initial_a initial_b ))
        (not (and (<= new_a new_b) (h new_a new_b)))))) ;(not P2)

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$\exists h \neg \exists a, b \neg P_1(h, a, b) \vee \neg P_2(h, a, b)$

The induction algorithm checks

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SMT-Lib Encoding

```
(define-fun h ((x Int) (y Int)) Bool (>= x 0))

(declare-fun initial_b () Int)
(declare-fun initial_a () Int)
(declare-fun new_a () Int)
(declare-fun new_b () Int)

(assert (or
    (not (and (<= initial_a initial_b) (h 0 1))) ;(not P1)
    (and (and (<= initial_a initial_b) (h initial_a initial_b))
        (= new_a initial_b)
        (= new_b (+ initial_a initial_b ))
        (not (and (<= new_a new_b) (h new_a new_b))))))) ;(not P2)

(check-sat)
```

UNSAT iff $\neg\exists a, b\ \neg P_1(h, a, b) \vee \neg P_2(h, a, b)$

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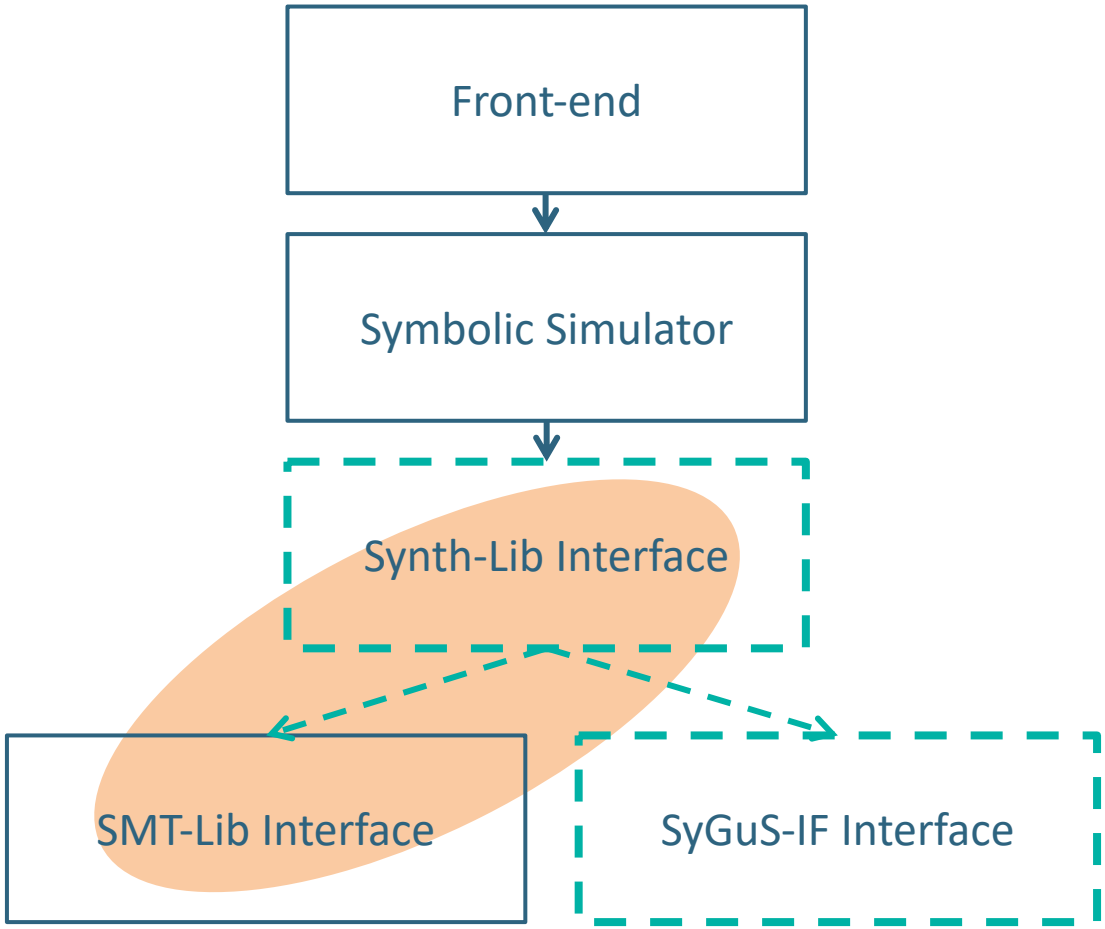

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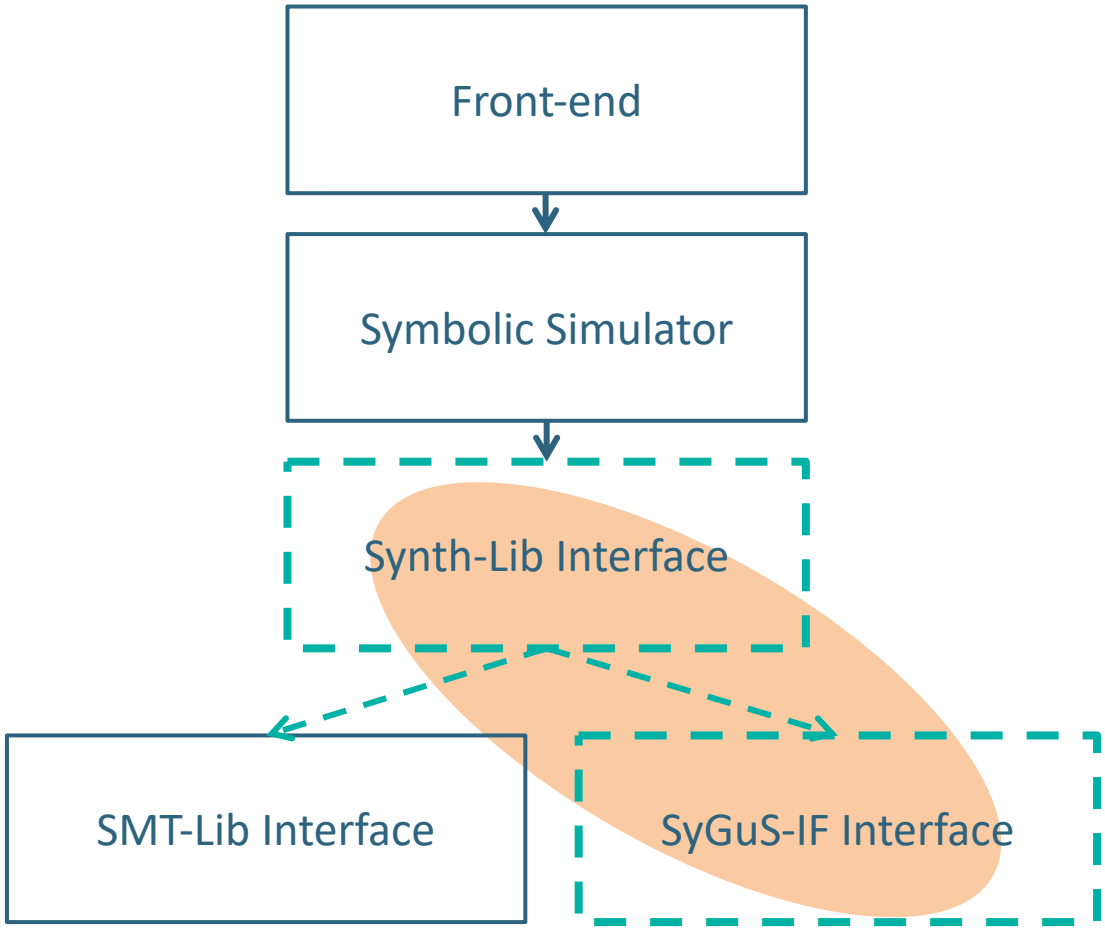

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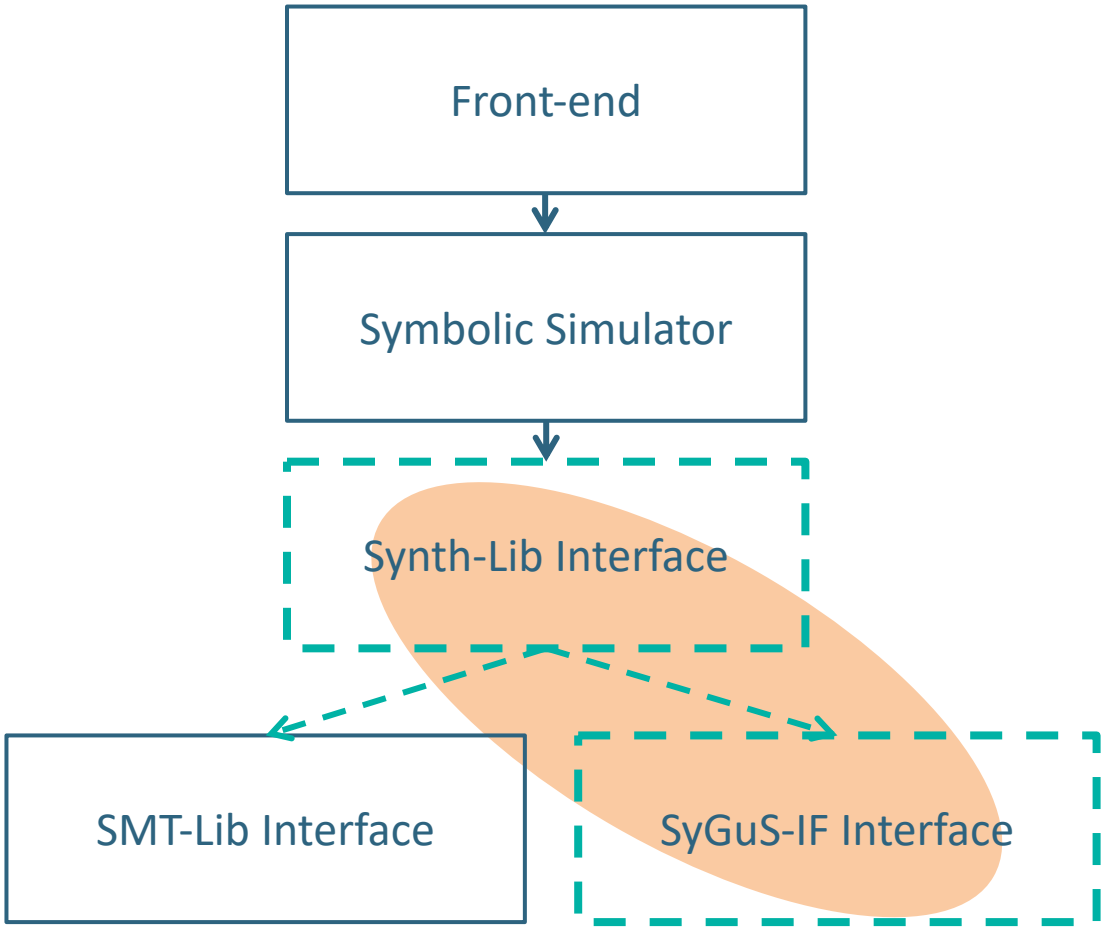

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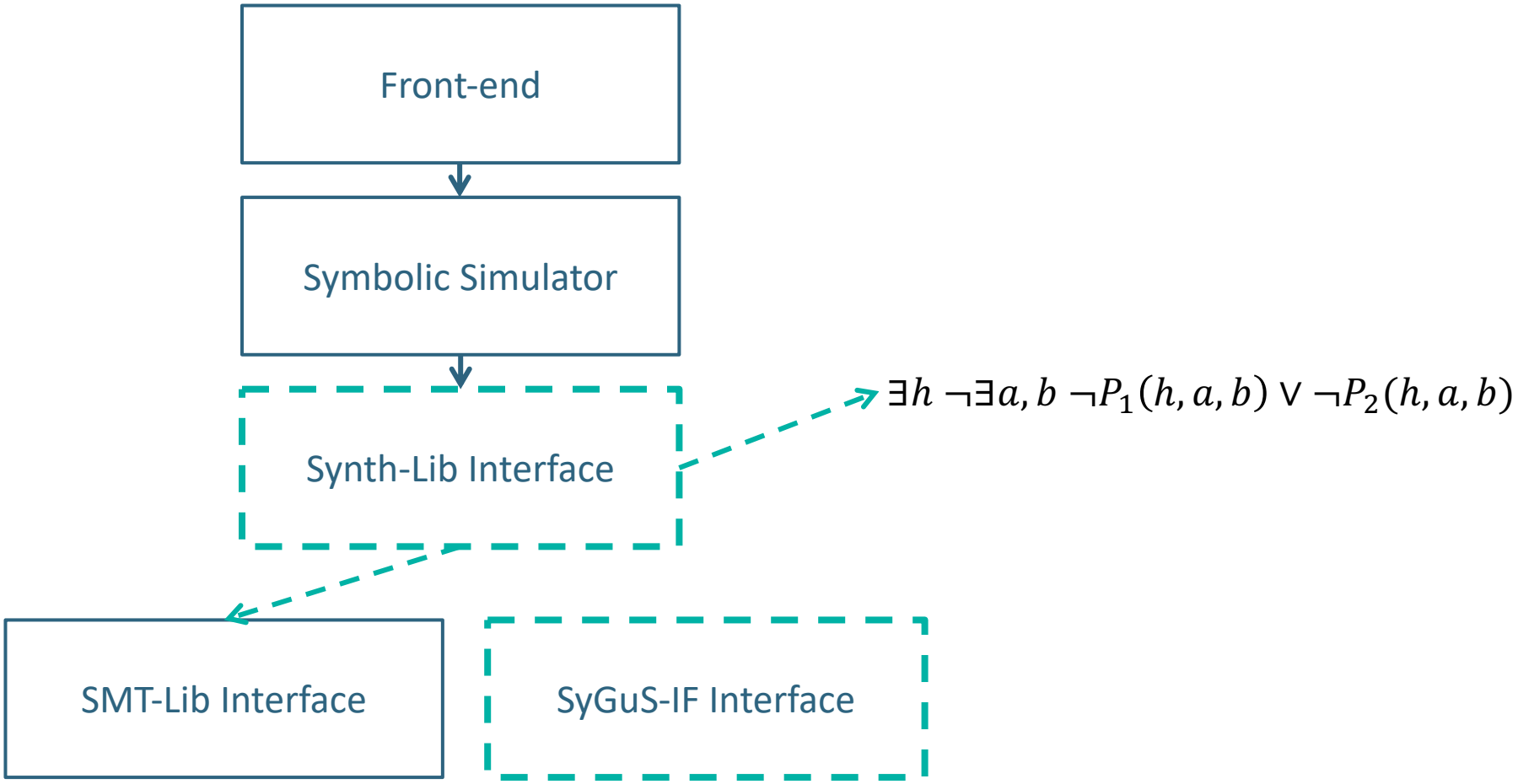

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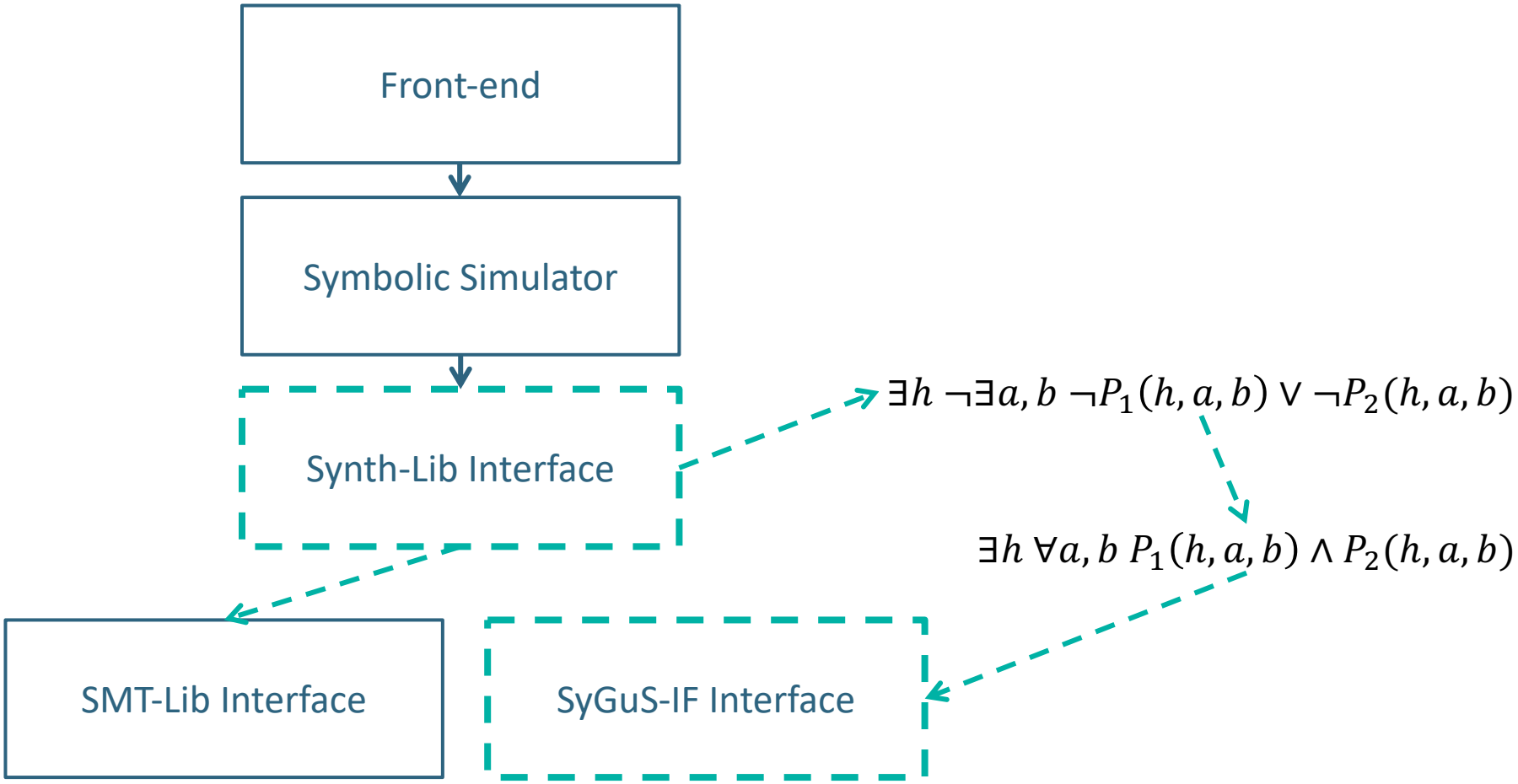

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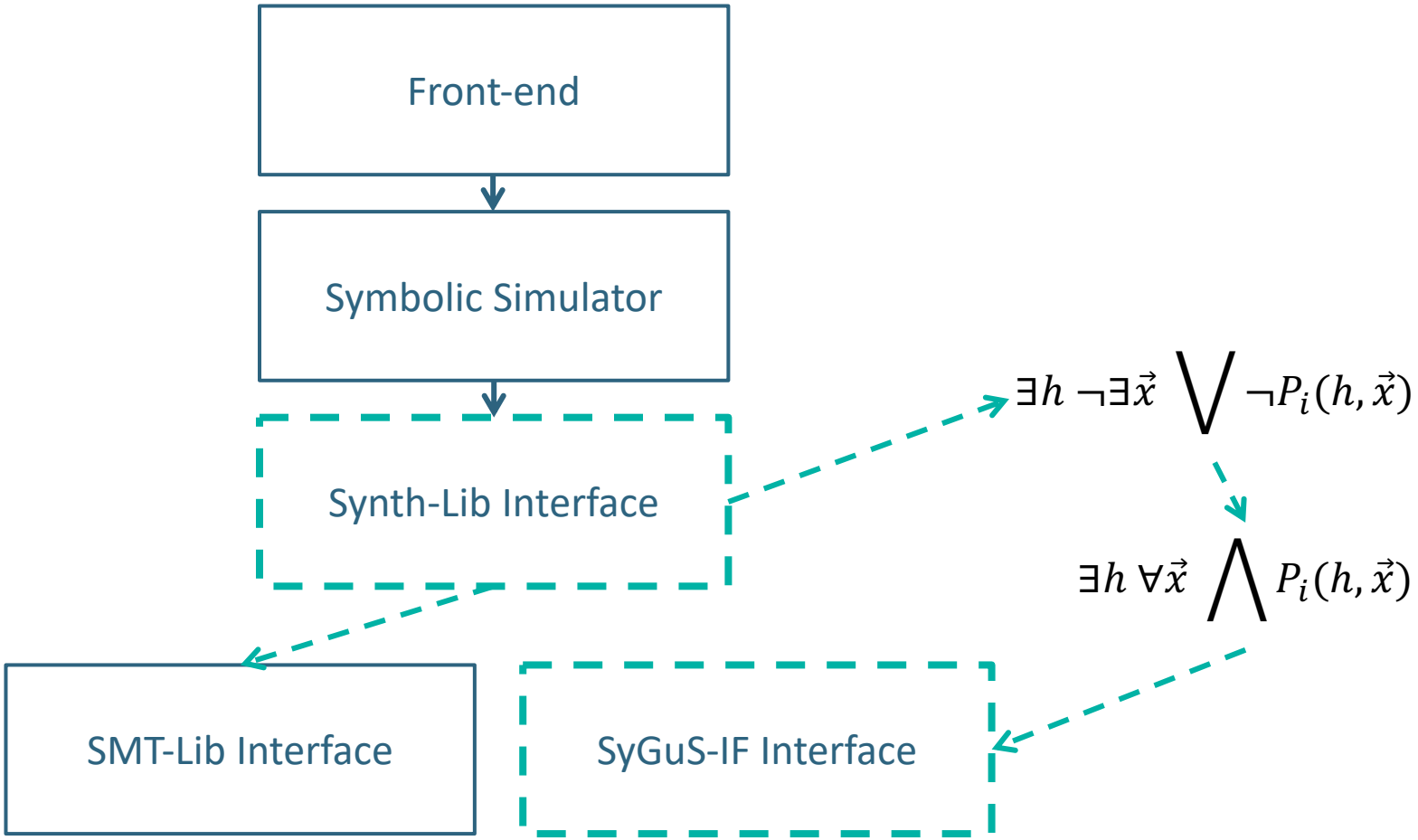

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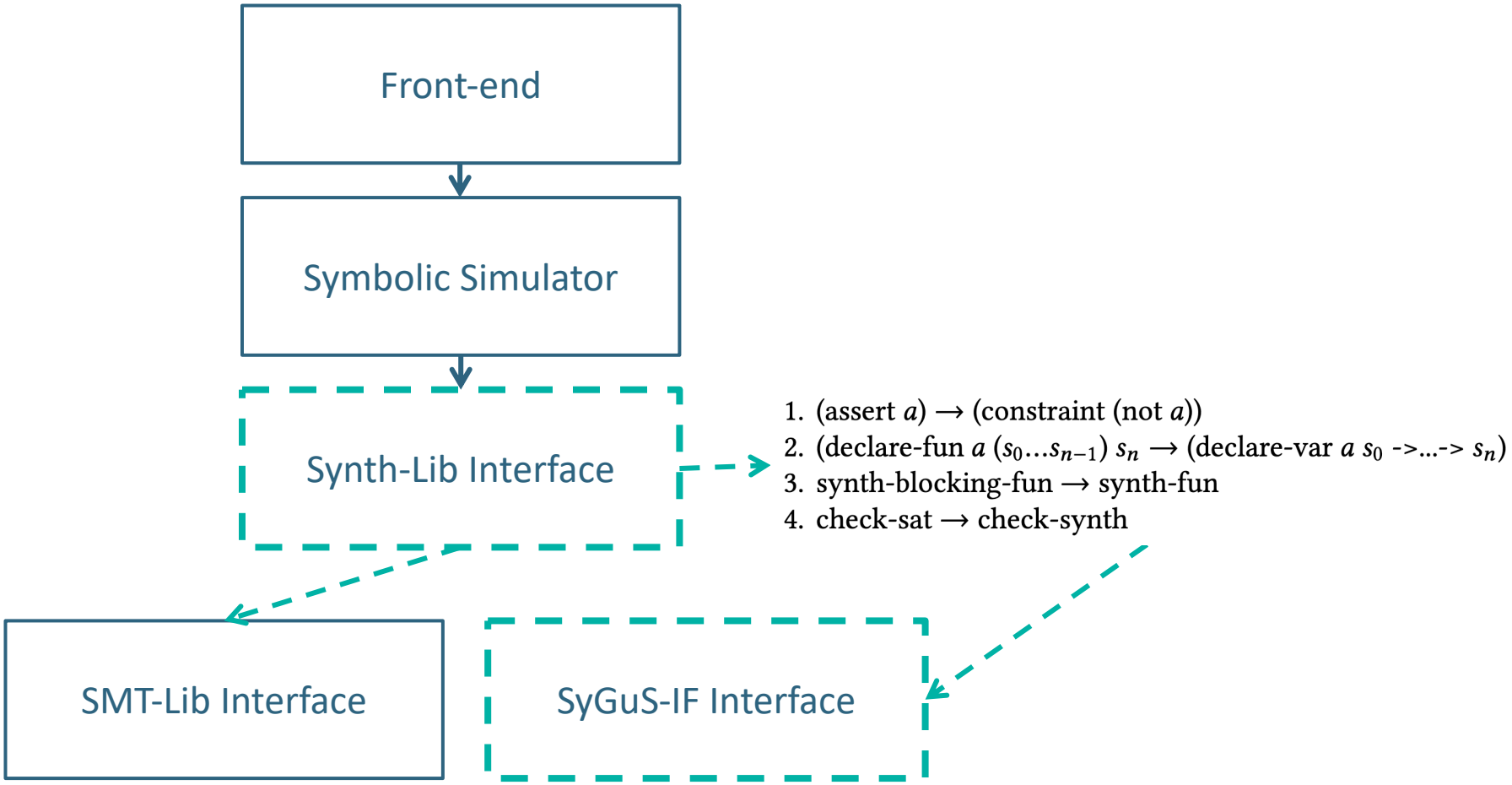

The Benchmarks

One example out of 25

Benchmark Example [5]

```
…
define pi_balance(p : bv8, b : bv16) : bv16 =
    b[15:8] ++ (b[7:0] + p);
…
init {
    /*-------------------------------------------------------------+
    | Injective Trace enumeration Witness (I): Property 12 |
    | ==================================== |
    | Makes use of enumeration predicate (pi_balance) defined above.
    |
    | - Mapping initial state. |
    +-------------------------------------------------------------*/
    assume (acct1.balance == pi_balance(p1, acct0.balance));
    assume (acct2.balance == pi_balance(p2, acct0.balance));
}
…
```

[5] Sahai, Shubham, et al. "Verification of Quantitative Hyperproperties Using Trace Enumeration Relations." CAV '20

Benchmark Example [5]

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Benchmark Example [5]

```
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…
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    | ==================================== |
    | Makes use of enumeration predicate (pi_balance) defined above.
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    | - Mapping initial state. |
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    - (k-induction, bounded model checking, …), and
  - for any kind of specification
    - (linear temporal logic, invariants, sequential assertions, …).
- Unfortunately, we are pushing the limits of state-of-the-art synthesis engines.
- Fortunately, that means there's a lot of work left to be done!
  - For example, optimizing synthesis-for-verification encodings,
  - improving solvers, and so on…

Thank you!

Paper

Code

Benchmarks

```
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  synthesis function h(x : integer, y : integer) : boolean;
  var a, b : integer;

  init {
    a = 0;
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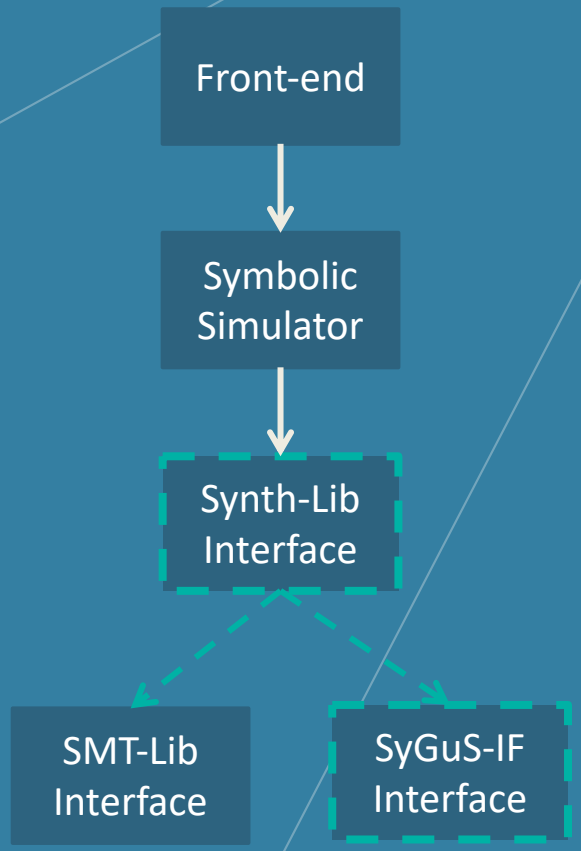

Extra Stuff

Manual Work #1 of 3

Strengthening Invariants

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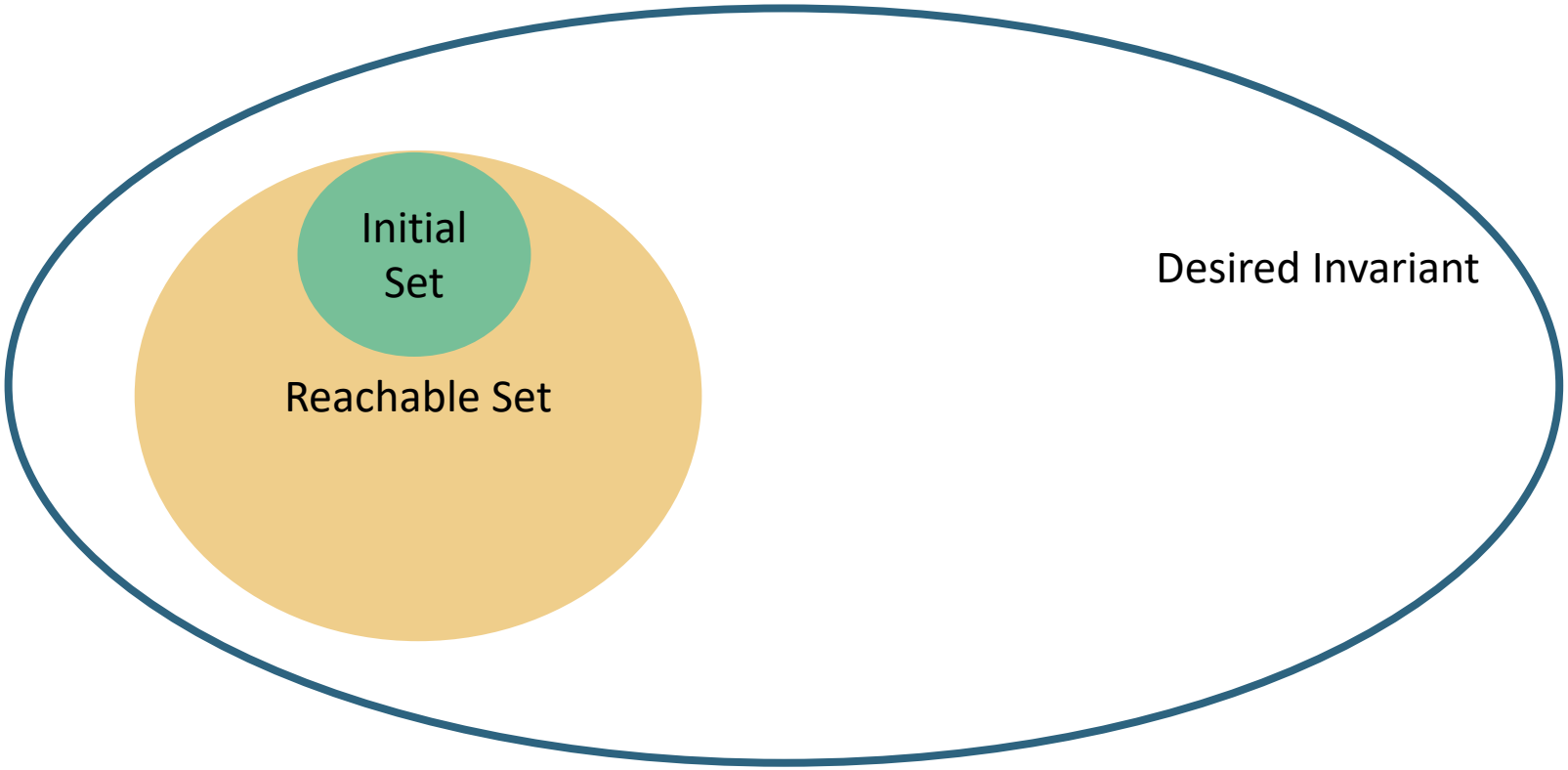
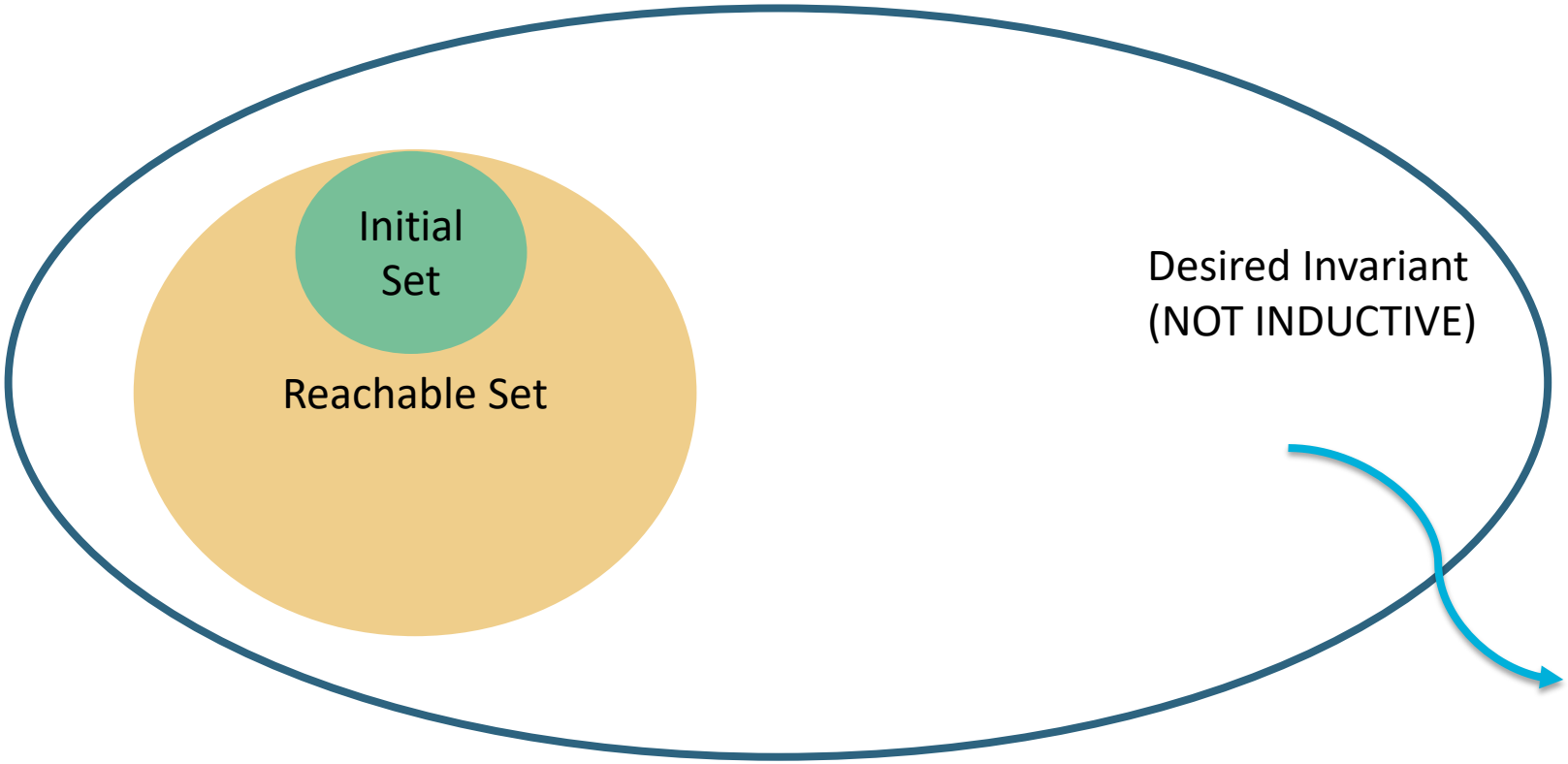
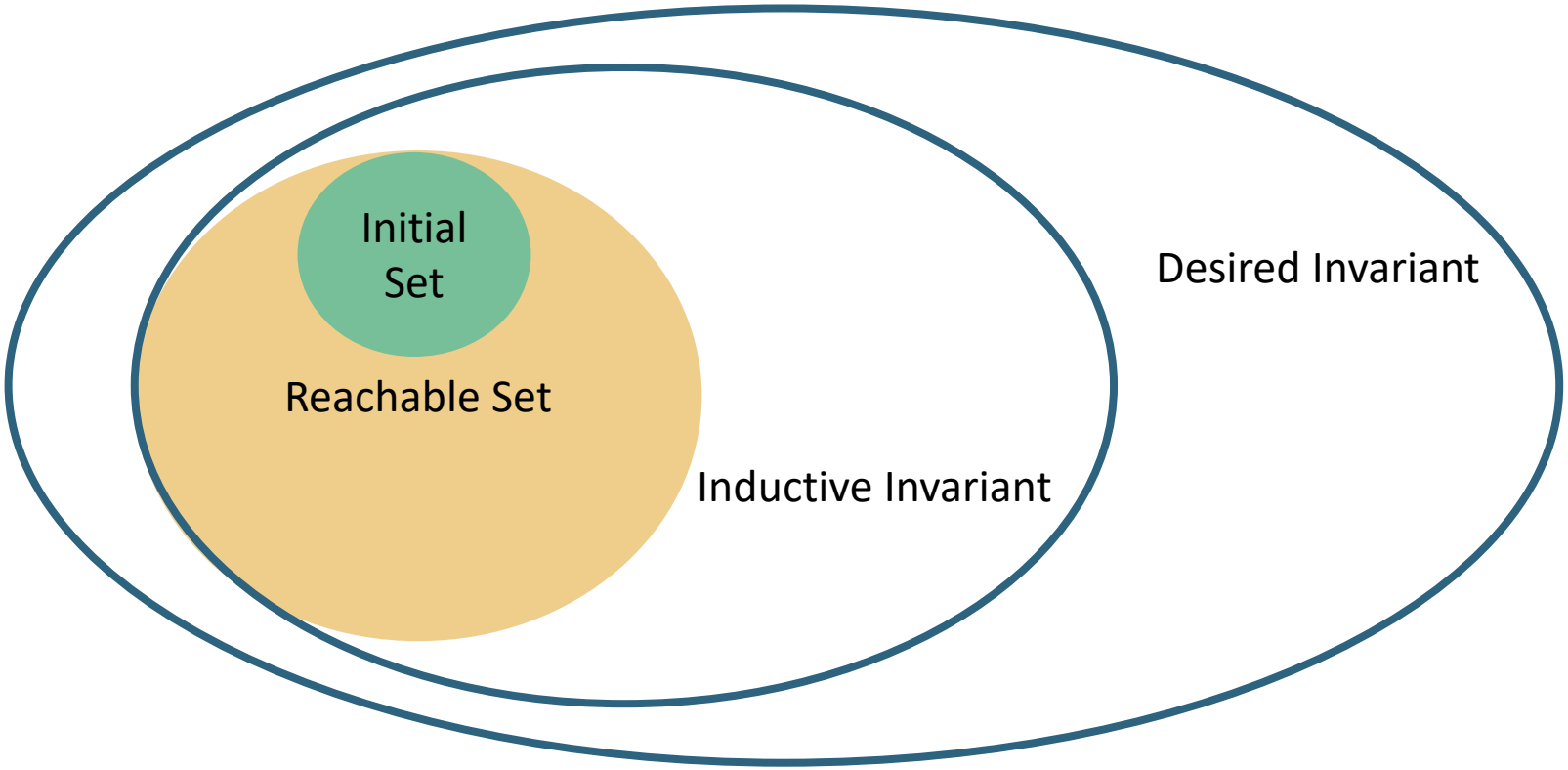


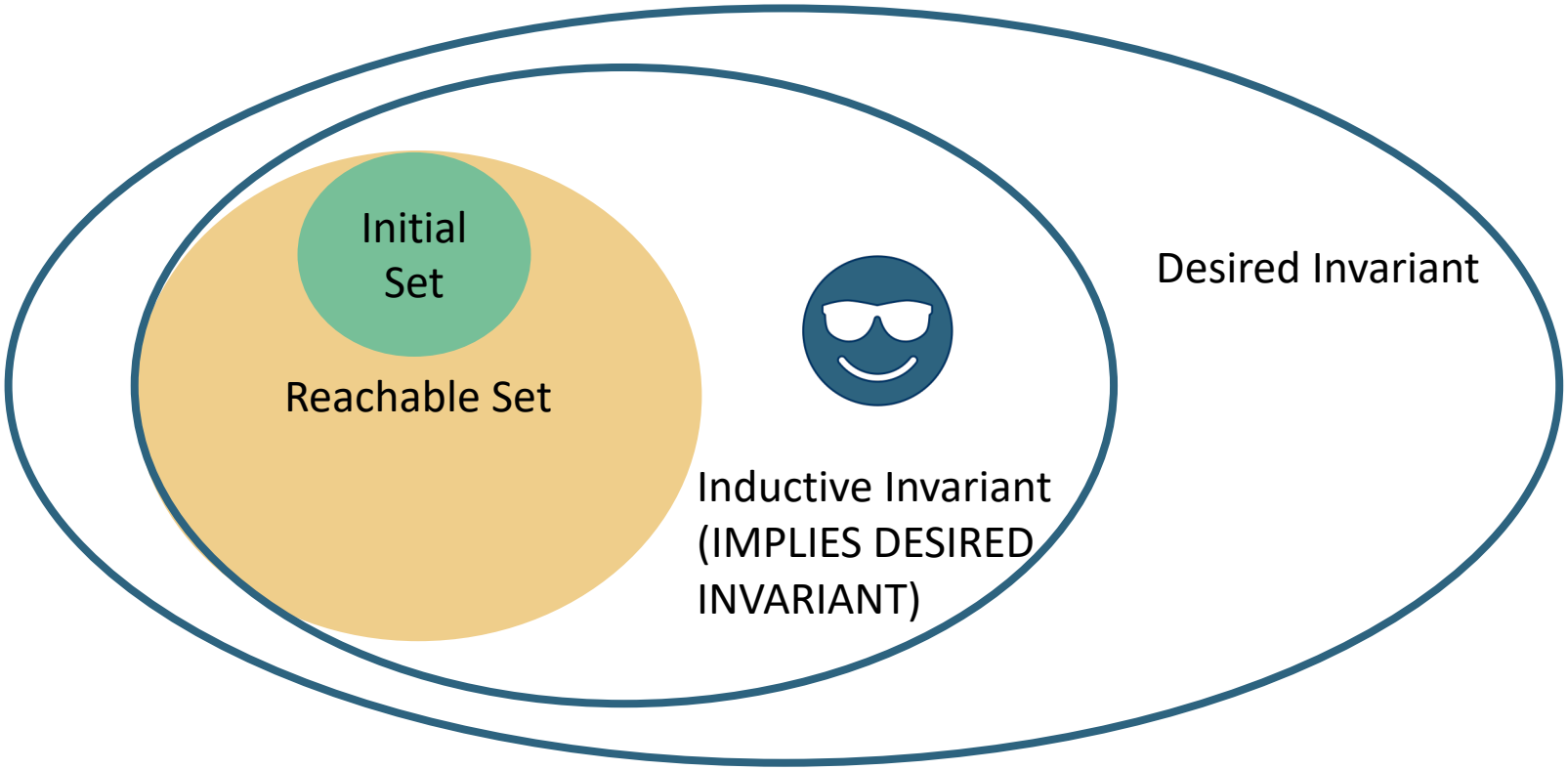
Strengthening Invariants



Strengthening Invariants



Strengthening Invariants



Manual Work #2 of 3

Annotating functions with pre- and post-conditions

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```
procedure searchQ() returns (found : boolean)
    requires (count >= 0 && count <= SIZE);
    ensures (in_queue(data) <==> found);
{
    var i : integer;
    i = 0;
    found = false;
    while (i < count)
        invariant (i >= 0 && i <= count);
    {
        if (contents[itemIndex(i)] == data) {
            found = true;
        }
        i = i + 1;
    }
}
```

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    }
}
```

Manual Work #3 of 3

Modelling the Environment and System Calls

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```
var a, b : integer;

init {
    a = time();
    b = time();
}

property bigger_than_a : (b >= a);
```

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