On Optimally Combining Static and Dynamic Analyses For Intensional Program Properties

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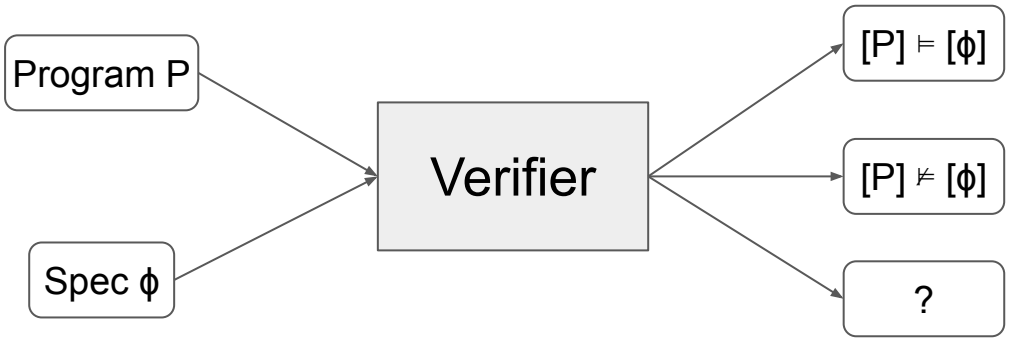
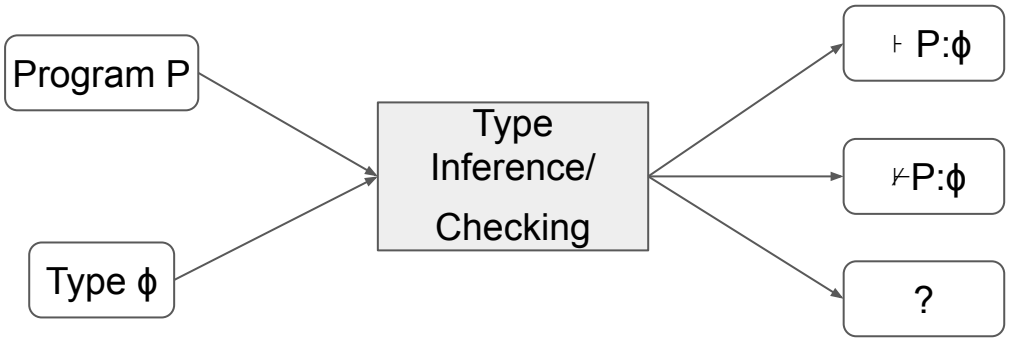
Motivation

Recipe for designing automated, efficient, sound, and complete program verification tools

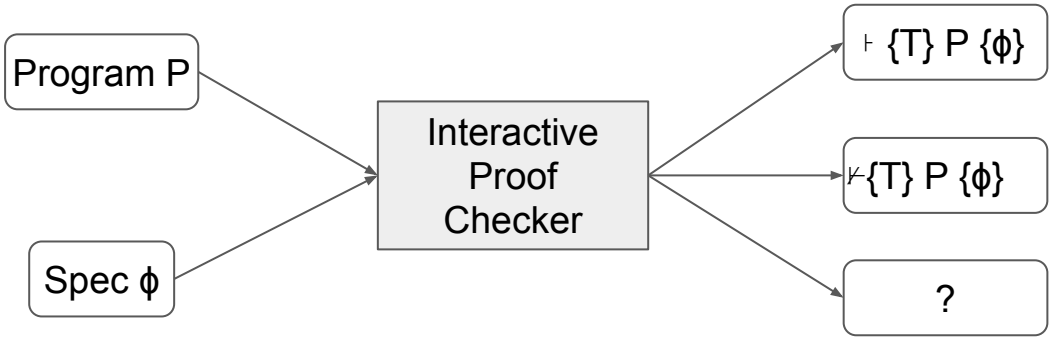
What is program verification?



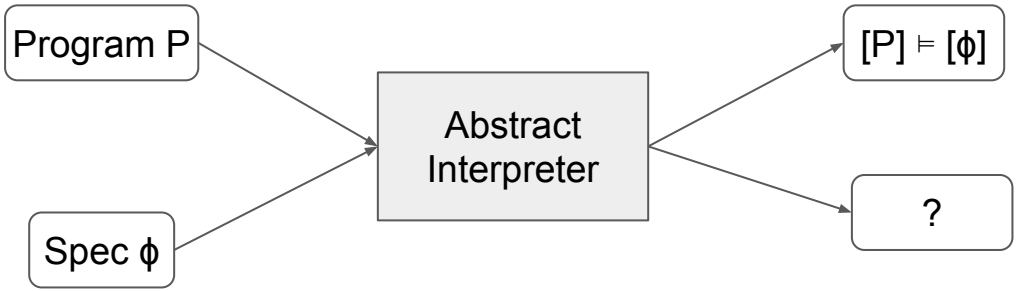
Static Verifiers - Type Systems



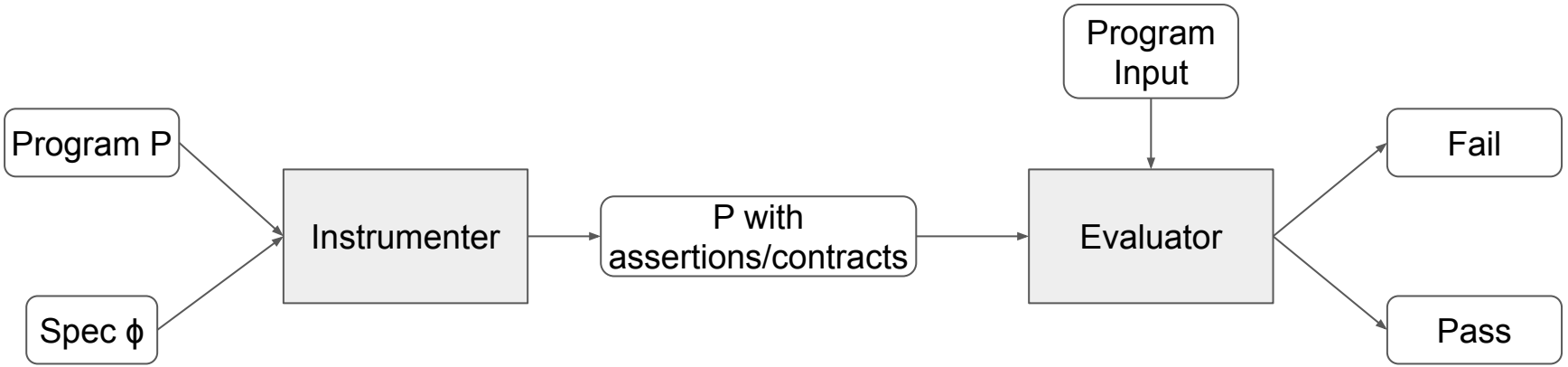
Static Verifiers - Program Logics



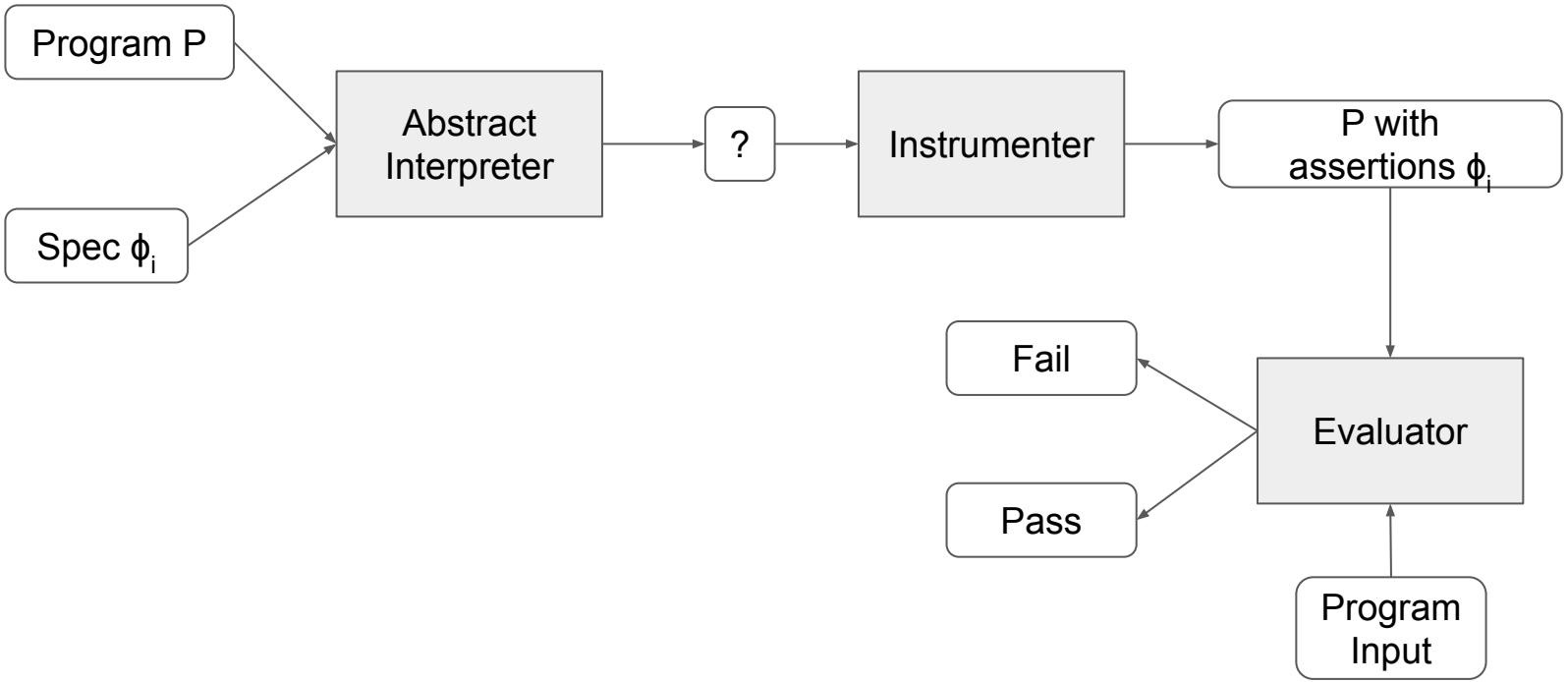
Static Verifiers - Program Analyses



Dynamic Verifiers



Let’s combine!



Are we done?

Yes, and no :(

- Yes, for ‘extensional’ or ‘local’ properties
  - Properties about the results of computations
  - Can be answered by observing the current program state

- No, for ‘intensional’ properties
  - Properties about how computations execute

Intensional Properties

- Track how computations execute
- Examples - taint tracking, datarace checking, program complexity, etc.
- Instrumented semantics - Augment the states of standard semantics with instrumentation data
  - Ex. <P,S> ⇝ <P’,S’> modified to <P,S,I> ⇝ <P’,S’,I’>

What is the problem?

- Combined verification only removes runtime assertions but not additional instrumentation
  - High overheads!

- No existing general framework for combining static and dynamic verifiers with a focus on efficiency

Idea!

- Remove “all” dynamic instrumentation “associated” with statically proven assertions

- Challenges:
  - How to communicate information from static to dynamic verifier?
  - How to formally define the notions of “all” and “associated” in the statement above?
  - How to automatically discover “all associated” instrumentation for a given assertion?

- Approach:
  - “Parameterize” static and dynamic verifiers
  - Notions of “all” and “associated” defined with respect to this parameterization

A taint analysis example

```
void main() {
    A o1 = src1();
    B o2 = src2();
    A o3 = foo(o1);
    B o4 = bar(o2);
    assert(o3 not tainted);
    sink1(o3);
    assert(o4 not tainted);
    sink2(o4);
}
```

```
A foo(A a) {
    .
    x = san(a);
    .
    return x;
}
```

```
B foo(B b) {
    .
    .
    return y;
}
```

An interlude: Some definitions

$\text{eval} : \text{State} \longrightarrow \text{State}$ (evaluator for the language)

$\text{abs\_int} : \text{Abs\_State} \longrightarrow \text{Abs\_State}$ (abstract interpreter)

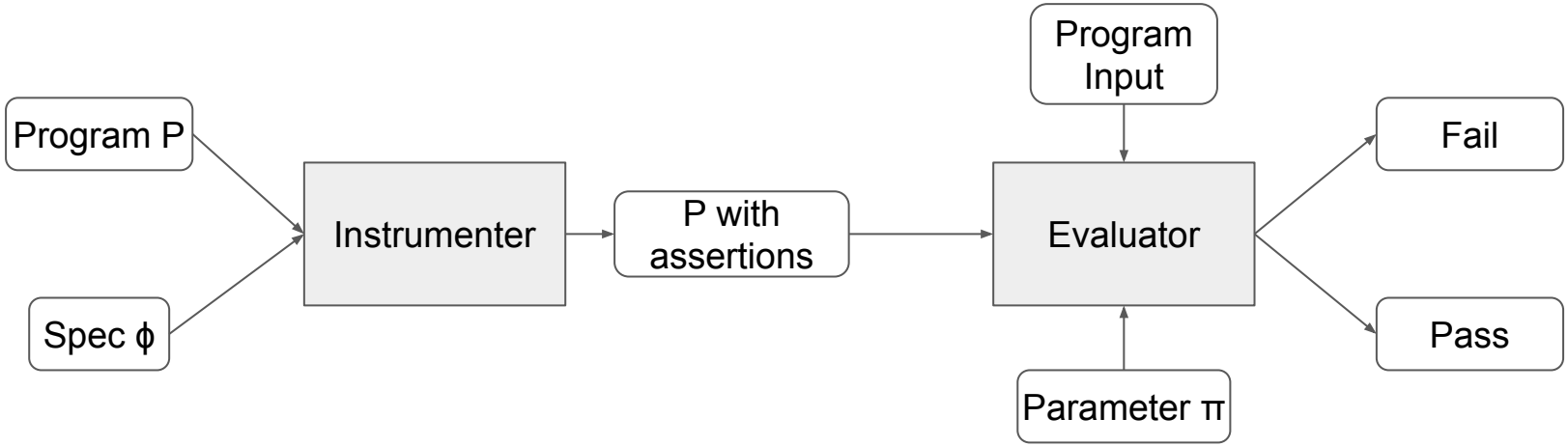
$\alpha : 2^{\text{State}} \longrightarrow \text{Abs\_State}$ (abstraction function)

$\alpha\{\text{eval}(s) | s \in X\} \sqsubseteq \text{abs\_int}(\alpha(X))$ (relationship between eval and abs_int)

$\text{erase} : \text{State} \longrightarrow \text{Uninstrumented\_State}$

$\text{extract} : \text{State} \longrightarrow \text{Instrumentation\_Data}$

Parametric Verifiers - Dynamic

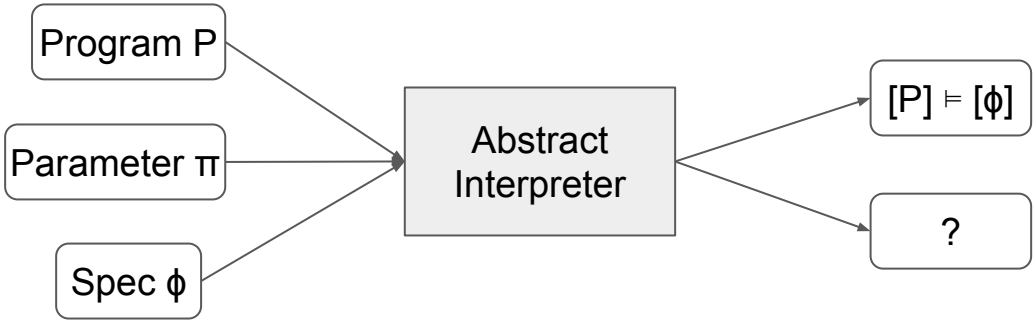


$eval_\pi$: Parameter x State ⟶ State (parametric evaluator for the language)

$\forall\, s,\pi.\quad (erase(eval_\pi(\pi,s)) = erase(eval(s)))\ \vee\ (eval_\pi(\pi,s) = fail_i)$

$\forall\, \pi_1,\pi_2.\quad \pi_1 \preccurlyeq \pi_2 \Rightarrow \exists s,i,j.(\ (eval_\pi(\pi_1,s) = fail_i) \Rightarrow (eval_\pi(\pi_2,s) = fail_j))$

Parametric Verifiers - Static

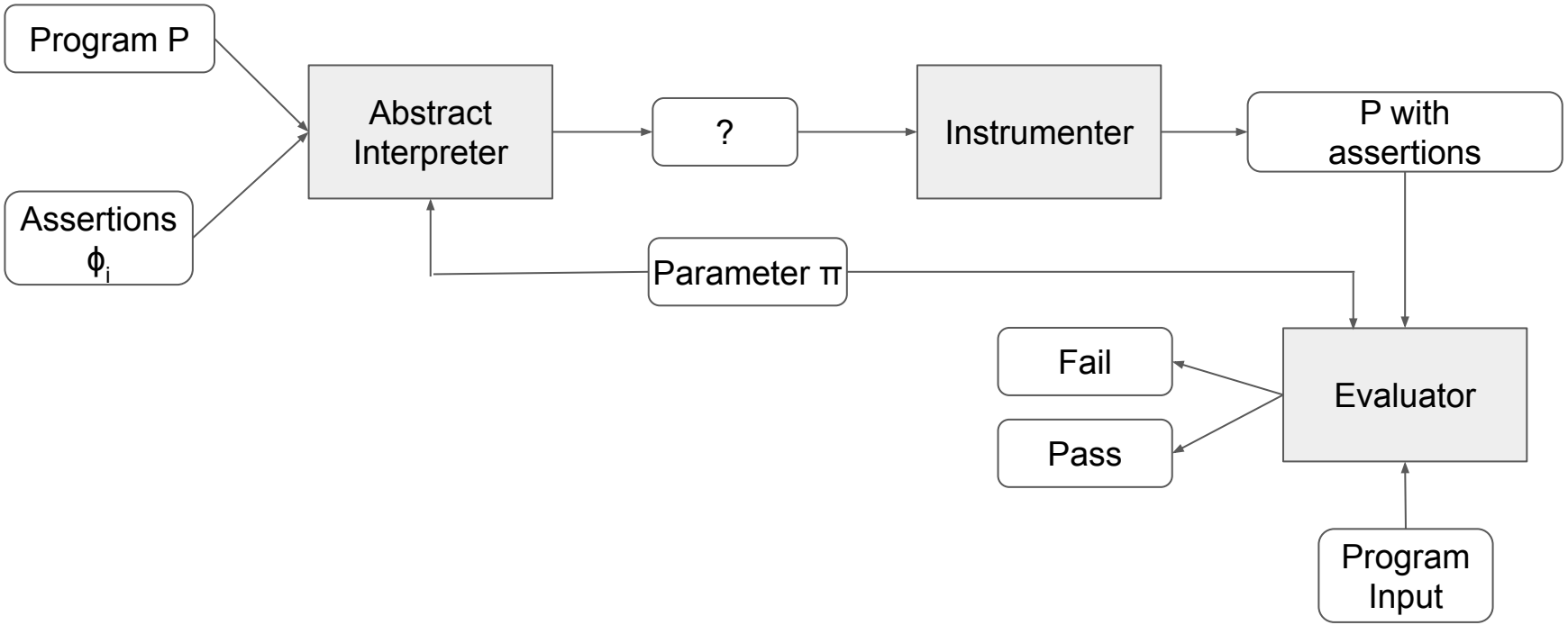


abs_int_π: Parameter x Abs_State ⟶ Abs_State (parametric abstract interpreter)

$\forall X,\pi.\quad \alpha\{eval_\pi(\pi,s) | s \in X\} \sqsubseteq abs\_int_\pi(\pi,\alpha(X))$

$\forall \pi_1,\pi_2.\quad \pi_1 \preccurlyeq \pi_2 \quad \Rightarrow \quad fails(abs\_int_\pi(\pi_1,init)) \subseteq fails(abs\_int_\pi(\pi_2,init))$

Let’s combine, again!



Minimal Parameter Problem (MPP)

- Find minimal parameter π such that,

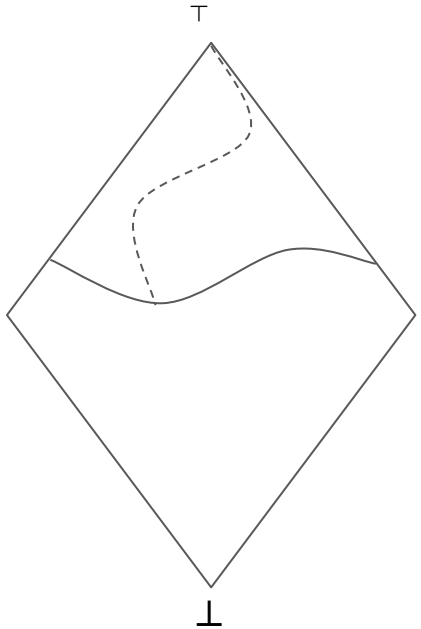
$$\forall\, s,i.\ (\mathrm{eval}_{\pi}(\top,s) = \mathrm{fail}_{i}) \ \Rightarrow\ (\mathrm{eval}_{\pi}(\pi,s) = \mathrm{fail}_{i})$$

- Finding the minimal parameter is equivalent to removing “all dynamic” instrumentation “associated” with statically proven assertions!

- MPP is not tractable, but we can approximately solve it by exploiting the relationship between our parametric static and dynamic verifiers

A simple parameter search algorithm

Parameter Space



Analysis designer’s responsibilities

- Parameterize static and dynamic verifiers with a shared parametric notion

- Ensure:
  - $\alpha\{\text{eval}(s) | s \in X\} \sqsubseteq \text{abs\_int}(\alpha(X))$
  - $\forall\, s,\pi. \quad (\text{erase}(\text{eval}_\pi(\pi,s)) = \text{erase}(\text{eval}(s))) \quad \vee \quad (\text{eval}_\pi(\pi,s) = \text{fail}_i)$
  - $\forall\, \pi_1,\pi_2. \quad \pi_1 \preccurlyeq \pi_2 \quad \Rightarrow \quad \exists s,i,j.(\ (\text{eval}_\pi(\pi_1,s) = \text{fail}_i) \ \Rightarrow\ (\text{eval}_\pi(\pi_2,s) = \text{fail}_j))$
  - $\forall\, X,\pi. \quad \alpha\{\text{eval}_\pi(\pi,s) | s \in X\} \sqsubseteq \text{abs\_int}_\pi(\pi,\alpha(X))$
  - $\forall\, \pi_1,\pi_2. \quad \pi_1 \preccurlyeq \pi_2 \quad \Rightarrow \quad \text{fails}(\text{abs\_int}_\pi(\pi_1,\text{init})) \subseteq \text{fails}(\text{abs\_int}_\pi(\pi_2,\text{init}))$

- And then,

Can we improve?

- Improve parameter search:
  - Exploit the structure of static verifier proofs
  - Leverage existing work on finding best abstractions

- Further reduce dynamic verifier overheads
  - Make optimistic/speculative assumptions statically to prove more assertions
  - Check these assumptions at runtime
  - Reduced instrumentation due to more proven assertions vs Overhead of checking assumptions

- Connections to gradual typing and hybrid typing (Please help!)

Thank You!