Building your own compositional static analyzer with Infer.AI

Sam Blackshear, Dino Distefano, Jules Villard
Facebook

Roadmap

1. Infer.AI architecture
2. Building intraprocedural analyzers
3. Building compositional interprocedural analyzers

Need scalable, incremental tools that are easy to extend

millions of
lines of code

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100K commits/
week

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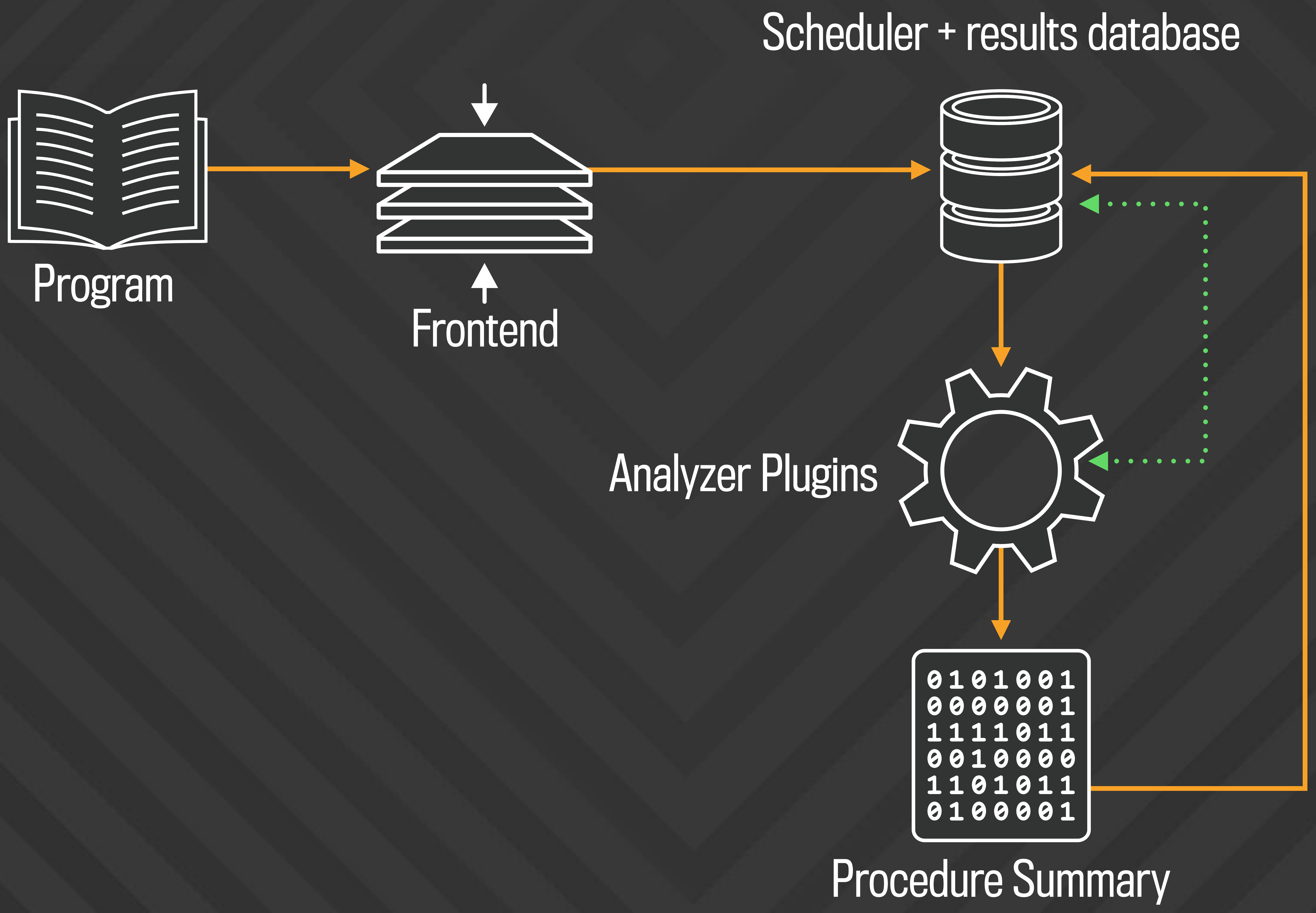
Need scalable, incremental tools
that are easy to extend

Small team of
analysis experts

Recipe for a scalable/extensible analyzer



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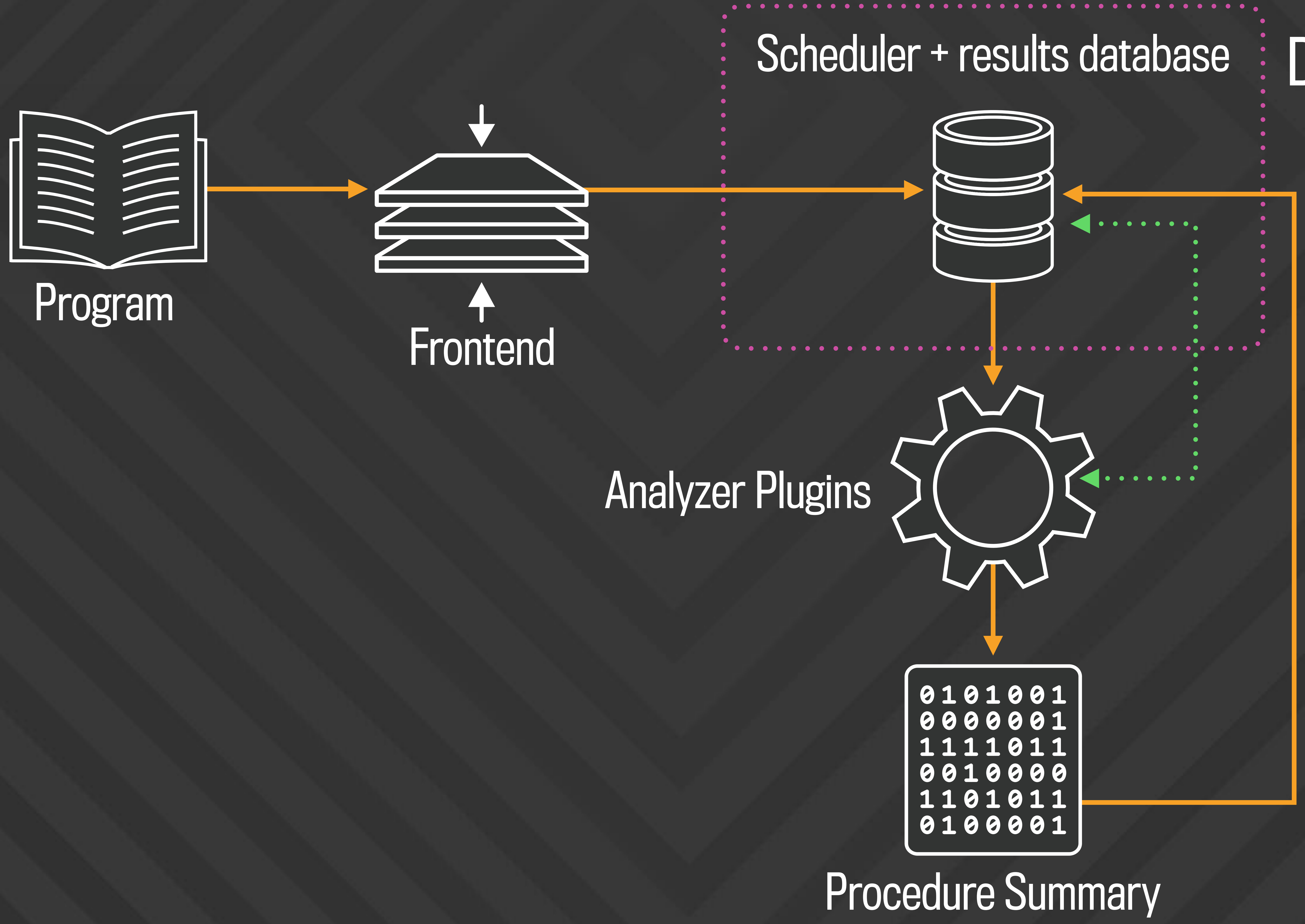
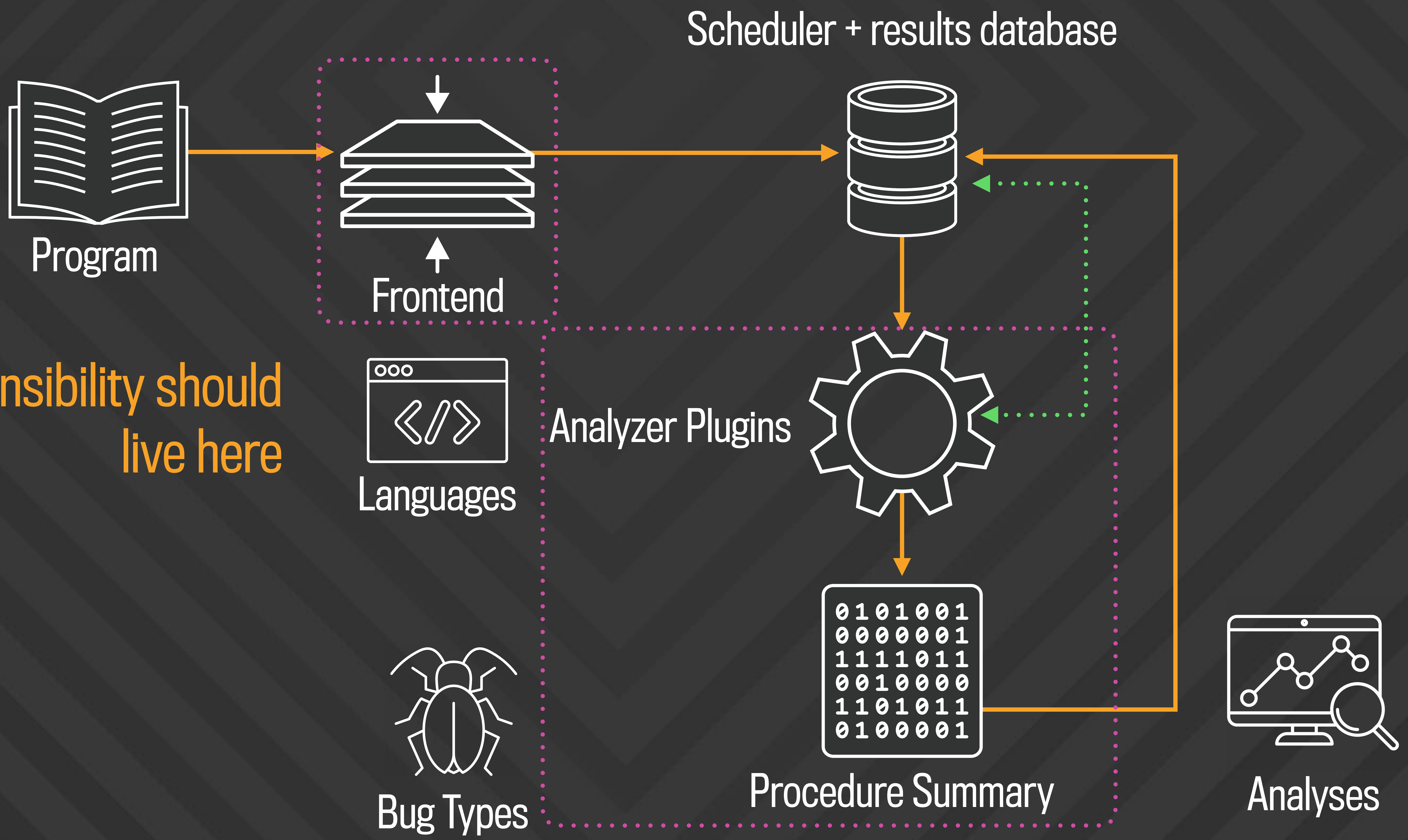


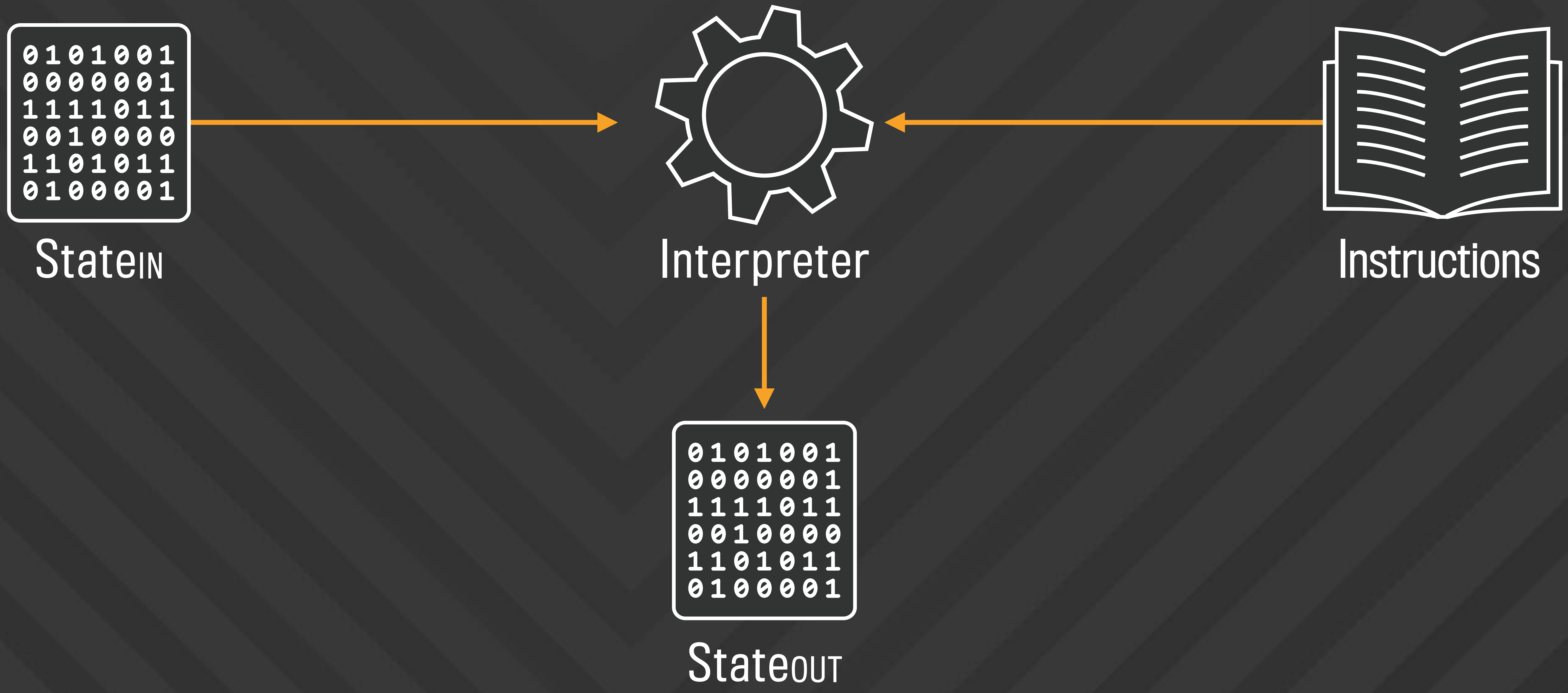
Don't want to change

Recipe for a scalable/extensible analyzer



Extensibility should live here

Intraprocedural static analyzers are interpreters



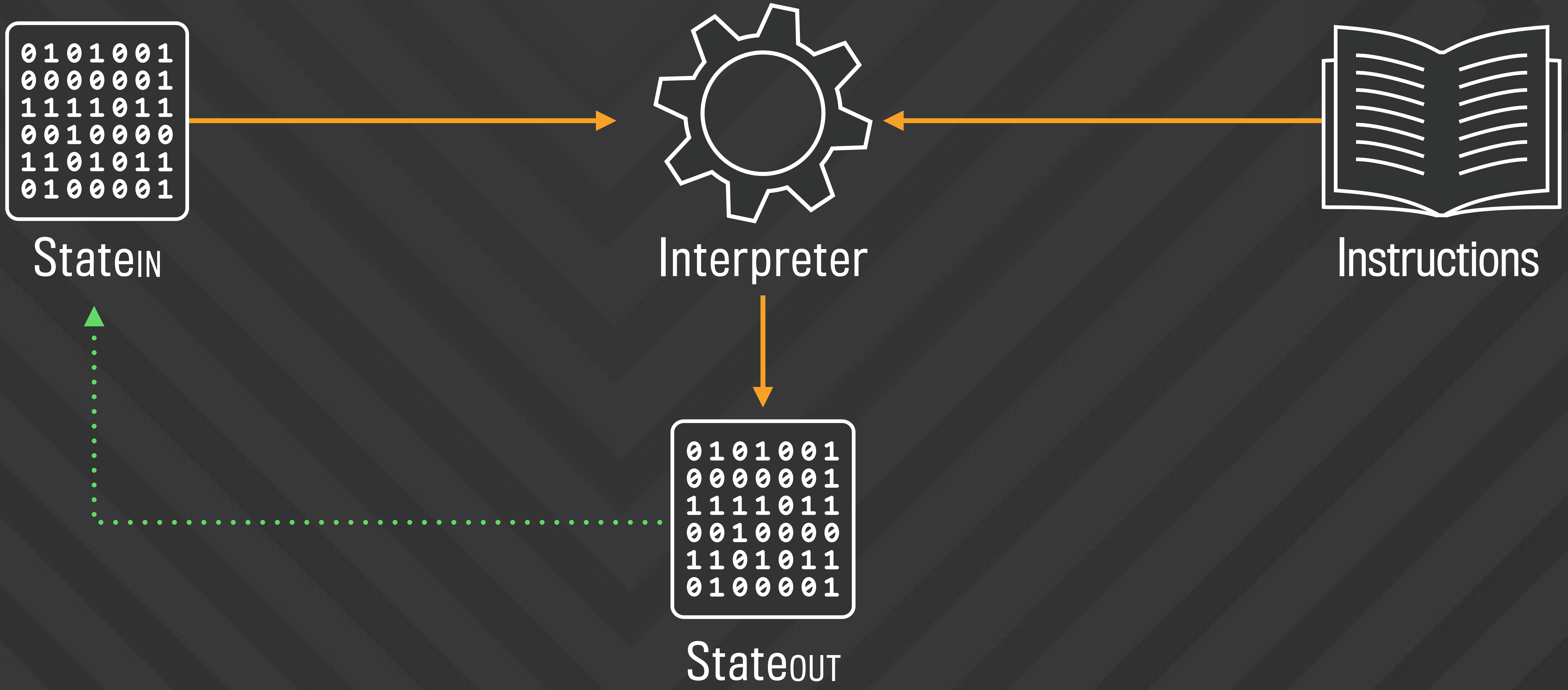
StateIN

Interpreter

Instructions

StateOUT

Intraprocedural static analyzers are interpreters



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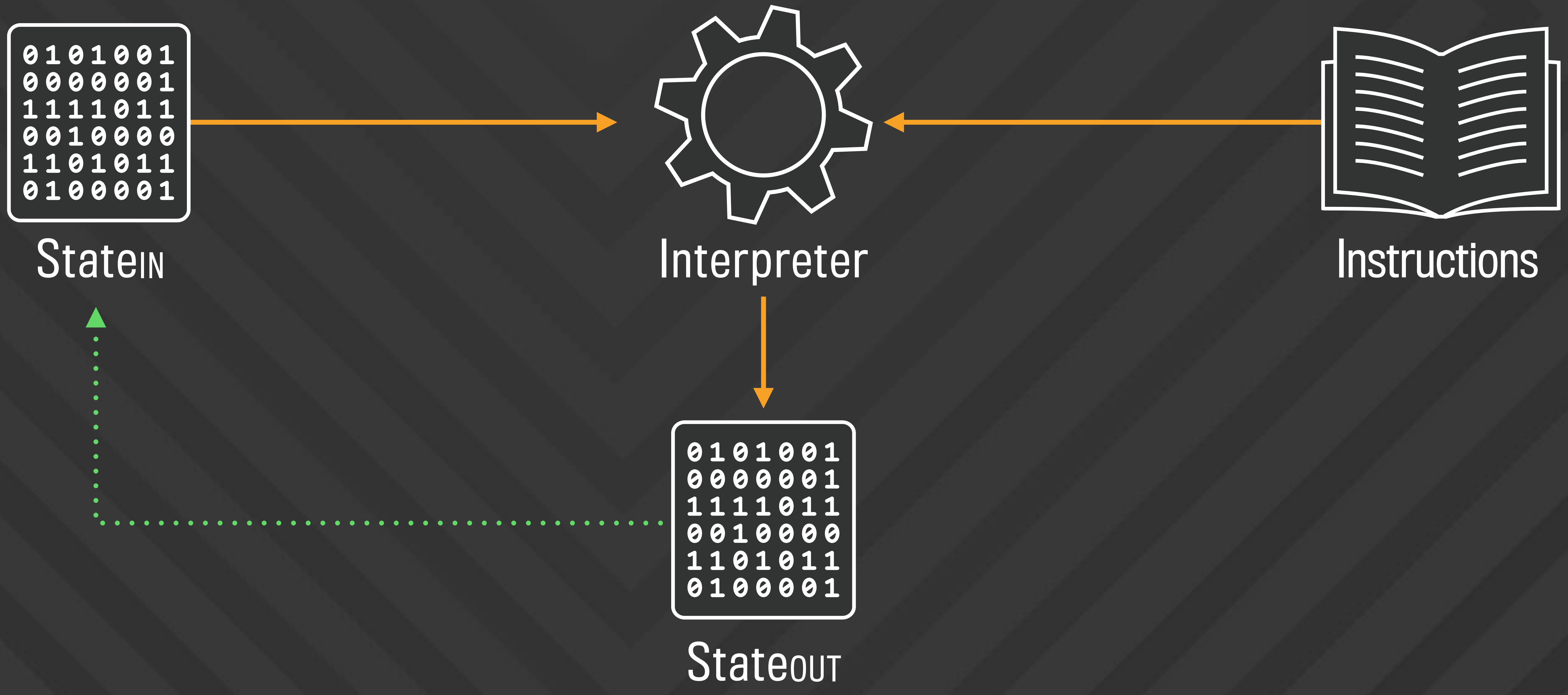
Monolithic interpreters are hard to extend



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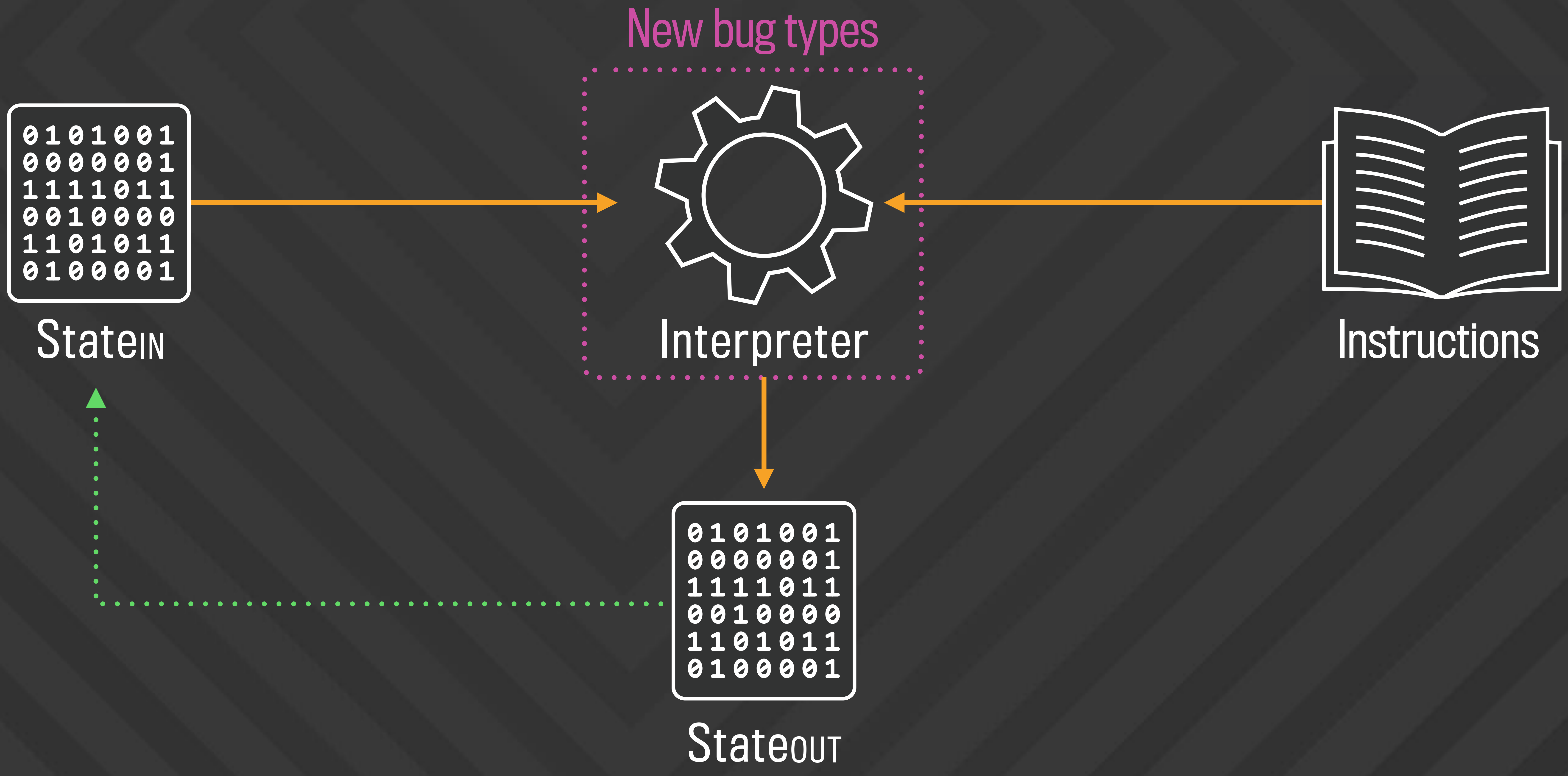

New bug types

StateIN

Interpreter

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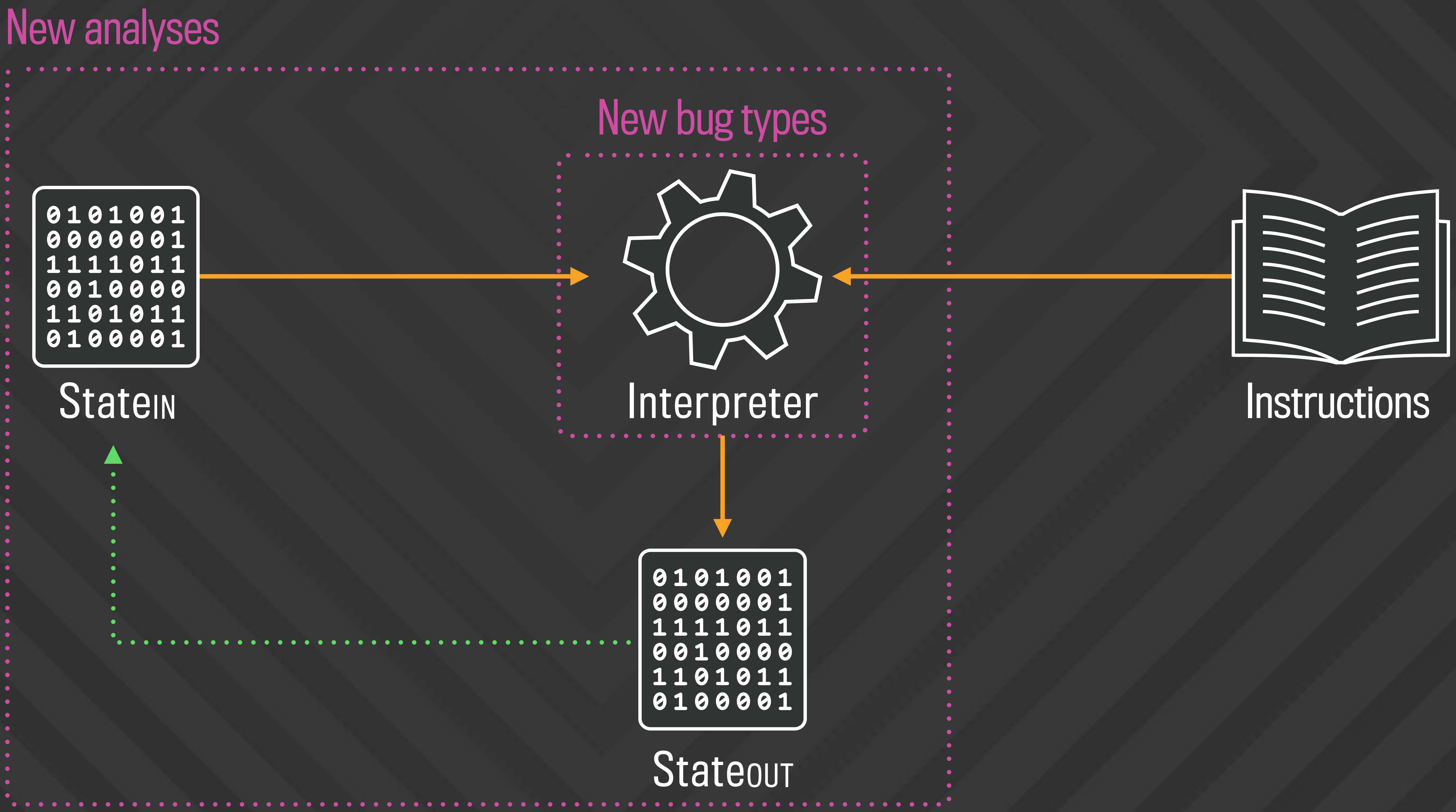

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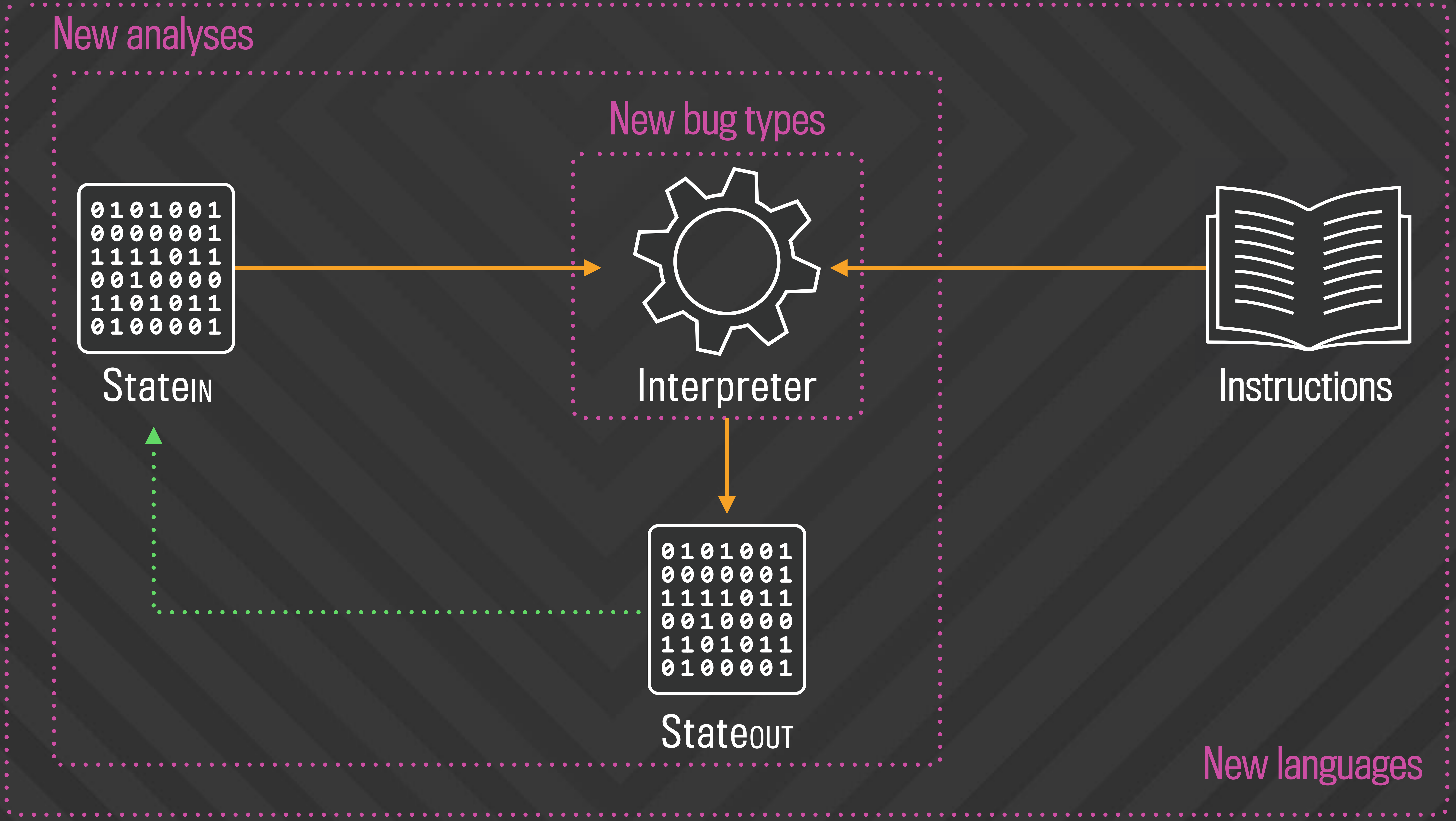

New analyses

New bug types

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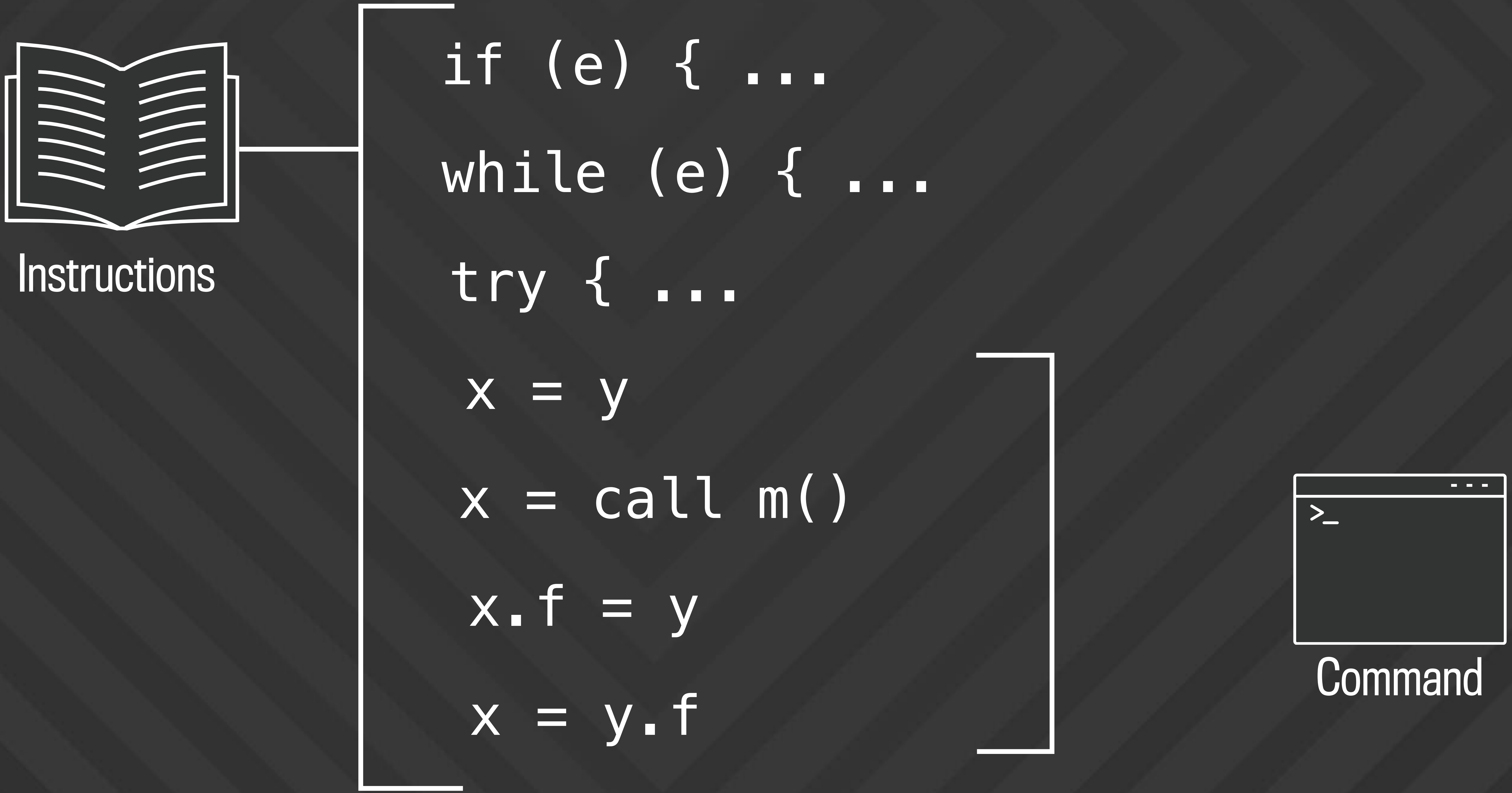
New languages

Separating instructions and commands

Instructions

```
if (e) { ...
while (e) { ...
try { ...
x = y
x = call m()
x.f = y
x = y.f
```

Separating instructions and commands



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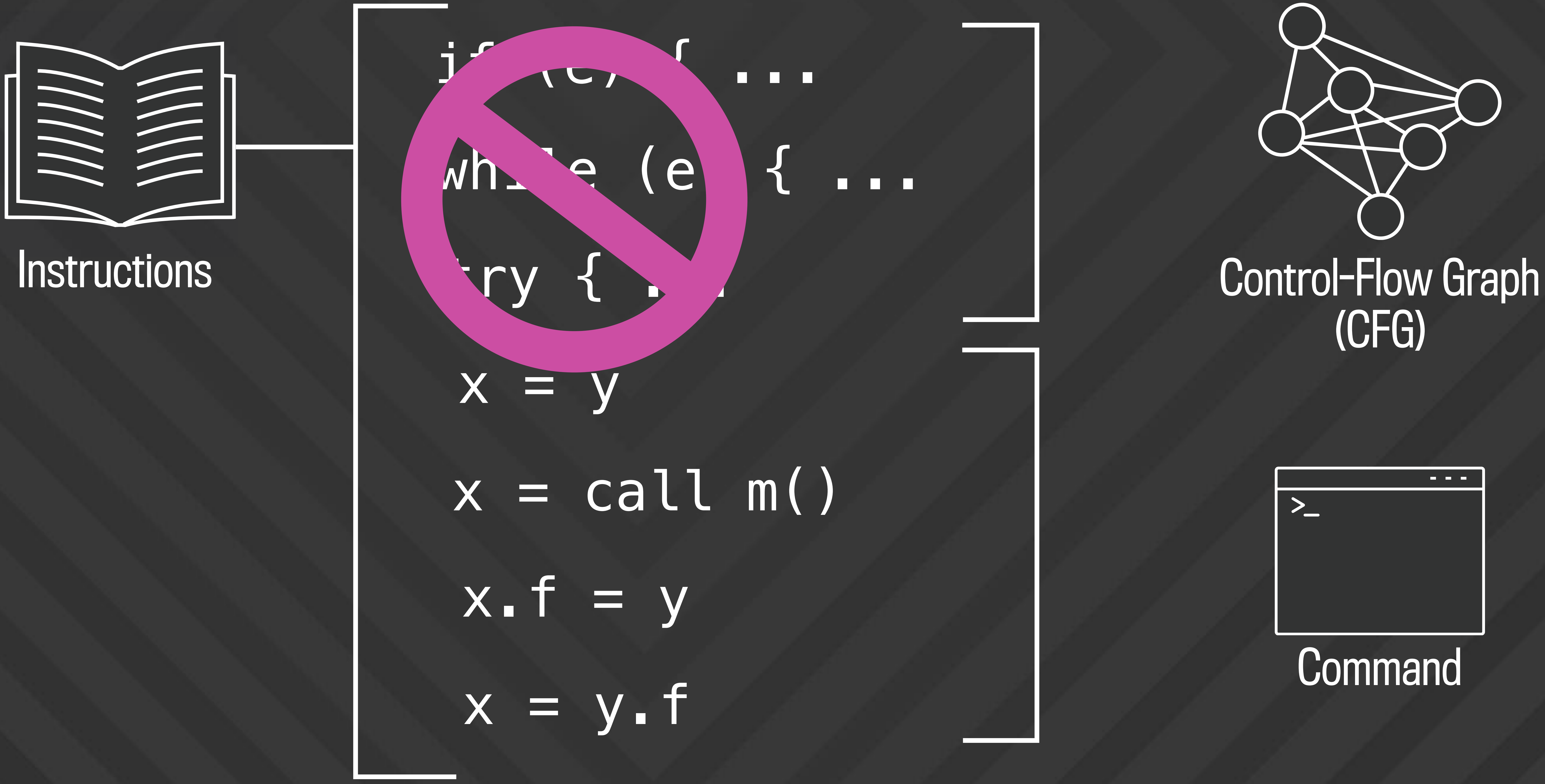
Command

Separating instructions and commands



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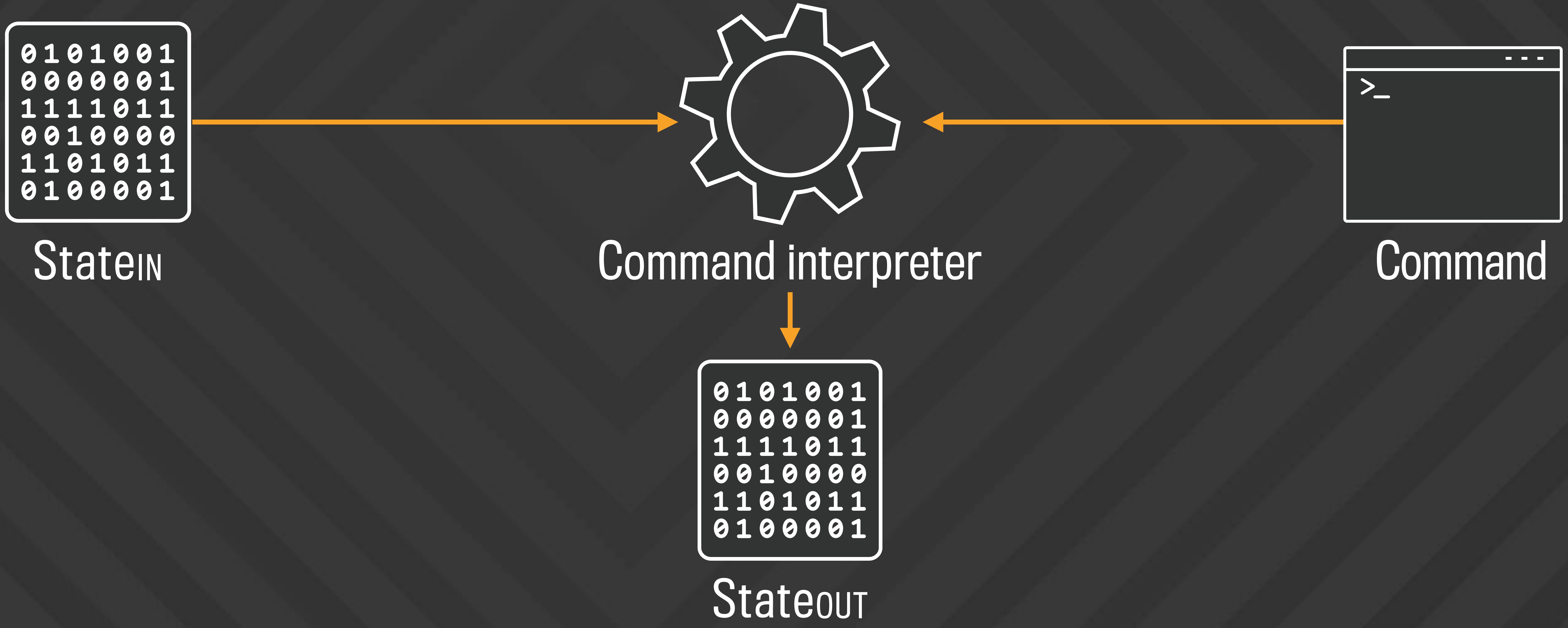
Control-Flow Graph
(CFG)

Command

Splitting the interpreter



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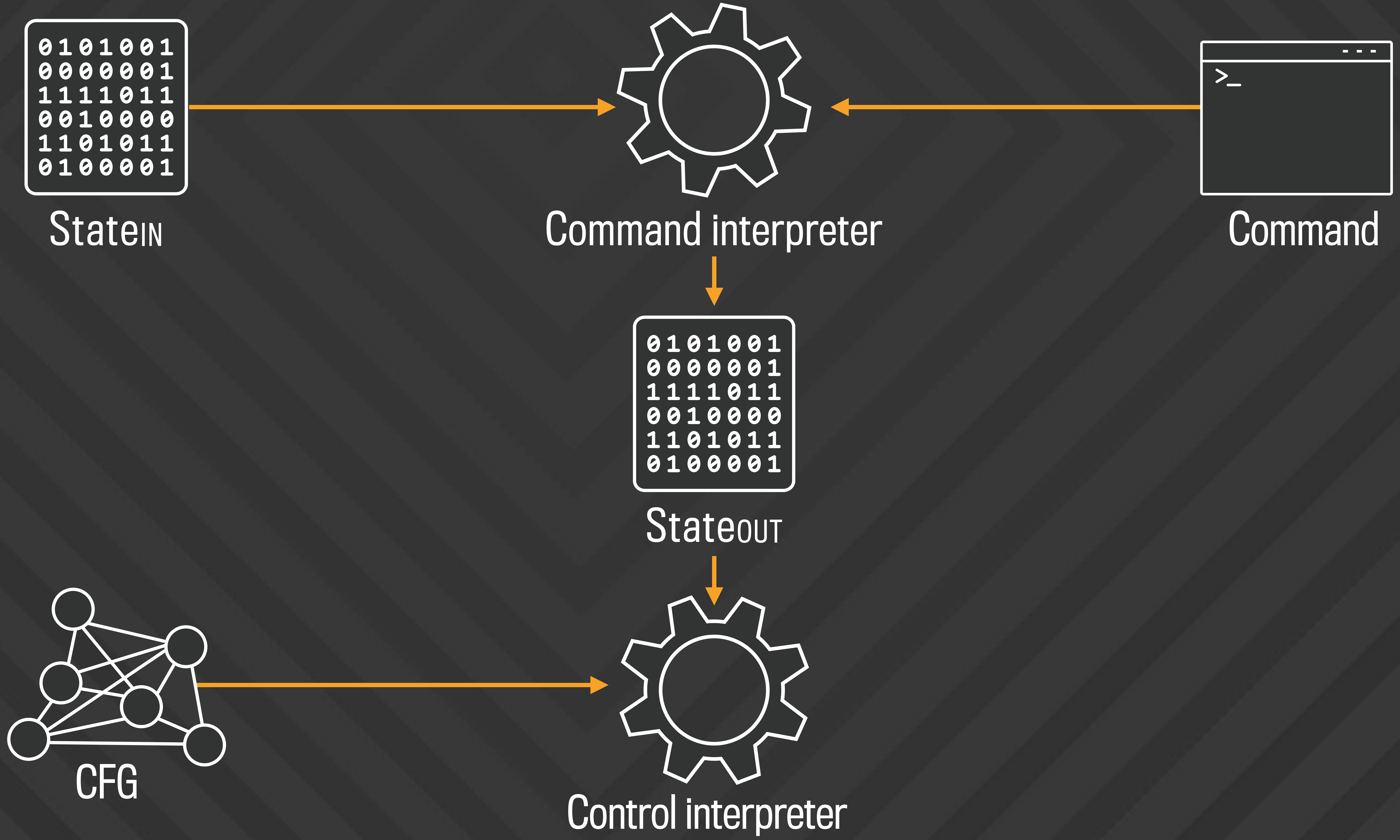


StateIN

Command interpreter

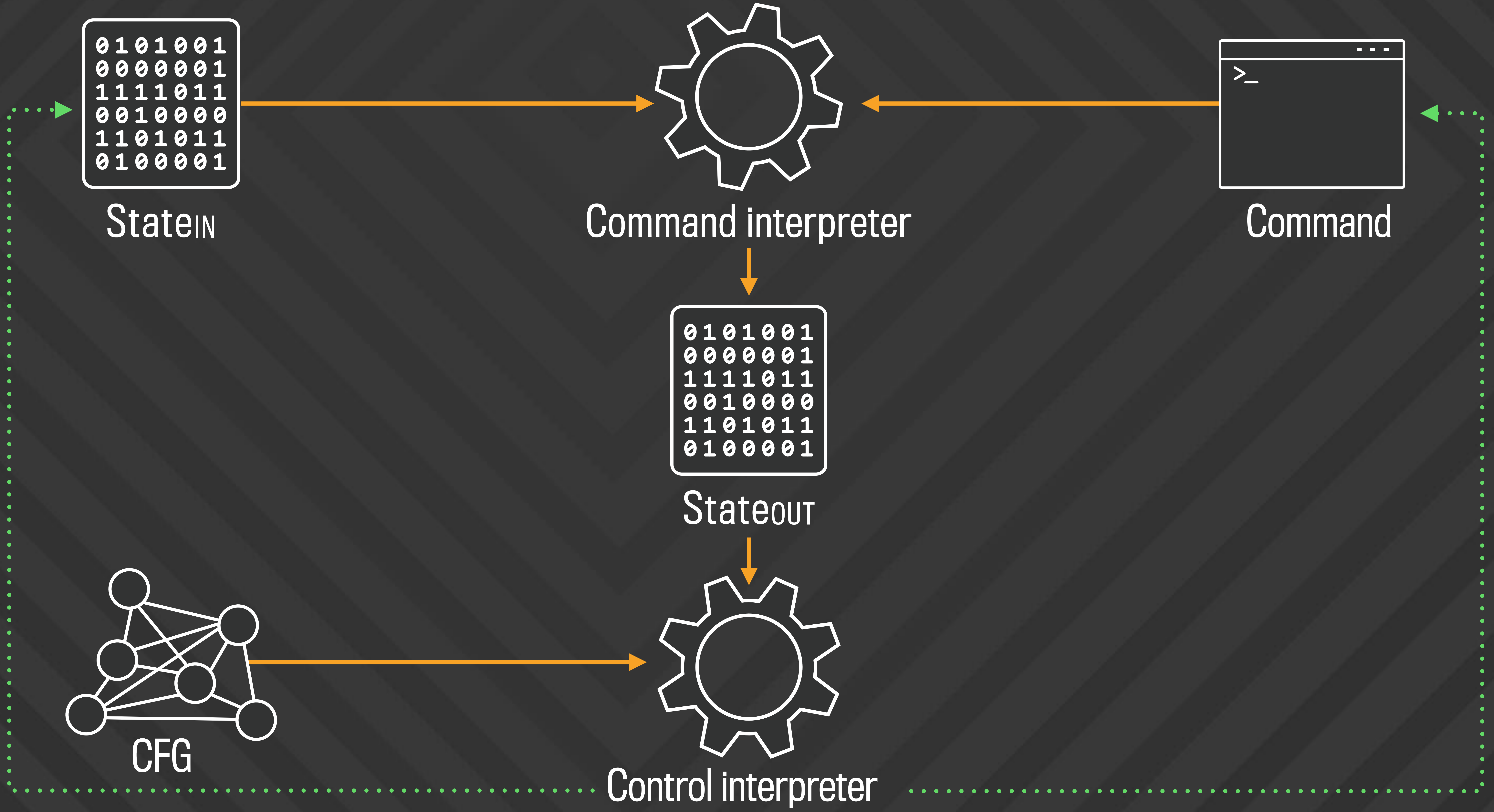
Command

StateOUT

CFG

Control interpreter

Splitting the interpreter



StateIN

Command interpreter

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Control interpreter

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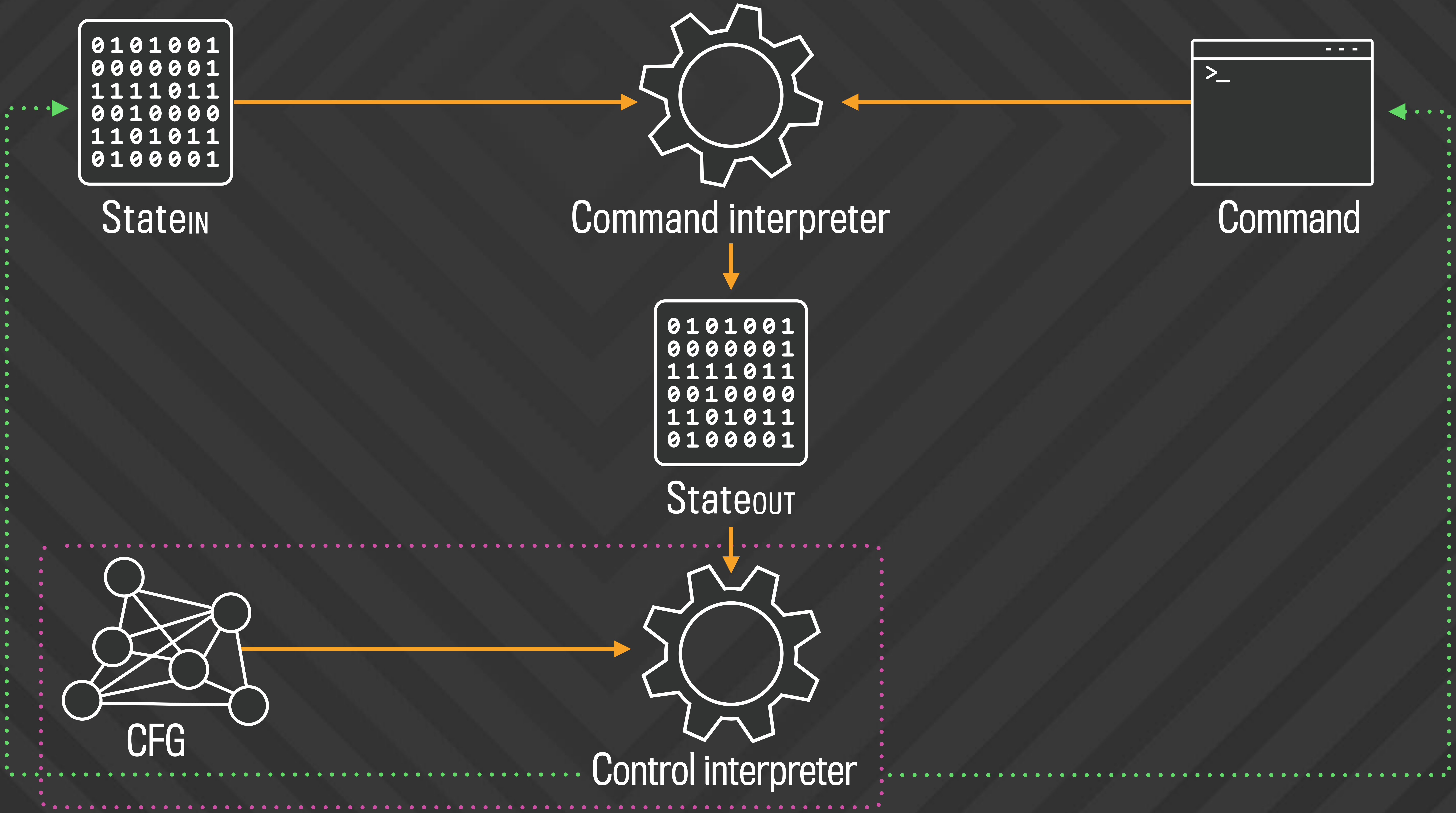

StateIN

Command interpreter

Command

StateOUT

CFG

Control interpreter

Generalizing to multiple paths

```
STATE
if(...) {
 command 1;
 STATE₁
} else {
 command 2;
 STATE₂
}
[???]
command 3;
```

Generalizing to multiple paths

```
STATE
if(...) {
 command 1;
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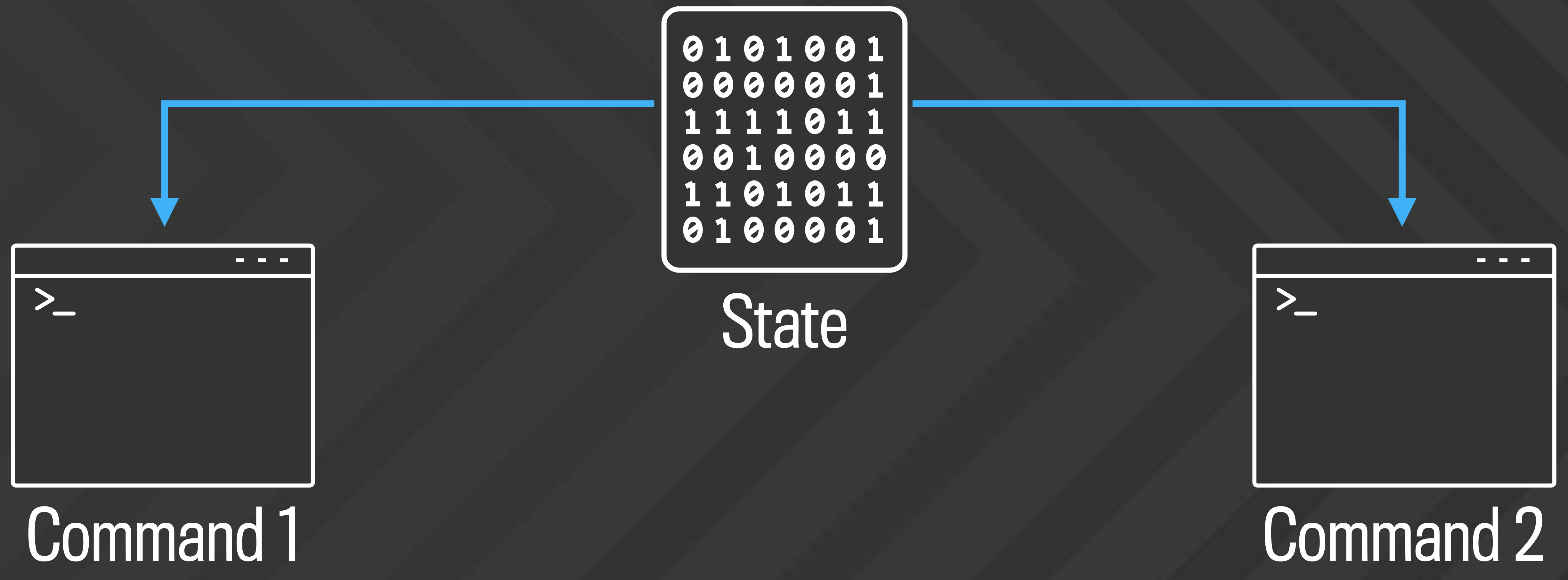

Generalizing to multiple paths

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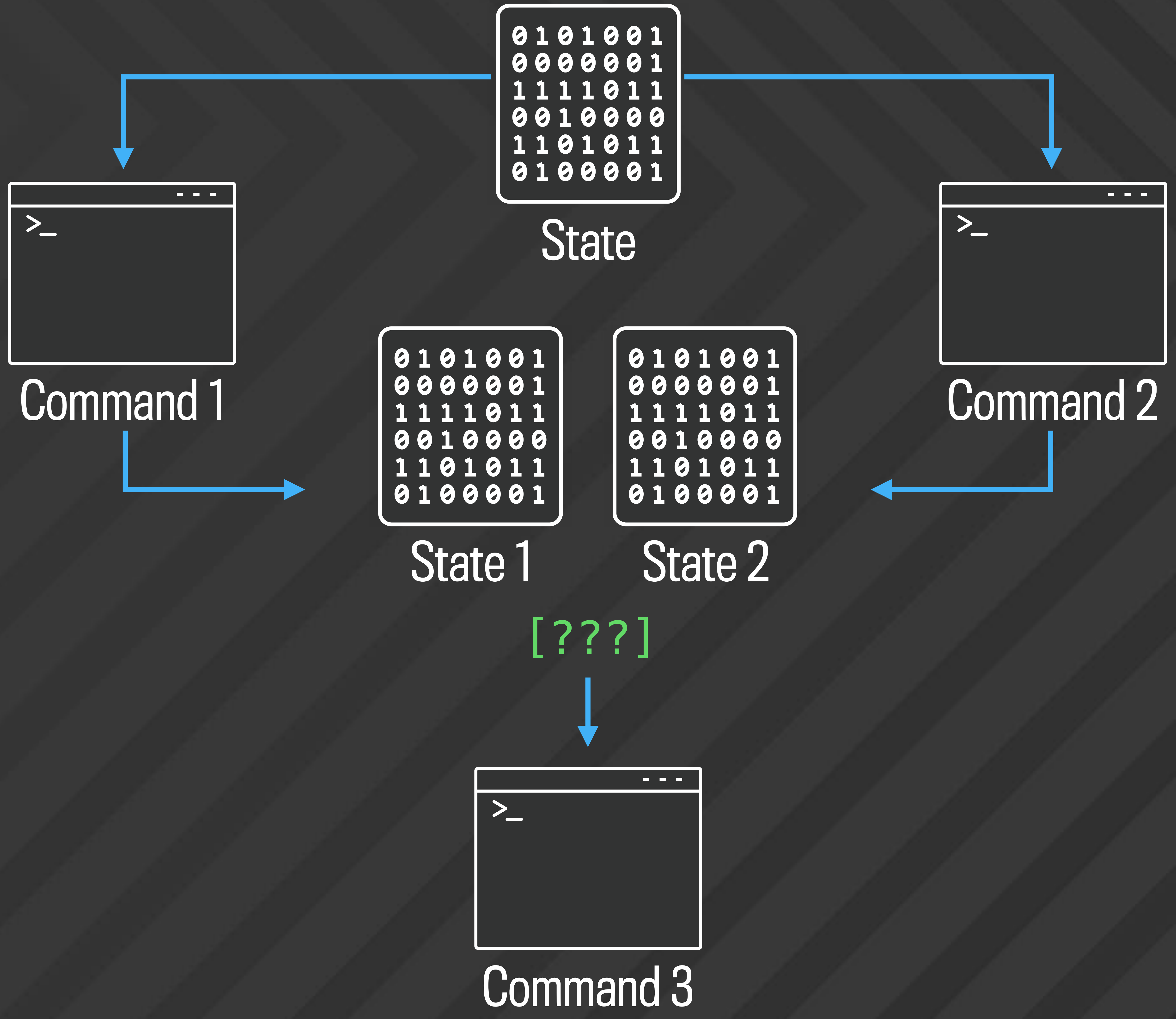

Generalizing to multiple paths

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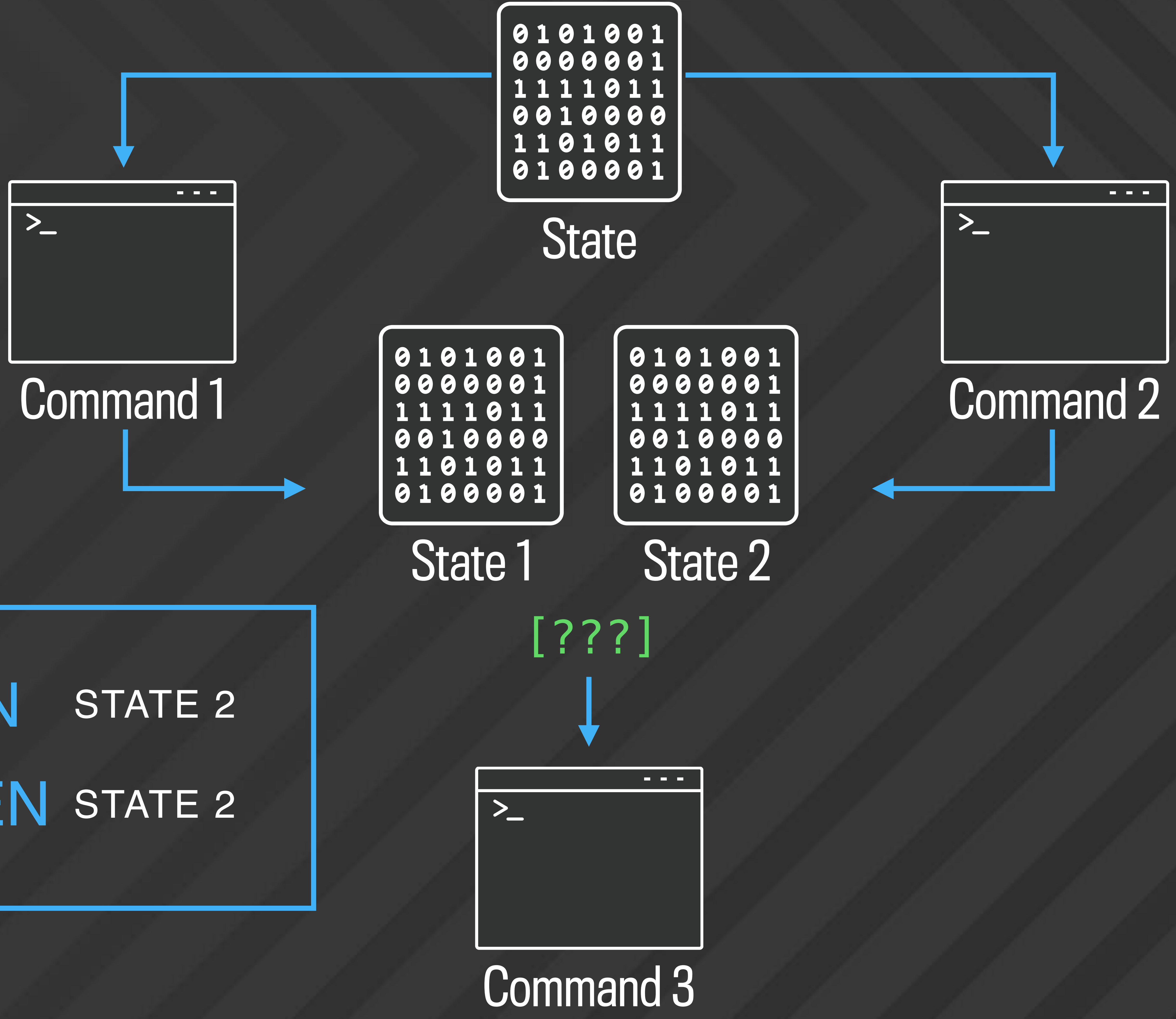
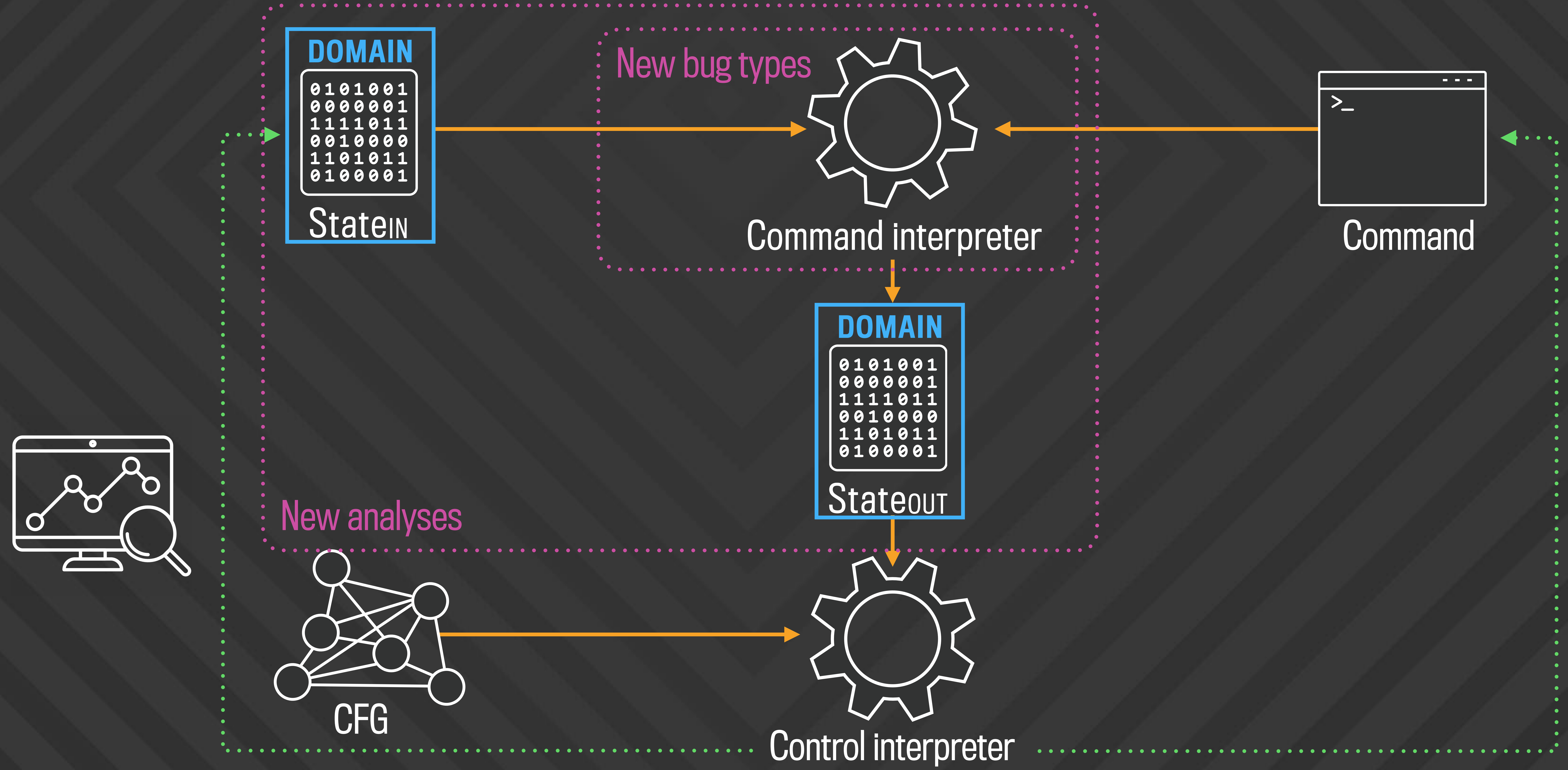


DOMAIN

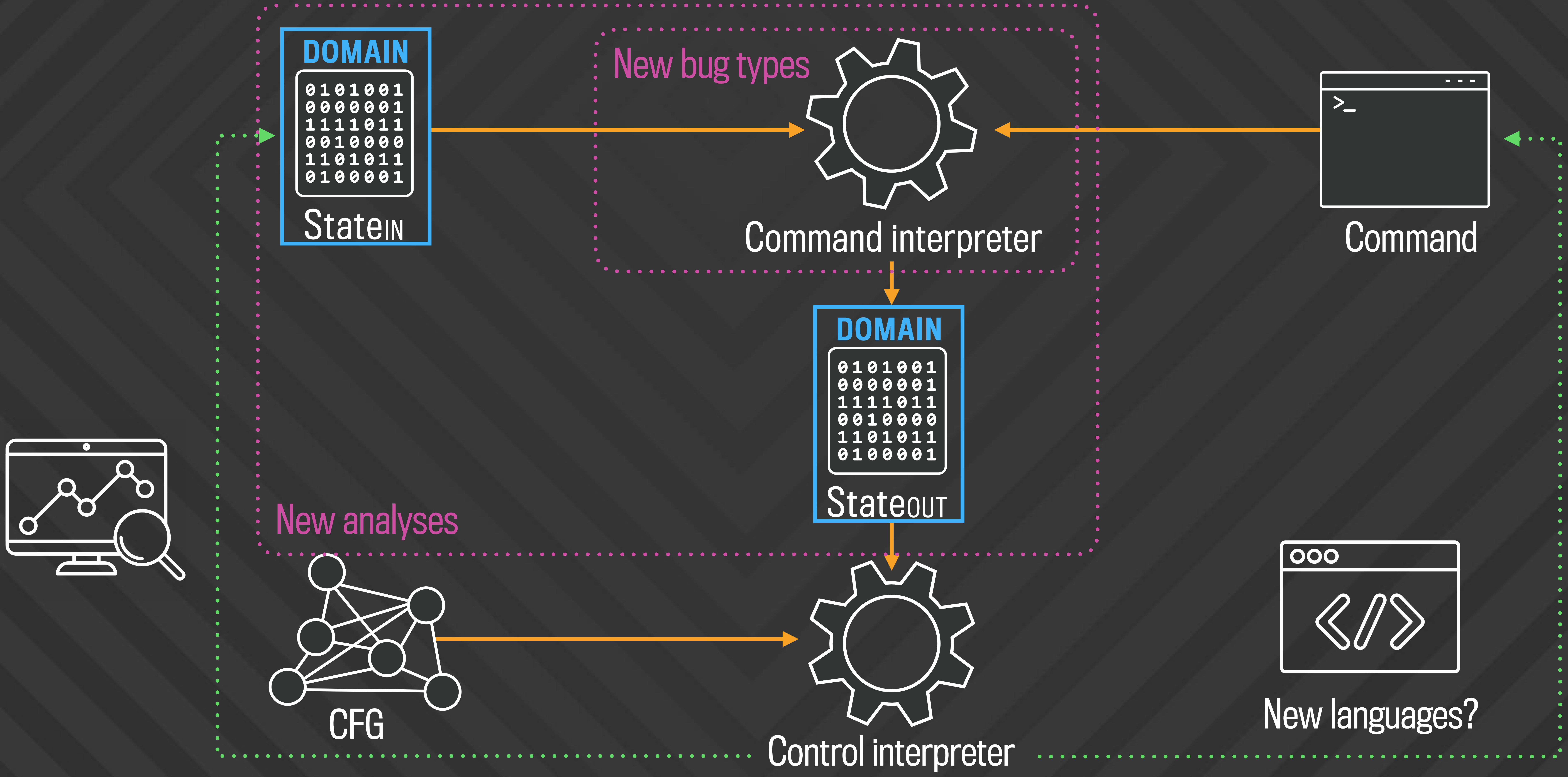
STATE 1 **JOIN** STATE 2

STATE 1 **WIDEN** STATE 2

Putting it all together



Putting it all together


DOMAIN

StateIN

New bug types

Command interpreter

Command

DOMAIN

StateOUT

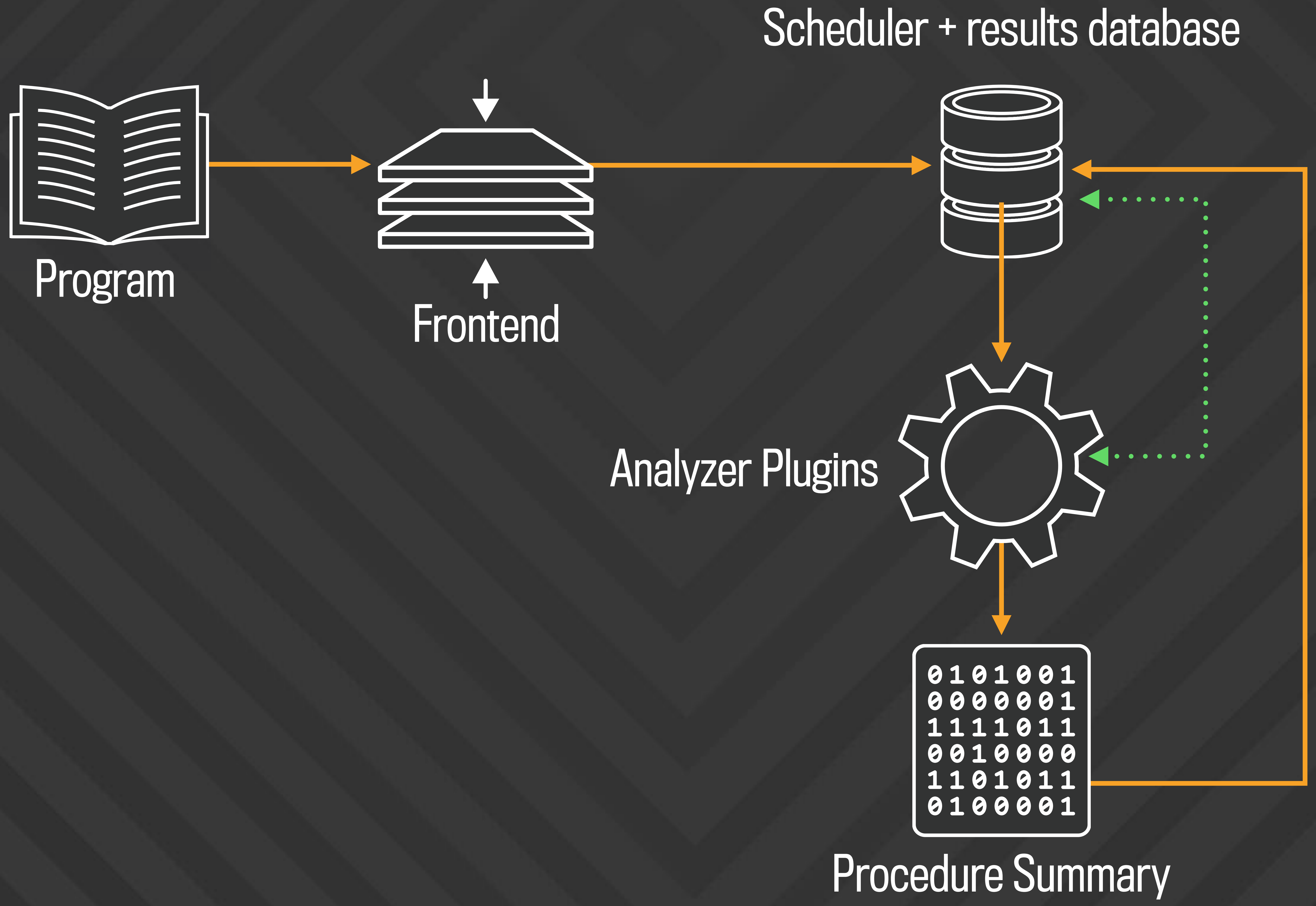
New analyses

CFG

Control interpreter

New languages?

Recipe for an scalable/extensible analyzer


Scheduler + results database

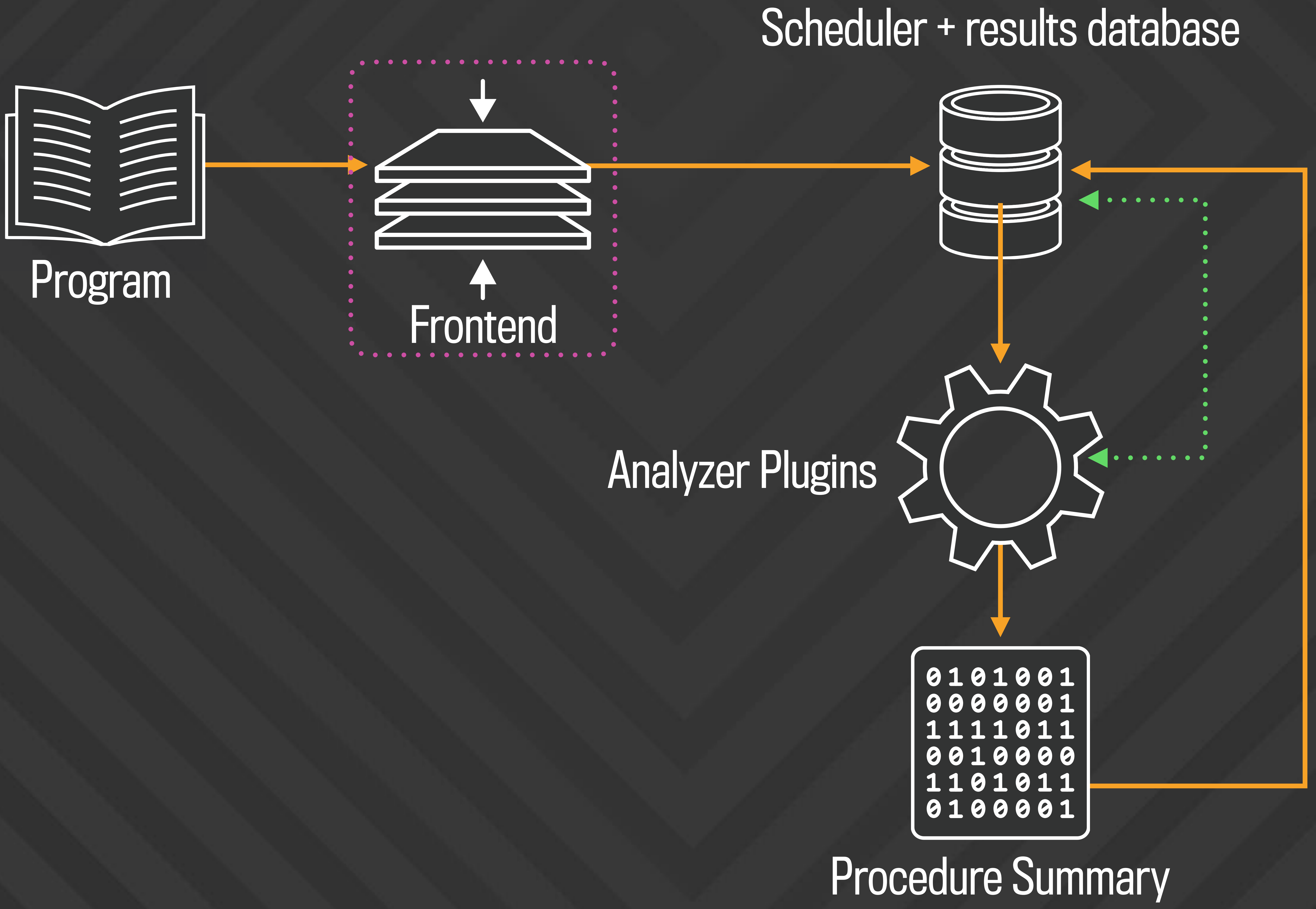
Program

Frontend

Analyzer Plugins

Procedure Summary

Recipe for an scalable/extensible analyzer



Program

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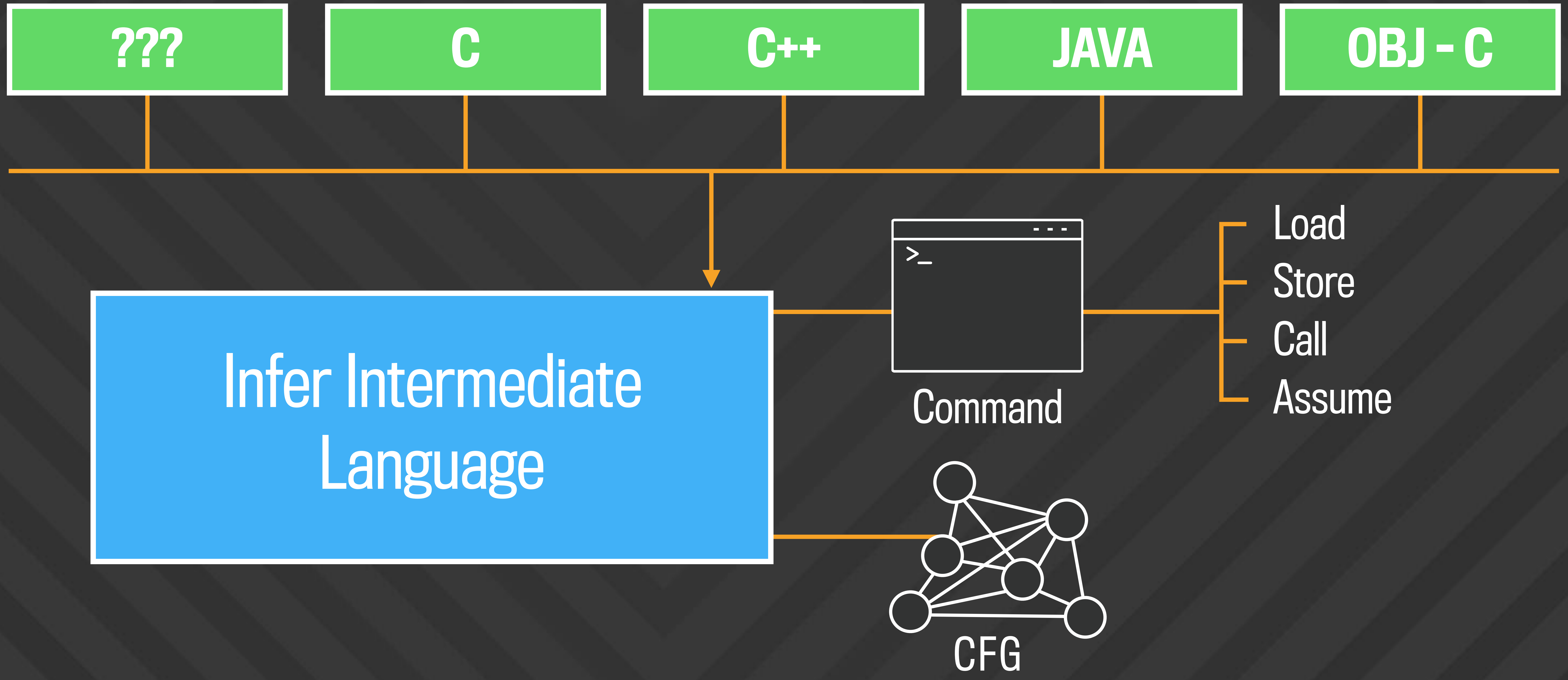

???
C
C++
JAVA
OBJ - C
Infer Intermediate Language
>_
Command
Load
Store
Call
Assume
CFG

Roadmap

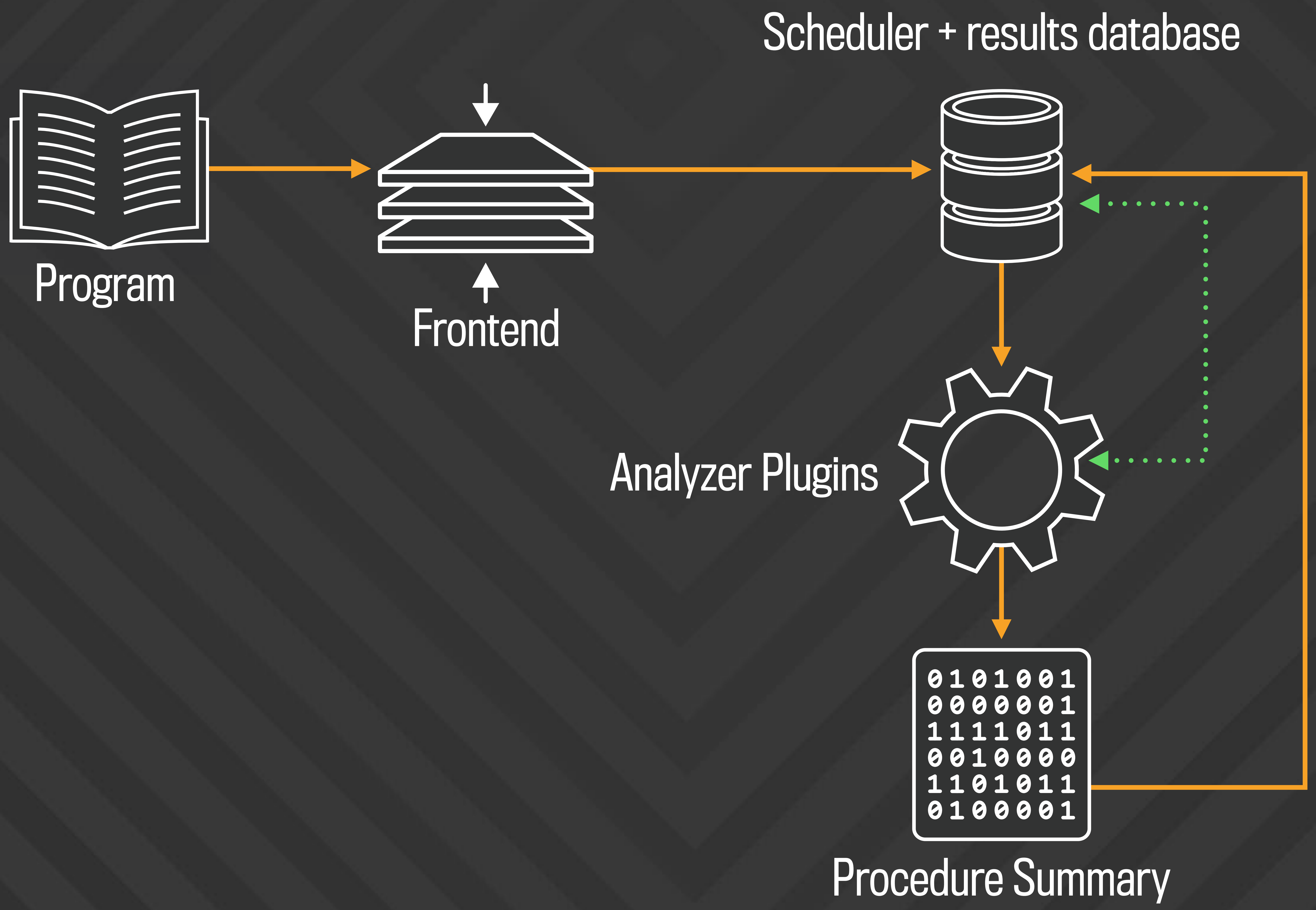
1. Infer.AI architecture
2. Building intraprocedural analyzers
3. Building compositional interprocedural analyzers

Roadmap

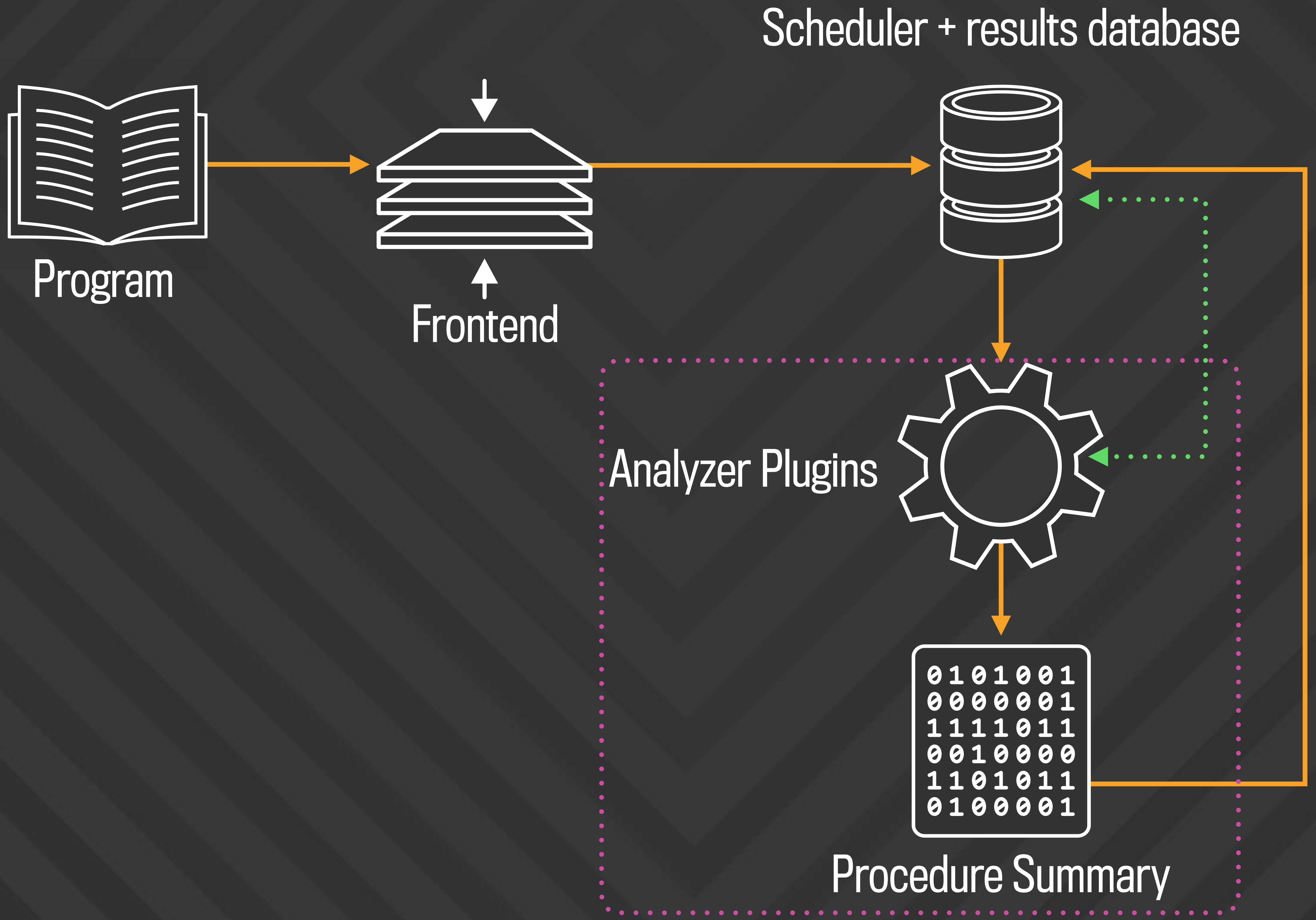
2 Building intraprocedural analyzers

- Domains and domain combinators
- Transfer functions
- Control-flow graphs
- Putting it all together

Extensible analysis architecture



Extensible analysis architecture



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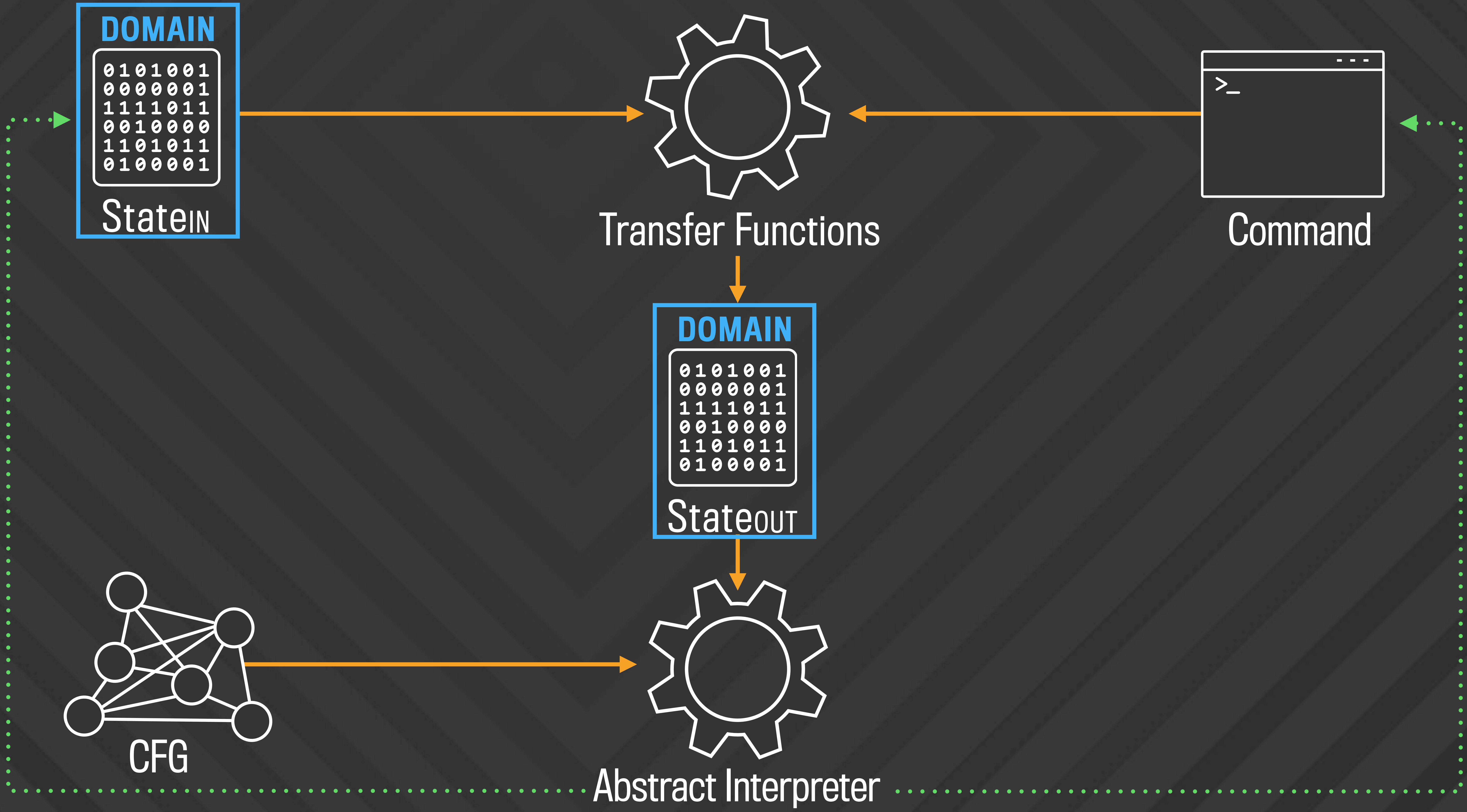
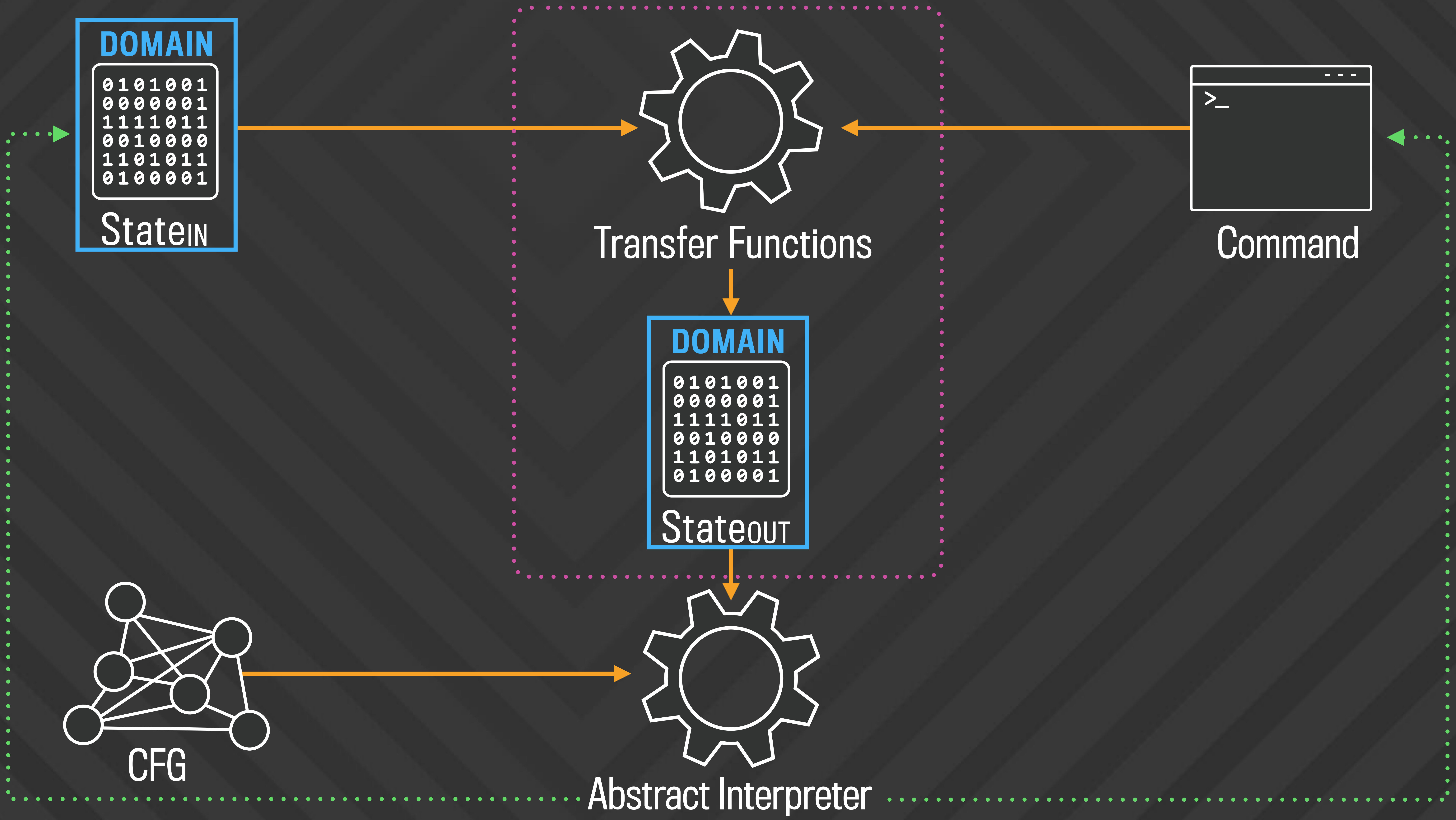
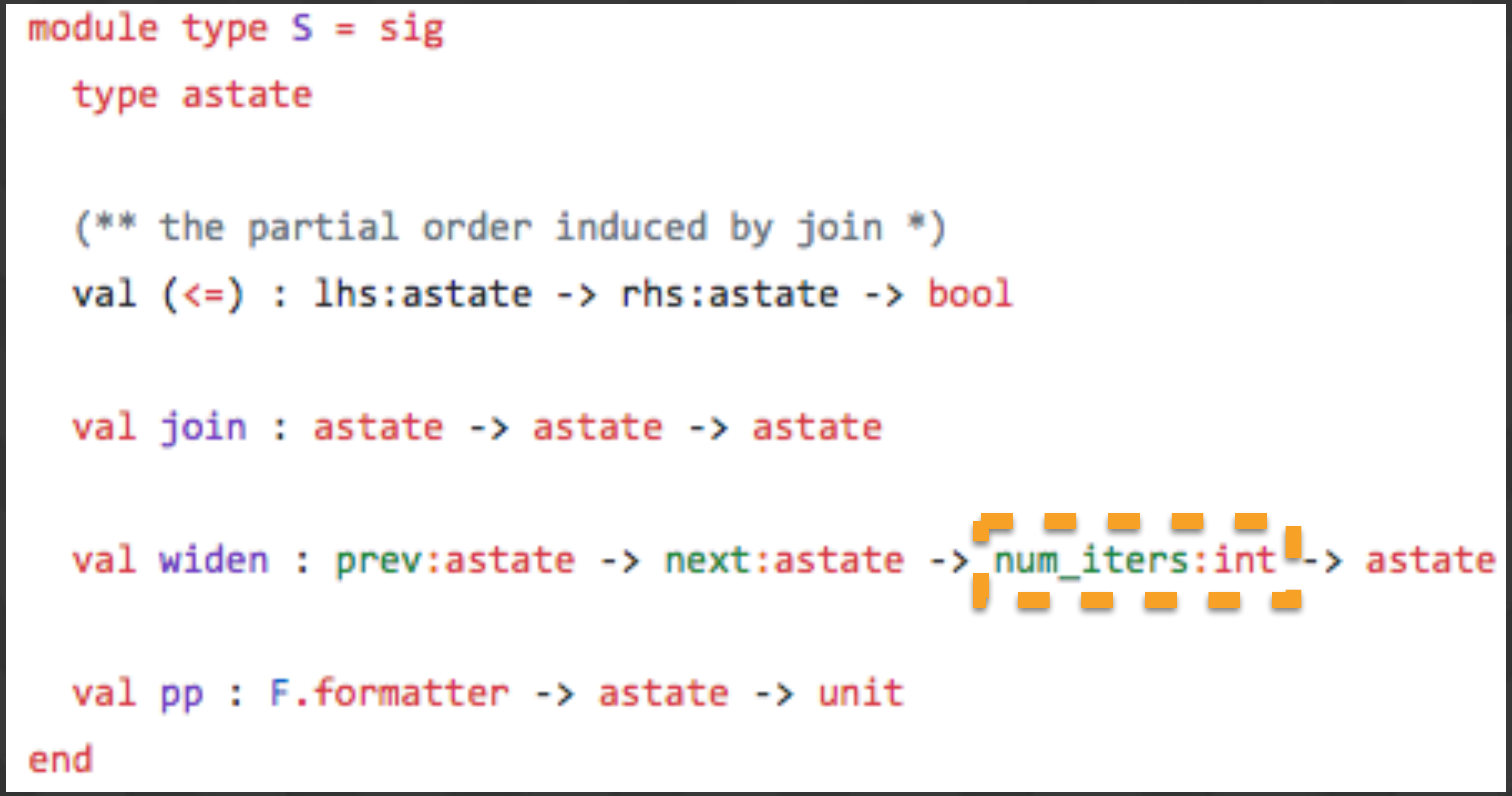


Extensible analysis architecture



Abstract domains are simple (AbstractDomain.ml)



```
module type S = sig
  type astate

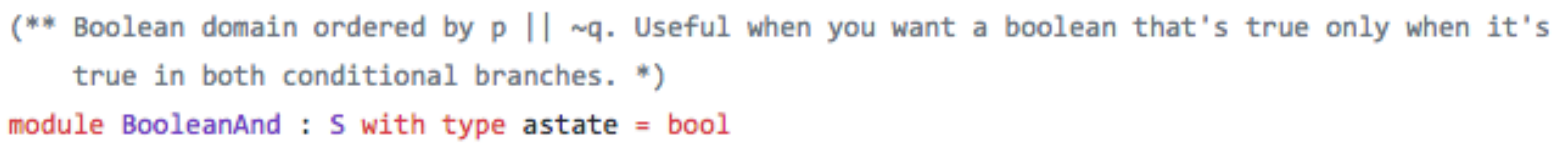
  (** the partial order induced by join *)
  val (<=) : lhs:astate -> rhs:astate -> bool

  val join : astate -> astate -> astate

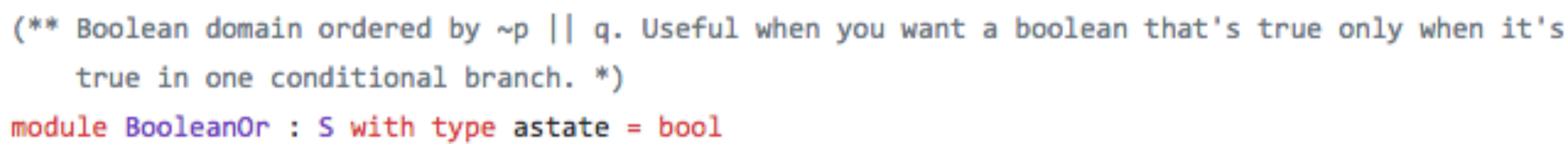
  val widen : prev:astate -> next:astate -> num_iters:int -> astate

  val pp : F.formatter -> astate -> unit
end
```

Built-in domains: booleans



```
(** Boolean domain ordered by p || ~q. Useful when you want a boolean that's true only when it's
    true in both conditional branches. *)
module BooleanAnd : S with type astate = bool
```



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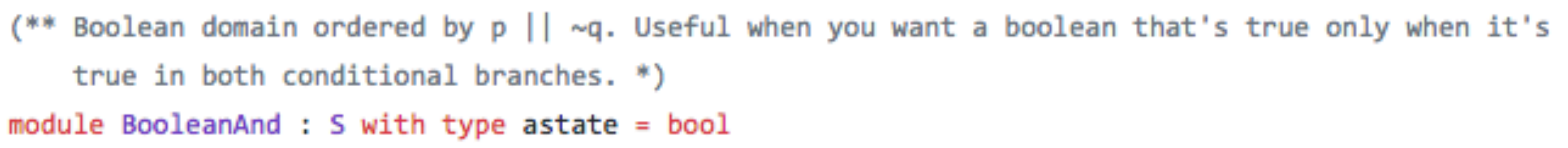
Built-in domains: booleans

- Boolean domains



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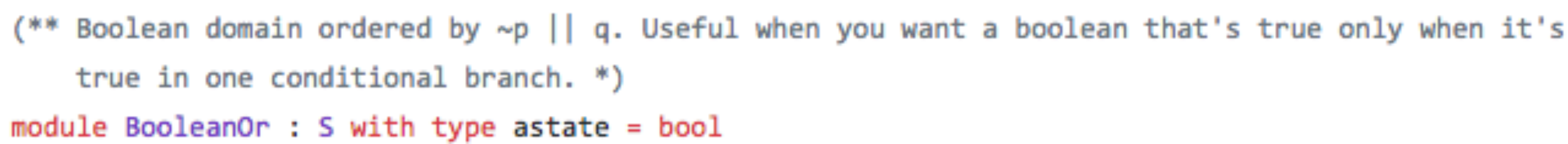

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Built-in domains: access paths

$x \in Var$

$f \in Fld$

$AP ::= x \mid AP\ .\ f \mid AP\ [e] \mid AP\ *$

$e \in \hat{Exp} ::= AP \mid \ldots$

[Jones and Muchnick POPL '79 ***Flow analysis and optimization of LISP-like structures*****]**

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- Examples:

  $x \quad x.f \quad x[i].g \quad x.f.g$

[Jones and Muchnick POPL '79 *Flow analysis and optimization of LISP-like structures*]

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- Concretization: all addresses that may be read via given path at current program point

[**Jones and Muchnick POPL '79** ***Flow analysis and optimization of LISP-like structures***]

Built-in domains: access paths

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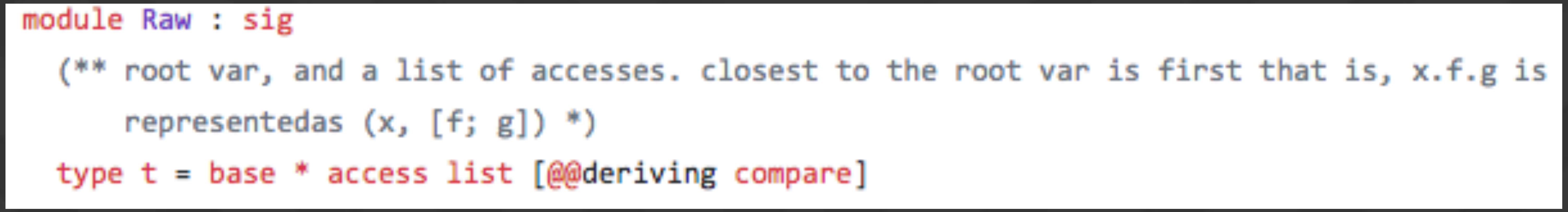
$e \in E\hat{x}p ::= AP \mid \ldots$

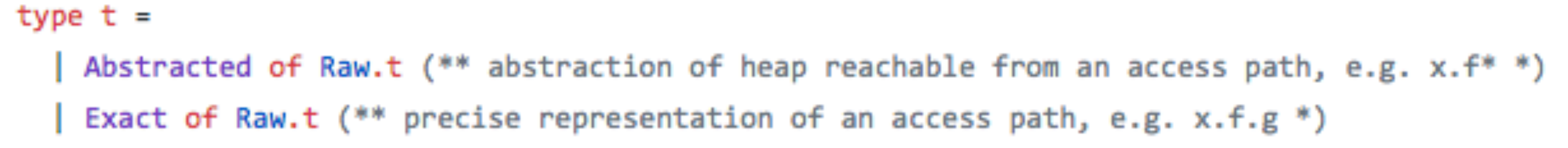
- Excellent domain for prototyping; simple, very close to concrete syntax
- Hard to handle aliasing well. Any two access paths can alias if the types of the last accesses are compatible: $type(ap_1) <: type(ap_2) \vee type(ap_2) <: type(ap_1)$

[Jones and Muchnick POPL '79 *Flow analysis and optimization of LISP-like structures*]

Built-in domains: access paths (AccessPath.ml)



```
module Raw : sig
  (** root var, and a list of accesses. closest to the root var is first that is, x.f.g is
      representedas (x, [f; g]) *)
  type t = base * access list [@@deriving compare]
```



```
type t =
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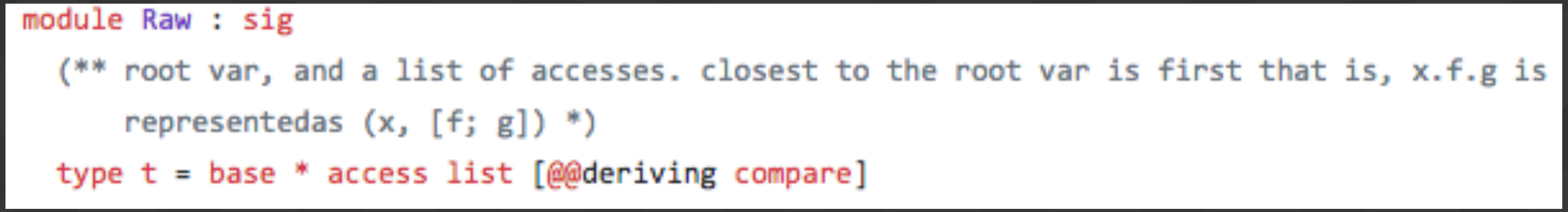
```

Built-in domains: access paths (AccessPath.ml)

- AccessPath.Raw.t (no length bounding)



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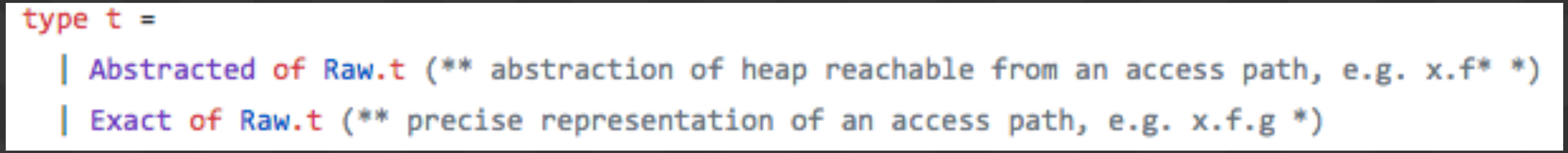

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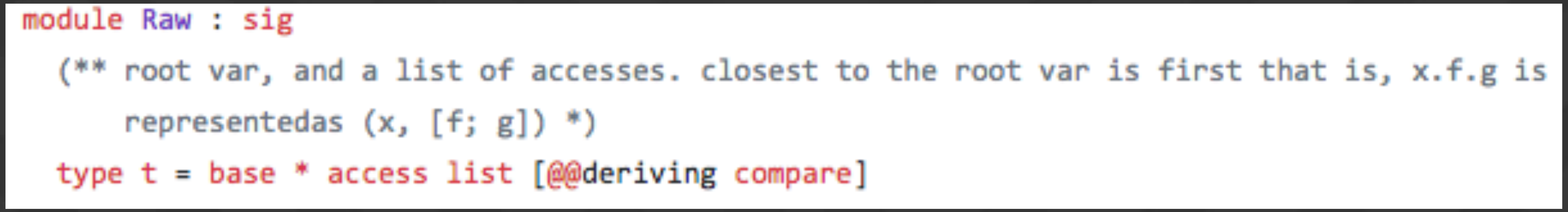

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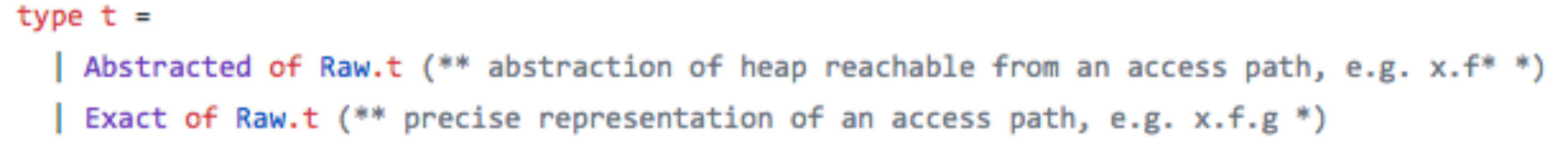

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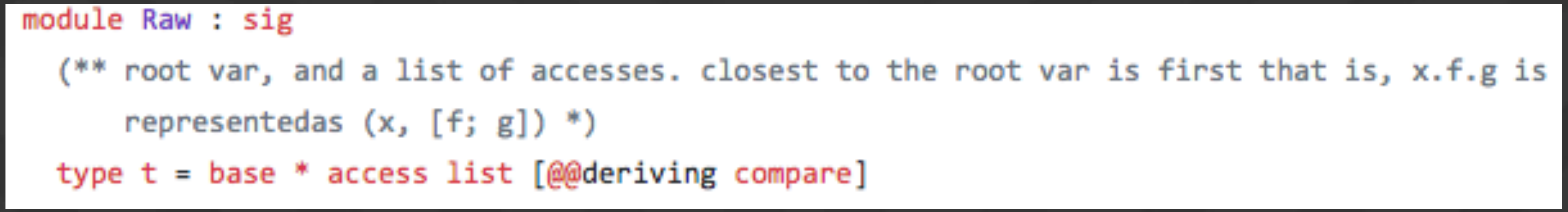

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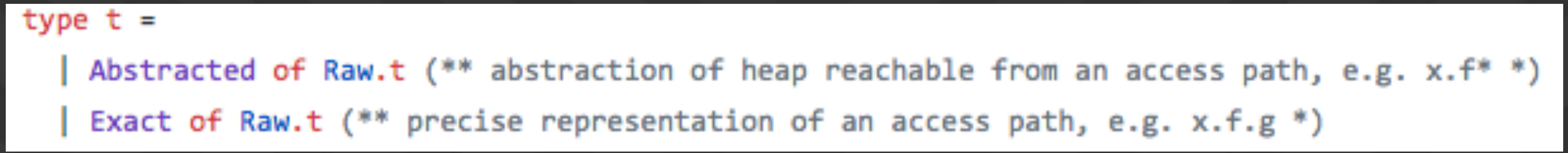

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```
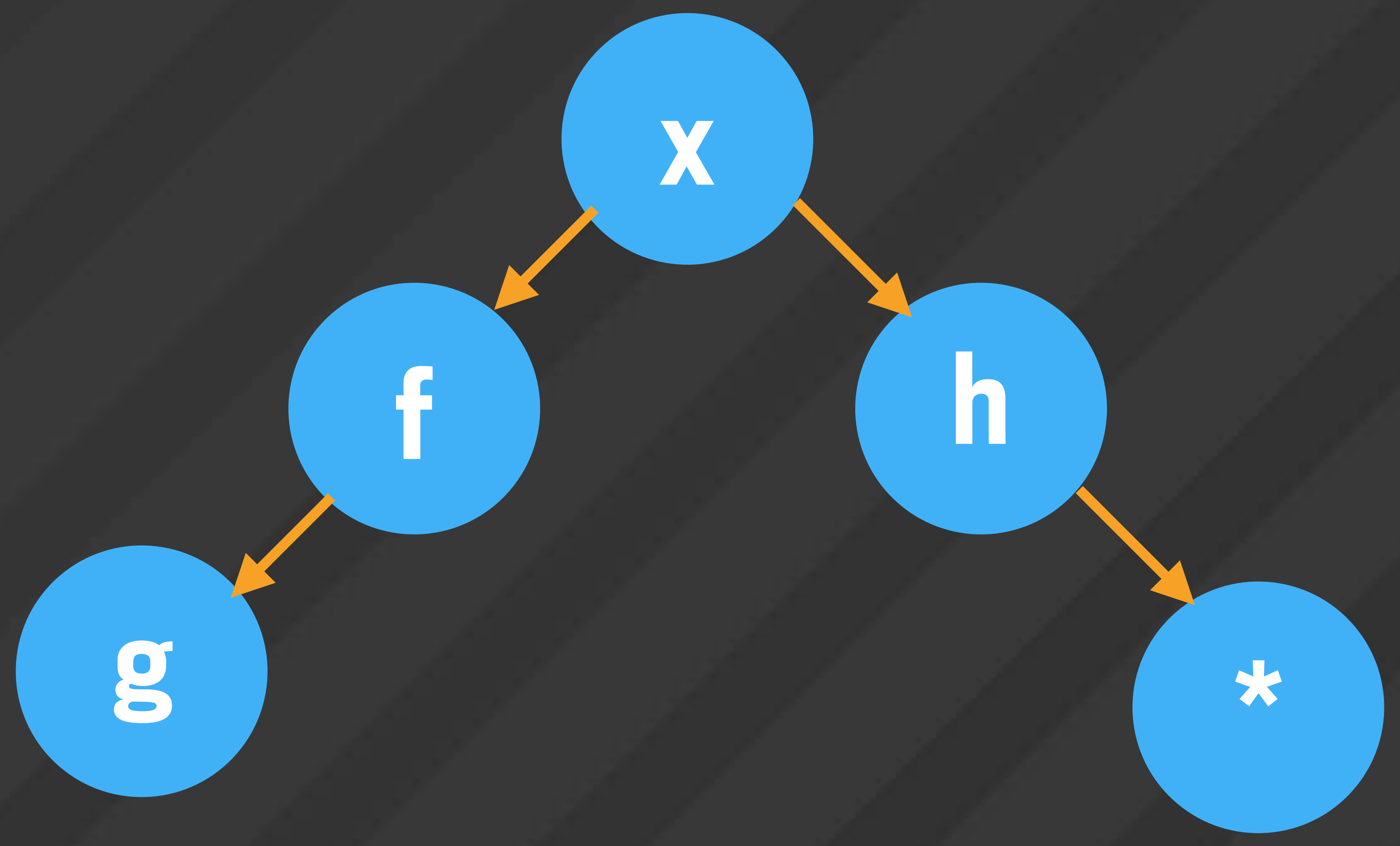
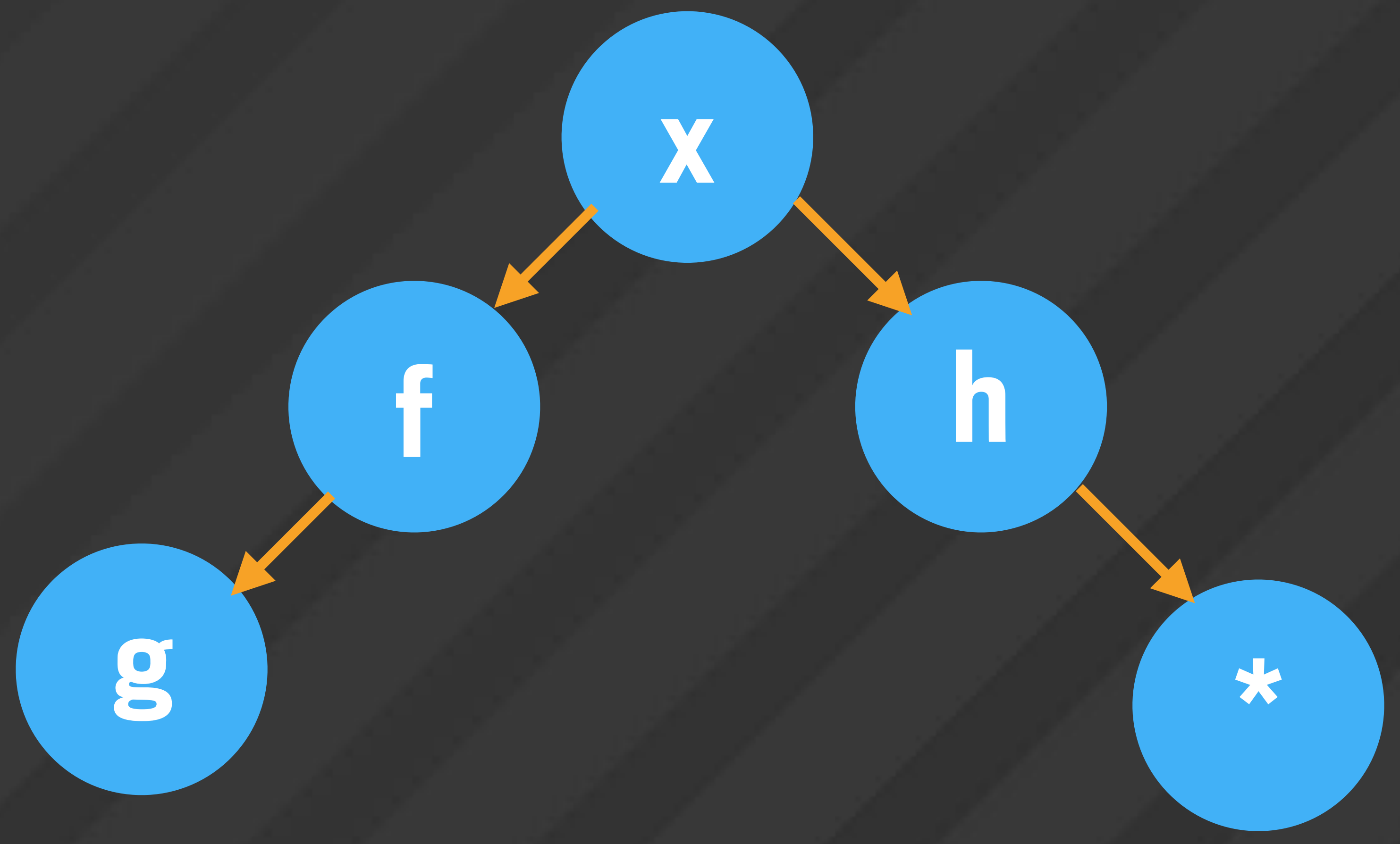

- AccessPathDomains.Set (add-only set of paths w/ normalization)

Built-in domains: access tree



Built-in domains: access tree

- Trie where nodes are bases (at level 0) or accesses (at level n > 0)



Built-in domains: access tree

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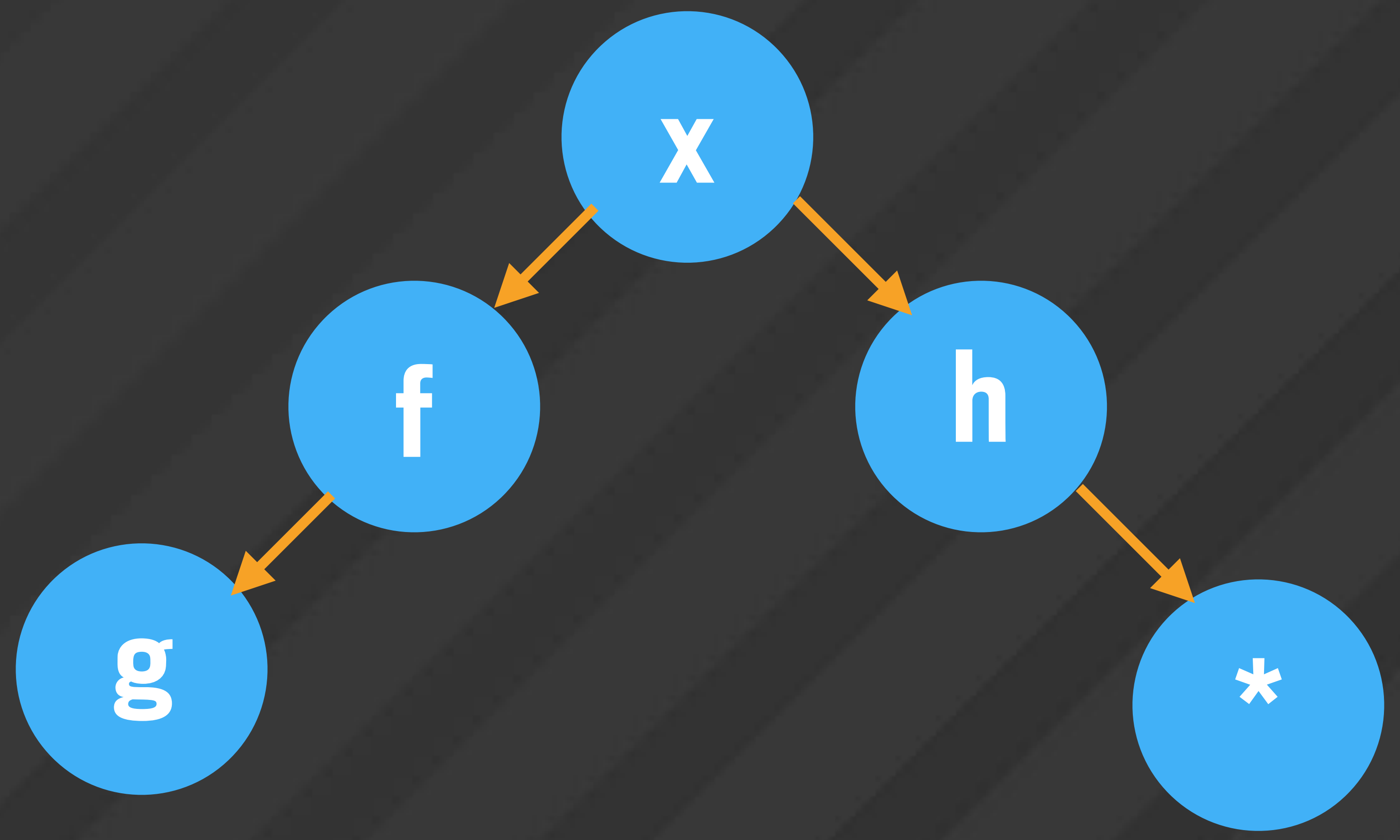
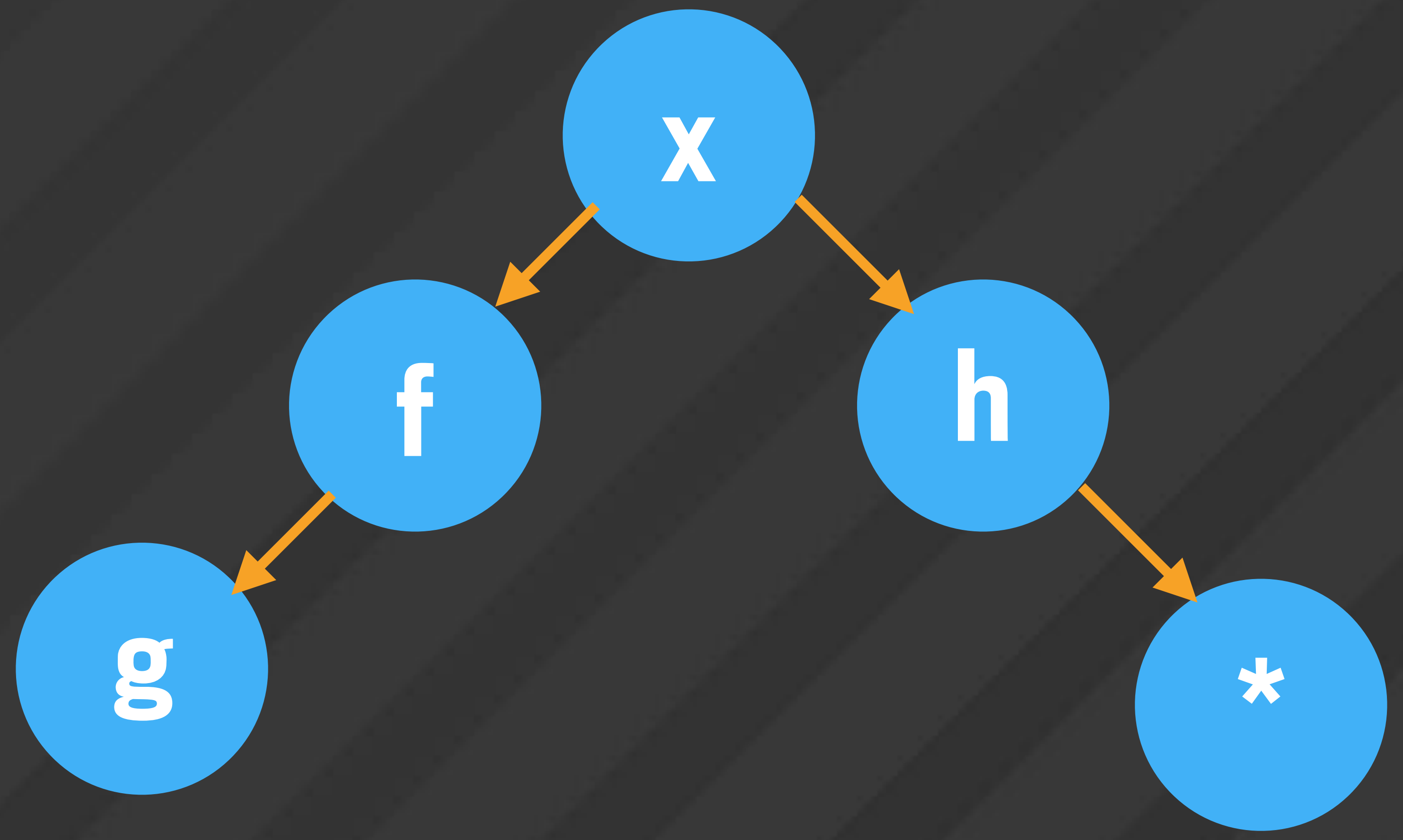


- Sparse representation of set of access paths, fast membership queries and....

Built-in domains: access tree

- Trie where nodes are bases (at level 0) or accesses (at level n > 0)
- E.g., { x.f, x.f.g, x.h* } =



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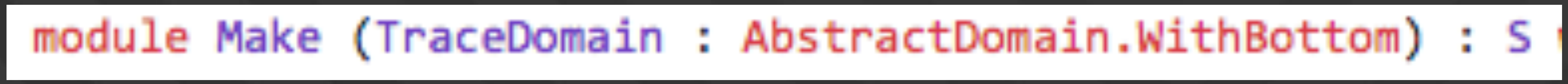
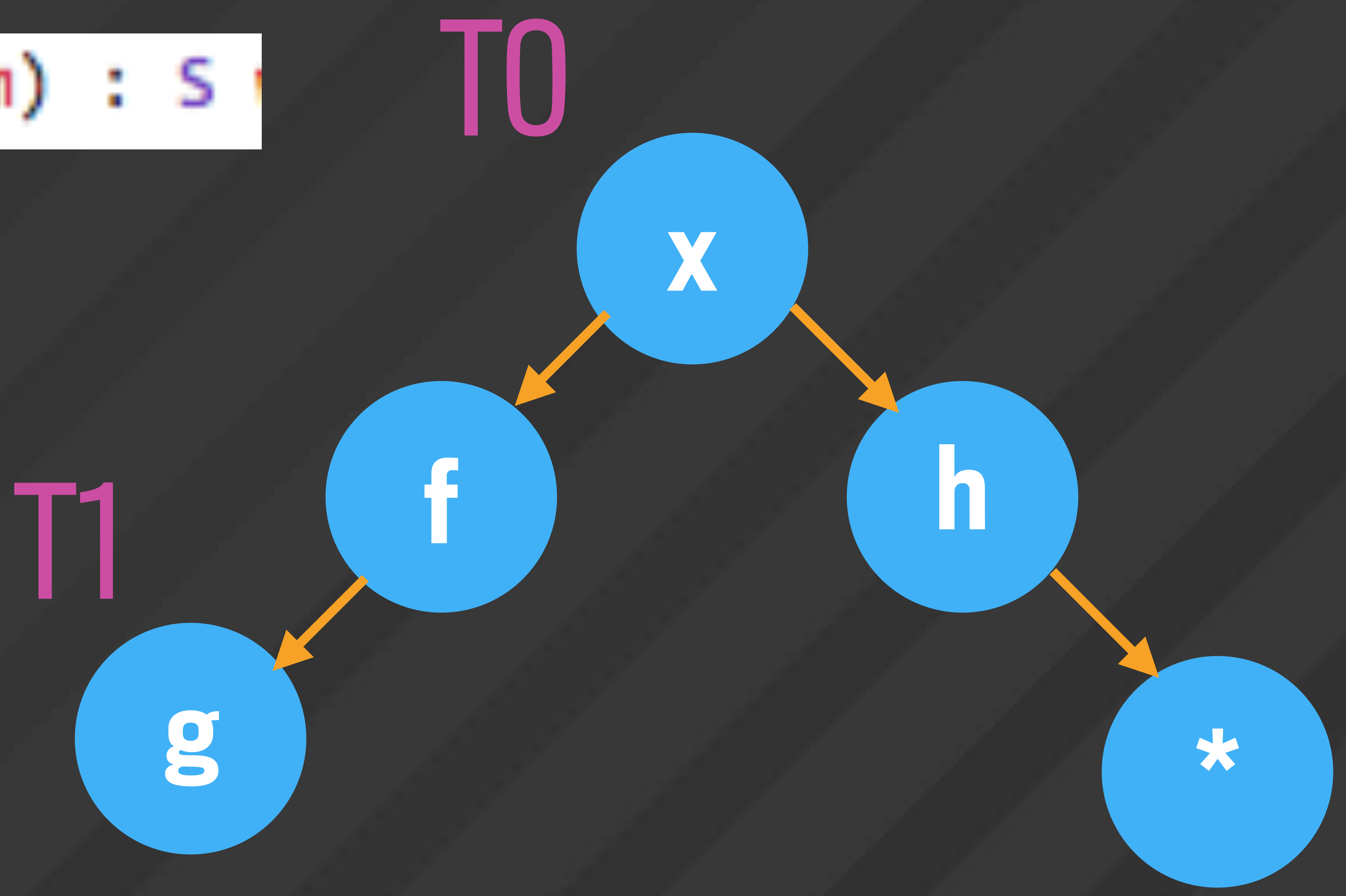
Built-in domains: access tree

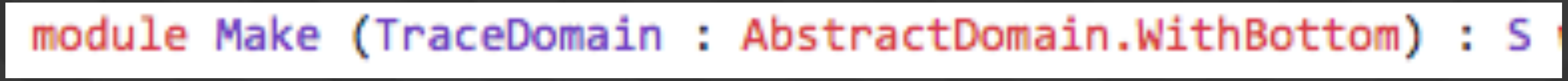


```
module Make (TraceDomain : AbstractDomain.WithBottom) : S
```



Built-in domains: access tree

- Can associate abstract value with each node + look it up fast



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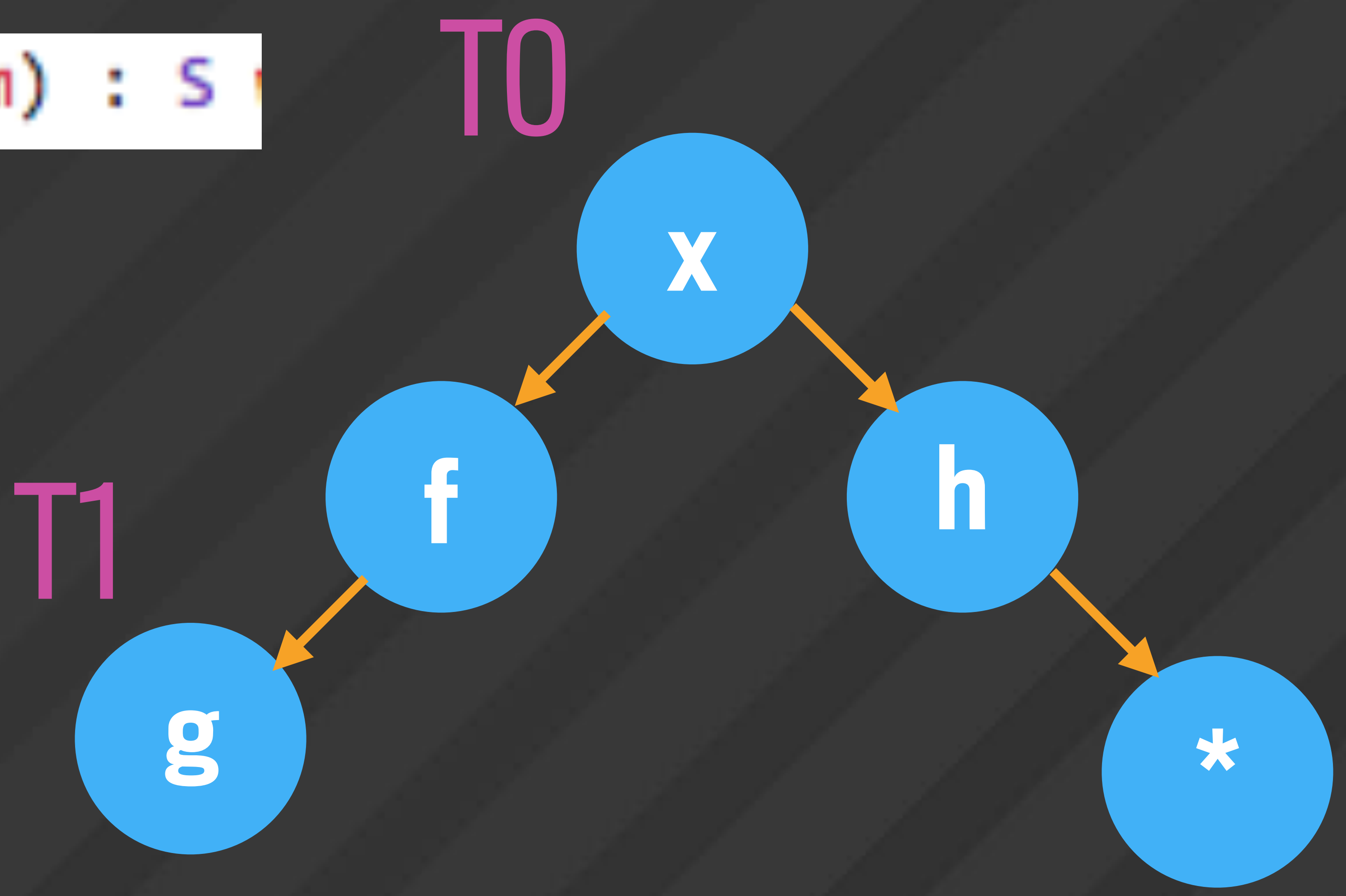
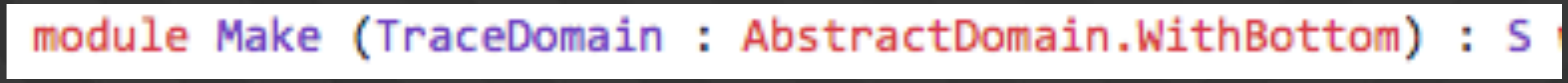


Built-in domains: access tree

- Can associate abstract value with each node + look it up fast



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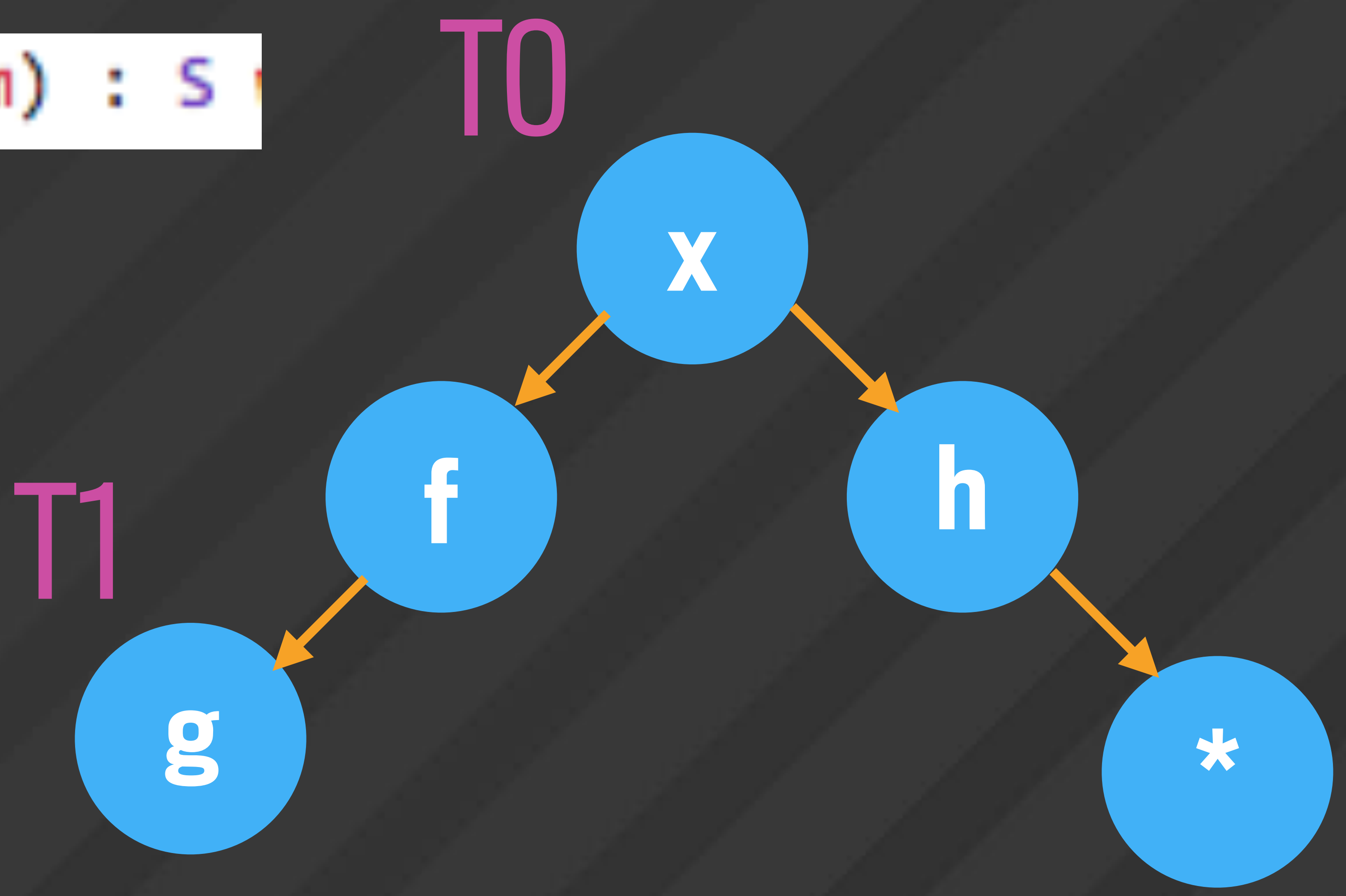
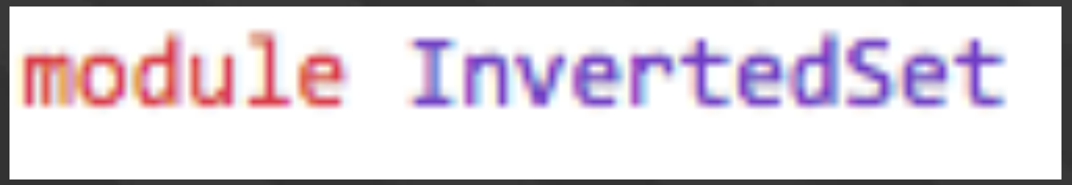


- Used in taint analysis to remember execution history for each memory location

Domain combinators facilitate building new domains

```
module FiniteSet (Element : PrettyPrintable.PrintableOrderedType)
```



```
module InvertedSet
```

```
module Map (Key : PrettyPrintable.PrintableOrderedType) (ValueDomain : S)
```

```
module InvertedMap
```

Domain combinators facilitate building new domains

- Powerset domains

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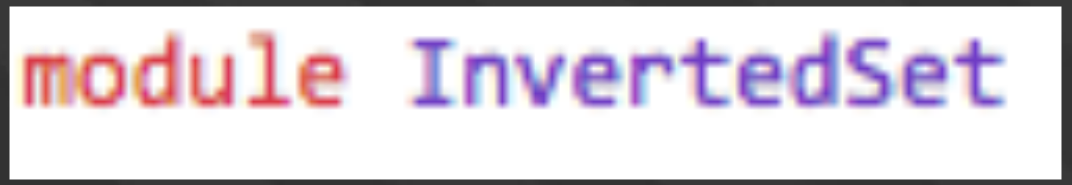

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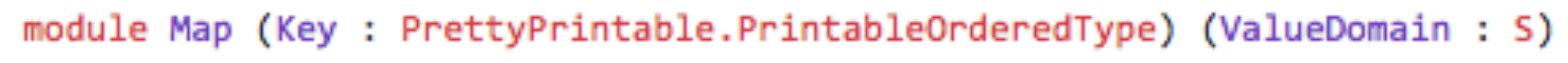
- Map domains



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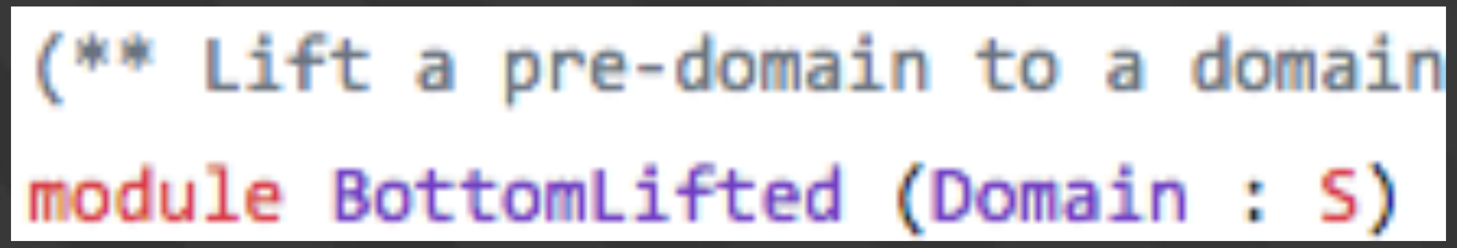
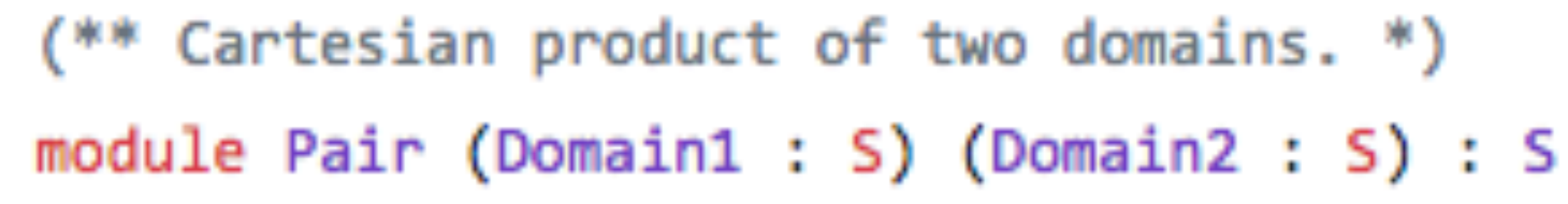
Domain combinators facilitate building new domains



```
(** Lift a pre-domain to a domain
module BottomLifted (Domain : S)
```

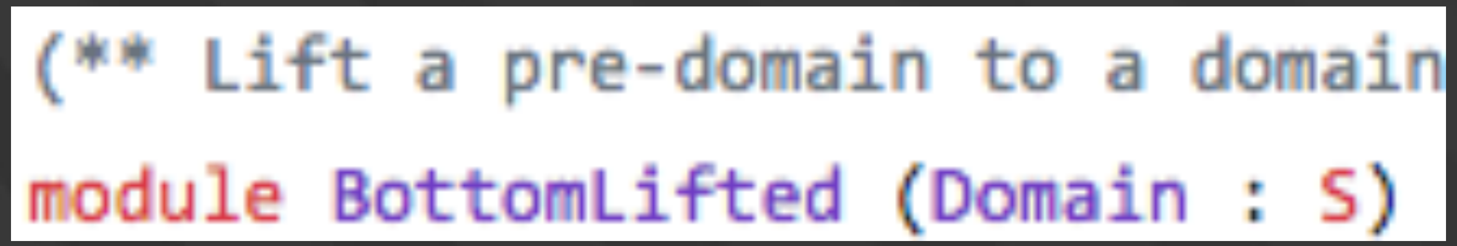
```
module TopLifted (Domain : S)
```



```
(** Cartesian product of two domains. *)
module Pair (Domain1 : S) (Domain2 : S) : S
```

Domain combinators facilitate building new domains

- Introducing dummy top/bottom values



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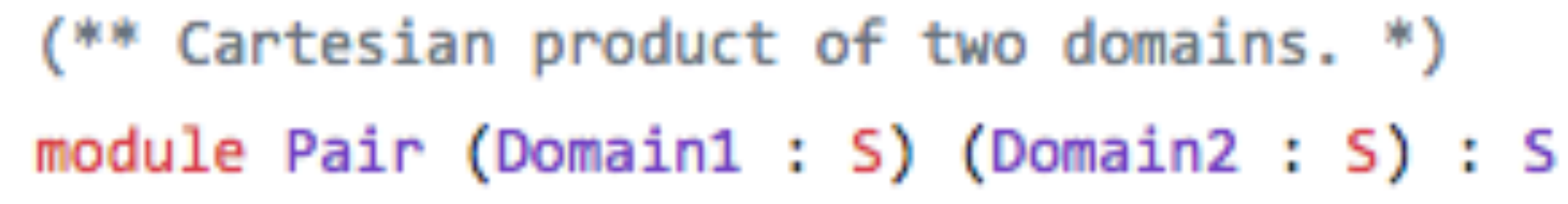

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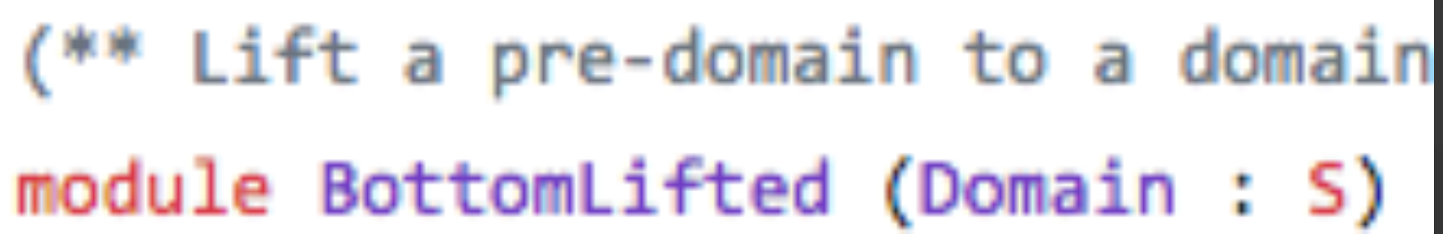

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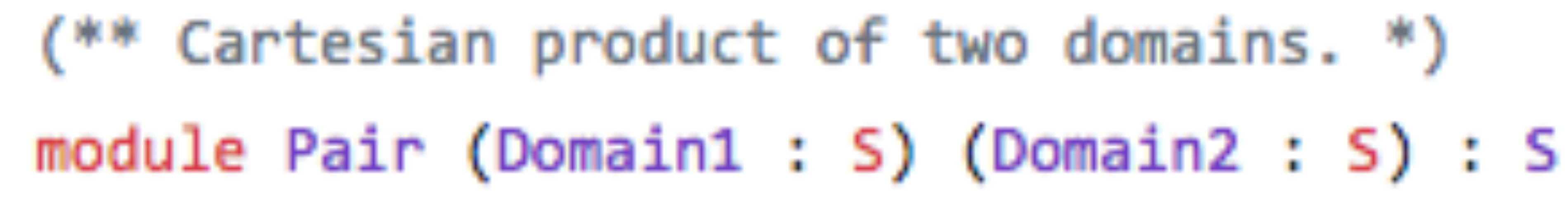

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Control flow graphs (CFGs)

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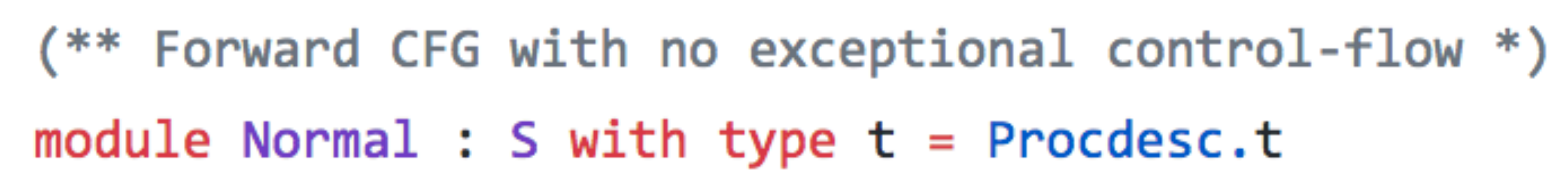
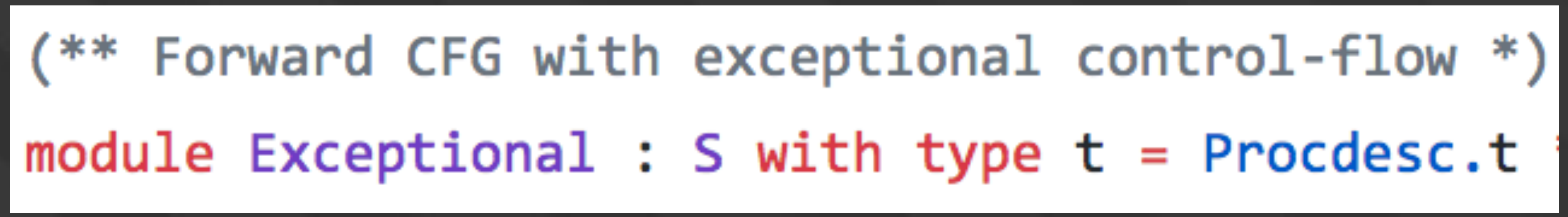
Control flow graphs (CFGs)

- Cfg module (Cfg.ml) is a collection of CFGs for every procedure in a file
- ProcCfg module limits view to a single procedure (almost always what you want)

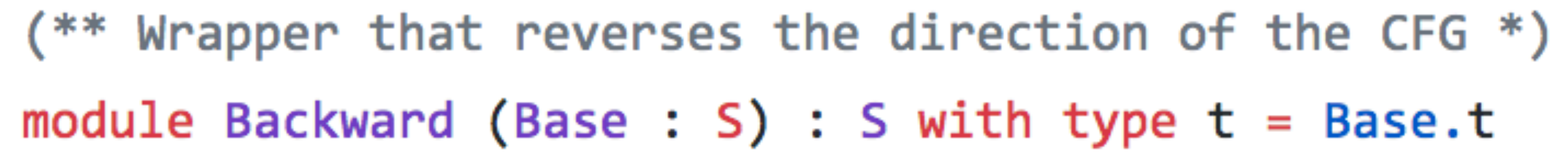
CFGs: customize view of control-flow (ProcCfg.ml)



```
(** Forward CFG with no exceptional control-flow *)
module Normal : S with type t = Procdesc.t
```



```
(** Forward CFG with exceptional control-flow *)
module Exceptional : S with type t = Procdesc.t
```

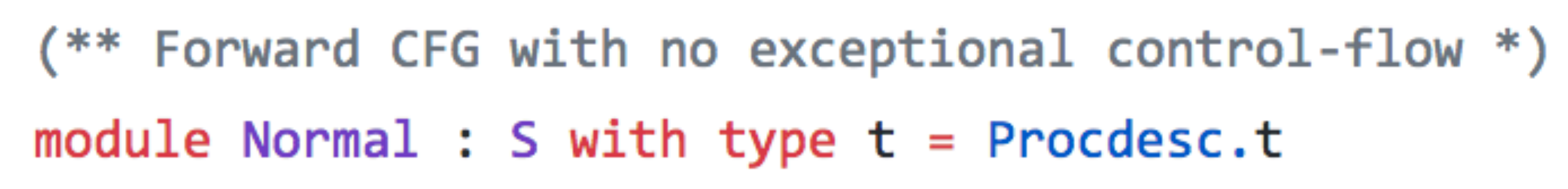


```
(** Wrapper that reverses the direction of the CFG *)
module Backward (Base : S) : S with type t = Base.t
```

```
module OneInstrPerNode (Base : S
```

CFGs: customize view of control-flow (ProcCfg.ml)

- With/without exceptional edges



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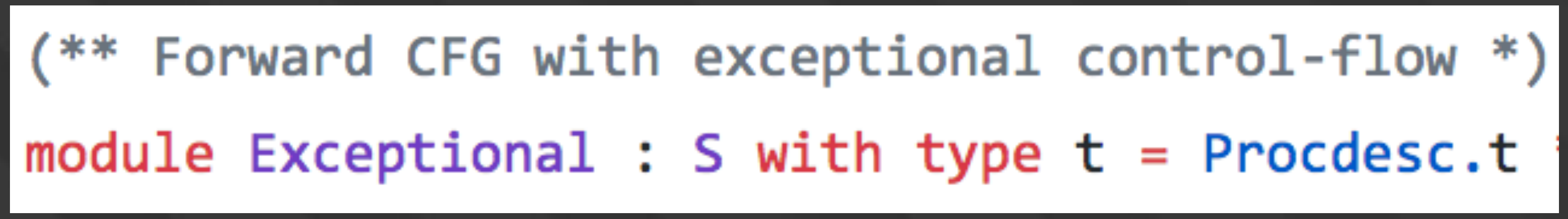

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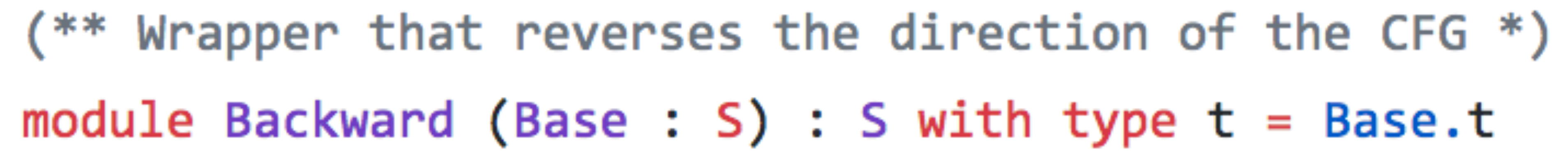

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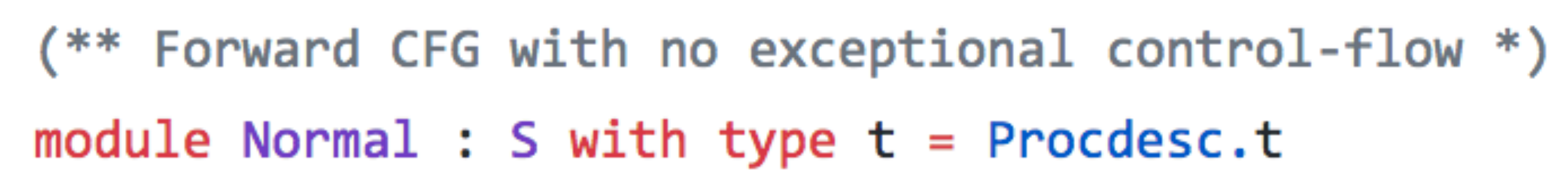

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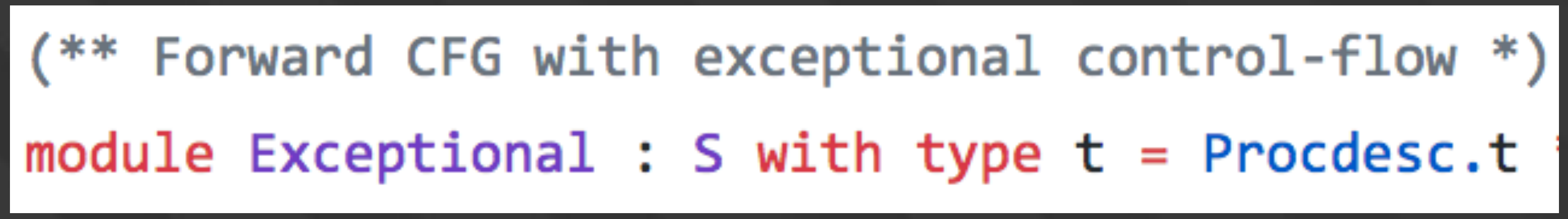

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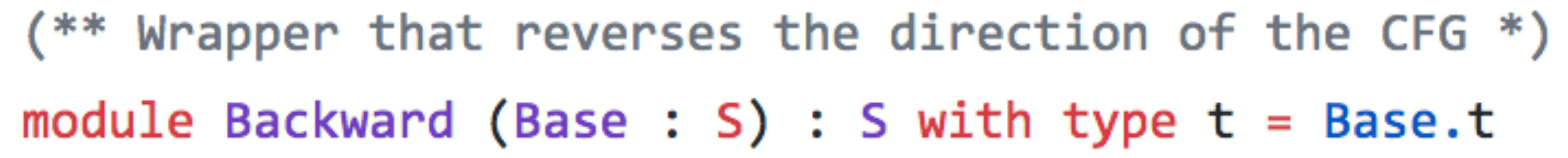
- Backward analysis



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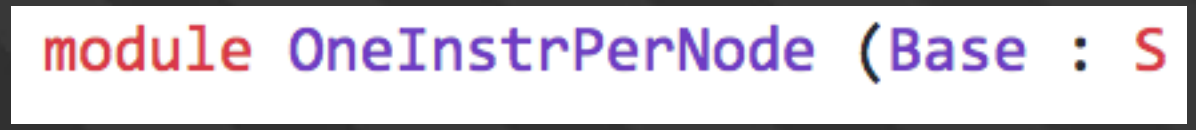

```
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```
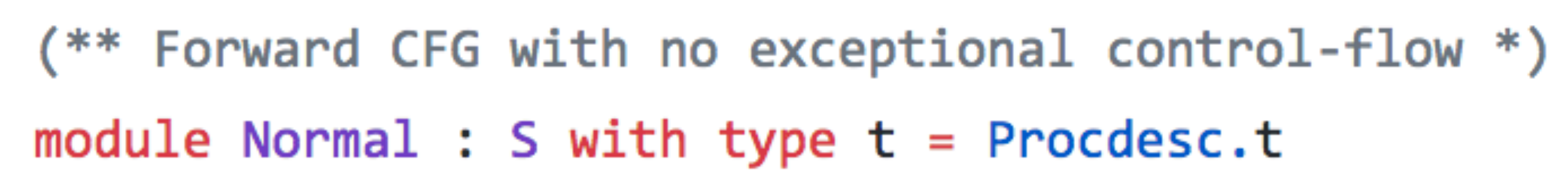

CFGs: customize view of control-flow (ProcCfg.ml)

- With/without exceptional edges



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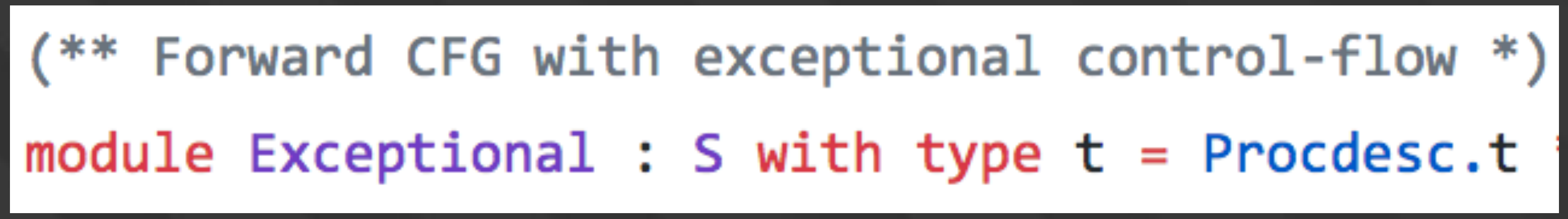

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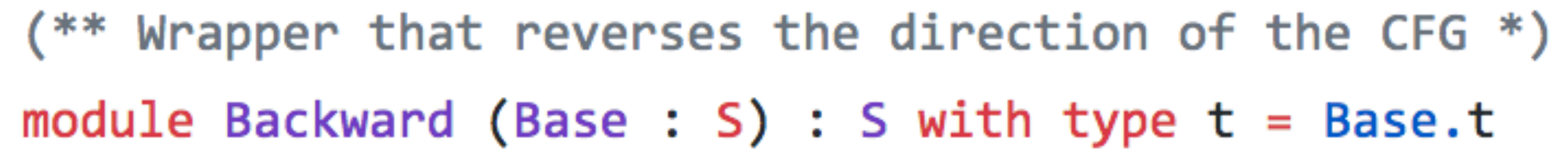

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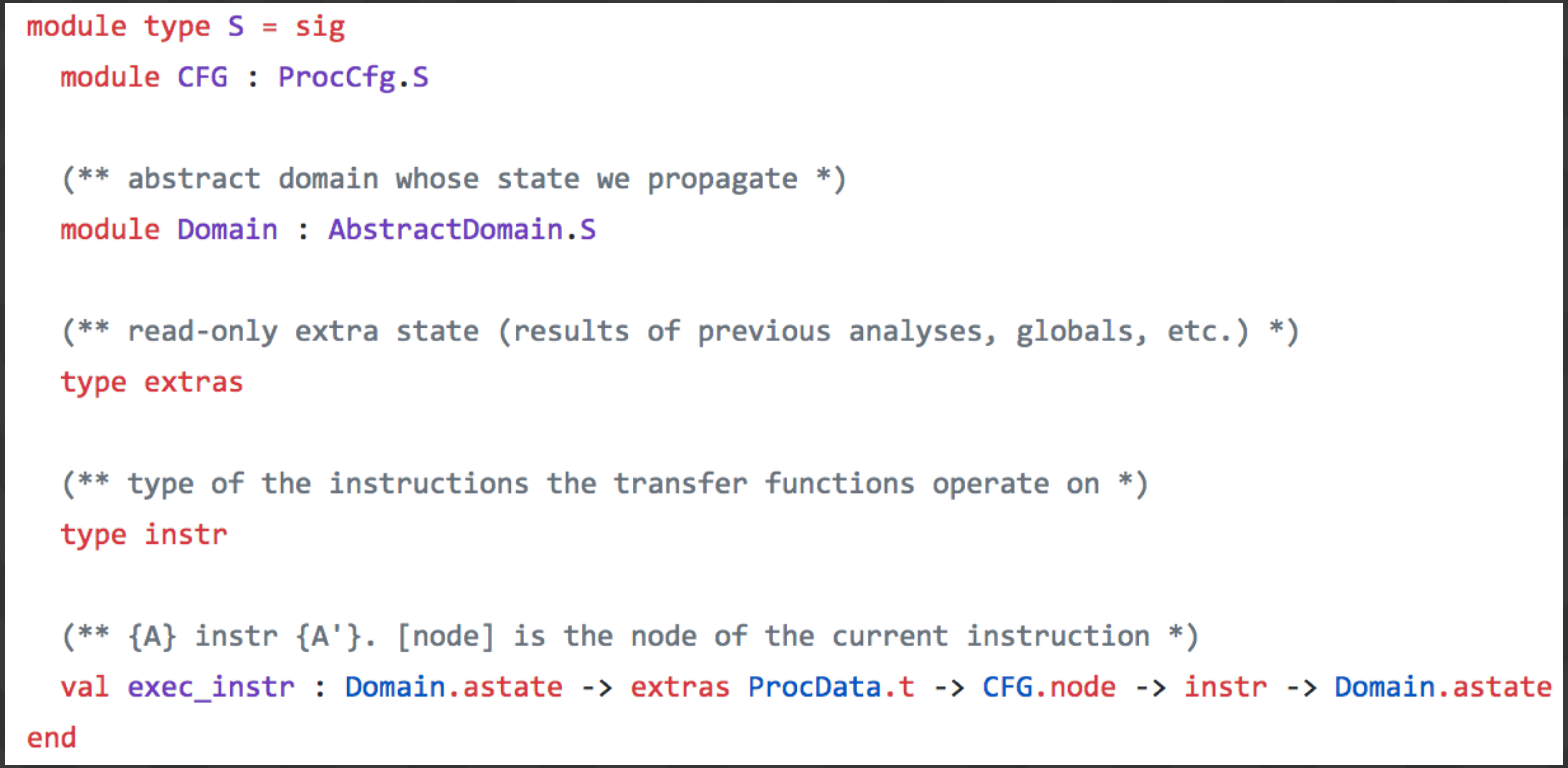
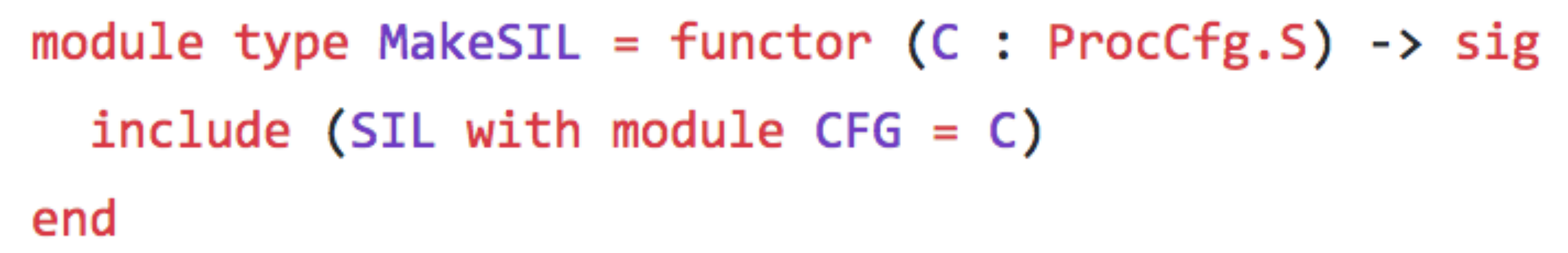
- Changing granularity of blocks

```
module OneInstrPerNode (Base : S
```

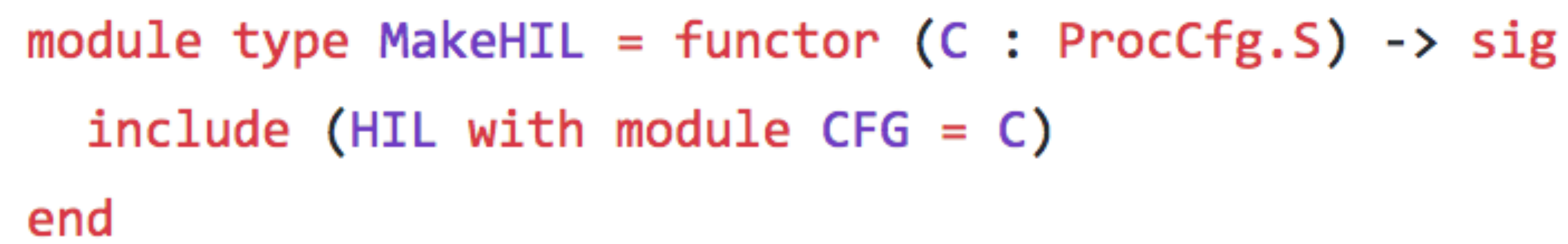
Transfer functions (TransferFunctions.ml)



```
module type S = sig
  module CFG : ProcCfg.S

  (** abstract domain whose state we propagate *)
  module Domain : AbstractDomain.S

  (** read-only extra state (results of previous analyses, globals, etc.) *)
  type extras

  (** type of the instructions the transfer functions operate on *)
  type instr

  (** {A} instr {A'}. [node] is the node of the current instruction *)
  val exec_instr : Domain.astate -> extras ProcData.t -> CFG.node -> instr -> Domain.astate
end
```

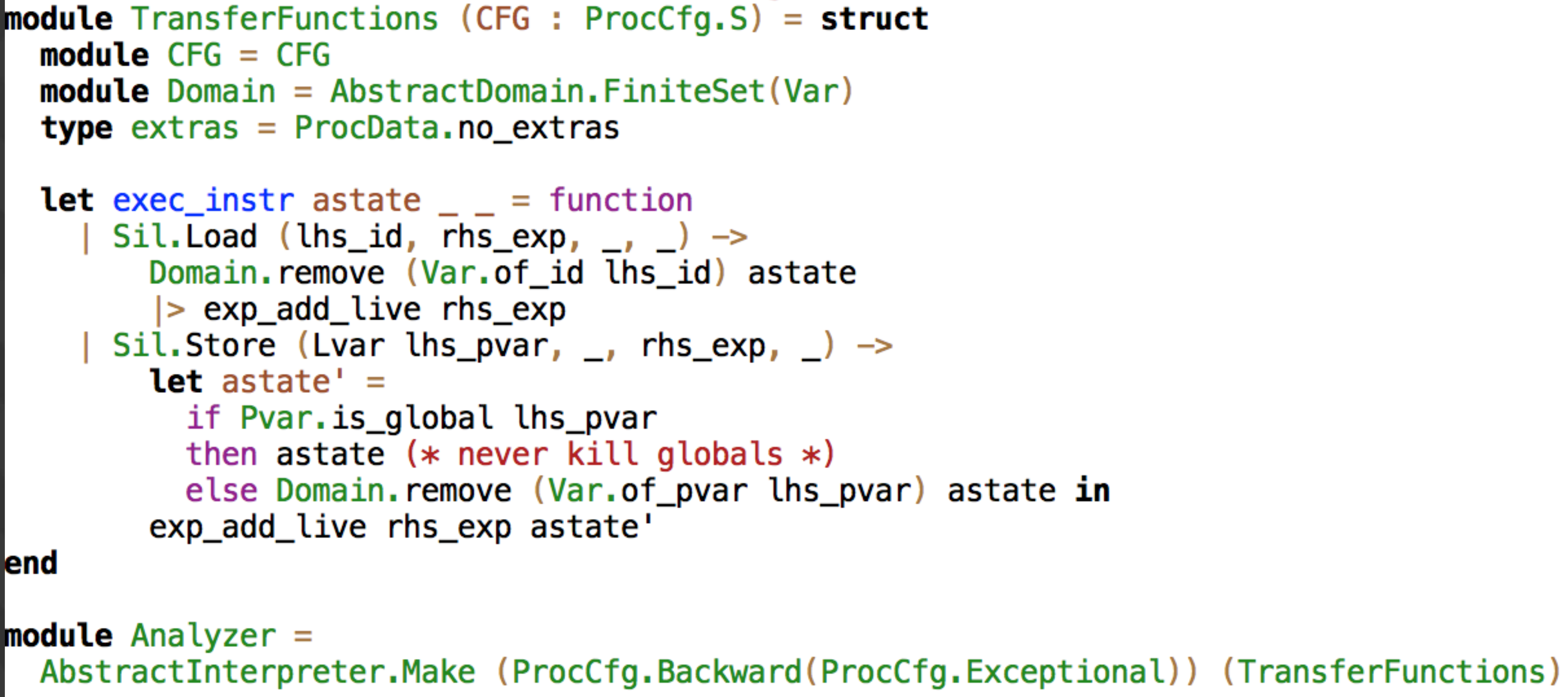


```
module type MakeSIL = functor (C : ProcCfg.S) -> sig
  include (SIL with module CFG = C)
end
```



```
module type MakeHIL = functor (C : ProcCfg.S) -> sig
  include (HIL with module CFG = C)
end
```

Putting it all together: simple liveness analysis (Liveness.ml)



```
module TransferFunctions (CFG : ProcCfg.S) = struct
  module CFG = CFG
  module Domain = AbstractDomain.FiniteSet(Var)
  type extras = ProcData.no_extras

  let exec_instr astate _ _ = function
    | Sil.Load (lhs_id, rhs_exp, _, _) ->
        Domain.remove (Var.of_id lhs_id) astate
        |> exp_add_live rhs_exp
    | Sil.Store (Lvar lhs_pvar, _, rhs_exp, _) ->
        let astate' =
          if Pvar.is_global lhs_pvar
          then astate (* never kill globals *)
          else Domain.remove (Var.of_pvar lhs_pvar) astate in
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end

module Analyzer =
  AbstractInterpreter.Make (ProcCfg.Backward(ProcCfg.Exceptional)) (TransferFunctions)
```
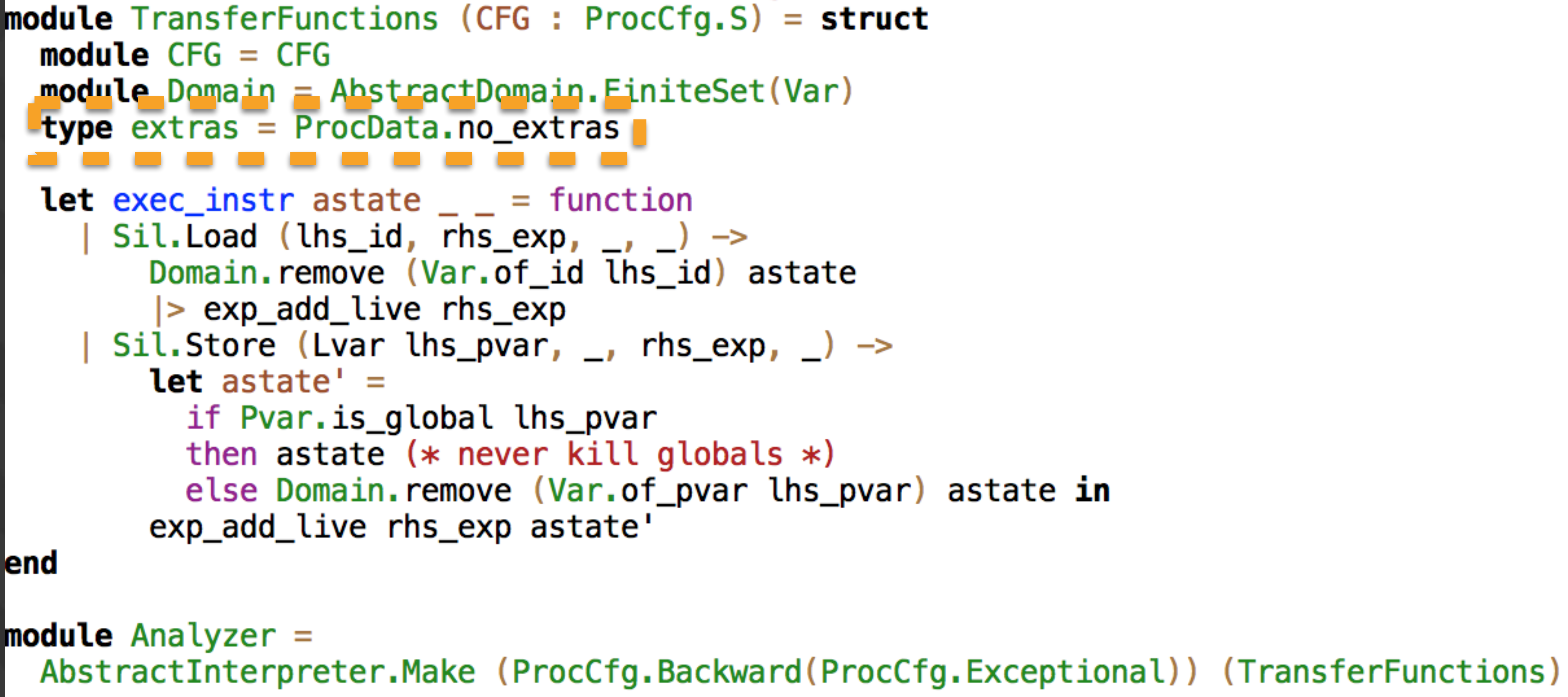

Putting it all together: simple liveness analysis (Liveness.ml)



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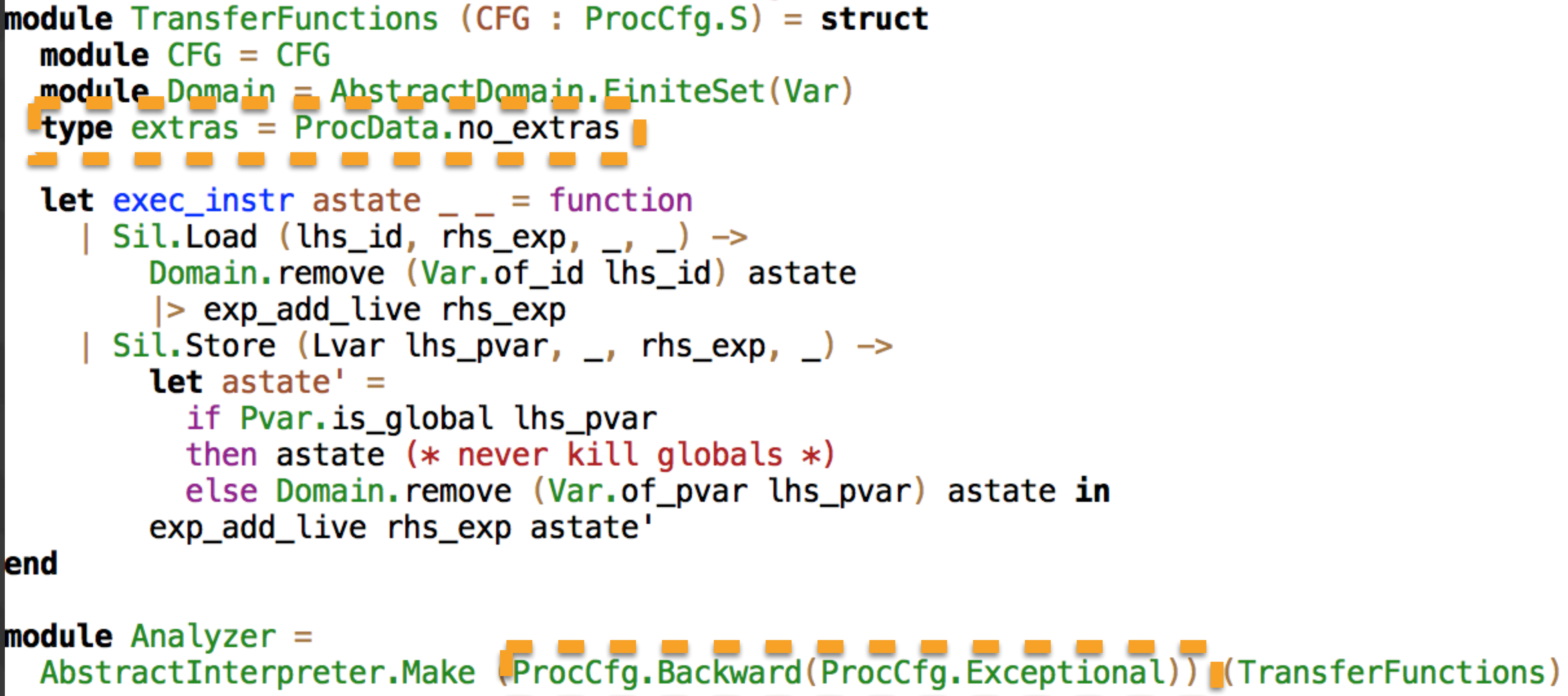

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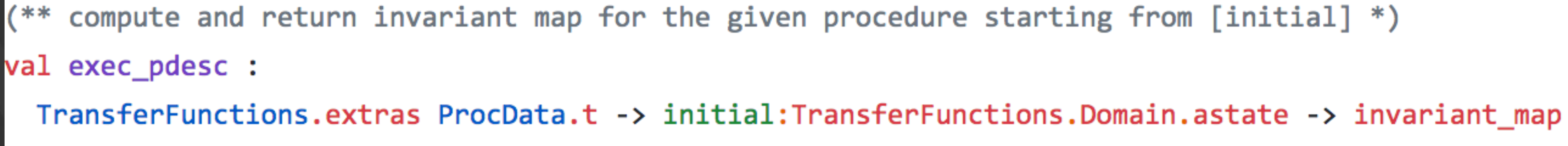
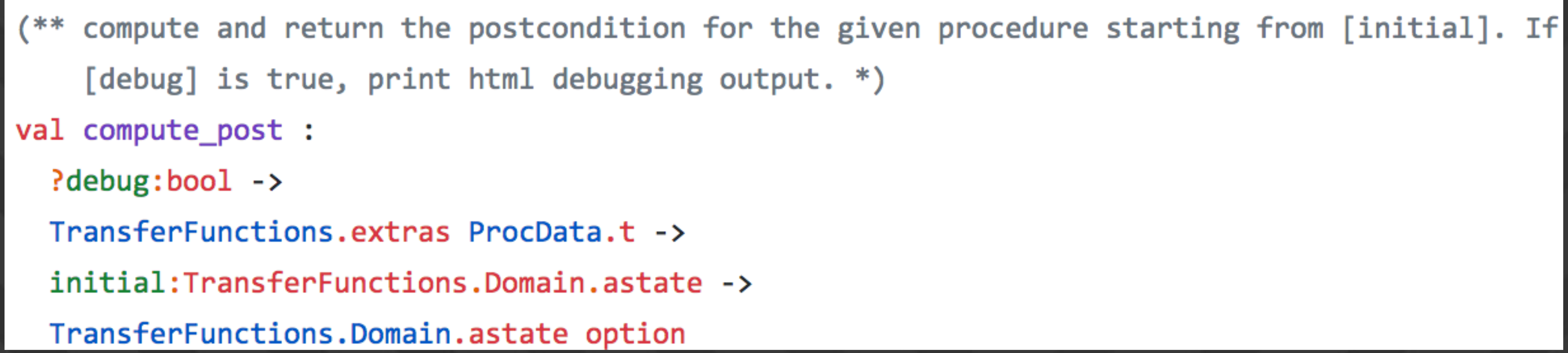
Analyzing procedures (AbstractInterpreter.ml)



```
(** compute and return invariant map for the given procedure starting from [initial] *)
val exec_pdesc :
  TransferFunctions.extras ProcData.t -> initial:TransferFunctions.Domain.astate -> invariant_map
```



```
(** compute and return the postcondition for the given procedure starting from [initial]. If
    [debug] is true, print html debugging output. *)
val compute_post :
  ?debug:bool ->
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```
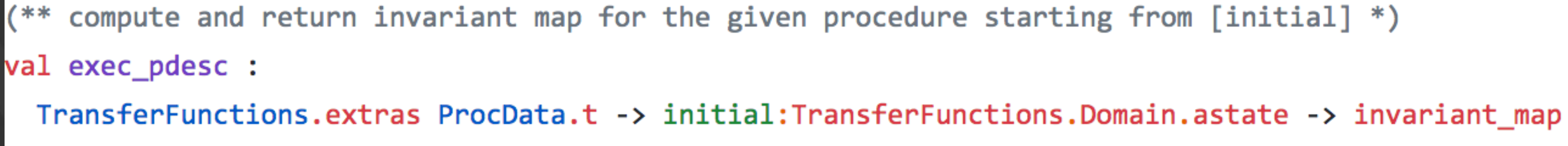

Analyzing procedures (AbstractInterpreter.ml)

- Get invariant map from node id -> abstract state



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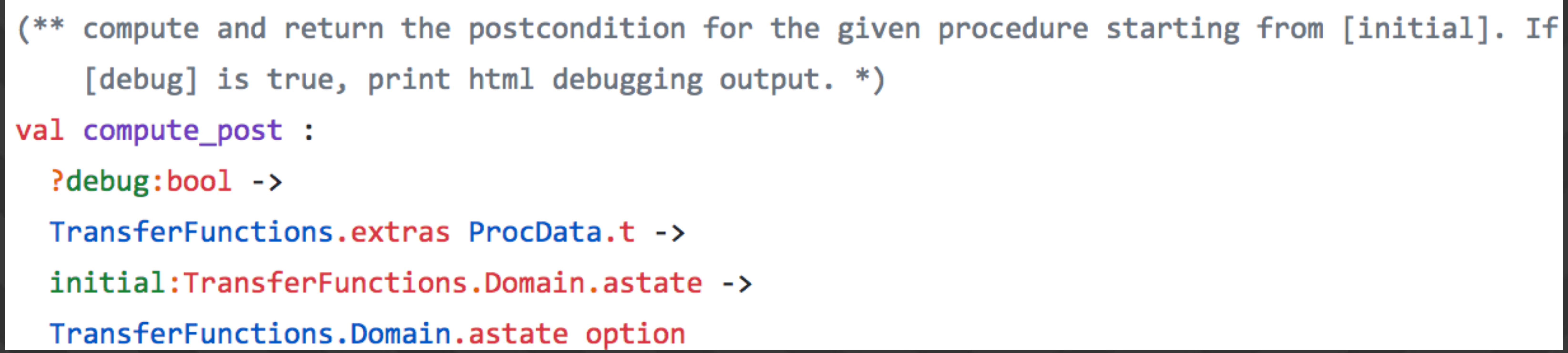

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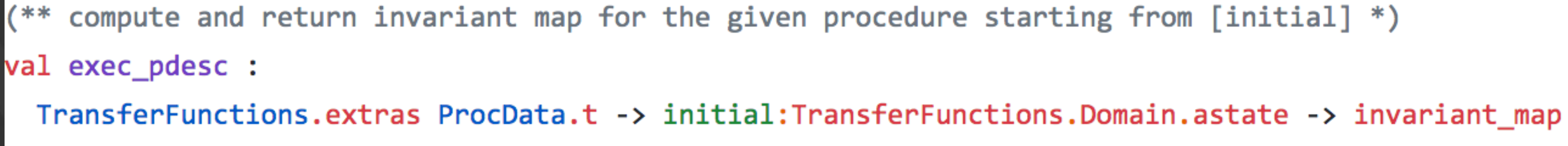

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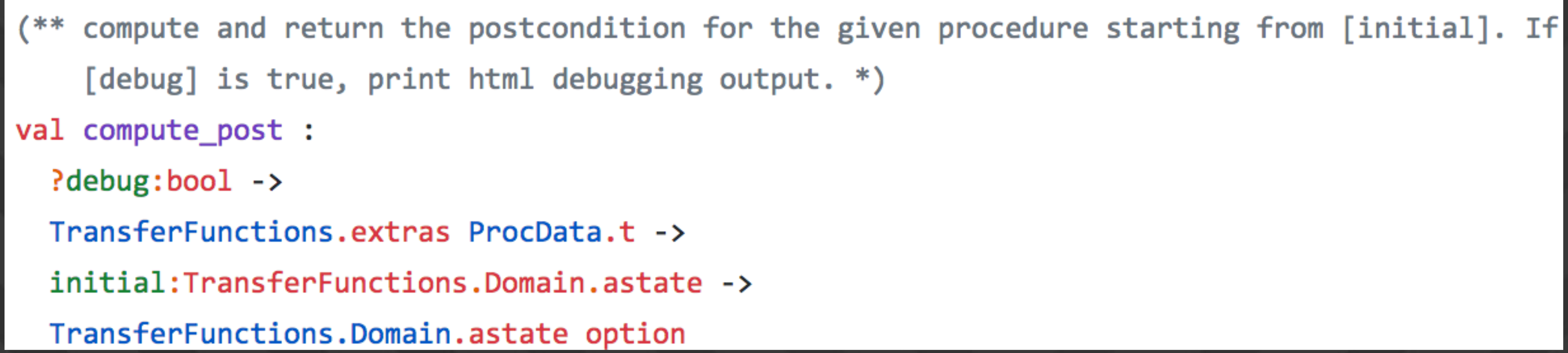
- Just grab the postcondition



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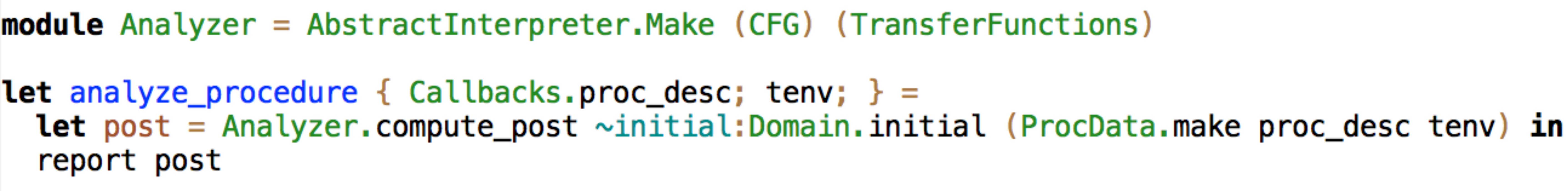
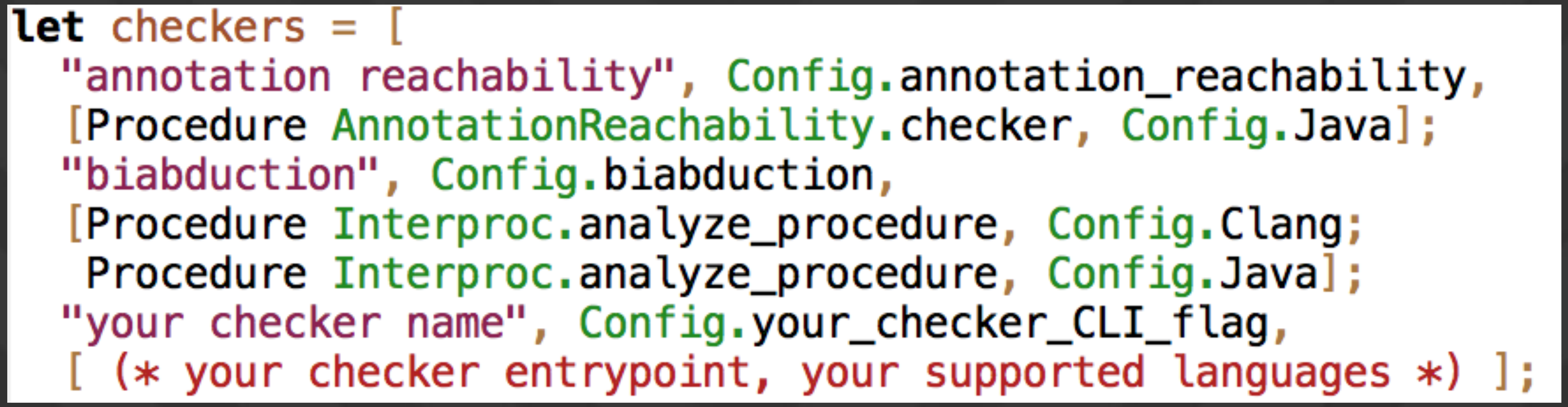
Hooking up your checker (RegisterCheckers.ml)



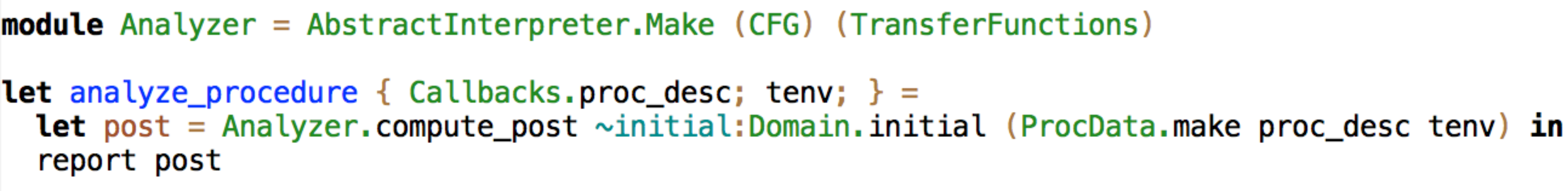
```
module Analyzer = AbstractInterpreter.Make (CFG) (TransferFunctions)

let analyze_procedure { Callbacks.proc_desc; tenv; } =
  let post = Analyzer.compute_post ~initial:Domain.initial (ProcData.make proc_desc tenv) in
  report post
```



```
let checkers = [
  "annotation reachability", Config.annotation_reachability,
  [Procedure AnnotationReachability.checker, Config.Java];
  "biabduction", Config.biabduction,
  [Procedure Interproc.analyze_procedure, Config.Clang;
   Procedure Interproc.analyze_procedure, Config.Java];
  "your checker name", Config.your_checker_CLI_flag,
  [ (* your checker entrypoint, your supported languages *) ];
```

Hooking up your checker (RegisterCheckers.ml)

- Define entrypoint for analyzing single procedure



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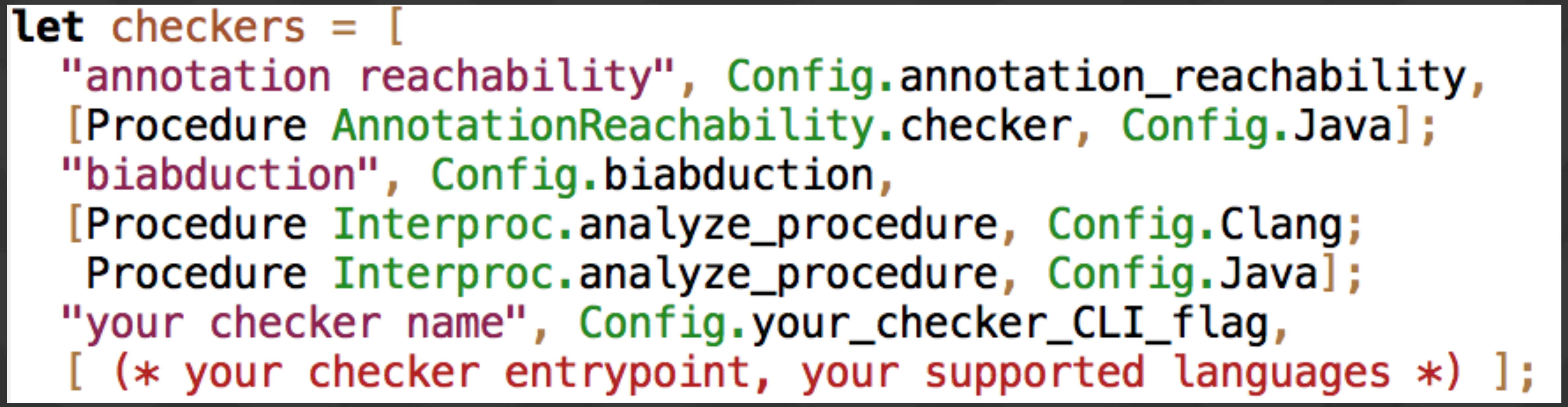

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Hooking up your checker (RegisterCheckers.ml)

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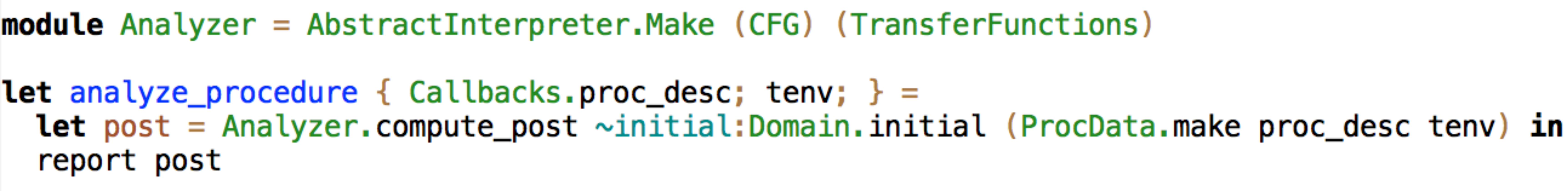

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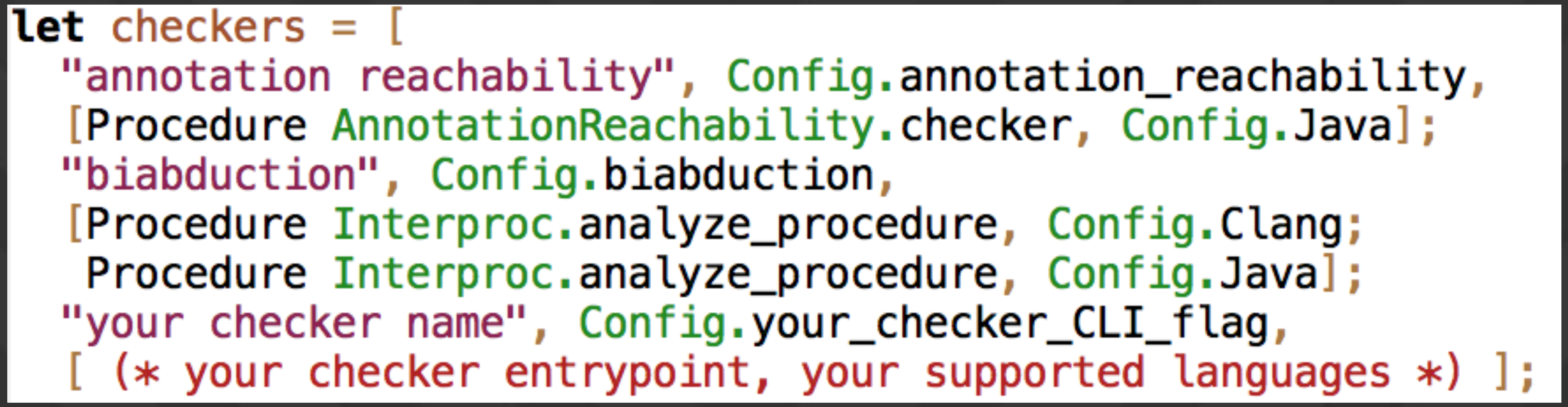
- Add entrypoint to RegisterCheckers module



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Roadmap

1 | Infer.AI architecture

2 | Building intraprocedural analyzers

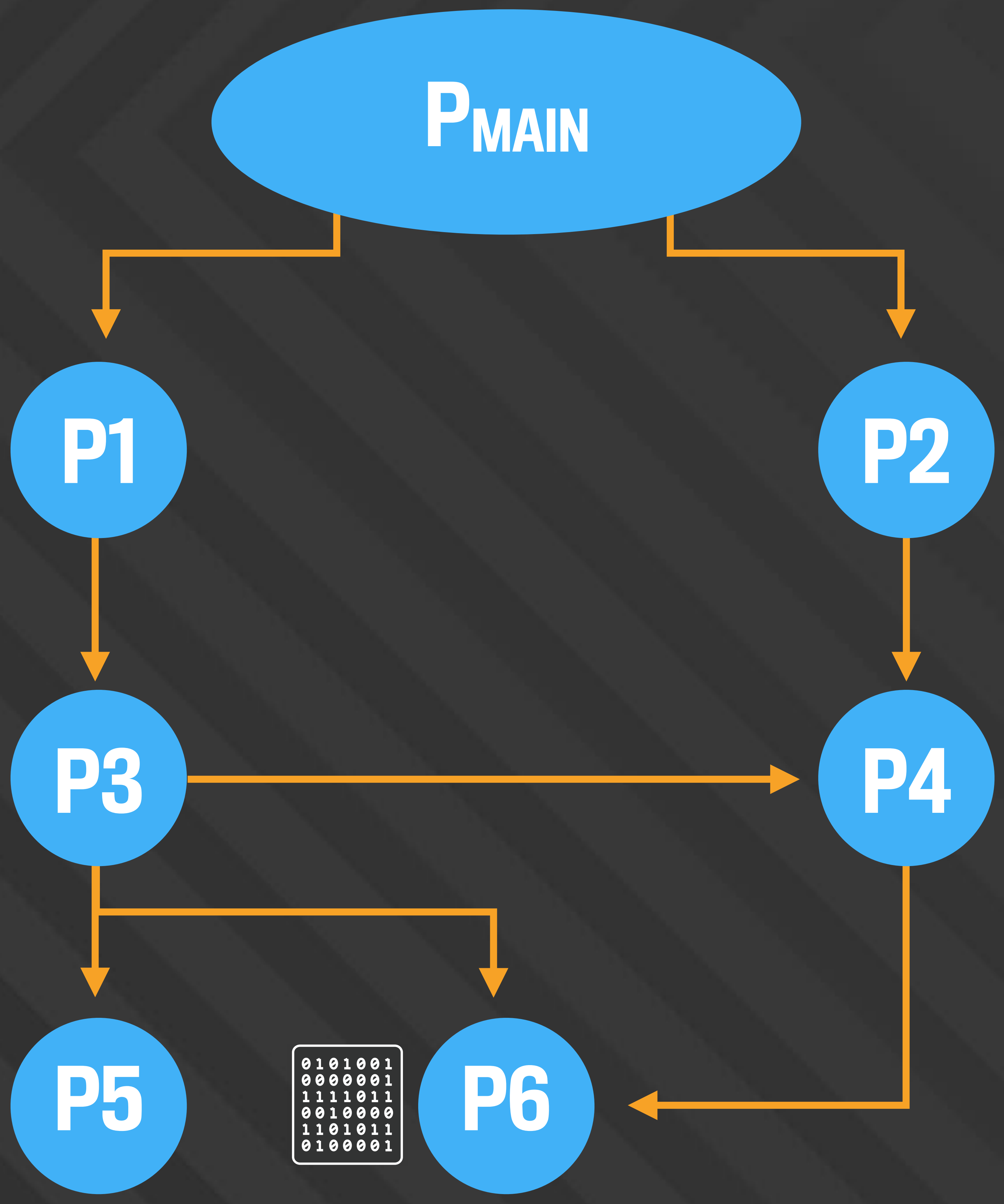
3 | Building compositional interprocedural analyzers

Roadmap

- Summaries
- Bottom-up modular/compositional analysis
- Real-world case study: thread-safety analysis
- Designing compositional domains

3 | Building compositional interprocedural analyzers

Bottom up modular/compositional analysis



- Compute call graph, do topological sort
- Analyze each procedure once using reverse postorder scheduling
- Break call cycles by iterating to fixed point

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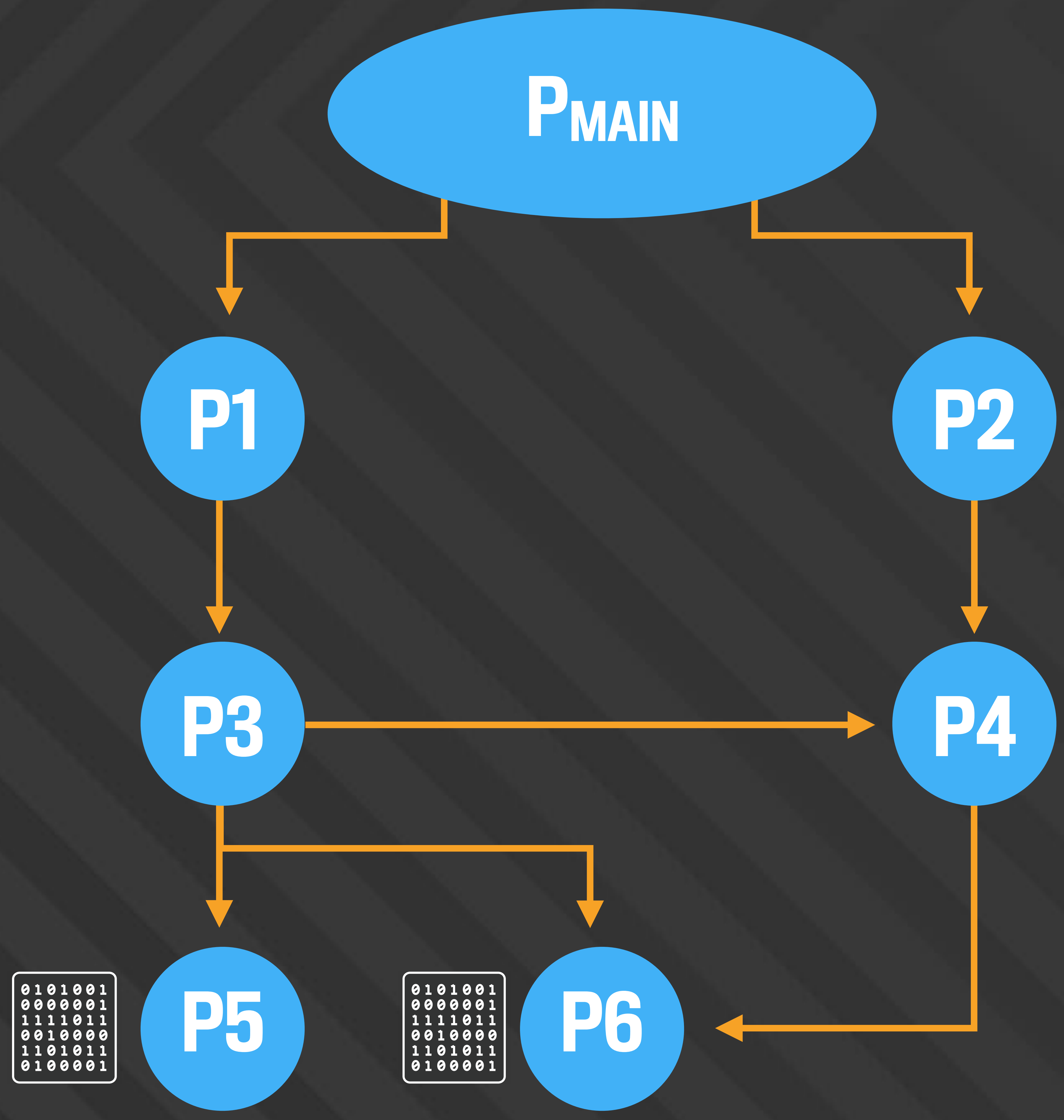

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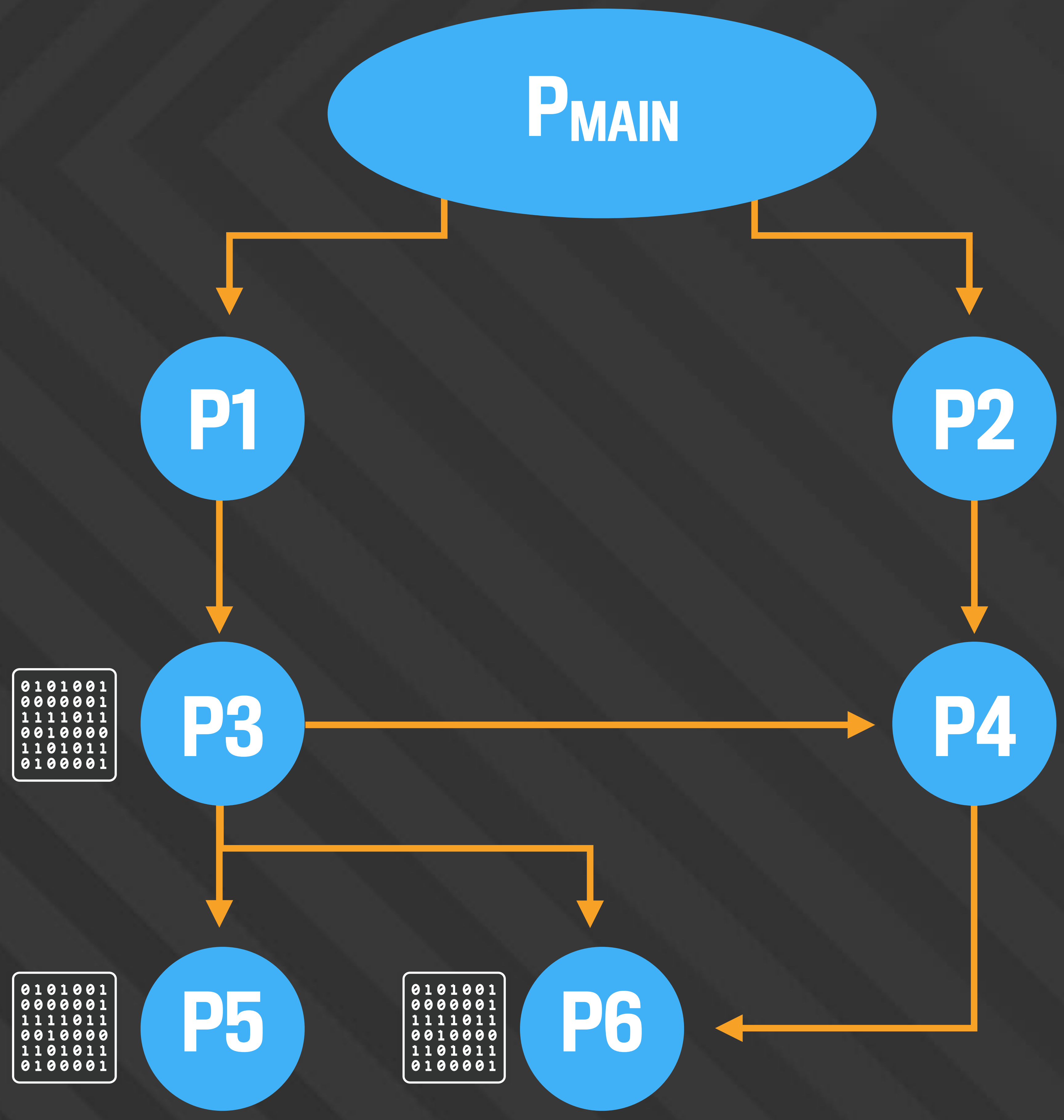

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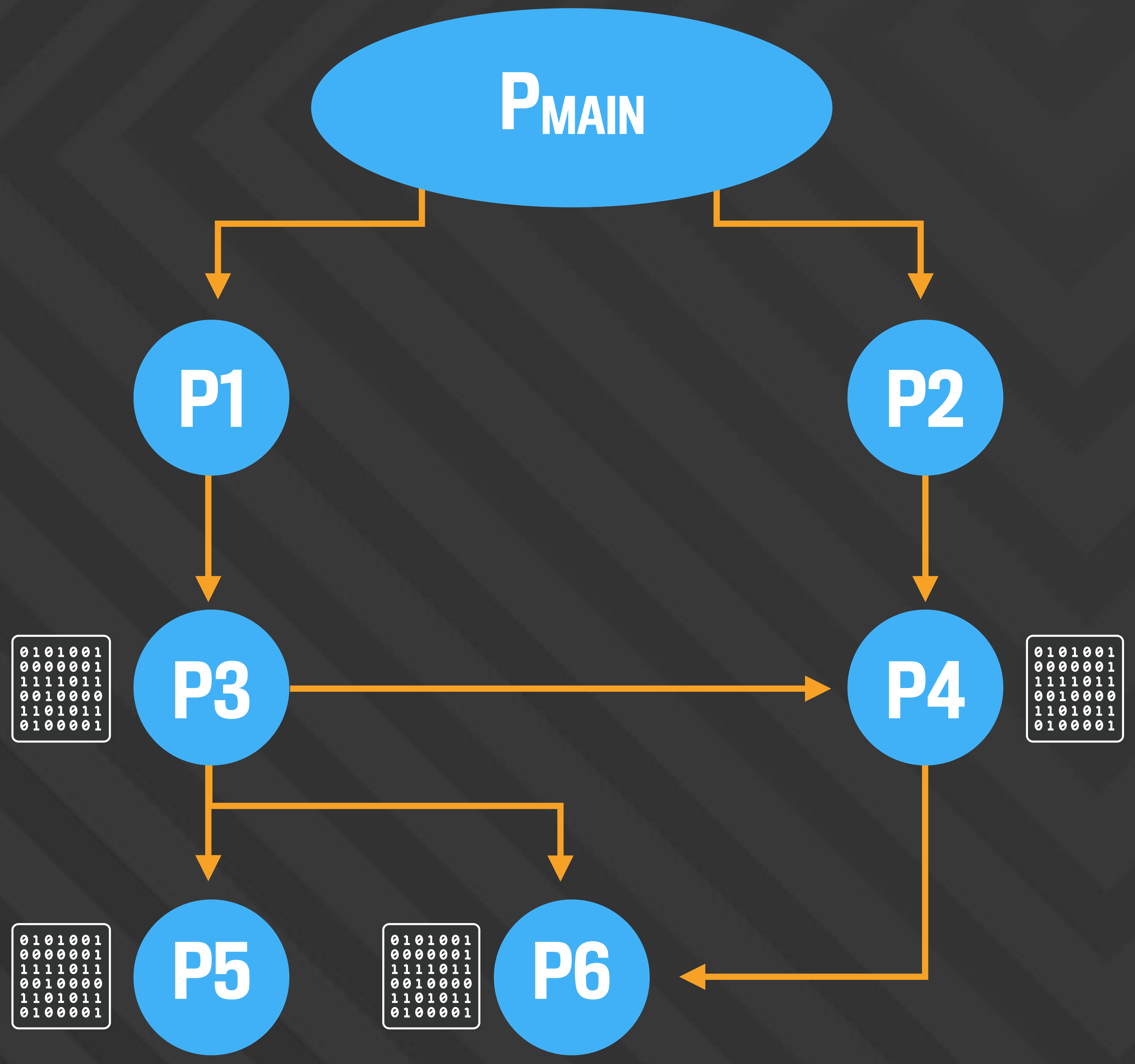

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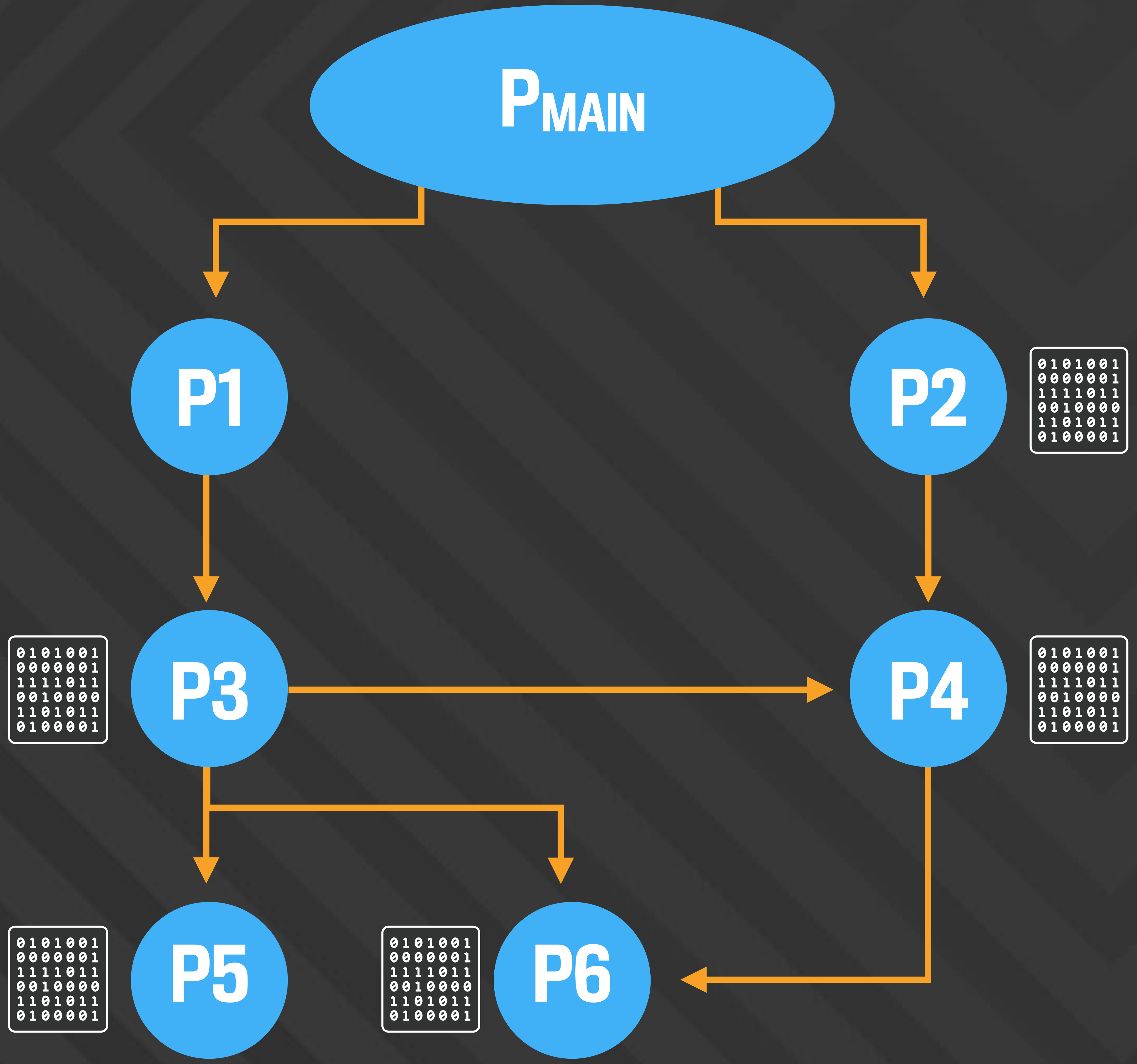

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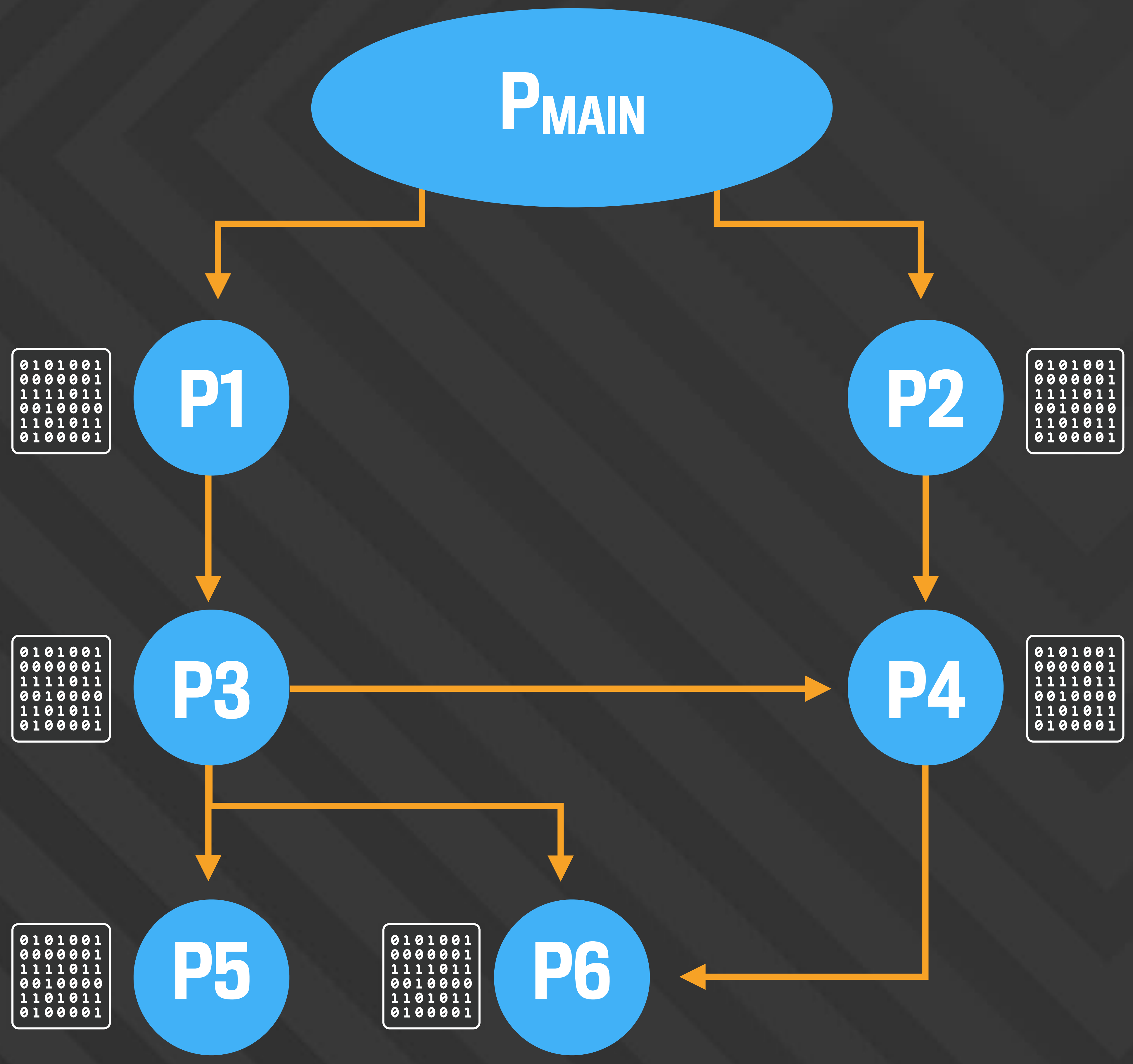

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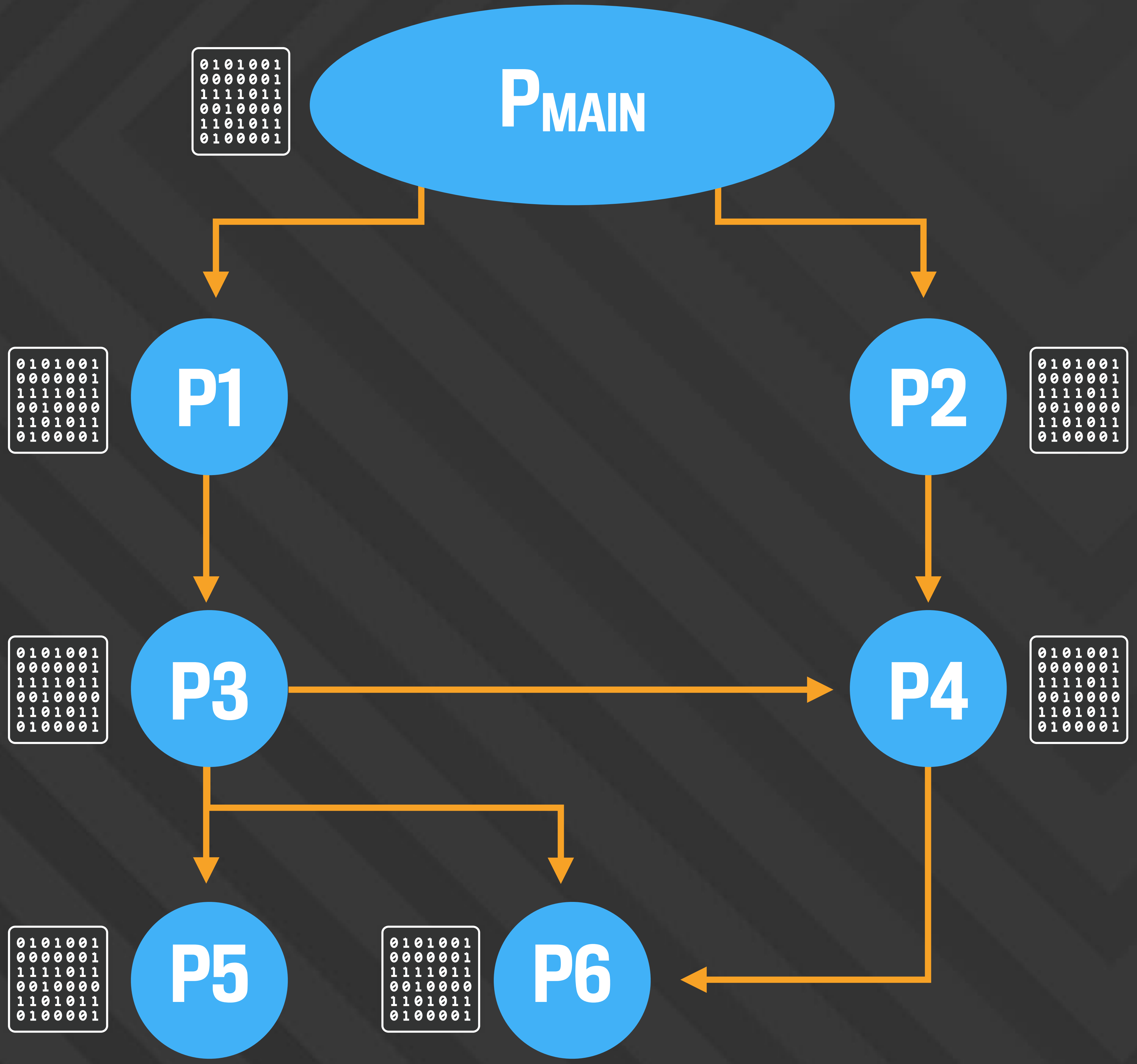

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Why modular + compositional definitions

Modular: analyze one procedure (+ deps) at a time

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No global view

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Why modular + compositional definitions

Modular: analyze one procedure (+ deps) at a time

No global view

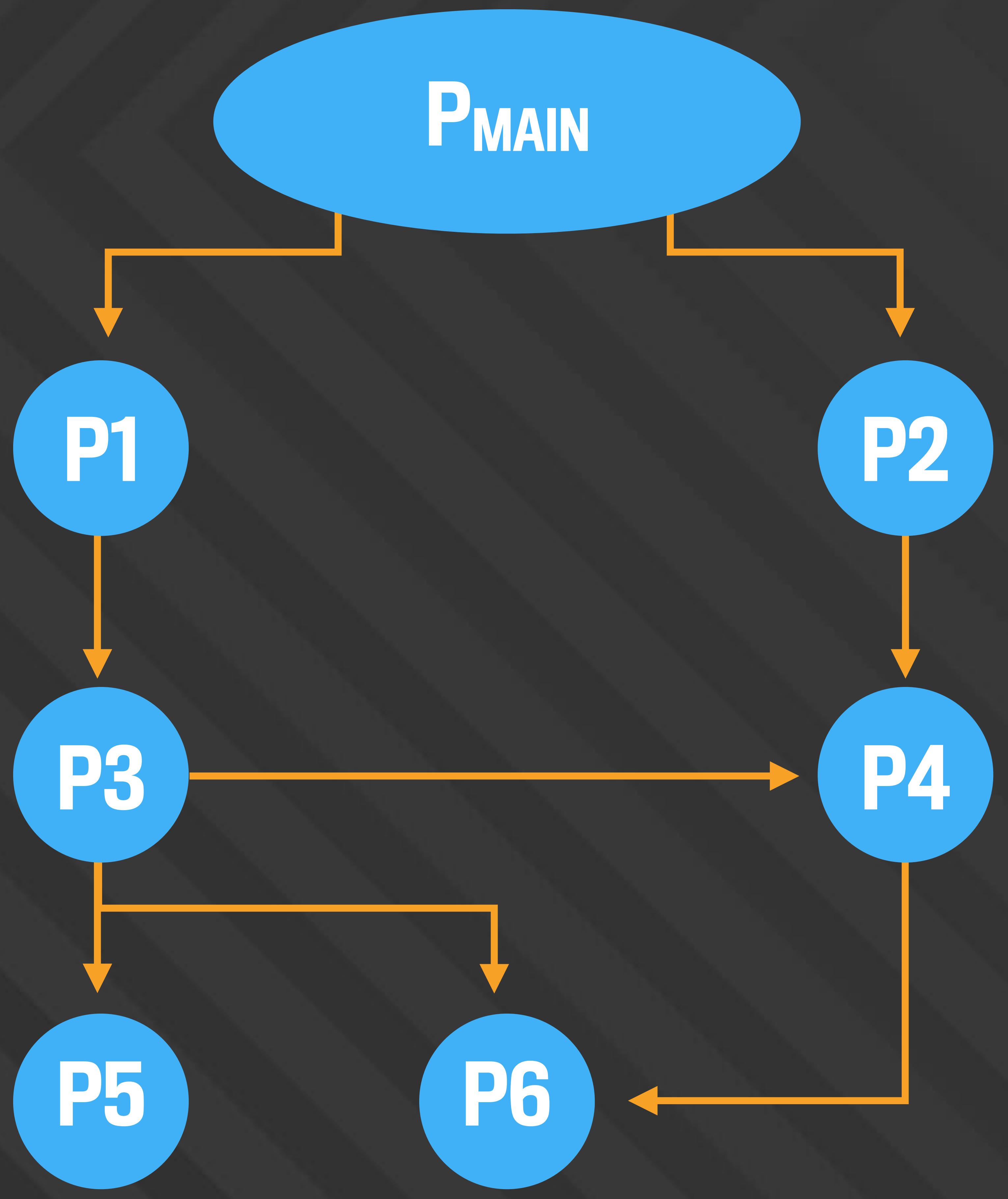
Compositional: summary for a procedure can be used in all calling contexts

Never need to reanalyze procedure in new context

Why modular + compositional matters

- Scalable: linear in the number of procedures
- Incremental: easy to transition from-scratch analysis -> diff analysis
- Extensible: for new analysis, just need new domain + transfer functions

Constraints of bottom-up analysis



- Will have summary for callee P6
- But don't know anything about callers P2, P3
- Need to compute summary usable in **any** calling context

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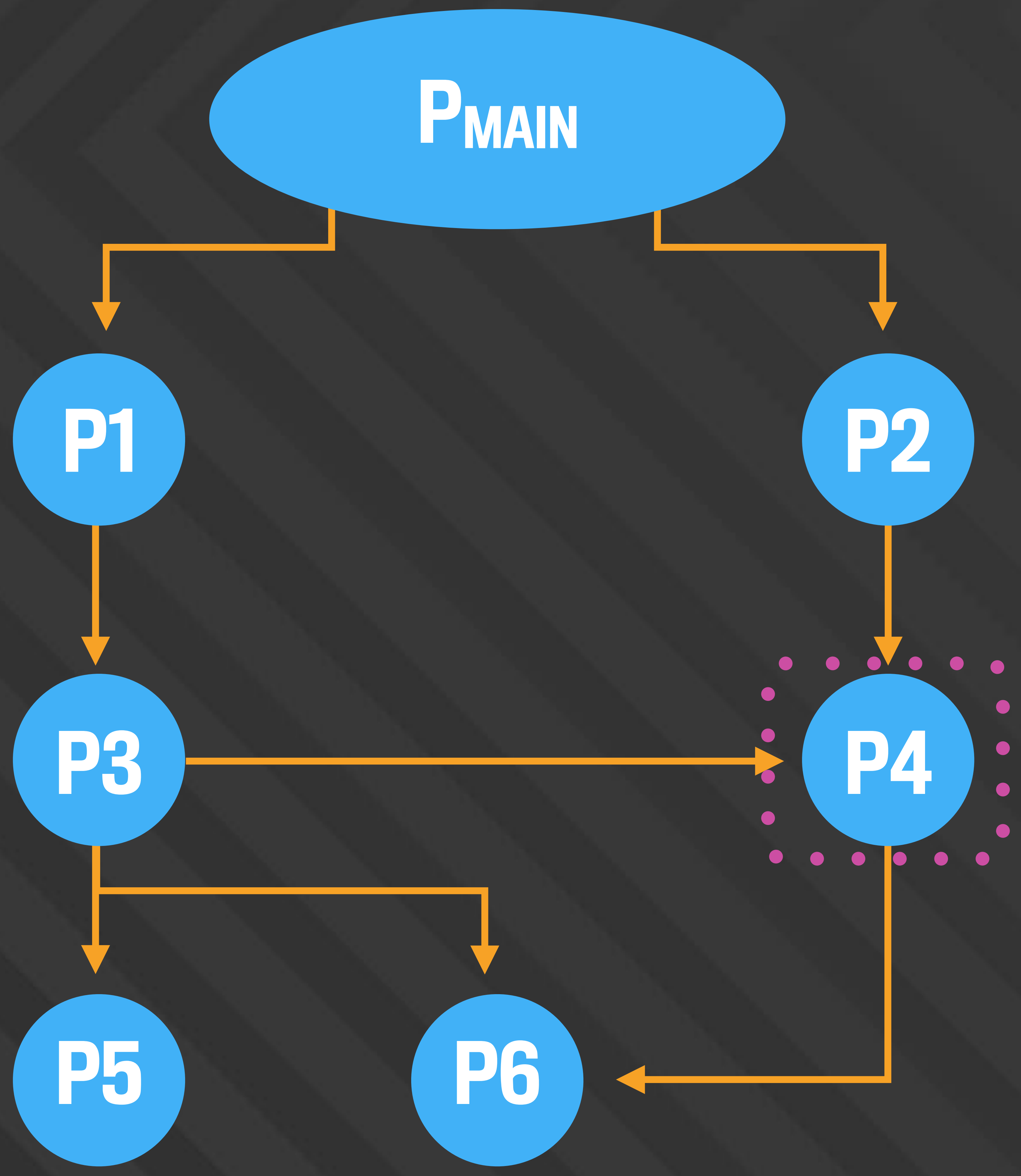

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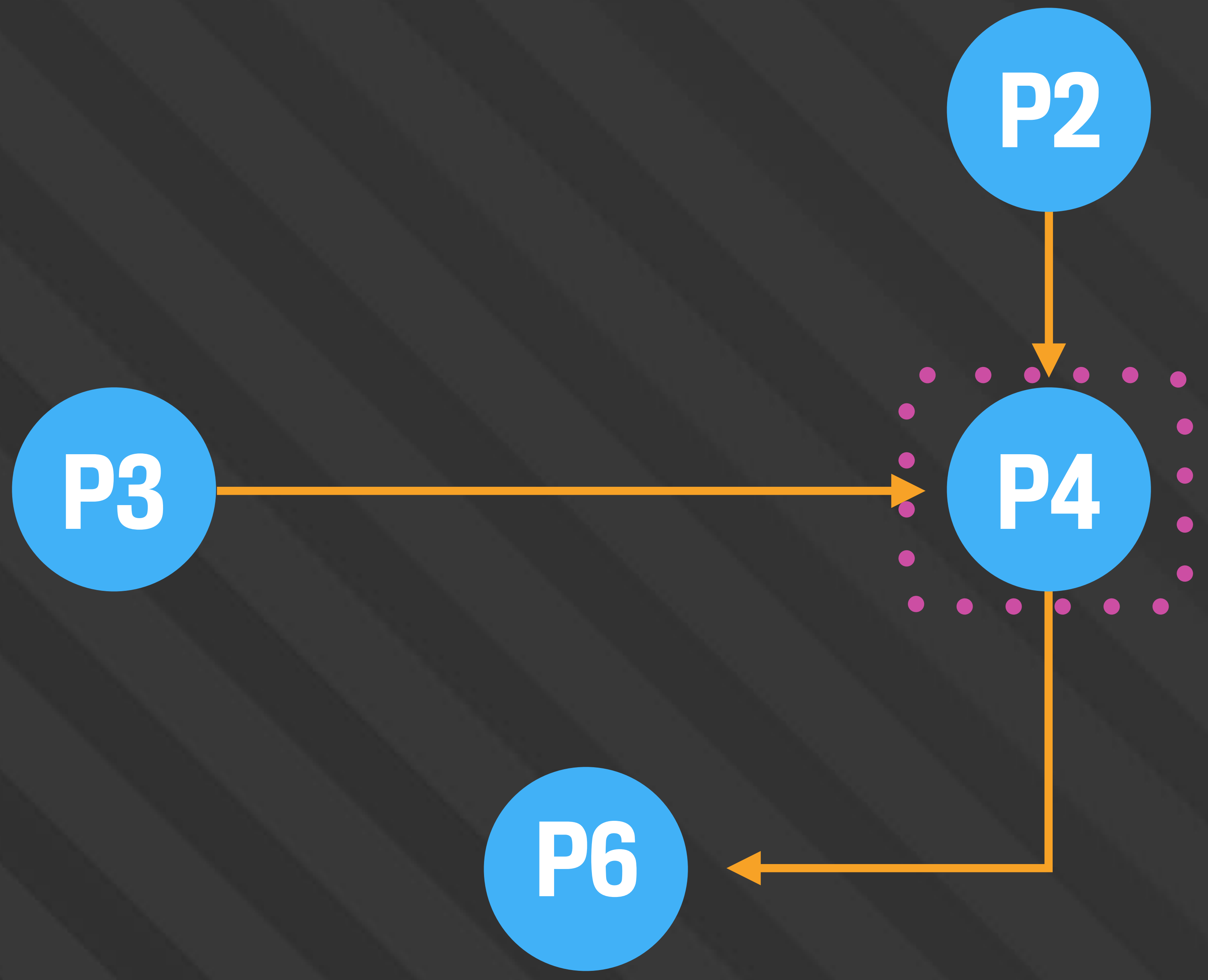
Compositionality and modularity challenges



1. How do we combine the callee summary with the current state? (compositionality)
2. How do we represent state from the caller during analysis? (modularity)

Brief detour into related work: modular/compositional analysis

- "Symbolic relational separate analysis", introduced in [Cousot and Cousot **Static determination of dynamic properties of recursive procedures** IFIP '77, **Modular static program analysis** CC '02]

Brief detour into related work: modular/compositional analysis

- Lots of papers use this approach for one kind of analysis or another (too many to list here, just chase reverse refs of Cousot paper)
- But few general guidelines for designing modular/compositional domains…

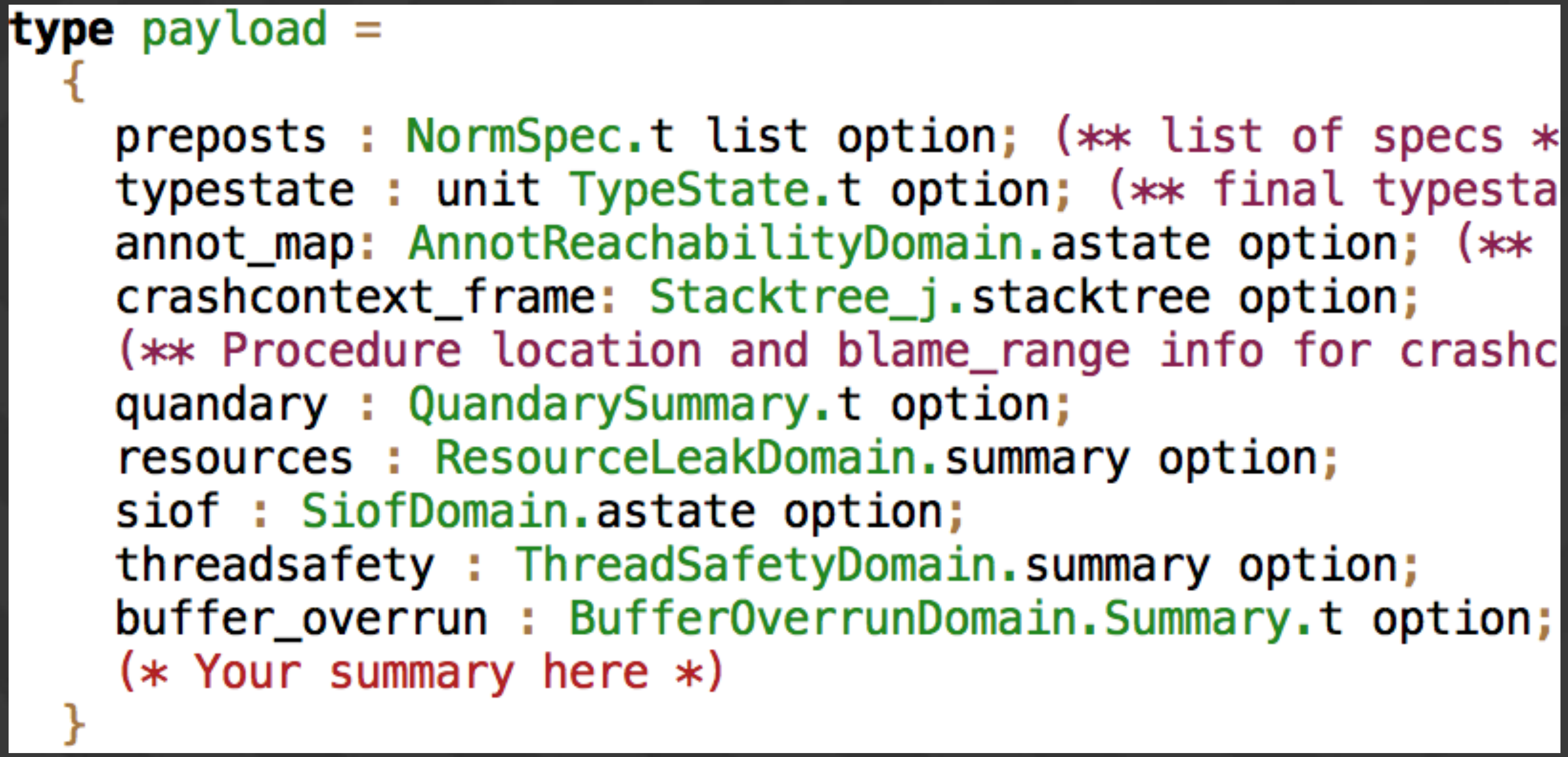
Brief detour into related work: modular/compositional analysis

- [**Generating Precise and Concise Procedure Summaries** Yorsh et al. POPL '08] shows how to design domains yielding summaries that compose efficiently and precisely
- Complex domains assume existence of global points-to analysis...

Brief detour into related work: modular/compositional analysis

- Infer.AI doesn't impose any structure on summaries or provide automatic summary instantiation
- Makes it easy to experiment with different ideas
- Informal tips on domain/summary design later in talk

Interprocedural analysis: defining summaries (Specs.ml)



```
type payload =
  {
    preposts : NormSpec.t list option; (** list of specs *
    typestate : unit TypeState.t option; (** final typesta
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    crashcontext_frame: Stacktree_j.stacktree option;
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    buffer_overrun : BufferOverrunDomain.Summary.t option;
    (* Your summary here *)
  }
```

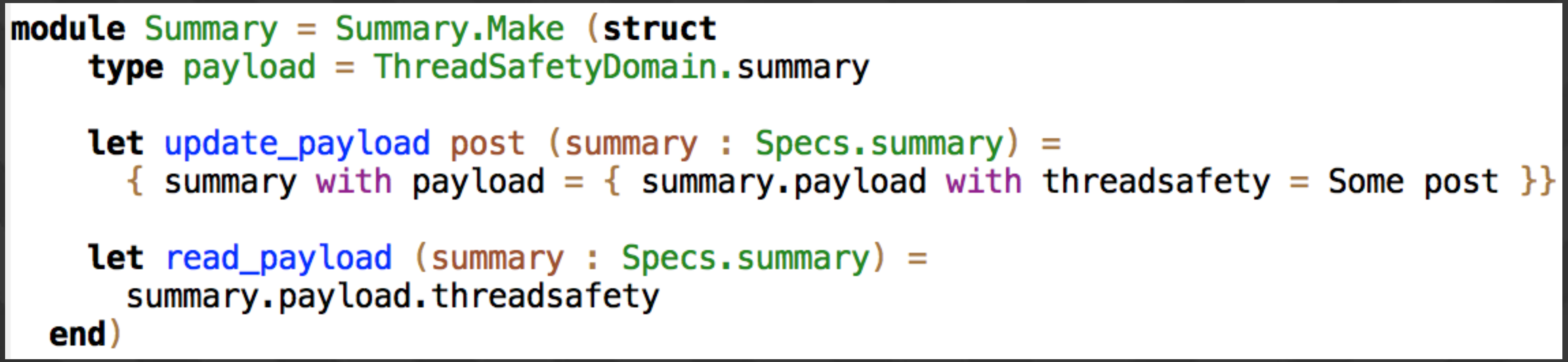

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module Summary = Summary.Make (struct
    type payload = ThreadSafetyDomain.summary

    let update_payload post (summary : Specs.summary) =
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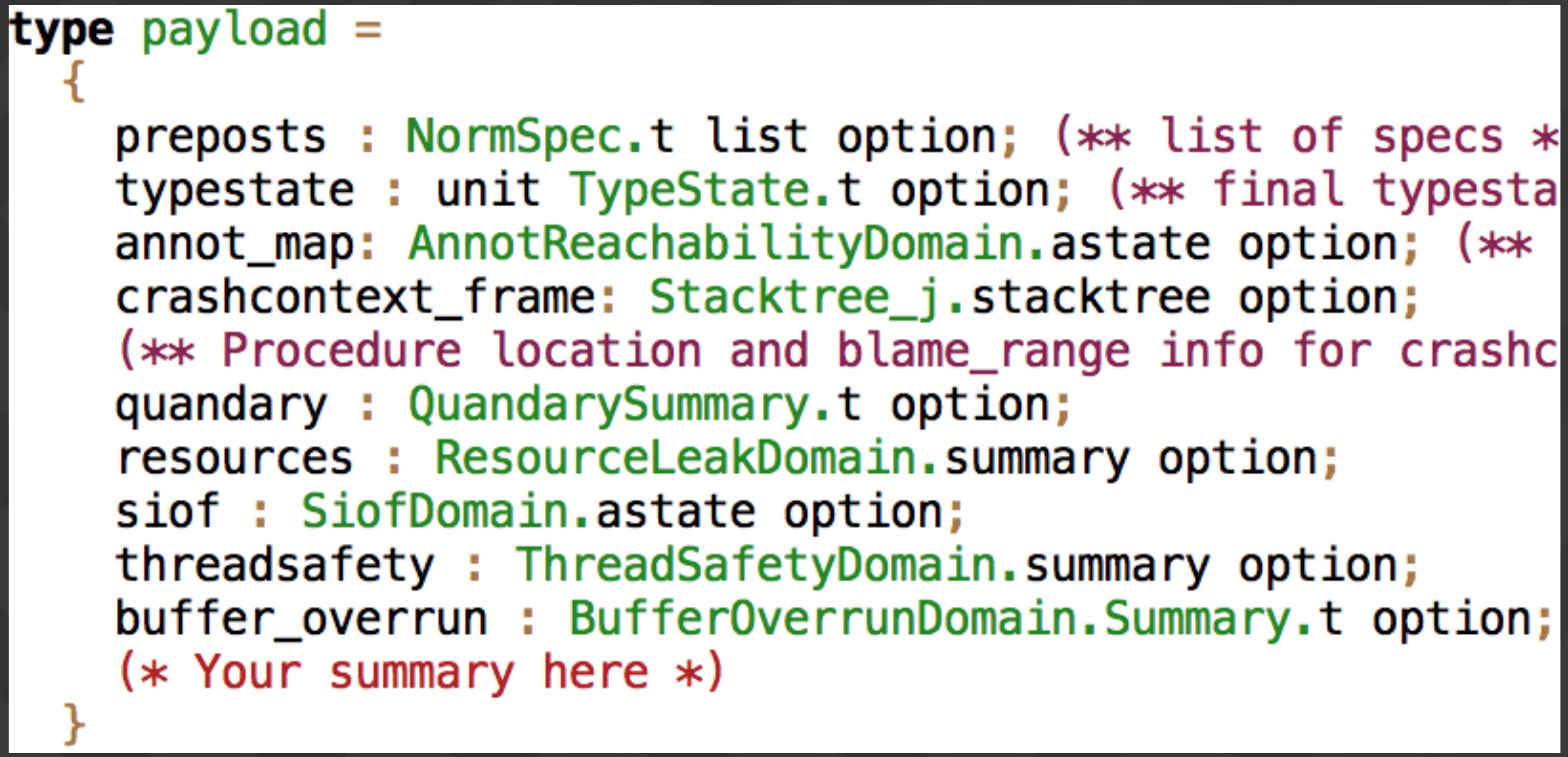
Interprocedural analysis: defining summaries (Specs.ml)

- Add your summary type to master summary "payload"



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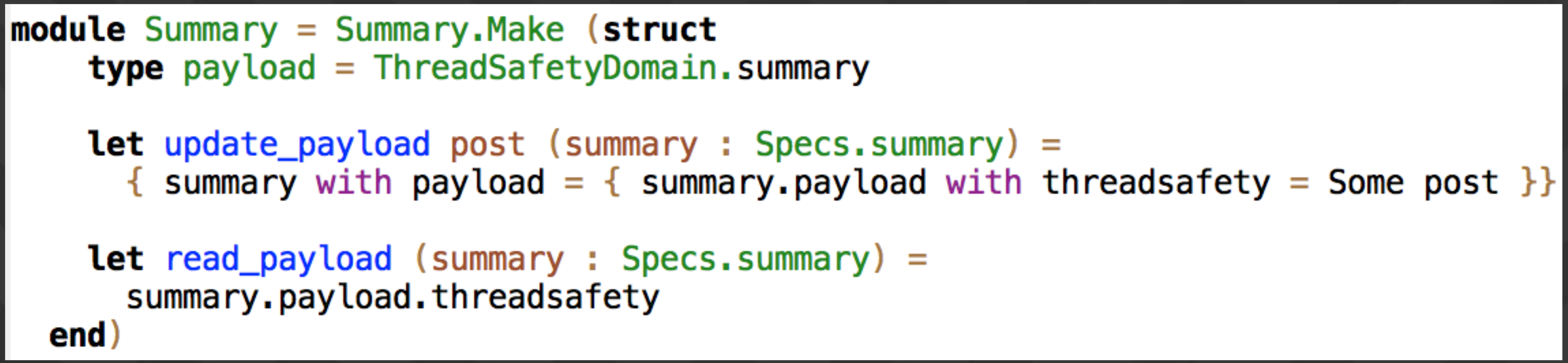

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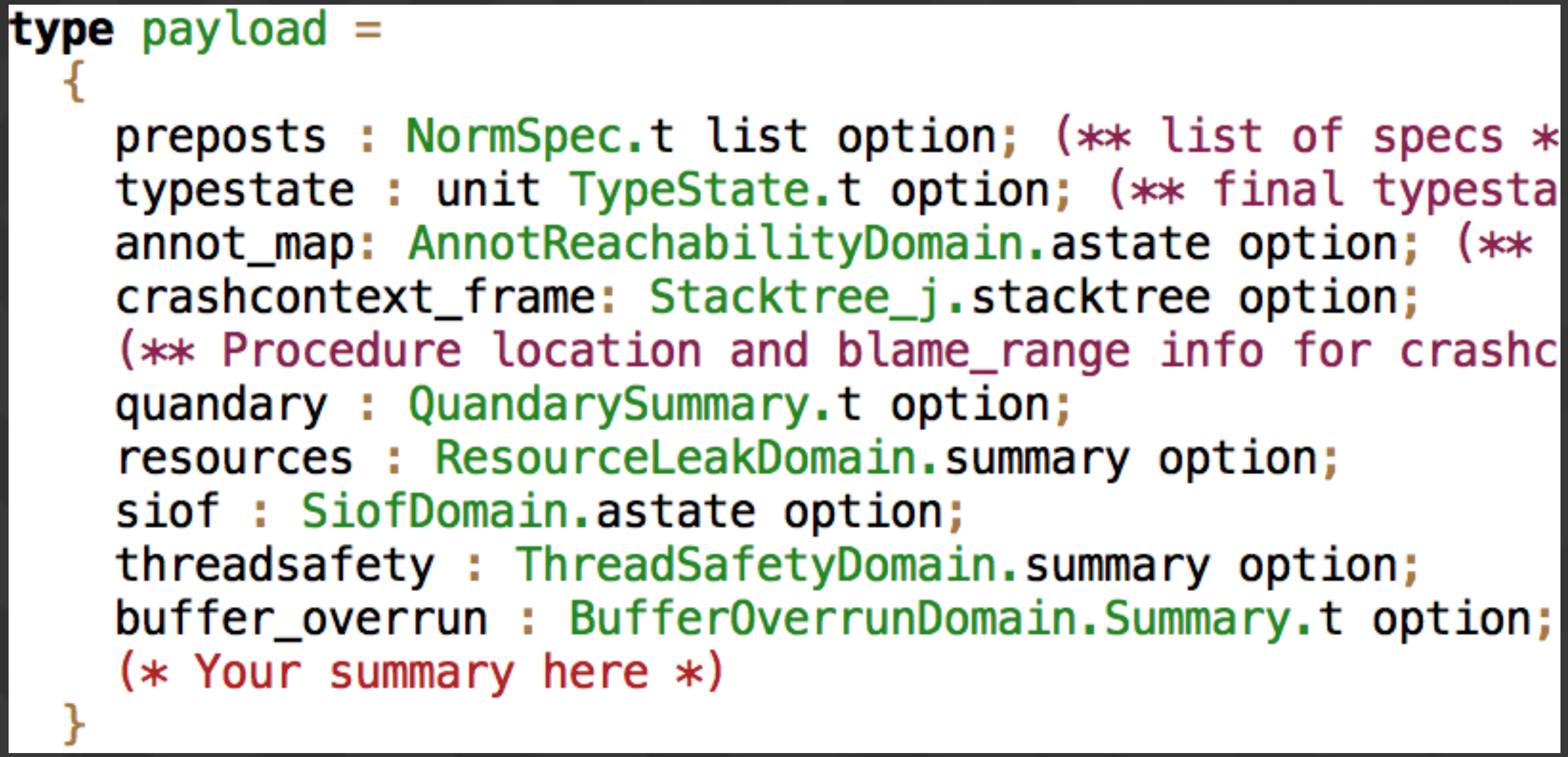

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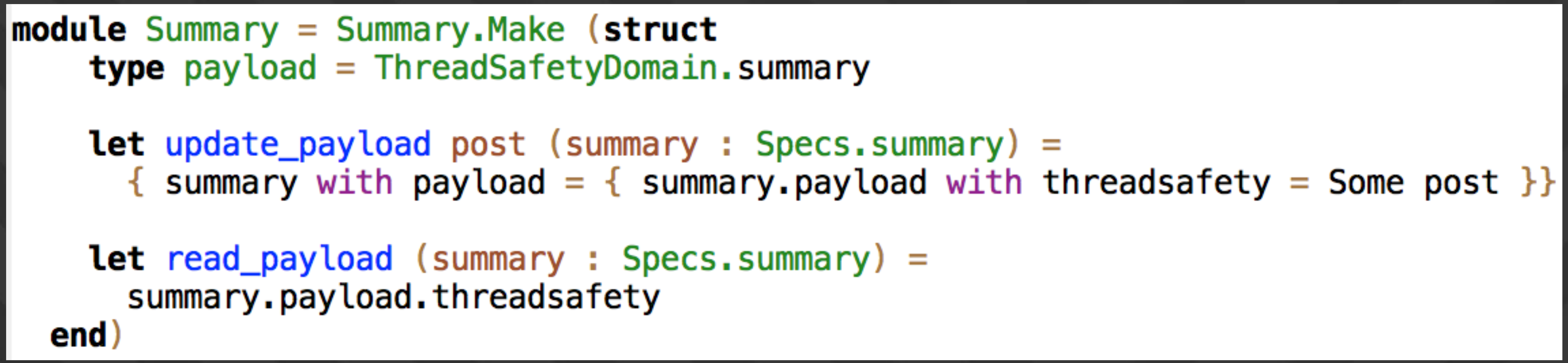
```

- Define helper module for updating/reading payload with your summary



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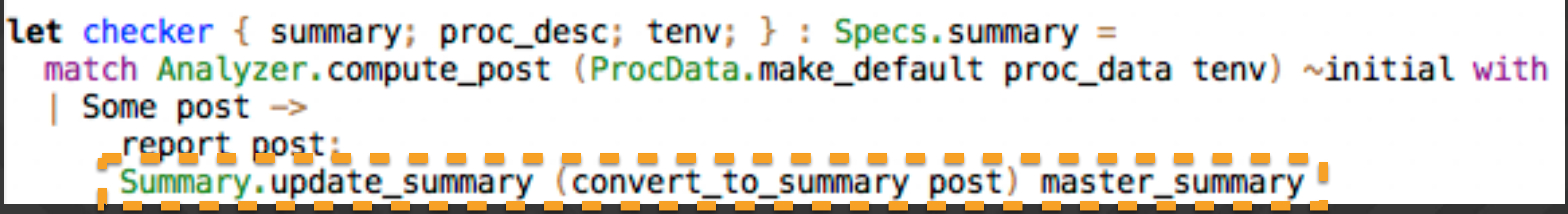
Interprocedural analysis: storing summaries



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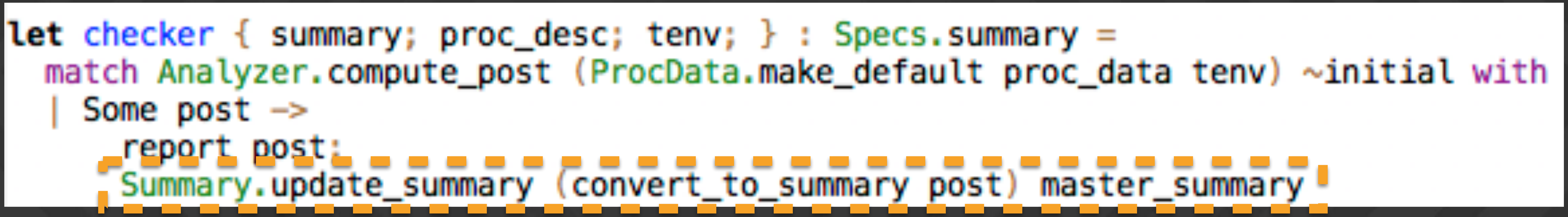

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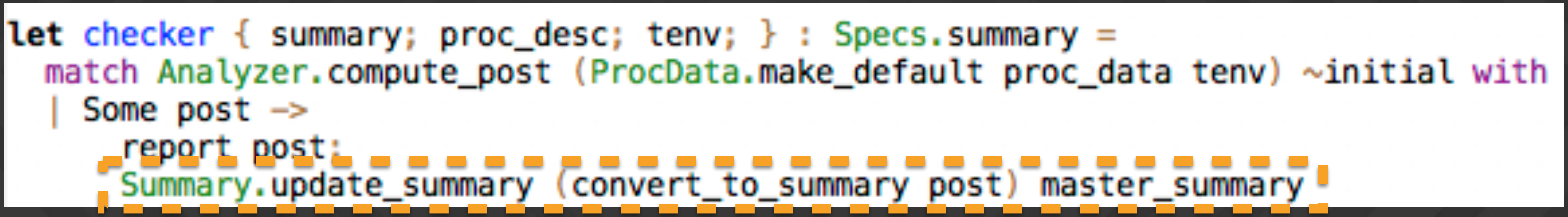
Interprocedural analysis: storing summaries



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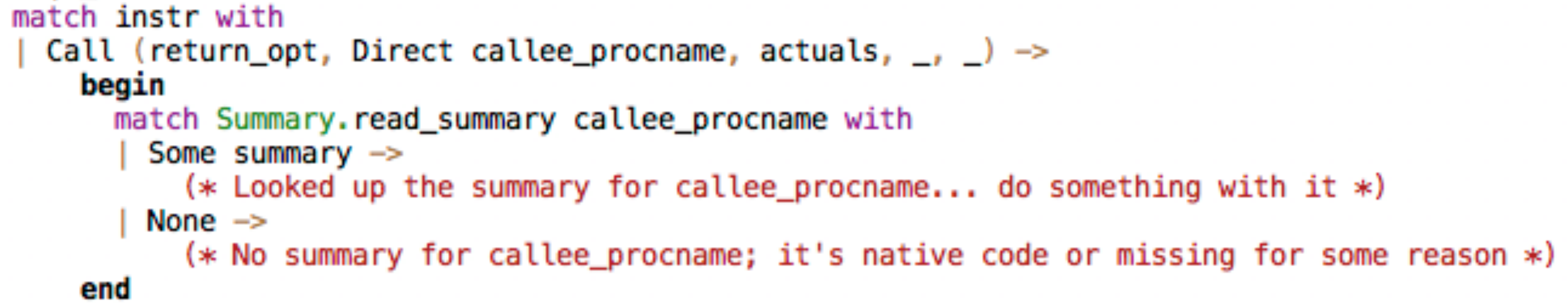
1. Convert postcondition to a summary (can be same)
2. Call Summary.update_summary

Interprocedural analysis: using summaries



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    begin
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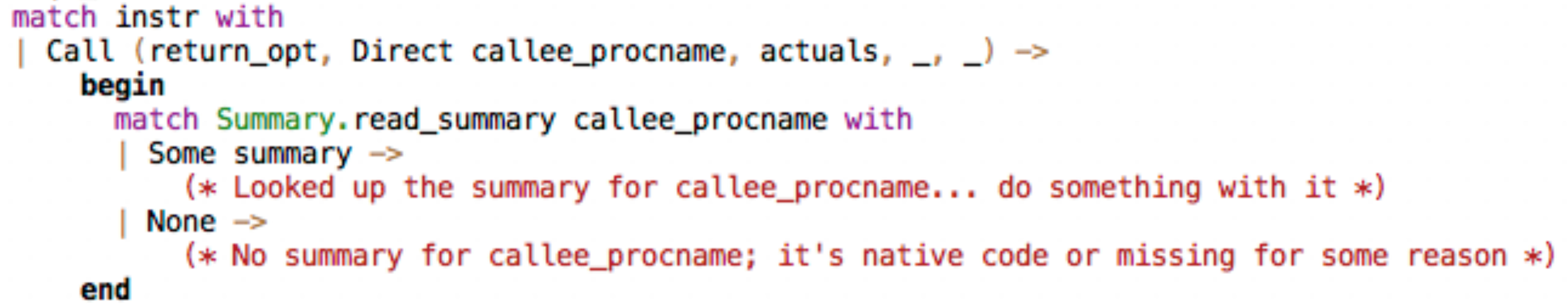

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    end
```

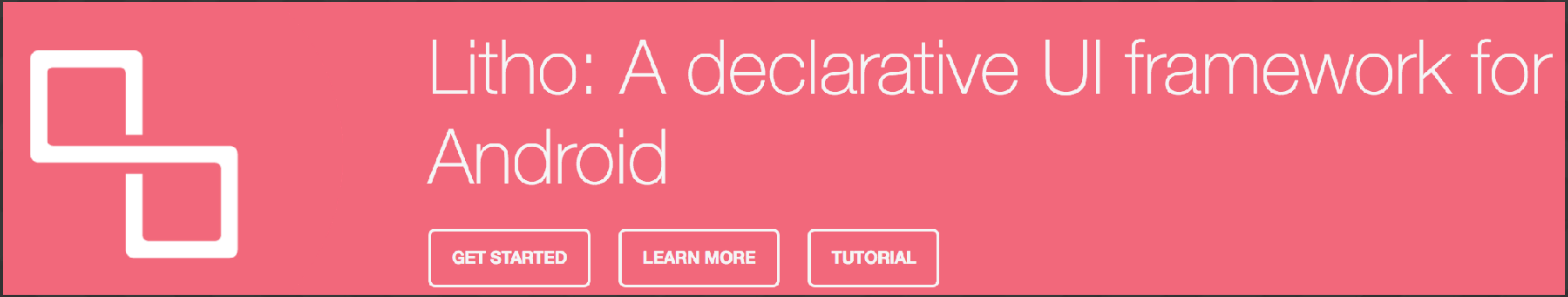
- In transfer functions, just grab summary and use it

Roadmap

- Summaries
- Bottom-up modular/compositional analysis
- **Real-world case study: thread-safety analysis**
- Designing compositional domains

3 | Building compositional interprocedural analyzers

Who wants concurrency analysis?



Litho: A declarative UI framework for Android

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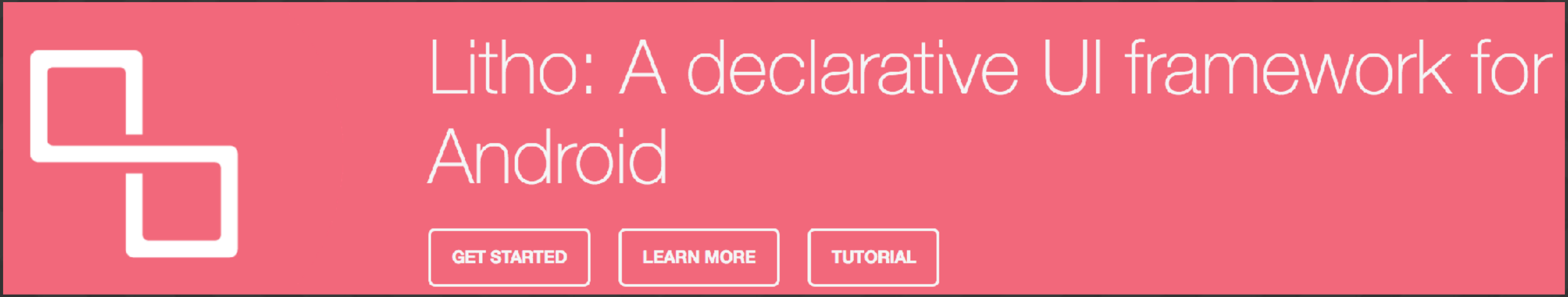

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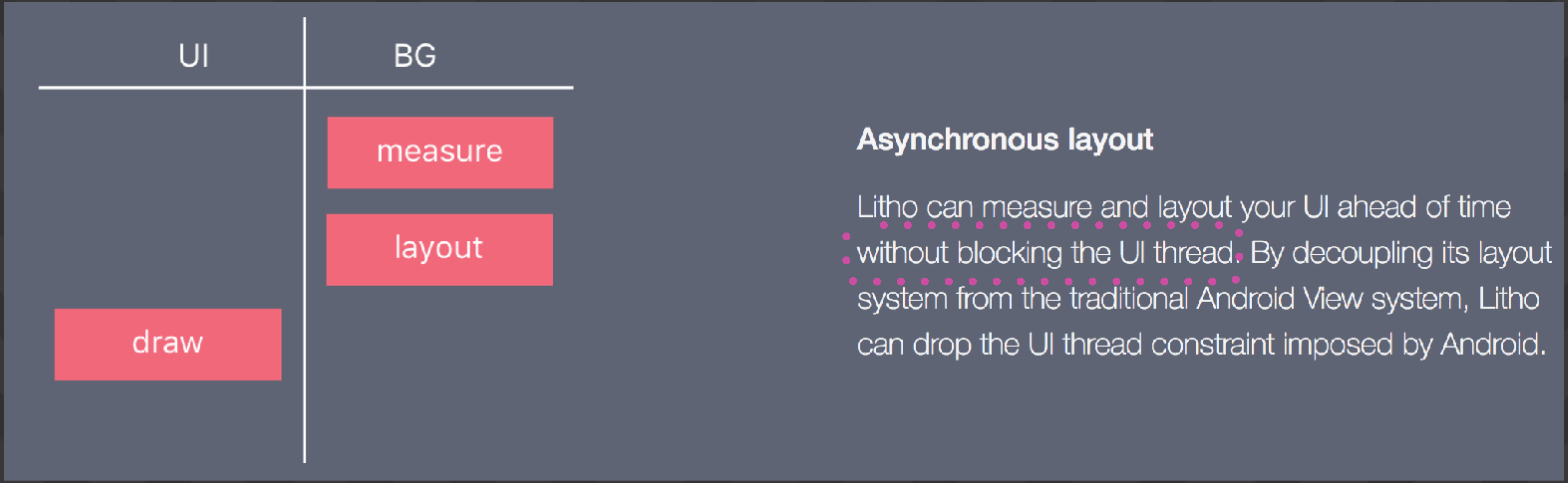


Asynchronous layout

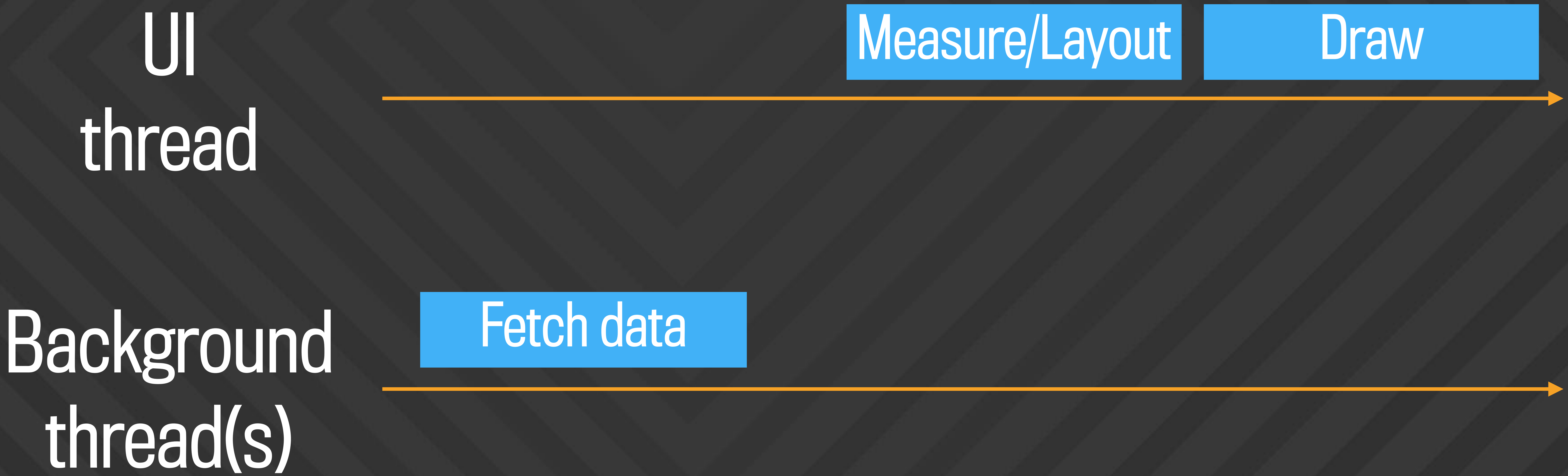
Litho can measure and layout your UI ahead of time without blocking the UI thread. By decoupling its layout system from the traditional Android View system, Litho can drop the UI thread constraint imposed by Android.

Litho: framework for building Android UI

Litho Component

Fetch data	Talk to network
Measure/Layout	Determine size and position
Draw	Render and attach

Improve performance by moving layout to background



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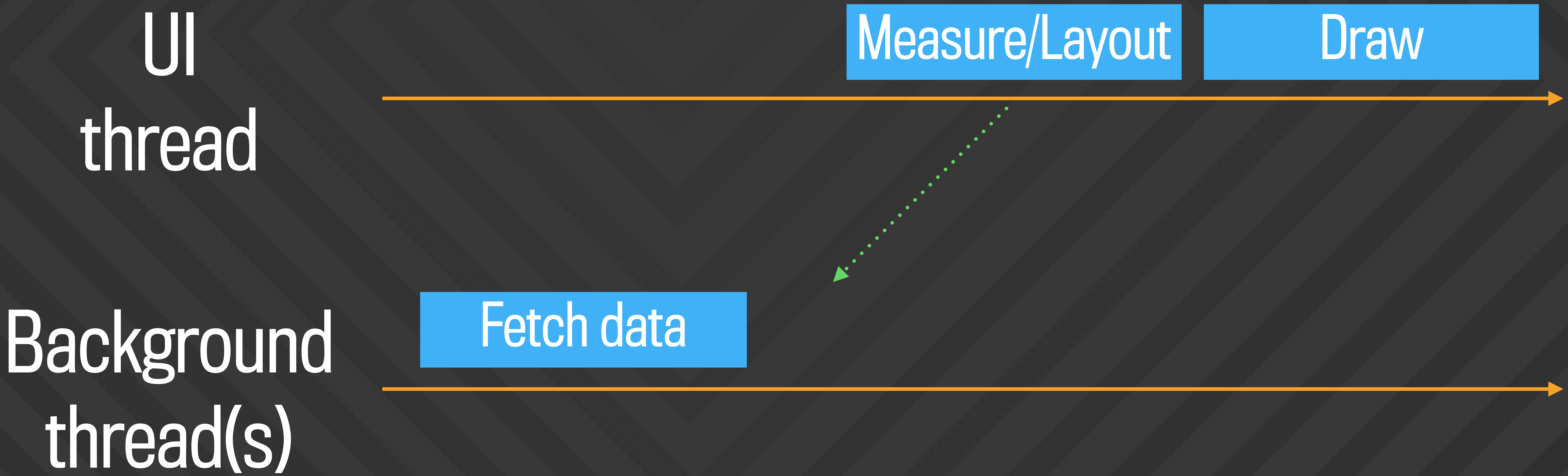
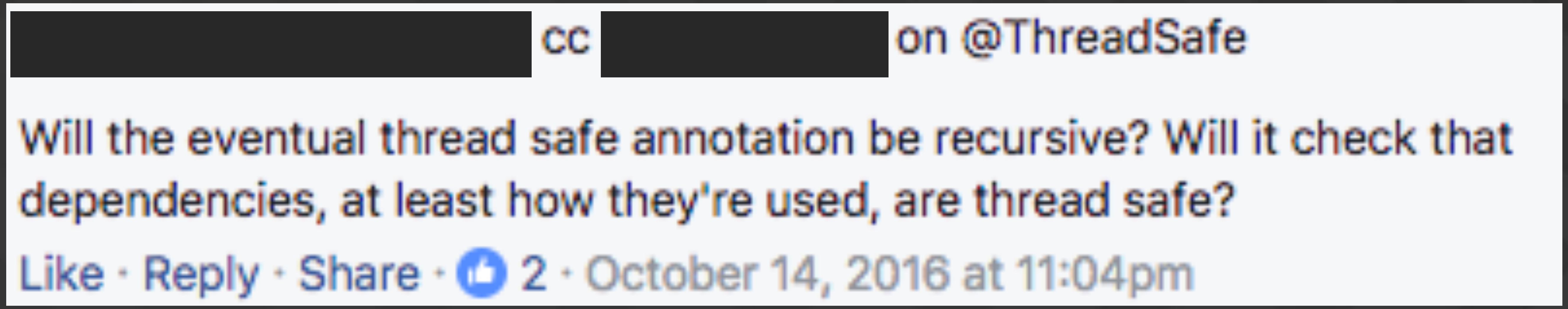


Measure/Layout step needs to be thread-safe

Requirements for thread-safety analysis

Interprocedural



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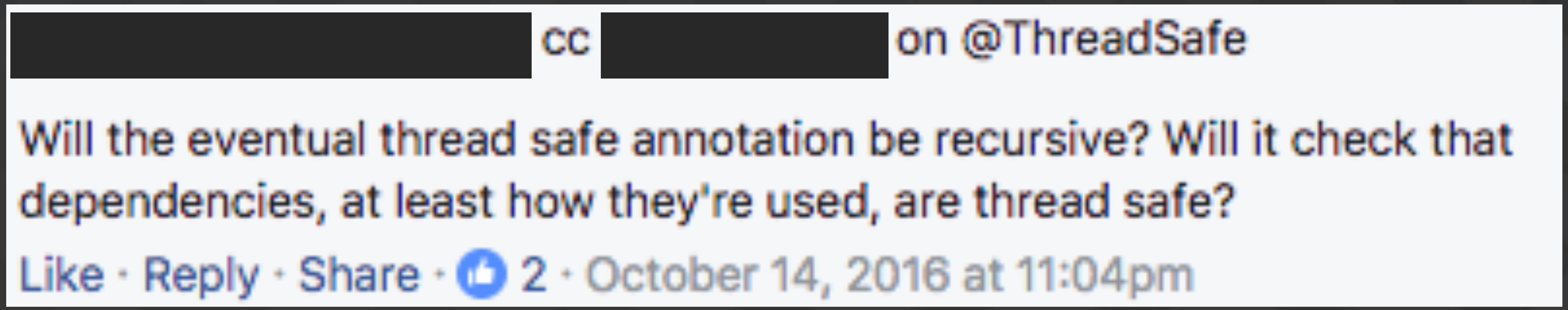

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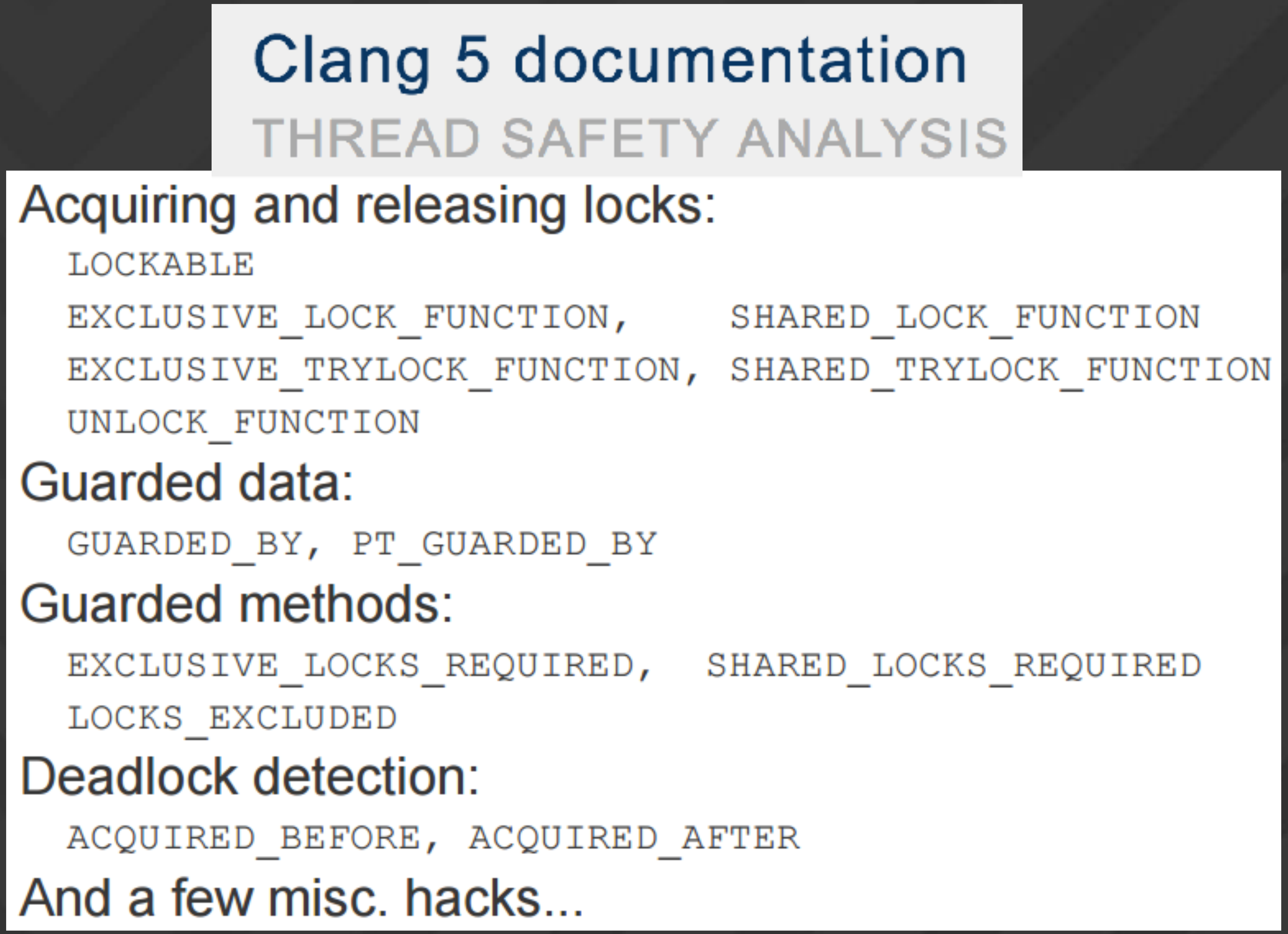
Like · Reply · Share · 2 · October 14, 2016 at 11:04pm

Low annotation burden



Clang 5 documentation

THREAD SAFETY ANALYSIS

Acquiring and releasing locks:

```
LOCKABLE
EXCLUSIVE_LOCK_FUNCTION,    SHARED_LOCK_FUNCTION
EXCLUSIVE_TRYLOCK_FUNCTION, SHARED_TRYLOCK_FUNCTION
UNLOCK_FUNCTION
```

Guarded data:

```
GUARDED_BY, PT_GUARDED_BY
```

Guarded methods:

```
EXCLUSIVE_LOCKS_REQUIRED,  SHARED_LOCKS_REQUIRED
LOCKS_EXCLUDED
```

Deadlock detection:

```
ACQUIRED_BEFORE, ACQUIRED_AFTER
```

And a few misc. hacks...

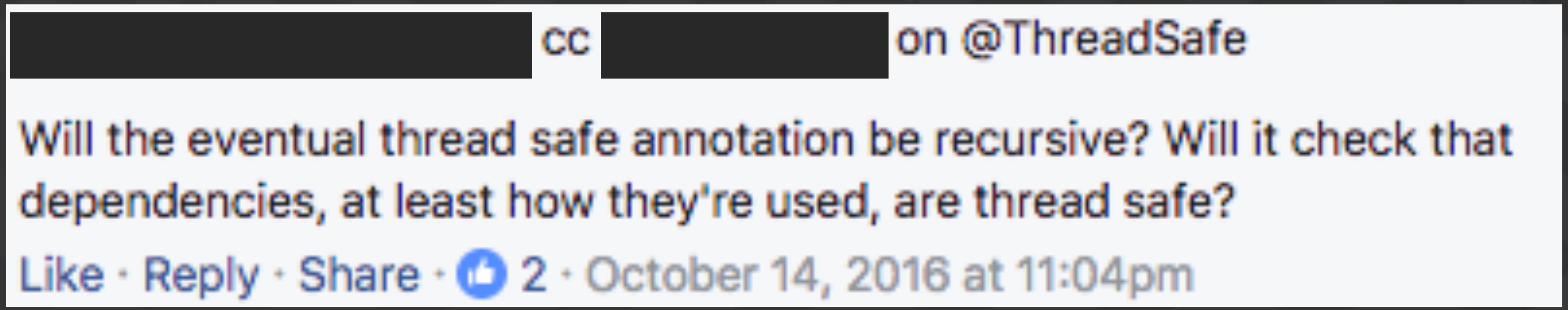
Requirements for thread-safety analysis

Interprocedural

Low annotation burden

Modular

Compositional



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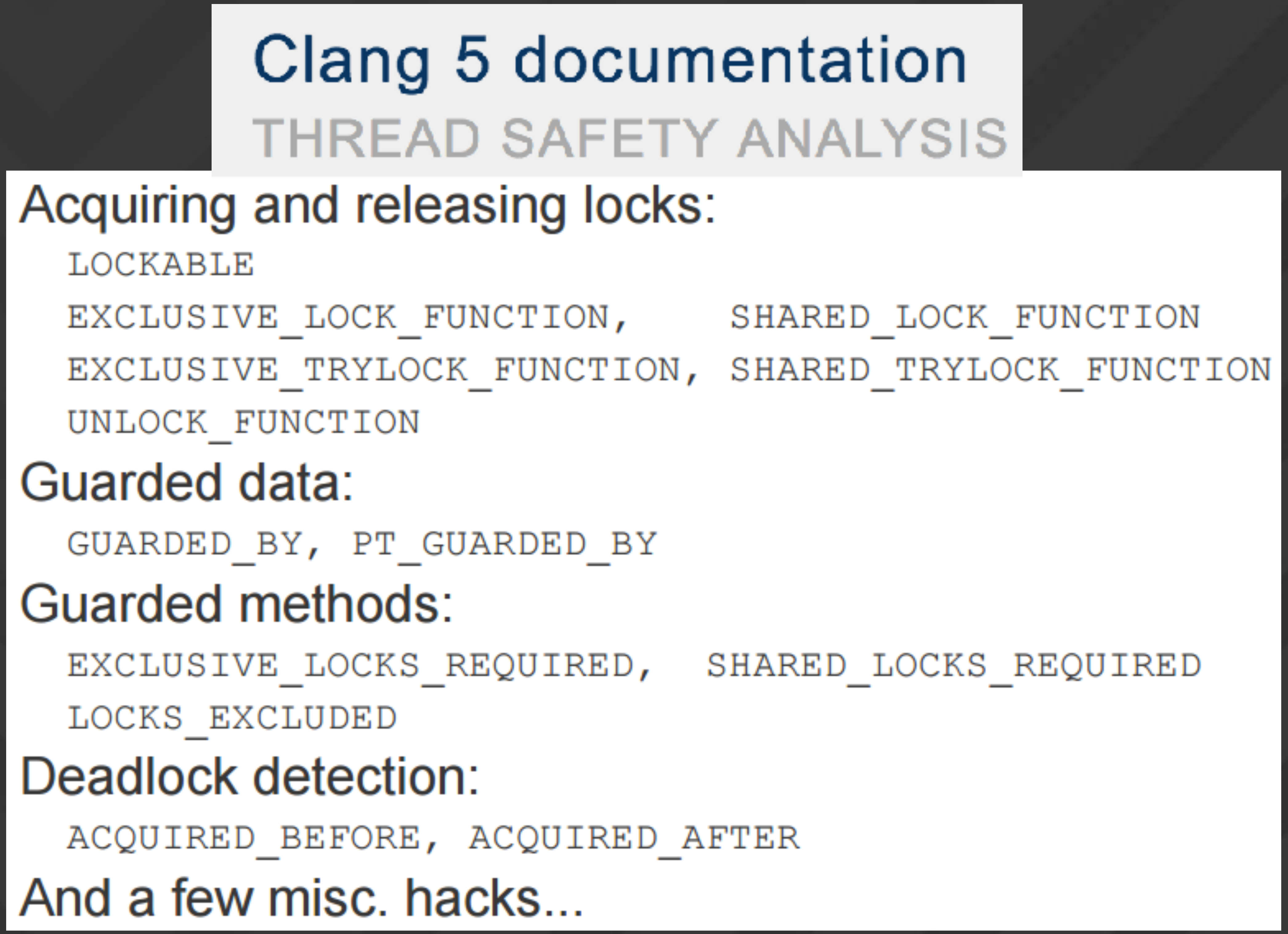

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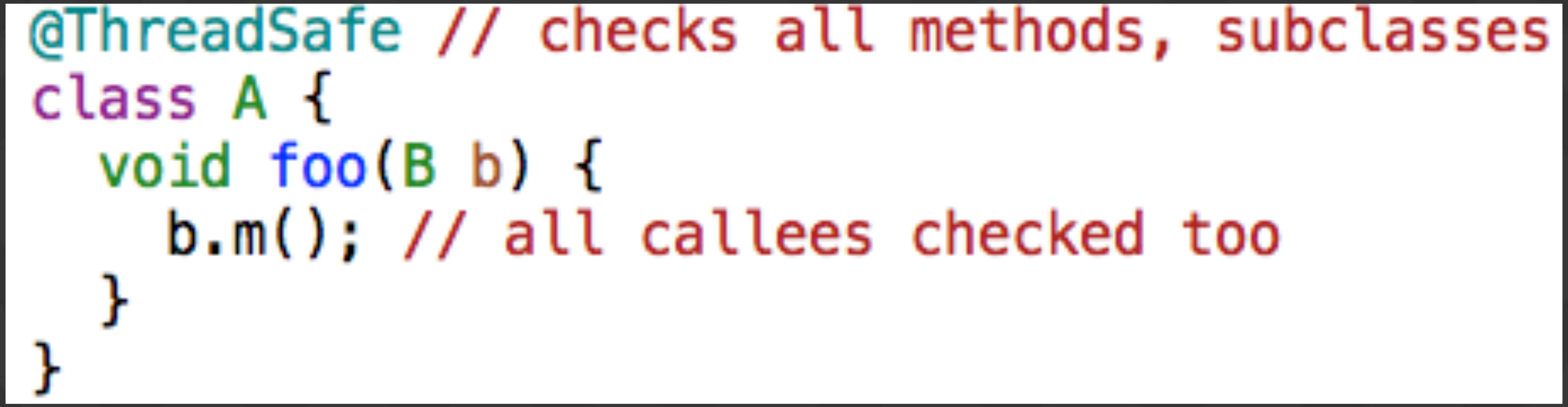
How to trigger analysis: just add @ThreadSafe



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@ThreadSafe // checks all methods, subclasses
class A {
  void foo(B b) {
    b.m(); // all callees checked too
  }
}
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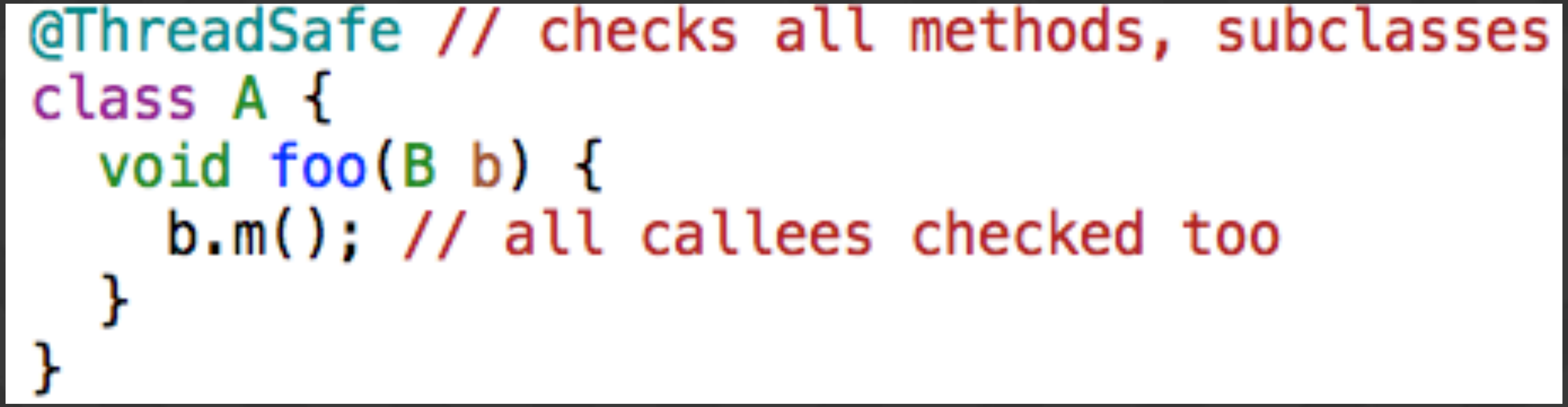

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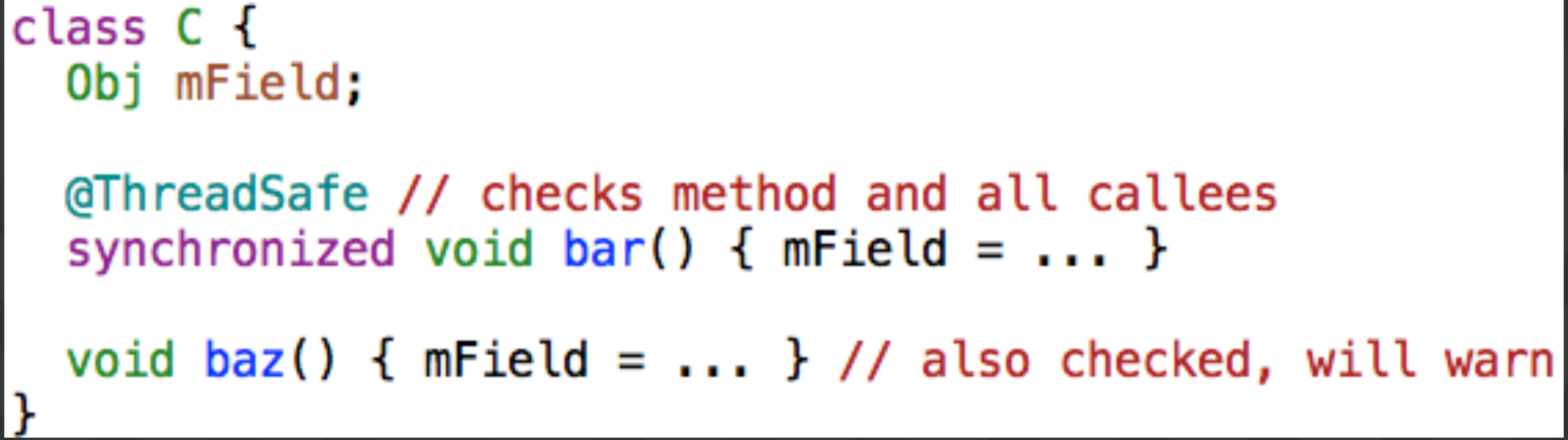

```
class C {
  Obj mField;

  @ThreadSafe // checks method and all callees
  synchronized void bar() { mField = ... }

  void baz() { mField = ... } // also checked, will warn
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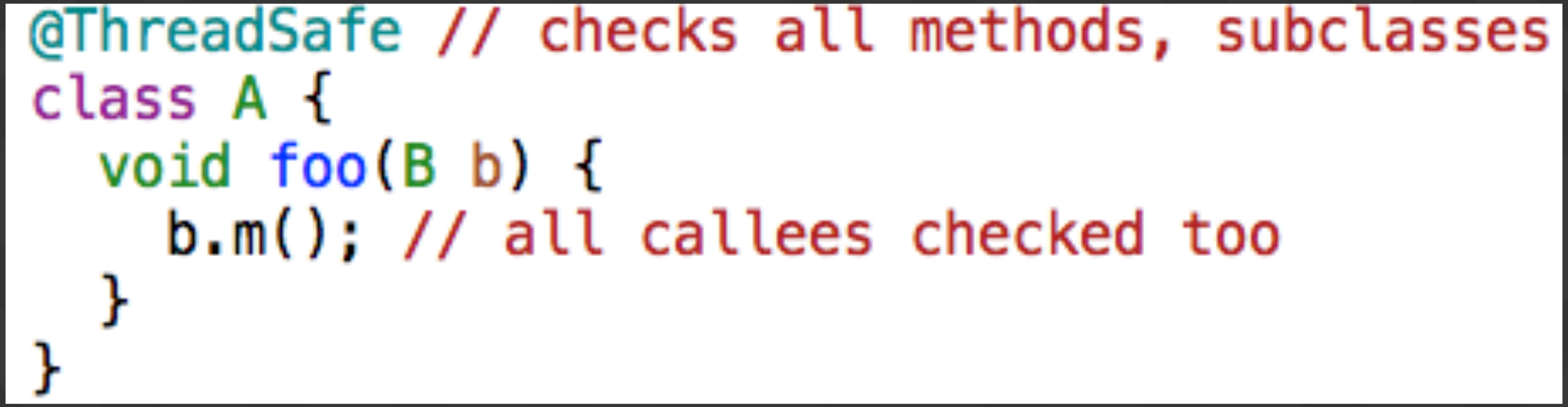

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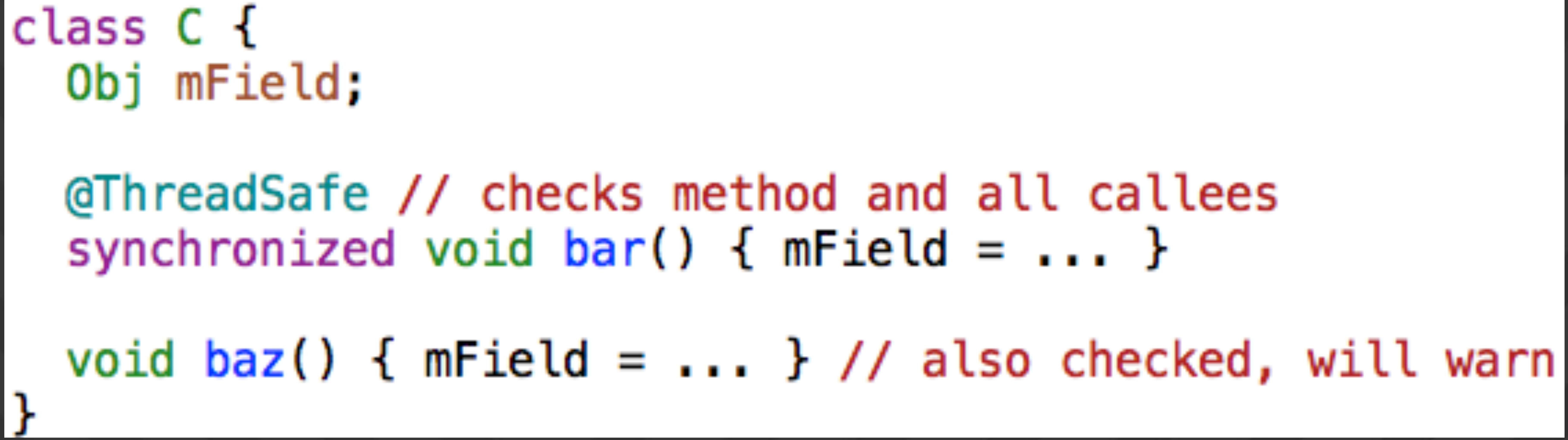

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```
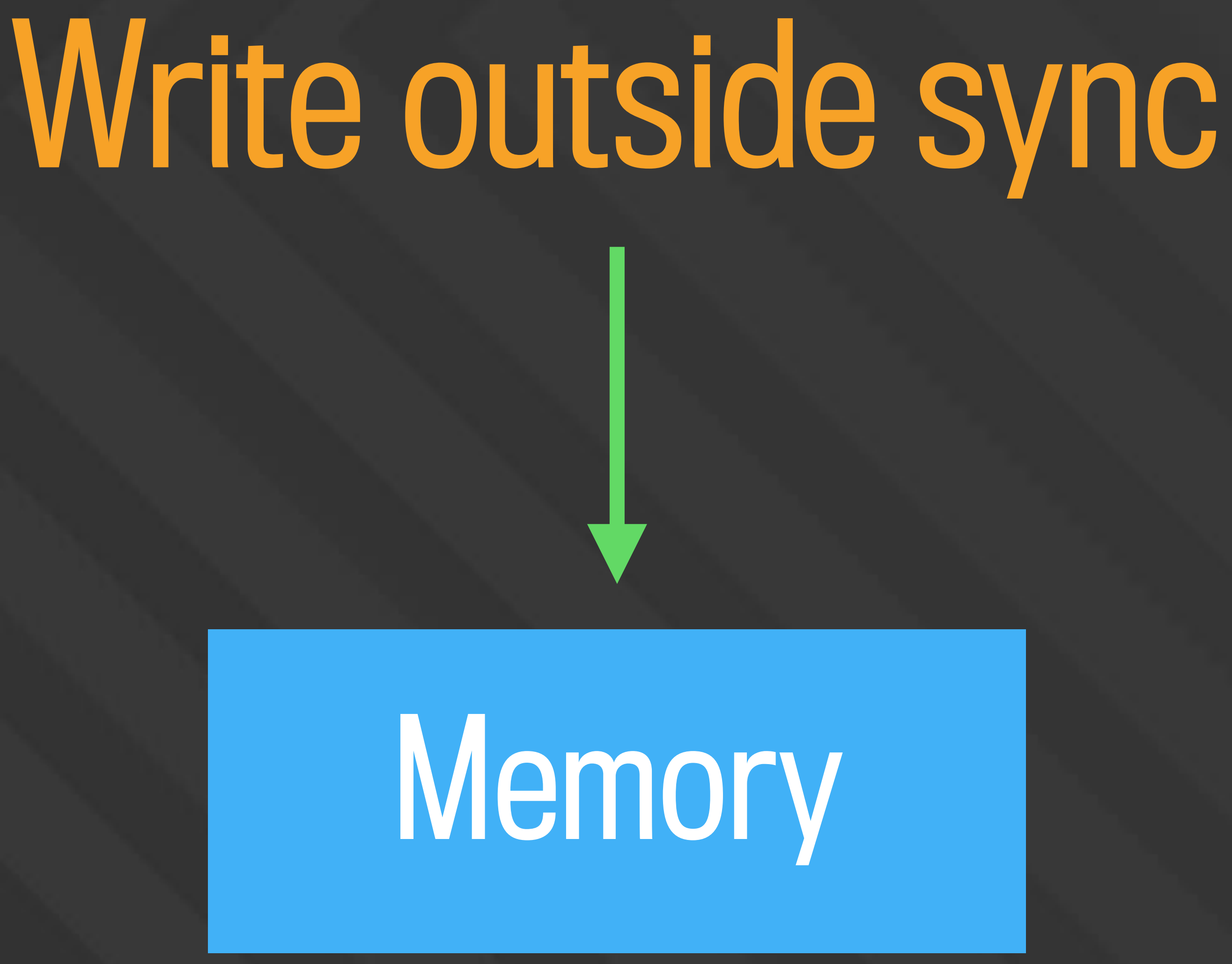

```
@ThreadSafe(enableChecks = false) class D {} // won't warn
```

Infer thread-safety analysis: what should it do?

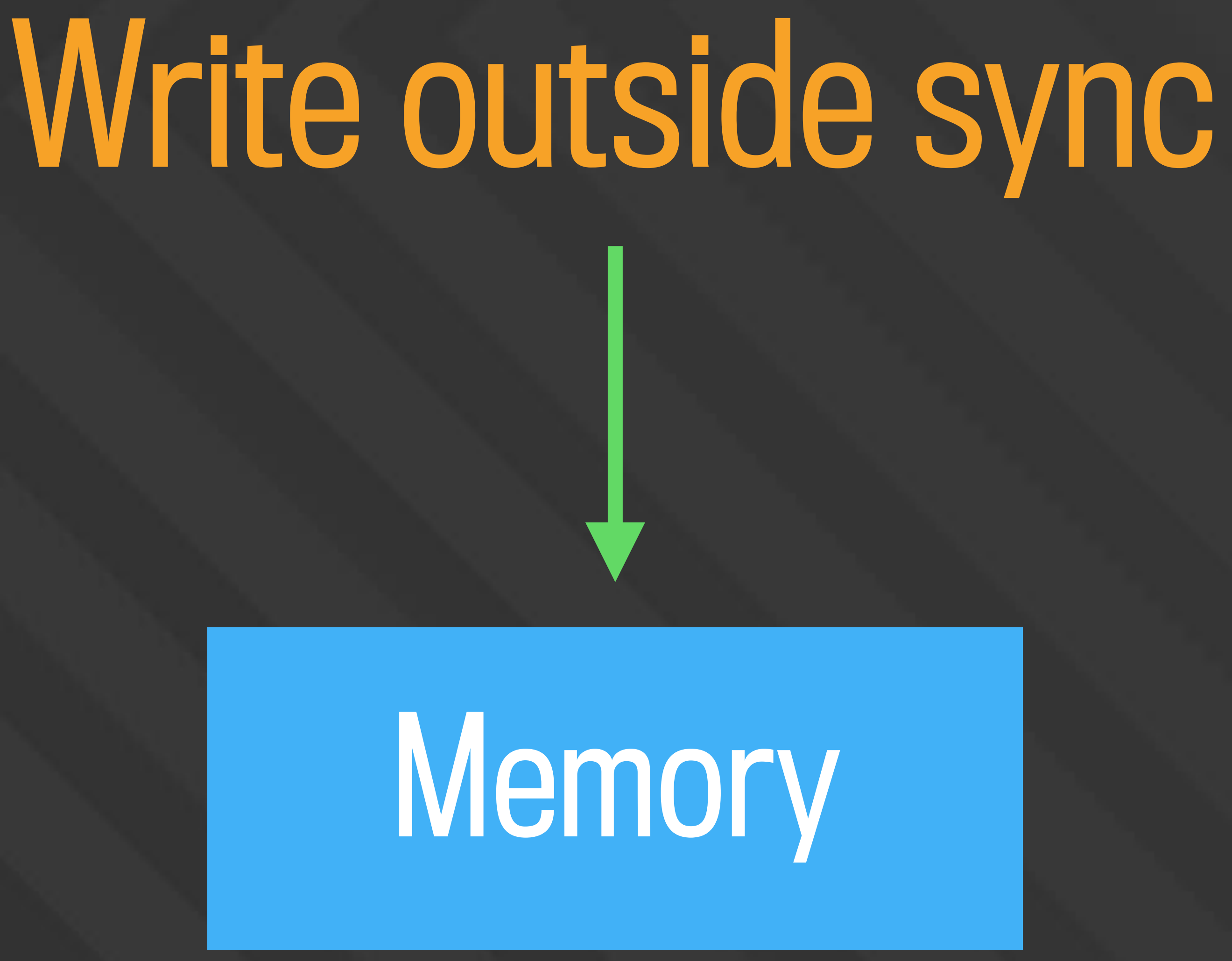
Find data races:
two simultaneous accesses to the
same memory location
where at least one is a write.

Report data races with two warning types



Unprotected write
warning (self-race)

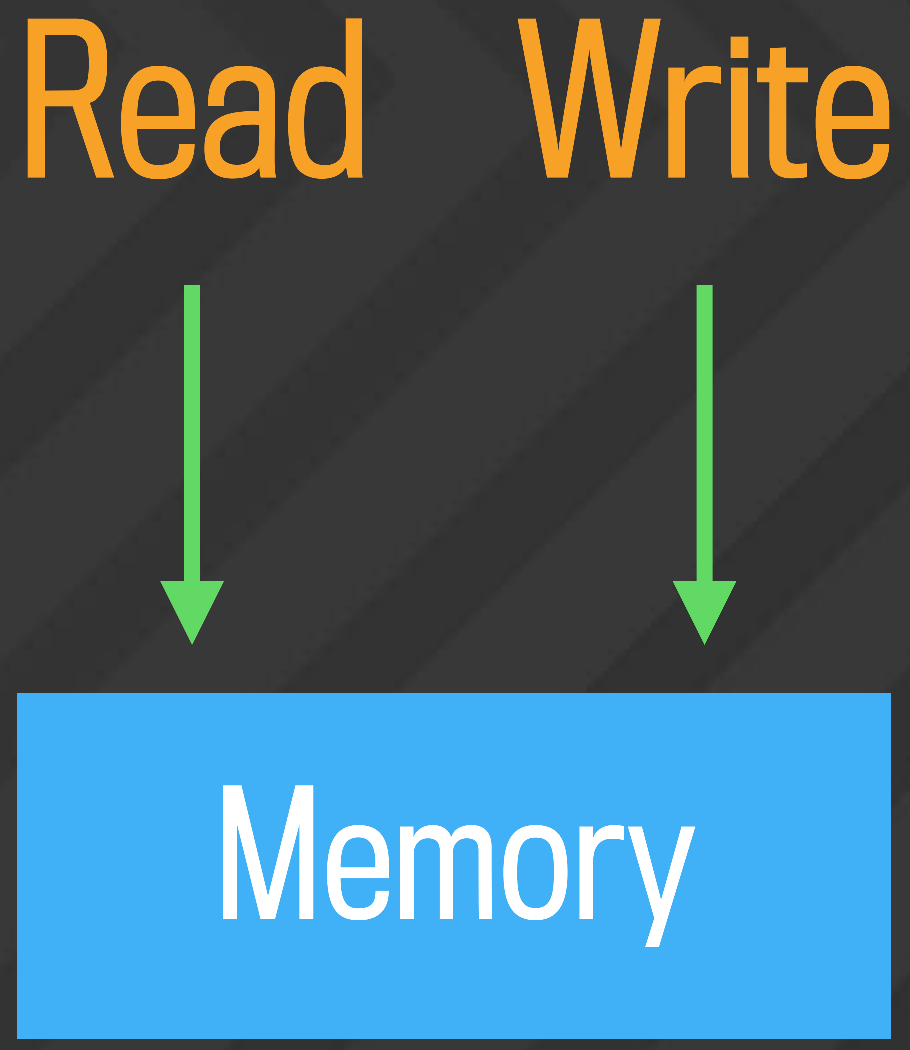
Report data races with two warning types



Write outside sync

Memory

Unprotected write warning (self-race)



Read Write

Memory

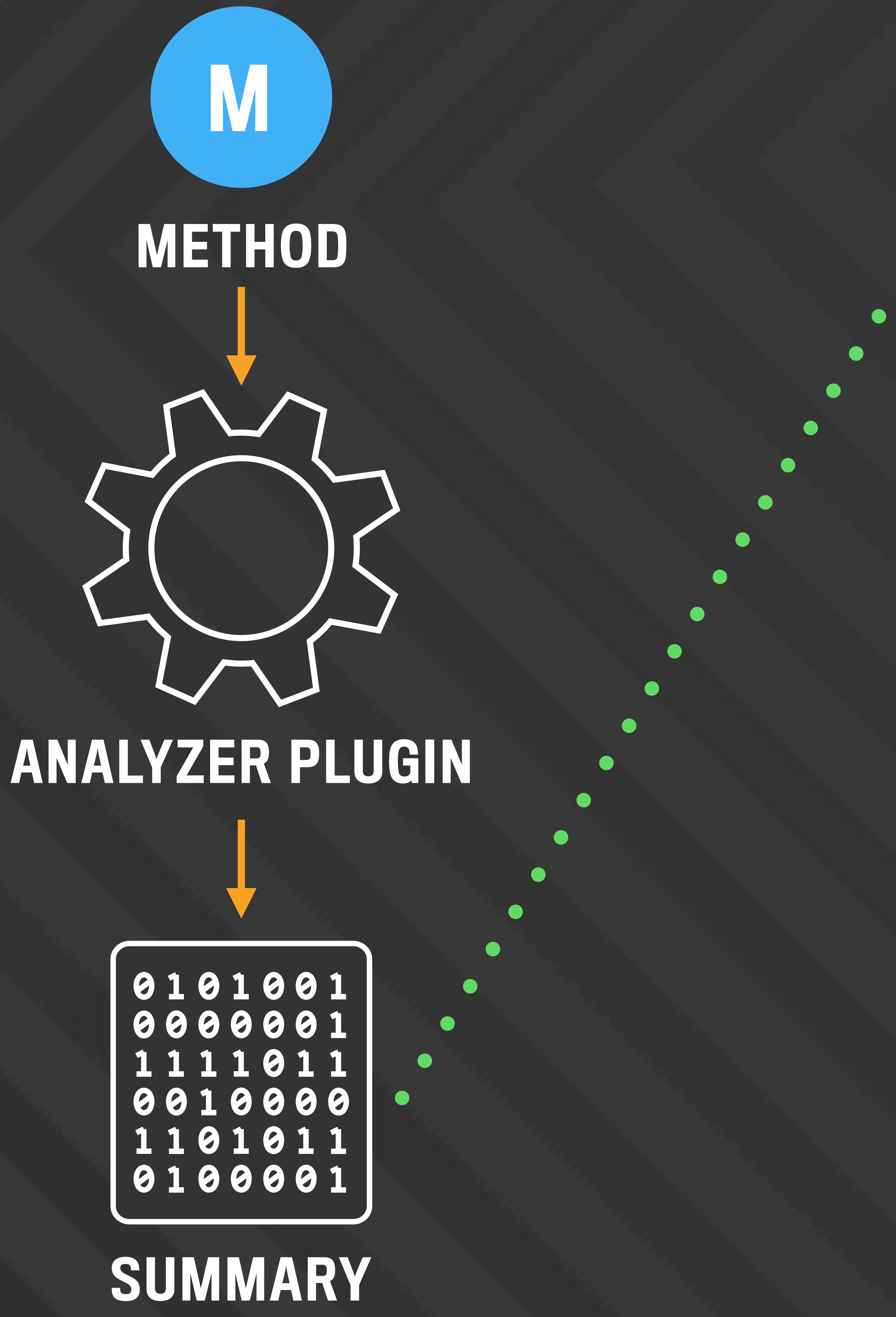
Read/write race warning

Minimum viable analysis

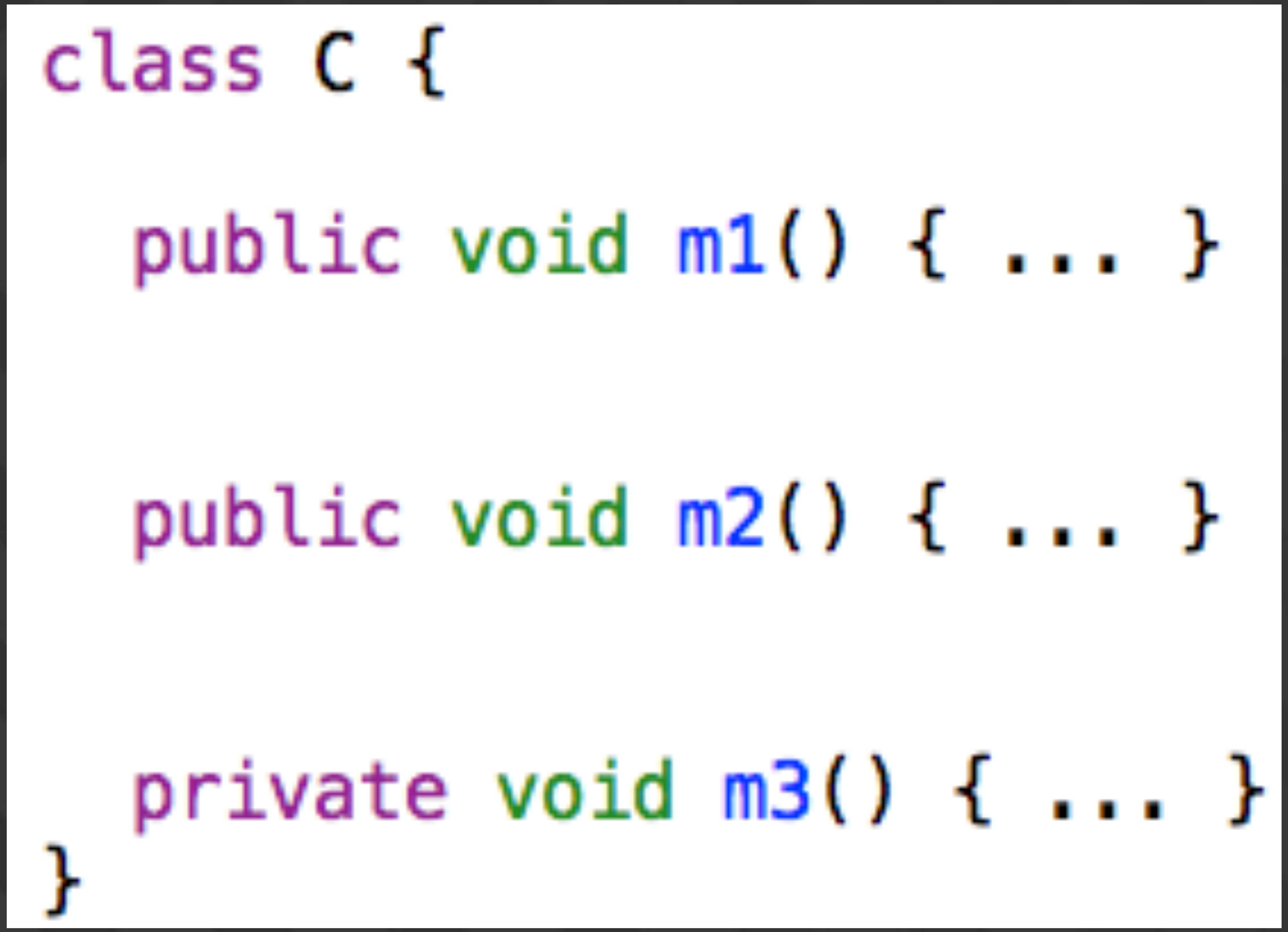
- Analysis triggered by @ThreadSafe annotation
- Assume all non-private methods in a single @ThreadSafe class can run in parallel
- Report full call stack to any field accessed outside of synchronization

How does it work?

(1) Stack trace to access
(2) Lock(s) held
(3) Current thread
(4) Ownership info

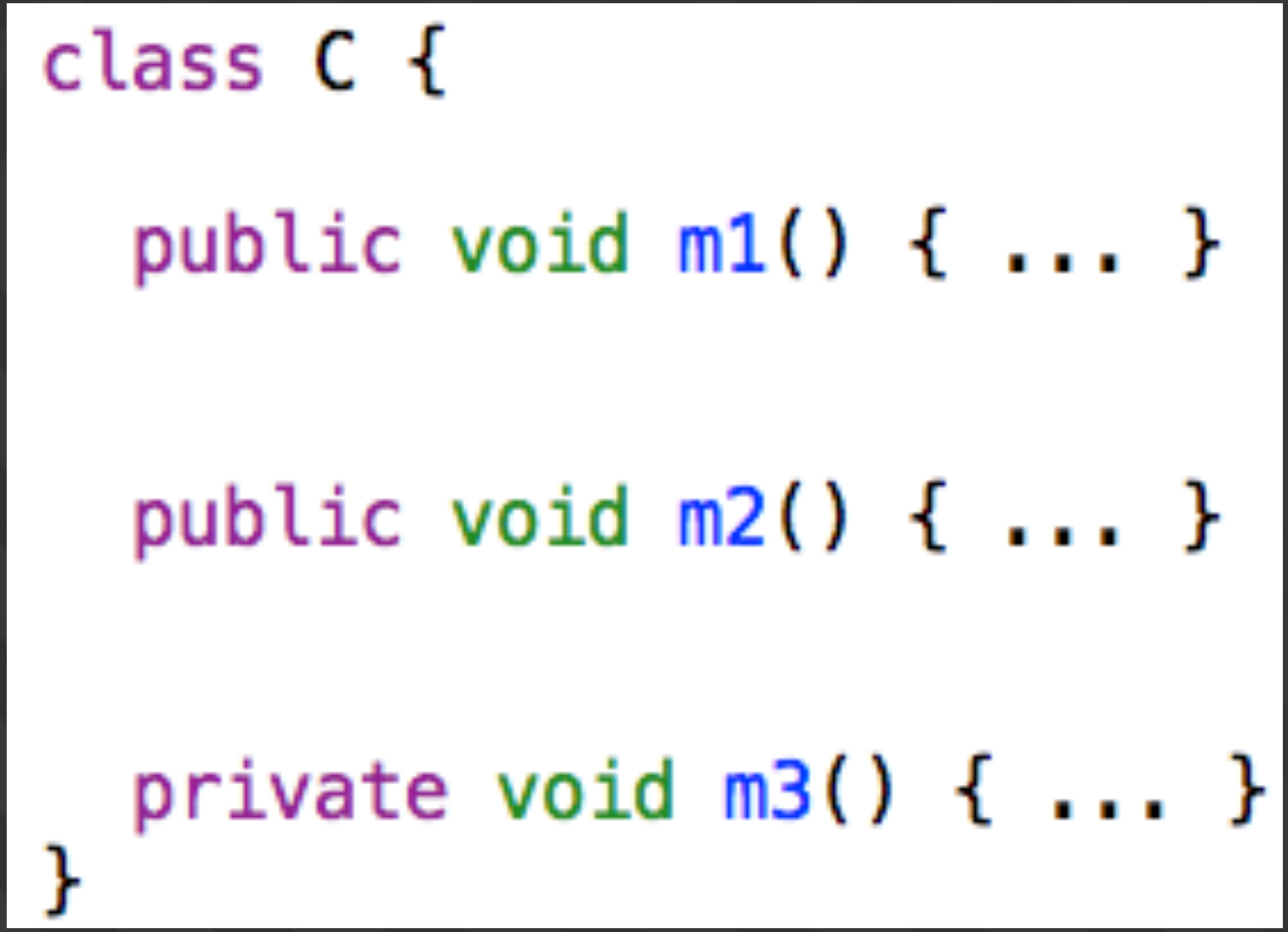


Aggregate summaries for class and report



```
class C {

  public void m1() { ... }


  public void m2() { ... }


  private void m3() { ... }
}
```

Aggregate summaries for class and report



```
class C {

  public void m1() { ... }


  public void m2() { ... }


  private void m3() { ... }
}
```

Report when:

- reachable from non-private method
- can find conflicting access(es)

Start with a very simple domain

SUMMARY

Need to track:

- Name, location of accessed field. Use access paths
- Locks. Use boolean for "must be held"
- Threads. Use boolean for "on main thread"

Computing summaries: simple intraprocedural case

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1) }
```

Computing summaries: simple intraprocedural case

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1) }
```

```
void setFWithSync(Obj o) {
  synchronized(o) {
    lockHeld
    o.f = ...;
  }
}
summ: { }
```

Applying summaries

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1, _) }
```

```
private void callSetF(Obj x) {
  x.g = ... // line 2
  { (x.g, 2, _) }
  setF(x); // summ: { (o.f, 1, setF) }
  { (x.g, 2, _) } |_| project(summ, x) }
}
summ: { (x.g, 2, _), (x.f, 1, setF) }
```

Applying summaries

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1, _) }
```

```
private void callSetF(Obj x) {
  x.g = ... // line 2
  { (x.g, 2, _) }
  setF(x); // summ: { (o.f, 1, setF) }
  { (x.g, 2, _) } |_| project(summ, x) }
}
summ: { (x.g, 2, _), (x.f, 1, setF) }
```

project binds callee formals to caller actuals

Applying summaries with join loses call stack

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1, _) }
```

```
private void callSetF(Obj x) {
  x.g = ... // line 1
  setF(x); // summ: { (o.f, 1, setF) }
  someOtherFunction1()
}
summ: { (x.f, 1, setF), (x.g, 2, callSetF) }
```

Applying summaries with join loses call stack

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1, _) }
```

```
private void callSetF(Obj x) {
  x.g = ... // line 1
  setF(x); // summ: { (o.f, 1, setF) }
  someOtherFunction1()
}
summ: { (x.f, 1, setF), (x.g, 2, callSetF) }
```

```
@ThreadSafe public void reportHere(Obj y) {
  callSetF(y); // summ: { (x.f, 1, setF), ... }
  someOtherFunction2()
}
summ: { (y.f, 1, setF), (y.g, 2, callSetF) }
```

Applying summaries with join loses call stack

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, 1, _) }
```

```
private void callSetF(Obj x) {
  x.g = ... // line 1
  setF(x); // summ: { (o.f, 1, setF) }
  someOtherFunction1()
}
summ: { (x.f, 1, setF), (x.g, 2, callSetF) }
```

```
@ThreadSafe public void reportHere(Obj y) {
  callSetF(y); // summ: { (x.f, 1, setF), ... }
  someOtherFunction2()
}
summ: { (y.f, 1, setF), (y.g, 2, callSetF) }
```

Can't recover call stack!

Attempt 1: track call stack explicitly

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, [(1, _)]) }
```

```
private void callSetF(Obj x) {
  setF(x); // line 2 summ: { (o.f, [(1, _)]) }
  { } |_| (2, _) :: project(summ, x)
  someOtherFunction1();
}
summ: { (x.f, [(2, _) :: (1, setF)] }
```

Attempt 1: track call stack explicitly

```
private void setF(Obj o) {
  o.f = ... // line 1
}
summ: { (o.f, [(1, _)]) }
```

```
private void callSetF(Obj x) {
  setF(x); // line 2 summ: { (o.f, [(1, _)]) }
  { } |_| (2, _) :: project(summ, x)
  someOtherFunction1();
}
summ: { (x.f, [(2, _) :: (1, setF)] }
```

```
public void publicMethod(Obj y) {
  callSetF(y); // line 3
  someOtherFunction2();
}
summ: { (y.f, [(3, _) :: (2, callSetF) :: (1, setF)] }
```

Explicit call stack tracking bloats summaries

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { (o.f, [(1, _)]),
         o.g, [(2, _)] }
```

Explicit call stack tracking bloats summaries

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { (o.f, [(1, _)]),
         o.g, [(2, _)] }
```

```
private void callSetF(Obj x) {
  setF(x); // line 2
  someOtherFunction1();
}
summ: { (x.f, [(2, _) :: (1, setF)],
        (x.g, [(2, _) :: (2, setF)}
```

Explicit call stack tracking bloats summaries

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { (o.f, [(1, _)]),
         o.g, [(2, _)] }
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```
private void callSetF(Obj x) {
  setF(x); // line 2
  someOtherFunction1();
}
summ: { (x.f, [(2, _) :: (1, setF)],
        (x.g, [(2, _) :: (2, setF)}
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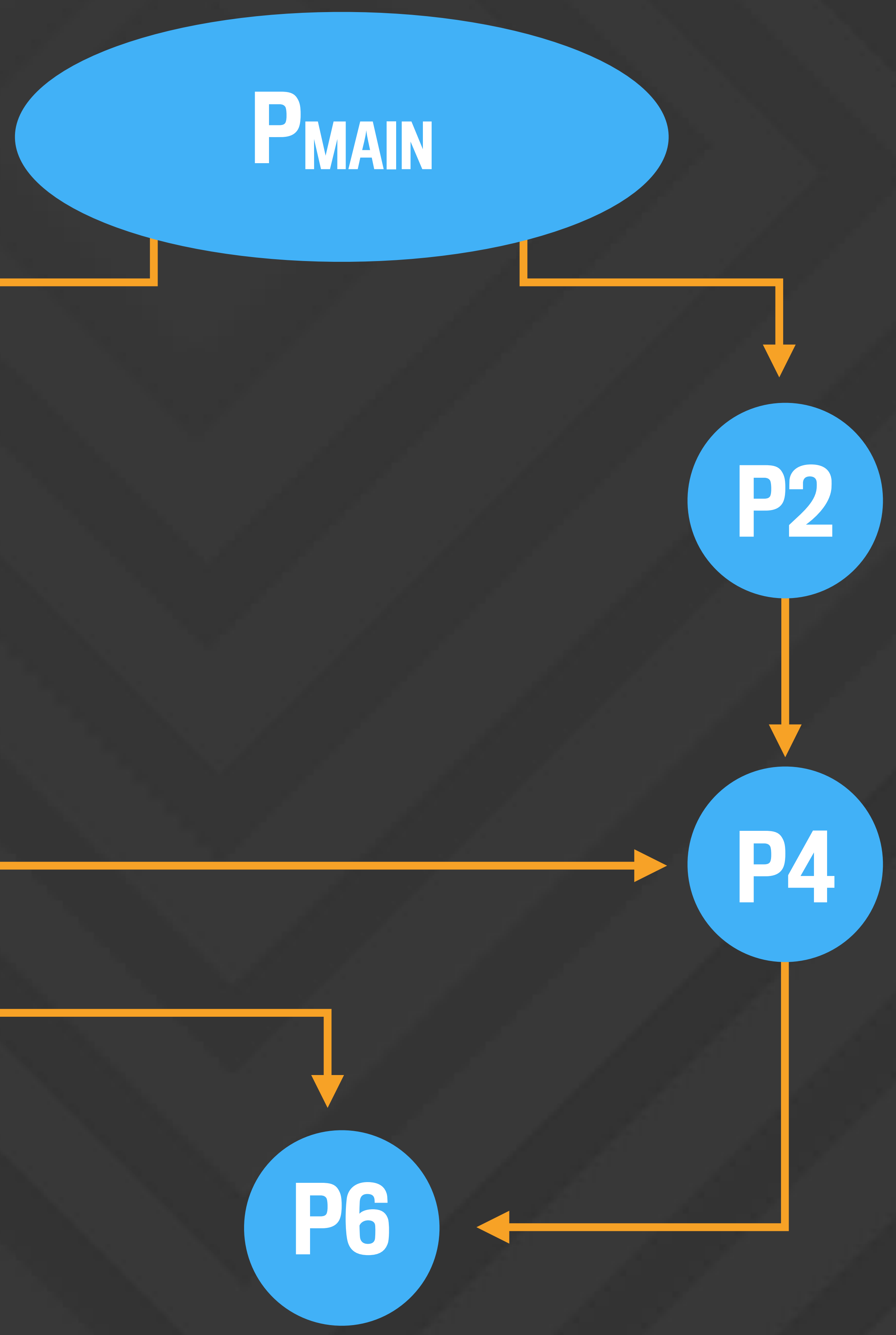
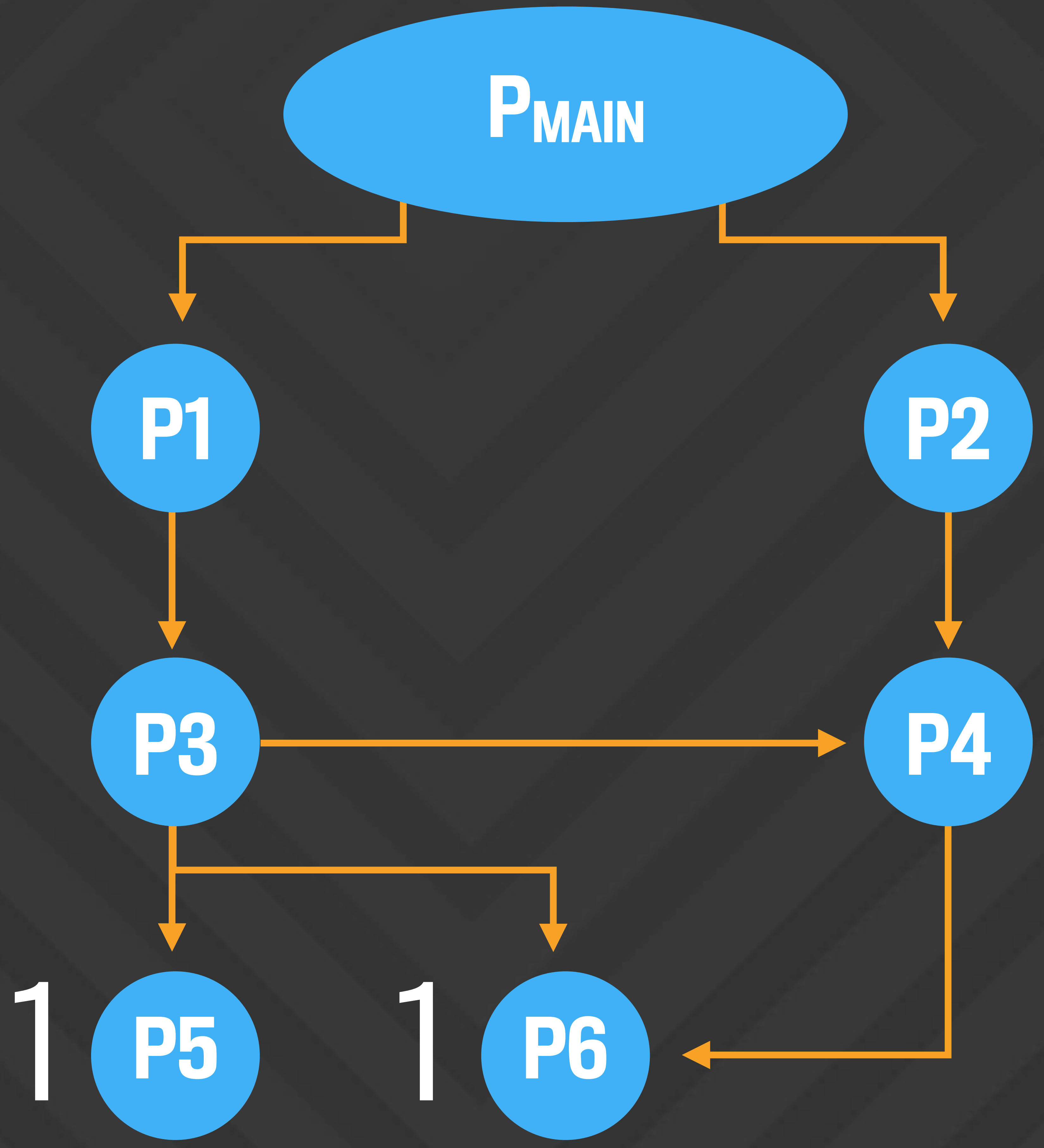
```
public void publicMethod(Obj y) {
  callSetF(y); // line 3
  someOtherFunction2();
}
summ: { (y.f, [(3, _) :: (2, callSetF) :: (1, setF)],
        (y.g, [(3, _) :: (2, callSetF) :: (2, setF)] }
```

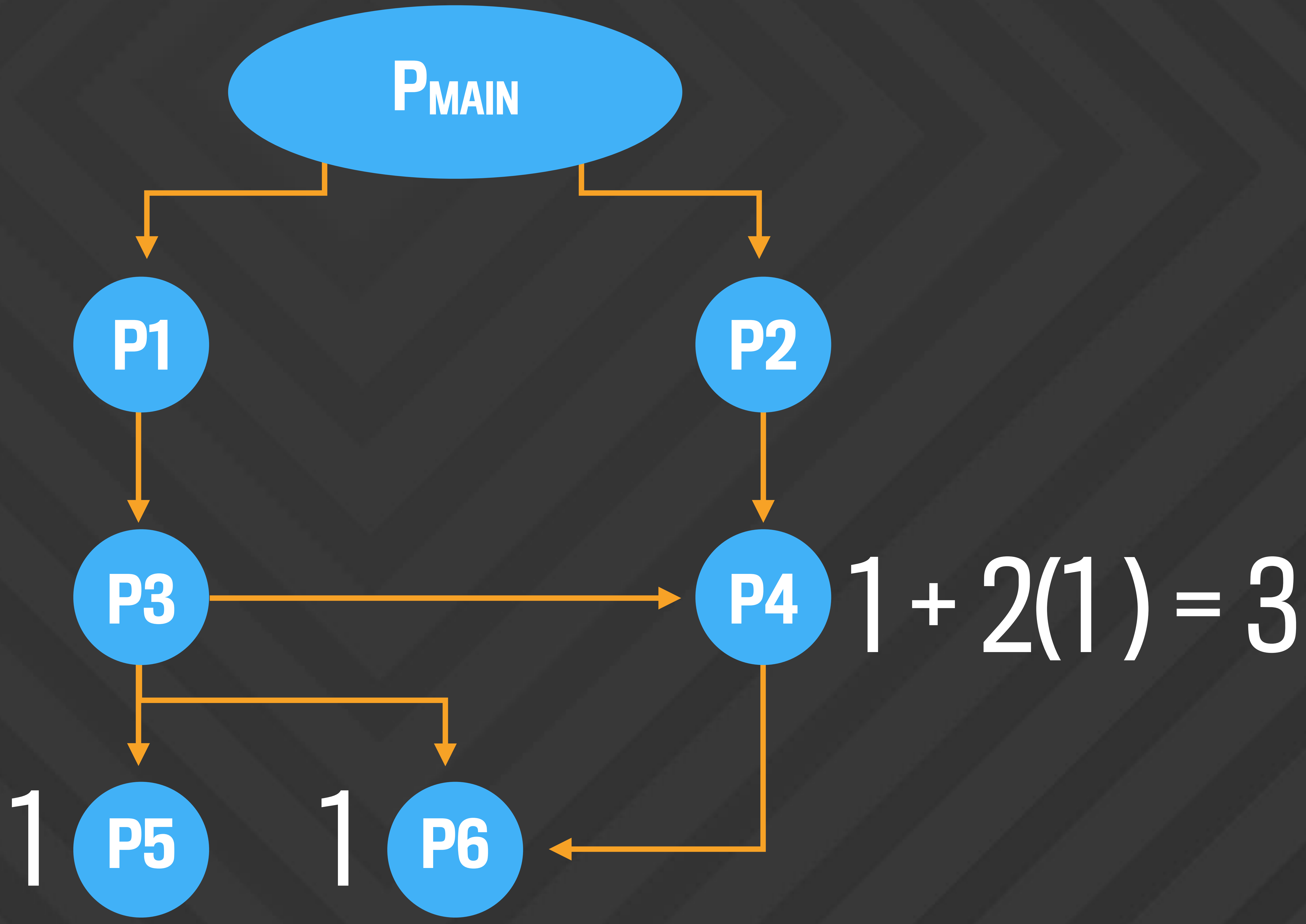
Visualization of summary size explosion



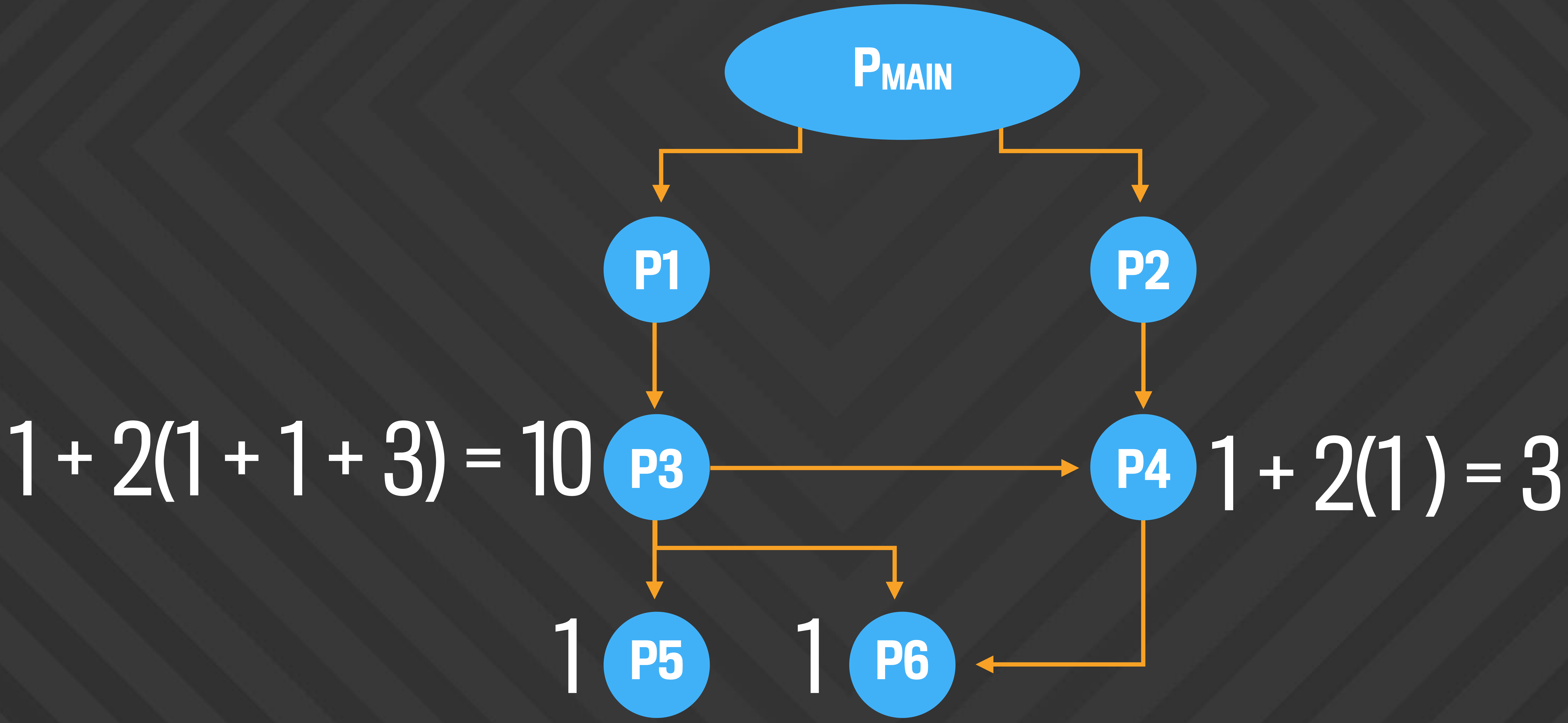
Visualization of summary size explosion



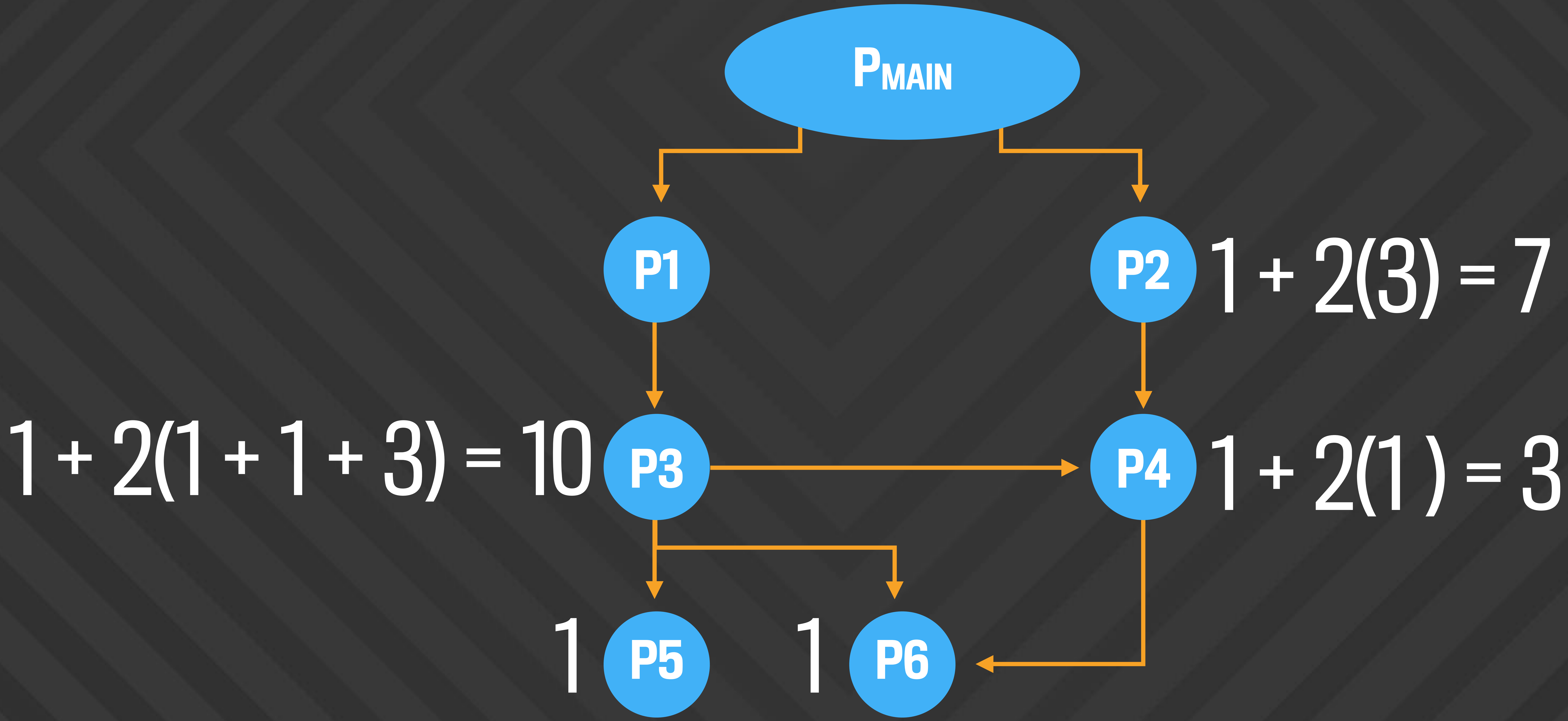
Visualization of summary size explosion



Visualization of summary size explosion



Visualization of summary size explosion



P_{MAIN}

P1

P2 $1 + 2(3) = 7$

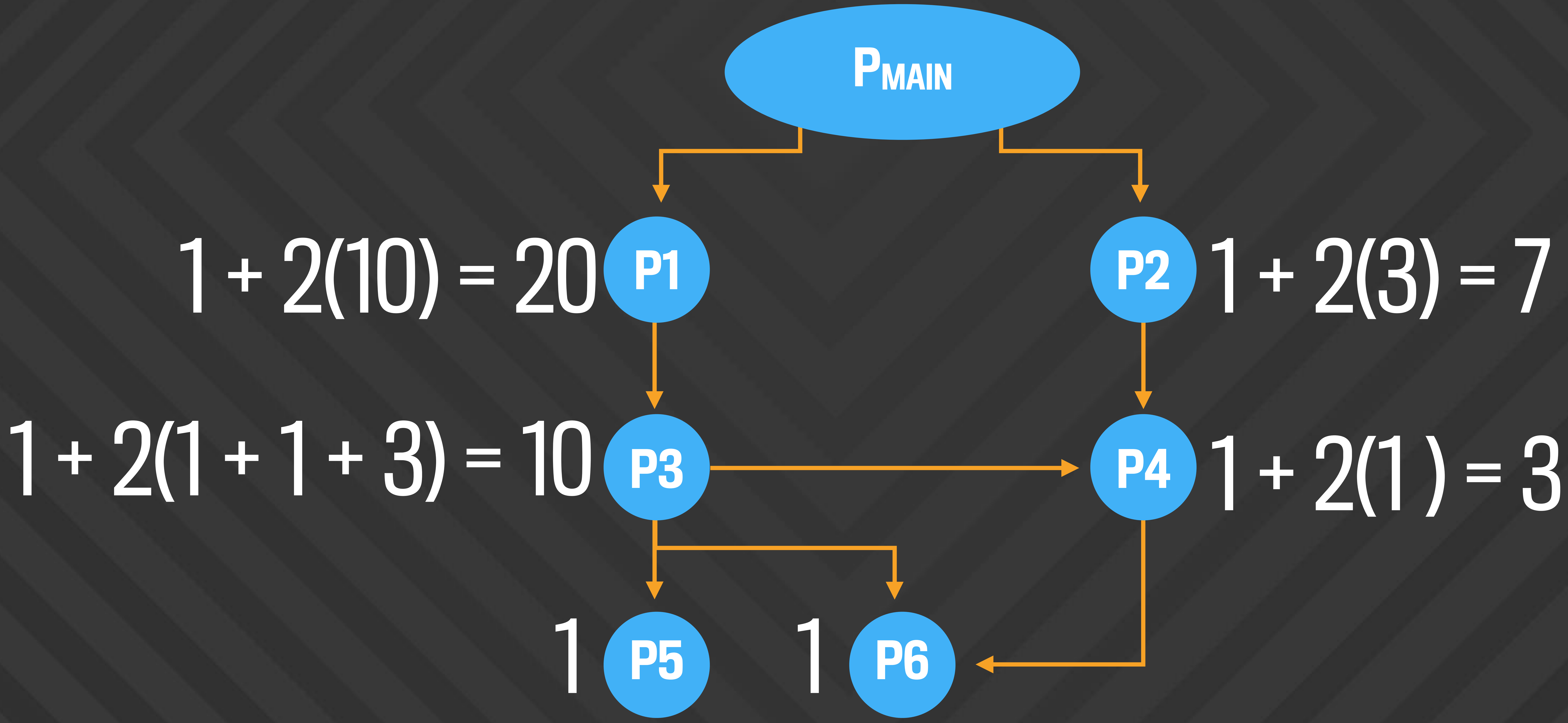
$1 + 2(1 + 1 + 3) = 10$ P3

P4 $1 + 2(1) = 3$

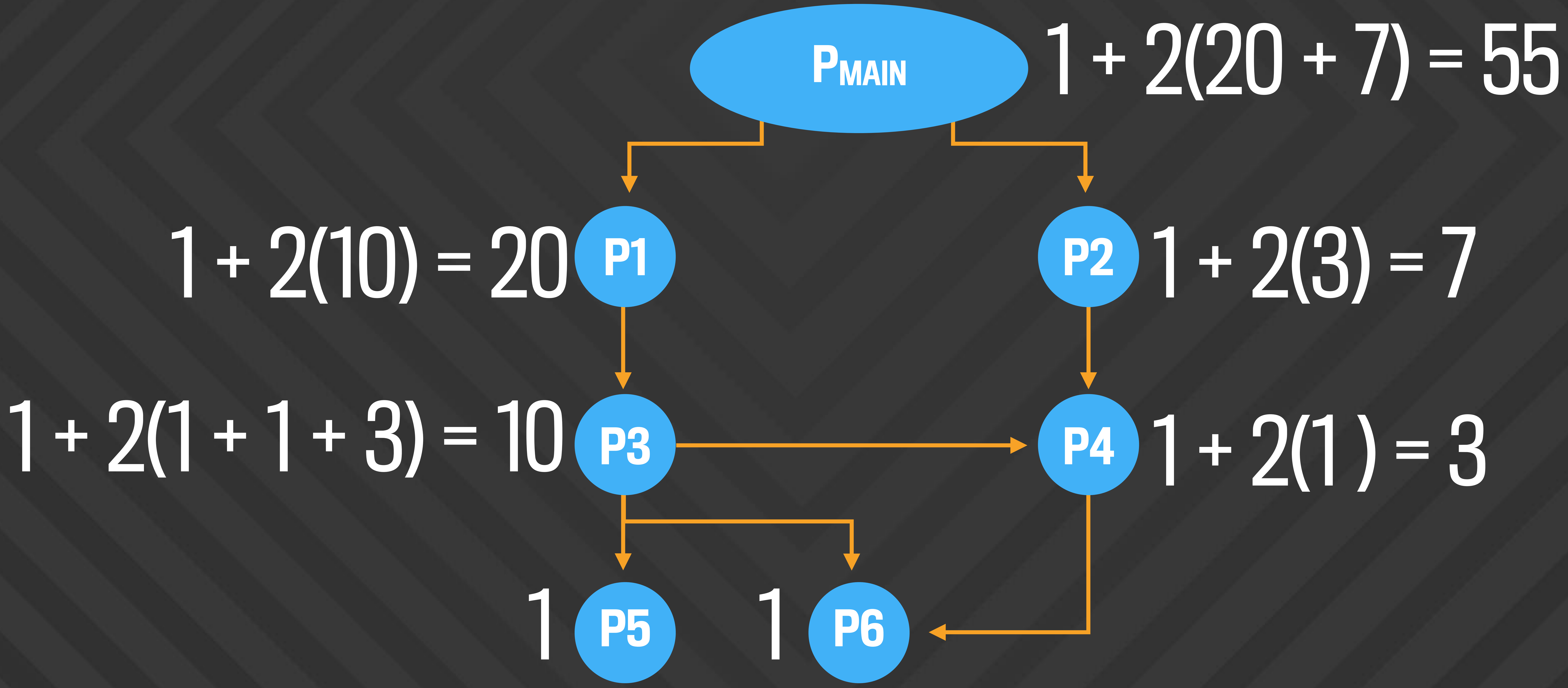
1 P5

1 P6

Visualization of summary size explosion



Visualization of summary size explosion



Solution: track **last** call that leads to access OOS

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { o.f, (1, _),
        o.g, (2, _) }
```

Solution: track **last** call that leads to access OOS

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { o.f, (1, _),
        o.g, (2, _) }
```

```
private void callSetF(Obj o) {
  setF(o); // line 2
  someOtherFunction1();
}
summ: { (o.f, (2, setF),
        (o.g, (2, setF)}
```

Solution: track **last** call that leads to access OOS

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { o.f, (1, _),
        o.g, (2, _) }
```

```
private void callSetF(Obj o) {
  setF(o); // line 2
  someOtherFunction1();
}
summ: { (o.f, (2, setF),
        (o.g, (2, setF)}
```

```
public void publicMethod(Obj o) {
  callSetF(o); // line 3
  someOtherFunction2();
}
summ: { (o.f, (3, callSetF),
        (o.g, (3, callSetF) }
```

Solution: track **last** call that leads to access OOS

```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { o.f, (1, _),
        o.g, (2, _) }
```

```
private void callSetF(Obj o) {
  setF(o); // line 2
  someOtherFunction1();
}
summ: { (o.f, (2, setF),
        (o.g, (2, setF)}
```

```
public void publicMethod(Obj o) {
  callSetF(o); // line 3
  someOtherFunction2();
}
summ: { (o.f, (3, callSetF),
        (o.g, (3, callSetF) }
```

Solution: track **last** call that leads to access OOS

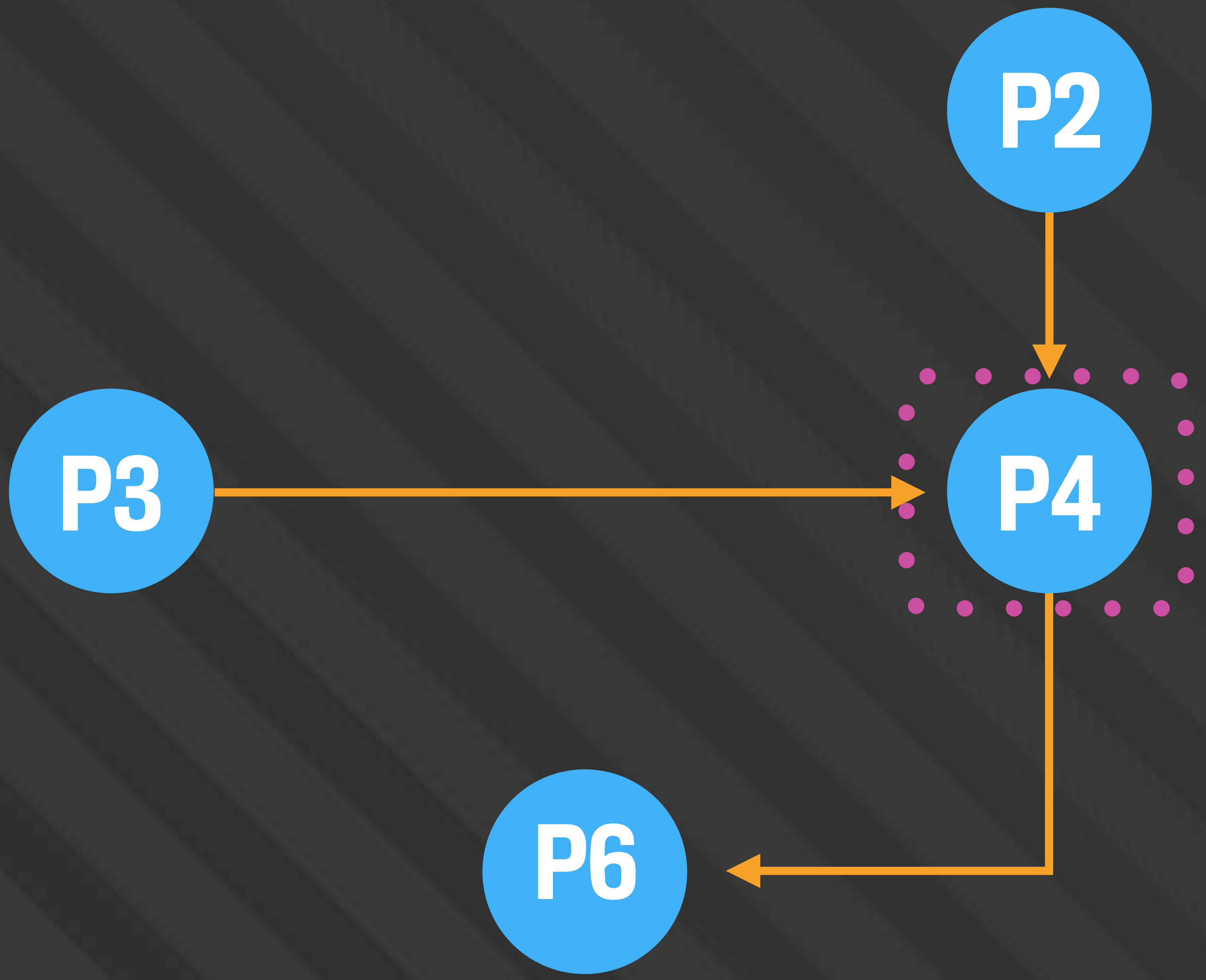
```
private void setF(Obj o) {
  o.f = ... // line 1
  o.g = ...
}
summ: { o.f, (1, _),
        o.g, (2, _) }
```

```
private void callSetF(Obj o) {
  setF(o); // line 2
  someOtherFunction1();
}
summ: { (o.f, (2, setF),
        (o.g, (2, setF)}
```

```
public void publicMethod(Obj o) {
  callSetF(o); // line 3
  someOtherFunction2();
}
summ: { (o.f, (3, callSetF),
        (o.g, (3, callSetF) }
```

Recover call stack by unrolling summaries when reporting

Compositionality and modularity challenges



1. How do we combine the callee summary with the current state? (compositionality)
2. How do we represent state from the caller during analysis? (modularity)

Mutating owned objects leads to false positives

```
Obj local = new Obj();
local.f = ... // safe write
global.g = ... // unsafe write
```

Mutating owned objects leads to false positives

```
Obj local = new Obj();
local.f = ... // safe write
global.g = ... // unsafe write
```

```
Obj objFactory() {
  return new Obj();
}

Obj local = objFactory();
local.f = ... // safe write
```

Mutating owned objects leads to false positives

```
Obj local = new Obj();
local.f = ... // safe write
global.g = ... // unsafe write
```

False positives

```
Obj objFactory() {
  return new Obj();
}

Obj local = objFactory();
local.f = ... // safe write
```

Mutating owned objects leads to false positives

```
Obj local = new Obj();
local.f = ... // safe write
global.g = ... // unsafe write
```

Local ownership

False positives

```
Obj objFactory() {
  return new Obj();
}

Obj local = objFactory();
local.f = ... // safe write
```

Returning ownership

Ownership can be conditional

```
private void writeF(Obj a) {
  a.f = ...
}

Obj o = new Obj();
writeF(o); // safe
```

Ownership can be conditional

```
private void writeF(Obj a) {
  a.f = ...
}

Obj o = new Obj();
writeF(o); // safe
```

```
Builder setX(X x) {
  this.x = x;
  return this;
}


new Builder().setX(x).setY(y); // safe
global.set(X).f = 7; // not safe
```

Ownership can be conditional

```
private void writeF(Obj a) {
  a.f = ...
}

Obj o = new Obj();
writeF(o); // safe
```

False positives

```
Builder setX(X x) {
  this.x = x;
  return this;
}


new Builder().setX(x).setY(y); // safe
global.set(X).f = 7; // not safe
```

Ownership can be conditional

```
private void writeF(Obj a) {
  a.f = ...
}

Obj o = new Obj();
writeF(o); // safe
```

Safe if formal is owned by caller

False positives

```
Builder setX(X x) {
  this.x = x;
  return this;
}


new Builder().setX(x).setY(y); // safe
global.set(X).f = 7; // not safe
```

Returns ownership if formal is owned by caller

Track owned locals + owned return value

```
Obj local = new Obj();
owned(local), {}
local.f = ... // safe write
global.g = ... // unsafe write
owned(local), { (g, 3) }
```

Track owned locals + owned return value

```
Obj local = new Obj();
owned(local), {}
local.f = ... // safe write
global.g = ... // unsafe write
owned(local), { (g, 3) }
```

```
Obj objFactory() {
  return new Obj();
}
summ: owned(ret)

Obj local = objFactory();
owned(local)
local.f = ... // safe write
```

Need to track ownership in summaries

```
private void writeF(Obj a) {
  a.f = ...
}
summ: { (a.f, 1) if ¬owned(a) }

Obj o = new Obj();
owned(o)
writeF(o);
owned(o) |_| project(summ, o)
owned(o) ^ { (a.f, 1) if ¬owned(o) }
owned(o) ^ {}
```

Need to track ownership in summaries

```
Builder setX(X x) {
  this.x = x;
  return this;
}
summ: { (this.x if ¬owned(this) } ^
        owned(ret) if owned(this)
owned(a)
Builder b = a.setX(x);
owned(a) ^ project(summ, b, a, x)
owned(a) ^ owned(b) if owned(a)
         ^ { (this.x if ¬owned(a) }
             owned(b) if owned(a)
owned(a) ^ owned(b) ^ {}
b.setY(y); // safe by similar reasoning
```

Thread-safety analysis makes conversion faster/safer

- 100+ Litho components moved to background layout with very few crashes
- Analysis enabled for all Litho component diffs
- 300+ thread-safety regressions caught/ fixed on diffs

Minimum viable analysis -> formalism + sound tool

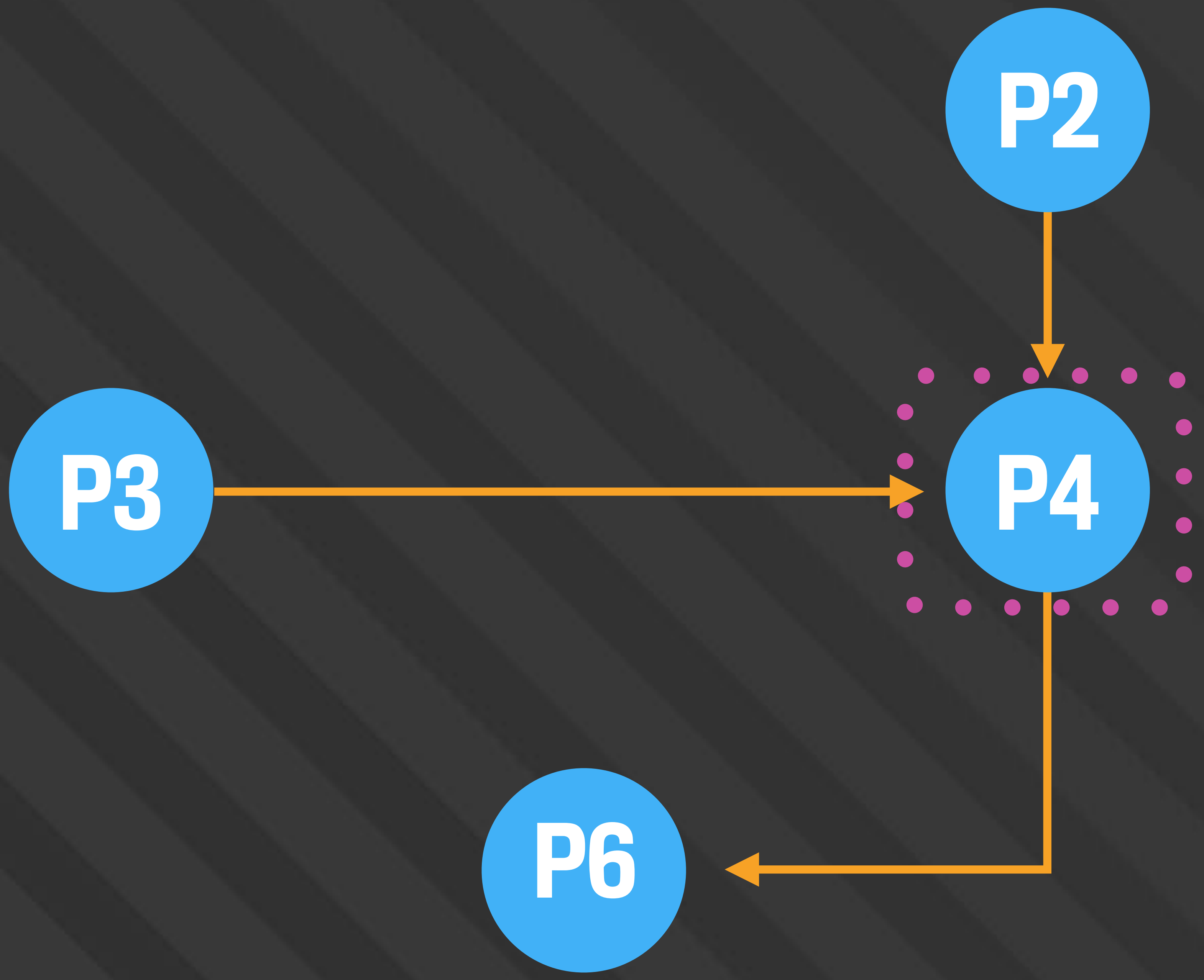
- Boolean lock abstraction -> infer permissions associated with locks/threads (collaboration with UCL)
- Access paths -> separation logic
- Proof of soundness
- Transfer formalism into tool

Roadmap

- Summaries
- Bottom-up modular/compositional analysis
- Real-world case study: thread-safety analysis
- **Designing compositional domains**

3 | Building compositional interprocedural analyzers

Compositionality and modularity challenges



1. How do we represent state from the caller during analysis? (modularity)
2. How do we combine the callee summary with the current state? (compositionality)

Modularity: representing state from the caller

$x, y \in Var$

$e \in Exp ::= x \mid \ldots$

$c \in Cmd ::= e_1 = e_2 \mid y = \texttt{call}\ p(\vec{x})$

Modularity: representing state from the caller

$x, y \in Var$

$e \in Exp ::= x \mid \ldots$

$c \in Cmd ::= e_1 = e_2 \mid y = \texttt{call}\ p(\vec{x})$

$\hat{Val} ::= \hat{x} \mid FP(x)$

Add ghost variable for "footprint" value read from environment

Modularity: representing state from the caller

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

Add ghost variable for "footprint" value read from environment

$$\frac{y \notin dom(\hat{\sigma}) \qquad \hat{\sigma}' = update(x, \hat{\sigma}, FP(y))}{\{\hat{\sigma}\} \quad x = y \quad \{\hat{\sigma}'\}}$$

Modularity: representing state from the caller

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

Add ghost variable for "footprint" value
read from environment

When we read a variable that isn't
defined, introduce ghost variable

$$\frac{y \notin dom(\hat{\sigma}) \quad \boxed{\hat{\sigma}' = update(x, \hat{\sigma}, FP(y))}}{\{\hat{\sigma}\} \quad x = y \quad \{\hat{\sigma}'\}}$$

Modularity: representing state from the caller

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

Add ghost variable for "footprint" value read from environment

When we read a variable that isn't defined, introduce ghost variable

$$\frac{y \notin dom(\hat{\sigma}) \quad \boxed{\hat{\sigma}' = update(x, \hat{\sigma}, FP(y))}}{\{\hat{\sigma}\} \quad x = y \quad \{\hat{\sigma}'\}}$$

Easiest implementation: $\hat{\sigma}[\hat{x} \mapsto FP(y)]$

Modularity: representing state from the caller

- Summaries are parameterized by footprint values
- Generic: fully context-insensitive, but each caller can fill in context when applying the summary

Modularity: representing state from the caller

- Summaries are parameterized by footprint values
- Generic: fully context-insensitive, but each caller can fill in context when applying the summary

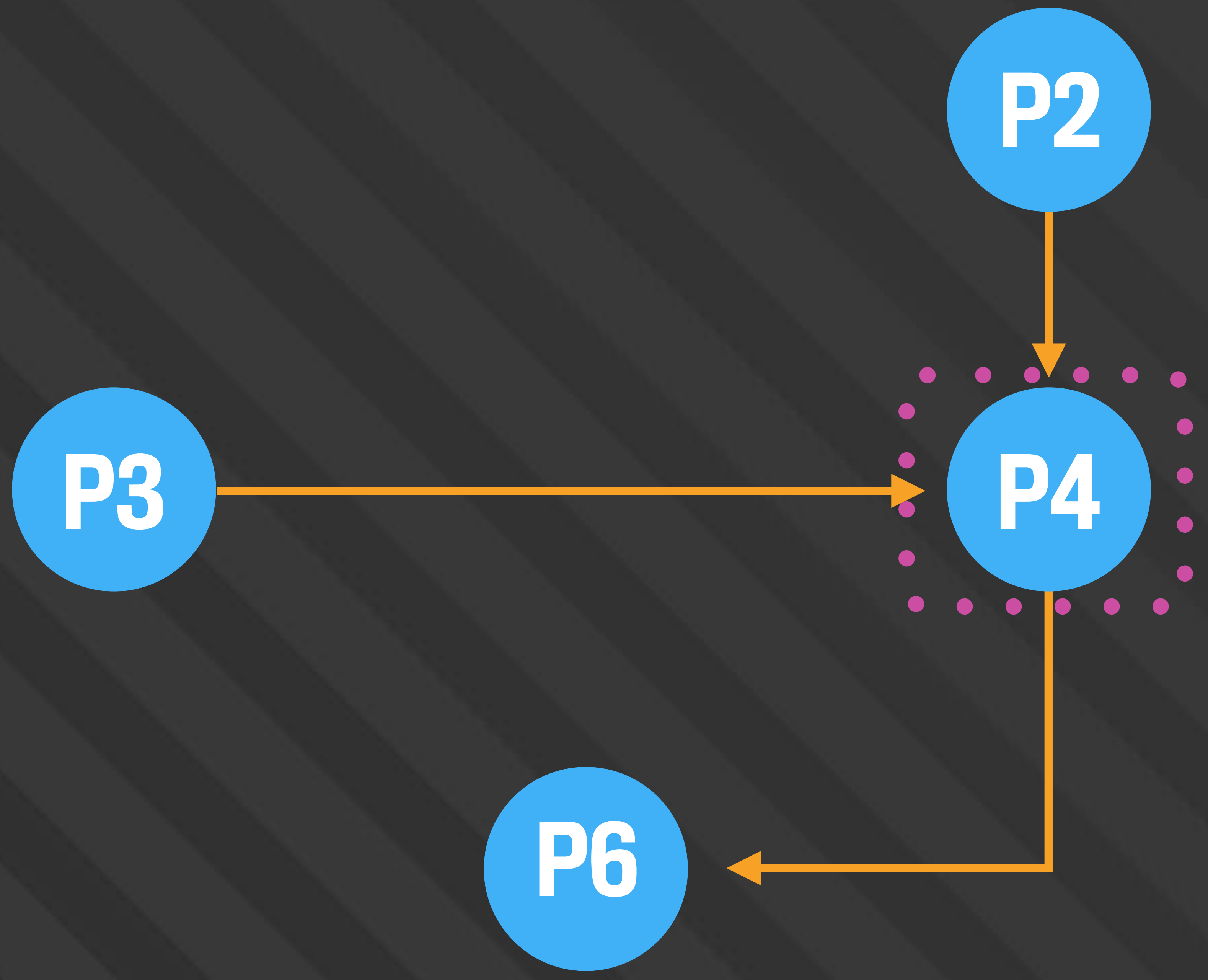
```
private void writeF(Obj a) {
  a.f = ...
}
summ: { (a.f, 1) if ¬owned(a) } =~
λ a. if owned(a) {} else { (a.f, 1) }
```

Modularity: representing state from the caller

$$\frac{y \notin dom(\hat{\sigma}) \quad \hat{\sigma}' = update(x, \hat{\sigma}, FP(y))}{\{\hat{\sigma}\} \quad x = y \quad \{\hat{\sigma}'\}}$$

- Use for formals, globals, field/array reads from env
- Used in bi-abduction analysis [Compositional shape analysis by means of bi-abduction, Calcagno et al. JACM '11]
- Useful in subsequent Infer analyses: thread-safety, Quandary taint analysis, ...

Compositionality and modularity challenges



1. How do we represent state from the caller during analysis? (modularity)
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Compositionality: combining callee state with current state

$\hat{\sigma}_p$: summary for procedure p

$$\frac{\hat{\sigma}'_p = project(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) \qquad \hat{\sigma}' = \hat{\sigma} \oplus \hat{\sigma}'_p}{\{\hat{\sigma}\} \quad y = \texttt{call } p(\vec{x}) \quad \{\hat{\sigma}'\}}$$

Compositionality: combining callee state with current state

$\hat{\sigma}_p$: summary for procedure p

Replace footprint variables in summary with actuals
Bind return value from summary to return variable

$$\frac{\hat{\sigma}'_p = \boxed{project(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p)} \qquad \hat{\sigma}' = \hat{\sigma} \oplus \hat{\sigma}'_p}{\{\hat{\sigma}\} \quad y = \texttt{call}\ p(\vec{x}) \quad \{\hat{\sigma}'\}}$$

Compositionality: combining callee state with current state

$$\frac{\hat{\sigma}'_p = project(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) \qquad \boxed{\hat{\sigma}' = \hat{\sigma} \oplus \hat{\sigma}'_p}}{\{\hat{\sigma}\} \quad y = \texttt{call}\ p(\vec{x}) \quad \{\hat{\sigma}'\}}$$

Compositionality: combining callee state with current state

- Join for weak updates
- Append for traces
- Domain-specific operator for strong updates...

$$\frac{\hat{\sigma}'_p = project(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) \quad \boxed{\hat{\sigma}' = \hat{\sigma} \oplus \hat{\sigma}'_p}}{\{\hat{\sigma}\} \quad y = \texttt{call}\ p(\vec{x}) \quad \{\hat{\sigma}'\}}$$

Example: interprocedural allocation counting

$$\hat{\sigma} \in Nat \cup \{\top\}$$

Overapproximate number of allocated heap cells

$$\frac{}{\{\hat{\sigma}\}\ \texttt{x = malloc(...)}\ \ \{\hat{\sigma} + 1\}}$$

Example: interprocedural allocation counting

$$\hat{\sigma} \in Nat \cup \{\top\}$$

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$$\hat{\sigma} \in Nat \cup \{\top\}$$

$$\mathrm{project}(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) = \hat{\sigma}_p$$

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$$\hat{\sigma} \in Nat \cup \{\top\}$$

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$$\hat{\sigma} \oplus \hat{\sigma}_p = +^{\top}$$

Example: interprocedural allocation counting

$$\hat{\sigma} \in Nat \cup \{\top\}$$

$$\text{project}(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) = \hat{\sigma}_p$$

$$\hat{\sigma} \bigoplus \hat{\sigma}_p = +^{\top}$$

We don't care about caller state or strong updates w.r.t callee. Easy.

Example: interprocedural escape analysis

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

$$\hat{\sigma} \subseteq 2^{\hat{Val}}$$

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Set of local variables holding addresses that may escape scope of current function

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$$\hat{Val} ::= \hat{x} \mid FP(x)$$

$$\hat{\sigma} \subseteq 2^{\hat{Val}}$$

Set of local variables holding addresses that may escape scope of current function

$$\frac{y \text{ is local}}{\{\hat{\sigma}\}\ \texttt{x.f = y}\ \{\hat{\sigma} \cup \{\hat{y}\}\}} \qquad \frac{y \text{ is formal}}{\{\hat{\sigma}\}\ \texttt{x.f = y}\ \{\hat{\sigma} \cup \{FP(y)\}\}}$$

Example: interprocedural escape analysis

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

$$\hat{\sigma} \subseteq 2^{\hat{Val}}$$

$$\begin{array}{l} \text{project}(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) = \\ \quad \displaystyle\bigcup_{x_i} \begin{array}{l} \{\hat{x}_i\} \text{ if } FP(x_i) \in \hat{\sigma}_p \wedge x_i \text{ is local} \\ \{FP(x_i)\} \text{ if } FP(x_i) \in \hat{\sigma}_p \wedge x_i \text{ is formal} \\ \{\} \text{ otherwise} \end{array} \end{array}$$

Example: interprocedural escape analysis

$$\hat{Val} ::= \hat{x} \mid FP(x)$$

$$\hat{\sigma} \subseteq 2^{\hat{Val}}$$

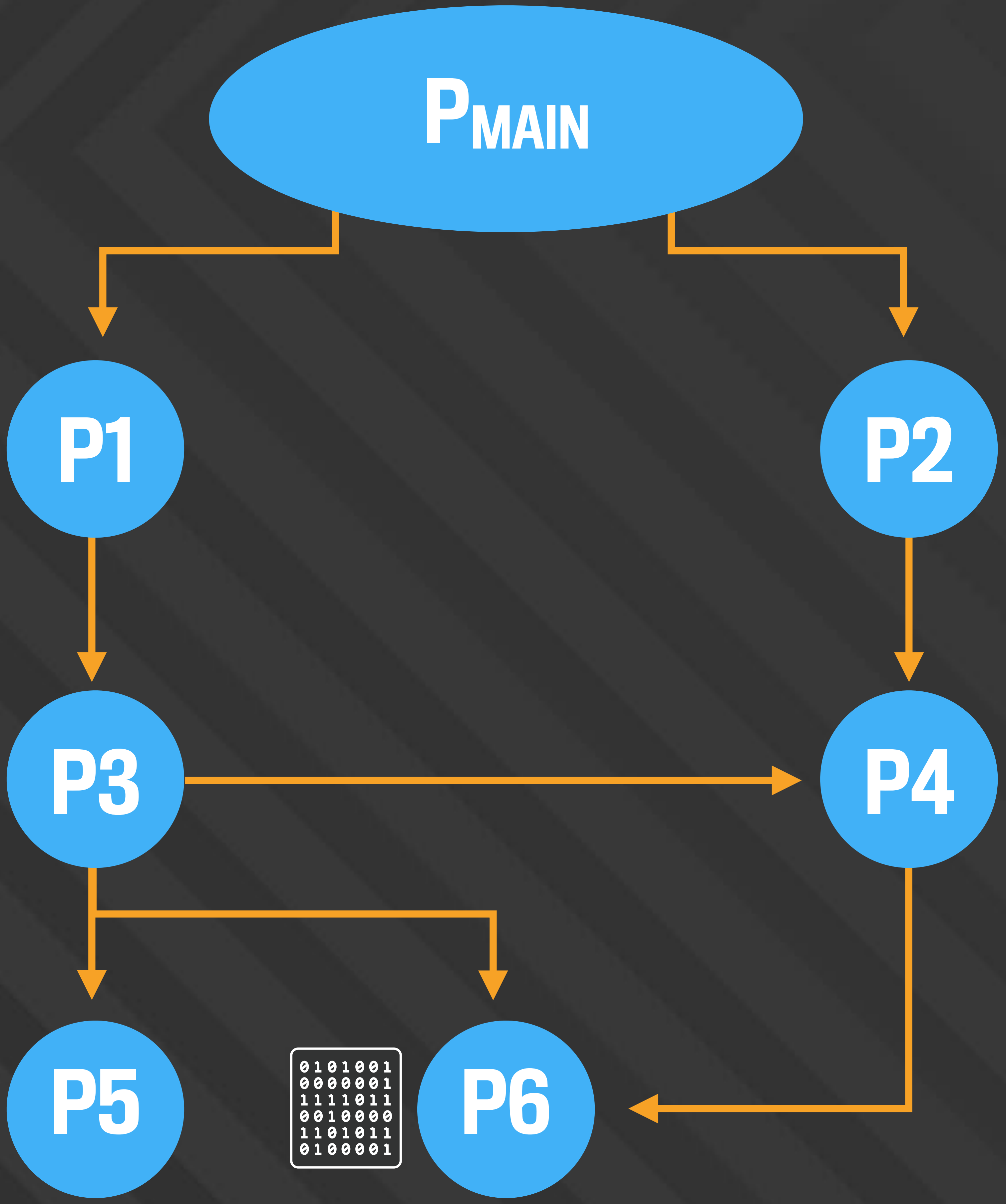
$$\text{project}(\vec{x}, y, \hat{\sigma}, \hat{\sigma}_p) = \bigcup_{x_i} \begin{cases} \{\hat{x}_i\} \text{ if } FP(x_i) \in \hat{\sigma}_p \wedge x_i \text{ is local} \\ \{FP(x_i)\} \text{ if } FP(x_i) \in \hat{\sigma}_p \wedge x_i \text{ is formal} \\ \{\} \text{ otherwise} \end{cases}$$

$$\hat{\sigma} \bigoplus \hat{\sigma}_p = \cup$$

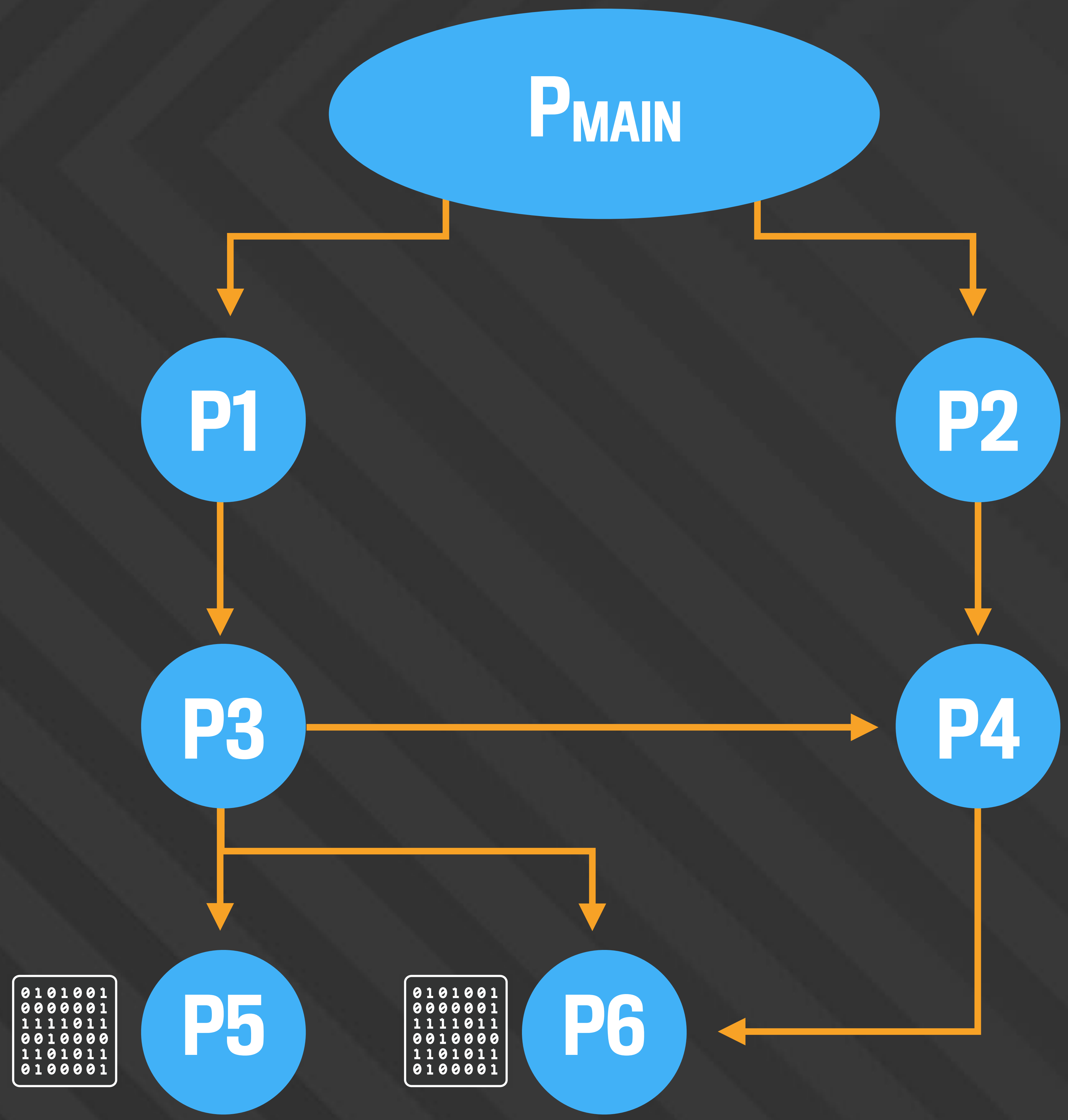
Incrementalizing modular + compositional analyses is easy

- Each summary is a function of its instructions + callee summaries
- Simple change propagation algorithm over call graph works
- Can piggyback on incremental build systems for free distributed cache

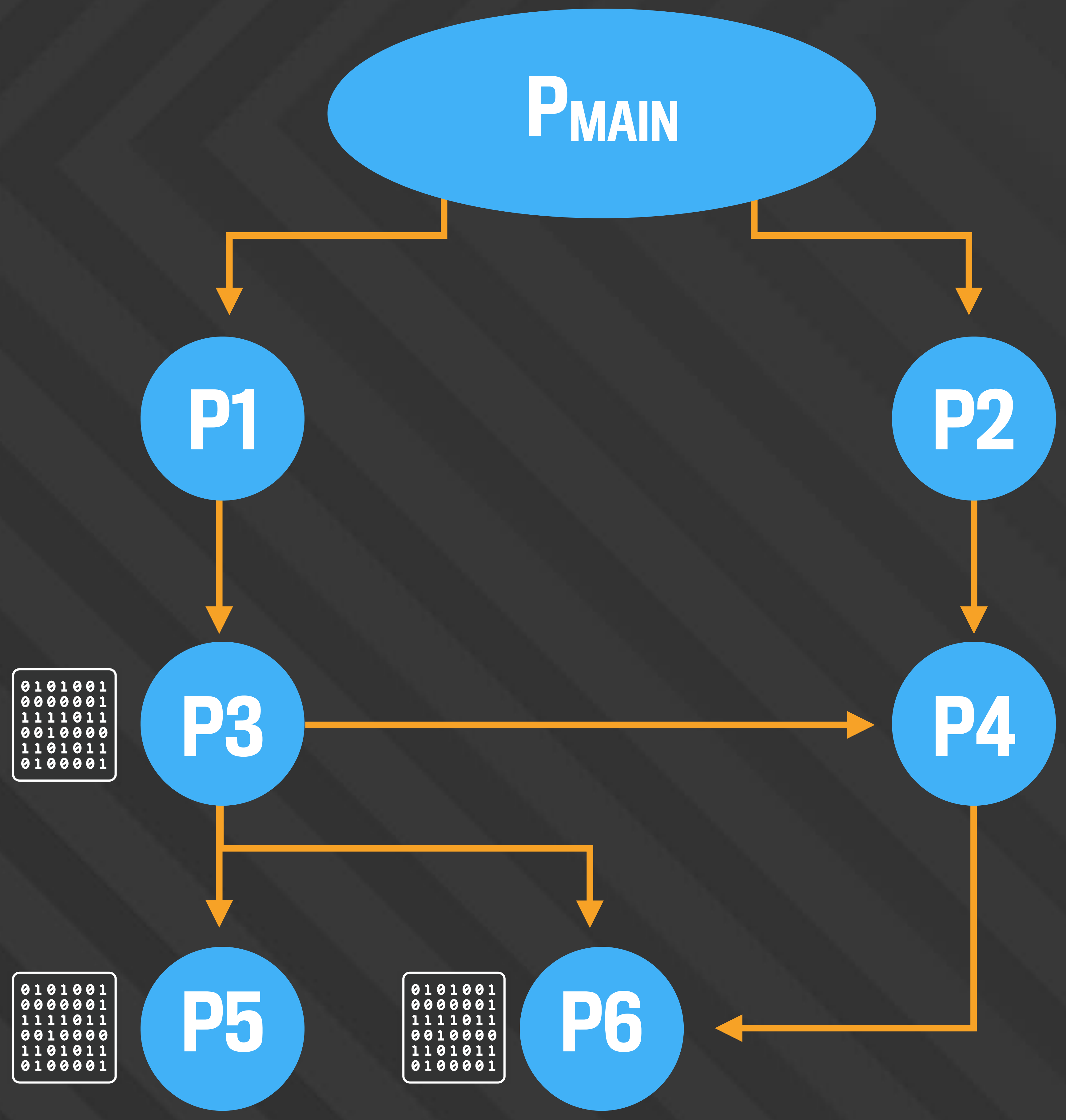
From-scratch analysis



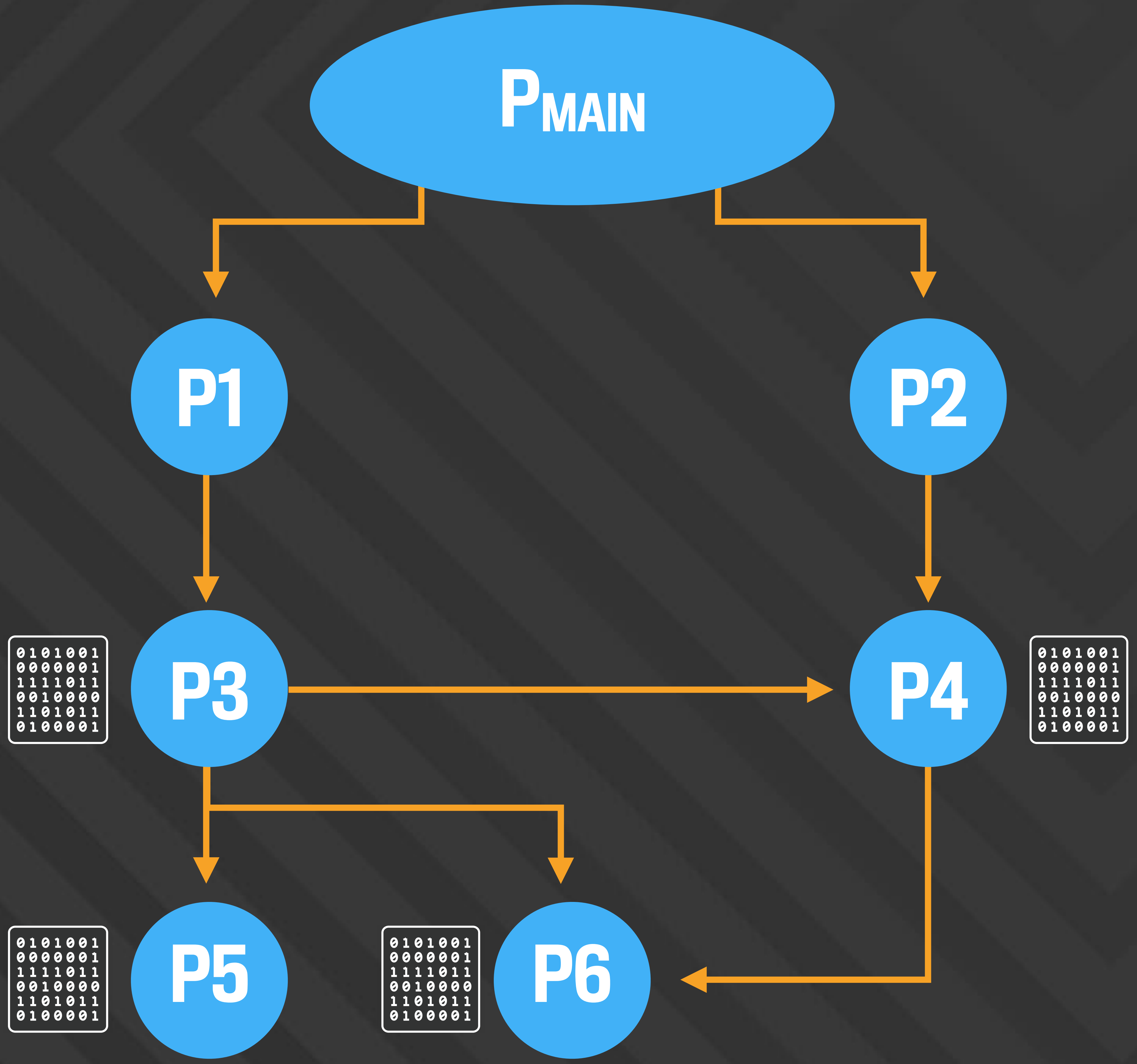
From-scratch analysis



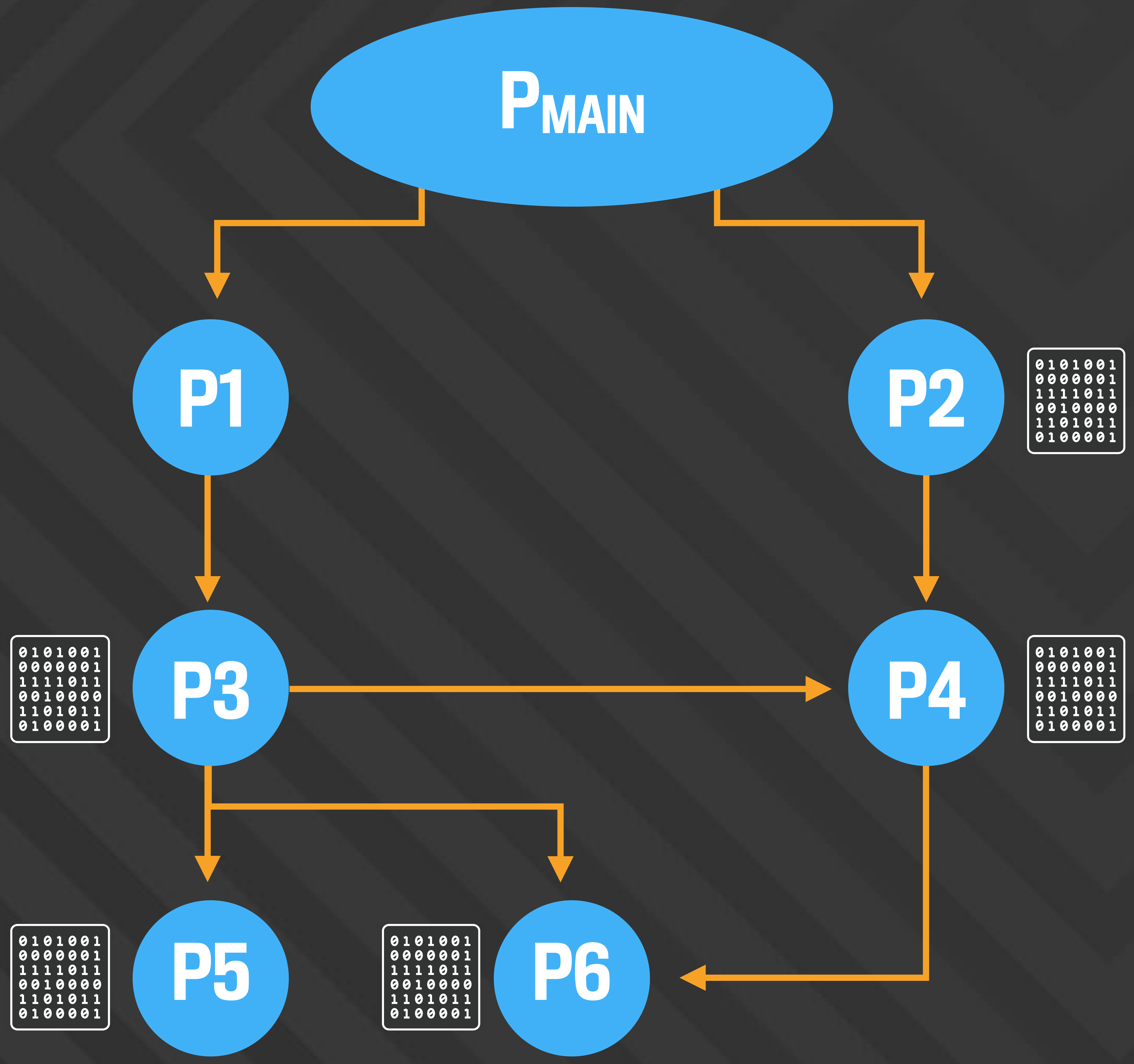
From-scratch analysis



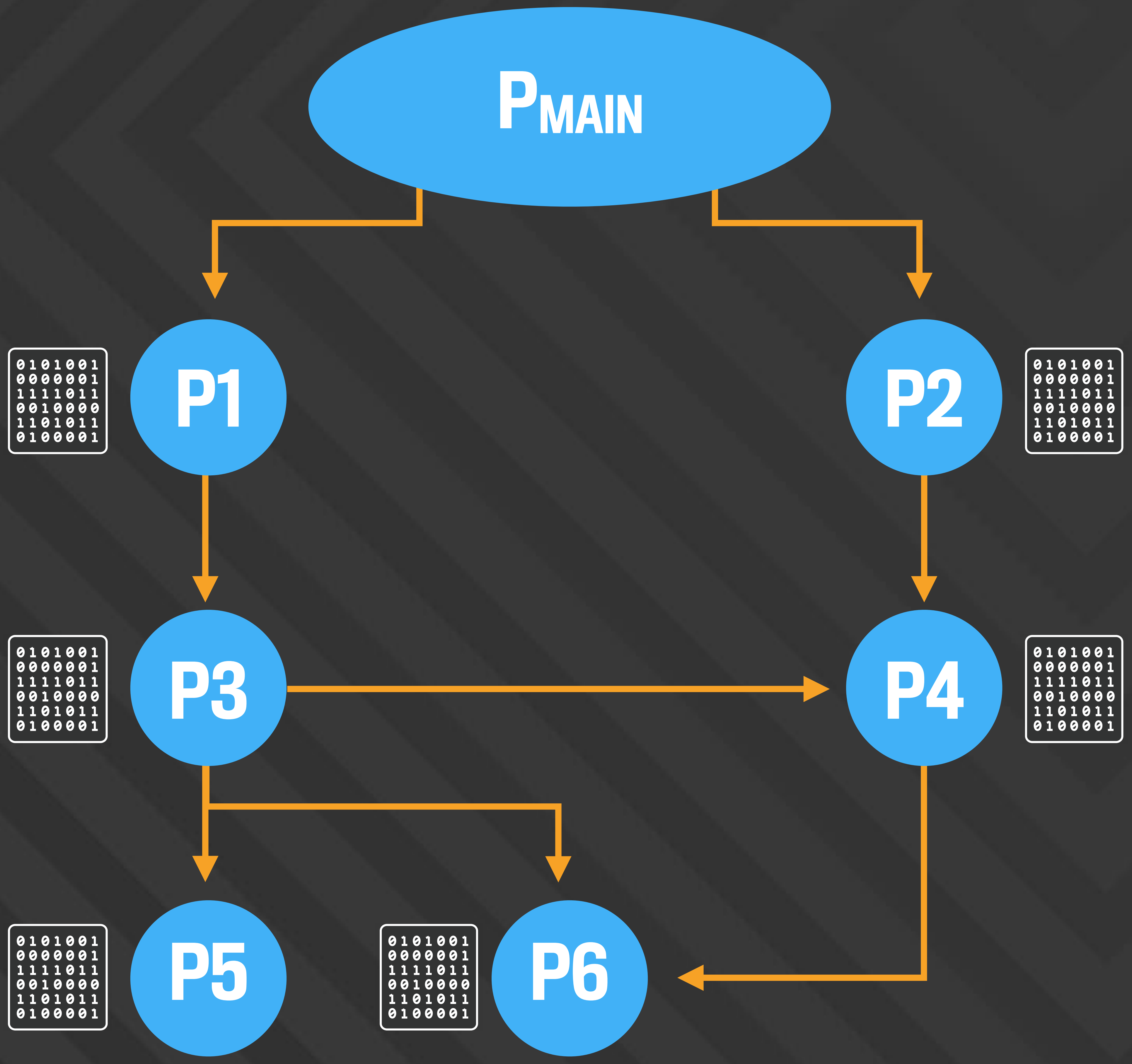
From-scratch analysis



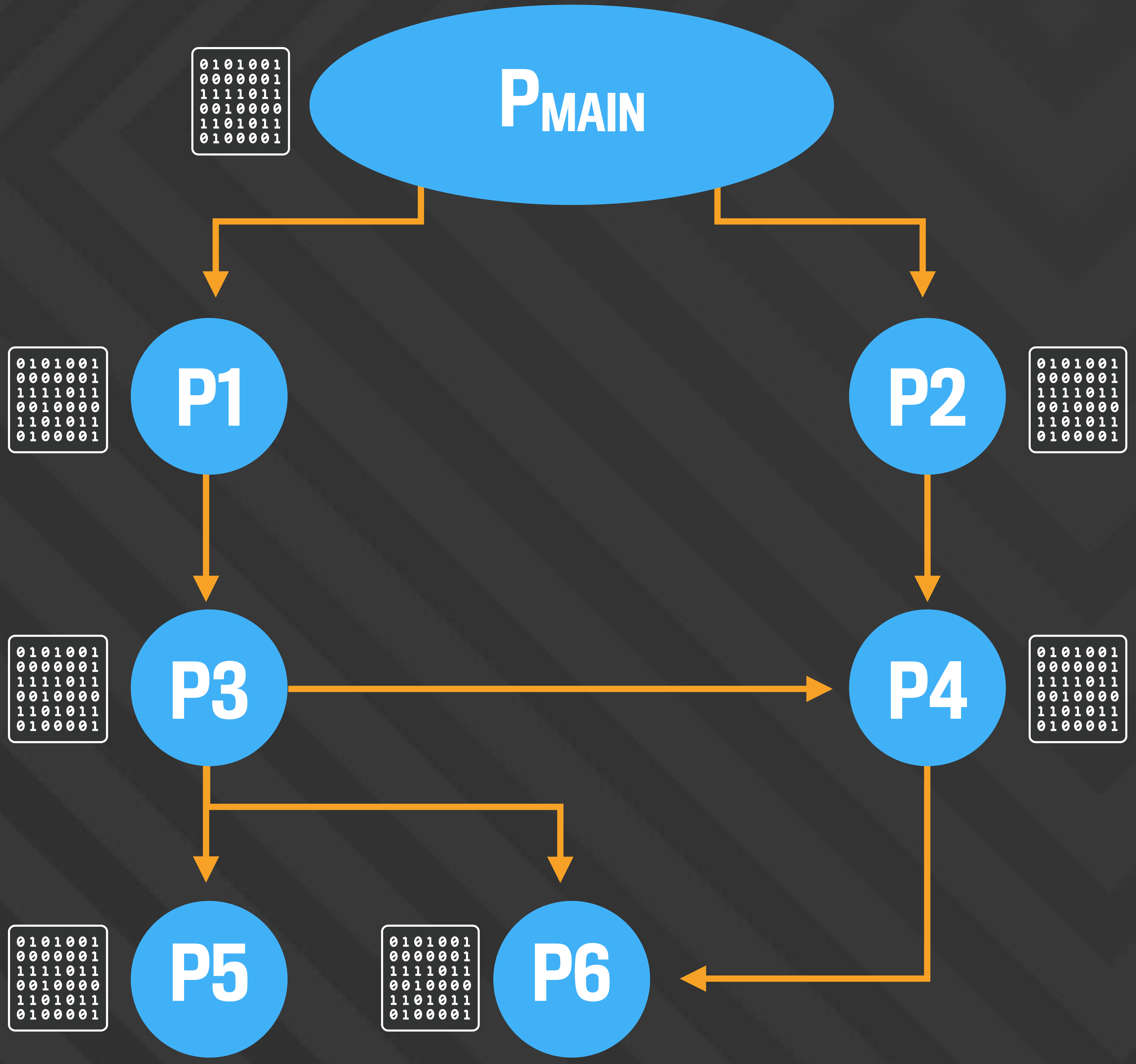
From-scratch analysis



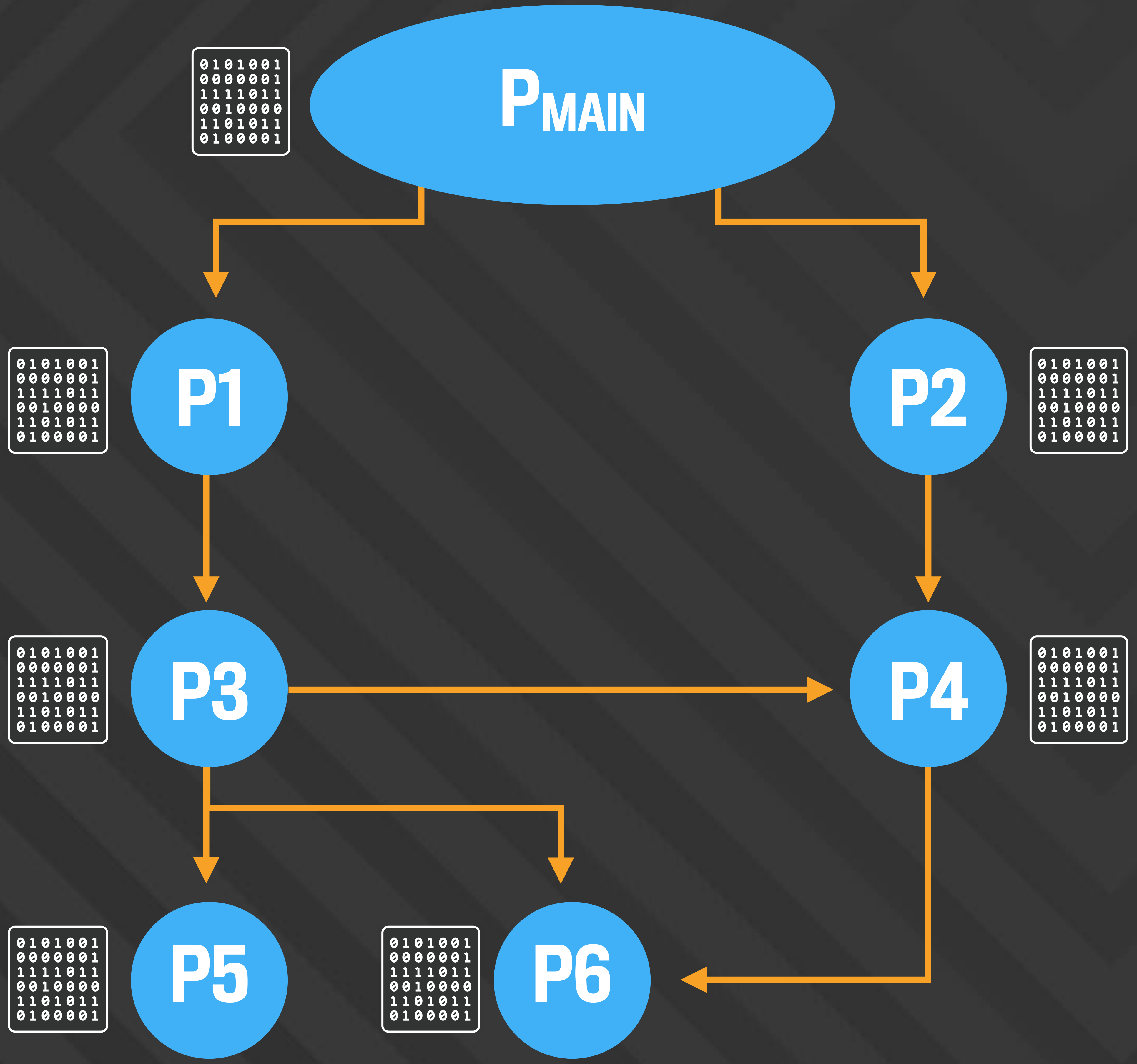
From-scratch analysis



From-scratch analysis



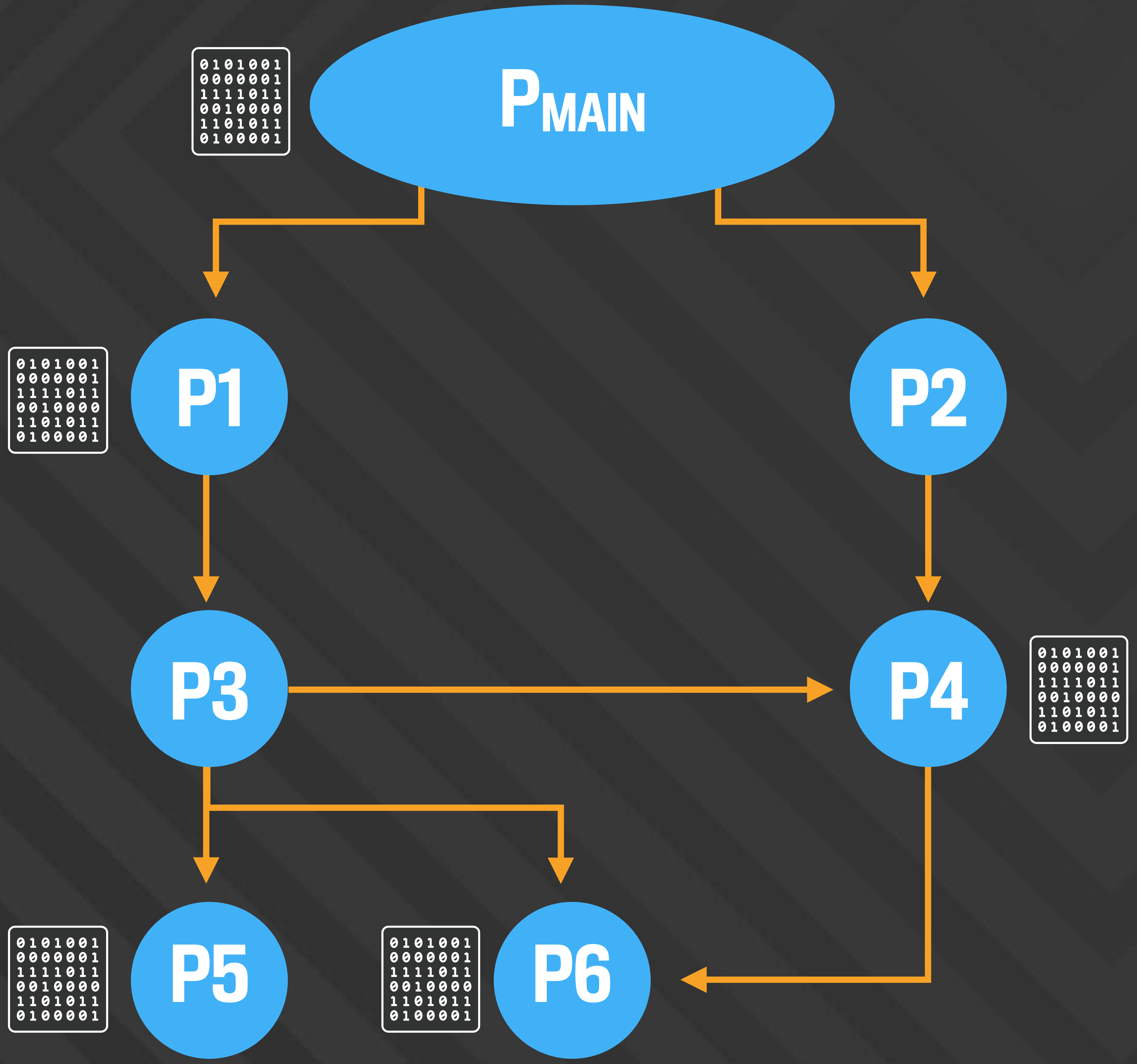
From-scratch analysis



Go bottom-up, compute summary for all procedures.

Report all bugs found.

Incremental analysis: full

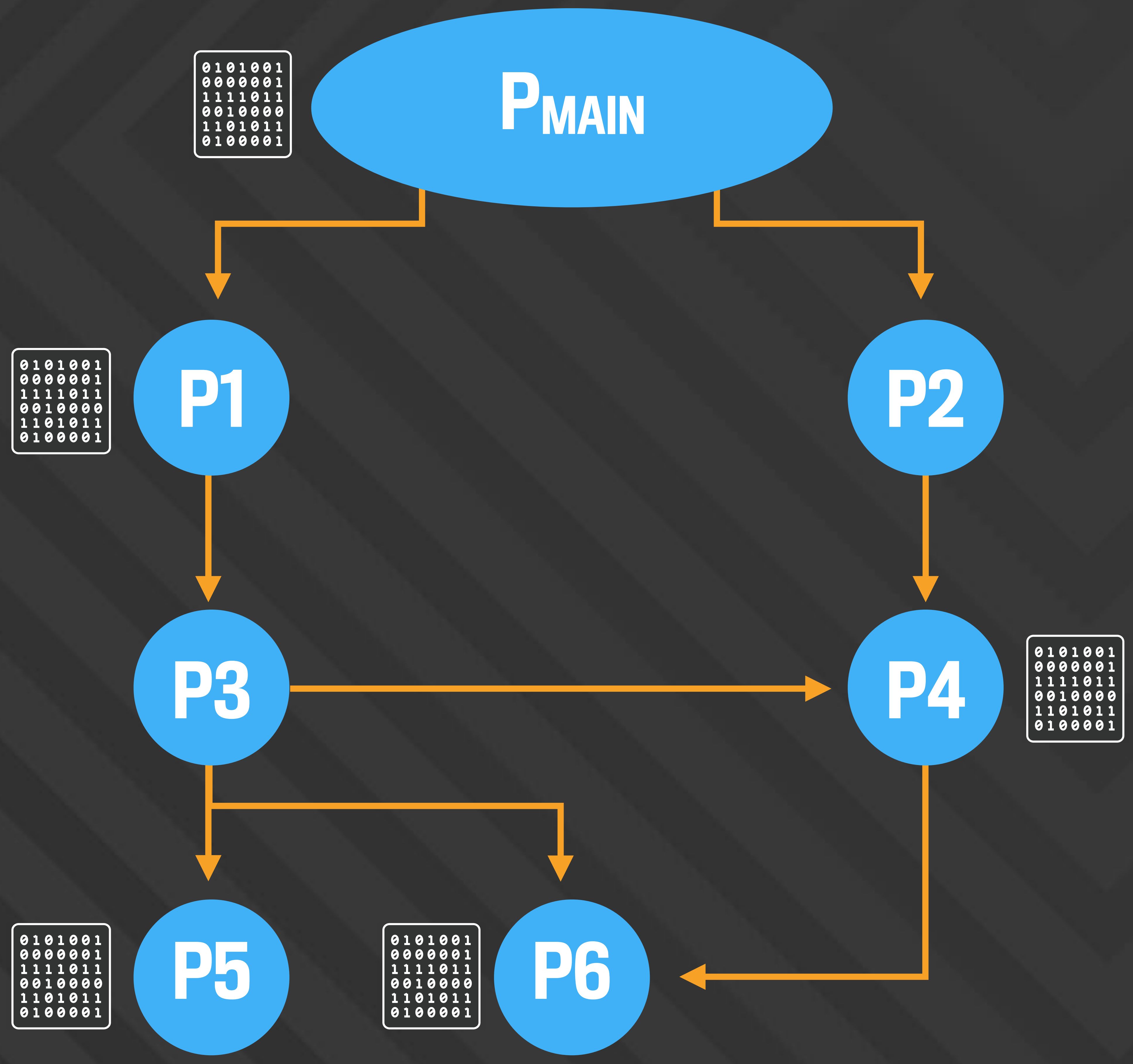


Change P2, P3

If P3 changes, need to re-analyze P1

If P1 or P2 changes, need to re-analyze PMain

Incremental analysis: full



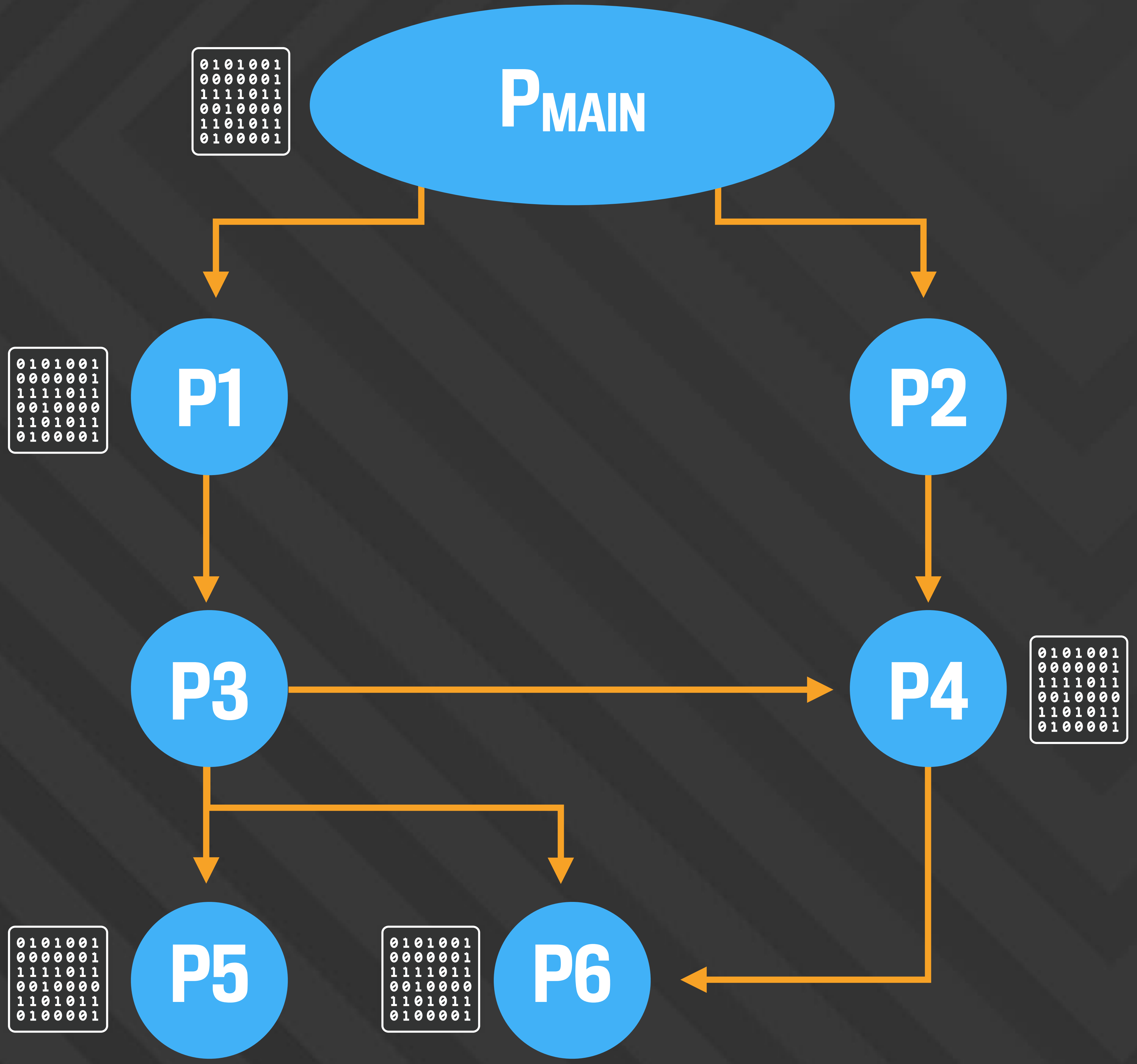
Change P2, P3

Re-analyze P2, P3

If P3 changes, need to re-analyze P1

If P1 or P2 changes, need to re-analyze PMain

Incremental analysis: changed code only



Change P2, P3

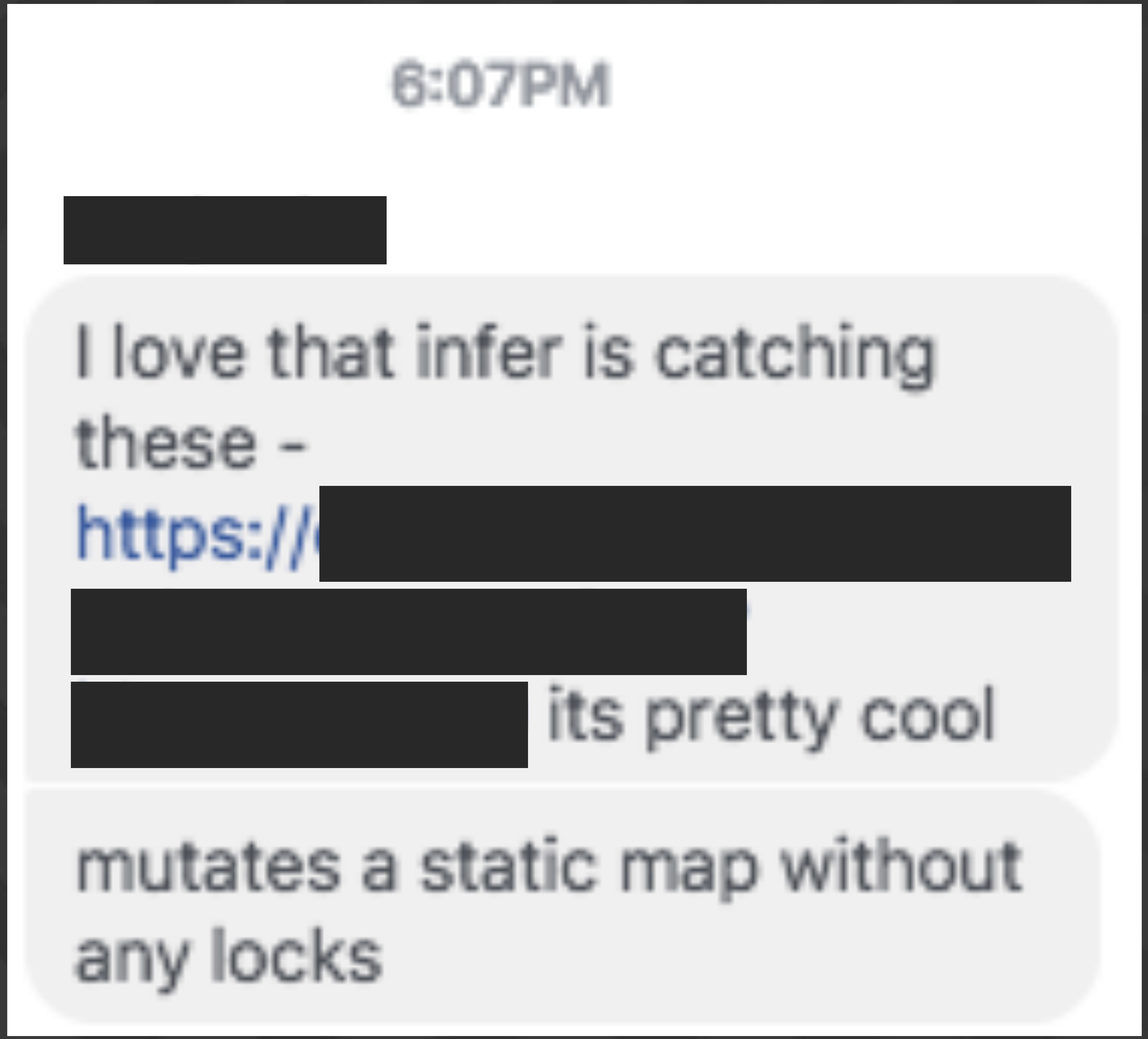
Re-analyze P2, P3

Can stop there if we only care about reporting errors in P2, P3

Why modular + compositional matters

- Scalable: linear in the number of procedures
- Incremental: easy to transition from-scratch analysis -> diff analysis
- Extensible: for new analysis, just need new domain + transfer functions

Conclusion: try out your analysis ideas in Infer



6:07PM

[redacted]

I love that infer is catching these - https://[redacted] its pretty cool

mutates a static map without any locks

- Frontends for Java, C, C++, Obj-C
- Framework for writing modular/compositional interprocedural analyses
- Your analyses can make real programmers happy

fbinfer.com/docs/absint-framework.html

Lab exercise: building your own compositional analyzer

github.com/facebook/infer/infer/src/labs/lab.md