Static Analysis of Dynamically Typed Languages made Easy

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Overview

- Work done as two internships at Google (2009 summer and 2010 summer)

- Motivation:
  - The *Grok* Project: static analysis of all code at Google (C++, Java, JavaScript, Python, Sawzall, Protobuf …)
  - Initial goal was not ambitious:
    - Implement "IDE-like" code-browsing
    - Turns out to be hard for Python

Achieved Goals

- Build high-accuracy semantic indexes
- Detect and report semantic bugs
  - type errors
  - missing return statement
  - unreachable code
  - …

Demo Time

Go

Problems Faced by Static Analysis of Dynamically Typed Languages

1. Problems with Dynamic Typing

- Dynamic typing makes it hard to resolve some names

- Mostly happen in *polymorphic functions*

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A: ... wherever we defined ‘x’

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A: Uhh…

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Solution:

- use a static type system
- use inter-procedural analysis to infer types

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Static Type System for Python

Mostly a usual type system, with two extras: *union* and *dict*

- primitive types
  - int, str, float, bool
- tuple types
  - (int,float), (A, B, C)
- list types
  - [int], [bool], [(int,bool)]
- **dict types**
  - {int => str}, {A => B}
- class types
  - ClassA, ClassB
- **union types**
  - {int | str}, {A | B | C}
- recursive types
  - #1(int, 1), #2(int -> 2)
- function types
  - int -> bool, A -> B

2. Problems with Control-Flow Graph

- CFGs are tricky to build for high-order programs
- Attempts to build CFGs have led to complications and limitations in *control-flow analysis*
  - Shivers 1988, 1991
    - build CFG after CPS
  - Might & Shivers 2006,2007
    - solve problems introduced by CFG
  - Vardoulakis & Shivers 2010,2011
    - solve problems introduced by CPS

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def g(f,x):
   return f(x)

def h1(x):
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def h2(x):
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Solution:

- Don’t CPS the input program
- Don’t try constructing the CFG
- Use direct-style, recursive *abstract interpreter*

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- Classes are not affect by the change

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- import hacks
- eval
- ...

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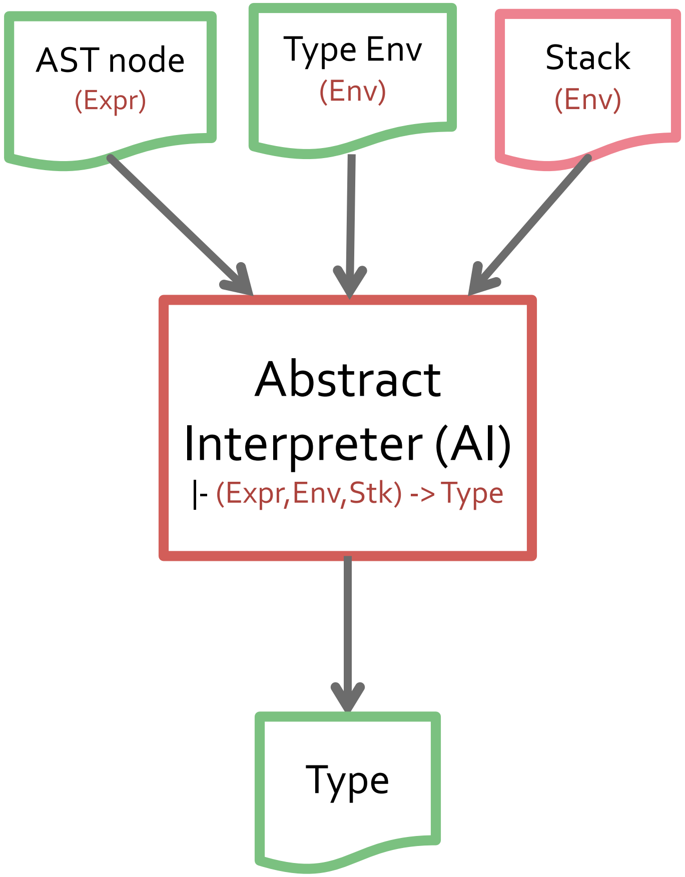
Solution:
"Python Style Guide"

Overall Structure of Analysis



AST node (Expr)

Type Env (Env)

Stack (Env)

Abstract Interpreter (AI)

|- (Expr,Env,Stk) -> Type

Type

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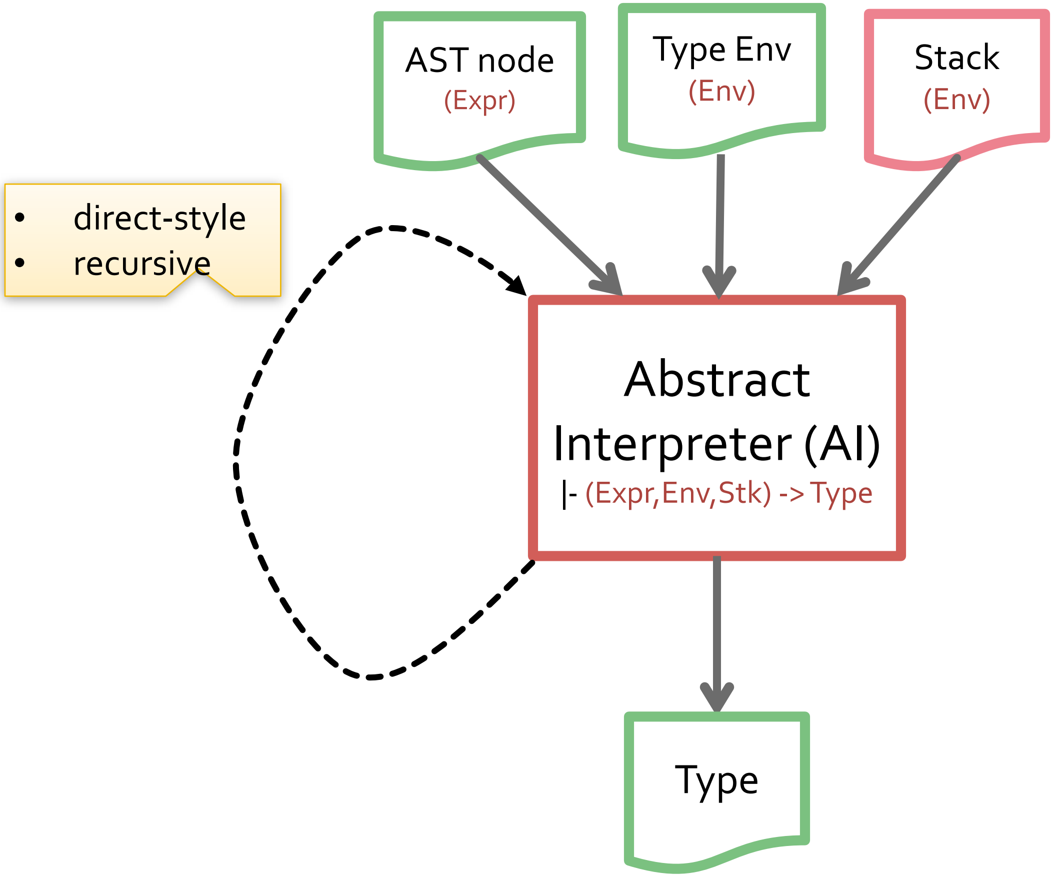

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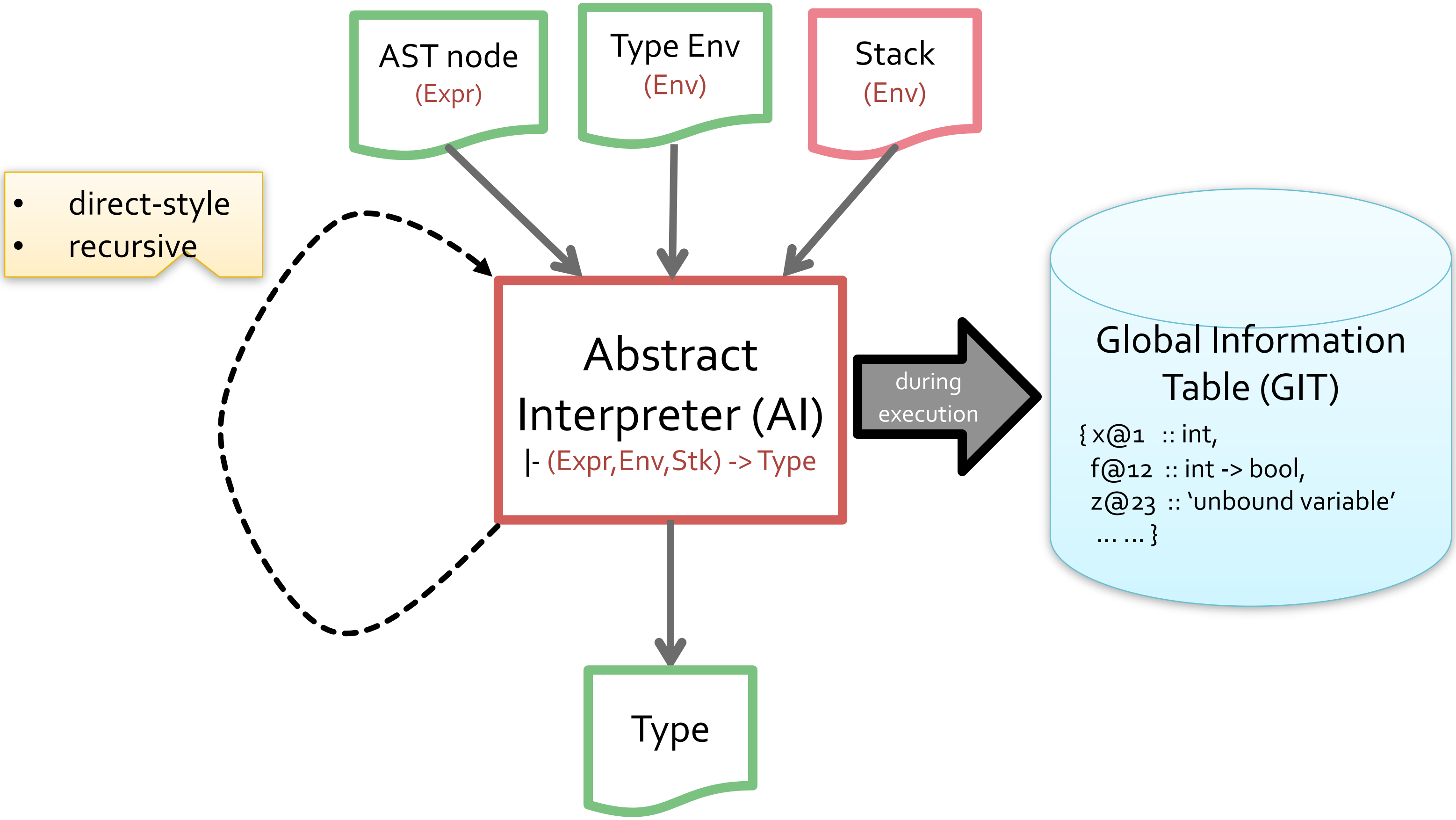
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  … … }
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- no CFG generated
- keep it "clean" (don't record anything on it)

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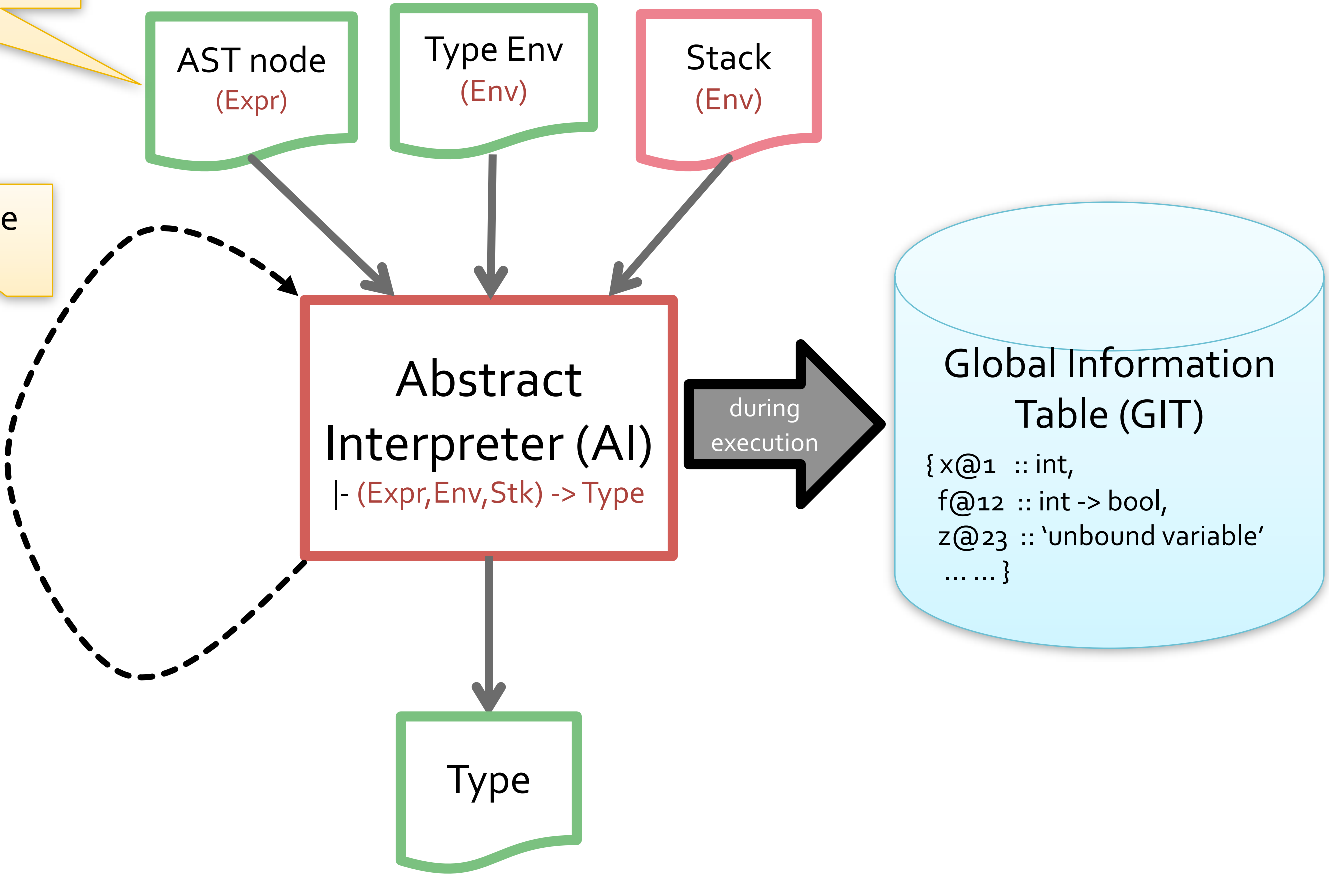

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purely functional data structures

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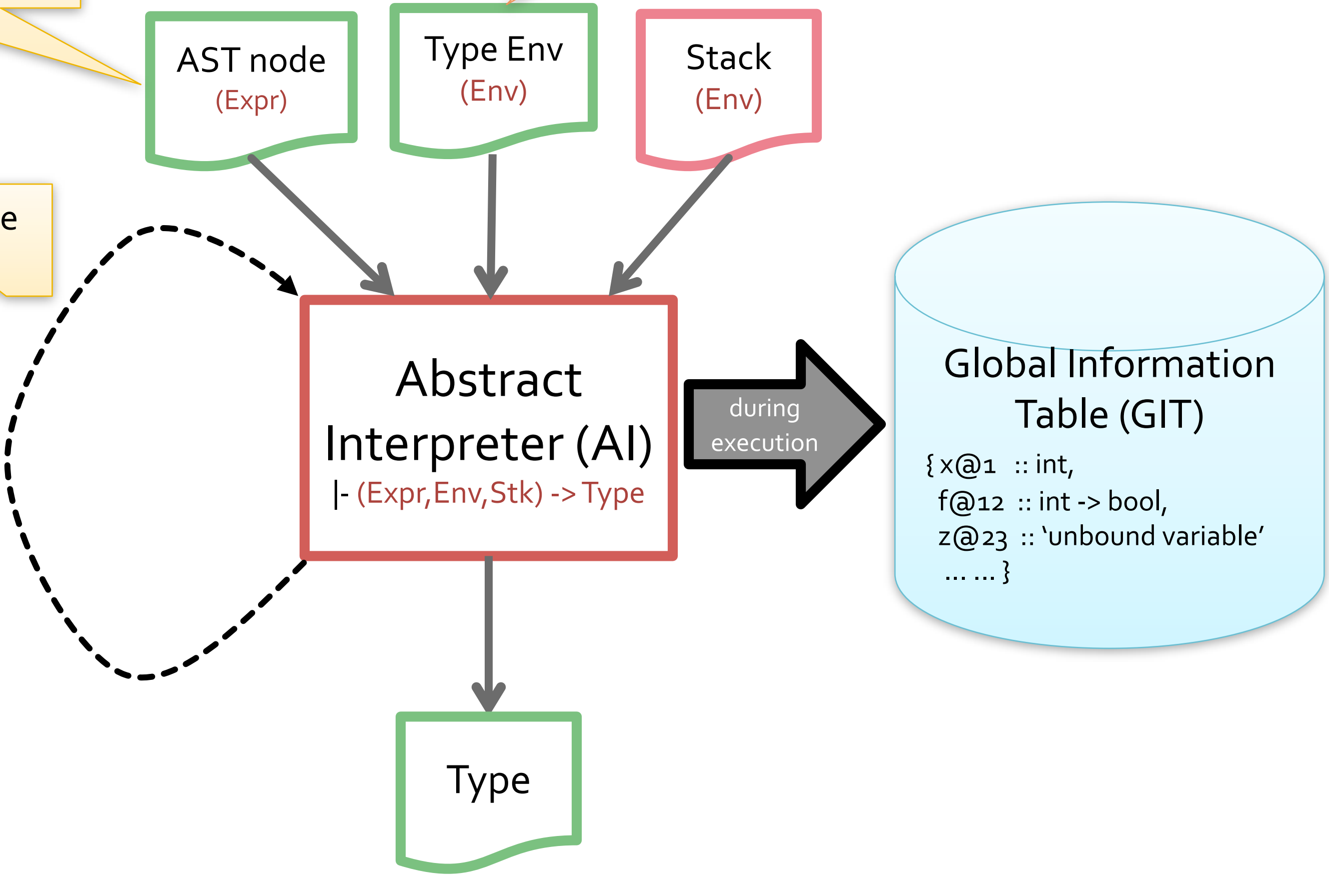
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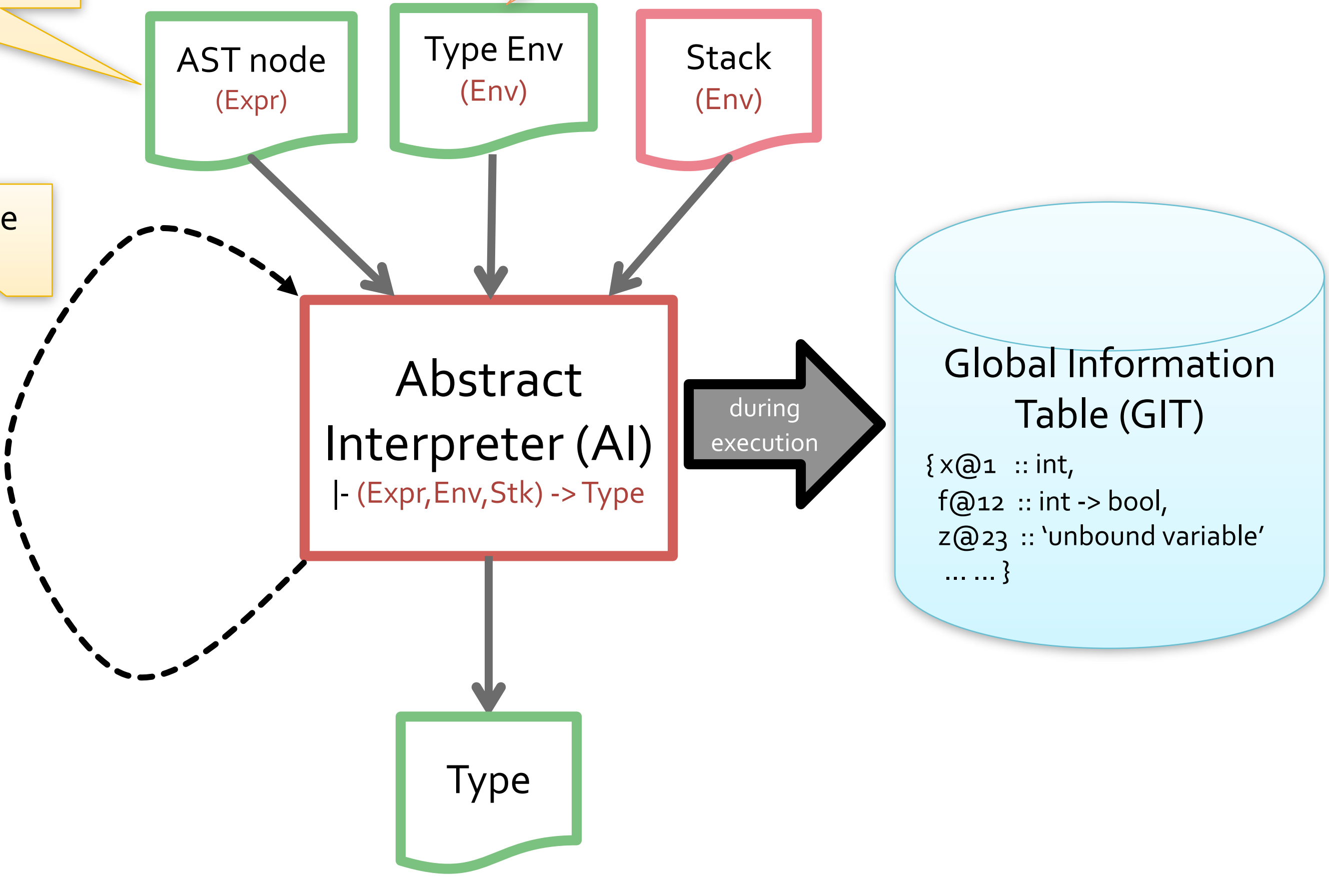
loop detection (using stack)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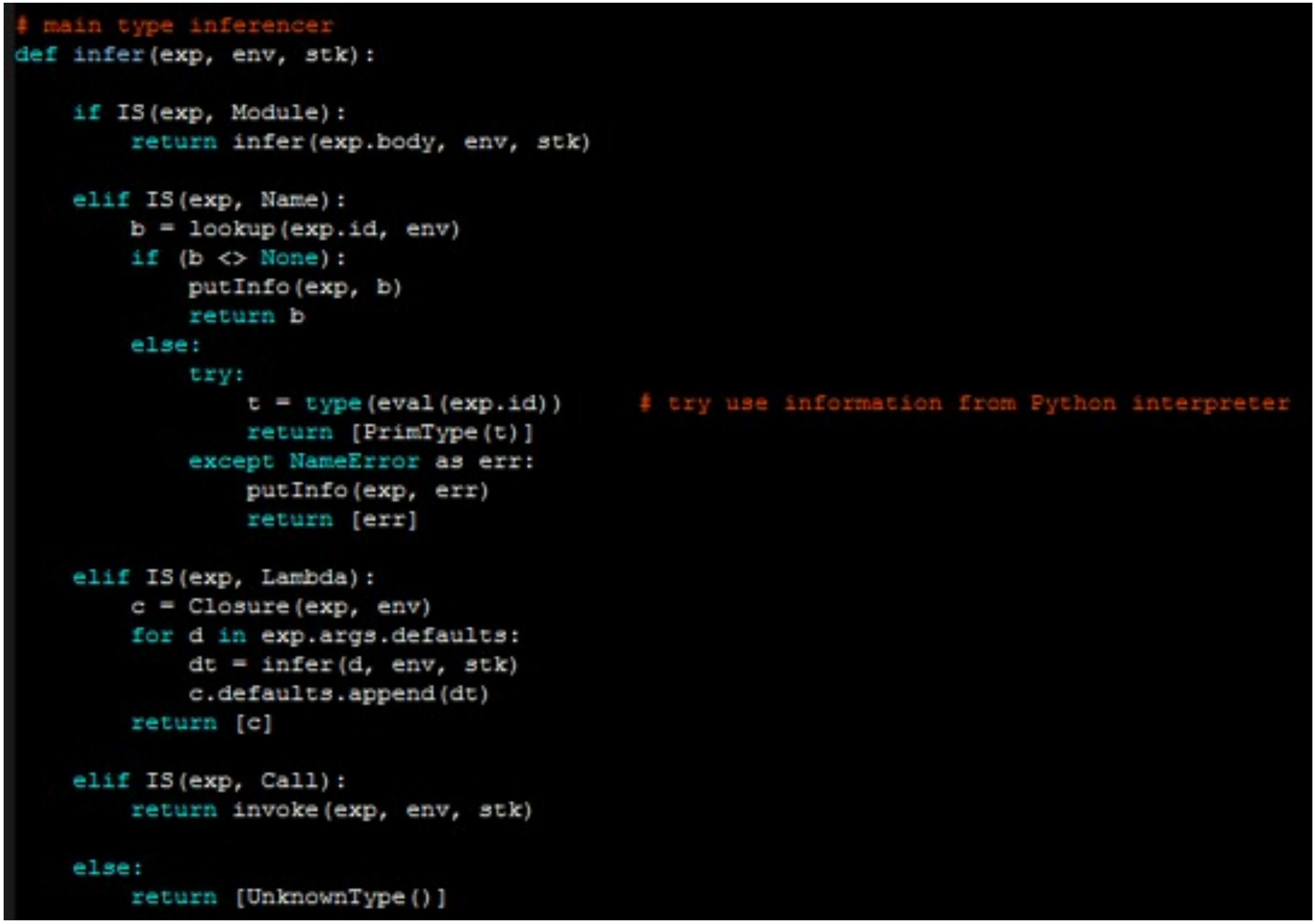
Actual Code of Main Interpreter



```
# main type inferencer
def infer(exp, env, stk):

    if IS(exp, Module):
        return infer(exp.body, env, stk)

    elif IS(exp, Name):
        b = lookup(exp.id, env)
        if (b <> None):
            putInfo(exp, b)
            return b
        else:
            try:
                t = type(eval(exp.id))      # try use information from Python interpreter
                return [PrimType(t)]
            except NameError as err:
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    elif IS(exp, Lambda):
        c = Closure(exp, env)
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        return [c]

    elif IS(exp, Call):
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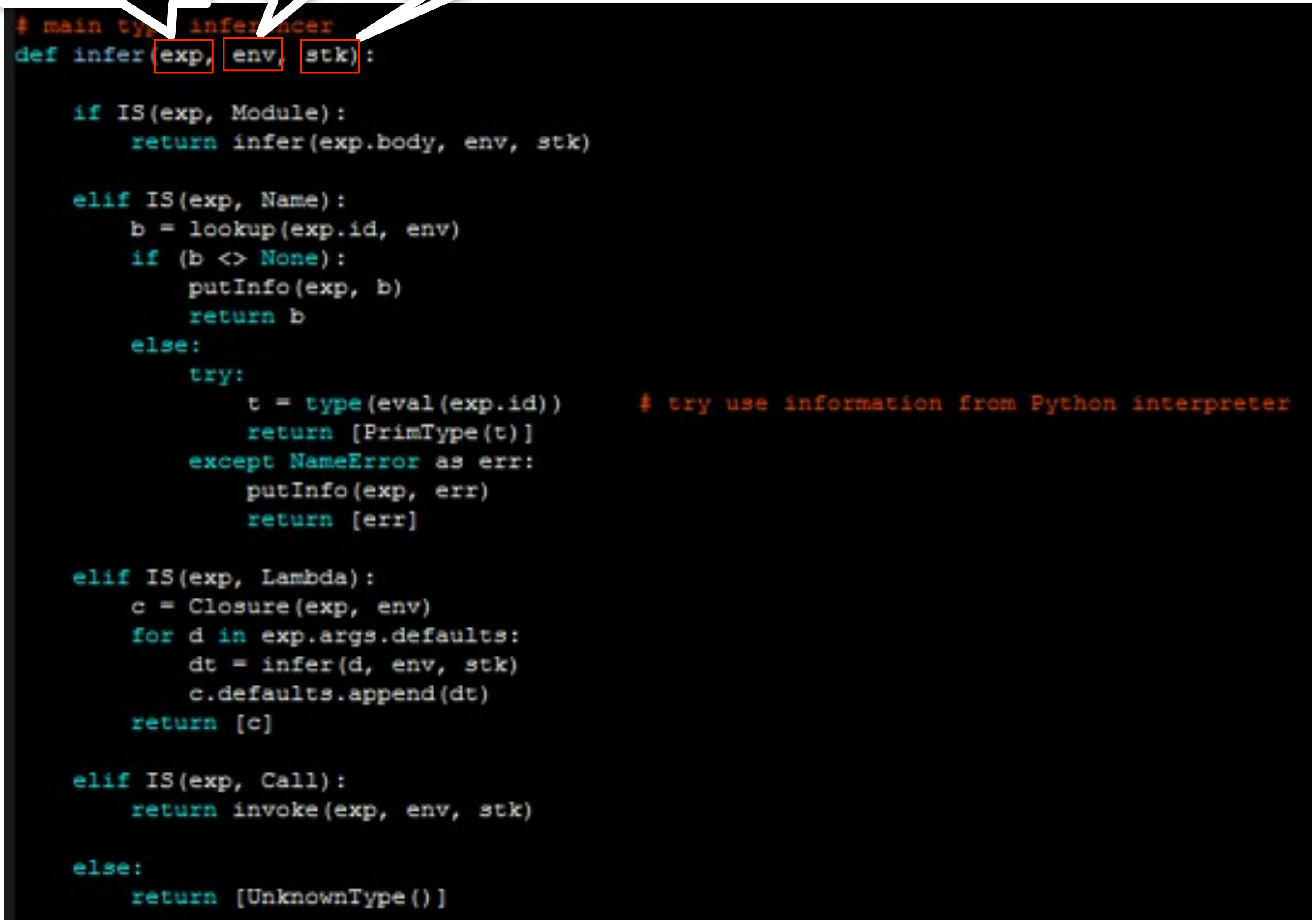
Actual Code of Main I

input expression

type environment

stack of nodes on path (recursion detection)



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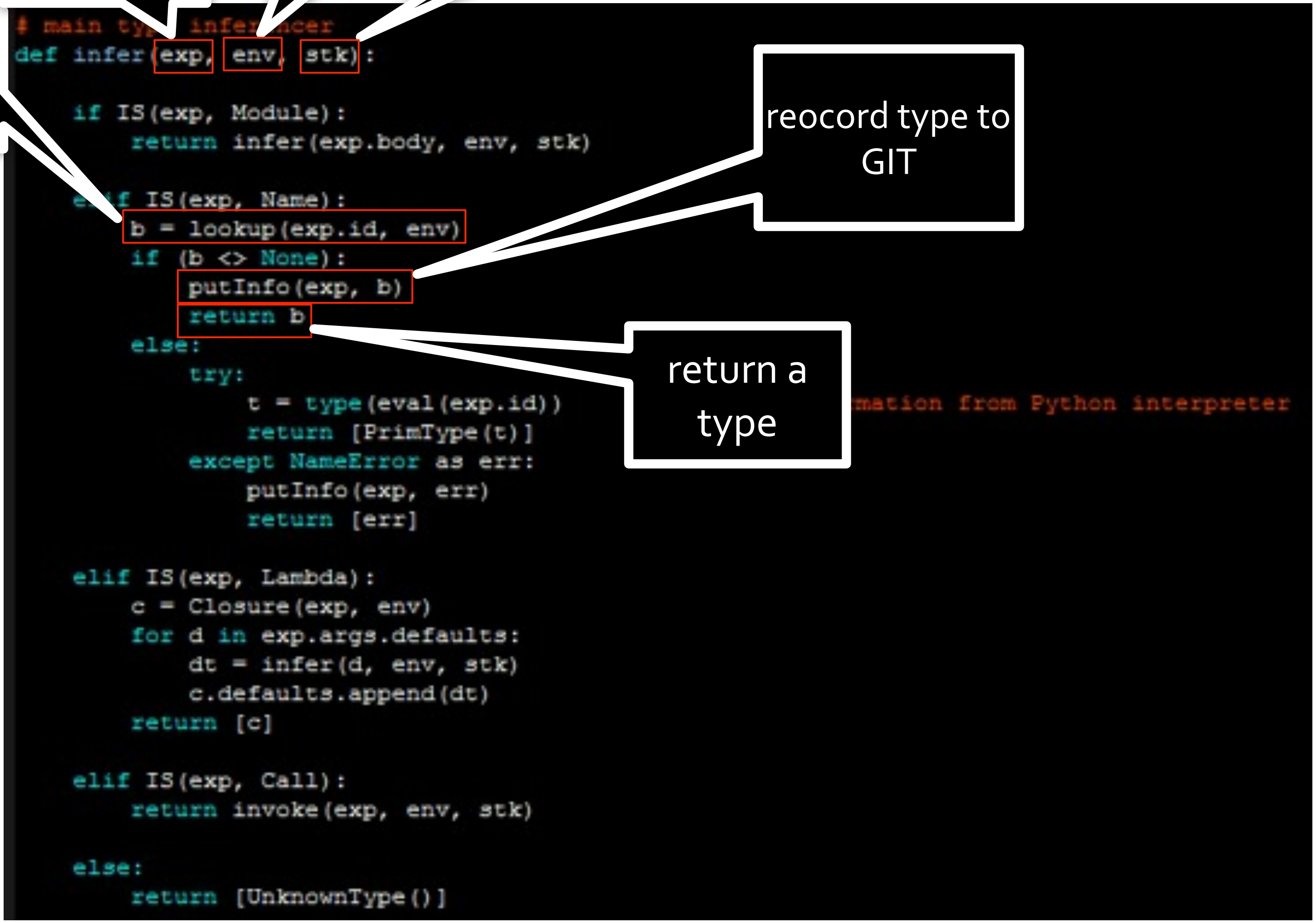

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lookup variable's type

reocord type to GIT

return a type

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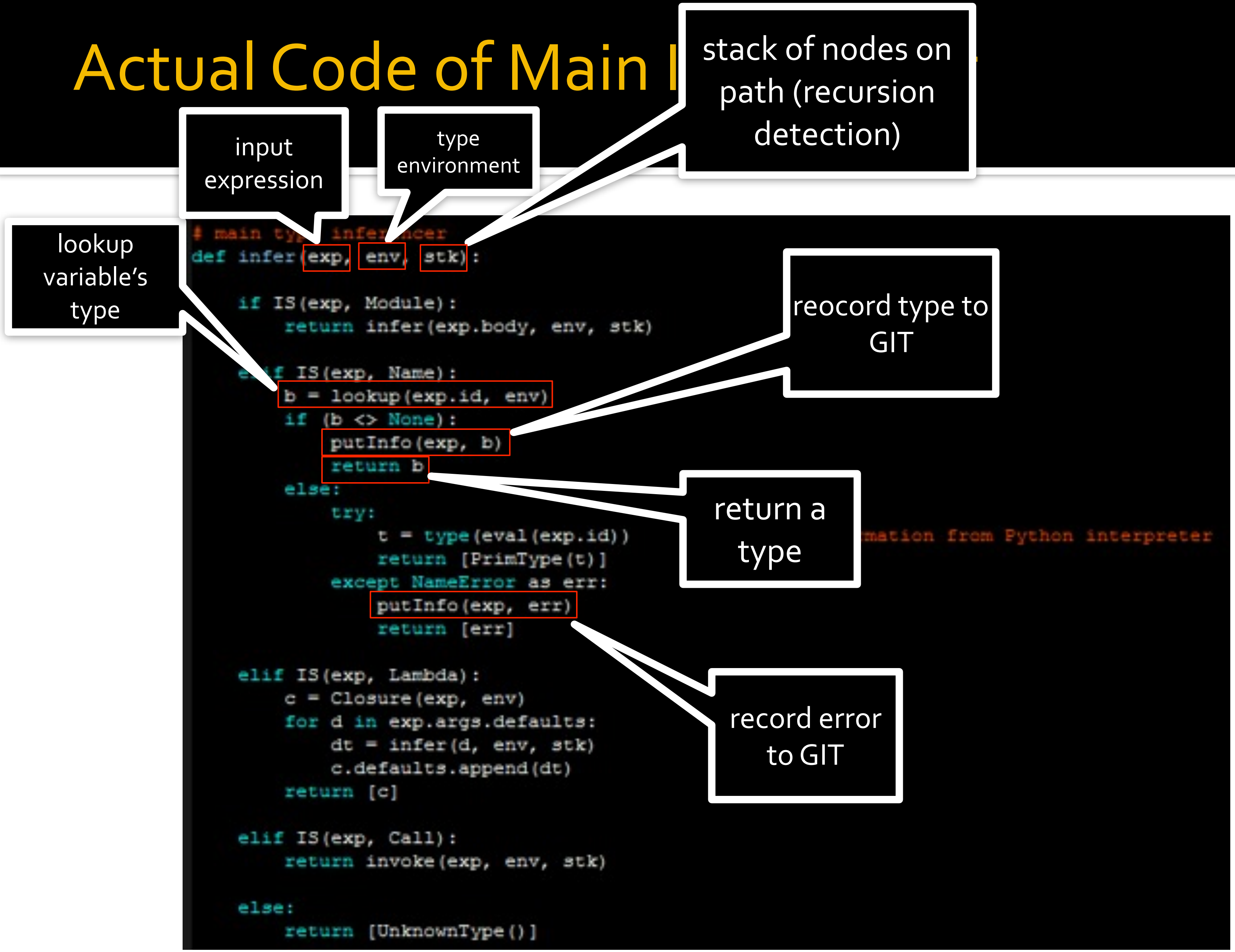

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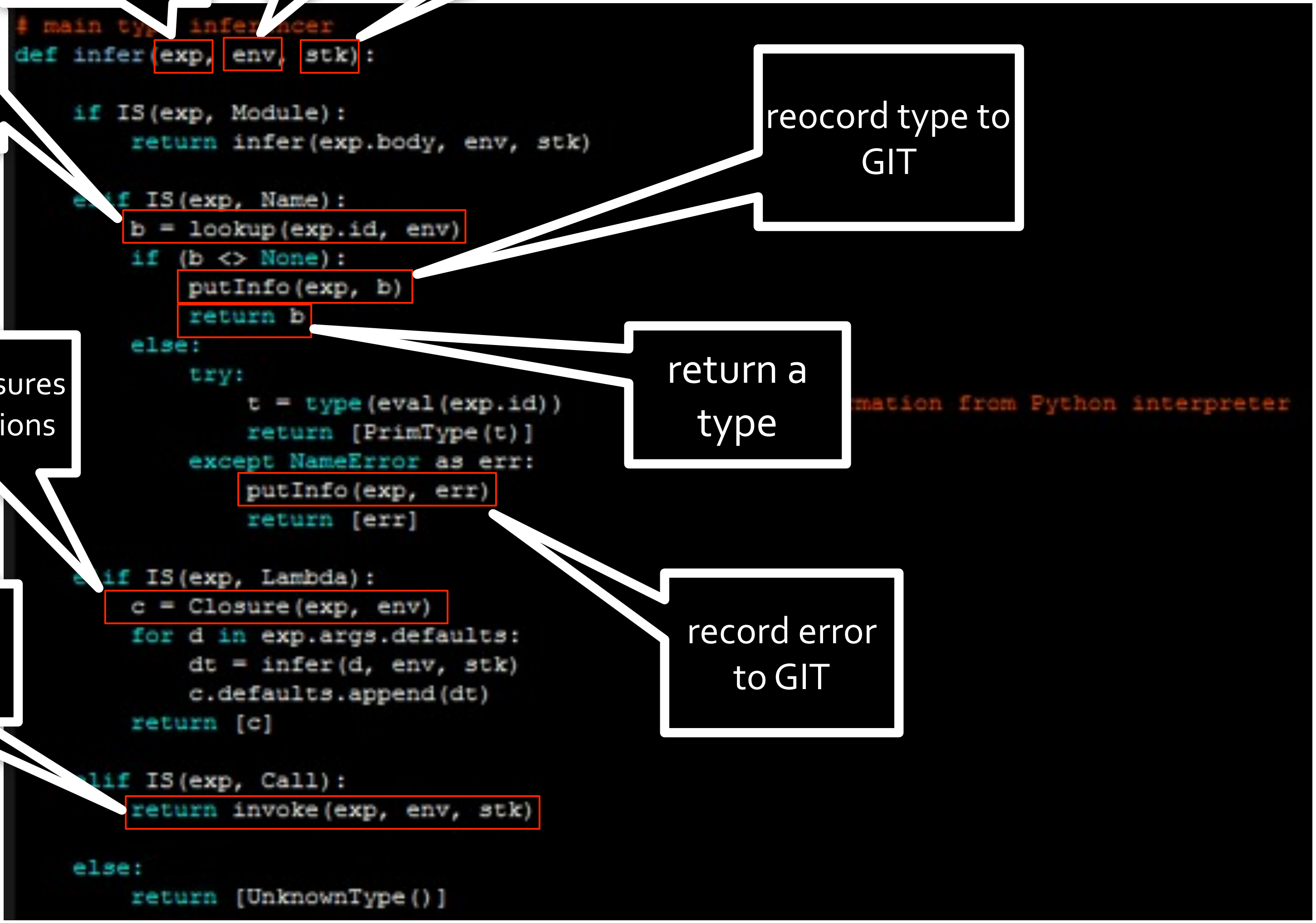

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stack of nodes on path (recursion detection)

input expression

type environment

lookup variable's type

reocord type to GIT

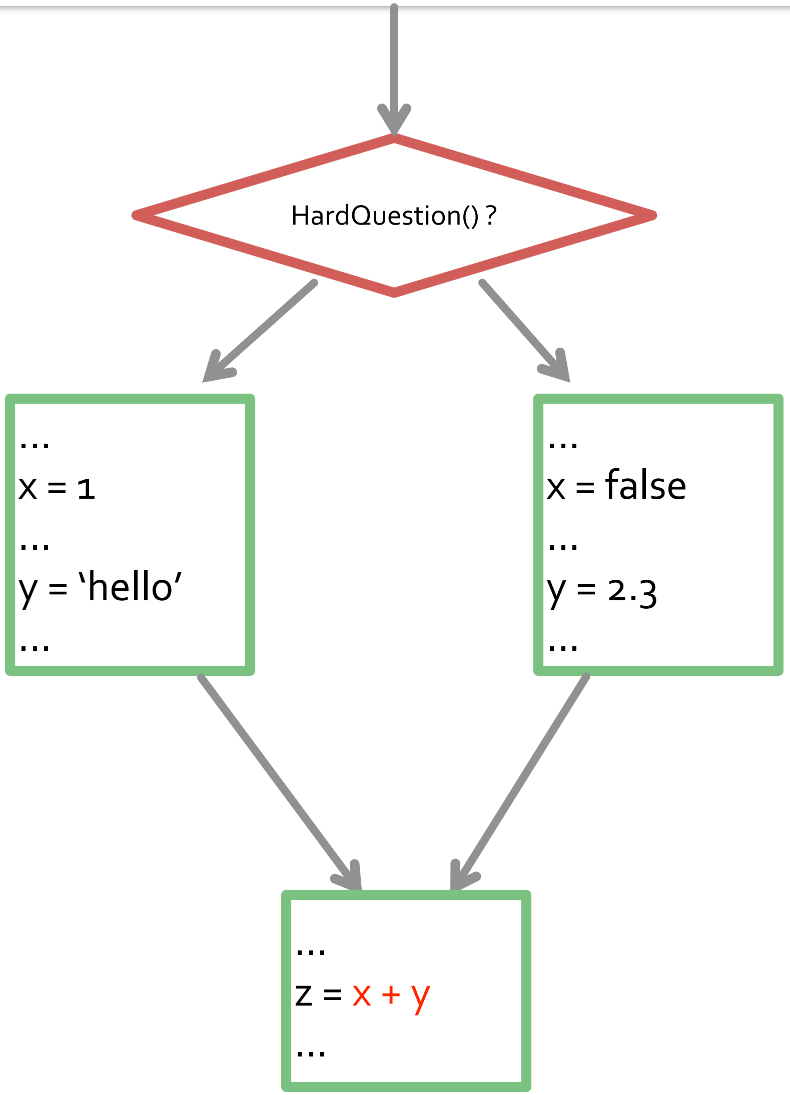
return a type

make closures for functions

record error to GIT

invoke function (closure)

“Multiple-Worlds Model”



HardQuestion() ?

```
…
x = 1
…
y = ‘hello’
…
```

```
…
x = false
…
y = 2.3
…
```

```
…
z = x + y
…
```

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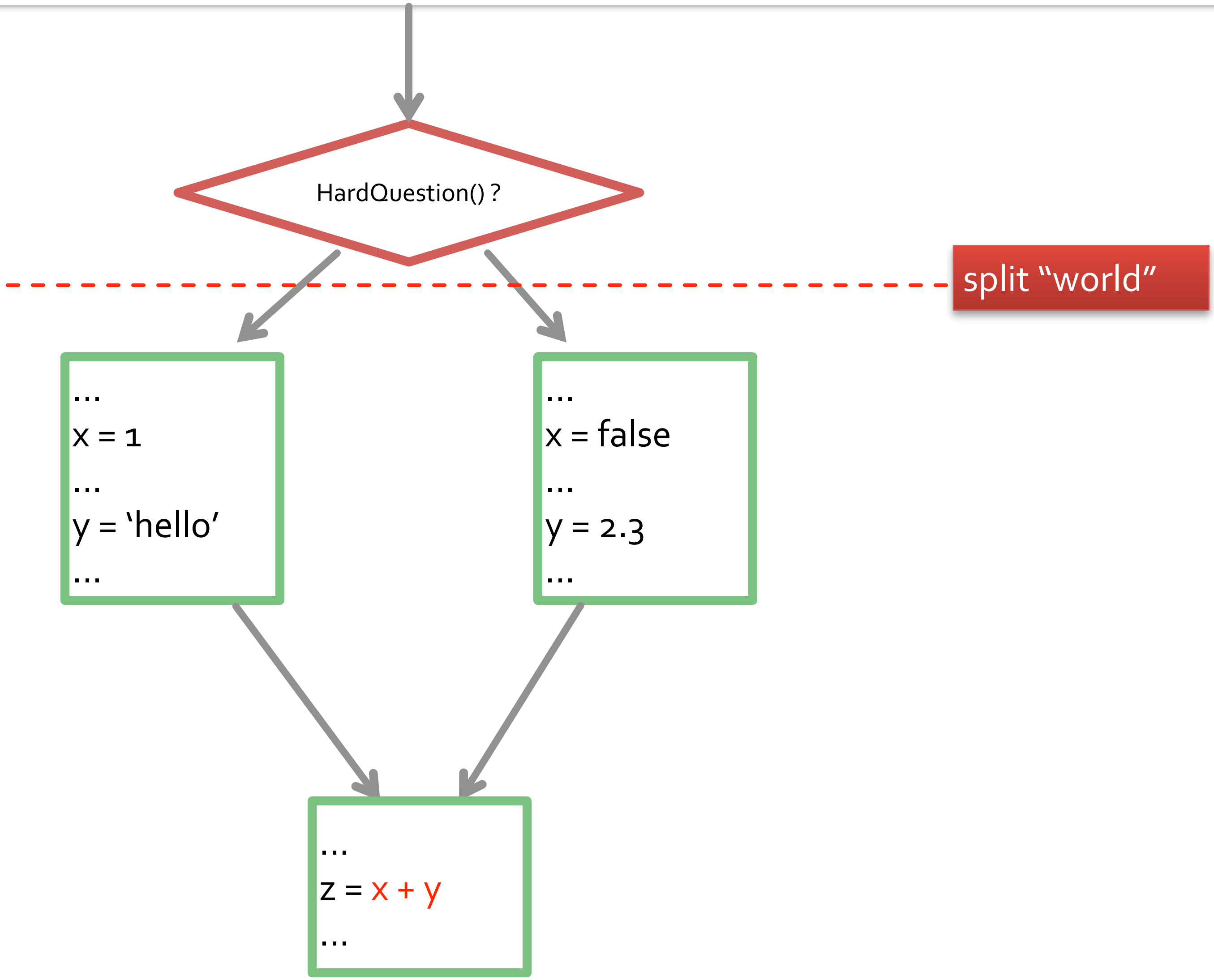

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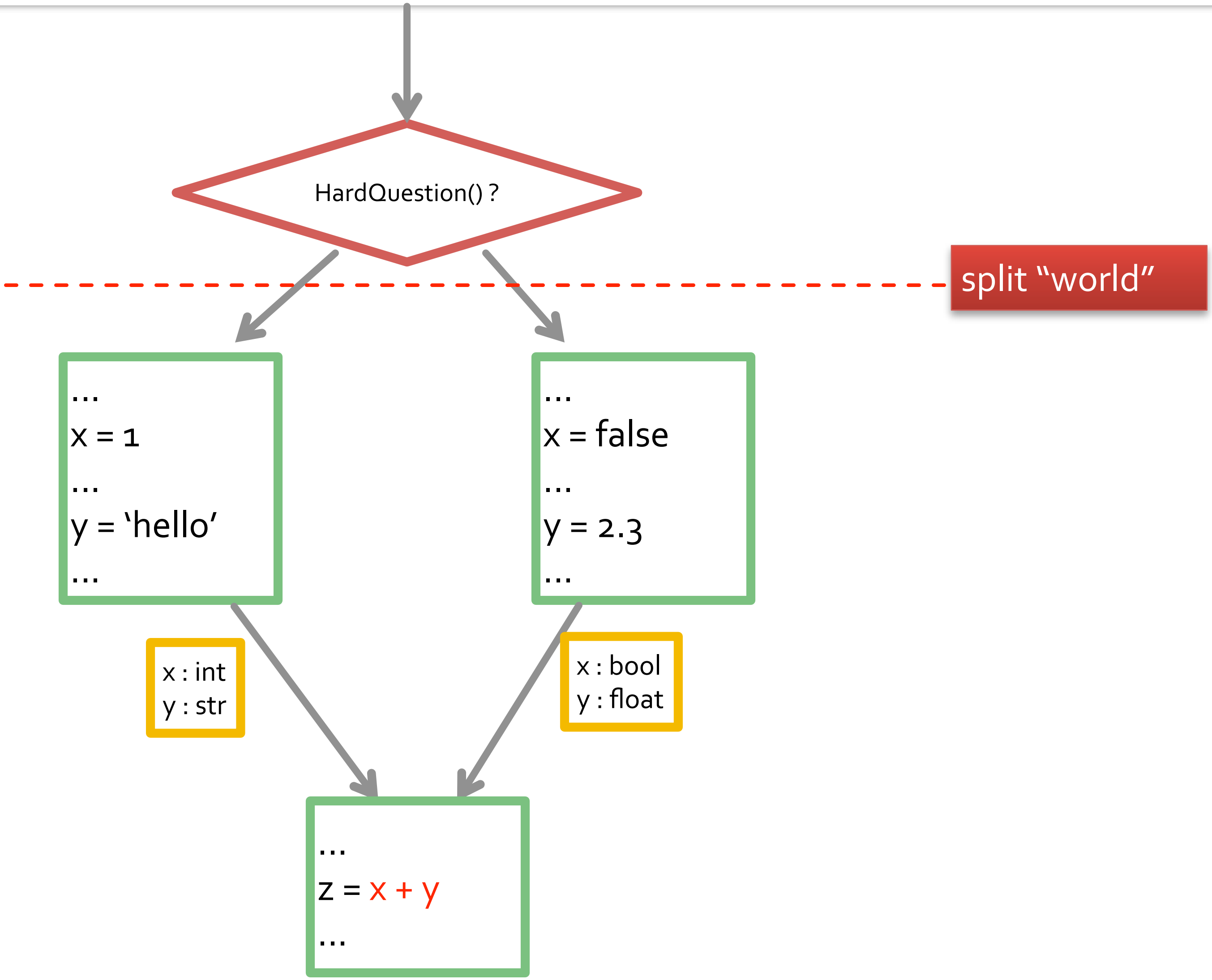

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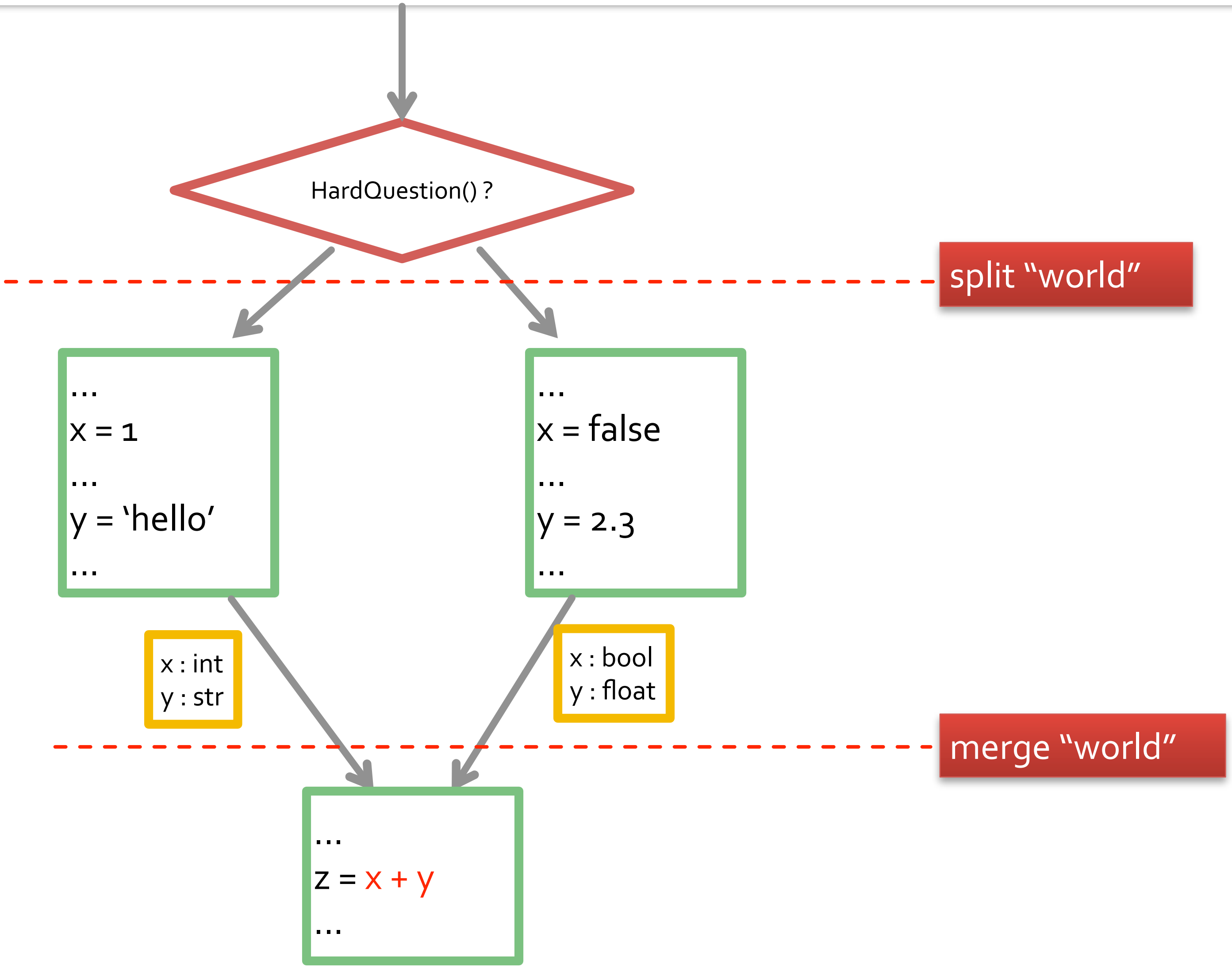

HardQuestion() ?

split “world”

```
…
x = 1
…
y = ‘hello’
…
```

x : int
y : str

```
…
x = false
…
y = 2.3
…
```

x : bool
y : float

merge “world”

```
…
z = x + y
…
```

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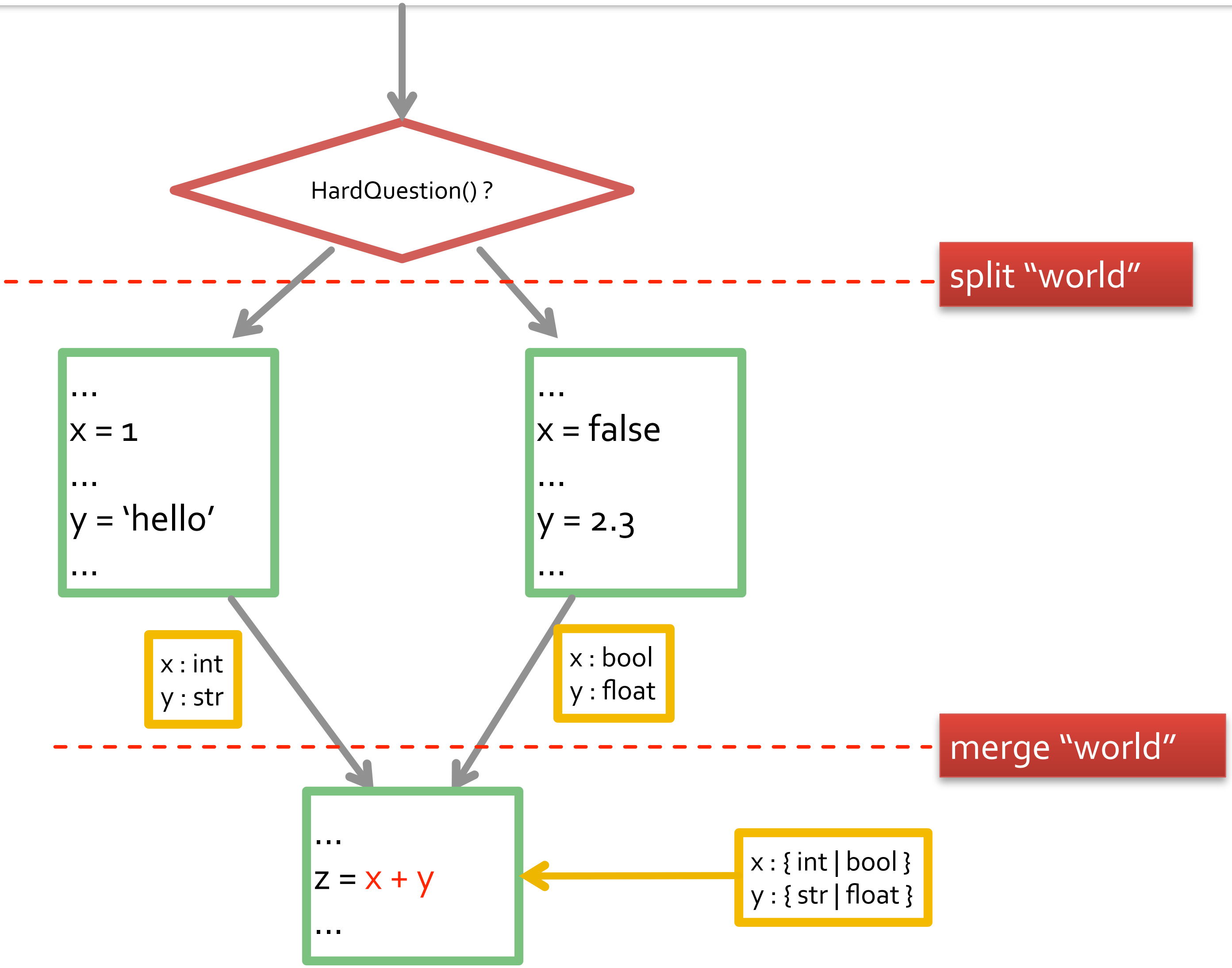

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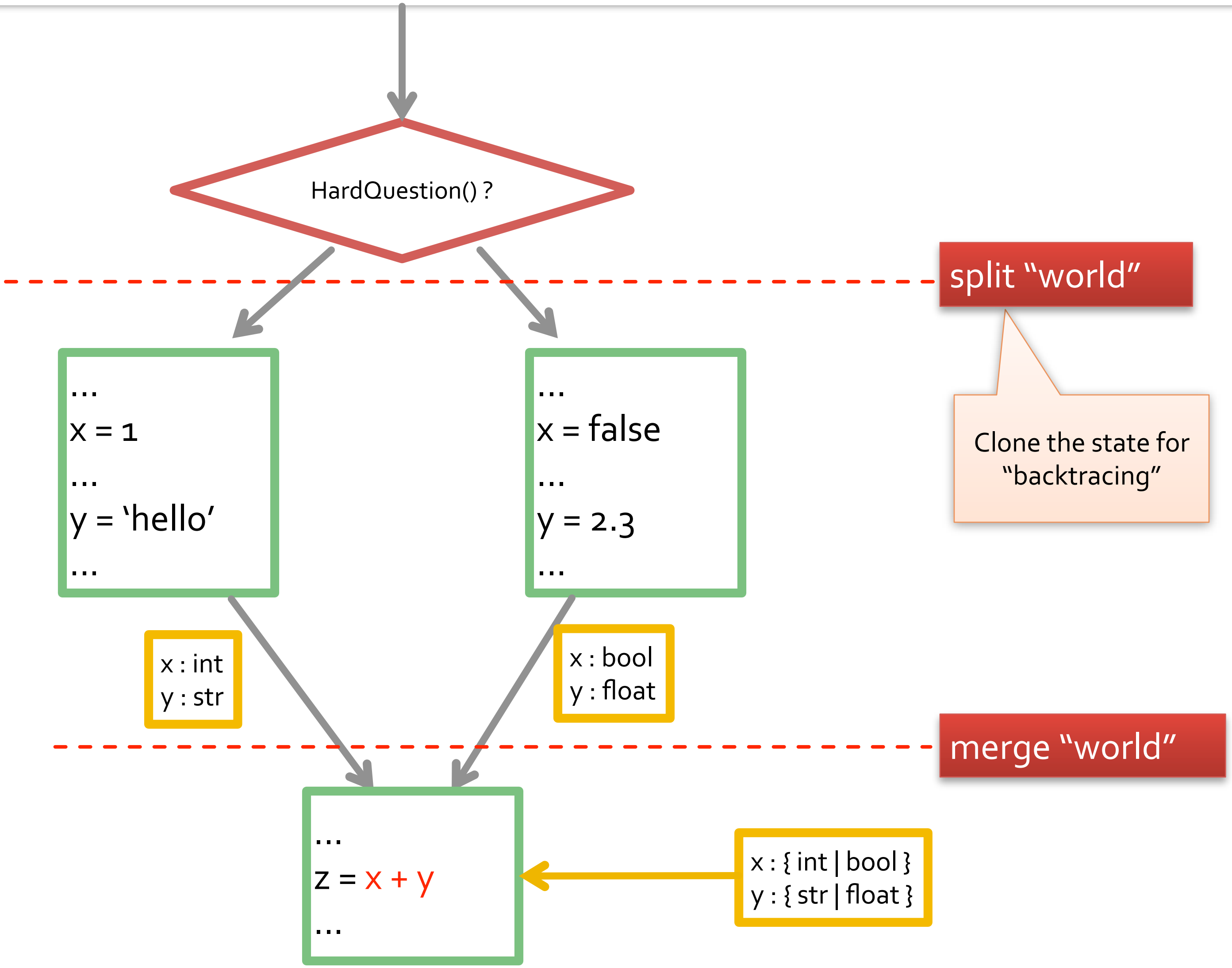

Recursion Detection (1)

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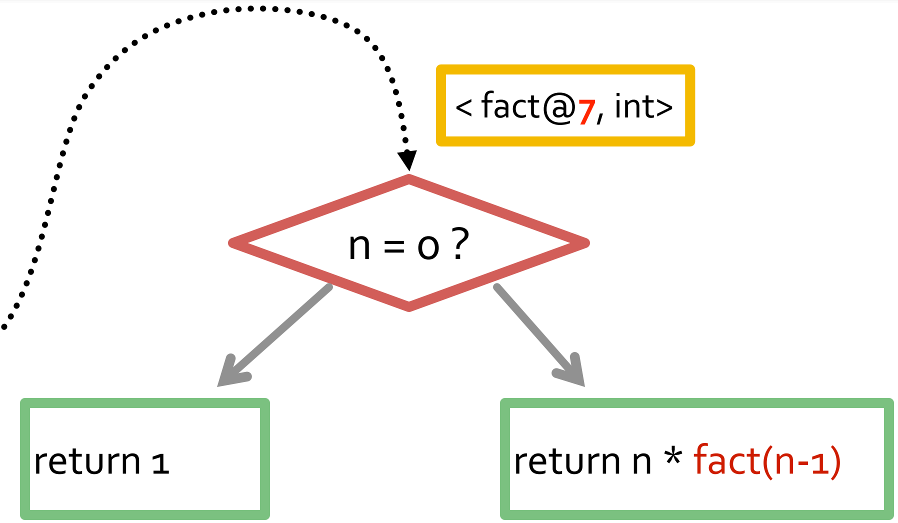

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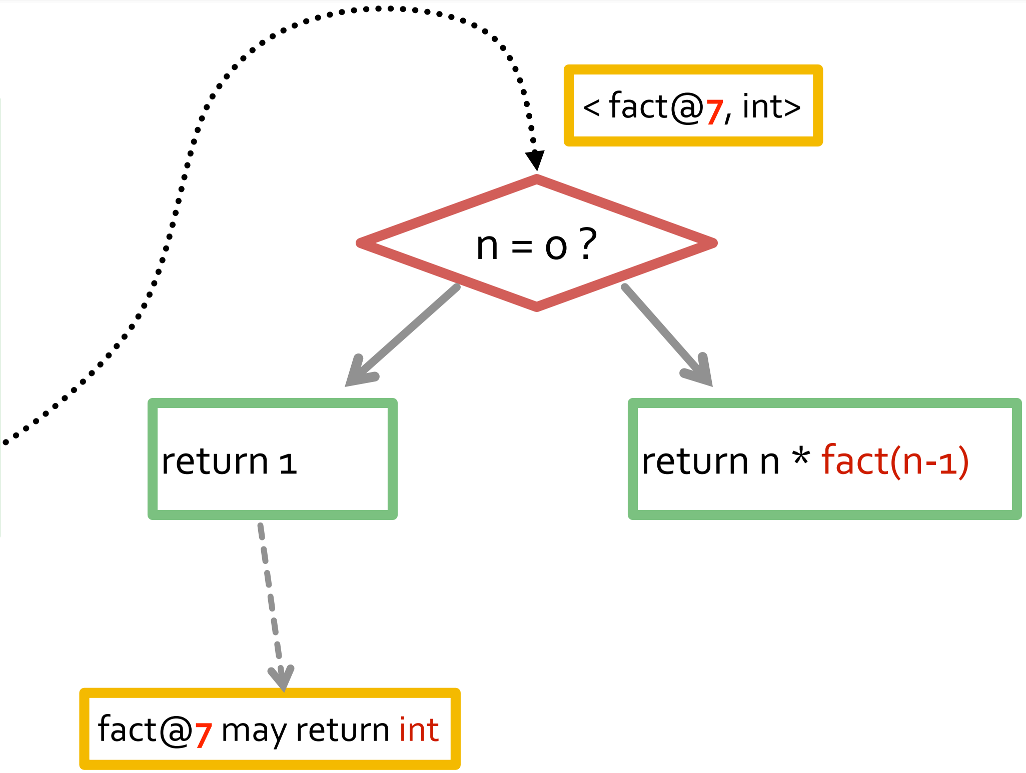

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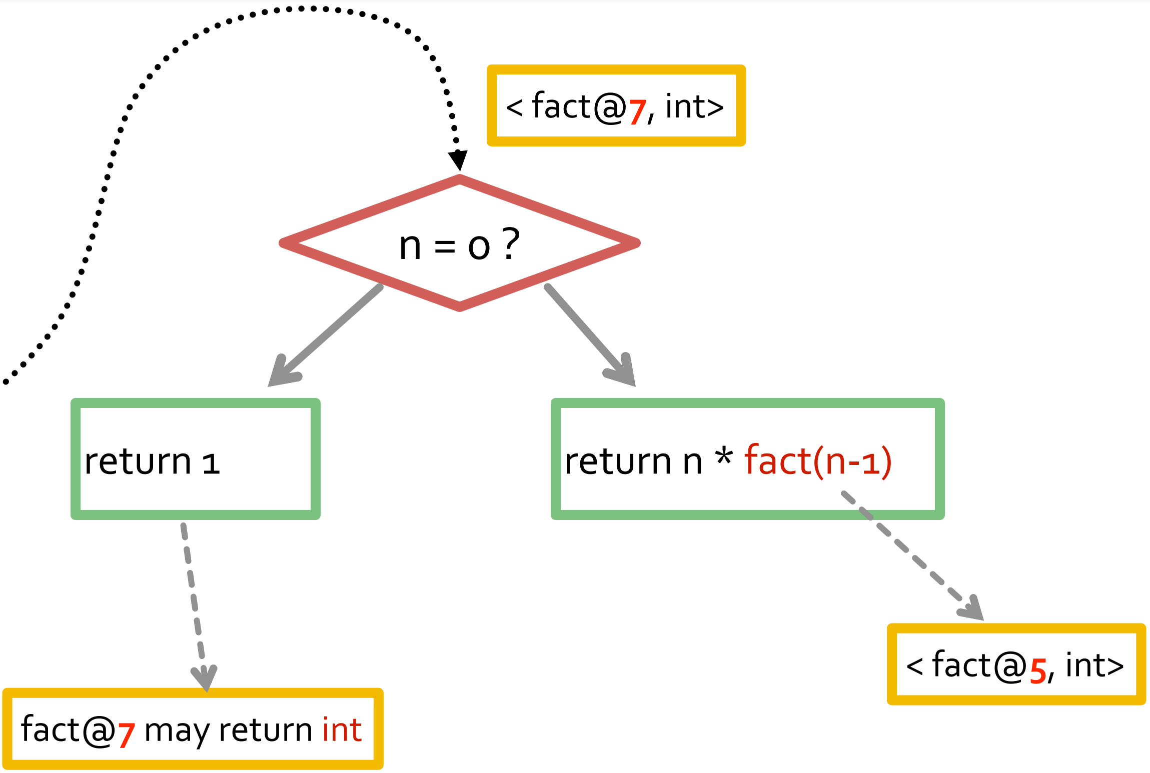

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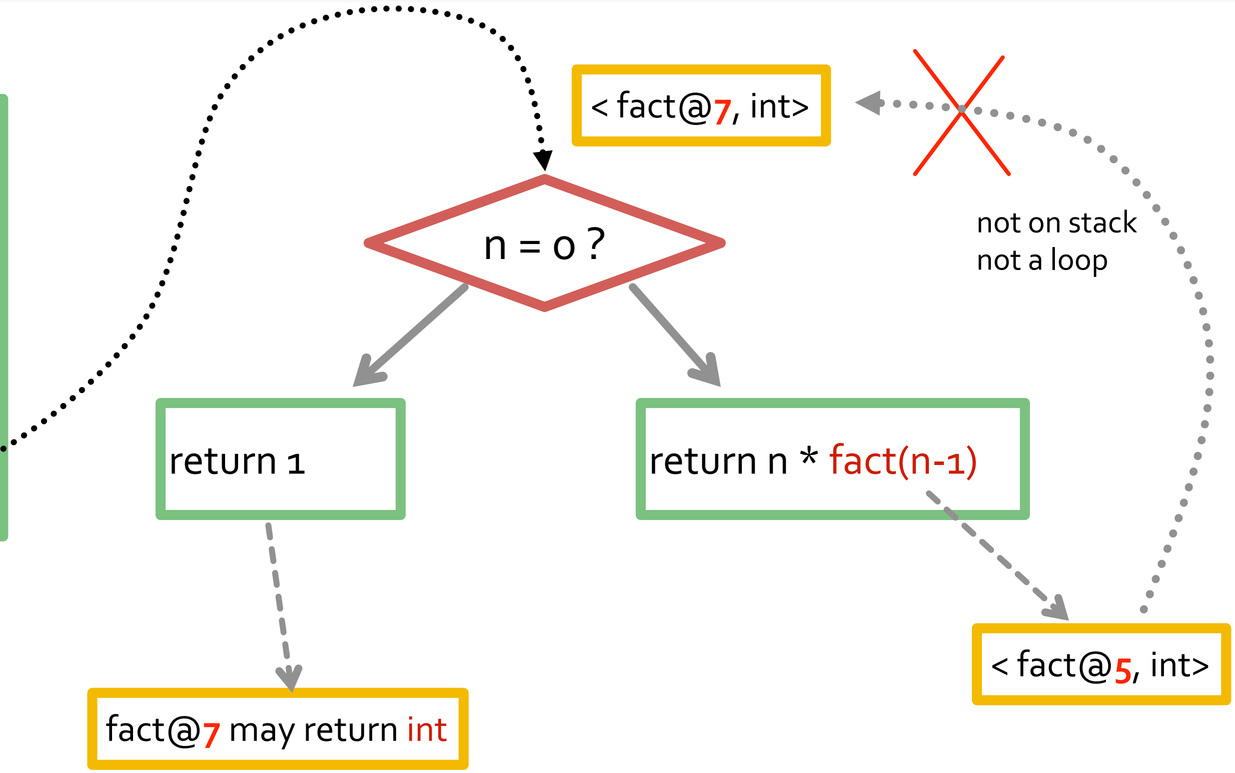


< fact@7, int>

n = 0 ?

return 1

return n * fact(n-1)

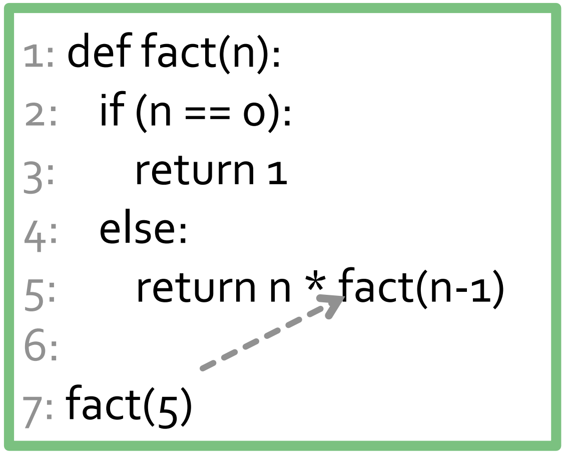
fact@7 may return int

< fact@5, int>

not on stack
not a loop

Assumption: the same *call site* with the same *argument types* always produces the same *output type (or nontermination)*

Recursion Detection (2)



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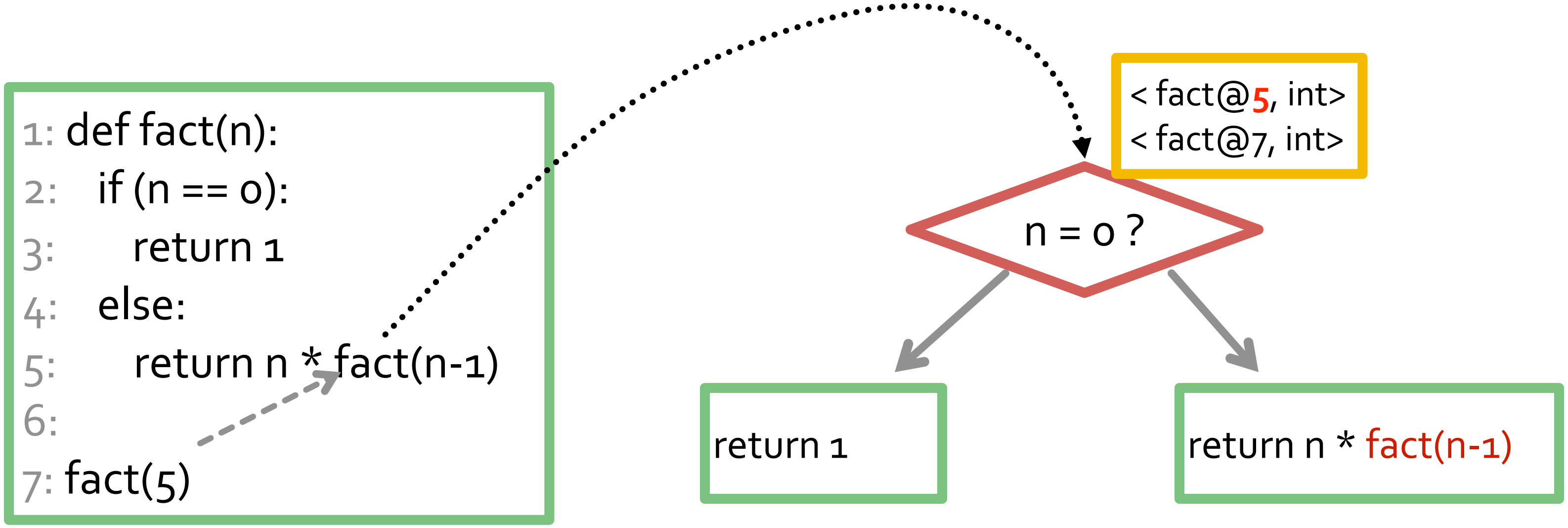

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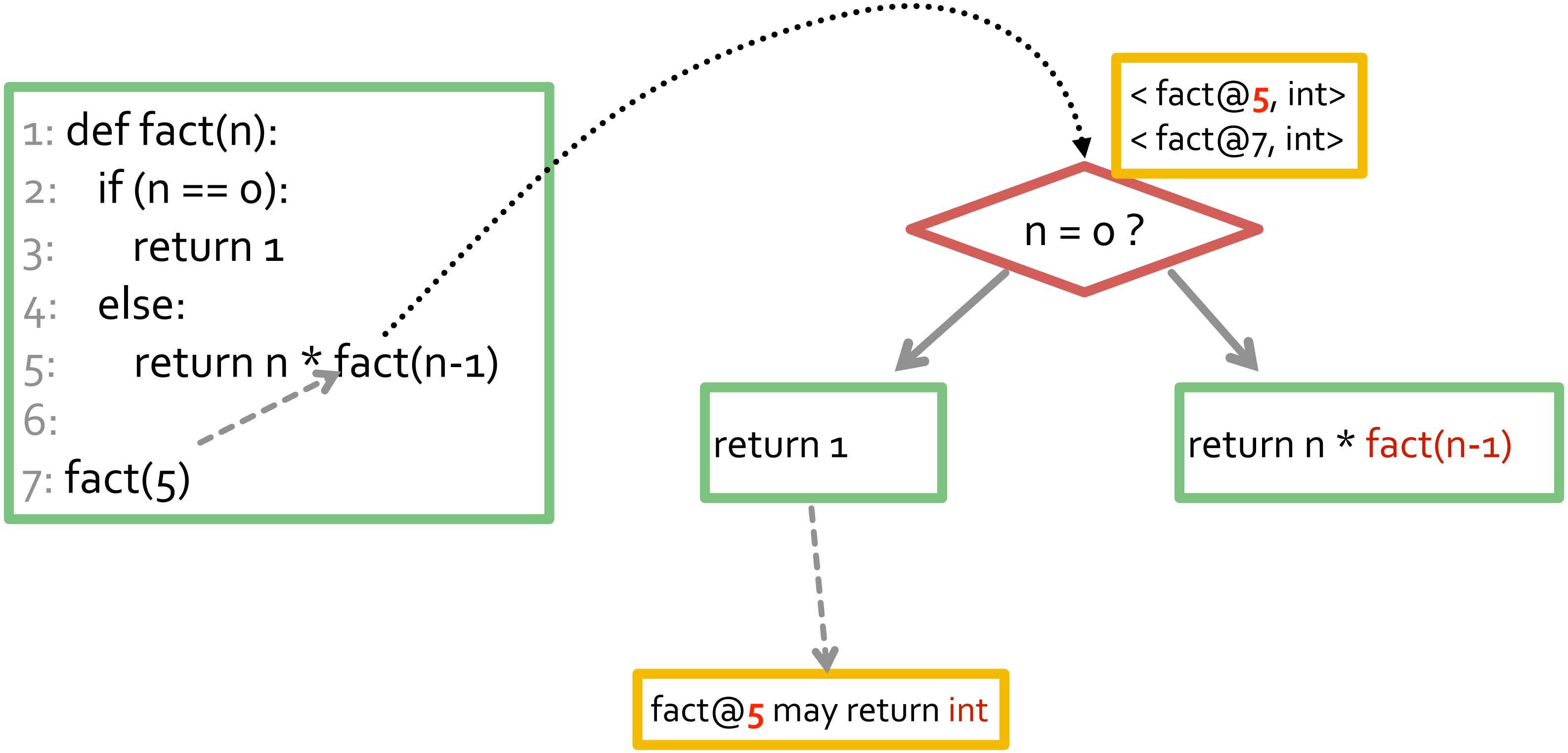

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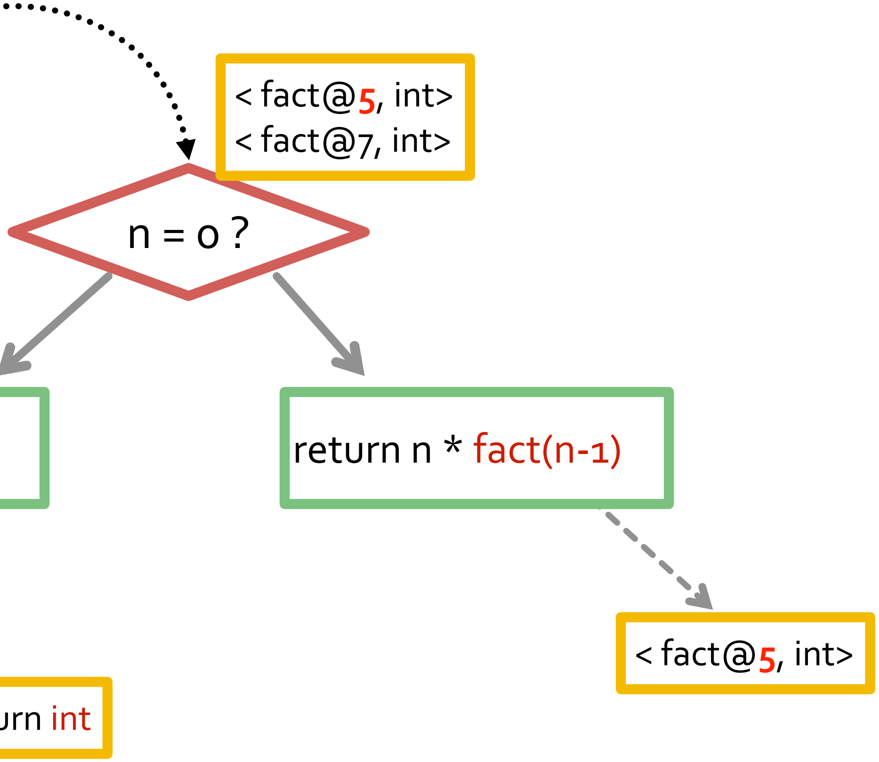

< fact@5, int>
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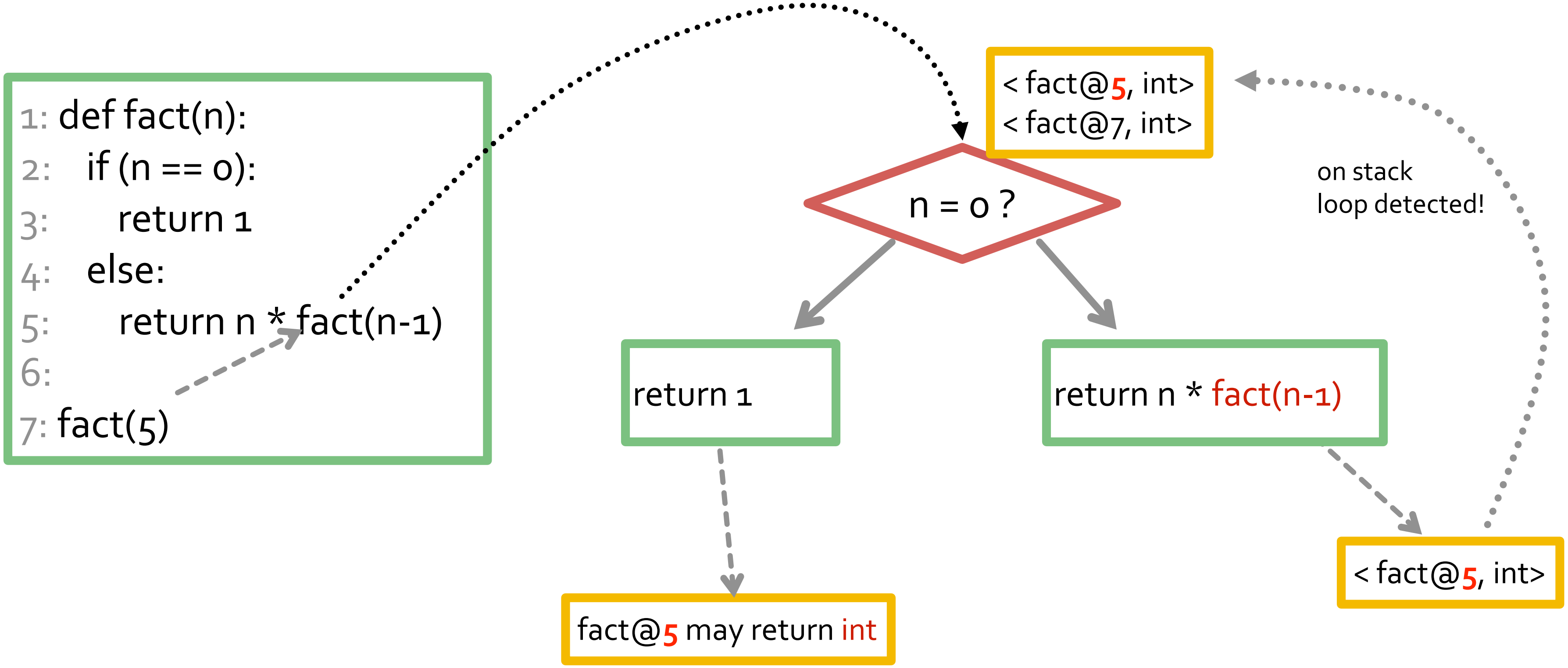
fact@5 may return int

< fact@5, int>

Recursion Detection (2)



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6:
7: fact(5)
```

< fact@5, int>
< fact@7, int>

n = 0 ?

return 1

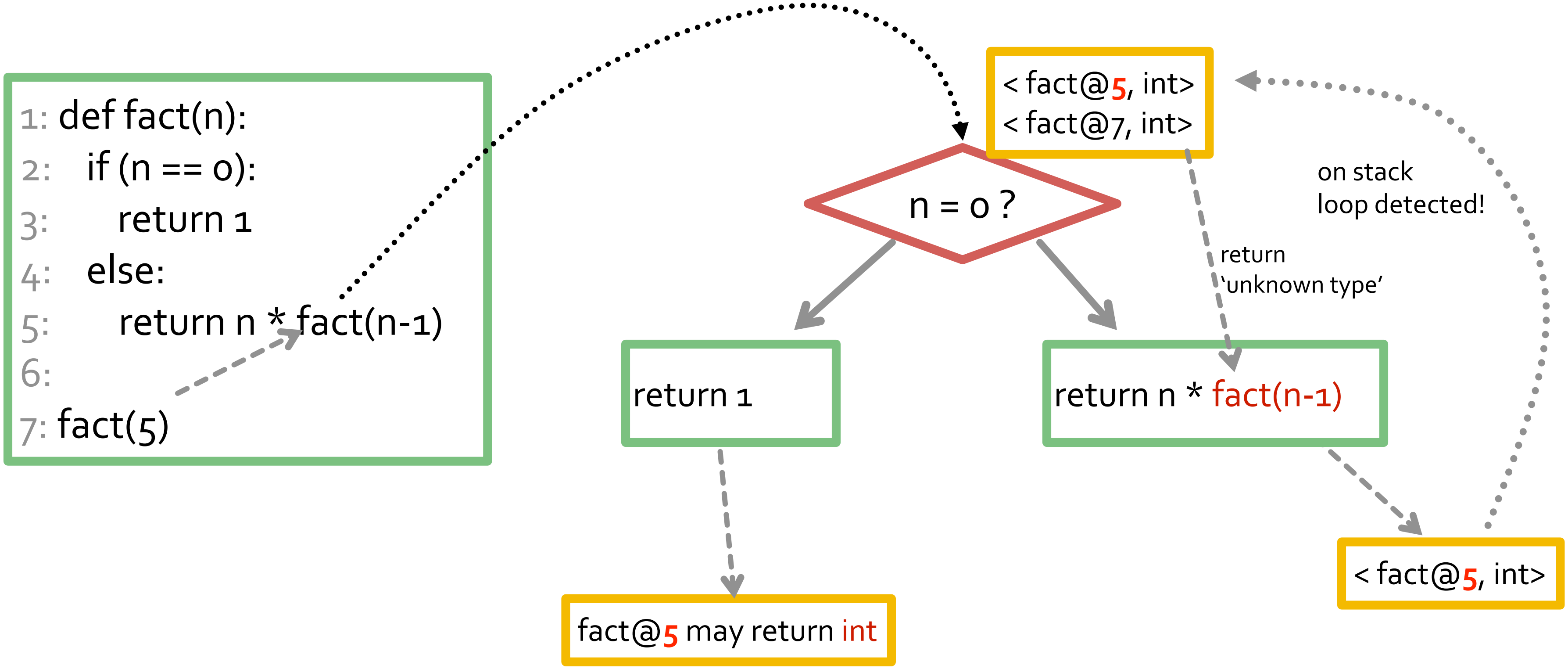
return n * fact(n-1)

fact@5 may return int

< fact@5, int>

on stack
loop detected!

Recursion Detection (2)



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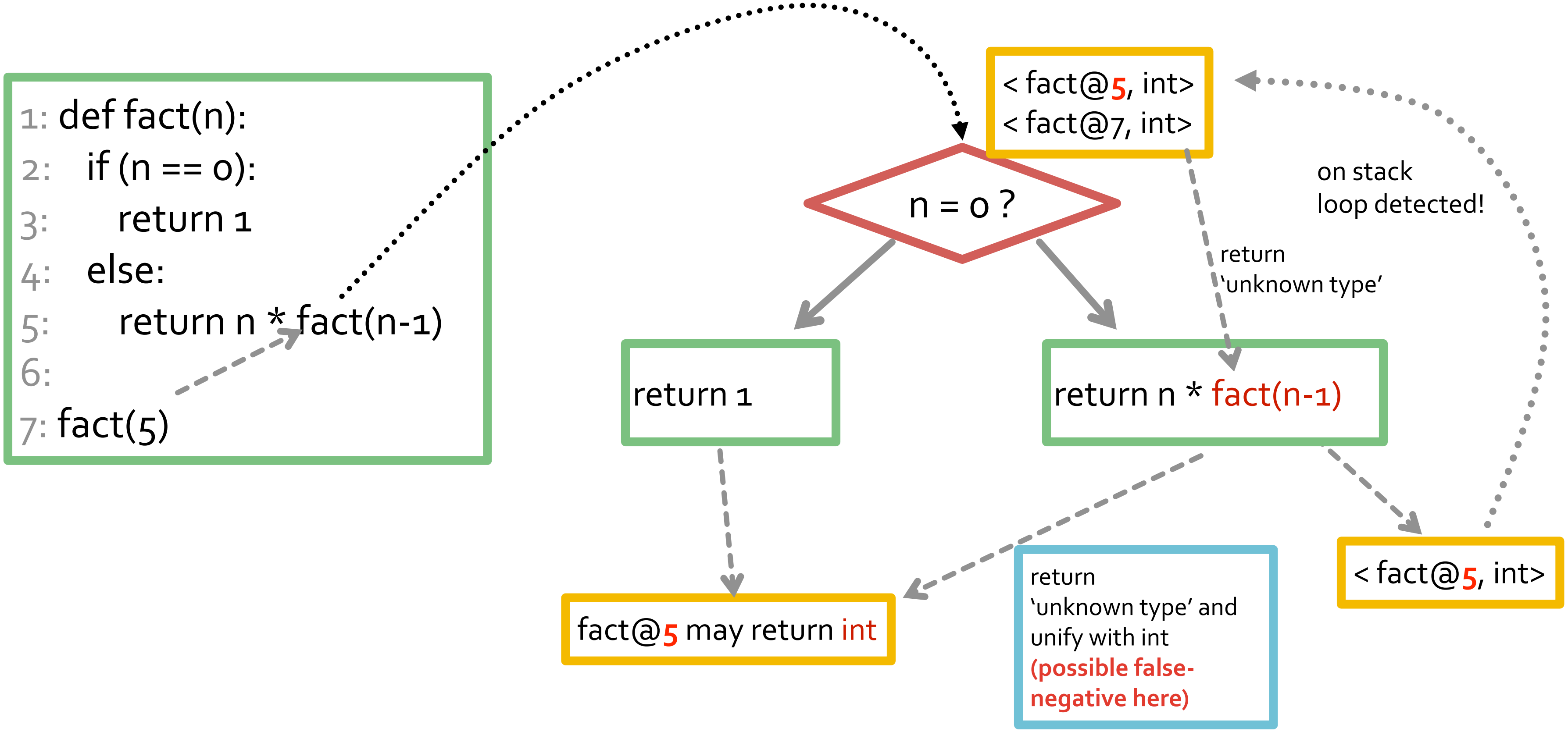

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unify with int
(possible false-negative here)

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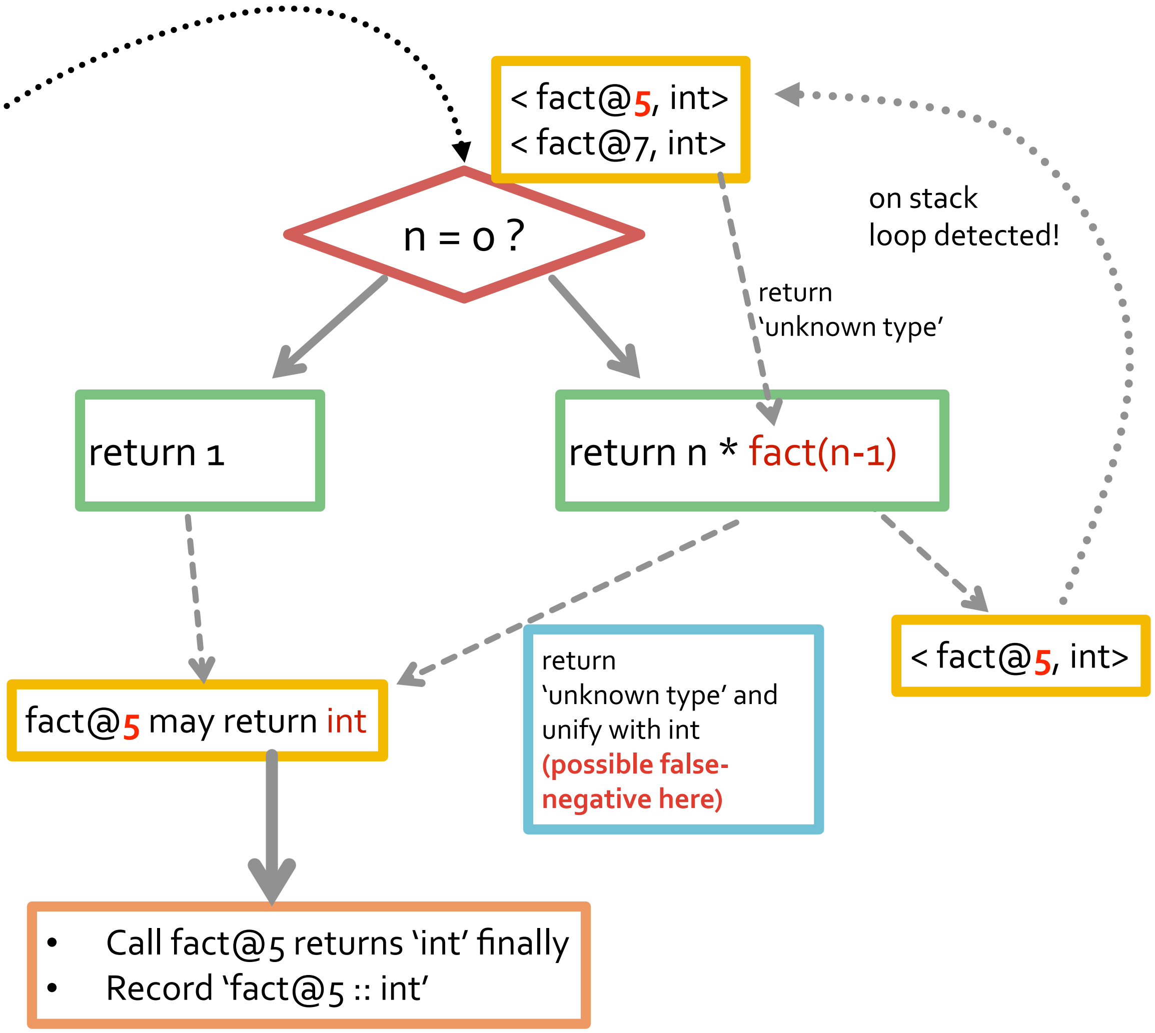

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- Call fact@5 returns 'int' finally
- Record 'fact@5 :: int'

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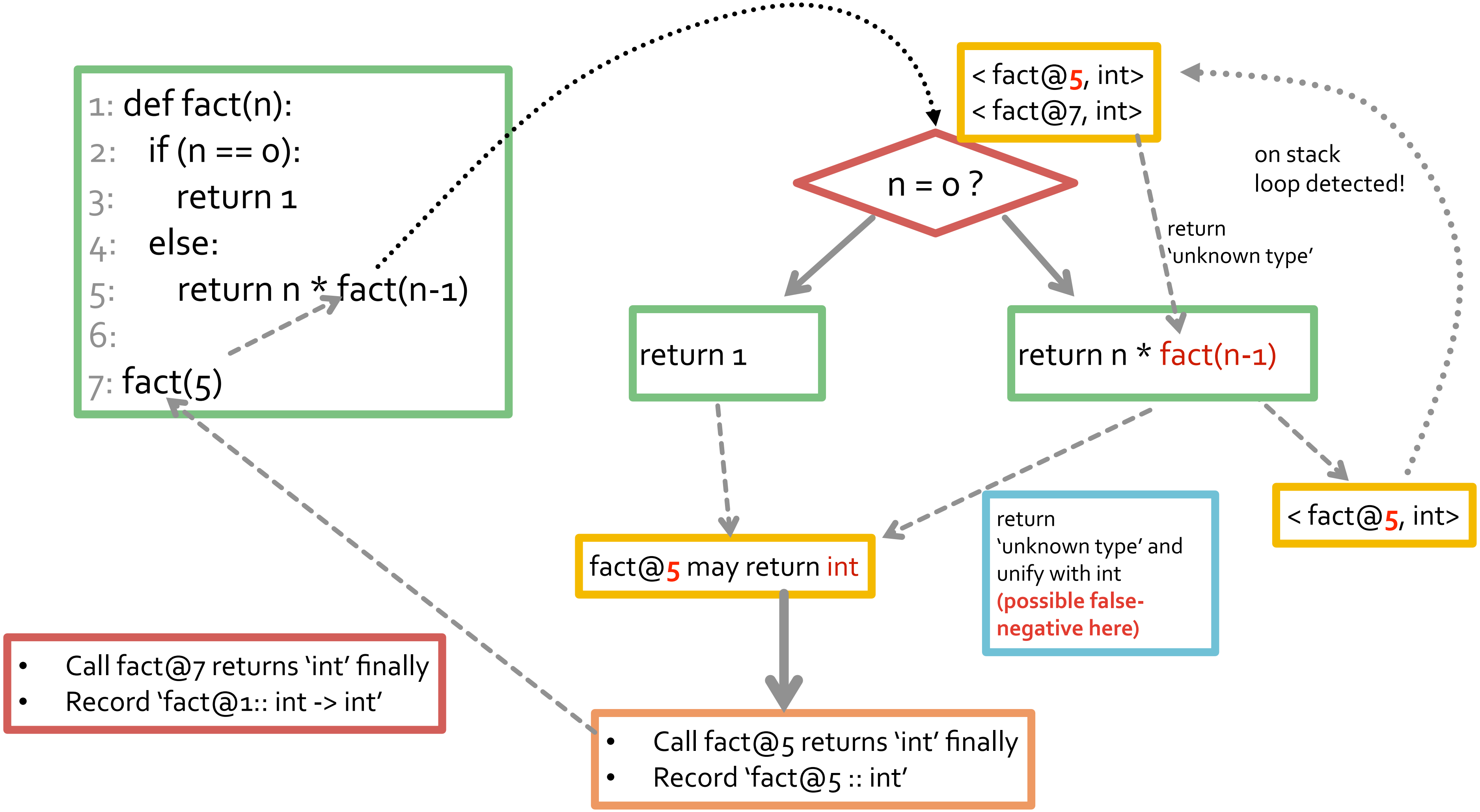

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fact@5 may return int

return 'unknown type' and unify with int **(possible false-negative here)**

- Call fact@5 returns 'int' finally
- Record 'fact@5 :: int'

- Call fact@7 returns 'int' finally
- Record 'fact@1:: int -> int'

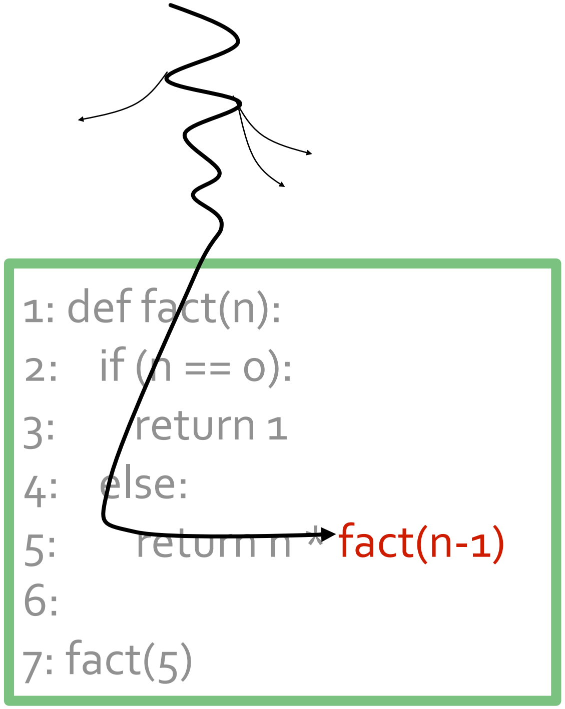
Correctness of Recursion Detection

```
def fact(n):
    if (n == 0):
        return 1
    else:
        return n * fact(n-1)

fact(5)
```

- Every program is a dynamic circuit
- Every call site is a ‘*conjuction point*’ in the dynamic circuit, because it connects to an *instance of a function body*
- The same call site with the same arguments is a unique joint point in the process graph, with a deterministic ‘future’
- If the same <*call site, argument type*> combination has appear before in the path, there must be a loop

Correctness of Recursion Detection



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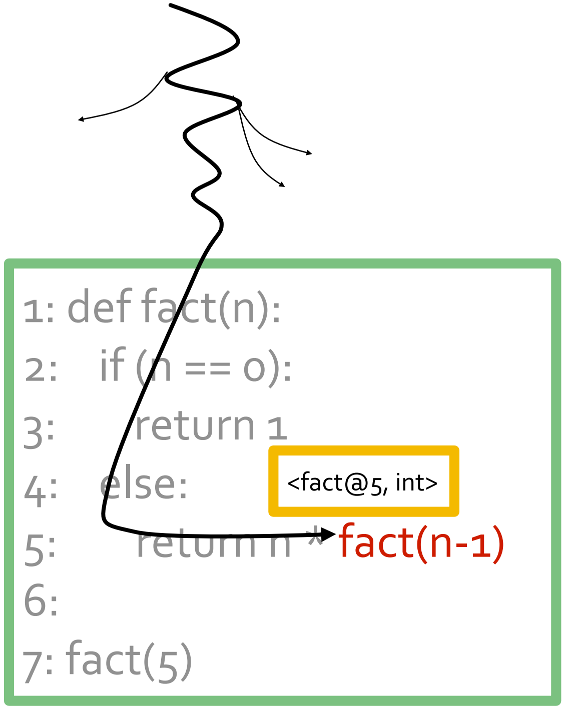

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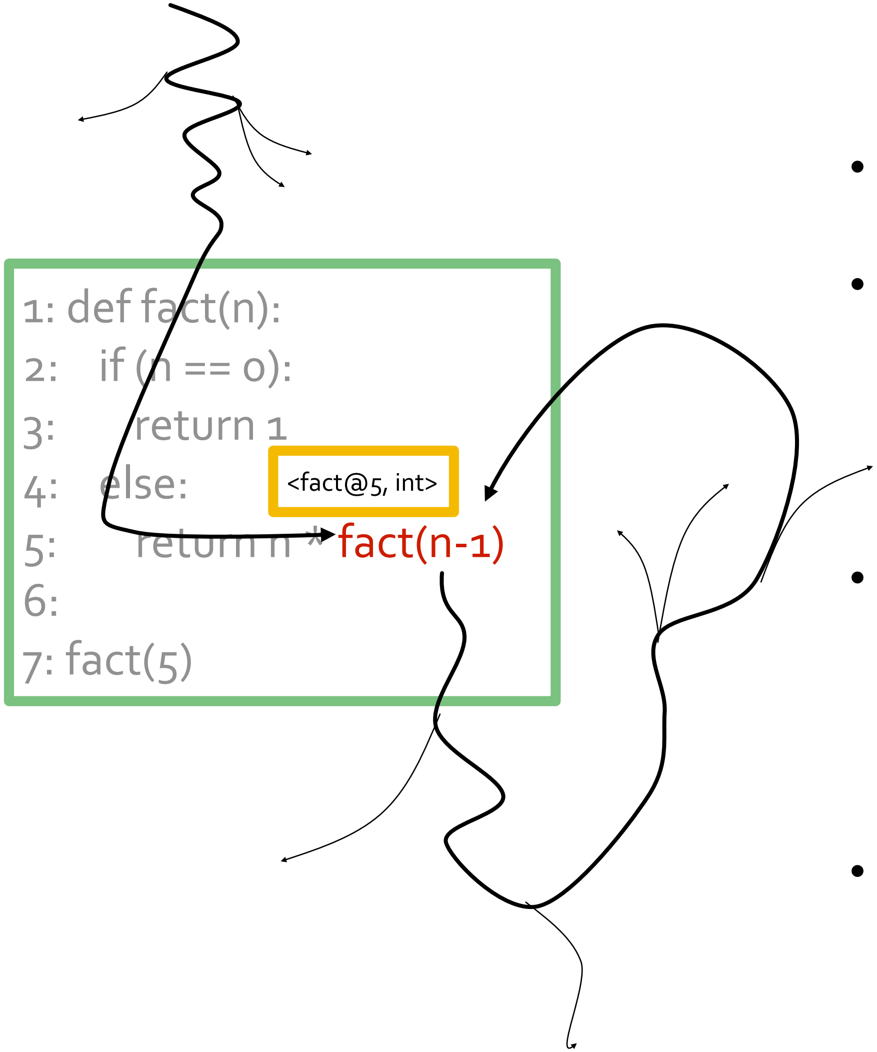

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Related Work

- Similar to "control-flow analyses", but much simpler
  - No need to build CFG (as in original CFAs)
  - No need to maintain stack manually (as in CFA2)
  - "CFG" here is dynamic and implicit (maybe impossible to build statically)
  - Doesn't record any information on the AST
  - Recursive style leads to *full utilization of host language*

- Much simpler than type inferencer of JSCompiler (Google's type inference and static checker for JavaScript)
  - JSCompiler also needs type annotations, iirc

- Very similar to NCI (Near Concrete Interpretation)
  - But using another way to detect recursion

Connections to “Deeper” Theories

- In essence, the analysis is doing a simple version of “supercompilation”
- Similar to technique used by automatic theorem provers such as ACL2
- Does not track as much information (only type information is tracked)
- Termination technique is more efficient (no expensive “*homeomorphic embedding*” checks)
  - .. but may not be as accurate
  - may cause false-negatives!

Limitations

- Doesn’t process bytecode. Needs all source code to be available (except for built-ins which was hard-coded or mocked)
- Does not track value/range of numbers
- Does not track heap storage (assume side-effects on heap won’t affect typing)
- May produce false-negatives at recursions
- Worst-case complexity is high
  - More approximations can be used to improve efficiency (at the cost of reducing accuracy)
- Error reports are not user-friendly for deep bugs

Applicability

- A general way of type inference/static analysis
- Can be applied to any programming language
- More useful for *dynamic languages* because type annotations of static languages make it a lot easier and more *modular*
- There are always trade-offs though

Availability

- 2009 version “Jython Indexer” (in Java, open-source)
  - *modular analysis* with unification (similar to HM system)
  - can’t resolve some names
  - fast
  - currently used by Google for building code index
  - open-sourced to Jython

- 2010 version “PySonar” (in Java, not open-source)
  - *inter-procedural analysis*
  - *can resolve most names*
  - *can detect deeper semantic bugs*
  - *slow*

- *2011 version “mini-pysonar” (in Python, open-source)*
  - *available from GitHub*
  - *contains only the essential parts for illustrating the idea*

Possible Future Work

- Apply the technique to other (hopefully simpler) languages
- Publish a paper about the general method
- Derive other ideas from the same intuition

Thank you!