Program Analysis

Dynamic Analysis Frameworks

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Warm-up Quiz

What does this Python code print?

```
from goto import label, goto, comefrom

i = 3
comefrom .repeat
i = i - 1
print(i)
if i == 1:
    goto .end
label .repeat
label .end
print("End")
```

2, 1, End

2, 1, 0

Something else

Warm-up Quiz

What does this Python code print?

```
from goto import label, goto, comefrom

i = 3
comefrom .repeat
i = i - 1
print(i)
if i == 1:
    goto .end
label .repeat
label .end
print("End")
```

There is no `goto` or `comefrom` in Python!

(But it was announced on April 1, 2004, as a joke.)

2, 1, End

2, 1, 0

Something else

Outline

1. **Introduction**
2. **Special-Purpose Dynamic Analysis**
3. **General-Purpose Frameworks**

Relevant papers:

- *Valgrind: A Framework for Heavyweight Dynamic Binary Instrumentation*, Nethercote et al., PLDI 2007
- *Jalangi: A Selective Record-Replay and Dynamic Analysis Framework for JavaScript*, Sen et al., FSE 2013
- *DynaPyt: A Dynamic Analysis Framework for Python*, Eghbali et al., FSE 2022

Dynamic Analysis

- Execute an instrumented program to gather information that can be analyzed to learn about a property of interest
- Precise: All observed behavior actually happens
- Incomplete: Very difficult to cover all possible behaviors

Examples

- **Coverage**: Track which lines or branches get executed
- **Call graph**: Track which functions call which other functions
- **Slicing**: Track dependencies to produce a reduced program
- We'll see more in upcoming lectures

Examples

- **Coverage**: Track which lines or branches get executed
- **Call graph**: Track which functions call which other functions
- **Slicing**: Track dependencies to produce a reduced program
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Different goals, similar challenges:

Use a common framework

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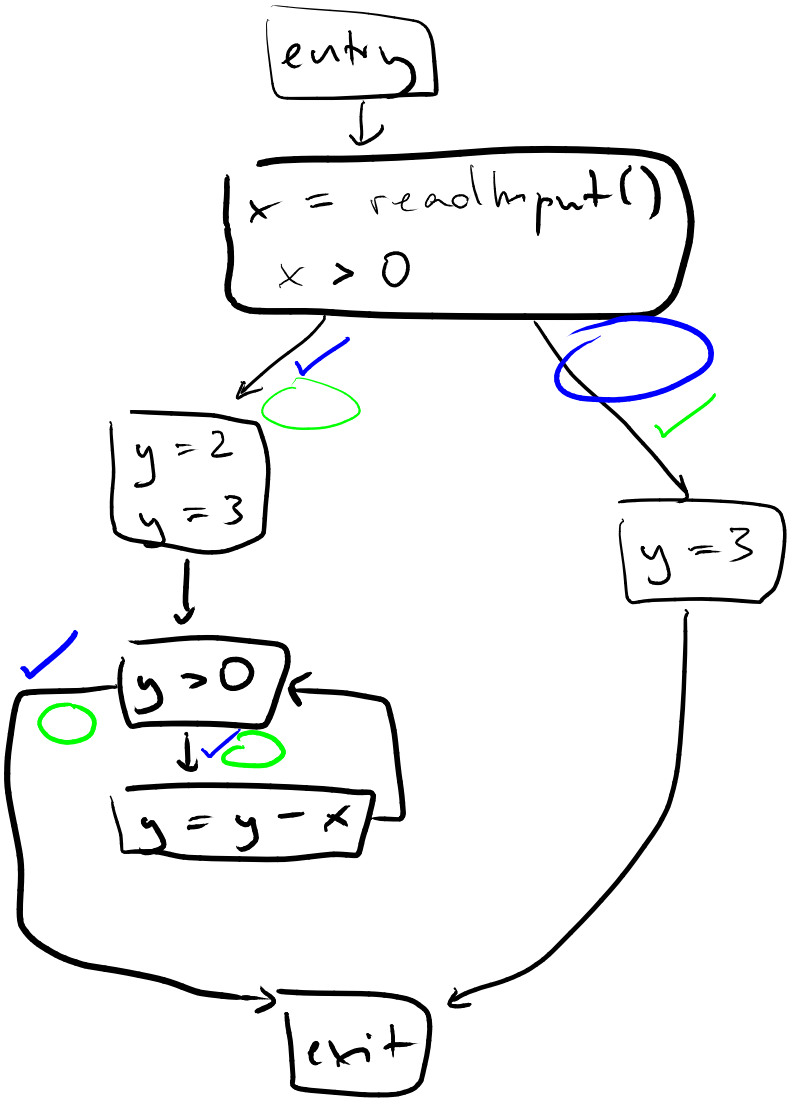
Coverage Analysis

Goal: Track which branches are executed

```
x = readInput();
if (x > 0) {
  y = 2;
  y = 3
  while (y > 0) {
    y = y - x;
  }
} else {
  y = 3
}
```



Input 1: 5

3/4 branches covered

Input 2: -5

1/4 branches covered

Instrumented Program

Add instrumentation code at beginning of each basic block

```
x = readInput();
if (x > 0) {
  y = 2;
  y = 3
  while (y > 0) {
    y = y - x;
  }
} else {
  y = 3
}
```

```
cov = [false, false, false, false];
x = readInput();
if (x > 0) {
  cov[0] = true;
  y = 2;
  y = 3
  while (y > 0) {
    cov[3] = true;
    y = y - x;
  }
  cov[2] = true;
} else {
  cov[1] = true;
  y = 3
}
```

Quiz

```
cov = [false, false, false, false];
x = readInput();
if (x > 0) {
  cov[0] = true;
  y = 2;
  y = 3
  while (y > 0) {
    cov[3] = true;
    y = y - x;
  }
  cov[2] = true;
} else {
  cov[1] = true;
  y = 3
}
```

Given the input 1, what's the branch coverage?

Quiz

```
cov = [false, false, false, false];
x = readInput();
if (x > 0) {
  cov[0] = true;
  y = 2;
  y = 3
  while (y > 0) {
    cov[3] = true;
    y = y - x;
  }
  cov[2] = true;
} else {
  cov[1] = true;
  y = 3
}
```

Given the input 1, what's the branch coverage?

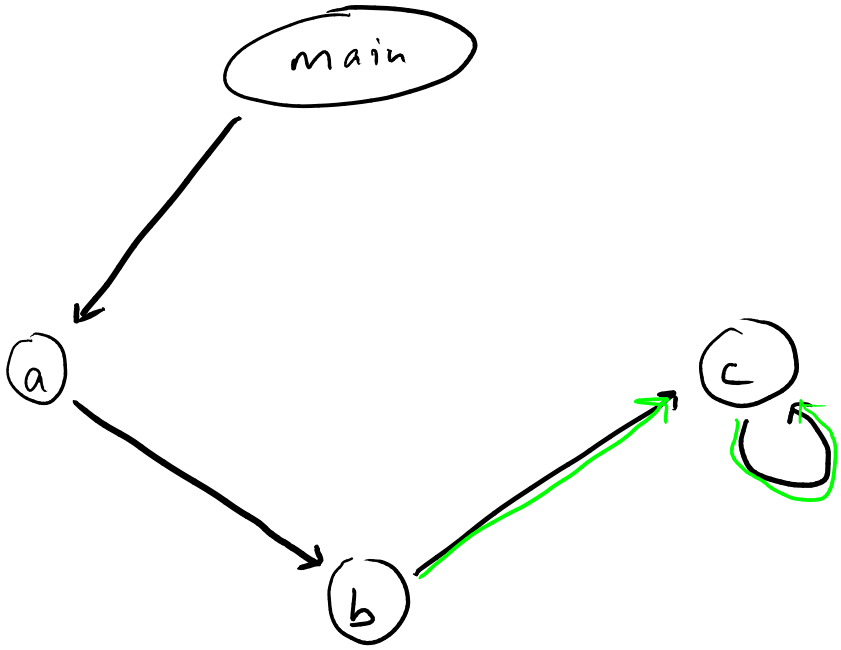
Answer:

`[true, false, true, true]`

Call Graph Analysis

Goal: Track "calls" relationships between functions

```
n = readInput();
function a() {
  b();
}
function b() {
  if (n == 5) {
    c();
  }
}
function c() {
  if (n == 5) {
    c();
    n--;
  }
}
a();
```



static overapproximation of call graph

Instrumented Program

Add instrumentation code at each call site

```
n = readInput();
function a() {
  b();
}
function b() {
  if (n == 5) {
    c();
  }
}
function c() {
  if (n == 5) {
    c();
    n--;
  }
}
a();
```

```
calls = new Set();
n = readInput();
function a() {
  calls.add("a->b"); b();
}
function b() {
  if (n == 5) {
    calls.add("b->c"); c();
  }
}
function c() {
  if (n == 5) {
    calls.add("c->c"); c();
    n--;
  }
}
calls.add("main->a"); a();
```

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Commonalities

Different dynamic analyses, but many commonalities

- Specific runtime events to track
- Analysis updates some state in response to events

Commonalities

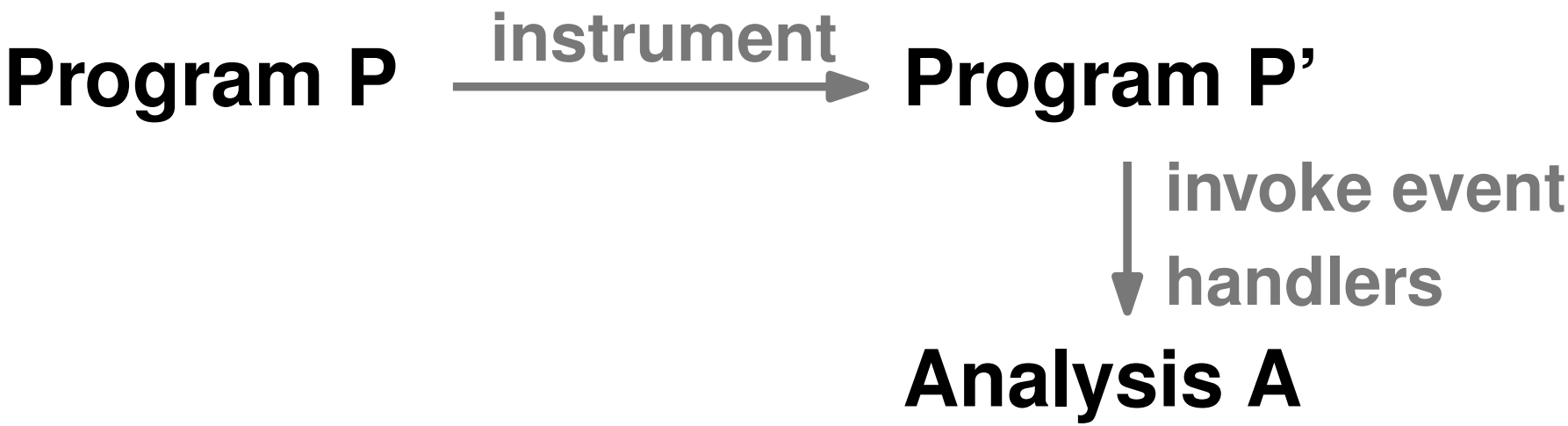
Different dynamic analyses, but many commonalities

- Specific runtime events to track
- Analysis updates some state in response to events

Can avoid re-implementing everything from scratch for each new analysis?

Dynamic Analysis Frameworks

- Set of kinds of runtime events
- Analysis can register for specific events
- At runtime, instrumented program invokes event handlers



Typical Runtime Events

Event	Example
Arithmetic operation	`2+3`
Boolean operation	`a > 0`
Branch	`if (c) ...`
Function call	`g()`
Return from function call	`x = g()`
Write into variable or field	`x.f = z`
Read of variable or field	`x.f = z`

(and many others)

Example

```
a = readInput();
b = a + 3;
if (b == -23) {
  foo();
} else {
  b = 5;
}
```

Runtime events:

- Arithmetic operations
- Boolean operations
- Reads of variables
- Writes into variables
- Function calls

Input: -26

What sequence of events get triggered?

Runtime Events: Example

- call of readInput
- write -26 into a
- read of a (-26)
- arithmetic operation (-26 + 3 = -23)
- write -23 into b
- read b (-23)
- boolean operation (-23 == -23 ⇝ true)
- call to foo()

Extended Operational Semantics

- Tracking runtime events: Additional behavior performed during program execution
- Formally describe by extending the operational semantics

Extending Small-Step Operational Semantics

Events: - write to variable → "write 3 to x"

- branch → "true branch taken"

Extend configuration into:

$\langle P, s, e \rangle$ where • P, s as before

e ... sequence of events (represented as strings)

•

Replace all actions & rules to use triple configuration, e.g.,

$$\frac{}{\langle !\ell, s\rangle \rightarrow \langle n, s\rangle \quad \text{if } s(\ell) = n} \text{ (var)}$$

becomes

$$\frac{}{\langle !\ell, s, e\rangle \rightarrow \langle n, s, e\rangle \quad \text{if } s(\ell) = n} \text{ (var)}$$

events remain the same

Revise axioms & rules to create new events

1) write to variables:

$$\frac{}{\langle l := n,\ s \rangle \longrightarrow \langle skip,\ s[l \mapsto n] \rangle}\ (:=)$$

becomes

$$\frac{}{\langle l := n,\ s,\ e \rangle \longrightarrow \langle skip,\ s[l \mapsto n],\ e \circ \text{"write of } n \text{ to } l\text{"} \rangle}\ (:=)$$

append to sequence

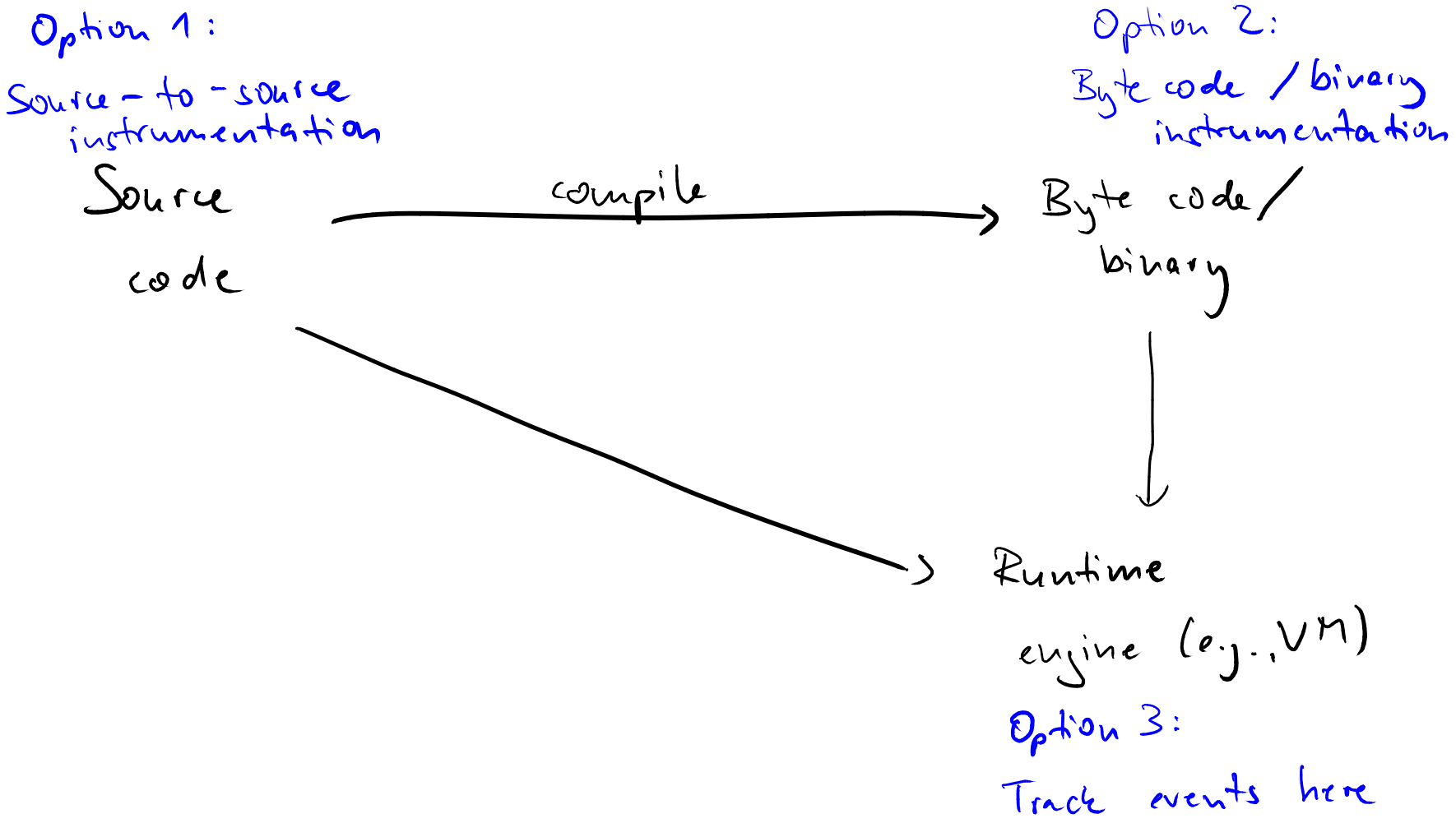
21 Quiz: Extend axioms & rules for tracing branches

$$\frac{}{\langle \text{if True then } c_1 \text{ else } c_2, s, e\rangle \rightarrow \langle c_1, s, e \circ \text{"true branch taken"}\rangle}\ (\text{if}_T)$$

(analogous for False)

Implementing Dynamic Analyses

How to implement a dynamic analysis framework in practice?


Option 1:
Source-to-source instrumentation
Source code
compile
Byte code / binary
Option 2:
Byte code / binary instrumentation
Runtime engine (e.g., VM)
Option 3:
Track events here

Source Code Instrumentation

Naive approach:

Find and extend particular statements via regular expressions

Example:

```
// Before: x=y; foo(); a=b;
// After:  x=y; foo(); evt('call'); a=b;
regex = /; (\w+\(\))/g;
code.replaceAll(regex, "; $1; evt('call')")
```

Source Code Instrumentation

Naive approach:

Find and extend particular statements via regular expressions

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Identify function calls

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Add call that logs the 'call' event

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```

Cumbersome and extremely brittle:

Don't do this

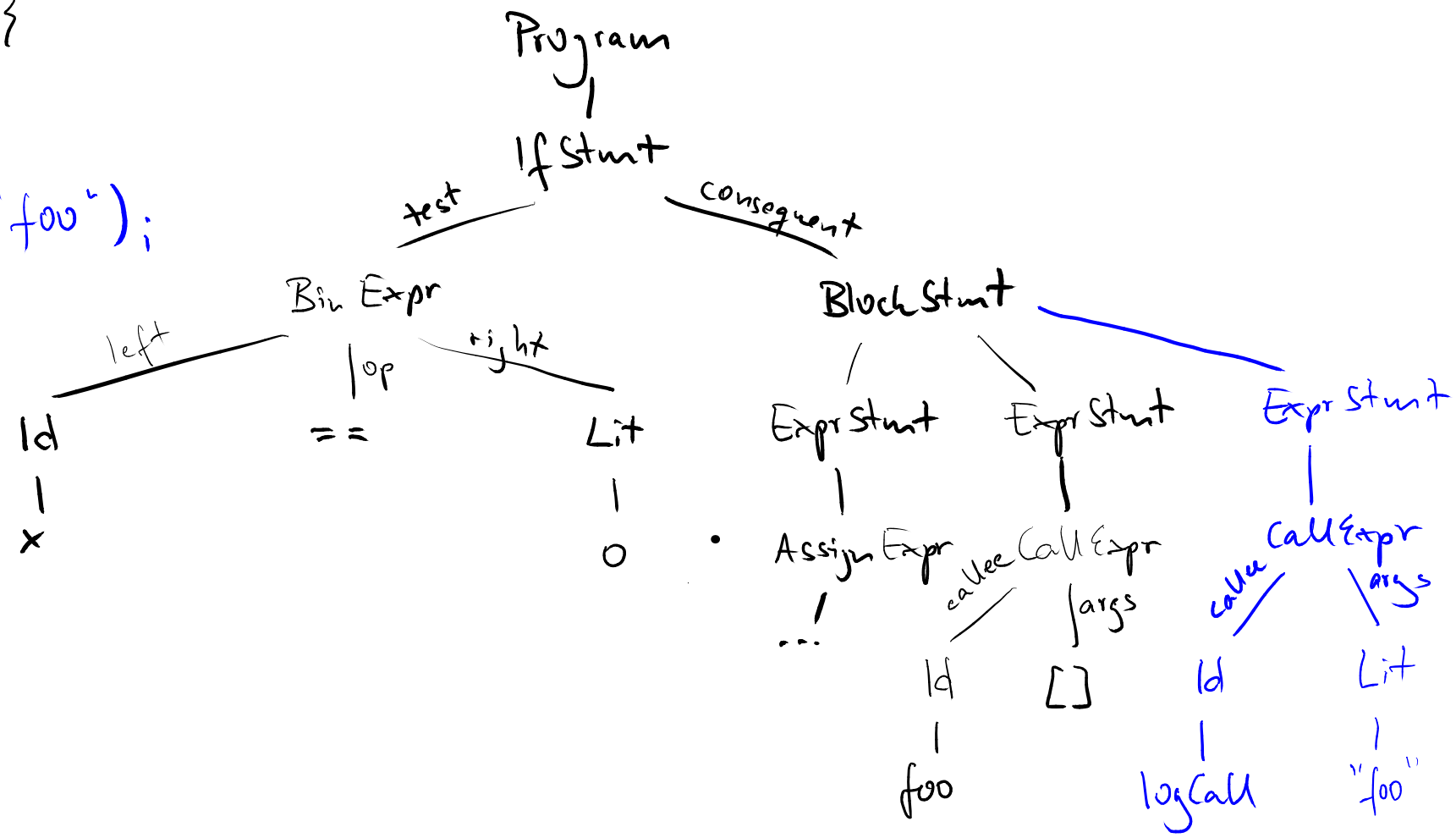
AST-based Instrumentation

More reliable approach:

- **Parse code into AST**
- **Manipulate AST, e.g., by adding subtrees**
- **Pretty-print AST into code again**

AST example

```
if (x == 0) {
    y = 3;
    foo();
    logCall("foo");
}
```



Real-World Tools

Name	Target language
Pin	x86 binaries
Valgrind	x86 binaries
DiSL	Java
RoadRunner	Java
Jalangi	JavaScript
Wasabi	WebAssembly
DynaPyt	Python

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To be used in course project

Developed by my group