Program Analysis

Dynamic Analysis Frameworks

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Warm-up Quiz

```
var a;
var a, a;
var a, a, a = a;
a = eval("var a;")
a = function a(a, a) {
    return a;
}
a = a(null, a);
console.log(a.name);
```

Warm-up Quiz

```
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var a, a;
var a, a, a = a;
a = eval("var a;")
a = function a(a, a) {
    return a;
}
a = a(null, a);
console.log(a.name);
```

Result: a

Warm-up Quiz

```
var a;
var a, a;
var a, a, a = a;
a = eval("var a;")
a = function a(a, a) {
    return a;
}
a = a(null, a);
console.log(a.name);
```

a is a function that returns the second argument, i.e., the function itself

Result: a

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
- *Wasabi: A Framework for Dynamically Analyzing WebAssembly*, Lehmann et al., ASPLOS 2019

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

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- **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
}
```

Instrumented Program

Add instrumentation code at **beginning of each basic block**

```
x = readInput();
if (x > 0) {

  y = 2;
  y = 3
  while (y > 0) {

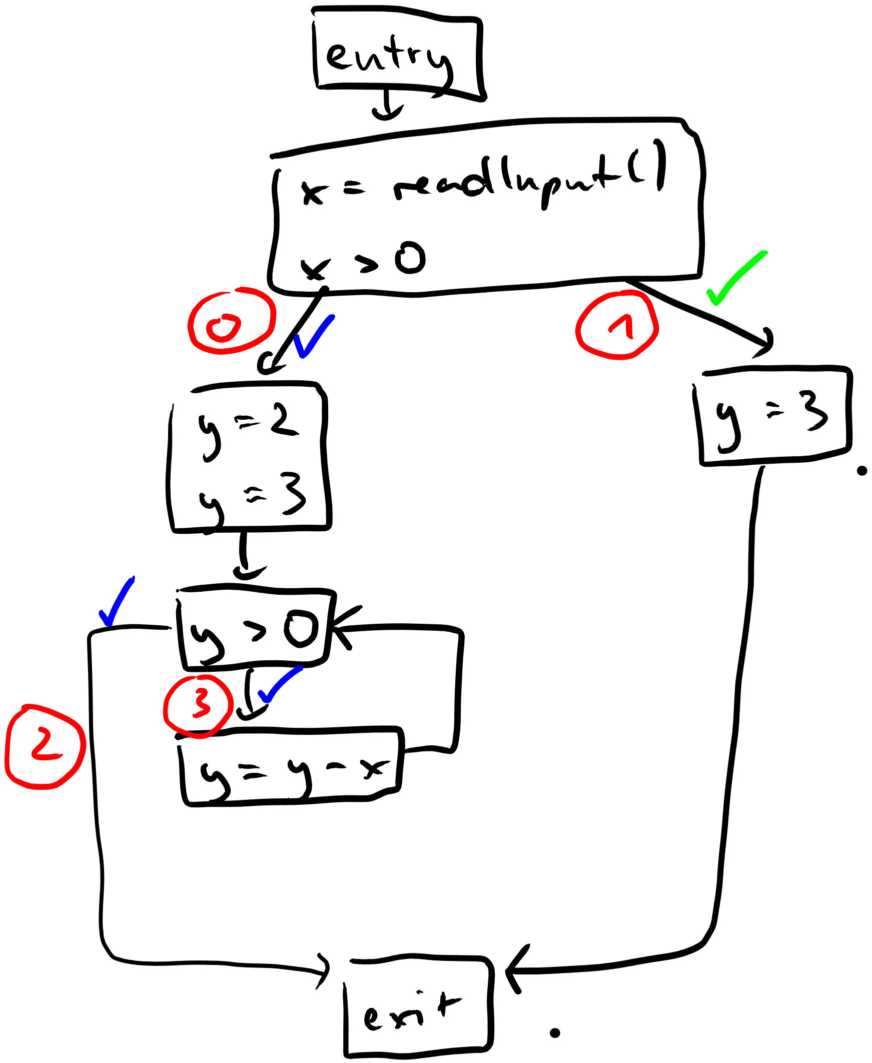
    y = y - x;
  }

} 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
}
```



Input 1 : 5

Input 2 : -5

3/4 branches covered

1/4 branches covered

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?

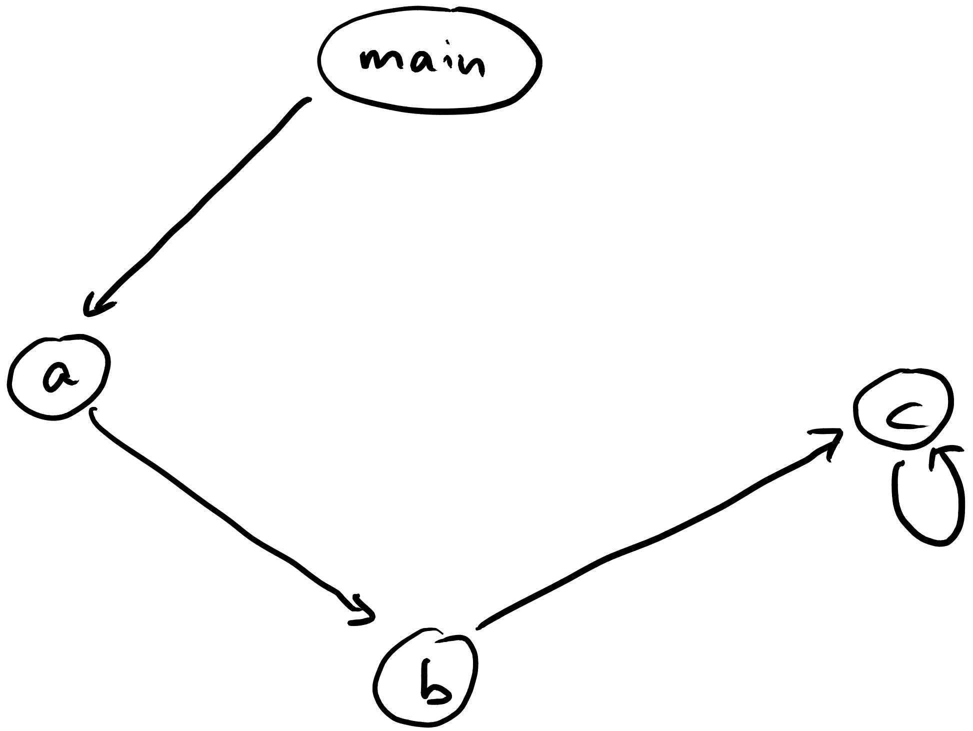
Answer:

`[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

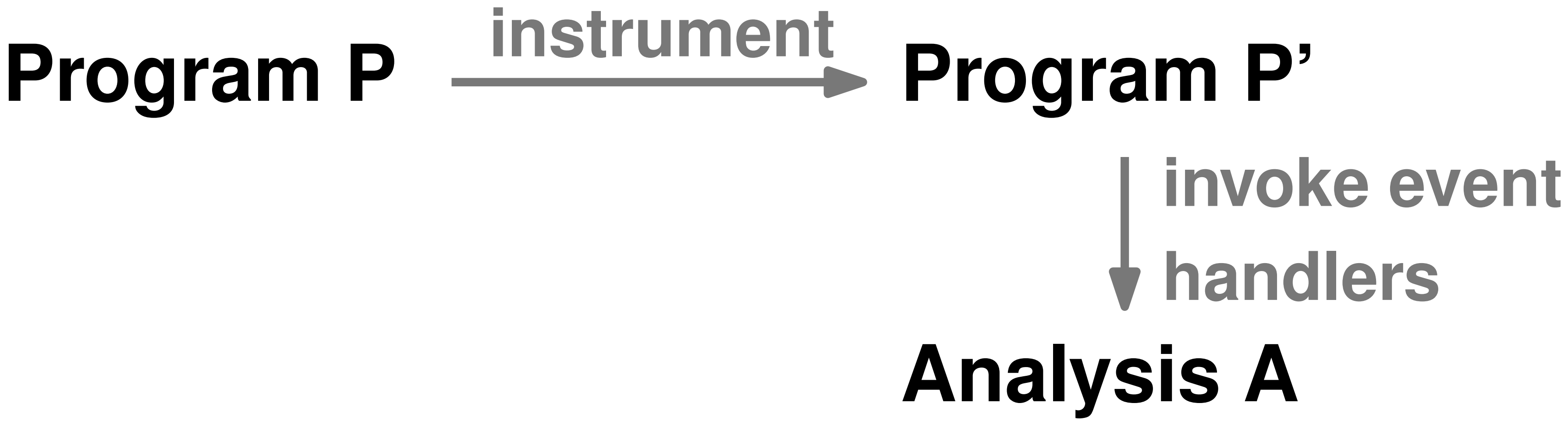
Different dynamic analyses, but many commonalities

- 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 of -23 into b
- read of b (-23)
- boolean operation (-23 == -23 ⇝ true)
- call of 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"

Extending configuration into :

⟨P, s, e⟩ where P, s as before

e .. sequence of events (represented as strings)

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

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

becomes

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

events remain the same

Revise some axioms & rules to create new events

1) writes to variables:

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

becomes

$$\frac{}{\langle \ell := n , s , e \rangle \longrightarrow \langle \mathsf{skip} , s[\ell \mapsto n] , e \underset{\text{append to sequence}}{\circ} \text{"write } n \text{ to } \ell\text{"} \rangle}\ (:=)$$

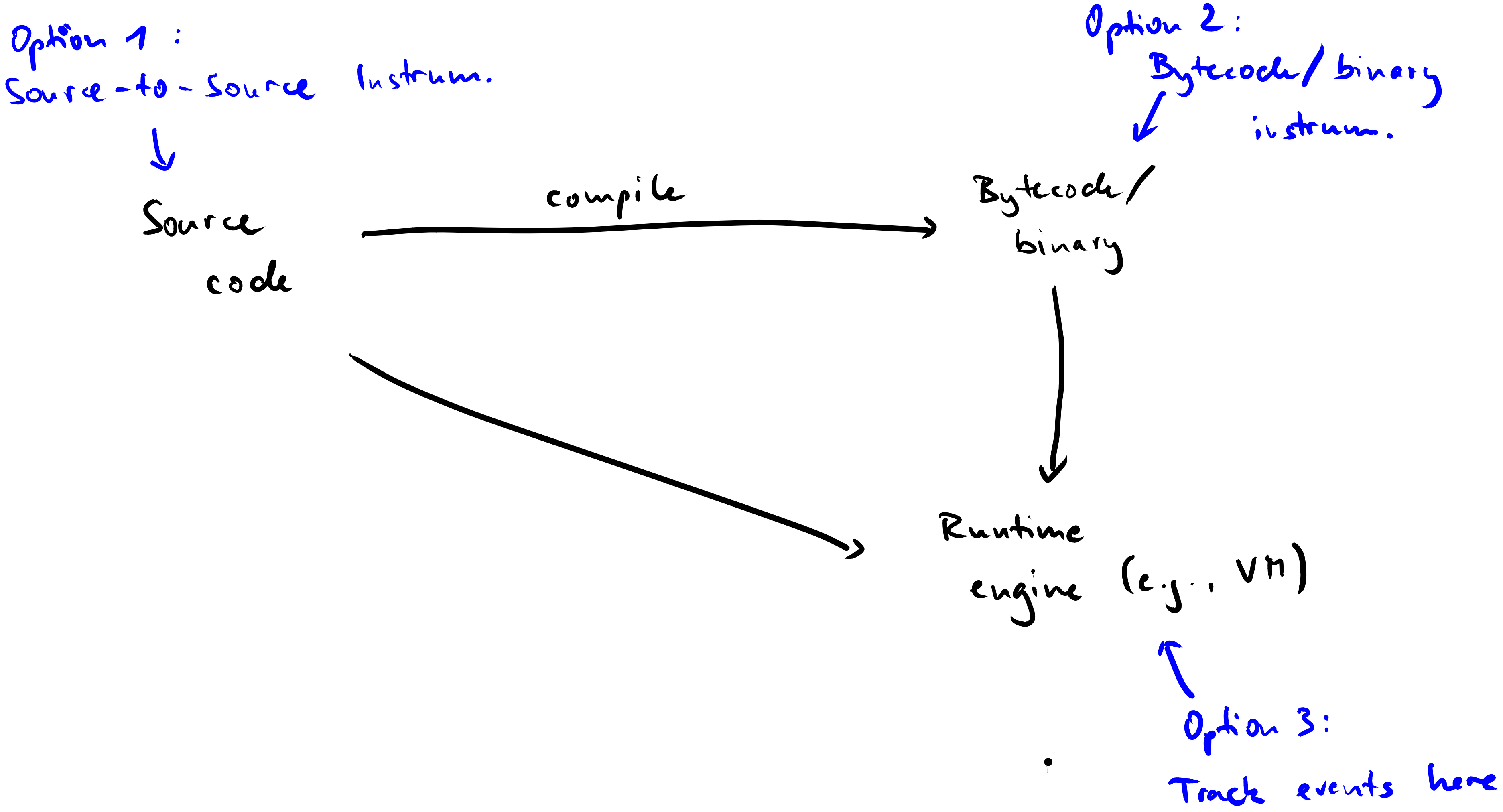
Quiz: Extend axioms & rules for tracking branches

$$\frac{}{\langle \text{if True then } C_1 \text{ else } C_2 , s, e \rangle \to \langle C_1, s, e \circ \text{"true branch taken"} \rangle} \quad (\text{if}_T)$$

(analogous for False)

Implementing Dynamic Analyses

How to **implement a dynamic analysis framework** in practice?


Option 1 :
Source-to-Source Instrum.
Source code
compile
Bytecode/ binary
Option 2 :
Bytecode/ binary instrum.
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

Example:

Identify function calls

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Identify function calls

Add call that logs the ’call’ event

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regex = /; (\w+\(\))/g;
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```

Cumbersome and extremely brittle:
Don’t do this

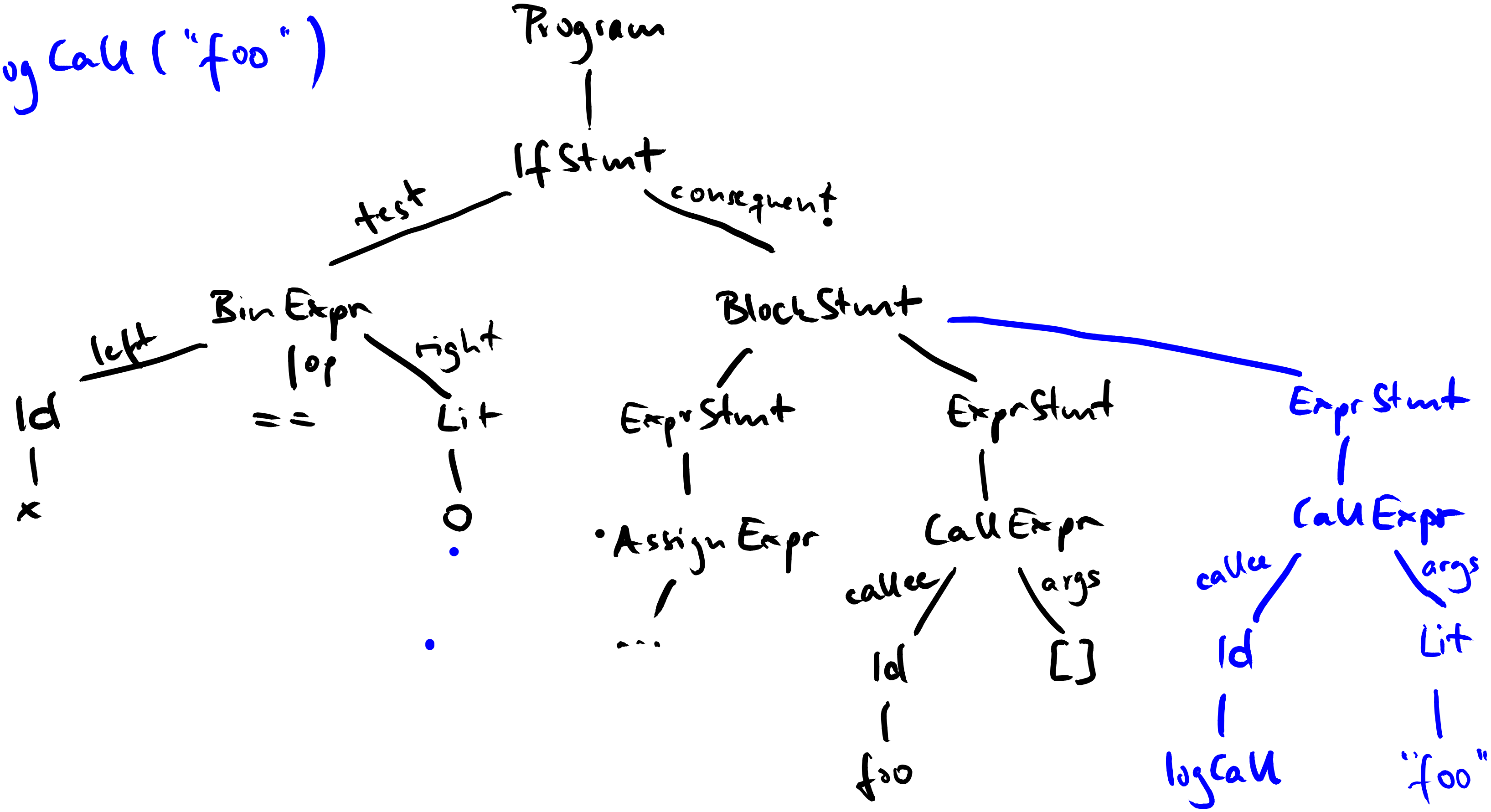
AST-based Instrumentation

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

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To be used in course project

Developed by my group (main author: Daniel Lehmann)