Finding software bugs with the Clang Static Analyzer

Ted Kremenek, Apple Inc.

Findings Bugs with Compiler Techniques

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Compile-time warnings

```
% clang t.c

t.c:38:13: warning: invalid conversion '%lb'
  printf("%s%lb%d", "unix", 10, 20);
         ~~~~^~~~~
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Static Analysis

- Checking performed by compiler warnings inherently limited
- Find path-specific bugs
- Deeper bugs: memory leaks, buffer overruns, logic errors

Benefits of Static Analysis

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Early discovery of bugs

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Systematic checking of all code

- Static analysis reasons about all corner cases

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- Static analysis reasons about all corner cases

Find bugs without test cases

- Useful for finding bugs in hard-to-test code
- Not a replacement for testing

This Talk: Clang “Static Analyzer”

Clang-based static analysis tool for finding bugs

- Supports C and Objective-C (C++ in the future)

Outline

- Demo
- How it works
- Design and implementation
- Looking forward

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Clang-based static analysis tool for finding bugs

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- How it works
- Design and implementation
- Looking forward

http://clang.llvm.org

Demo

How does static analysis work?

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- Per-statement, per-function, whole-program all important

```
int f(int y) {
  int x;

  if (y)
    x = 1;

  printf("%d\n", y);

  return x;
}
```

compiler warnings (simple checks)

```
% gcc -Wall -O1 -c t.c
t.c: In function ‘f’:
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this function

% clang -warn-uninit-values t.c
t.c:13:12: warning: use of uninitialized variable
    return x;
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How does static analysis work?

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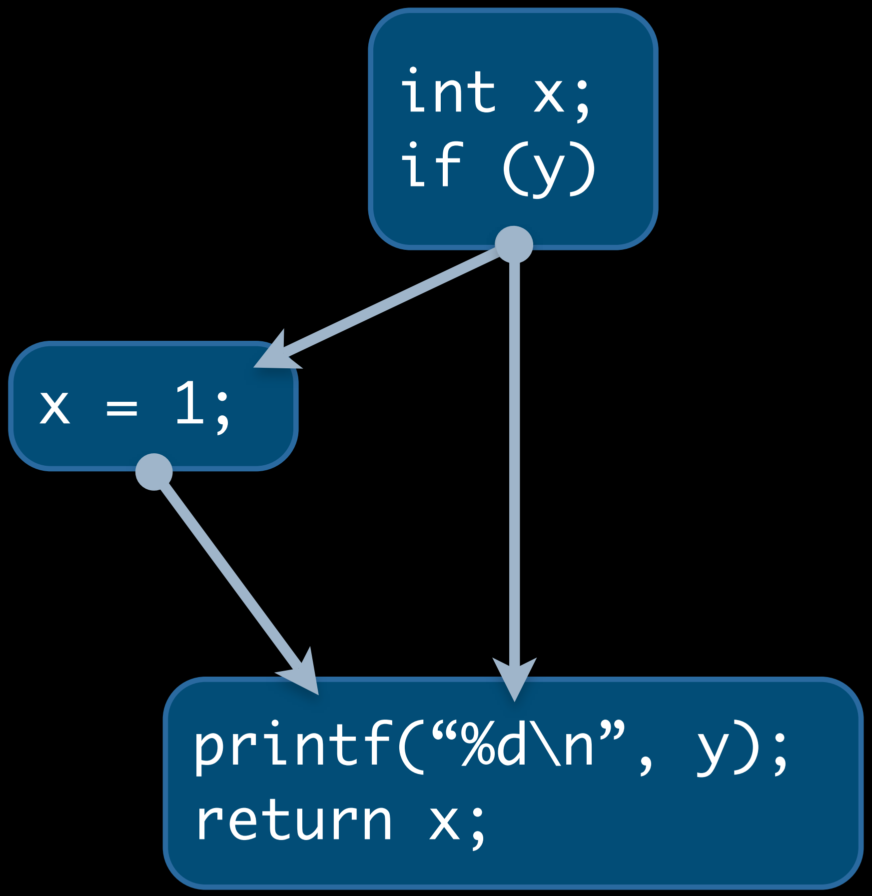
control-flow graph



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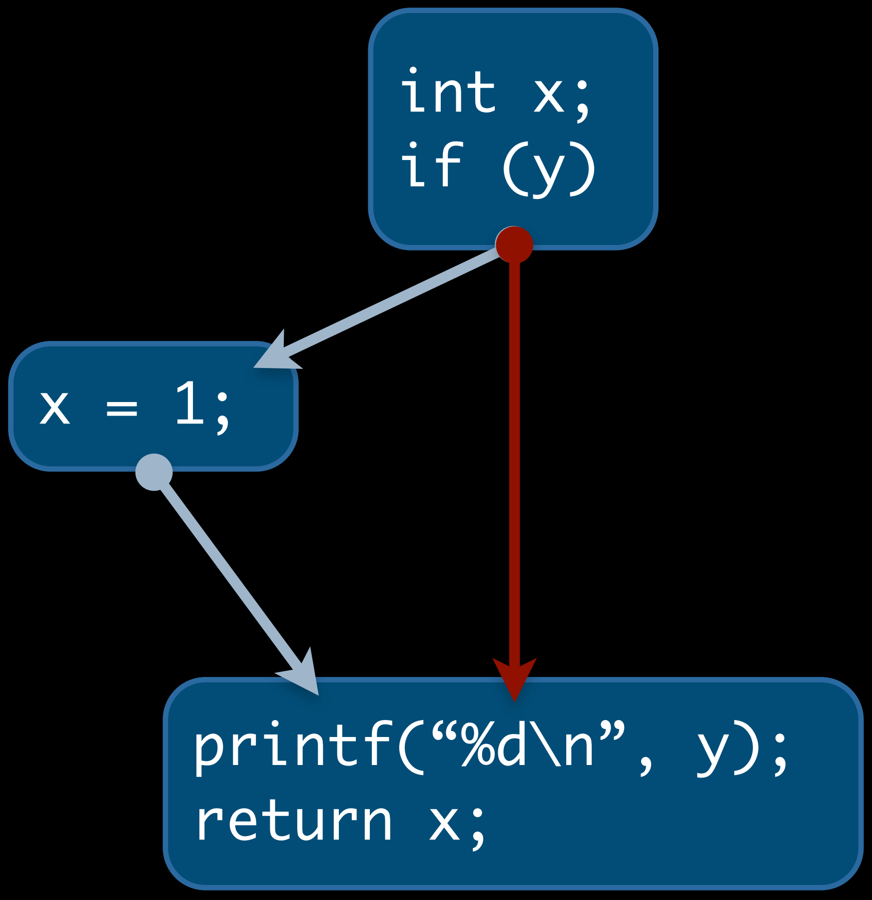

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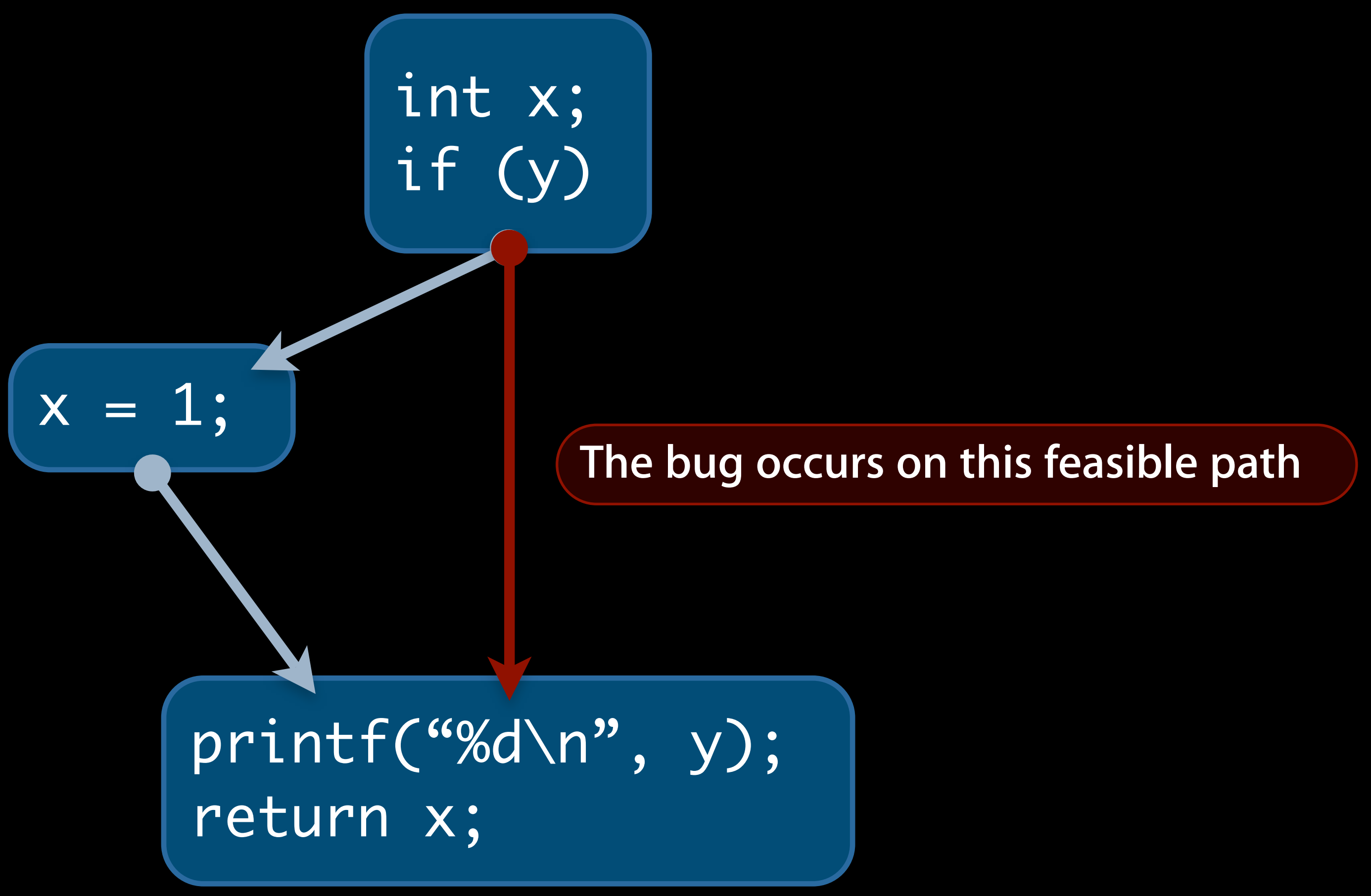

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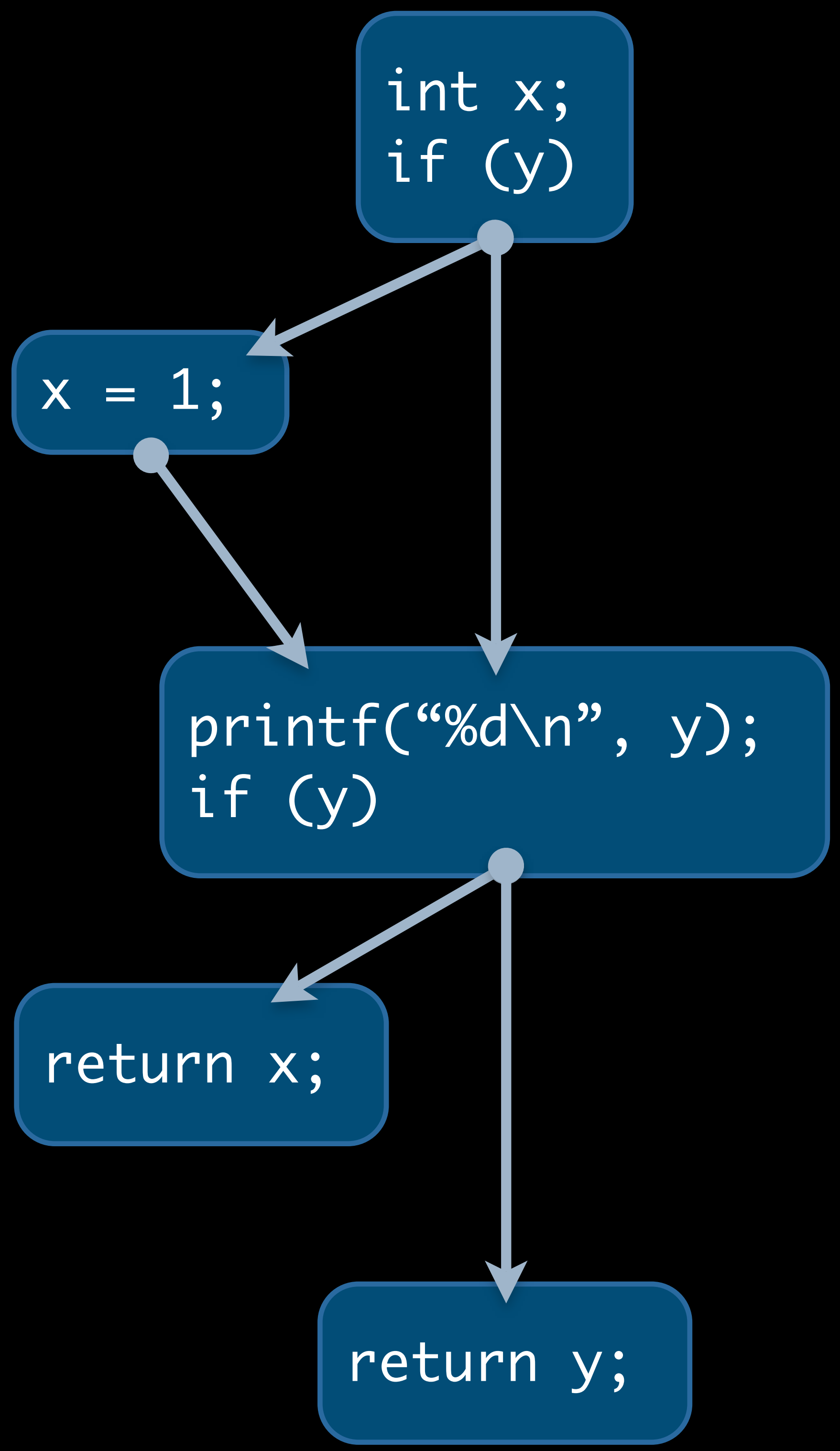

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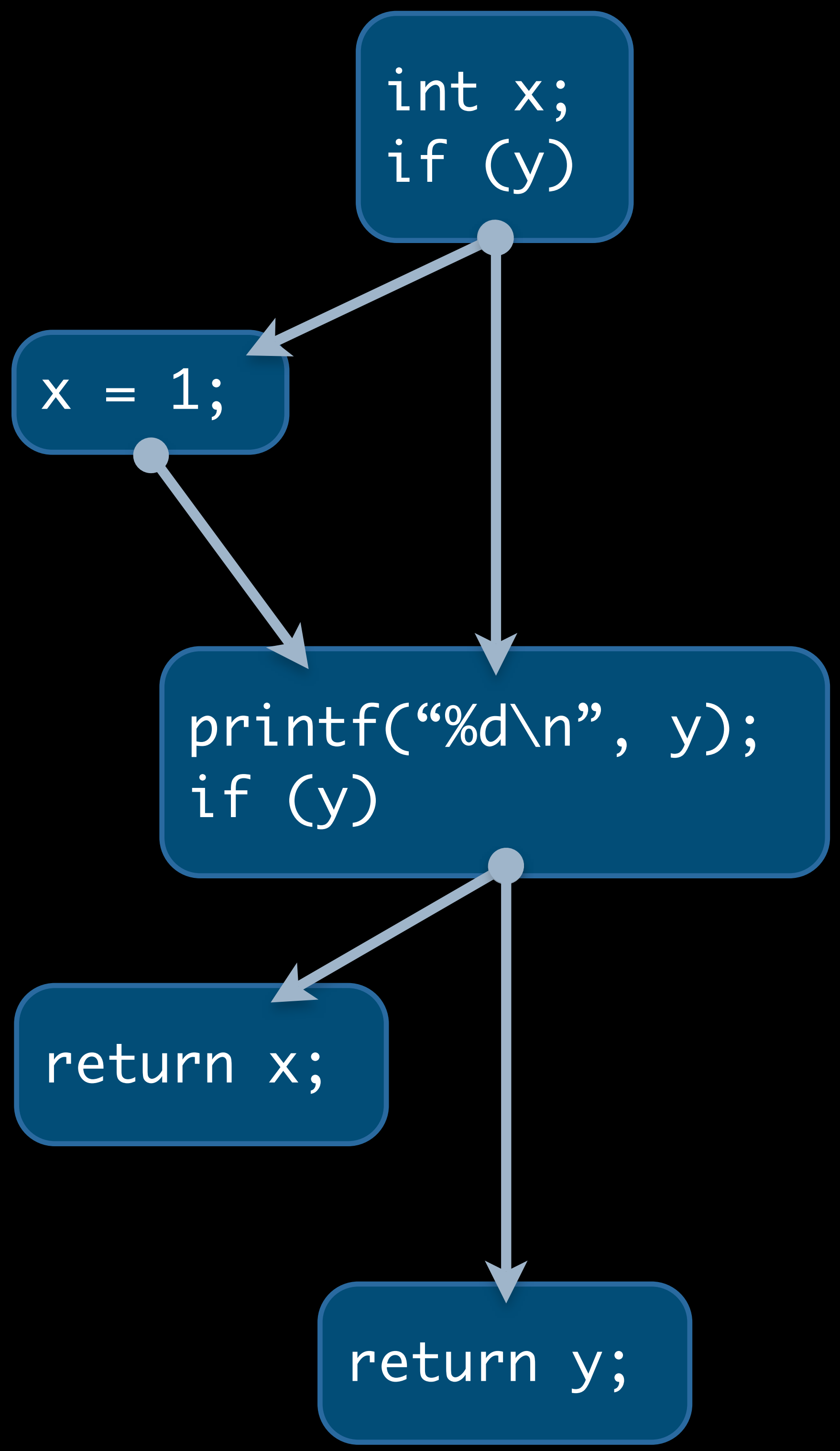

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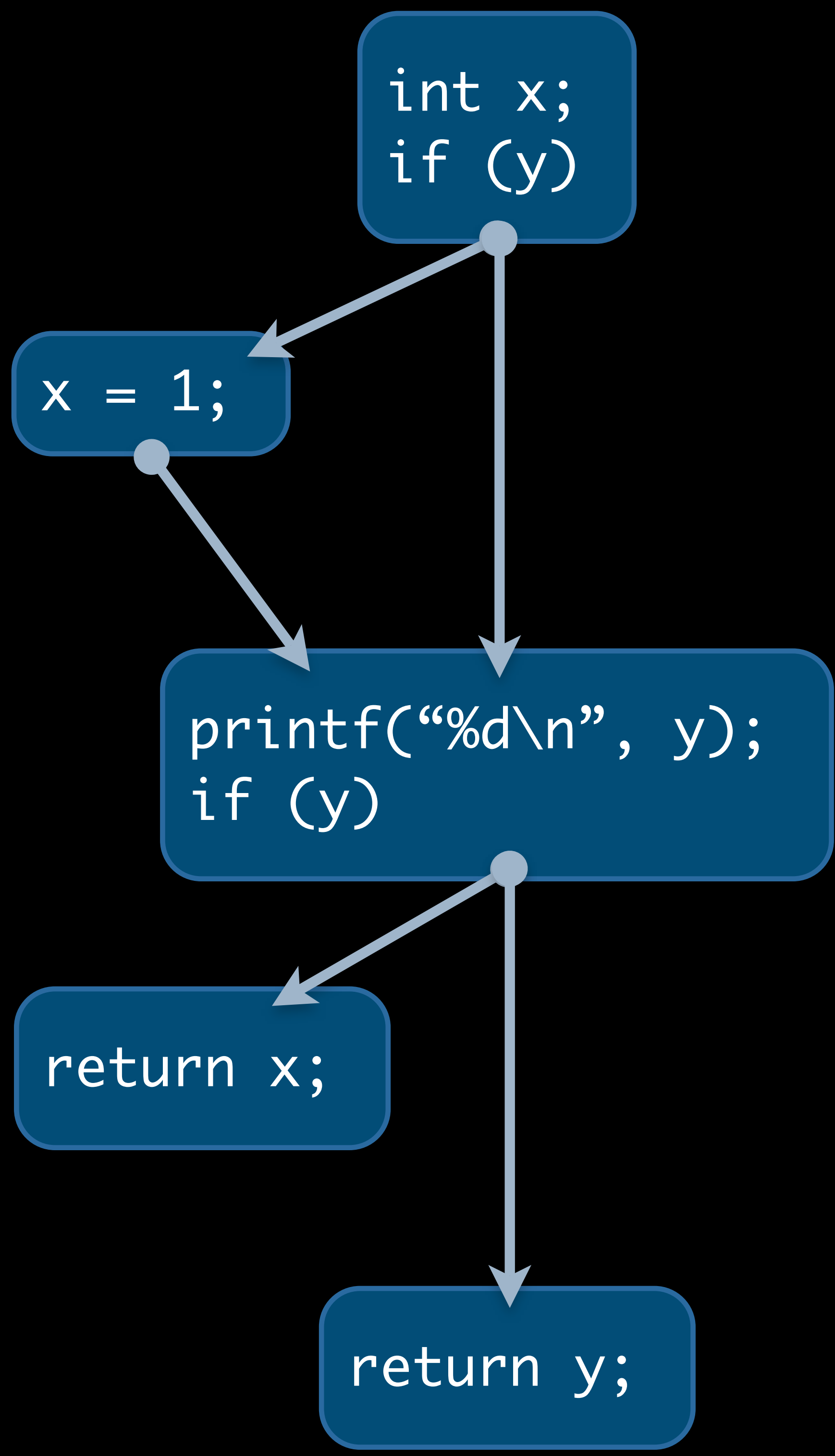


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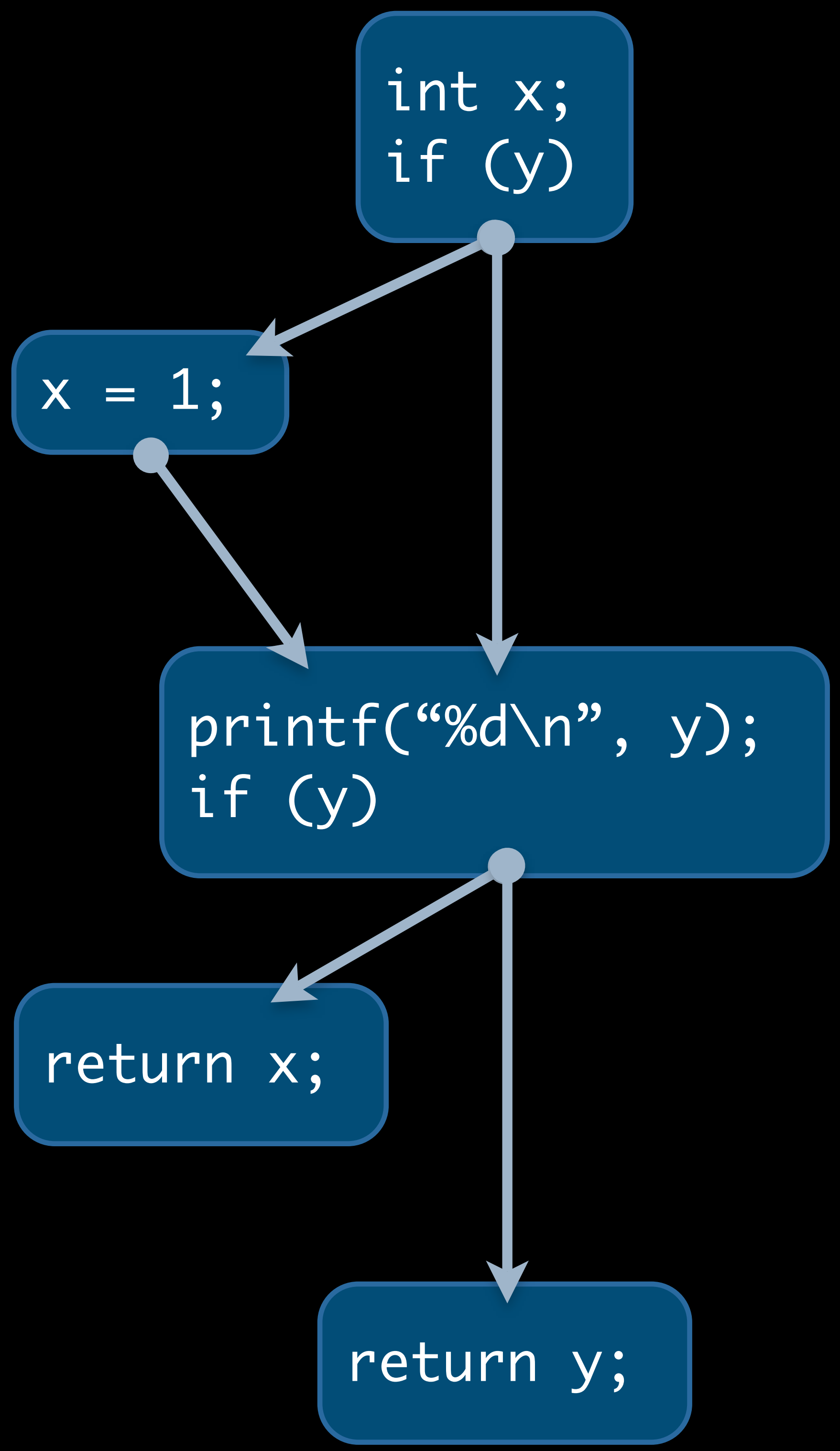


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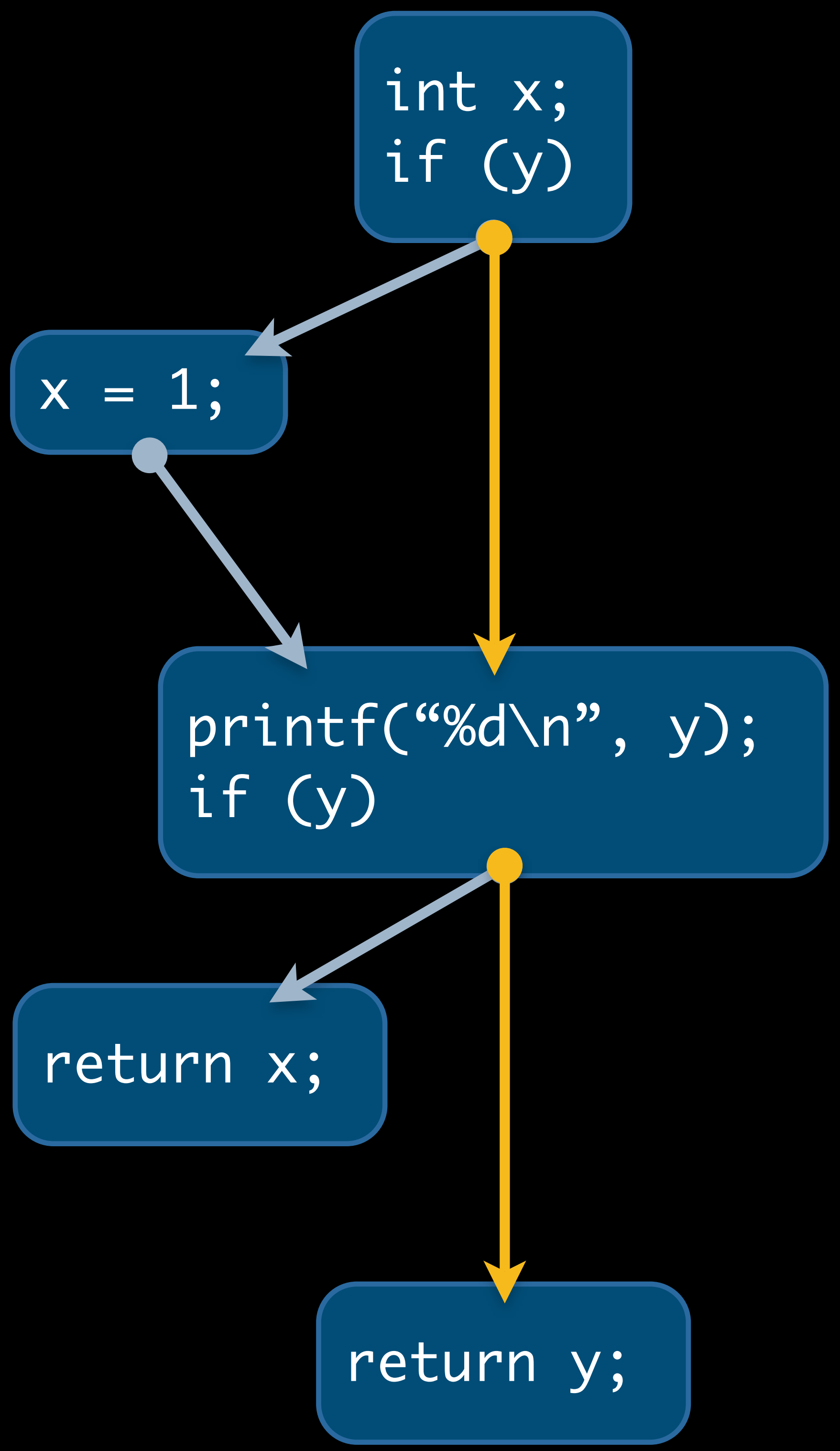


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- Neither branch taken (y == 0)

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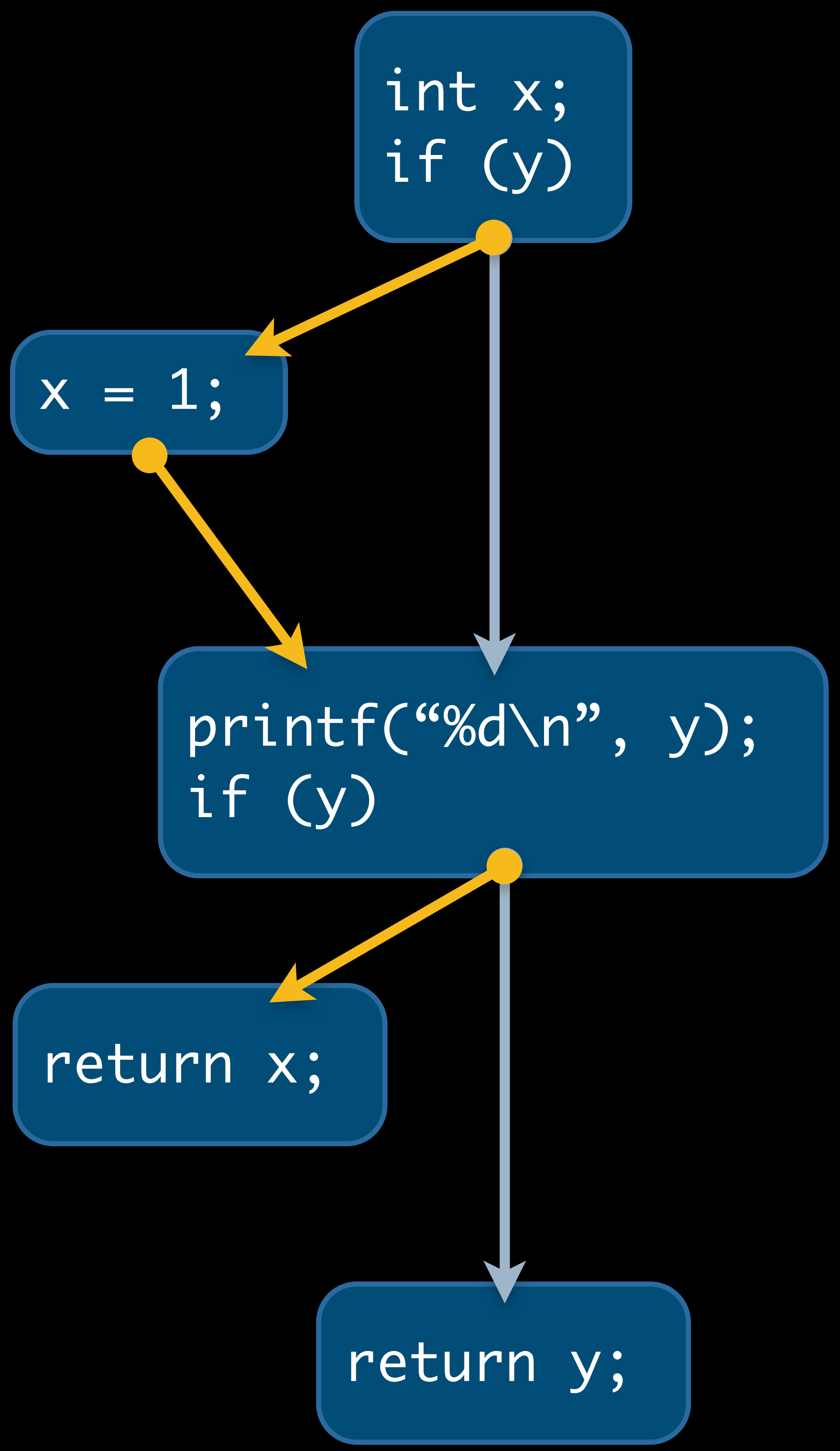


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Two feasible paths:

- Neither branch taken (y == 0)
- Both branches taken (y != 0)

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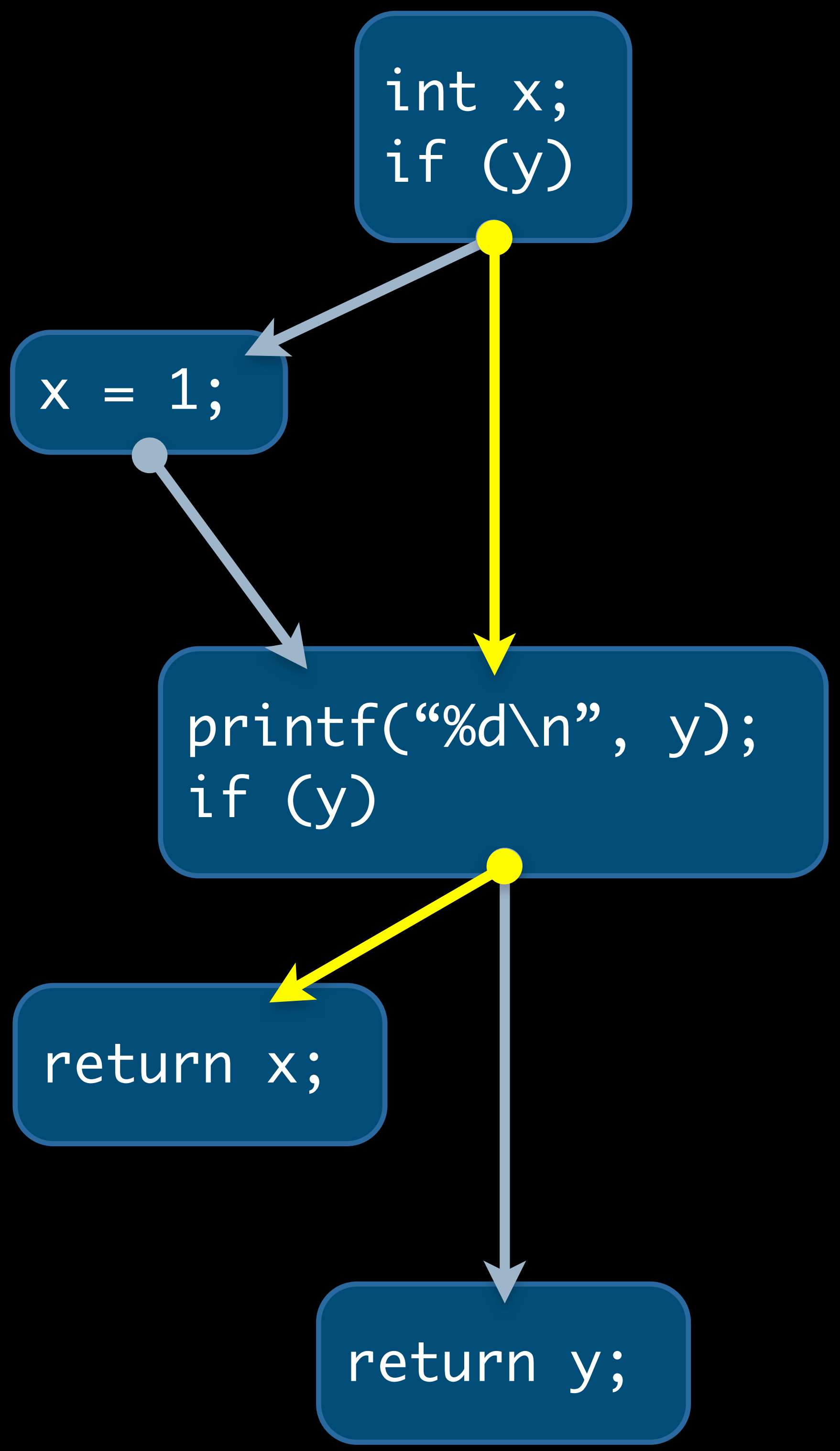

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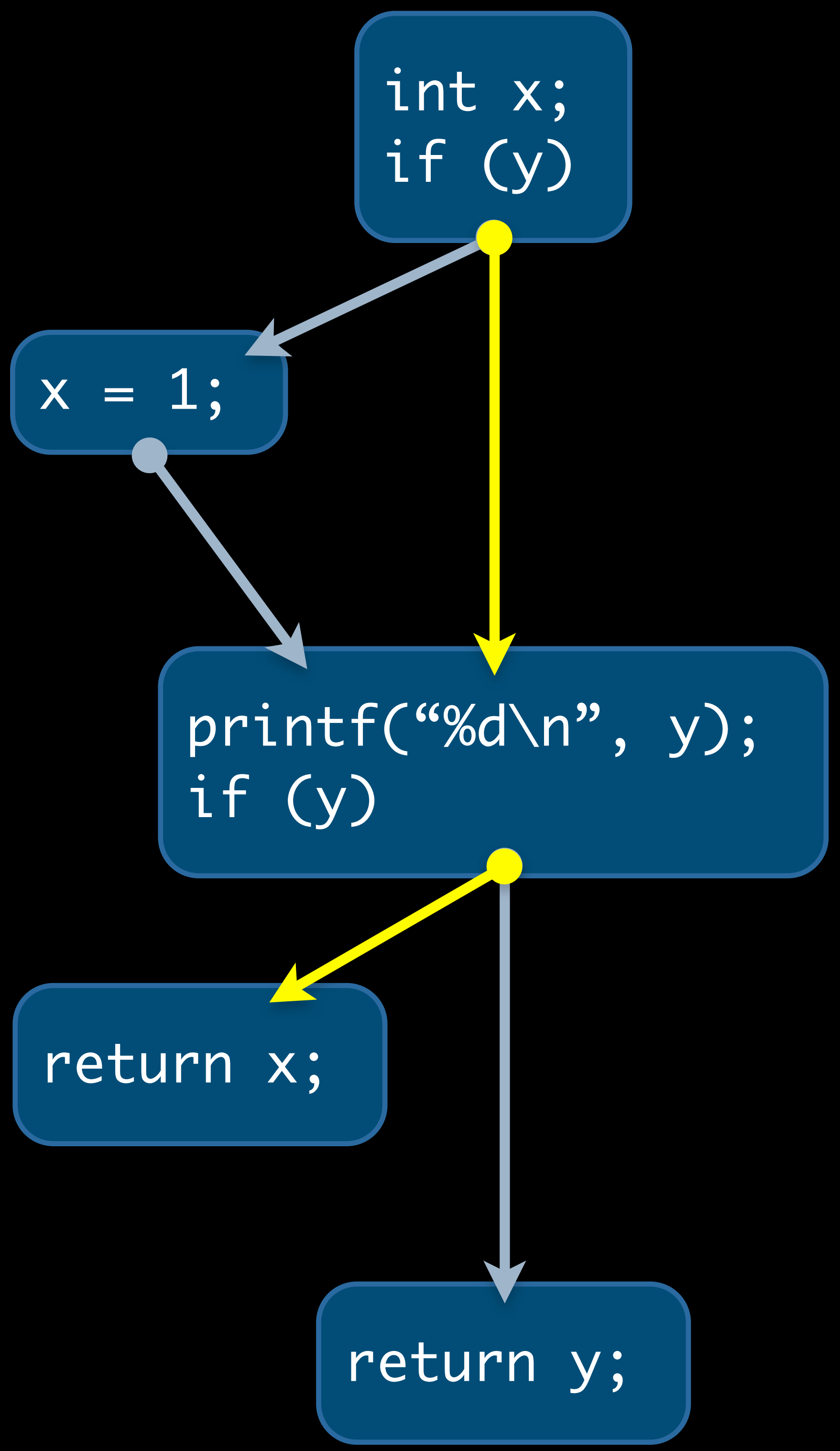

Bogus warning occurs on infeasible path:

- Don't take first branch (y == 0)
- Take second branch (y != 0)

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  - False paths
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- False positives can occur due to analysis imprecision
  - False paths
  - Insufficient knowledge about the program
- Many ways to reduce false positives
  - More precise analysis
  - Difficult to eliminate false positives completely

Flow-Sensitive Analyses

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- Flow-sensitive analyses reason about flow of values

```
y = 1;
x = y + 2;  // x == 3
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- No path-specific information

```
if (x == 0)
  ++x;          // x == ?
else
  x = 2;        // x == 2
y = x;          // x == ?, y == ?
```

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- LLVM's SSA form designed for flow-sensitive algorithms

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- LLVM's SSA form designed for flow-sensitive algorithms
- Linear-time algorithms
  - Used by optimization algorithms and compiler warnings

Path-Sensitive Analyses

Path-Sensitive Analyses

- Reason about individual paths and guards on branches

```
if (x == 0)
  ++x;          // x == 1
else
  x = 2;        // x == 2
y = x;          // (x == 1, y == 1) or (x == 2, y == 2)
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Path-Sensitive Analyses

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- Uninitialized variables example:
  - Path-sensitive analysis picks up only 2 paths
  - No false positive

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- Uninitialized variables example:
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  - No false positive
- Worst-case exponential-time
  - Complexity explodes with branches and loops
  - Lots of clever tricks to reduce complexity in practice
- Clang static analyzer uses flow- and path-sensitive analyses

Finding leaks in Objective-C code

Memory Management in Objective-C

Objective-C in a Nutshell

- Used to develop Mac/iPhone apps
- C with object-oriented programming extensions

Memory management

- Objective-C objects have embedded reference counts
- Reference counts obey strict ownership idiom
- Garbage collection also available… but there are subtle rules

Ownership Idiom

Ownership Idiom

```
// Allocate an NSString. Since the object is newly allocated,
// ‘str’ is an owning reference (+1 retain count).
NSString* str = [[NSString alloc] initWithCString:“hello world”
                                  encoding:NSASCIIStringEncoding];
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// count we have because ‘str’ is an owning reference.
foo(str);
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foo(str);

// We’re done using str. Decrement our ownership count.
[str release];
```

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foo(str);

// We’re done using str. Decrement our ownership count.
// LEAK!
```

Memory Leak: Colloquy

```
32
33 - (void) interpretKeyEvents:(NSArray *) eventArray {
```

[1] Method returns an object with a +1 retain count (owning reference).

```
34         NSMutableArray *newArray = [[NSMutableArray allocWithZone:nil] init];
35         NSEnumerator *e = [eventArray objectEnumerator];
36         NSEvent *anEvent = nil;
37
```

[2] Taking true branch.

```
38         if( ! [self isEditable] ) {
```

[3] Object allocated on line 34 and stored into 'newArray' is no longer referenced after this point and has a retain count of +1 (object leaked).

```
39                 [super interpretKeyEvents:eventArray];
40                 return;
41         }
42
```

Ownership DFA

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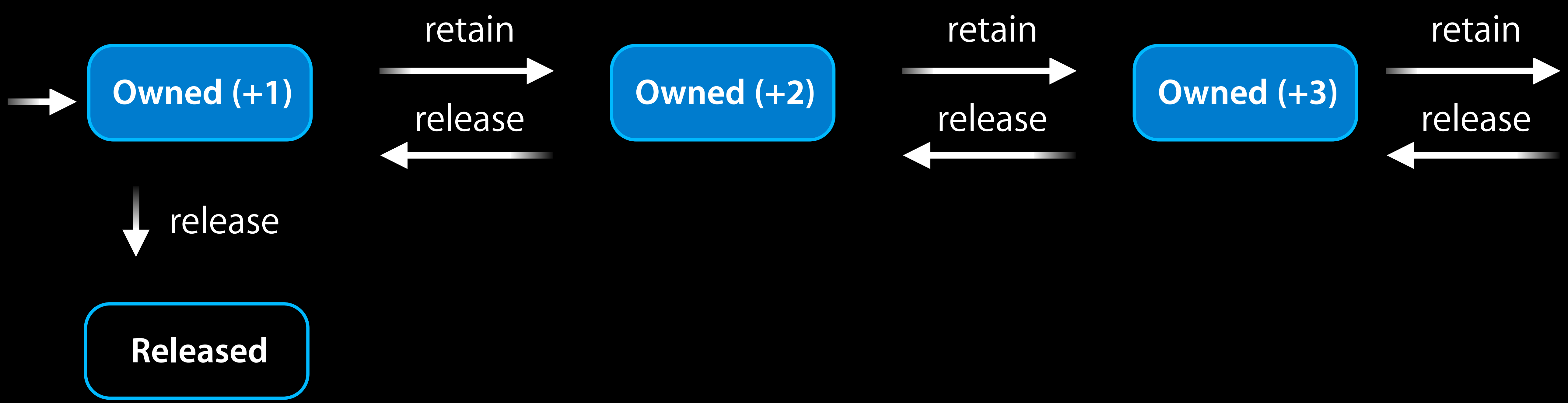

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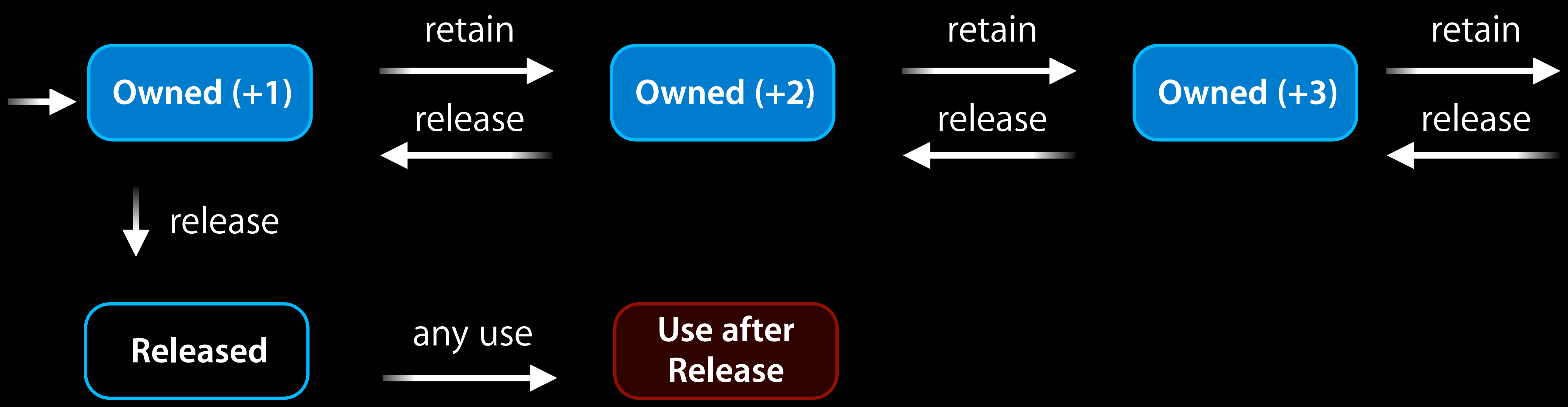

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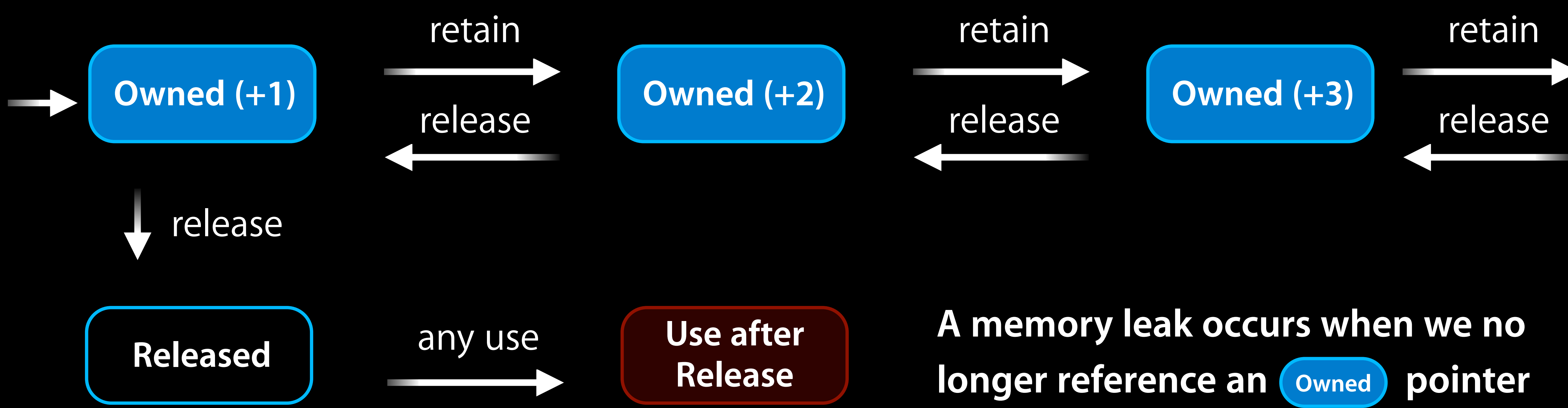
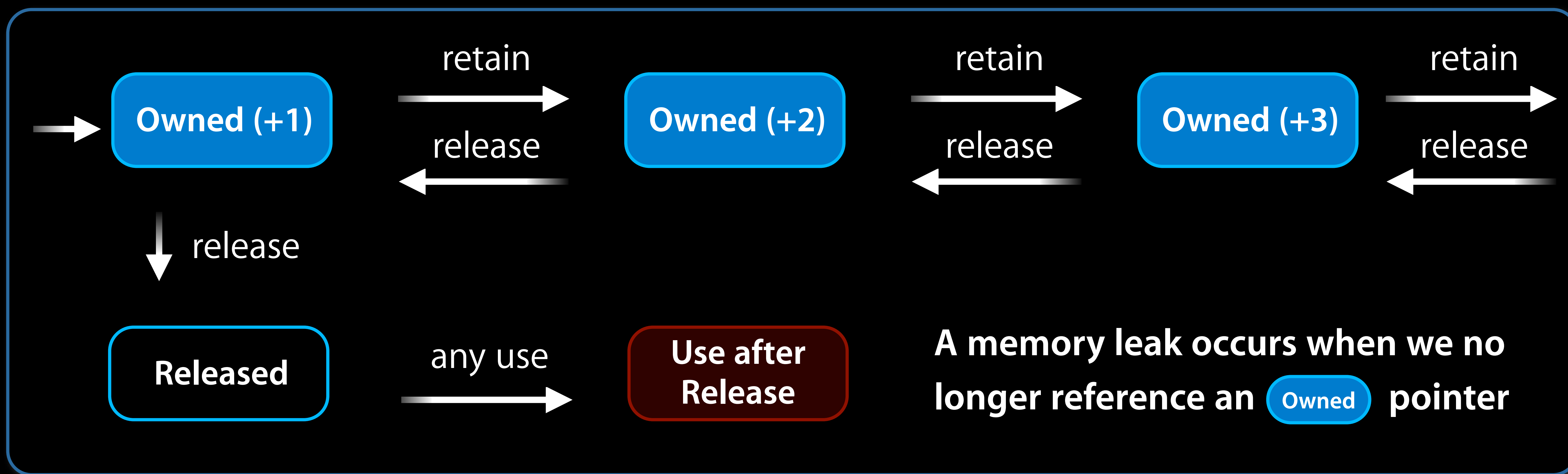
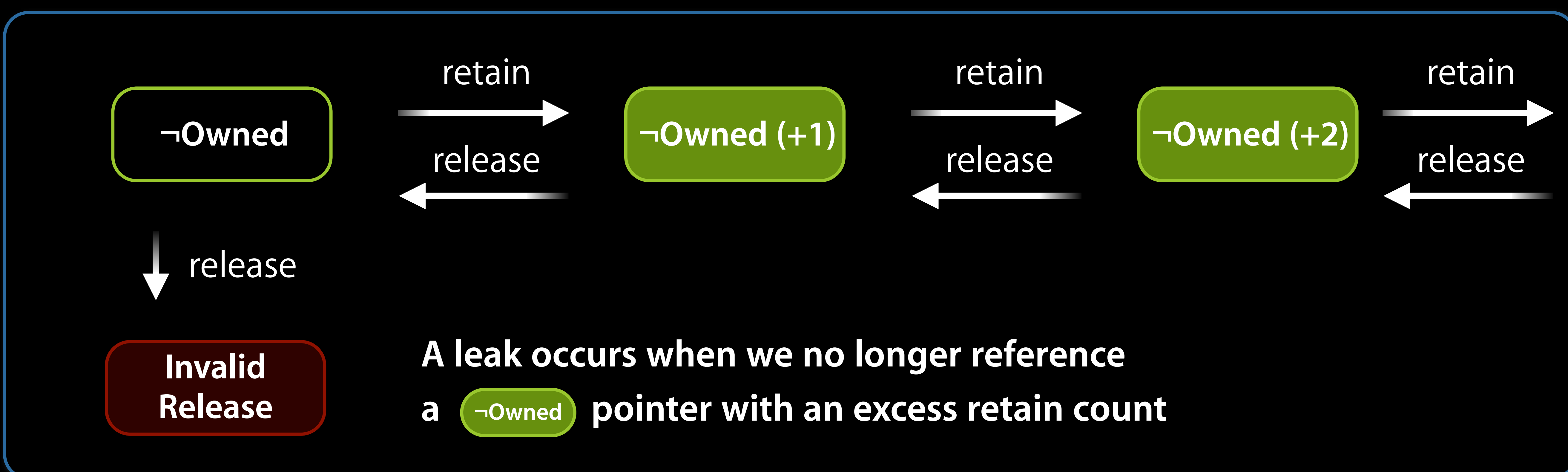


A memory leak occurs when we no longer reference an Owned pointer

Ownership DFA





Miscellanea

Checker-specific issues

- Autorelease pools
- Objective-C 2.0 Garbage Collection
- API-specific ownership rules
- Educational diagnostics

Analysis issues

- Aliasing
- Plenty of room for improvement

Checker Results

- Used internally at Apple
- Announced in June 2008 (WWDC)
  - Hundreds of downloads of the static analyzer
  - Thousands of bugs found

Some Implementation Details

Why Analyze Source Code?

Bug-finding requires excellent diagnostics

- Tool must **explain** a bug to the user
- Users cannot fix bugs they don't understand
- Need rich source and type information

What about analyzing LLVM IR?

- Loss of source information
- High-level types discarded
- Compiler lowers language constructs
- Compiler makes assumptions (e.g., order of evaluation)

Clang Libraries

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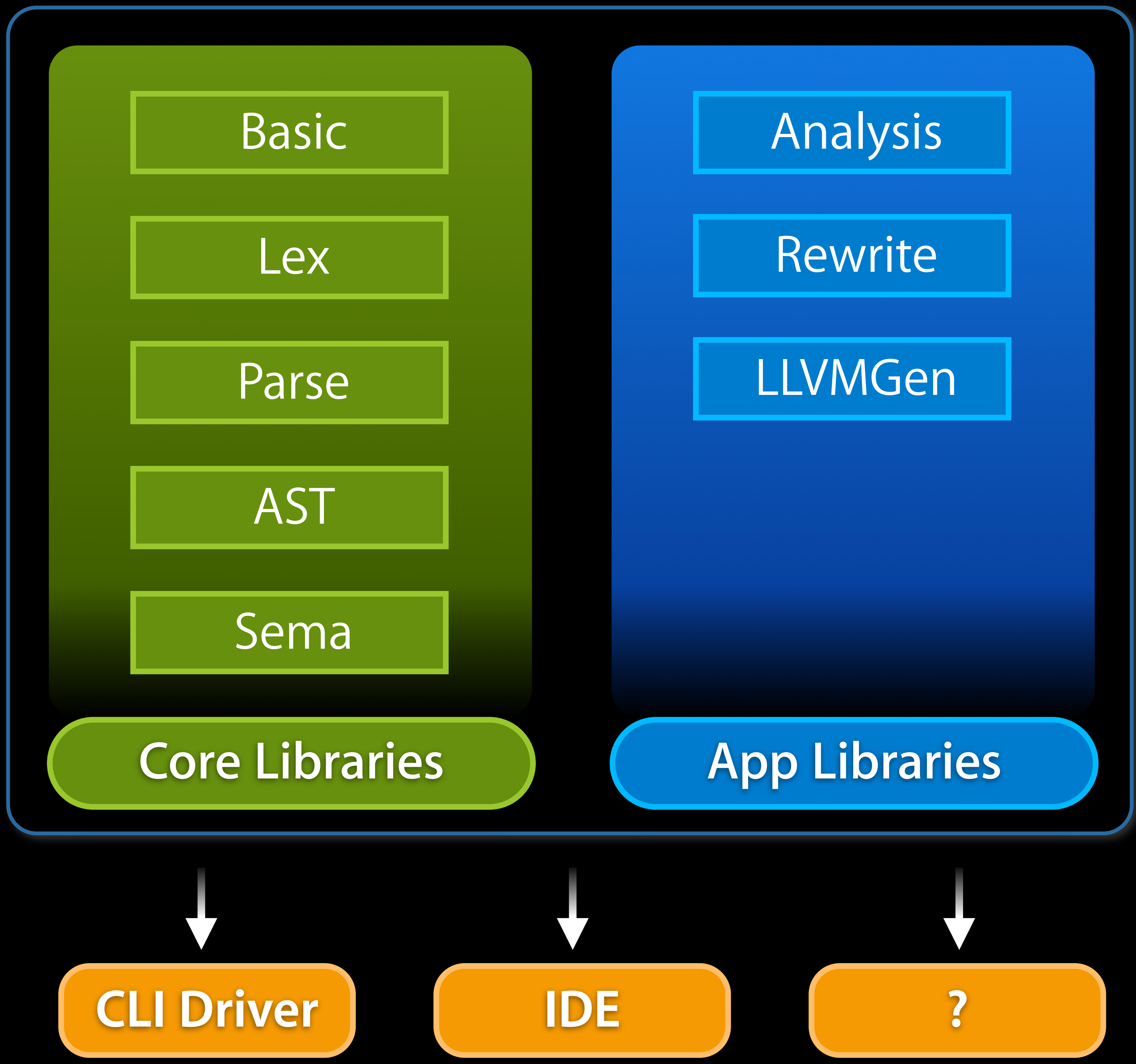

Clang Libraries

libAnalysis

libAnalysis

Intra-Procedural Analysis

- Source-level Control-Flow Graphs (CFGs)
- Flow-sensitive dataflow solver
  - Live Variables
  - Uninitialized Values
- Path-sensitive dataflow engine
  - Retain/Release checker
  - Logic bugs (e.g., null dereferences)
- Various checks and analyses
  - Dead stores
  - API checks

libAnalysis

libAnalysis

Path Diagnostics (Bug-Reporting)

- `PathDiagnosticClient`
  - Abstract interface to implement a “view” of bug reports
  - Separates report visualization from generation
  - HTMLDiagnostics (renders HTML, uses libRewrite)
- `BugReporter`
  - Helper class to generate diagnostics for `PathDiagnosticClient`

Looking Forward

- Richer Diagnostics
- Inter-procedural Analysis (IPA)
- Lots of Checks
- Scriptability
- Multiple Analysis Engines

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