CMPT 880
Special Topics:

Program Analysis & Reliability

Nick Sumner - Spring 2014

Much adapted from Xiangyu Zhang, Antony Hosking, Sorin Lerner,
Jonathan Aldrich, Sam Blackshear

Today

- Administrivia
- Dive right in!
  - Overview
  - Program Representations
  - Slicing
  - Basic Static Analysis
  - LLVM Basics

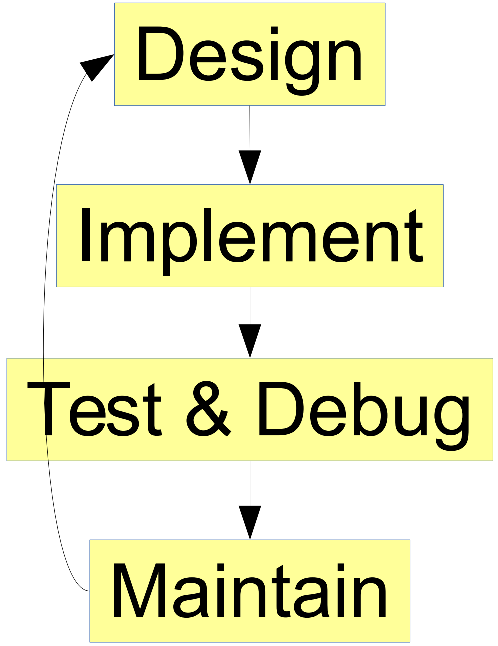
Time permitting

Course Website

- www.cs.sfu.ca/~wsumner/teaching/880-13/
  - Schedule
  - Policies
  - Assignments
  - Paper Suggestions

Why are you here?

- Programs are big, complex, and difficult to reason about.



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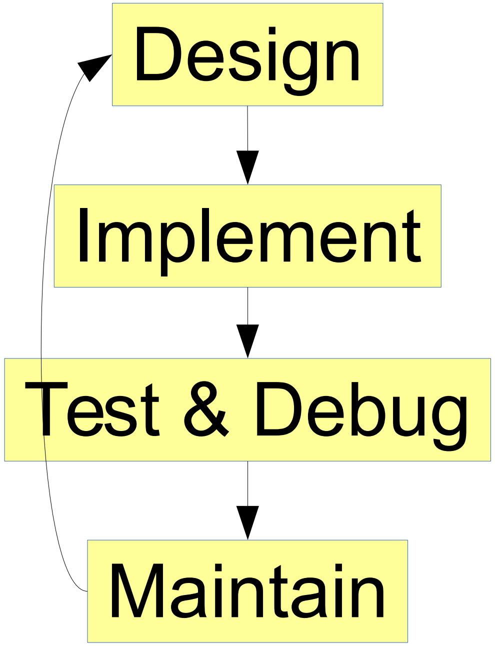

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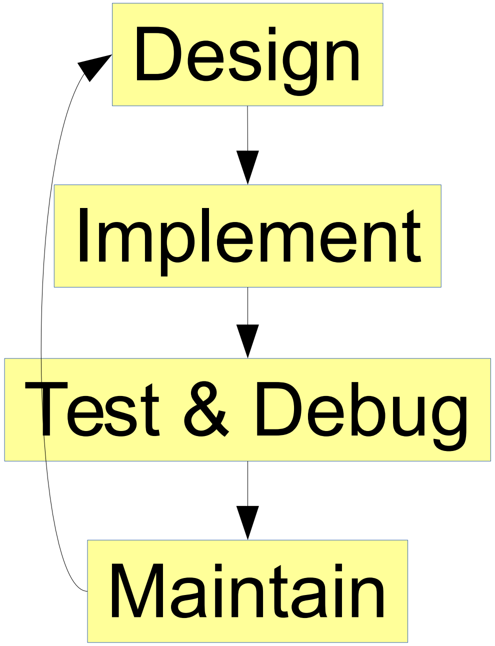

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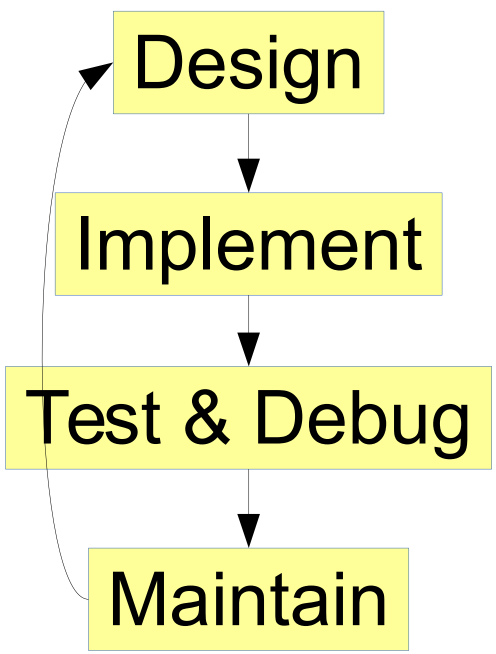

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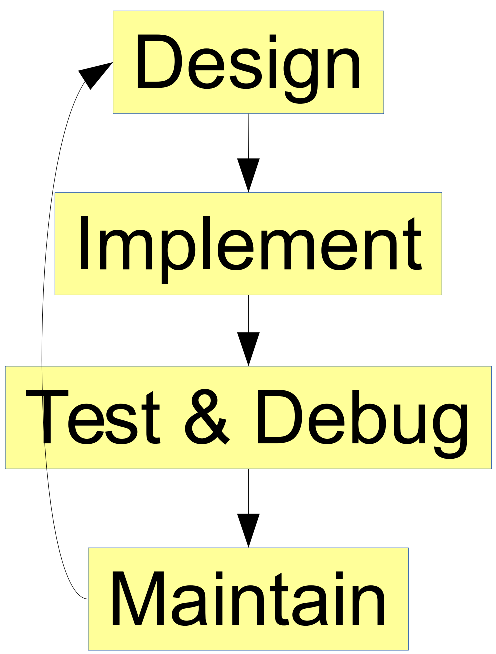

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How do I find security vulnerabilities?
Can I protect against them?

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  - Billions in lost profits and savings
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People are bad at tedious, subtle tasks, but computers are great at them!

Goal

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    - Profiling

(Speed, Potential Concurrency, Memory, ...)

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    - Testing

More effective tests. Bridge testing & verification

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    - Profiling
    - Testing
    - Debugging

      Explaining or locating the causes of bugs

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    - Debugging
    - Concurrency

How to explain race conditions?

Atomicity violations?

How to find 'Heisenbugs'?

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  - Survey of *program analysis* techniques & papers
    - Profiling
    - Testing
    - Debugging
    - Concurrency
    - Security

How to find vulnerabilities before attackers.

(...or as attackers)

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- First few weeks (2-3) are review & background
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  - I present.
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- Reading foundational & new papers
  - 2 student presentations & paper discussions per week
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- 2 small projects to introduce LLVM
- Course projects presented at end.

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- Guidelines on website
- 2 Goals
  - Help reinforce the material for the class
  - Lead an interesting discussion to examine the trade offs of each technique. (I'll be helping.)

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- Guidelines on website
- 2 Goals
  - Help reinforce the material for the class
  - Lead an interesting discussion to examine the trade offs of each technique. (I'll be helping.)
- Show how the technique behaves in the best case
- Show or lead discussion on where it might behave poorly

Critiques

- Guidelines on website
- 1-2 page response to 1 paper each week that you do not present.
- Primarily meant to prepare you for the discussion on the paper that week.

Term Projects

- Groups of 1 or 2.
- 1 page proposals due March 3.
- Find something that interests (or irritates) you and go after it!
  - Maybe look at how these techniques can help your existing research

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- Reproducing Remote Bugs
- ...

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- ng Remote

- I have planned out a survey, but we can customize it for interest
- The last few weeks will be chosen by your interests already

Program Representations

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- Difficult models:
  - Compiled binaries
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    - Very language specific
- Need something better

Program Representation

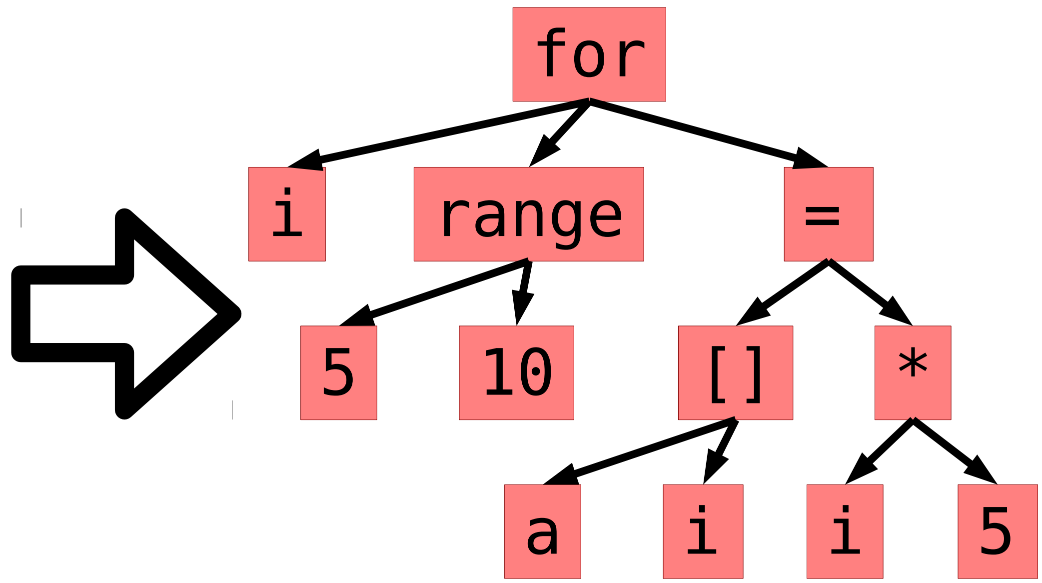
Core Representations for Analysis:

1) Abstract Syntax Trees
2) Control Flow Graphs
3) Program Dependence Graphs
4) Call Graphs
5) Points-to Graphs

1) Abstract Syntax Trees

- Lifts the source into a canonical semantic form
  - Internal nodes are operators, statements, etc.
  - Leaves are values, variables, operands

```
for i in range(5,10):
    a[i] = i * 5
```



2) Control Flow Graphs

- Express the possible decisions and possible paths through a program

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cond = input()
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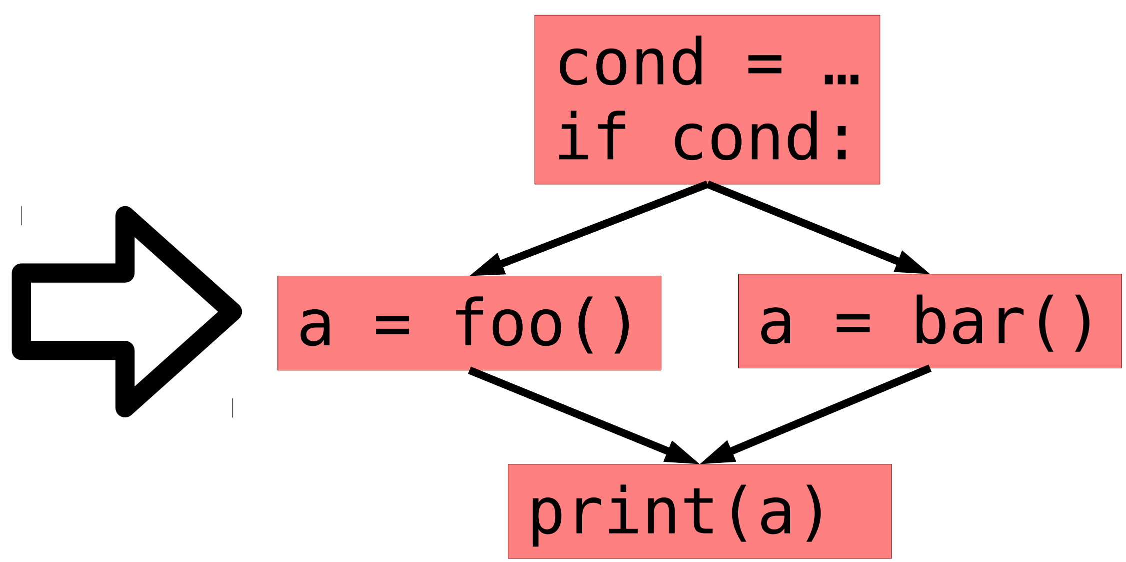

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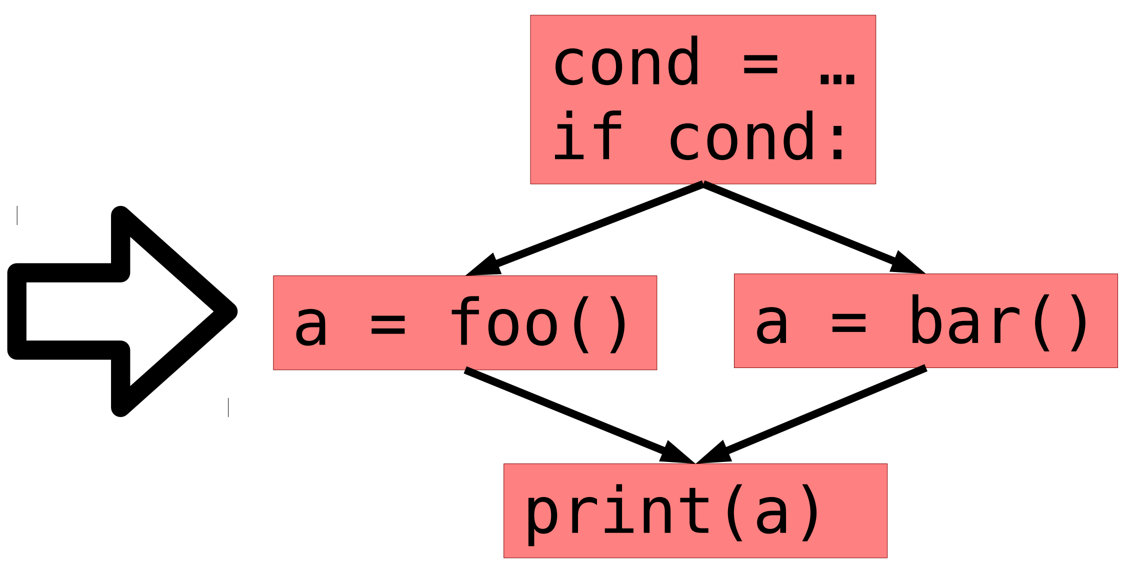

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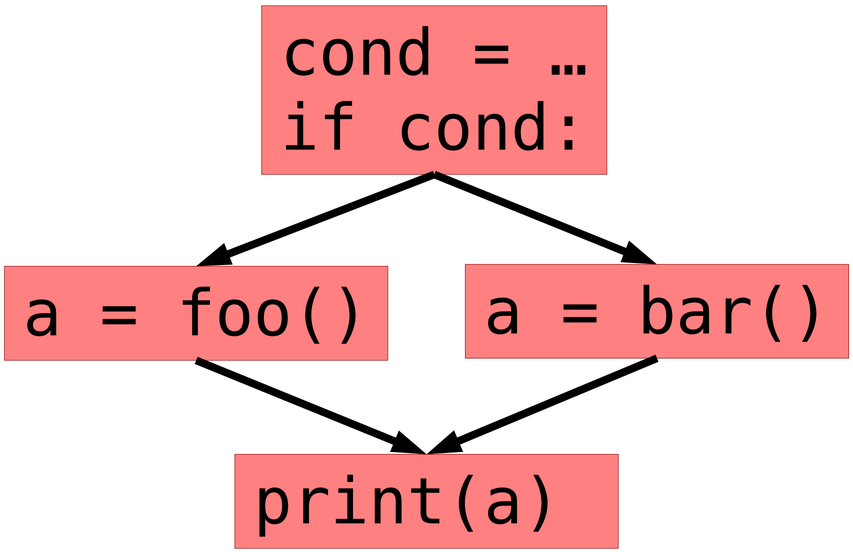

2) Control Flow Graphs

- Express the possible decisions and possible paths through a program
  - Basic Blocks (Nodes) are straight line code
  - Edges show how decisions can lead to different basic blocks
  - Paths through the graph are potential paths through the program

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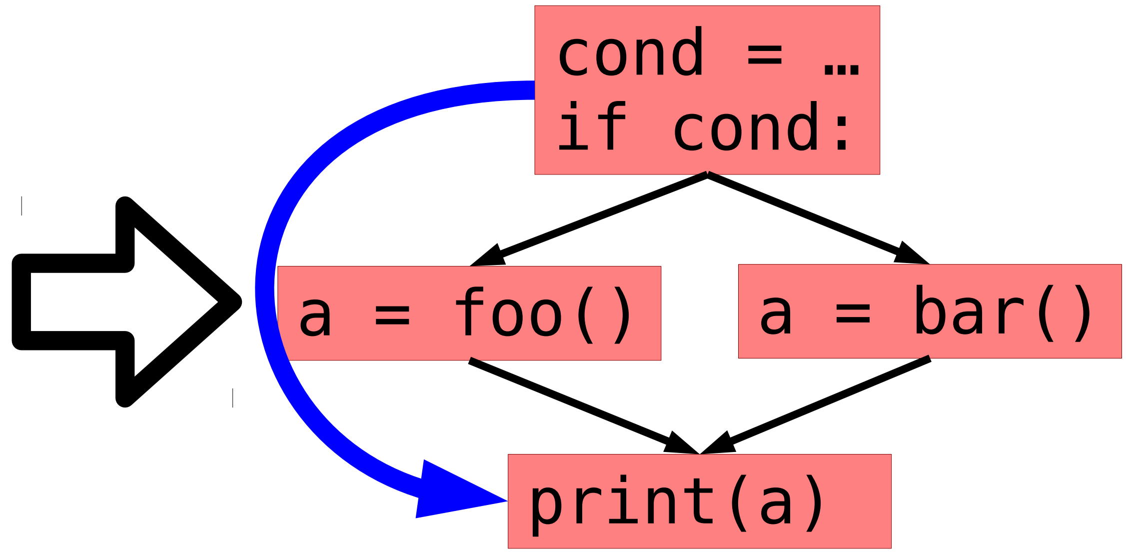
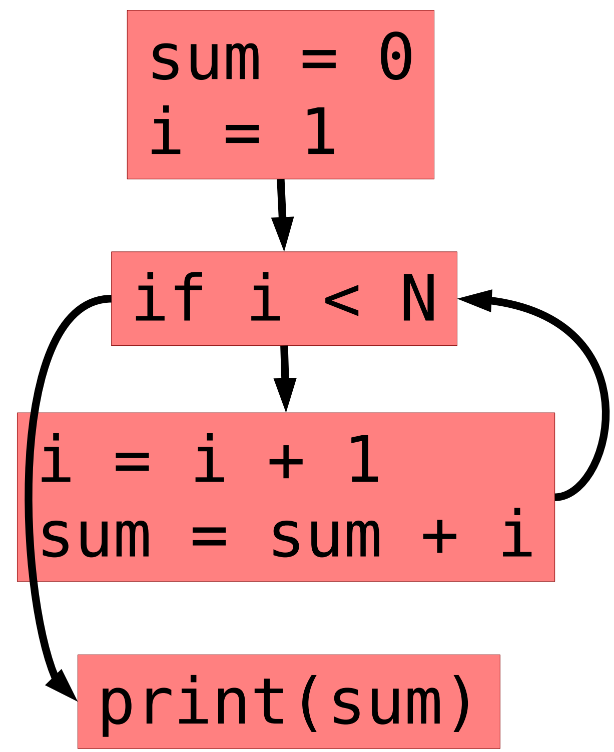


2) Control Flow Graphs (CFGs)

- Language specific features are often abstracted away

The 'while' is gone

```
sum = 0
i = 1
while 1 < N:
  i = i + 1
  sum = sum + i
print(sum)
```



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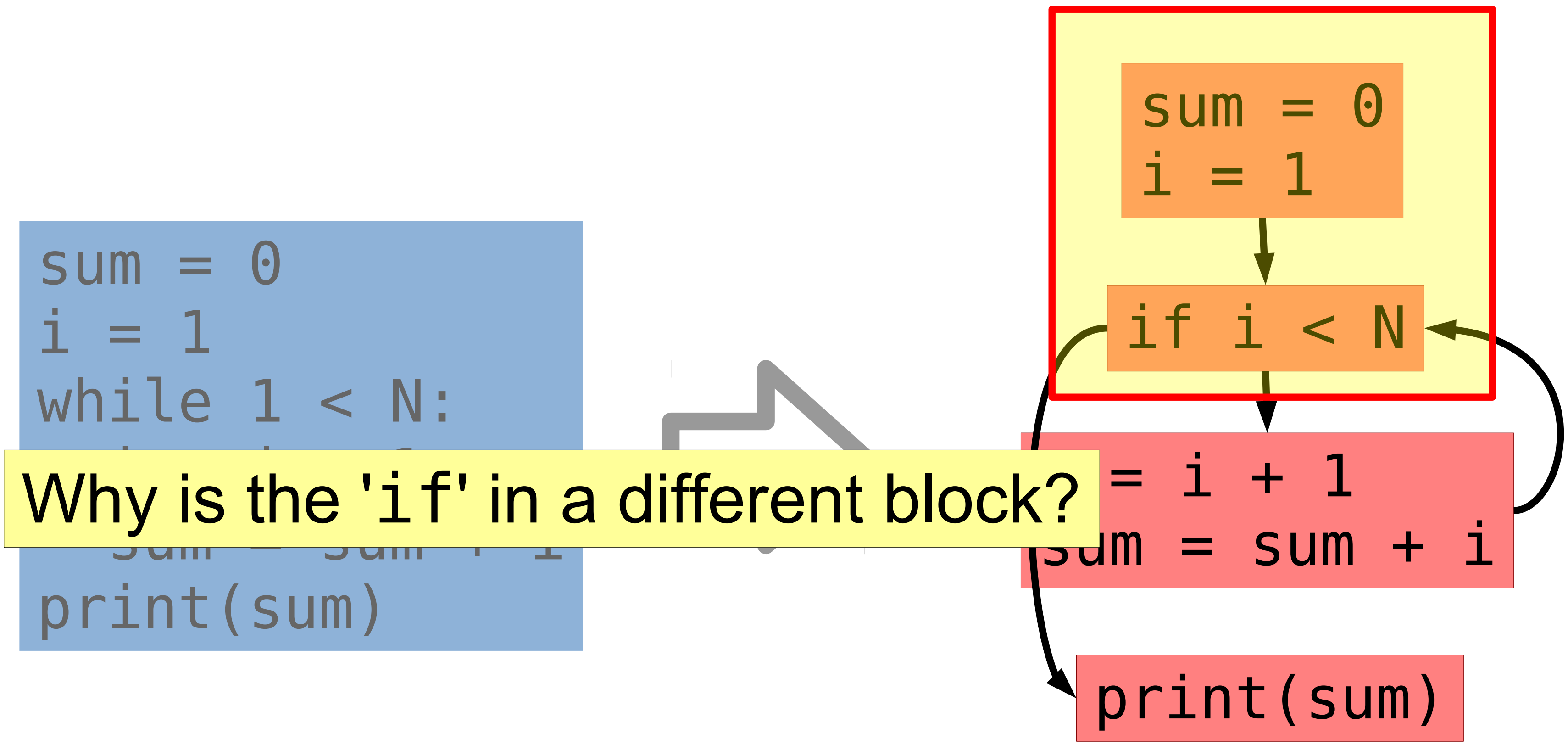

3)Program Dependence Graph (PDG)

- Instruction X depends on Y if Y *can influence* X
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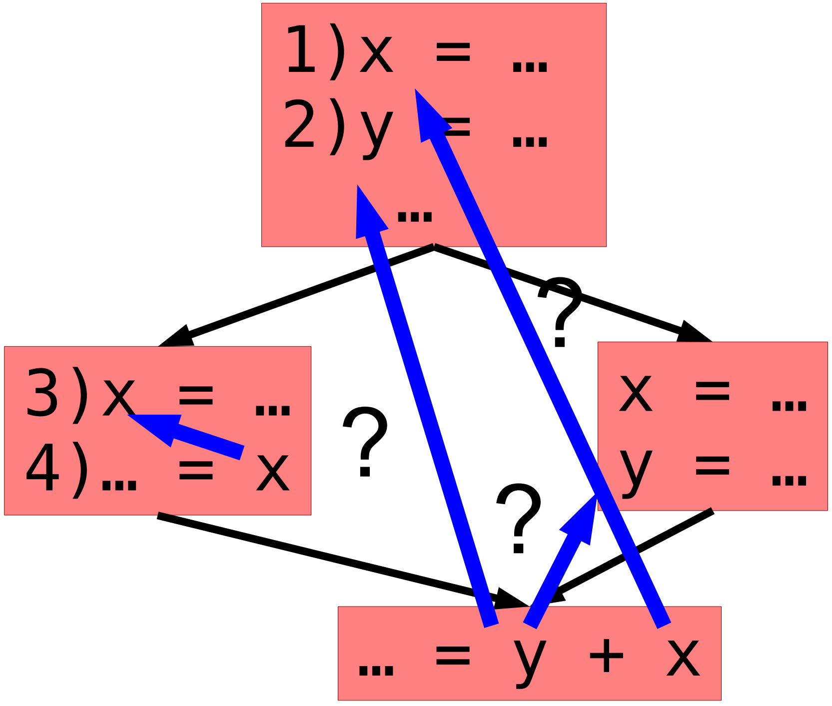
- 2 main types of influence:
  - Data dependence
  - Control dependence

Data Dependence

X data depends on Y if

- There exists a path from Y to X in the CFG
- A variable/value definition at Y is used at X



Control Dependence

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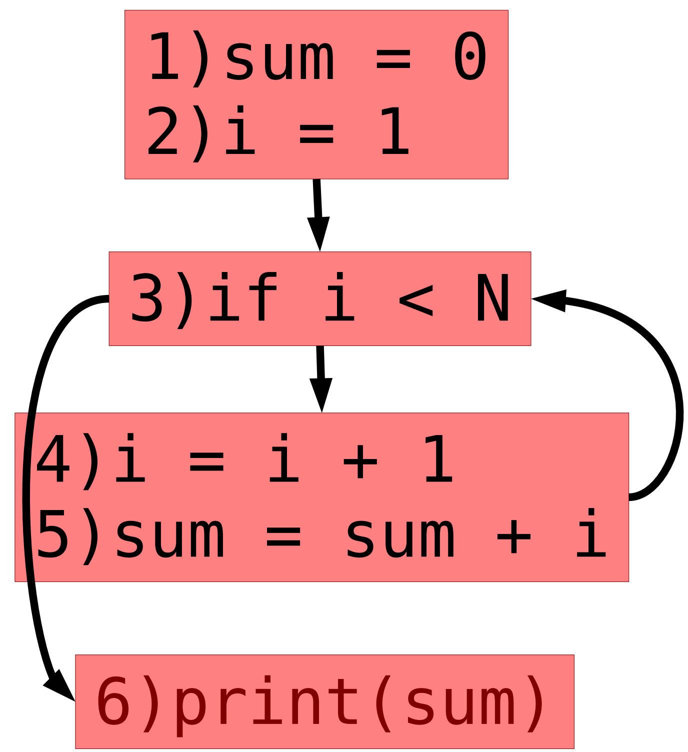

DOM(6)={1,2,3,6}   IDOM(6)=3

Control Dependence

Preliminary: X dominates Y if

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  - strict, normal, & immediate dominance

What does this mean intuitively?

```
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2)
3)
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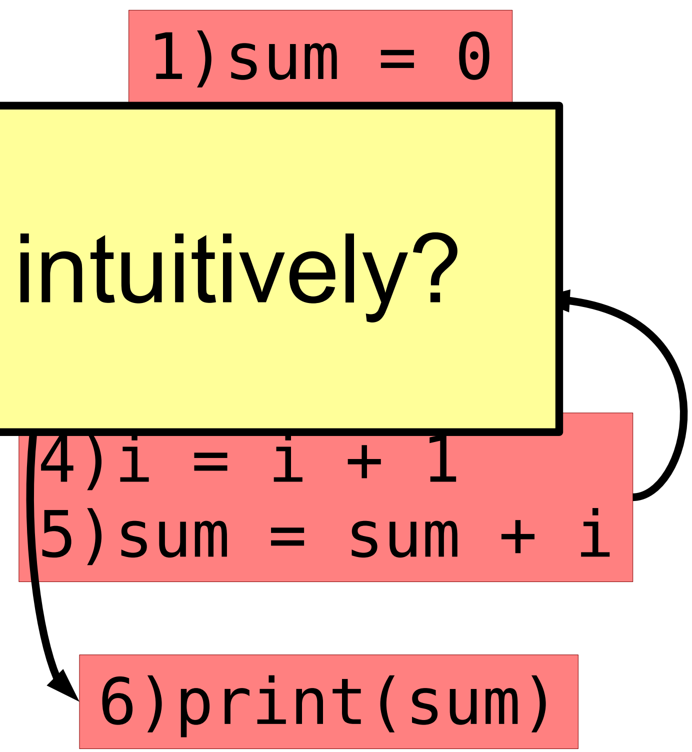
```



DOM(6)={1,2,3,6}   IDOM(6)=3

Control Dependence

Preliminary: X post dominates Y if

- every path from the Y to exit passes X
  - strict, normal, & immediate dominance

```
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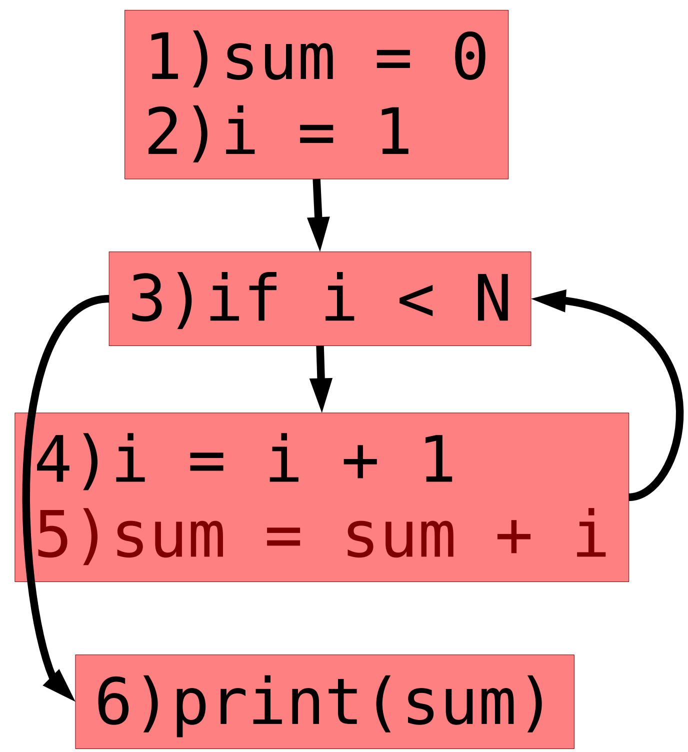


PDOM(5)={3,5,6}   IPDOM(5)=3

Control Dependence (Finally)

Y is control dependent on X iff

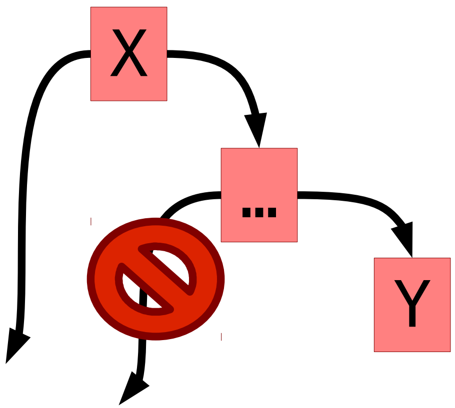
- Definition 1:

  X directly decides whether Y executes

Control Dependence (Finally)

Y is control dependent on X iff

- Definition 1:
  X directly decides whether Y executes
- Definition 2:
  - There exists a path from X to Y s.t. Y post dominates every node between X and Y.
  - Y does not strictly post dominate X



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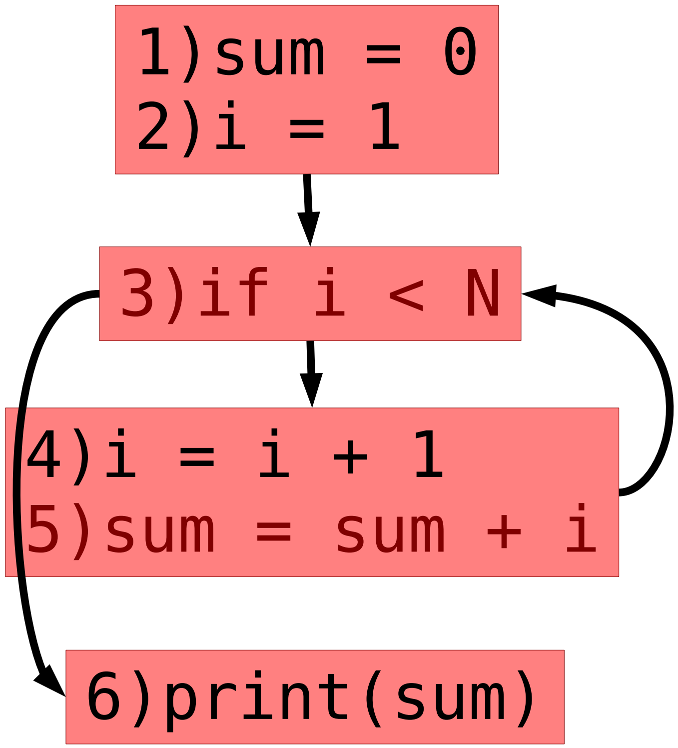

What is CD(5)? CD(3)

Control Dependence

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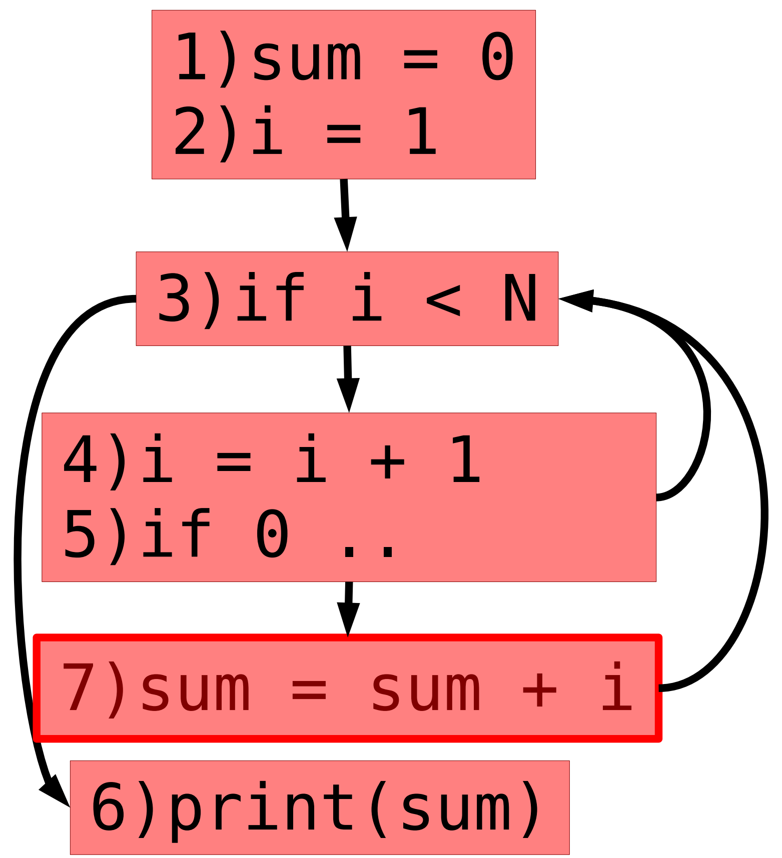
```
1)sum = 0
2)i = 1
3)while 1 < N:
4)  i = i + 1
5)  if 0 == i%2:
6)    continue
7)  sum = sum + i
8)print(sum)
```

What is CD(7)?



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```
1)if X or Y:
2)  print(X)
3)print(Y)
```

What is CD(2)?

Control Dependence

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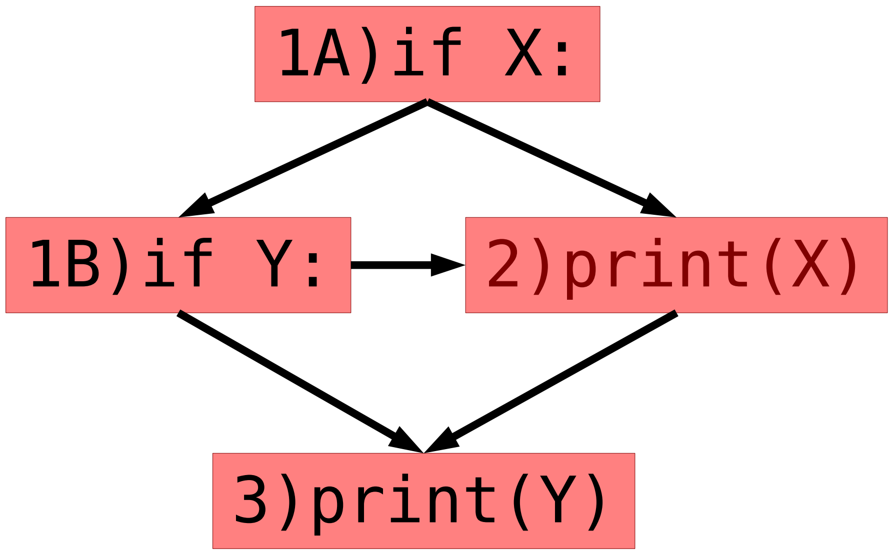

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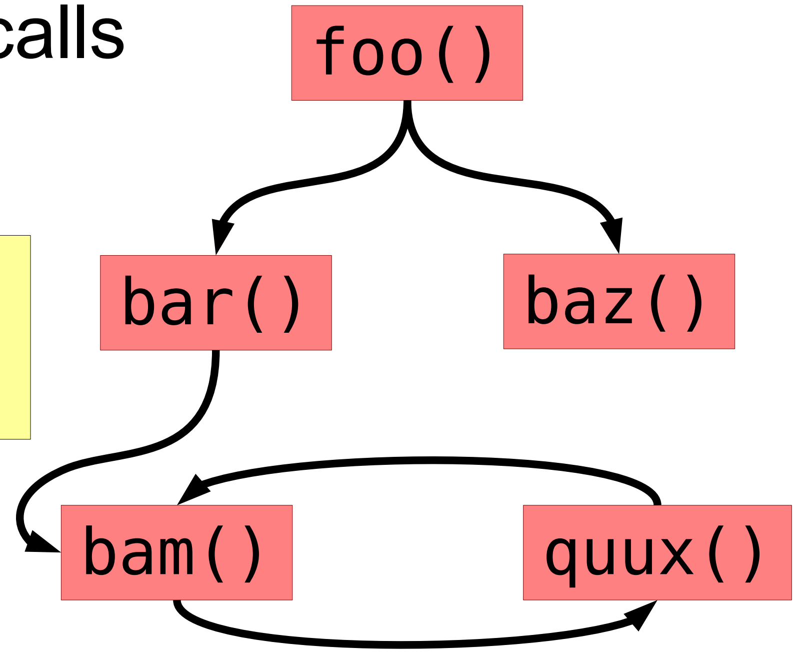
Recall: Edges identify *potential influence*

- Debugging: What may have caused a bug?
- Security: Can sensitive information leak?
- Testing: How can I reach a statement?
- ...

4) Call Graph (Multigraph)

- Captures the composition of a program
  - Nodes are functions
  - Edges show possible calls

How should we handle function pointers?



5) Points-to Graphs

Aliasing:

- Multiple variables may denote the same memory location

Multiple Targets:

- One variable may potentially denote several different targets in memory.

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```
x.lock()
…
y.unlock()
```

```
x = password
…
broadcast(y)
```

5) Points-to Graphs

- The relation (p,x) where p MAY/MUST point to x
  - Both MAY and MUST information can be useful

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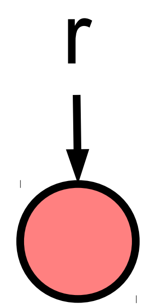

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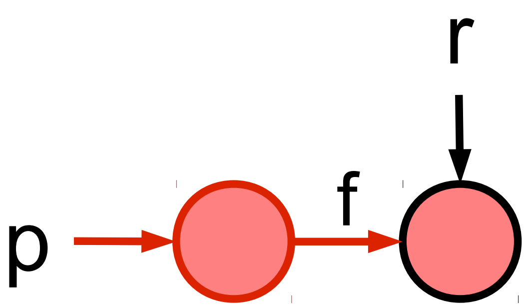

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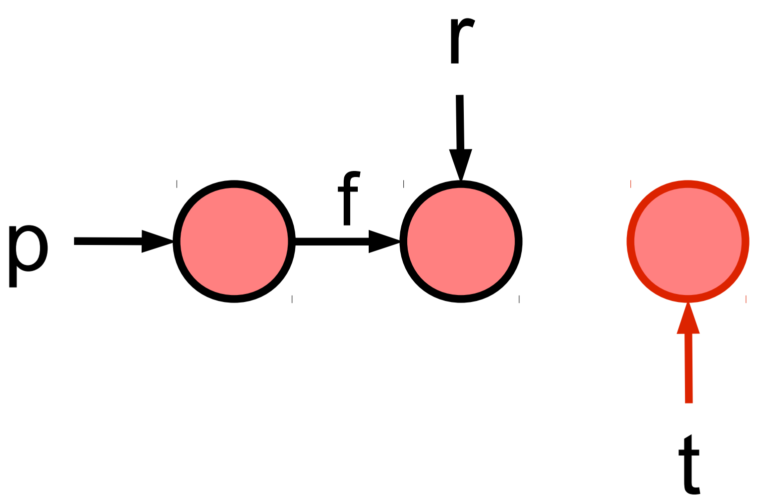

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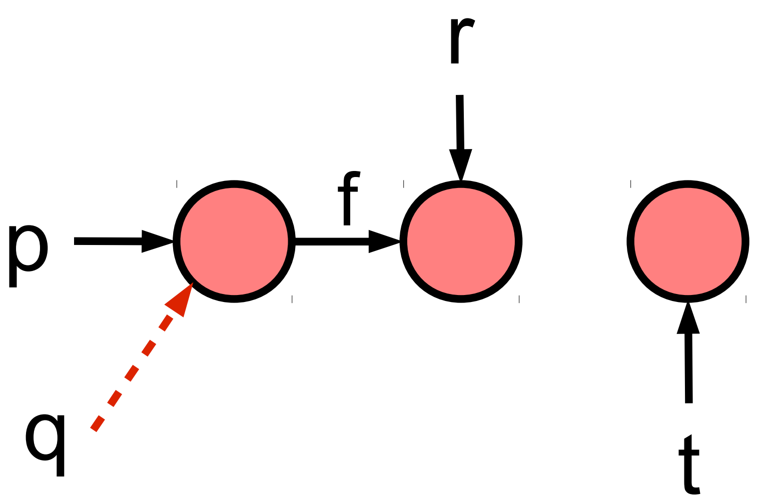

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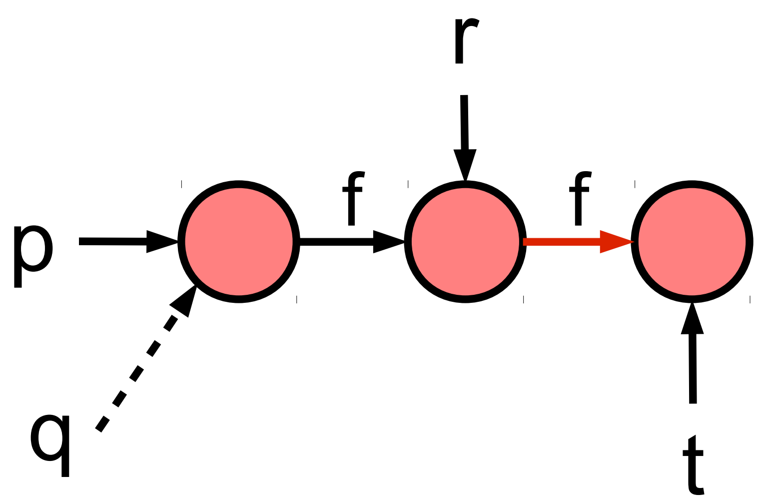

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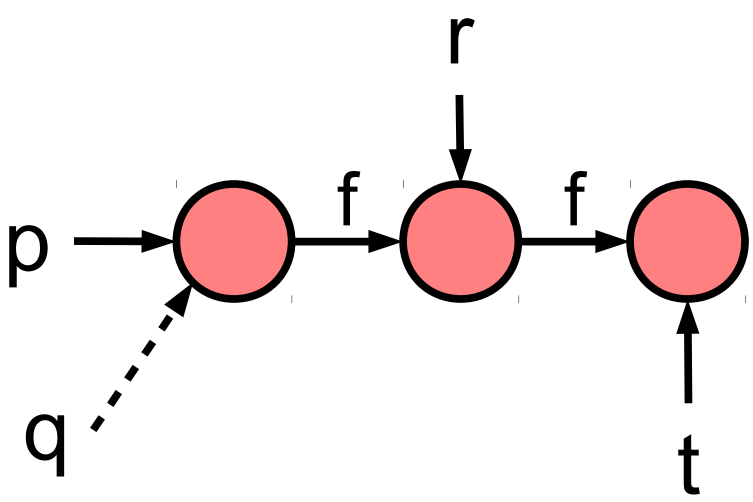


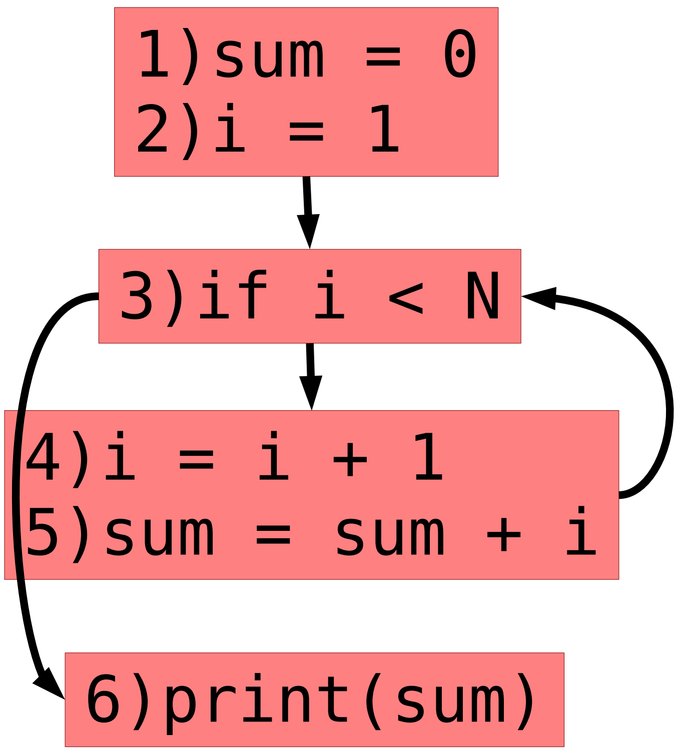
p.f.f MUST ALIAS t
q MAY ALIAS p

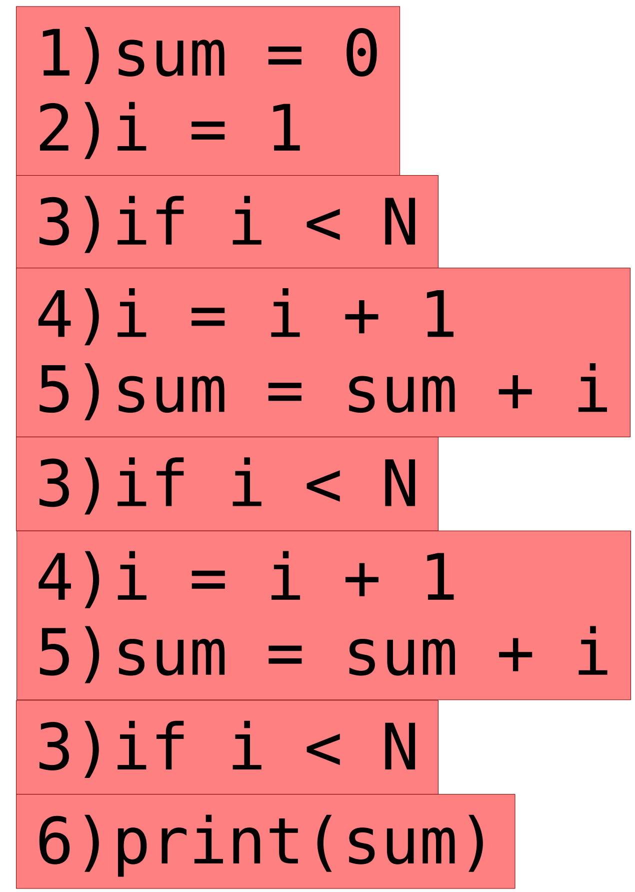
Execution Representations

- Program Representations are *static*
  - All possible program behaviors at once
  - Usually projected onto the CFG

- Execution Representations are *dynamic*
  - Only the behavior of a single real execution
  - Multiple instances of an instruction occur multiple times

Control Flow Trace





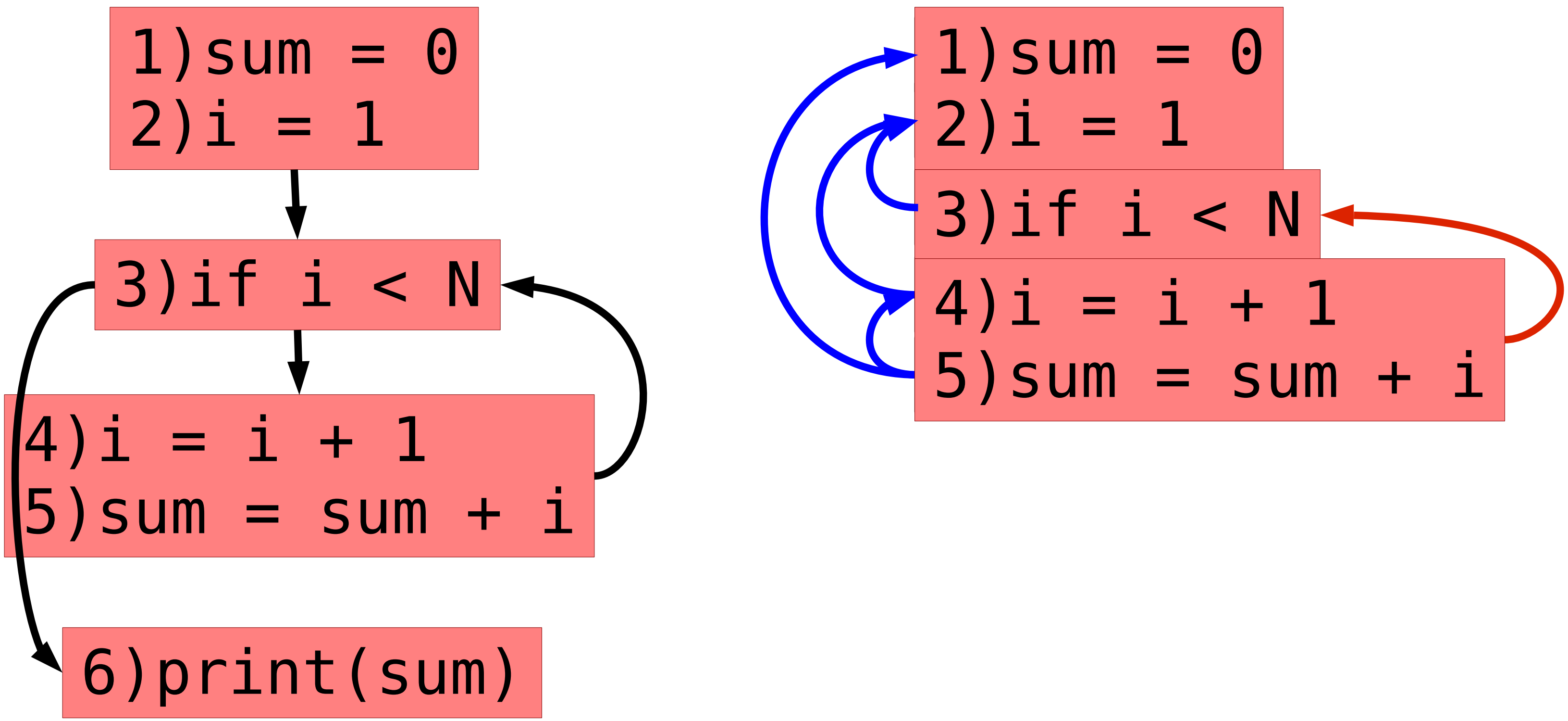
$1_1\ 2_1\ 3_1\ 4_1\ 5_1\ 3_2\ 4_2\ 5_2\ 3_3\ 6_1$

$1_1\ 3_1\ 4_1\ 3_2\ 4_2\ 3_3\ 6_1$

TTF

} All Equivalent

Dynamic Dependence Graph



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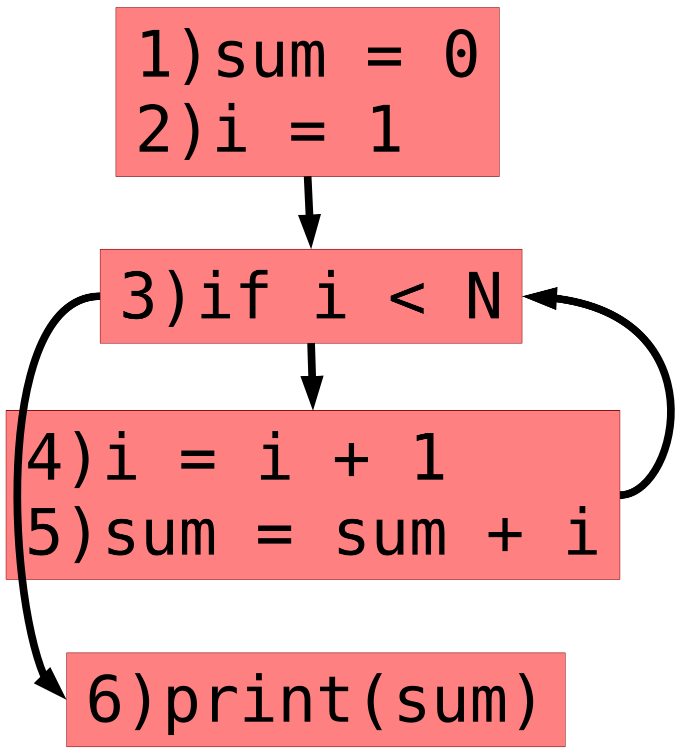

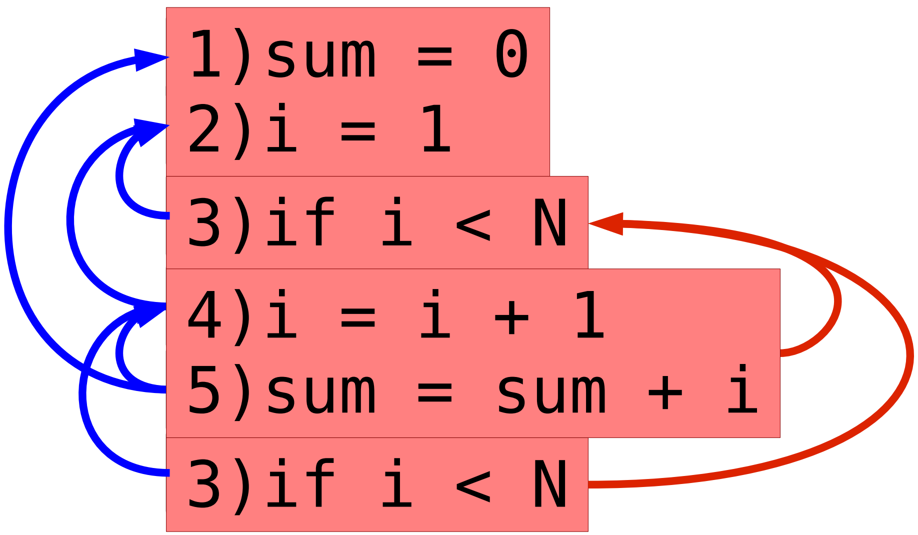

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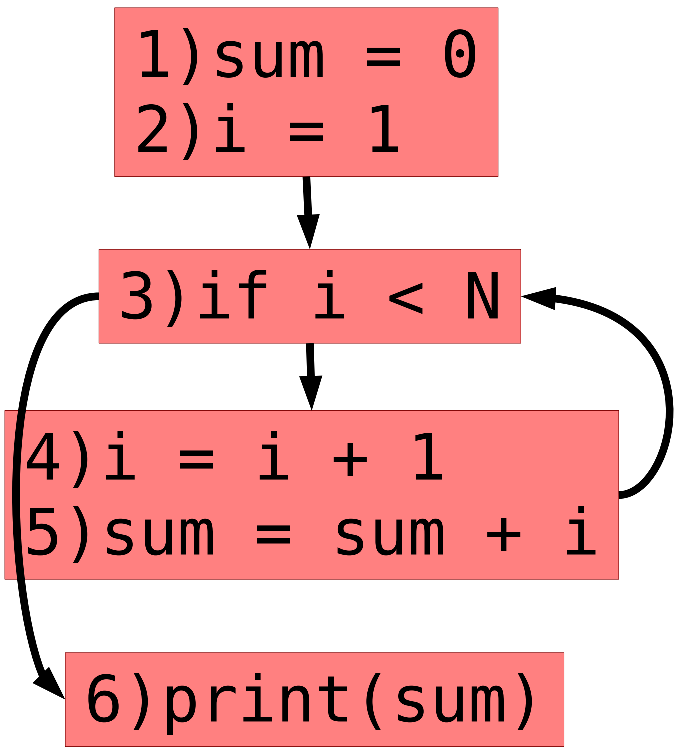

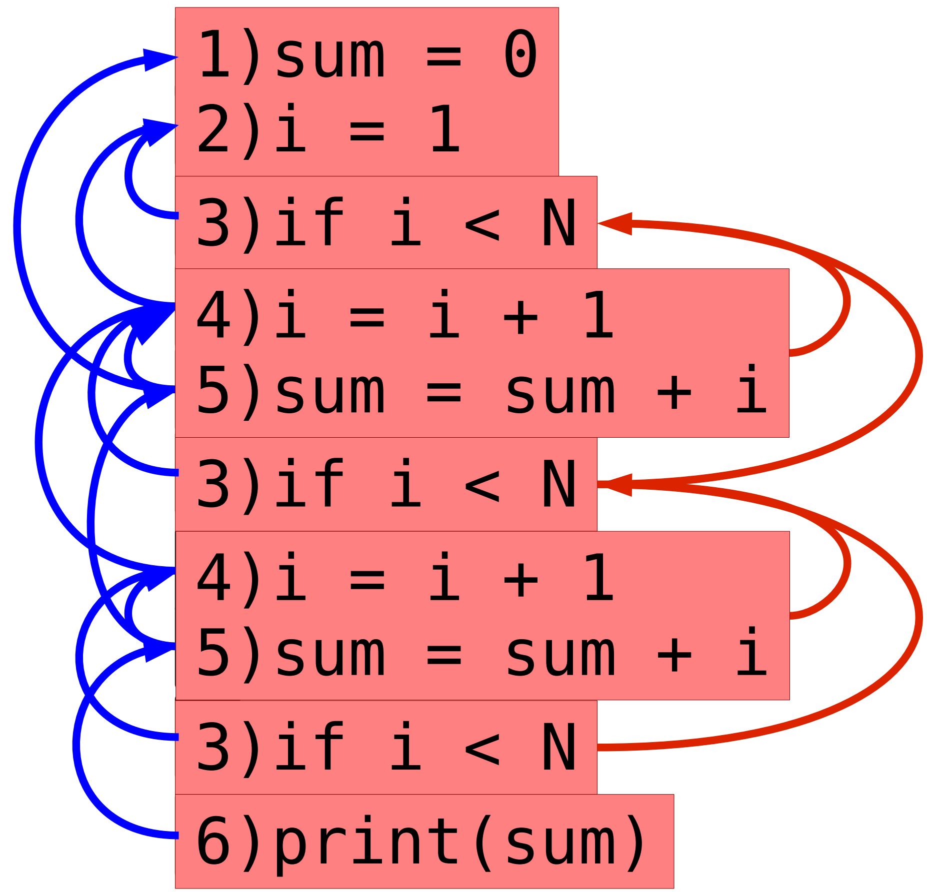

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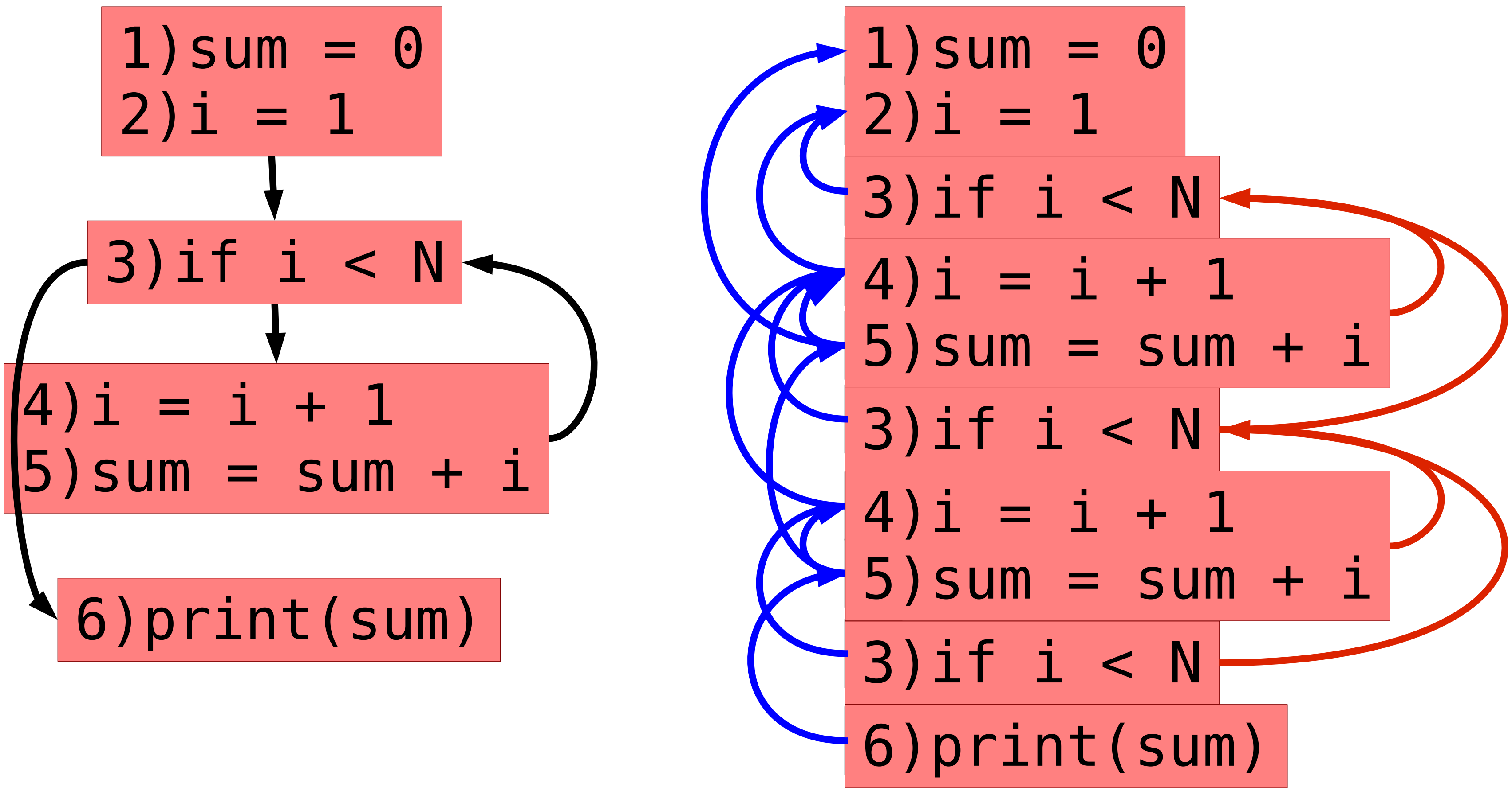

Notably a bit difficult for a human to wade through.

Program Representations

Given these models, we can start to discuss interesting transformations and analyses on real programs.

Such as...

Slicing

Program Slicing

- The *slice* of a value v at a statement s is:
  - the set of statements involved in computing v's value at s. [Weiser 82]

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2)i = 1
3)while 1 < N:
4)  i = i + 1
5)  sum = sum + i
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- The statements that may influence v...
  - Data dependence
  - Control dependence
  - Compute using the PDG!

Program Slicing Uses

- Debugging
- Testing
- Reverse Engineering
- Optimization
- Design Profiling
- Malware analysis
- ...

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  - Start from v and just follow edges backward

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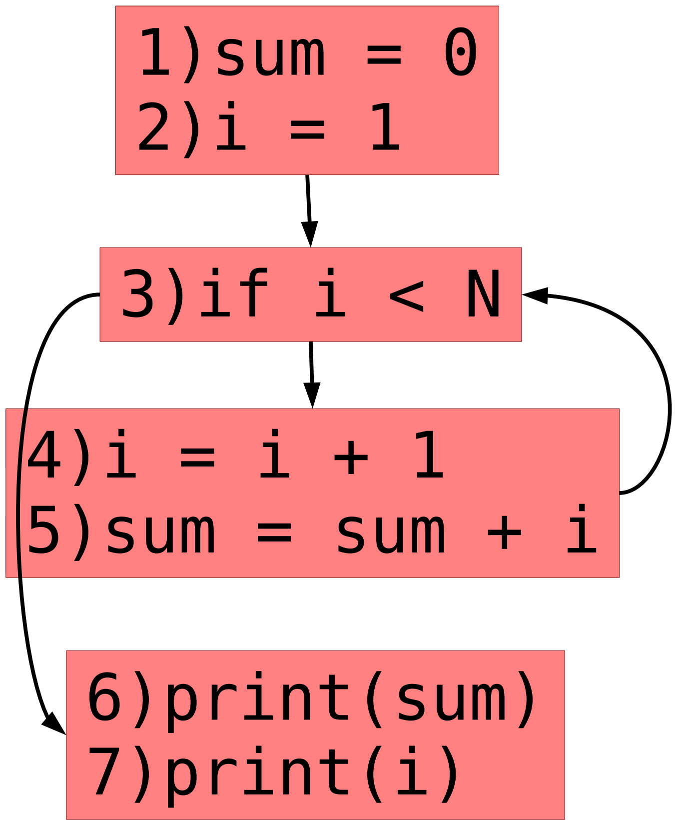

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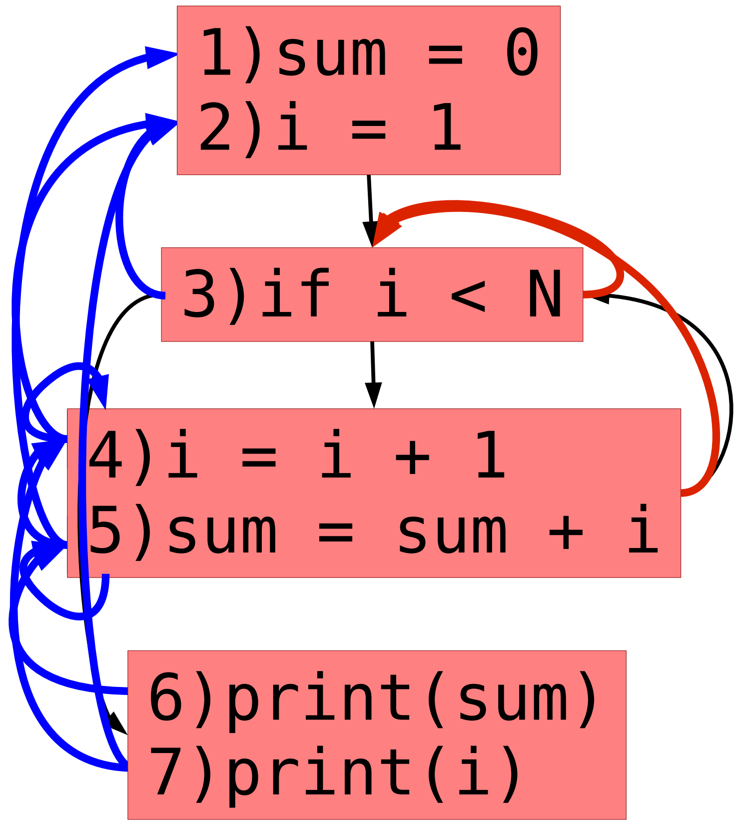

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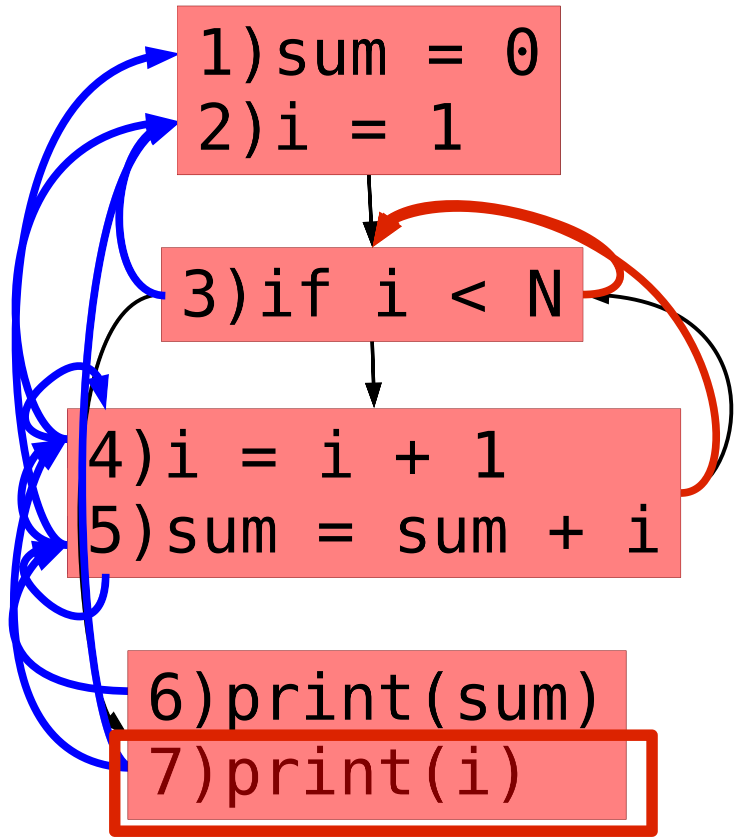

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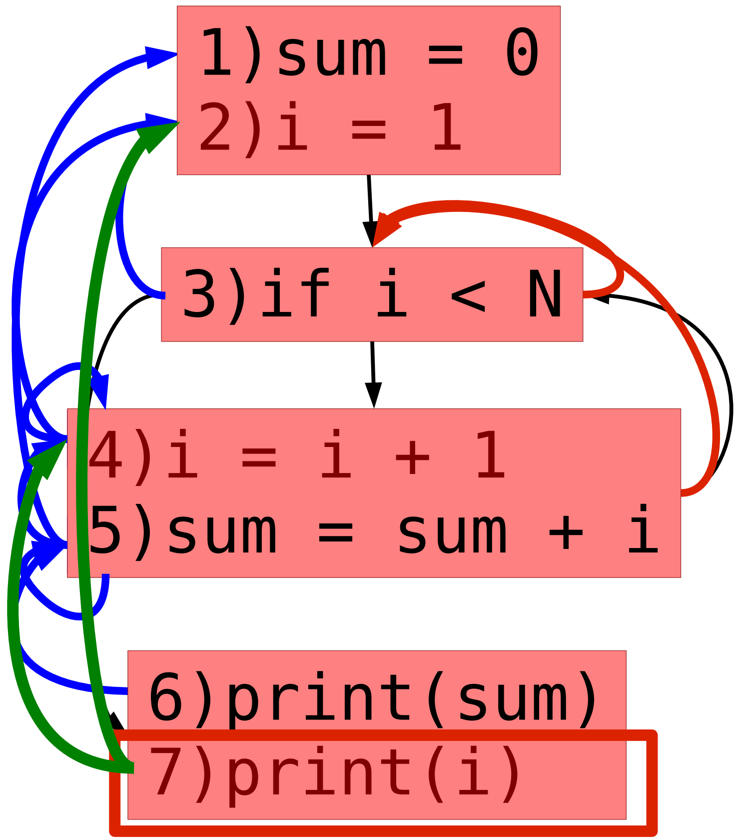

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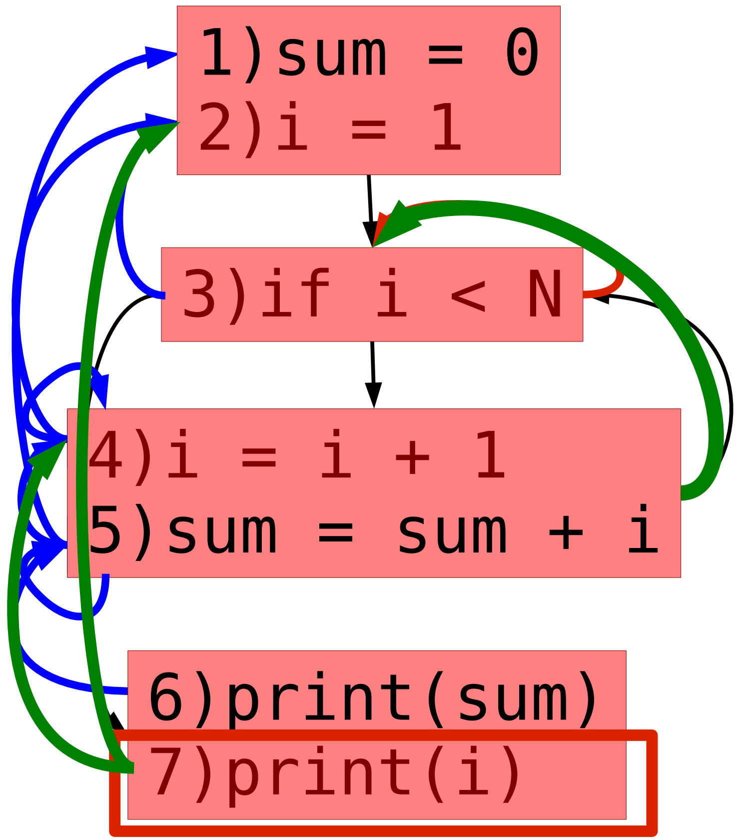

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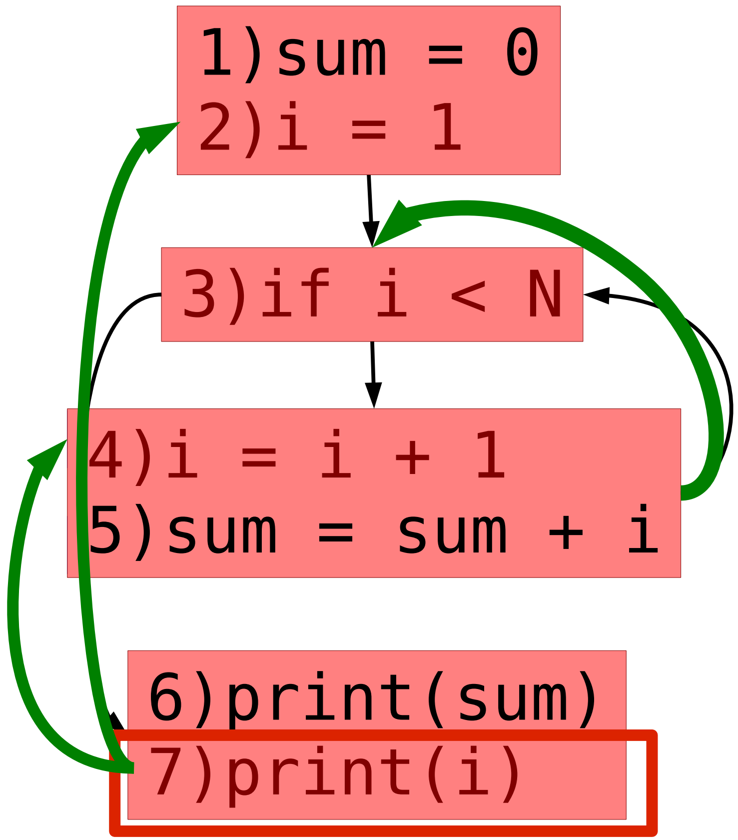


Very Configurable

- Static vs. Dynamic (PDG vs. DDG)
- Backward vs. Forward
- Executable vs. Nonexecutable

What do forward and backward *mean*?

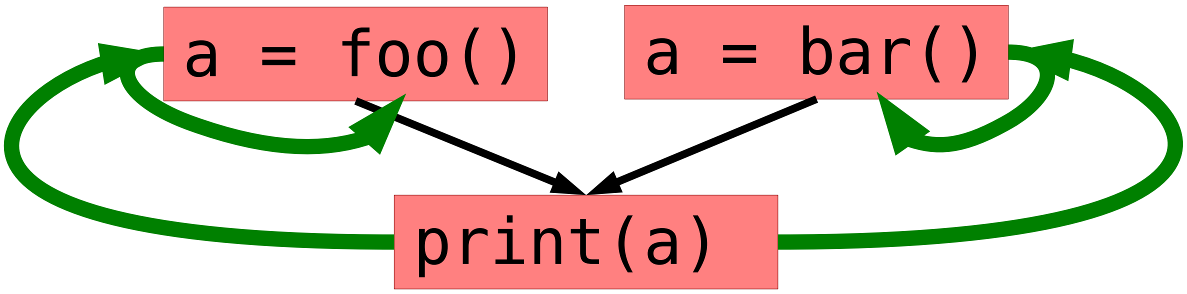
Why might a slice not be executable?

Strengths of Static Slicing

- Considers all possible executions
  - Necessary for conservative analyses
  - (“Might I leak secret information?”)
- Fast to compute
- Space efficient

Issues with Static Slicing

- Multiple program paths



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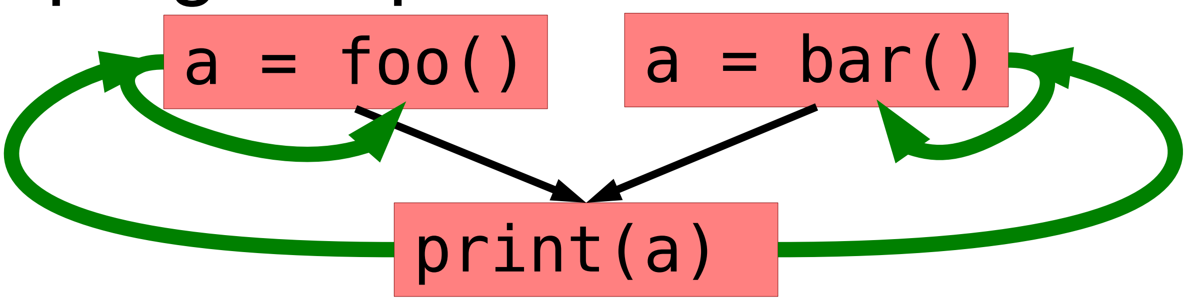
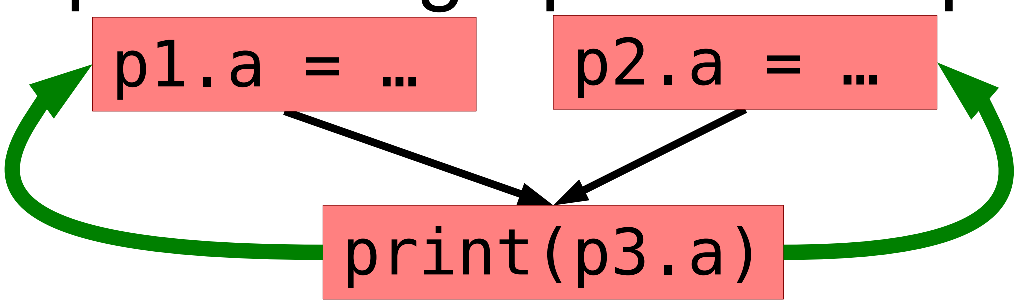


- Pointers – points-to graphs are imprecise



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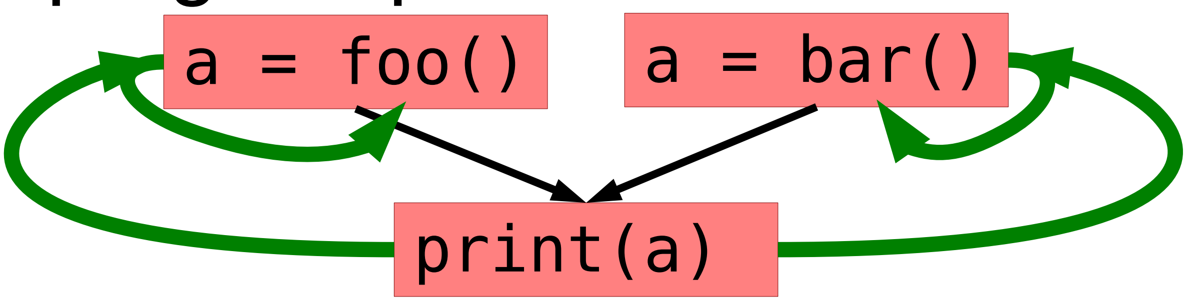

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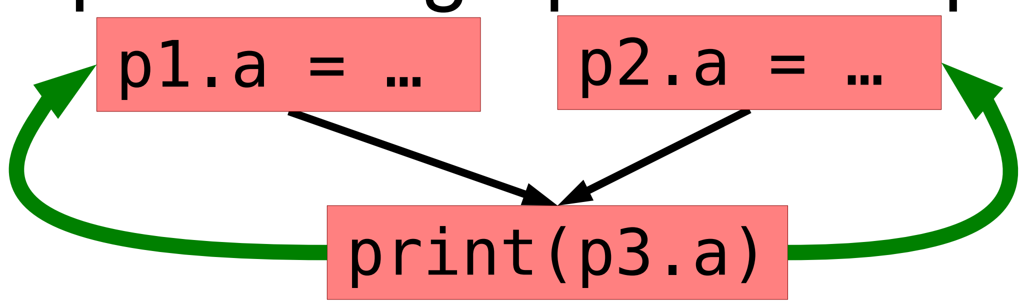

- Function pointers – must consider all possible call targets

Strengths of Dynamic Slicing

- Precisely considers a single execution (DDG)
  - "Did I ..."
- No imprecision from aliasing or multiple paths
  - Why?
- Cover fewer static program statements

Issues with Dynamic Slicing

- Capturing a trace and computing a DDG is expensive
  - (GB sized trace files)
- Slow to compute
  - Churn a great deal of memory
- Very many statement instances and dynamic dependences to examine
- Misses alternative histories
  - What would have happened if … ?

Coping with Scale

Both types of slicing benefit from techniques that *prune* or *focus* slices on just what is *interesting*

Coping with Scale

Both types of slicing benefit from techniques that *prune* or *focus* slices on just what is *interesting*

- *Thin Slicing*- Focus on propagating v, ignoring data structures [PLDI07]
- *Chopping*- Combine forward & backward info [ASE05]
- *Confidence Analysis*- Instructions used to compute correct values less likely to be buggy [PLDI06]
- *Guided Browsers*- Zoom in on demand [ICSE06]
- Much more...

Static Analysis

Static Analysis

Static analyses consider all possible behaviors of a program without running it.

- Look for a property of interest
  - Do I dereference NULL pointers?
  - Do I leak memory?
  - Do I violate a protocol specification?
  - Is this file open?
  - Does my program terminate?

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- Only if answers must be perfect.

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Overapproximate or underapproximate the problem, and try to solve this simpler version.

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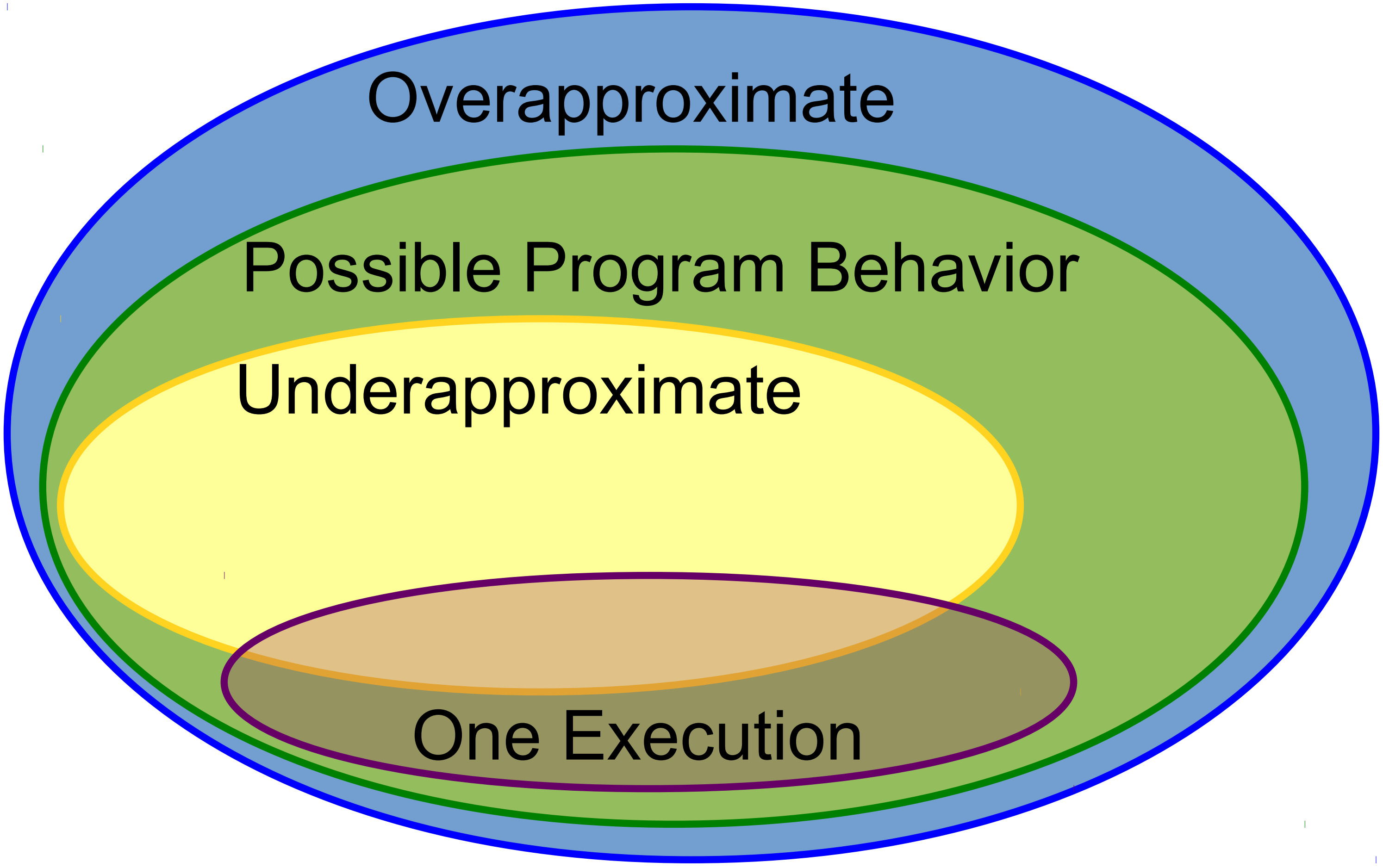
  - Guaranteed to find violations of property
  - May raise false alarms
- Comlete analyses
  - Underapproximate
  - Reported violations are real
  - May miss violations

Striking the right balance is key to a useful analysis

Static Analysis

Modeled program behaviors



A Simple Example

Q: Is a particular number ever negative?

- Might be an offset into invalid memory!

Approximate the problem

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- Concrete domain: integers
- Abstract domain: {-,0,+} $\cup$ {$\top$,$\bot$}

concrete(x) = 5 → abstract(x) = +
concrete(y) = -3 → abstract(y) = -
concrete(z) = 0 → abstract(z) = 0

Combines sets of the concrete domain

A Simple Example

- Transfer Functions show how to evaluate this approximated program:
  - **+** + **+** → **+**
  - **-** + **-** → **-**
  - **0** + **0** → **0**
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  - …
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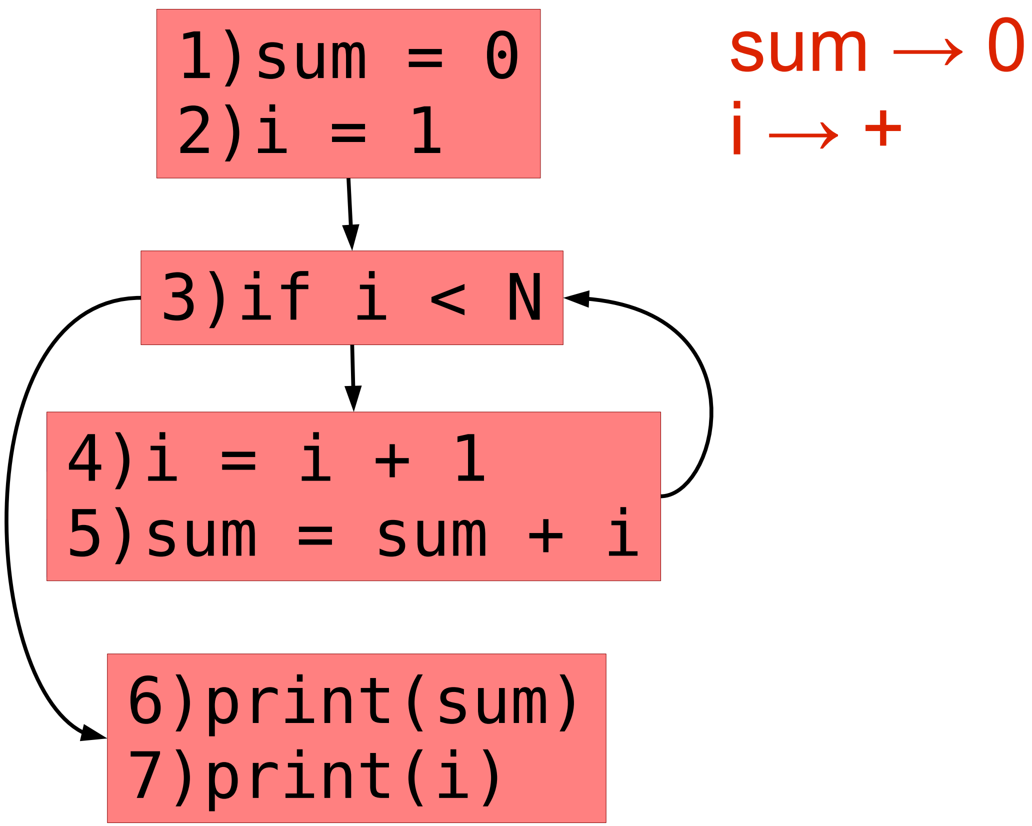
Consider a divide by 0 analysis.
What are:
True Positives
False Positives
True Negatives
False Negatives

- Can be subtle.
  - The above is not sound or complete. Why?

Data Flow Analysis

- Now model the abstract program state and propagate through the CFG.



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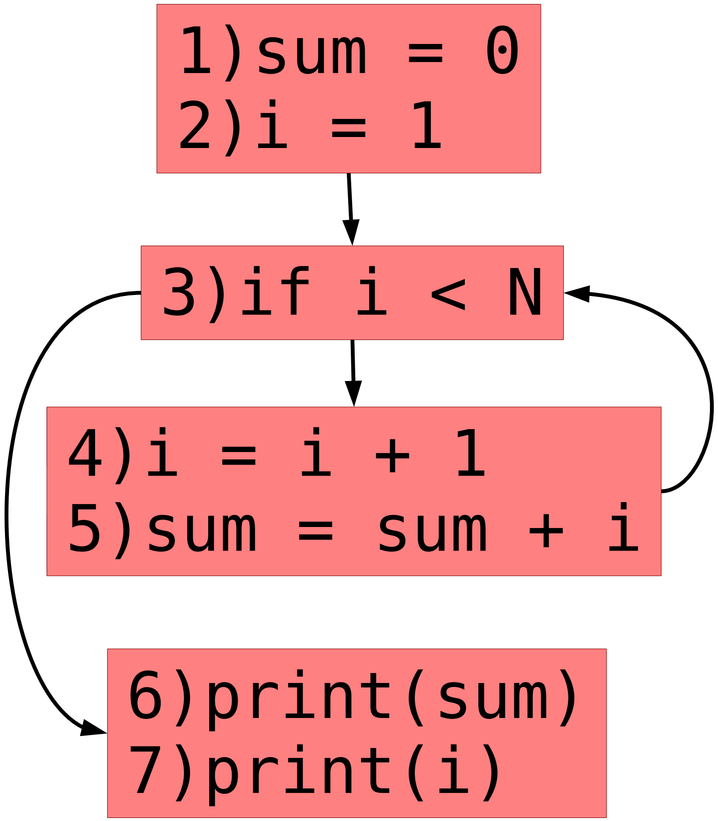

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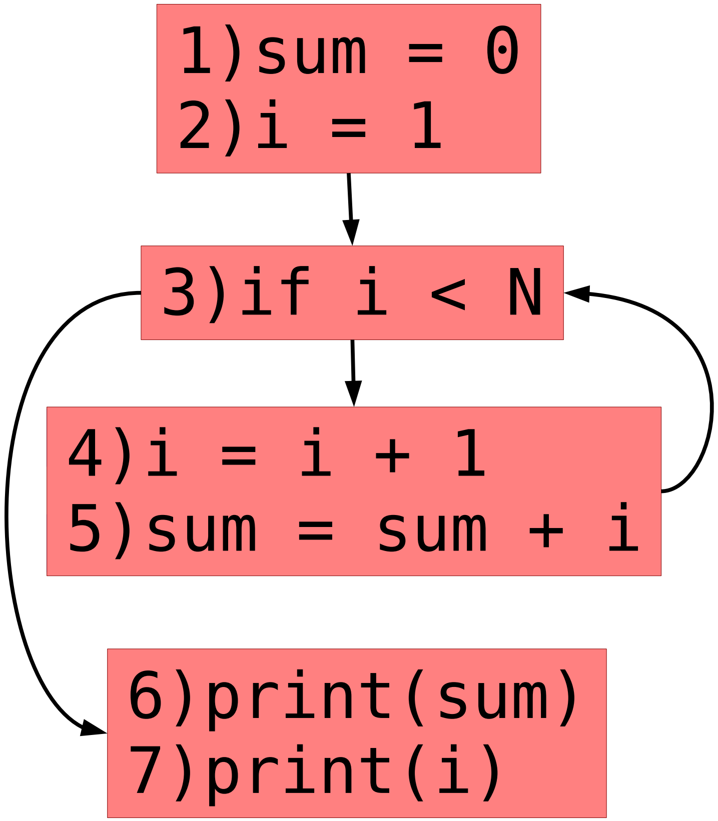

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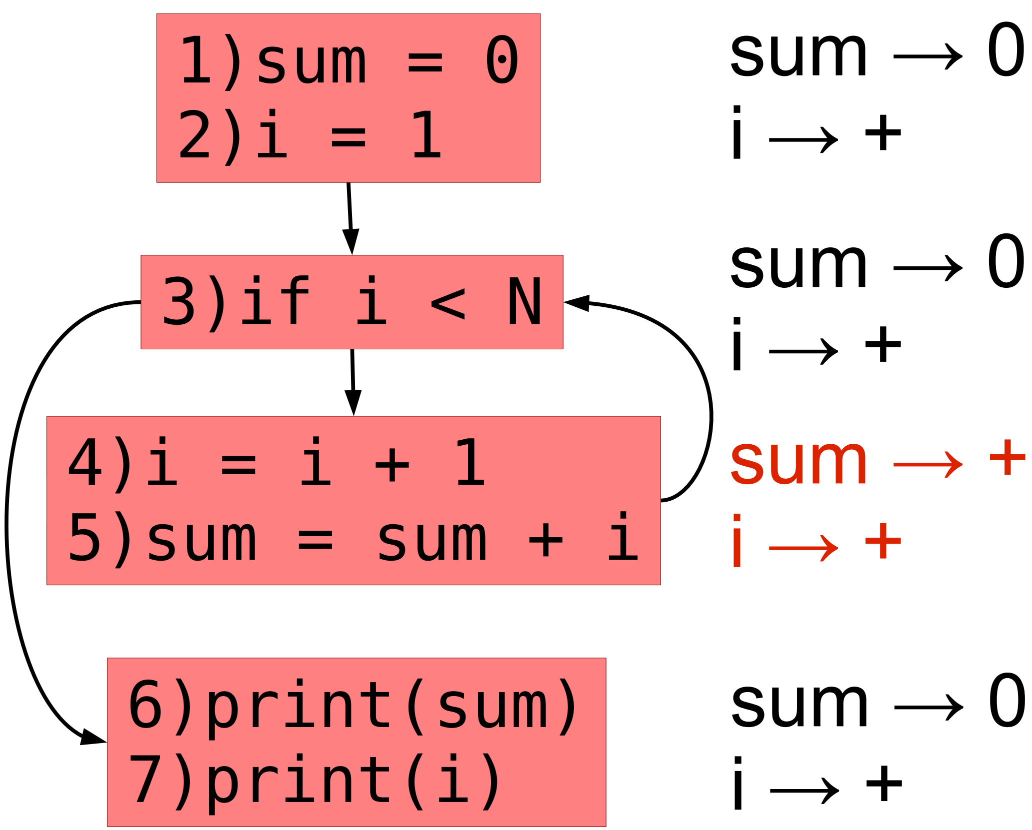

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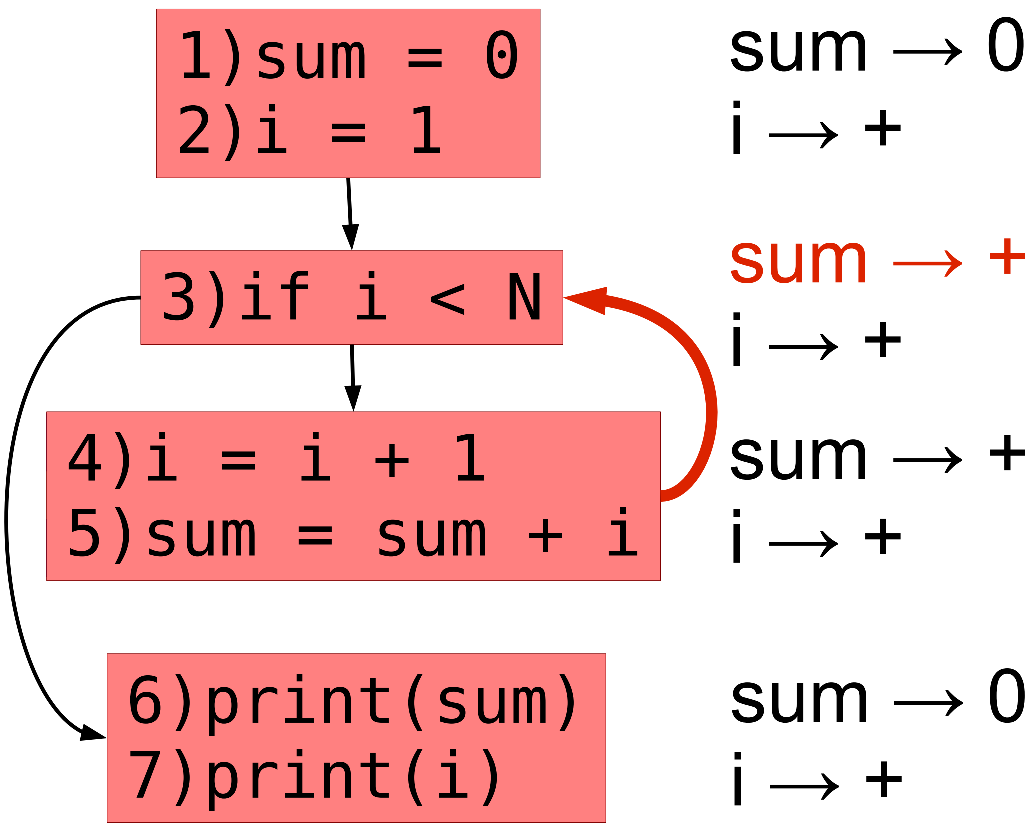

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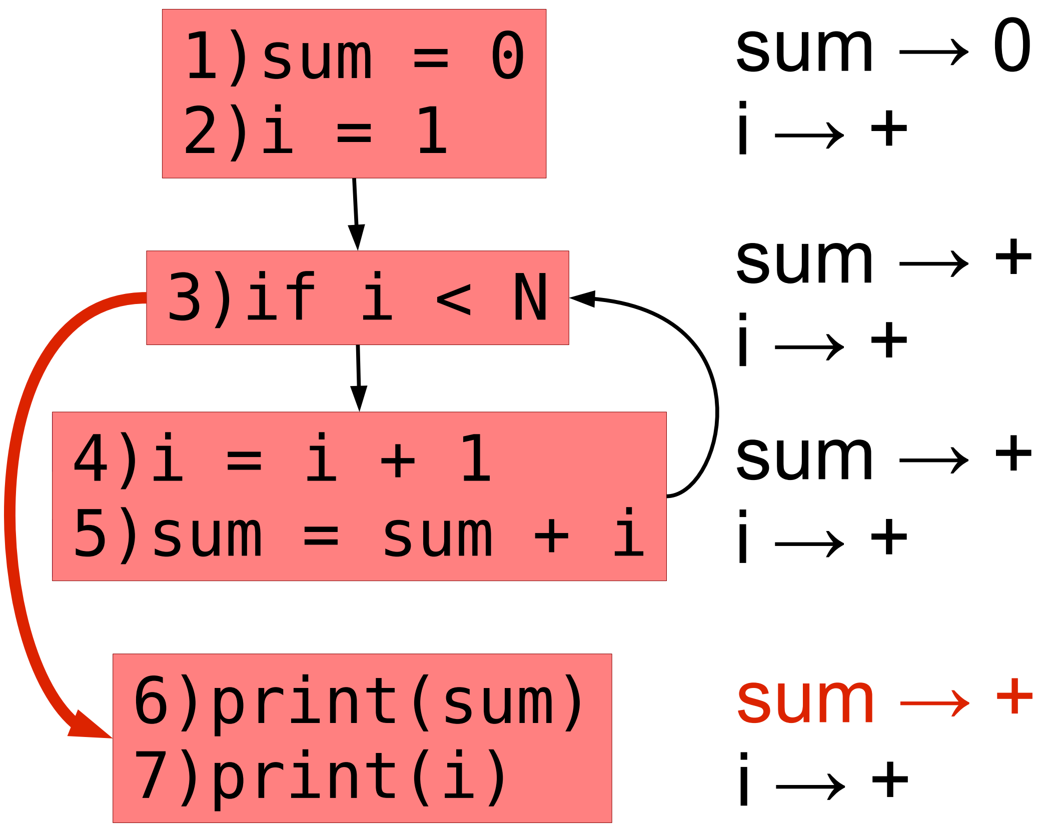

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Will it always terminate?

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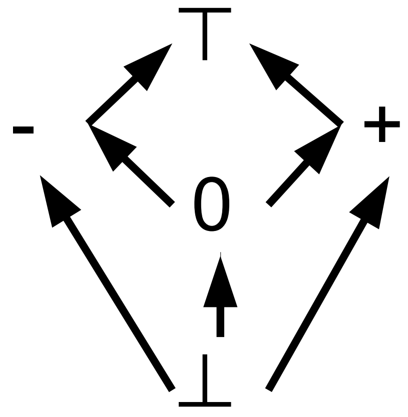

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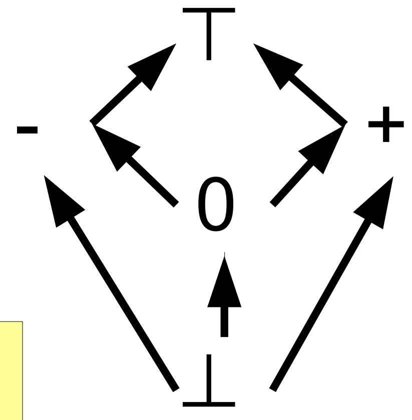

Why is this enough?

Data Flow Analysis

- Note: need to model program state at each statement
- Proper ordering & a work list algorithm improves the efficiency

Static Analysis

- We've already seen a few static analyses:
  - Call graph construction
  - Points-to graph construction (What are MAY/MUST?)
  - Static slicing

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- We've already seen a few static analyses:
  - Call graph construction
  - Points-to graph construction (What are MAY/MUST?)
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- The choices for approximation are why these analyses are imprecise.

Flow Insensitive Analysis

- Saw *flow sensitive* analysis
  - Modeling state at each statement is expensive
  - Scales to functions and small components
  - Usually not beyond 1000s of lines

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- Saw *flow sensitive* analysis
  - Modeling state at each statement is expensive
  - Scales to functions and small components
  - Usually not beyond 1000s of lines
- *Flow insensitive* analyses aggregate into a global state
  - Better scalability
  - Less precision
  - "Does this function modify global variable X?"

Context Sensitive Analyses

- Program behavior may be dependent on the call stack / calling context.
  - "If bar() is called by foo(), then it is exception free."
  - Can enable more precise *interprocedural* analyses

Static Analysis

- We'll cover this further as necessary during the semester

Project 1 & LLVM

Next Week:
Dynamic Analysis,
Profiling,
Testing,
Concurrency
Security