Software QA w/ Generative AI (CS598): Program Analysis Basics

Spring 2024

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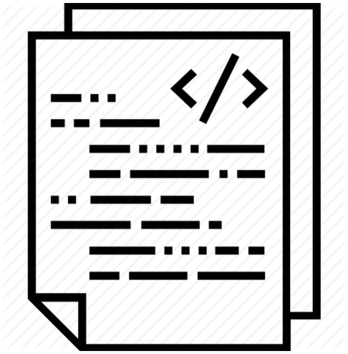
Program analysis



Program

+

Program Analysis

=

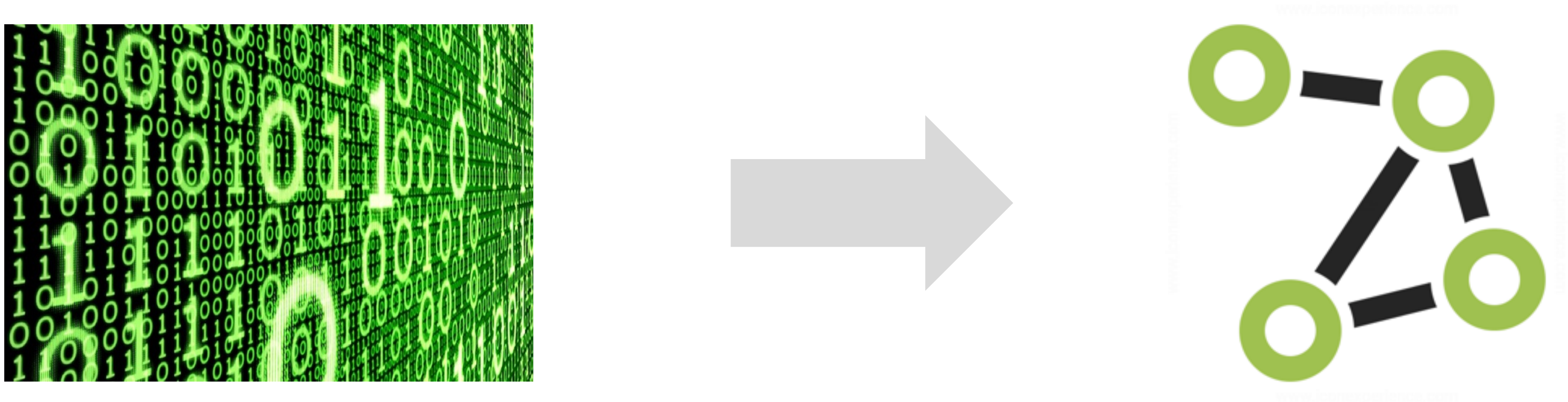
- Is it correct?
- Is it robust?
- Is it safe?
- Is it optimizable?
- …

Program analyzers aim to automatically **statically** analyze the behavior of computer programs regarding certain properties

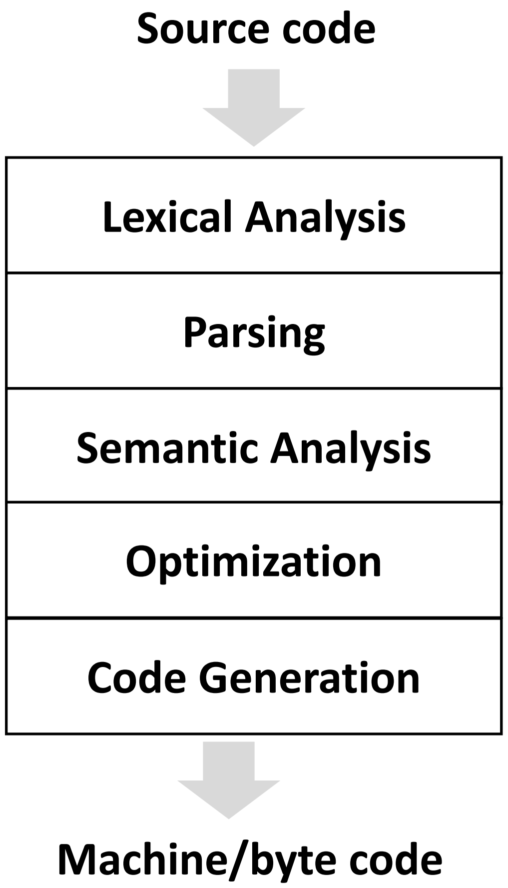
How do we analyze arbitrary programs?

Abstraction!

- Transform programs under analysis into structured code representations
  - Easier parsing
  - Easier modification
  - Easier generation

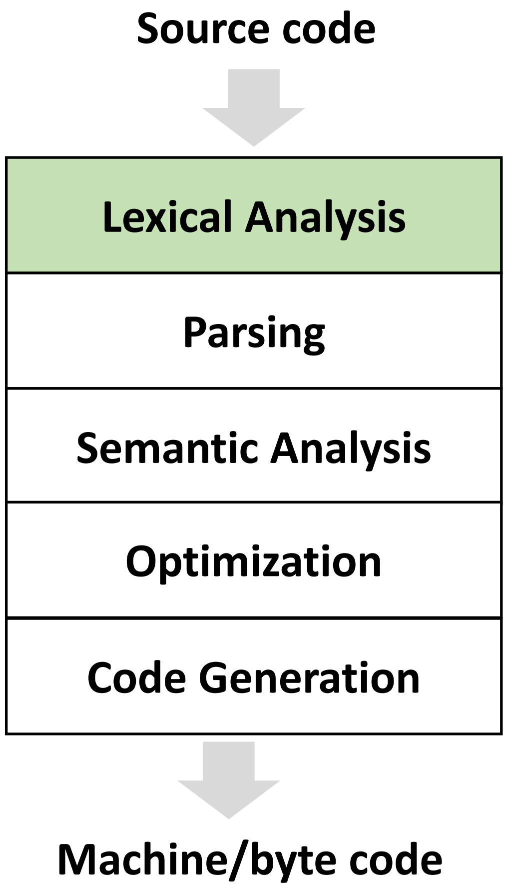


What code representations are used in a typical compiler pass?



Lexical analysis

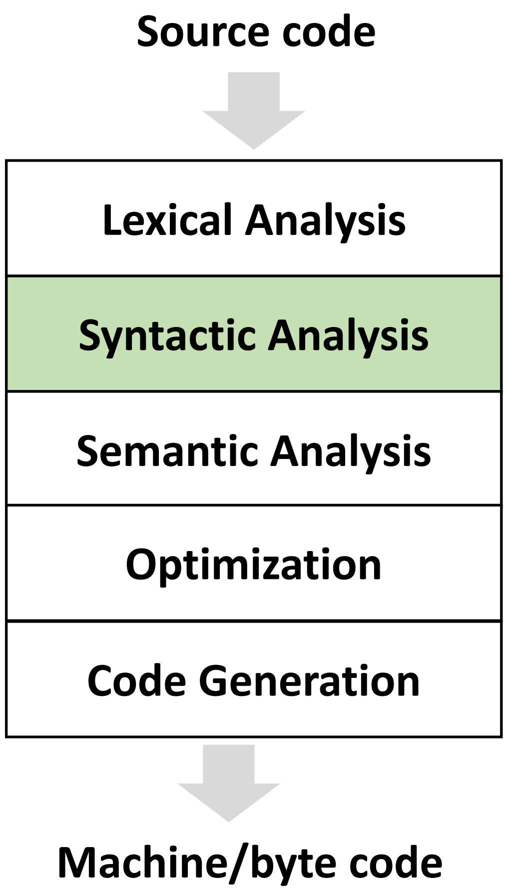
- **Input**: source code text (sequence of chars)
- **Output**: sequence of tokens




```
while (y < z) {
    x = a + b;
    y += x;
}
```

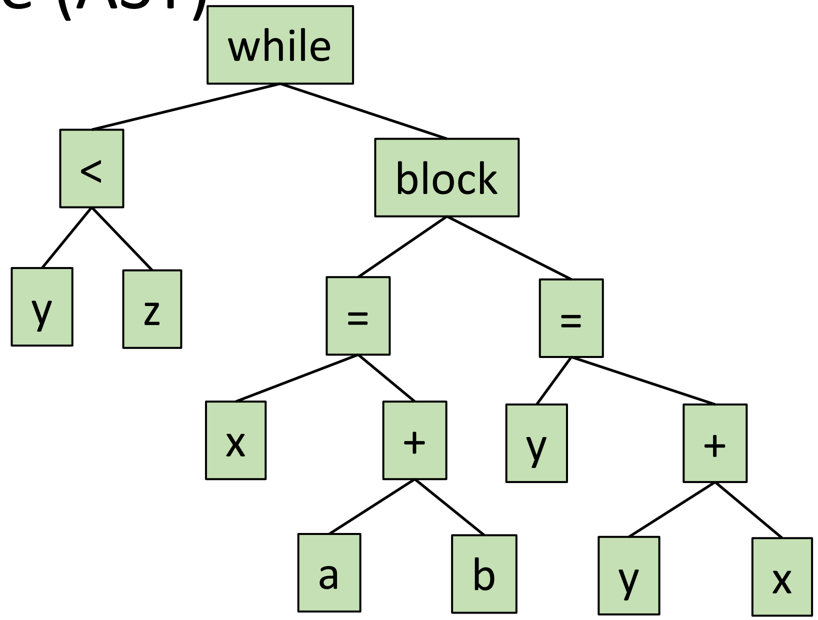
```
T_While
T_LeftParen
T_Identifier y
T_Less
T_Identifier z
T_RightParen
T_OpenBrace
T_Identifier x
T_Assign
T_Identifier a
T_Plus
T_Identifier b
T_Semicolon
T_Identifier y
T_PlusAssign
T_Identifier x
T_Semicolon
T_CloseBrace
```

Syntactic analysis

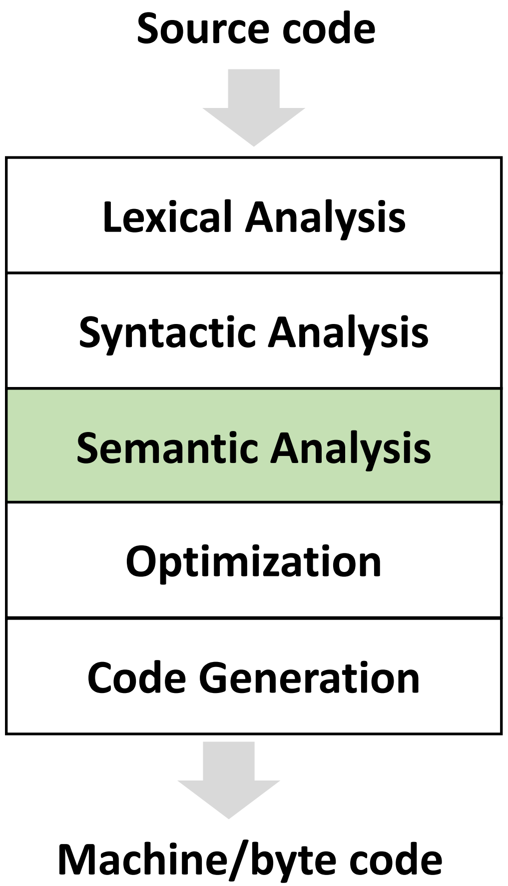


- **Input**: sequence of tokens from lexical analysis
- **Output**: abstract syntax tree (AST)

```
while (y < z) {
    x = a + b;
    y += x;
}
```

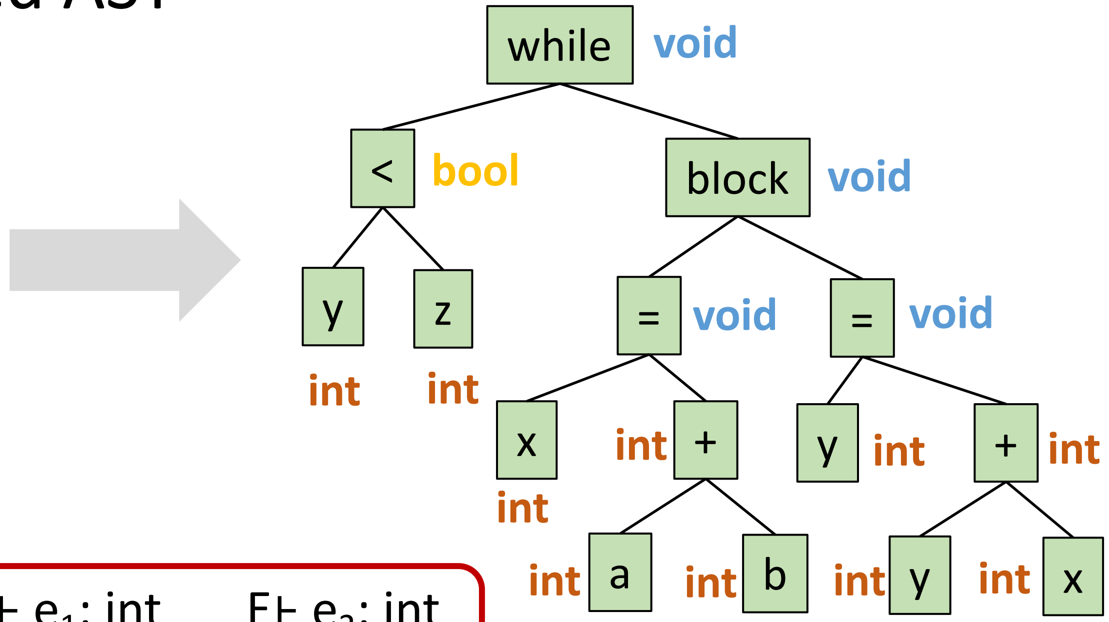


Semantic analysis



- **Input**: abstract syntax tree (AST)
- **Output**: annotated AST

```
while (y < z) {
    x = a + b;
    y += x;
}
```



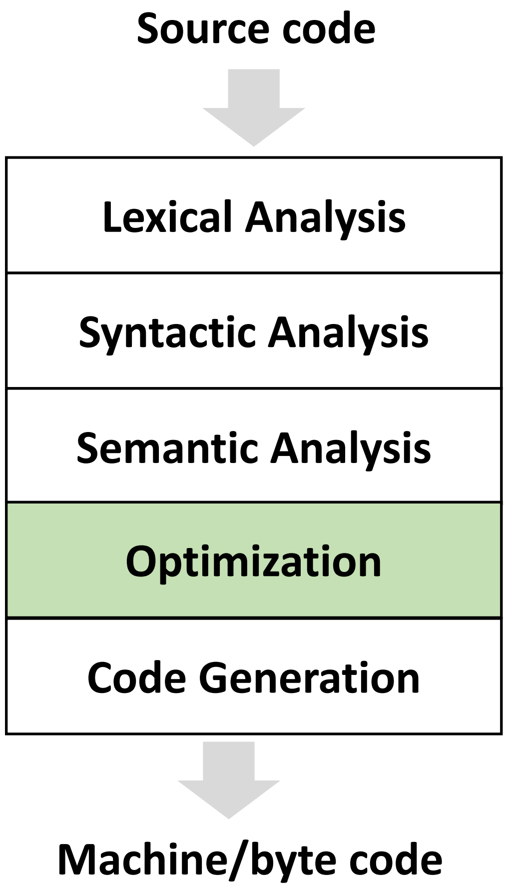
$$\frac{\text{i is an integer literal}}{E \vdash i : int} \qquad \frac{E \vdash e_1 : int \qquad E \vdash e_2 : int}{E \vdash e_1 + e_2 : int}$$

...

$$\frac{x{:}T \text{ is in } E}{E \vdash x : T} \qquad \frac{E \vdash e_1 : int \qquad E \vdash e_2 : int}{E \vdash e_1 * e_2 : int}$$

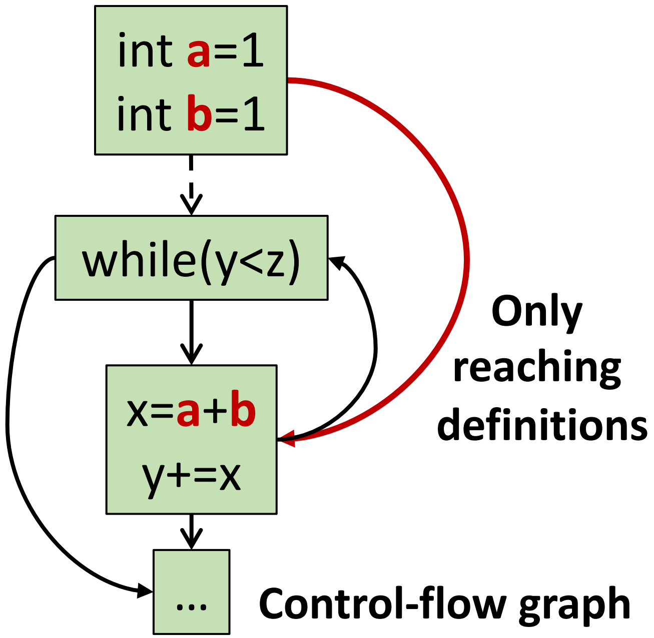
Type checking rules

Optimization



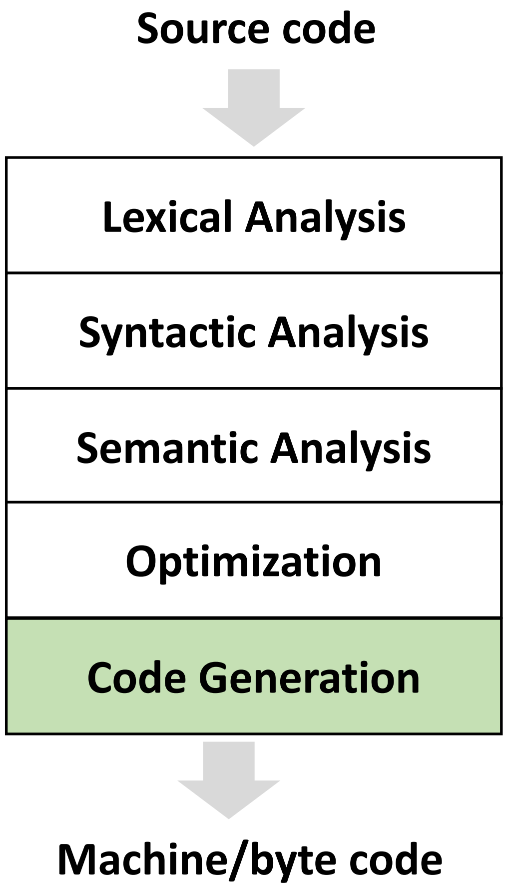
- **Input**: original code representation
- **Output**: optimized code representation

```
int a=1;
int b=1;
…
while (y < z) {
    x = a + b;
    y += x;
}
```




```
int a=1;
int b=1;
…
while (y < z) {
    y += 2;
}
```

Code generation



- **Input**: optimized code representation
- **Output**: final target code

```
while (y < z) {
    x = a + b;
    y += x;
}
```

Topics

- Abstract syntax tree (AST)
- Control-flow graph (CFG)
- Control-flow-based code coverage
- Data-flow analysis
- Data-flow-based code coverage

How do we describe a programming language?

Example program:

```
while (y < z) {
   x = a + b;
   y += x;
}
```

A grammar covering this program and similar ones:

Stmt → WhileStmt | AssignStmt | CompoundStmt
WhileStmt → "while" "(" Exp ")" Stmt
AssignStmt → ID "=" Exp ";"
CompoundStmt → "{" StmtList "}”
StmtList → ε | Stmt StmtList
Exp → Less | Add | ID
Less → Exp "<" Exp
Add → Exp "+" Exp

Context-free grammar

- A context-free grammar G = **⟨Σ, N, P, S⟩**, where
  - ***Σ***: alphabet (finite set of symbols, or terminals)
    - Often written in lowercase
  - **N**: a finite, nonempty set of nonterminal symbols, $\mathbf{N} \cap \boldsymbol{\Sigma} = \emptyset$
    - Often at least the first letter in UPPERCASE
  - **P**: the set of production rules, each with the form $\mathbf{X} \longrightarrow \mathbf{Y_1\ Y_2 \ldots Y_n}$
    - where $\mathbf{X \in N}$, $\mathbf{n \geq 0}$, and $\mathbf{Y_k \in N \cup \Sigma}$
  - **S**: the start symbol (one of the nonterminals), i.e., $\mathbf{S \in N}$

Grammar (P):

E ⟶ E+E

E ⟶ E*E

E ⟶ (E)

E ⟶ id

=

Grammar (P):

E ⟶ E+E

| E*E

| (E)

| id

Σ: +, * (,), id

N: E

S: E

Context-free grammar

Example program:

```
while (y < z) {
    x = a + b;
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```

A grammar covering this program and similar ones:

Stmt ⟶ WhileStmt | AssignStmt | CompoundStmt

WhileStmt ⟶ "while" "(" Exp ")" Stmt

AssignStmt ⟶ ID "=" Exp ";"

CompoundStmt ⟶ "{" StmtList "}”

StmtList ⟶ ε | Stmt StmtList

Exp ⟶ Less | Add | ID

Less ⟶ Exp "<" Exp

Add ⟶ Exp "+" Exp

Σ: ID, “while”, “(”, “=”, “{”, …

N: Stmt, WhileStmt, …

S: Stmt

Context-free grammar: generating strings

- **G** defines a language **L(G)** over the alphabet Σ
- Σ^* is the set of all possible sequences of Σ symbols
- **L(G)** is the subset of Σ^* that can be derived from the start symbol **S**, by following the production rules **P**
  - A **derivation** is such a sequence of productions applied

Grammar:

E → E+E
  | E*E
  | (E)
  | id

E → E+E
→ E * E+E
→ id * E + E
→ id * id + E
→ id * id + id

Derivation

id
id * id
id * id + id
id * id + id *id
id + id + id + id
…

L(G)

Context-free grammar: parsing strings

- Checking if input string (e.g., code) **s** ∈ **L(G)**, i.e., checking for **acceptance**
- Algorithm: Find a derivation starting from the start symbol of **G** to **s**

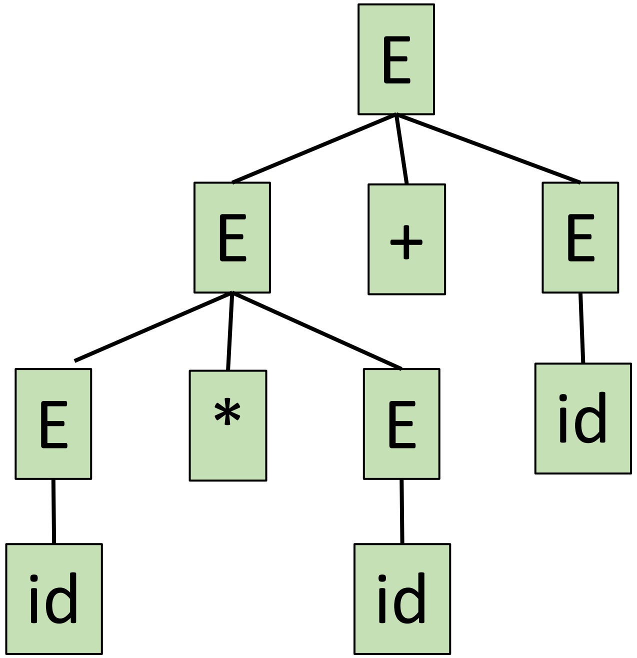
Language grammar:
E ⟶ E+E | E*E | (E) | id

id * id + id

Source

E ⟶ E+E
⟶ E * E+E
⟶ id * E + E
⟶ id * id + E
⟶ id * id + id

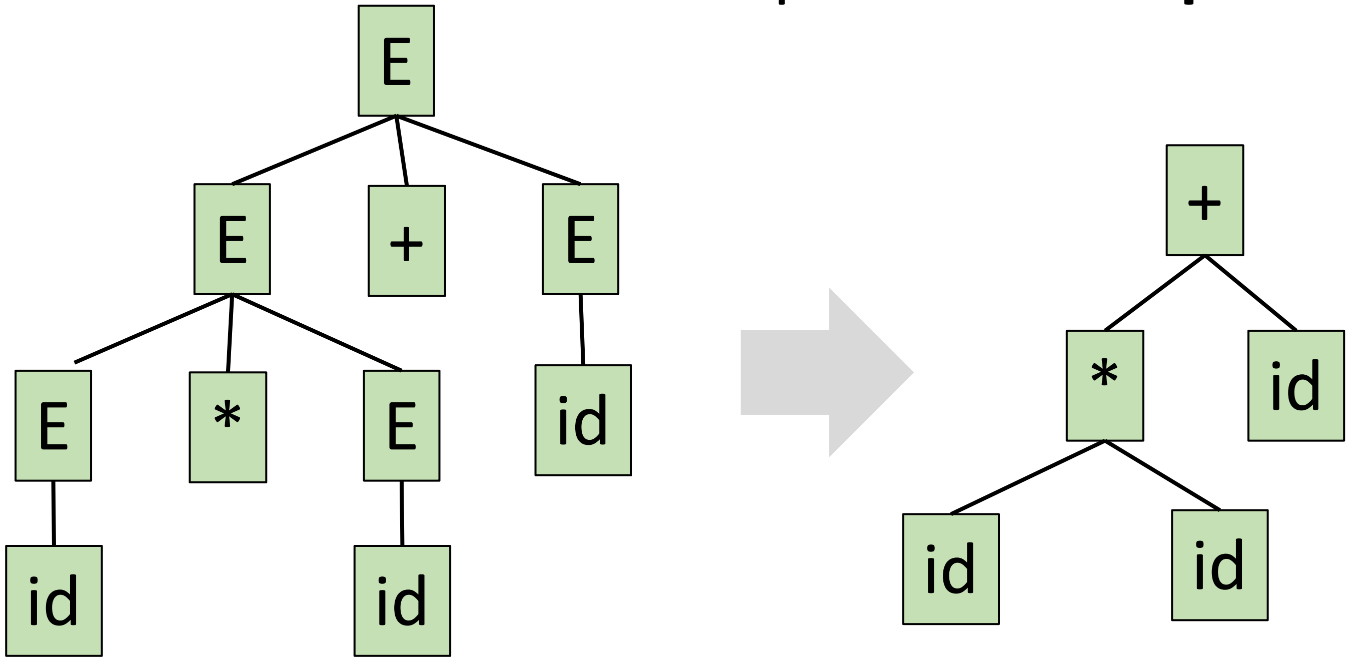
Derivation



Parse tree

Abstract syntax tree (AST)

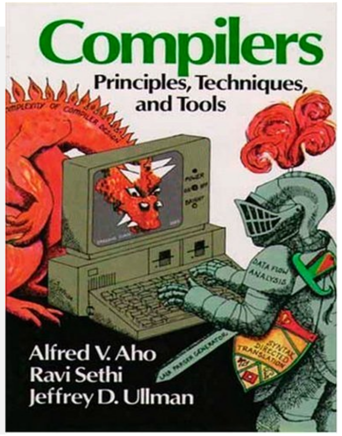
- Simplified syntactic representations derived from code parse tree
- Represents the abstract syntactic structure of a language construct
- Usually the interior and root nodes represent **operators**, and the children of each node represent the **operands** of that operator



Parse tree

AST

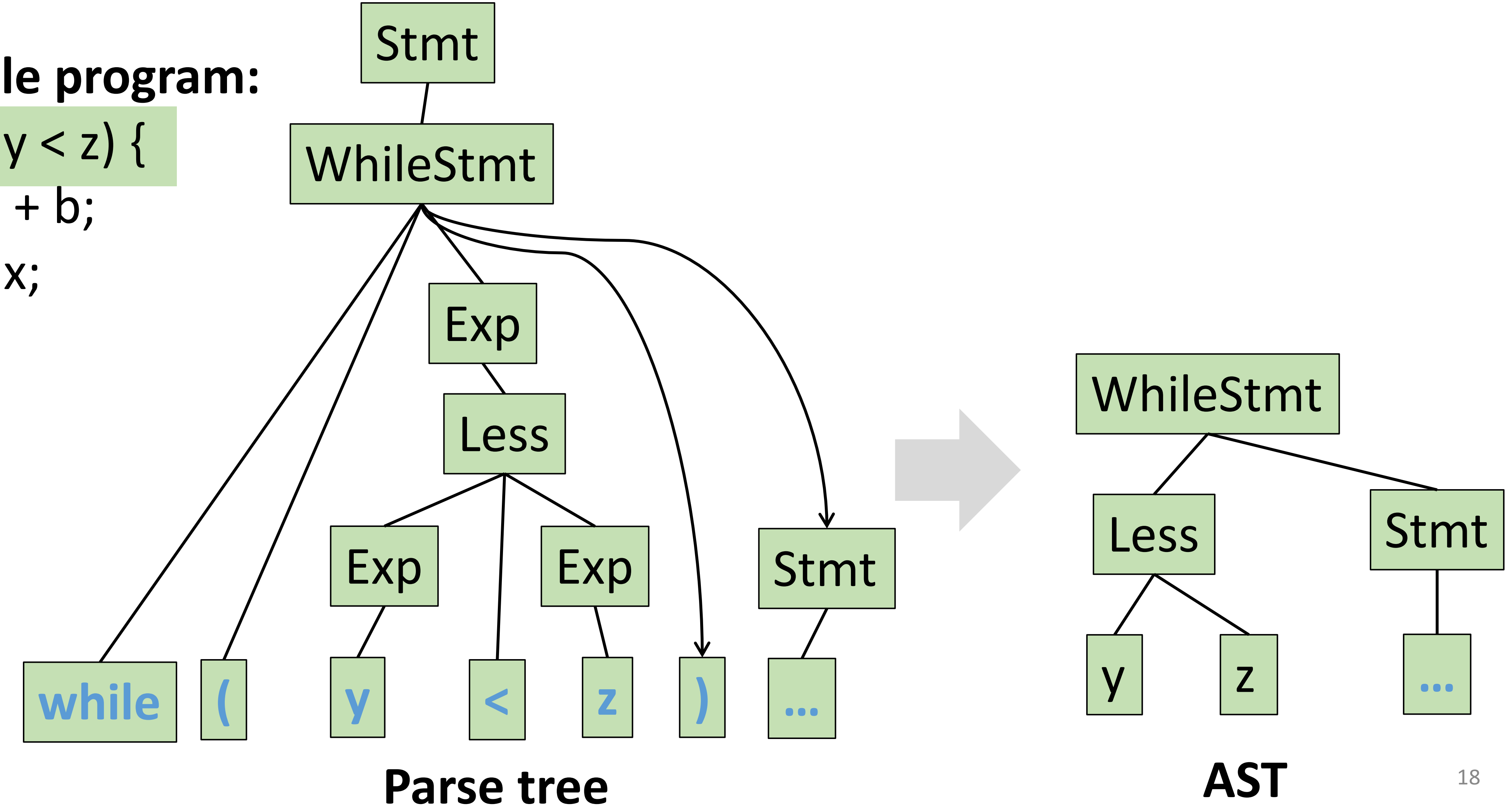
ASTs differ from parse trees because superficial distinctions of form, unimportant for translation, do not appear in syntax trees…



AST: more examples

Example program:

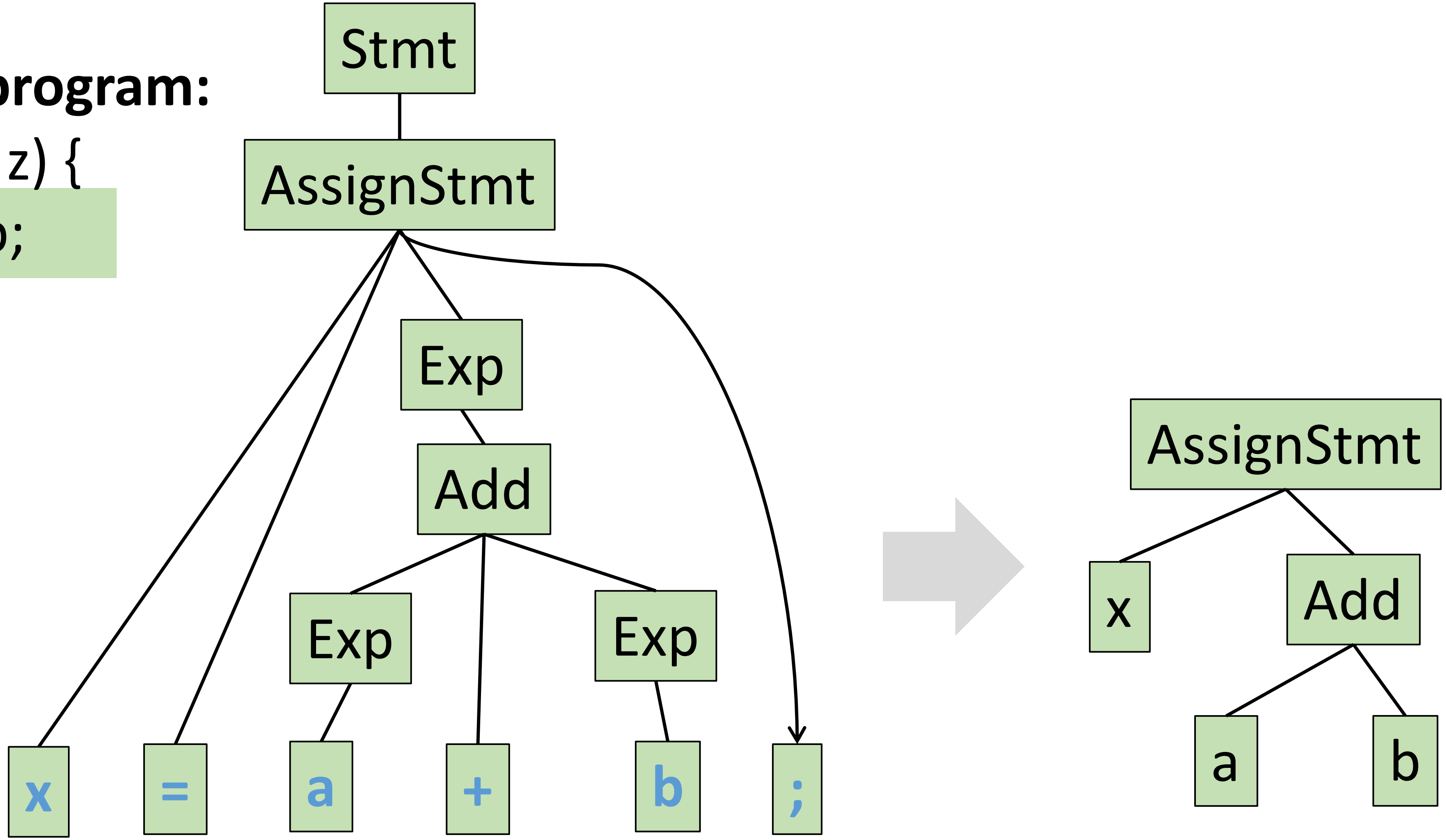
```
while (y < z) {
    x = a + b;
    y += x;
}
```



AST: more examples

Example program:

```
while (y < z) {
    x = a + b;
    y += x;
}
```



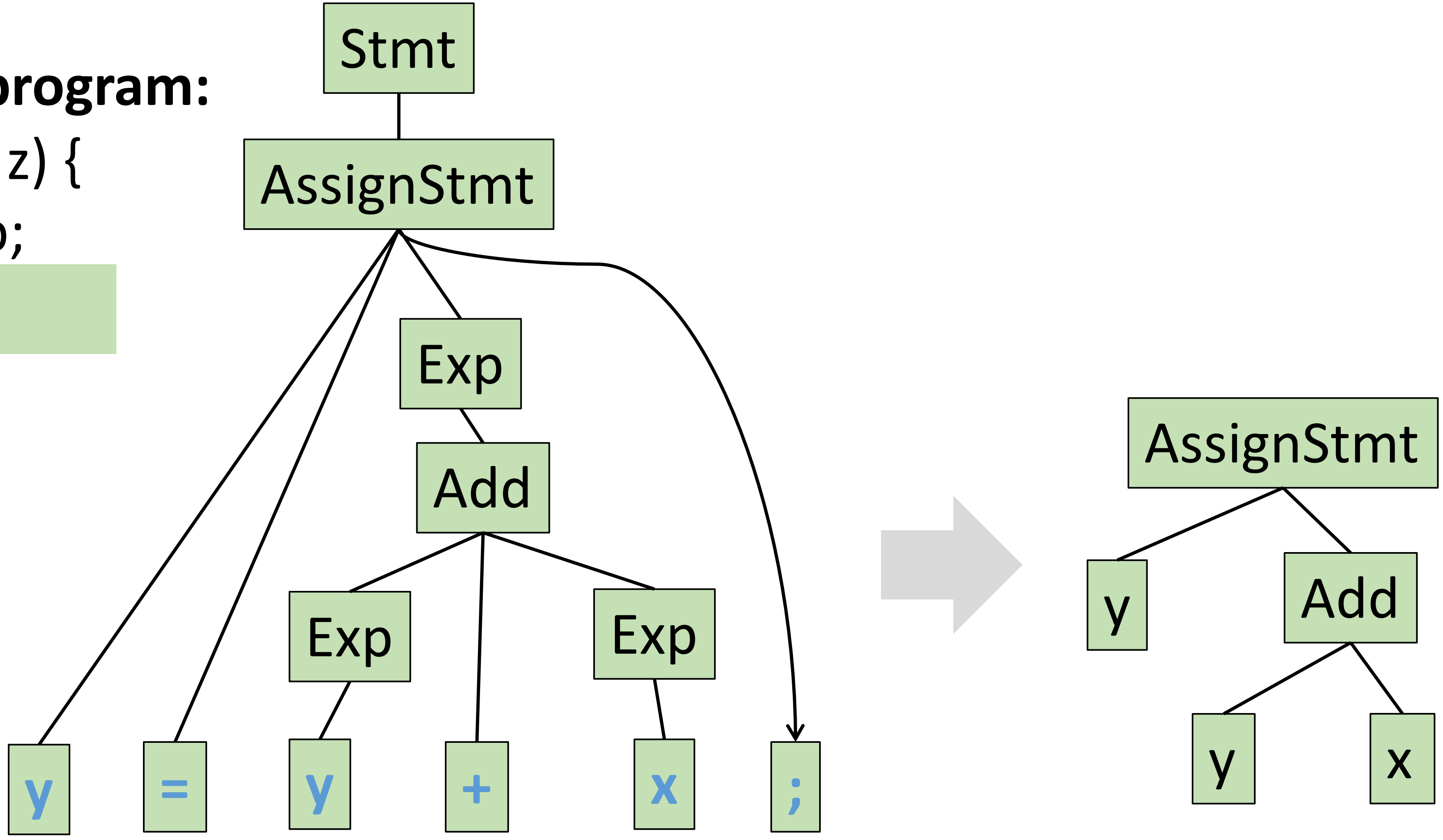
Parse tree

AST

AST: more examples

Example program:

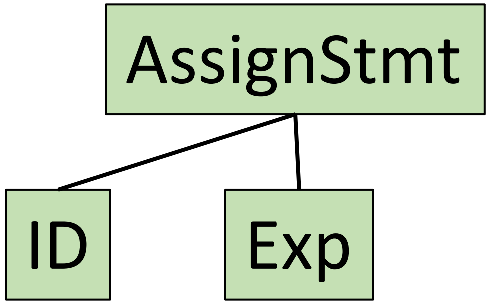
```
while (y < z) {
    x = a + b;
    y += x;
}
```



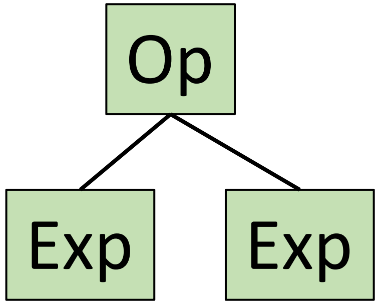
Parse tree

AST

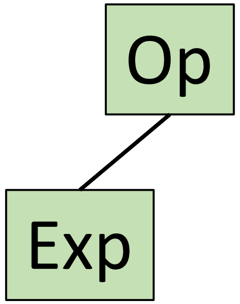
AST: typical structures



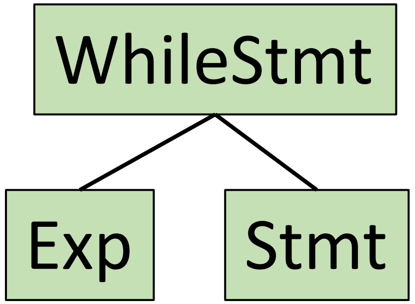
Assignment



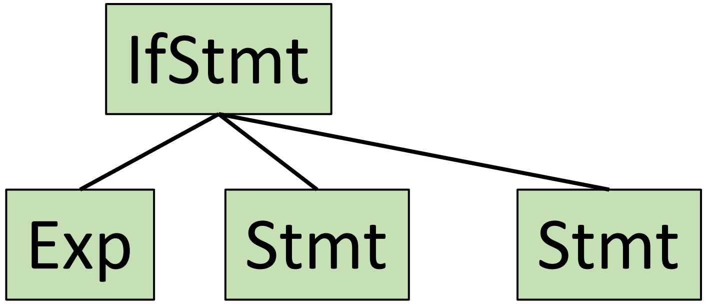
Binary operator



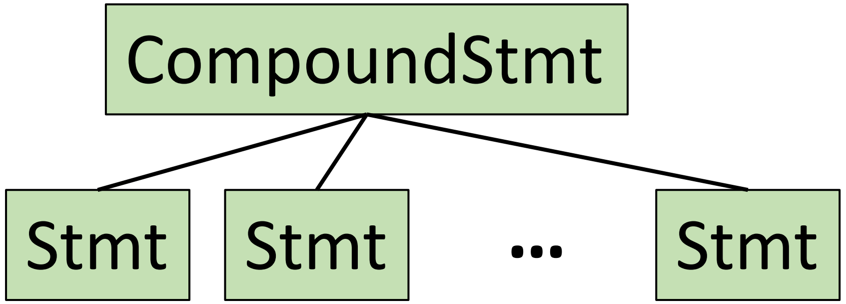
Unary operator



Loop



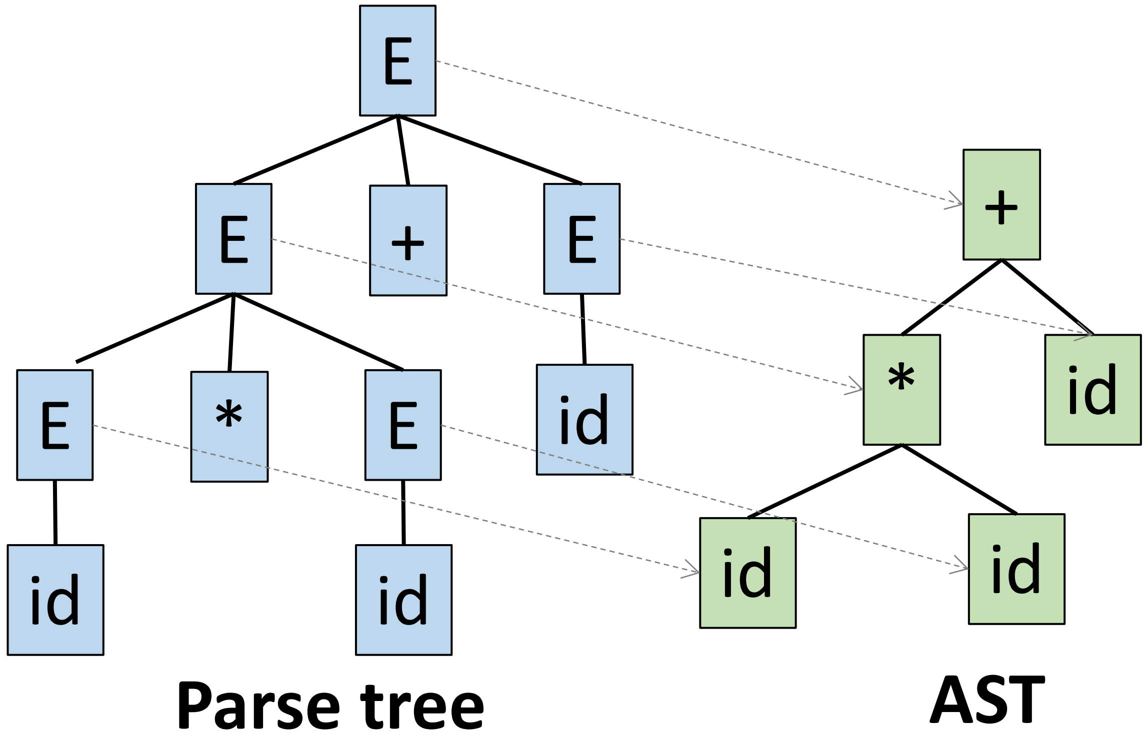
Conditional check



Compound statement

Mapping between parse tree and AST

Production	Semantic Rules
$E \longrightarrow E_1+E_2$	E.node = new Node("+", E_1.node, E_2.node)
$E \longrightarrow E_1*E_2$	E.node = new Node("*", E_1.node, E_2.node)
$E \longrightarrow (E_1)$	E.node = E_1.node
$E \longrightarrow$ id	E.node = new Leaf(id, id.entry)



AST applications

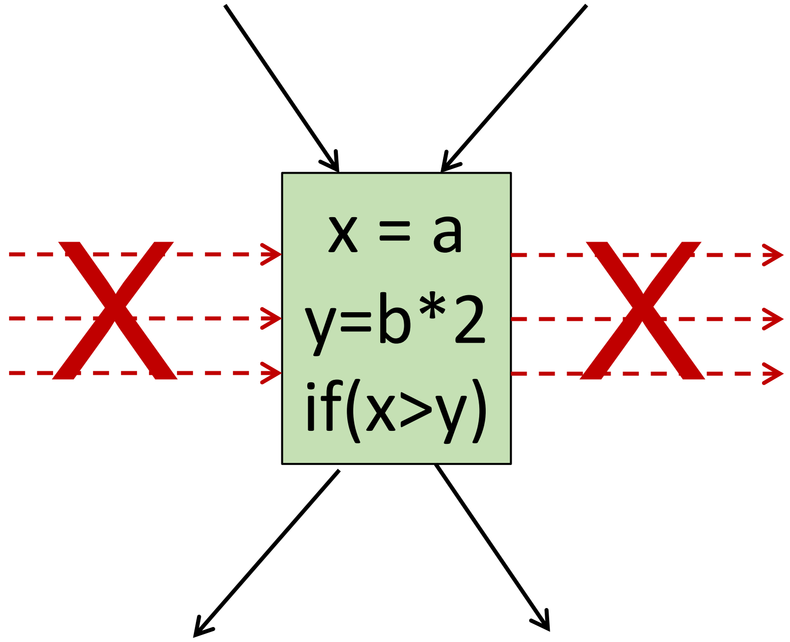
- AST provides a basic model of source code, supporting reading, modifying, and even generating source code in a systematic way
  - Compilers
  - Program analysis
  - Source code instrumentation
  - Automated program repair
  - Code generation and program synthesis
  - …

Topics

- Abstract syntax tree (AST)
- Control-flow graph (CFG)
- Control-flow-based code coverage
- Data-flow analysis
- Data-flow-based code coverage

Basic block

- A basic block is a sequence of straight-line code that can be entered only at the beginning and exited only at the end



Building basic blocks:

1. Identify leaders :
   - The first instruction in a procedure, or
   - The target of any branch, or
   - An instruction immediately following a branch
2. Gobble all subsequent instructions until the next leader

Basic block example

Building basic blocks:

1. Identify leaders :
   - The first instruction in a procedure, or
   - The target of any branch, or
   - An instruction immediately following a branch
2. Gobble all subsequent instructions until the next leader

Program

```
1  while (x < y) {
2     y = f (x, y);
3     if (y == 0) {
4        break;
5     } else if (y<0) {
6        y = y*2;
7        continue;
8     }
9     x = x + 1;
10 }
11 print (y);
```

Leaders

1

2

4

5

6

9

11

Basic blocks

1: while (x<y)

2: y=f(x,y)
3: if(y==0)

4: break

5: else if(y<0)

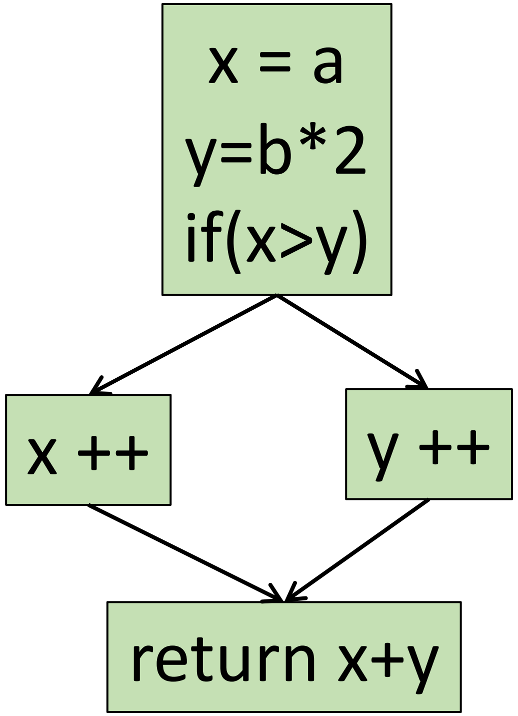
6: y=y*2
7: continue

9: x=x+1

11: print(y)

Control-flow graph (CFG)

- A control-flow graph (CFG) is a rooted directed graph **G=⟨N, E⟩**
  - **N** is the set of basic blocks
  - **E** is the flow of control between basic blocks



Building CFG:

1. Each CFG node represents a basic block
2. There is an edge from node **i** to **j** if
   - Last statement of block **i** branches to the first statement of **j**, or
   - Block **i** is immediately followed in program order by block **j** (fall through)

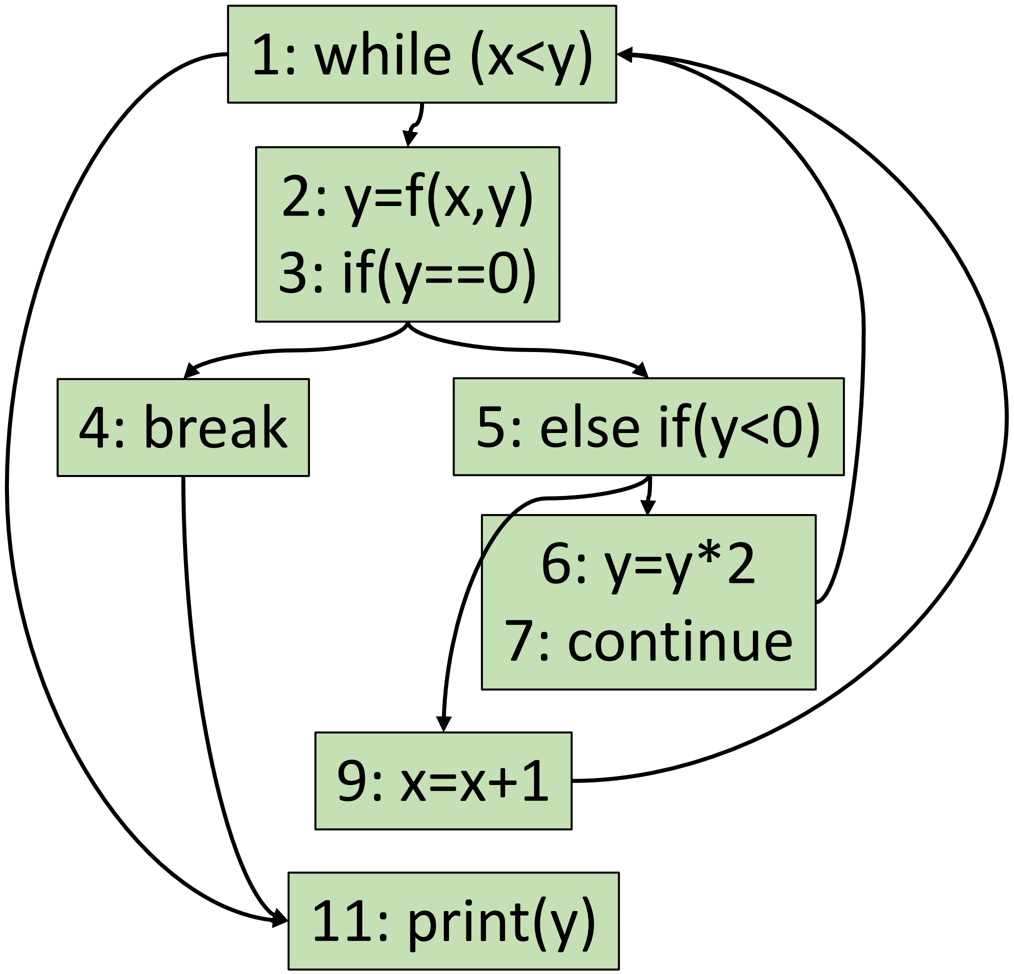
That said, as long as the execution of node **i** could be followed by node **j**, connect them!

CFG example

Program

```
1   while (x < y) {
2      y = f (x, y);
3      if (y == 0) {
4         break;
5      } else if (y<0) {
6         y = y*2;
7         continue;
8      }
9      x = x + 1;
10  }
11  print (y);
```

CFG



Topics

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- Control-flow graph (CFG)
- Control-flow-based code coverage
- Data-flow analysis
- Data-flow-based code coverage

Control-flow-based code coverage

- Given the CFG, define a coverage target and write tests to achieve it
  - Higher coverage=> more code portions tested=> potentially better tests!
- **A practical way to measure test quality!**
- Typical control-flow-based code coverage
  - Statement coverage
  - Branch coverage (aka decision coverage)
  - Path coverage
  - Condition coverage
  - Condition/decision coverage
  - Modified condition/decision coverage (MCDC)
  - …

Statement coverage

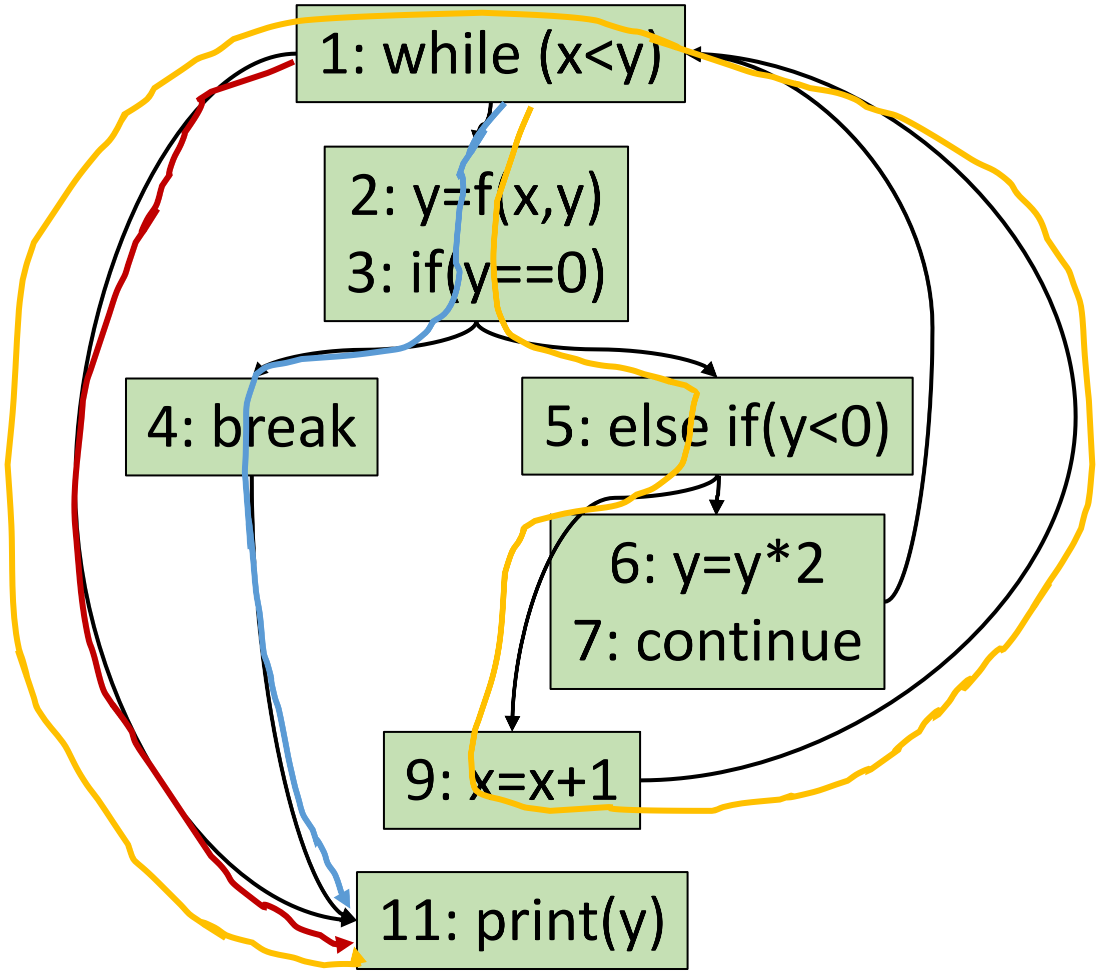
- **Target**: covering all CFG nodes

Test1: 1-11
Test2: 1-2-3-4-11
Test3: 1-2-3-5-9-1-11

Are they covering all statements?

NO, statement coverage: 7/9,
statements 6 and 7 never covered!

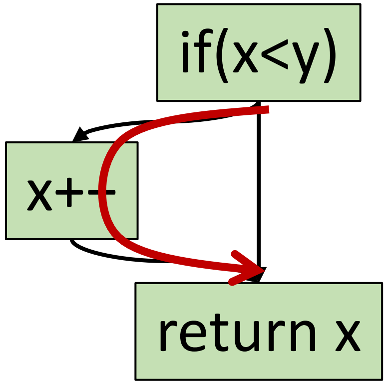
CFG



Branch coverage (decision coverage)

- **Target**: covering all CFG edges
- Equivalent to covering all branches of the predicate nodes
  - True and false branches of each **if** node
  - The two branches corresponding to the condition of a loop
  - All alternatives in a **switch** node
- Is branch coverage equivalent to statement coverage?

```
if (x < y) {
  x++;
}
return x;
```



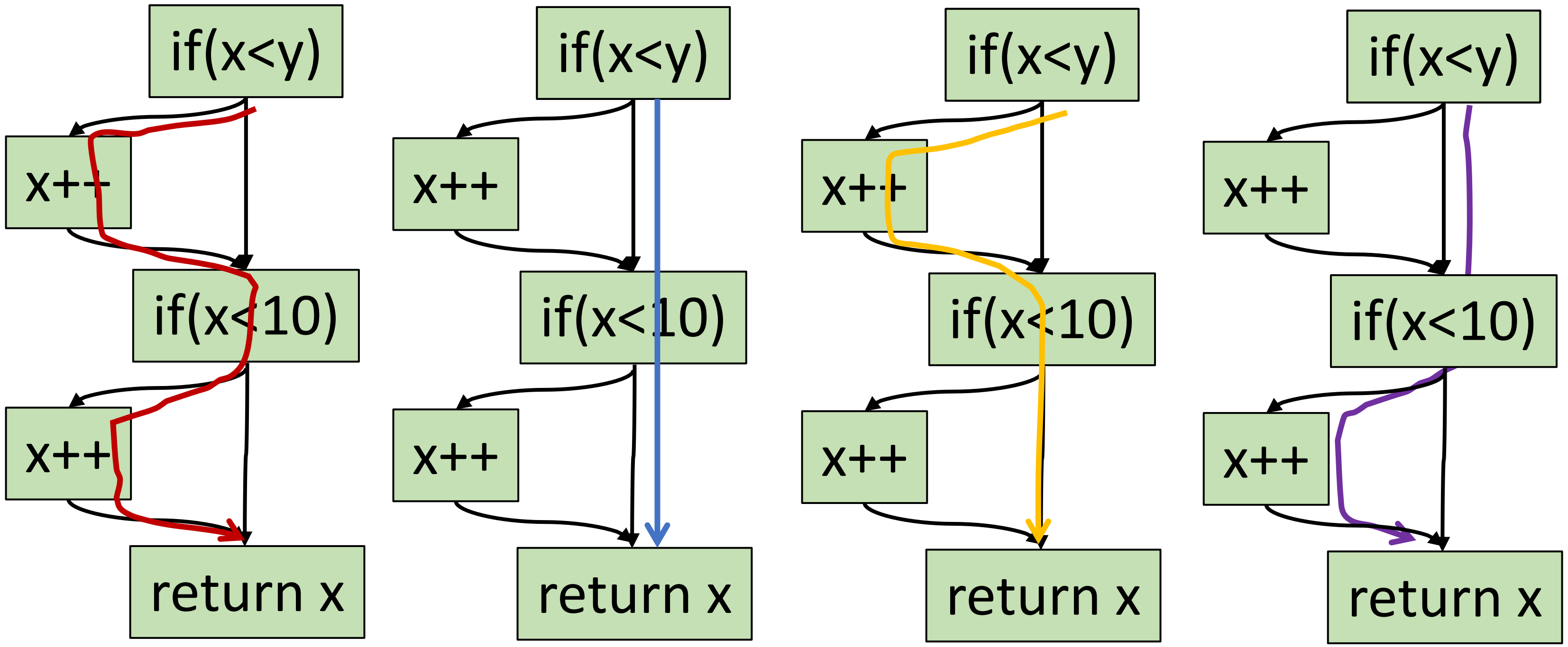
Test1: x=1, y=2

Statement coverage: 3/3

Branch coverage: 1/2

Path coverage

- **Target**: covering all possible paths on CFG
- Is path coverage equivalent to branch coverage?



Test1: x=1, y=2

Test2: x=10, y=2

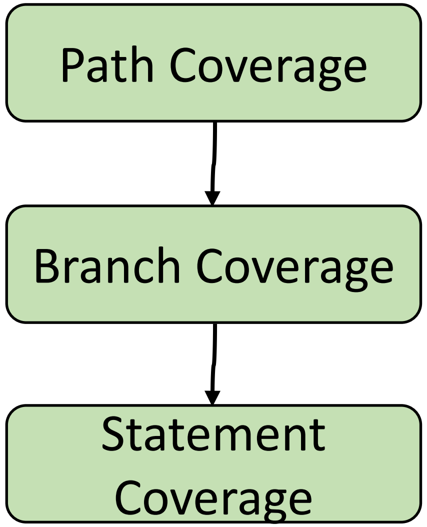
Branch coverage: 4/4

Path coverage: 2/4

The number of paths could be infinite (loops) or exponential (branches)!

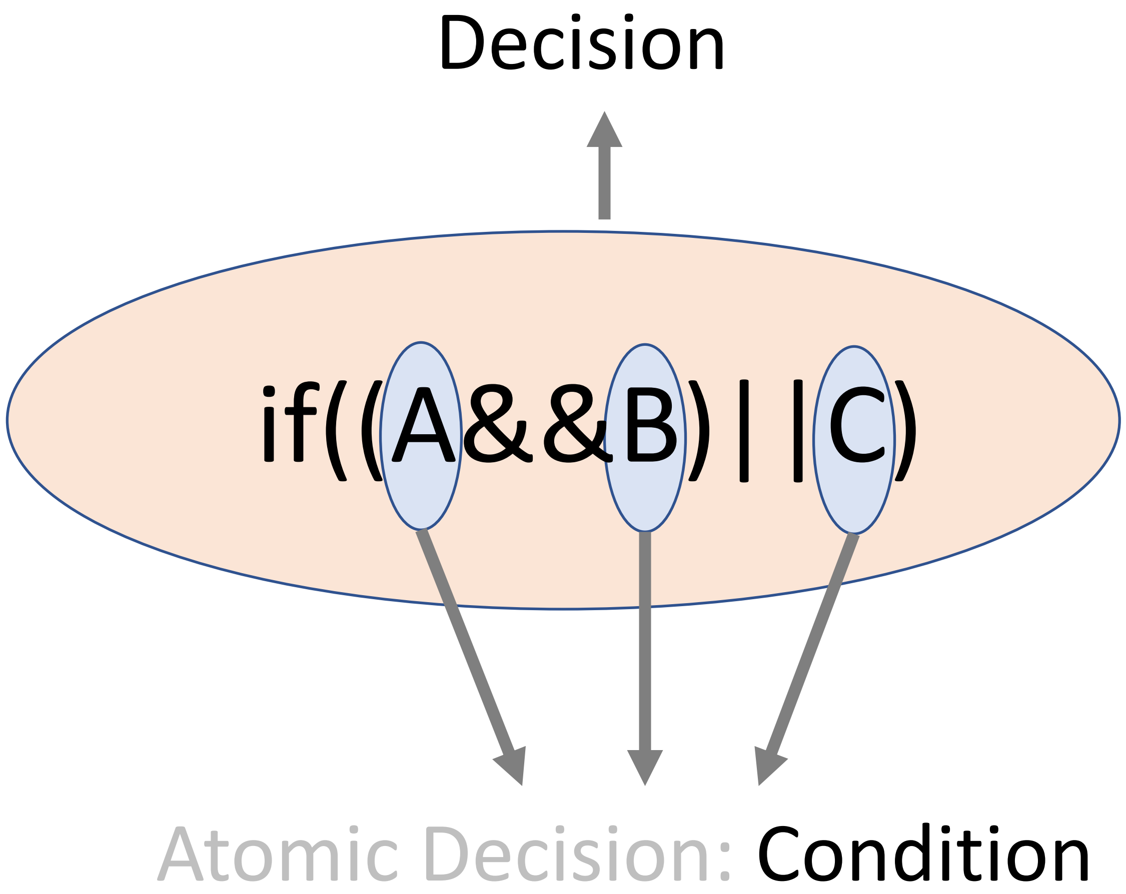
Control-flow-based coverage: summary

- Path coverage strictly subsumes branch coverage
- Branch coverage in turn strictly subsumes statement coverage



Coverage subsumption graph

More control-flow coverage



- Condition coverage
- Condition/decision coverage
- Modified condition/decision coverage (MCDC)
- …

Topics

- Abstract syntax tree (AST)
- Control-flow graph (CFG)
- Control-flow-based code coverage
- Data-flow analysis
- Data-flow-based code coverage

Deadlines

- Jan 26 (11:59pm)
  - Presentation choice submission
- Feb 6 (11:59pm)
  - HW1: MSP Pretraining for Code

Check Campuswire ”Assignments” frequently!

Data-flow analysis

- A framework for proving facts (e.g., reaching definitions) about programs
- Operates on control-flow graphs (CFGs), typically
- Works best on properties about how program computes
- Based on all paths through program
  - Including infeasible paths

Variable definition/use

- A program variable is **defined** whenever its value is modified:
  - On the left-hand side of an assignment statement: **y = 17**
  - In an input statement: **read(y)**
  - As a call-by-reference parameter in a subroutine call: **update(x, &y)**
- A program variable is **used** whenever its value is read:
  - **P-use** (predicate-use): use in the predicate of a branch statement
  - **C-use** (computation-use): all other uses

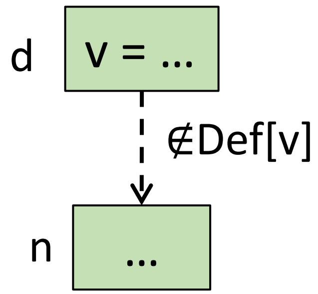
```
if ( x > 0 ){
  print(y);
}
```

P-use

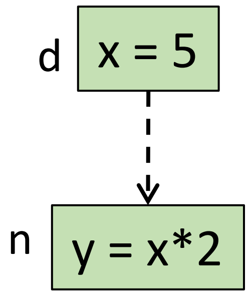
C-use

A typical analysis: reaching definitions

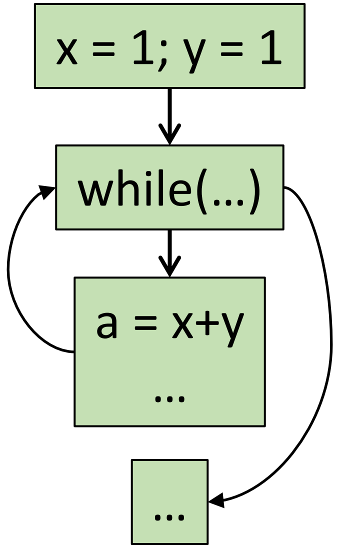
- A definition (statement) **d** of a variable **v** **reaches** CFG node **n** if there is a path from **d** to **n** such that **v** is not redefined along that path



- Reaching definitions applications:
  - Build use/def chains
  - Constant propagation
  - Loop invariant code motion

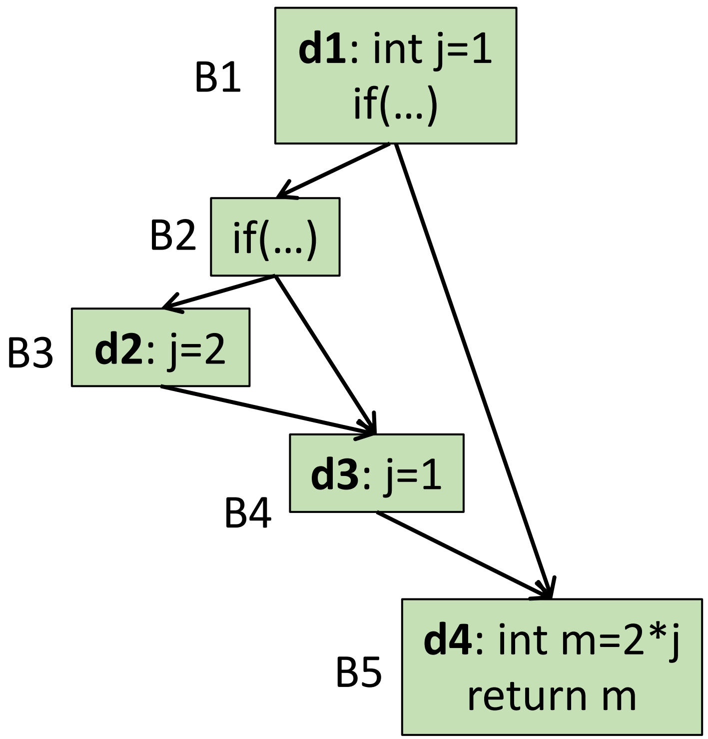


Is this the only def of **x** reaching **n**?
Can we replace **y=x*2** with **y=10**?



Any other reaching definitions of **x/y** in the loop?
Can we move “**a=x+y**” out of the loop?

Reaching definitions: example

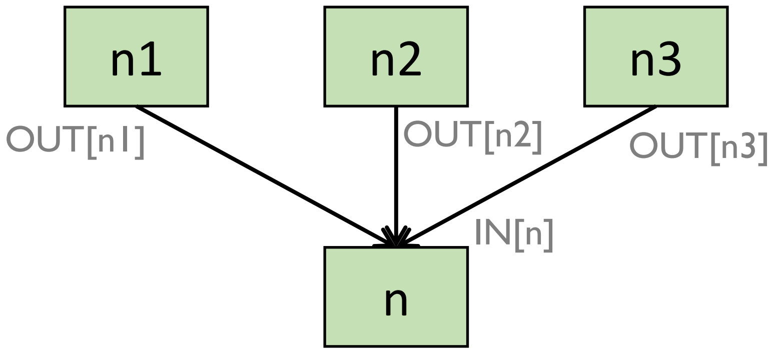


n	IN[n]	OUT[n]
B1	Ø	{d1}
B2	{d1}	{d1}
B3	{d1}	{d2}
B4	{d1, d2}	{d3}
B5	{d1, d3}	{d1, d3, d4}

IN[n]: set of facts (reaching definitions) at entry of node n
OUT[n]: set of facts (reaching definitions) at exit of node n

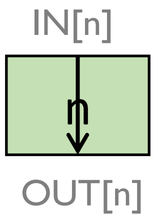
Constant propagation can be applied to B5 as j is always 1!

Reaching definitions: transfer functions



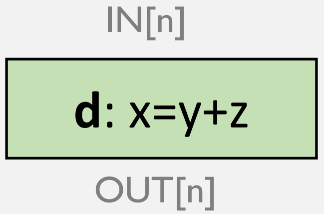
IN[n]=OUT[n1] ∪ OUT[n2] ∪ OUT[n3]

$$IN[n] = \bigcup_{n' \in predecessors(n)} OUT[n']$$



KILL[n] = a set of definitions killed by definitions in node n
GEN[n] = a set of locally available definitions in node n

$$OUT[n] = (IN[n] - KILL[n]) \cup GEN[n]$$



GEN[n] = {d}

KILL[n] = Def[x] – {d}, where Def[x] : set of all definitions of **x**

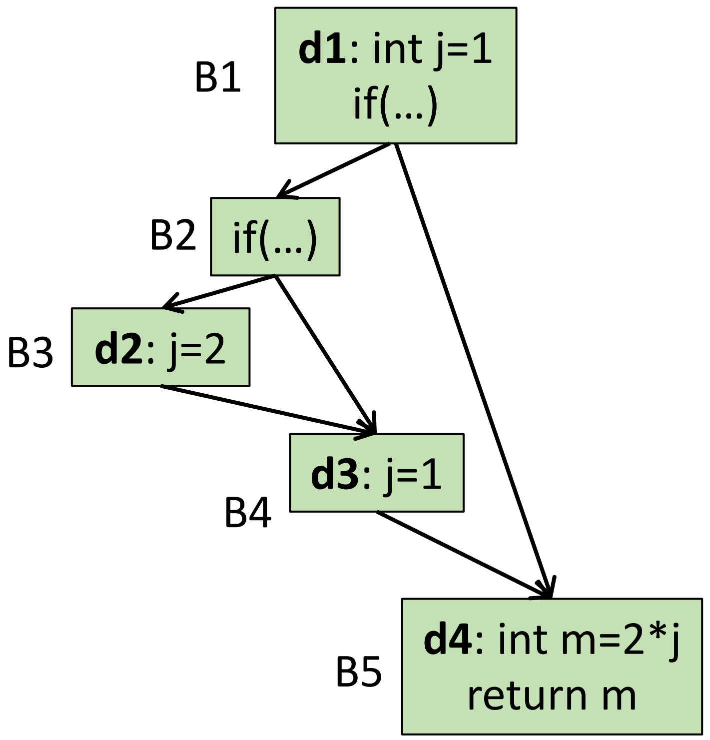
Reaching definitions algorithm

for (each node n):
    $IN[n] = OUT[n] = \emptyset$

for (each node n):
    $IN[n] = \bigcup_{n' \in predecessors(n)} OUT[n']$
    $OUT[n] = (IN[n] - KILL[n]) \cup GEN[n]$

Any issues?

Reaching definitions: example



n	IN[n]	OUT[n]
B1	Ø	{d1}
B2	{d1}	{d1}
B3	{d1}	{d2}
B4	{d1}	{d3}
B5		

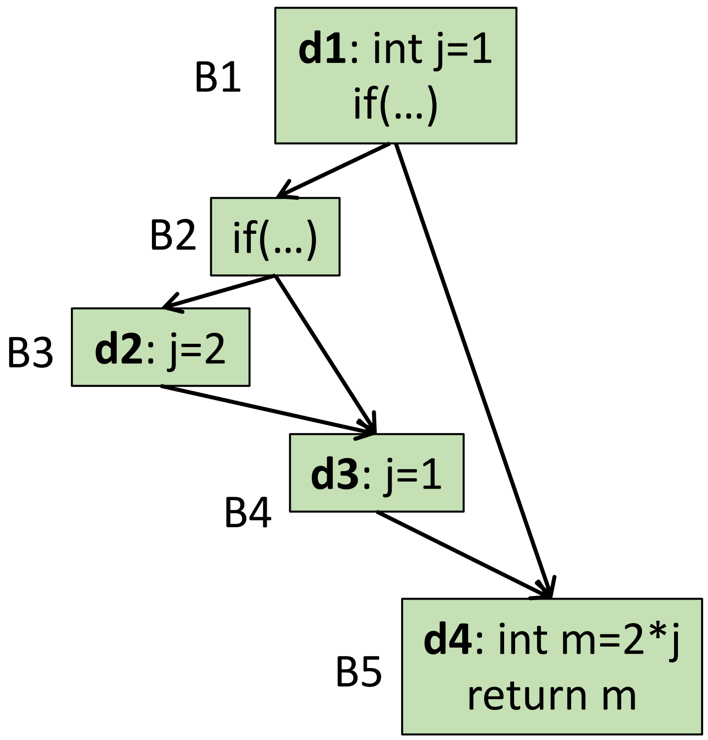
Order matters!

The IN set for B4 is incorrect (should be {d1,d2})!

Reaching definitions algorithm: revised

```
for (each node n):
    IN[n] = OUT[n] = Ø
repeat:
for (each node n):
    IN[n] = U n' ∈ predecessors(n) OUT[n']
    OUT[n] = (IN[n] - KILL[n]) ∪ GEN[n]
until fixed point: IN[n] and OUT[n] stop changing for all n
```

Reaching definitions: revisit the example



n	GEN[n]	Kill[n]	IN[n]	OUT[n]
B1	{d1}	{d2, d3}	∅	{d1}
B2	∅	∅	{d1}	{d1}
B3	{d2}	{d1, d3}	{d1}	{d2}
B4	{d3}	{d1, d2}	{d1, d2}	{d3}
B5	{d4}	∅	{d1, d3}	{d1, d3, d4}

$IN[n] = \bigcup_{n' \in predecessors(n)} OUT[n']$

$OUT[n] = (IN[n] - KILL[n]) \cup GEN[n]$

IN[n] = a set of **reaching definitions** before n
OUT[n] = a set of **reaching definitions** after n
KILL[n] = a set of **definitions** killed by definitions in node n
GEN[n] = a set of locally available **definitions** in node n

Does it always terminate?

The two operations of reaching definitions analysis are monotonic

---

IN and OUT sets never shrink, only grow

Largest they can be is set of all definitions in program, i.e., finite

---

IN and OUT cannot grow forever

IN and OUT will stop changing after some iteration

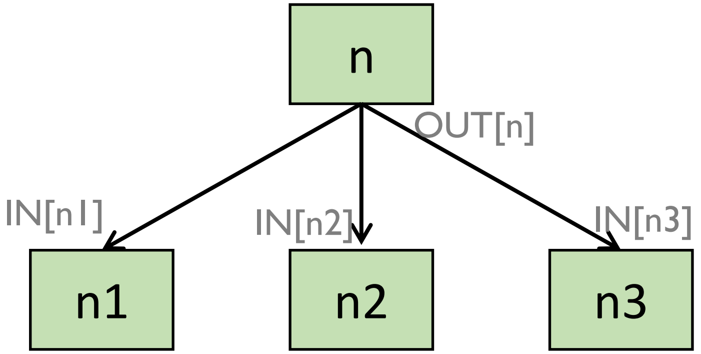
$IN[n] = \bigcup_{n' \in predecessors(n)} OUT[n']$

$OUT[n] = (IN[n] - KILL[n]) \cup GEN[n]$

Other classical dataflow analyses

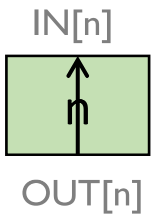
- **Live Variables Analysis:** for dead code elimination
  - Determine for each program point which variables could be *live* at the point's exit
  - A variable is **live** if there is a path to a use of the variable that doesn't redefine the variable
- **Available Expressions Analysis**: don't recompute expressions that are still available
  - Determine, for each program point, which expressions must already have been computed, and not later modified, on all paths to the program point
- **Very Busy Expressions Analysis:** move expressions to a common point
  - An expression is very *busy* at a program point **p** if, no matter what path is taken from **p**, the expression is evaluated before any of its variables is redefined

Live variables: transfer functions



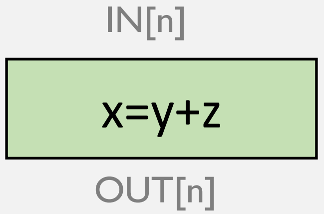
OUT[n]=IN[n1] ∪ IN[n2] ∪ IN[n3]

$$OUT[n] = \bigcup_{n' \in successors(n)} IN[n']$$



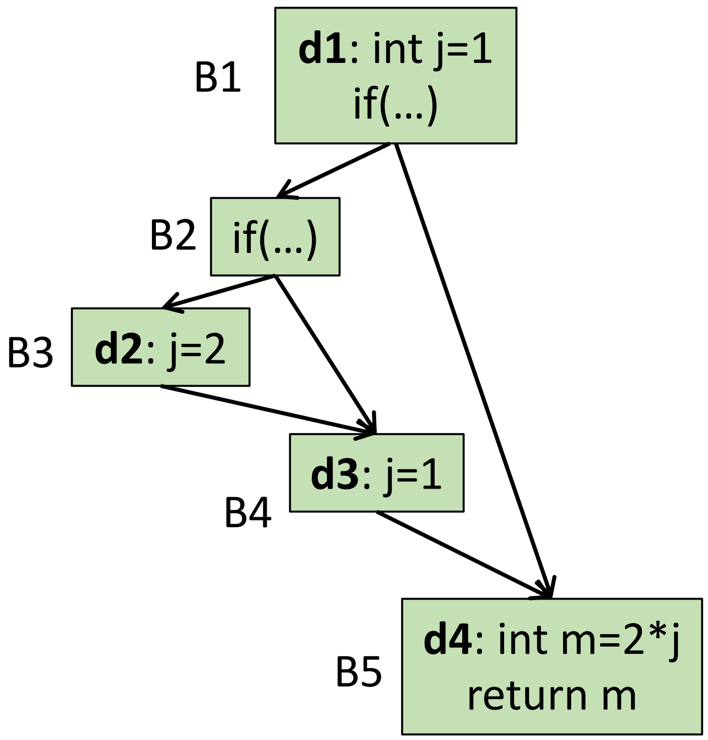
KILL[n] = a set of **variables** defined in node n
GEN[n] = a set of **variables** used in node n

IN[n] = (OUT[n] - KILL[n]) ∪ GEN[n]



GEN[n] = {y, z}
KILL[n] = {x}

Live variables analysis: example



n	GEN[n]	Kill[n]	IN[n]	OUT[n]
B1	Ø	{j}	Ø	{j}
B2	Ø	Ø	Ø	Ø
B3	Ø	{j}	Ø	Ø
B4	Ø	{j}	Ø	{j}
B5	{j}	{m}	{j}	Ø

$$OUT[n] = \bigcup_{n' \in succcessors(n)} IN[n']$$

$$IN[n] = (OUT[n] - KILL[n]) \cup GEN[n]$$

IN[n] = a set of **live variables** before n
OUT[n] = a set of **live variables** after n
KILL[n] = a set of **variables** defined in node n
GEN[n] = a set of **variables** used in node n

Reaching definitions vs. live variables

- Facts: set of definitions
- Direction: forward
- Join operator: ∪
- Transfer functions:
  - $IN[n] = \bigcup_{n' \in predecessors(n)} OUT[n']$
  - $OUT[n] = (IN[n] - KILL[n]) \cup GEN[n]$

Reaching definitions

- Facts: set of variables
- Direction: backward
- Join operator: ∪
- Transfer functions:
  - $OUT[n] = \bigcup_{n' \in succcessors(n)} IN[n']$
  - $IN[n] = (OUT[n] - KILL[n]) \cup GEN[n]$

Live variables

Classifying all four dataflow analyses

	May	**Must**
Forward	Reaching Definitions	Available Expressions
Backward	Live Variables	Very Busy Expressions

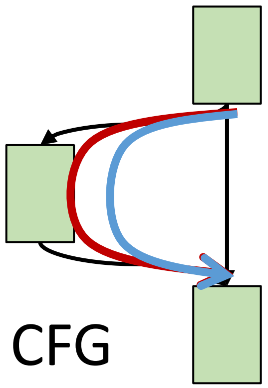
- Forward = Data flow from in to out
- Backward = Data flow from out to in
- Must = At join point, property must hold on all paths that are joined
- May = At join point, property may hold on some paths that are joined

Topics

- Abstract syntax tree (AST)
- Control-flow graph (CFG)
- Control-flow-based code coverage
- Data-flow analysis
- Data-flow-based code coverage

Dataflow-based code coverage

- Why another family of code coverage?



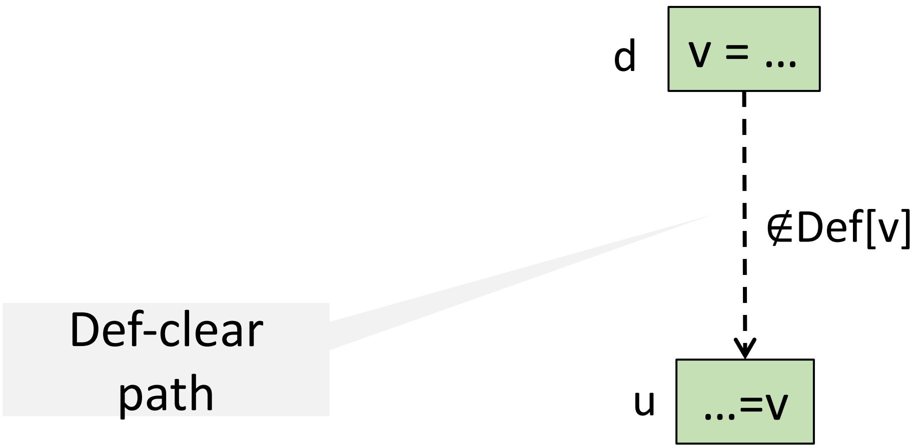
Are test1 and test2 always identical?

Although the paths are the same, different tests may have different variable values defined/used!

- A family of dataflow criteria is then defined, each providing a different degree of **data** coverage
  - Existing control-flow coverage criteria only consider the execution paths (**structure**)
  - In the program paths, which variables are defined and then used should also be covered (**data**)

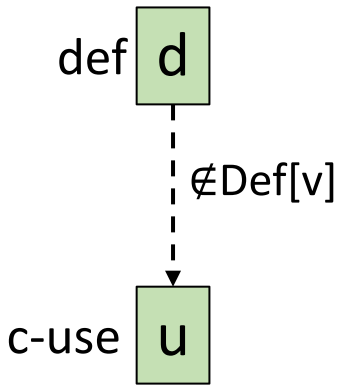
Def-clear path

- A path ⟨**d, n_1, …, n_m, u**⟩ is a **def-clear path** from **d** to **u** with respect to **v** if it has no variable re-definition of **v** on the path
  - I.e., the definition of **v** at **d** can reach **u**



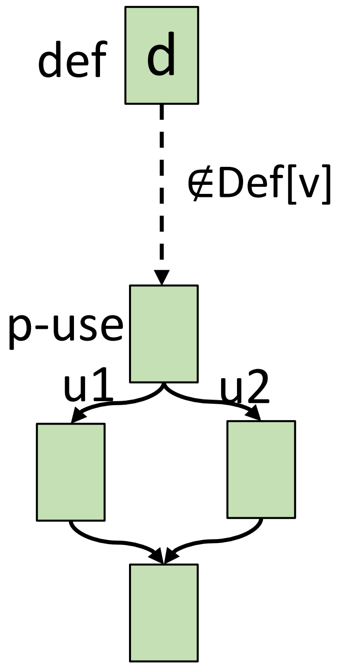
DU-pair

- A **DU-pair** with respect to a variable **v** is a pair (**d**,**u**) such that
  - **d** is a node defining **v**
  - **u** is a node or edge using **v**
    - When it is a p-use of **v**, **u** is an outgoing edge of the predicate statement
  - There is a def-clear path with respect to **v** from **d** to **u**



c-use

Du pair:
(d, u)

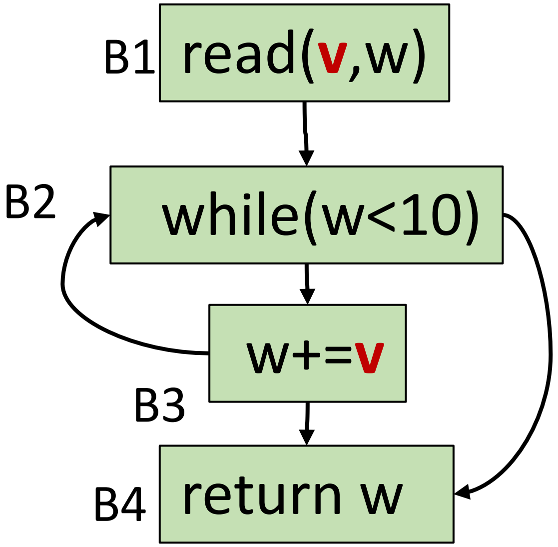


p-use

Du pairs:
(d, u1)
(d, u2)

DU-path

- A path **$\langle n_1, \ldots, n_j, n_k \rangle$** is a **DU-pat**h for variable **v** if **n_1** contains a definition of **v** and either
  - **n_k** is a c-use of **v** and **$\langle n_1, \ldots, n_j, n_k \rangle$** is a def-clear **simple** path[1] for **v** (all nodes, except possibly **n_1** and **n_k**, are distinct), or
  - **$\langle n_j, n_k \rangle$** is a p-use of **v** and **$\langle n_1, \ldots, n_j \rangle$** is a def-clear **loop-free** path for x (all nodes are distinct)

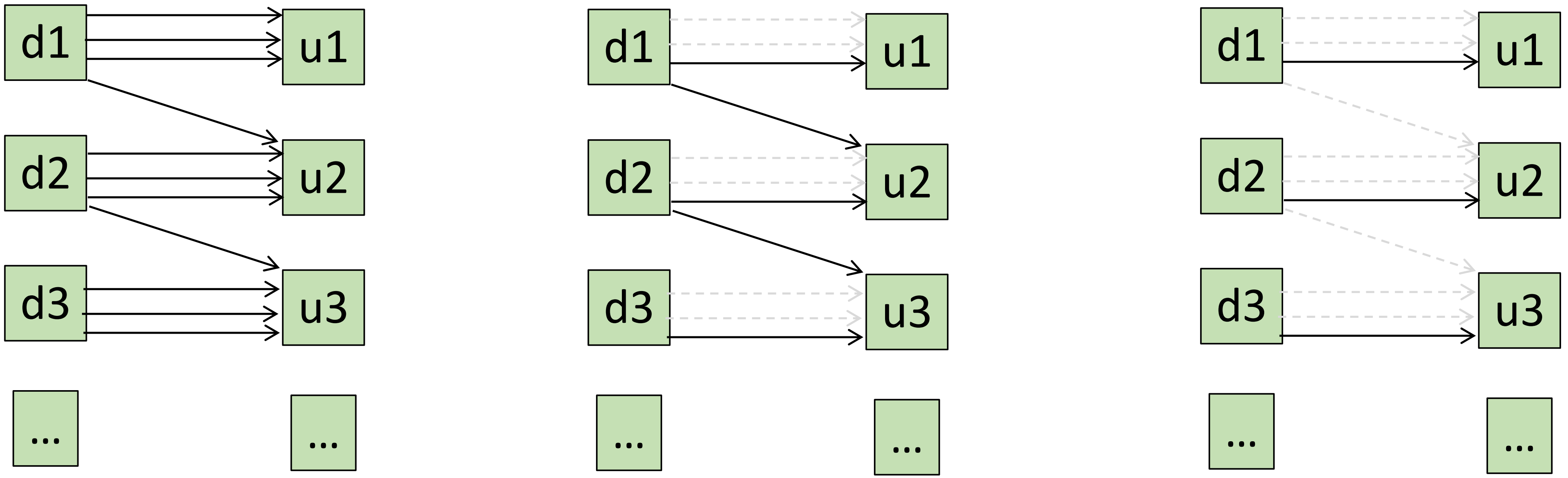


Def-clear paths	**DU paths**
1-2-3	1-2-3
1-2-3-2-3	~~1-2-3-2-3~~
1-2-3-2-3-2-3	~~1-2-3-2-3-2-3~~
1-2-3-2-3-2-3-2-3	~~1-2-3-2-3-2-3-2-3~~
…	…

[1]Introduction to software testing. P Ammann, J Offutt

Typical dataflow-based coverage

- Identify all DU pairs and construct test cases that cover these pairs
  - Variations with different "strength"

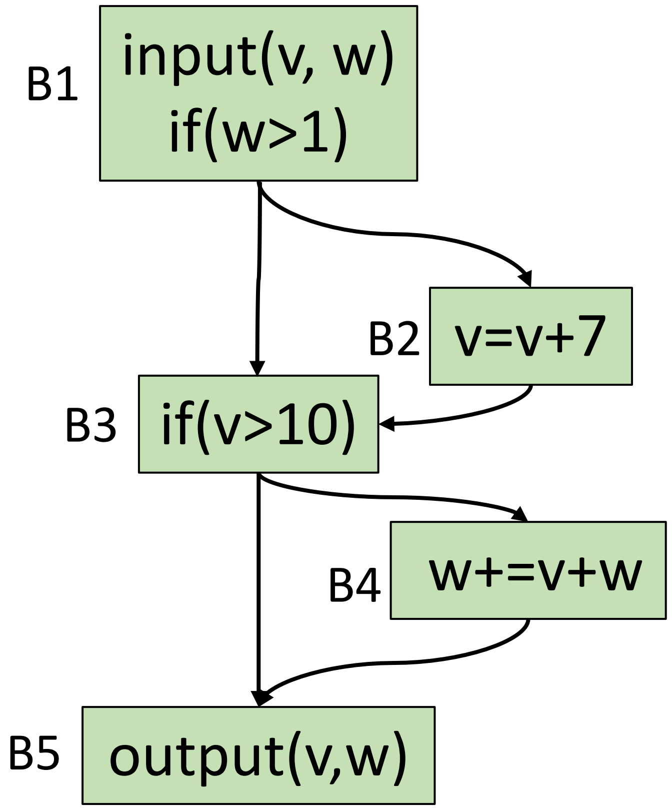


All-DU-Paths **All-Uses** **All-Defs**

Typical dataflow-based coverage: definitions

- **All-DU-paths**: for every du-pair **(d, u)** of every variable **v**, cover all possible def-clear DU paths from **d** to **u**
- **All-Uses**: for every du-pair **(d, u)** of every variable **v**, cover at least one def-clear path from **d** to **u**
- **All-Defs:** for each definition **d** of each variable **v**, cover at least one du-pair for **d**

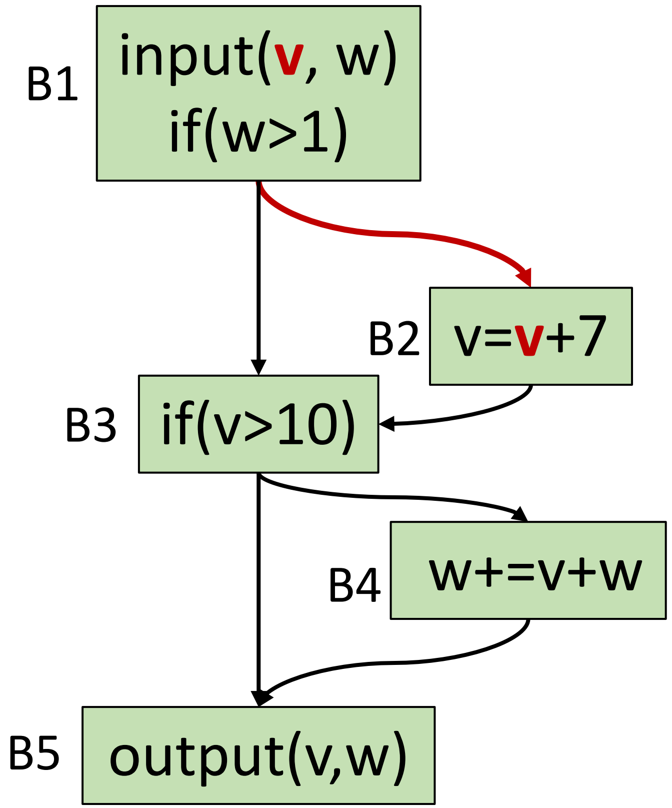
Typical dataflow-based coverage: example



du-pair	**path(s)**
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>

With respect to variable **v**
(**w** should be analyzed similarly)

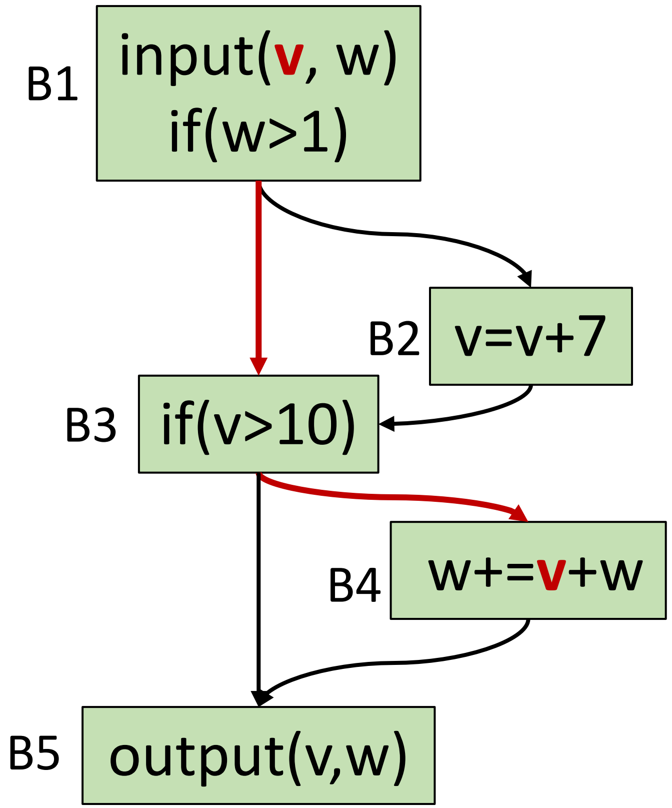
Typical dataflow-based coverage: example



du-pair	path(s)
(1,2)	**<1,2>**
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>

With respect to variable **v**
(**w** should be analyzed similarly)

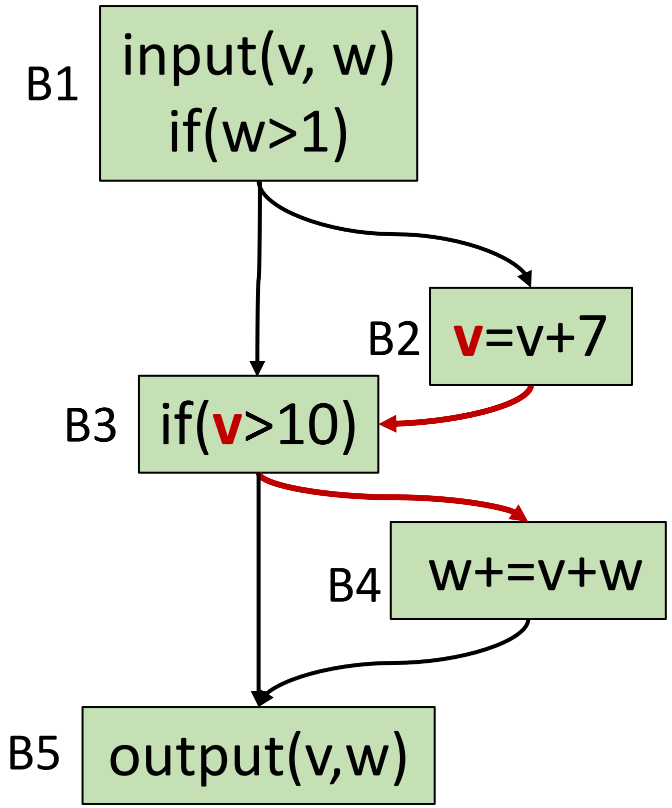
Typical dataflow-based coverage: example



du-pair	path(s)
(1,2)	<1,2>
(1,4)	**<1,3,4>**
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>

With respect to variable **v**
(**w** should be analyzed similarly)

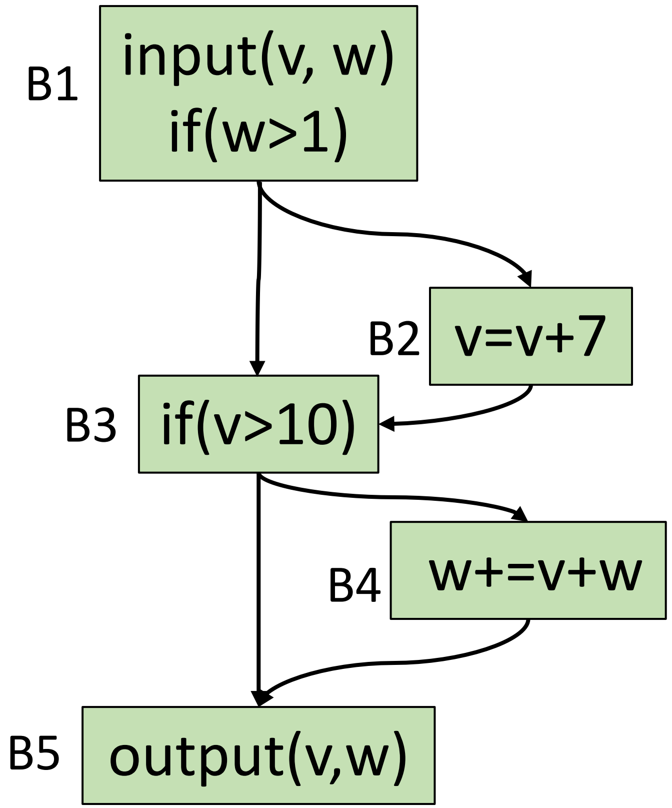
Typical dataflow-based coverage: example



du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	**<2,3,4>**
(2,<3,5>)	<2,3,5>

With respect to variable **v**
(**w** should be analyzed similarly)

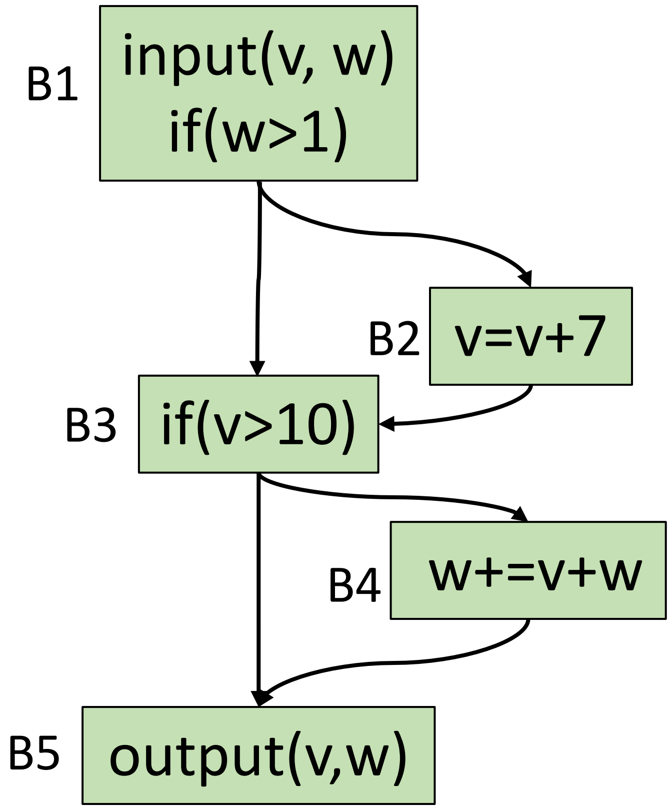
Typical dataflow-based coverage: example



du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>

With respect to variable **v**
(**w** should be analyzed similarly)

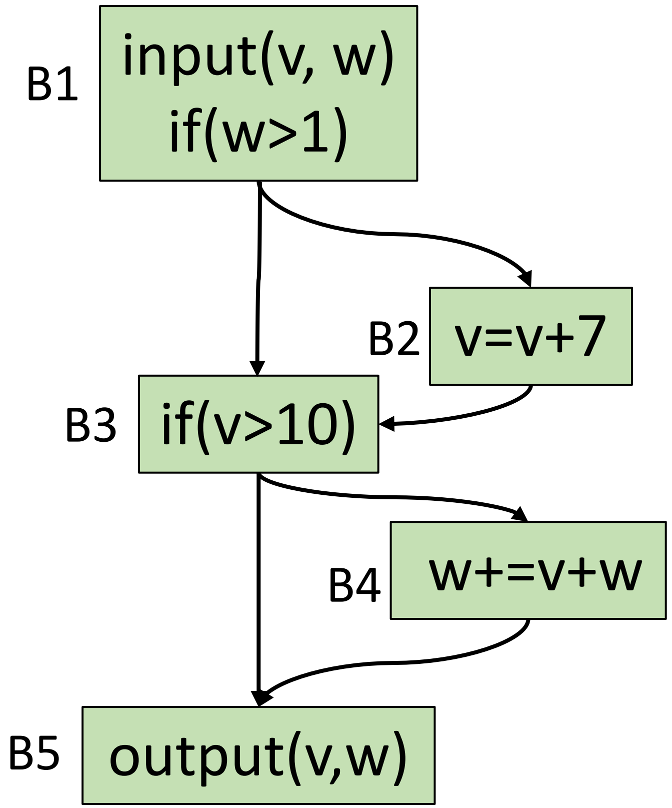
Typical dataflow-based coverage: example



du-pair	path(s)	All-Defs
(1,2)	<1,2>	X
(1,4)	<1,3,4>	
(1,5)	<1,3,4,5>	
	<1,3,5>	
(1,<3,4>)	<1,3,4>	
(1,<3,5>)	<1,3,5>	
(2,4)	<2,3,4>	X
(2,5)	<2,3,4,5>	
	<2,3,5>	
(2,<3,4>)	<2,3,4>	
(2,<3,5>)	<2,3,5>	

With respect to variable **v**
(**w** should be analyzed similarly)

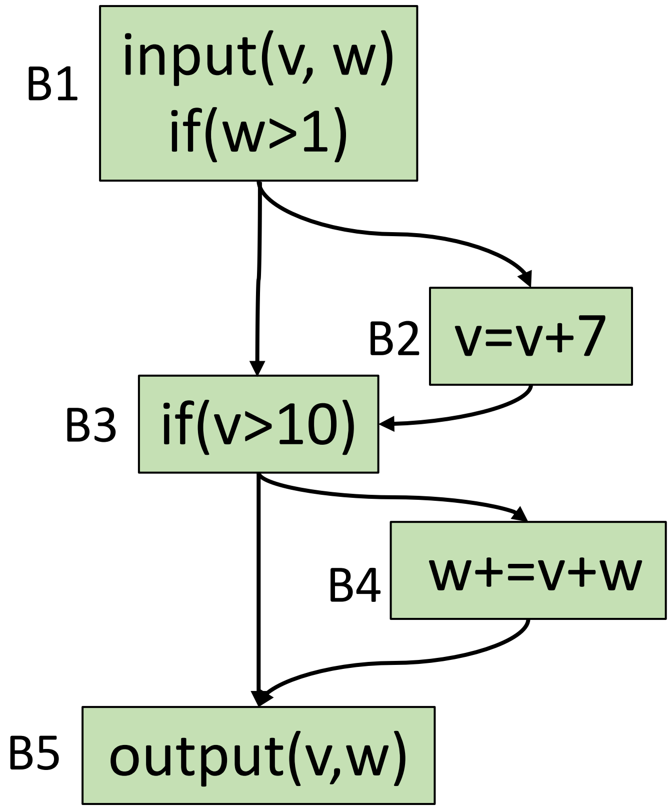
Typical dataflow-based coverage: example



du-pair	**path(s)**	**All-Defs**	**All-Uses**
(1,2)	<1,2>	X	X
(1,4)	<1,3,4>		X
(1,5)	<1,3,4,5>		X
	<1,3,5>		
(1,<3,4>)	<1,3,4>		X
(1,<3,5>)	<1,3,5>		X
(2,4)	<2,3,4>	X	X
(2,5)	<2,3,4,5>		X
	<2,3,5>		
(2,<3,4>)	<2,3,4>		X
(2,<3,5>)	<2,3,5>		X

With respect to variable **v**
(**w** should be analyzed similarly)

Typical dataflow-based coverage: example

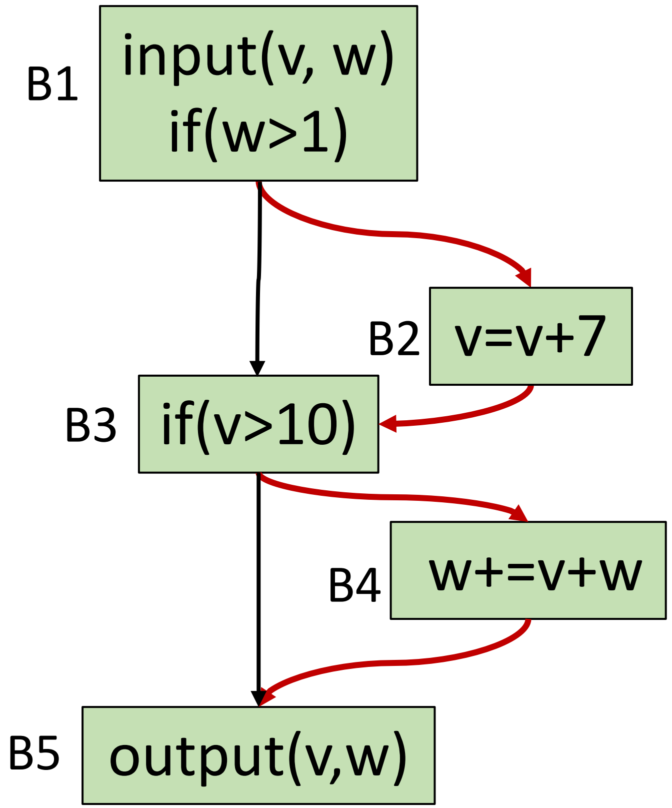


du-pair	path(s)	All-Defs	All-Uses	All-DU-Paths
(1,2)	<1,2>	X	X	X
(1,4)	<1,3,4>		X	X
(1,5)	<1,3,4,5>		X	X
	<1,3,5>			X
(1,<3,4>)	<1,3,4>		X	X
(1,<3,5>)	<1,3,5>		X	X
(2,4)	<2,3,4>	X	X	X
(2,5)	<2,3,4,5>		X	X
	<2,3,5>			X
(2,<3,4>)	<2,3,4>		X	X
(2,<3,5>)	<2,3,5>		X	X

With respect to variable **v**

(**w** should be analyzed similarly)

Typical dataflow-based coverage: example



du-pair	path(s)	Covered
(1,2)	<1,2>	X
(1,4)	<1,3,4>	
(1,5)	<1,3,4,5>	
	<1,3,5>	
(1,<3,4>)	<1,3,4>	
(1,<3,5>)	<1,3,5>	
(2,4)	<2,3,4>	X
(2,5)	<2,3,4,5>	X
	<2,3,5>	
(2,<3,4>)	<2,3,4>	X
(2,<3,5>)	<2,3,5>	

With respect to variable **v**
(**w** should be analyzed similarly)

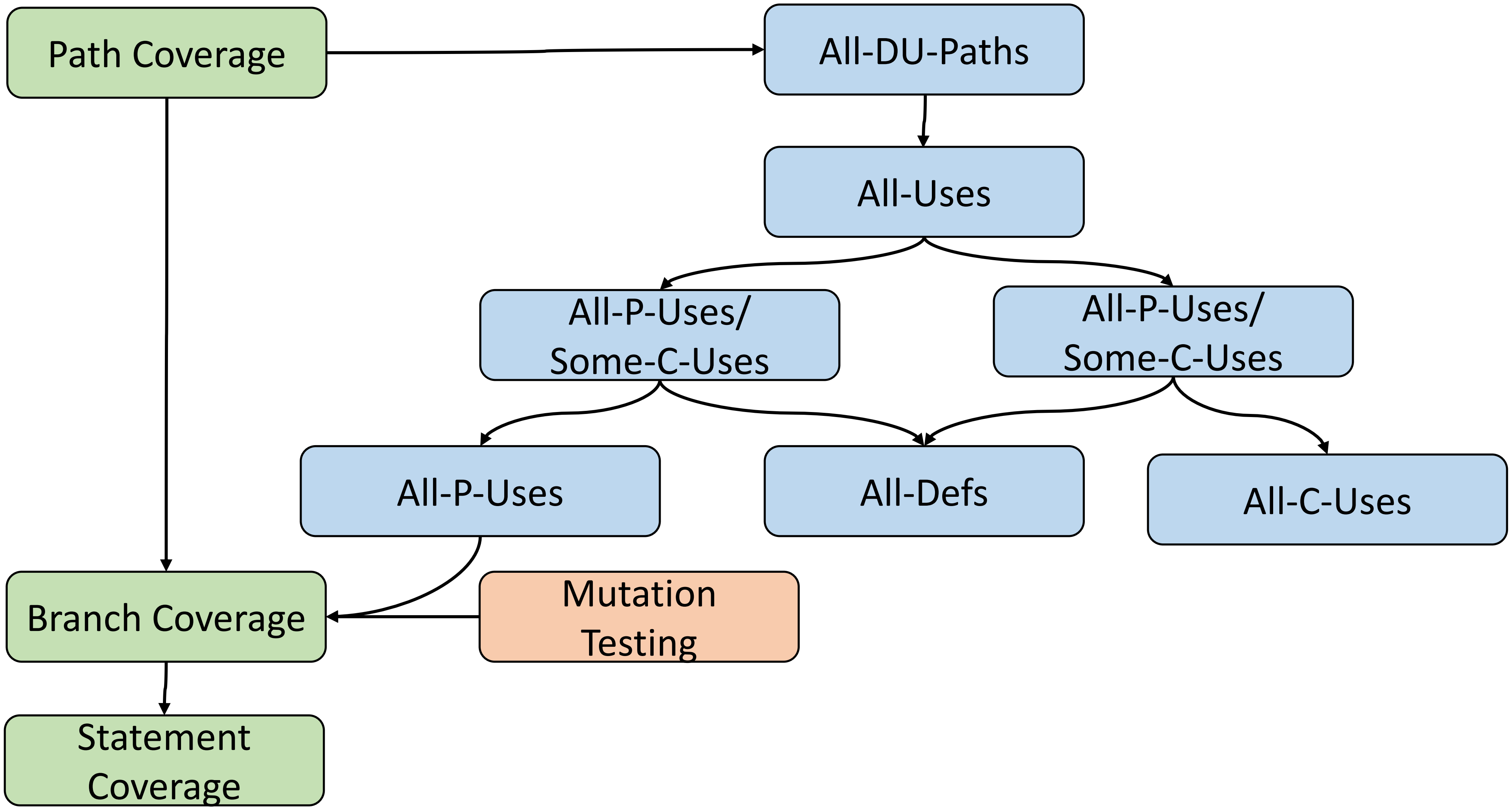
Test1: 1-2-3-4-5

Only All-Defs,
needs more tests!

More dataflow coverage

- **All-P-Uses/Some-C-Uses**: for each definition **d** of each variable **v**, cover at least one def-clear path from **d** to ***any*** p-use of **v**
  - If no p-use of **v**, at least one def-clear path to ***one*** c-use of **v** must be covered
- **All-C-Uses/Some-P-Uses**: for each definition **d** of each variable **v**, cover at least one def-clear path from **d** to ***any*** c-use of **v**
  - If no c-use of **v**, at least one def-clear path to ***one*** p-use of **v** must be covered
- **All-P-Uses**: for each definition **d** of each variable **v**, cover at least one def-clear path from **d** to ***any*** p-use of **v**
- **All-C-Uses**: for each definition **d** of each variable **v**, cover at least one def-clear path from **d** to ***any*** c-use of **v**

Coverage subsumption graph



Interprocedural analysis

- So far, all the program analyses we covered are **intraprocedural**
  - Analyzing each function (a.k.a, method/procedure) separately
- However, real-world programs usually involve the connection of a large number of functions, thus we need **interprocedural** analysis:
  - **Call-graph analysis**: analyzing the potential invocation relationship between different functions [Tip et al.]
  - **Interprocedural CFG**: connecting intraprocedural CFGs with call-graph
  - **Interprocedural dataflow analysis**: analyzing dataflow across functions [Reps et al.]
  - **Taint analysis**: tracking how private information flows through the program and if it is leaked to public observers [Arzt et al.]

❑ Tip et al., Scalable Propagation-Based Call Graph Construction Algorithms, 2000, OOPSLA
❑ Reps et al., Precise Interprocedural Dataflow Analysis via Graph Reachability, 1987, POPL
❑ Arzt et al., FlowDroid: Precise Context, Flow, Field, Object-sensitive and Lifecycle-aware Taint Analysis for Android Apps, 2014, PLDI

Do I need to implement such basic program analyses from scratch?

- Language-agnostic (Python, Java, C/C++, etc.)
  - Tree-sitter (https://tree-sitter.github.io/tree-sitter/): A parser generator tool and an incremental parsing library
- Java
  - **JavaParser** (https://javaparser.org/): A lightweight source code analysis and manipulation framework
  - **Eclipse JDT** (https://www.eclipse.org/jdt/): A source-level code analysis and manipulation framework
  - **ASM** (https://asm.ow2.io/): A lightweight bytecode-level analysis and manipulation framework
- C/C++
  - **LLVM** (http://llvm.org/): Highly customizable and modular compiler framework

Further readings

- Aho et al., Compilers: Principles, Techniques, and Tools (2nd Edition)
- Rapps and Weyuker. Selecting Software Test Data Using Data Flow Information. 1985, TSE
- Ferrante et al., The program dependence graph and its use in optimization, 1987, TOPLAS
- Horwitz et al., Interprocedural slicing using dependence graphs, 1988, PLDI
- Reps et al., Precise Interprocedural Dataflow Analysis via Graph Reachability, 1995, POPL

Thanks and stay safe!