Program analysis

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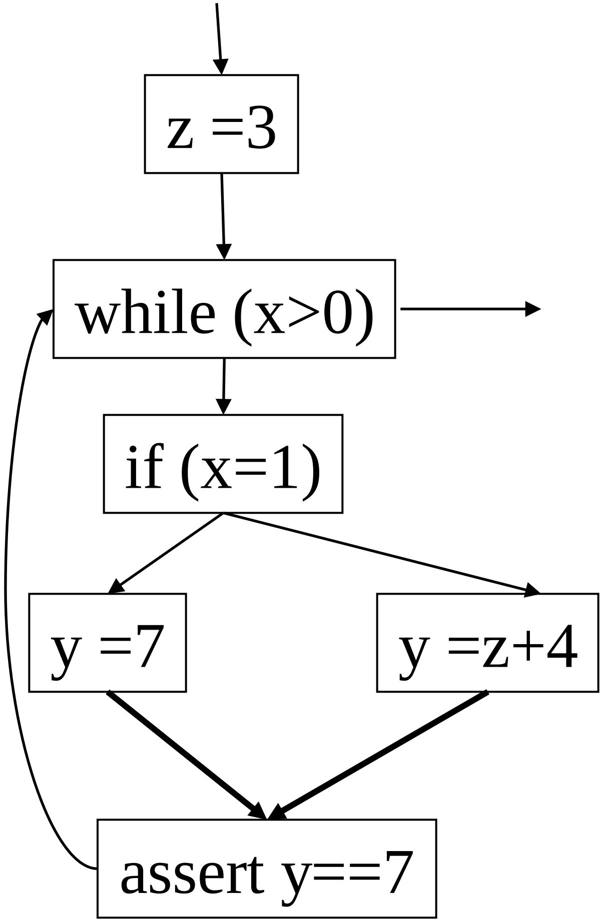
html://www.cs.tau.ac.il/~msagiv/courses/wcc12-13.html

Abstract Interpretation
Static analysis

- Automatically identify program properties
  - No user provided loop invariants
- Sound but incomplete methods
  - But can be rather precise
- Non-standard interpretation of the program operational semantics
- Applications
  - Compiler optimization
  - Code quality tools
    - Identify potential bugs
    - Prove the absence of runtime errors
    - Partial correctness

Control Flow Graph(CFG)

```
z = 3
while (x>0) {
        if (x = 1)
            y = 7;
        else
           y =z + 4;
         assert y == 7
}
```



z =3

while (x>0)

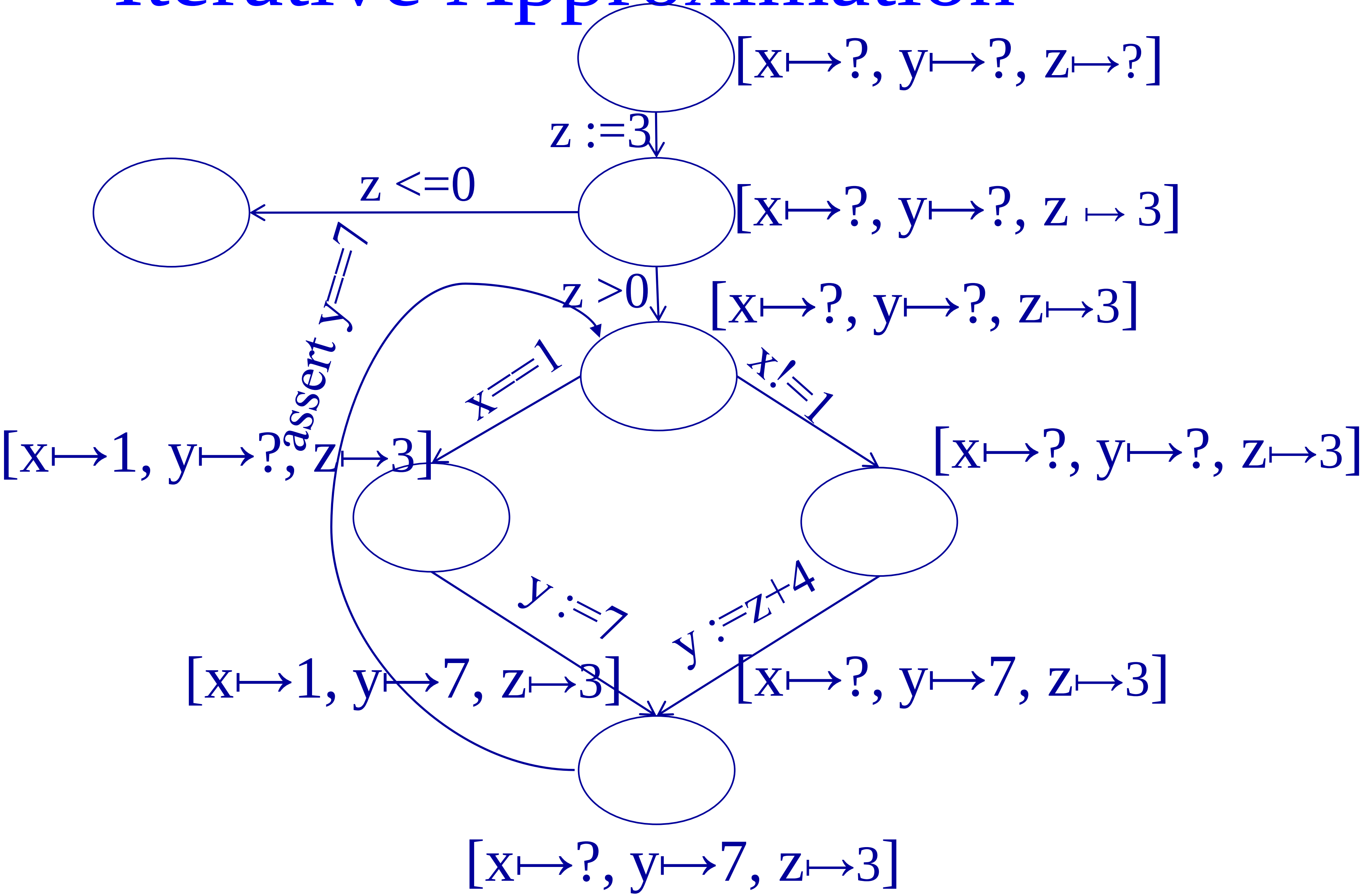
if (x=1)

y =7

y =z+4

assert y==7

Iterative Approximation



[x↦?, y↦?, z↦?]

z :=3

z <=0

[x↦?, y↦?, z ↦ 3]

z >0

[x↦?, y↦?, z↦3]

assert y==7

x==1

x!=1

[x↦1, y↦?, z↦3]

[x↦?, y↦?, z↦3]

y :=7

y :=z+4

[x↦1, y↦7, z↦3]

[x↦?, y↦7, z↦3]

[x↦?, y↦7, z↦3]

Memory Leakage

```
List reverse(Element *head)
{
    List rev, n;
    rev = NULL;
    while (head != NULL) {
        n = head →next;
        head → next = rev;
        head = n;
        rev = head;
    }
    return rev;
}
```

potential leakage of address pointed to by head

Memory Leakage

```
Element∗ reverse(Element ∗head)
{
  Element ∗rev, ∗n;
   rev = NULL;
   while (head != NULL) {
        n = head → next;
        head → next = rev;
        rev = head;
        head = n;
   }
   return rev; }
```

👍No memory leaks

A Simple Example

```
void foo(char *s )
{
     while ( *s != ‘ ‘ )
               s++;
     *s = 0;
}
```

Potential buffer overrun:

offset(s) ≥ alloc(base(s))

A Simple Example

```
void foo(char *s) @require string(s)
{
    while ( *s != ‘ ‘&& *s != 0)
            s++;
    *s = 0;
}
```

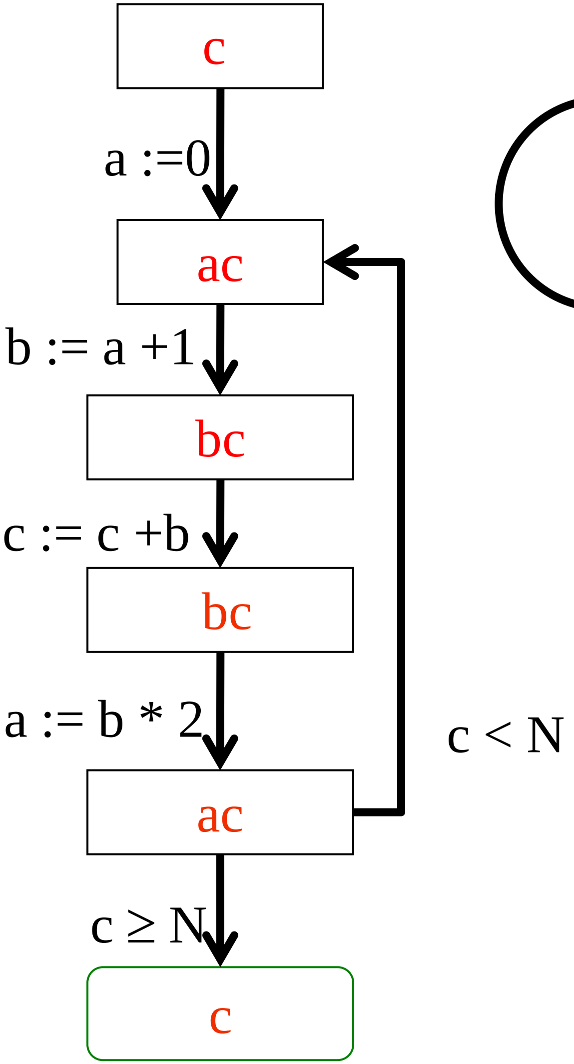
☞No buffer overruns

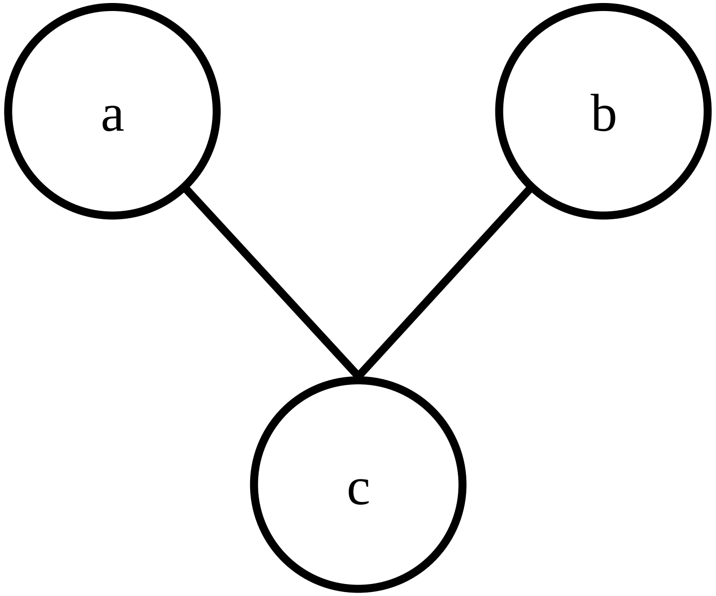
Example Static Analysis Problem

- Find variables which are live at a given program location
- Used before set on some execution paths from the current program point

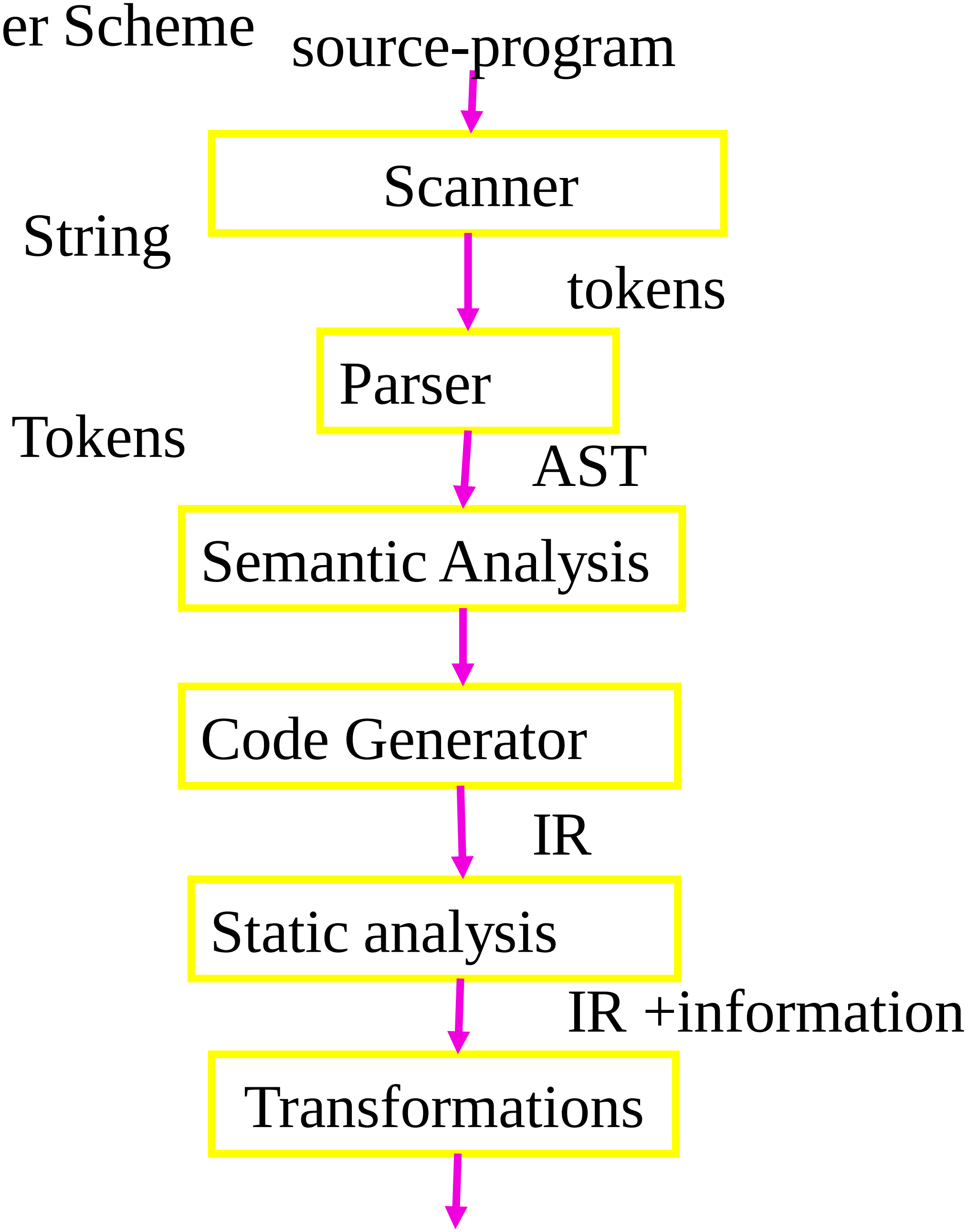
A Simple Example

```
/* c  */
L0:      a := 0
/* ac */
L1:     b := a + 1
/* bc */
        c := c + b
/* bc */
        a := b * 2
/* ac */
        if c < N goto L1
/* c  */
         return c
```





Compiler Scheme



source-program

Scanner

String

tokens

Parser

Tokens

AST

Semantic Analysis

Code Generator

IR

Static analysis

IR +information

Transformations

Undecidability issues

- It is impossible to compute exact static information
- Finding if a program point is reachable
- Difficulty of interesting data properties

Undecidabily

- A variable is live at a given point in the program
  - if its current value is used after this point prior to a definition in some execution path
- It is undecidable if a variable is live at a given program location

Proof Sketch

Pr

L: x := y

Is y live at L?

Conservative (Sound)

- The compiler need not generate the optimal code
- Can use more registers (“spill code”) than necessary
- Find an upper approximation of the live variables
- Err on the safe side
- A superset of edges in the interference graph
- Not too many superfluous live variables

Conservative(Sound) Software Quality Tools

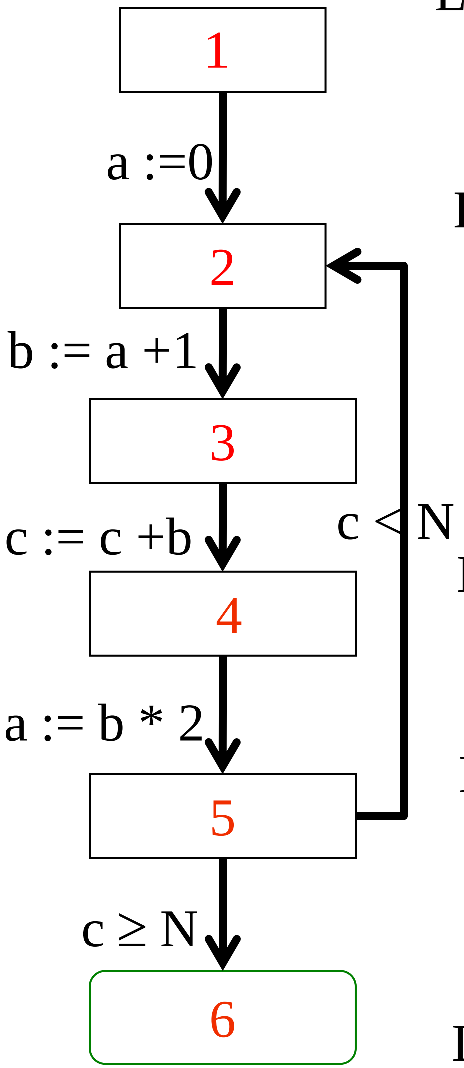
- Can never miss an error
- But may produce false alarms
  - Warning on non existing errors

Iterative Solution

- Generate a system of equations per procedure
  - Defines the live variables recursively
- The live variables at the return of the procedure is known
- The live variables before a statement (basic block) are defined in terms of the live variables after the procedure
- The live variables at control flow join is the union of live variables at successor nodes
- Compute the minimal solution

The System of Equations

```
/* c  */
L0:        a := 0
/* ac */
L1:        b := a + 1
/* bc */
           c := c + b
/* bc */
           a := b * 2
/* ac */
           if c < N goto L1
/* c  */
           return c
```



$$Lv[1] = Lv[2] - \{a\} \cup \emptyset$$

$$Lv[2] = Lv[3] - \{b\} \cup \{a\}$$

$$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$$

$$Lv[4] = Lv[5] - \{a\} \cup \{b\}$$

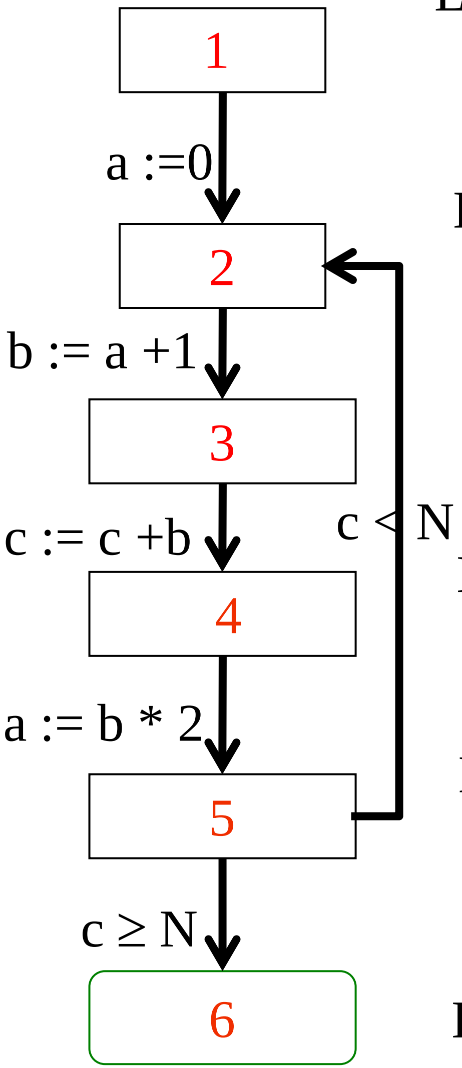
$$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$$

$$Lv[6] = \{c\}$$

Transfer Functions LiveVariables

- If a and c are potentially live after “a = b *2”
  - then b and c are potentially live before
- For “x = exp;”
  - LiveIn = (Livout – {x}) ∪ arg(exp)

The System of Equations / Solutions



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$	{c}	{c}	{c, d}
$Lv[2] = Lv[3] - \{b\} \cup \{a\}$	{a, c}	{a, c}	{a, c, d}
$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$	{b, c}	{b, c}	{b, c, d}
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$	{b, c}	{b, c}	{b, c, d}
$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup$ $(Lv[6] - \emptyset \cup \{c\})$	{a, c}	{ c}	{a, c, d}
$Lv[6] = \{c\}$	{ c}	{ c}	{ c}

The Simultaneous Least Solution

- Every equation is monotone in the inputs
- Unique least solution
- Guaranteed to be sound
  - Every live variable is detected
    - May be overly conservative
- Optimal under the condition that every control flow path is feasible
- Can be computed iteratively on O(nested loops * N)

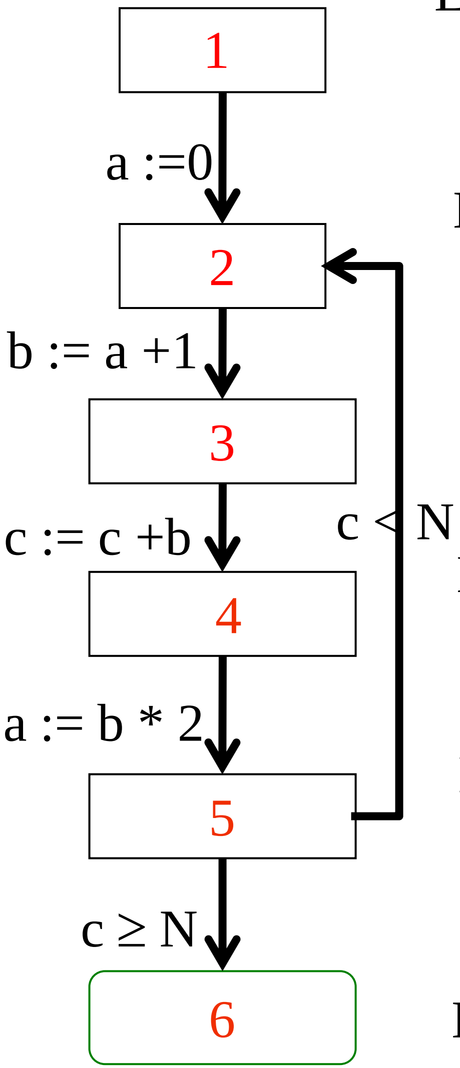
Iterative computation of conservative static information

- Construct a control flow graph(CFG)
- Optimistically start with the best value at every node
- “Interpret” every statement in a conservative way
- Backward traversal of CFG
- Stop when no changes occur

Pseudo Code

```
live_analysis(G(V, E): CFG, exit: CFG node, initial: value){
   // initialization
  lv[exit]:= initial
  for each v ∈ V – {exit} do lv[v] := ∅
   WL = {exit}
   while WL != {} do
        select and remove a node v ∈WL
        for each u ∈ V such that (u, v)  do
              lv[u] := lv[u] ∪  ((lv[v] – kill[u, v]) ∪ gen[u, v]
              if lv[u] was changed WL := WL ∪ {u}
```

The System of Equations / Iteration 1



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$ $\{\}$

$Lv[2] = Lv[3] - \{b\} \cup \{a\}$ $\{\}$

$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$ $\{\}$

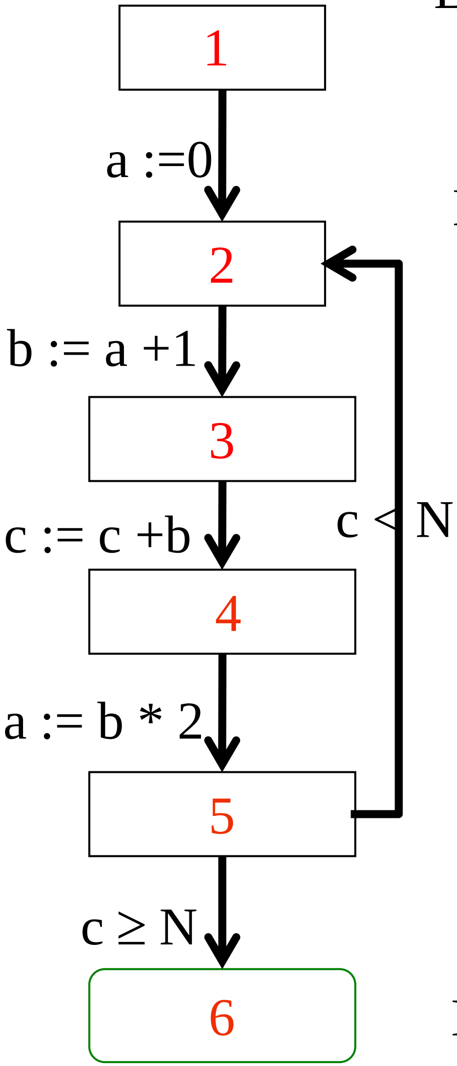
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$ $\{\}$

$$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$$ $\{\}$

$Lv[6] = \{c\}$ $\{c\}$

WL={5}

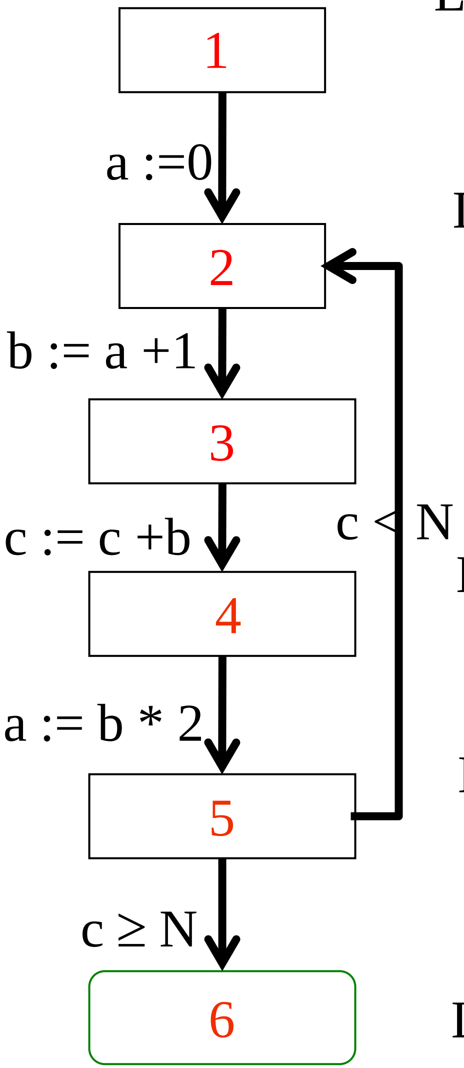
The System of Equations / Iteration 2



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$	$\{\}$
$Lv[2] = Lv[3] - \{b\} \cup \{a\}$	$\{\}$
$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$	$\{\}$
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$	$\{\}$
$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$	$\{c\}$
$Lv[6] = \{c\}$	$\{c\}$

WL={4}

The System of Equations / Iteration 3



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$ $\{\}$

$Lv[2] = Lv[3] - \{b\} \cup \{a\}$ $\{\}$

$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$ $\{\}$

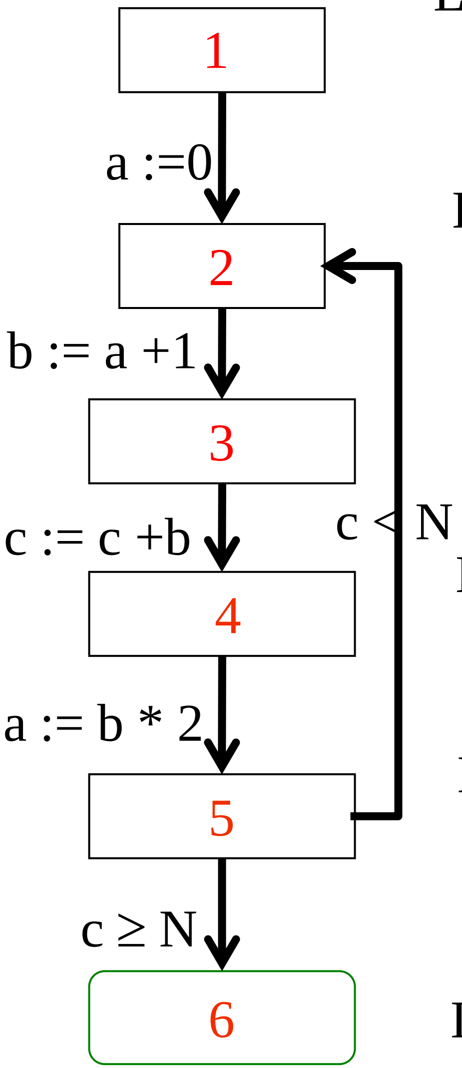
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$ $\{c, b\}$

$WL=\{3\}$

$$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$$ $\{c\}$

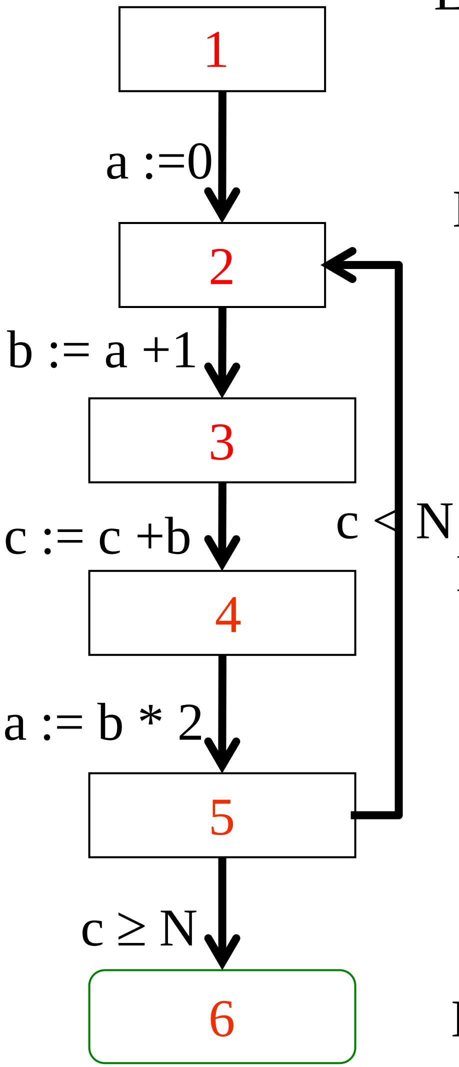
$Lv[6] = \{c\}$ $\{c\}$

The System of Equations / Iteration 4



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$	$\{\}$	
$Lv[2] = Lv[3] - \{b\} \cup \{a\}$	$\{\}$	
$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$	$\{c, b\}$	WL={2}
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$	$\{c, b\}$	
$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup$ $(Lv[6] - \emptyset \cup \{c\})$	$\{c\}$	
$Lv[6] = \{c\}$	$\{c\}$	

The System of Equations / Iteration 5



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$ $\{\}$

$Lv[2] = Lv[3] - \{b\} \cup \{a\}$ $\{c, a\}$ WL={1, 5}

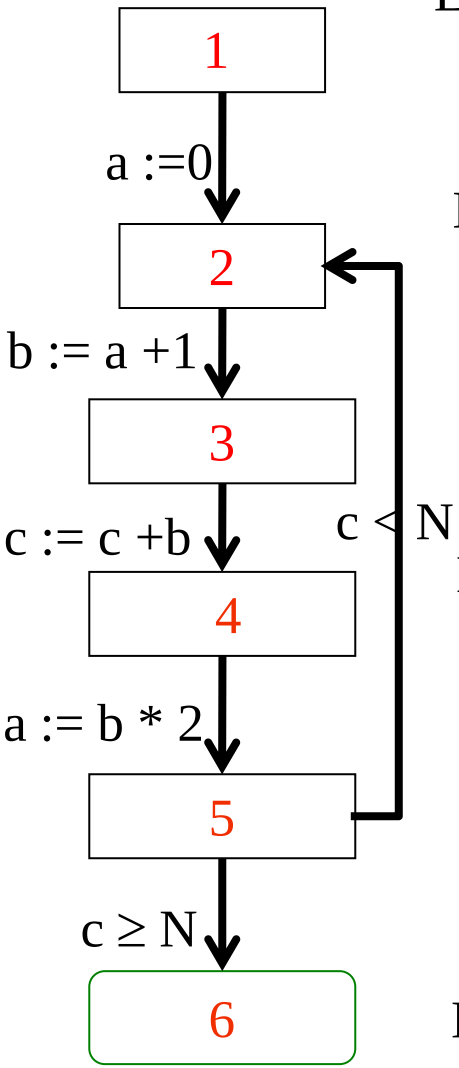
$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$ $\{c, b\}$

$Lv[4] = Lv[5] - \{a\} \cup \{b\}$ $\{c, b\}$

$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$ $\{c\}$

$Lv[6] = \{c\}$ $\{c\}$

The System of Equations / Iteration 6



$Lv[1] = Lv[2] - \{a\} \cup \emptyset$ $\{\}$

$Lv[2] = Lv[3] - \{b\} \cup \{a\}$ $\{c, a\}$

$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$ $\{c, b\}$

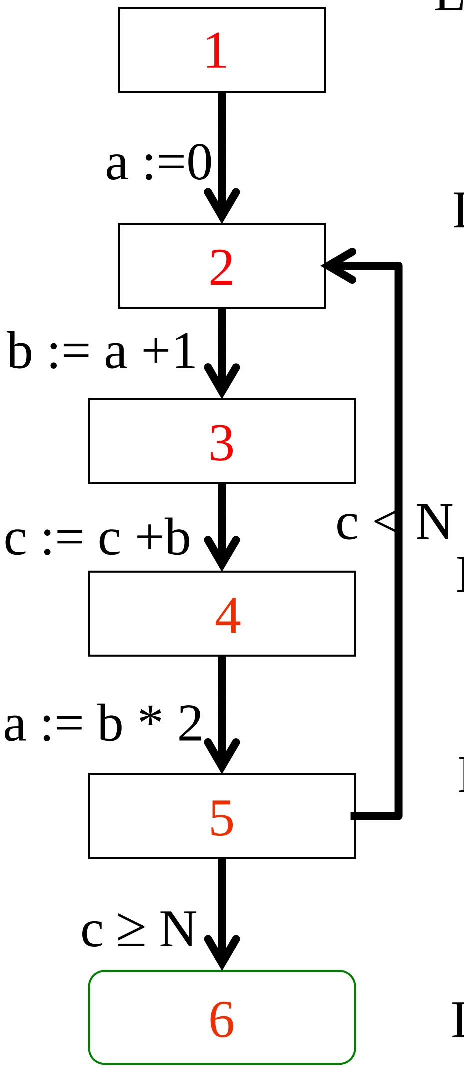
$Lv[4] = Lv[5] - \{a\} \cup \{b\}$ $\{c, b\}$

$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$ $\{c, a\}$

WL={1}

$Lv[6] = \{c\}$ $\{c \}$

The System of Equations / Iteration 7



WL={}

$Lv[1] = Lv[2] - \{a\} \cup \emptyset$ $\{c\}$

$Lv[2] = Lv[3] - \{b\} \cup \{a\}$ $\{c, a\}$

$Lv[3] = Lv[4] - \{c\} \cup \{c, b\}$ $\{c, b\}$

$Lv[4] = Lv[5] - \{a\} \cup \{b\}$ $\{c, b\}$

$Lv[5] = (Lv[2] - \emptyset \cup \{c\}) \cup (Lv[6] - \emptyset \cup \{c\})$ $\{c, a\}$

$Lv[6] = \{c\}$ $\{c\}$

Summary Iterative Procedure

- Analyze one procedure at a time
  - More precise solutions exit
- Construct a control flow graph for the procedure
- Initializes the values at every node to the most optimistic value
- Iterate until convergence