CS412/CS413

Introduction to Compilers

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Lecture 25: Liveness and Copy Propagation

28 March 05



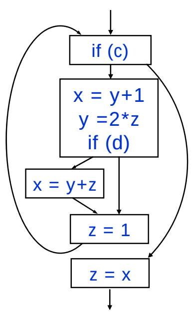
# Control Flow Graphs

- Control Flow Graph (CFG) = graph representation of computation and control flow in the program
  - framework to statically analyze program control-flow
- In a CFG:
  - Nodes are basic blocks; they represent computation
  - Edges characterize control flow between basic blocks
- Can build the CFG representation either from the high IR or from the low IR



# Build CFG from High IR

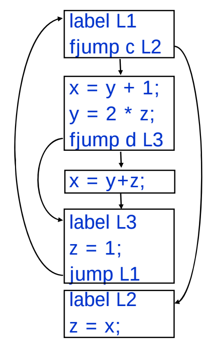
```
while (c) {
    x = y + 1;
    y = 2 * z;
    if (d)  x = y+z;
    z = 1;
}
z = x;
```






# Build CFG from Low IR

```
label L1
fjump c L2
x = y + 1;
y = 2 * z;
fjump d L3
x = y+z;
label L3
z = 1;
jump L1
label L2
z = x;
```





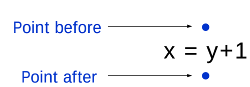

# Using CFGs

- Next: use CFG representation to statically extract information about the program
  - Reason at compile-time
  - About the run-time values of variables and expressions in all program executions
- Extracted information example: live variables
- Idea:
  - Define program points in the CFG
  - Reason statically about how the information flows between these program points



# Program Points

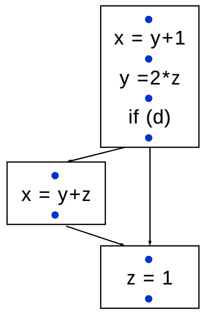
- Two program points for each instruction:
  - There is a program point before each instruction
  - There is a program point after each instruction




- In a basic block:
  - Program point after an instruction = program point before the successor instruction

## Program Points: Example

- Multiple successor blocks means that point at the end of a block has multiple successor program points
- Depending on the execution, control flows from a program point to one of its successors
- Also multiple predecessors
- How does information propagate between program points?



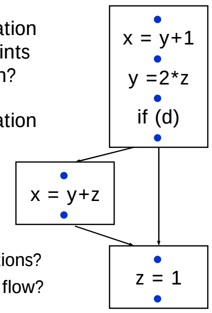



## Flow of Extracted Information

- Question 1: how does information flow between the program points before and after an instruction?
- Question 2: how does information flow between successor and predecessor basic blocks?
- ... in other words:

  Q1: what is the effect of instructions?

  Q2: what is the effect of control flow?






## Using CFGs

- To extract information: reason about how it propagates between program points
- Rest of this lecture: how to use CFGs to compute information at each program point for:
  - Live variable analysis, which computes which variables are live at each program point
  - Copy propagation analysis, which computes the variable copies available at each program point



## Live Variable Analysis

- Computes live variables at each program point
  - I.e., variables holding values that may be used later (in some execution of the program)
- For an instruction I, consider:
  - in[I] = live variables at program point before I
  - out[I] = live variables at program point after I
- For a basic block B, consider:
  - in[B] = live variables at beginning of B
  - out[B] = live variables at end of B
- If I = first instruction in B, then in[B] = in[I]
- If I' = last instruction in B, then out[B] = out[I']

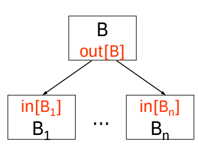


## How to Compute Liveness?

- Answer question 1: for each instruction I, what is the relation between in[I] and out[I] ?

in[I]
I
out[I]

- Answer question 2: for each basic block B with successor blocks $B_1$, ..., $B_n$, what is the relation between out[B] and in[$B_1$], ..., in[$B_n$]?






## Part 1: Analyze Instructions

- Question: what is the relation between sets of live variables before and after an instruction?

in[I]
I
out[I]

- Examples:

| | | | |
|---|---|---|---|
| conclude | in[I] = {y,z} | in[I] = {y,z,t} | in[I] = {x,t} |
| | x = y+z; | x = y+z; | x = x+1; |
| assume | out[I] = {z} | out[I] = {x,t} | out[I] = {x,t} |

- ... is there a general rule?

## Analyze Instructions

- Yes: knowing variables live after I, can compute variables live before I:
  - All variables live after I are also live before I, unless I defines (writes) them
  - All variables that I uses (reads) are also live before instruction I

in[I]
I
out[I]

- Mathematically:

  in[I] = ( out[I] – def[I] ) ∪ use[I]

  where:
  - def[I] = variables defined (written) by instruction I
  - use[I] = variables used (read) by instruction I



## Computing Use/Def

- Compute use[I] and def[I] for each instruction I:

  if I is x = y OP z : use[I] = {y, z} def[I] = {x}
  if I is x = OP y : use[I] = {y} def[I] = {x}
  if I is x = y : use[I] = {y} def[I] = {x}
  if I is x = addr y : use[I] = {} def[I] = {x}
  if I is if (x) : use[I] = {x} def[I] = {}
  if I is return x : use[I] = {x} def[I] = {}
  if I is x = f($y_1$ ,..., $y_n$) : use[I] = {$y_1$, ..., $y_n$}
  def[I] = {x}

  (For now, ignore load and store instructions)



## Example

- Example: block B with three instructions I1, I2, I3:

  Live1 = in[B] = in[I1]
  Live2 = out[I1] = in[I2]
  Live3 = out[I2] = in[I3]
  Live4 = out[I3] = out[B]

- Relation between Live sets:

  Live1 = ( Live2-{x} ) ∪ {y}
  Live2 = ( Live3-{y} ) ∪ {z}
  Live3 = ( Live4-{} ) ∪ {d}

Block B

| | |
|---|---|
| | Live1 |
| I1 | x = y+1 |
| | Live2 |
| I2 | y =2*z |
| | Live3 |
| I3 | if (d) |
| | Live4 |



## Backward Flow

- Relation:

  in[I] = ( out[I] – def[I] ) ∪ use[I]

in[I]
I
out[I]

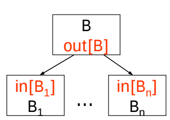
- The information flows backward!
- Instructions: can compute in[I] if we know out[I]
- Basic blocks: information about live variables flows from out[B] to in[B]

In[B]
x = y+1
y =2*z
if (d)
out[B]

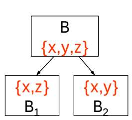


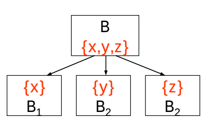
## Part 2: Analyze Control Flow

- Question: for each basic block B with successor blocks $B_1$, ..., $B_n$, what is the relation between out[B] and in[$B_1$], ..., in[$B_n$]?




- Examples:



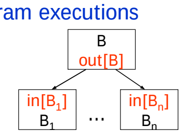

- What is the general rule?



## Analyze Control Flow

- Rule: A variables is live at end of block B if it is live at the beginning of one (or more) successor blocks
- Characterizes all possible program executions
- Mathematically:

  $\text{out}[B] = \bigcup_{B' \in succ(B)} \text{in}[B']$




- Again, information flows backward: from successors B' of B to basic block B

# Constraint System

- Put parts together: start with CFG and derive a system of constraints between live variable sets:

$$\begin{cases} in[I] = (\, out[I] - def[I]\,) \cup use[I] & \text{for each instruction I} \\ out[B] = \bigcup_{B' \in succ(B)} in[B'] & \text{for each basic block B} \end{cases}$$

- Solve constraints:
  - Start with empty sets of live variables
  - Iteratively apply constraints
  - Stop when we reach a fixed point



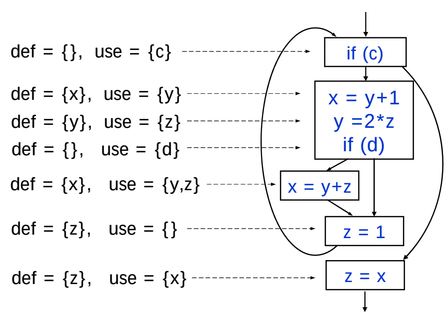
# Constraint Solving Algorithm

**for** all instructions I **do** in[I] = out[I] = ∅;
**repeat**
  **select** an instuction I (or a basic block B) such that
    $in[I] \neq (\, out[I] - def[I]\,) \cup use[I]$
  or (respectively)
    $out[B] \neq \bigcup_{B' \in succ(B)} in[B']$

  and update in[I] (or out[B]) accordingly
**until** no such change is possible

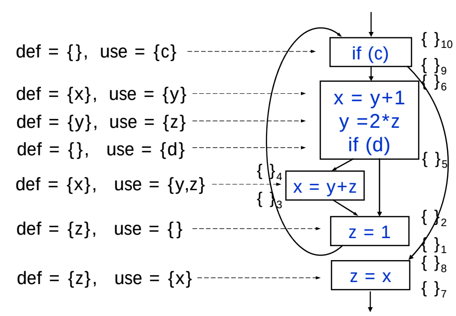


# Example





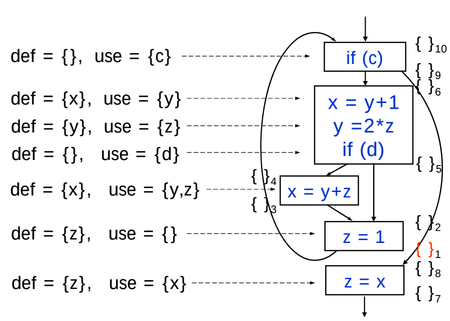

# Example




**strategy**: pick program points in postorder



# Example



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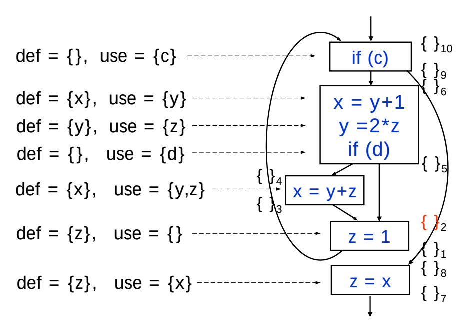

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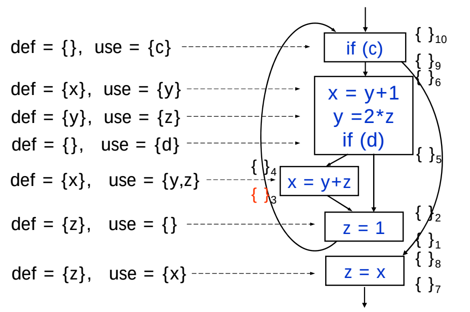




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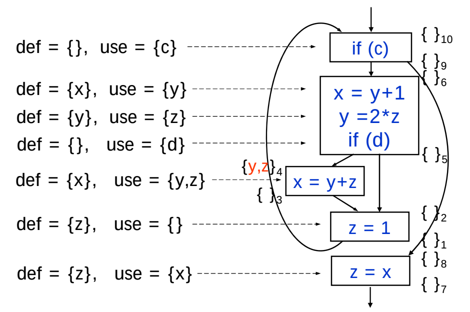




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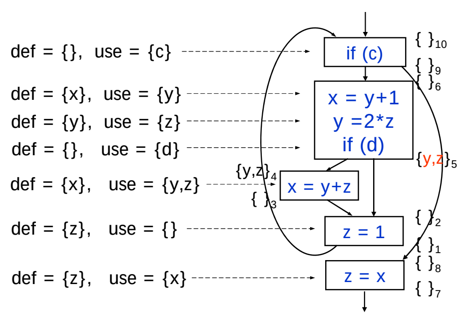




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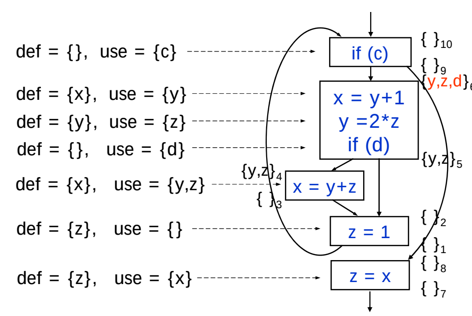




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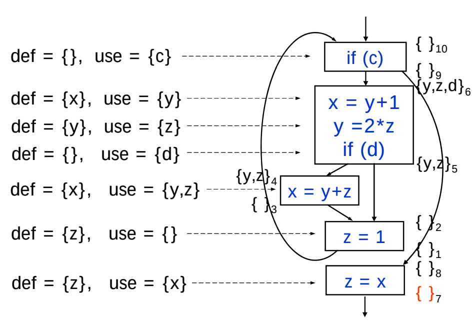




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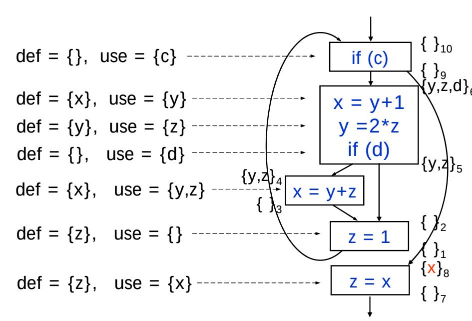

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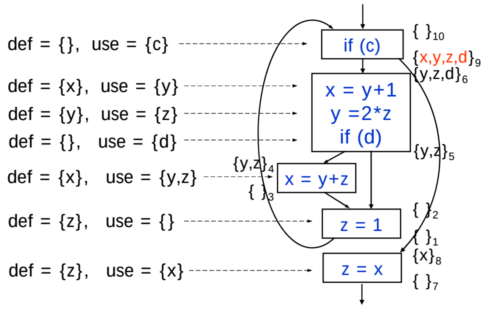


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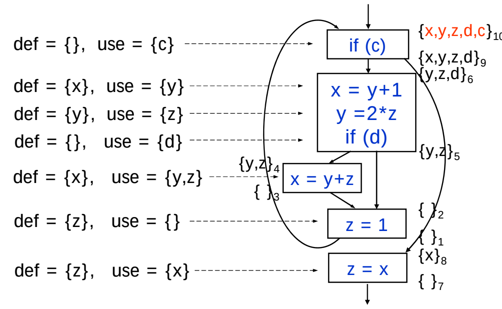
# Example

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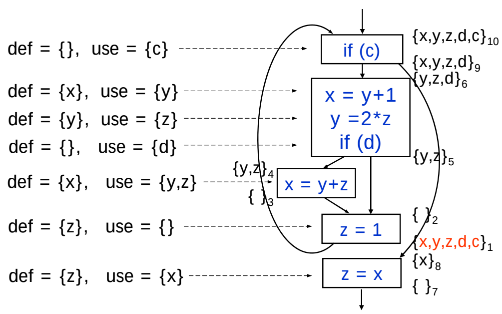
# Example

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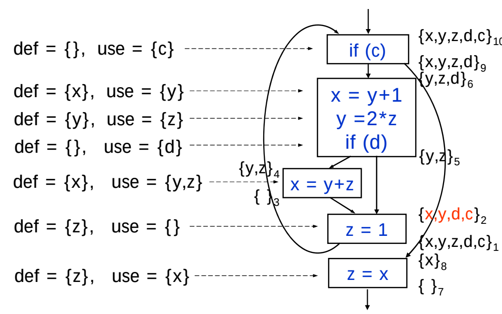
# Example

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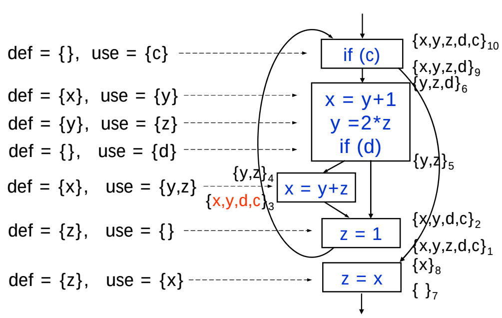
# Example

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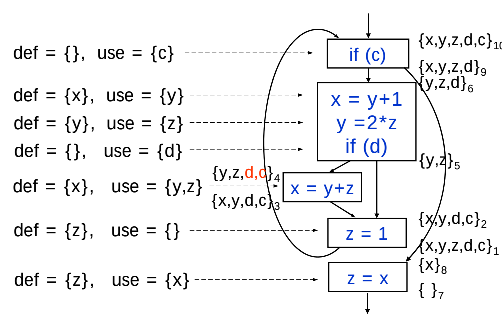
# Example

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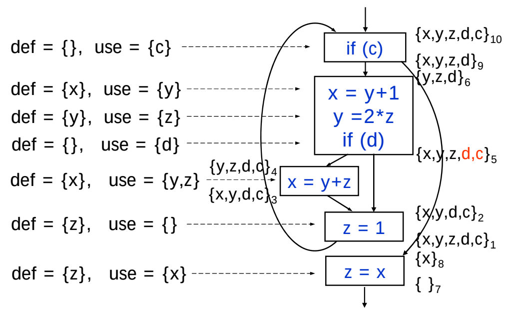
## Example



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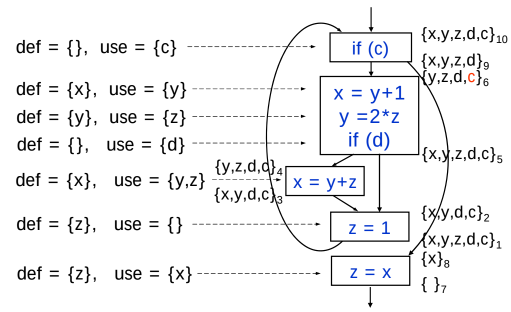




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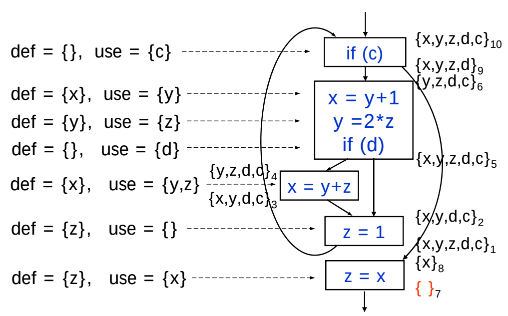




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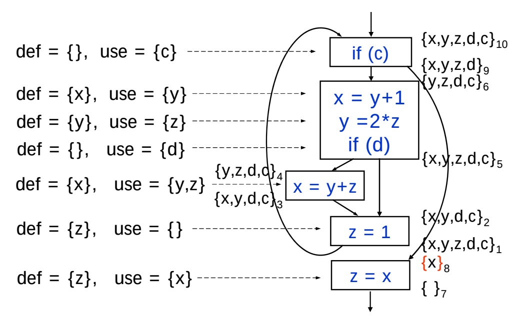




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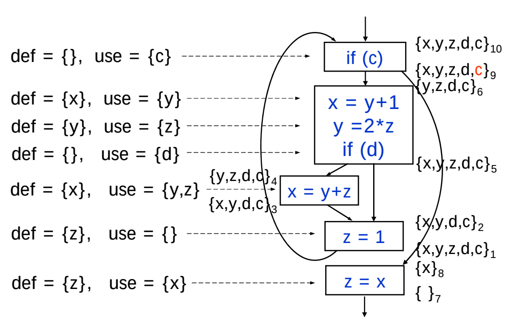
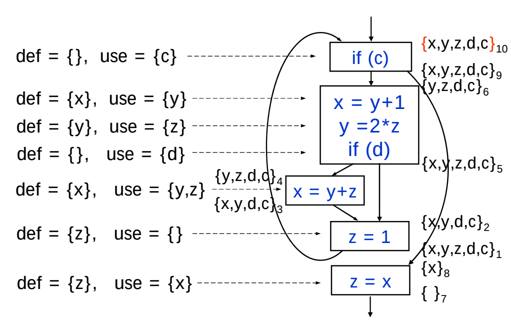
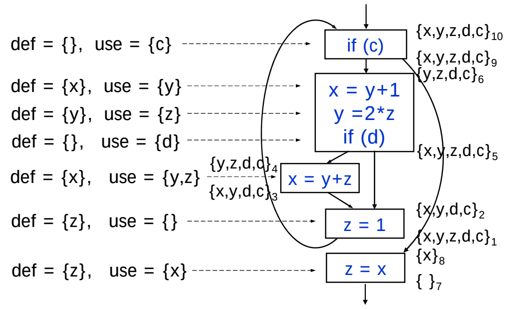





## Example



## Fixed Point Reached






## Copy Propagation

- Goal: determine copies available at each program point
- Information: set of copies <x=y> at each point
- For each instruction I:
  - in[I] = copies available at program point before I
  - out[I] = copies available at program point after I
- For each basic block B:
  - in[B] = copies available at beginning of B
  - out[B] = copies available at end of B
- If I = first instruction in B, then in[B] = in[I]
- If I' = last instruction in B, then out[B] = out[I']



## Same Methodology

1. Express flow of information (i.e., available copies):
   - For points before and after each instruction (in[I], out[I])
   - For points at exit and entry of basic blocks (in[B], out[B])
2. Build constraint system using the relations between available copies
3. Solve constraints to determine available copies at each point in the program



## Analyze Instructions

- Knowing in[I], can compute out[I]:
  - Remove from in[I] all copies <u=v> if variable u or v is written by I
  - Keep all other copies from in[I]
  - If I is of the form x=y, add it to out[I]

in[I]
I
out[I]

- Mathematically:

  out[I] = ( in[I] – kill[I] ) ∪ gen[I]

  where:
  - kill[I] = copies "killed" by instruction I
  - gen[I] = copies "generated" by instruction I



## Computing Kill/Gen

- Compute kill[I] and gen[I] for each instruction I:

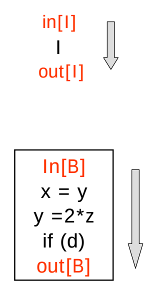
if I is x = y OP z : gen[I] = {} kill[I] = {u=v|u or v is x}
if I is x = OP y : gen[I] = {} kill[I] = {u=v|u or v is x}
if I is x = y : gen[I] = {x=y} kill[I] = {u=v|u or v is x}
if I is x = addr y : gen[I] = {} kill[I] = {u=v|u or v is x}
if I is if (x) : gen[I] = {} kill[I] = {}
if I is return x : gen[I] = {} kill[I] = {}
if I is x = f($y_1$ ,…, $y_n$) : gen[I] = {} kill[I] = {u=v| u or v is x}

(again, ignore load and store instructions)



## Forward Flow

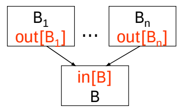
- Relation:
  out[I] = ( in[I] – kill[I] ) ∪ gen[I]
- The information flows forward!
- Instructions: can compute out[I] if we know in[I]
- Basic blocks: information about available copies flows from in[B] to out[B]



# Analyze Control Flow

- Rule: A copy is available at beginning of block B if it is available at the end of all predecessor blocks
- Characterizes all possible program executions
- Mathematically:

$$in[B] = \bigcap_{B' \in pred(B)} out[B']$$




- Information flows forward: from predecessors B' of B to basic block B



# Constraint System

- Build constraints: start with CFG and derive a system of constraints between sets of available copies:

$$\begin{cases} out[I] = ( in[I] - kill[I] ) \cup gen[I] & \text{for each instruction I} \\ in[B] = \bigcap_{B' \in pred(B)} out[B'] & \text{for each basic block B} \end{cases}$$

- Solve constraints:
  - Start with empty set of available copies at start and universal set of available copies everywhere else
  - Iteratively apply constraints
  - Stop when we reach a fixed point



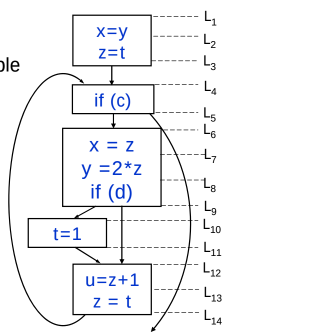
# Example

- What are the available copies at the end of the program?

x=y?

z=t?

x=z?





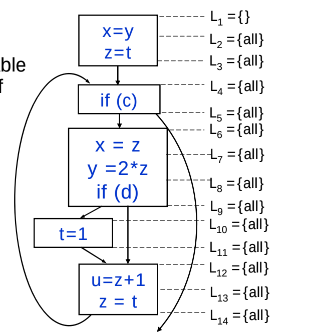

# Example

- What are the available copies at the end of the program?

x=y?

z=t?

x=z?





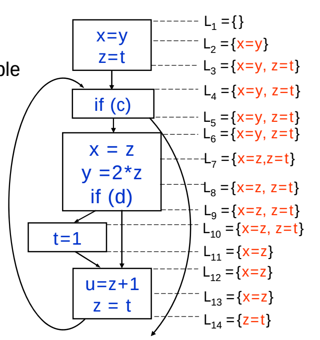

# Iteration 1

- What are the available copies at the end of the program?

x=y?

z=t?

x=z?





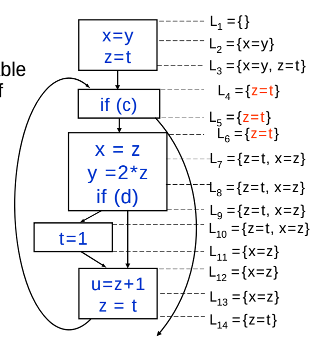

# Iteration 2

- What are the available copies at the end of the program?

x=y?

z=t?

x=z?



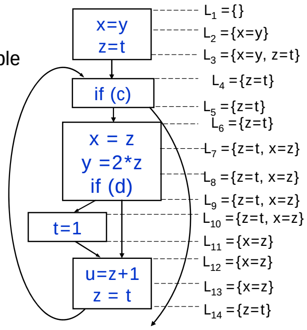
## Fixed Point Reached!

- What are the available copies at the end of the program?

x=y? NO

z=t? YES

x=z? NO






## Summary

- Extracting information about live variables and available copies is similar
  - Define the required information
  - Define information before/after instructions
  - Define information at entry/exit of blocks
  - Build constraints for instructions/control flow
  - Solve constraints to get needed information
- ...is there a general framework?
  - Yes: dataflow analysis!