CS412/CS413

Introduction to Compilers

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Lecture 26: Dataflow Analysis Frameworks

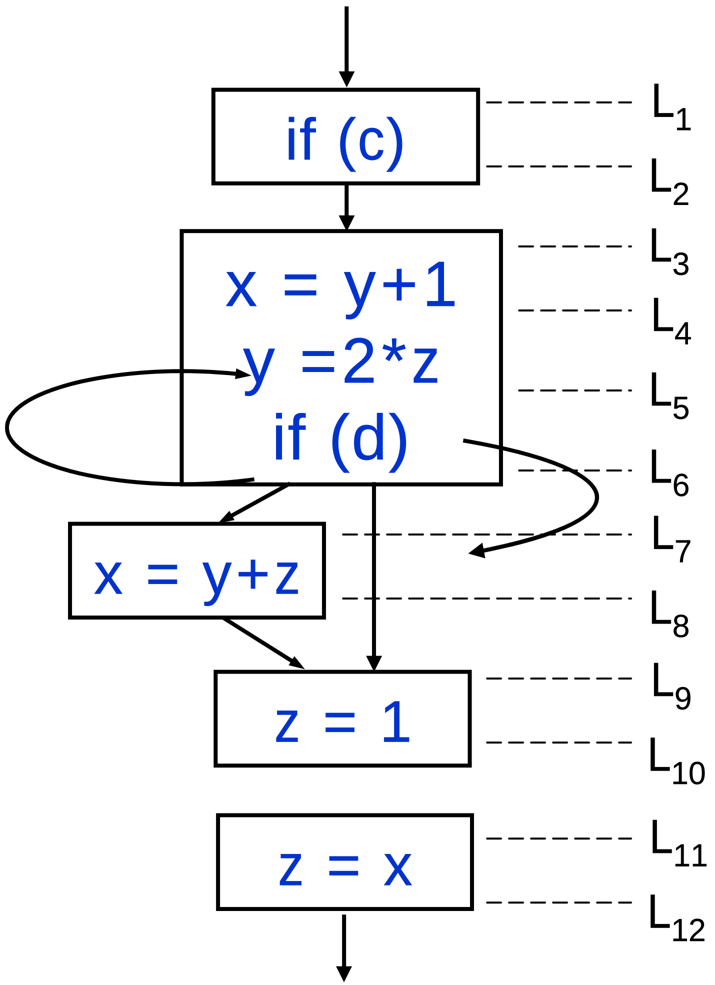
28 March 08

Live Variable Analysis

What are the live variables at each program point?

Method:

1. Define sets of live variables
1. Build constraints
2. Solve constraints



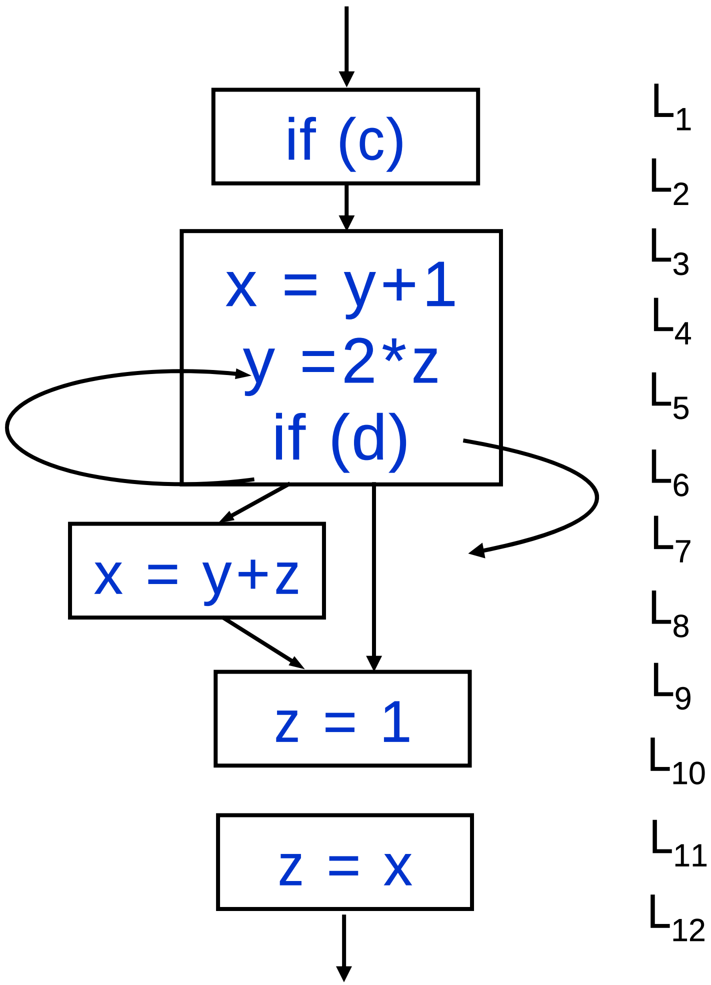
Derive Constraints

Constraints for each instruction:

$$in[I]=(out[I]-def[I]) \cup use[I]$$

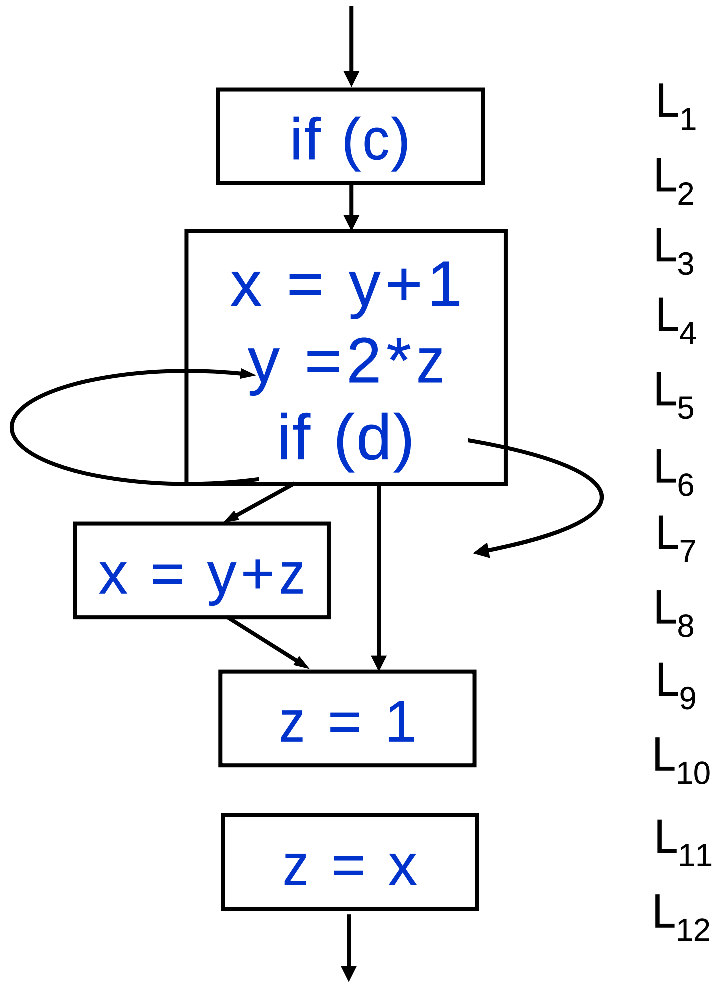
Constraints for control flow:

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



Derive Constraints

$L_1 = L_2 \cup \{c\}$
$L_2 = L_3 \cup L_{11}$
$L_3 = (L_4 - \{x\}) \cup \{y\}$
$L_4 = (L_5 - \{y\}) \cup \{z\}$
$L_5 = L_6 \cup \{d\}$
$L_6 = L_7 \cup L_9$
$L_7 = (L_8 - \{x\}) \cup \{y,z\}$
$L_8 = L_9$
$L_9 = L_{10} - \{z\}$
$L_{10} = L_1$
$L_{11} = (L_{12} - \{z\}) \cup \{x\}$



Initialization

$L_1 = L_2 \cup \{c\}$

$L_2 = L_3 \cup L_{11}$

$L_3 = (L_4 - \{x\}) \cup \{y\}$

$L_4 = (L_5 - \{y\}) \cup \{z\}$

$L_5 = L_6 \cup \{d\}$

$L_6 = L_7 \cup L_9$

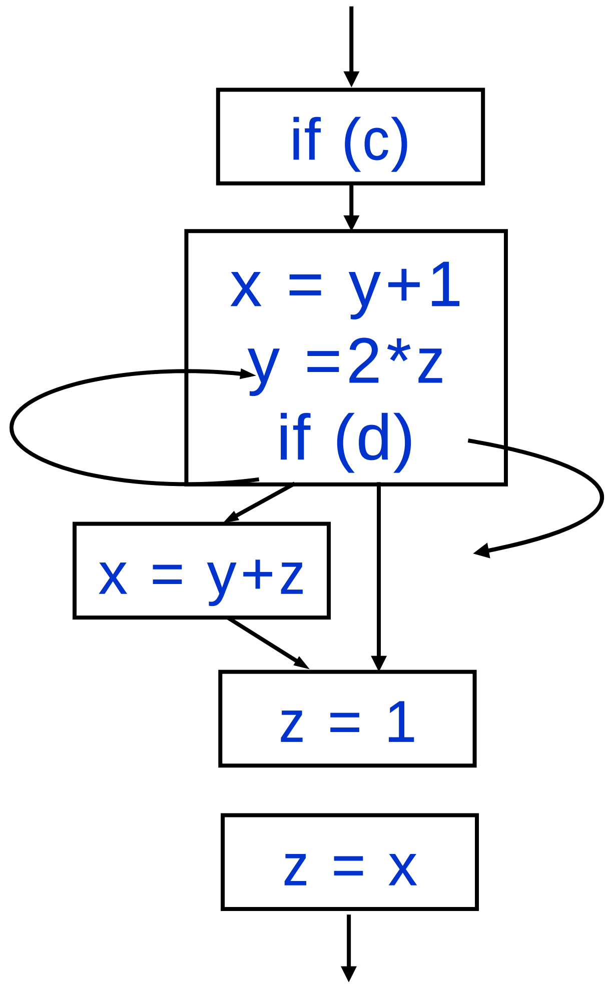
$L_7 = (L_8 - \{x\}) \cup \{y,z\}$

$L_8 = L_9$

$L_9 = L_{10} - \{z\}$

$L_{10} = L_1$

$L_{11} = (L_{12} - \{z\}) \cup \{x\}$



$L_1 = \{\}$

$L_2 = \{\}$

$L_3 = \{\}$

$L_4 = \{\}$

$L_5 = \{\}$

$L_6 = \{\}$

$L_7 = \{\}$

$L_8 = \{\}$

$L_9 = \{\}$

$L_{10} = \{\}$

$L_{11} = \{\}$

$L_{12} = \{\}$

Iteration 1

$L_1 = L_2 \cup \{c\}$
$L_2 = L_3 \cup L_{11}$
$L_3 = (L_4 - \{x\}) \cup \{y\}$
$L_4 = (L_5 - \{y\}) \cup \{z\}$
$L_5 = L_6 \cup \{d\}$
$L_6 = L_7 \cup L_9$
$L_7 = (L_8 - \{x\}) \cup \{y,z\}$
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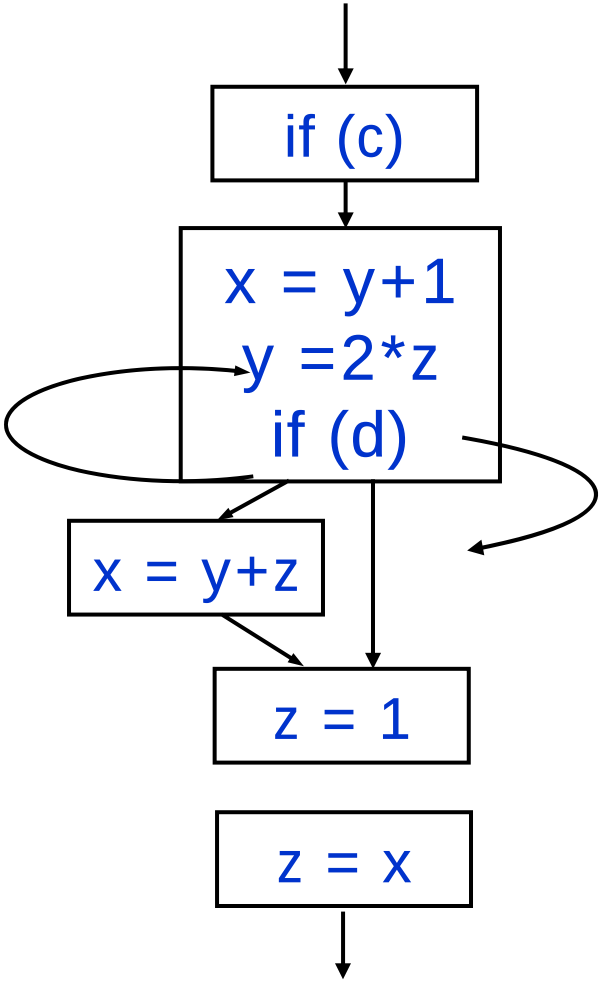
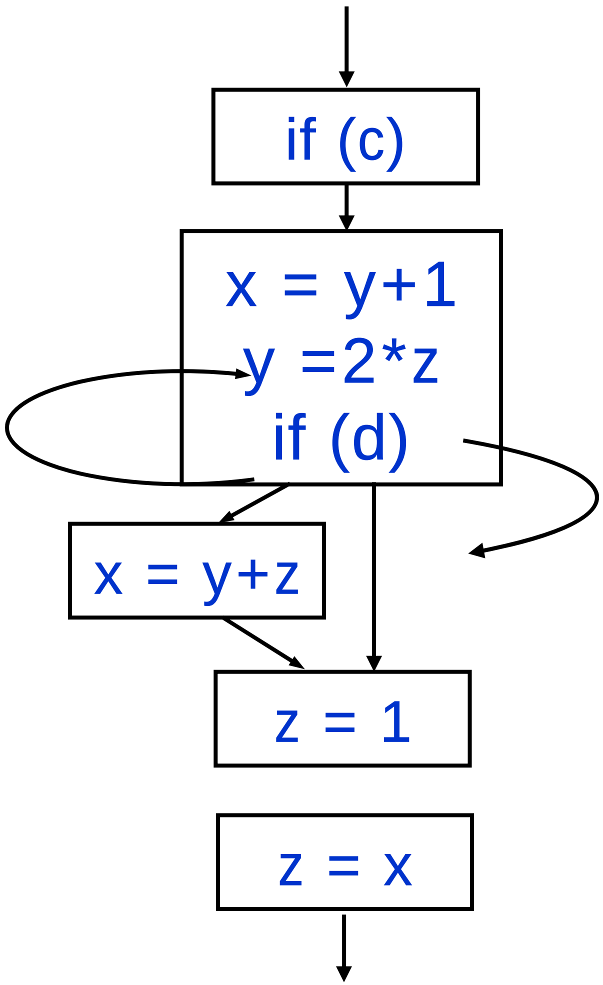
$L_{11} = (L_{12} - \{z\}) \cup \{x\}$



$L_1 = \{x,y,z,c,d\}$
$L_2 = \{x,y,z,d\}$
$L_3 = \{y,z,d\}$
$L_4 = \{z,d\}$
$L_5 = \{y,z,d\}$
$L_6 = \{y,z\}$
$L_7 = \{y,z\}$
$L_8 = \{\}$
$L_9 = \{\}$
$L_{10} = \{\}$
$L_{11} = \{x\}$
$L_{12} = \{\}$

Iteration 2

$L_1 = L_2 \cup \{c\}$
$L_2 = L_3 \cup L_{11}$
$L_3 = (L_4 - \{x\}) \cup \{y\}$
$L_4 = (L_5 - \{y\}) \cup \{z\}$
$L_5 = L_6 \cup \{d\}$
$L_6 = L_7 \cup L_9$
$L_7 = (L_8 - \{x\}) \cup \{y,z\}$
$L_8 = L_9$
$L_9 = L_{10} - \{z\}$
$L_{10} = L_1$
$L_{11} = (L_{12} - \{z\}) \cup \{x\}$



$L_1 = \{x,y,z,c,d\}$
$L_2 = \{x,y,z,c,d\}$
$L_3 = \{y,z,c,d\}$
$L_4 = \{x,z,c,d\}$
$L_5 = \{x,y,z,c,d\}$
$L_6 = \{x,y,z,c,d\}$
$L_7 = \{y,z,c,d\}$
$L_8 = \{x,y,c,d\}$
$L_9 = \{x,y,c,d\}$
$L_{10} = \{x,y,z,c,d\}$
$L_{11} = \{x\}$
$L_{12} = \{\}$

Fixed-point!

$L_1 = L_2 \cup \{c\}$
$L_2 = L_3 \cup L_{11}$
$L_3 = (L_4 - \{x\}) \cup \{y\}$
$L_4 = (L_5 - \{y\}) \cup \{z\}$
$L_5 = L_6 \cup \{d\}$
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$L_7 = (L_8 - \{x\}) \cup \{y,z\}$
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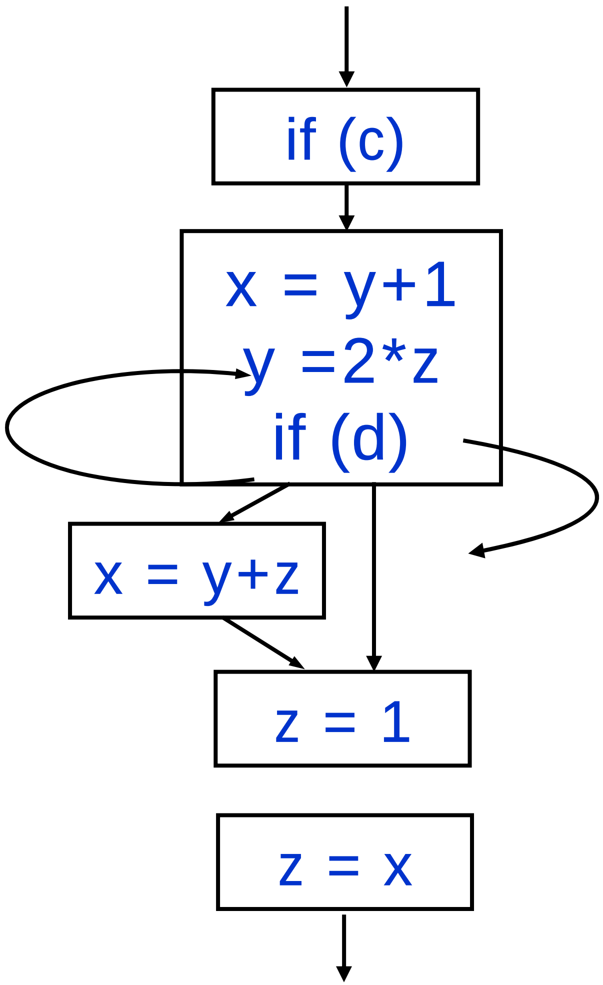
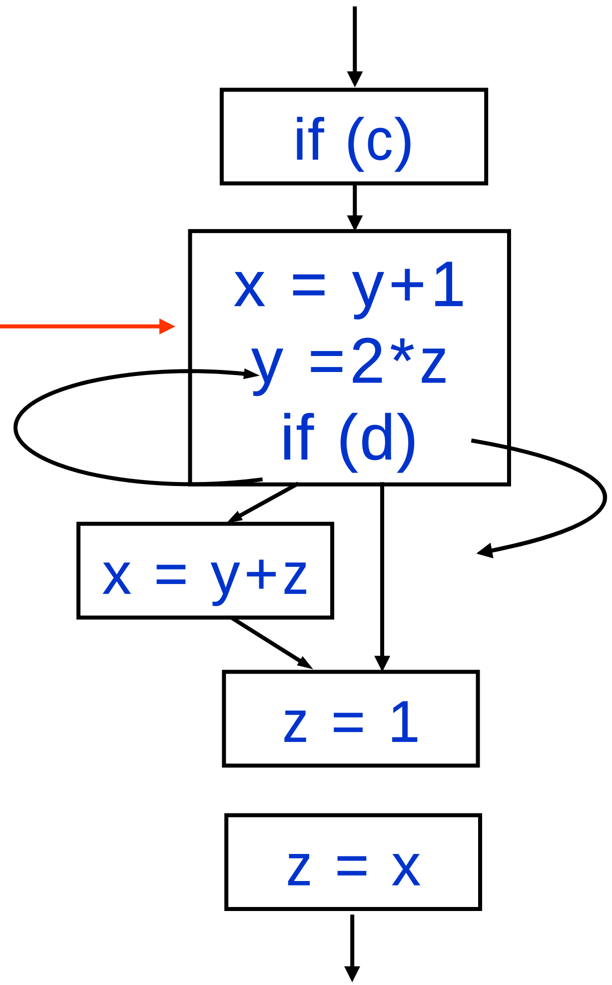
$L_{11} = (L_{12} - \{z\}) \cup \{x\}$



$L_1 = \{x,y,z,c,d\}$
$L_2 = \{x,y,z,c,d\}$
$L_3 = \{y,z,c,d\}$
$L_4 = \{x,z,c,d\}$
$L_5 = \{x,y,z,c,d\}$
$L_6 = \{x,y,z,c,d\}$
$L_7 = \{y,z,c,d\}$
$L_8 = \{x,y,c,d\}$
$L_9 = \{x,y,c,d\}$
$L_{10} = \{x,y,z,c,d\}$
$L_{11} = \{x\}$
$L_{12} = \{\}$

Final Result

x live here !

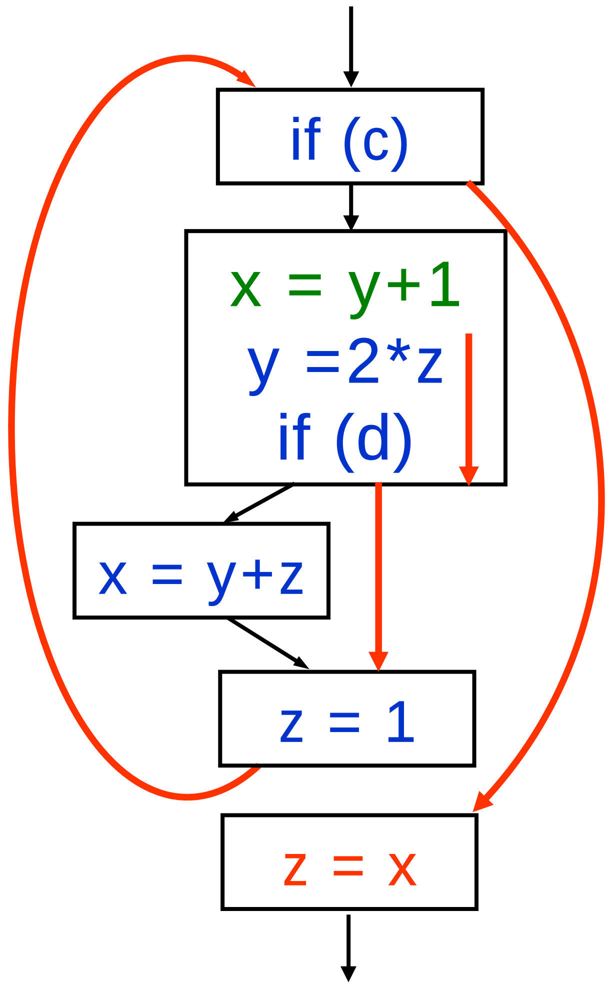


L_1={x,y,z,c,d}
L_2 ={x,y,z,c,d}
L_3 ={y,z,c,d}
L_4 ={x,z,c,d}
L_5 ={x,y,z,c,d}
L_6 ={x,y,z,c,d}
L_7 ={y,z,c,d}
L_8 ={x,y,c,d}
L_9 ={x,y,c,d}
L_{10} ={x,y,z,c,d}
L_{11} ={x}
L_{12} ={}

Final result: sets of live variables at each program point

Characterize All Executions

The analysis detects that there is an execution that uses the value x = y+1



L_1 = {x,y,z,c,d}
L_2 = {x,y,z,c,d}
L_3 = {y,z,c,d}
L_4 = {x,z,c,d}
L_5 = {x,y,z,c,d}
L_6 = {x,y,z,c,d}
L_7 = {y,z,c,d}
L_8 = {x,y,c,d}
L_9 = {x,y,c,d}
L_{10} = {x,y,z,c,d}
L_{11} = {x}
L_{12} = {}

Generalization

- Live variable analysis and detection of available copies are similar:
  - Define some information that they need to compute
  - Build constraints for the information
  - Solve constraints iteratively:
    - The information always “increases” during iteration
    - Eventually, it reaches a fixed point.
- We would like a general framework
  - Framework applicable to many other analyses
  - Live variable/copy propagation = instances of the framework

Dataflow Analysis Framework

- Dataflow analysis = a common framework for many compiler analyses
  - Computes some information at each program point
  - The computed information characterizes all possible executions of the program

- Basic methodology:
  - Describe information about the program using an algebraic structure called a lattice
  - Build constraints that show how instructions and control flow influence the information in terms of values in the lattice
  - Iteratively solve constraints

Partial Order Relations

- Lattice definition builds on the concept of a partial order relation
- A partial order $(P,\sqsubseteq)$ consists of:
  - A set P
  - A partial order relation $\sqsubseteq$ that is:
    1. Reflexive $x \sqsubseteq x$
    2. Anti-symmetric $x \sqsubseteq y,\ y \sqsubseteq x \Rightarrow x = y$
    3. Transitive: $x \sqsubseteq y,\ y \sqsubseteq z \Rightarrow x \sqsubseteq z$
- Called a "*partial* order" because not all elements are comparable, in contrast with a *total* order, in which
  - $\neg$4. Total $x \sqsubseteq y$ or $y \sqsubseteq x$

Example

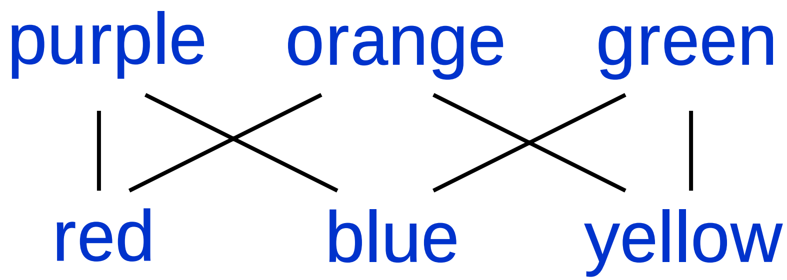
- P is {red, blue, yellow, purple, orange, green}
- $\sqsubseteq$

red $\sqsubseteq$ purple,
blue $\sqsubseteq$ purple,
yellow $\sqsubseteq$ orange,
red $\sqsubseteq$ red,
blue $\sqsubseteq$ blue,
yellow $\sqsubseteq$ yellow,
purple $\sqsubseteq$ purple,
orange $\sqsubseteq$ orange,
green $\sqsubseteq$ green

red $\sqsubseteq$ orange,
blue $\sqsubseteq$ green,
blue $\sqsubseteq$ green,

Hasse Diagrams

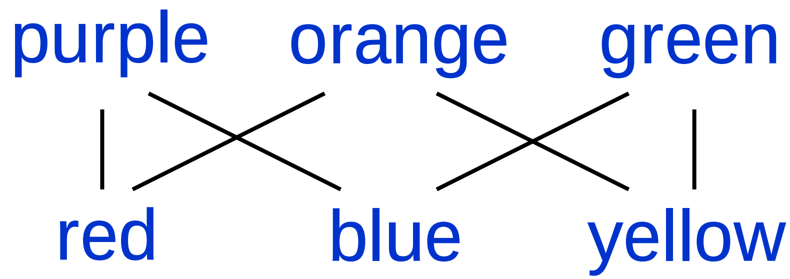
- A graphical representation of a partial order, where
  - x and y are on the same level when they are incomparable
  - x is below y when $x \sqsubseteq y$ and $x \neq y$
  - x is below y and connected by a line when $x \sqsubseteq y$, $x \neq y$, and there is no z such that $x \sqsubseteq z$, $z \sqsubseteq y$, $x \neq z$, and $y \neq z$



Lower/Upper Bounds

- If (P, $\sqsubseteq$) is a partial order and $S \subseteq P$, then:
  1. $x \in P$ is a lower bound of S if $x \sqsubseteq y$, for all $y \in S$
  2. $x \in P$ is an upper bound of S if $y \sqsubseteq x$, for all $y \in S$
- There may be multiple lower and upper bounds of the same set S

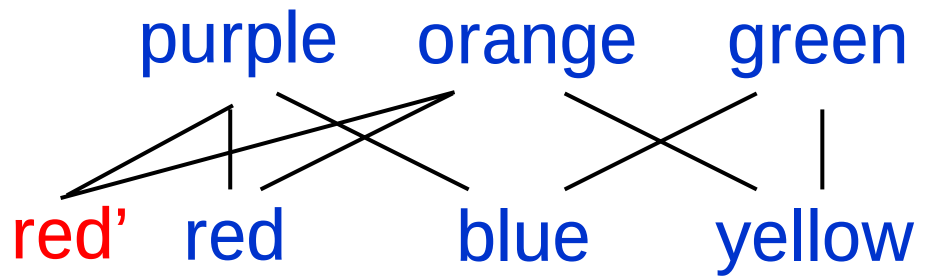
Example, cont.



red is lower bound for {purple, orange}
blue is lower bound for {purple, green}
yellow is lower bound for {orange, green}
no lower bound for {purple, orange, green}
no lower bound for {red, blue}
no lower bound for {red, yellow}
no lower bound for {blue, yellow},
etc.

purple is upper bound for {red, blue}
orange is upper bound for {red, yellow}
green is upper bound for {orange, green}
no upper bound for {red, bule, yellow}
no upper bound for {purple, orange}
no upper bound for {orange, green}
no upper bound for {purple, green}
etc.

Example, cont.



red is lower bound for {purple, orange}
blue is lower bound for {purple, green}
yellow is lower bound for {orange, green}
no lower bound for {purple, orange, green}
no lower bound for {red, blue}
no lower bound for {red, yellow}
no lower bound for {blue, yellow},
etc.

purple is upper bound for {red, blue}
orange is upper bound for {red, yellow}
green is upper bound for {orange, green}
no upper bound for {red, bule, yellow}
no upper bound for {purple, orange}
no upper bound for {orange, green}
no upper bound for {purple, green}
etc.

red' is also a lower bound for {purple, orange}

LUB and GLB

- Define least upper bound (LUB) and greatest lower bound (GLB) as follows:
- If $(P, \sqsubseteq)$ is a partial order and $S \subseteq P$, then:

  1. $x \in P$ is GLB of S if:

     a) x is a lower bound of S

     b) $y \sqsubseteq x$, for any lower bound y of S

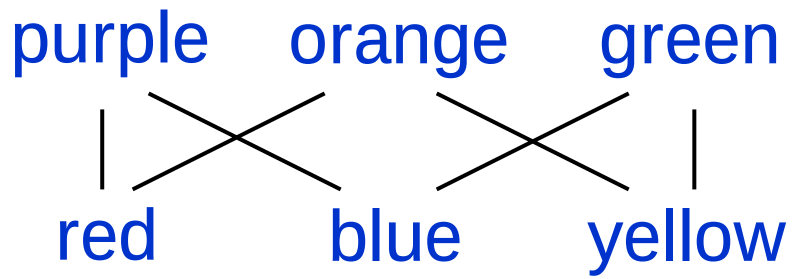
  2. $x \in P$ is a LUB of S if:

     a) x is an upper bound of S

     b) $x \sqsubseteq y$, for any upper bound y of S

- ... are GLB and LUB unique?

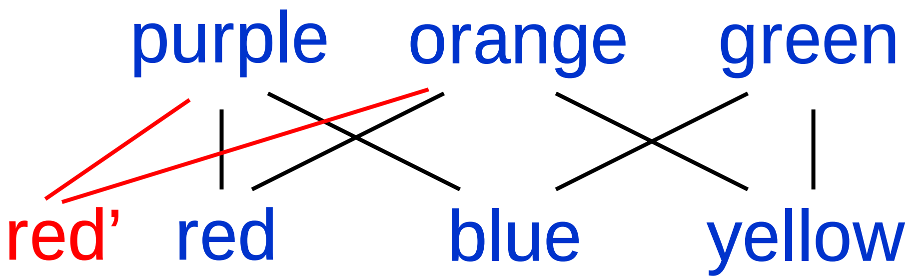
Example, cont.



red is GLB for {purple, orange}
blue is GLB for {purple, green}
yellow is GLB for {orange, green}

purple is LUB for {red, blue}
orange is LUB for {red, yellow}
green is LUB for {orange, green}

Example'



blue is GLB for {purple, green}
yellow is GLB for {orange, green}

red' is a lower bound for {purple, orange}
red is a lower bound for {purple, orange}
There is no GLB for {purple, orange}

purple is LUB for {red, blue}
orange is LUB for {red, yellow}
green is LUB for {orange, green}
purple is LUB for {red', blue}
orange is LUB for {red', yellow}

Lattices

- A pair (L, $\sqsubseteq$) is a lattice if:

1. (L, $\sqsubseteq$) is a partial order
2. Any finite non-empty subset S $\subseteq$ L has a LUB and a GLB

Example”

- L is natural numbers {0, 1, 2, 3, ... }
- ⊑ is ≤

Every finite subset of L has a LUB
Every subset of L has a GLB
Therefore (L, ≤) is a lattice
No infinite subset of L has a LUB

Complete Lattices

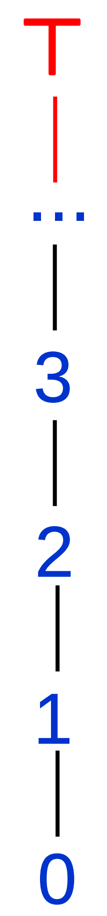
- A pair (L, ⊑) is a complete lattice if:
  1. (L, ⊑) is a partial order
  2. Any non-empty subset S ⊆ L has a LUB and a GLB

- Can identify and name two special elements:
  1. Bottom element: $\bot$ = GLB(L)
  2. Top element: $\top$ = LUB(L)

- All finite lattices are complete

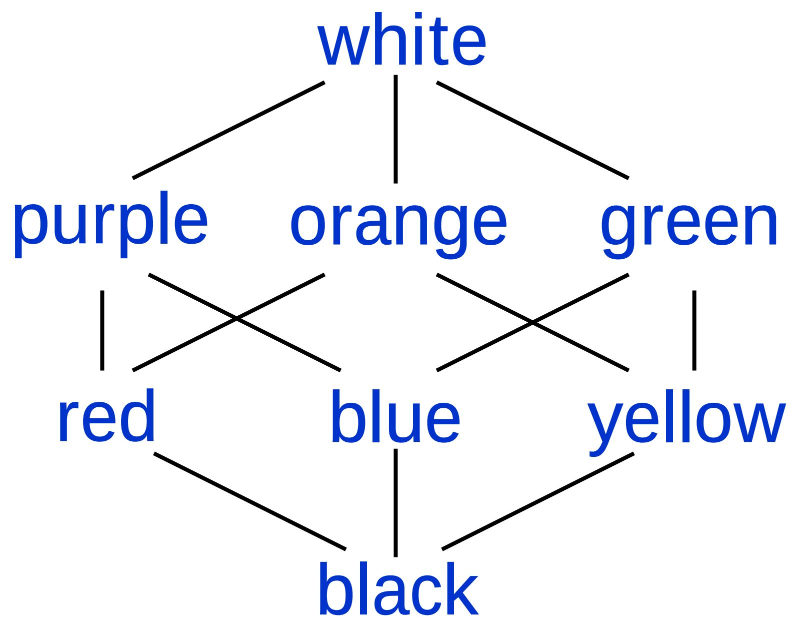
Example”’

- L is natural numbers {0, 1, 2, 3, ... }
- ⊑ is ≤



Every finite subset of L has a GLB and LUB
Therefore (L, ≤) is a lattice
Every infinite subset of L has a LUB
Therefore (L, ≤) is a complete lattice
However, L has infinite ascending chains

Example''''

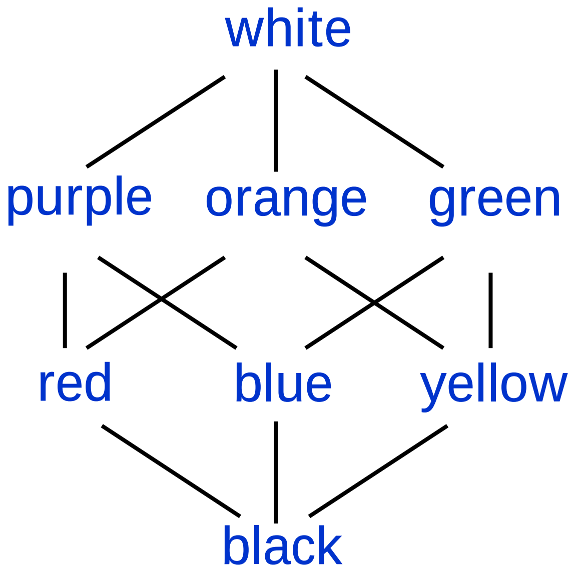


black is GLB for {red, blue, yellow}

white is LUB for {purple, orange, green}

Meet and Join

- By definition, for any lattice L, GLBs and LUBs are defined for finite sets
- Define operators meet (⊓) and join (⊔) as
  - $x \sqcap y = GLB(\{x,y\})$
  - $x \sqcup y = LUB(\{x,y\})$
  - For any finite set $S \subseteq L$
    - $\sqcap S = GLB(S)$
    - $\sqcup S = LUB(S)$

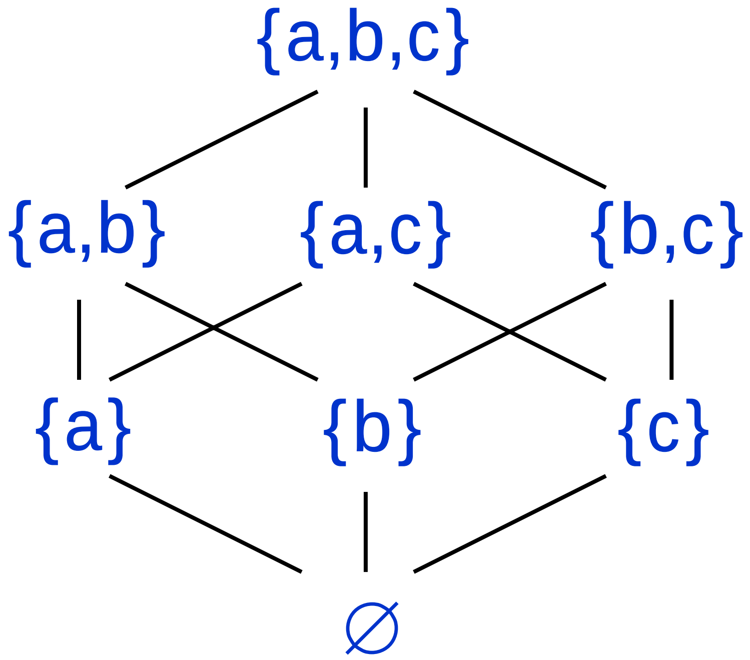


Example''''' Lattice

- Consider S = {a,b,c} and its power set P = {∅, {a}, {b}, {c}, {a,b}, {b,c}, {a,c} {a,b,c}}
- Define partial order as set inclusion: $X \subseteq Y$
  - Reflexive $X \subseteq X$
  - Anti-symmetric $X \subseteq Y, Y \subseteq X \Rightarrow X = Y$
  - Transitive $X \subseteq Y, Y \subseteq Z \Rightarrow X \subseteq Z$
- Also, for any two elements of P, there is a set that includes both and another set that is included in both
- Therefore (P, ⊆) is a (complete) lattice

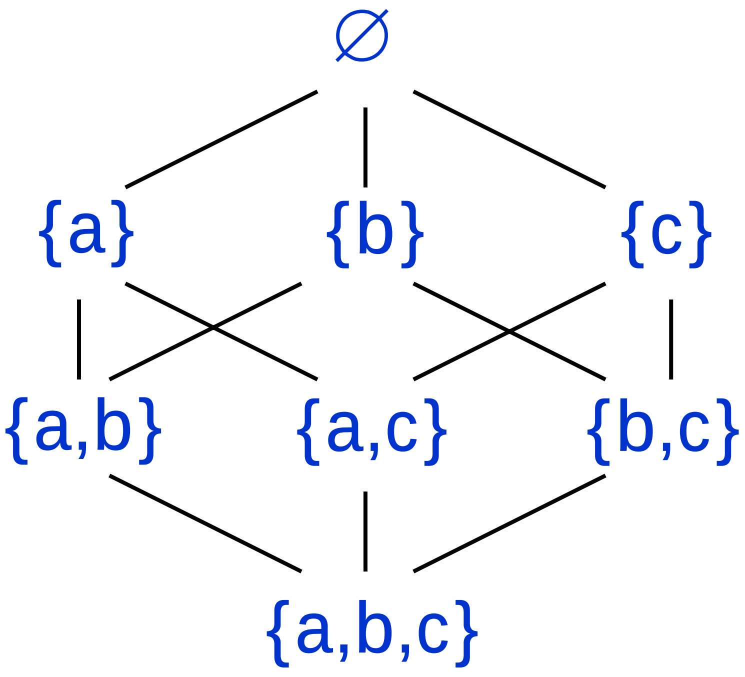
Power Set Lattice

- Partial order: ⊆
  (set inclusion)
- Meet: ∩
  (set intersection)
- Join: ∪
  (set union)
- Top element: {a,b,c}
  (whole set)
- Bottom element: ∅
  (empty set)



Reversed Lattice

- Partial order: ⊇
  (set inclusion)
- Meet: ∪
  (set union)
- Join: ∩
  (set intersection)
- Top element: ∅
  (empty set)
- Bottom element: {a,b,c}
  (whole set)



Relation To Dataflow Analysis

- Information computed by live variable analysis and available copies can be expressed as elements of lattices

- Live variables: if V is the set of all variables in the program and P the power set of V, then:
  - (P, $\subseteq$) is a lattice
  - sets of live variables are elements of this lattice

Relation To Dataflow Analysis

- Copy Propagation:

  - V is the set of all variables in the program

  - V x V the Cartesian product representing all possible copy instructions

  - P the power set of V x V

- Then:
  – (P, $\subseteq$) is a lattice
  – sets of available copies are lattice elements

Using Lattices

- Assume information we want to compute in a program is expressed using a lattice L
- To compute the information at each program point we need to:
  - Determine how each instruction in the program changes the information
  - Determine how information changes at join/split points in the control flow

Transfer Functions

- Dataflow analysis defines a transfer function $F : L \rightarrow L$ for each instruction in the program
- Describes how the instruction modifies the information
- Consider in[I] is information before I, and out[I] is information after I
- Forward analysis: out[I] = F(in[I])
- Backward analysis: in[I] = F(out[I])

Basic Blocks

- Can extend the concept of transfer function to basic blocks using function composition

- Consider:
  - Basic block B consists of instructions (I_1, ..., I_n) with transfer functions F_1, ..., F_n
  - in[B] is information before B
  - out[B] is information after B

- Forward analysis:

$$out[B] = F_n(...(F_1(in[B]))) = F_n \circ ... \circ F_1(in[B])$$

- Backward analysis:

$$in[I] = F_1(... (F_n(out[i]))) = F_1 \circ ... \circ F_n(out[B])$$

Split/Join Points

- Dataflow analysis uses meet/join operations at split/join points in the control flow

- Consider in[B] is lattice information at beginning of block B and out[B] is lattice information at end of B

- Forward analysis: $in[B] = \sqcap \{out[B'] \mid B' \in pred(B)\}$
- Backward analysis: $out[B] = \sqcap \{in[B'] \mid B' \in succ(B)\}$

- Can alternatively use join operation $\sqcup$ (equivalent to using the meet operation $\sqcap$ in the reversed lattice)

Cartesian Products

- Let $L_1, ..., L_n$ be sets
- Cartesian product of $L_1,...,L_n$ is
  $\{ <x_1,...,x_n> \mid x_i \in L_i\}$
- If $L_1, ..., L_n$ are (complete) lattices then their Cartesian product is a (complete) lattice, where $\sqsubseteq$ is defined by
  $<x_1,...,x_n> \sqsubseteq <y_1,...,y_n>$ iff for all i, $x_i \sqsubseteq y_i$

Information as Cartesian Product

- Consider a program analysis in which n program analysis variables range over lattice L
- We view the analysis as computing an n-tuple of L-values, i.e., a point in the n-ary Cartesian product of L
- Each change of one program analysis variable changes one component of the n-tuple
- Analysese will terminate because we will only consider
  - Lattices with no infinite descending chains
  - “Monotonic” transfer functions that move us down (or not at all) in the lattice

More About Lattices

- In a lattice $(L, \sqsubseteq)$, the following are equivalent:
  1. $x \sqsubseteq y$
  2. $x \sqcap y = x$
  3. $x \sqcup y = y$

- Note: meet and join operations were defined using the partial order relation

Proof (1 & 2)

- Prove that $x \sqsubseteq y$ implies $x \sqcap y = x$:
  - x is a lower bound of {x,y}
  - All lower bounds of {x,y} are less= than x,y
  - In particular, they are less= than x

- Prove that $x \sqcap y = x$ implies $x \sqsubseteq y$:
  - x is a lower bound of {x,y}
  - x is less= than x and y
  - In particular, x is less= than y

Properties of Meet and Join

- The meet and join operators are:
  1. Associative $(x \sqcap y) \sqcap z = x \sqcap (y \sqcap z)$
  2. Commutative $x \sqcap y = y \sqcap x$
  3. Idempotent: $x \sqcap x = x$

- Property: If "$\sqcap$" is an associative, commutative, and idempotent operator, then the relation "$\sqsubseteq$" defined as $x \sqsubseteq y$ iff $x \sqcap y = x$ is a partial order

- Above property provides an alternative definition of a partial orders and lattices starting from the meet (join) operator