

Global Optimization

CS143

Lecture 15

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Slide design by Prof. Alex Aiken, with modifications

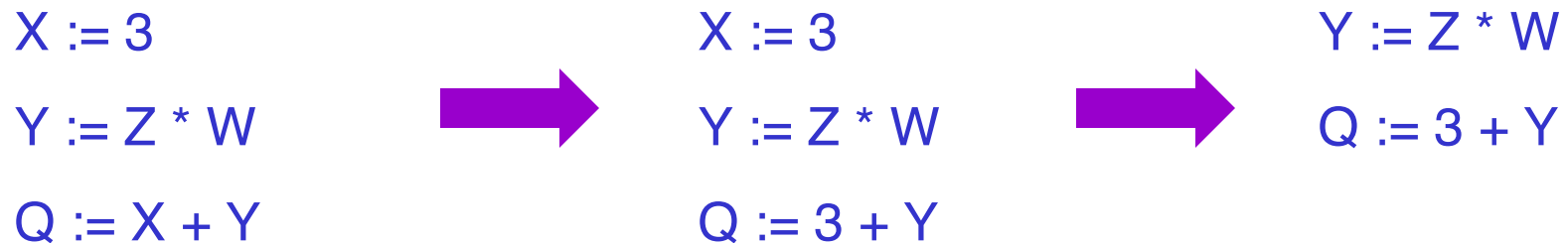
Lecture Outline

- Global flow analysis
- Global constant propagation
- Liveness analysis

Local Optimization

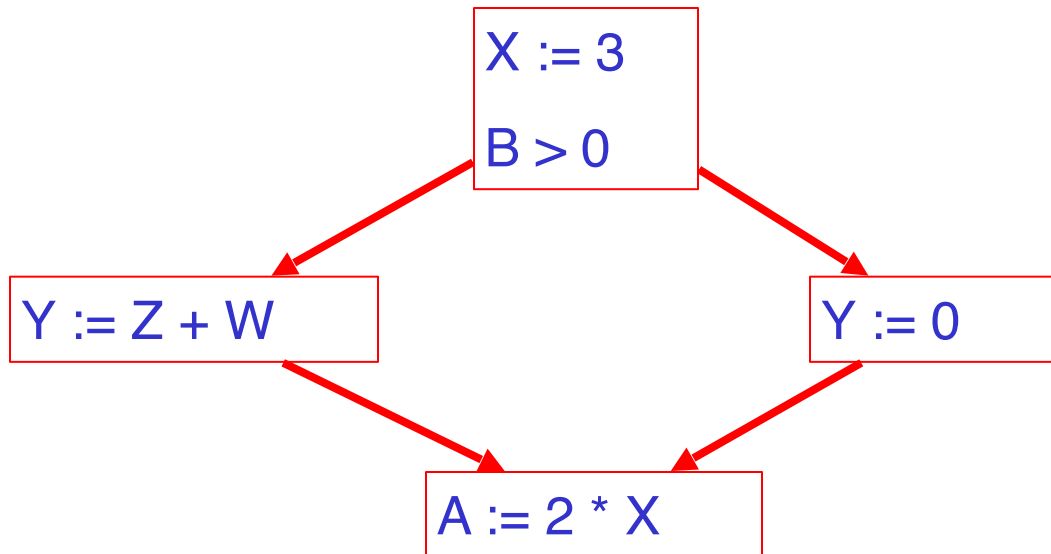
Recall the simple basic-block optimizations

- Constant propagation
- Dead code elimination



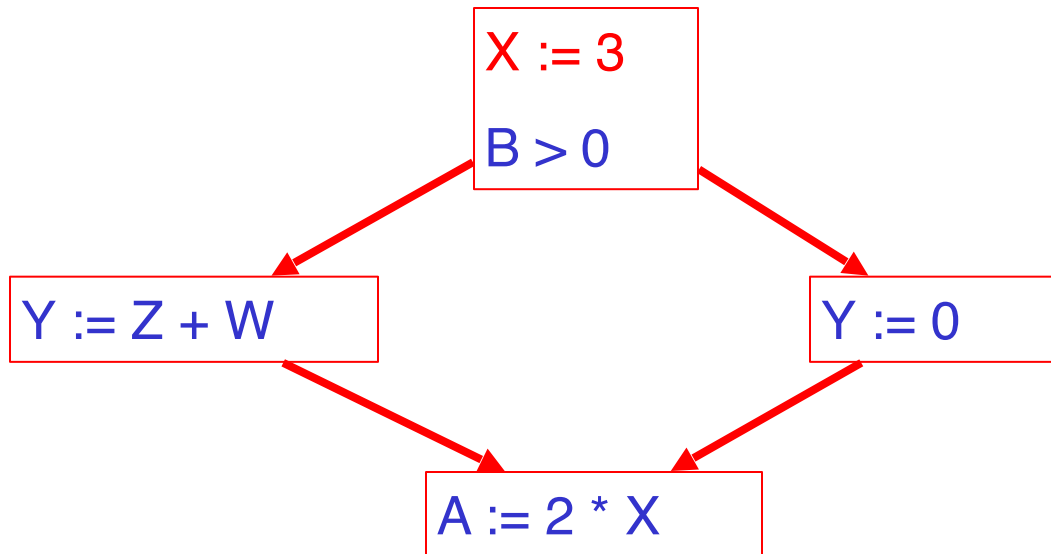
Global Optimization

These optimizations can be extended to an entire control-flow graph



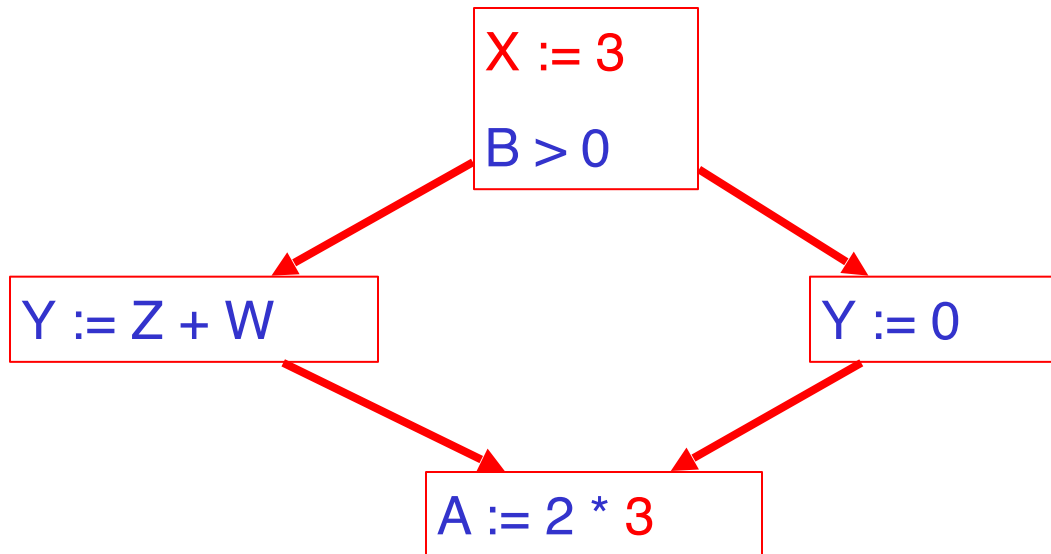
Global Optimization

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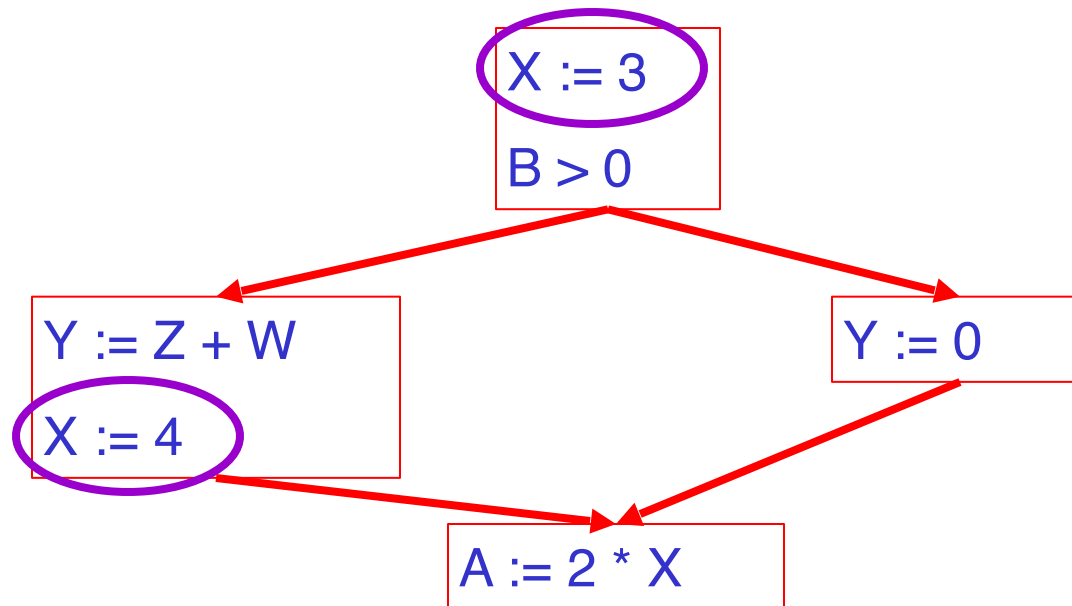
Global Optimization

These optimizations can be extended to an entire control-flow graph



Correctness

- How do we know it is OK to globally propagate constants?
- There are situations where it is incorrect:

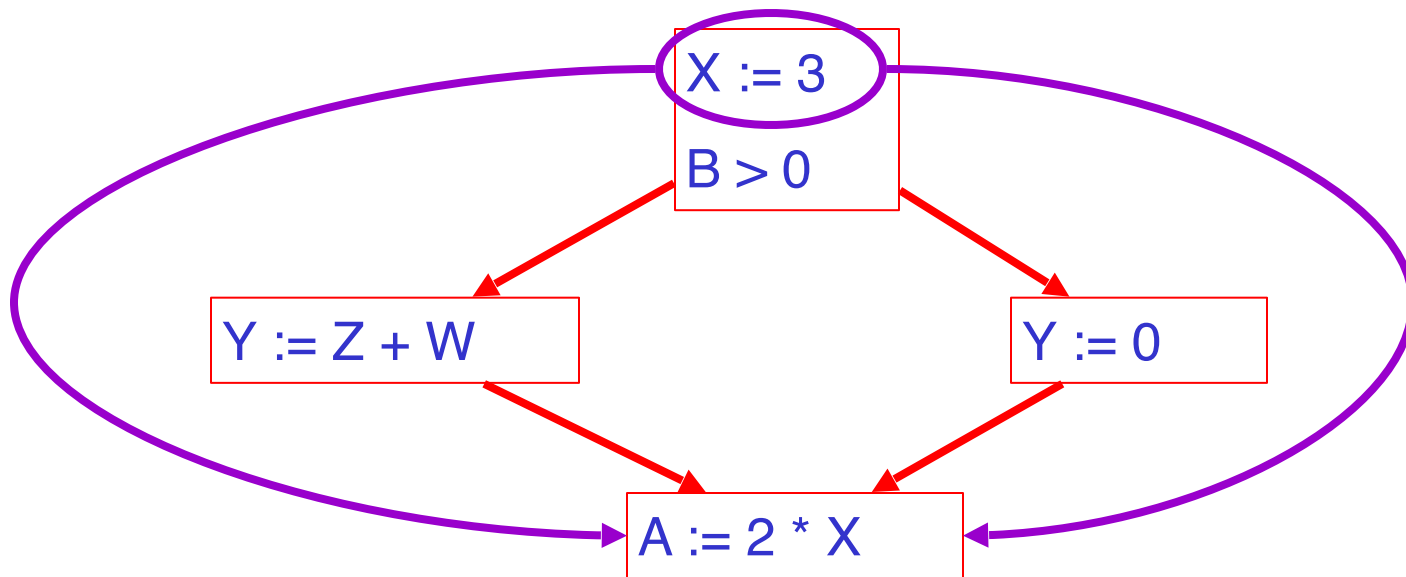


Correctness (Cont.)

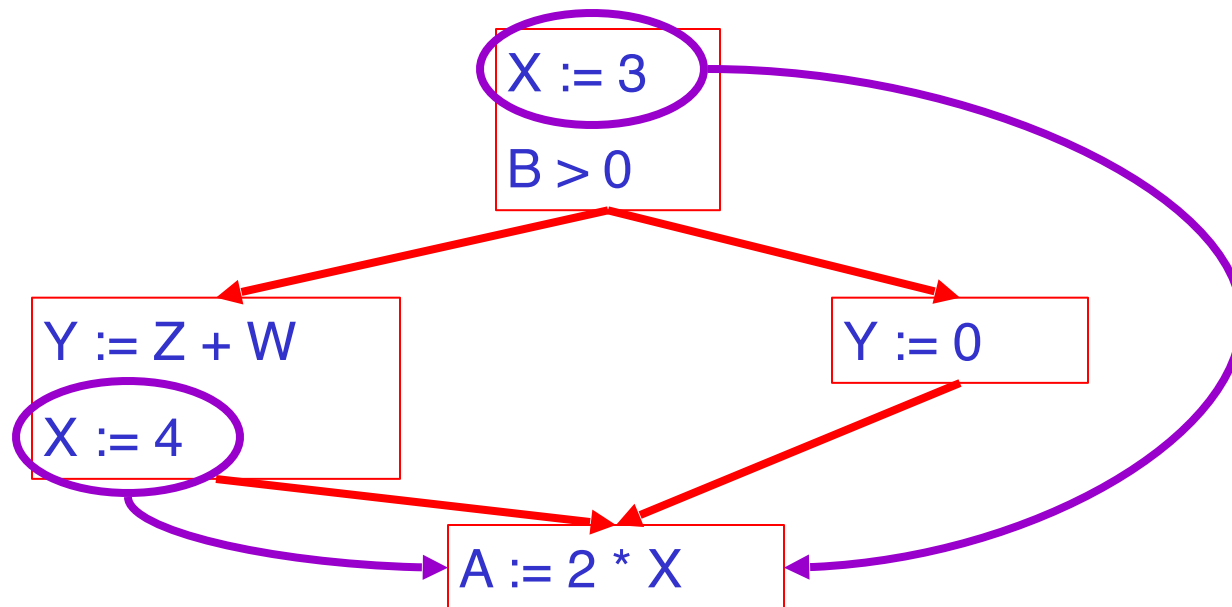
To replace a use of x by a constant k we must know that:

On every path to the use of x , the last assignment to x is $x := k$ **

Example 1 Revisited



Example 2 Revisited



Discussion

- The correctness condition is not trivial to check
- “All paths” includes paths around loops and through branches of conditionals
- Checking the condition requires global analysis
 - An analysis of the entire control-flow graph

Global Analysis

Global optimization tasks share several traits:

- The optimization depends on knowing a property X at a particular point in program execution
- Proving X at any point requires knowledge of the entire function
- It is OK to be conservative. If the optimization requires X to be true, then want to know either
 - X is definitely true
 - Don't know if X is true
- It is always safe to say “don't know”

Global Analysis (Cont.)

- Global dataflow analysis is a standard technique for solving problems with these characteristics
- Global constant propagation is one example of an optimization that requires global dataflow analysis

Global Constant Propagation

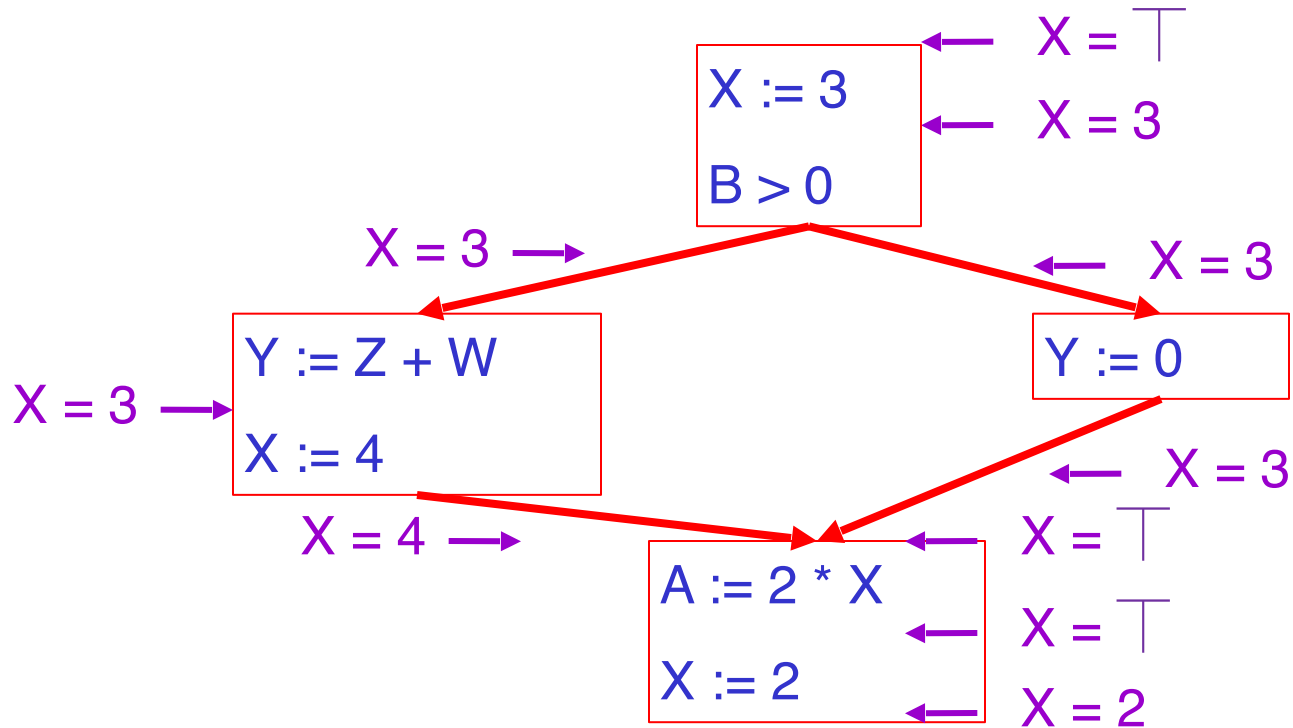
- Global constant propagation can be performed at any point where $**$ holds
- Consider the case of computing $**$ for a single variable X at all program points

Global Constant Propagation (Cont.)

- To make the problem precise, we associate one of the following values with X at every program point

value	interpretation
\perp	This statement never executes
c	$X = \text{constant } c$
T	X is not a constant

Example



Using the Information

- Given global constant information, it is easy to perform the optimization
 - Simply inspect the $x = ?$ associated with a statement using x
 - If x is constant at that point replace that use of x by the constant
- But how do we compute the properties $x = ?$

The Idea

The analysis of a complicated program can be expressed as a combination of simple rules relating the change in information between adjacent statements

Explanation

- The idea is to “push” or “transfer” information from one statement to the next
- For each statement s , we compute information about the value of x immediately before and after s

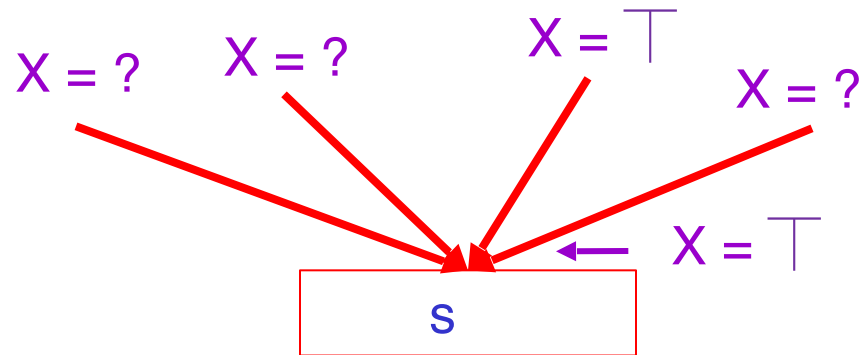
$C(s,x,in)$ = value of x before s

$C(s,x,out)$ = value of x after s

Transfer Functions

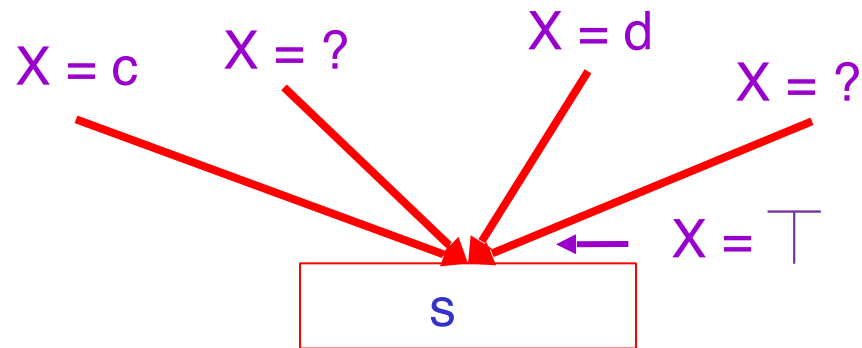
- Define a transfer function that transfers information from one statement to another
- In the following rules, let statement s have immediate predecessor statements p_1, \dots, p_n

Rule 1



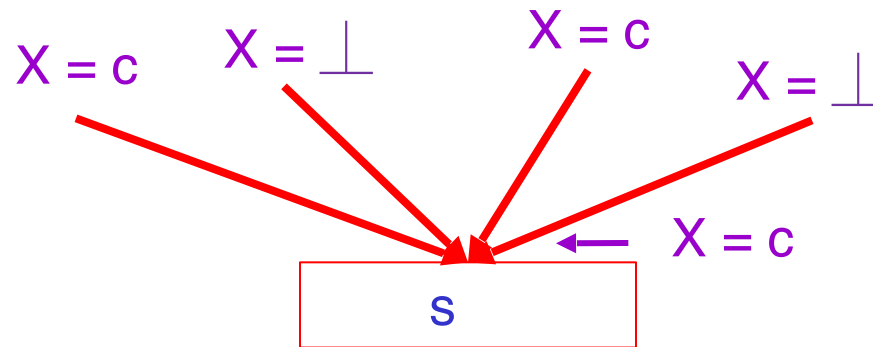
if $C(p_i, x, \text{out}) = \top$ for any i , then $C(s, x, \text{in}) = \top$

Rule 2



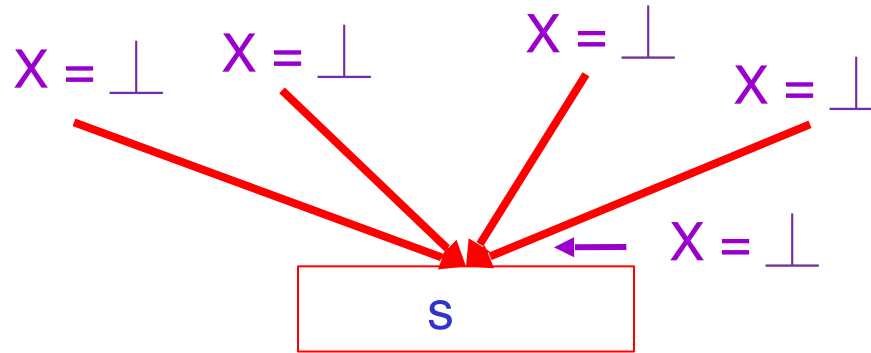
$C(p_i, x, \text{out}) = c \ \& \ C(p_j, x, \text{out}) = d \ \& \ d \diamond c \ \text{then}$
 $C(s, x, \text{in}) = \perp$

Rule 3



if $C(p_i, x, \text{out}) = c$ or \perp for all i ,
then $C(s, x, \text{in}) = c$

Rule 4



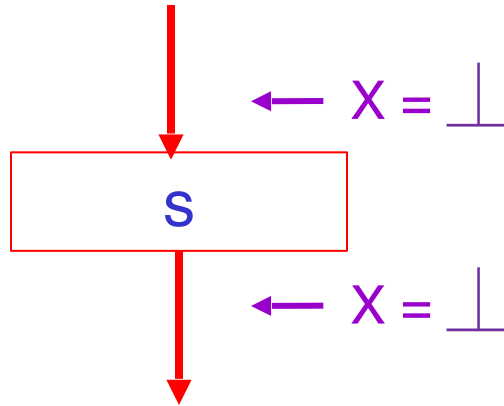
if $C(p_i, x, \text{out}) = \perp$ for all i ,

then $C(s, x, \text{in}) = \perp$

The Other Half

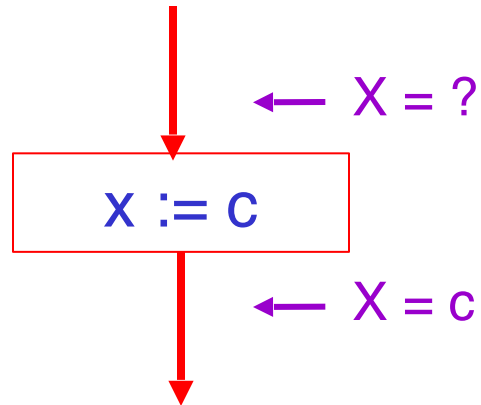
- Rules 1-4 relate the out of one statement to the in of the next statement
- Now we need rules relating the in of a statement to the out of the same statement

Rule 5



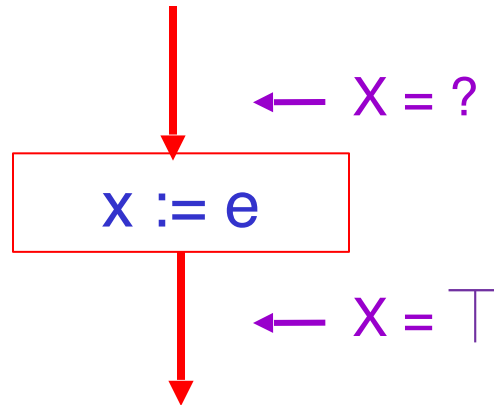
$$C(s, x, \text{out}) = \perp \text{ if } C(s, x, \text{in}) = \perp$$

Rule 6



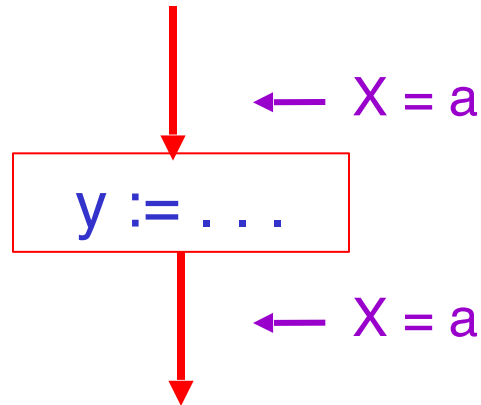
$C(x := c, x, \text{out}) = c$ if c is a constant

Rule 7



$C(x := e, x, \text{out}) = \top$, where e is an expression that is not a constant

Rule 8



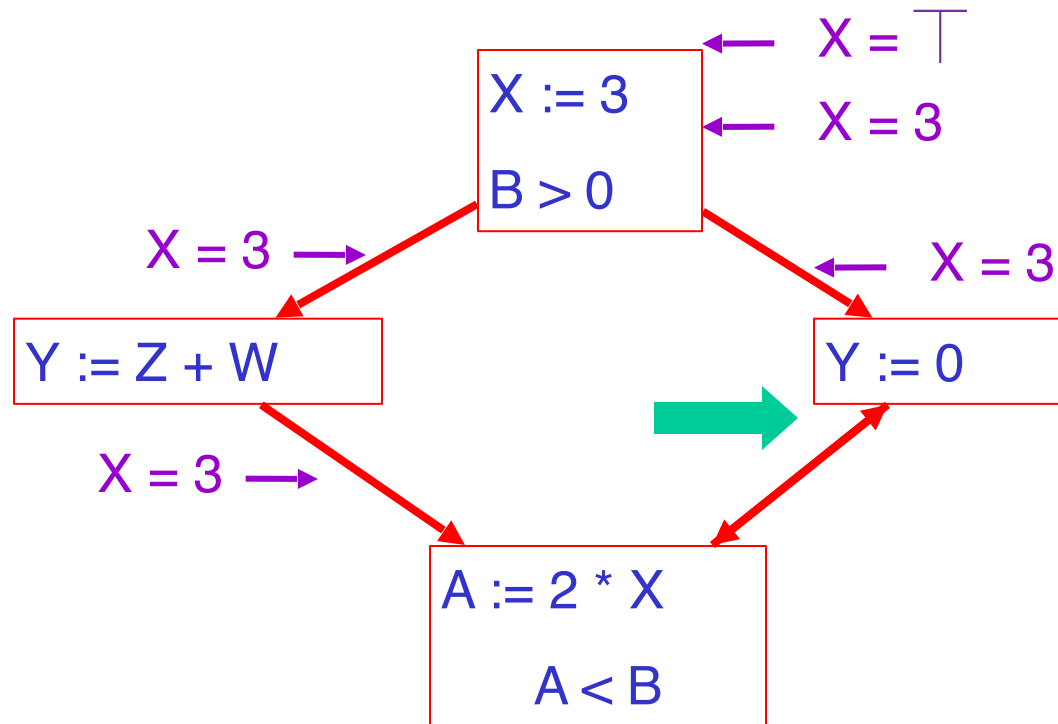
$$C(y := \dots, x, \text{out}) = C(y := \dots, x, \text{in}) \quad \text{if } x \diamond y$$

An Algorithm

1. For every entry s to the program, set $C(s, x, \text{in}) = \top$
2. Set $C(s, x, \text{in}) = C(s, x, \text{out}) = \perp$ everywhere else
3. Repeat until all points satisfy 1-8:
Pick s not satisfying 1-8 and update using the appropriate rule

The Value **Z**

- To understand why we need \perp , look at a loop



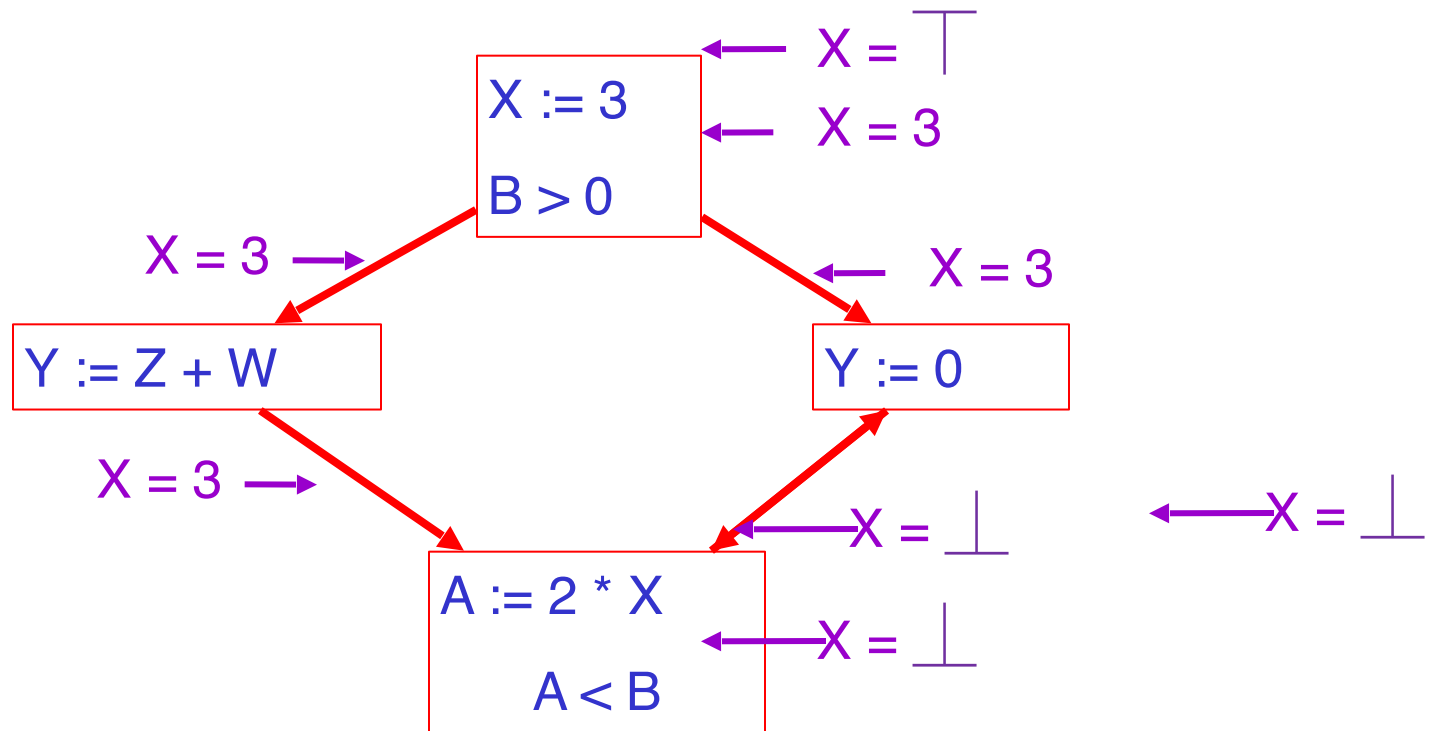
Discussion

- Consider the statement $Y := 0$
- To compute whether X is constant at this point, we need to know whether X is constant at the two predecessors
 - $X := 3$
 - $A := 2 * X$
- But info for $A := 2 * X$ depends on its predecessors, including $Y := 0$!

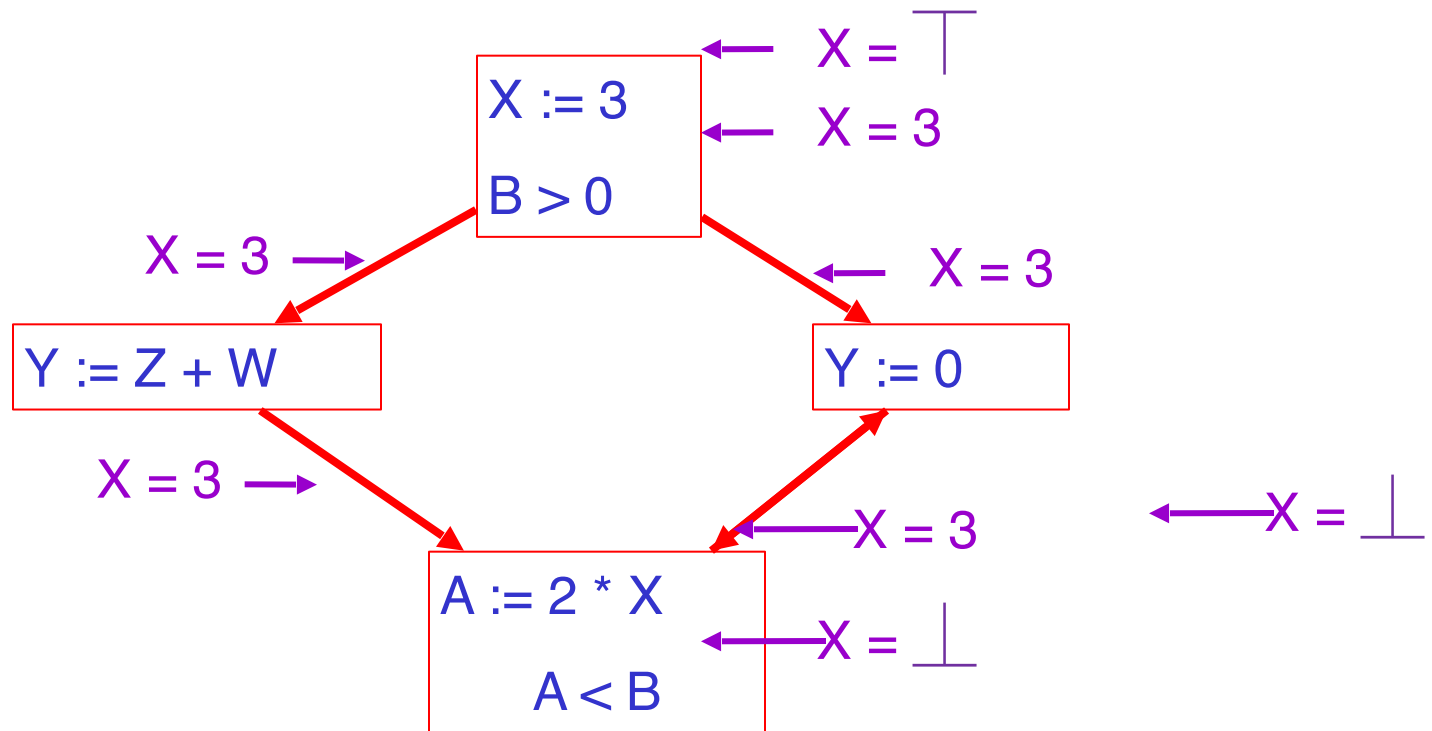
The Value **Z** (Cont.)

- Because of cycles, all points must have values at all times
- Intuitively, assigning some initial value allows the analysis to break cycles
- The initial value \perp means “So far as we know so far, control never reaches this point”

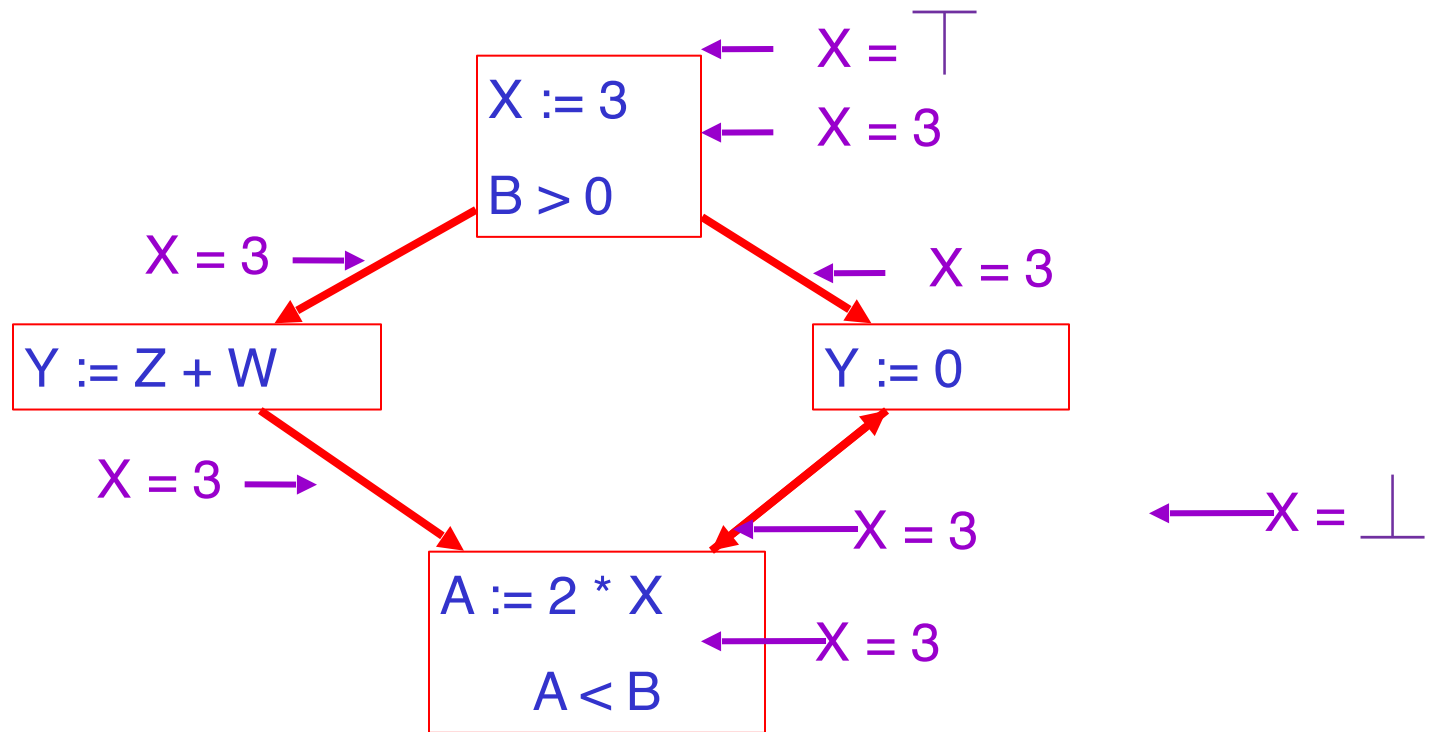
Example



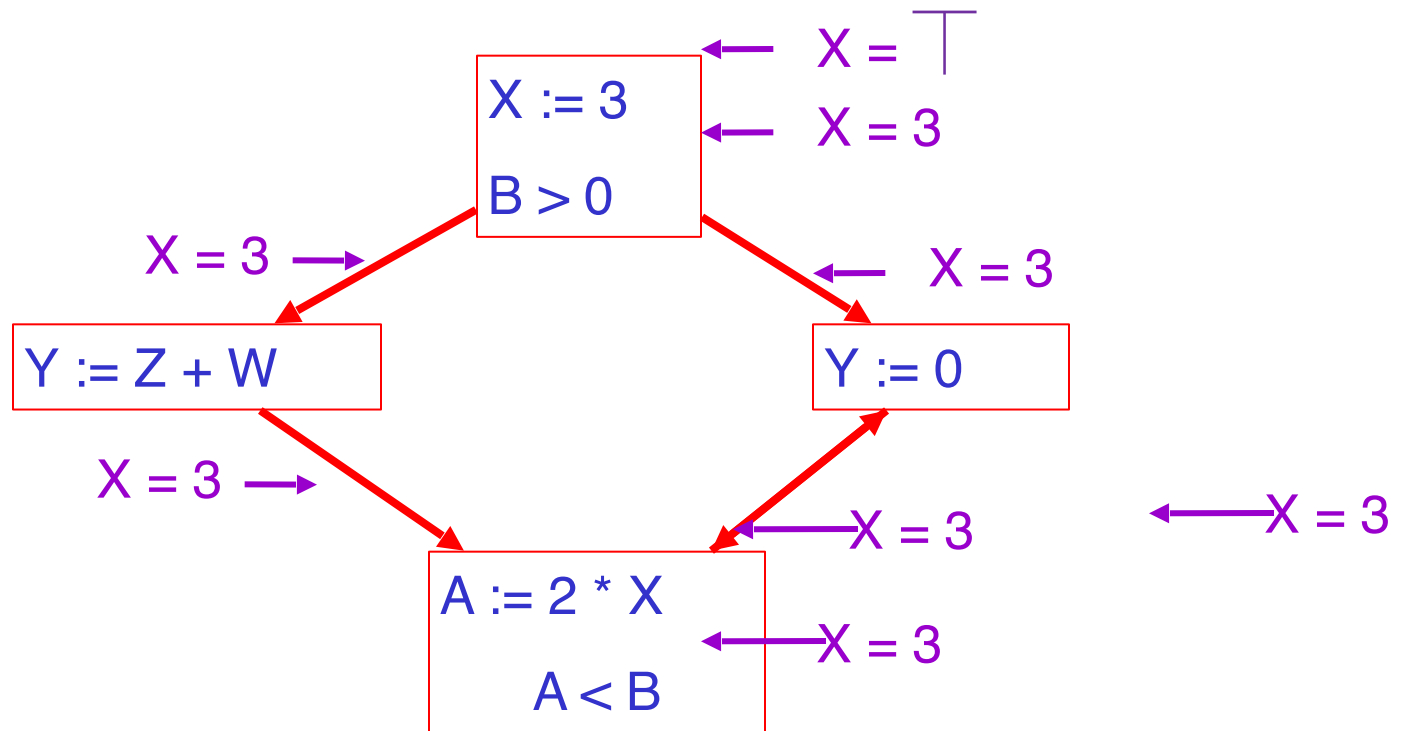
Example



Example



Example

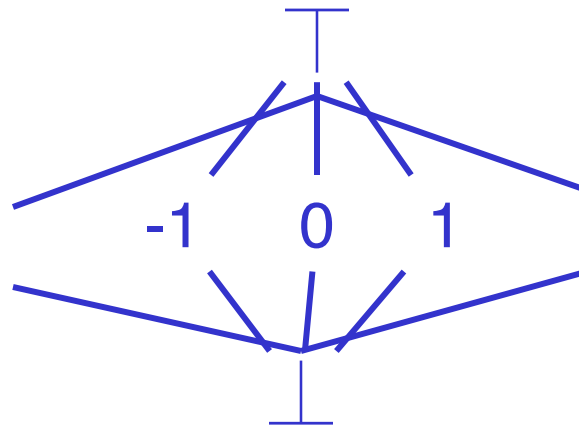


Orderings

- We can simplify the presentation of the analysis by ordering the values

$$\perp < c < \top$$

- Drawing a picture with “lower” values drawn lower, we get



Orderings (Cont.)

- \top is the greatest value, \perp is the least
 - All constants are in between and incomparable
- Let lub be the least-upper bound in this ordering
- Rules 1-4 can be written using lub:
$$C(s, x, in) = \text{lub} \{ C(p, x, out) \mid p \text{ is a predecessor of } s \}$$

Termination

- Simply saying “repeat until nothing changes” doesn’t guarantee that eventually nothing changes
- The use of lub explains why the algorithm terminates
 - Values start as \perp and only increase
 - \perp can change to a constant, and a constant to \top
 - Thus, $C(s, x, _)$ can change at most twice

Termination (Cont.)

Thus the algorithm is linear in program size

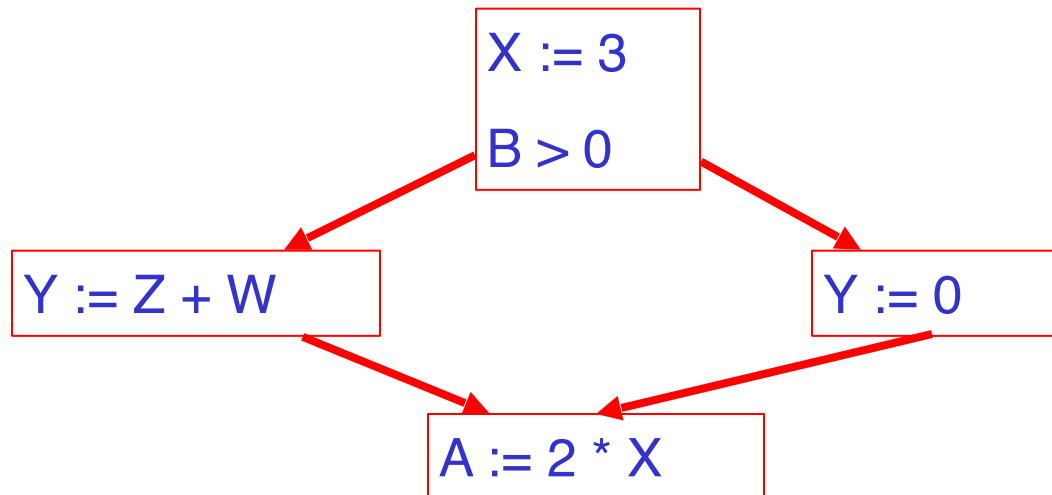
Number of steps =

Number of $C(\dots)$ value computed $\times 2 =$

Number of program statements $\times 4$

Liveness Analysis

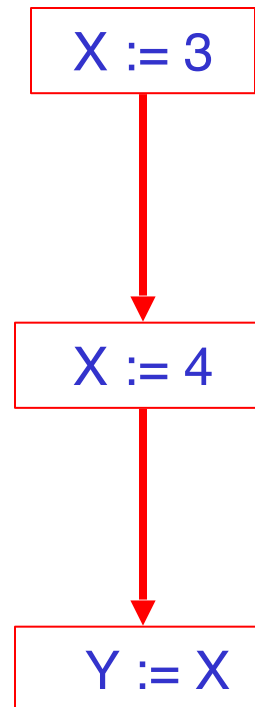
Once constants have been globally propagated, we would like to eliminate dead code



After constant propagation, `X := 3` is dead (assuming `X` not used elsewhere)

Live and Dead

- The first value of x is dead (never used)
- The second value of x is live (may be used)
- Liveness is an important concept



Liveness

A variable x is live at statement s if

- There exists a statement s' that uses x
- There is a path from s to s'
- That path has no intervening assignment to x

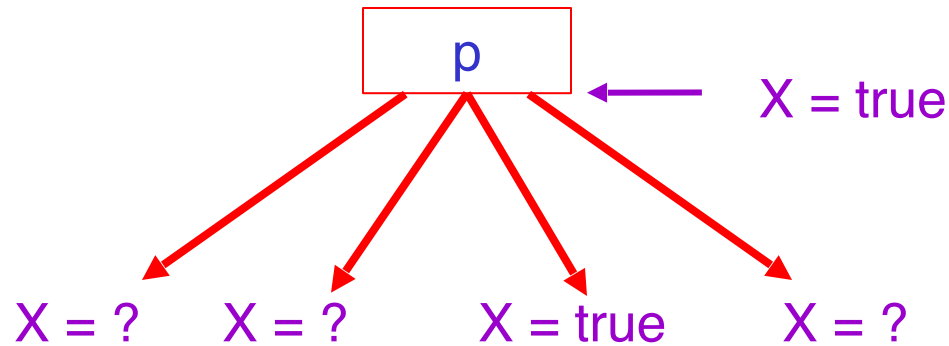
Global Dead Code Elimination

- A statement $x := \dots$ is dead code if x is dead after the assignment
- Dead statements can be deleted from the program
- But we need liveness information first . . .

Computing Liveness

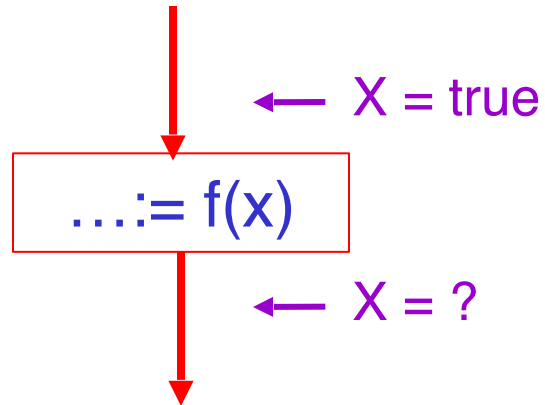
- We can express liveness in terms of information transferred between adjacent statements, just as in copy propagation
- Liveness is simpler than constant propagation, since it is a boolean property (true or false)

Liveness Rule 1



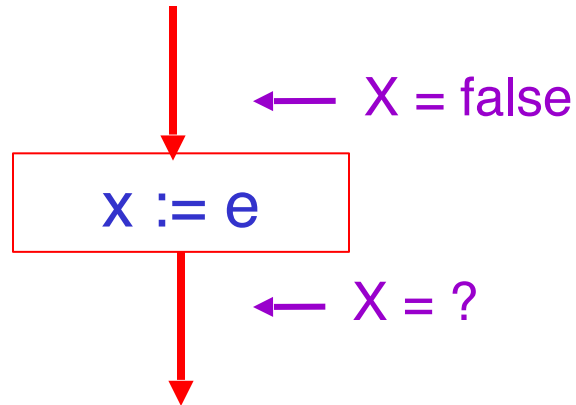
$$L(p, x, \text{out}) = \vee \{ L(s, x, \text{in}) \mid s \text{ a successor of } p \}$$

Liveness Rule 2



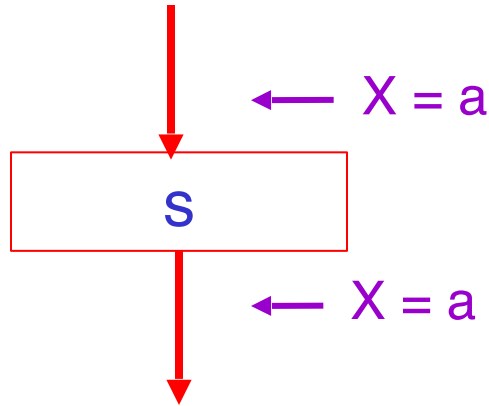
$L(s, x, \text{in}) = \text{true}$ if s refers to x on the rhs

Liveness Rule 3



$L(x := e, x, \text{in}) = \text{false}$ if e does not refer to x

Liveness Rule 4



$L(s, x, \text{in}) = L(s, x, \text{out})$ if s does not refer to x

Algorithm

1. Let all $L(\dots) = \text{false}$ initially
2. Repeat until all statements s satisfy rules 1-4
Pick s where one of 1-4 does not hold and update using the appropriate rule

Termination

- A value can change from **false** to **true**, but not the other way around
- Each value can change only once, so termination is guaranteed
- Once the analysis is computed, it is simple to eliminate dead code

Forward vs. Backward Analysis

We've seen two kinds of analysis:

Constant propagation is a forwards analysis:
information is pushed from inputs to outputs

Liveness is a backwards analysis: information is
pushed from outputs back towards inputs

Analysis

- There are many other global flow analyses
- Most can be classified as either forward or backward
- Most also follow the methodology of local rules relating information between adjacent program points