Global Optimizations

Martin Kellogg

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  - This issue has been fixed as of this morning
  - Discuss with class: do y'all need another extension on PA3? I am open to giving one.
    - First rule of compilers: semantics >>> optimization

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    - First rule of compilers: semantics >>> optimization
- I will be out of town on Wednesday 4/30 (for ICSE)
  - I've therefore rearranged the calendar a bit
  - My PhD student Erfan Arvan will give a lecture on exceptions

Agenda

- Super-local Value Numbering
- Other regional optimizations
- Intro to global optimizations
- Dataflow analysis basics

Review: Local Value Numbering

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- LVN allows us to trivially identify **redundant computations**
  - it's straightforward to extend it to other local optimizations, like constant folding

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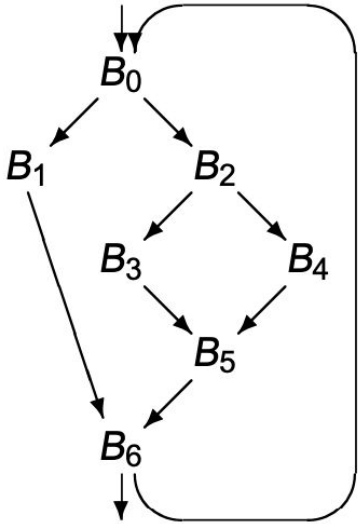
  - Most local optimizations can operate on EBBs with small modifications
- Formally, an EBB is a **maximal** collection of basic blocks with unique entry and exit blocks

Extended Basic Blocks: Example



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B_1: $p_0 \leftarrow c_0 + d_0$
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B_5: $e_2 \leftarrow \phi(e_0, e_1)$
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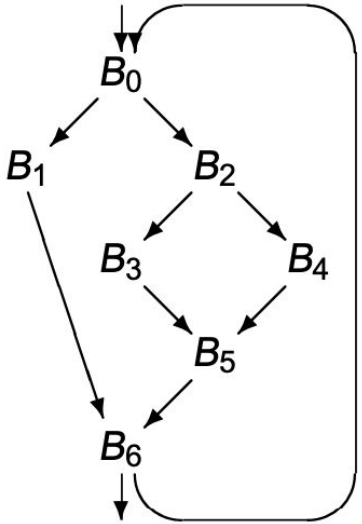
(don’t worry about the details)

Super-local Value Numbering



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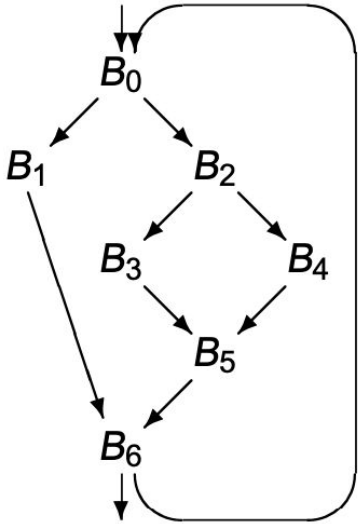

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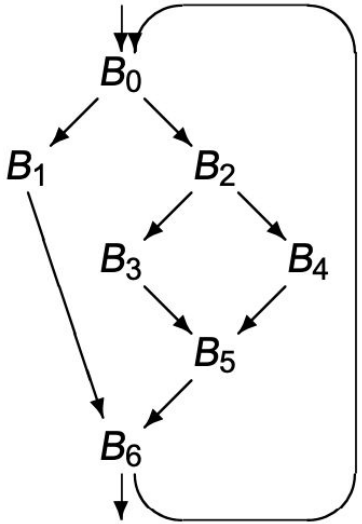

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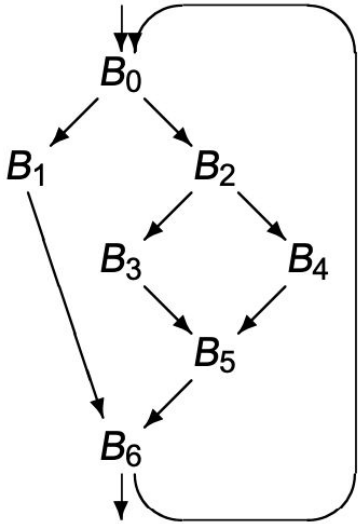

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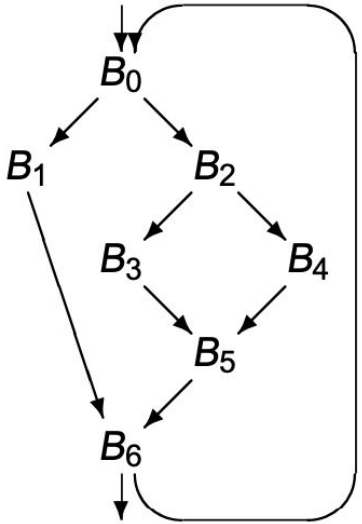

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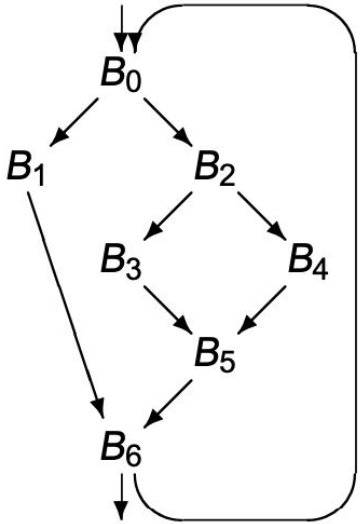

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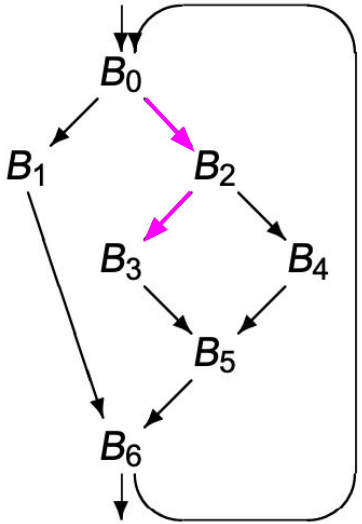
- Any block with multiple predecessors, such as B_5, can use a fresh hashtable

S-LVN: Example



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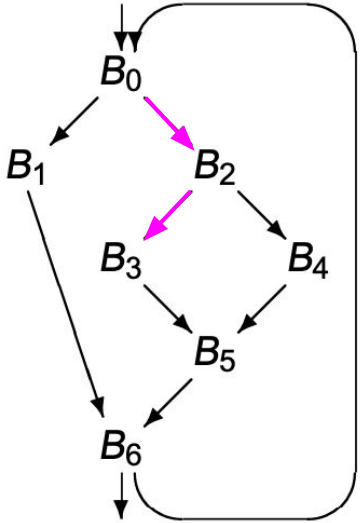

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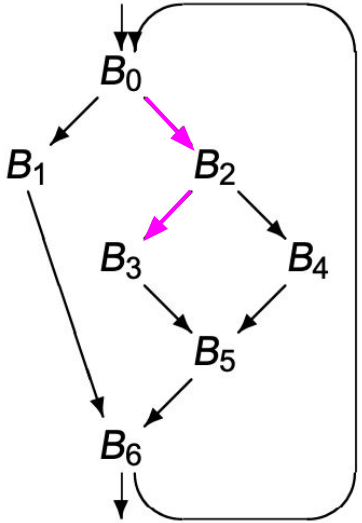

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LVN can discover this redundancy on its own…

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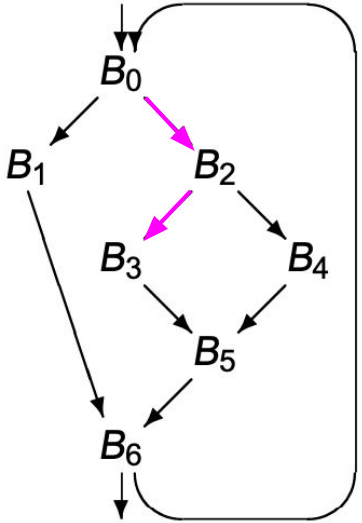

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...but we need S-LVN to discover these two!

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For more details on this algorithm, see the book.

Other Regional Optimizations

- Loop unrolling
- Code motion
- Loop induction variable elimination

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- Loop unrolling changes the **ratio** of arithmetic to memory operations in the loop

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Whether or not to unroll a loop often depends on these factors, so there is **no one-size-fits-all algorithm** for deciding whether to unroll

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- Benefit: avoids **redundant computation** each time around the loop

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> ***Strength reduction*** means replacing expensive operations with equivalent but less expensive operations
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> - e.g., `x*2` -> `x+x`

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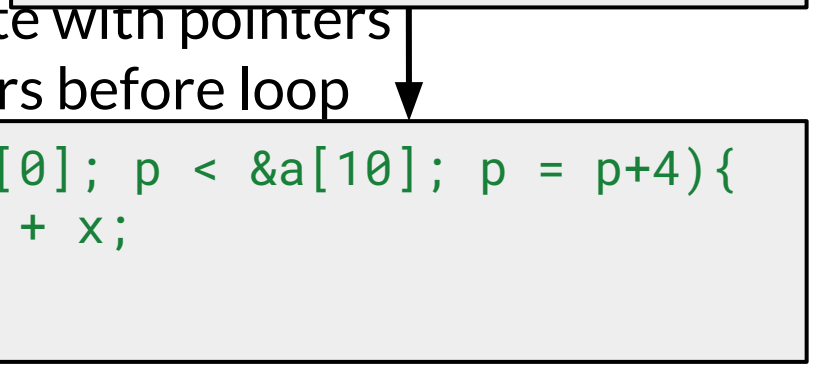

```
for (p = &a[0]; p < &a[10]; p = p+4){
    *p = *p + x;
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  - This means that they are inherently **more risky** than their local cousins
- Nearly all local optimizations can be extended to work at the regional level

Summary: Regional Optimizations

- Regional optimizations offer **more opportunities** than local optimizations
- Generally operate on **extended basic blocks** with one entry/exit
  - commonly, the **body of a loop**
- Benefits of a regional optimization often depend on **indirect effects**, such as spatial locality
  - This means that they are inherently **more risky** than their local cousins
- Nearly all local optimizations can be extended to work at the regional level
  - Which you want to use is up to you!

Trivia Break: CS + Pop Culture

This American has been a professor of both cognitive science and computer scientist, though his PhD (from the University of Oregon) is actually in Physics. His dissertation work was one of the early examples of modern scientific data visualization. However, he is most famous not for his academic work but for his nonfiction writing: his 2007 book *I Am a Strange Loop* won the Los Angeles Times Book Prize for Science and Technology, and his 1979 book *Gödel, Escher, Bach: An Eternal Golden Braid* won the Pulitzer Prize for general nonfiction and a National Book Award (at that time called The American Book Award) for Science.

Trivia Break: Technology and Business

This Seattle-based ecommerce company's first order from a non-employee was a copy of Douglas Hofstadter's *Fluid Concepts*, on April 3, 1995. The company survived the dot-com crash in the early 2000s and went on to become one of the world's largest companies, with a market capitalization of more than 1.8 trillion USD. Internally, its corporate culture is focused on the concept of a "flywheel" between different parts of the business: that is, that growth in one part should encourage growth in other parts, creating positive feedback loops.

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  - These analyses have a lot in common with abstract interpretation, which we covered earlier in the course
  - Like an abstract interpretation, flow analyses are built out of **simple transfer functions** and can work forwards or backwards.

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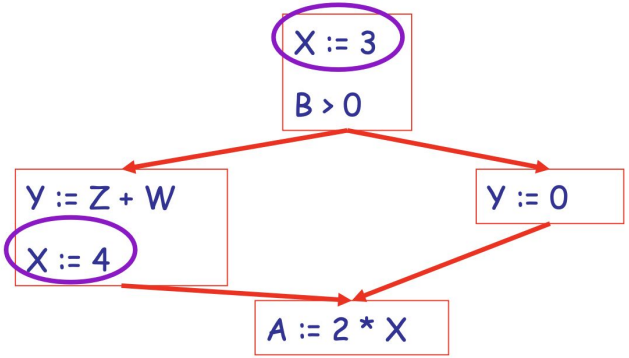

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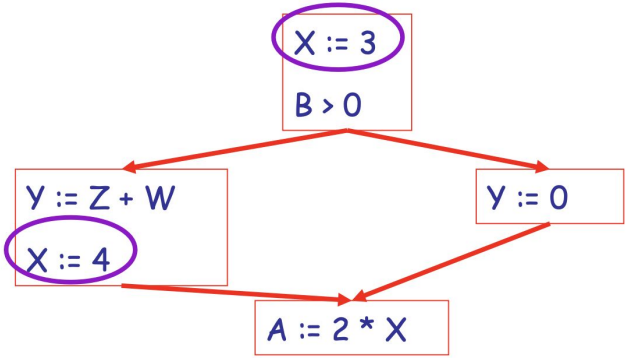

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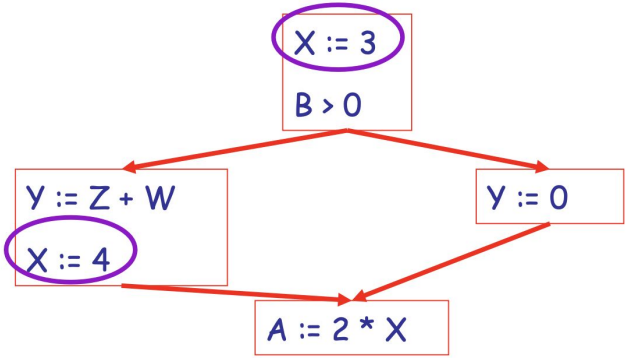

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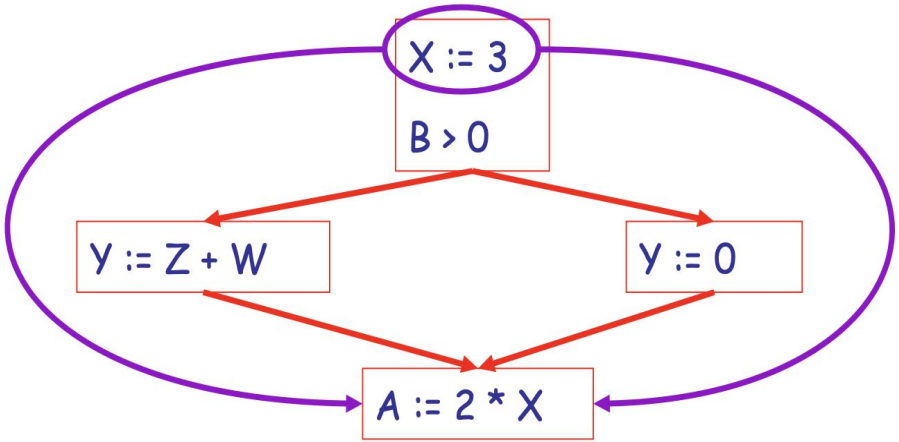

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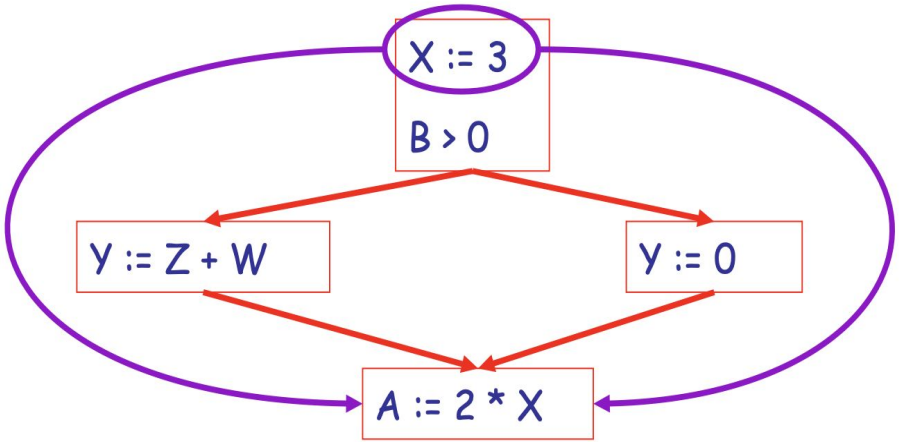

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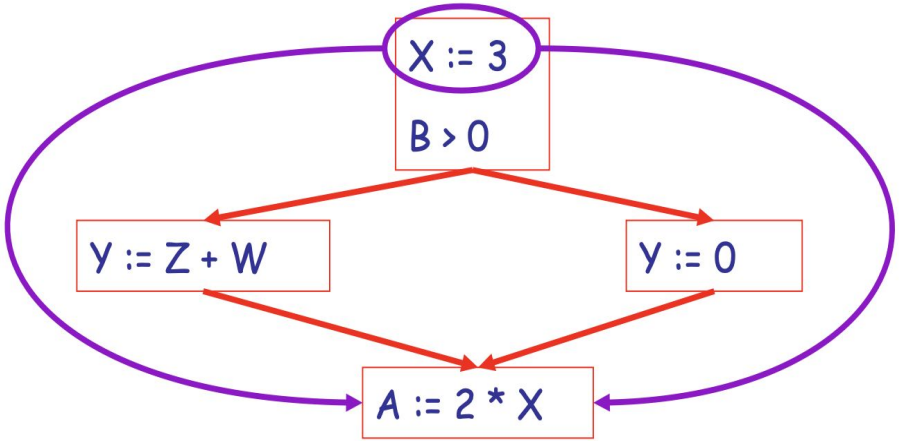

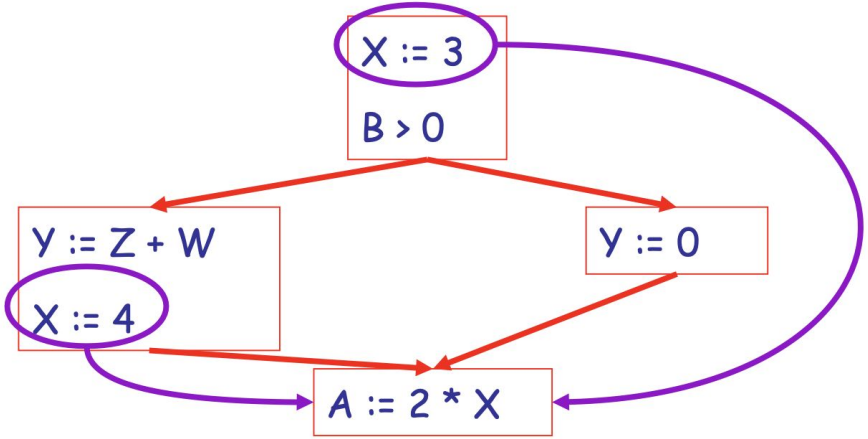

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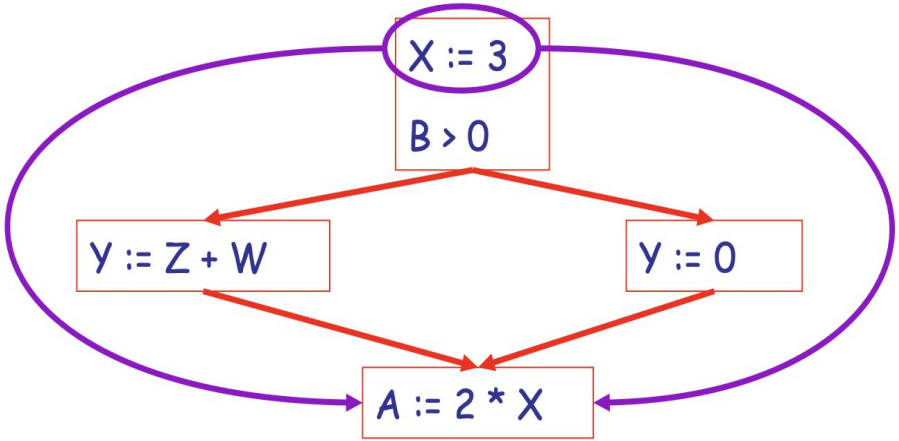

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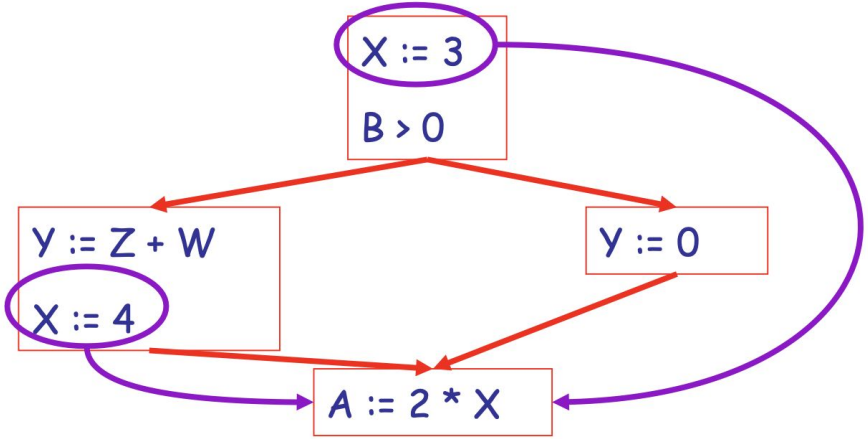

not ok to constant fold:
one path has X := 3, the other has X := 4

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- ***Dataflow analysis*** is a common global analysis
  - called “dataflow” analysis because it propagates information about how data moves through the control-flow graph

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> **"interesting"** in this context means "not trivial", i.e., not uniformly true or false for all programs

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Rice's theorem caveats:

- only applies to **semantic** properties (syntactic properties are decidable)
- "programs" only includes programs **with loops**

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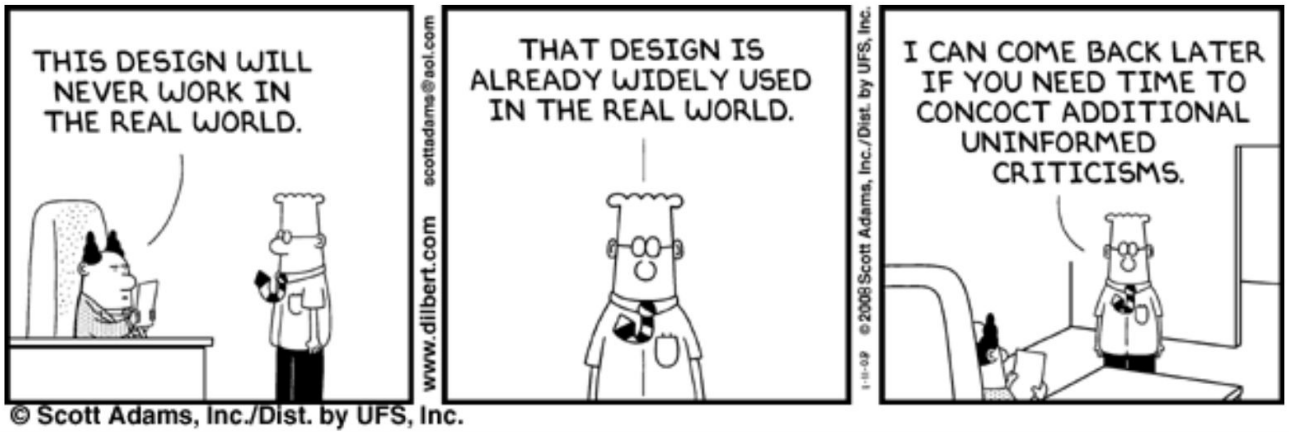

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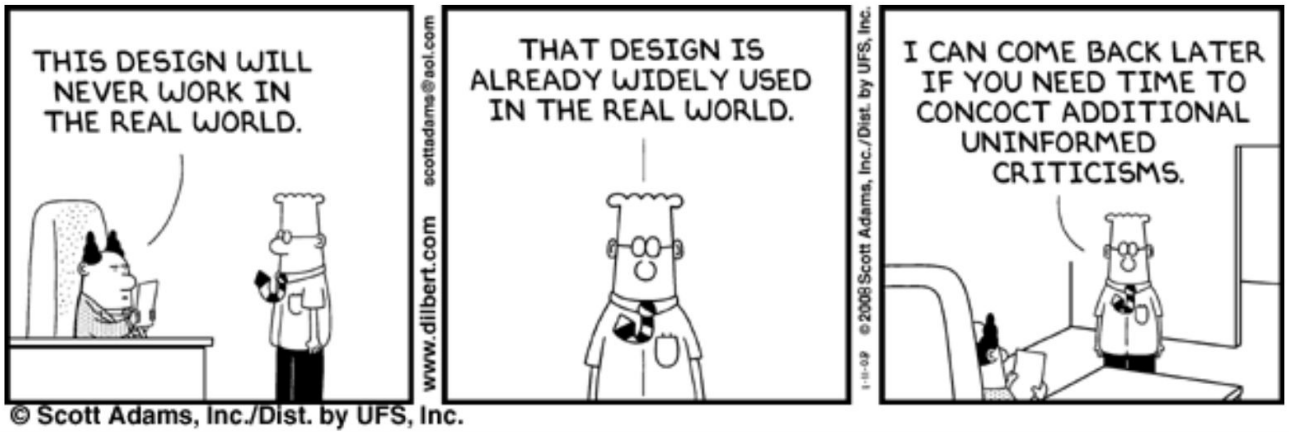

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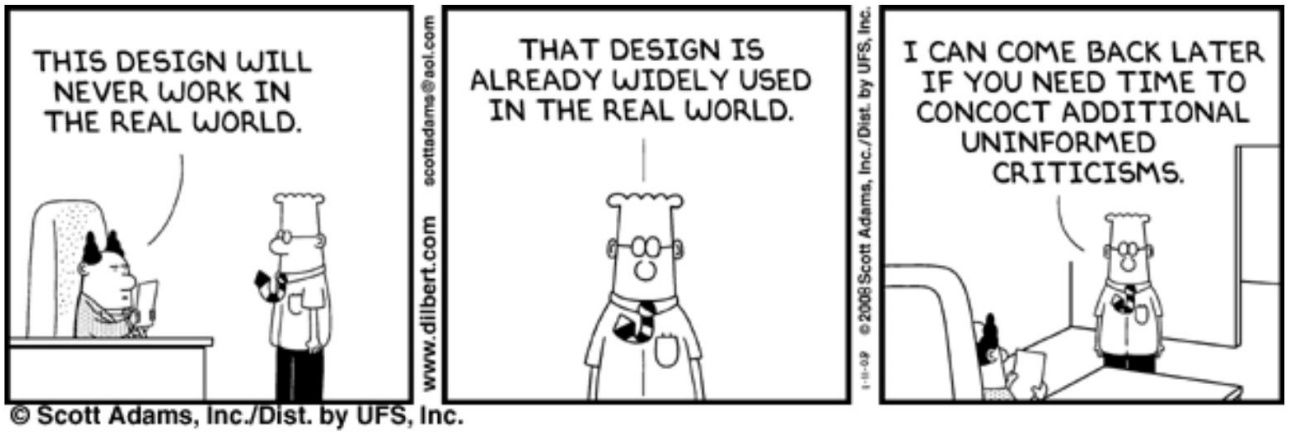

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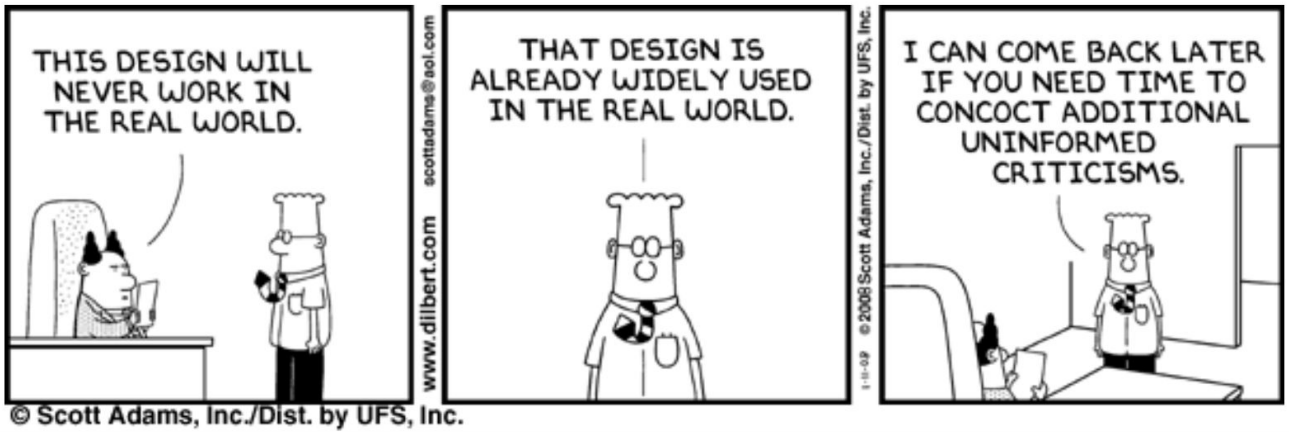

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- A ***sound*** program analysis has no false negatives
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- Our dataflow analyses for enabling optimizations will be sound and conservative
  - i.e., we will **not optimize** when they say "I don't know"

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- Let's consider the case of computing the correctness condition at all program points for a single variable **X**
  - We can easily extend this to other variables later
  - Keep in mind what you know about **abstract interpretation** as we go through this, and look for the similarities
    - there are many!

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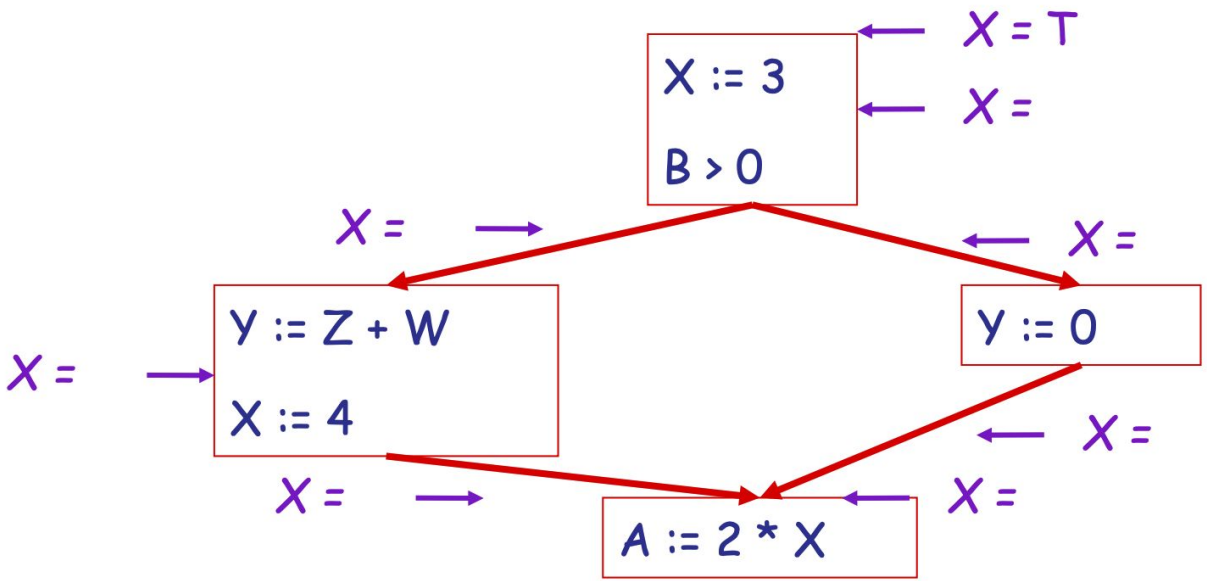
Global Constant Folding: Formalized

Get out a piece of paper. Fill in these blanks:



Recall:
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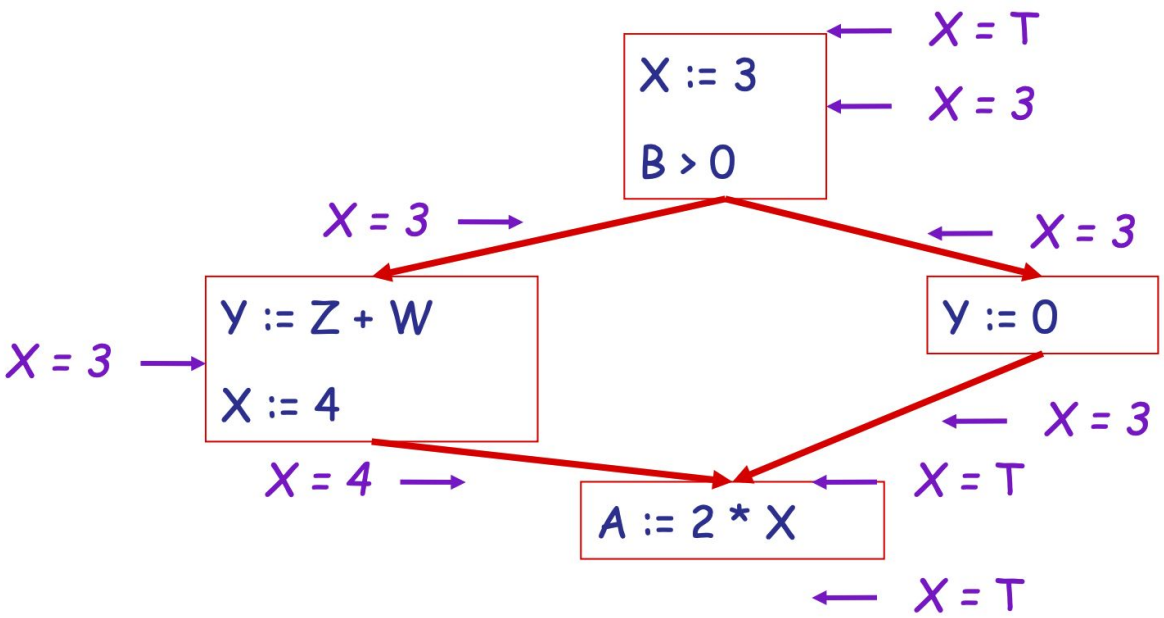

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- But how can an **algorithm** compute *x* = *?*

Key Idea

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

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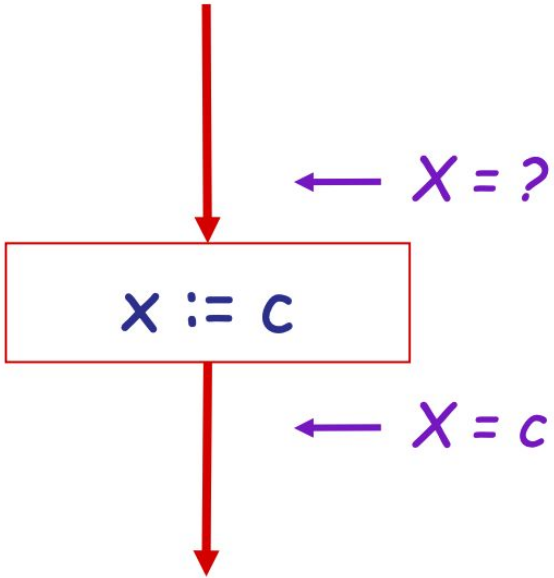
Definition: a ***transfer function*** expresses the relationship between $C_{in}(x, s)$ and $C_{out}(x, s)$

Transfer functions: rule 1

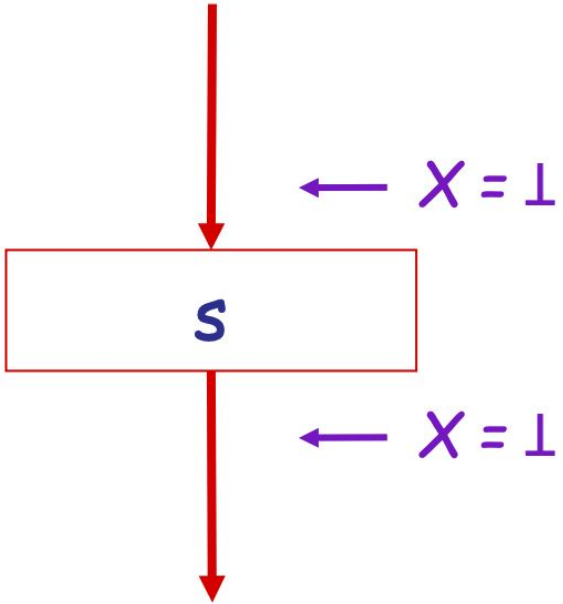


$C_{out}(x, x := c) = c$ if c is a constant

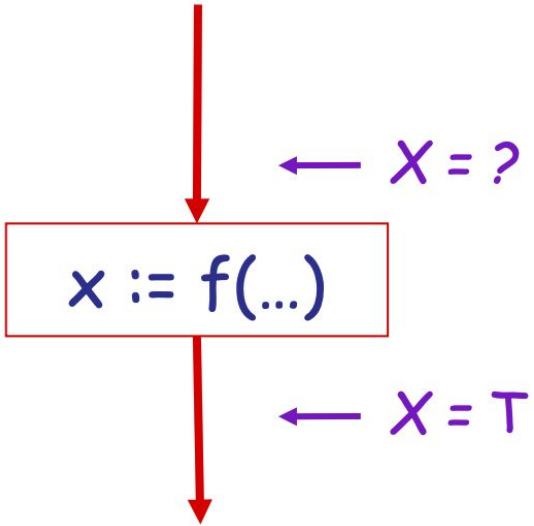
Transfer functions: rule 2

$C_{out}(x, s) = \text{bottom if } C_{in}(x, s) = \text{bottom}$

Recall bottom = “unreachable code”



Transfer functions: rule 3



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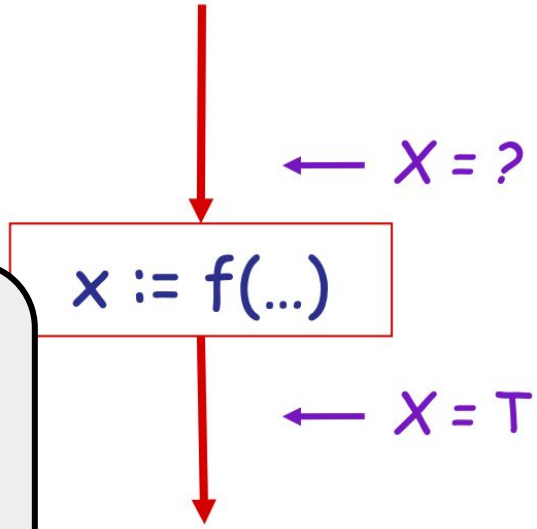
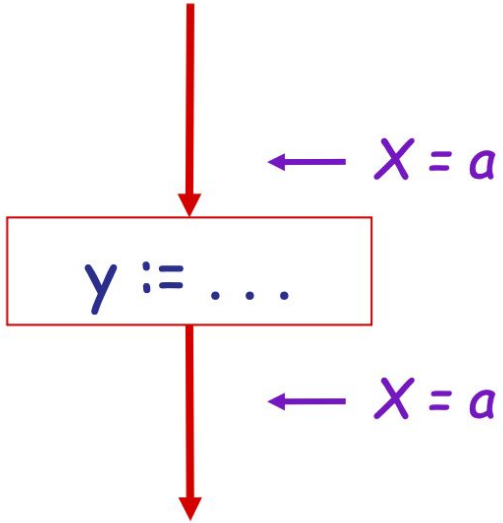


This is a **conservative approximation**! f(...) might always return a constant, but we don't even try!

$C_{out}(x, x := f(...)) = T$

Transfer functions: rule 4



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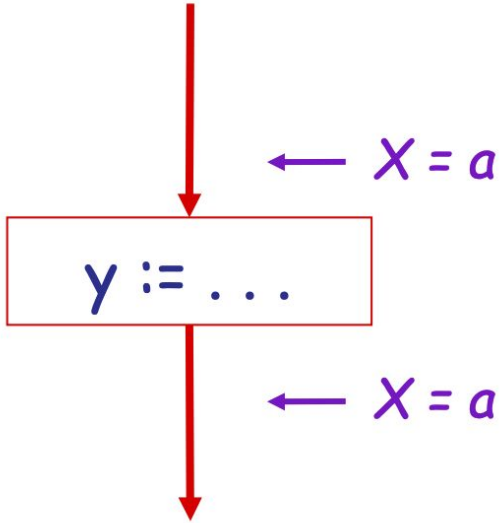

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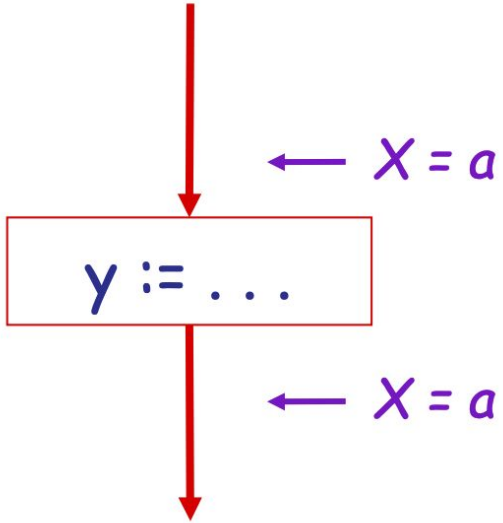

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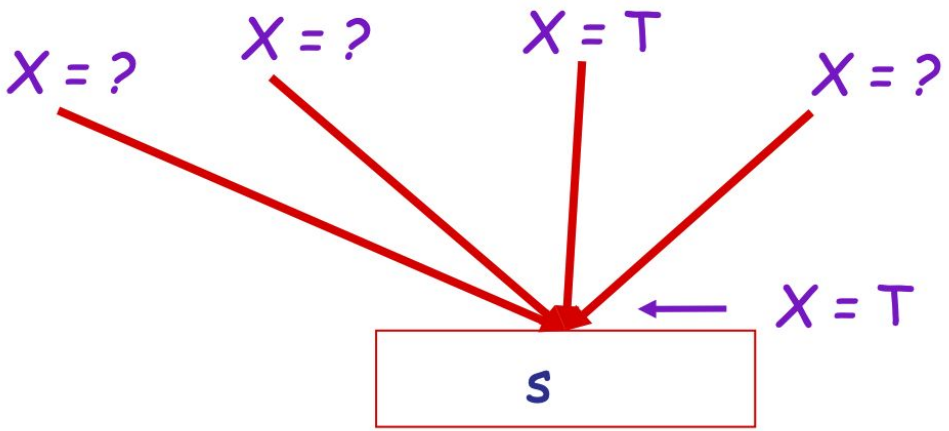
- In the following rules, let statement s have immediate predecessor statements p_1 , …, p_n

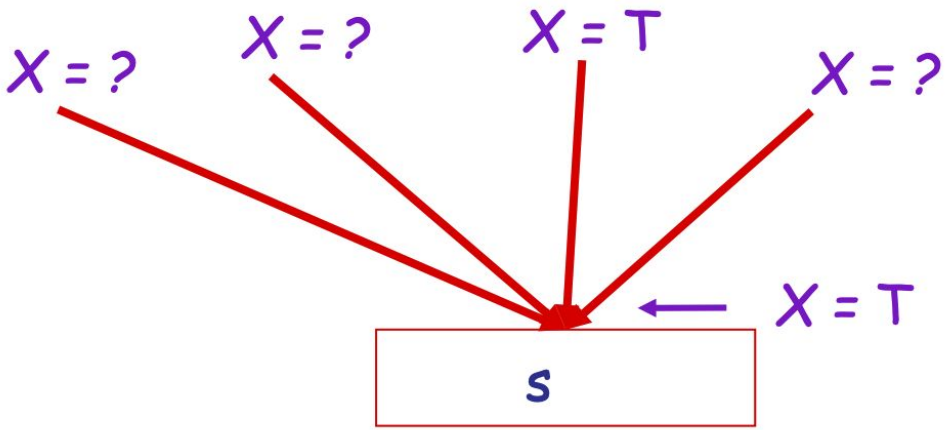
Transfer functions: rule 5



if $C_{out}(x, p_i) = T$ for some i, then $C_{in}(x, s) = T$

Transfer functions: rule 5

If there's **any** path on which we don't know, then we don't know at all



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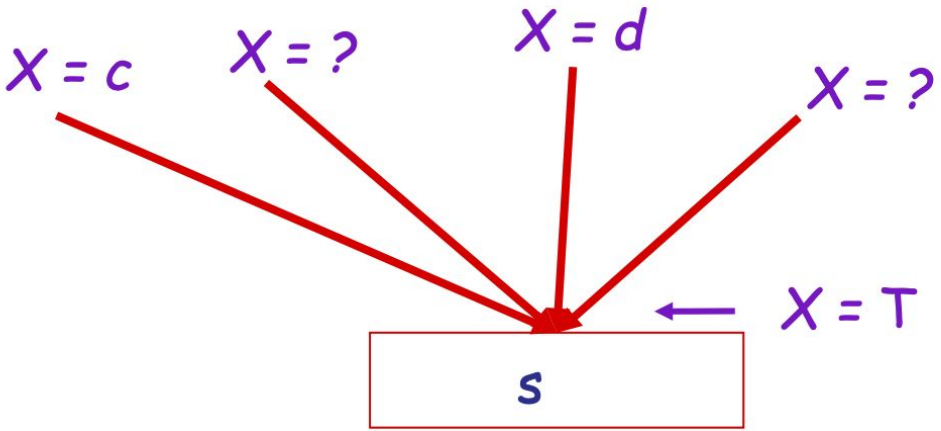
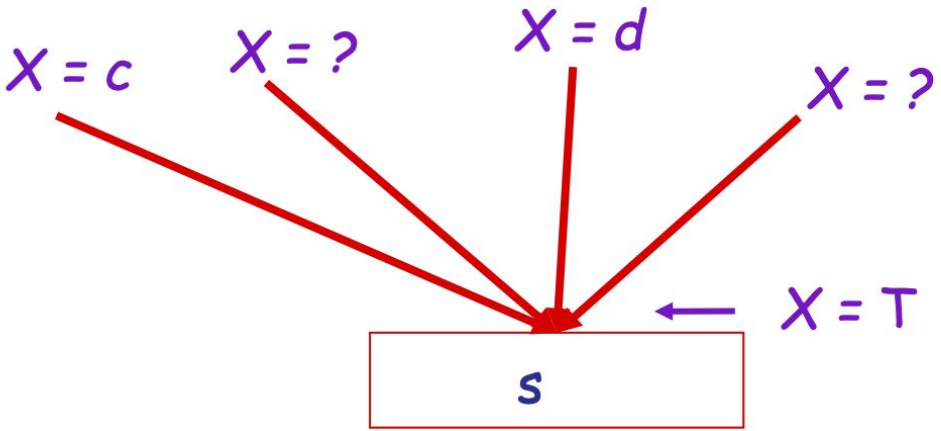
Transfer functions: rule 6



if $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$ then $C_{in}(x, s) = T$

Transfer functions: rule 6



We **don't know** which of the paths a given execution will take (so assume T)

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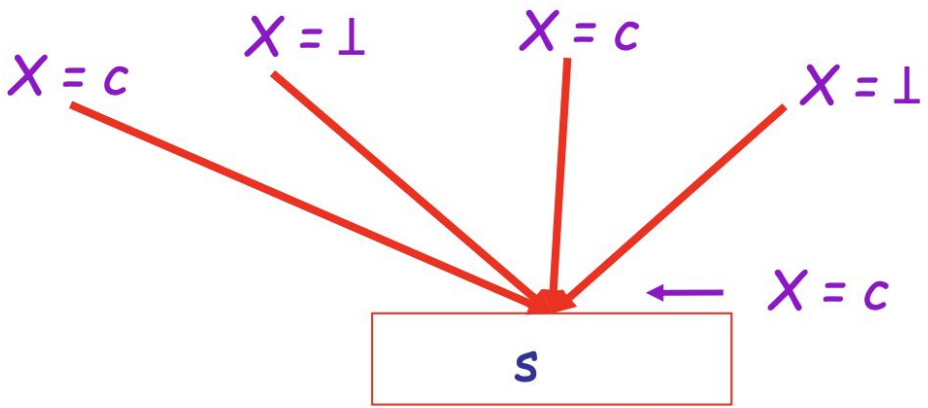
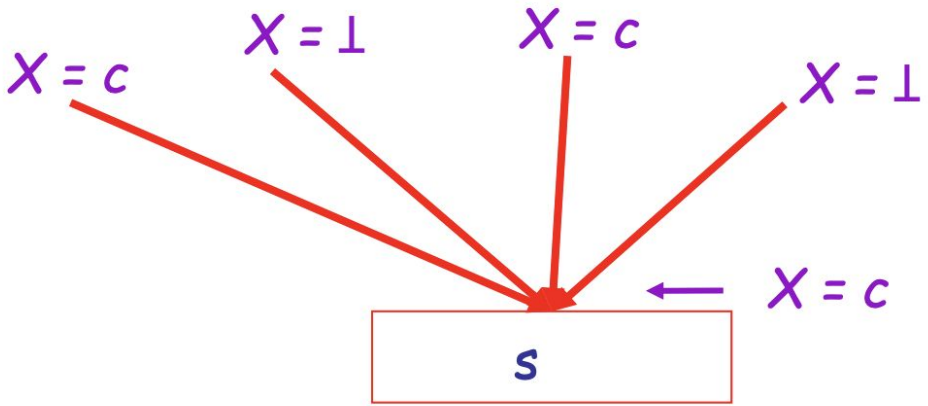
Transfer functions: rule 7



if $C_{out}(x, p_i) = c$ or bottom for all i, then $C_{in}(x, s) = c$

Transfer functions: rule 7

If x has the **same** value (or bottom) on all input edges, it has that value in s



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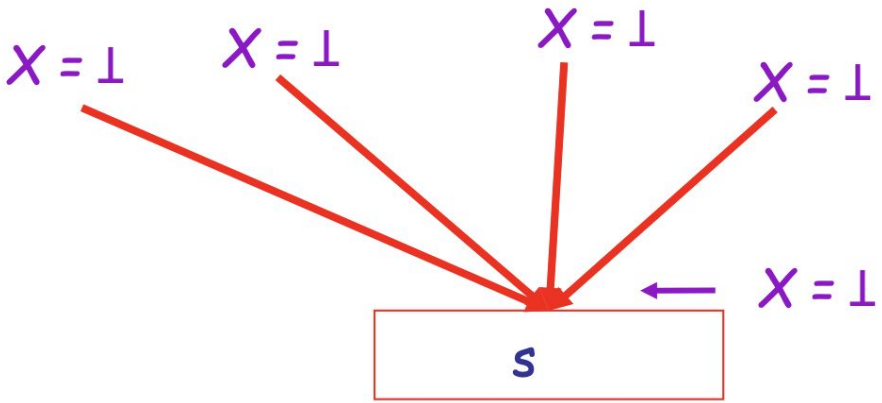

if $C_{out}(x, p_i) = \text{bottom}$ for all i, then $C_{in}(x, s) = \text{bottom}$

The Dataflow Analysis Algorithm

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- For every **entry point** *e* to the procedure, set $C_{in}(x, e) = T$

A static analysis algorithm

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This is a ***fixpoint*** (or ***fixed point***) ***iteration*** algorithm. Such algorithms are characterized by a finite set of rules, which are applied until they "reach fixpoint", which means that applying any rule produces no change.

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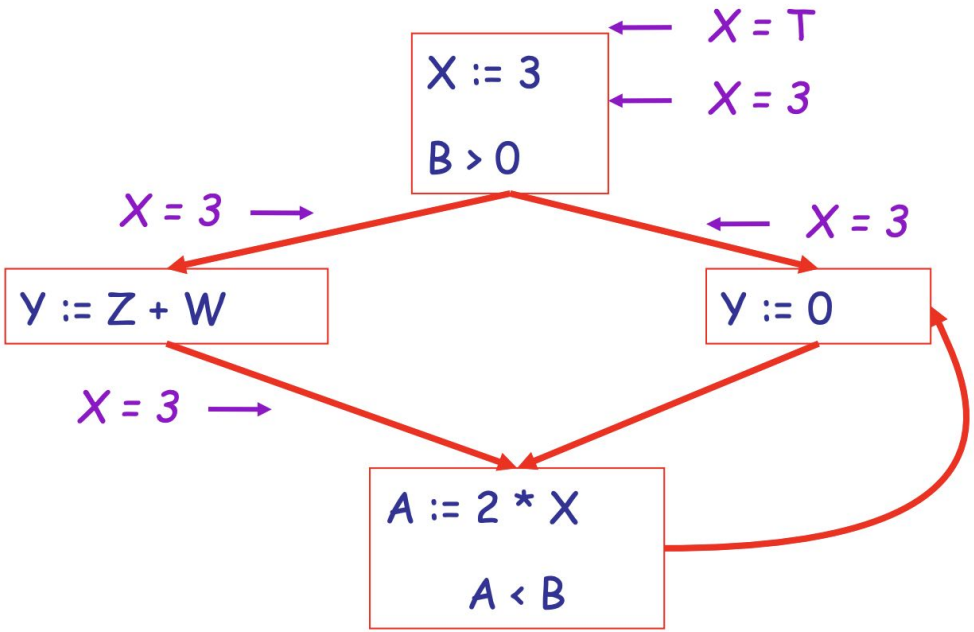
- To understand why we need to set non-entry points to bottom initially, consider a program with a loop:



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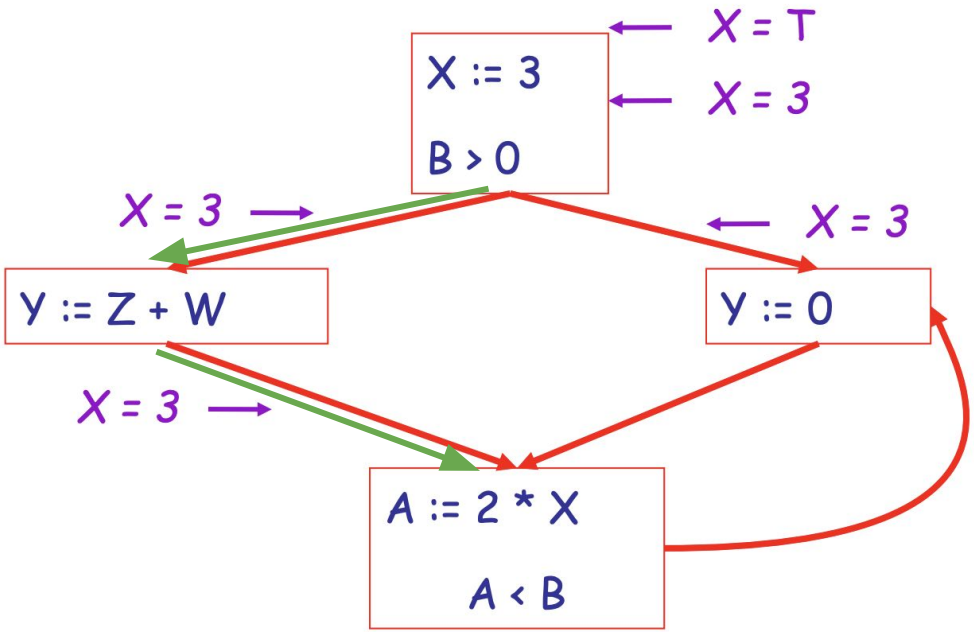

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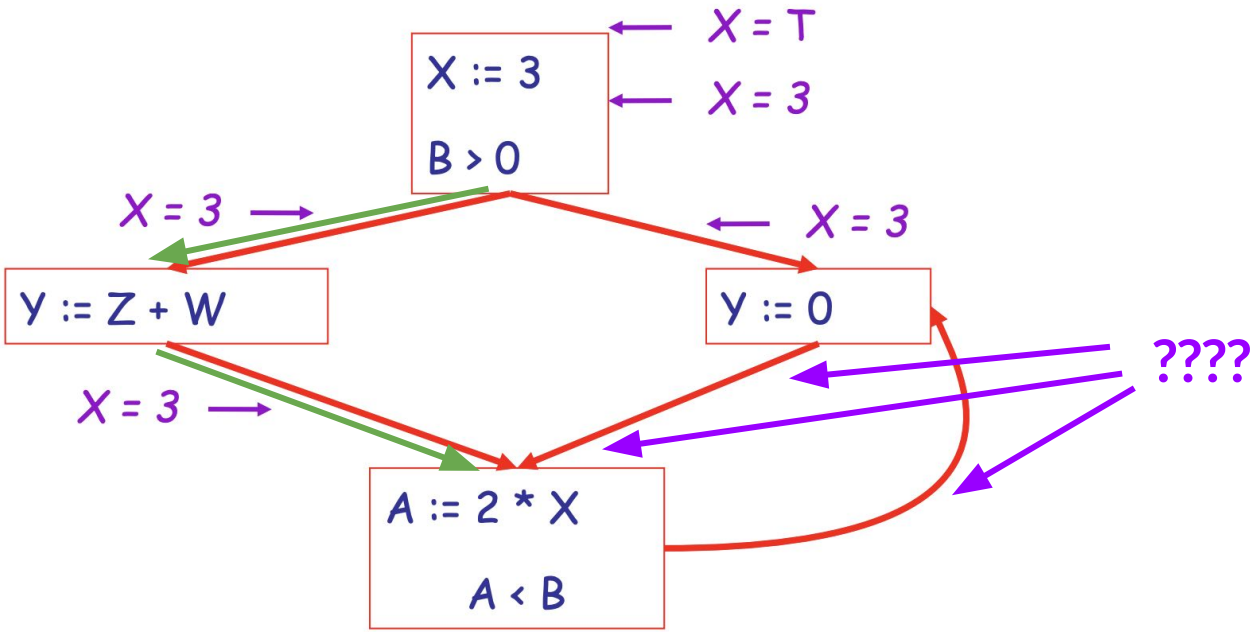

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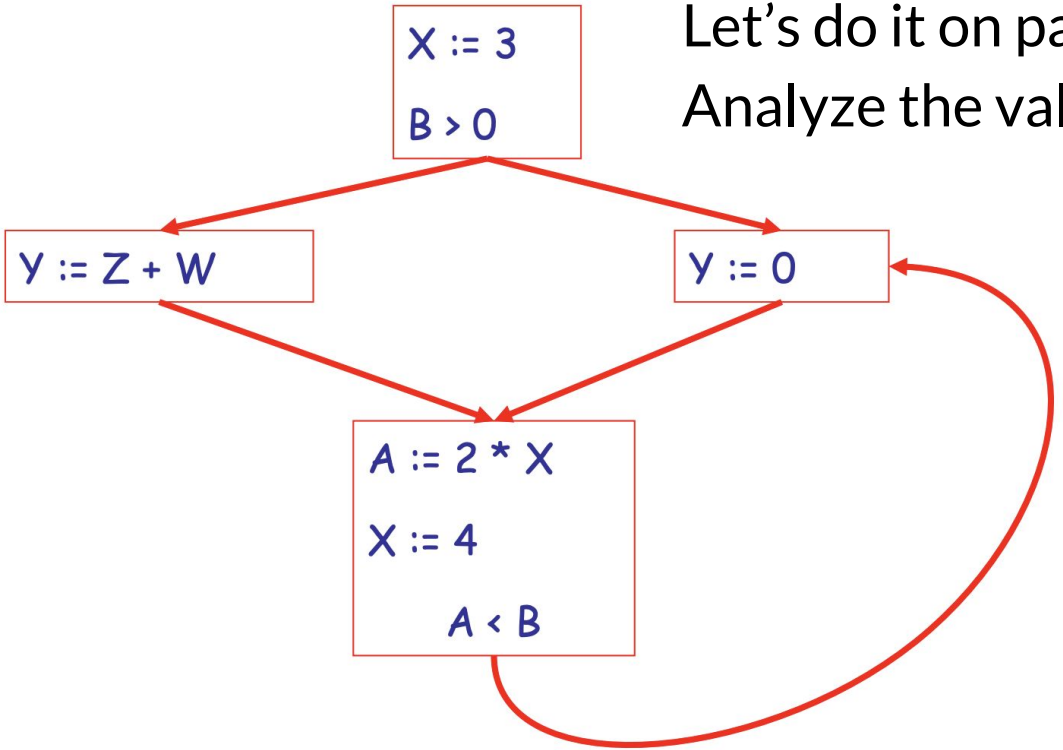
- The initial value bottom means "**we have not yet analyzed control reaching this point**"

Another example: dealing with loops



Let's do it on paper!
Analyze the value of X.

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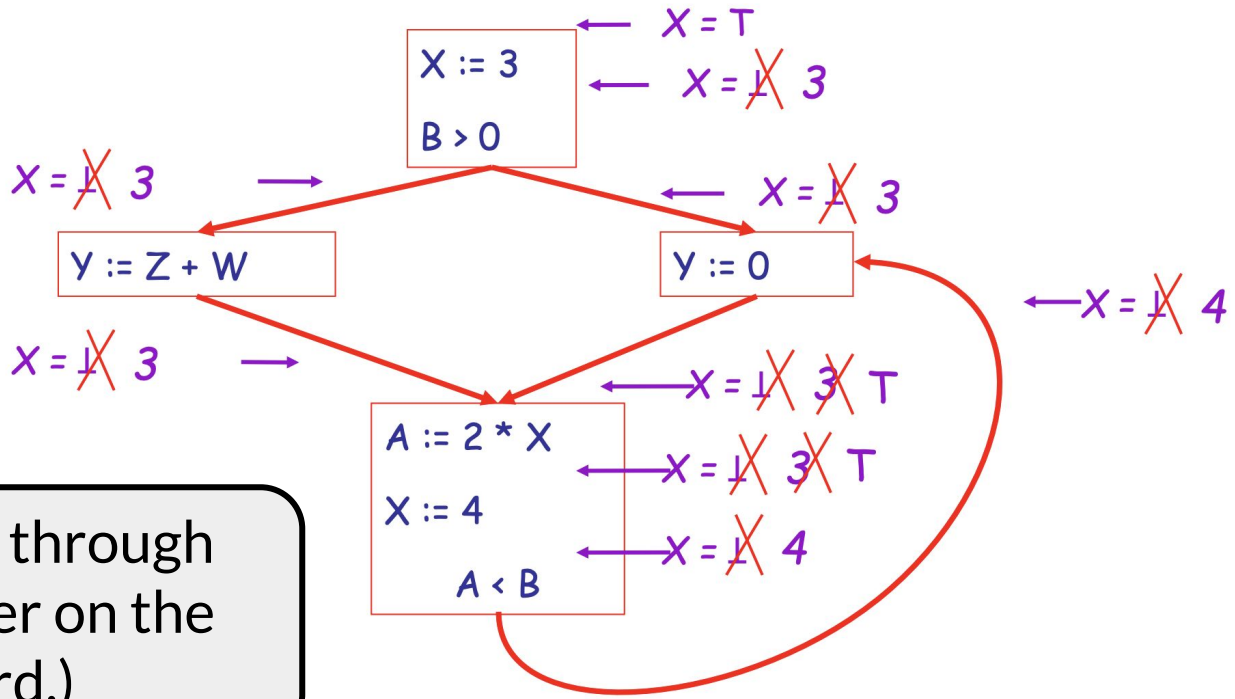

(We went through this answer on the whiteboard.)

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    - but never go back to bottom!
  - Locations whose current value is T never change

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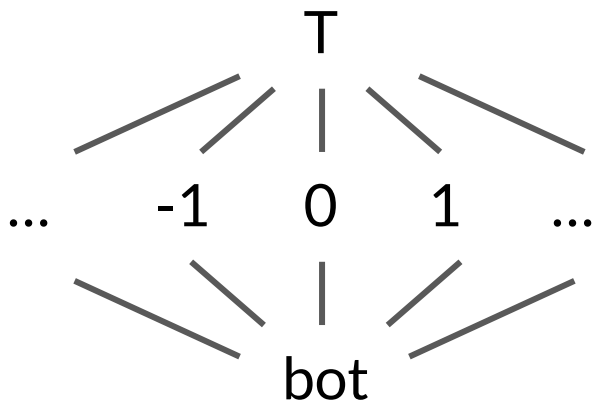
This structure between values is a ***lattice*** (just like in AI!):



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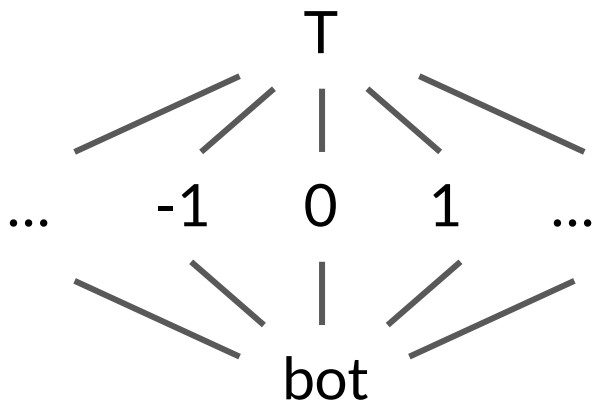

Review of how to read a lattice:

- abstract values **higher** in the lattice are **more general** (e.g., T is true of more things than 0)
- easy to compute ***least upper bound***: it's the lowest common ancestor of two abstract values

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    $C_{in}(x, s) = \text{lub}\{ C_{out}(x, p) \mid p \text{ is a predecessor of } s \}$

Lattices (continued)

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lub is the reason dataflow analysis is an **algorithm**: because lub is monotonic, we only need to analyze each loop **as many times as the lattice is tall**

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- The use of **lub** explains why the algorithm terminates:
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  - bottom can change to a constant, and a constant to T
  - thus, C_(x, s) can change at most **twice** (= lattice height minus one)

Next Time

- More dataflow analysis
  - “liveness analysis” for dead code elimination
- Inter-procedural analyses
  - Inlining, tail call optimization, and more

Course Announcements

- As many of you have noticed, there was an issue with the PA3 autograder that prevented anyone from passing tests 16+
  - This issue has been fixed as of this morning
  - Discuss with class: do y'all need another extension on PA3? I am open to giving one.
    - First rule of compilers: semantics >>> optimization
- I will be out of town on Wednesday 4/30 (for ICSE)
  - I've therefore rearranged the calendar a bit
  - My PhD student Erfan Arvan will give a lecture on exceptions