Static Analysis (1/2)

Martin Kellogg

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Today's agenda:

- Reading Quiz
- Motivations for static analysis
- Basics of dataflow analysis

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Today's goal: discuss other **automated** static analysis techniques that complement testing and code review in a quality assurance process

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This is especially true for certain kinds of hard-to-test-for defects that might not be apparent even if you do exercise them, such as **resource leaks**

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  - API Protocols: device drivers, GUI frameworks
  - Exceptions: arithmetic, library, user-defined
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There are **rules** for doing each of these things **correctly**, and a static analysis can automate those rules.

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- an **abstraction**, in this context, is a **selective representation** of the program that is simpler to analyze
  - **key idea**: the abstraction will have fewer states to explore
    - hopefully, many fewer!

Key ideas in static analysis design

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- Programs **As Data**
  - Programs are just trees, graphs or strings
  - And we know how to analyze and manipulate those (e.g., visit every node in a graph)

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  - ***semantics*** is a fancy word for “meaning”
  - semantics are relevant for properties related to **context** - that is, where the question to be decided depends on the rest of the program

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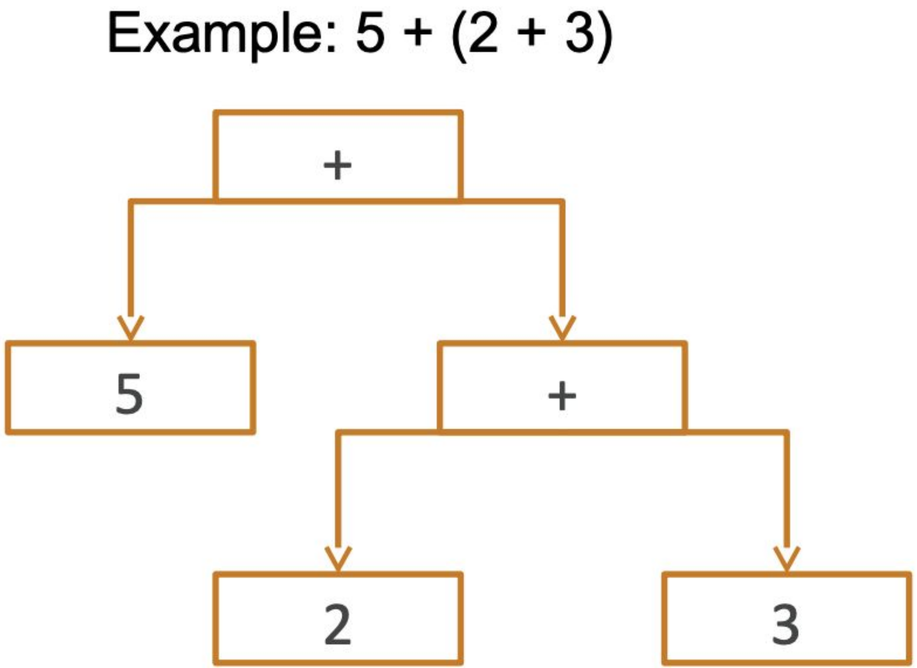
- usually produced by a **parser**
- nodes in the tree represent syntactic constructs
  - parent-child relationships in the AST represent **compound expressions** in the source code (e.g., a "plus node" might have two children: the left and right side expressions)

Treating programs as data: AST example



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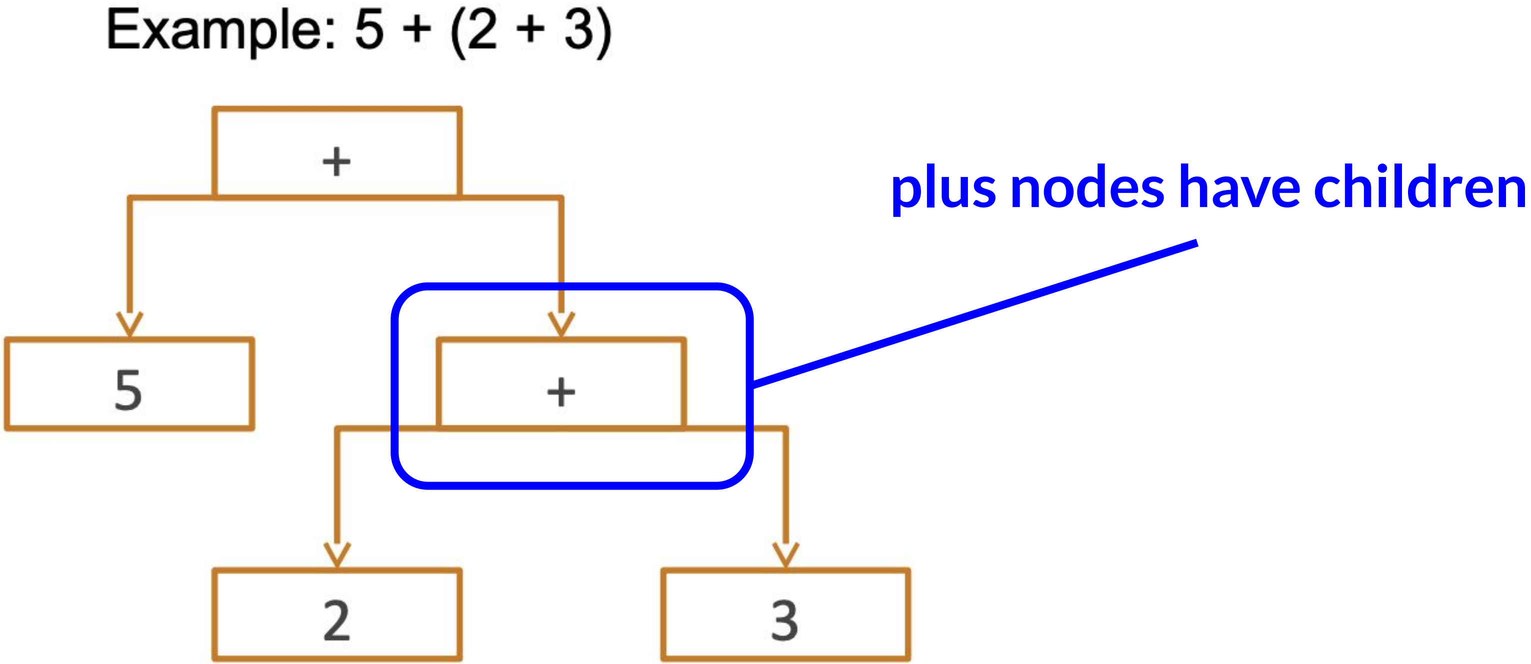

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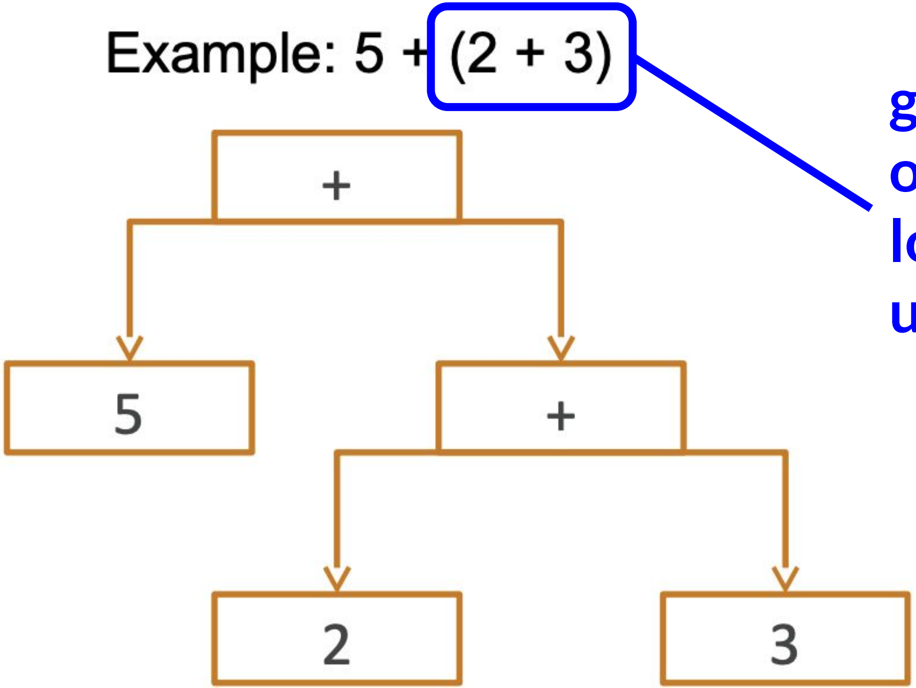

grouping parentheses and other disambiguation is no longer necessary (AST is unambiguous, unlike text)

Treating programs as data: three ways

#3: treat the program **as a graph**

Definition: a ***control flow graph*** (or ***CFG***) is a TODO definition

Treating programs as data: three ways

TODO CFG example

Dataflow analysis

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  - Dataflow analyses take programs as input

Example dataflow analyses

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1. an analysis for finding **definite** null-pointer dereferences

   "Whenever execution reaches *ptr at program location L, ptr will be NULL"

2. an analysis for finding **potential** secure information leaks

   "We read in a secret string at location L, but there is a possible future public use of it"

Definite vs potential

A “**definite**” null-pointer dereference exists if and only the pointer is NULL on **every** program execution

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A "**potential**" secure information leak exists if and only if the secure information leaks on **any** program execution

The use of "**every**" and "**any**" here guarantee that we must reason about **all paths** through the program!

Definite vs potential = false positives vs negatives

Can X **actually** happen?

Did a tool **warn** us about X?	YES	NO
YES	True positive	False positive
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Useful analyses in practice often have **both** false positives and false negatives.

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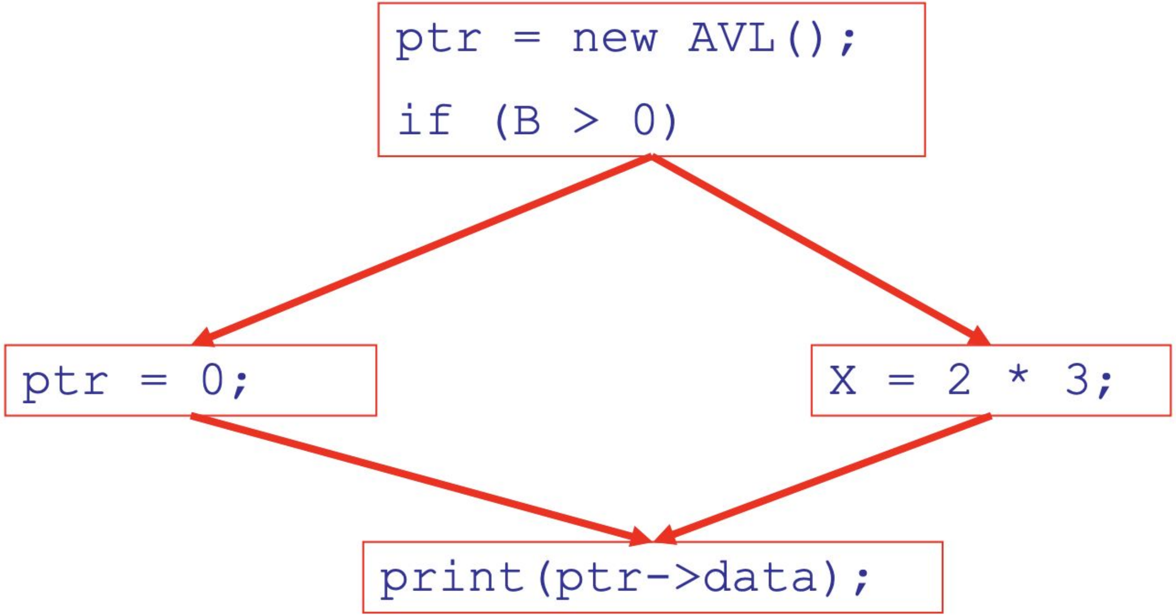

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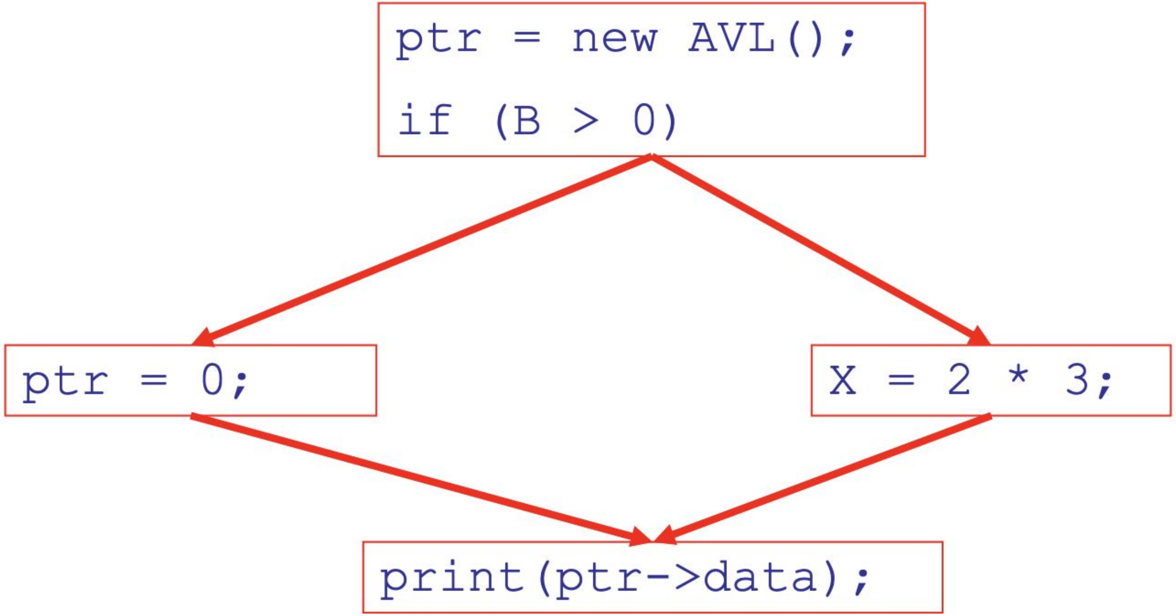

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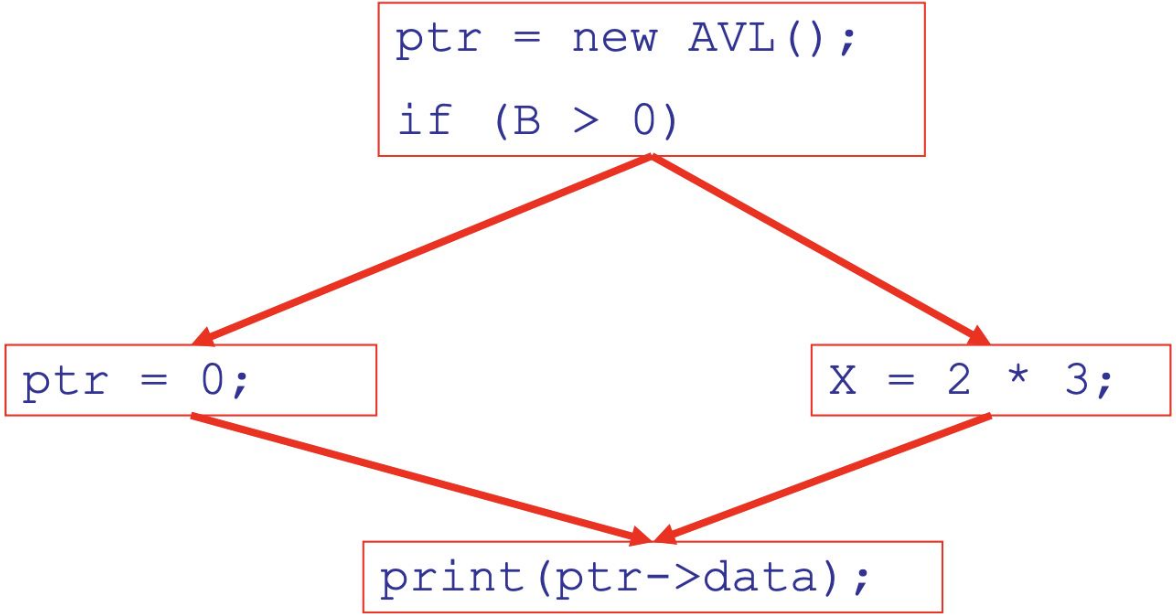

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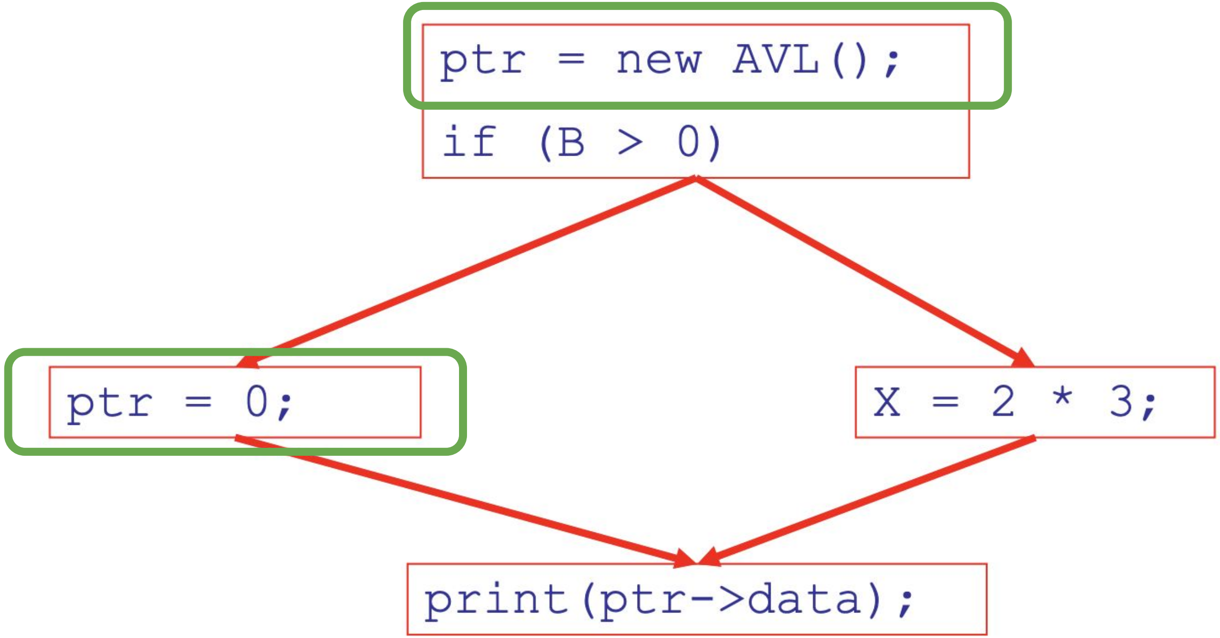

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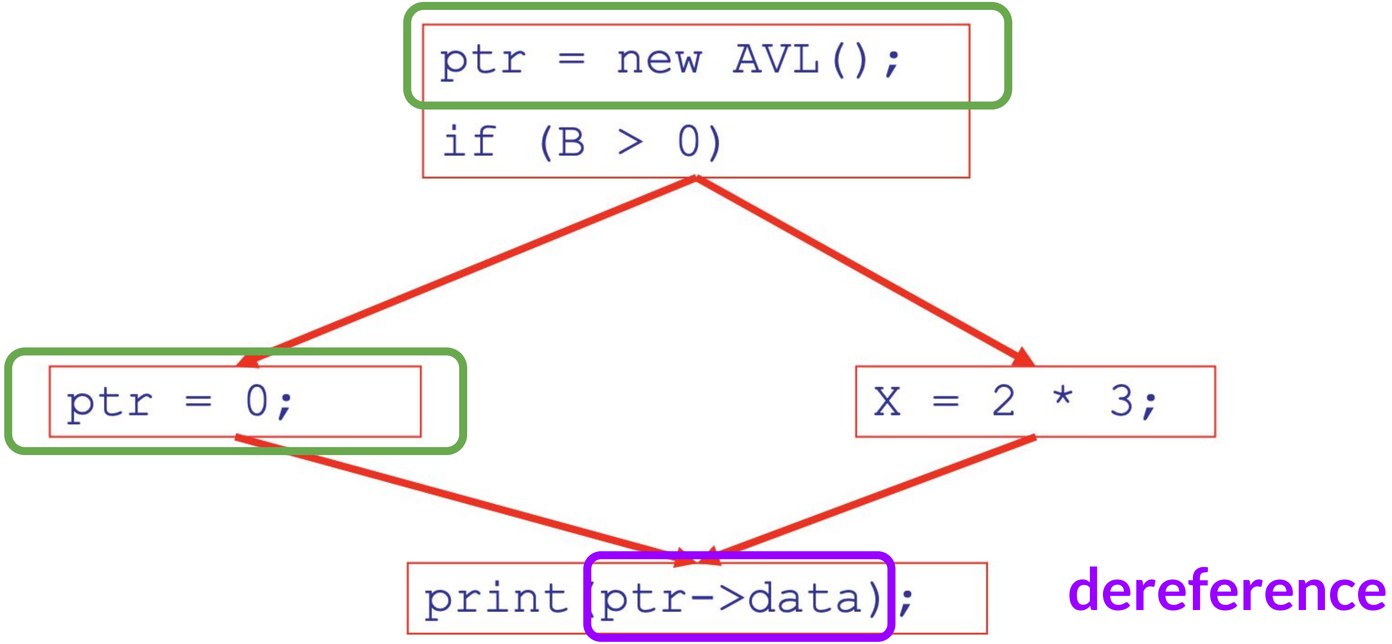

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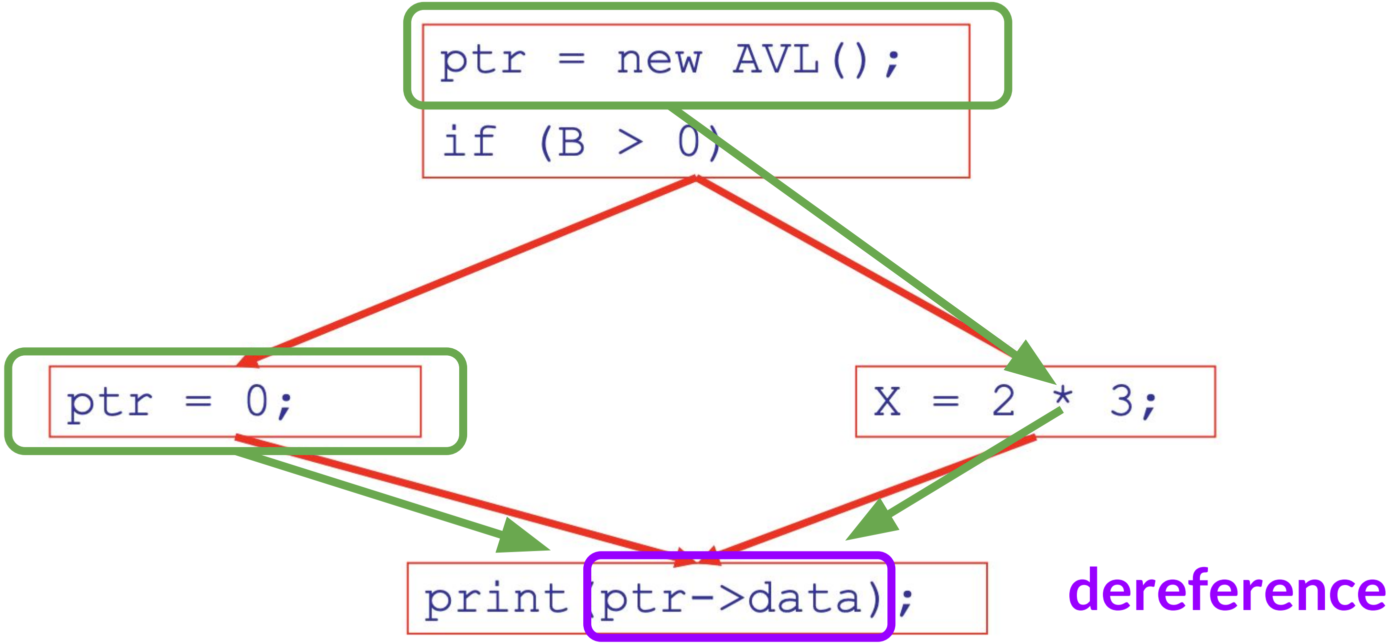

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- Property P is typically **undecidable**

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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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- An algorithm always terminates
  - So a dataflow analysis algorithm must terminate even if the input program loops
- This is one source of imprecision
  - “imprecision” = “not always getting the right answer”
  - Suppose you dereference the null pointer on the 500th iteration but we only analyze 499 iterations

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Definition: a ***sound*** program analysis has no false negatives

- always answers "I don't know" if there is a **potential** bug

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- always answers "I don't know" if there is a **potential** bug

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Conservative program analysis

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    - also relevant in practice: “fast”, “easy to use”, etc.

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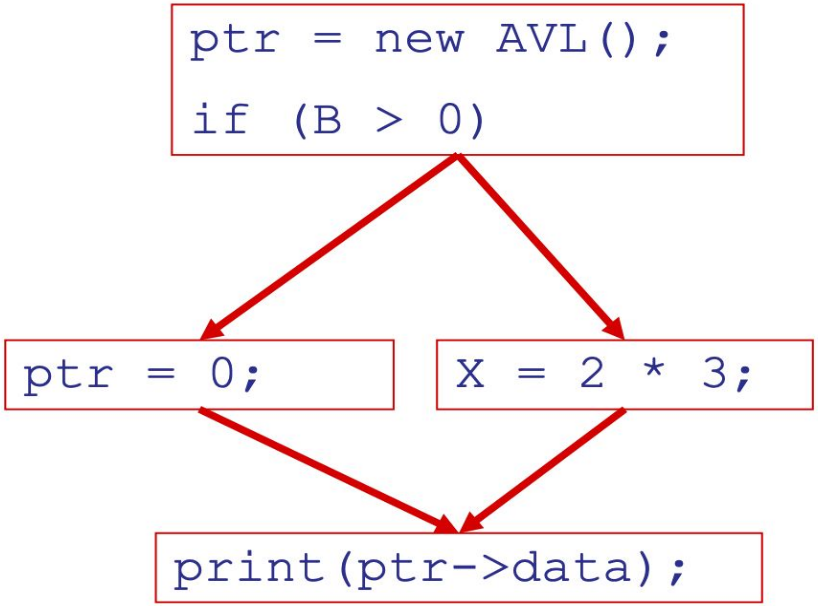
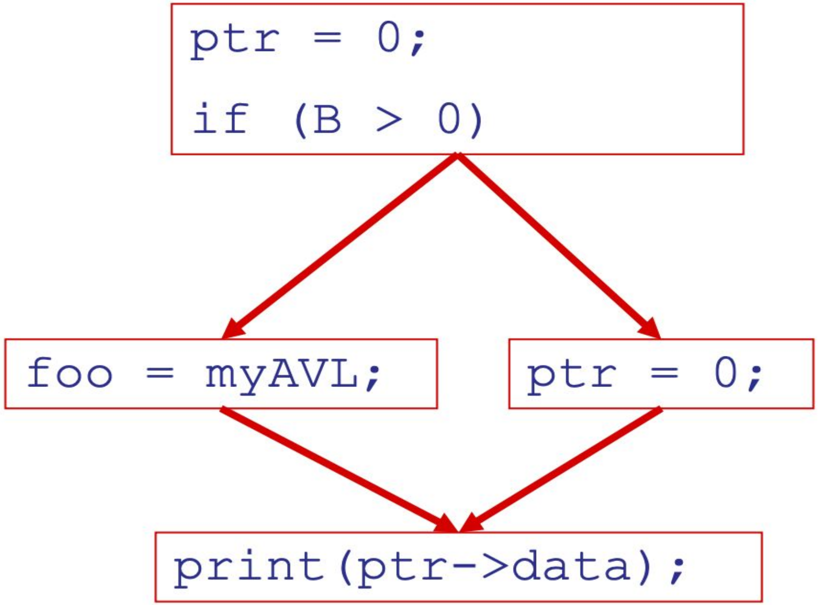
  - few complete analyses exist in practice
    - theory is underdeveloped, but another area of active research!

Null-pointer analysis example

Question: is `ptr` ***always*** null when it is dereferenced?





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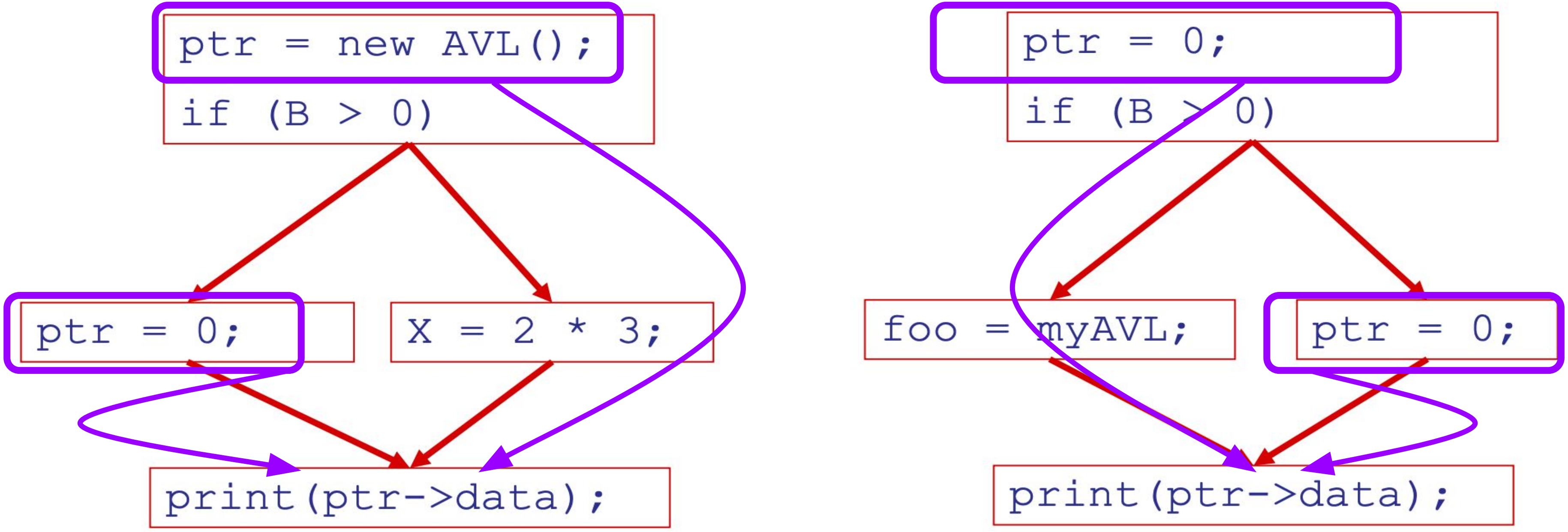

Static analysis (2/2?)

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- nullness analysis: how it works
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- limitations of static analysis
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Announcements:

- reminder: revised project plan due today (submit on Canvas)
- optional reading #1 due at the end of the week
    - Saturday night
- sprint 1 mentor meetings: schedule for ~3/20, 3/21

Static analysis (2/2?)

- **reading quiz**
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Reading Quiz: static analysis (2)

Q1: **TRUE** or **FALSE**: the verifier described by the author is too expensive to run in continuous integration, so AWS provisioned special weekly jobs to re-check the codebase

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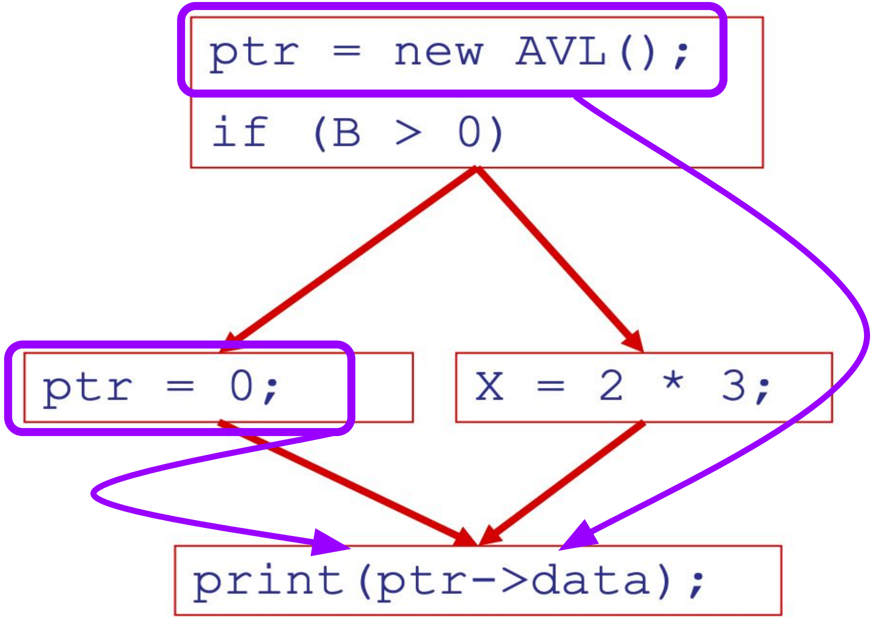
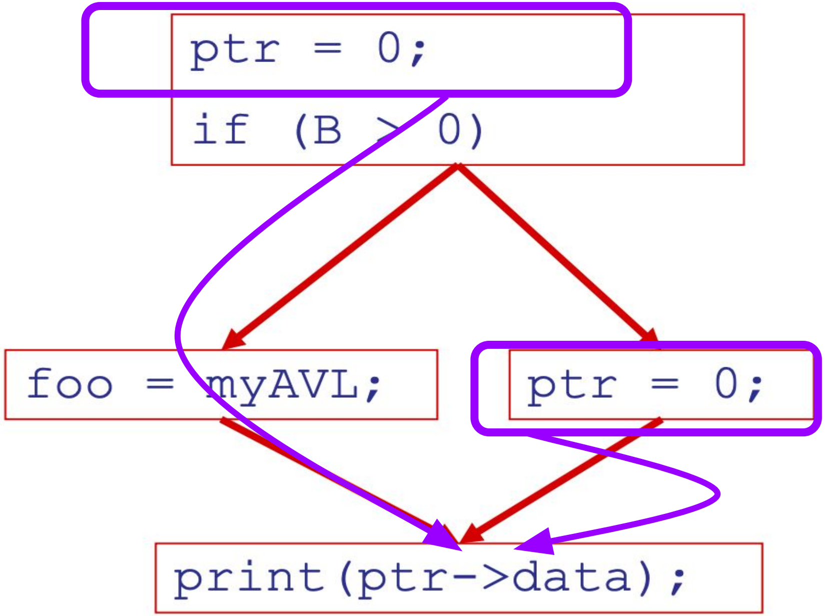


NO: only sometimes null



YES: always null

Null-pointer analysis example: abstraction

Formalizing our reasoning:

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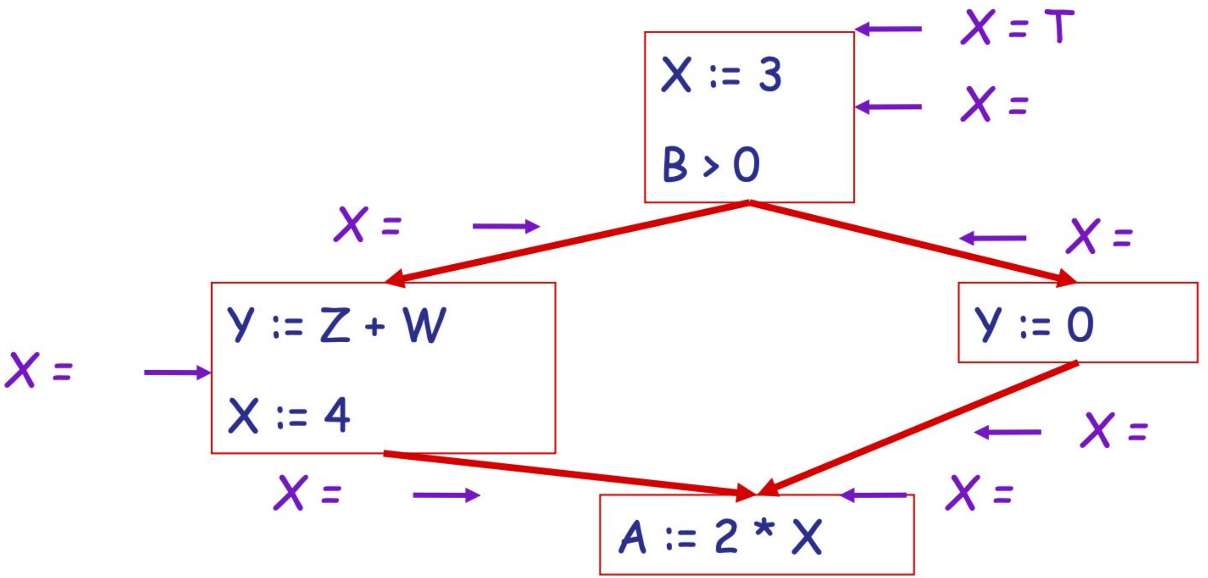
  - ⊥ ("bottom") = "X has no value here"

Null-pointer analysis example: formalized

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



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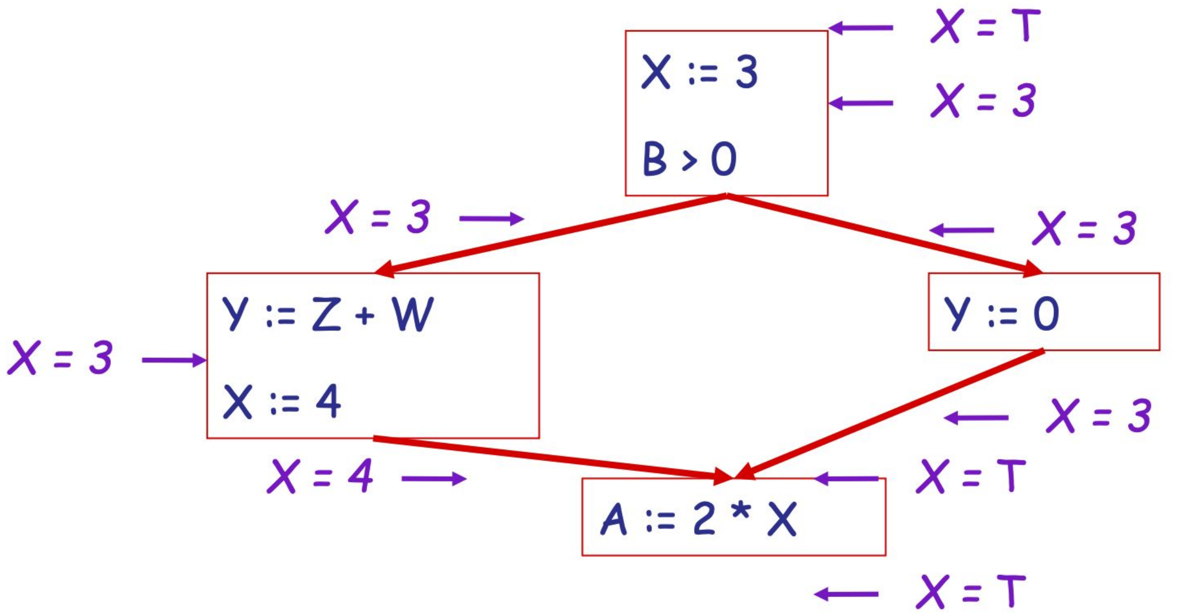

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- But how can an **algorithm** compute $x = ?$

Key idea behind dataflow analysis

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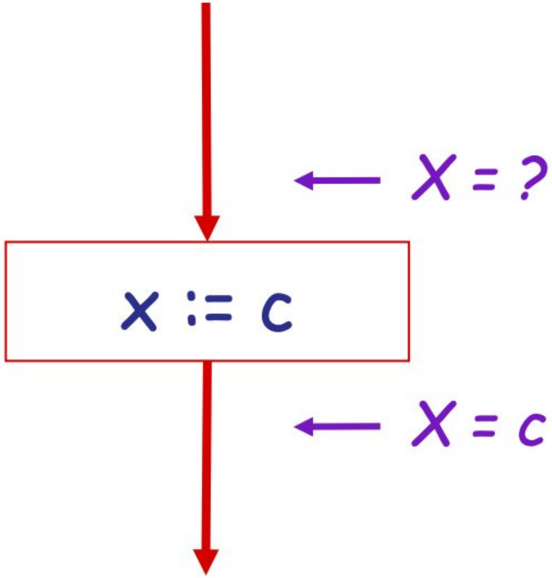
Definition: a ***transfer function*** expresses the relationship between $C_{in}(x, s)$ and $C_{out}(x, s)$

Transfer functions: rule 1

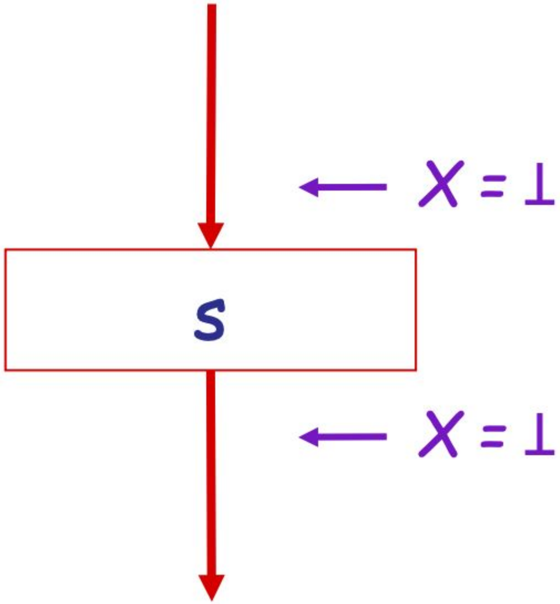


$C_{out}(x, x := c) = c$ if c is a constant

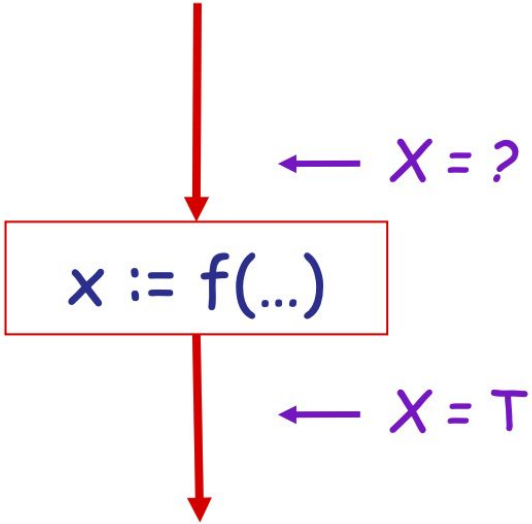
Transfer functions: rule 2

$C_{out}(x, s)$ = □ if $C_{in}(x, s)$ = □

Recall □ = "unreachable code"



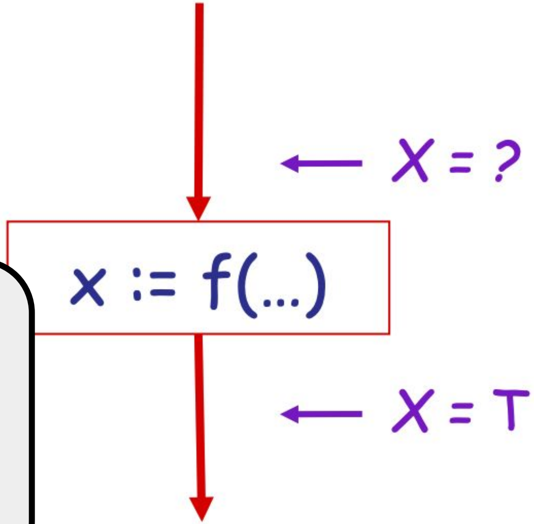
Transfer functions: rule 3



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

Transfer functions: rule 3

This is a **conservative approximation**! f(...) might always return 0, but we don't even try!



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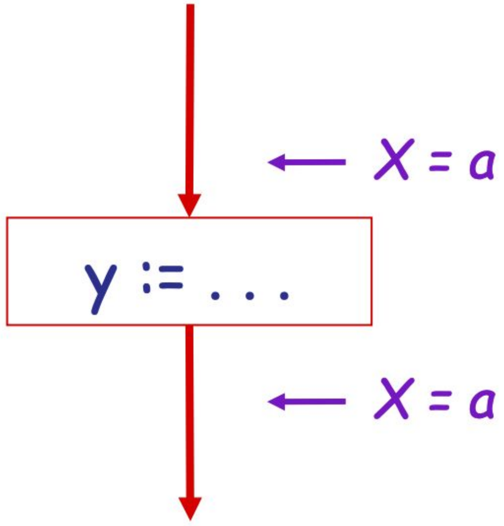
Transfer functions: rule 4



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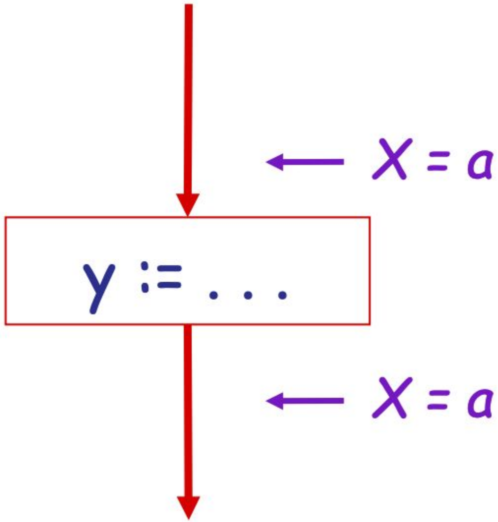

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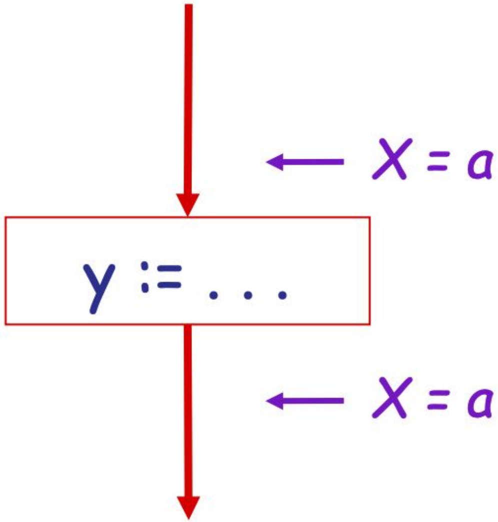
How hard is it to check if x ≠ y on all executions? (oh no)



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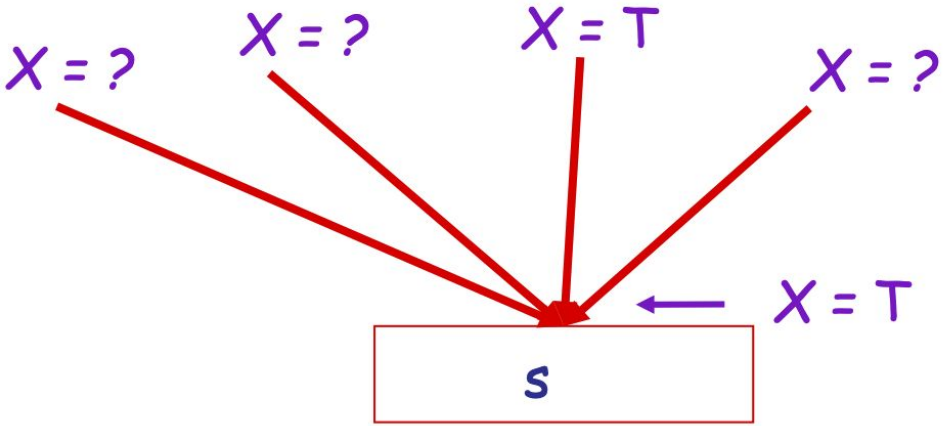
- In the following rules, let statement s have immediate predecessor statements $p_1, \ldots, p_n$

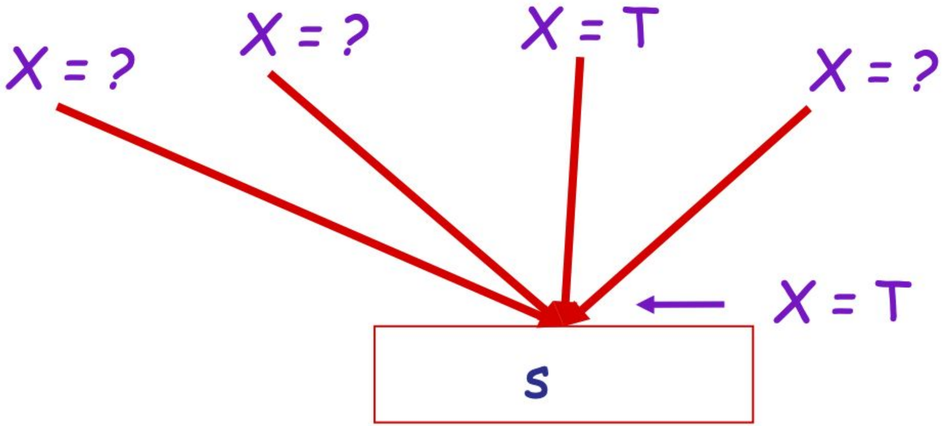
Transfer functions: rule 5



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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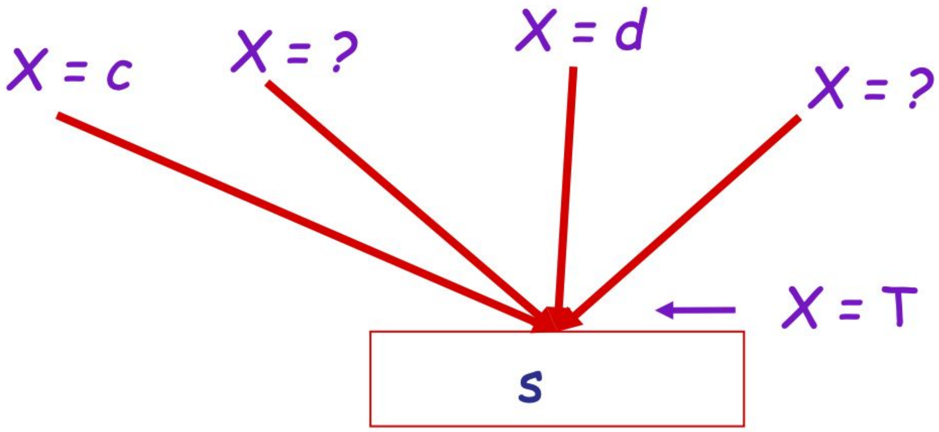
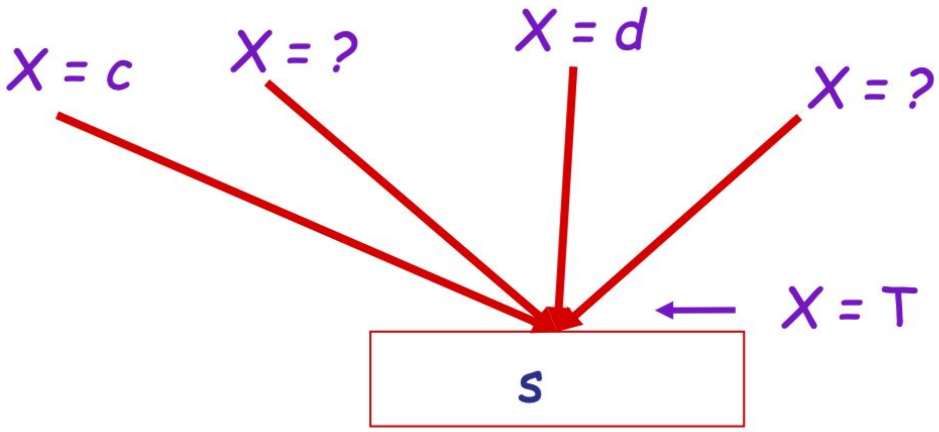


if $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$ then $C_{in}(x, s) = T$

Transfer functions: rule 6



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

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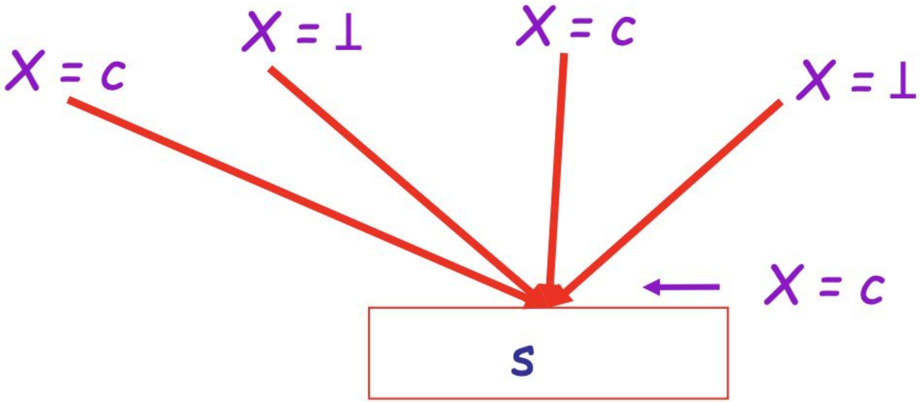
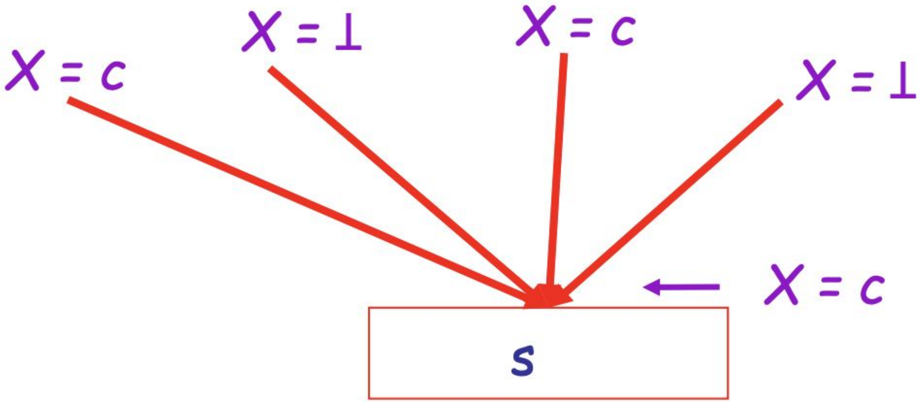
Transfer functions: rule 7



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

Transfer functions: rule 7

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



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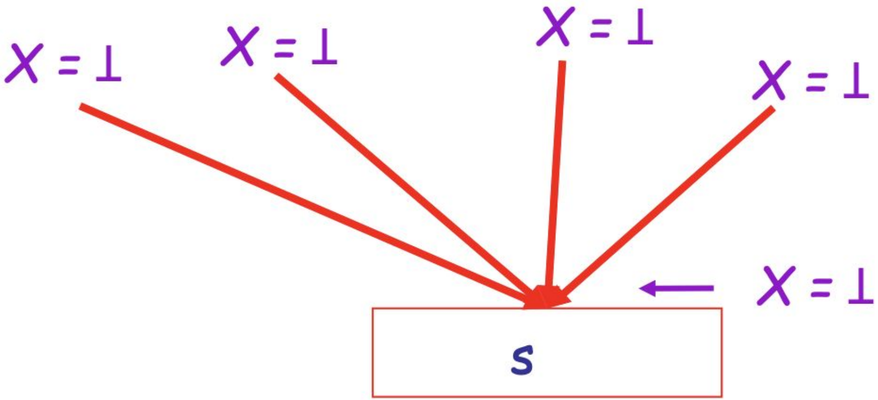

if $C_{out}(x, p_i) = \bot$ for all i, then $C_{in}(x, s) = \bot$

A static analysis algorithm

A static analysis algorithm

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

A static analysis alg

Definition: an ***entry point*** of a program is any program location *L* for which there exists an execution trace beginning with *L*

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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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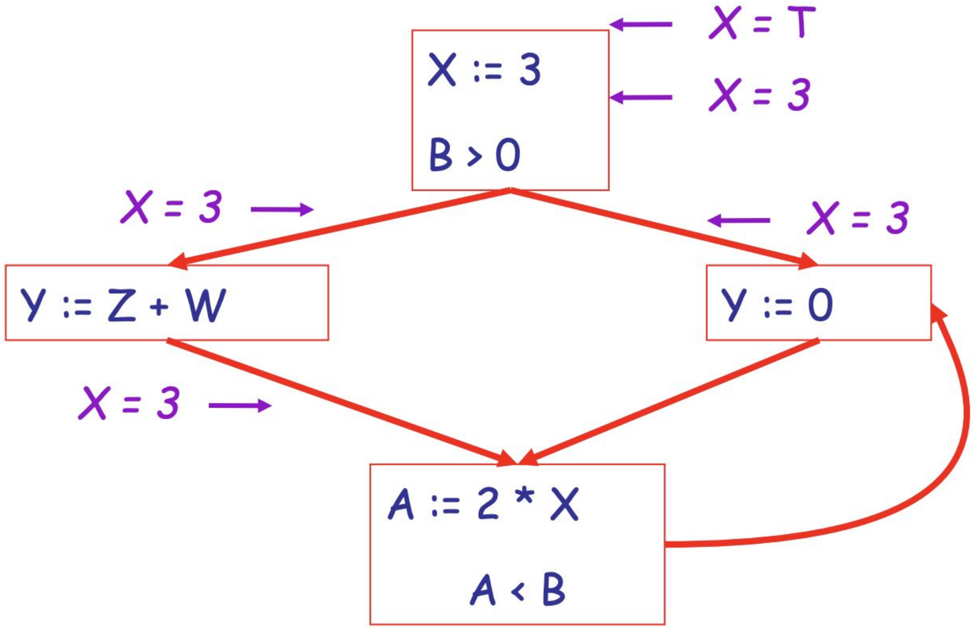

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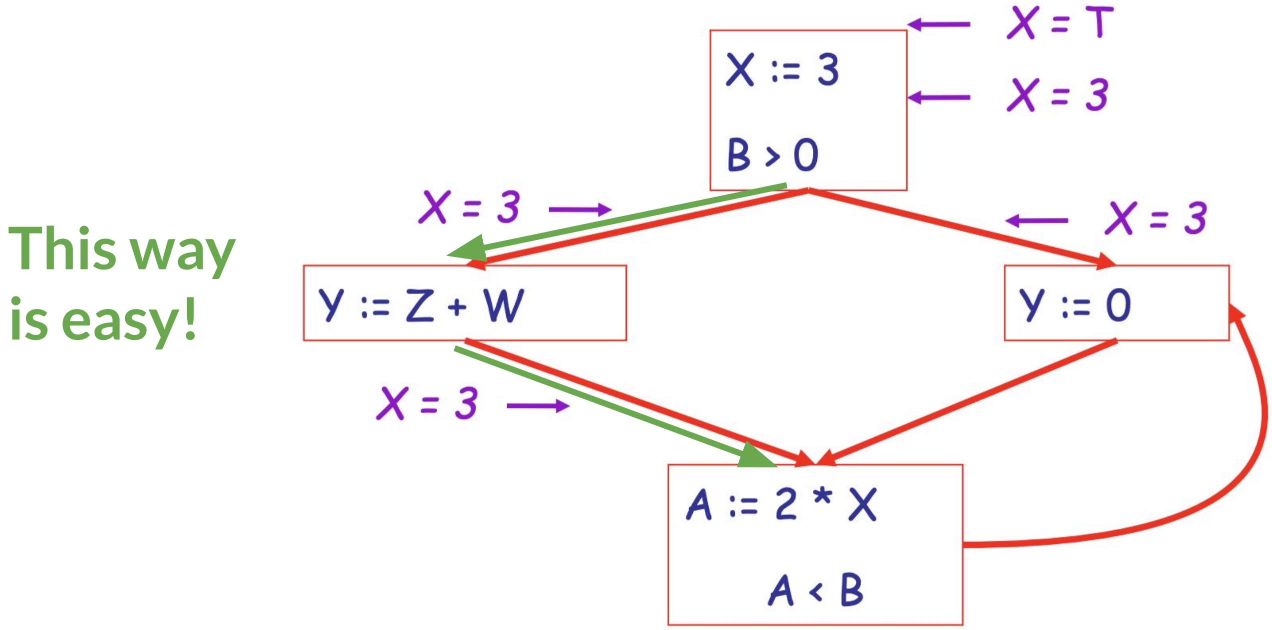

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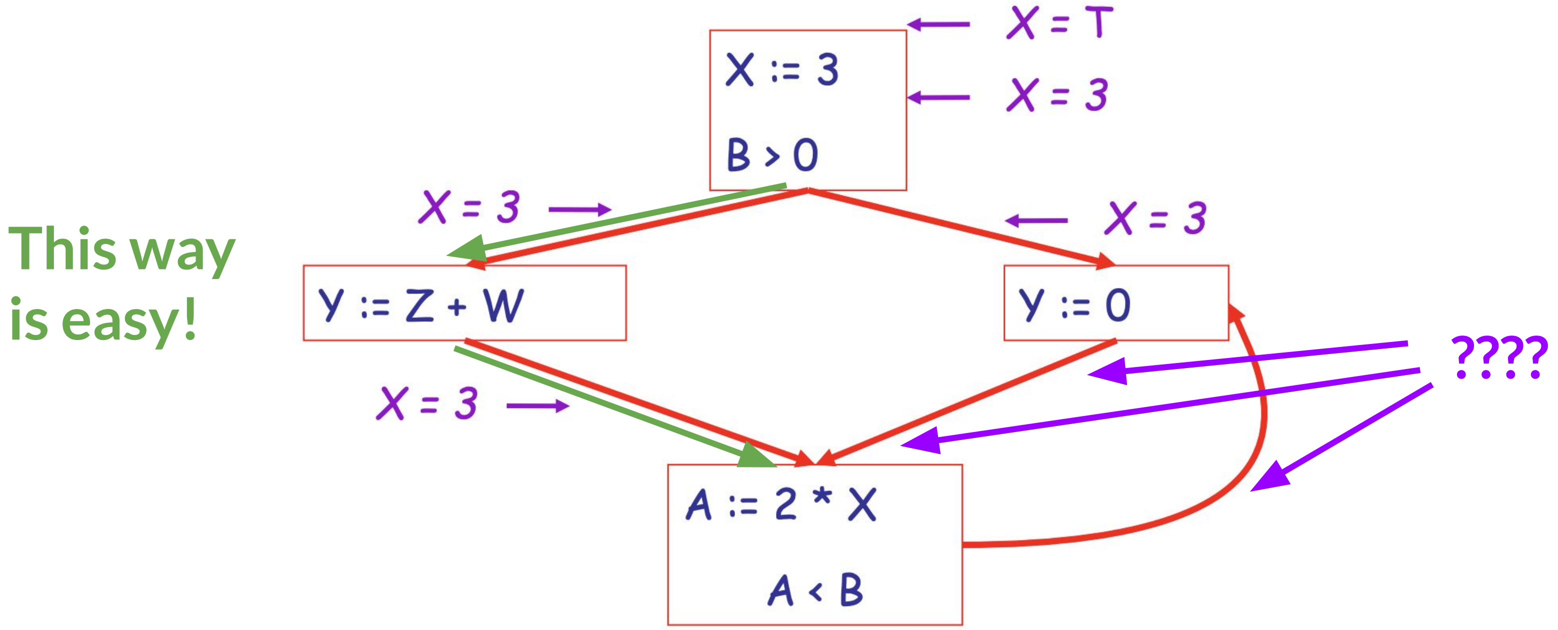

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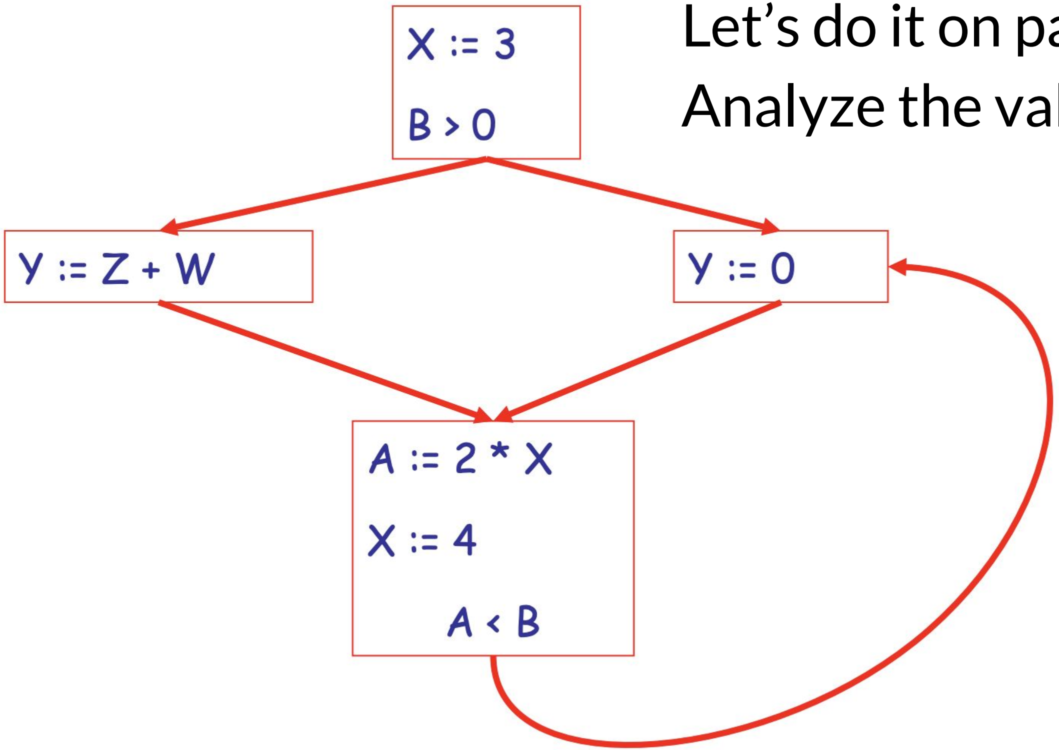
- The initial value □ means "**we have not yet analyzed control reaching this point**"

Another example: dealing with loops



Let's do it on paper!

Analyze the value of X.

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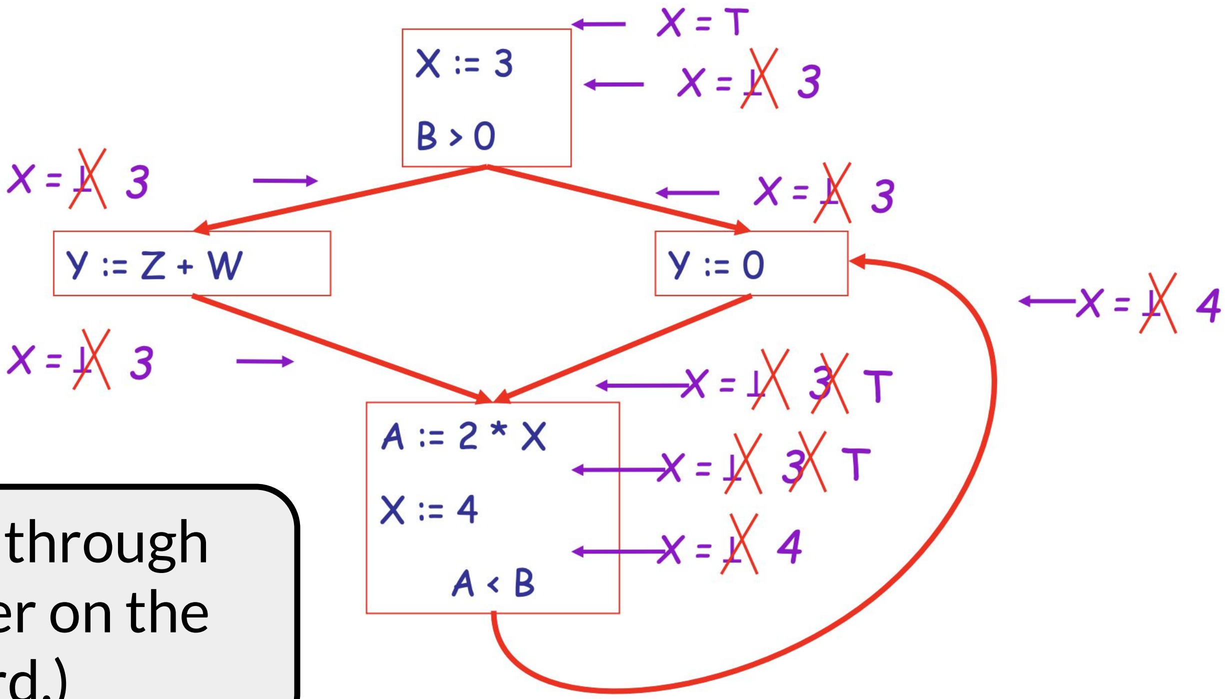

(We went through this answer on the whiteboard.)

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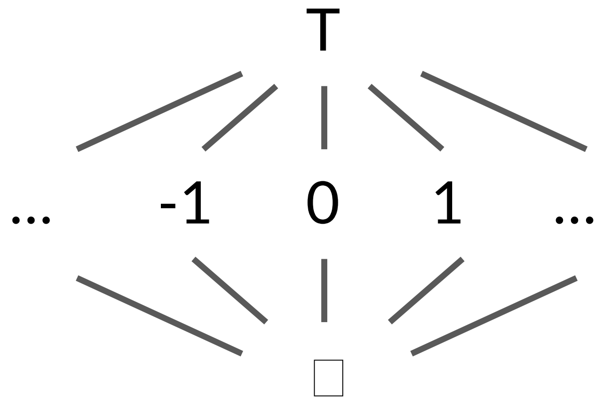
  - Locations whose current value is c might become T
    - but never go back to □!
  - Locations whose current value is T never change

Lattices & Orderings

This structure between values is called a ***lattice***:



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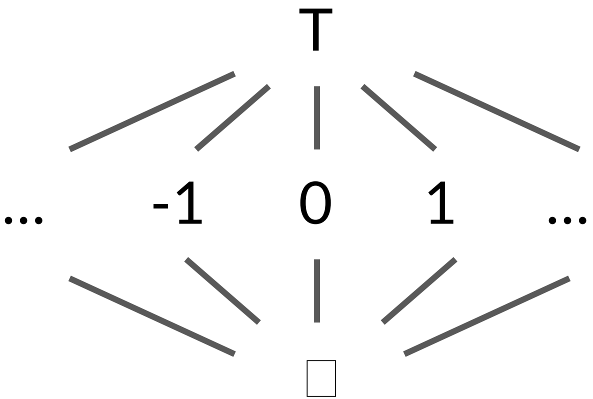

How to read a lattice:

- 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

Lattices (continued)

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

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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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  - thus, C_(x, s) can change at most **twice** (= lattice height minus one)

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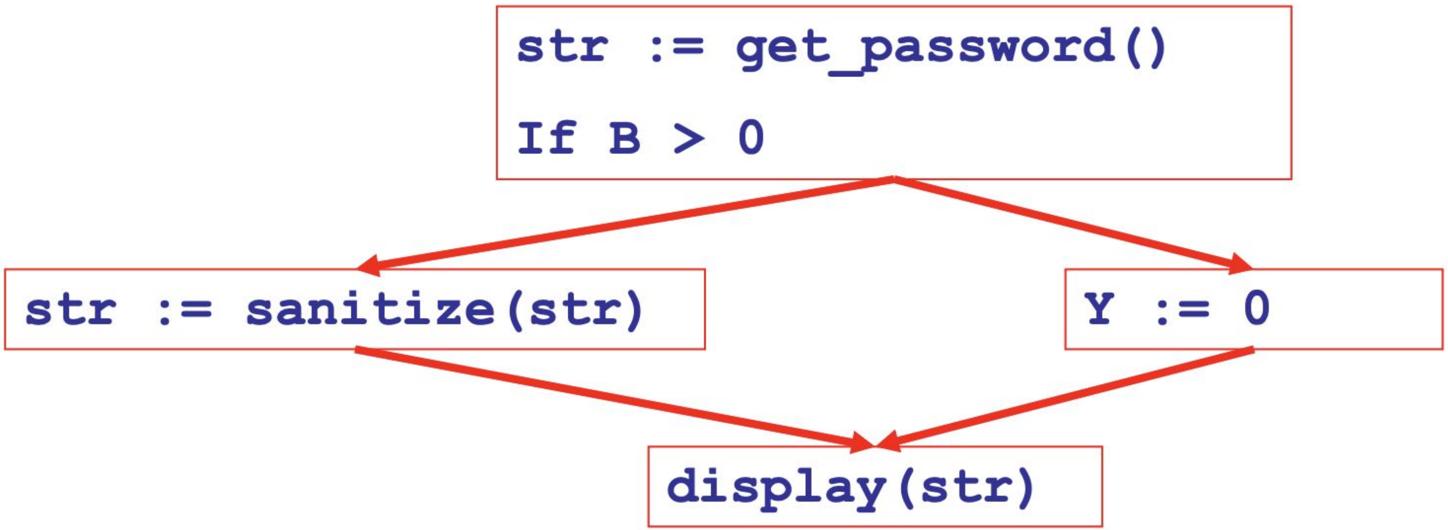

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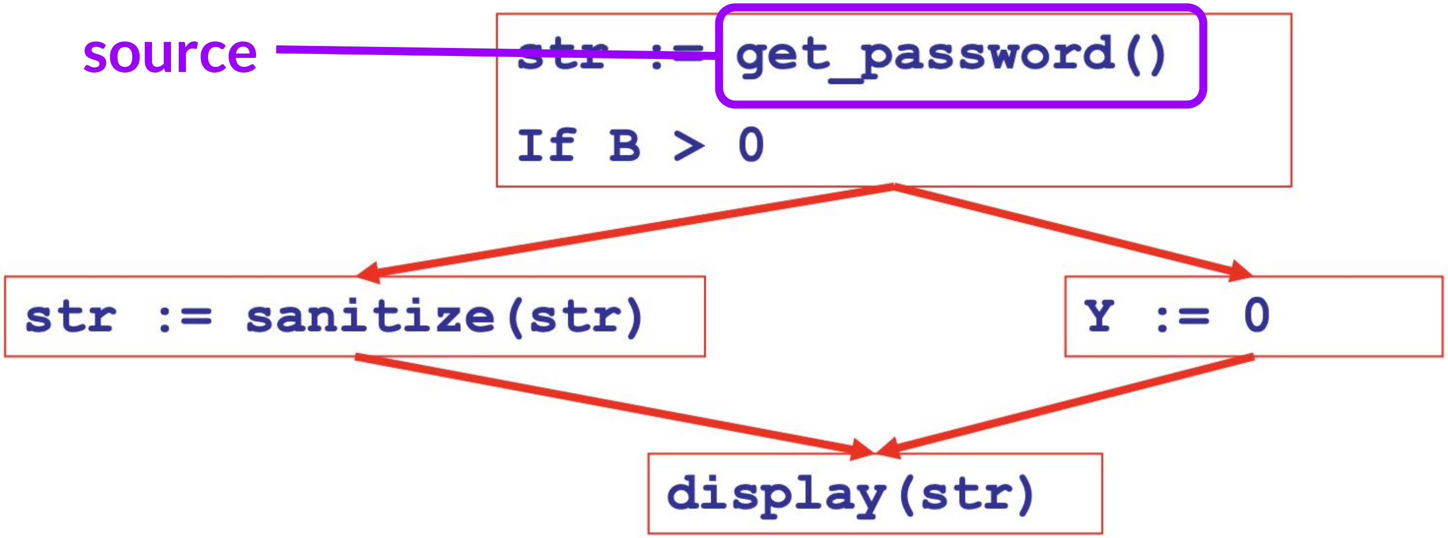

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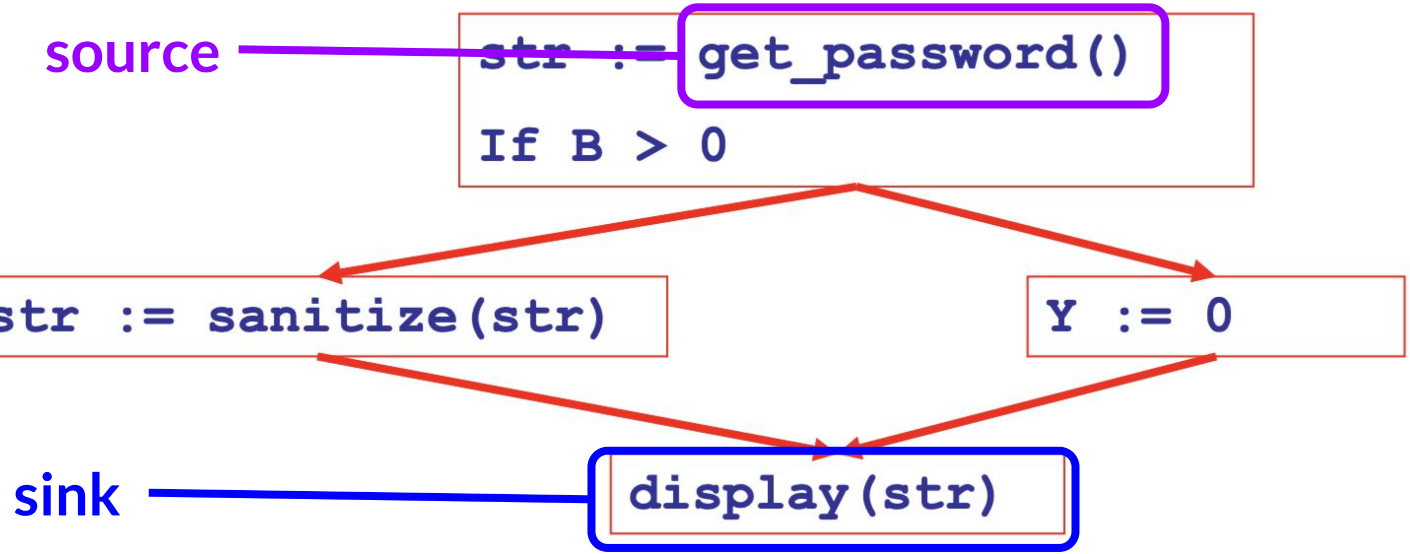

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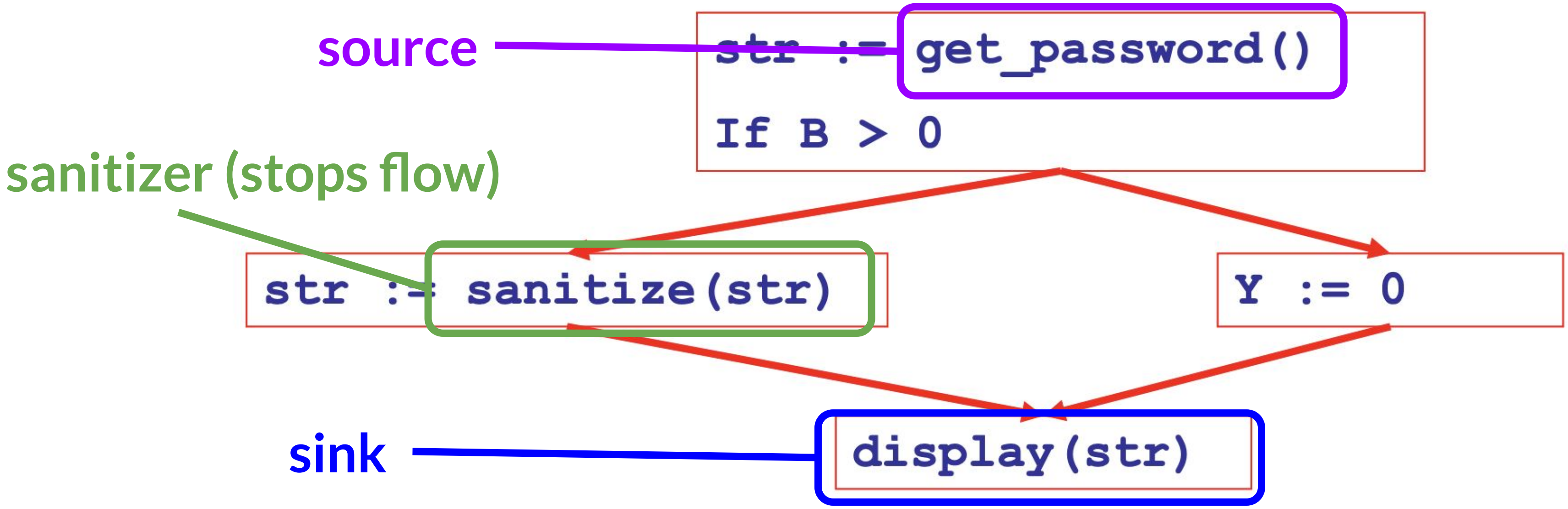

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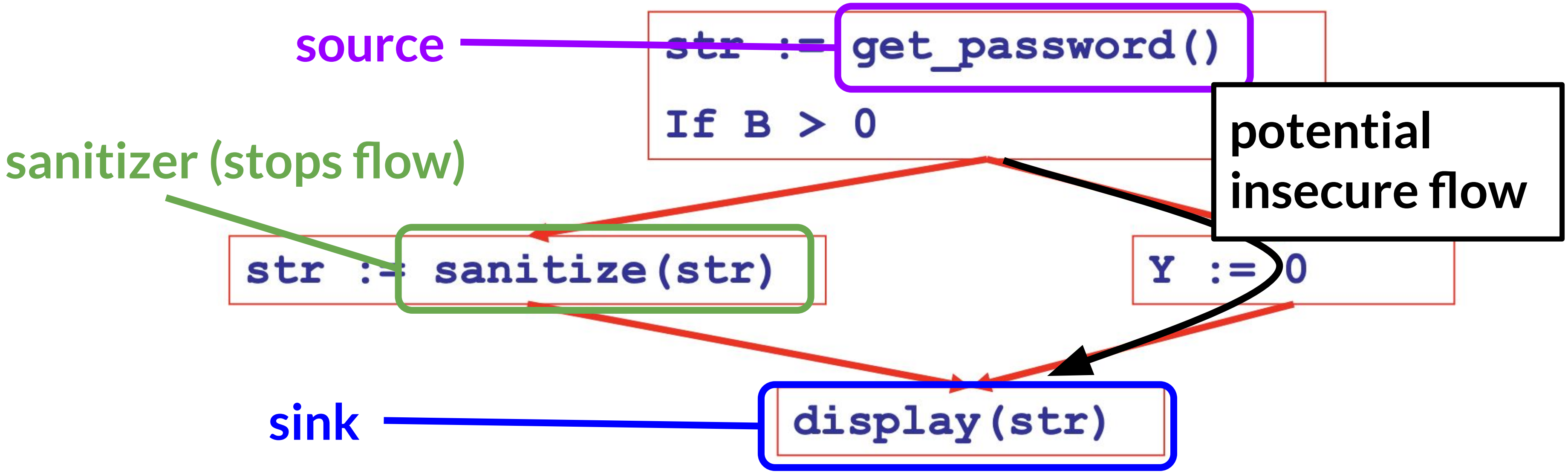

Taint analysis

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- applications in security: e.g., secure information flow
- stand-in here for a broad class of dataflow analyses
- how would we build it?
  - we'll write a set of rules, just as we did for our nullness analysis

Secure information flow analysis

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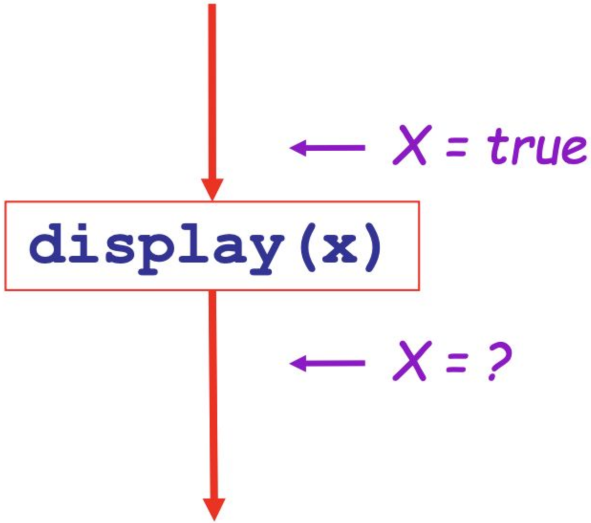
- second step: **statement-by-statement rules** to express how this works

Secure information flow analysis: rule 1



$H_{in}(x, s)$ = true if s displays x publicly

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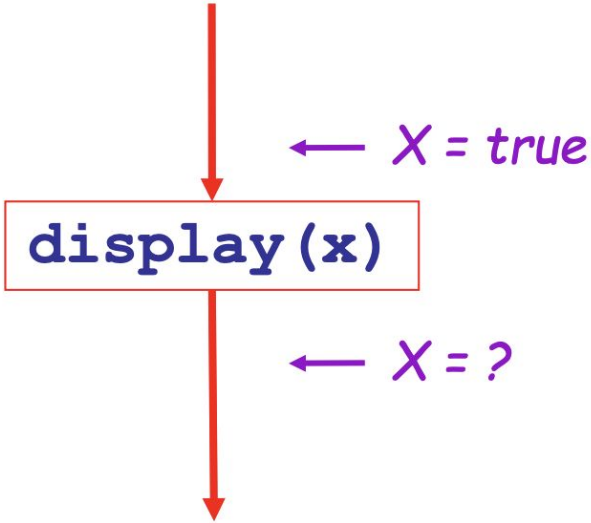
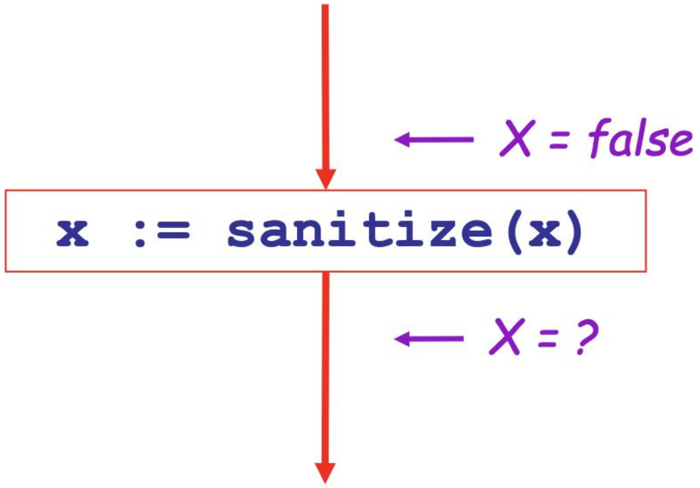


$H_{in}(x, s)$ = true if s displays x publicly

Recall, true means "if this ends up being a secret variable then we have a bug!"

Secure information flow analysis: rule 2

$H_{in}(x, x := e) = \text{false}$



Secure information flow analysis: rule 2

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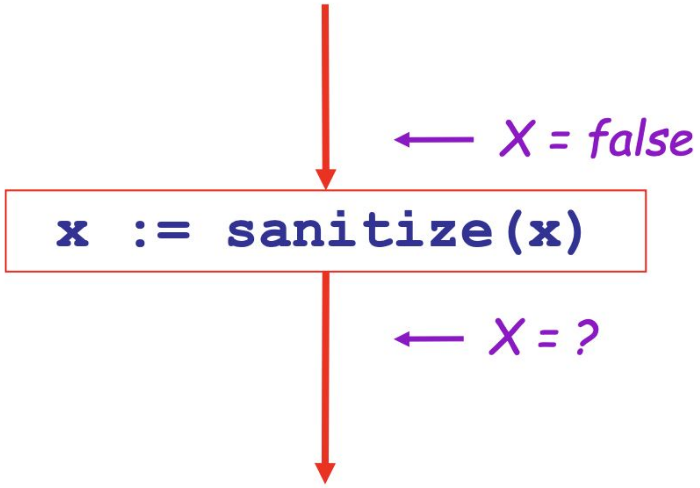
This means any subsequent use of x is safe after we assign to it.



Secure information flow analysis: rule 2

Does this rule say anything about the sanitize() method?

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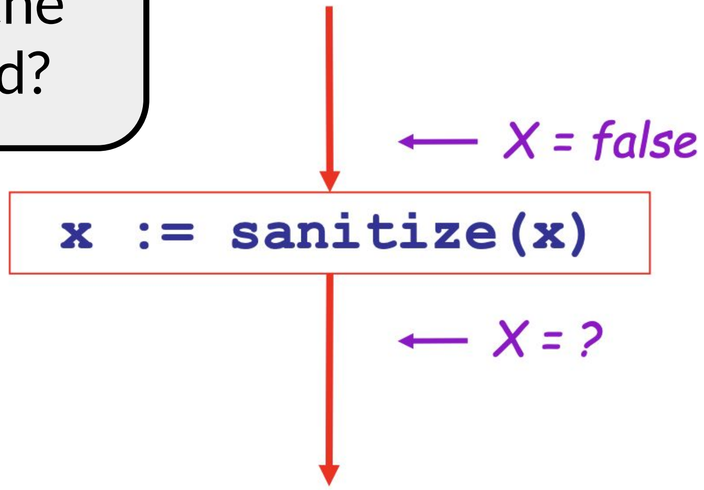
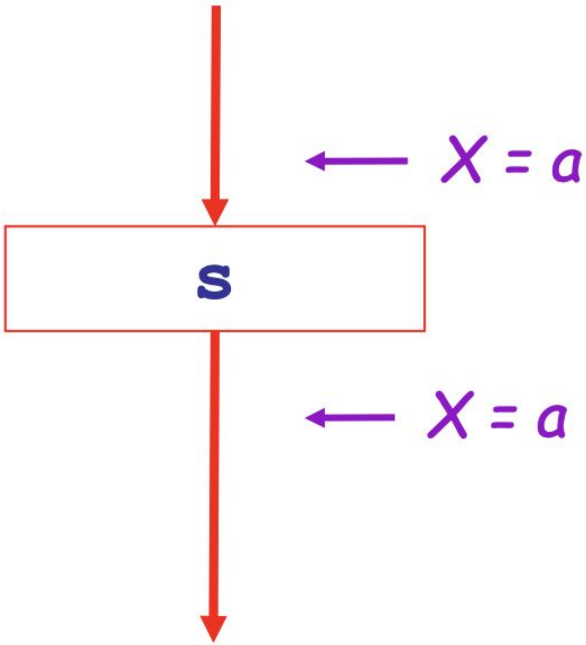
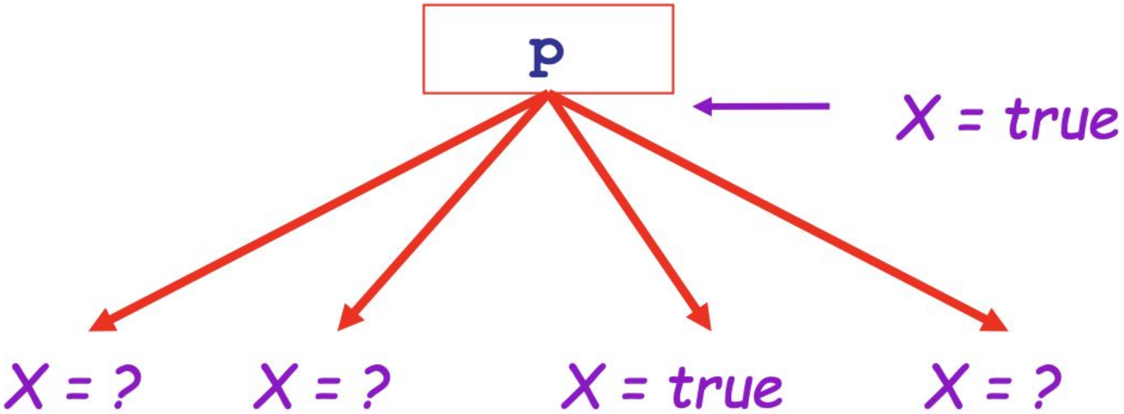


Secure information flow analysis: rule 3



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

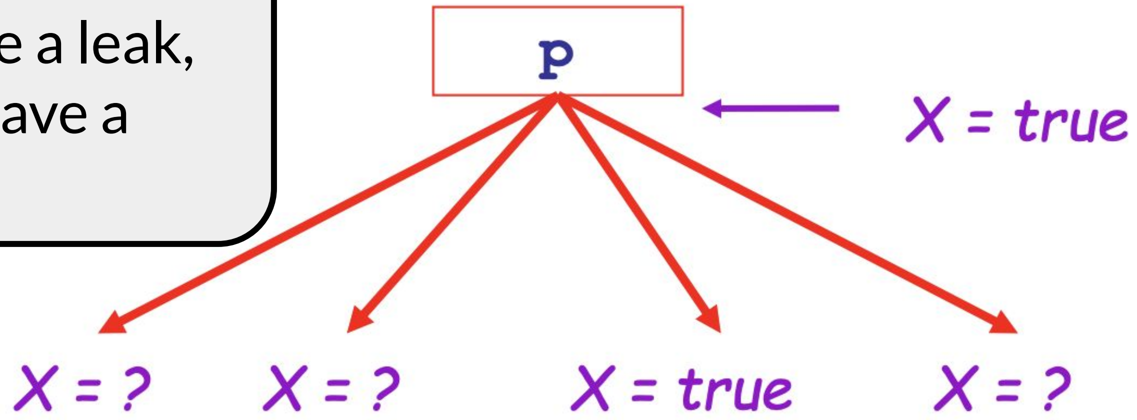
Secure information flow analysis: rule 4



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

Secure information flow analysis: rule 4

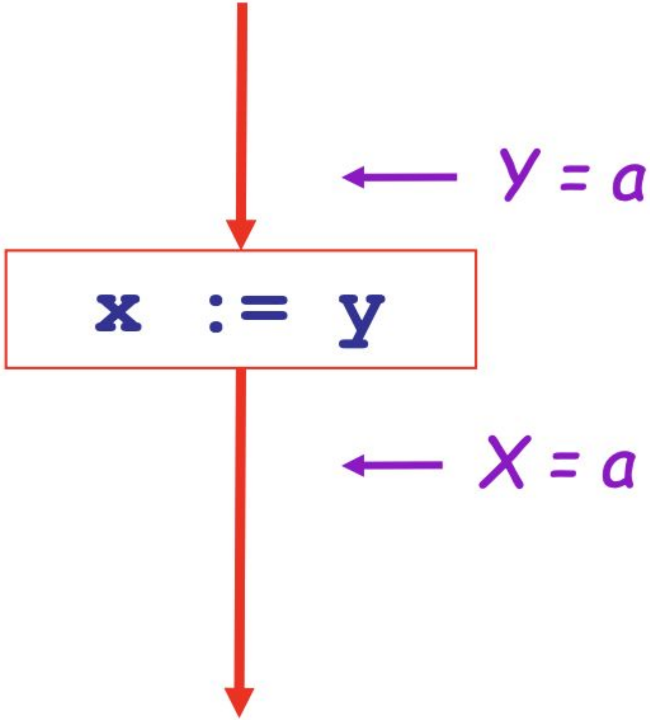
if there is **even one** way to have a leak, we might have a leak!



$H_{out}(x, p) = \lor \{ H_{in}(x, s) \mid s \text{ is a successor of } p \}$

Secure information flow analysis: rule 5

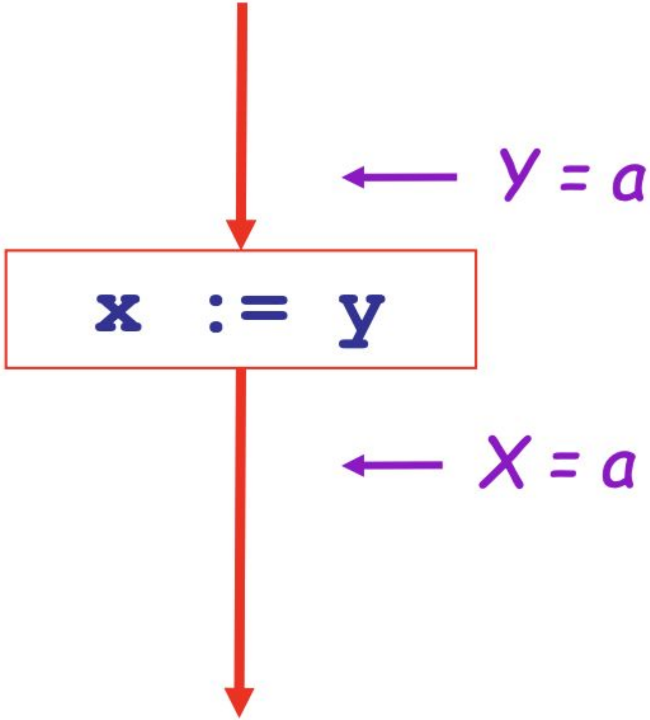
$H_{in}(y, x := y) = H_{out}(x, x := y)$



Secure information flow analysis: rule 5

$H_{in}(y, x := y) = H_{out}(x, x := y)$

(To see why, imagine the next statement is display(x). Do we care about y?)



Secure information flow analysis: algorithm

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false is like □ in our nullness analysis!

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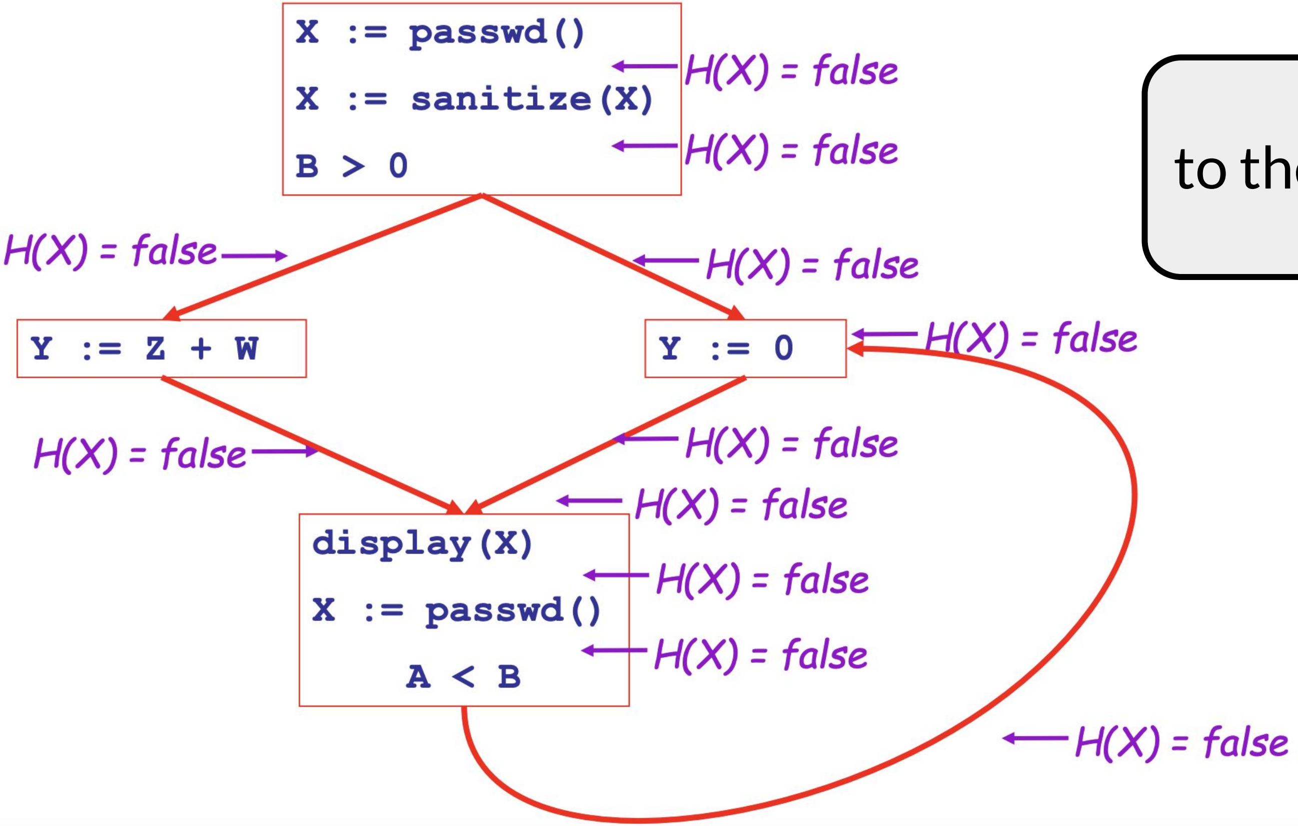
3. once the analysis reaches a fixed point, **issue a warning** at any source (x, s) where $H_{out}(x, s)$ is true (= leaks sensitive information)

Secure information flow analysis: example



to the whiteboard!

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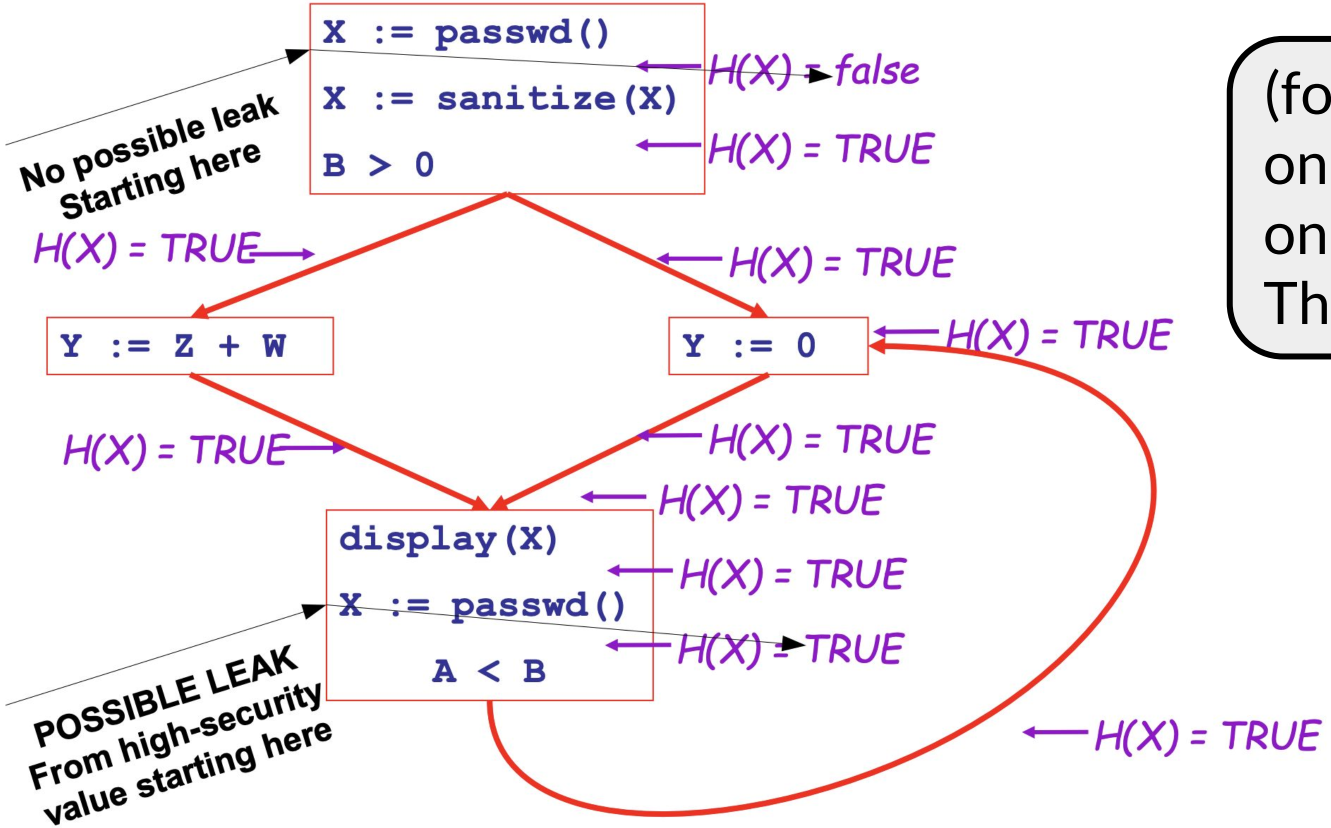

(for those reading online later, solved on the whiteboard. This is the solution.)

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    - but, in practice, we can get very close

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    - security rules, etc.

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heuristic is a fancy word for "best effort"

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  - widely used in industry:
    - ErrorProne at Google, Infer at Meta, SpotBugs at many places (including Amazon), Coverity, Fortify, etc.

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What is a pluggable type?

```
@Positive int x
```

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designing better (more expressive, more usable, etc.) pluggable type systems is an area of active research (mine!)

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  - tool verifies that code matches that specification
  - very high effort, but enables sound reasoning about complex properties (= worth it for very high value systems)

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    - but these tools (e.g., Coq) are **much harder to use**
- soundness theorems also usually make some **assumptions** about the code being analyzed (e.g., no calls to native code, no reflection)

Static analysis: summary

- static analysis is very good at enforcing **simple rules**
  - **much** better than humans at this
- all interesting semantic properties of programs are **undecidable**, so all static analyses must **approximate**
  - goal in analysis design is to **abstract away unimportant details**, but keep important details
  - **dataflow analysis** is one technique for static analysis
  - trade-offs between false positives, false negatives, analysis time
- soundness & completeness are **possible, but rare**
  - all soundness guarantees come with caveats about the TCB