Dataflow Analysis

Martin Kellogg

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- **last few slides of static vs dynamic analysis**
- key ideas in static analysis design
- dataflow analysis
  - nullness analysis example
  - secure information flow analysis example
- limitations of static analysis
- static analysis in practice

Review: static vs dynamic analyses

Dynamic analyses:

- Concrete execution
    - slow if exhaustive
- Precise
    - no approximation
- Unsound
    - does not generalize

Static analyses:

- Abstract domain
    - slow if precise
- Conservative
    - due to abstraction
- Sound
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  - typically **conservative** / **pessimistic** elsewhere
    - i.e., assume that unmodeled state is unsafe

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- **key ideas in static analysis design**
- dataflow analysis
  - nullness analysis example
  - secure information flow analysis example
- limitations of static analysis
- static analysis in practice

Review: what is a static analysis?

Definition: ***static analysis*** is the systematic examination of an abstraction of program state space

- static analysis **does not execute** the program
  - in contrast to a **dynamic analysis**, such as testing, which does execute the program
- 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!

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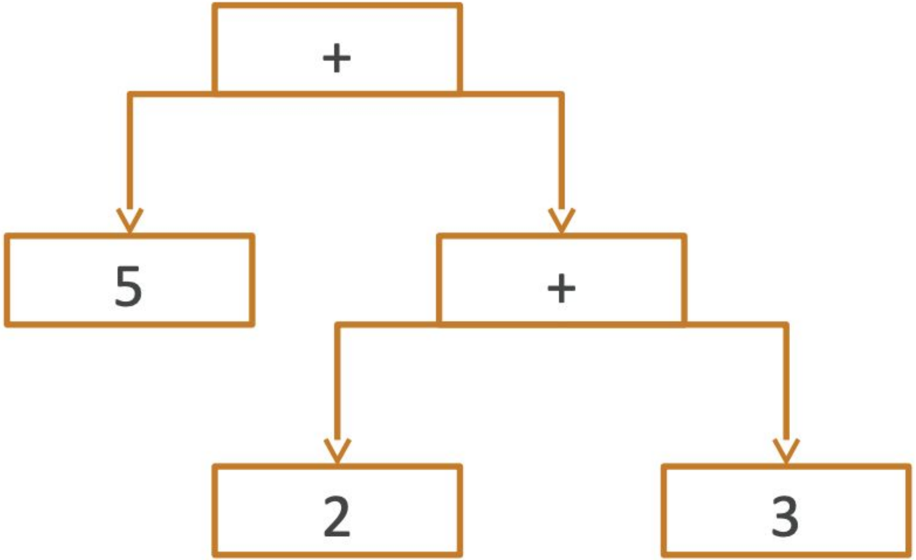
- usually produced by a **parser**
- nodes in the tree represent syntactic constructs
  - parent-child relationships in the AST represent **compound expressions** in the source code (e.g., a "plus node" might have two children: the left and right side expressions)

Treating programs as data: AST example

Example: 5 + (2 + 3)



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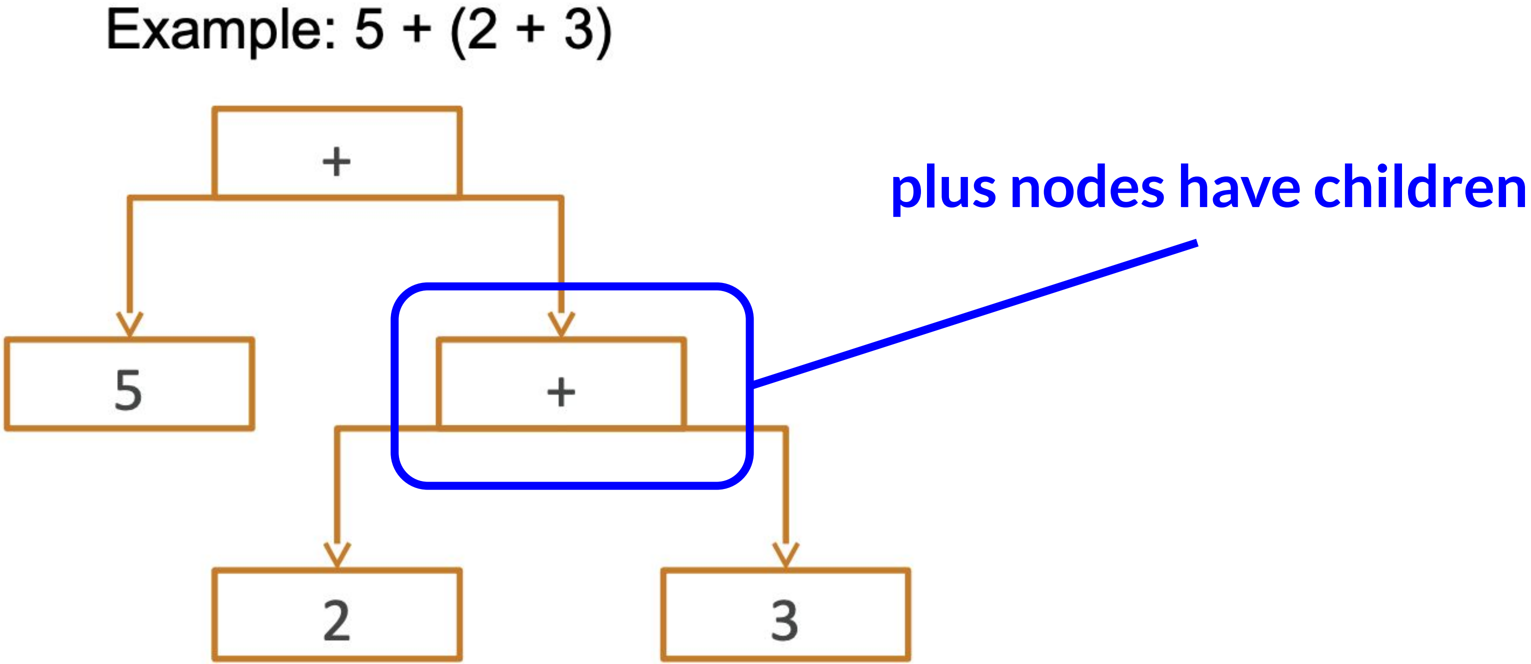

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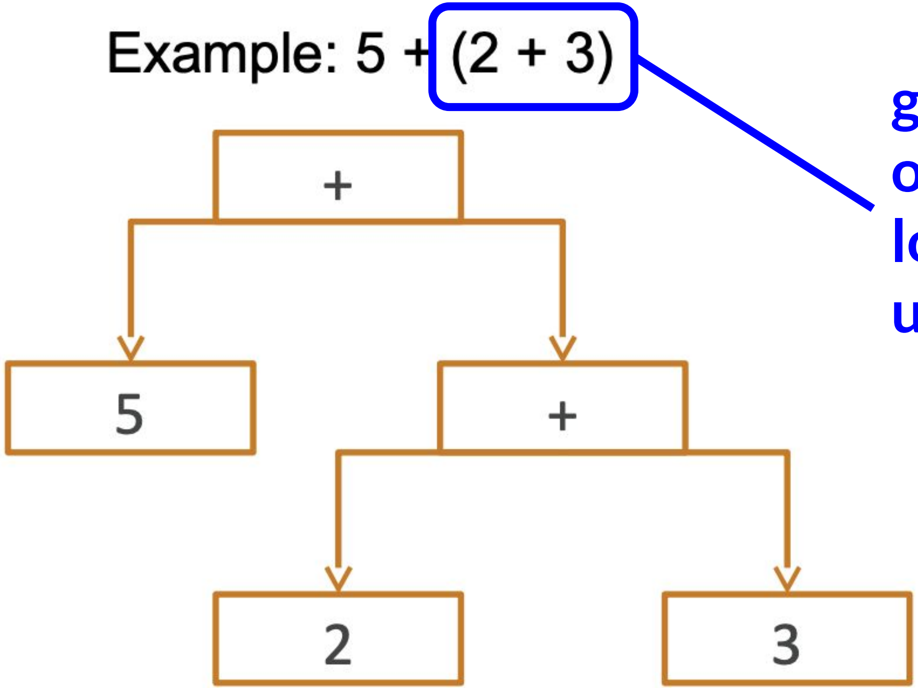

grouping parentheses and other disambiguation is no longer necessary (AST is unambiguous, unlike text)

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- this is the internal representation used by most static analysis tools

Dataflow analysis

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  - Dataflow analyses take programs as input

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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

A “**potential**” secure information leak exists if and only if the secure information leaks on **any** 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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Null-pointer analysis example

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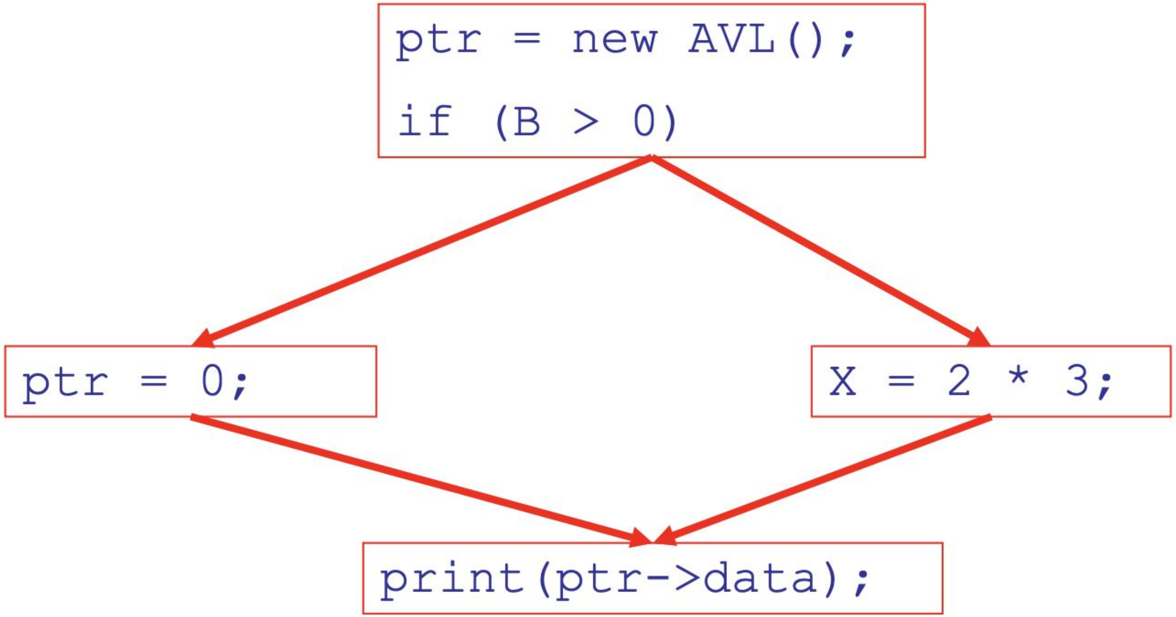
Question: is `ptr` ***always*** null when it is dereferenced?



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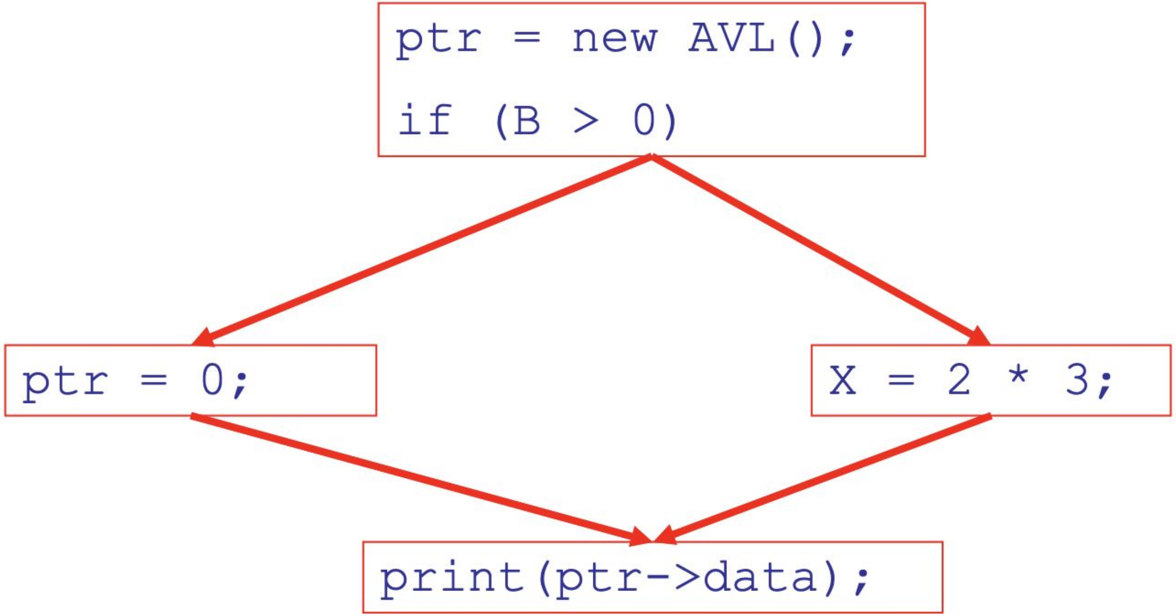

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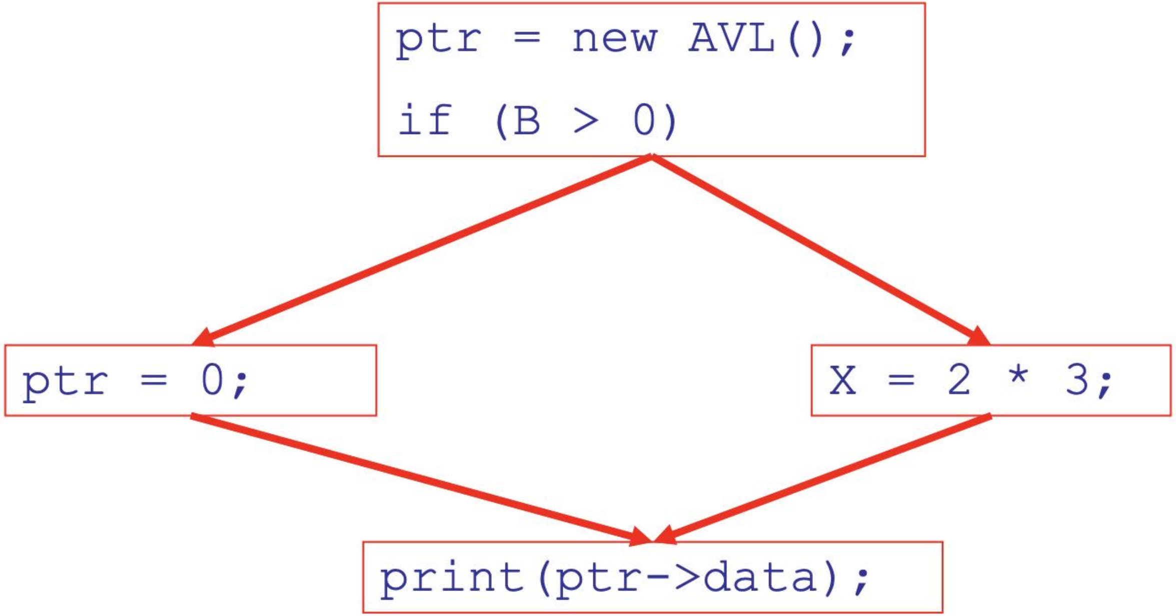

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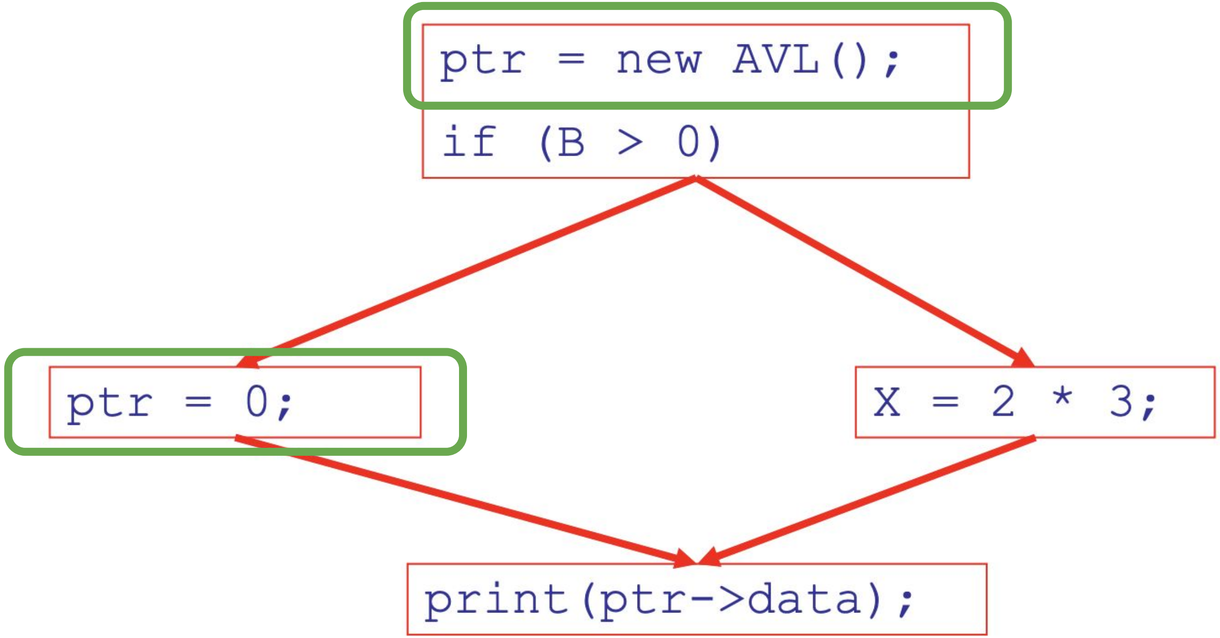

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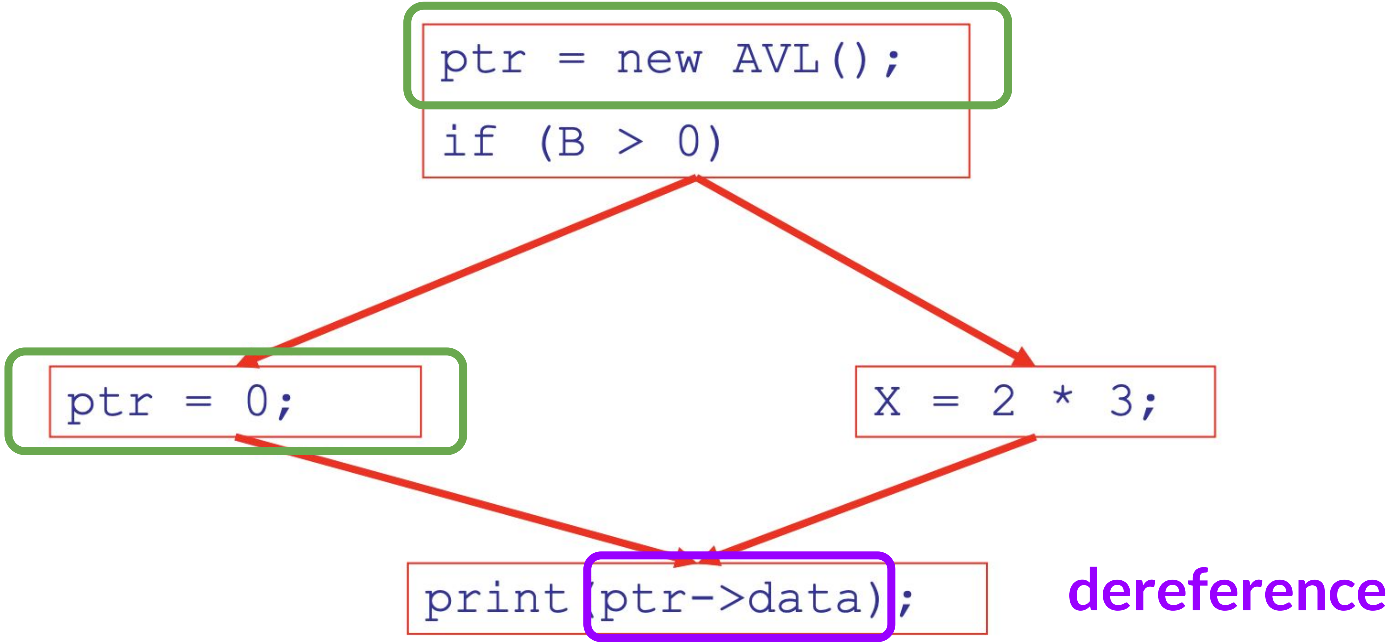

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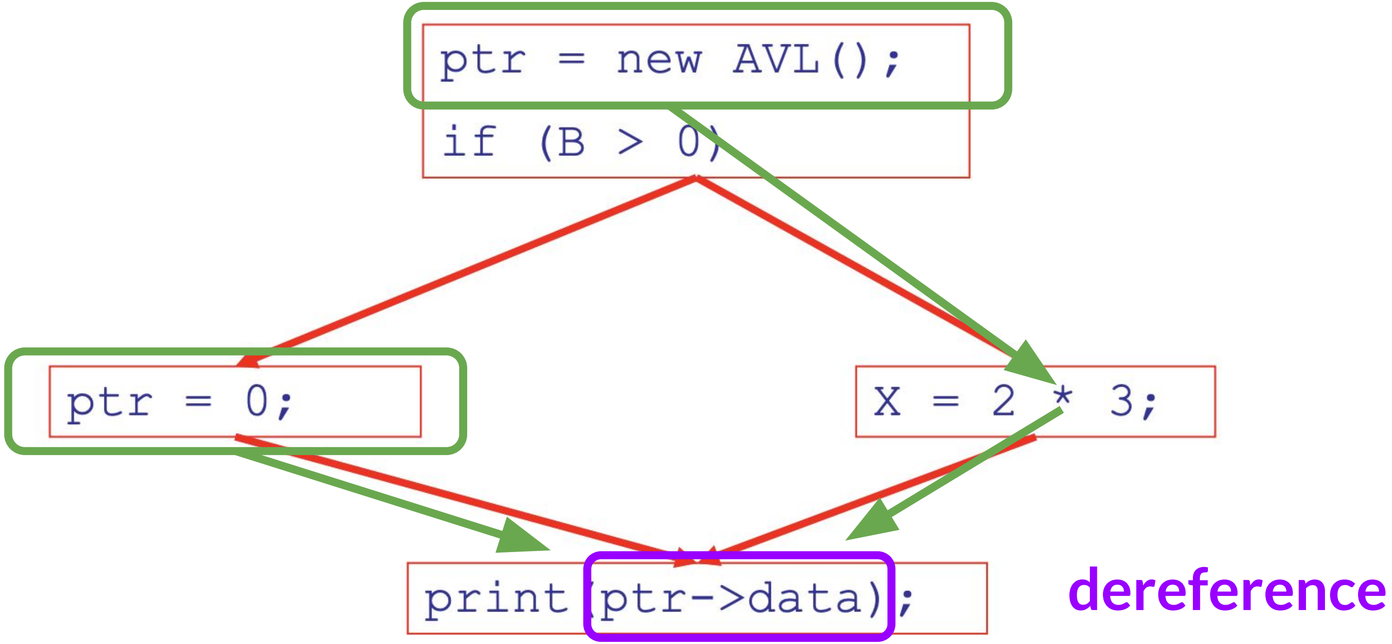

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"**interesting**" in this context means "not trivial", i.e., not uniformly true or false for all programs

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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 (remember your theory class!)
  - 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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  - this is called ***conservative*** analysis

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

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    - "I don't know" = don't issue a warning

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        - “I don’t know” = don’t issue a warning
    - Are you writing a bug-finding analysis for aircraft autopilots? False negatives cause crashes, so choose soundness.

Soundness vs completeness

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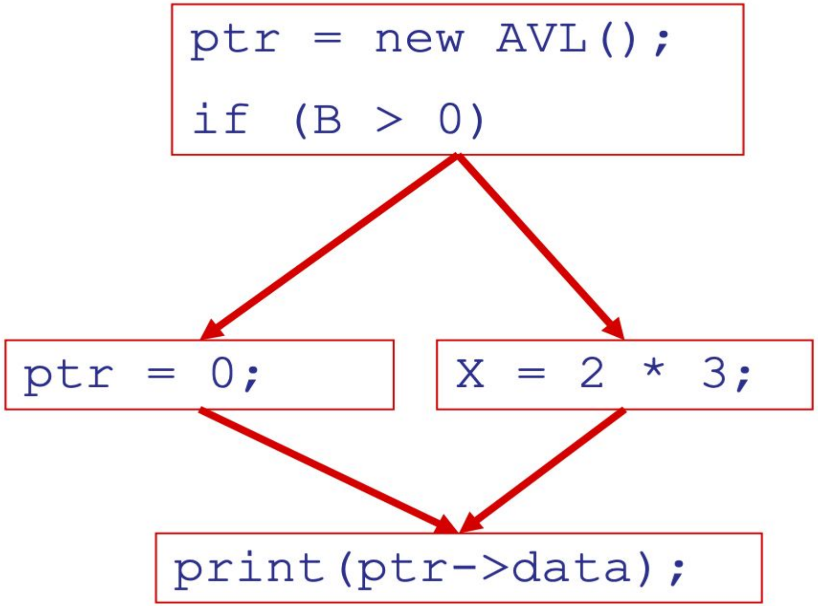
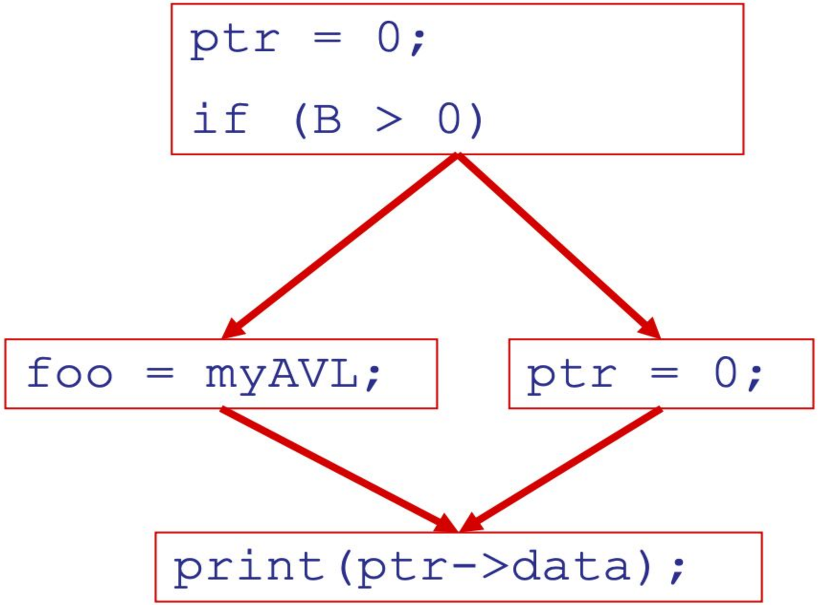
  - few complete static analyses exist in practice
    - theory is underdeveloped, but another area of active research! (ask me more after class!)

Null-pointer analysis example

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





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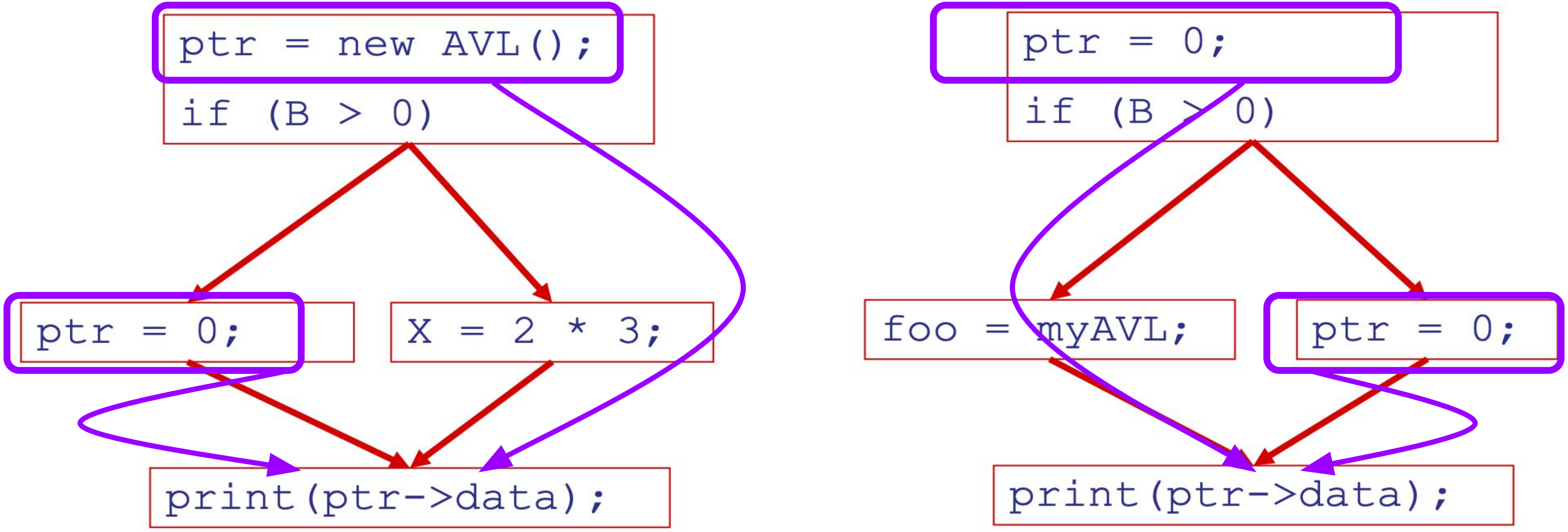

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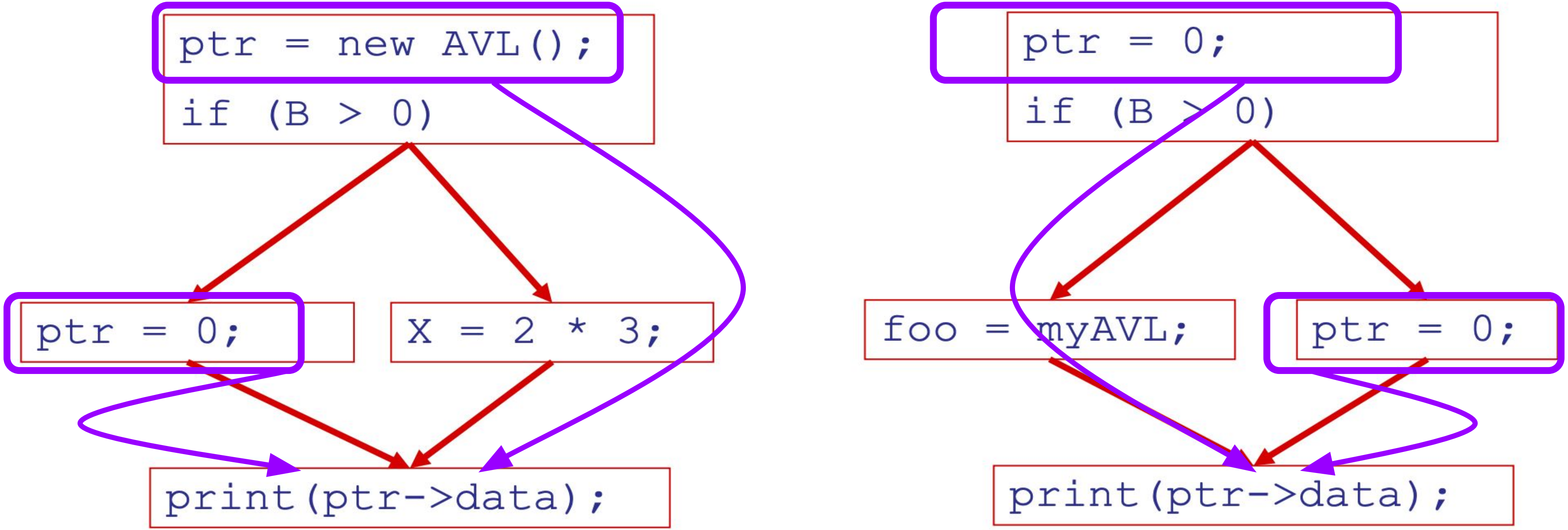

NO: only sometimes null

YES: always null

Null-pointer analysis example: abstraction

Formalizing our reasoning:

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Null-pointer analysis example: formalized

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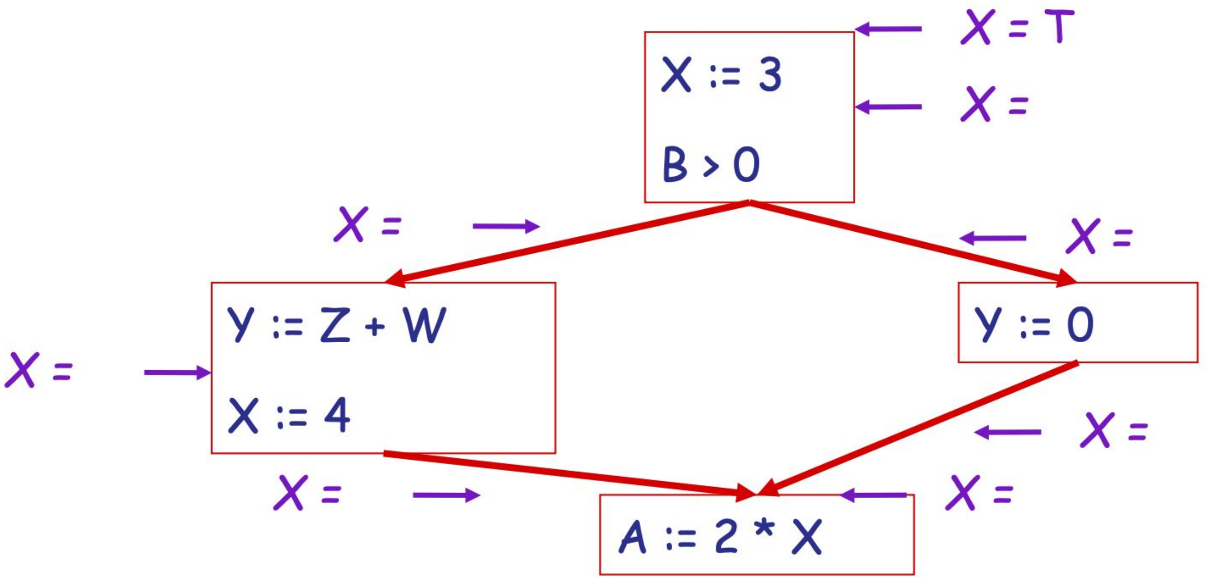

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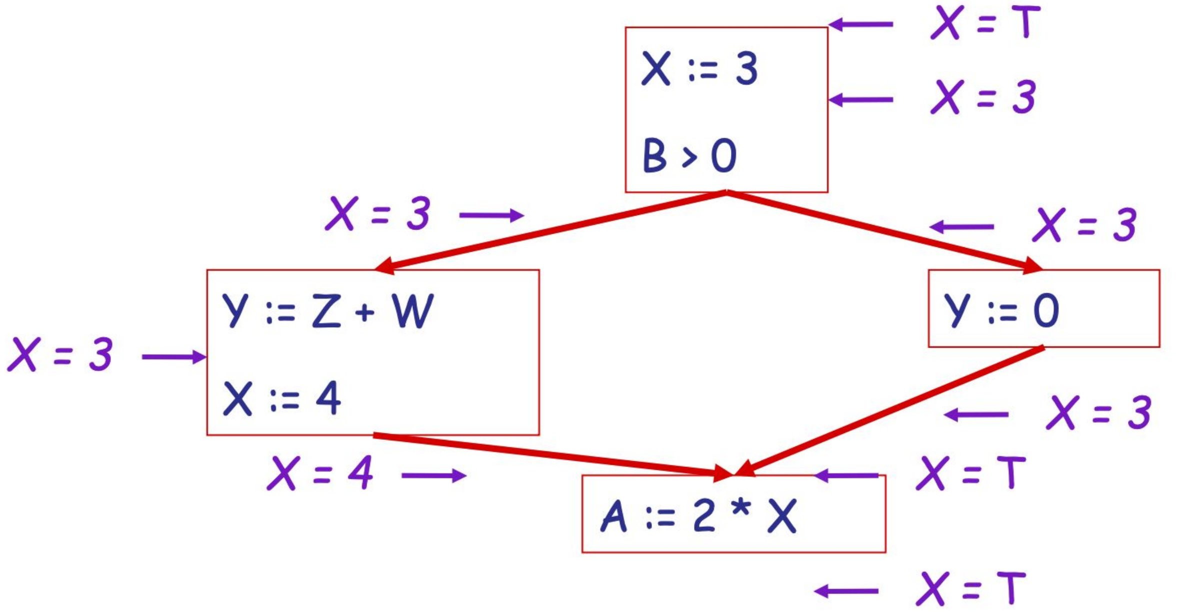

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- But how can an **algorithm** compute $x = ?$

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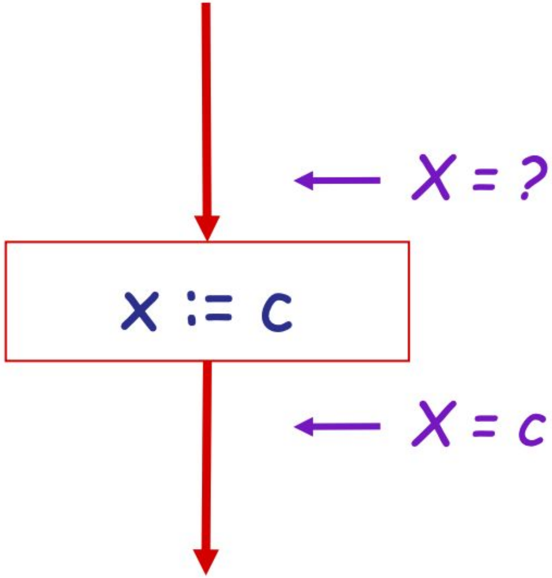
Definition: a ***transfer function*** expresses the relationship between $C_{in}(x, s)$ and $C_{out}(x, s)$

Transfer functions: rule 1

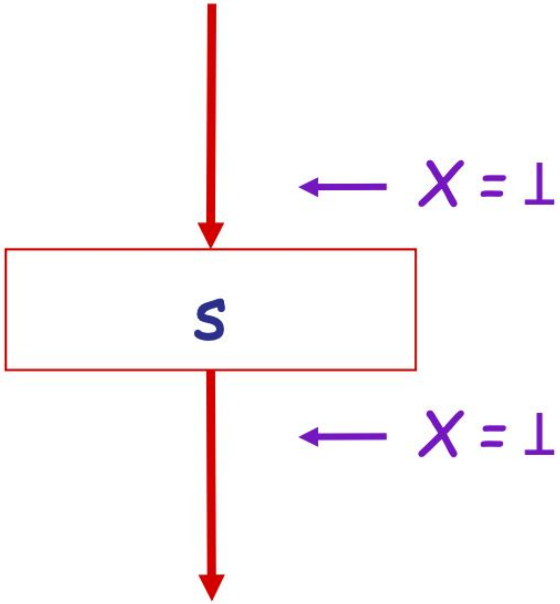


$C_{out}(x, x := c) = c$ if c is a constant

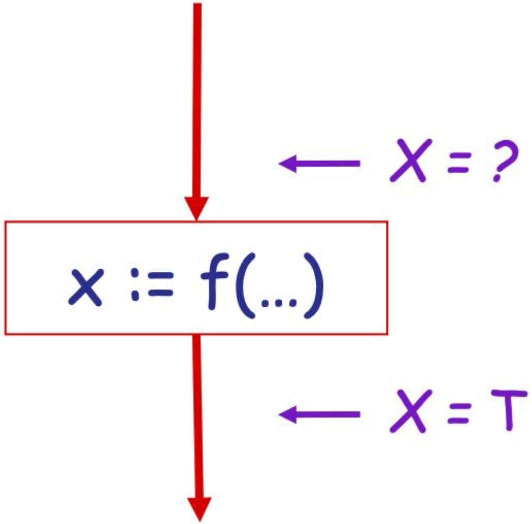
Transfer functions: rule 2

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

Recall bottom = “unreachable code”



Transfer functions: rule 3



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

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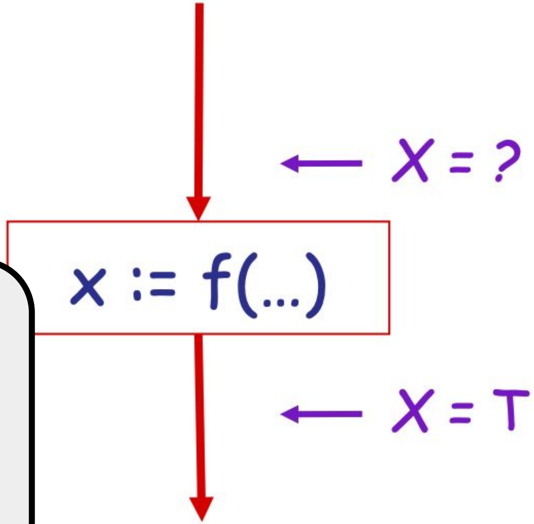
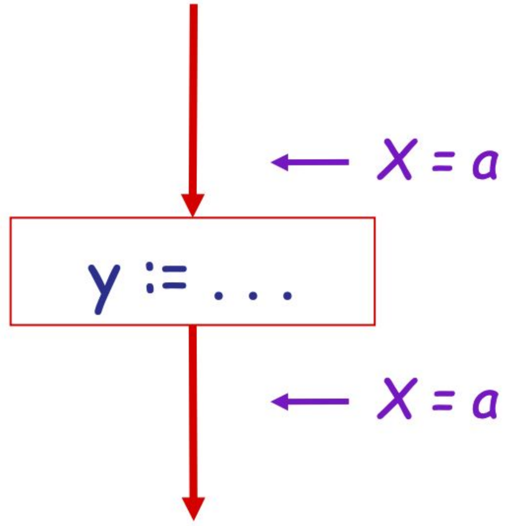


This is a **conservative approximation**! f(...) might always return 0, but we don't even try!

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

Transfer functions: rule 4



$C_{out}(x, y := \ldots) = C_{in}(x, y := \ldots)$ if $x \neq y$

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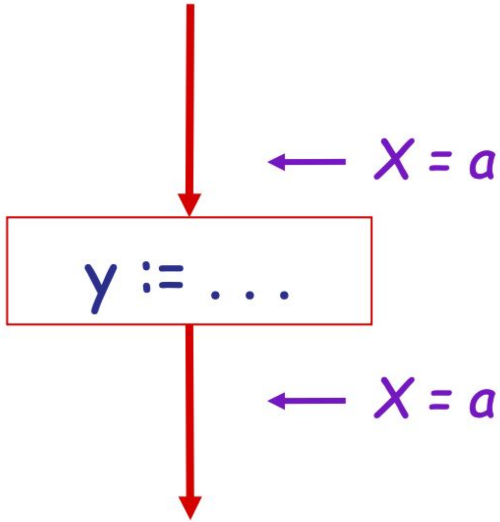

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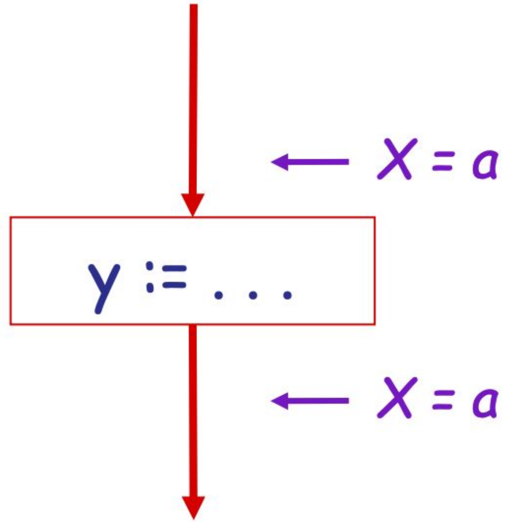
How hard is it to check if x ≠ y on all executions? (oh no)



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Propagation between statements

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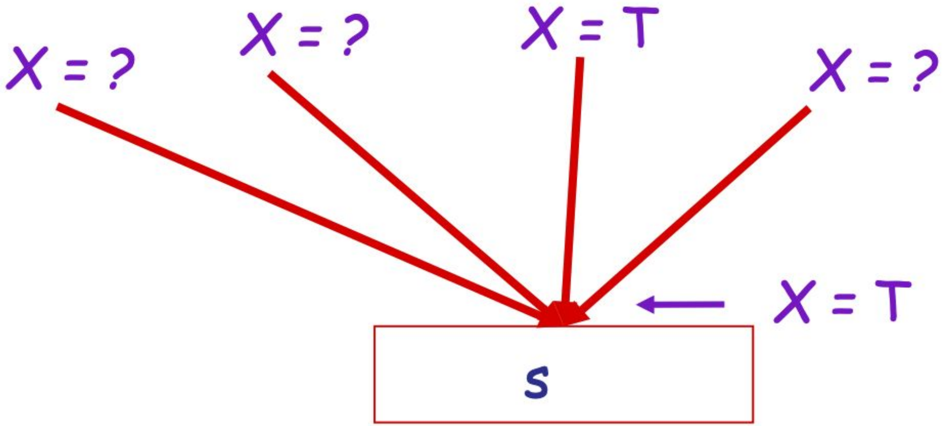
- In the following rules, let statement s have immediate predecessor statements $p_1, \ldots, p_n$

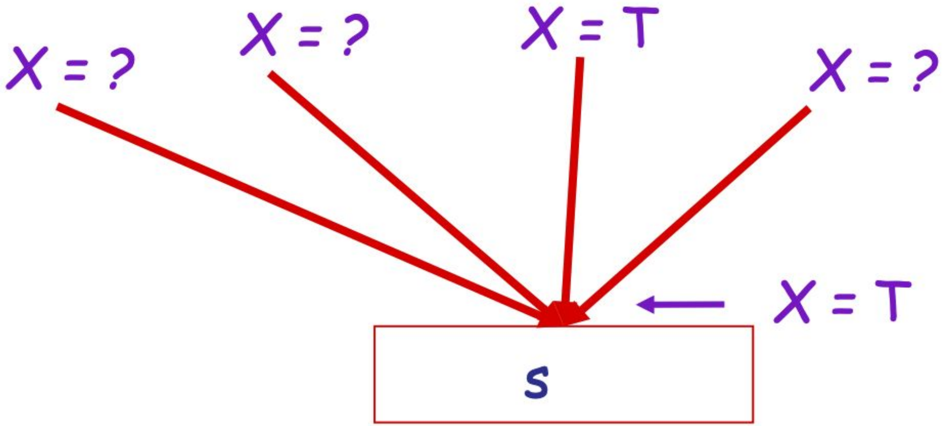
Transfer functions: rule 5



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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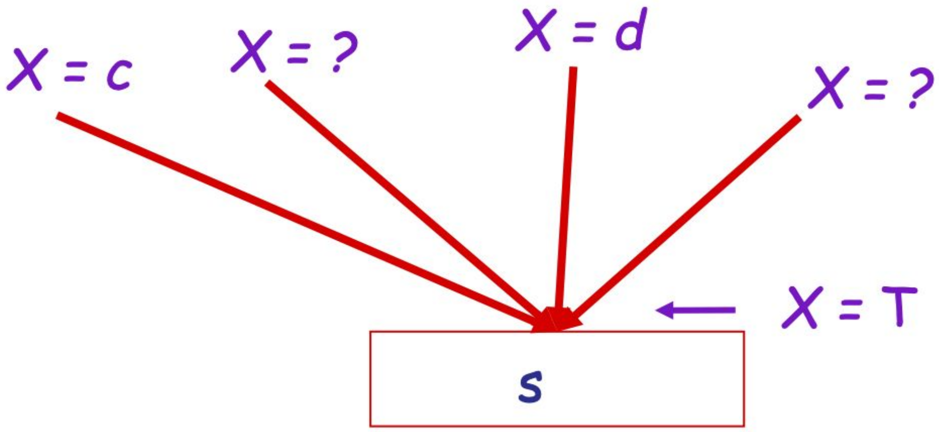
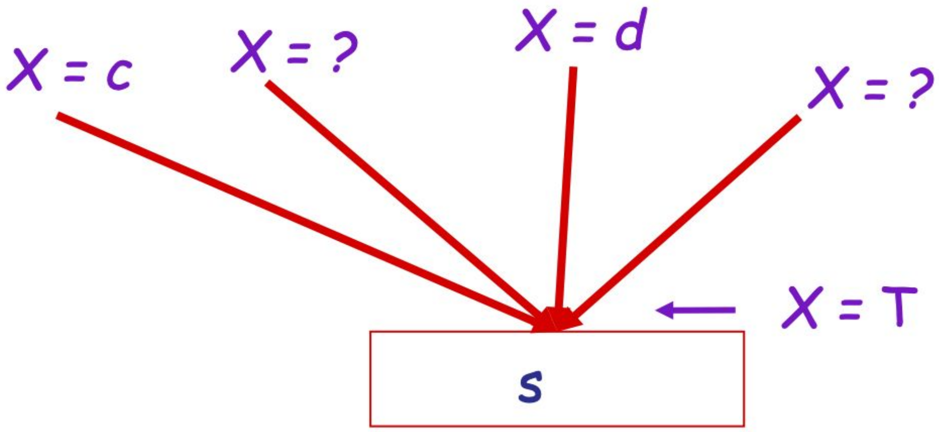


if $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$ then $C_{in}(x, s) = T$

Transfer functions: rule 6



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

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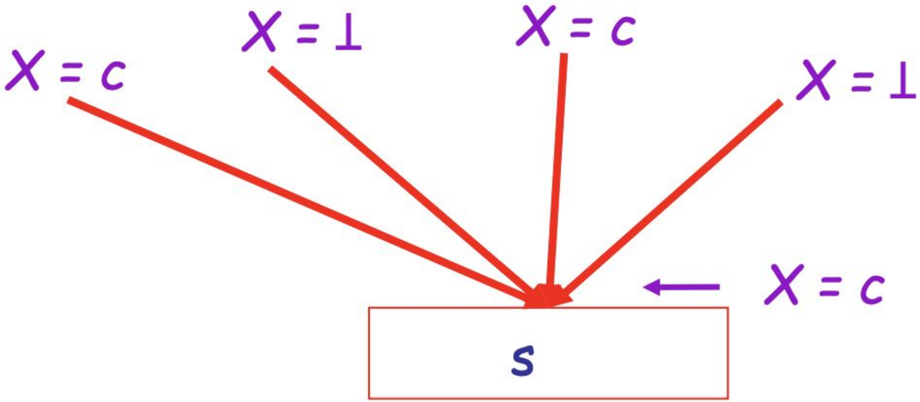
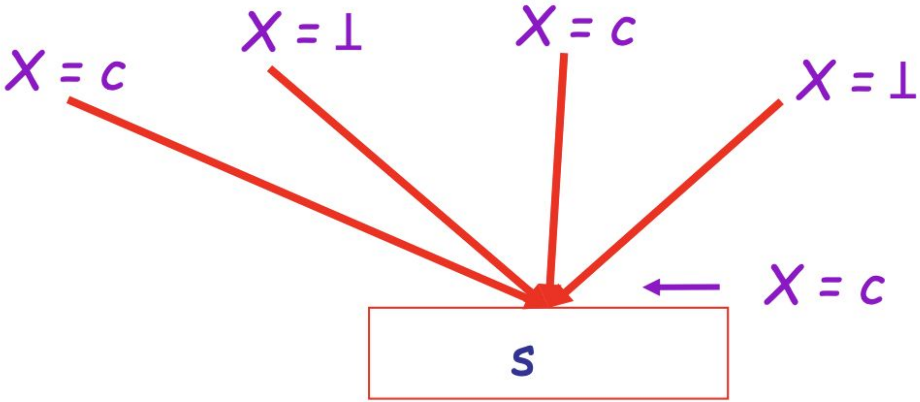
Transfer functions: rule 7



if $C_{out}(x, p_i) = c$ or 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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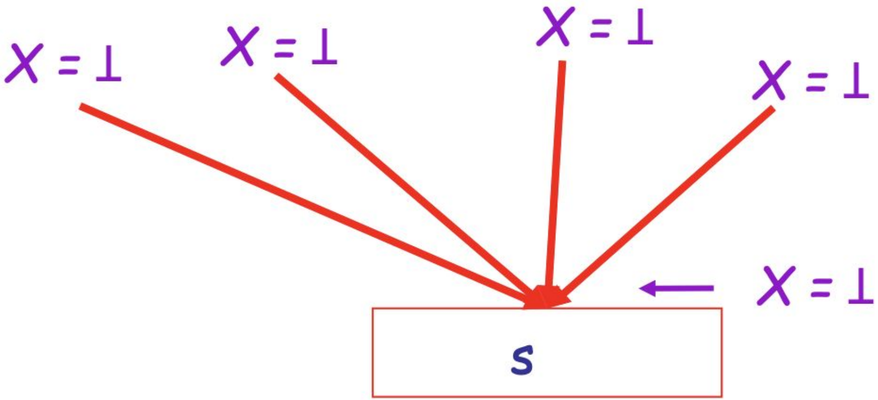

if $C_{out}(x, p_i) =$ bottom for all i, then $C_{in}(x, s) =$ bottom

A static analysis algorithm

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- 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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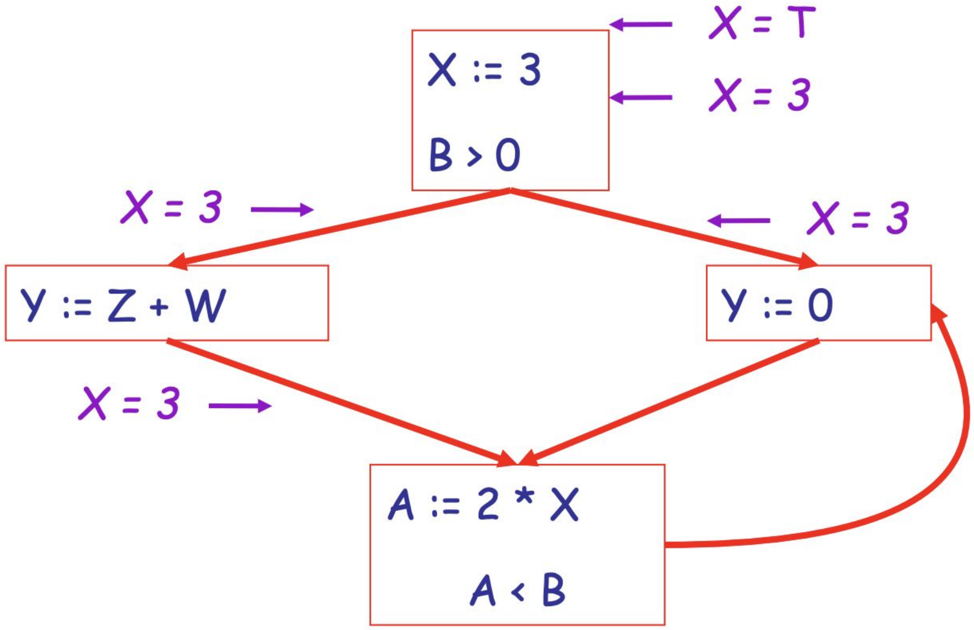

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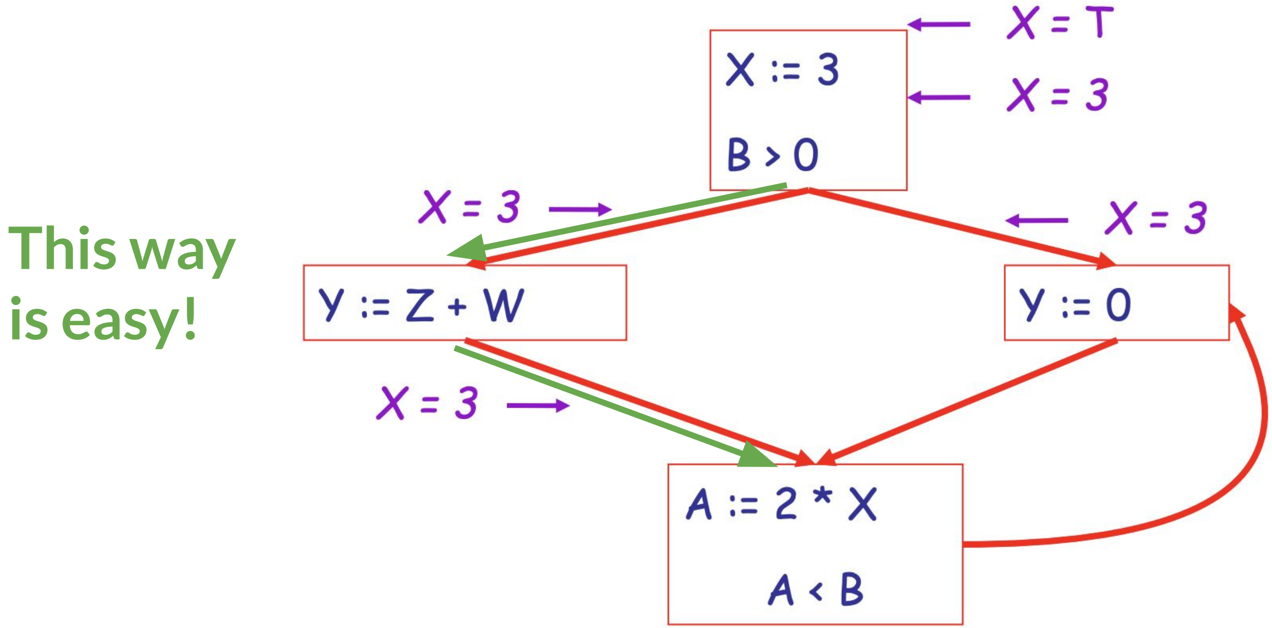

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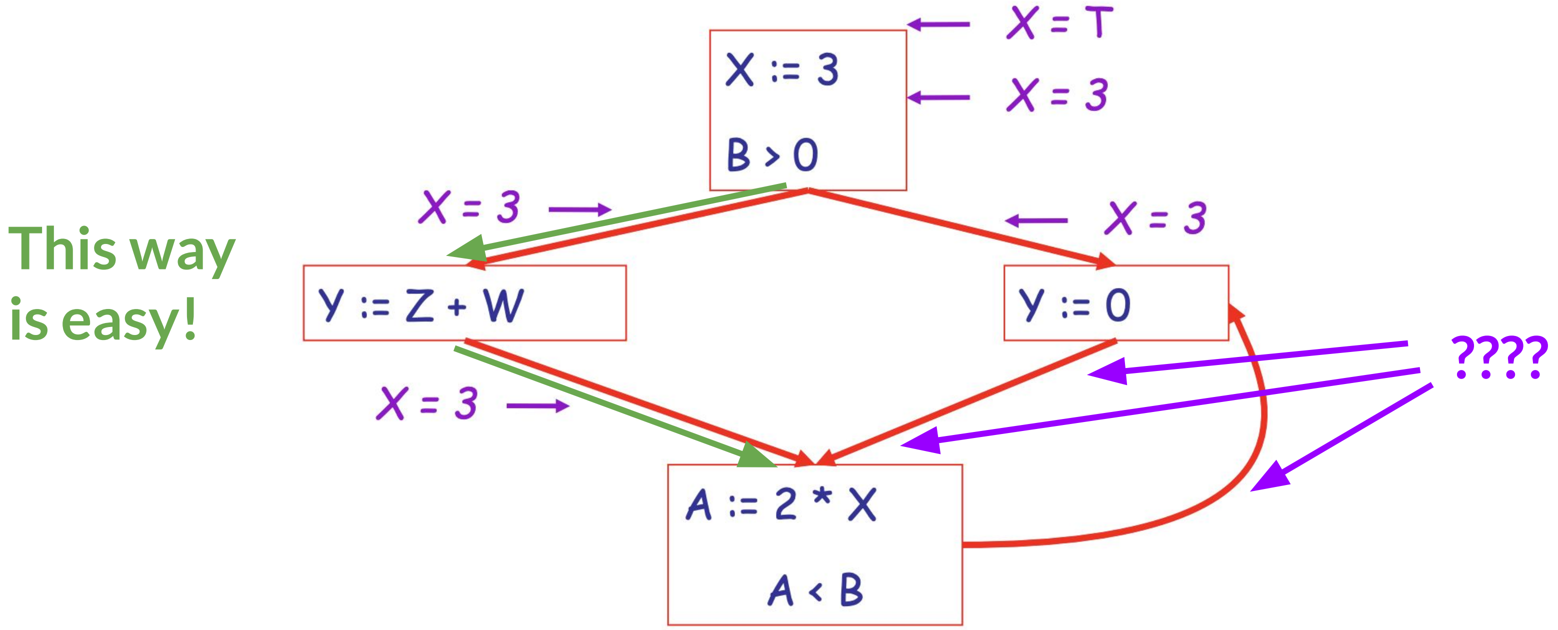

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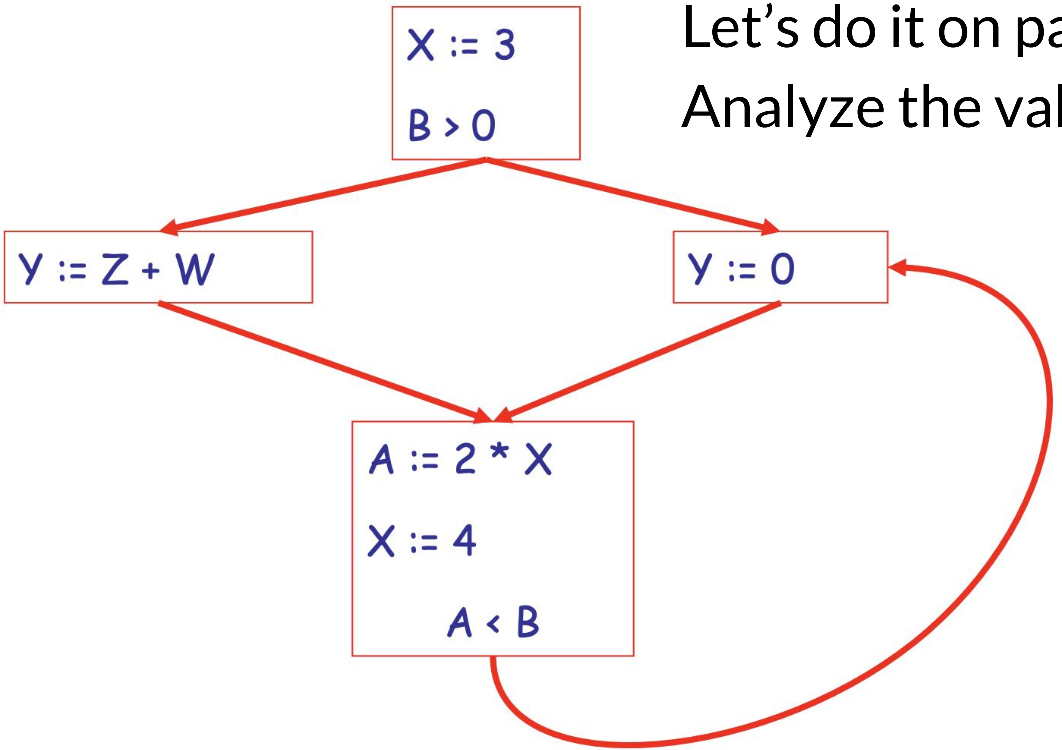
- The initial value bottom means "**we have not yet analyzed control reaching this point**"

Another example: dealing with loops



Let's do it on paper!

Analyze the value of X.

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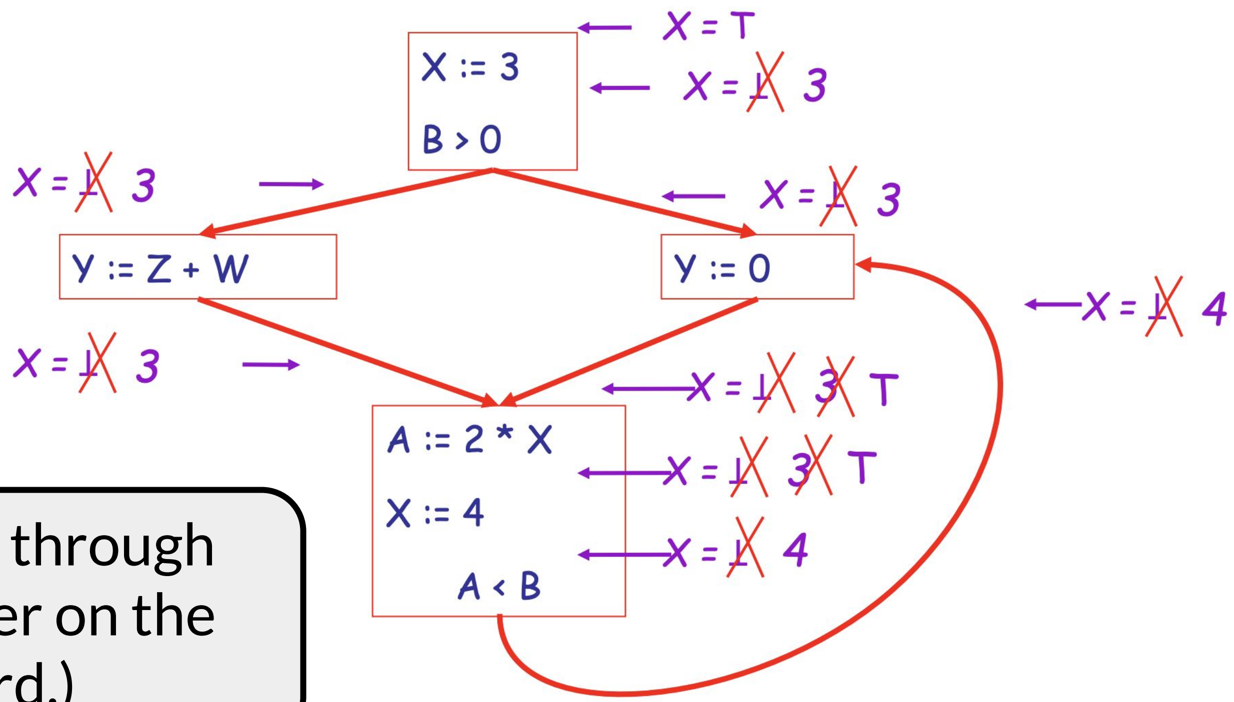

(We went through this answer on the whiteboard.)

Lattices & Orderings

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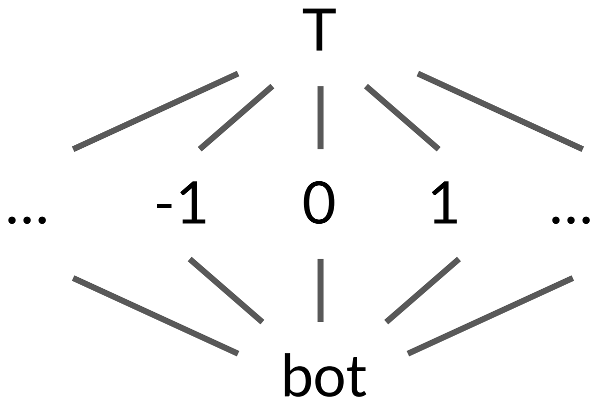
Lattices & Orderings

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



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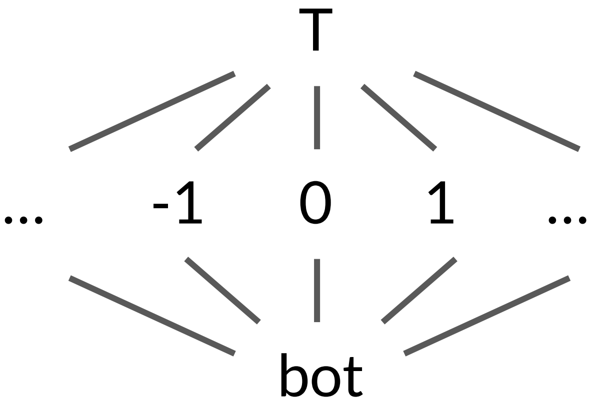

How to read a lattice:

- 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

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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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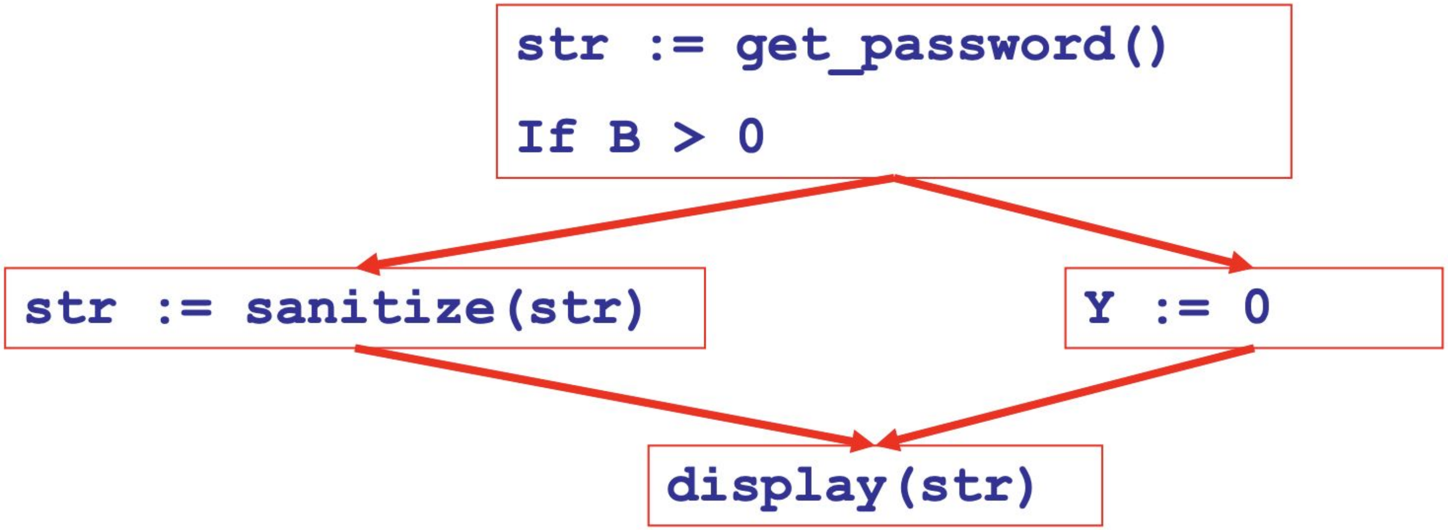

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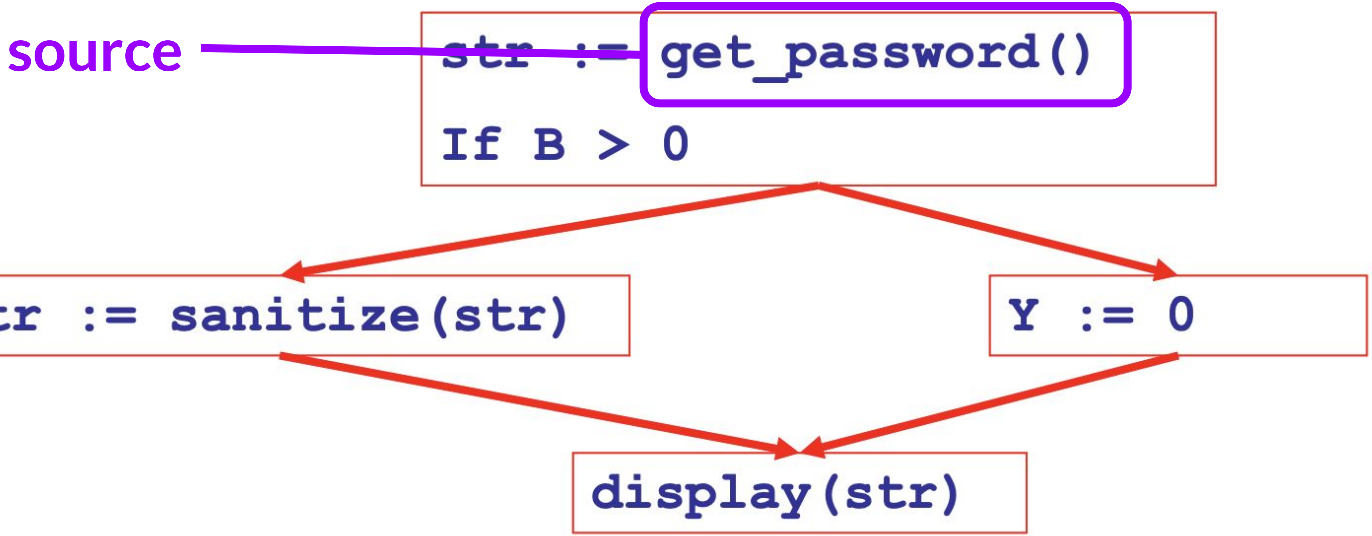

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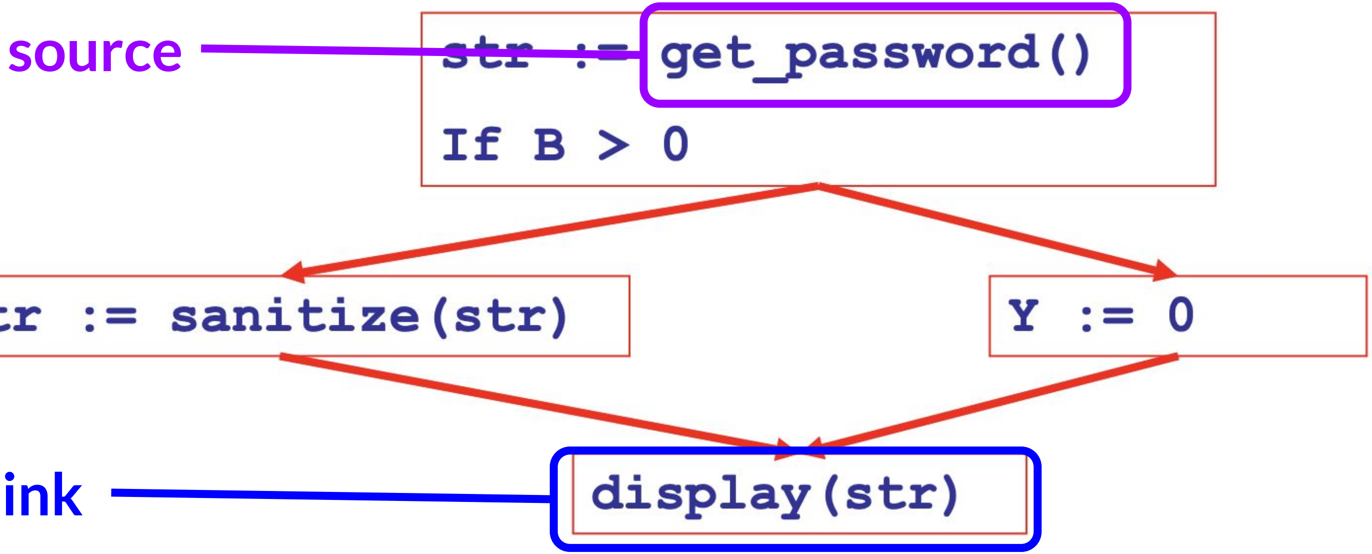

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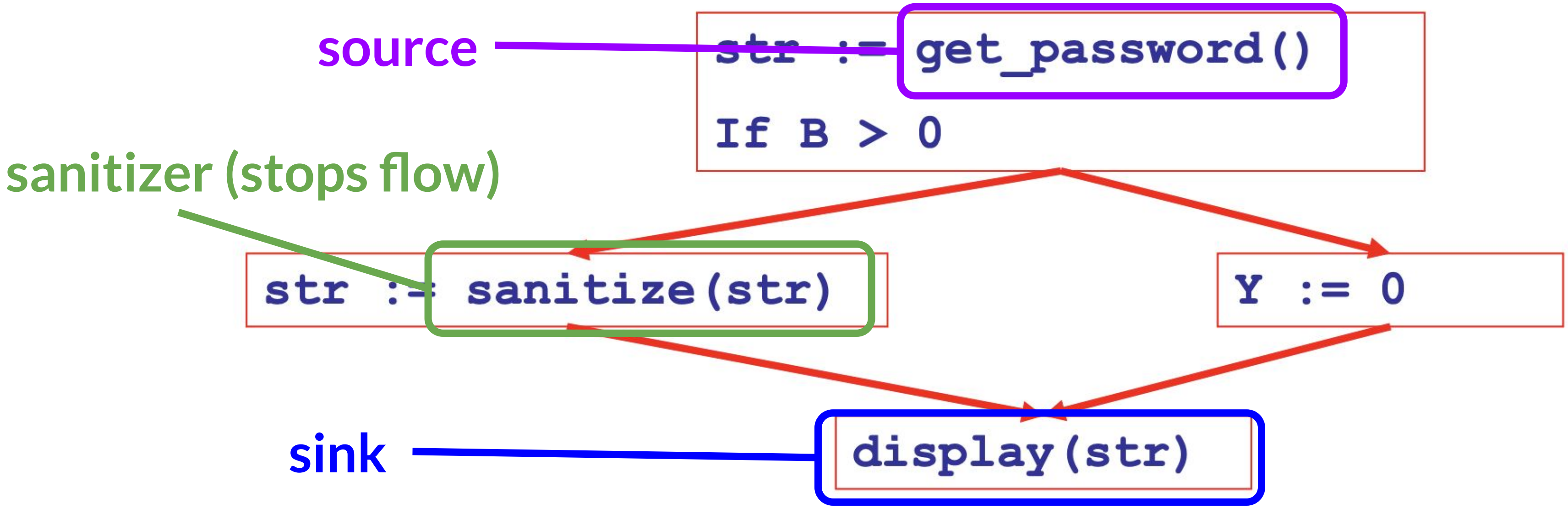

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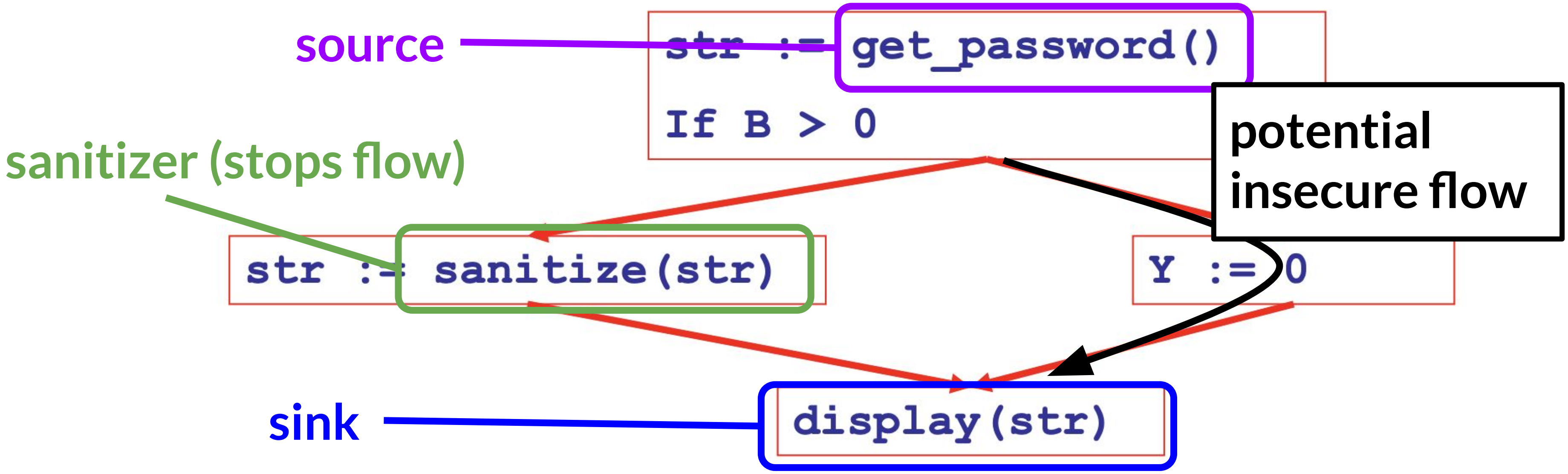

Taint analysis

Definition: A ***taint analysis*** (or ***reachability analysis***) tracks whether (any/all) value(s) from a set of sources reach a set of sinks

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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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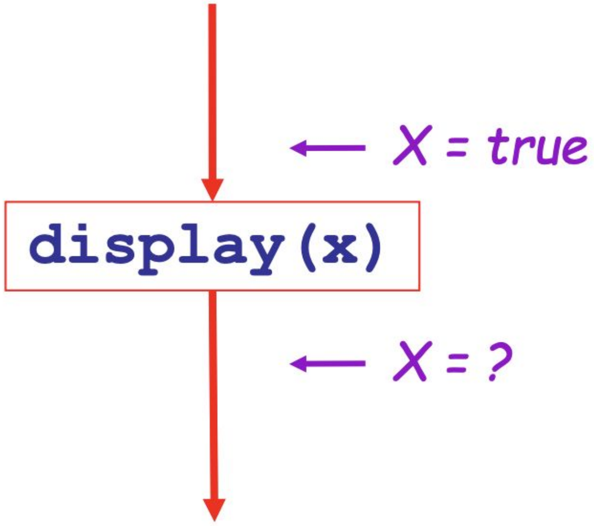
Note that the rules for this analysis are intended to be applied "backwards"

Secure information flow analysis: rule 1



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

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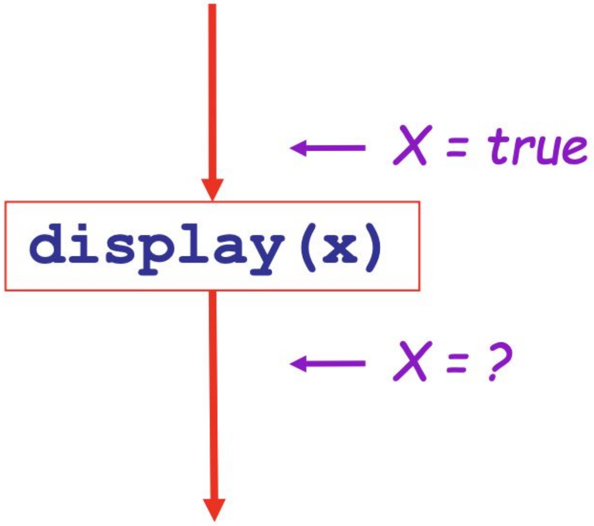
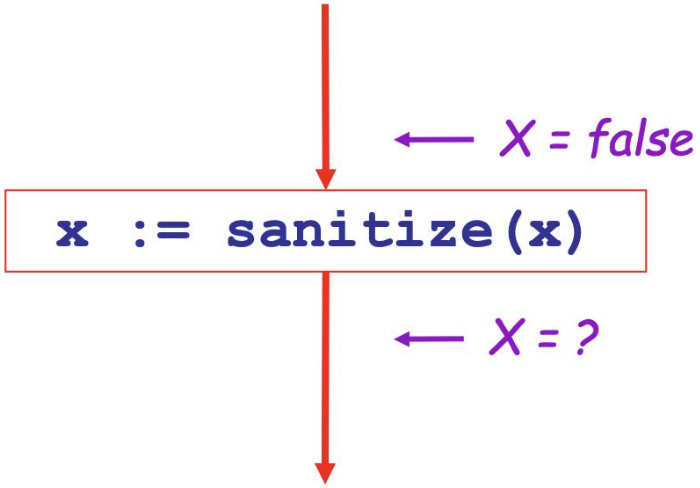


$H_{in}(x, s)$ = true if s displays x publicly

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

Secure information flow analysis: rule 2

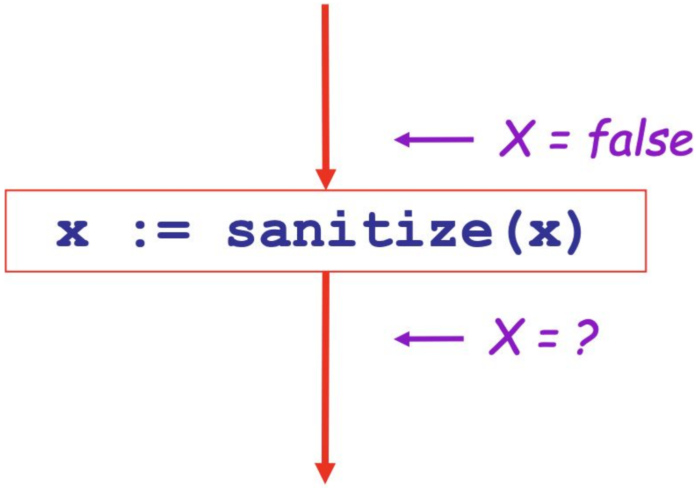
$H_{in}(x, x := e) = \text{false}$



Secure information flow analysis: rule 2

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

This means any value that is sanitized is not sensitive



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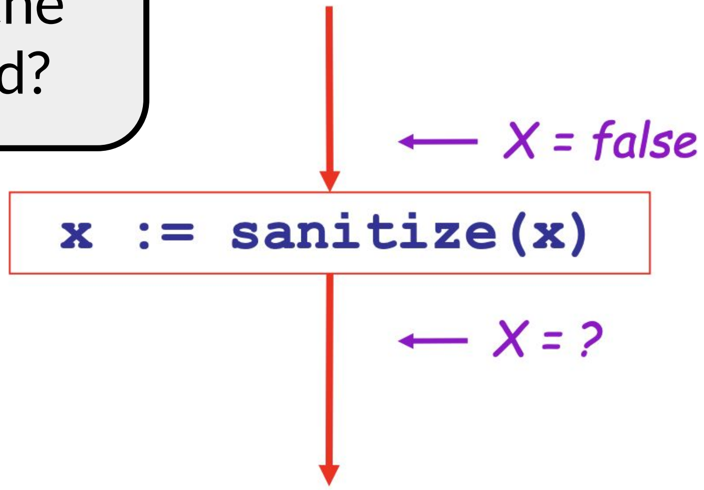
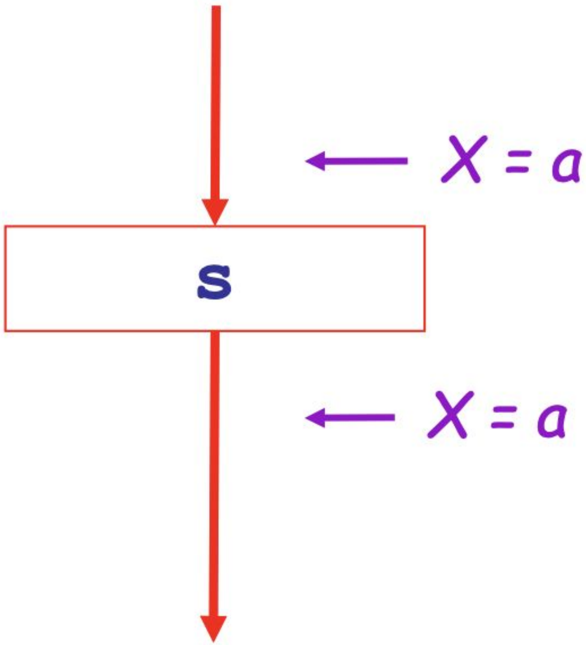
Does this rule say anything about the sanitize() method?

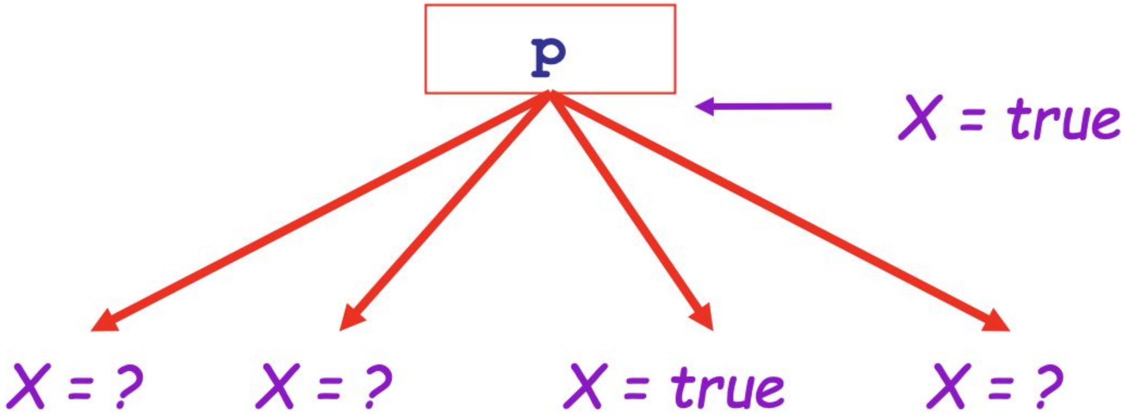


Secure information flow analysis: rule 3



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

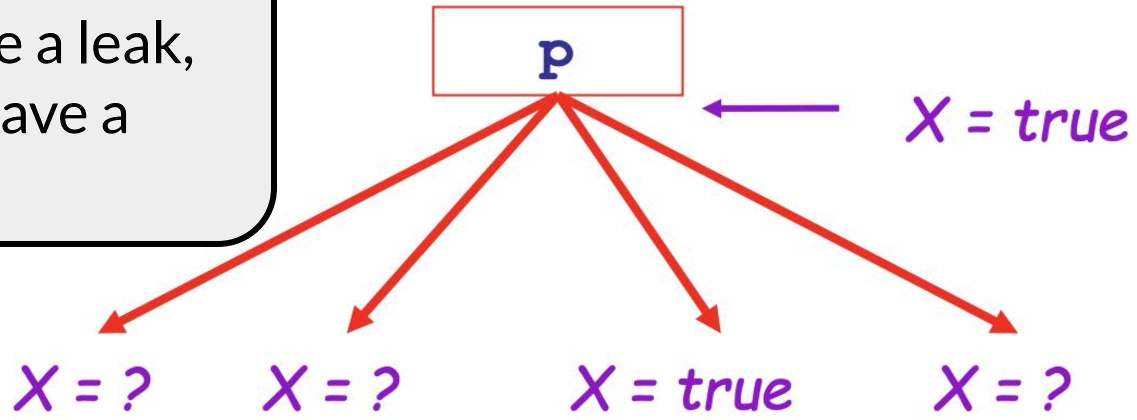
Secure information flow analysis: rule 4



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

Secure information flow analysis: rule 4

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



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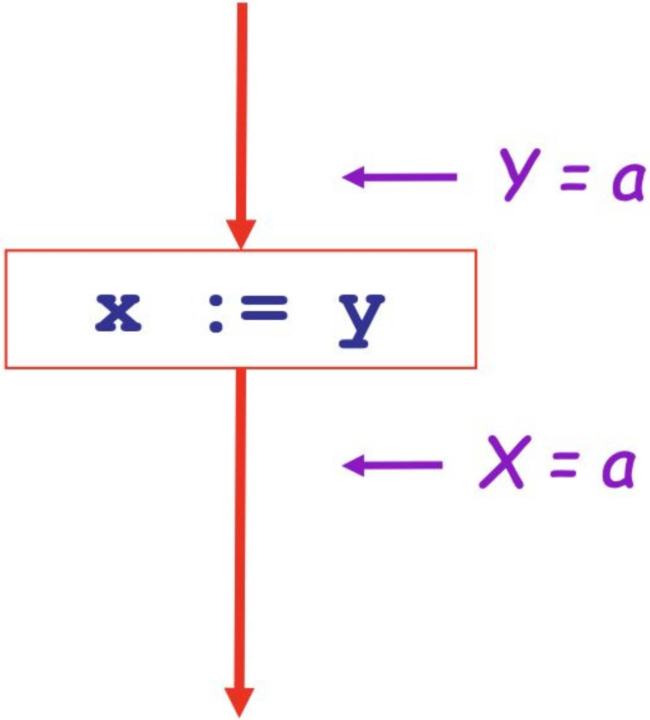
Secure information flow analysis: rule 5

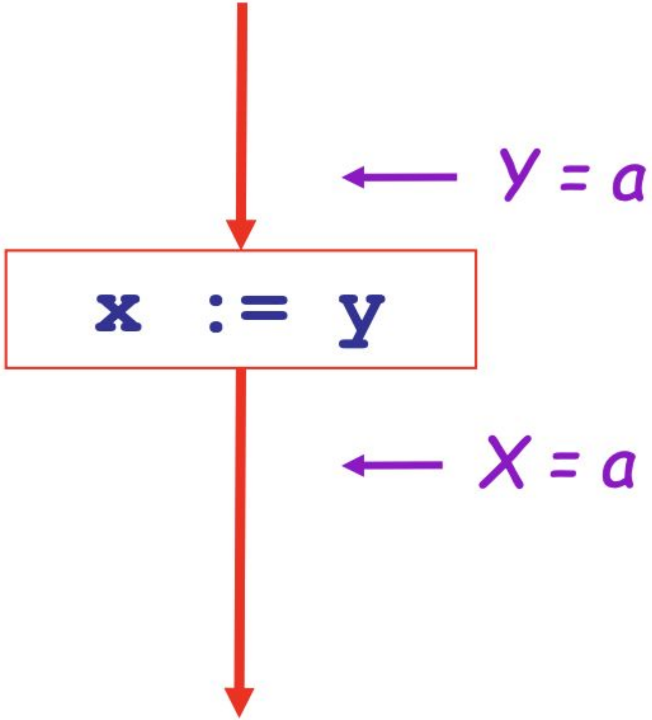
$H_{in}(y, x := y) = H_{out}(x, x := y)$



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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1. let all H_(...) = **false initially**

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false is like bottom in our nullness analysis!

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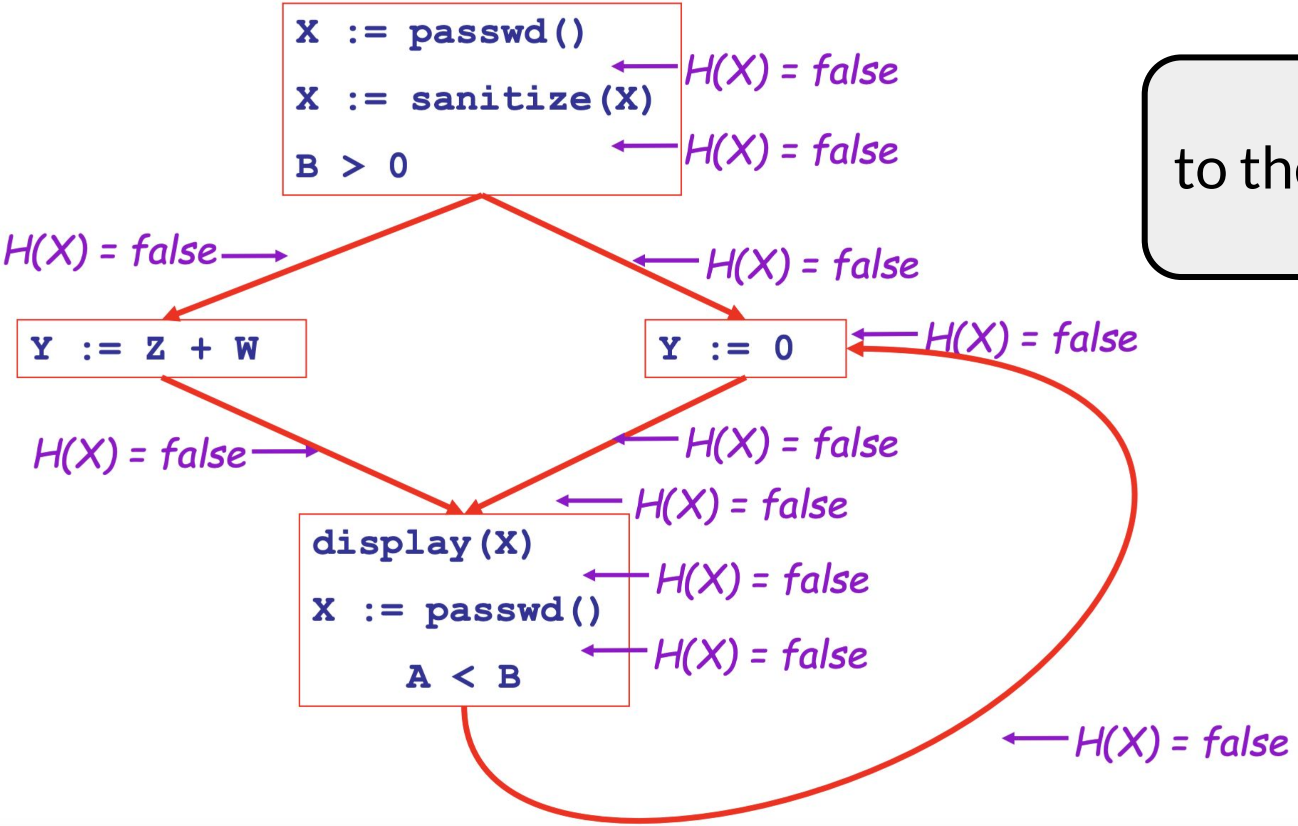
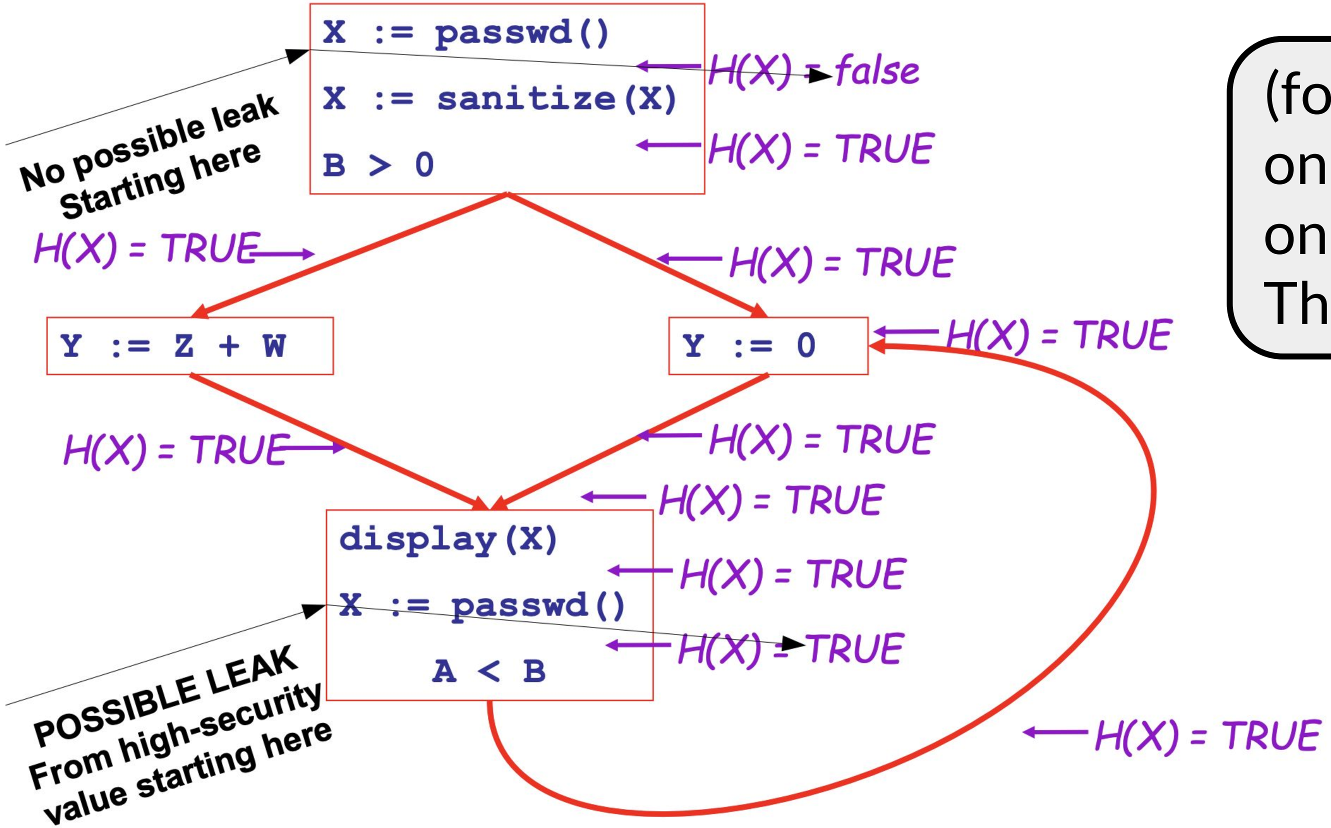
3. once the analysis reaches a fixed point, **issue a warning** at any source (x, s) where H_{out}(x, s) is true (= leaks sensitive information)

Secure information flow analysis: example



to the whiteboard!

Secure information flow analysis: example



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

Agenda: dataflow analysis

- last few slides of static vs dynamic analysis
- key ideas in static analysis design
- dataflow analysis
    - nullness analysis example
    - secure information flow analysis example
- **limitations of static analysis**
- static analysis in practice

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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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used in HW7

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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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  - 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)

Course announcements

- Any remaining time today: start HW7
  - HW7 involves running the Infer static analyzer on some subject programs and then analyzing the results (by hand)
- I have your midterms with me at the front of the room if you'd like them back
  - (they are sorted by UCID, so please tell me your UCID)