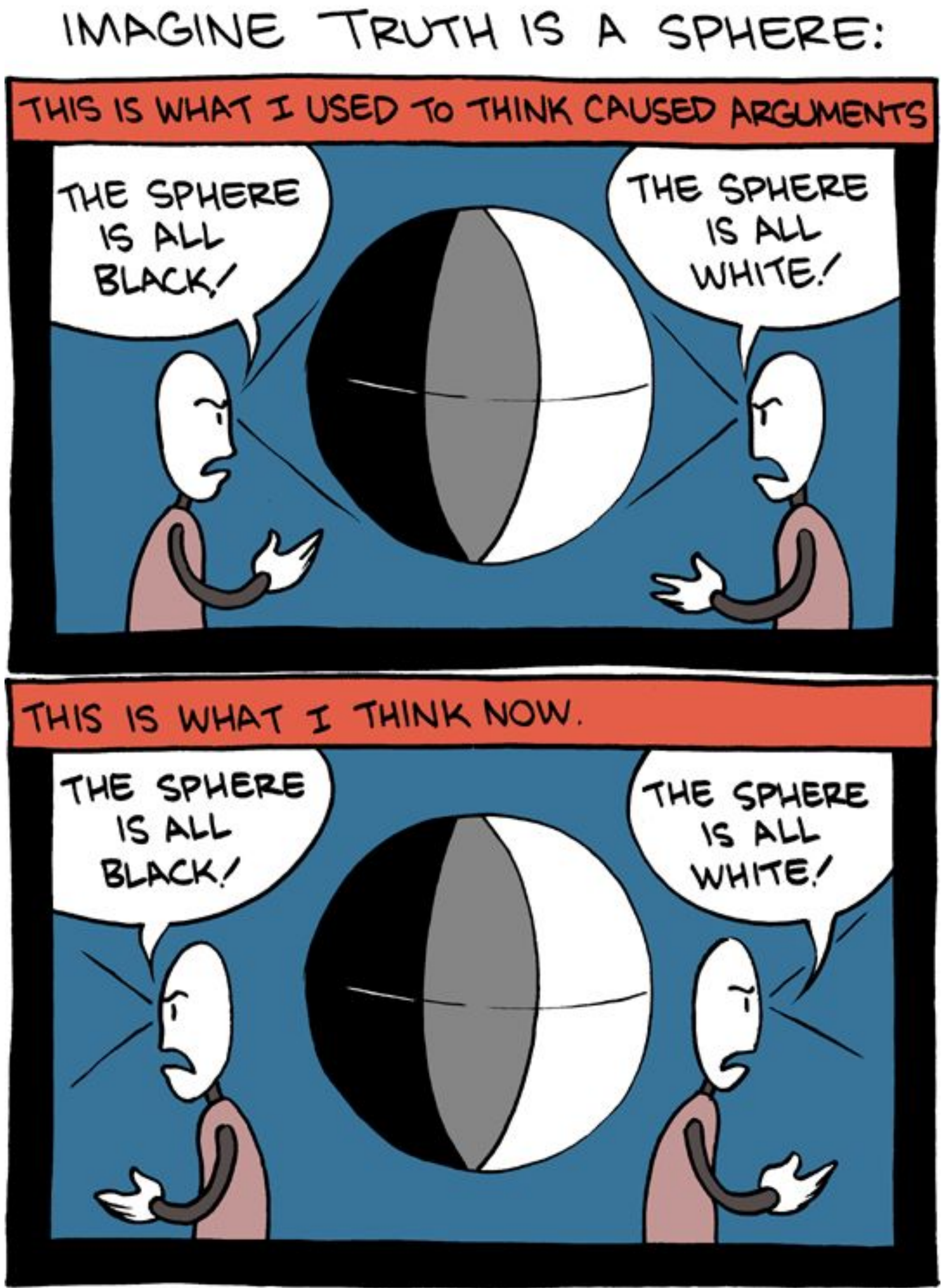


Static and Dataflow Analysis

(two-part lecture)

```
Foo(ptr, x) {
    if (x > 10) {
        deref ptr
    }
}
```

```
Foo(ptr, x, y, z, ...) {
   if (x > 10) {
      deref ptr
   }
   ...
}
```

The Story So Far …

- Quality assurance is critical to software engineering.
- Testing is the most common **dynamic** approach to QA.
  - But: race conditions, information flow, profiling …
- Code review and code inspection (next week) are common **static** approaches to QA.
- Today: **(automated) static analyses**

One-Slide Summary

- **Static analysis** is the systematic examination of an **abstraction** of program state space with respect to a property. Static analyses reason about all possible executions but they are **conservative**.
- **Dataflow analysis** is a popular approach to static analysis. It tracks a few broad values (“secret information” vs. “public information”) rather than exact information. It can be computed in terms of a local **transfer** of information.

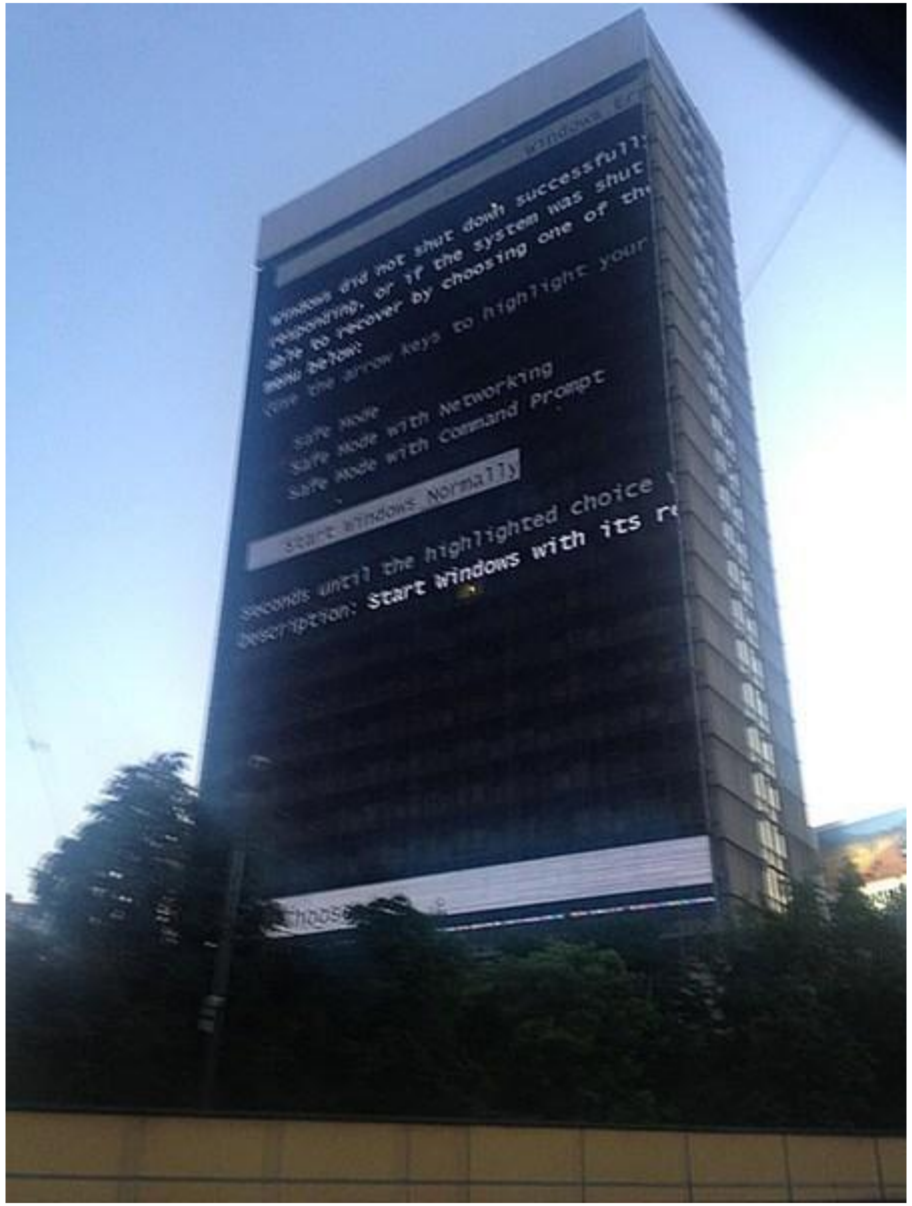
Fundamental Concepts

- **Abstraction**
  - Capture semantically-relevant details
  - Elide other details
  - Handle “I don't know”: think about developers
- **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)

```
Foo(ptr, x, y, z, ...) {
   if (x > 10) {
      deref ptr
   }
   ...
}
```

goto fail;

Why care about **static** analysis?



"Unimportant" SSL Example

```
static OSStatus SSLVerifySignedServerKeyExchange(
                    SSLContext *ctx, bool isRsa,SSLBuffer signedParams,
                    uint8_t *signature,UInt16 signatureLen) {
   OSStatus err;
   ...
   if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
      goto fail;
   if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
      goto fail;
      goto fail;
   if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
      goto fail;
   ...
fail:
   SSLFreeBuffer(&signedHashes);
   SSLFreeBuffer(&hashCtx);
   return err;}
```

How do you reason about this program?

Linux Driver Example

```
/* from Linux 2.3.99 drivers/block/raid5.c */
static struct buffer_head *get_free_buffer(struct
stripe_head * sh,int b_size) {
  struct buffer_head *bh;
  unsigned long flags;
  save_flags(flags);
  cli(); // disables interrupts
  if ((bh = sh->buffer_pool) == NULL)
    return NULL;
  sh->buffer_pool = bh -> b_next;
  bh->b_size = b_size;
  restore_flags(flags); // enables interrupts
  return bh;
}
```

How do you reason about this program?

Could We Have Found Them? (Testing?)

- How often would those bugs trigger?
- Linux example:
  - What happens if you return from a device driver with interrupts disabled?
  - Consider: that's just one function

  … in a 2,000 LOC file

  … in a 60,000 LOC module

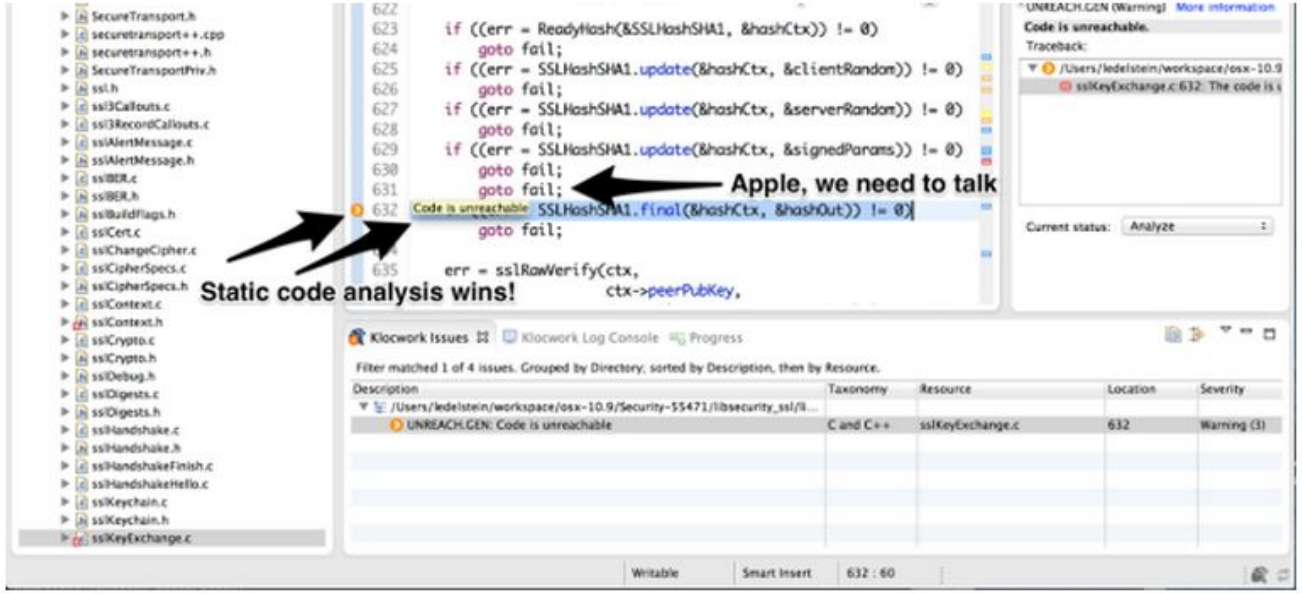
  … in the Linux kernel
- Some defects are very difficult to find via testing or manual inspection

Klocwork: Our source code analyzer caught Apple's 'gotofail' bug

If Apple had used a third-party source code analyzer on its encryption library, it could have avoided the "gotofail" bug.

by Declan McCullagh | February 28, 2014 1:13 PM PST

Follow



Klocwork's Larry Edelstein sent us this screen snapshot, complete with the arrows, showing how the company's product would have nabbed the "goto fail" bug.

(Credit: Klocwork)

It was a single repeated line of code -- "goto fail" -- that left millions of Apple users vulnerable to Internet attacks until the company finally fixed it Tuesday.

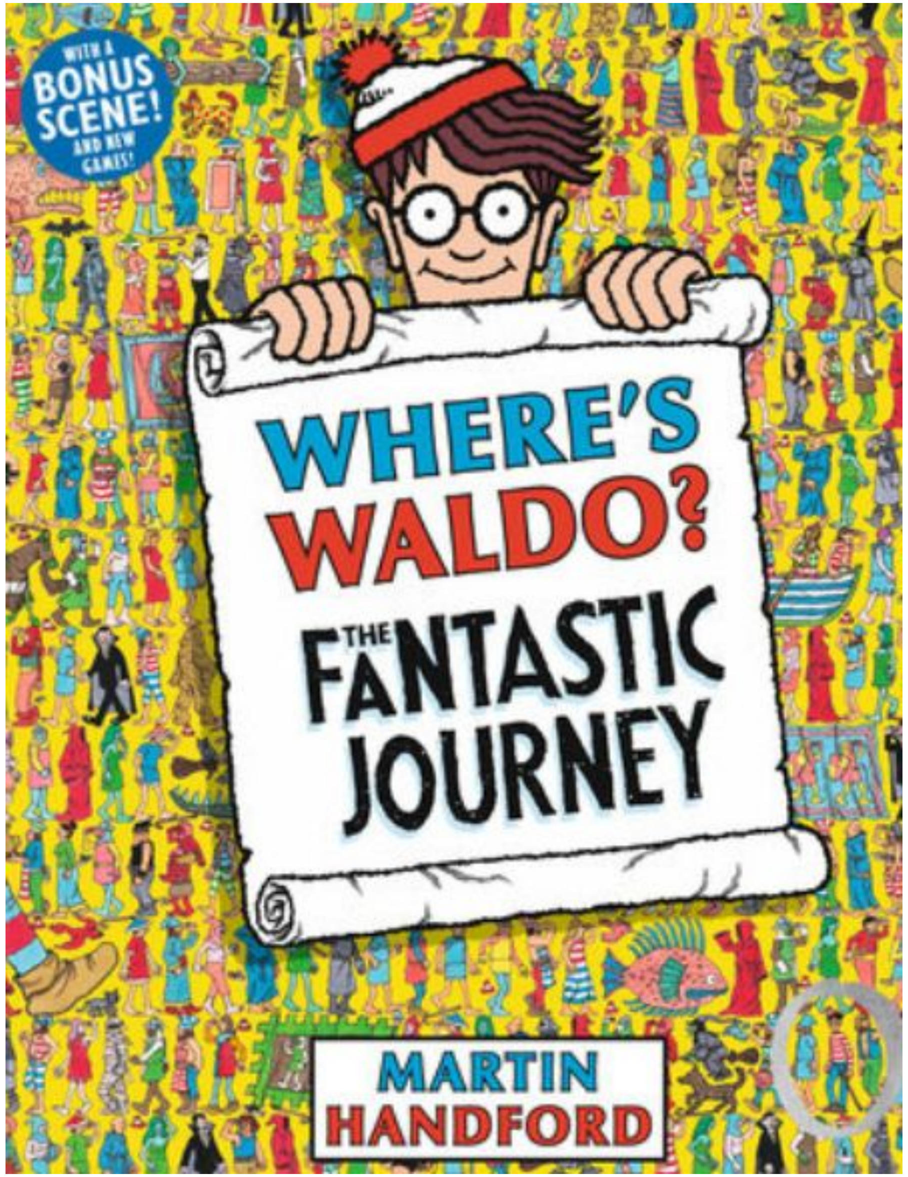
Many Interesting Defects

- … are on uncommon or difficult-to-exercise execution paths
  - Thus it is hard to find them via testing
- Executing or dynamically analyzing all paths concretely to find such defects is not feasible
- We want to learn about "all possible runs" of the program for particular properties
  - Without actually running the program!
  - Bonus: we don't need test cases!

Static Analyses Often Focus On

- Defects that result from inconsistently following simple, mechanical design rules
  - Security: buffer overruns, input validation
  - Memory safety: null pointers, initialized data
  - Resource leaks: memory, OS resources
  - API Protocols: device drivers, GUI frameworks
  - Exceptions: arithmetic, library, user-defined
  - Encapsulation: internal data, private functions
  - Data races (again!): two threads, one variable

How And Where Should We Focus?



Static Analysis - Abstractions!

- **Static analysis** is the systematic examination of an abstraction of program state space
  - **Static analyses do not execute the program!**
- An **abstraction** is a selective representation of the program that is simpler to analyze
  - Abstractions have fewer states to explore
- Analyses check if a particular property holds
  - Liveness: “some good thing eventually happens”
  - Safety: “some bad thing never happens”

Syntactic Analysis Example

- Goal – Find every instance of this pattern:

```
public foo() {
  …
   logger.debug("We have " + conn + "connections.");
}
```

```
public foo() {
  …
  if (logger.inDebug()) {
    logger.debug("We have " + conn + "connections.");
  }
}
```

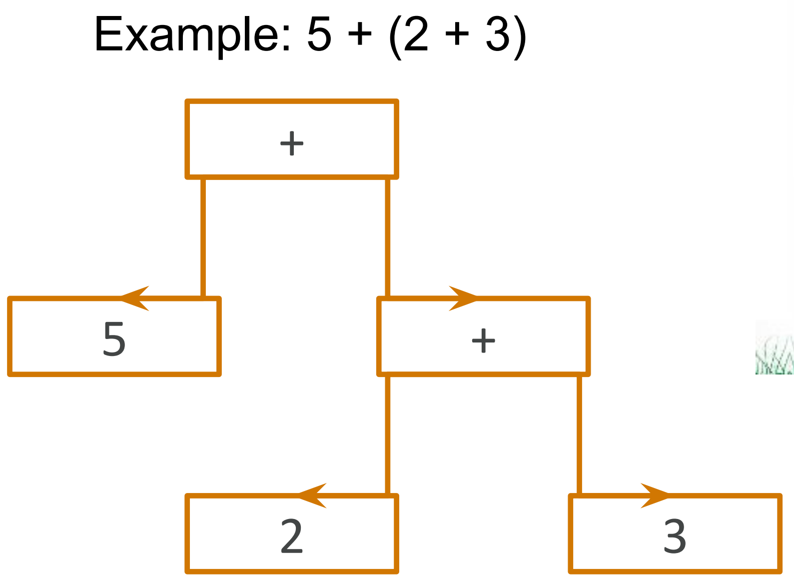
- What could go wrong? First attempt:

`grep logger\.debug -r source_dir`

Abstraction: Abstract Syntax Tree

- An **AST** is a tree representation of the syntactic structure of source code
  - Parsers convert concrete syntax into abstract syntax
- Records only semantically-relevant information
  - Abstracts away (, etc.

- AST captures program structure



Programs As Data

- “grep” approach: treat program as string
- AST approach: treat program as tree
- The notion of treating a program as data is fundamental
  - Recall from 370: instructions are input to a CPU
    - Writing different instructions causes different execution
- It relates to the notion of a Universal Turing Machine.
  - Finite state controller and initial tape represented with a string
    - Can be placed as tape input to another TM

Dataflow Analysis

- **Dataflow analysis** is a technique for gathering information about the possible set of values calculated at various points in a program
  - We first abstract the program to an AST or CFG
  - We then abstract what we want to learn (e.g., to help developers) down to a small set of values
  - We finally give rules for computing those abstract values
    - Dataflow analyses take programs as input

Two Exemplar Analyses

- *Definite* Null Dereference
  - "Whenever execution reaches *ptr at program location L, ptr will be NULL"
- *Potential* Secure Information Leak
  - "We read in a secret string at location L, but there is a possible future public use of it"

Discussion

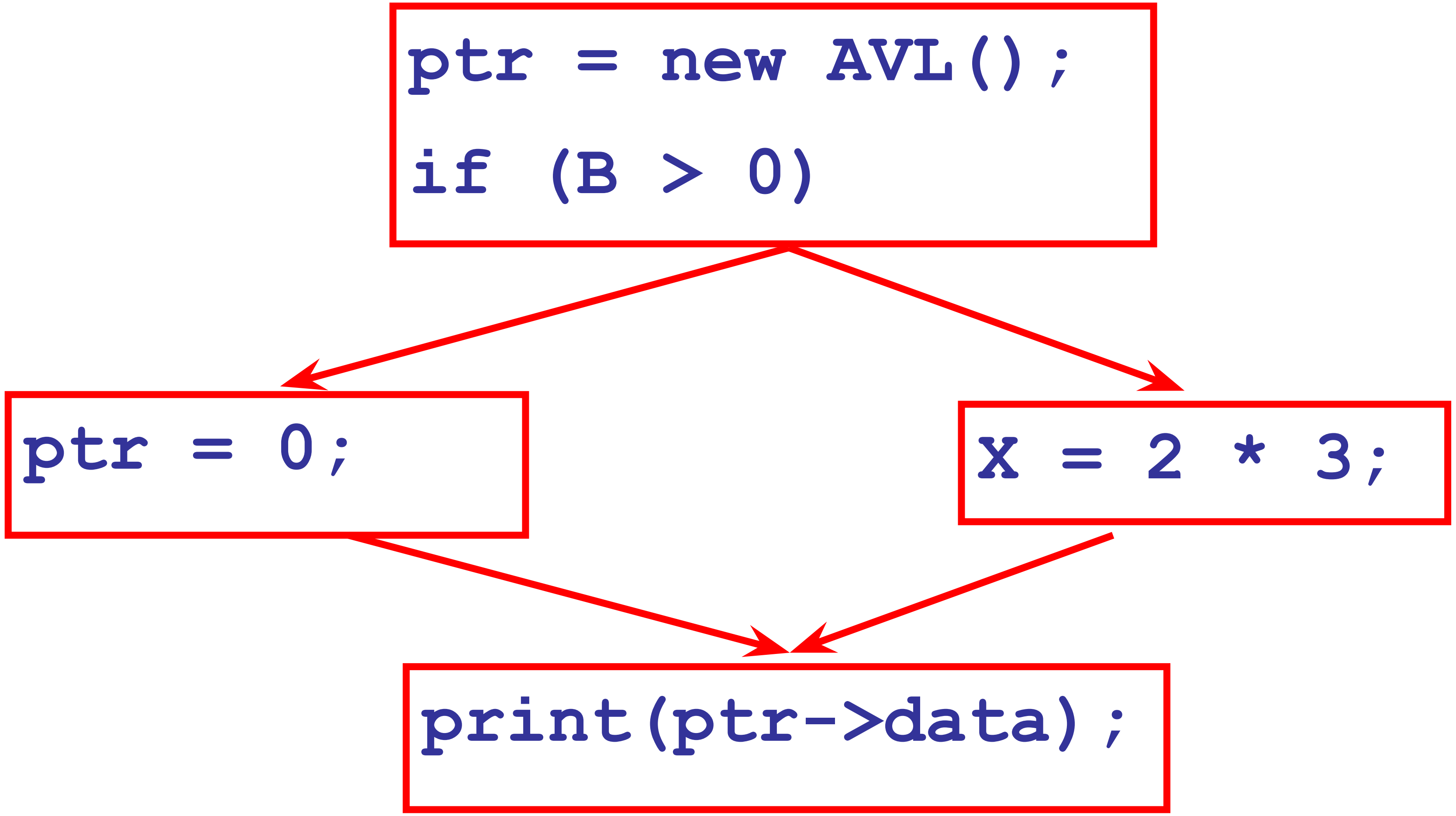
- These analyses are not trivial

- "Whenever execution reaches" $\longrightarrow$ "**all paths**" $\longrightarrow$ includes paths around loops and through branches of conditionals

- We will use **(global) dataflow analysis** to learn about the program
  - Global = an analysis of the entire method body, not just one { block }

Analysis Example

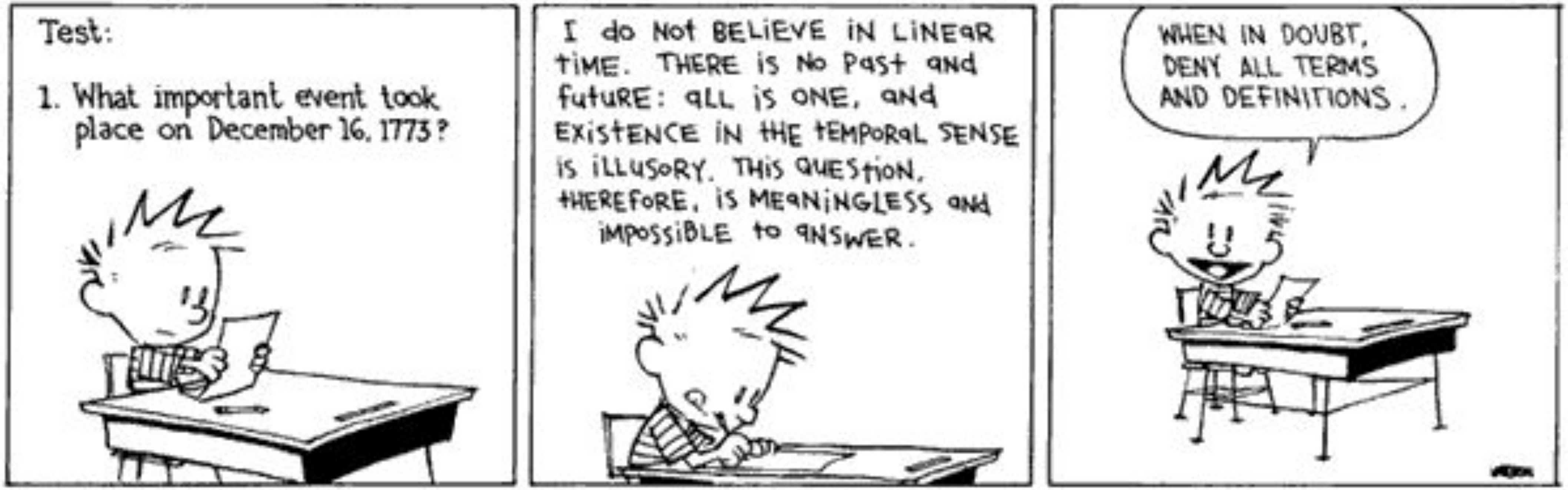
- Is **ptr** *always* null when it is dereferenced?



Correctness

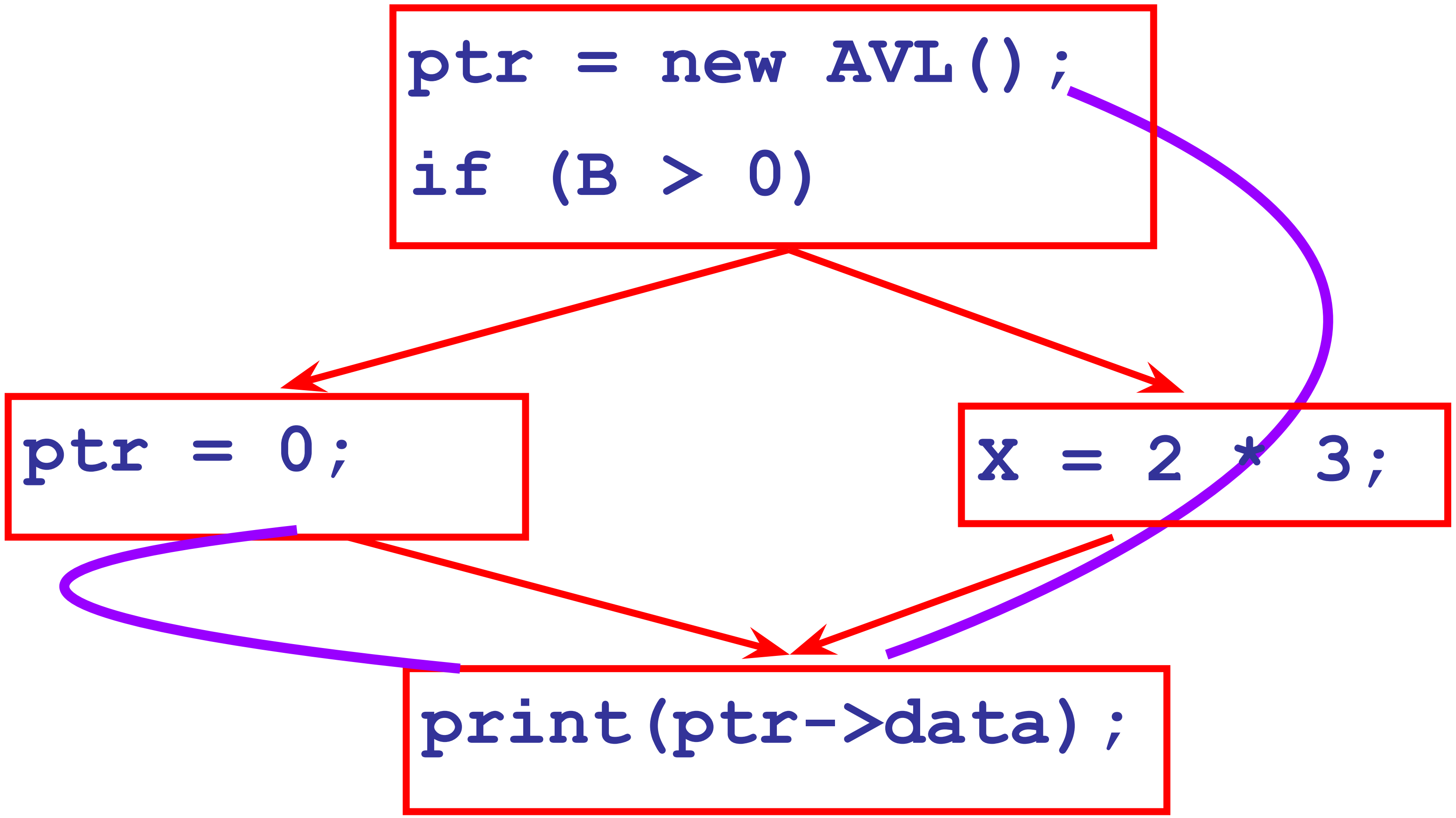
- To determine that a use of x is **always** null, we must know this **correctness condition**:

On every path to the use of x,
the last assignment to x is x := 0 **



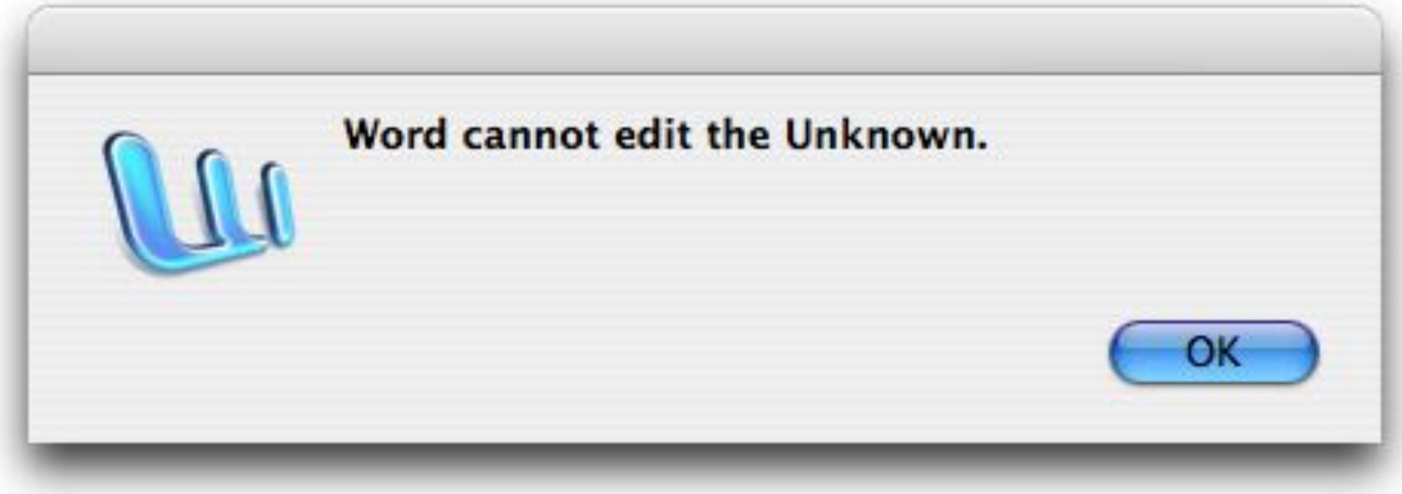
Analysis Example Revisited

- Is **ptr** *always* null when it is dereferenced?



Static Dataflow Analysis

- Static dataflow analyses share several traits:
  - Assuming a given property P (at particular program points)
  - Proving P at any point requires knowledge of the entire method body
  - **Property P is typically *undecidable*!**



Undecidability of Program Properties

- **Rice's Theorem**: Most interesting dynamic properties of a program are undecidable:
  - Does the program halt on all (some) inputs?
    - This is called the **halting problem**
  - Is the result of a function F always positive?
    - *Assume* we can answer this question precisely
    - Oops: We can now solve the halting problem.
    - Take function H and find out if it halts by testing function F(x) = { H(x); return 1; } to see if it has a positive result
    - *Contradiction!*

```
static int IsNegative(float arg)
{
   char*p = (char*) malloc(20);
   sprintf(p, "%f", arg);
   return p[0]=='-';
}
```

Undecidability of Program Properties

- So, if *interesting* properties are out, what can we do?

- Syntactic properties are decidable!
  - e.g., How many occurrences of "x" are there?

- Programs without looping are also decidable!

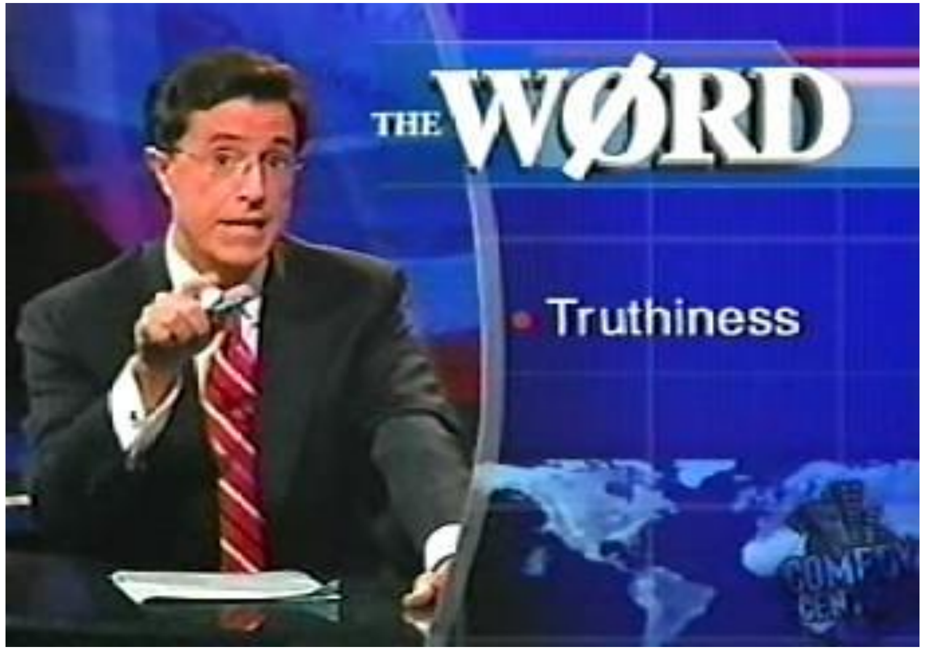
Looping

- Almost every important program has a loop
  - Often based on user input
- An algorithm always terminates
- So a dataflow analysis algorithm must terminate even if the input program loops (forever)

- But how to reason about all loop iterations?
  - Suppose you dereference the null pointer on the 500th iteration but we only analyze 499 iterations

Conservative Program Analyses

- We cannot tell for sure that **ptr** is always null
  - So how can we carry out any sort of analysis?
- It is OK to be **conservative**. If the goal is to check whether or not P is true, then (conservative) analysis reports either
  - P is definitely true
  - Don't know if P is true



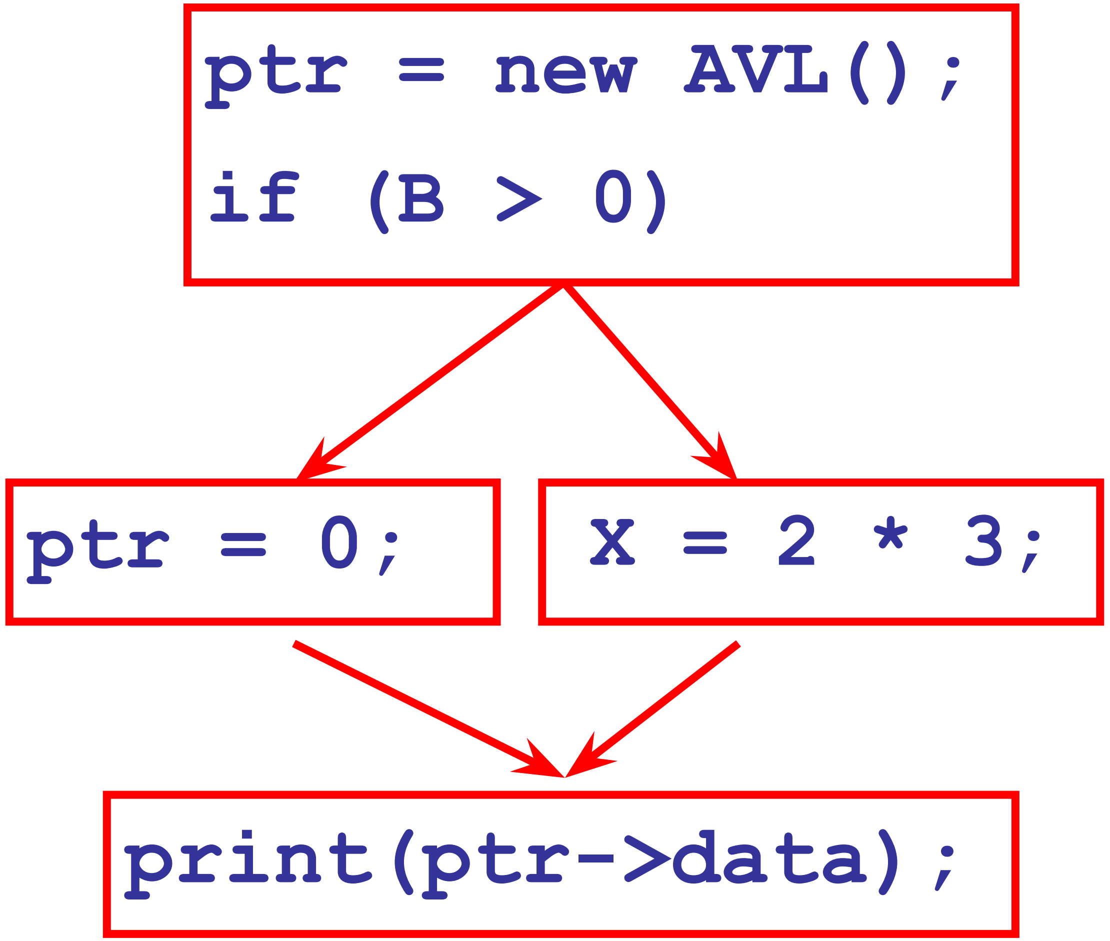
Conservative Program Analyses

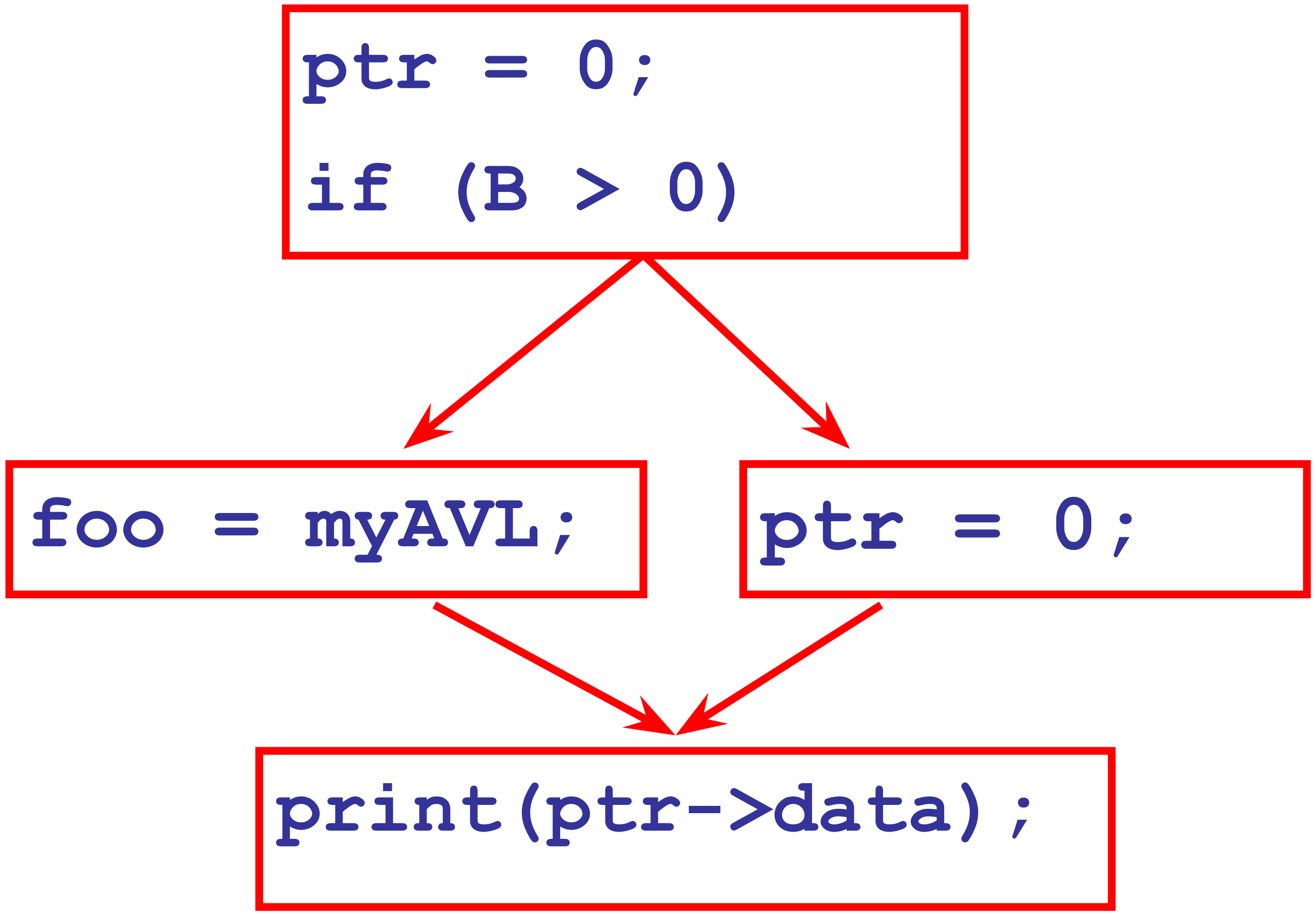
- It is always correct to say “don’t know”
  - We try to say don’t know as rarely as possible
- All program analyses are conservative

- Must think about your software engineering process
  - Bug finding analysis for developers?
    They hate “false positives”, so if we don't know, stay silent.
  - Bug finding analysis for airplane autopilot?
    Safety is critical, so if we don't know, give a warning.

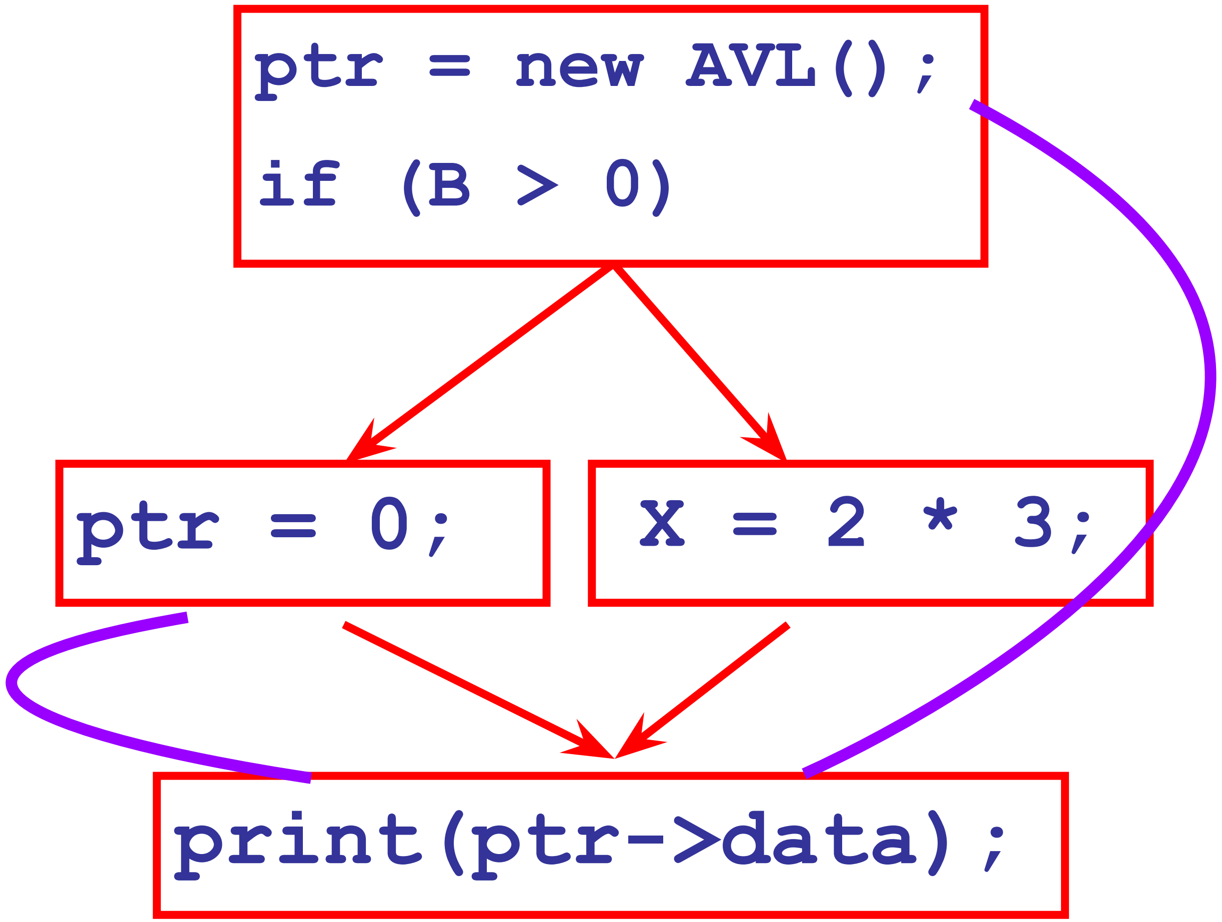
Definitely Null Analysis

- Is **ptr** *always* null when it is dereferenced?

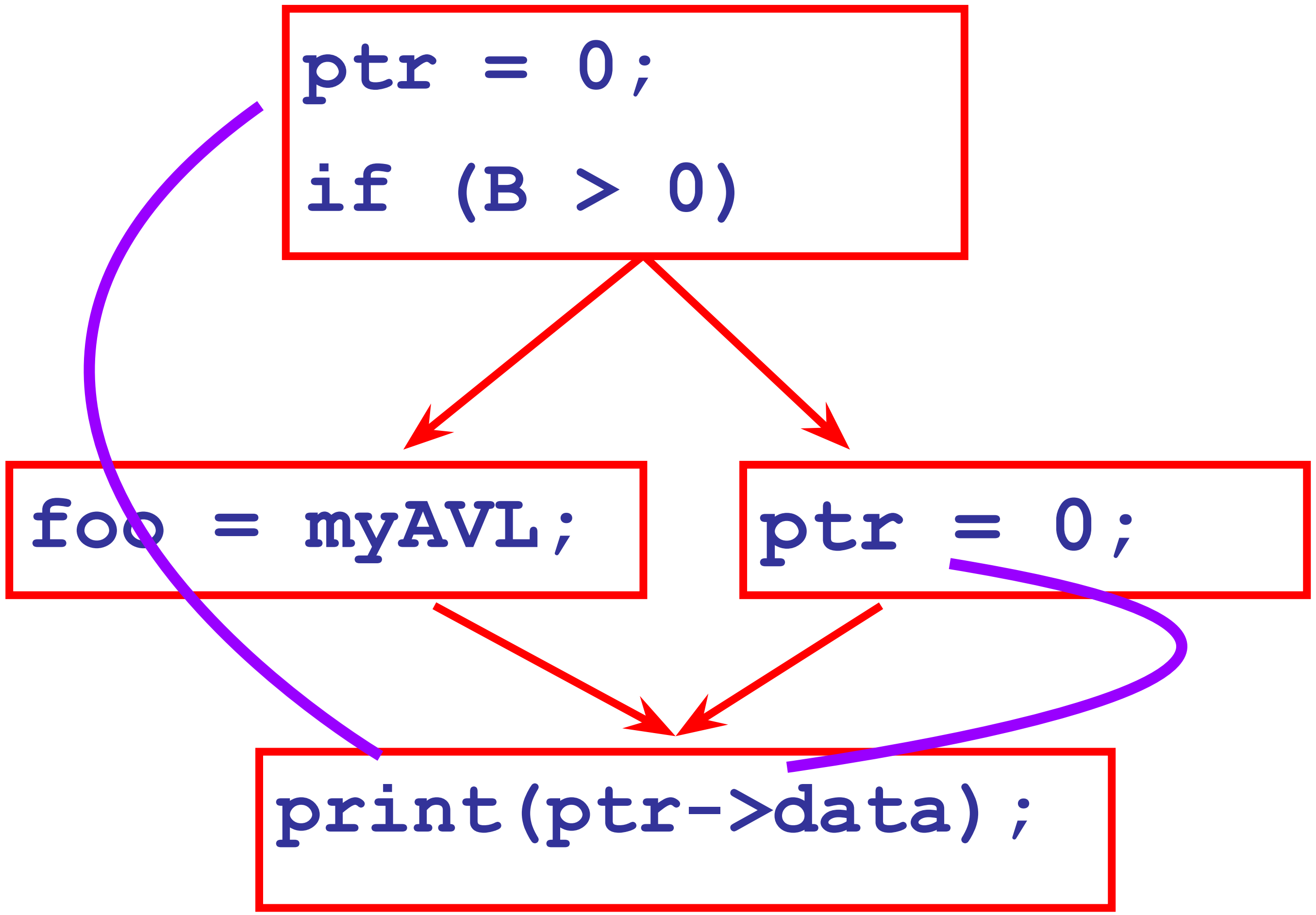




Definitely Null Analysis



No, not always.



Yes, always.

On every path to the use of ptr, the last assignment to ptr is ptr := 0 **

Definitely Null Information

- We can warn about definitely null pointers at any point where ** holds
  - … by computing ** for a single variable ptr at all program points

On every path to the use of ptr, the last assignment to ptr is ptr := 0 **

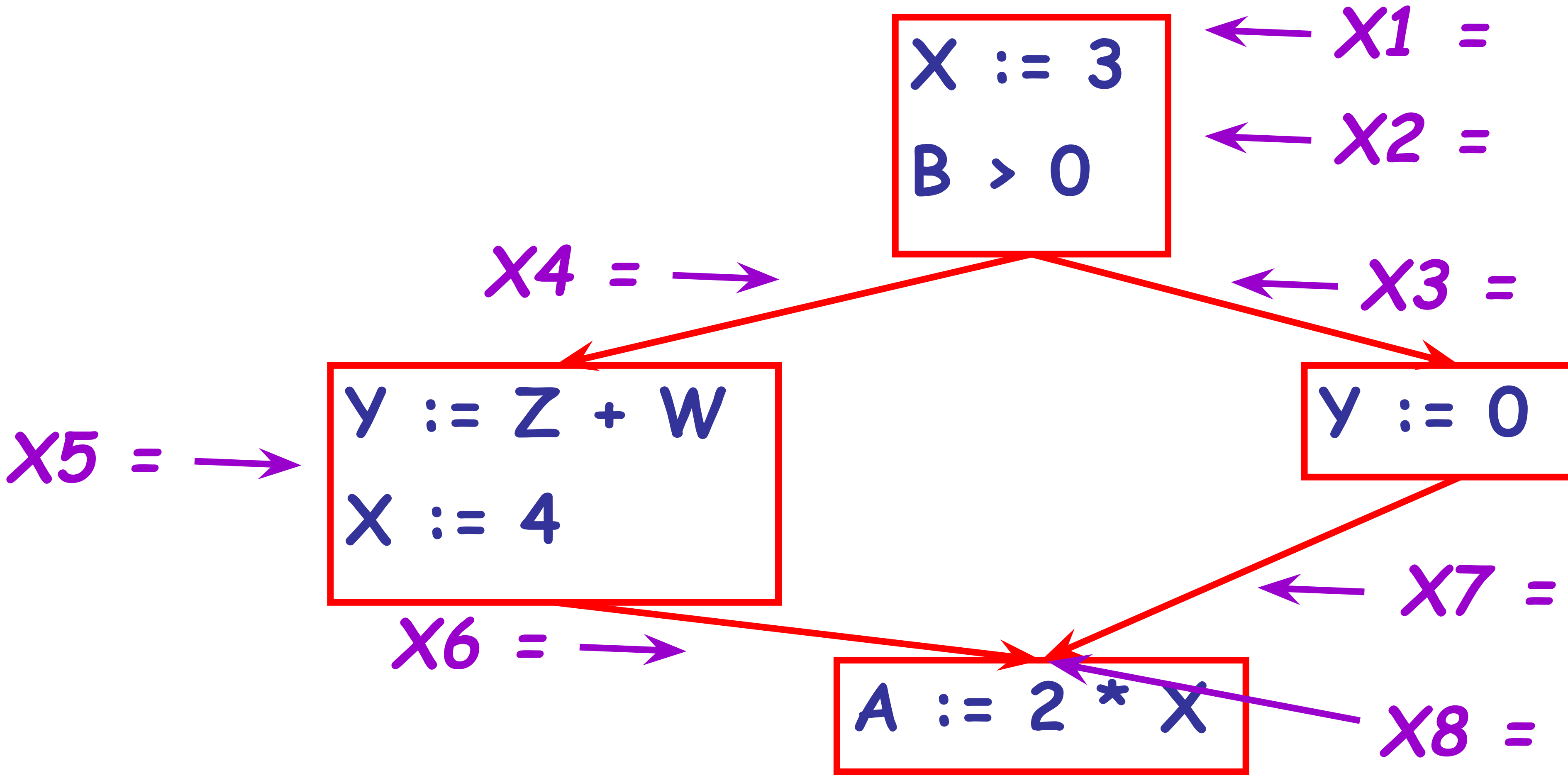
Definitely Null Analysis (Cont.)

- To define the problem, we associate one of the following values with ptr *at every program point*
  - Recall: abstraction and property

value	*interpretation*
⊥ (called ***Bottom***)	This statement is not reachable
c	X = constant c
⊤ (called ***Top***)	Don't know if X is a constant

Example

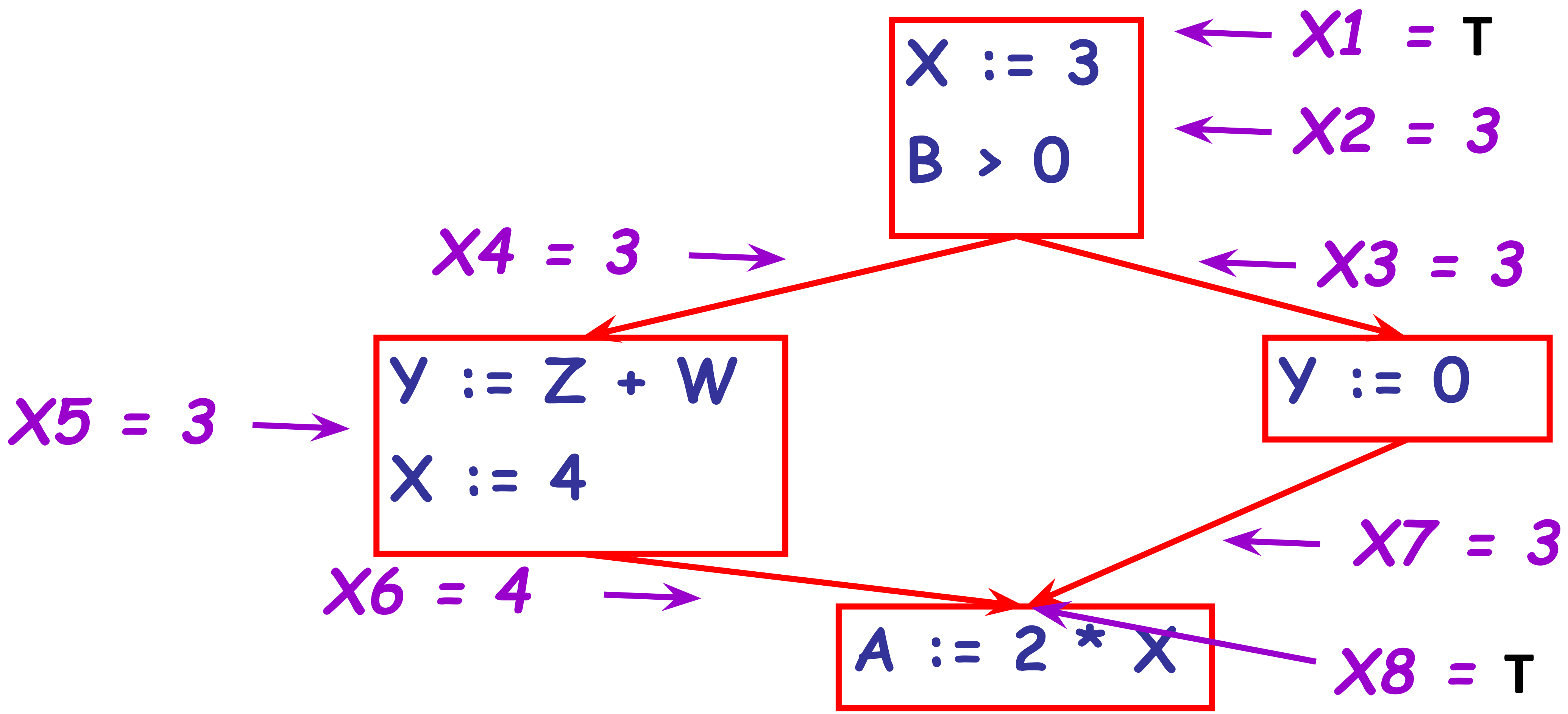
Let's fill in these blanks now.



Recall: ⊥ = not reachable, c = constant, ⊤ = don't know.

Example

Let's fill in these blanks now.



Recall: ⊥ = not reachable, c = constant, ⊤ = don't know.

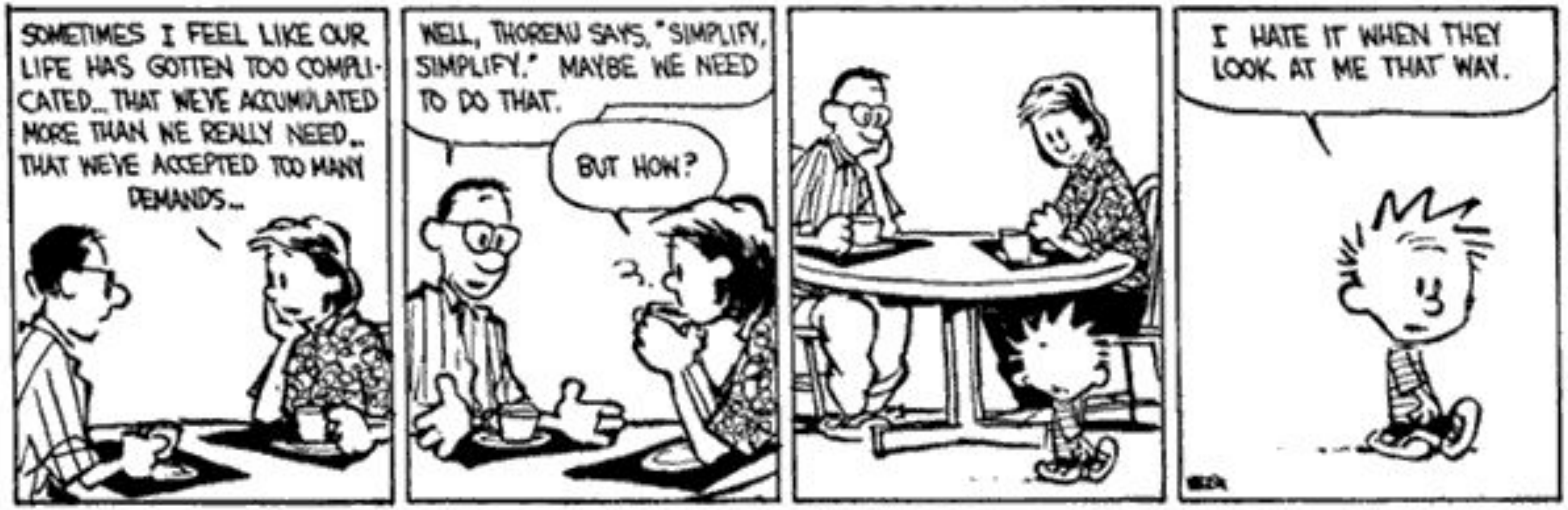
Using Abstract Information

- Given analysis information (and a policy about false positives/negatives), it is easy to decide whether or not to issue a warning
  - Simply inspect the x = ? associated with a statement using x
  - If x is the constant **0** at that point, issue a warning!

- **Big question: how can an algorithm compute 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

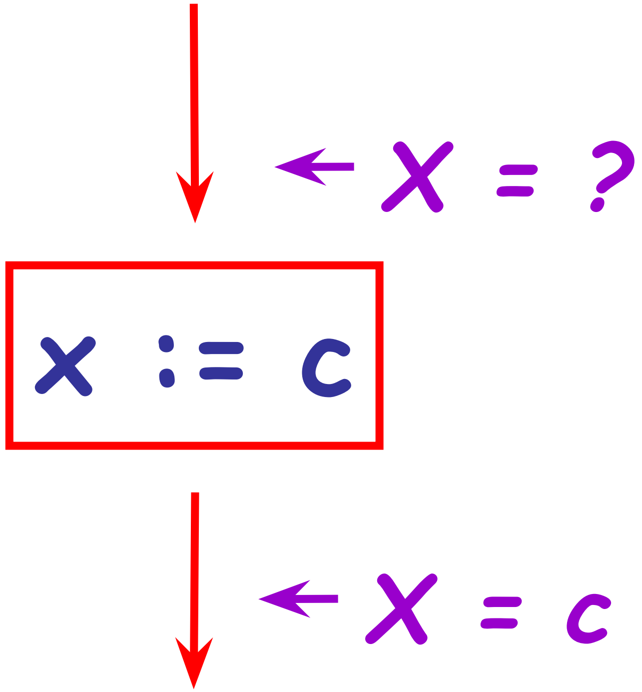
- The idea is to "push" or "**transfer**" information from one statement to the next

- For each statement s, we compute information about the value of x immediately before and after s
  - $C_{in}(x,s)$ = value of x before s
  - $C_{out}(x,s)$ = value of x after s

Transfer Functions

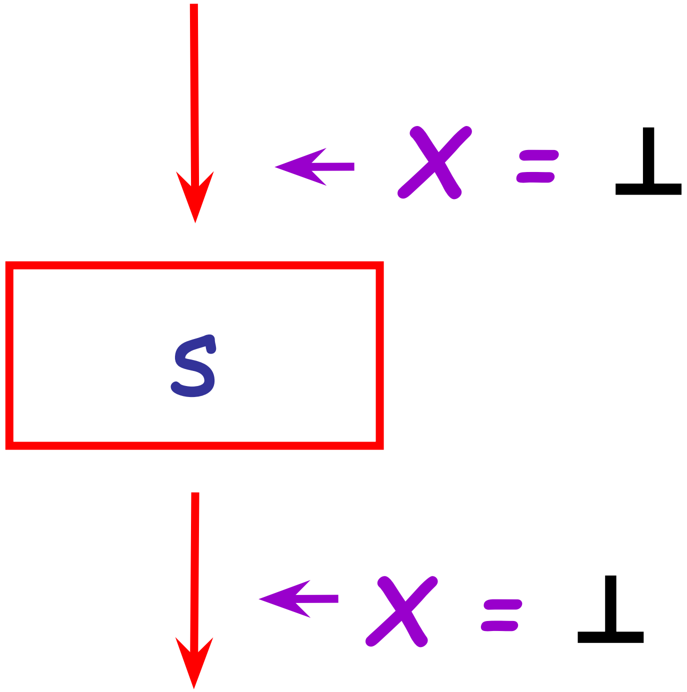
- Define a **transfer function** that transfers information from one statement to another

Rule 1



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

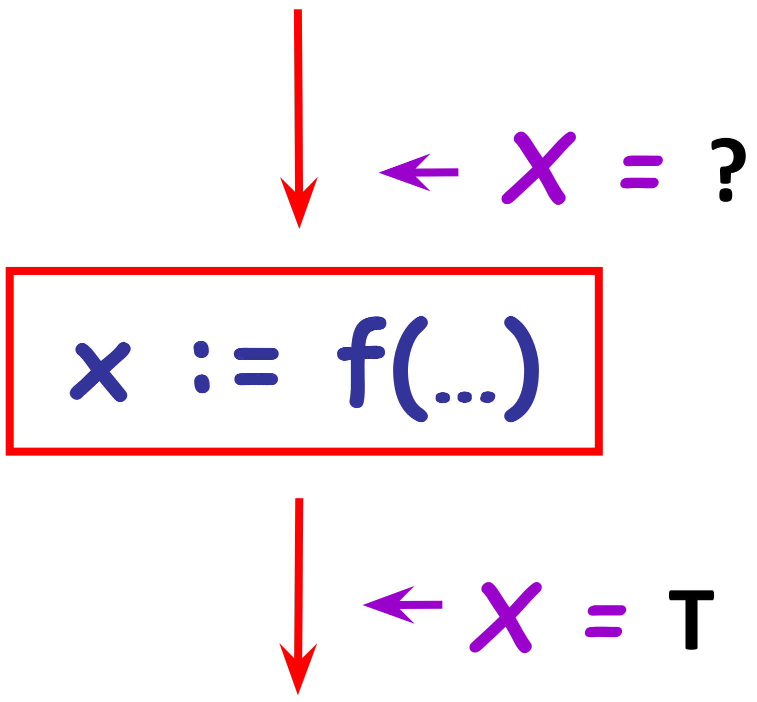
Rule 2



- $C_{out}(x, s) = \bot$ if $C_{in}(x, s) = \bot$

Recall: ⊥ = "unreachable code"

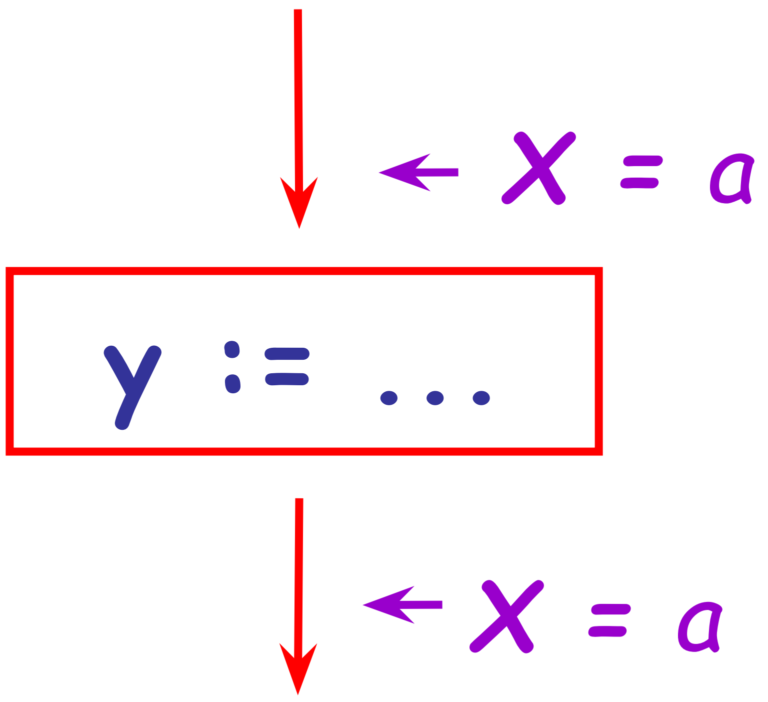
Rule 3



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

This is a conservative approximation! It might be possible to figure out that f(...) always returns 0, but we won't even try!

Rule 4

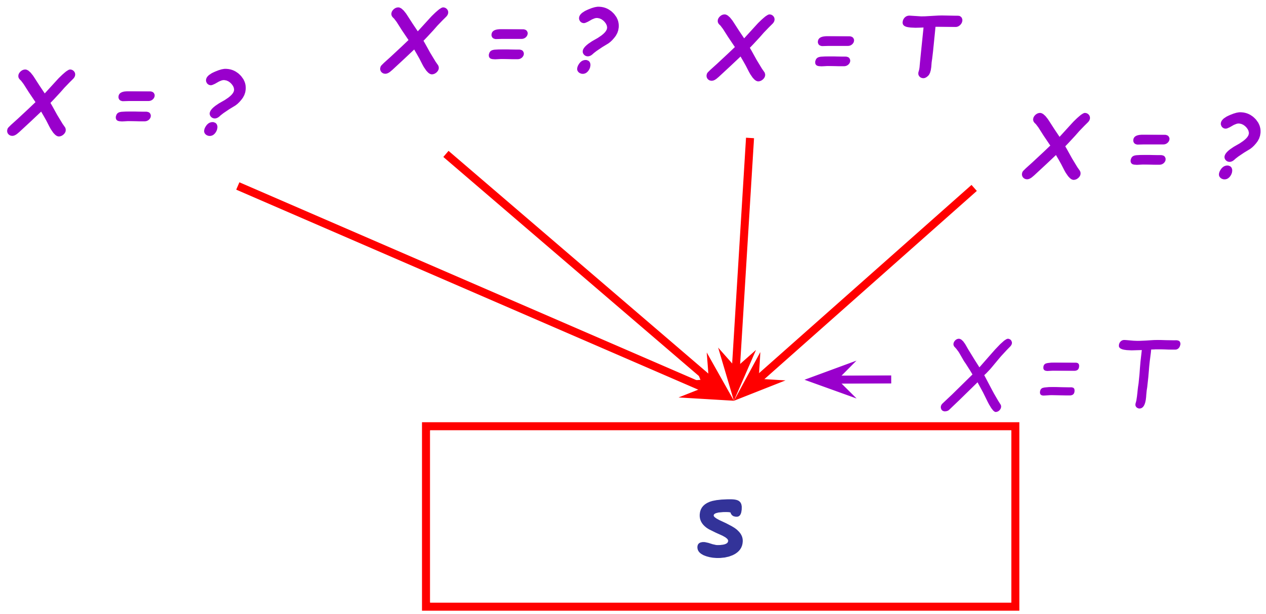


- $C_{out}(x, y := \ldots) = C_{in}(x, y := \ldots)$ if $x \neq y$

The Other Half

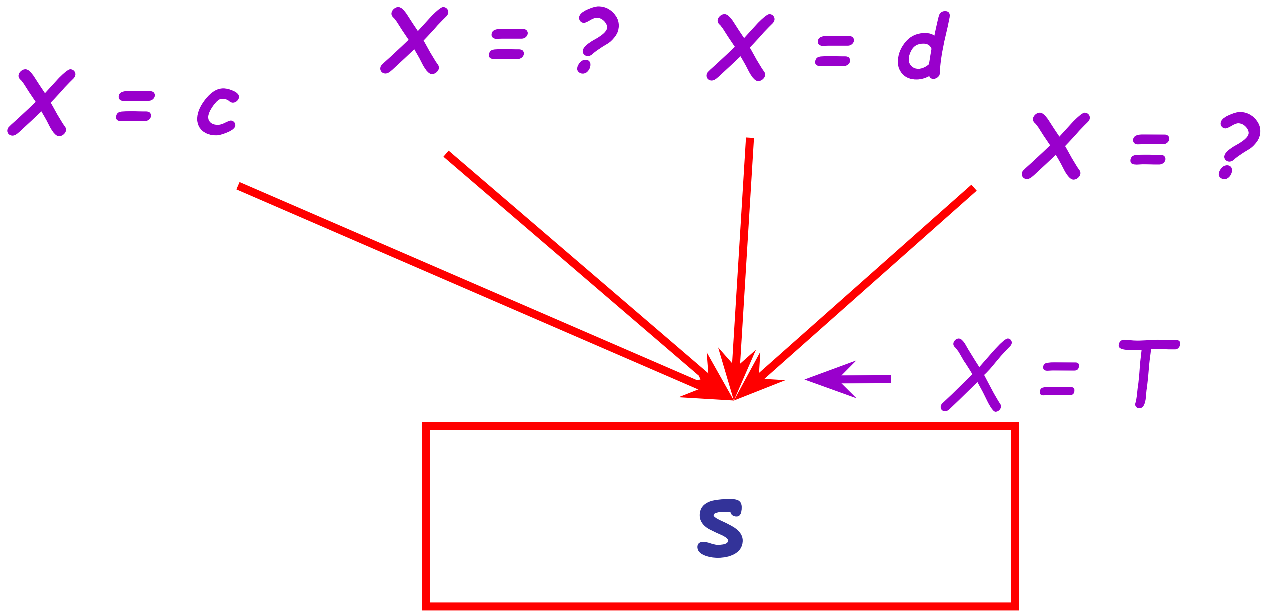
- Rules 1-4 relate the ***in*** of a statement **to** the ***out*** of the same statement
  - they propagate information through a statement
- Now we need rules relating the ***out*** of one statement **to** the ***in*** of the successor statement
  - to propagate information forward along paths
- In the following rules, let statement s have immediate predecessor statements $p_1,\ldots,p_n$

Rule 5



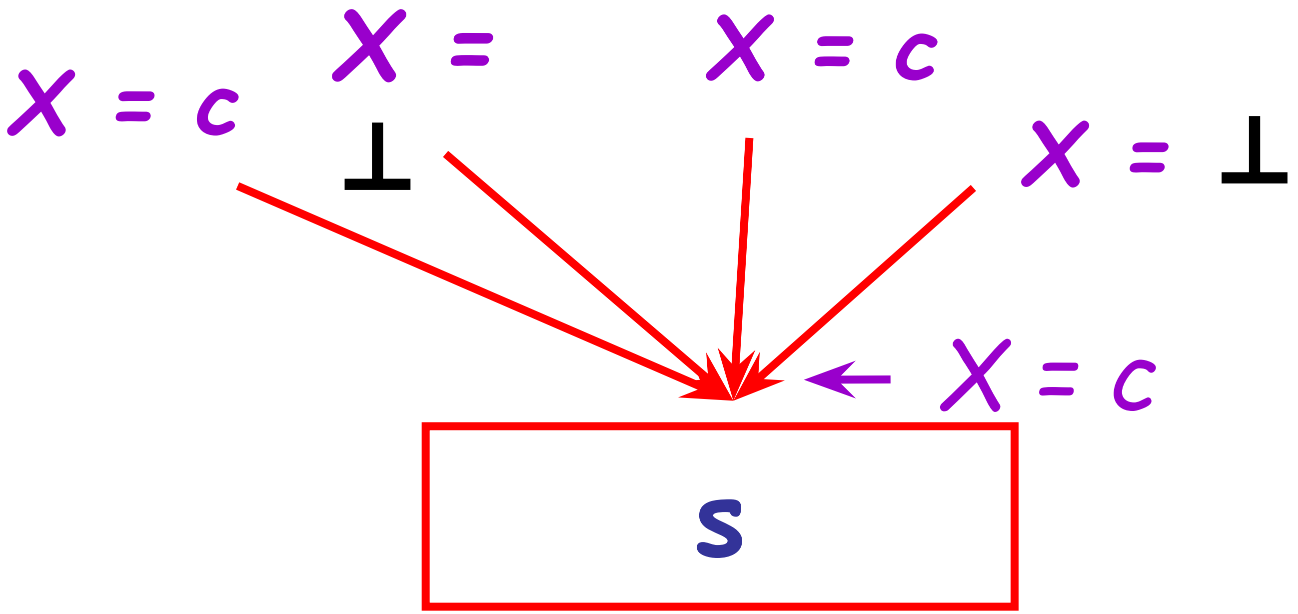
- if $C_{out}(x, p_i) = T$ for some i, then $C_{in}(x, s) = T$

Rule 6



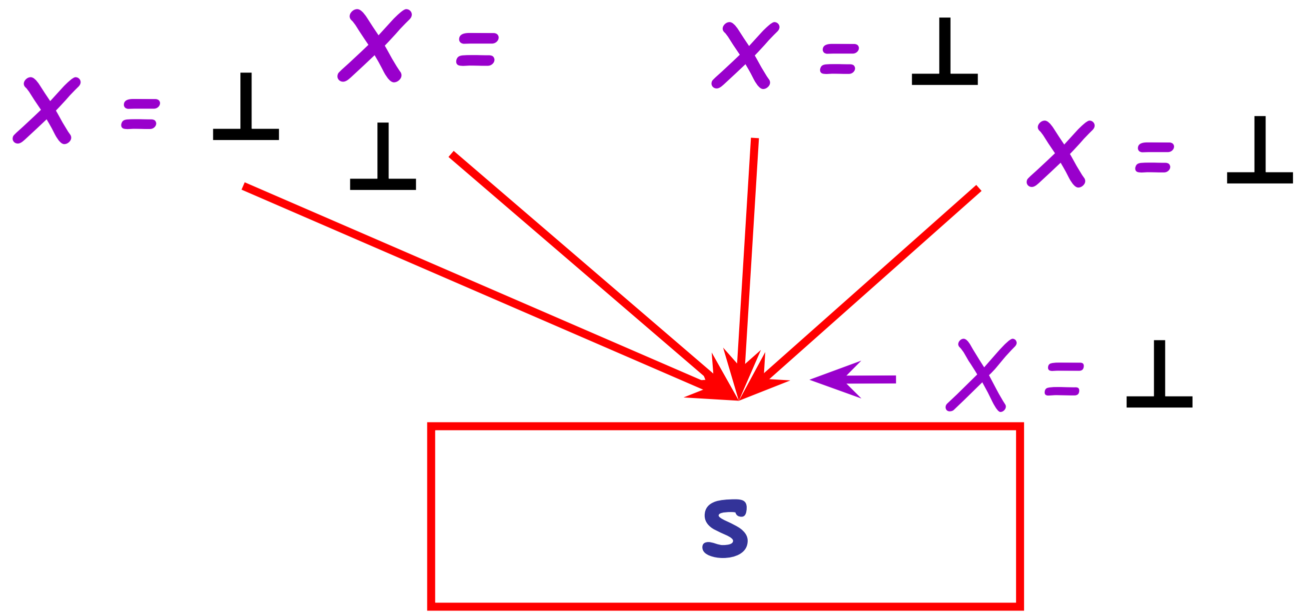
if $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$, then $C_{in}(x, s) = T$

Rule 7



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

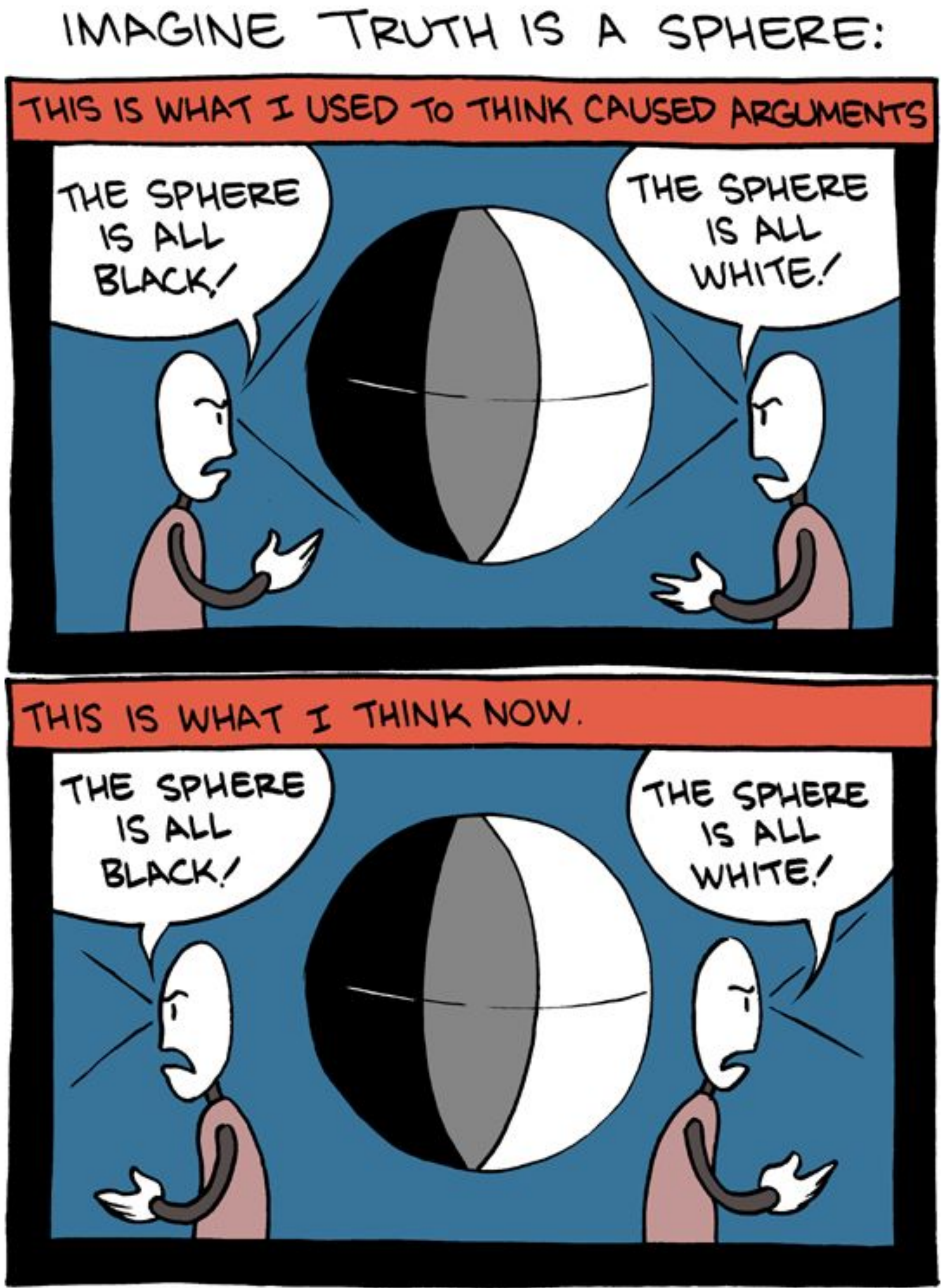
Rule 8



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

Static Analysis Algorithm

- For every entry s to the program, set $C_{in}(x, s) = T$
- Set $C_{in}(x, s) = C_{out}(x, s) = \bot$ everywhere else
- Repeat until all points satisfy rules 1-8:
  - Pick *s* not satisfying rules 1-8 and update using the appropriate rule



Static and Dataflow Analysis

(two-part lecture)

“Static” means?

Programs are viewed as ___?

Abstraction: what are special abstract values?

The Idea

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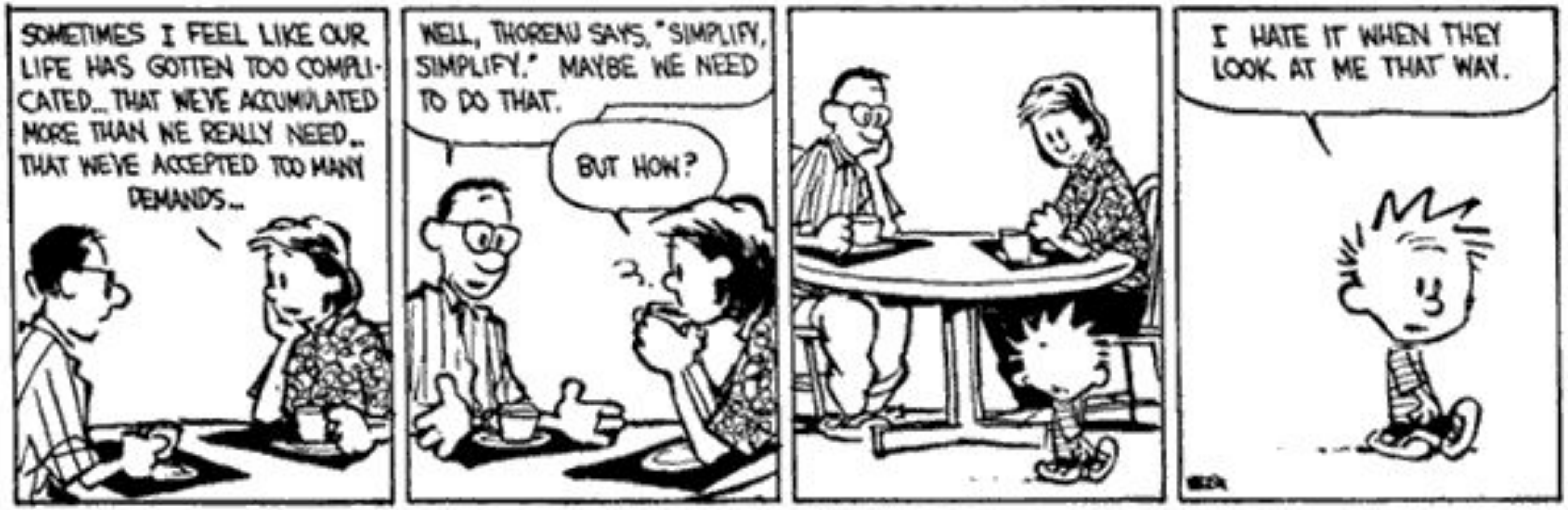

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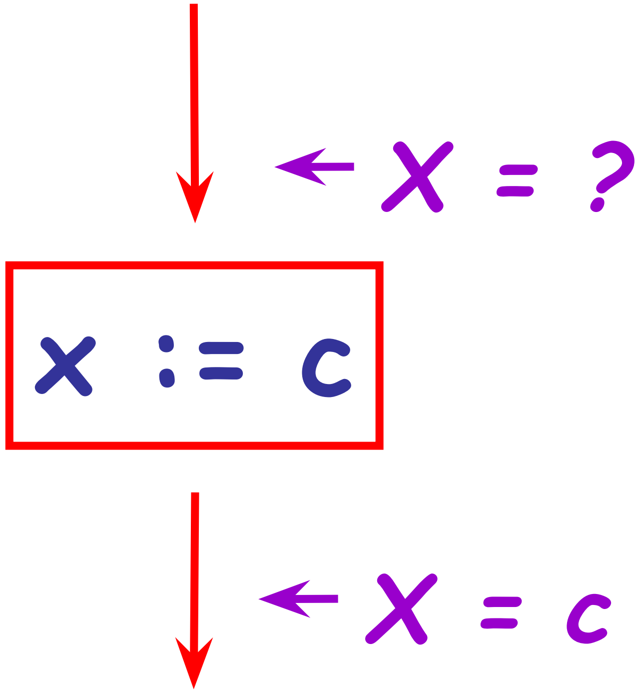

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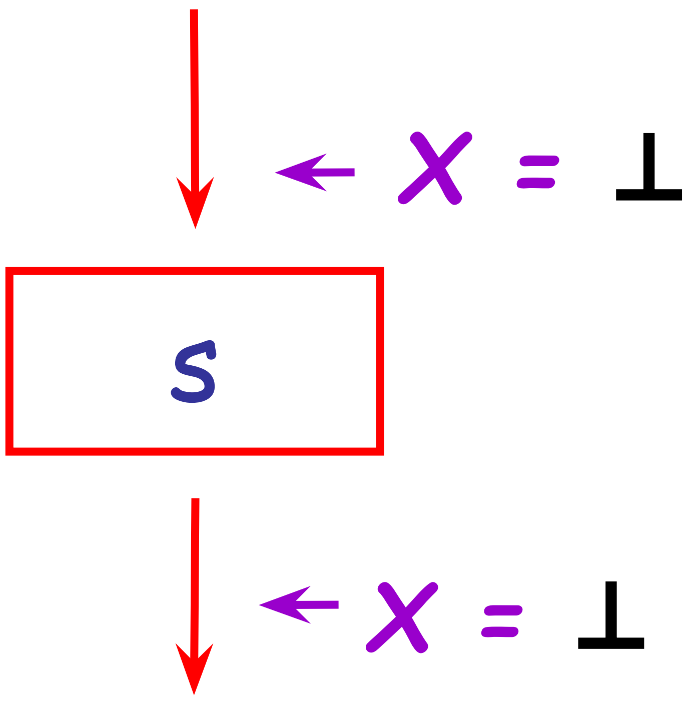

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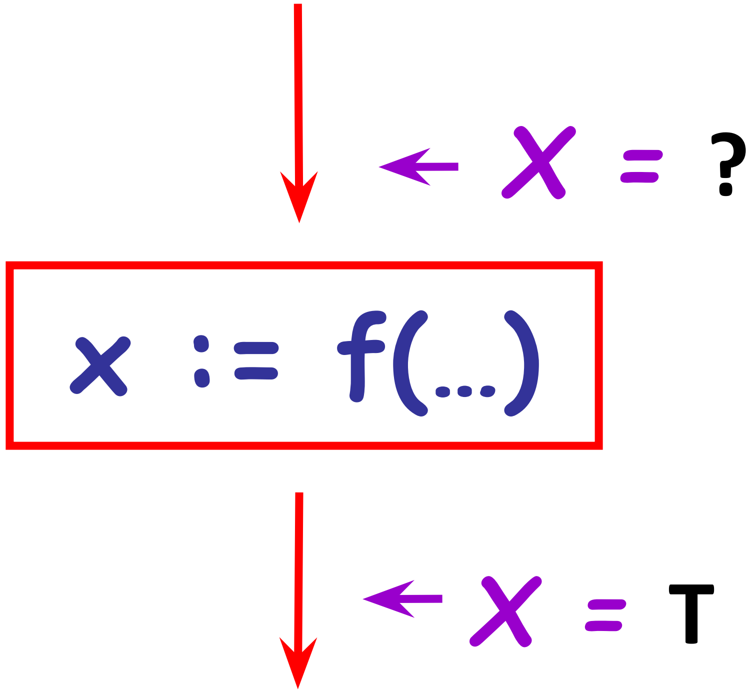

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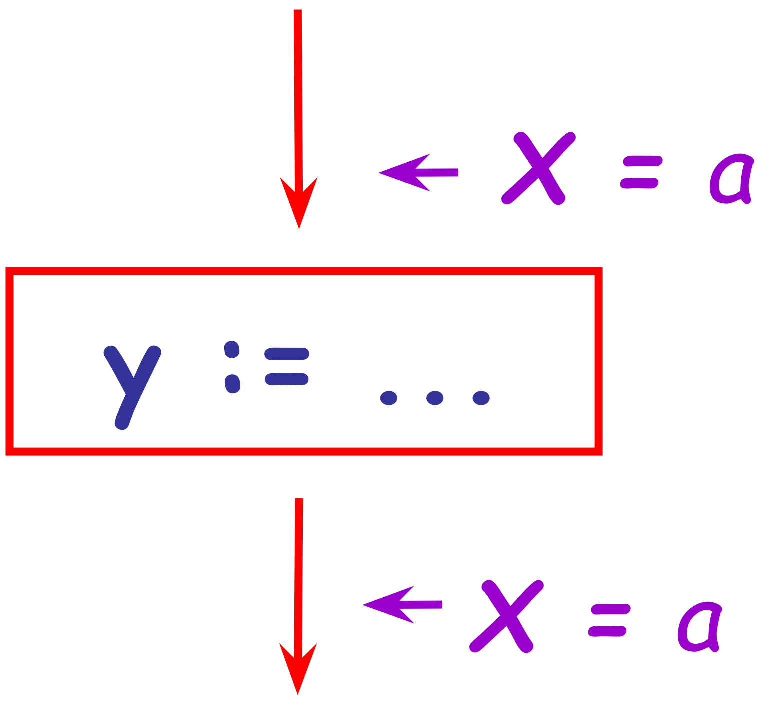

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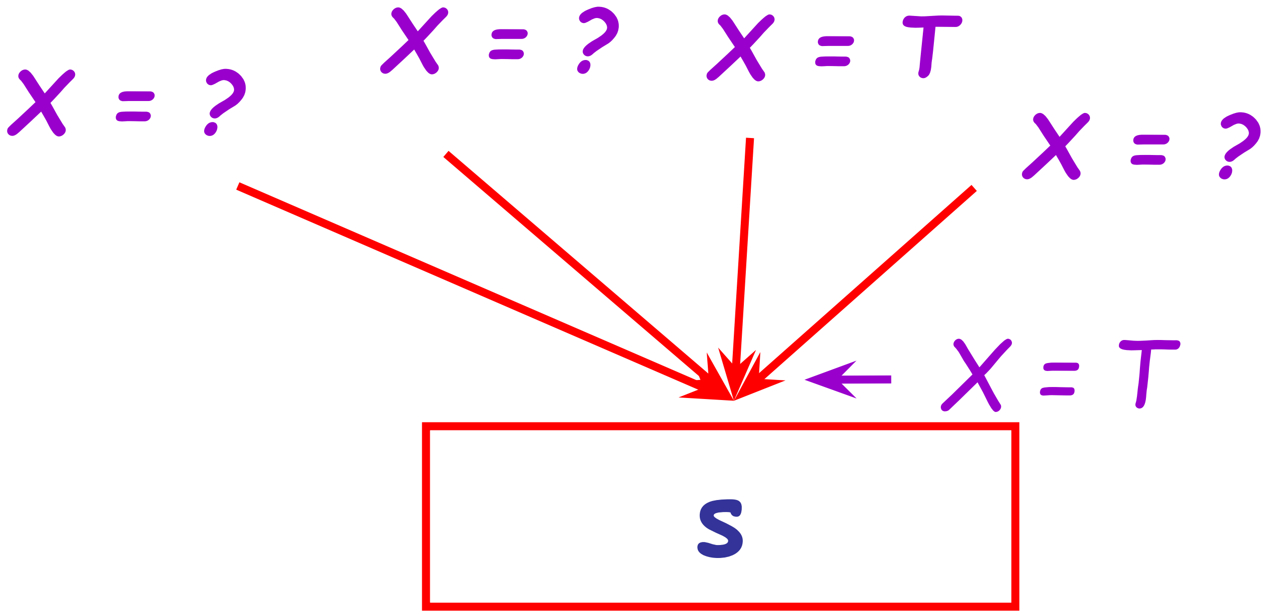

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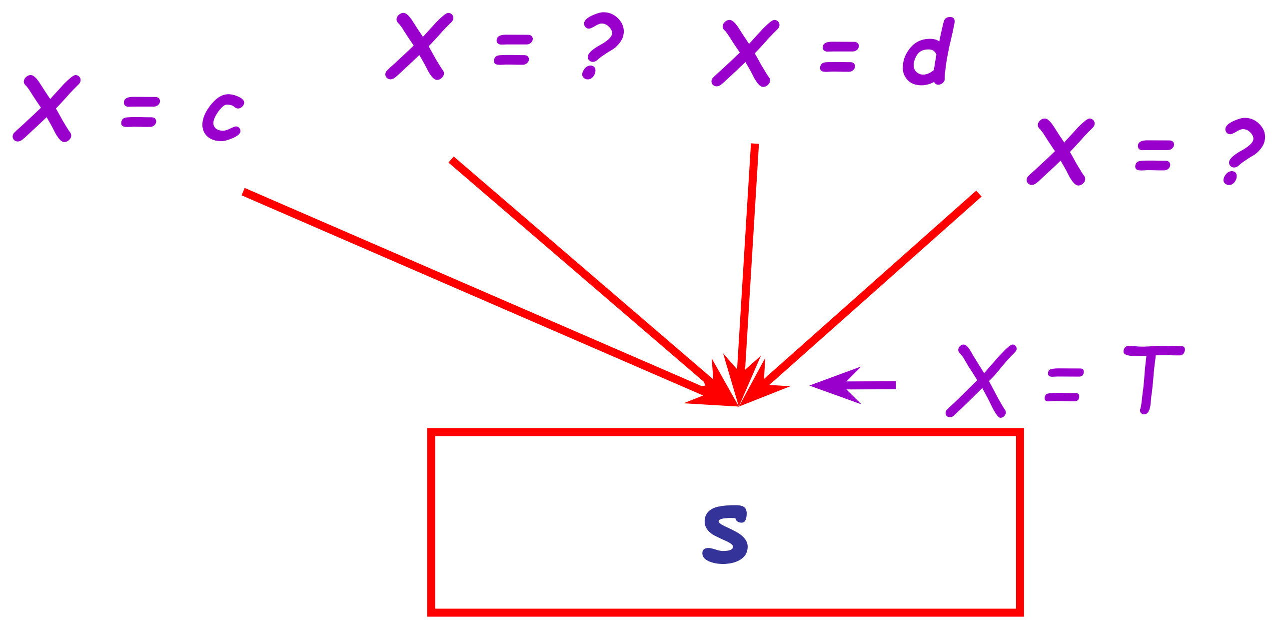

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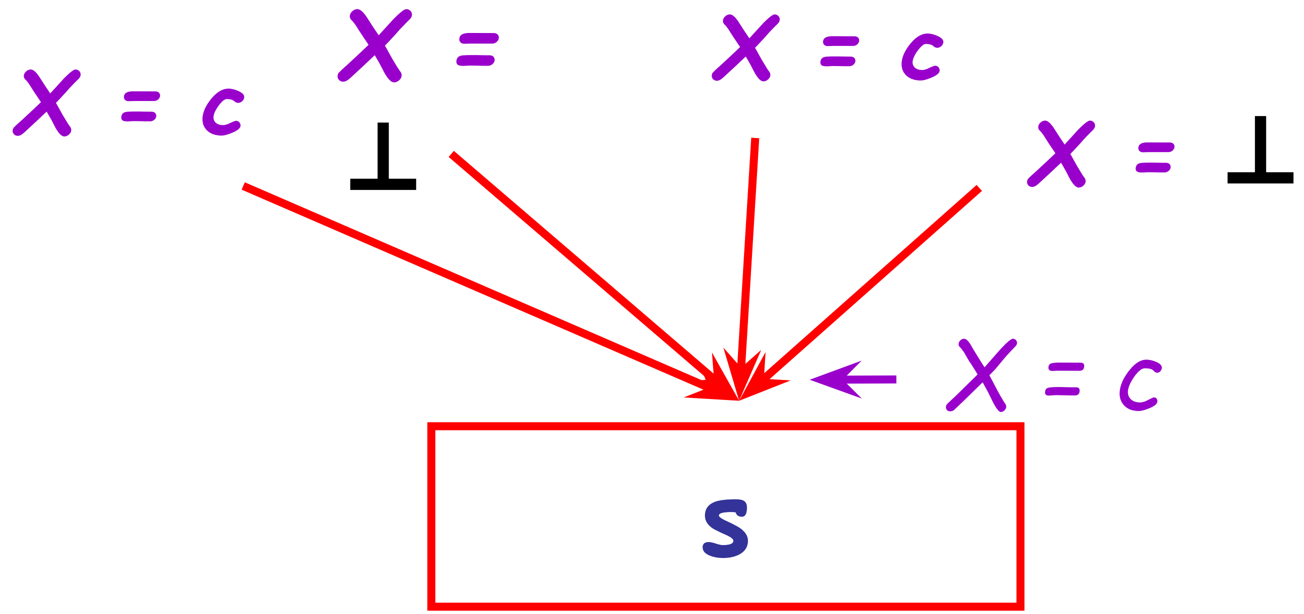

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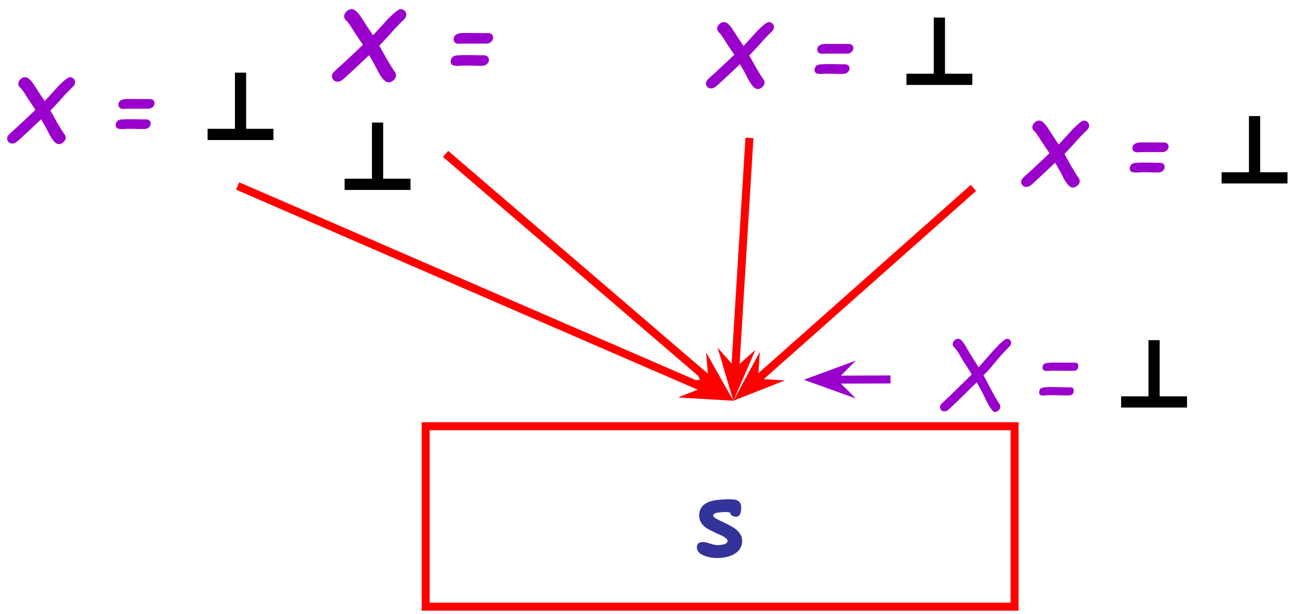

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Static Dataflow Analysis Algorithm

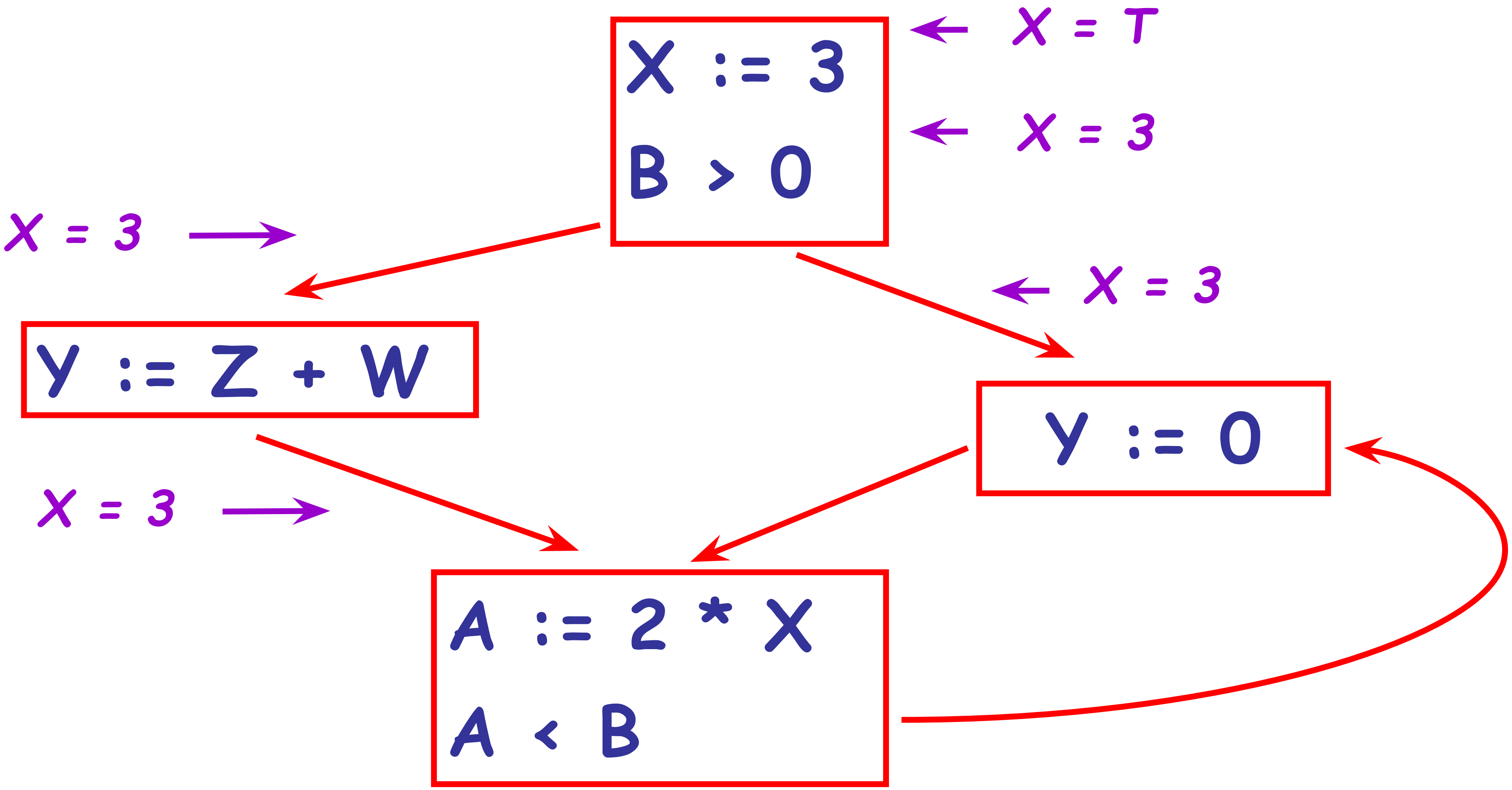
- For every entry s to the program, set $C_{in}(x, s) = T$

- ***Set $C_{in}(x, s) = C_{out}(x, s) = \bot$ everywhere else***

- Repeat until all points satisfy rules 1-8:
  - Pick *s* not satisfying rules 1-8 and update using the appropriate rule

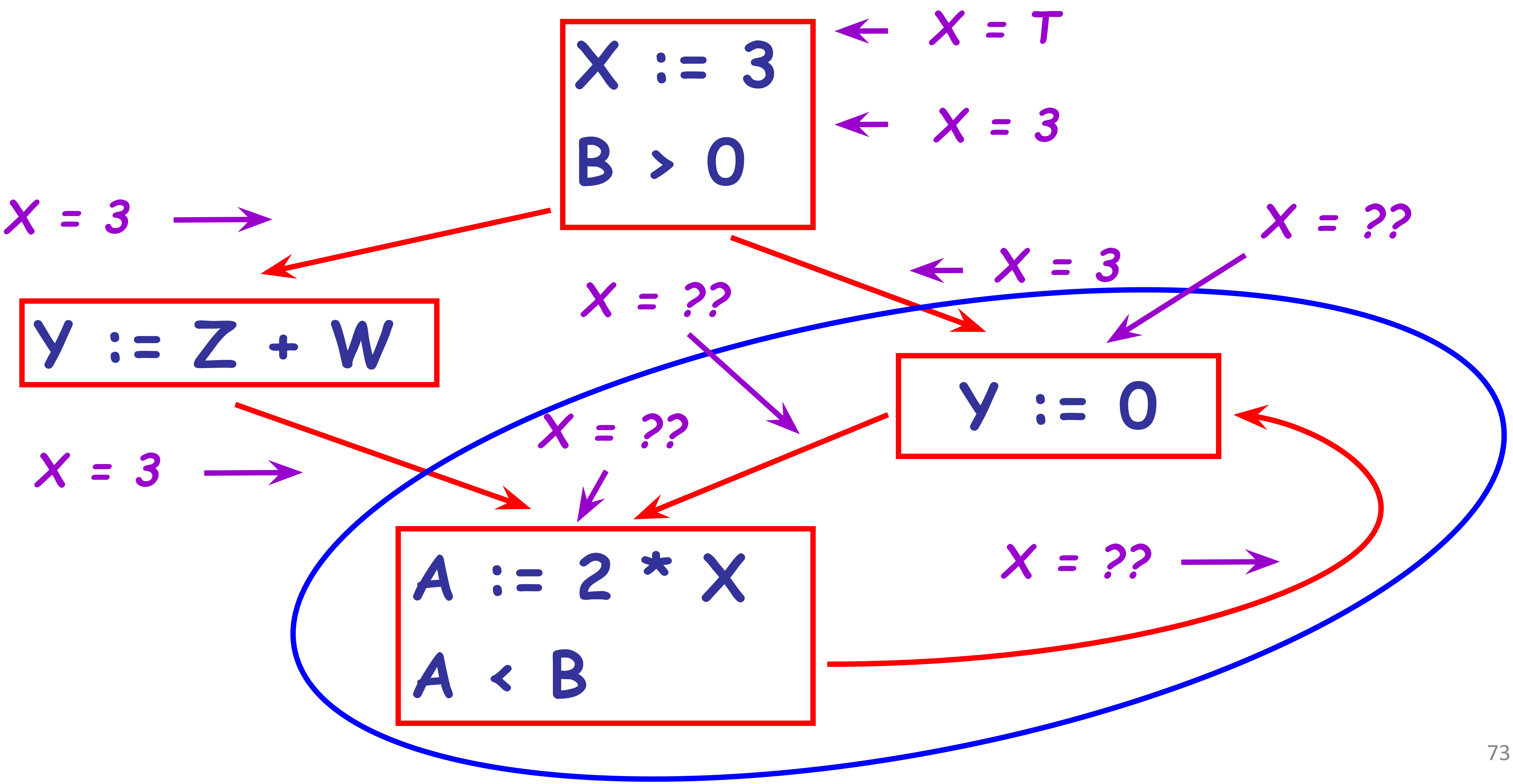
The Value ⊥

- To understand why we need ⊥, look at a loop



The Value ⊥

- To understand why we need ⊥, look at a loop



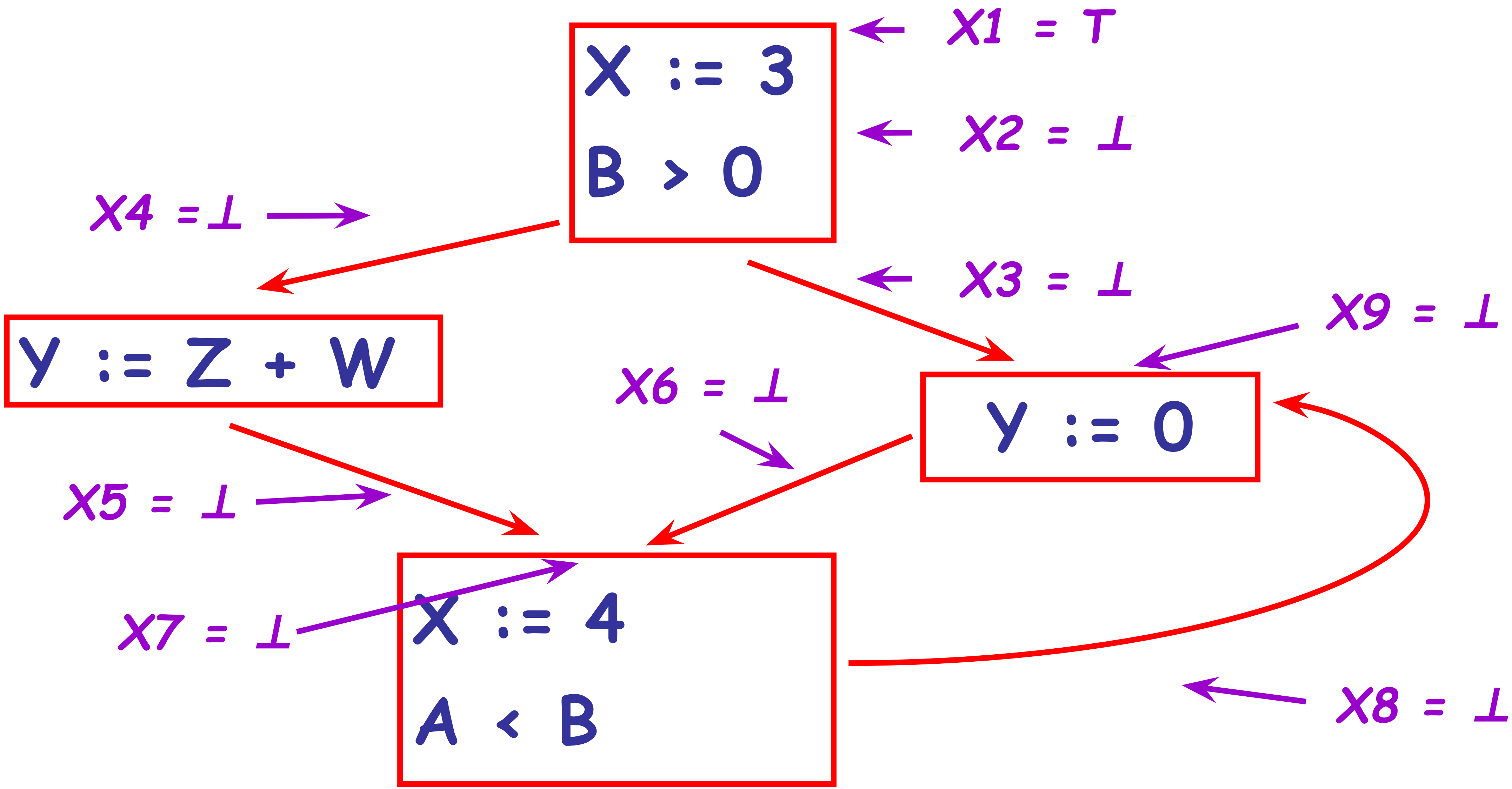
The Value $\bot$ (Cont.)

- We want all points to have values at all times during the analysis; but with cycles, we cannot…

- Solution: assigning **some initial value** allows the analysis to break cycles

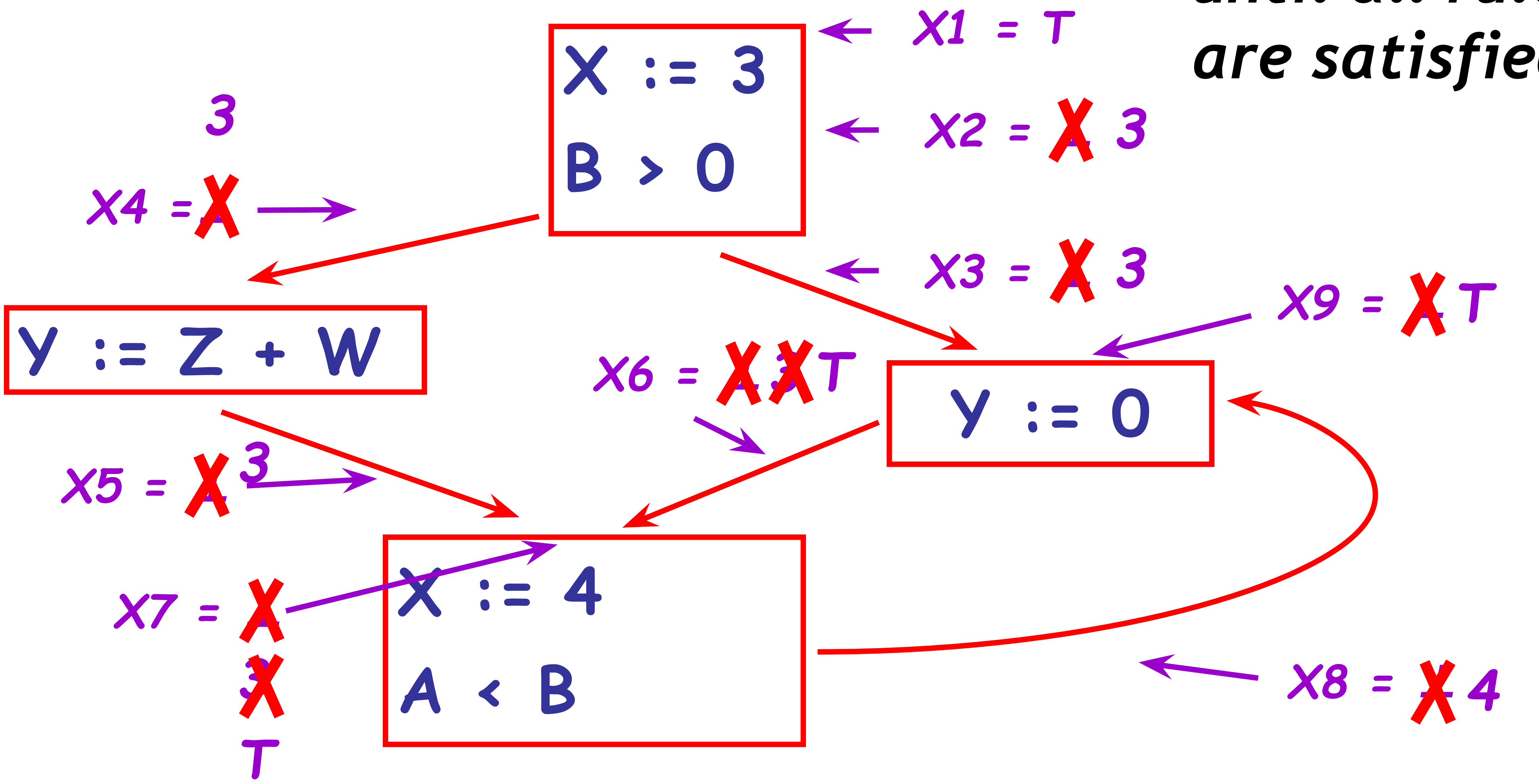
- The initial value $\bot$ means **"we have not yet analyzed control reaching this point"**

Another Example: Analyze the value of X …



Another Example: Analyze the value of X …

Must continue until all rules are satisfied !

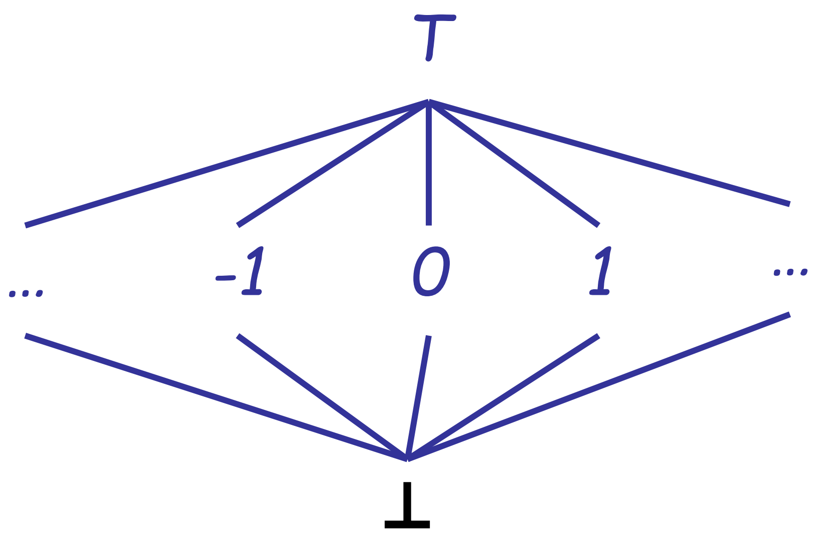


Orderings

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

$$\bot < c < T$$

- Making a picture with "lower" values drawn lower, we get



This is called a "lattice"

Orderings (Cont.)

- T is the greatest value, ⊥ is the least
  - All constants are in between and incomparable
    - (with respect to this analysis)
- Let ***lub*** be the least-upper bound in this ordering
  - cf. "least common ancestor" in Java/C++
- Rules 5-8 can be written using lub:
  - $C_{in}(x, s) = \text{lub} \{ C_{out}(x, p) \mid p \text{ is a predecessor of } s \}$

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 $\bot$ and only *increase*

    $\bot$ can change to a constant, and a constant to T
  - **Thus, C_(x, s) can change at most twice**

Number Crunching

- The algorithm is polynomial in program size:

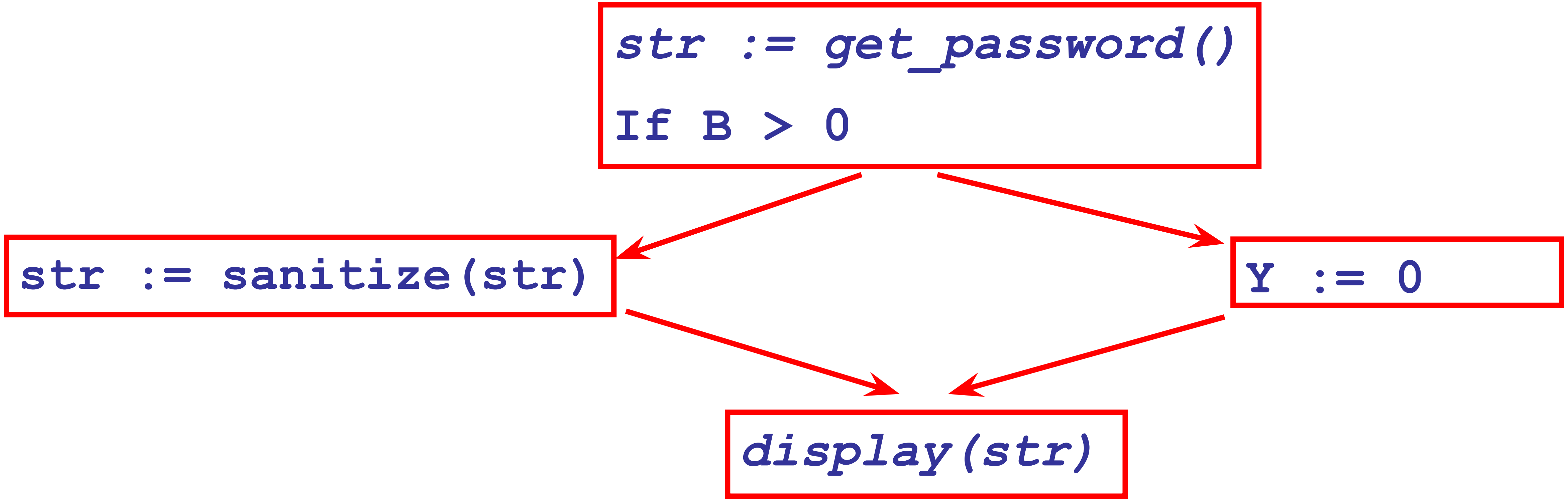
Number of steps

= Number of C_(….) values * 2

= (Number of program statements)^2 * 2

“Potential Secure Information Leak” Analysis

- Could **sensitive** information **possibly** reach an **insecure** use?



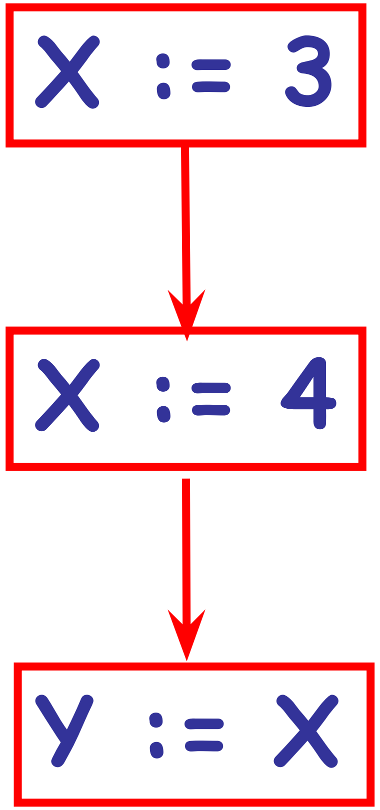
In this example, the password contents can potentially flow into a public display (depending on the value of B)

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
  - We can generalize it to reason about "potential secure information leaks"



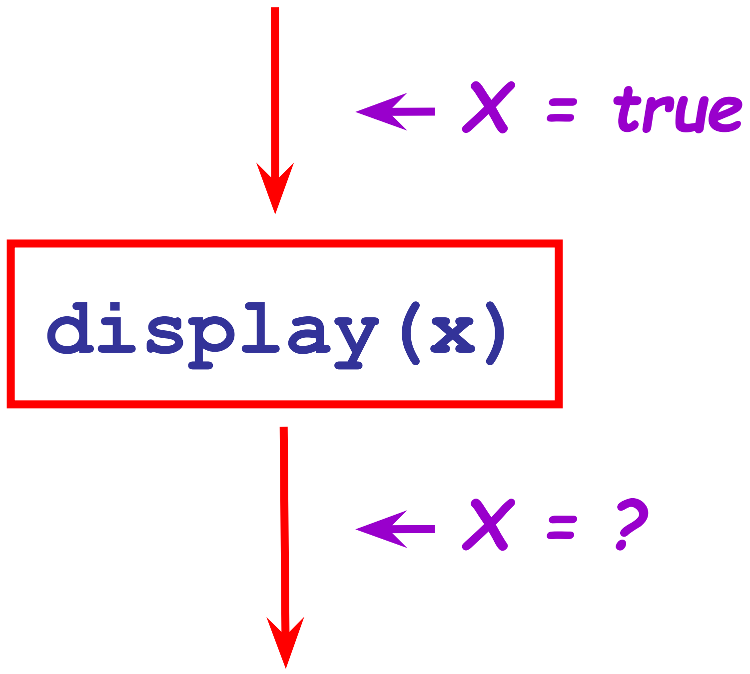
Sensitive Information

- A variable x at statement s is a **possible** sensitive (high-security) information leak if
  - There exists a ("display") statement s' that uses x
  - There is a path from s to s'
  - That path has **no intervening low-security assignment** to x

Computing Potential Leaks

- We can express **high- or low-security status** of a variable in terms of information transferred between adjacent statements, just as in our "definitely null" analysis
- In this formulation of security status we only care about "high" (secret) or "low" (public), not the actual value
  - We have *abstracted away* the value
- This time we will start at the public display of information and work backwards

Secure Information Flow Rule 1



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

true means “the value in x at this point can potentially be leaked”

Secure Information Flow Rule 2

← *X = false*

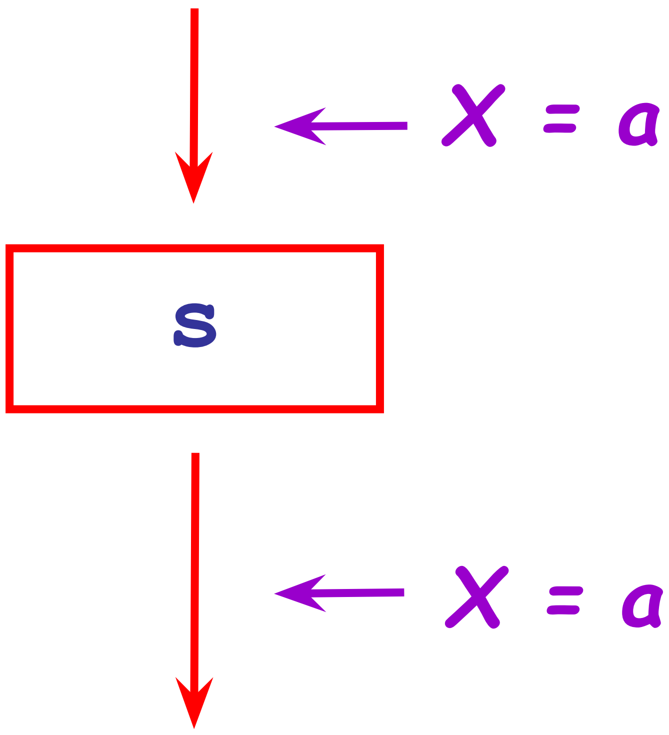
```
x := sanitize(x)
```

← *X = ?*

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

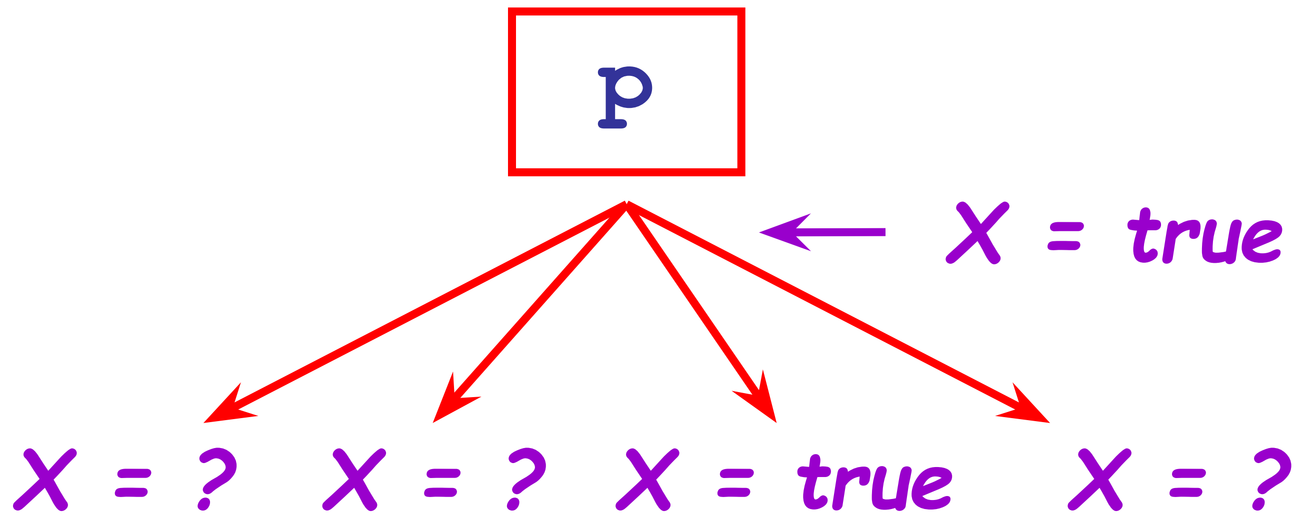
(any subsequent use is safe)

Secure Information Flow Rule 3



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

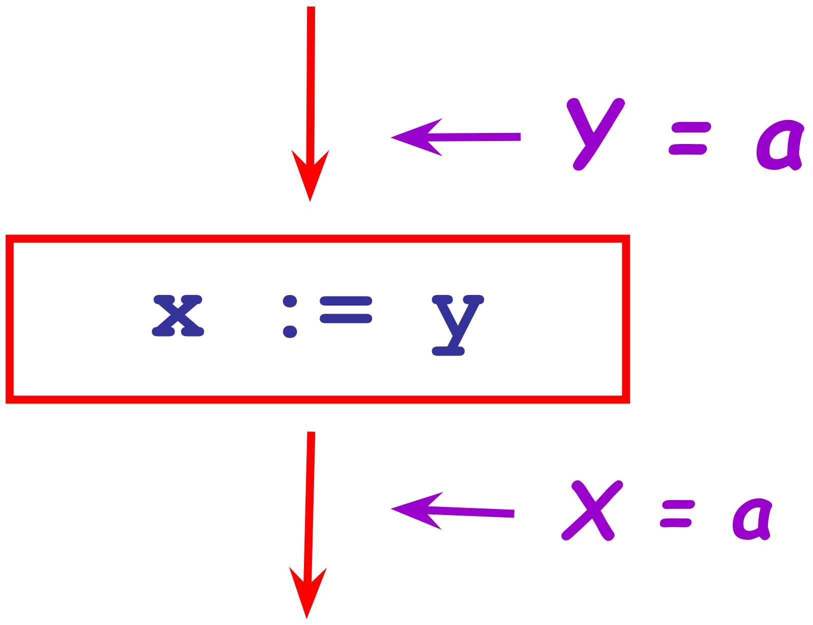
Secure Information Flow Rule 4



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

(if there is even one way to potentially have a leak, we potentially have a leak!)

Secure Information Flow Rule 5 (Bonus!)



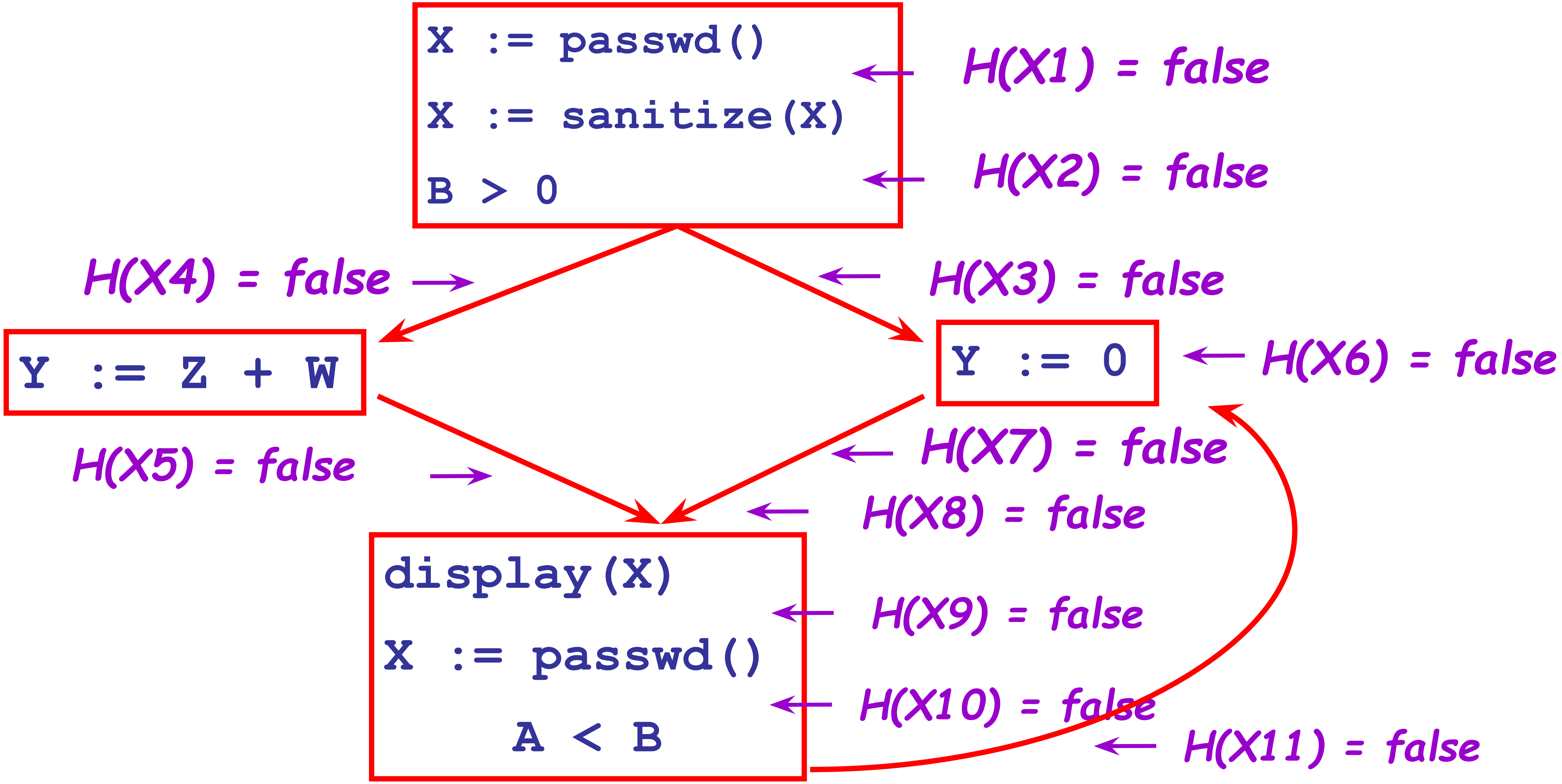
- $H_{in}(y, x := y) = H_{out}(x, x := y)$

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

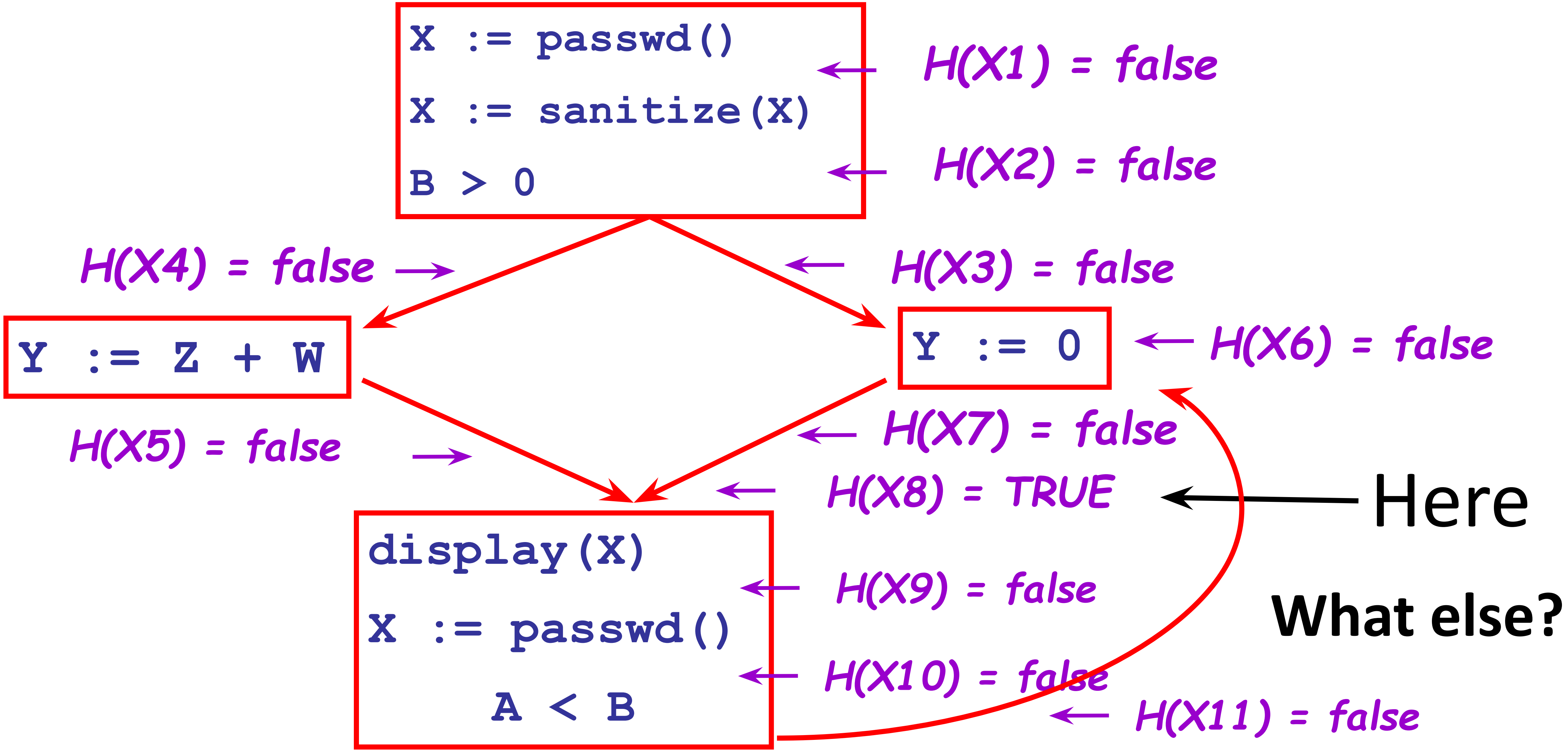
Algorithm

- Let all H_(...) = false initially
- Repeat process until all statements s satisfy rules 1-4 :
  - Pick s where one of 1-4 does not hold and update using the appropriate rule

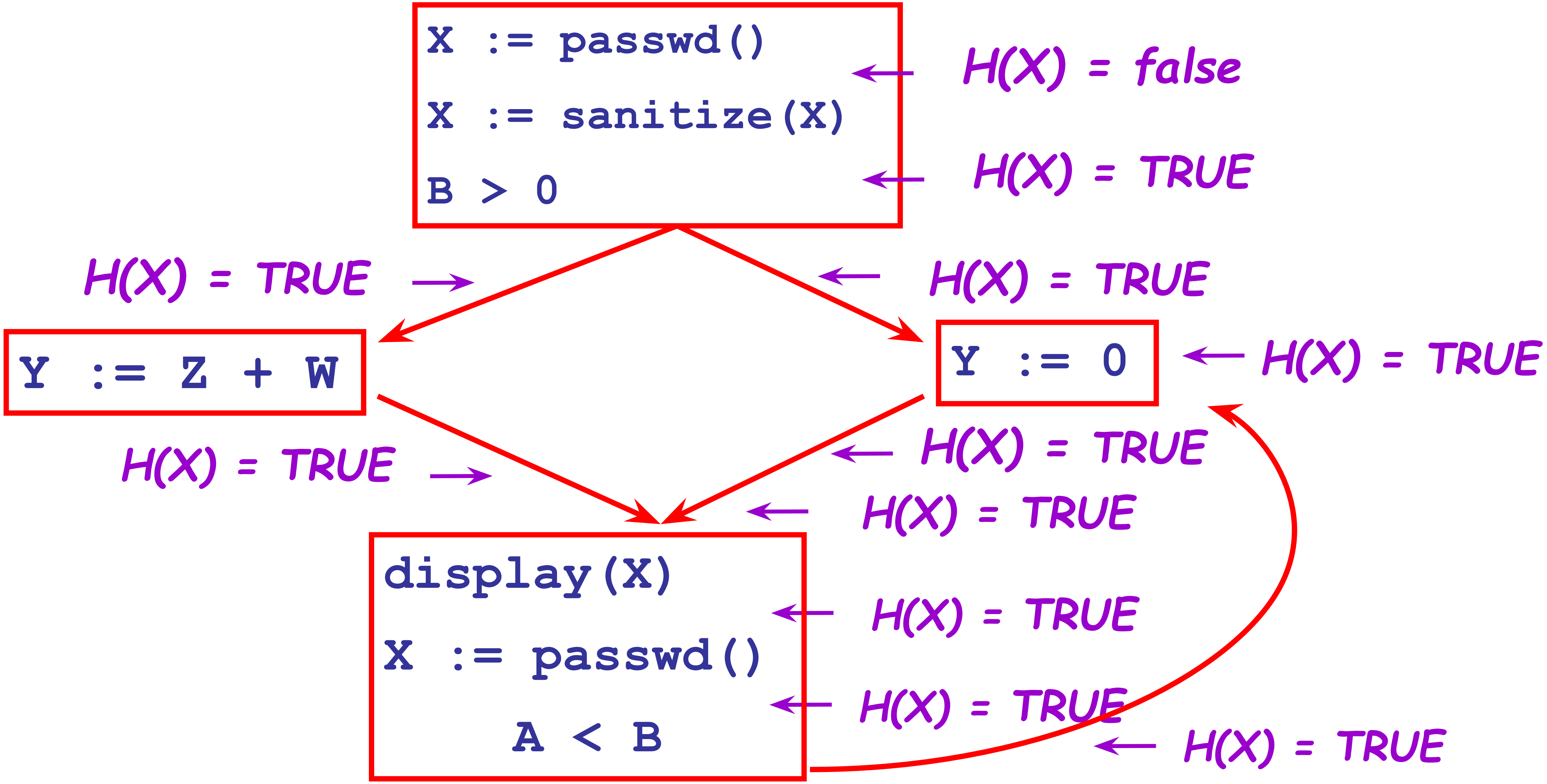
Secure Information Flow Example



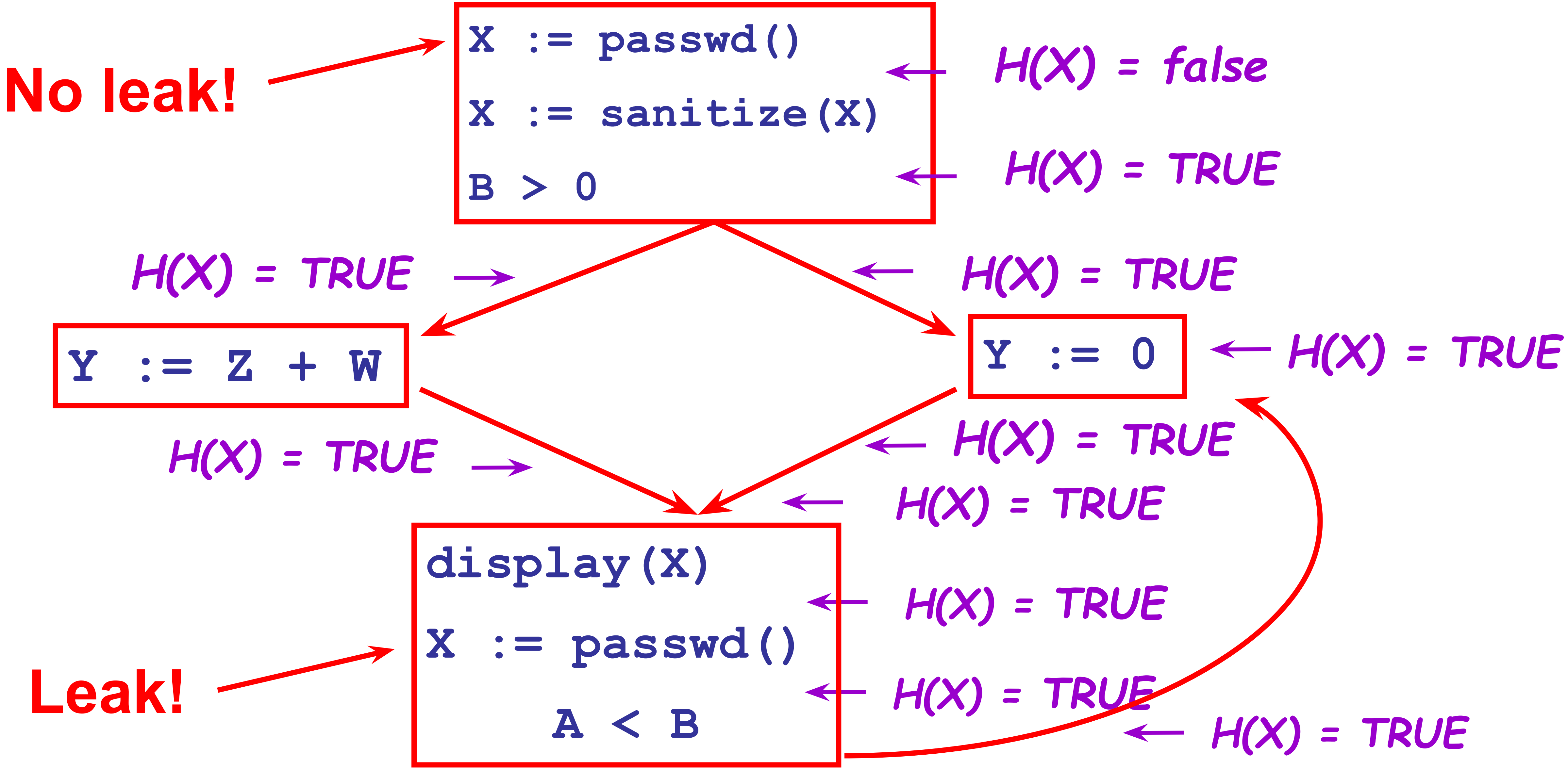
Secure Information Flow Example



Secure Information Flow Example



Secure Information Flow Example



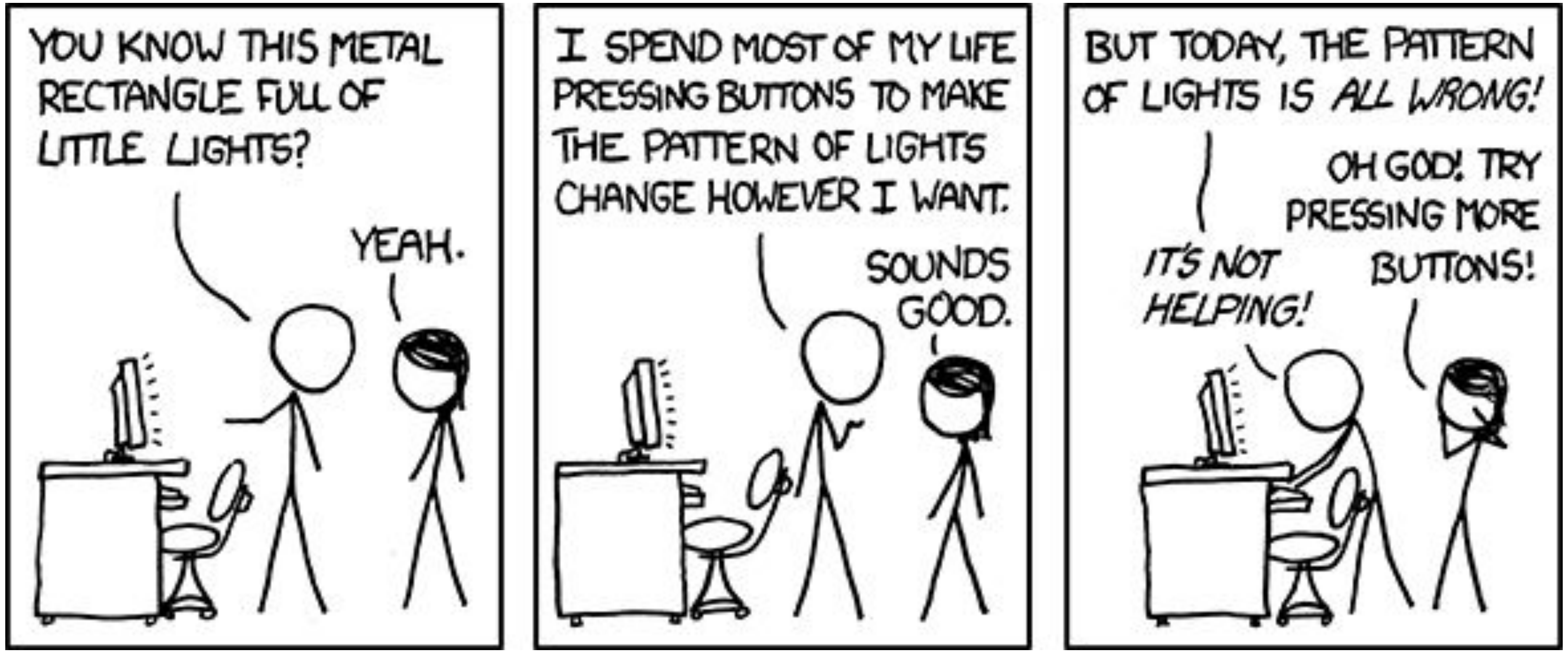
Termination

- 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 issue a warning at a particular sensitive information point (if right after it, the analysis says true)

Static Analysis Limitations

- Where might a static analysis go “wrong”?
- Construct the shortest program that causes a static analysis to get the “wrong” answer?



```
x = new AST()

y = identity(x)

deref y
```

Report Error!

(False Positive)

Static Analysis

- You are asked to design a static analysis to detect bugs related to **file handles**
  - A file starts out *closed*. A call to open() makes it *open*; open() may only be called on *closed* files. read() and write() may only be called on *open* files. A call to close() makes a file *closed*; close may only be called on *open* files.
  - Report if a file handle is potentially used incorrectly
- What abstract information do you track?
- What do your transfer functions look like?

Abstract Information

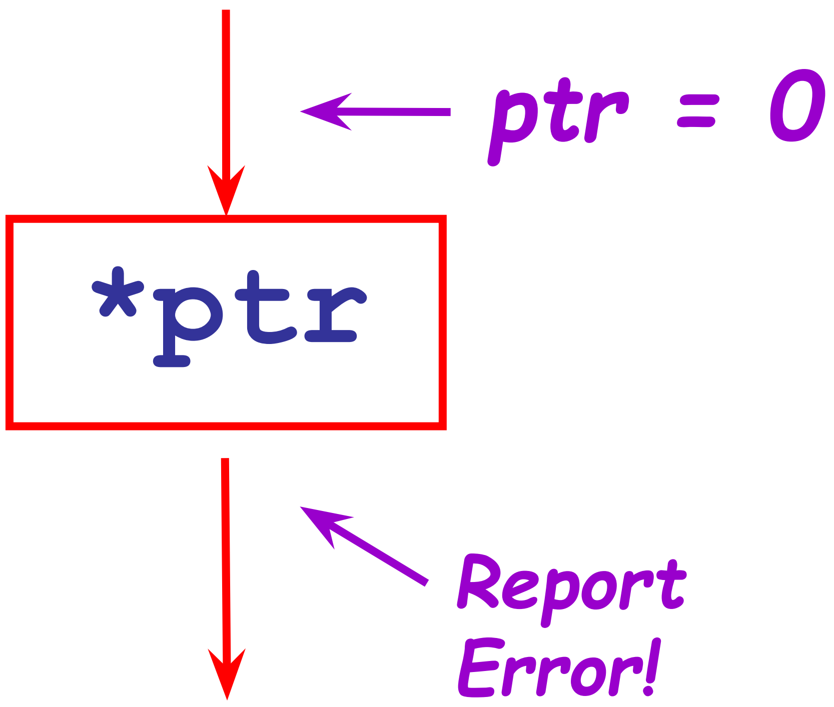
- We will keep track of an abstract value for a given file handle variable

- Values and Interpretations

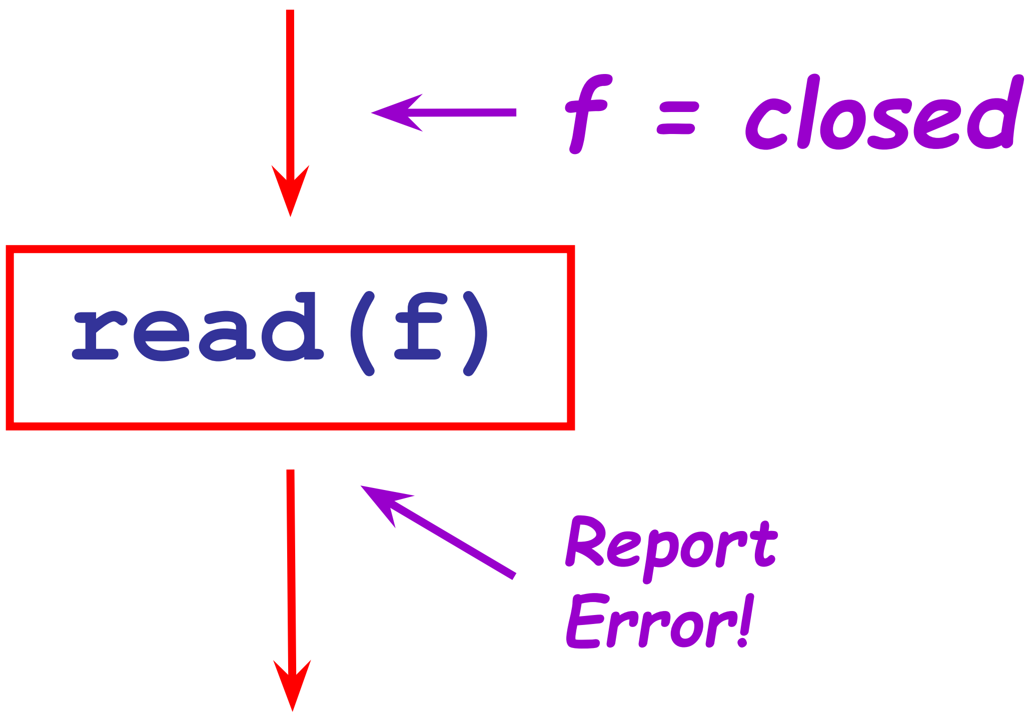
T	file handle state is unknown
⊥	haven't reached here yet
closed	file handle is closed
open	file handle is open

"Null Ptr" vs. "File Handles"

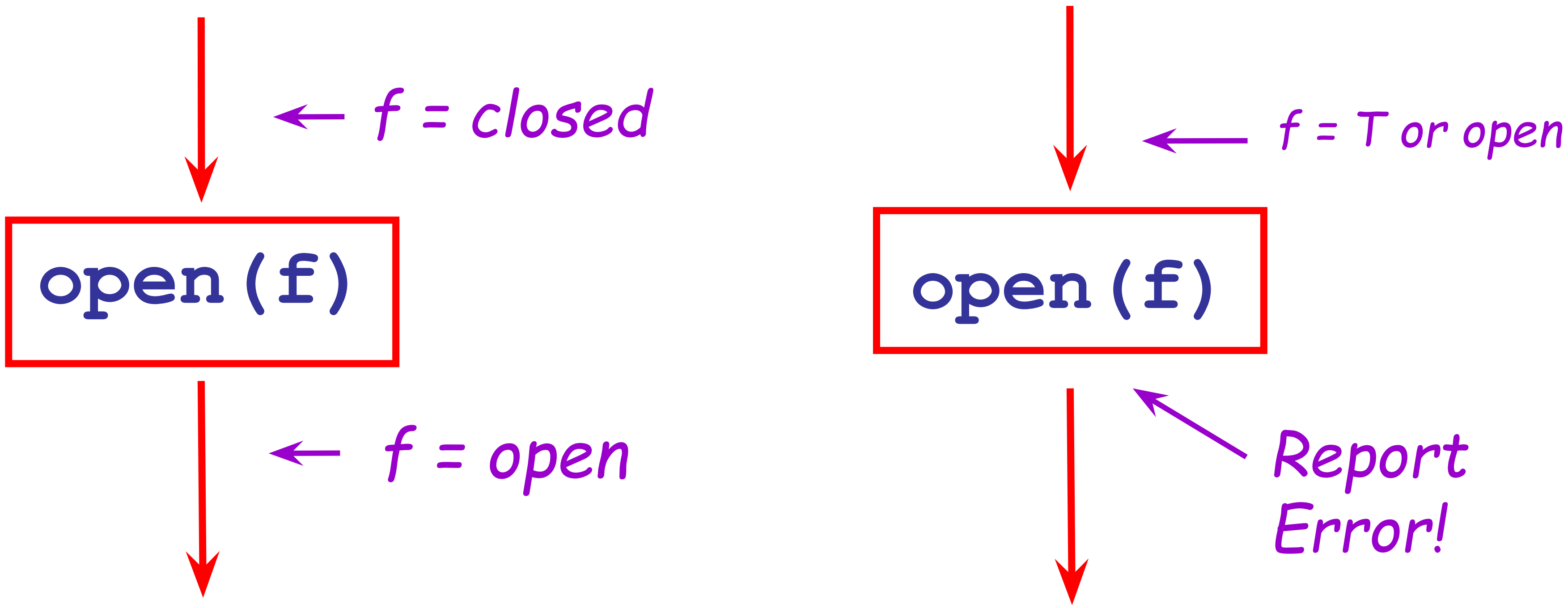
- Previously: "null ptr"



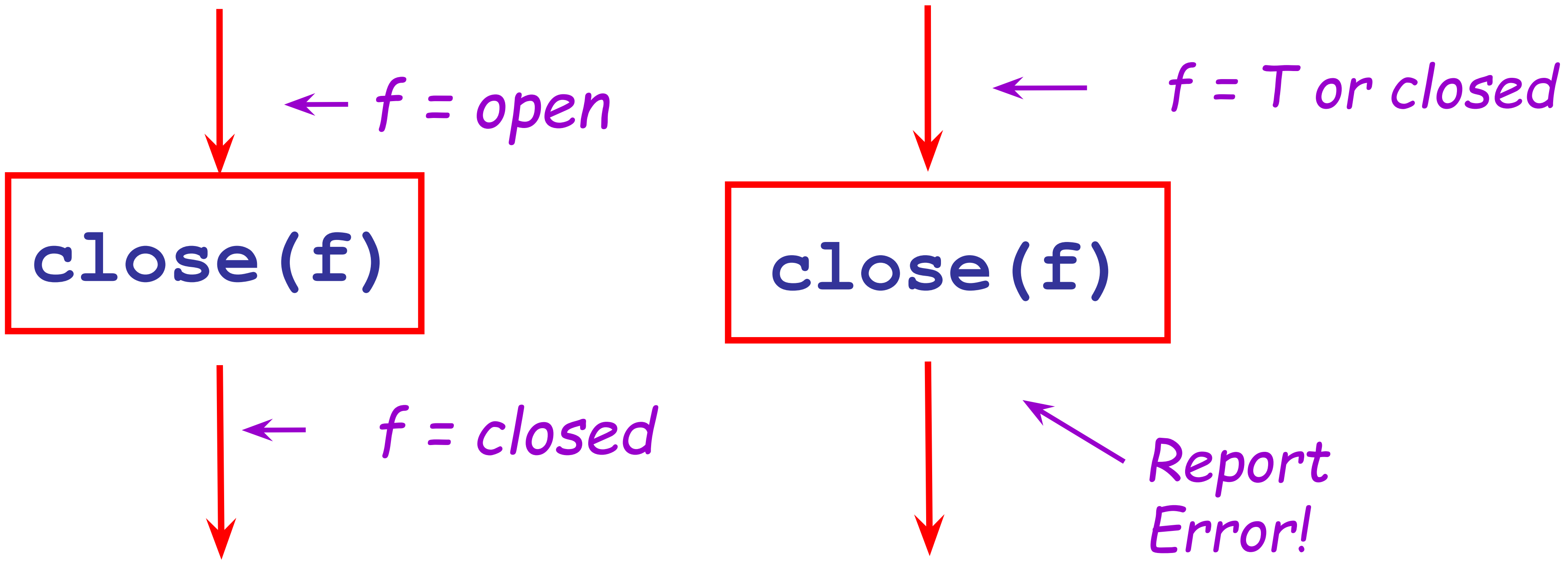
- Now: "file handles"



Rules: open

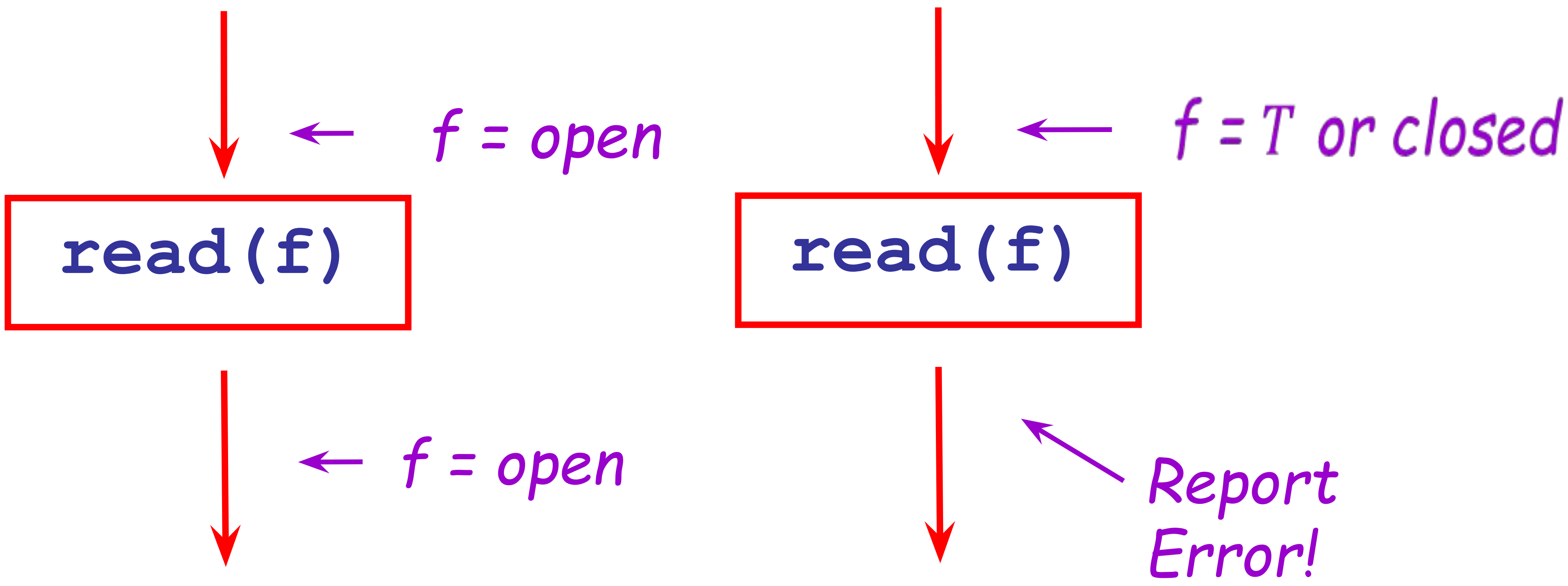


Rules: close

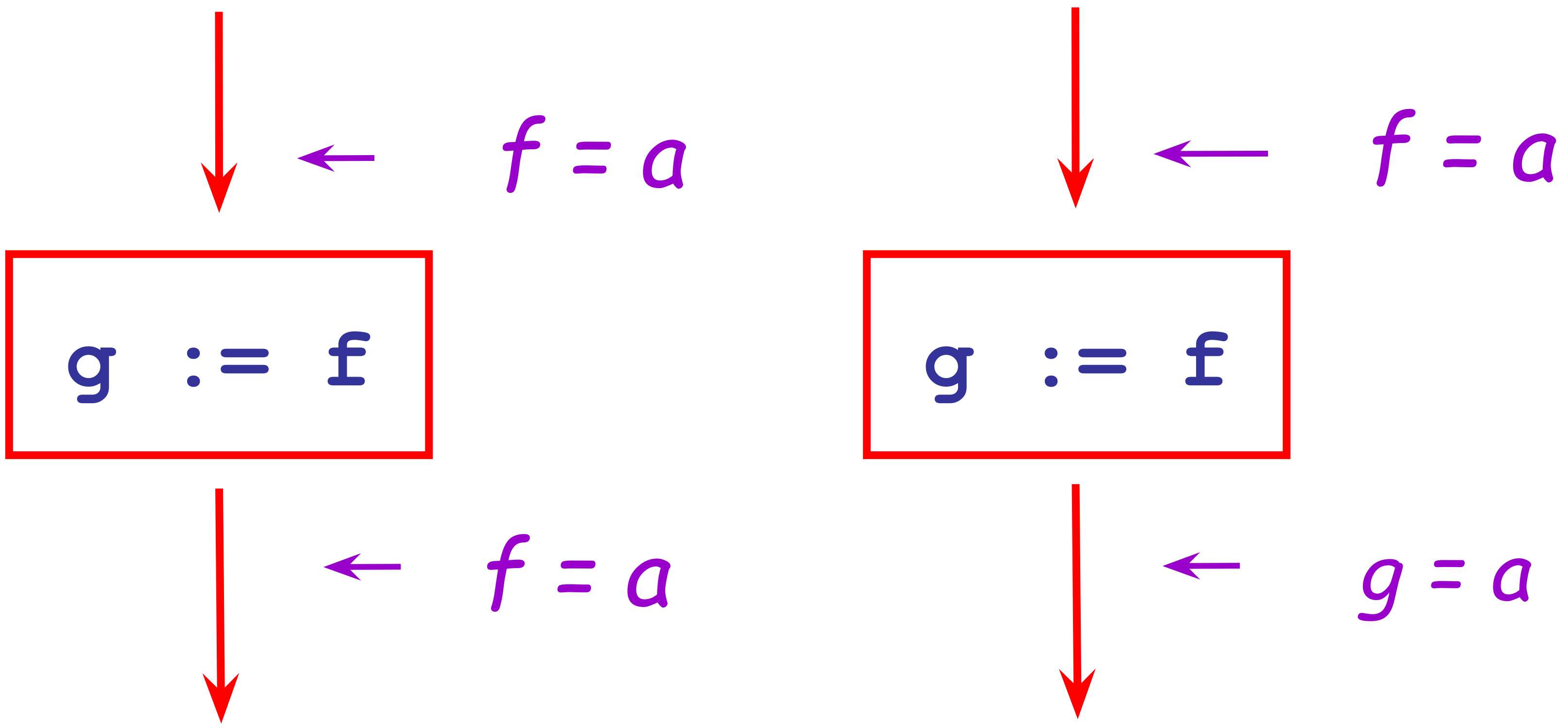


Rules: read/write

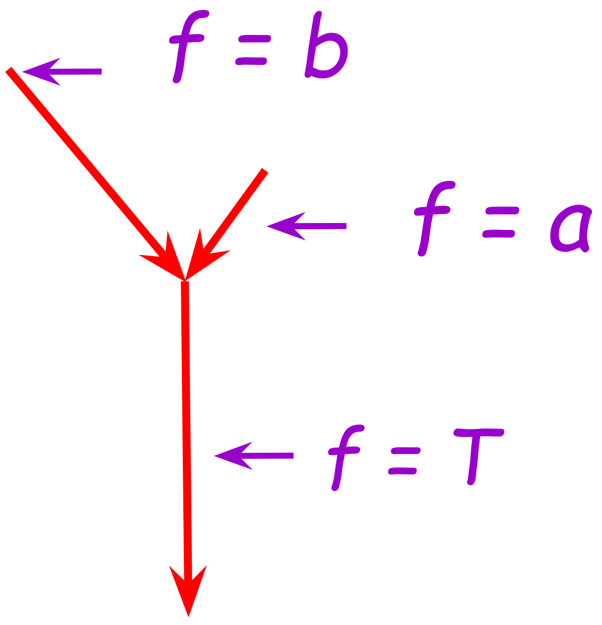
- only show read(f); write(f) is the same

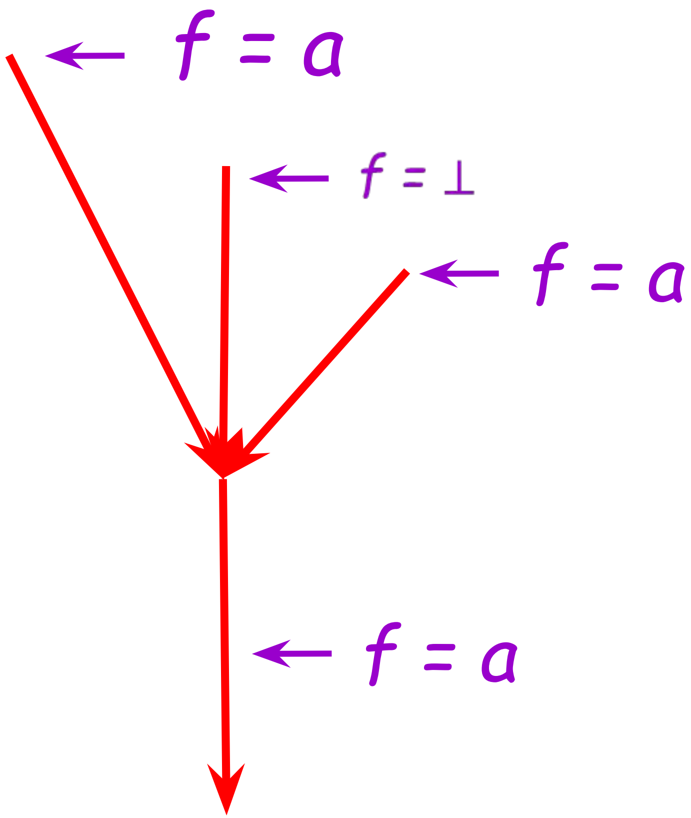


Rules: Assignment



Rules: Multiple Possibilities

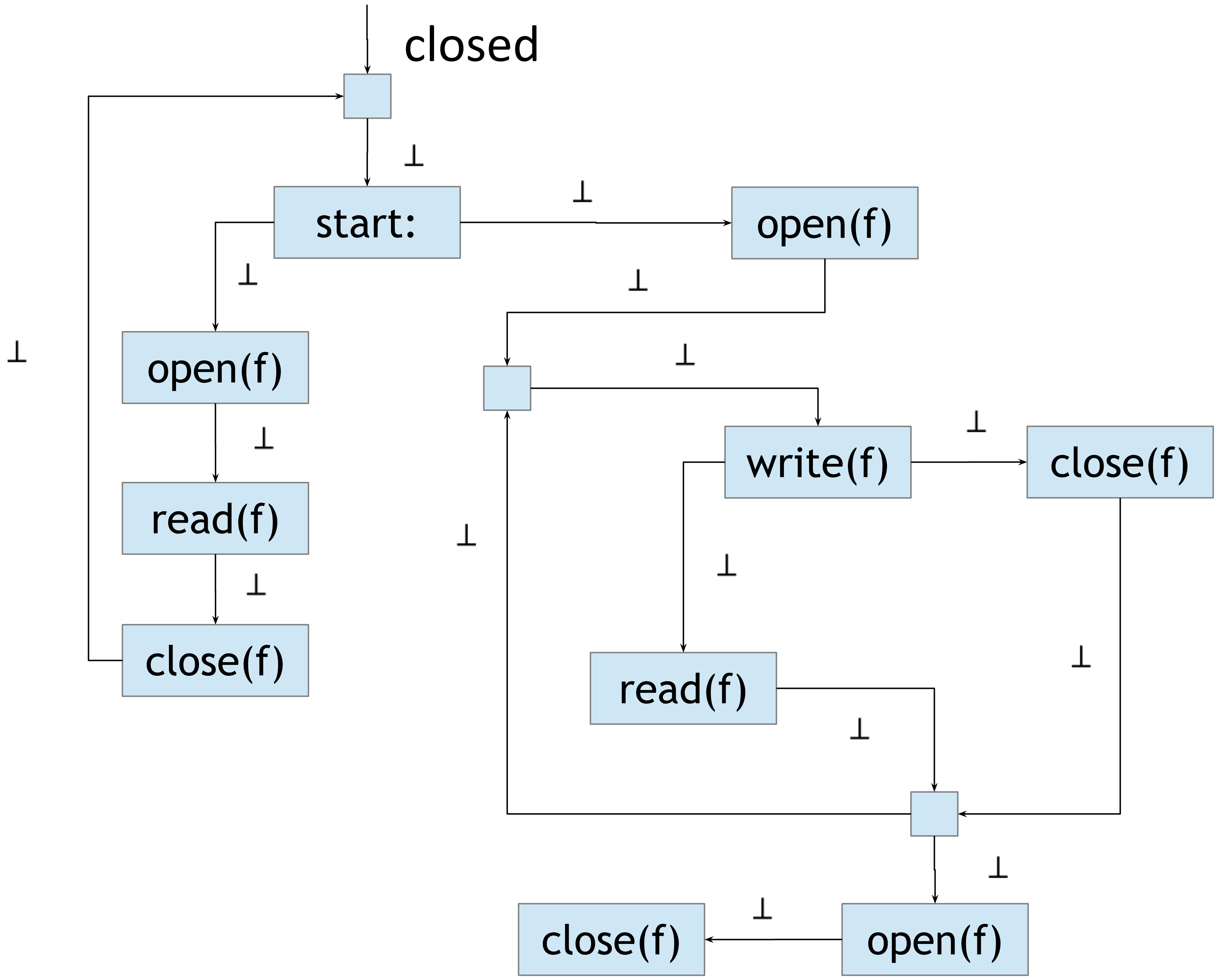


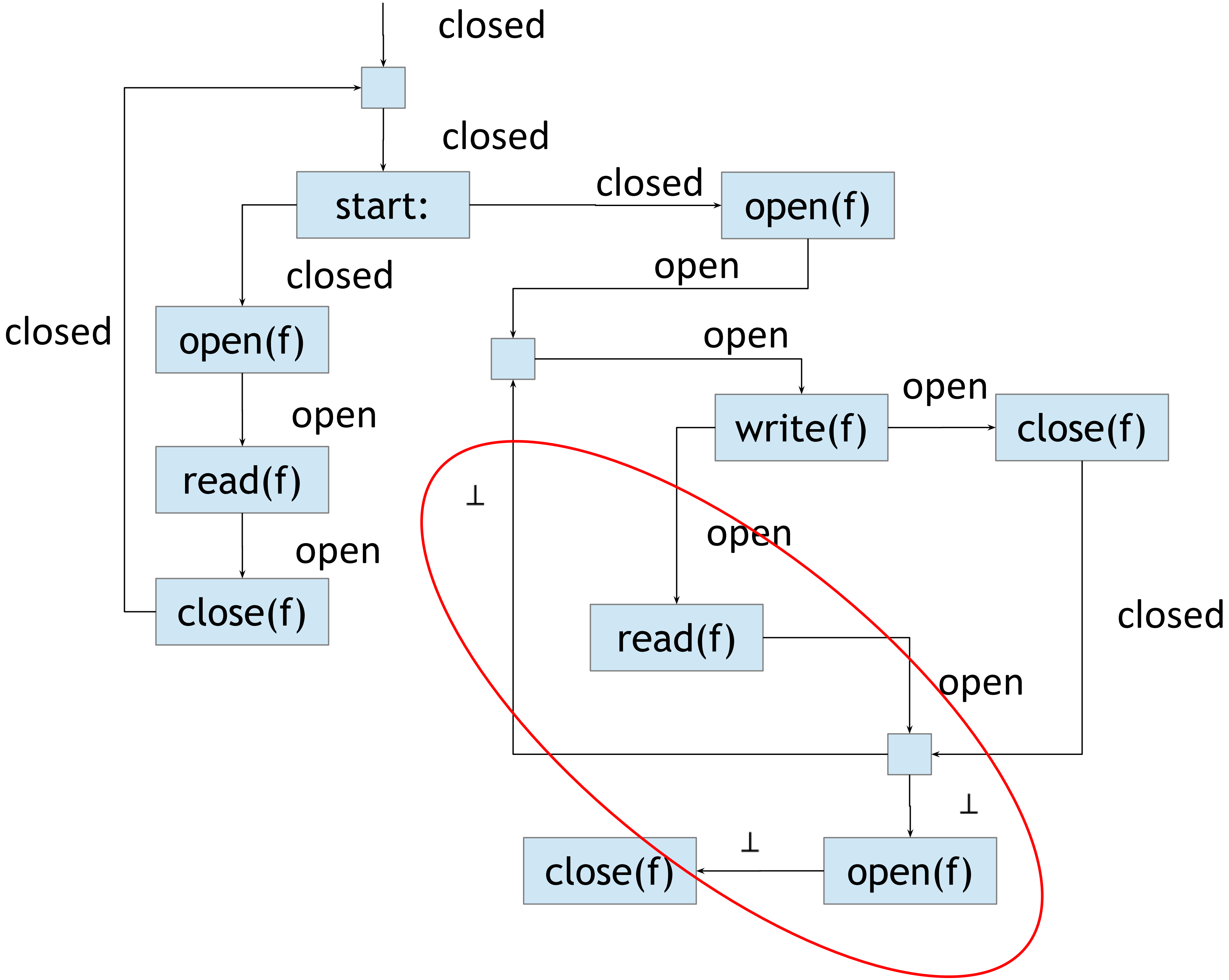


A Tricky Program

```
start:
switch (a)
  case 1: open(f); read(f); close(f); goto start
  default: open(f);
do {
  write(f) ;
  if (b):  read(f);
  else:  close(f);
} while (b)
open(f);
close(f);
```

```
start:
switch (a)
  case 1: open(f);
          read(f);
          close(f);
          goto start
  default: open(f);
do {
  write(f) ;
  if (b):  read(f);
  else:    close(f);
} while (b)
open(f);
close(f);
```




closed
closed
start:
closed
open(f)
open
closed
open(f)
closed
open
open
read(f)
write(f)
open
close(f)
open
close(f)
⊥
open
read(f)
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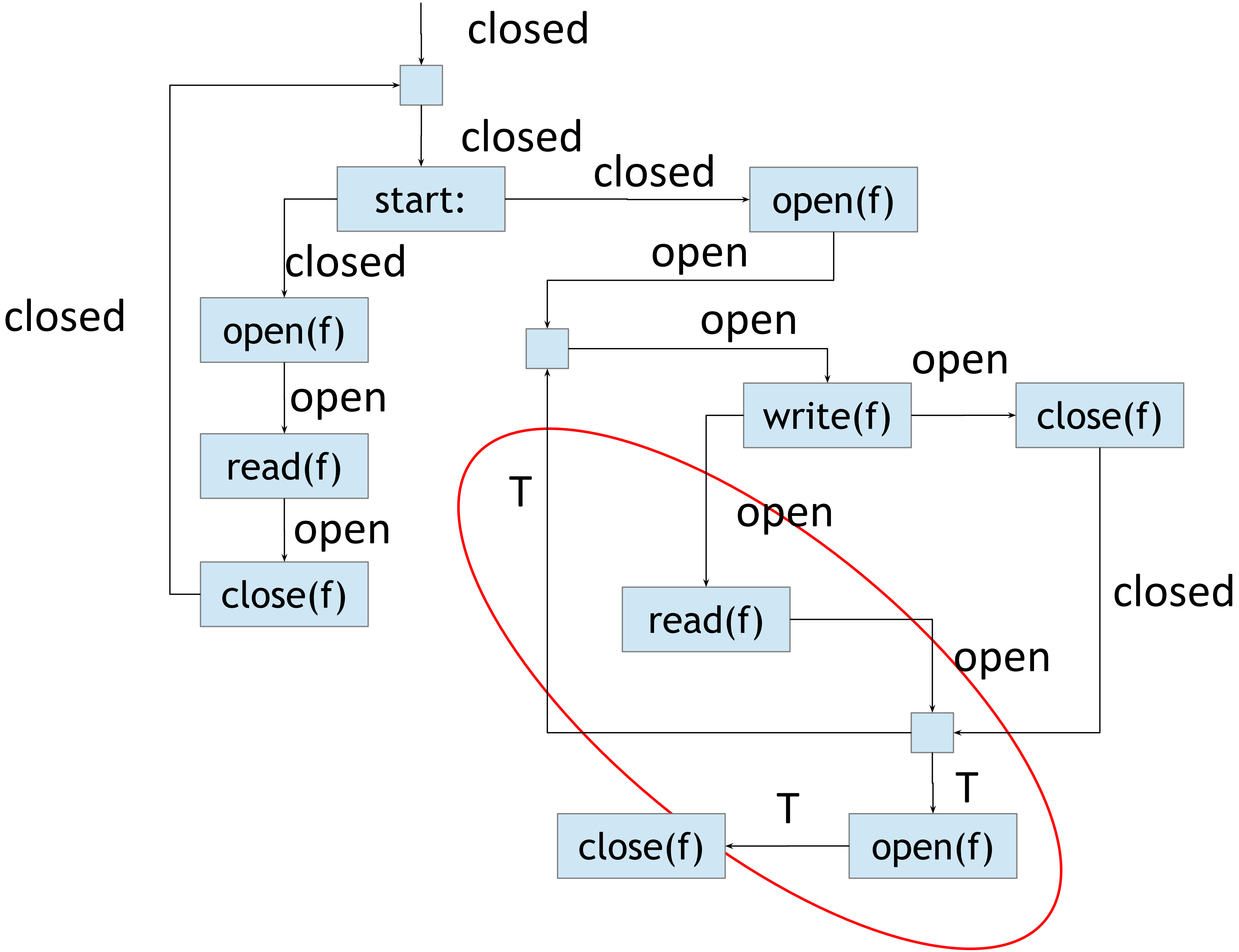
open
⊥
⊥
close(f)
open(f)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closed
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open(f)
closed
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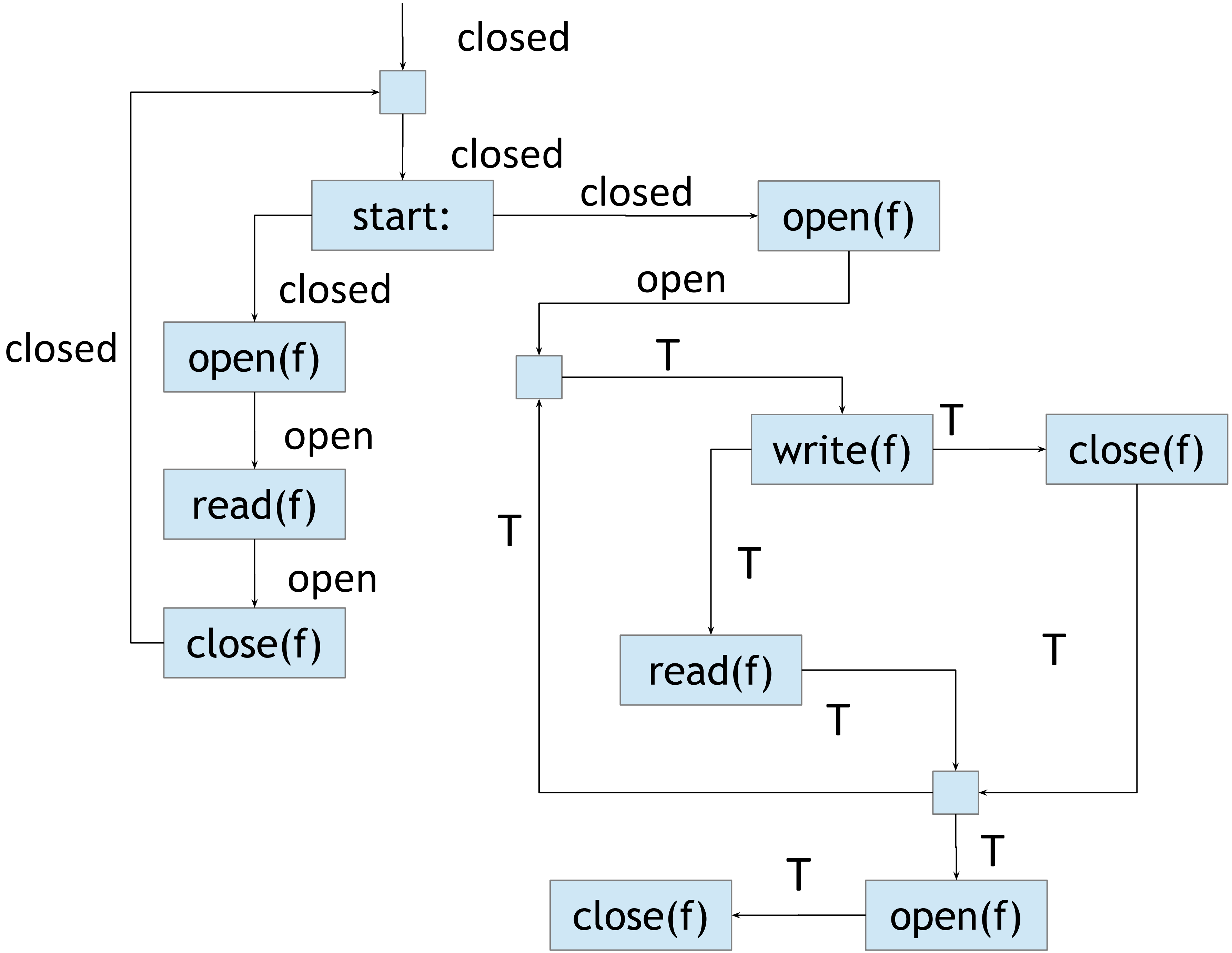
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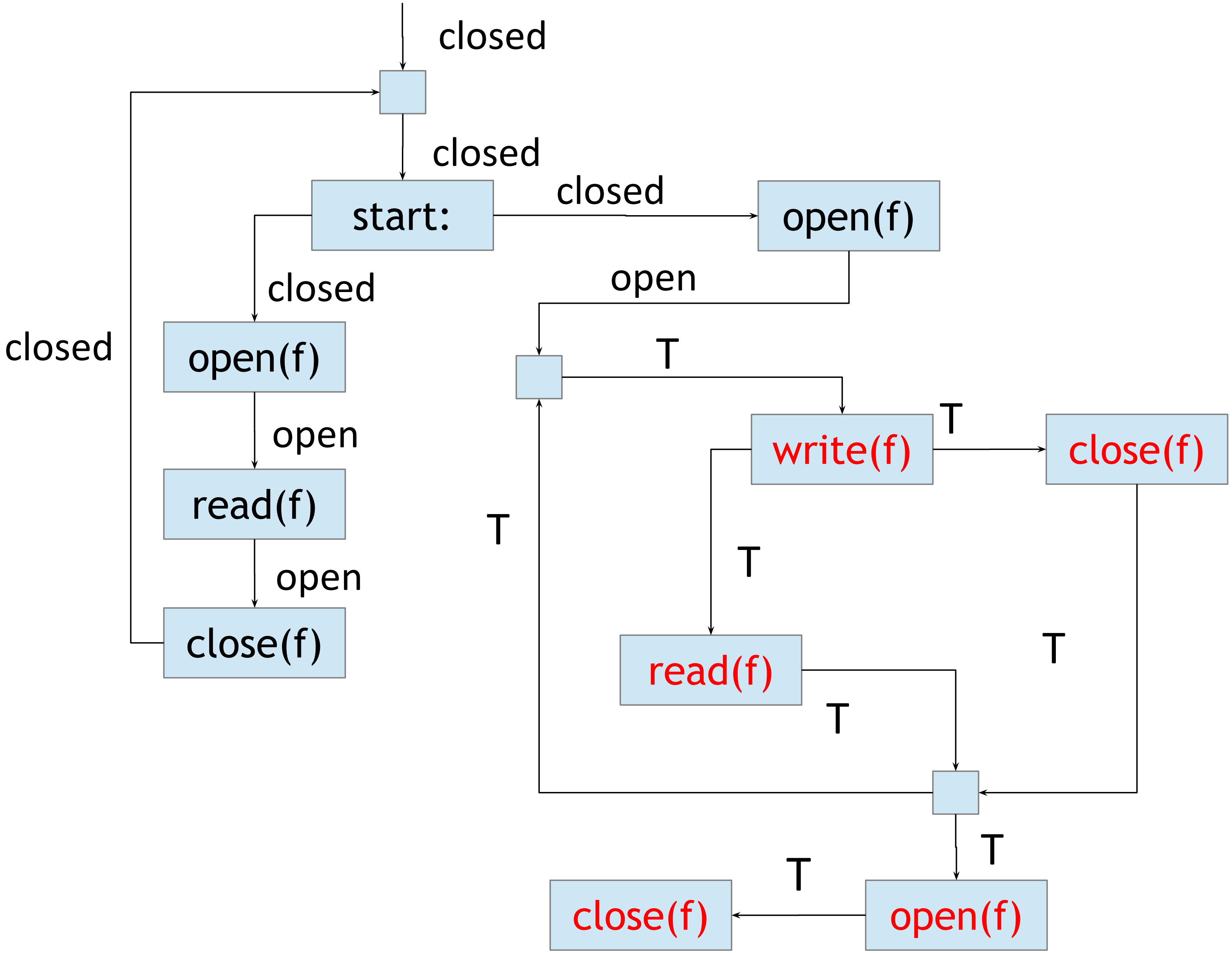
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open
close(f)
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close(f)
open(f)

Is There Really A Bug?

```
start:
switch (a)
   case 1: open(f); read(f); close(f); goto start
   default: open(f);
do {
   write(f) ;
   if (b): read(f);
   else: close(f);
} while (b)
open(f);
close(f);
```

Forward vs. Backward Analysis

- We've seen two kinds of analysis:

- Definitely null (cf. constant propagation) is a **forwards** analysis: information is pushed from inputs to outputs

- Secure information flow (cf. liveness) is a **backwards** analysis: information is pushed from outputs back towards inputs