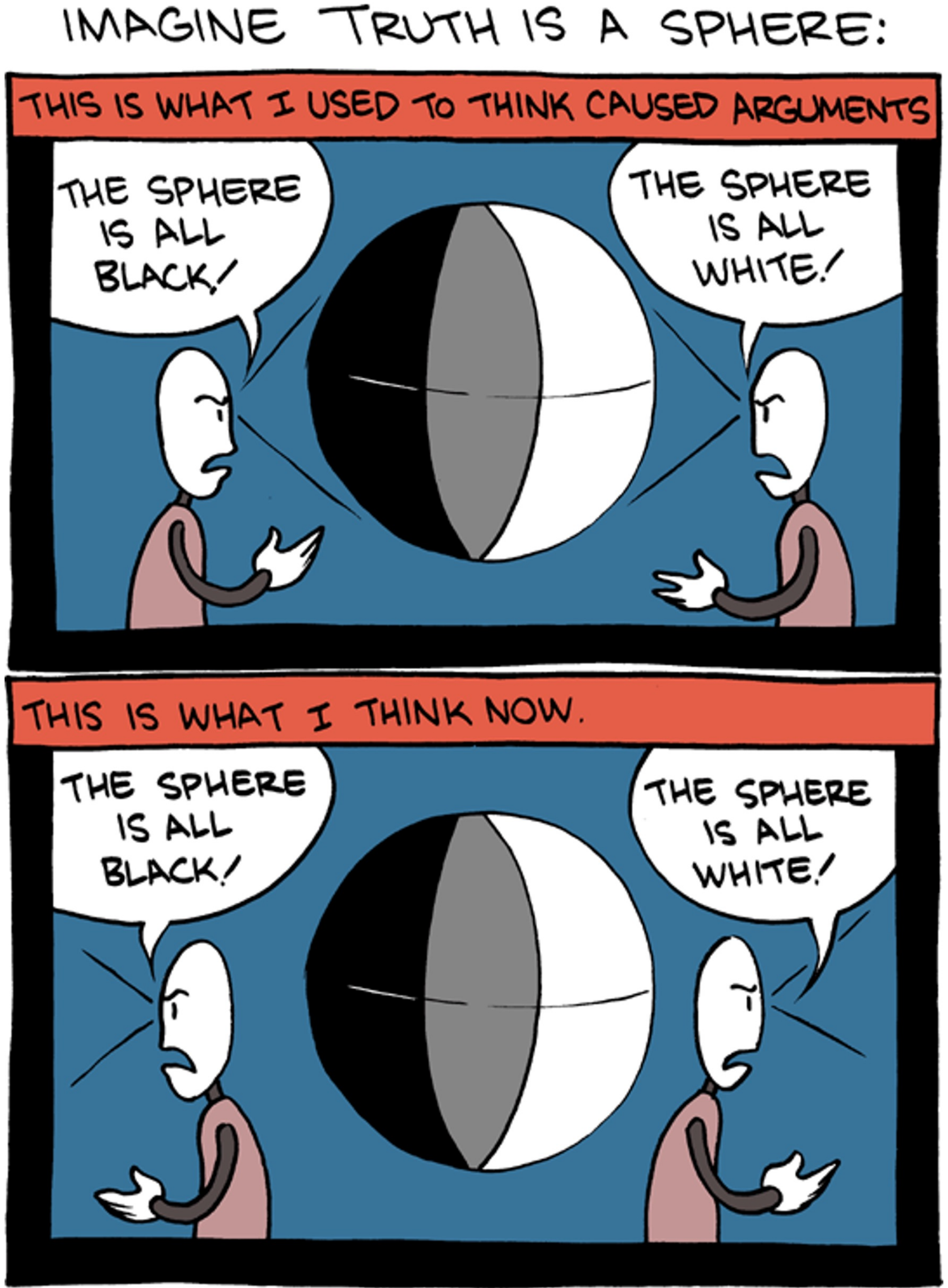


Static and Dataflow Analysis

(two or three-part lecture)

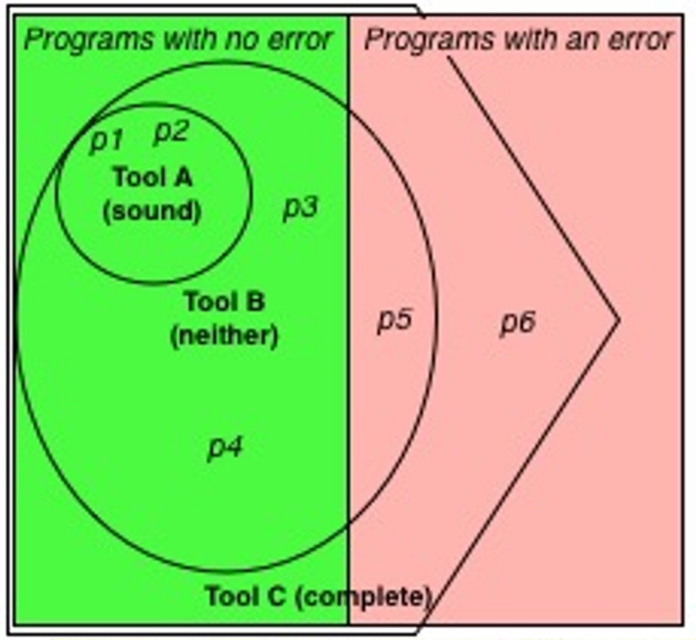
The Story So Far …

- 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 are the most common static approaches to QA.
- What other static analyses are commonly used and how do they work?

Review and Wrap-up: Dynamic Analysis

- Dynamic analyses involve *running* the program
  - You **instrument** the source code
    - Consider: what **property** do you care about?
    - What **information** do you need to understand that property?
    - What **mechanisms** can be used to collect that information?
    - What post-hoc **analyses** must be conducted on that information?
  - You **compile** the instrumented source code
  - You **execute** the instrumented program on test inputs

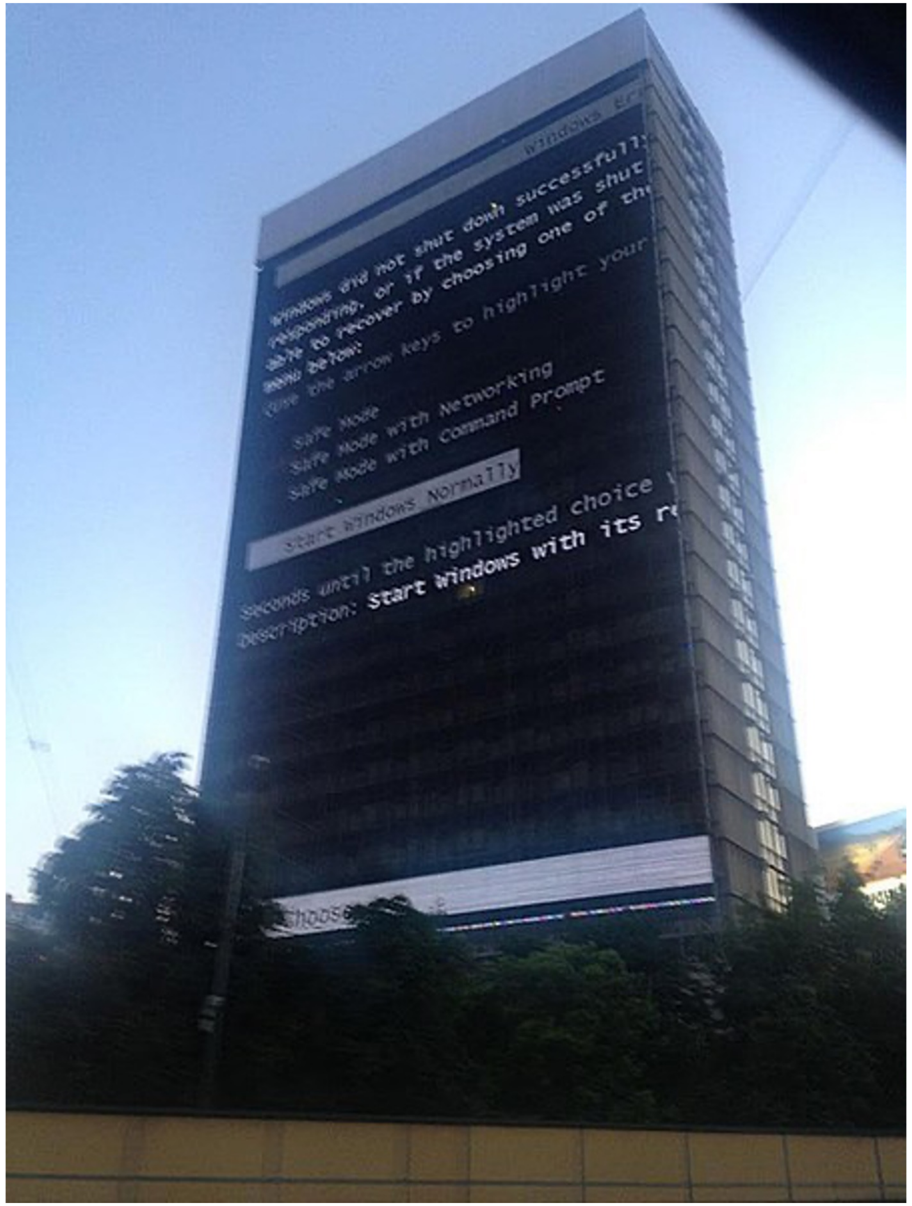
- Analyses of this sampled data entails **statistical errors**



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**.
  - TL;DR analyses of **code** (i.e., not runtime)
- **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.

goto fail;


Safe Mode
Safe Mode with Networking
Safe Mode with Command Prompt
Start Windows Normally

“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
;
}
```

The Apple goto fail vulnerability: lessons learned

David A. Wheeler

2021-01-16 (original 2014-11-23)

ns that we *should* learn from the Apple “goto fail” vulnerability. It first starts with some background, discusses the mis
ntifying what could have countered this, briefly discusses the Heartbleed countermeasures from my separate paper or

https://dwheeler.com/essays/apple-goto-fail.html

CNET › News › Security & Privacy › Klocwork: Our source code analyzer caught Apple's '...

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

57 223 23 5 More + Comments 25

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.

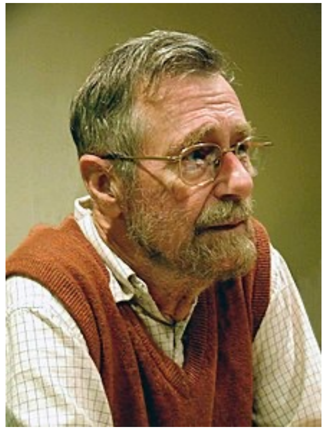
Featured Posts

Google unveils Androi wearables
Internet & Media

Most Popular

Connect With CNET

Facebook
Like Us



"GOTO Statement Considered Harmful"
-- Edsger Dijkstra

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;
}
```

Could We Have Found Them?

- 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: 15+ millions LOC
- Some defects are very difficult to find via testing or manual inspection

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!

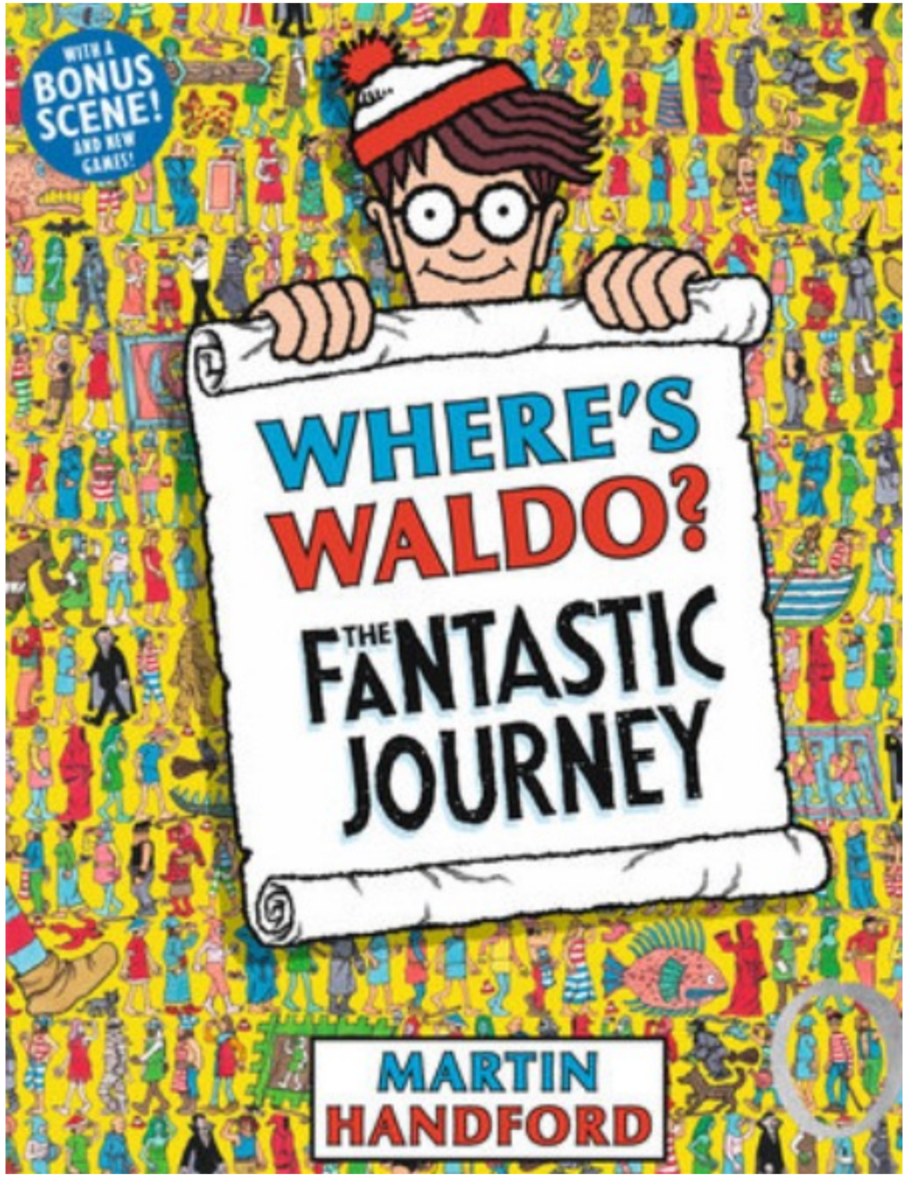
Fundamental Concepts

- 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)

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

- **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

- 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.”);
  }
}
```

- First attempt:

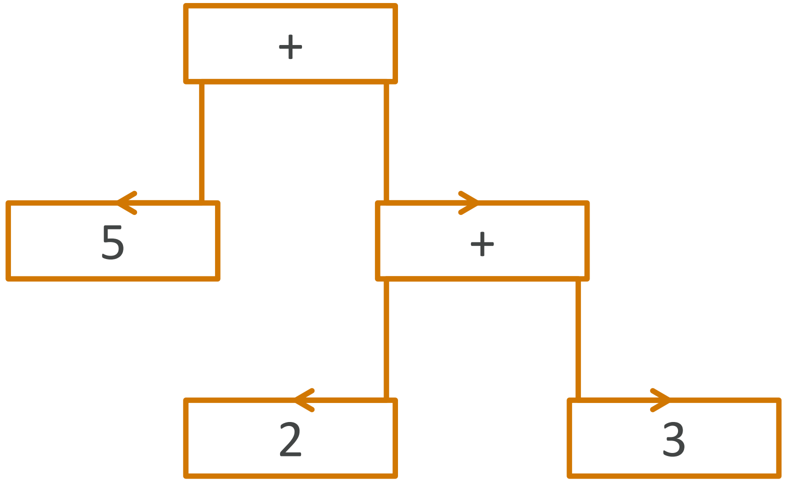
`grep logger\.debug -r source_dir`

- Is it enough?

Abstraction: Abstract Syntax Tree

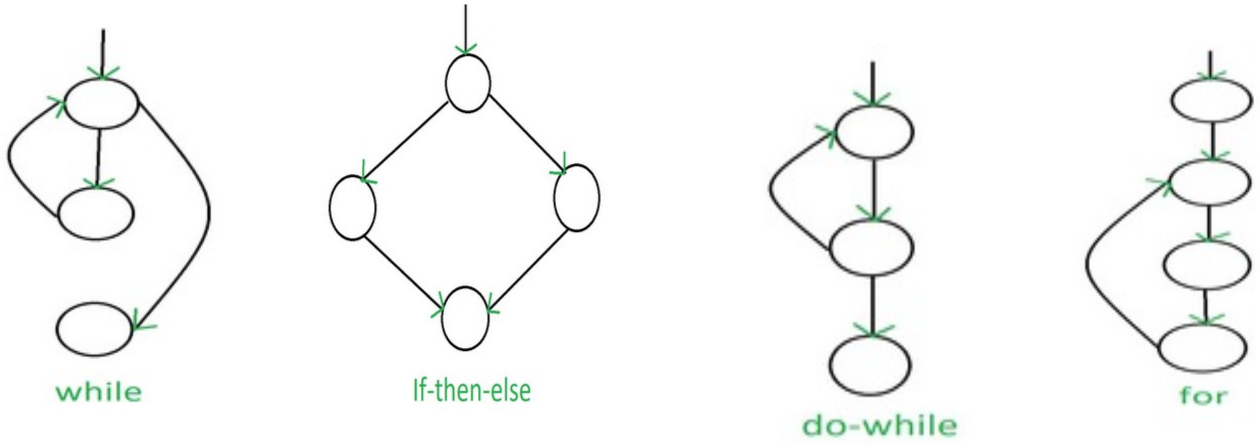
- An **AST** is a tree representation of the syntactic structure of source code
  - Parsers convert concrete syntax into abstract syntax
- Records only semantically-relevant information
  - Abstracts away (, etc.
- AST captures program structure

Example: 5 + (2 + 3)



Abstraction: Control Flow Graph

- A **CFG** is a representation, using graph notation, of all paths that might be traversed through a program during its execution.
- Process-oriented
- Directed graph



- a representation, using graph notation, of all paths that might be traversed through a program during its execution.

Programs As Data

- “grep” approach: treat program as string
- AST approach: treat program as tree
- CFG approach: treat program as a graph
- The notion of treating a program as data is fundamental
  - Recall from Computer Organization/Architecture: instructions are input to a CPU
    - Writing different instructions causes different execution

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

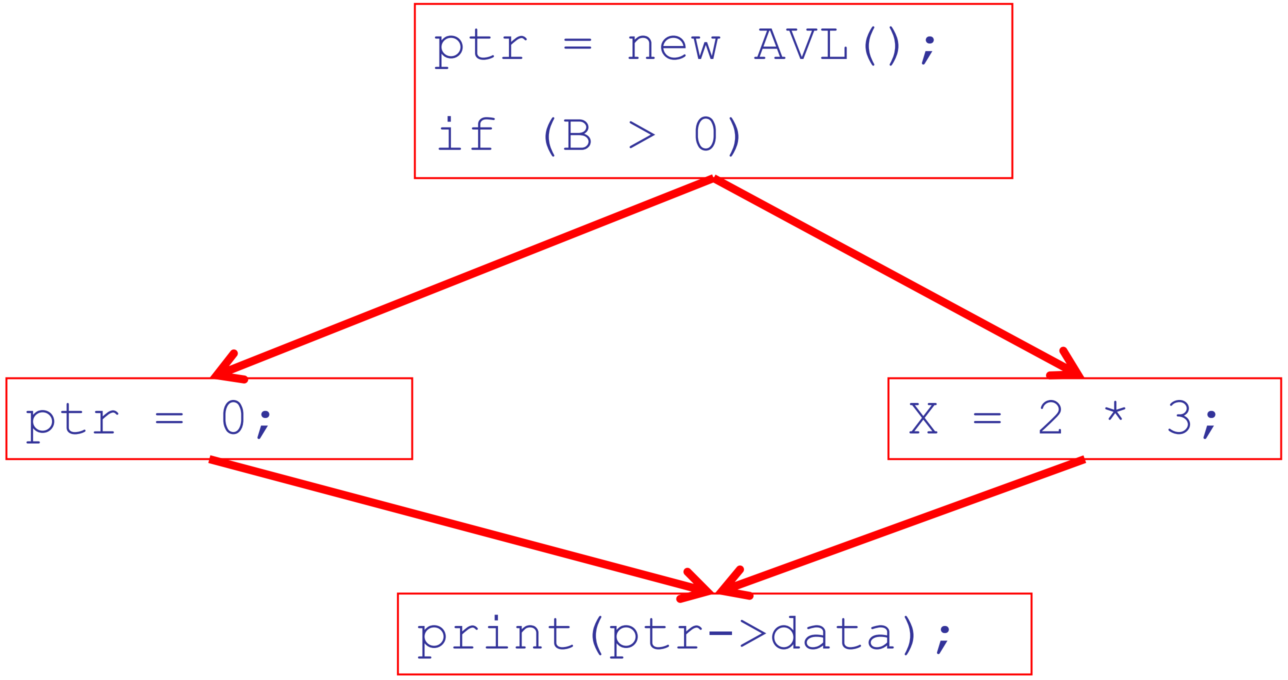
- *Definite* Null Dereference
  - "Whenever execution reaches *ptr at program location L, ptr will be NULL"
- *Potential* Secure Information Leak
  - "We read in a secret string at location L, but there is a possible future public use of it"

Discussion

- These analyses are not trivial to check
- "Whenever execution reaches" → "**all paths**" → 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 }

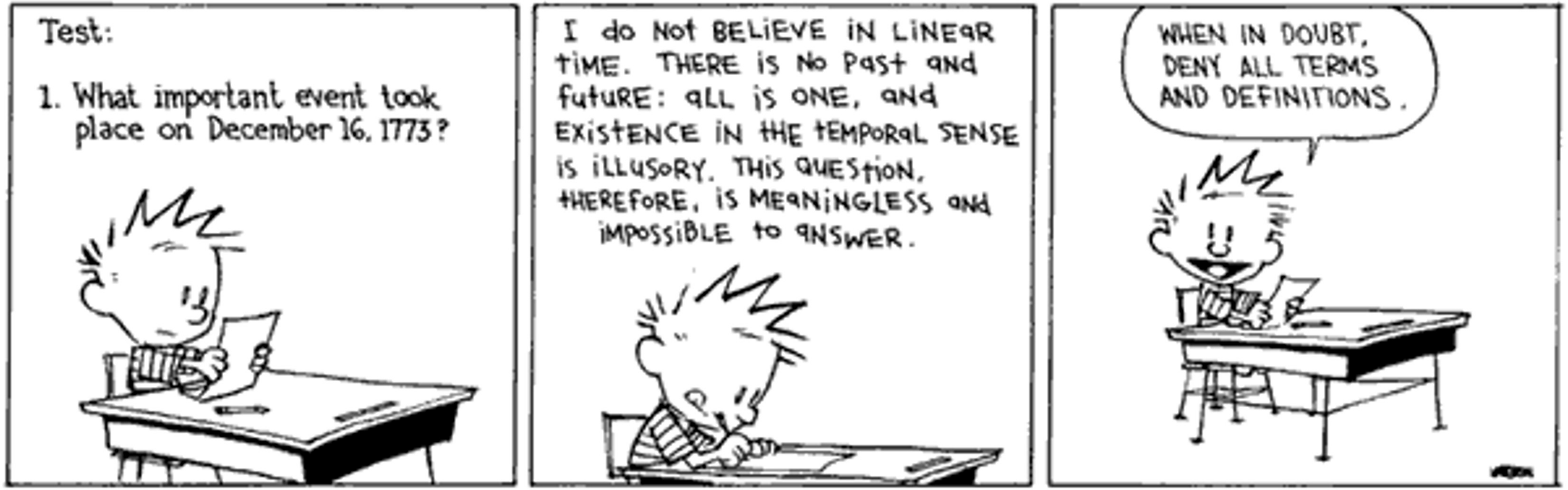
Analysis Example

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



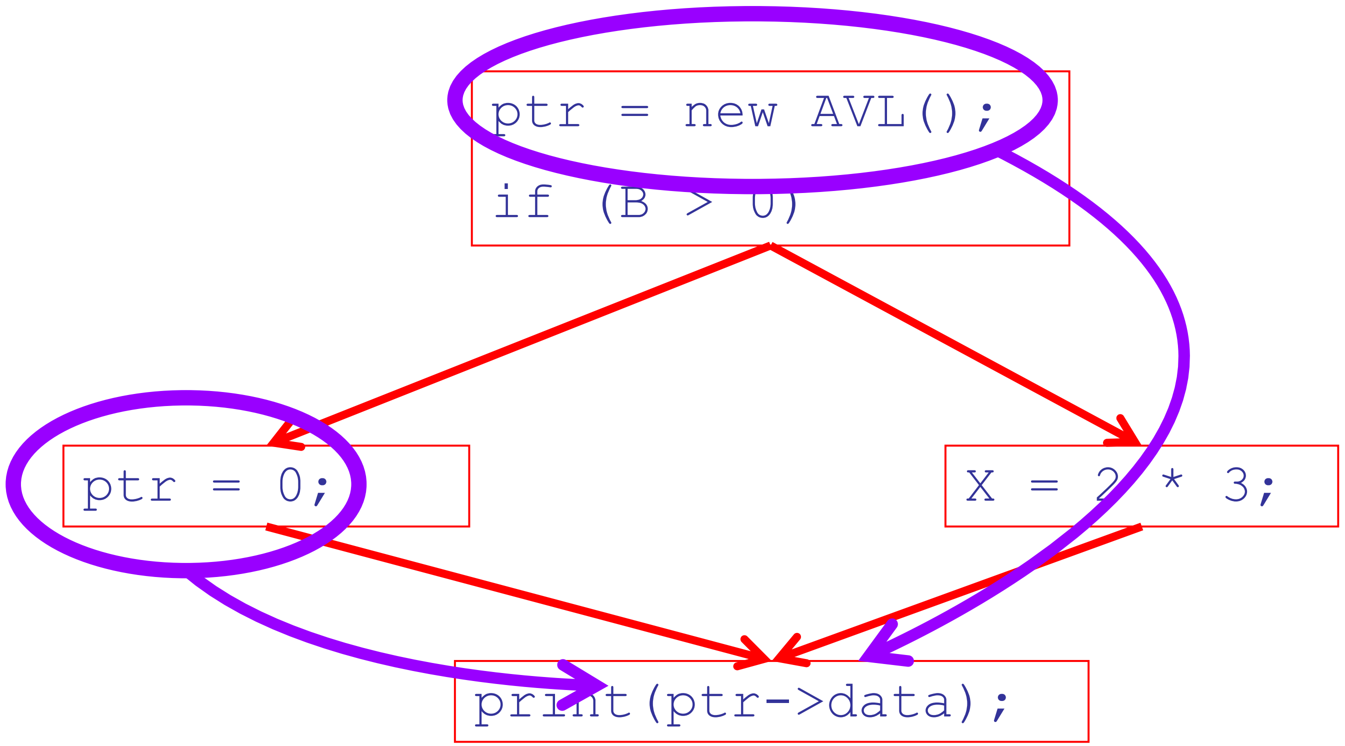
Correctness

- 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*** ****



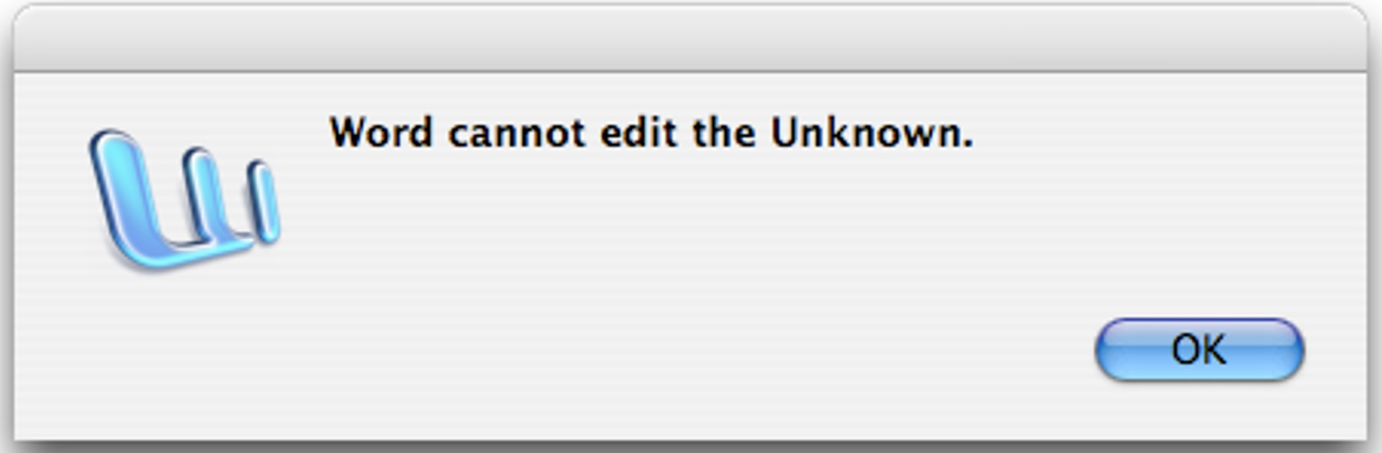
Analysis Example Revisited

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



Static Dataflow Analysis

- Static dataflow analyses share several traits:
  - The analysis depends on knowing a property P at a particular point in program execution
  - 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?
    - **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.
    - *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

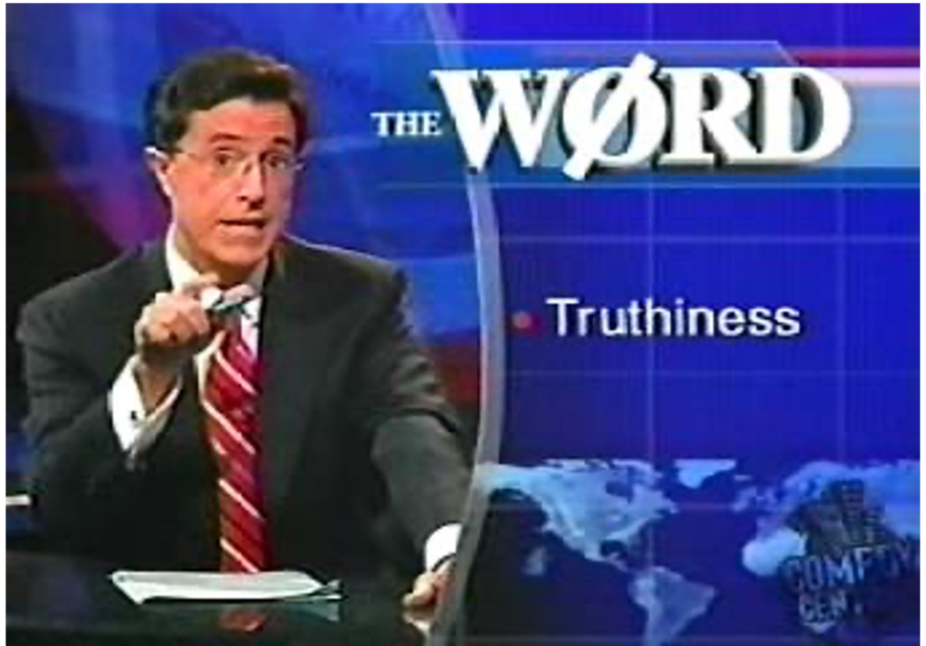
- Almost every important program has a loop
  - Often based on user input
- An algorithm always terminates
- So a dataflow analysis algorithm must terminate even if the input program loops
- This is one source of imprecision
  - Suppose you dereference the null pointer on the 500th iteration but we only 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**.

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 analysis depends on whether or not P is true, then want to know either
  - P is definitely true
  - Don't know if P is true

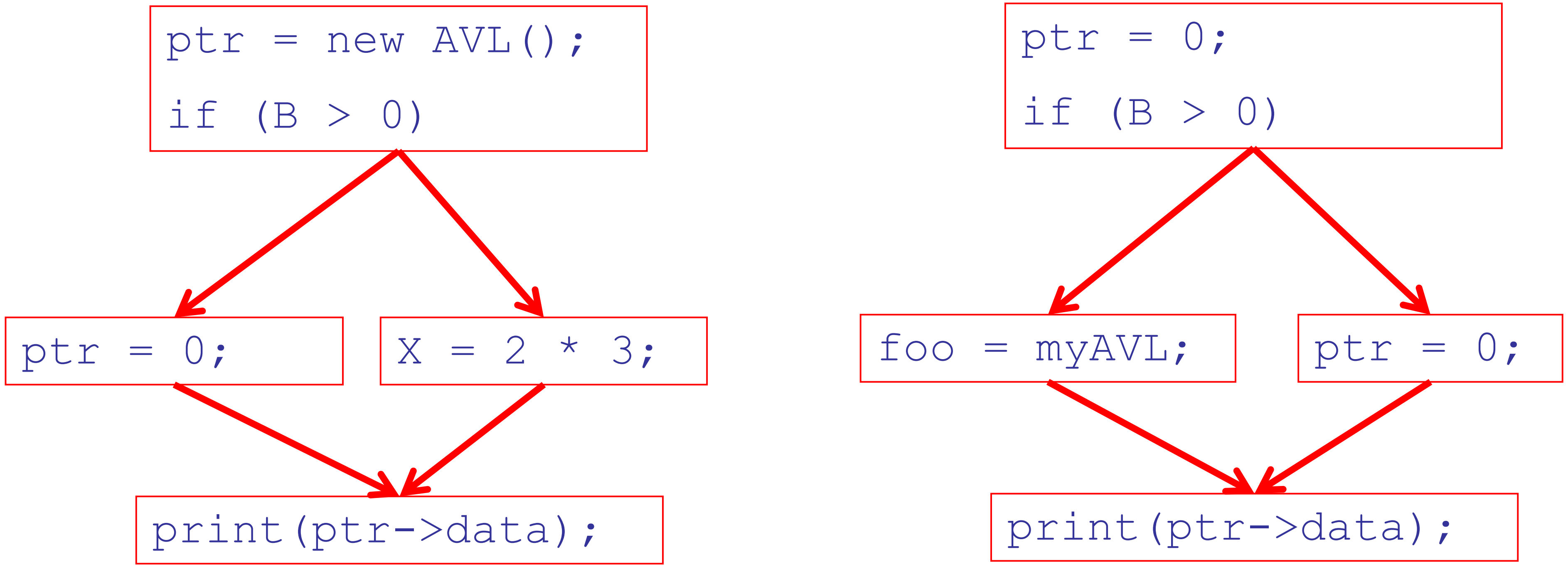


Conservative Program Analyses

- 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.

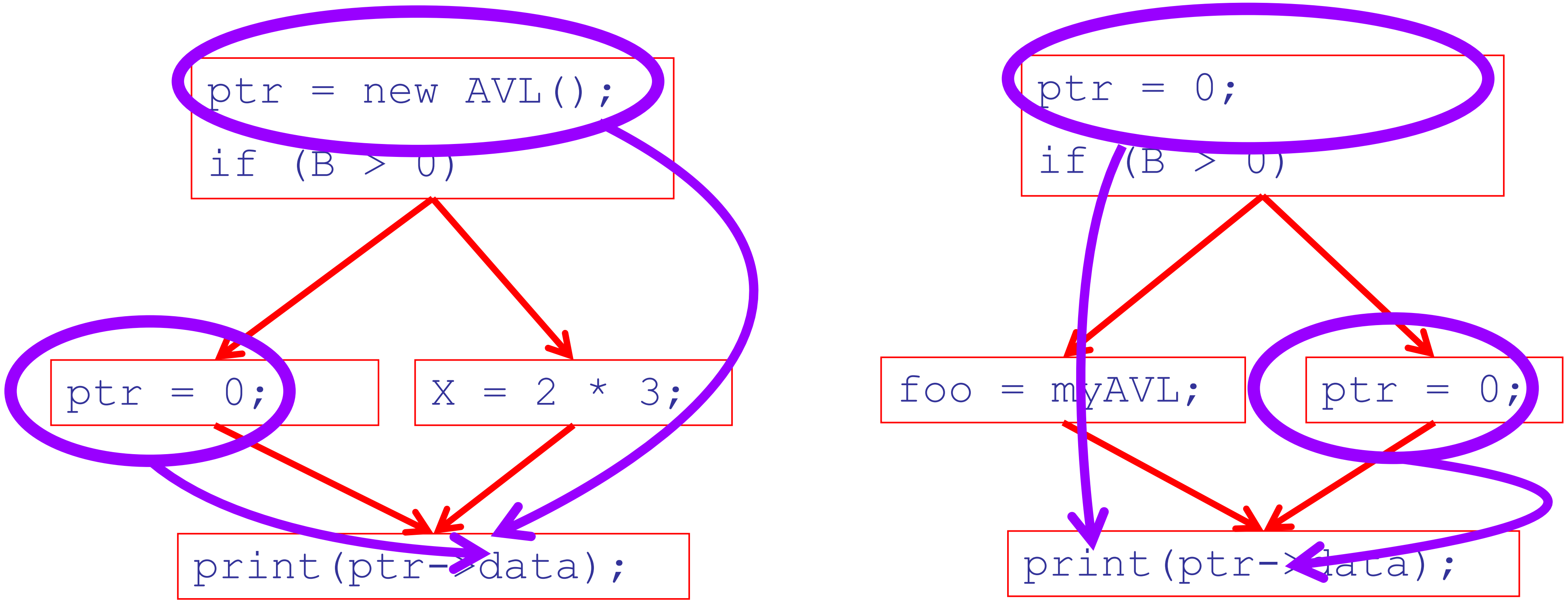
Definitely Null Analysis

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



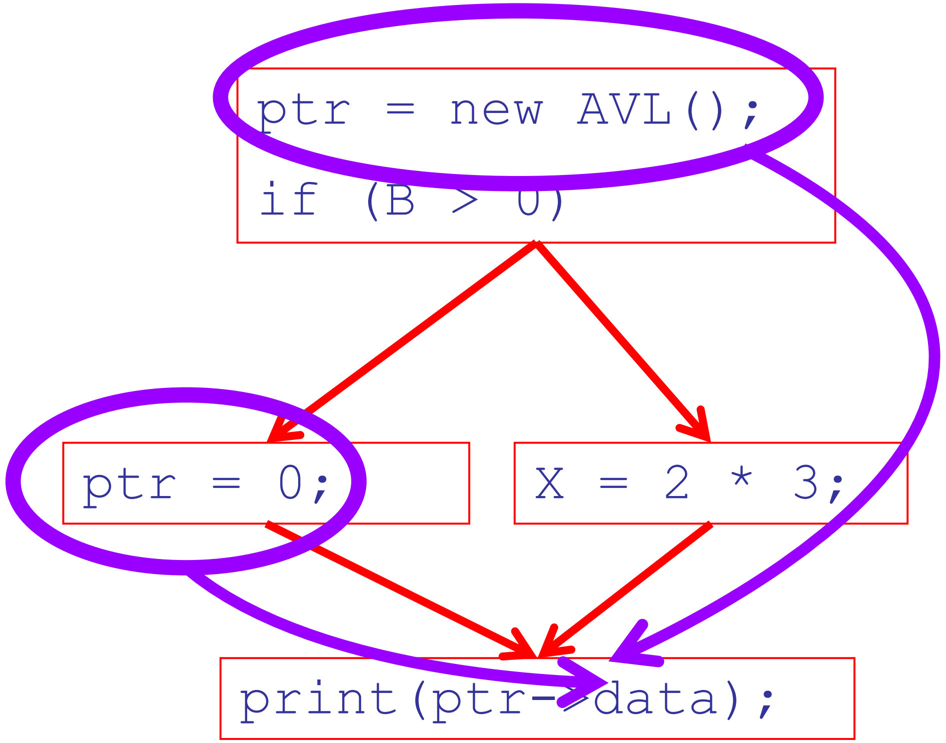
Definitely Null Analysis

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

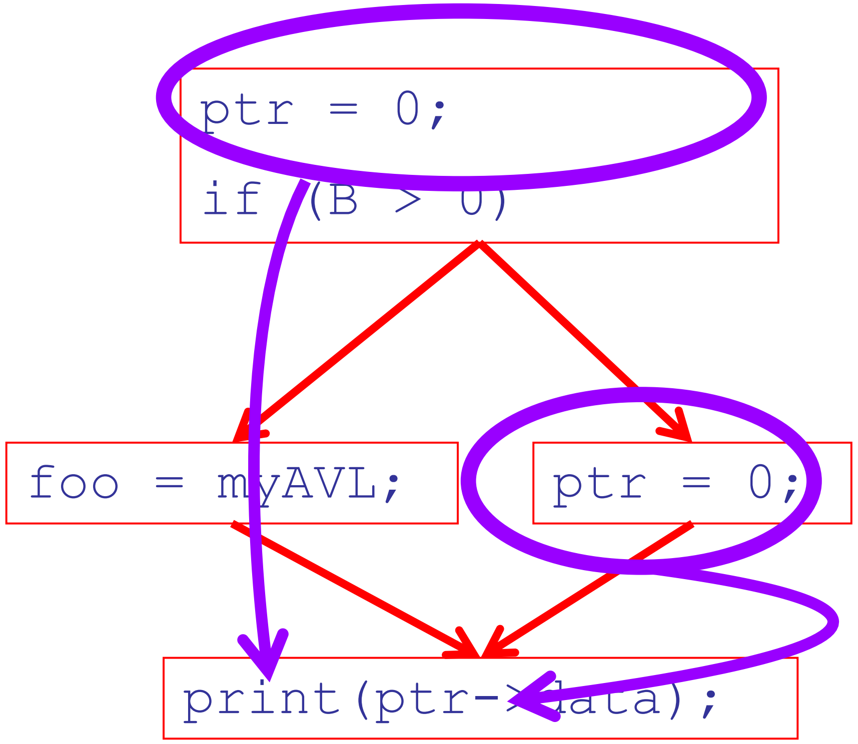


Definitely Null Analysis

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



No, not always.

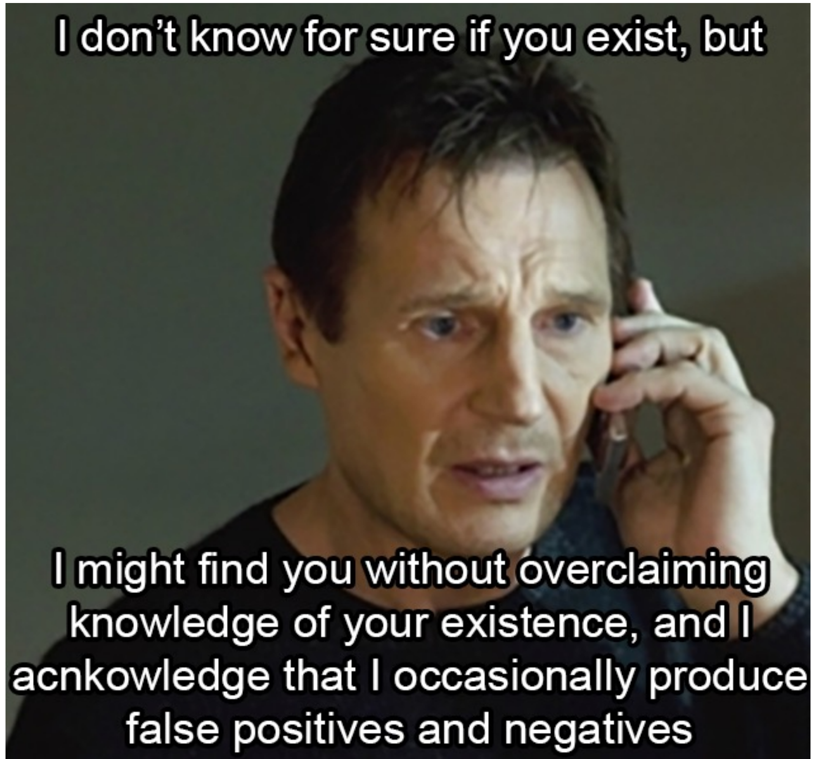


Yes, always.

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
- Consider the case of computing ** for a single variable ptr at all program points
- Valid points cannot hide!
- We will find you!
    - *(sometimes)*



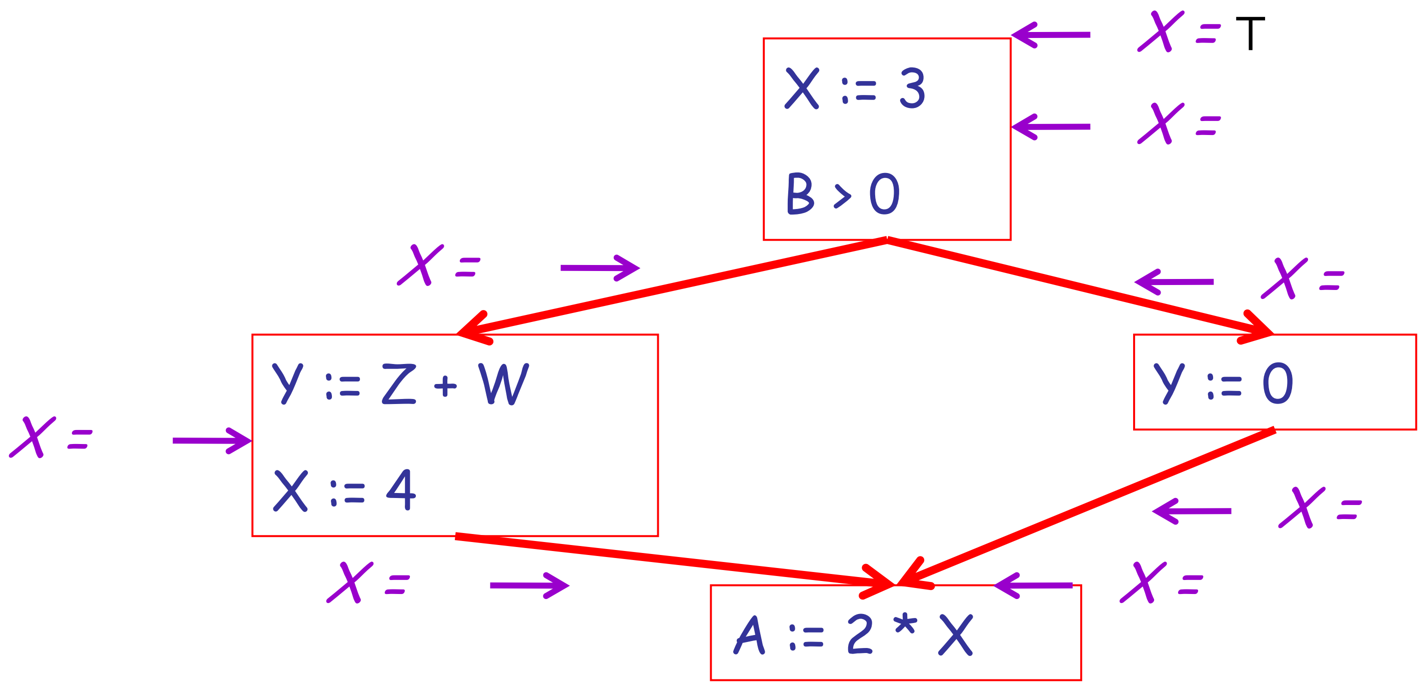
Definitely Null Analysis (Cont.)

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

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

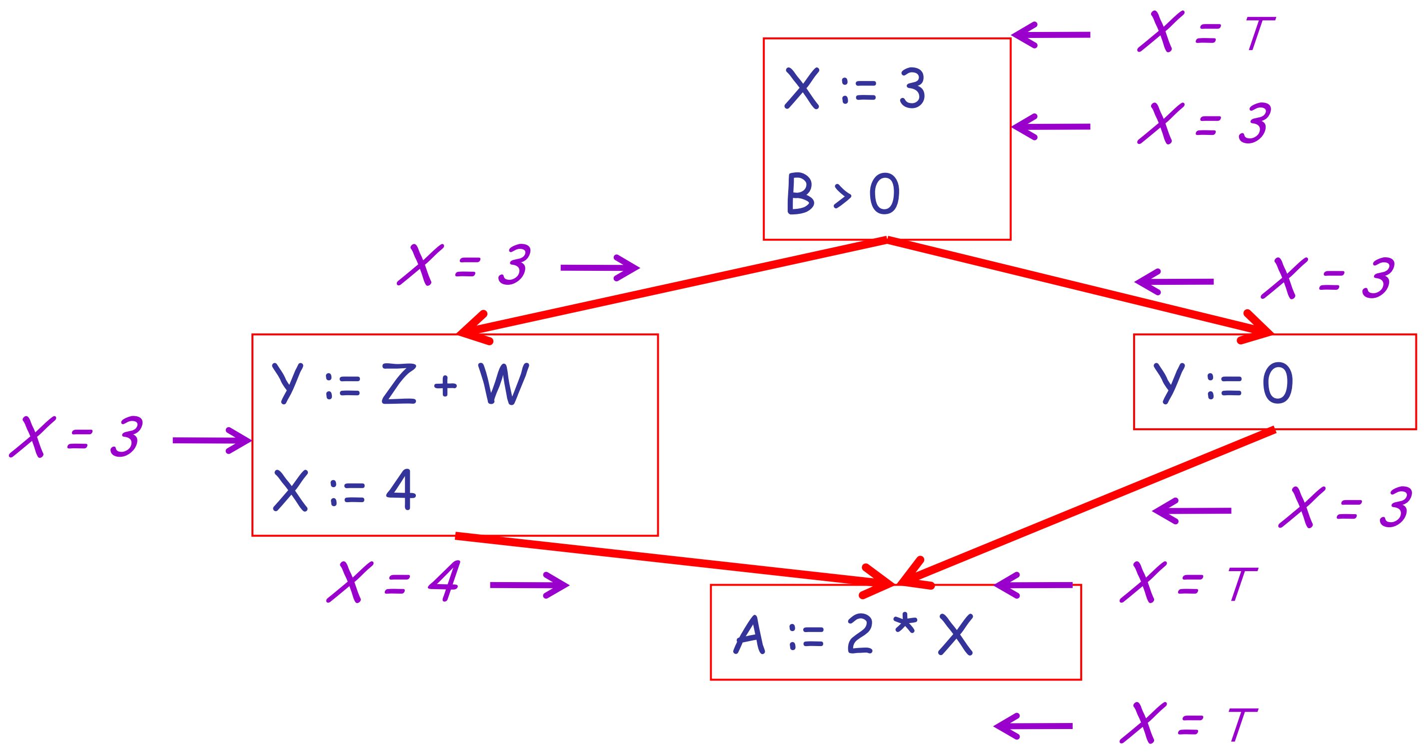
Example

Let's fill in these blanks now.



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

Example Answers



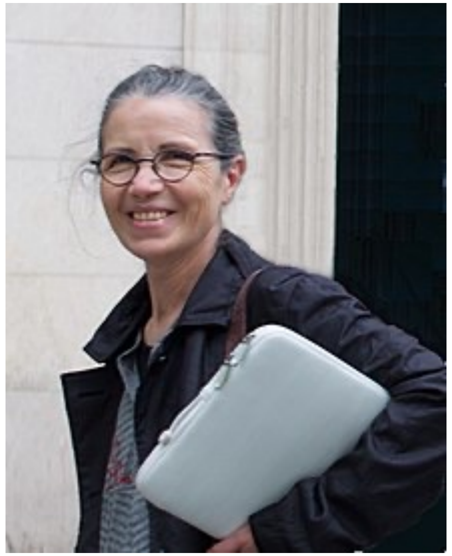
Recall: ⊥ = not reachable, c = constant, ⊤ = don't know.

Trivia: Abstract Interpretation

- This French computer scientist was known for inventing abstract interpretation.
- Abstract interpretation is a theory of sound approximation of the semantics of computer programs, based on monotonic functions over ordered sets, especially lattices. It can be viewed as a partial execution of a computer program which gains information about its semantics (e.g., control-flow, data-flow) without performing all the calculations.
- Its main concrete application is formal static analysis. Such analyses have two main usages:
  - Compilers: to analyse programs to decide whether certain optimizations or transformations are applicable;
  - Debugging or the certification of programs against classes of bugs.

Trivia: Abstract Interpretation

- This French computer scientist was known for inventing abstract interpretation.
- Abstract interpretation is a theory of sound approximation of the semantics of computer programs, based on monotonic functions over ordered sets, especially lattices. It can be viewed as a partial execution of a computer program which gains information about its semantics (e.g., control-flow, data-flow) without performing all the calculations.
- Its main concrete application is formal static analysis. Such analyses have two main usages:
    - Compilers: to analyse programs to decide whether certain optimizations or transformations are applicable;
    - Debugging or the certification of programs against classes of bugs.



Radhia Cousot (Together with Patrick Cousot)

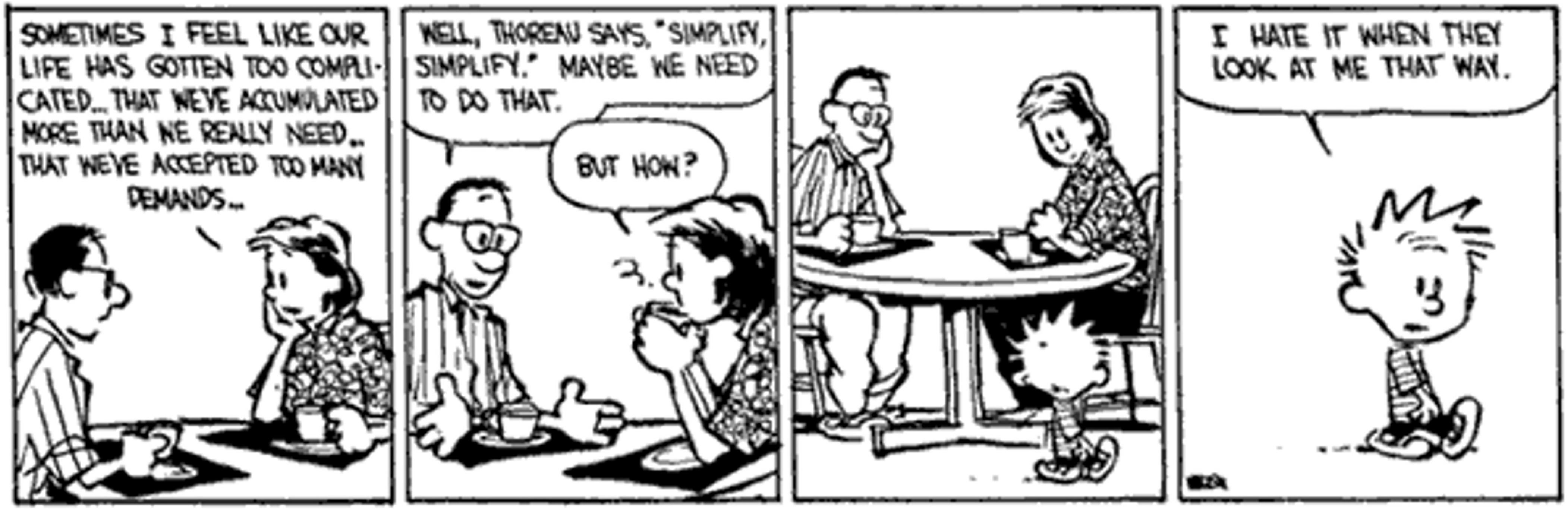
Using Abstract Information

- 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!

- But 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

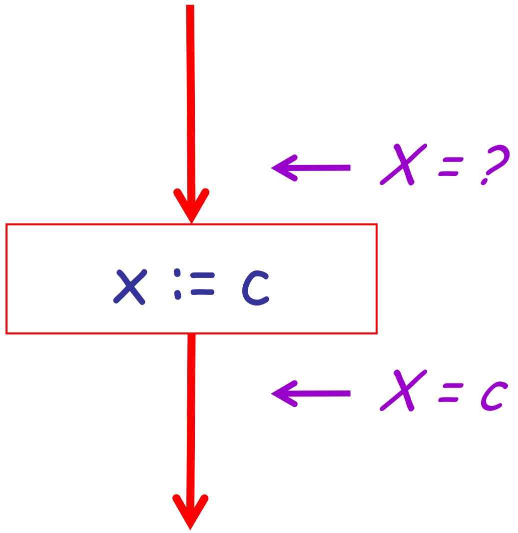
- The idea is to "push" or "**transfer**" information from one statement to the next

- 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

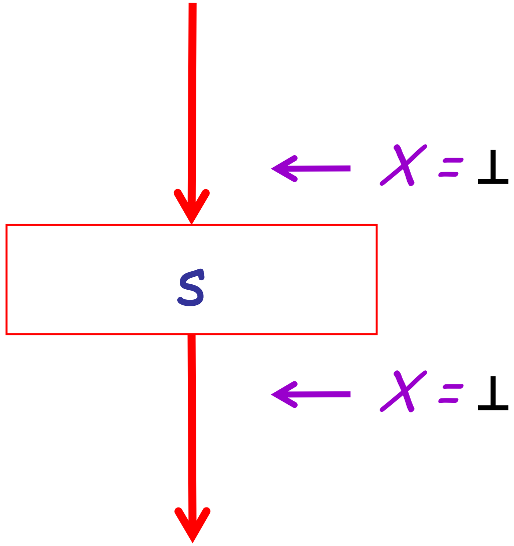
- Define a **transfer function** that transfers information from one statement to another

Rule 1



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

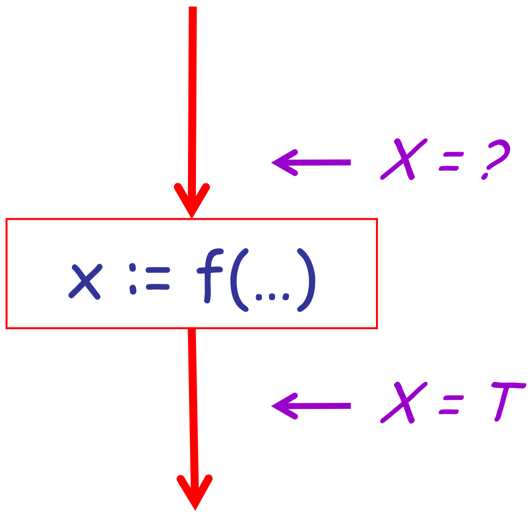
Rule 2



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

Recall: ⊥ = “unreachable code”

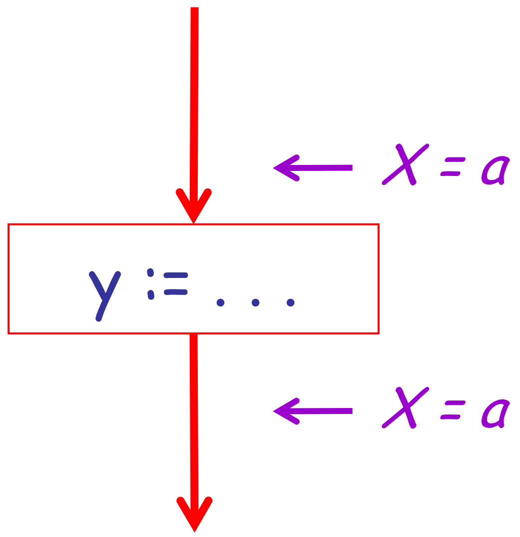
Rule 3



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

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

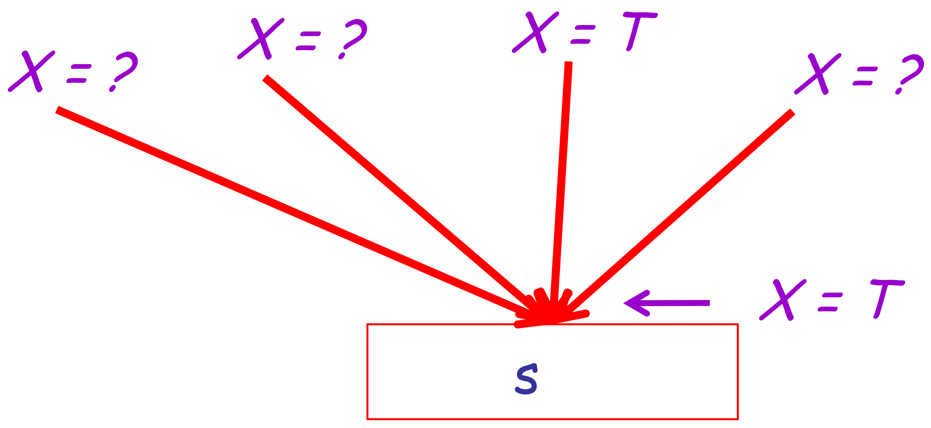


- $C_{out}(x, y := \ldots) = C_{in}(x, y := \ldots)$ if $x \neq y$

The Other Half

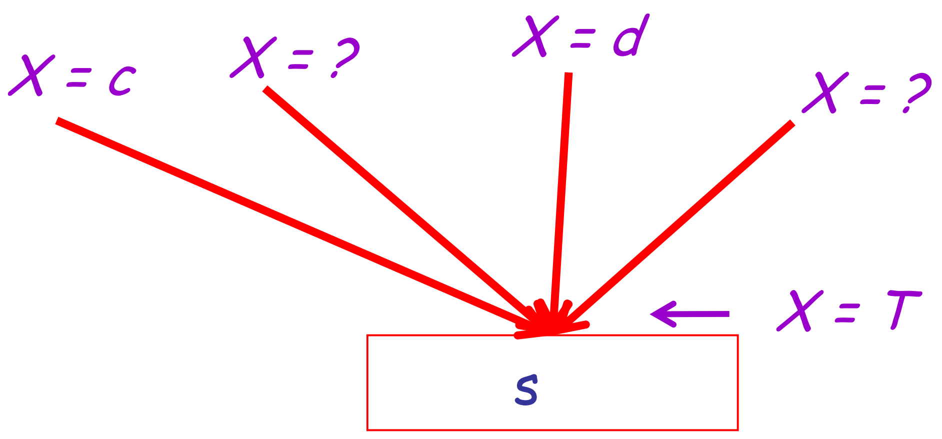
- Rules 1-4 relate the *in* of a statement to the *out* of the same statement
  - they propagate information across statements
- Now we need rules relating the *out* of one statement to the *in* of the successor statement
  - to propagate information forward along paths
- In the following rules, let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

Rule 5



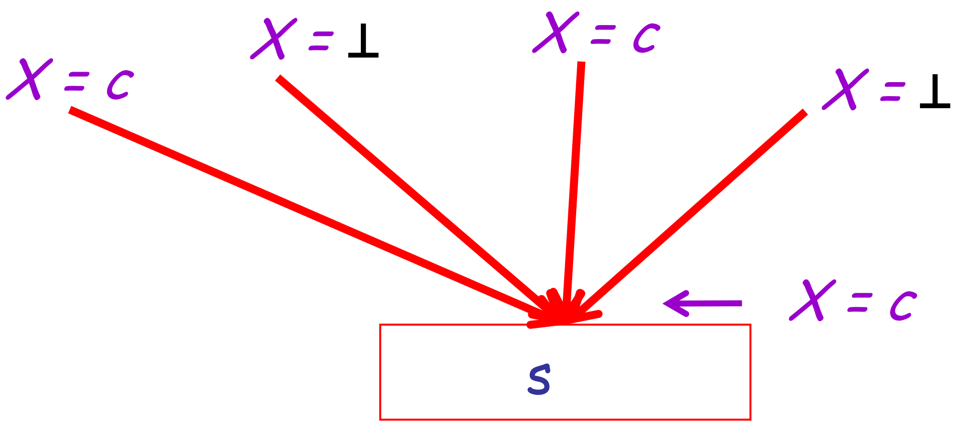
- if $C_{out}(x, p_i) = T$ for some i, then $C_{in}(x, s) = T$

Rule 6



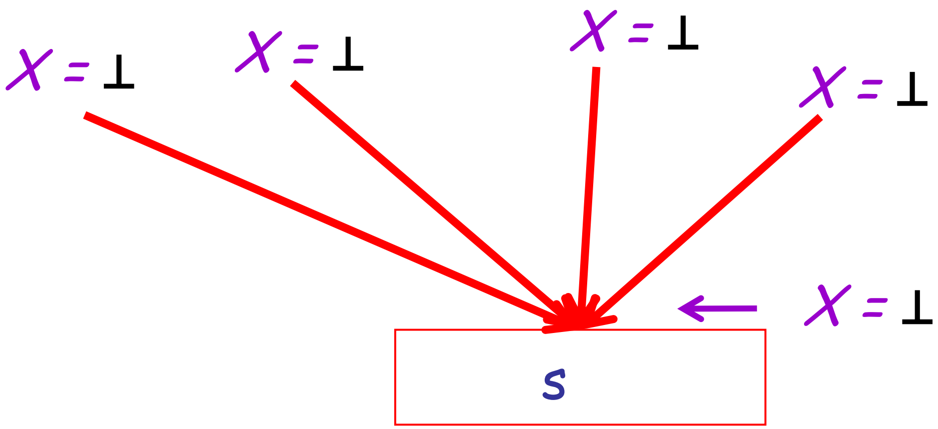
if $C_{out}(x, p_i) = c$ and $C_{out}(x, p_j) = d$ and $d \neq c$, then $C_{in}(x, s) = T$

Rule 7



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

Rule 8



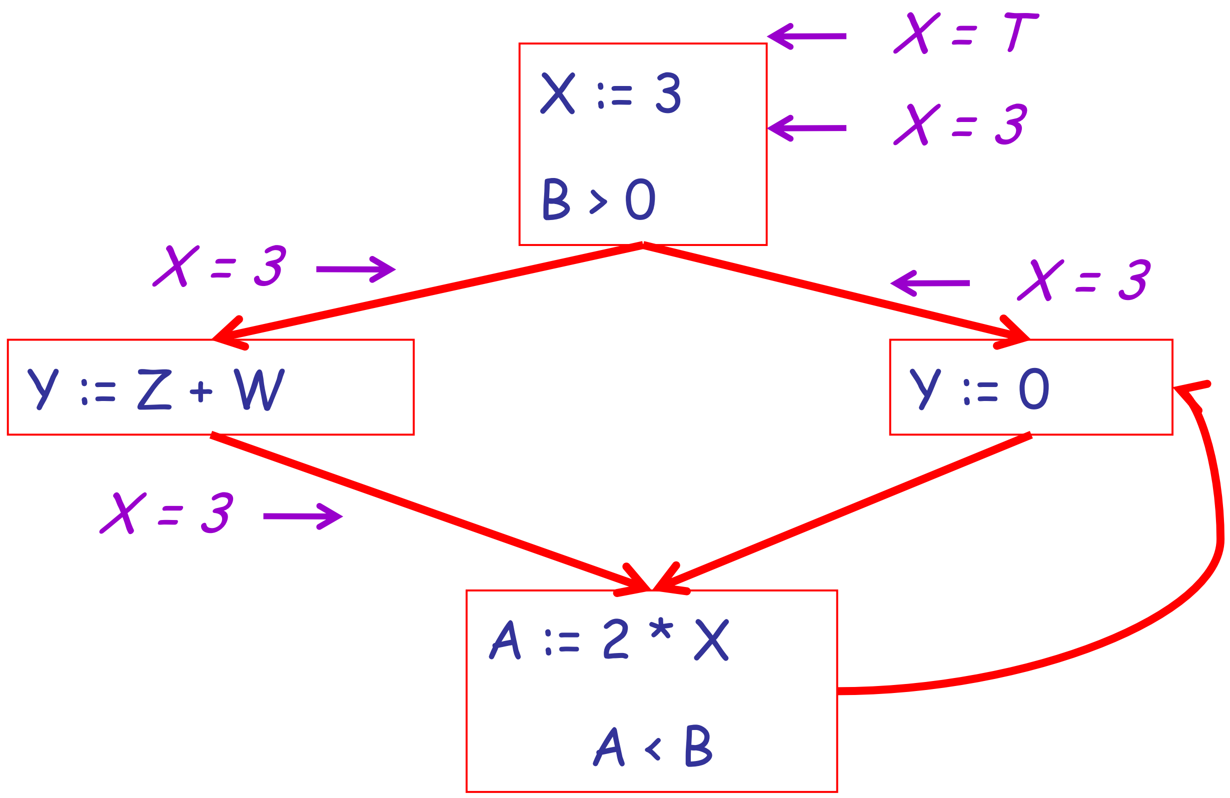
if $C_{out}(x, p_i) = \perp$ for all i, then $C_{in}(x, s) = \perp$

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 1-8:
  - Pick *s* not satisfying 1-8 and update using the appropriate rule

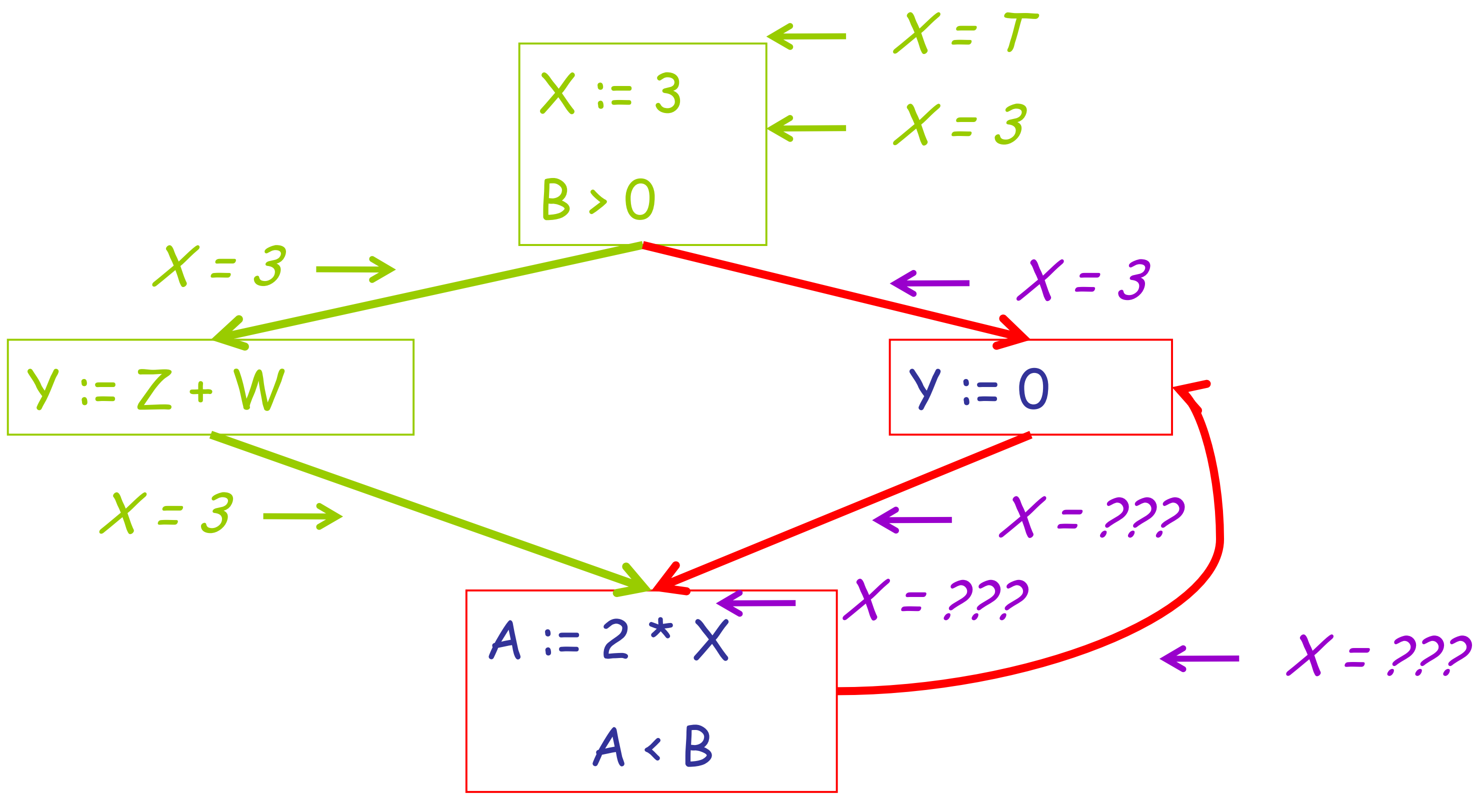
The Value ⊥

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



The Value ⊥

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



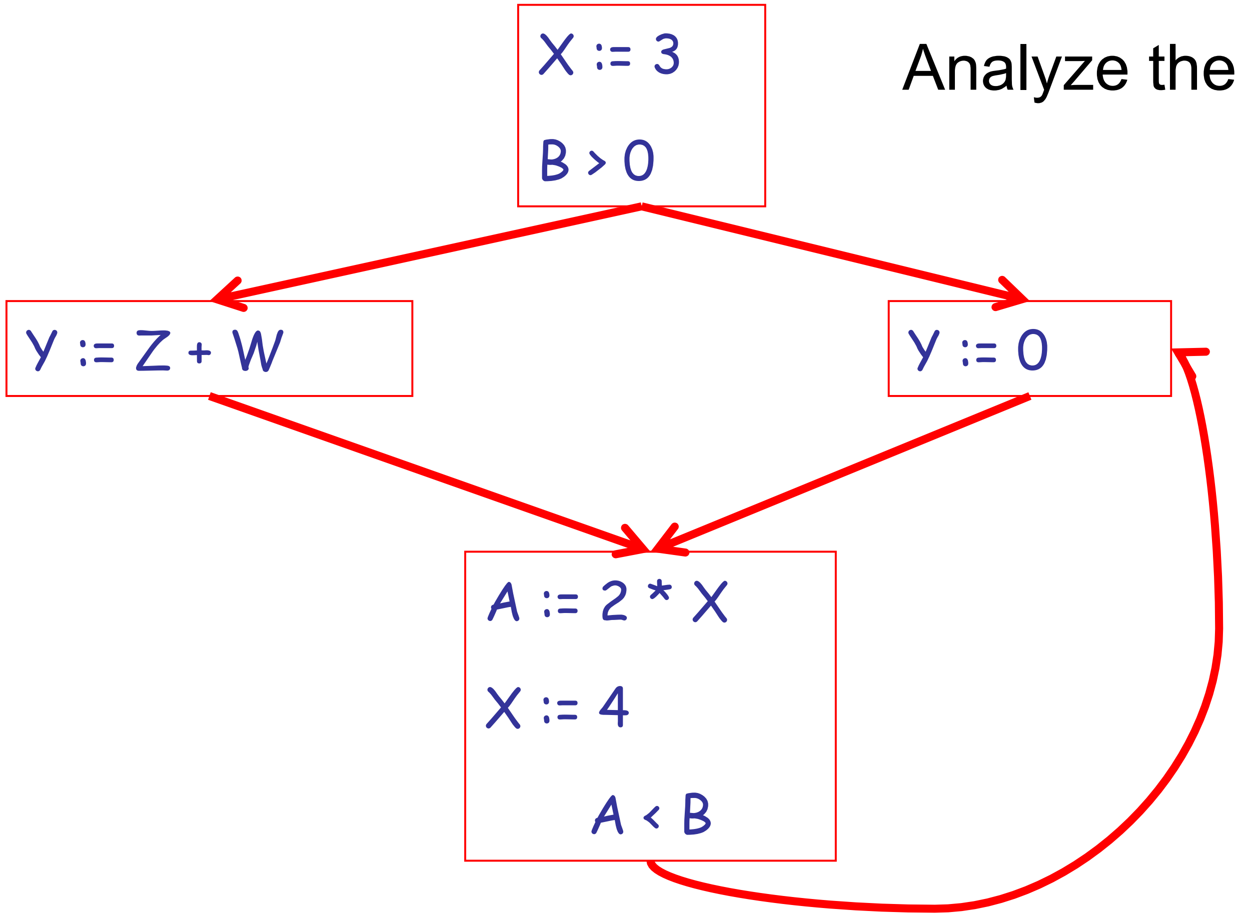
The Value ⊥ (Cont.)

- Because of cycles, all points must have values at all times during the analysis

- Intuitively, assigning some initial value allows the analysis to break cycles

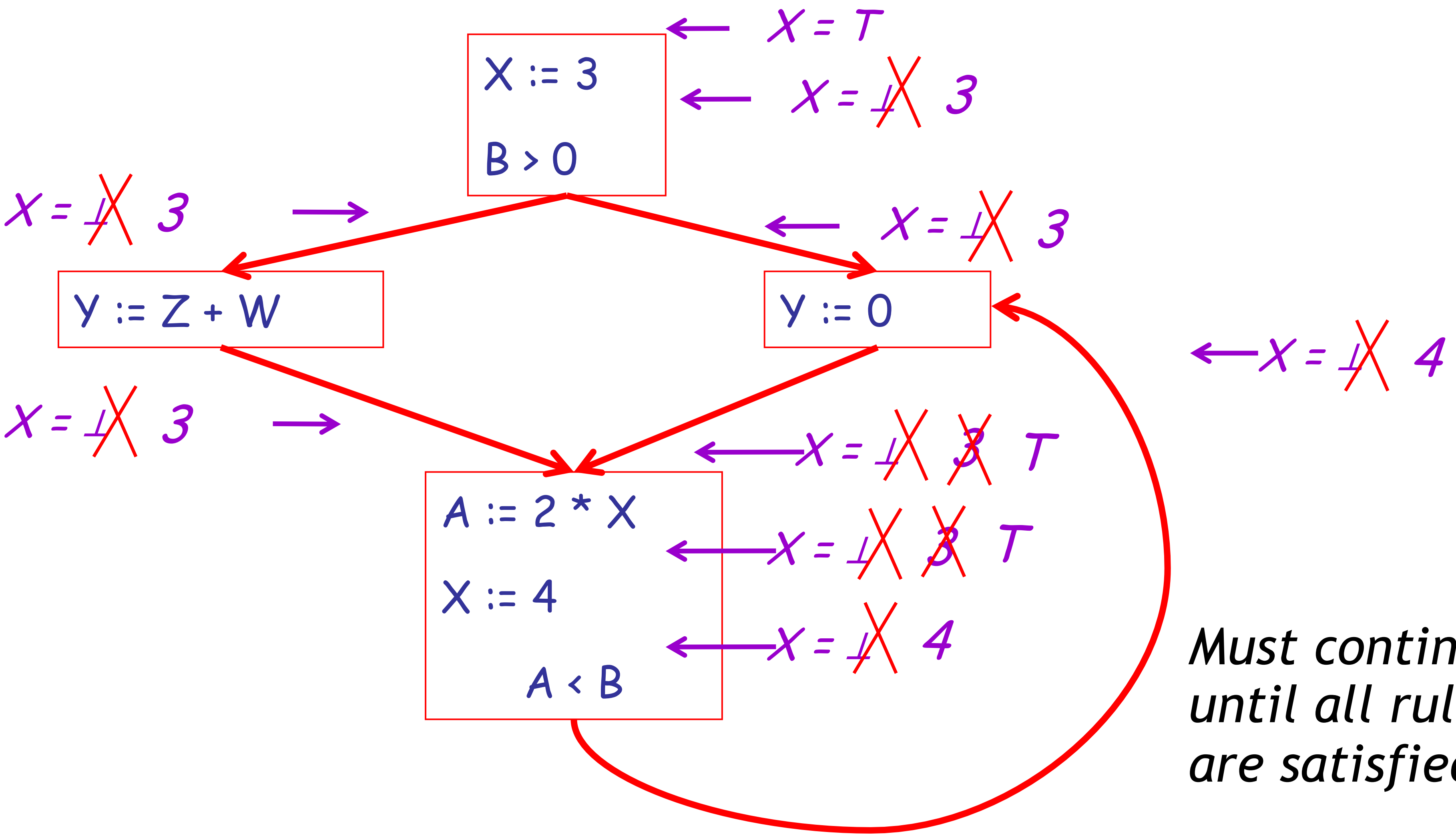
- The initial value ⊥ means "we have not yet analyzed control reaching this point"

Another Example



Analyze the value of X …

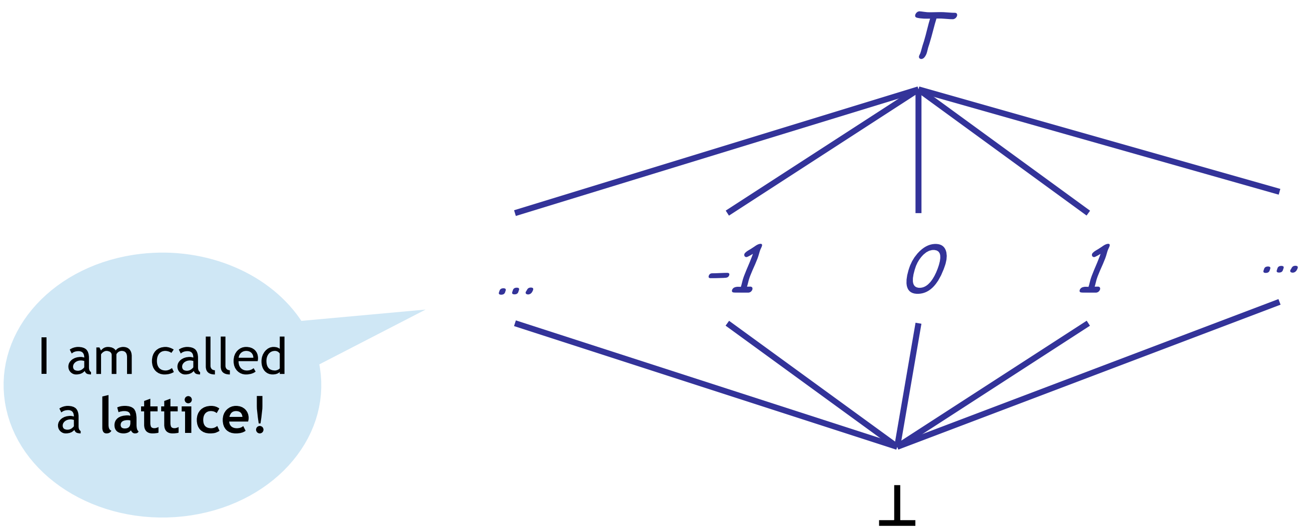
Another Example: Answer



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



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 ⊥ and only *increase*

⊥ can change to a constant, and a constant to T

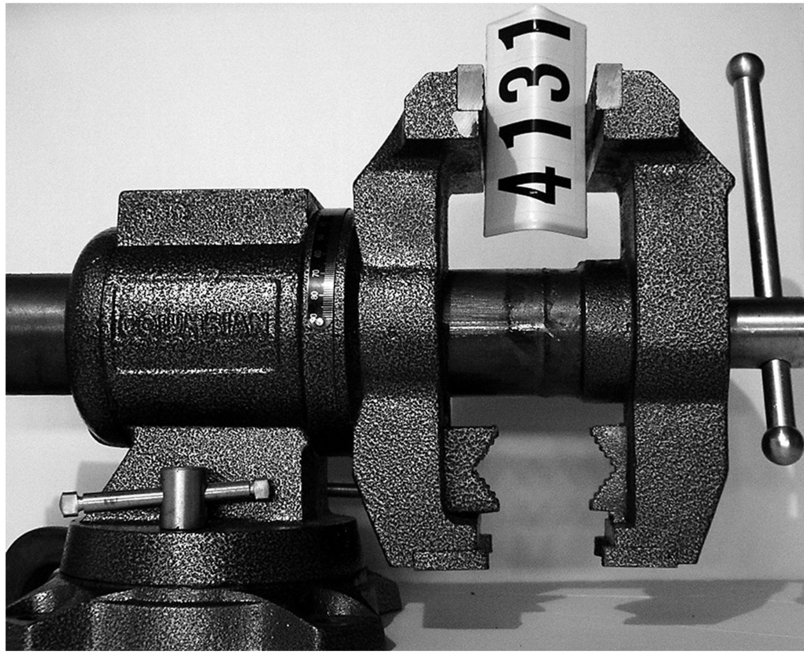
  - Thus, C_(x, s) can change at most twice

Number Crunching

- The algorithm is polynomial in program size:
- **Number of steps =**

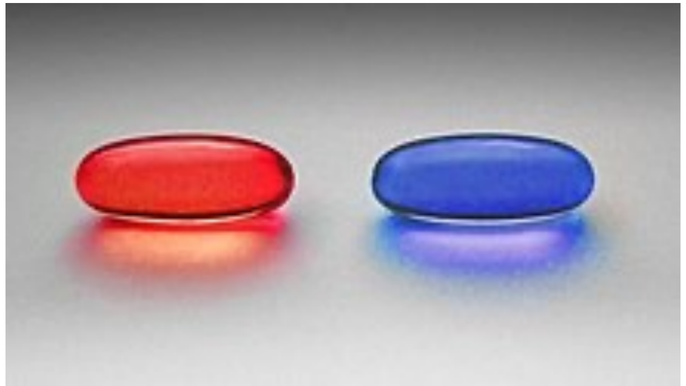
Number of C_(....) values changed * 2 =

(Number of program statements)^2 * 2



Trivia

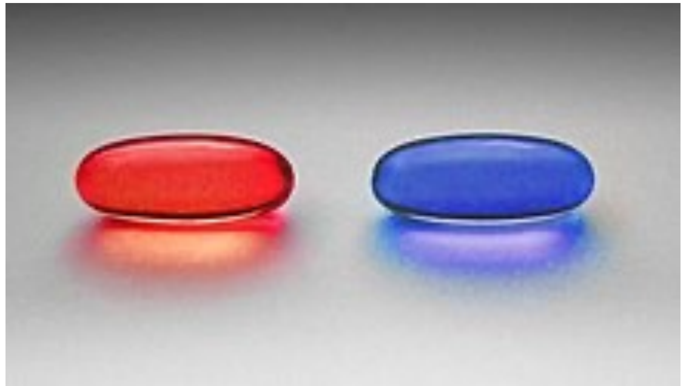
- This Polish computer security researcher is well known for the attack against Vista Kernel protection mechanism (Black Hat Briefings conference in LA, 2006) and the invention of **Blue Pill**, that uses hardware virtualization to move a running OS into a virtual machine.
- Later on, this researcher presented another attack against the Intel Trusted Execution Technology (TXT).
- This researcher demonstrated that certain types of hardware-based memory acquisition is unreliable and can be defeated.



Trivia

- This Polish computer security researcher is well known for the attack against Vista Kernel protection mechanism (Black Hat Briefings conference in LA, 2006) and the invention of **Blue Pill**, that uses hardware virtualization to move a running OS into a virtual machine.
- Later on, this researcher presented another attack against the Intel Trusted Execution Technology (TXT).
- This researcher demonstrated that certain types of hardware-based memory acquisition is unreliable and can be defeated.

Joanna Rutkowska

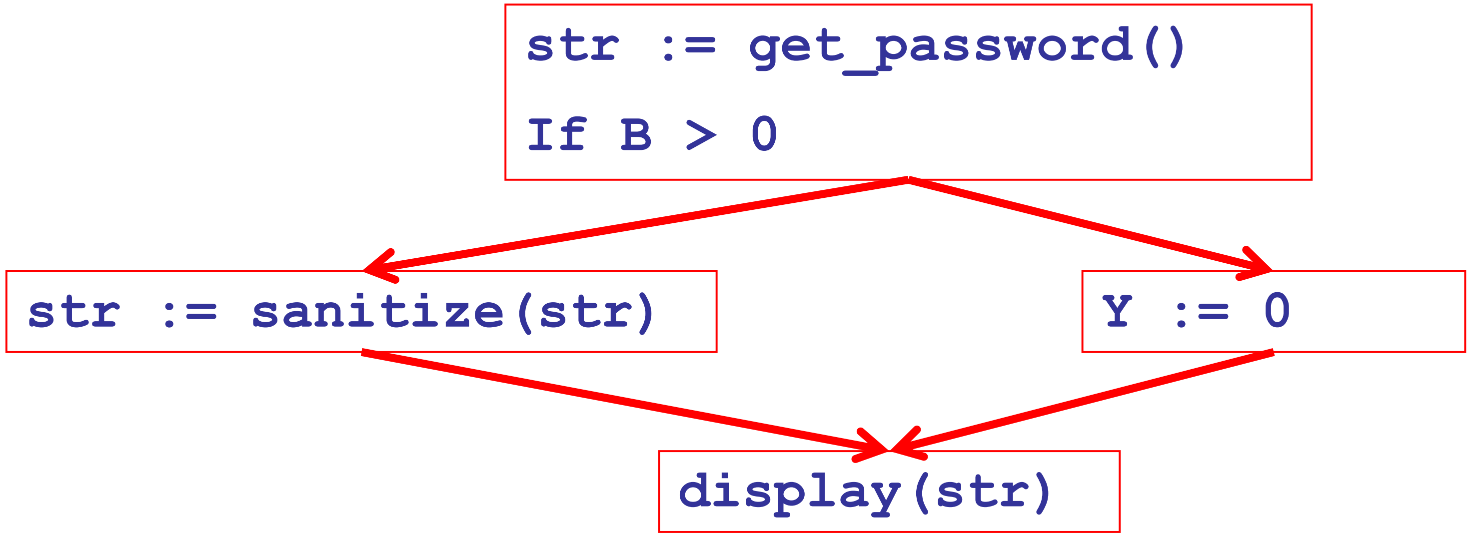


Two Exemplar Analyses

- *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"

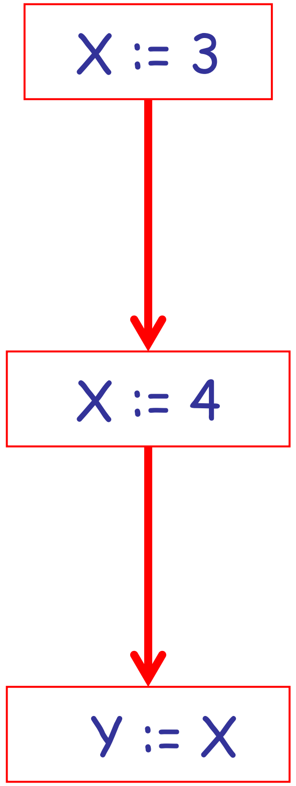
“Potential Secure Information Leak” Analysis

- 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)

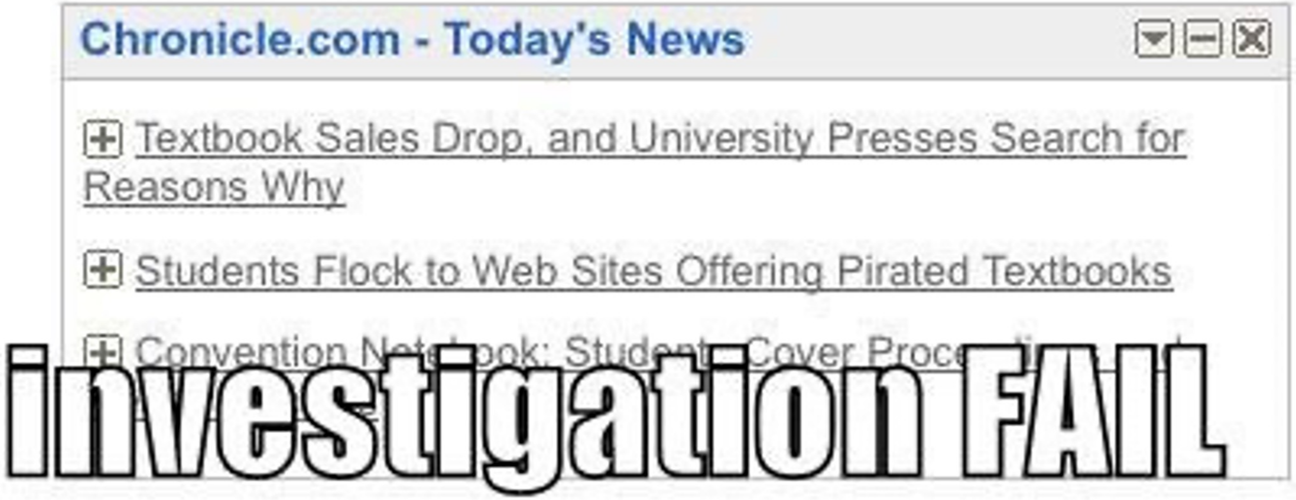
Live and Dead



- 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

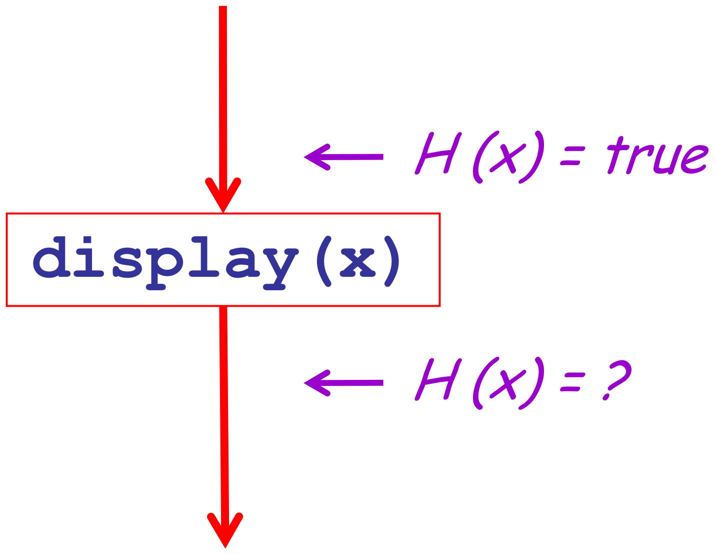
- A variable x at stmt s is a possible sensitive (high-security) information leak if
  - There exists a statement s’ that uses x
  - There is a path from s to s’
  - That path has no intervening low-security assignment to x



Computing Potential Leaks

- We can express the 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

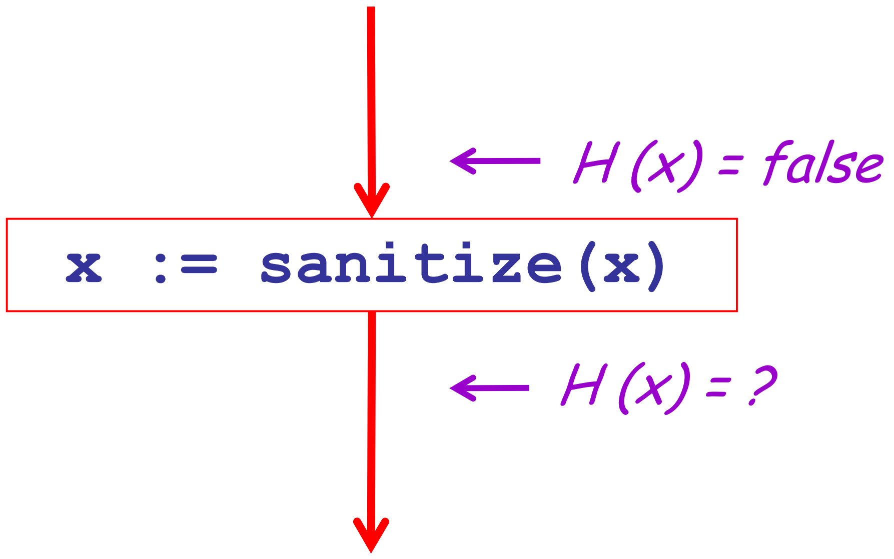


$H_{in}(x, s) = true$ if s displays x publicly

true means “if this ends up being a secret variable

then we have a bug!”

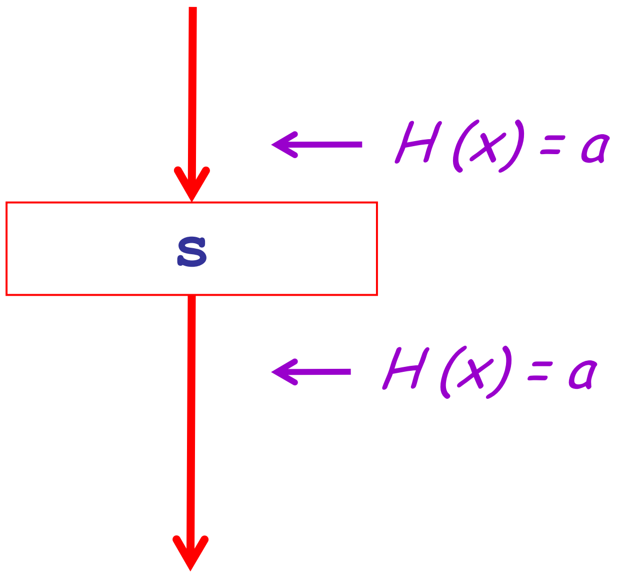
Secure Information Flow Rule 2



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

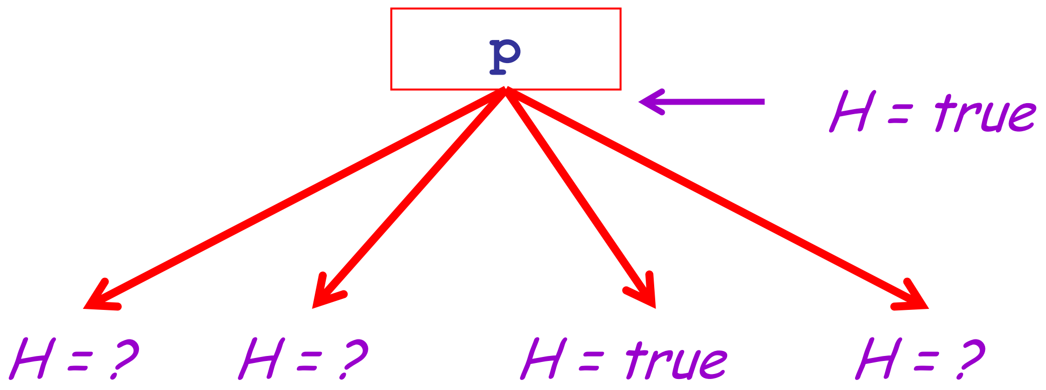
(any subsequent use is safe)

Secure Information Flow Rule 3



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

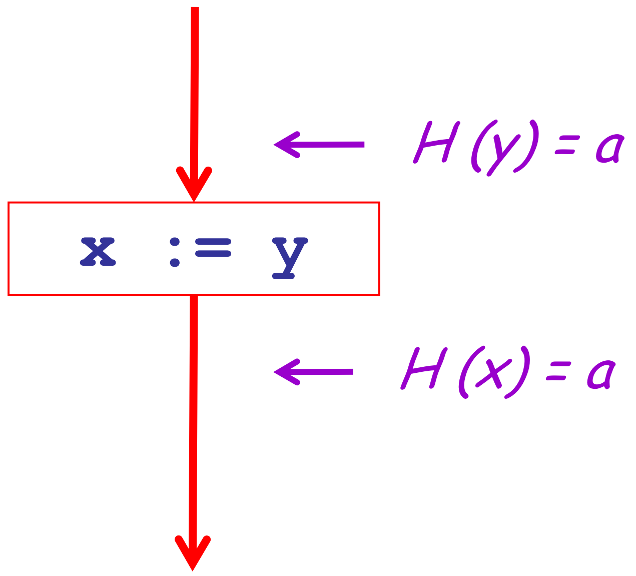
Secure Information Flow Rule 4



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

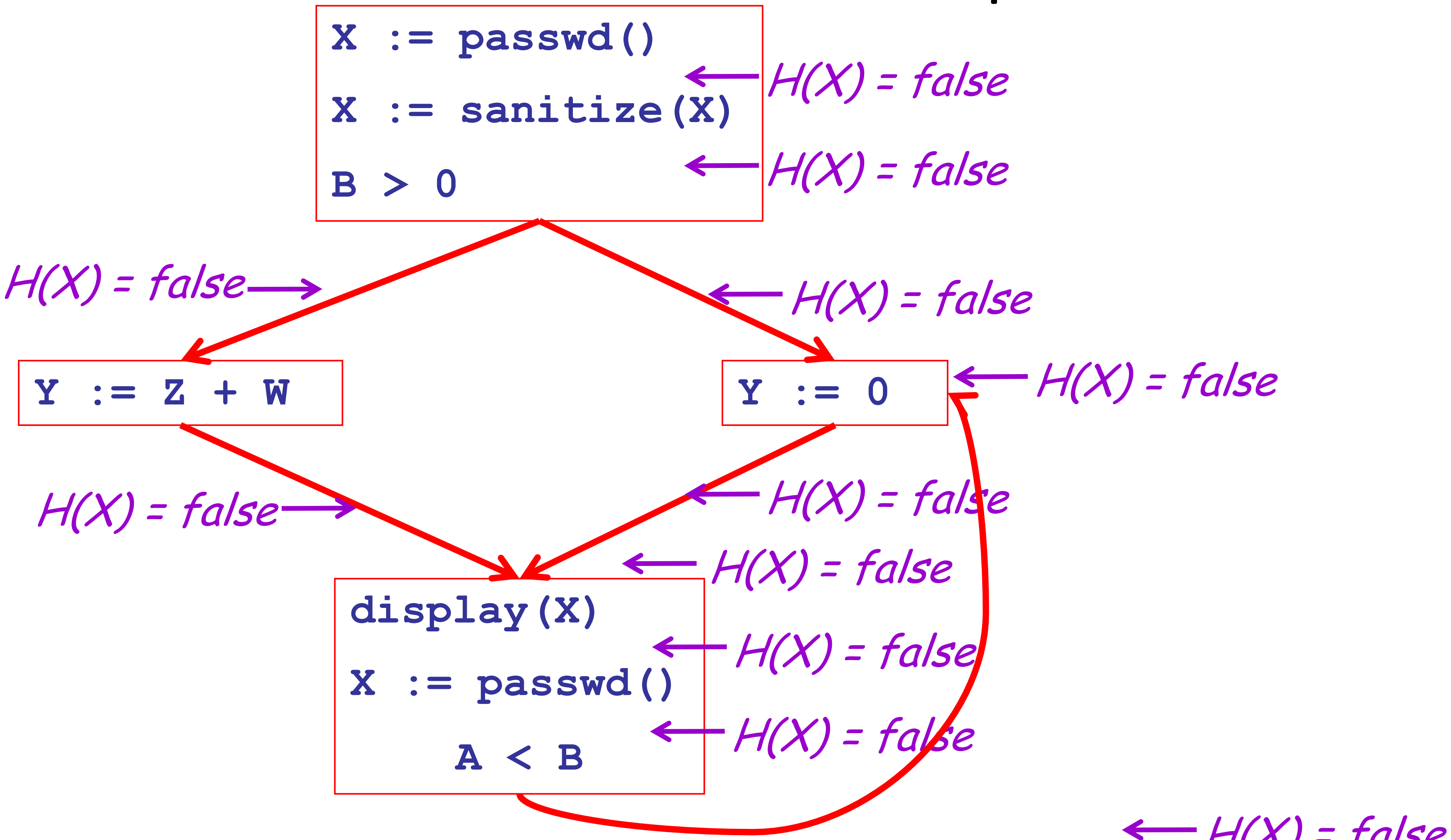
display(x). Do we care about y above?)

Algorithm

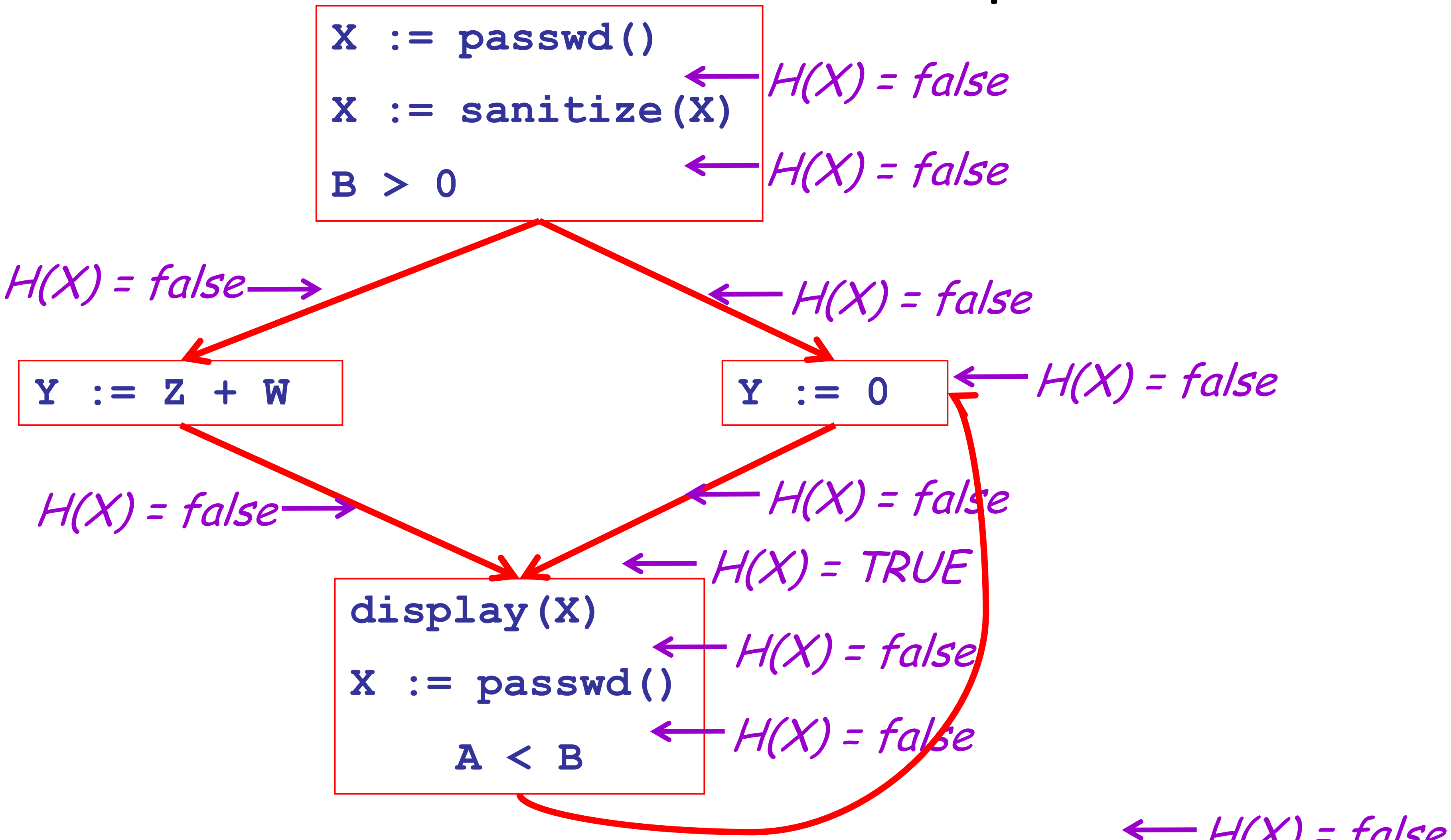
- Let all H_(…) = false initially

- 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

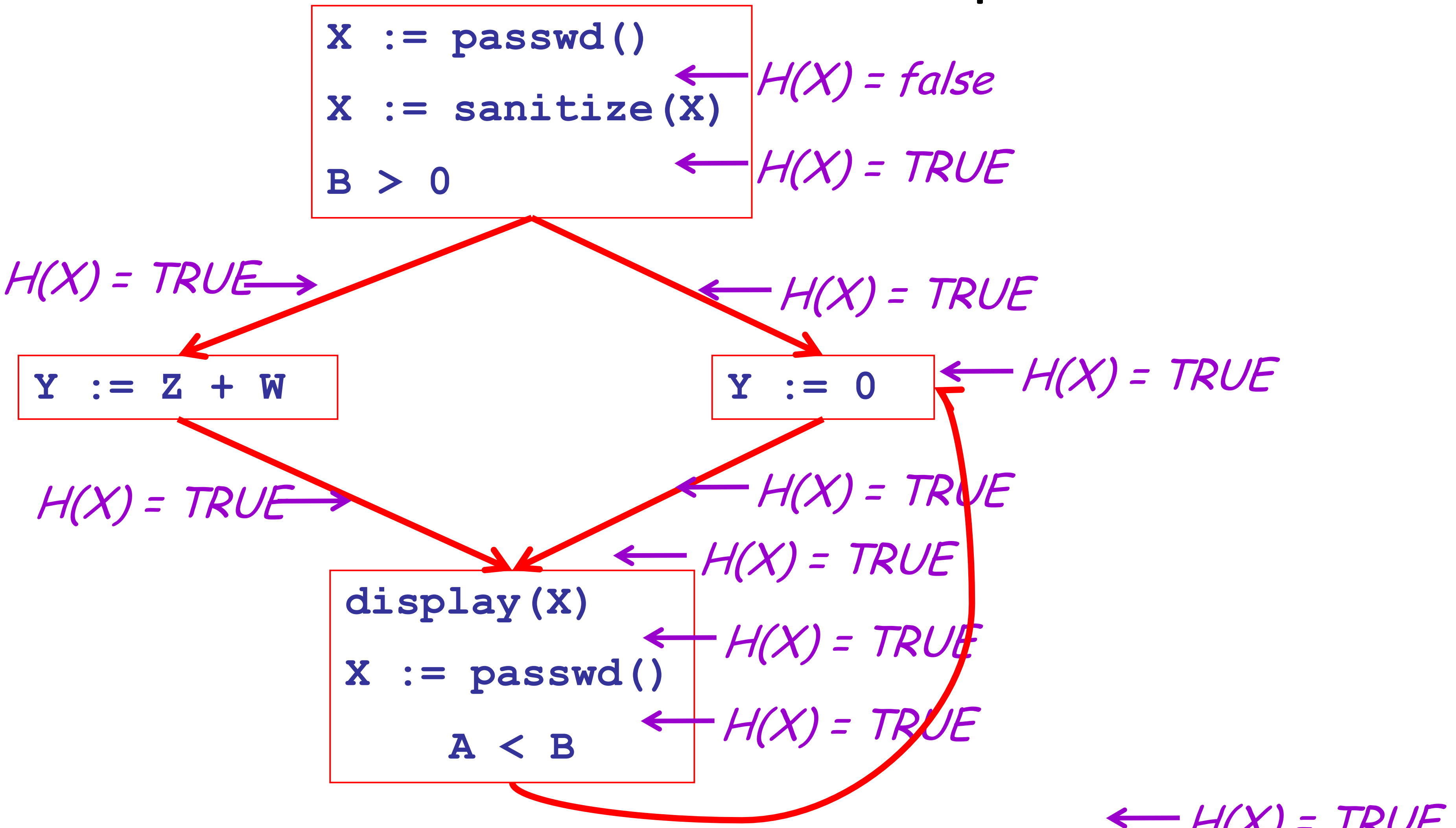
Secure Information Flow Example



Secure Information Flow Example

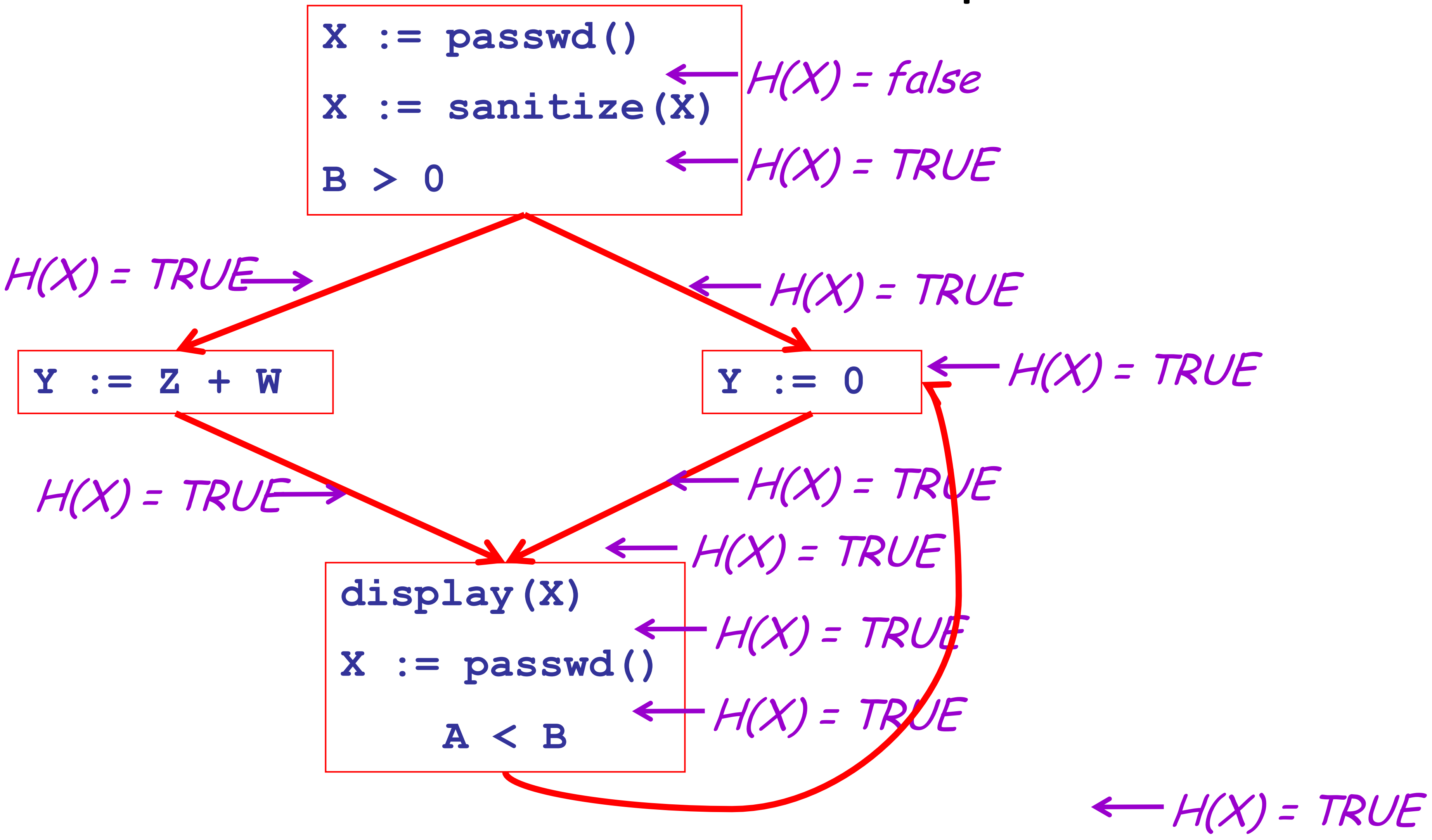


Secure Information Flow Example



Secure Information Flow Example

No possible leak Starting here



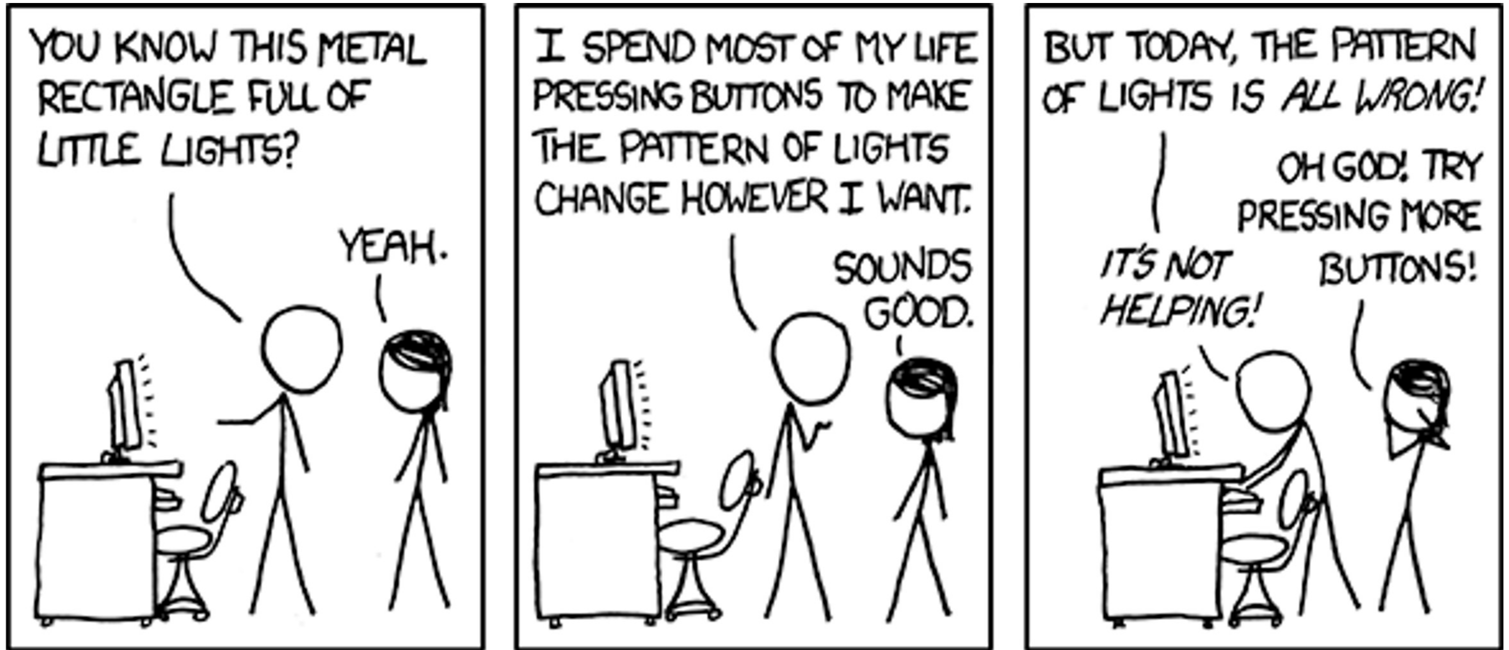
POSSIBLE LEAK From high-security value starting here

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 entry point for sensitive information

Static Analysis Limitations

- Where might a static analysis go wrong?
- If I asked you to construct the shortest program you can that causes one of our static analyses to get the "wrong" answer, what would you do?



Static Analysis

- You are asked to design a static analysis to detect bugs related to **file handle**s
  - 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?

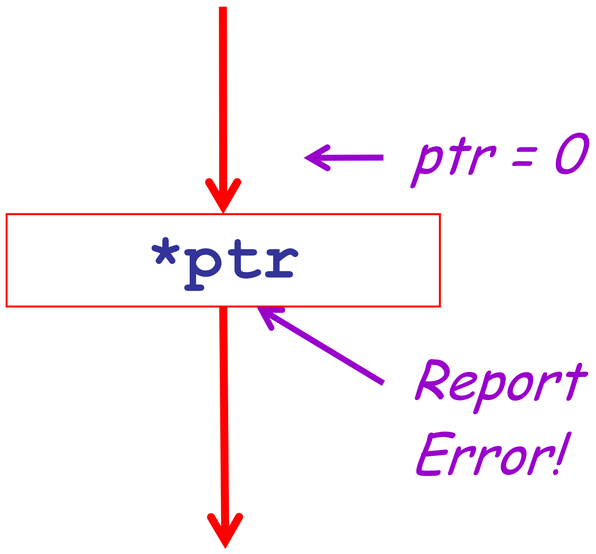
Abstract Information

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

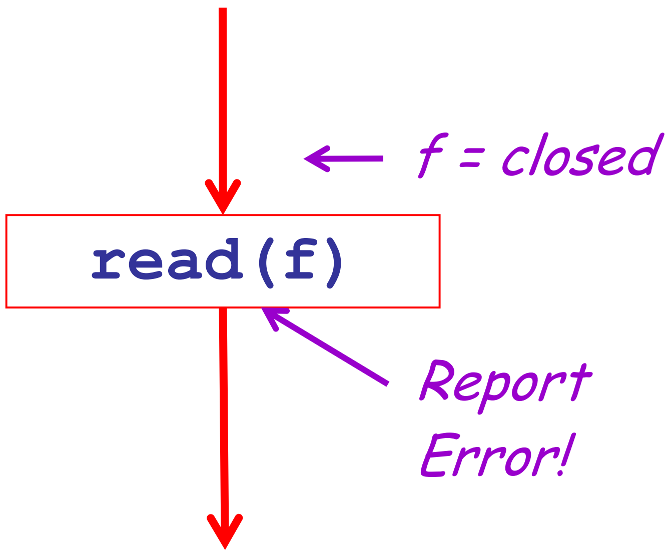
T	file handle state is unknown
⊥	haven't reached here yet
closed	file handle is closed
open	file handle is open

Rules

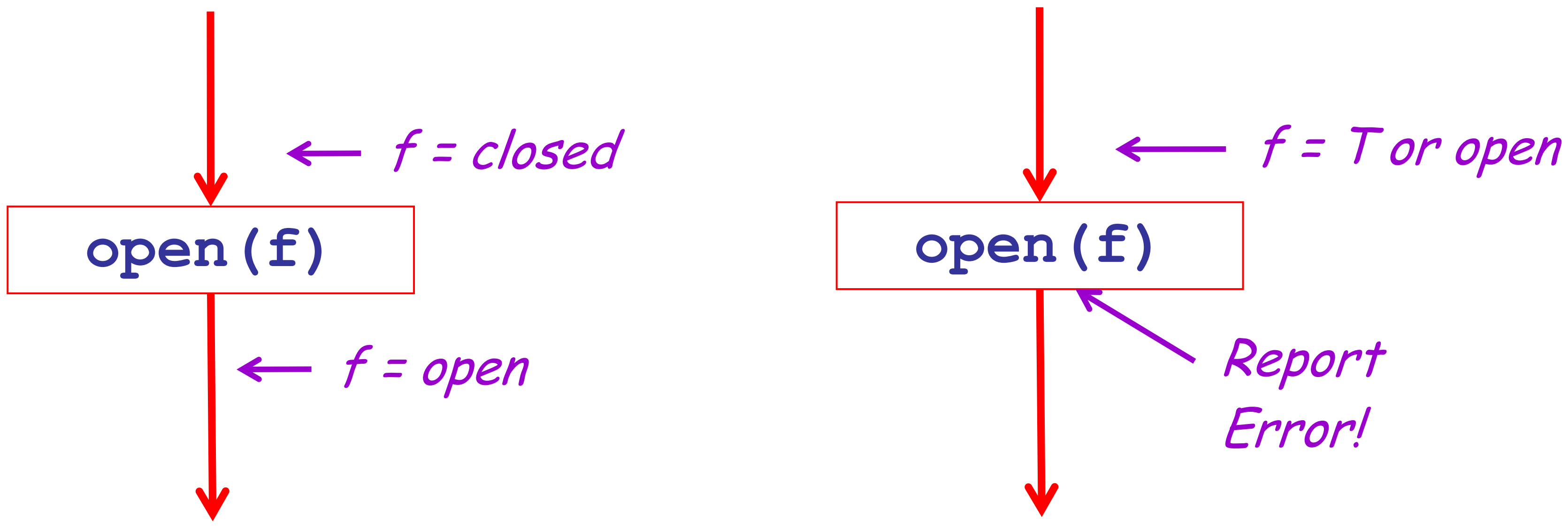
- Previously: "null ptr"



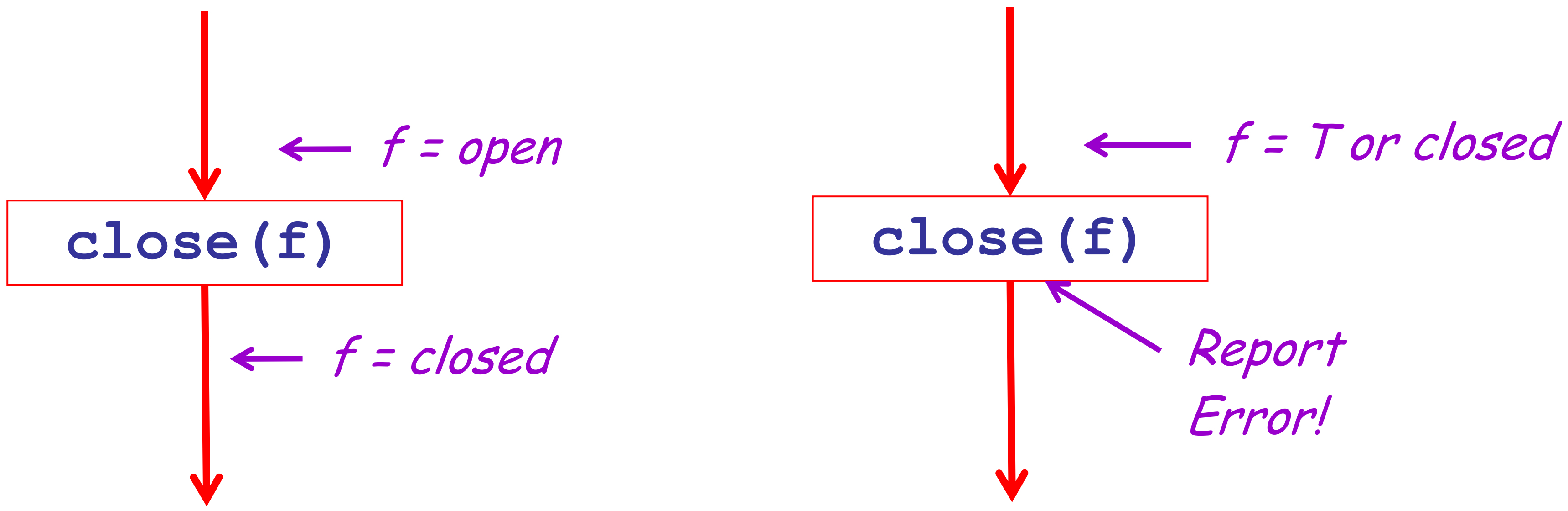
- Now: "file handles"



Rules: open

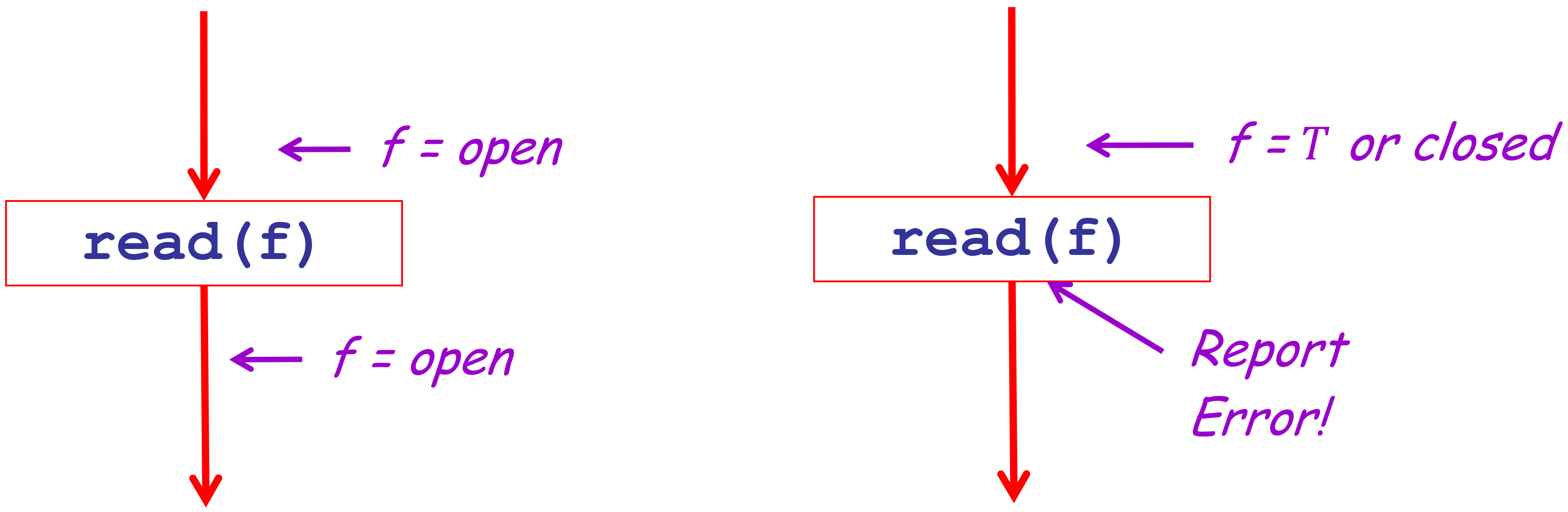


Rules: close

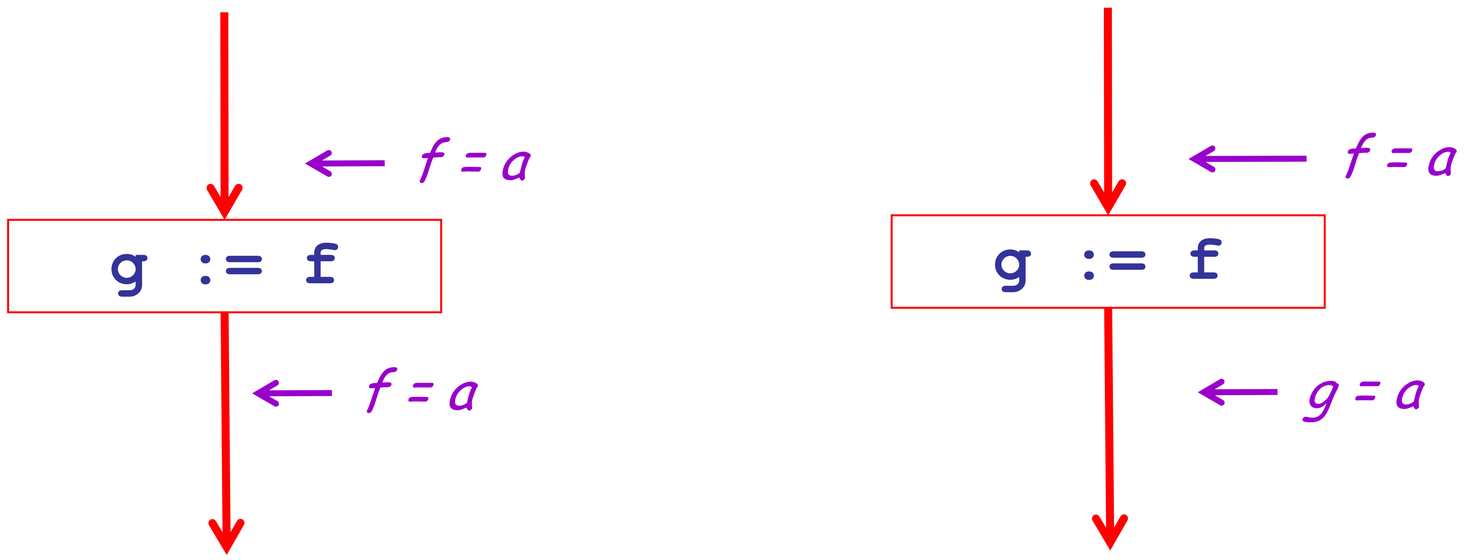


Rules: read/write

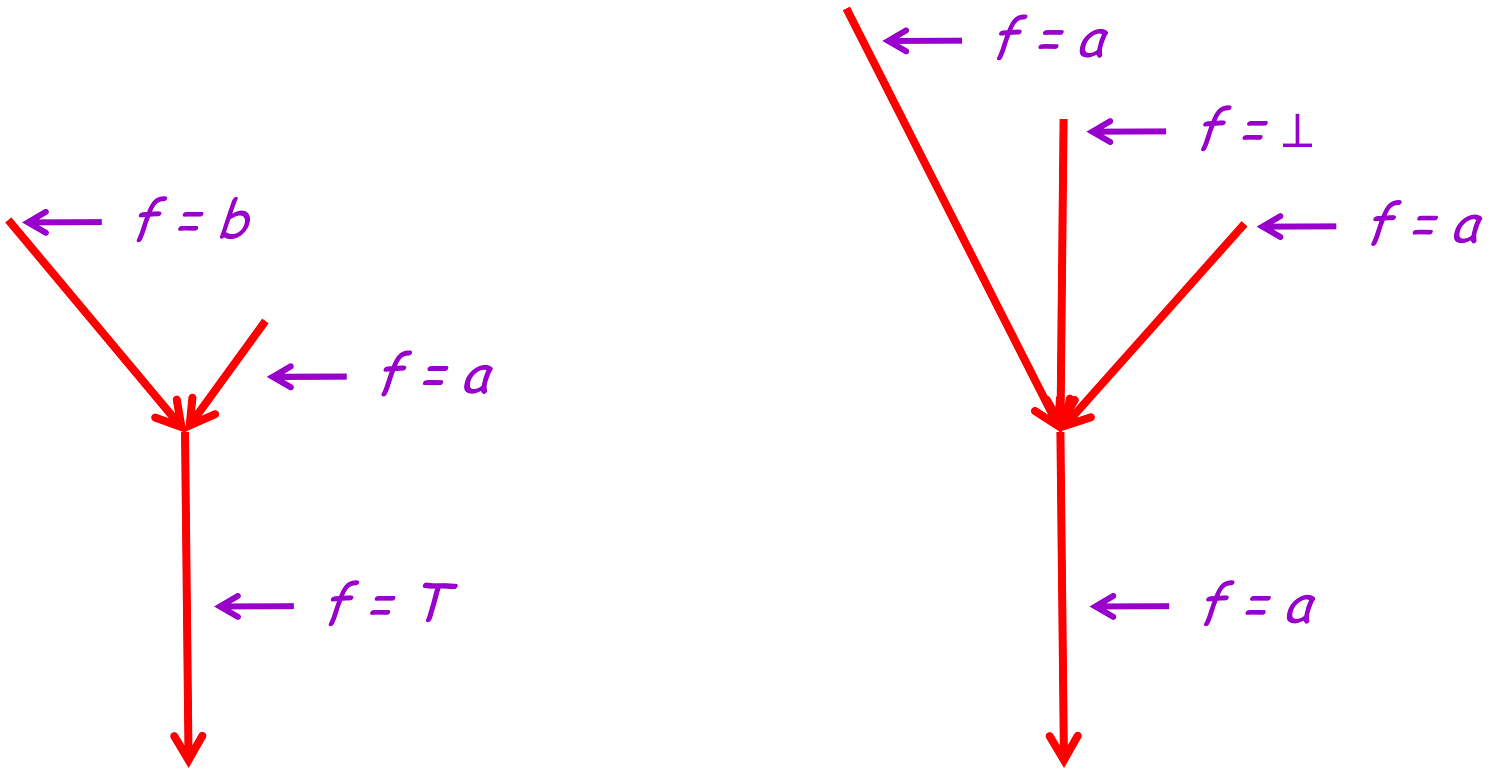
- (write is identical)



Rules: Assignment



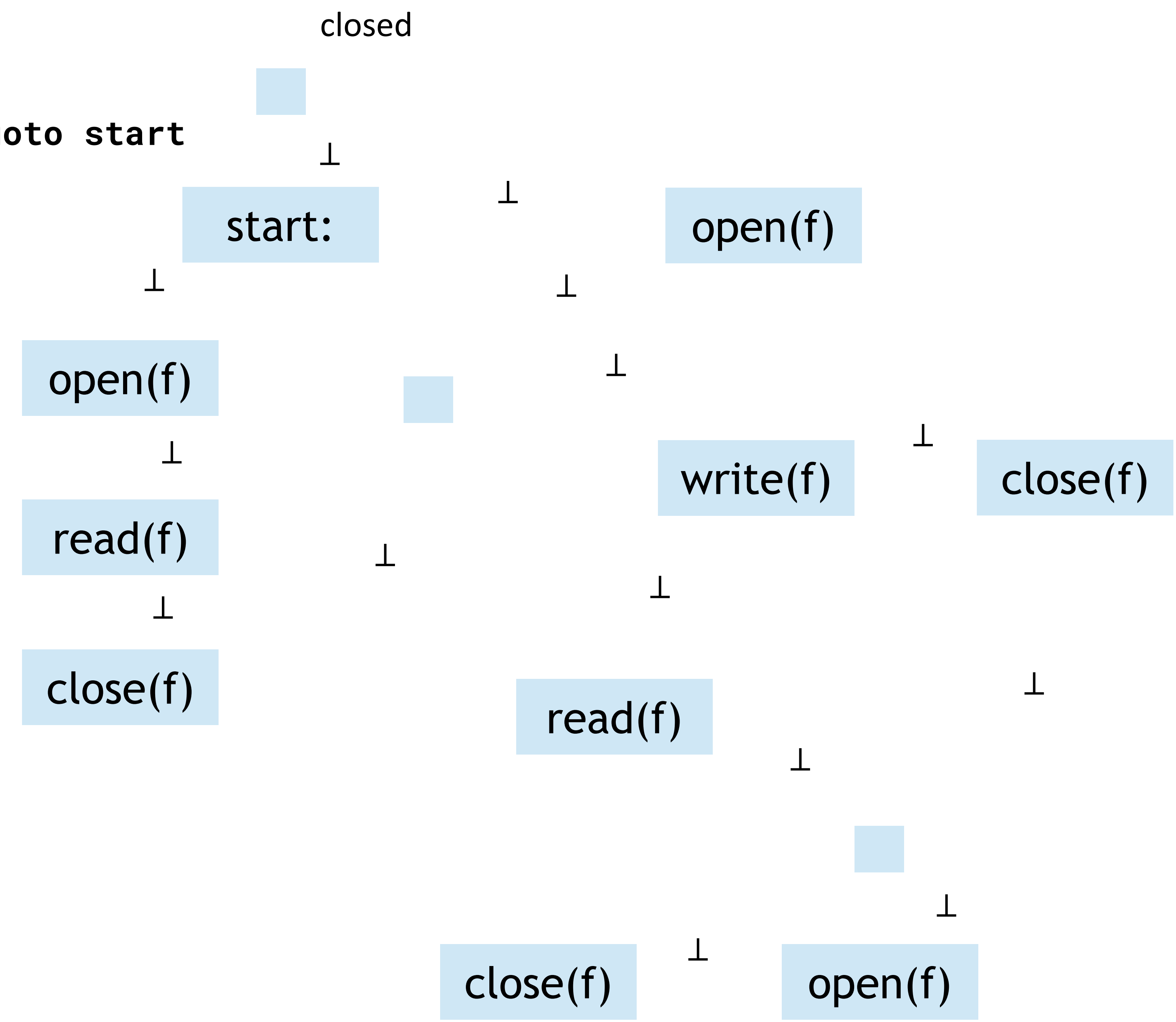
Rules: Multiple Possibilities

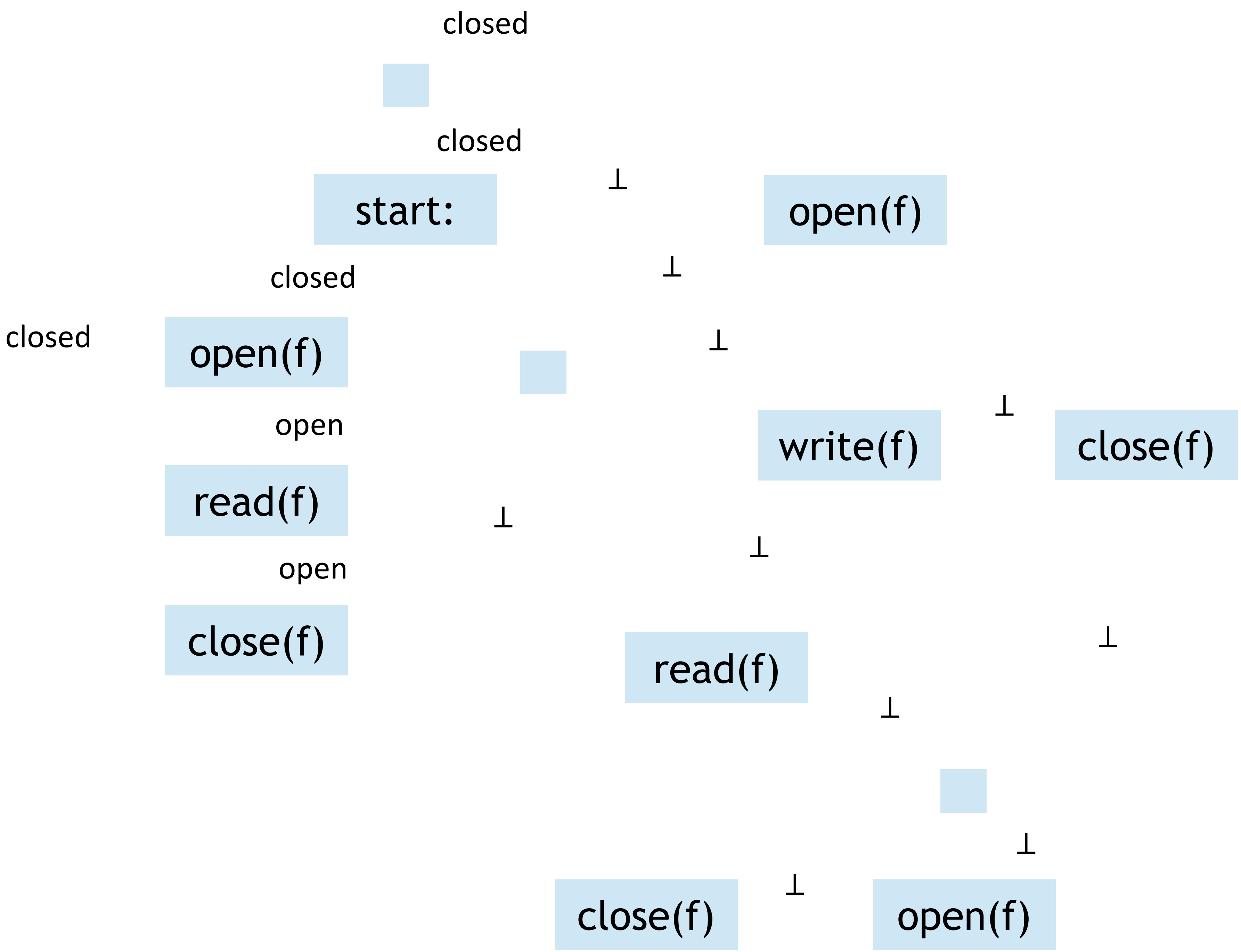


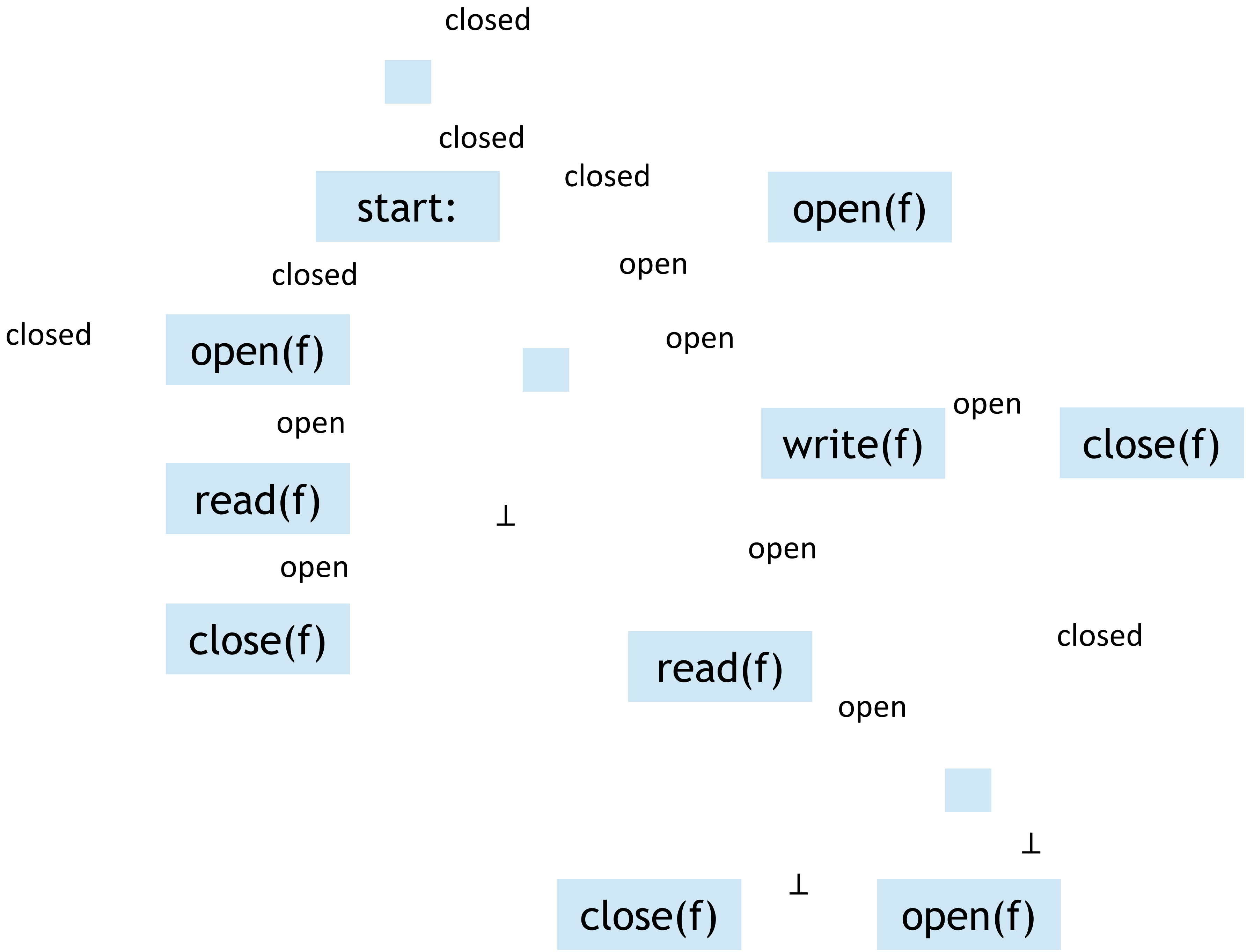
A Tricky Program

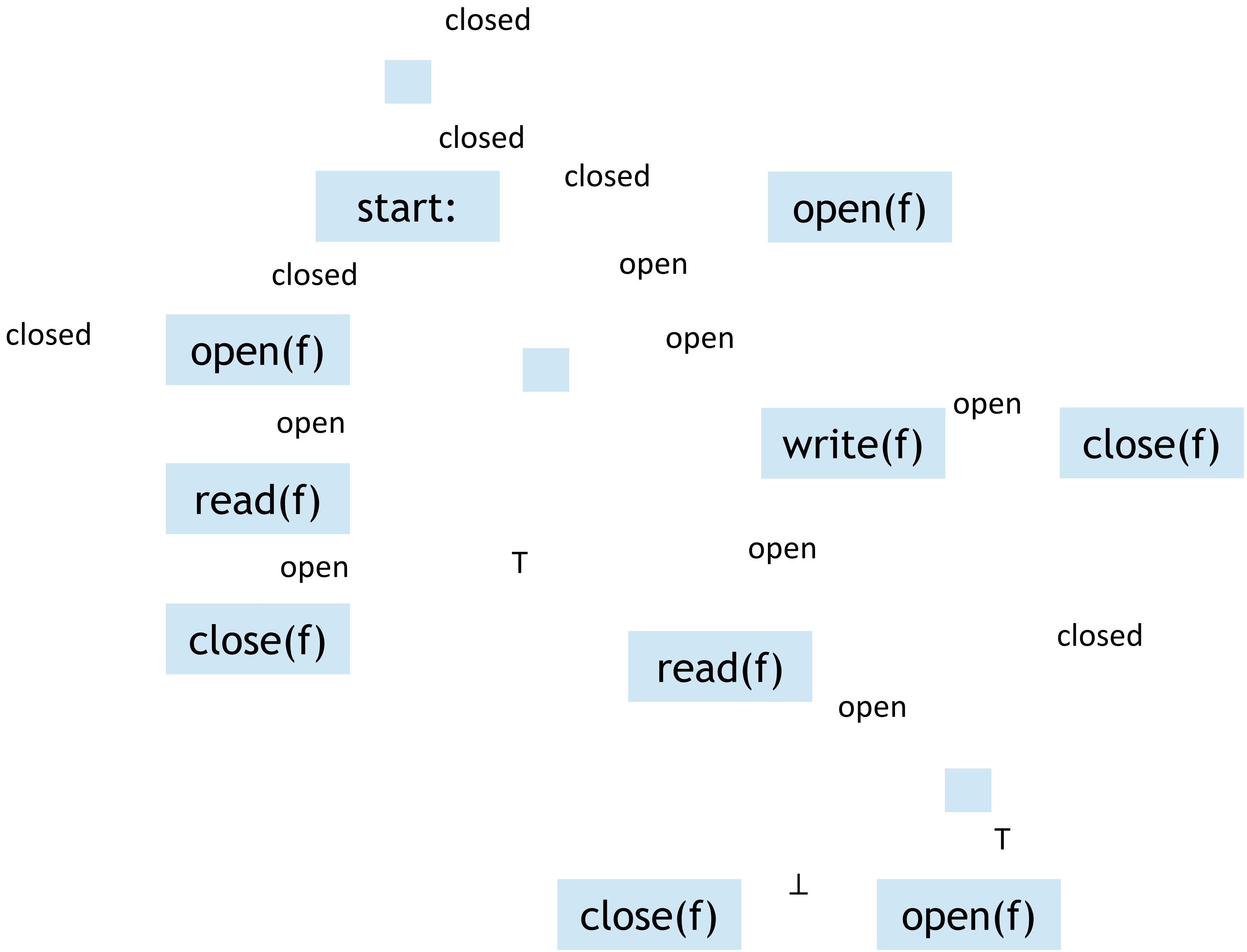
```
start:
switch (a)
  case 1: open(f); read(f); close(f); goto start
  default: open(f);
do {
  write(f) ;
  if (b):      read(f);
  else: close(f);
} while (b)
open(f);
close(f);
```

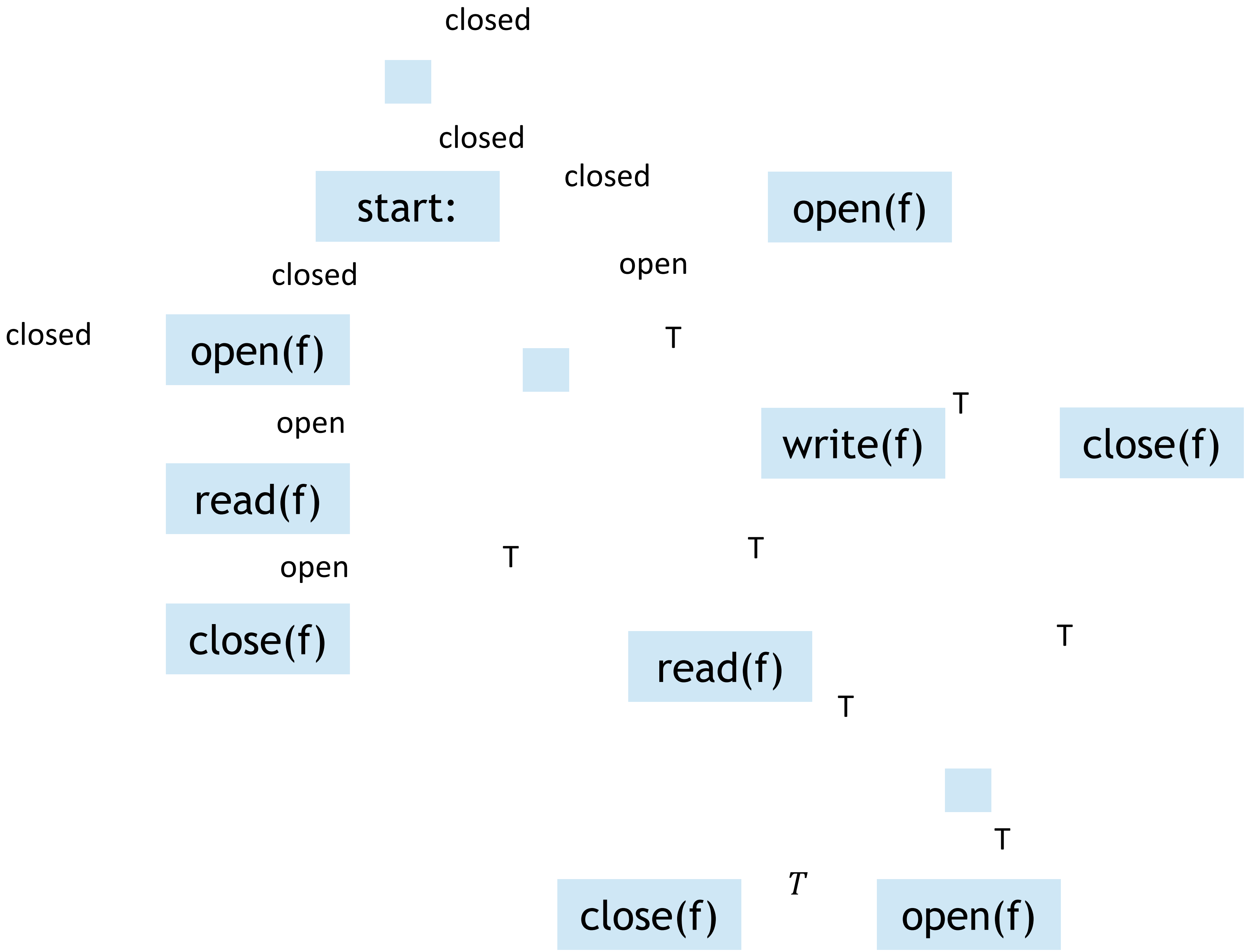
```
start:
switch (a)
  case 1: open(f); read(f); close(f); goto start
  default: open(f);
do {
  write(f) ;
  if (b):      read(f);
  else: close(f);
} while (b)
open(f);
close(f);
```

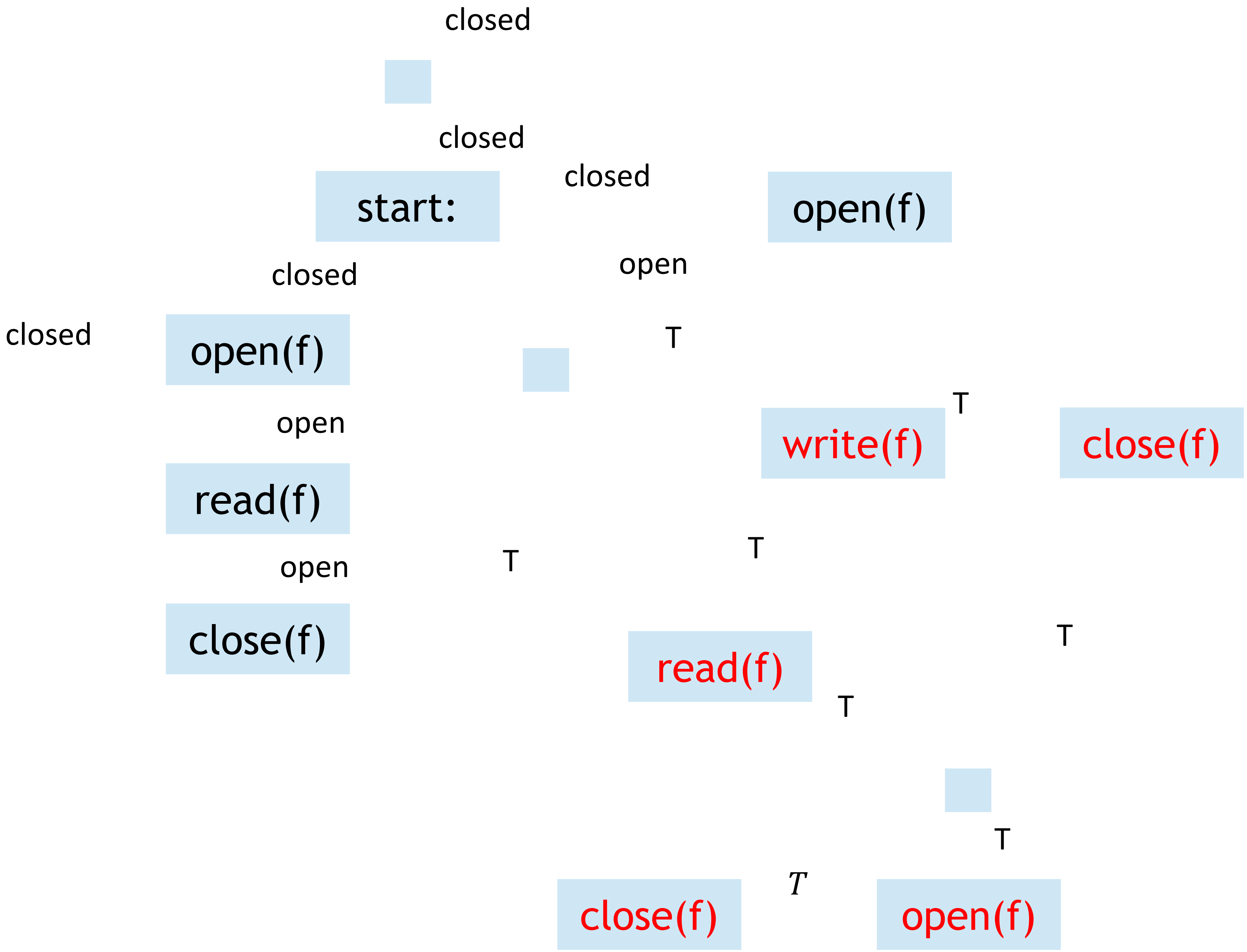



closed
closed
start:
⊥
open(f)
⊥
closed
closed
open(f)
⊥
⊥
write(f)
close(f)
open
read(f)
⊥
⊥
open
close(f)
⊥
read(f)
⊥
⊥
close(f)
⊥
open(f)


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


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


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


closed
closed
start:
closed
open(f)
closed
open
closed
open(f)
T
T
open
write(f)
close(f)
read(f)
open
T
T
close(f)
T
read(f)
T
T
T
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. Backwards Analysis

- We've seen two kinds of analysis:

- Definitely null (cf. constant propagation) is a **forward** 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

Questions?

- How's the homework going?

- Exam