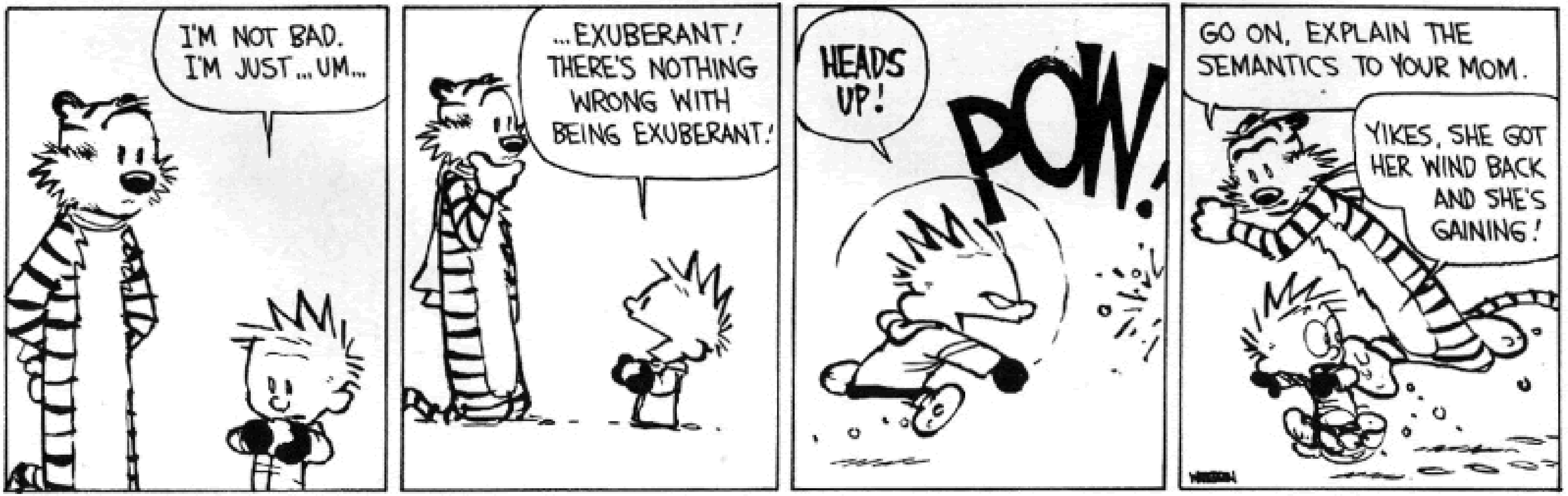
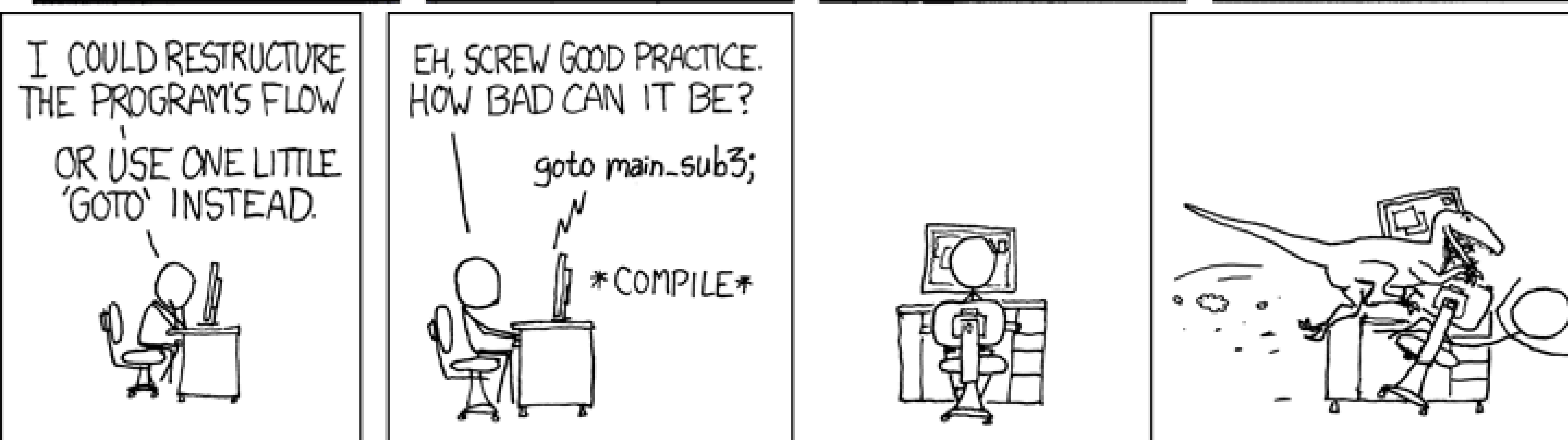
Symbolic Execution



One-Slide Summary

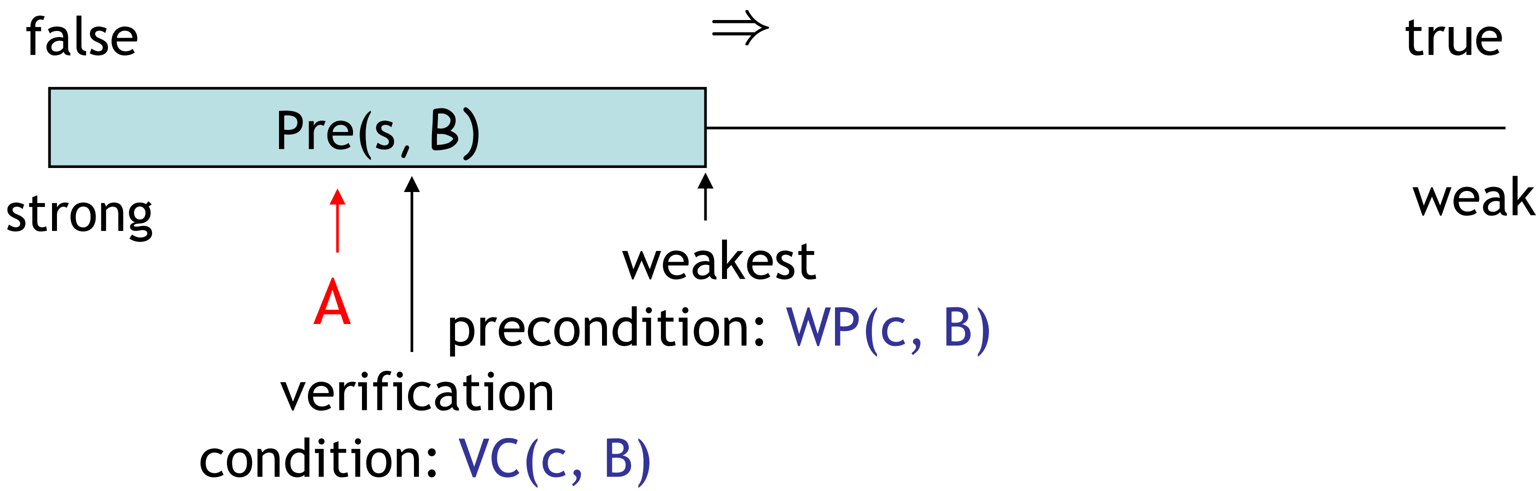
- **Verification Conditions** make axiomatic semantics practical. We can compute verification conditions **forward** for use on unstructured code (= assembly language). This is sometimes called **symbolic execution**.
- We can add extra invariants or drop paths (dropping is *unsound*) to help verification condition generation **scale**.
- We can model **exceptions**, **memory** operations and **data structures** using verification condition generation.

Symbolic Execution



Not Quite Weakest Preconditions

- Recall what we are trying to do:



- Construct a verification condition: VC(c, B)
  - Our loops will be annotated with loop invariants!
  - VC is guaranteed to be stronger than WP
  - But still weaker than A: $A \Rightarrow VC(c, B) \Rightarrow WP(c, B)$

Groundwork

- Factor out the hard work
  - Loop invariants
  - Function specifications (pre- and post-conditions)
- Assume programs are annotated with such specs
  - Good software engineering practice anyway
  - Requiring annotations = Kiss of Death?
- New form of while that includes a loop invariant:

$$\text{while}_{\text{Inv}}\ b\ \text{do}\ c$$

  - Invariant formula Inv must hold every time before b is evaluated
- A process for computing VC(annotated_command, post_condition) is called VCGen

Verification Condition Generation

- Mostly follows the definition of the wp function:

$$VC(\text{skip}, B) = B$$

$$VC(c_1; c_2, B) = VC(c_1, VC(c_2, B))$$

$$VC(\text{if } b \text{ then } c_1 \text{ else } c_2, B) =$$

$$b \Rightarrow VC(c_1, B) \wedge \neg b \Rightarrow VC(c_2, B)$$

$$VC(x := e, B) = [e/x]\, B$$

$$VC(\text{let } x = e \text{ in } c, B) = [e/x]\, VC(c, B)$$

$$VC(\text{while}_{\text{Inv}}\ b \text{ do } c, B) = ?$$

VCGen for WHILE

$VC(\text{while}_{Inv}\ e \text{ do } c, B) =$

$$Inv \land (\forall x_1 \ldots x_n.\ Inv \Rightarrow (e \Rightarrow VC(c, Inv)) \land \neg e \Rightarrow B))$$

Inv holds on entry

Inv is preserved in an arbitrary iteration

B holds when the loop terminates in an arbitrary iteration

- Inv is the loop invariant (provided externally)
- $x_1, \ldots, x_n$ are all the variables modified in c
- The $\forall$ is similar to the $\forall$ in mathematical induction:

$$P(0) \land \forall n \in \mathbb{N}.\ P(n) \Rightarrow P(n+1)$$

Example VCGen Problem

- Let's compute the VC of this program with respect to post-condition $x \neq 0$

x = 0;

y = 2;

while$_{x+y=2}$ y > 0 do

    y := y - 1;

    x := x + 1

First, what do we expect? **What pre-condition do we need** to ensure $x \neq 0$ after this?

Example of VC

- By the sequencing rule, first we do the while loop (call it w):

  $\text{while}_{x+y=2}\ y > 0 \text{ do}$

  $y := y - 1;$

  $x := x + 1$

- VCGen(w, $x \neq 0$) = $x+y=2 \wedge$

  $\forall x,y.\ x+y=2 \Rightarrow (y>0 \Rightarrow \text{VC}(c,\ x+y=2)\ \ \wedge y \leq 0 \Rightarrow x \neq 0)$

Preserve loop invariant

Ensure post on exit

- VCGen($y:=y-1$; $x:=x+1$, $x+y=2$) =

  $(x+1) + (y-1) = 2$

- w Result: $x+y=2 \wedge$

  $\forall x,y.\ x+y=2 \Rightarrow (y>0 \Rightarrow (x+1)+(y-1)=2\ \ \wedge y \leq 0 \Rightarrow x \neq 0)$

Example of VC (2)

- $VC(w, x \neq 0) = x+y=2 \wedge$

  $\forall x,y.\ x+y=2 \Rightarrow$

  $(y>0 \Rightarrow (x+1)+(y-1)=2 \ \wedge\ y \leq 0 \Rightarrow x \neq 0)$

- $VC(x := 0;\ y := 2\ ;\ w, x \neq 0) = 0+2=2 \wedge$

  $\forall x,y.\ x+y=2 \Rightarrow$

  $(y>0 \Rightarrow (x+1)+(y-1)=2 \ \wedge\ y \leq 0 \Rightarrow x \neq 0)$

- So now we ask an automated theorem prover to prove it.

Thoreau, Thoreau, Thoreau

```
$ ./Simplify
> (AND (EQ (+ 0 2) 2)
  (FORALL ( x y ) (IMPLIES (EQ (+ x y) 2)
     (AND (IMPLIES (> y 0)
                    (EQ (+ (+ x 1)(- y 1)) 2))
          (IMPLIES (<= y 0) (NEQ x 0))))))
1: Valid.
```

- Huzzah!
- Simplify is a non-trivial five megabytes
- Z3 is 15+ megabytes

Can We Mess Up VCGen?

- The invariant is from the user (= the adversary, the untrusted code base)
- Let's use a loop invariant that is too weak, like "true".
- VC = $true \wedge \quad \forall x,y.\ true \Rightarrow$

  $(y>0 \Rightarrow true \ \wedge\ y \leq 0 \Rightarrow x \neq 0)$
- Let's use a loop invariant that is false, like "$x \neq 0$".
- VC = $0 \neq 0 \wedge \quad \forall x,y.\ x \neq 0 \Rightarrow$

  $(y>0 \Rightarrow x+1 \neq 0 \ \wedge\ y \leq 0 \Rightarrow x \neq 0)$

Emerson, Emerson, Emerson

```
$ ./Simplify
> (AND TRUE
   (FORALL ( x y ) (IMPLIES TRUE
     (AND (IMPLIES (> y 0) TRUE)
          (IMPLIES (<= y 0) (NEQ x 0))))))
Counterexample: context:
     (AND
       (EQ x 0)
       (<= y 0)
     )
1: Invalid.
```

- OK, so we won't be fooled.

Soundness of VCGen

- Simple form

$$\models \{ VC(c,B) \}\ c\ \{ B \}$$

- Or equivalently that

$$\models VC(c, B) \Rightarrow wp(c, B)$$

- Proof is by induction on the structure of c
  - Try it!
- Soundness holds for any choice of invariant!
- Next: extensions to Symbolic Execution

Where Are We?

- Axiomatic Semantics: the meaning of a program is what is true after it executes
- Hoare Triples: {A} c {B}
- Weakest Precondition: { WP(c,B) } c {B}
- Verification Condition: $A \Rightarrow VC(c,B) \Rightarrow WP(c,b)$
  - Requires Loop Invariants
  - Backward VC works for structured programs
  - Here we are today …
  - Forward VC (Symbolic Exec) works for assembly

Today's Cunning Plan

- Symbolic Execution & Forward VCGen
- Handling Exponential Blowup
  - Invariants
  - Dropping Paths
- VCGen For Exceptions (double trouble)
- VCGen For Memory (McCarthyism)
- VCGen For Structures (have a field day)
- VCGen For "Dictator For Life"

VC and Invariants

- Consider the Hoare triple:

  $\{x \leq 0\}\ \text{while}_{I(x)}\ x \leq 5\ \text{do}\ x := x + 1\ \{x = 6\}$

- The VC for this is:

  $x \leq 0 \Rightarrow I(x) \wedge \forall x.\ (I(x) \Rightarrow (x > 5 \Rightarrow x = 6 \wedge$
  $x \leq 5 \Rightarrow I(x+1)\ ))$

- Requirements on the invariant:
  - Holds on entry $\forall x.\ x \leq 0 \Rightarrow I(x)$
  - Preserved by the body $\forall x.\ I(x) \wedge x \leq 5 \Rightarrow I(x+1)$
  - Useful $\forall x.\ I(x) \wedge x > 5 \Rightarrow x = 6$
- Check that $I(x) = x \leq 6$ satisfies all constraints

Forward VCGen

- Traditionally the VC is computed backwards
  - That's how we've been doing it in class
  - Backwards works well for structured code
- But it can also be computed forward
  - Works even for un-structured languages (e.g., assembly language)
  - Uses symbolic execution, a technique that has broad applications in program analysis
    - e.g., the PREfix tool (Intrinsa, Microsoft) does this
    - Test input generation, document generation, specification mining, security analyses, …

Forward VC Gen Intuition

- Consider the sequence of assignments

$$x_1 := e_1;\ x_2 := e_2$$

- The $VC(c, B) = [e_1/x_1]([e_2/x_2]B)$

$$= [e_1/x_1,\ e_2[e_1/x_1]/x_2]\ B$$

- We can compute the substitution in a forward way using symbolic execution (aka symbolic evaluation)
  - Keep a symbolic state that maps variables to expressions
  - Initially, $\Sigma_0 = \{ \}$
  - After $x_1 := e_1$, $\Sigma_1 = \{ x_1 \rightarrow e_1 \}$
  - After $x_2 := e_2$, $\Sigma_2 = \{x_1 \rightarrow e_1,\ x_2 \rightarrow e_2[e_1/x_1] \}$
  - Note that we have applied Σ_1 as a substitution to right-hand side of assignment $x_2 := e_2$

Simple Assembly Language

- Consider the language of instructions:

  I ::= x := e | f() | if e goto L | goto L |
  L: | return | inv e

- The "inv e" instruction is an annotation
  - Says that boolean expression e is true at that point
- Each function f() comes with Pre_f and $Post_f$ annotations (pre- and post-conditions)
- New Notation (yay!): I_k is the instruction at address k

Symex States

- We set up a symbolic execution state:

Σ : Var $\rightarrow$ SymbolicExpressions

$\Sigma(x)$ = the symbolic value of x in state Σ

$\Sigma[x:=e]$ = a new state in which x's value is e

- We use states as substitutions:

$\Sigma(e)$ - obtained from e by replacing x with $\Sigma(x)$

- Much like the opsem so far …

Symex Invariants

- The symbolic executor tracks invariants passed
- A new part of symex state: $Inv \subseteq \{1\ldots n\}$
- If $k \in Inv$ then I_k is an invariant instruction that we have already executed
- Basic idea: execute an inv instruction only twice:
  - The first time it is encountered
  - Once more time around an arbitrary iteration

Symex Rules

- Define a VC function as an interpreter:

$VC : Address \times SymbolicState \times InvariantState \to Assertion$

$VC(k, \Sigma, Inv) =$

$VC(L, \Sigma, Inv)$	if I_k = goto L
$e \Rightarrow VC(L, \Sigma, Inv) \quad \wedge$ $\neg e \Rightarrow VC(k+1, \Sigma, Inv)$	if I_k = if e goto L
$VC(k+1, \Sigma[x:=\Sigma(e)], Inv)$	if I_k = x := e
$\Sigma(Post_{current\text{-}function})$	if I_k = return
$\Sigma(Pre_f) \quad \wedge$ $\forall a_1..a_m.\Sigma'(Post_f) \Rightarrow$ $VC(k+1, \Sigma', Inv)$ (where $y_1, \ldots, y_m$ are modified by f) and $a_1, \ldots, a_m$ are fresh parameters and $\Sigma' = \Sigma[y_1 := a_1, \ldots, y_m := a_m]$	if I_k = f()

Recall: Inv = "invariants visited so far"

Symex Invariants (2a)

Two cases when seeing an invariant instruction:

1. We see the invariant for the first time
   - I_k = inv e
   - $k \notin$ Inv   (= "not in the set of invariants we've seen")
   - Let $\{y_1, \ldots, y_m\}$ = the variables that could be modified on a path from the invariant back to itself
   - Let $a_1, \ldots, a_m$ be fresh new symbolic parameters

$$VC(k, \Sigma, Inv) =$$

$$\Sigma(e) \wedge \forall a_1 \ldots a_m.\ \Sigma'(e) \Rightarrow VC(k+1, \Sigma', Inv \cup \{k\}])$$

with $\Sigma' = \Sigma[y_1 := a_1, \ldots, y_m := a_m]$

(like a function call)

Symex Invariants (2b)

- We see the invariant for the second time
  - I_k = inv E
  - $k \in Inv$

  $VC(k, \Sigma, Inv) = \Sigma(e)$

  (like a function return)
- Some tools take a more simplistic approach
  - Do not require invariants
  - Iterate through the loop a fixed number of times
  - PREfix, versions of ESC (DEC/Compaq/HP SRC)
  - Sacrifice completeness for usability

Symex Summary

- Let $x_1, \ldots, x_n$ be all the variables and $a_1, \ldots, a_n$ fresh parameters
- Let Σ_0 be the state $[x_1 := a_1, \ldots, x_n := a_n]$
- Let $\emptyset$ be the empty Inv set

- For all functions f in your program, prove:

$$\forall a_1 \ldots a_n.\ \Sigma_0(Pre_f) \Rightarrow VC(f_{entry}, \Sigma_0, \emptyset)$$

- If you start the program by invoking any f in a state that satisfies Pre_f, then the program will execute such that
  - At all "inv e" the e holds, and
  - If the function returns then $Post_f$ holds
- Can be proved w.r.t. a real interpreter (op sem)
- Or via a proof technique called co-induction (or, assume-guarantee)

Forward VCGen Example

- Consider the program

Precondition: $x \le 0$

```
Loop: inv x ≤ 6
        if x > 5 goto End
        x := x + 1
        goto Loop
End:  return
```

Postconditon: $x = 6$

Forward VCGen Example (2)

$$\forall x.\; x \leq 0 \Rightarrow x \leq 6 \wedge \forall x'.\; (x' \leq 6 \Rightarrow x' > 5 \Rightarrow x' = 6 \;\wedge\; x' \leq 5 \Rightarrow x' + 1 \leq 6\,)$$

- VC contains both proof obligations and assumptions about the control flow

VCs Can Be Large

- Consider the sequence of conditionals

  (if x < 0 then x := - x); (if x ≤ 3 then x += 3)

  – With the postcondition P(x)
- The VC is

  $$
  \begin{array}{lll}
  x < 0 \wedge -x \leq 3 & \Rightarrow P(-x + 3) & \wedge \\
  x < 0 \wedge -x > 3 & \Rightarrow P(-x) & \wedge \\
  x \geq 0 \wedge x \leq 3 & \Rightarrow P(x + 3) & \wedge \\
  x \geq 0 \wedge x > 3 & \Rightarrow P(x\ ) &
  \end{array}
  $$
- There is one conjunct for each path

  ⇒ exponential number of paths!

  – Conjuncts for infeasible paths have un-satisfiable guards!
- Try with $P(x) = x \geq 3$

English Prose

341. Van and Hitomi walked an inaudible distance from those guy's Van was hanging out with.

253. However, when he got into his chamber and sat down with a blank canvas propped up on its easel, his vision vanished as if it were nothing but a floating dust moat.

352. "Good evening my league." He picked her up by the wrist. "I think that you and I have some talking to do, actually I have a preposition"

Computer Science

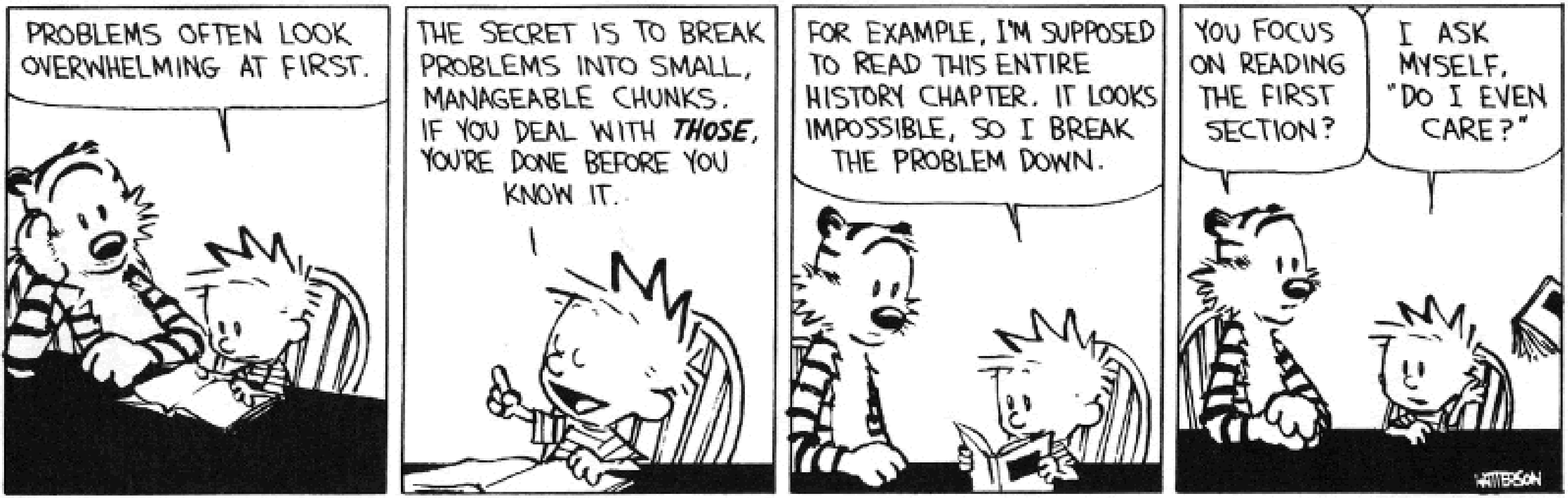
- This American Turing award winner is known for the "law" that "Adding humans to a late software project makes it later." The Turing Award citation notes landmark contributions to operating systems, software engineering and computer architecture. Notable works include *No Silver Bullet: Essence and Accidents of Software Engineering* and *The* ___ ___ ___.

Q: Theatre (019 / 842)

- Name the composer or the title of the 1937 musical that includes the lyrics: *"O Fortuna, velut luna statu variabilis, semper crescis aut decrescis; vita detestabilis nunc obdurat et tunc curat ludo mentis aciem, egestatem, potestatem dissolvit ut glaciem."*

VCs Can Be Exponential

- VCs are exponential in the size of the source because they attempt relative completeness:
  - Perhaps the correctness of the program must be argued independently for each path
- Unlikely that the programmer wrote a program by considering an exponential number of cases
  - But possible. Any examples? Any solutions?



VCs Can Be Exponential

- VCs are exponential in the size of the source because they attempt relative completeness:
  - Perhaps the correctness of the program must be argued independently for each path
- Standard Solutions:
  - Allow invariants even in straight-line code
  - And thus do not consider all paths independently!

Invariants in Straight-Line Code

- Purpose: modularize the verification task
- Add the command "after c establish Inv"
  - Same semantics as c (Inv is only for VC purposes)

$$VC(\text{after } c \text{ establish } Inv, P) =_{def}$$

$$VC(c, Inv) \wedge \forall x_i.\ Inv \Rightarrow P$$

    - where x_i are the ModifiedVars(c)
- Use when c contains many paths

after if $x < 0$ then $x := - x$ establish $x \geq 0$;

if $x \leq 3$ then x += 3 { P(x) }

- VC is now:

$$(x < 0 \Rightarrow - x \geq 0) \wedge (x \geq 0 \Rightarrow x \geq 0) \wedge$$

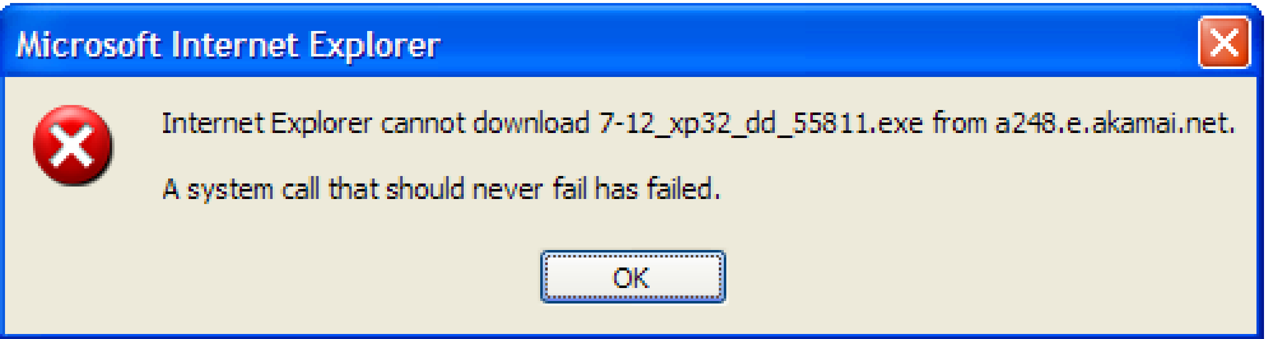
$$\forall x.\ x \geq 0 \Rightarrow (x \leq 3 \Rightarrow P(x+3) \wedge x > 3 \Rightarrow P(x))$$

Dropping Paths

- In absence of annotations, we can drop some paths
- VC(if E then c_1 else c_2, P) = choose one of
  - $E \Rightarrow VC(c_1, P) \wedge \neg E \Rightarrow VC(c_2, P)$ (drop no paths)
  - $E \Rightarrow VC(c_1, P)$ (drops "else" path!)
  - $\leftarrow \neg E \Rightarrow VC(c_2, P)$ (drops "then" path!)
- We sacrifice soundness! (we are now unsound)
  - No more guarantees
  - Possibly still a good debugging aid
- Remarks:
  - An established trend is to sacrifice soundness to increase usability (e.g., Metal, ESP, even ESC)
  - The PREfix tool considers only 50 non-cyclic paths through a function (almost at random)

VCGen for Exceptions

- We extend the source language with exceptions without arguments (cf. HW2):
  - throw — throws an exception
  - try c_1 catch c_2 — executes c_2 if c_1 throws
- Problem:
  - We have non-local transfer of control
  - What is VC(throw, P) ?



VCGen for Exceptions

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  - throw — throws an exception
  - try c_1 catch c_2 — executes c_2 if c_1 throws
- Problem:
  - We have non-local transfer of control
  - What is VC(throw, P) ?
- Standard Solution: use 2 postconditions
  - One for normal termination
  - One for exceptional termination

VCGen for Exceptions (2)

- VC(c, P, Q) is a precondition that makes c either not terminate, or terminate normally with P or throw an exception with Q
- Rules

$$VC(\text{skip}, P, Q) = P$$

$$VC(c_1; c_2, P, Q) = VC(c_1, VC(c_2, P, Q), Q)$$

$$VC(\text{throw}, P, Q) = Q$$

$$VC(\text{try } c_1 \text{ catch } c_2, P, Q) = VC(c_1, P, VC(c_2, P, Q))$$

$$VC(\text{try } c_1 \text{ finally } c_2, P, Q) = ?$$

VCGen Finally

- Given these:

  $VC(c_1; c_2, P, Q) = VC(c_1, VC(c_2, P, Q), Q)$

  $VC(\text{try } c_1 \text{ catch } c_2, P, Q) = VC(c_1, P, VC(c_2, P, Q))$

- Finally is somewhat like "if":

  $VC(\text{try } c_1 \text{ finally } c_2, P, Q) =$

  $VC(c_1, VC(c_2, P, Q), \text{true}) \quad \wedge$

  $VC(c_1, \text{true}, VC(c_2, Q, Q))$

- Which reduces to:

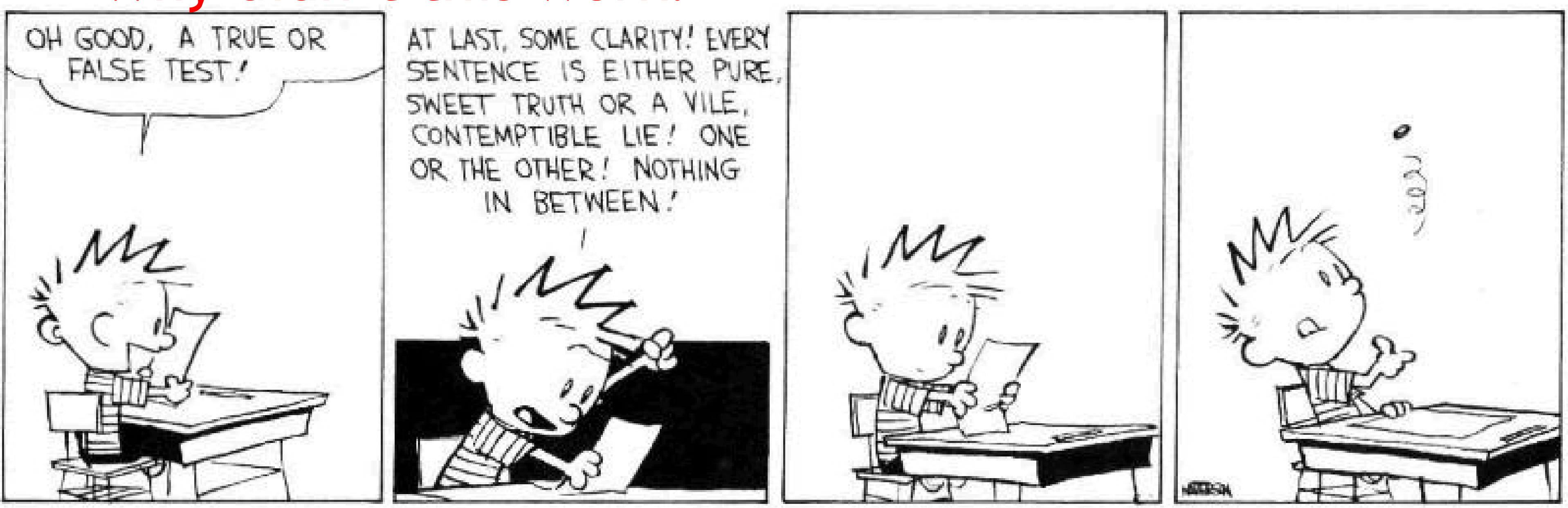
$$VC(c_1, VC(c_2, P, Q), VC(c_2, Q, Q))$$

Hoare Rules and the Heap

- When is the following Hoare triple valid?

  { A } *x := 5 { *x + *y = 10 }

- A *should be* "*y = 5 or x = y"
- The Hoare rule for assignment would give us:
  - [5/*x](*x + *y = 10) = 5 + *y = 10 =
  - *y = 5 (we lost one case)
- Why didn't this work?



Handling The Heap

- We do not yet have a way to talk about memory (the heap, pointers) in assertions
- Model the state of memory as a symbolic mapping from addresses to values:
  - If A denotes an address and M is a memory state then:
  - sel(M,A) denotes the contents of the memory cell
  - upd(M,A,V) denotes a new memory state obtained from M by writing V at address A

More on Memory

- We allow variables to range over memory states
  - We can quantify over all possible memory states
- Use the special pseudo-variable μ (mu) in assertions to refer to the current memory
- Example:

$$\forall i.\ i \geq 0 \wedge i < 5 \Rightarrow sel(\mu, A + i) > 0$$

says that entries 0..4 in array A are positive

Hoare Rules: Side-Effects

- To model writes we use memory expressions
  - A memory write changes the value of memory

$$\frac{}{\{ B[upd(\mu, A, E)/\mu] \}\ \mathbf{*A := E}\ \{B\}}$$

- Important technique: treat memory as a whole
- And reason later about memory expressions with inference rules such as (McCarthy Axioms, ~'67):

$$sel(upd(M, A_1, V), A_2) = \begin{cases} V & \text{if } A_1 = A_2 \\ sel(M, A_2) & \text{if } A_1 \neq A_2 \end{cases}$$

Memory Aliasing

- Consider again: { A } *x := 5 { *x + *y = 10 }
- We obtain:

A = [upd(μ, x, 5)/μ] (*x + *y = 10)

= [upd(μ, x, 5)/μ] (sel(μ, x) + sel(μ, y) = 10)

(1) = sel(upd(μ, x, 5), x) + sel(upd(μ, x, 5), y) = 10

= 5 + sel(upd(μ, x, 5), y) = 10

= if x = y then 5 + 5 = 10 else 5 + sel(μ, y) = 10

(2) = x = y or *y = 5

- Up to (1) is theorem generation
- From (1) to (2) is theorem proving

Alternative Handling for Memory

- Reasoning about aliasing can be expensive
  - It is NP-hard (and/or undecideable)
- Sometimes completeness is sacrificed with the following (approximate) rule:

$$\text{sel}(\text{upd}(M, A_1, V), A_2) = \begin{cases} V & \text{if } A_1 = \text{(obviously) } A_2 \\ \text{sel}(M, A_2) & \text{if } A_1 \neq \text{(obviously) } A_2 \\ P & \text{otherwise (p is a fresh new parameter)} \end{cases}$$

- The meaning of “obviously” varies:
  - The addresses of two distinct globals are ≠
  - The address of a global and one of a local are ≠
- PREfix and GCC use such schemes

VCGen Overarching Example

- Consider the program
  - Precondition: *B : bool ∧ A : array(bool, L)*

1: I := 0

R := B

3: *inv I ≥ 0 ∧ R : bool*

if I ≥ L goto 9

assert saferd(A + I)

T := *(A + I)

I := I + 1

R := T

goto 3

9: return R

  - Postcondition: *R : bool*

VCGen Overarching Example

$$
\begin{array}{l}
\forall A.\ \forall B.\ \forall L.\ \forall \mu \\
\quad B : \text{bool} \wedge A : \text{array}(\text{bool}, L) \Rightarrow \\
\quad\quad 0 \geq 0 \wedge B : \text{bool} \wedge \\
\quad\quad\quad \forall I.\ \forall R. \\
\quad\quad\quad\quad I \geq 0 \wedge R : \text{bool} \Rightarrow \\
\quad\quad\quad\quad\quad I \geq L \Rightarrow R : \text{bool} \\
\quad\quad\quad\quad\quad\quad \wedge \\
\quad\quad\quad\quad\quad I < L \Rightarrow \text{saferd}(A + I) \wedge \\
\quad\quad\quad\quad\quad\quad I + 1 \geq 0 \wedge \\
\quad\quad\quad\quad\quad\quad\quad \text{sel}(\mu, A + I) : \text{bool}
\end{array}
$$

- VC contains both proof obligations and assumptions about the control flow

Mutable Records - Two Models

- Let r : RECORD { f1 : T1; f2 : T2 } END
- For us, records are reference types
- Method 1: one "memory" for each record
  - One index constant for each field
  - r.f1 is sel(r,f1) and r.f1 := E is r := upd(r,f1,E)
- Method 2: one "memory" for each field
  - The record address is the index
  - r.f1 is sel(f1,r) and r.f1 := E is f1 := upd(f1,r,E)
- Only works in strongly-typed languages like Java
  - Fails in C where &r.f2 = &r + sizeof(T1)

VC as a "Semantic Checksum"

- Weakest preconditions are an expression of the program's semantics:
  - Two equivalent programs have logically equivalent WPs
  - No matter how different their syntax is!

- VC are almost as powerful

VC as a "Semantic Checksum" (2)

- Consider the "assembly language" program to the right

```
x := 4
x := (x == 5)
    assert x : bool
x := not x
    assert x
```

- High-level type checking is not appropriate here
- The VC is: ((4 == 5) : bool) $\wedge$ (not (4 == 5))
- No confusion from reuse of x with different types

Invariance of VC Across Optimizations

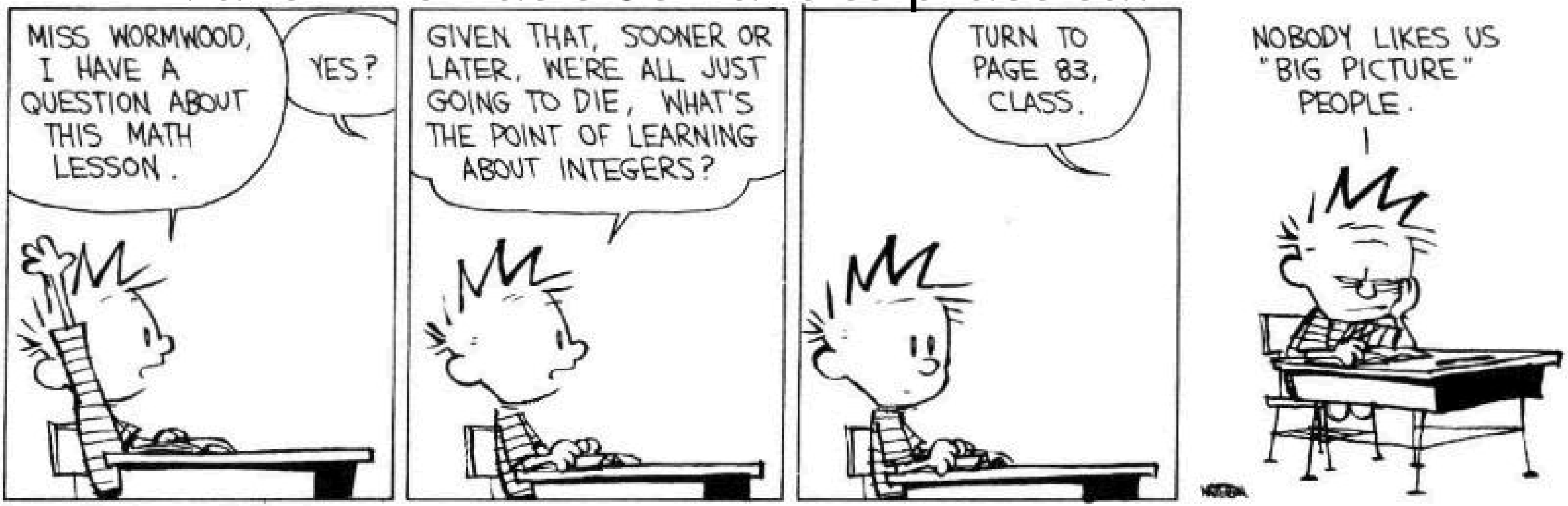
- VC is so good at abstracting syntactic details that it is *syntactically preserved* by many common optimizations
  - Register allocation, instruction scheduling
  - Common subexp elim, constant and copy propagation
  - Dead code elimination
- We have *identical* VCs whether or not an optimization has been performed
  - Preserves syntactic form, not just semantic meaning!
- This can be used to verify correctness of compiler optimizations (Translation Validation)

VC Characterize a Safe Interpreter

- Consider a fictitious "safe" interpreter
  - As it goes along it performs checks (e.g. "safe to read from this memory addr", "this is a null-terminated string", "I have not already acquired this lock")
  - Some of these would actually be hard to implement
- The VC describes all of the checks to be performed
  - Along with their context (assumptions from conditionals)
  - Invariants and pre/postconditions are used to obtain a finite expression (through induction)
- VC is valid $\Rightarrow$ interpreter *never fails*
  - We enforce same level of "correctness"
  - But better (static + more powerful checks)

VC Big Picture

- Verification conditions
  - Capture the semantics of code + specifications
  - Language independent
  - Can be computed backward/forward on structured/unstructured code
  - Make Axiomatic Semantics practical



Invariants Are Not Easy

- Consider the following code from QuickSort

```
int partition(int *a, int L0, int H0, int pivot) {
    int L = L0, H = H0;
    while(L < H) {
        while(a[L] < pivot) L ++;
        while(a[H] > pivot) H --;
        if(L < H) { swap a[L] and a[H] }
    }
    return L
}
```

- Consider verifying only memory safety
- What is the loop invariant for the outer loop ?

Done!

- Questions?