Static Analysis

15-313: Foundations of Software Engineering

Jonathan Aldrich

Find the Bug!

Source: Engler et al., *Checking System Rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '00.

```
/* 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();
        if ((bh = sh->buffer_pool) == NULL)
                return NULL;
        sh->buffer_pool = bh->b_next;
        bh->b_size = b_size;
        restore_flags(flags);
        return bh;
}
```

disable interrupts

ERROR: returning with interrupts disabled

re-enable interrupts

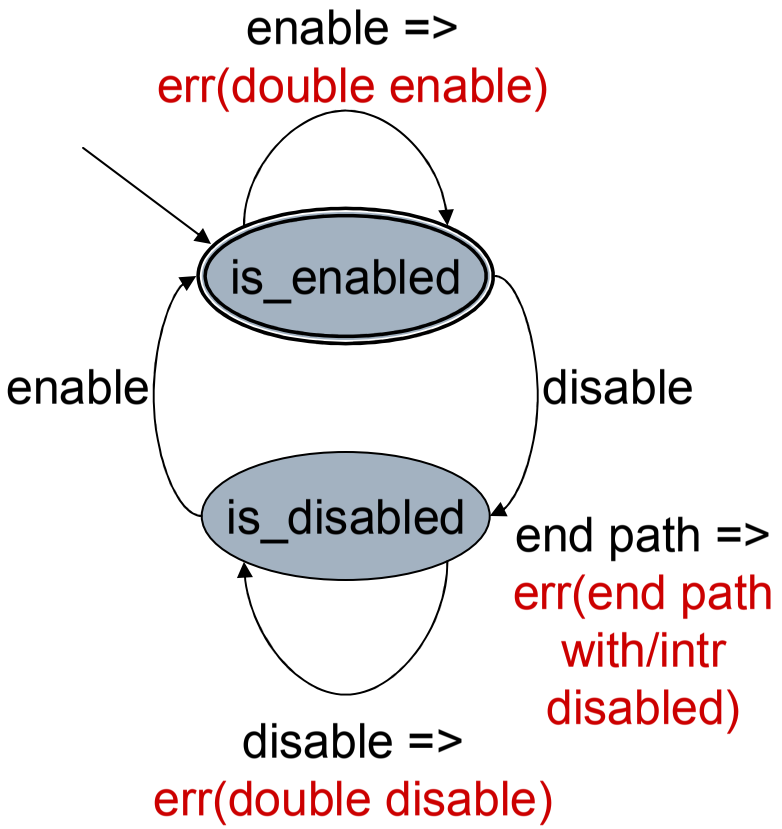
Metal Interrupt Analysis

Source: Engler et al., *Checking System Rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '00.

```
{ #include "linux-includes.h" }
sm check_interrupts {
  // Variables
  // used in patterns
  decl { unsigned } flags;

  // Patterns
  // to specify enable/disable functions.
  pat enable = { sti(); }
             | { restore_flags(flags); } ;
  pat disable = { cli(); };

  // States
  // The first state is the initial state.
  is_enabled: disable ==> is_disabled
     | enable ==> { err("double enable"); }
     ;
  is_disabled: enable ==> is_enabled
     | disable ==> { err("double disable"); }
     // Special pattern that matches when the SM
     // hits the end of any path in this state.
     | $end_of_path$ ==>
        { err("exiting w/intr disabled!"); }
     ;
}
```



Applying the Analysis

Source: Engler et al., *Checking System Rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '00.

```
/* From Linux 2.3.99 drivers/block/raid5.c */
static struct buffer_head *
get_free_buffer(struct stripe_head *sh,          <-- initial state is_enabled
                int b_size) {
        struct buffer_head *bh;
        unsigned long flags;

        save_flags(flags);
        cli();                                   <-- transition to is_disabled
        if ((bh = sh->buffer_pool) == NULL)
                return NULL;                     <-- final state is_disabled: ERROR!
        sh->buffer_pool = bh->b_next;
        bh->b_size = b_size;
        restore_flags(flags);                    <-- transition to is_enabled
        return bh;                               <-- final state is_enabled is OK
}
```

Outline

- Why static analysis?
  - The limits of testing and inspection
- What is static analysis?
- How does static analysis work?
- What do practical tools look like?
- How does it fit into an organization?

A problem has been detected and Windows has been shut down to prevent damage
to your computer.

The problem seems to be caused by the following file: SPCMDCON.SYS

PAGE_FAULT_IN_NONPAGED_AREA

If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:

Check to make sure any new hardware or software is properly installed.
If this is a new installation, ask your hardware or software manufacturer
for any Windows updates you might need.

If problems continue, disable or remove any newly installed hardware
or software. Disable BIOS memory options such as caching or shadowing.
If you need to use Safe Mode to remove or disable components, restart
your computer, press F8 to select Advanced Startup Options, and then
select Safe Mode.

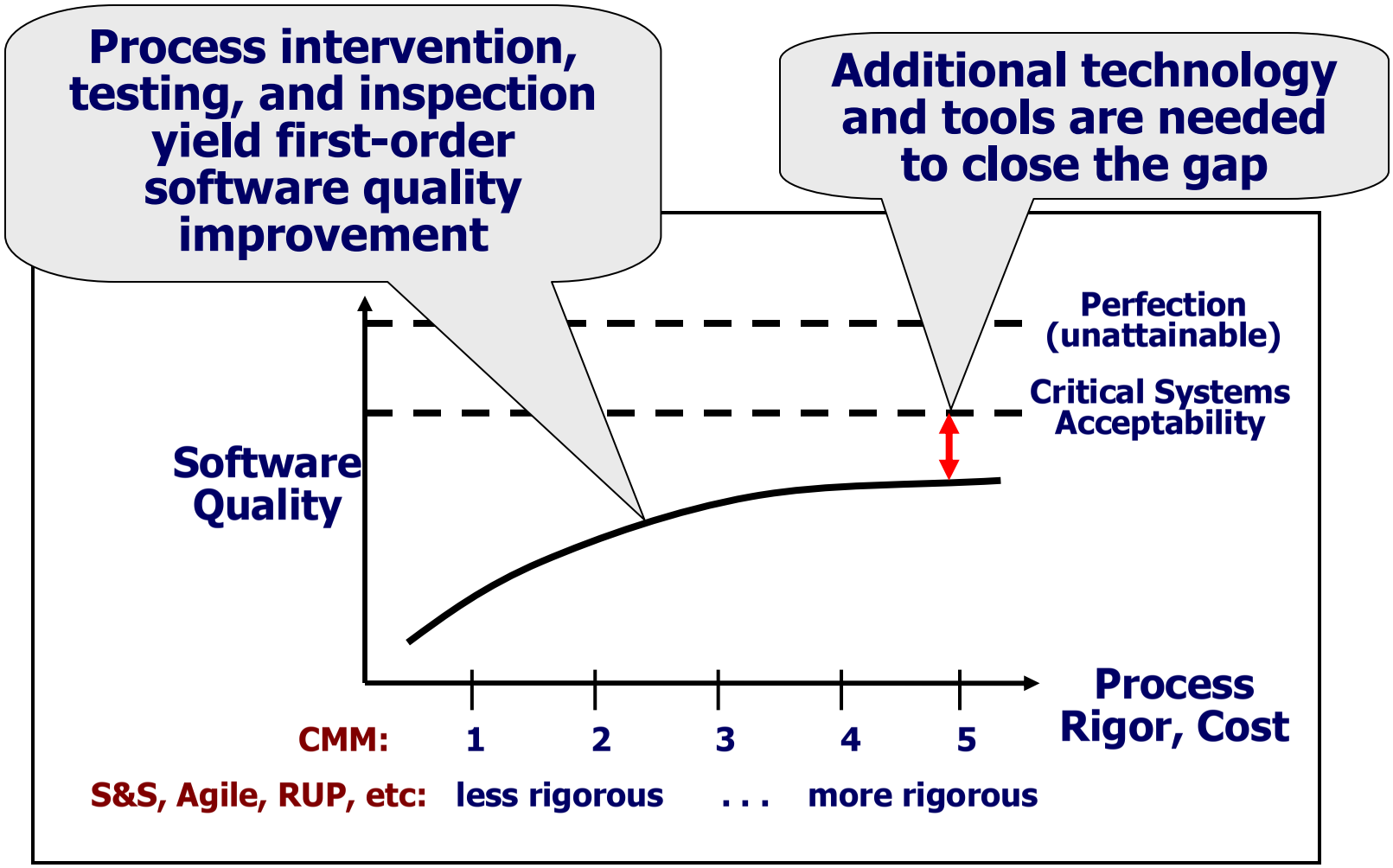
Technical information:

*** STOP: 0x00000050 (0xFD3094C2,0x00000001,0xFBFE7617,0x00000000)

*** SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, DateStamp 3d6dd67c

Process, Cost, and Quality

Slide: William Scherlis



Root Causes of Errors

- Requirements problems
  - Don't fit user needs

Static Analysis Contributions

- Design flaws
  - ★ Lacks required qualities ← Does design achieve goals?
  - ★ Lacks required qualities ← Is design implemented right?

Hard

- Implementation errors
  - Assign ← Is data initialized?
  - Checking ← Is dereference/indexing valid?
  - Algorithm
  - ★ Timing ← Are threads synchronized?
  - ★ Interface ← Are interface semantics followed?
  - ★ Relationship ← Are invariants maintained?

Security

Hard

Taxonomy: [Chillarege et al., Orthogonal Defect Classification]

Existing Approaches

- Testing: *is the answer right?*
  - Verifies features work
  - Finds algorithmic problems
- Inspection: *is the quality there?*
  - Missing requirements
  - Design problems
  - Style issues
  - Application logic

- Limitations
  - Non-local interactions
  - Uncommon paths
  - Non-determinism
- Static analysis: *will I get an answer?*
  - Verifies non-local consistency
  - Checks all paths
  - Considers all non-deterministic choices

Static Analysis Finds “Mechanical” Errors

- Defects that result from inconsistently following simple, mechanical design rules

- Security vulnerabilities
  - Buffer overruns, unvalidated input…
- Memory errors
  - Null dereference, uninitialized data…
- Resource leaks
  - Memory, OS resources…
- Violations of API or framework rules
  - e.g. Windows device drivers; real time libraries; GUI frameworks
- Exceptions
  - Arithmetic/library/user-defined
- Encapsulation violations
  - Accessing internal data, calling private functions…
- Race conditions
  - Two threads access the same data without synchronization

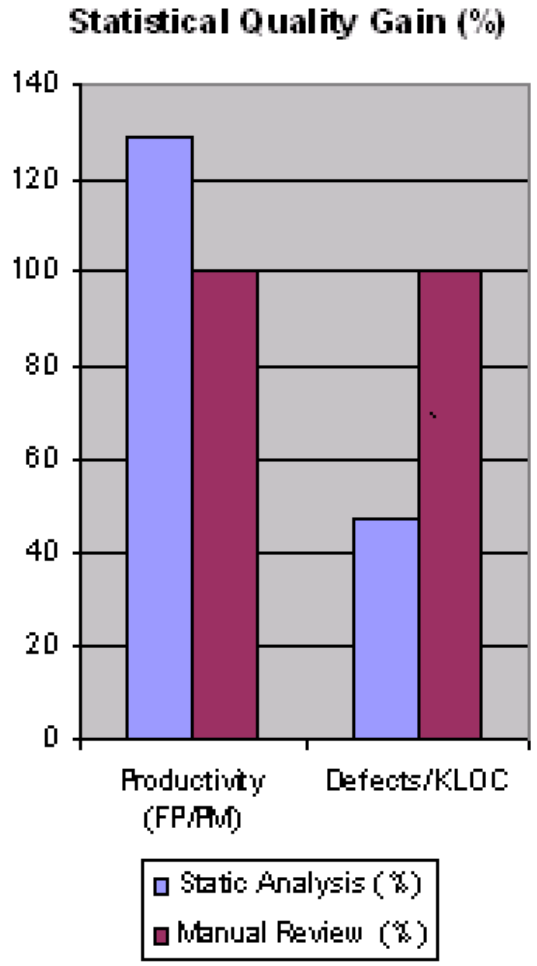
Empirical Results on Static Analysis

- Nortel study [Zheng et al. 2006]
  - 3 C/C++ projects
  - 3 million LOC total
  - Early generation static analysis tools

- Conclusions
  - Cost per fault of static analysis 61-72% compared to inspections
  - Effectively finds assignment, checking faults
  - Can be used to find potential security vulnerabilities

Empirical Results on Static Analysis

- InfoSys study [Chaturvedi 2005]
  - 5 projects
  - Average 700 function points each
  - Compare inspection with and without static analysis
- Conclusions
  - Fewer defects
  - Higher productivity



Adapted from [Chaturvedi 2005]

Quality Assurance at Microsoft (Part 1)

- Original process: manual code inspection
  - Effective when system and team are small
  - Too many paths to consider as system grew
- Early 1990s: add massive system and unit testing
  - Tests took weeks to run
    - Diversity of platforms and configurations
    - Sheer volume of tests
  - Inefficient detection of common patterns, security holes
    - Non-local, intermittent, uncommon path bugs
  - Was treading water in Windows Vista development
- Early 2000s: add static analysis
  - More on this later

Outline

- Why static analysis?
- What is static analysis?
  - Abstract state space exploration
- How does static analysis work?
- What do practical tools look like?
- How does it fit into an organization?

Static Analysis Definition

- Static program analysis is the systematic examination of an abstraction of a program's state space

- Metal interrupt analysis
  - Abstraction
    - 2 states: enabled and disabled
      - All program information—variable values, heap contents—is abstracted by these two states, plus the program counter
  - Systematic
    - Examines all paths through a function
      - What about loops? More later…
    - Each path explored for each reachable state
      - Assume interrupts initially enabled (Linux practice)
      - Since the two states abstract all program information, the exploration is exhaustive

Static Analysis Definition

- Static program analysis is the systematic examination of an abstraction of a program's state space

- Simple array bounds analysis
  - Abstraction
    - Given array *a*, track whether each integer variable and expression is <,=, or > than *length(a)*
      - Abstract away precise values of variables and expressions
      - Abstract away the heap
  - Systematic
    - Examines all paths through a function
    - Each path explored for each reachable state
      - Exploration is exhaustive, since abstract state abstracts all concrete program state

Array Bounds Example

```
1.  void foo(unsigned n) {
2.      char str = new char[n+1];
3.      int idx = 0;
4.      if (n > 5)
5.          idx = n
6.      else
7.          idx = n+1
8.      str[idx] = 'c';
9.  }
```

Path 1 (before stmt): then branch

2: ∅

3: n↦<

4: n↦<, idx↦<

5: n↦<, idx↦<

8: n↦<, idx↦<

9: n↦<, idx↦<

no errors

Array Bounds Example

```
1.  void foo(unsigned n) {
2.      char str = new char[n+1];
3.      int idx = 0;
4.      if (n > 5)
5.              idx = n
6.      else
7.              idx = n+1
8.      str[idx] = 'c';
9.  }
```

Path 1 (before stmt): else branch

2: ∅

3: n↦<

4: n↦<, idx↦<

7: n↦<, idx↦<,=

8: n↦<, idx↦<,=

9: n↦<, idx↦<,=

error: array out of bounds at line 8

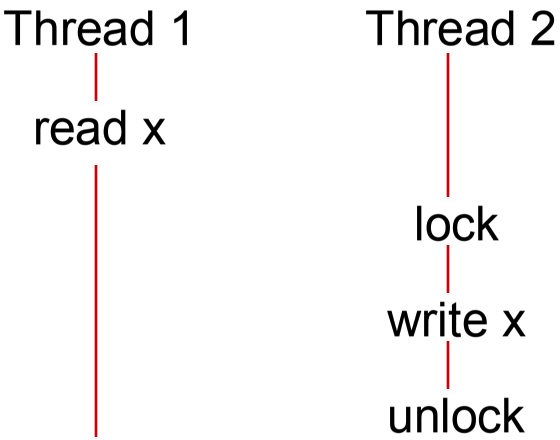
Static Analysis Definition

- Static program analysis is the systematic examination of an abstraction of a program's state space

- Simple model checking for race conditions
  - ***Race condition*** defined:
    [From Savage et al., *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*]
    - Two threads access the same variable
    - At least one access is a write
    - No explicit mechanism prevents the accesses from being simultaneous
  - Abstraction
    - Program counter of each thread, state of each lock
      - Abstract away heap and program variables
  - Systematic
    - Examine all possible interleavings of all threads
      - Flag error if no synchronization between accesses
      - Exploration is exhaustive, since abstract state abstracts all concrete program state

Model Checking for Race Conditions

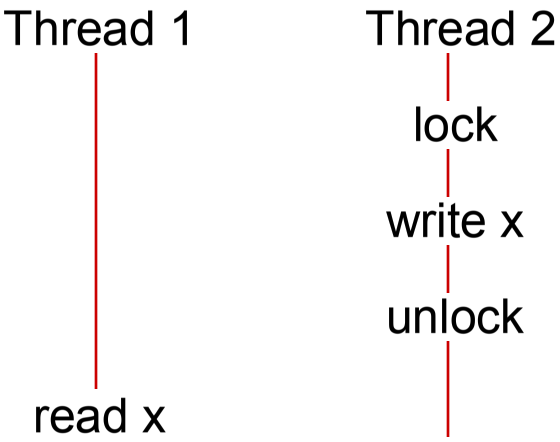
```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK

Model Checking for Race Conditions

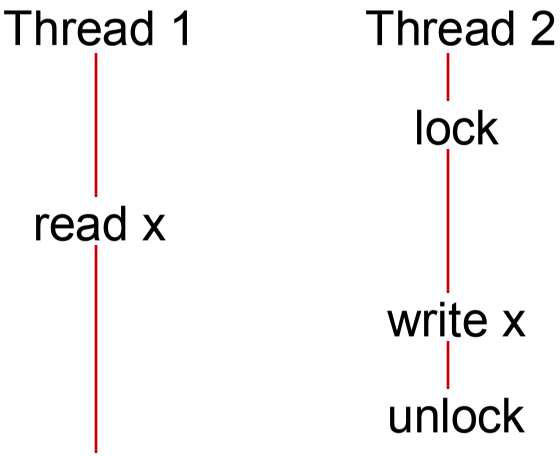
```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK
Interleaving 2: OK

Model Checking for Race Conditions

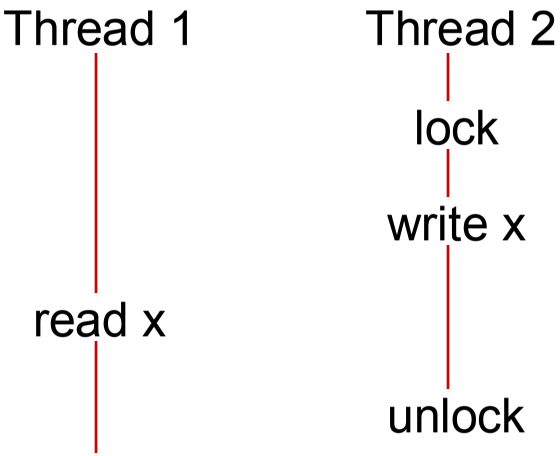
```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race

Model Checking for Race Conditions

```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race
Interleaving 4: Race

Compare Analysis to Testing, Inspection

- Why might it be hard to test/inspect for:
  - Array bounds errors?
  - Forgetting to re-enable interrupts?
  - Race conditions?

Compare Analysis to Testing, Inspection

- Array Bounds, Interrupts
  - Testing
    - Errors typically on uncommon paths or uncommon input
    - Difficult to exercise these paths
  - Inspection
    - Non-local and thus easy to miss
      - Array allocation vs. index expression
      - Disable interrupts vs. return statement
- Finding Race Conditions
  - Testing
    - Cannot force all interleavings
  - Inspection
    - Too many interleavings to consider
    - Check rules like “lock protects x” instead
      - But checking is non-local and thus easy to miss a case

Outline

- Why static analysis?
- What is static analysis?
- How does static analysis work?
  - Termination, Soundness, and Precision
- What do practical tools look like?
- How does it fit into an organization?

How can Analysis Search All Paths?

- How many paths are in a program?
  - Exponential # paths with if statements
  - Infinite # paths with loops
  - How could we possibly cover them all?
- Secret weapon: Abstraction
  - Finite number of (abstract) states
  - If you come to a statement and you've already explored a state for that statement, stop.
    - The analysis depends only on the code and the current state
    - Continuing the analysis from this program point and state would yield the same results you got before
  - If the number of states isn't finite, too bad
    - Your analysis may not terminate

Example

```
1.  void foo(int x) {
2.      if (x == 0)
3.              bar(); cli();
4.      else
5.              baz(); cli();
6.      while (x > 0) {
7.              sti();
8.              do_work();
9.              cli();
10.     }
11.     sti();
12. }
```

Path 1 (before stmt): true/no loop

2: is_enabled
3: is_enabled
6: is_disabled
11: is_disabled
12: is_enabled

no errors

Example

```
1.  void foo(int x) {
2.      if (x == 0)
3.              bar(); cli();
4.      else
5.              baz(); cli();
6.      while (x > 0) {
7.              sti();
8.              do_work();
9.              cli();
10.     }
11.     sti();
12. }
```

Path 2 (before stmt): true/1 loop

2: is_enabled
3: is_enabled
6: is_disabled
7: is_disabled
8: is_enabled
9: is_enabled
11: is_disabled

already been here

Example

```
1.  void foo(int x) {
2.      if (x == 0)
3.          bar(); cli();
4.      else
5.          baz(); cli();
6.      while (x > 0) {
7.          sti();
8.          do_work();
9.          cli();
10.     }
11.     sti();
12. }
```

Path 3 (before stmt): true/2+ loops

2: is_enabled
3: is_enabled
6: is_disabled
7: is_disabled
8: is_enabled
9: is_enabled
6: is_disabled

already been here

Example

```
1.  void foo(int x) {
2.      if (x == 0)
3.              bar(); cli();
4.      else
5.              baz(); cli();
6.      while (x > 0) {
7.              sti();
8.              do_work();
9.              cli();
10.     }
11.     sti();
12. }
```

Path 4 (before stmt): false

2: is_enabled

5: is_enabled

6: is_disabled

already been here

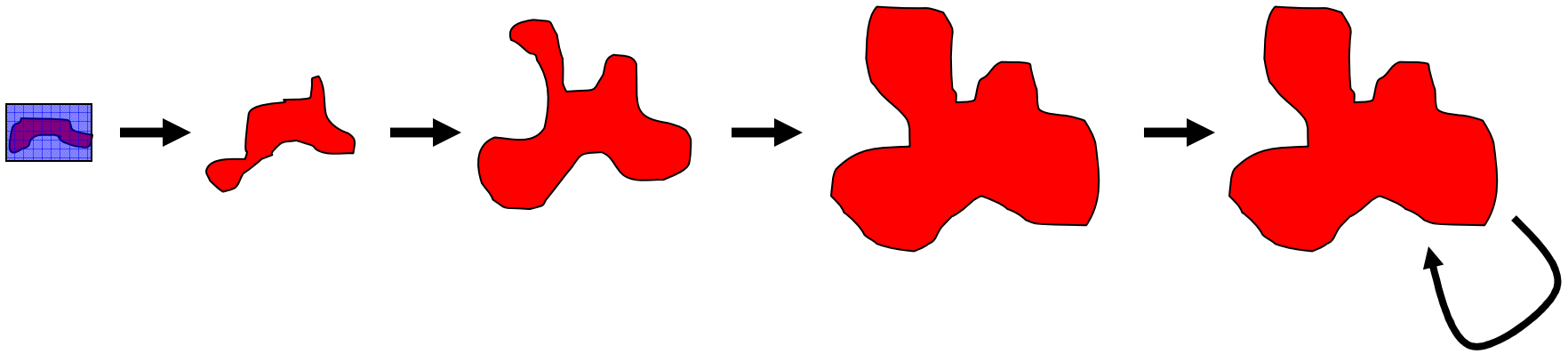
all of state space has been explored

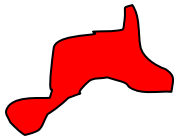
Sound Analyses

- A sound analysis never misses an error
  [of the relevant error category]
  - No *false negatives (missed errors)*
  - Requires exhaustive exploration of state space

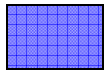
- Inductive argument for soundness
  - Start program with abstract state for all possible initial concrete states
  - At each step, ensure new abstract state covers all concrete states that could result from executing statement on any concrete state from previous abstract state
  - Once no new abstract states are reachable, by induction all concrete program executions have been considered

Soundness and Precision

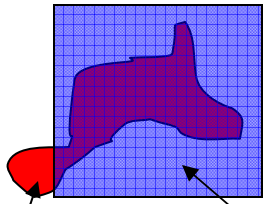




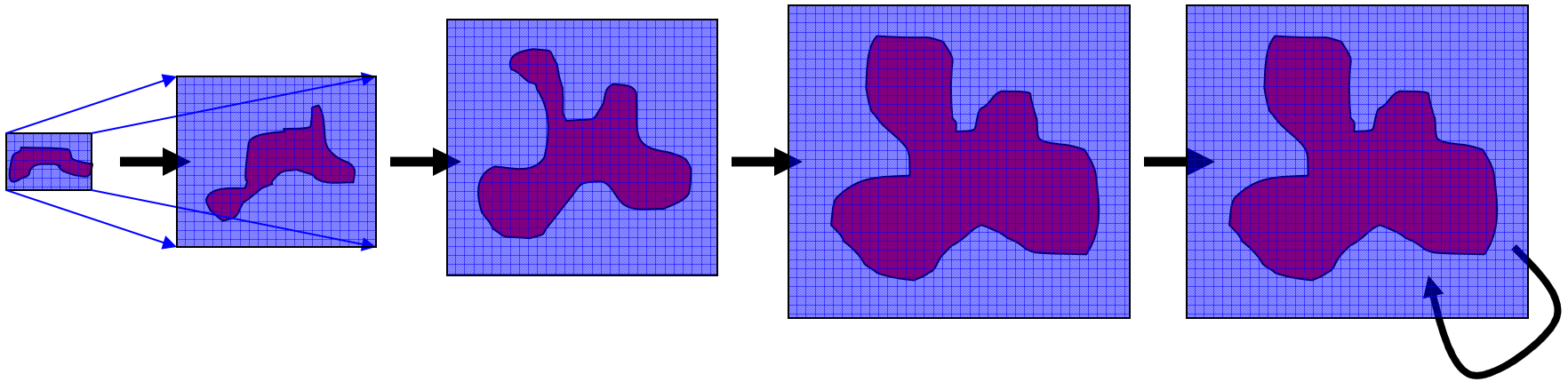
Program state covered in actual execution

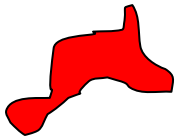


Program state covered by abstract execution with analysis

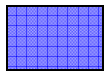


Soundness and Precision

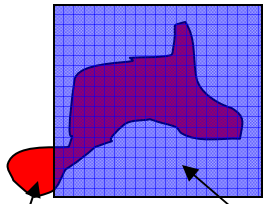




Program state covered in actual execution



Program state covered by abstract execution with analysis



Abstraction and Soundness

- Consider “Sound Testing”
  [testing that finds every bug]
  - Requires executing program on every input
    - (and on all interleavings of threads)
  - Infinite number of inputs for realistic programs
    - Therefore impossible in practice

- Abstraction
  - Infinite state space → finite set of states
  - Can achieve soundness by exhaustive exploration

Array Bounds Precision

```
1.  void foo(unsigned n) {
2.      char str = new char[n+1];
3.      int idx = n-1;
4.      idx = idx+1;
5.      str[idx] = 'c';
6.  }
```

What will be the result of static analysis?

Path 1 (before stmt):

2: ∅

3: n↦<

4: n↦<, idx↦<

5: n↦<, idx↦<,=

6: n↦<, idx↦<,=

error: array out of bounds at line 5

False positive! (not a real error)

What went wrong?

- At statement 4 we only know idx < length(str)
- We need to know idx < length(str)-1

Regaining Array Bounds Precision

- Keep track of exact value of index
  - Infinite states
    - or 2^{32}, close enough
- Add a <-1 state
  - Not general enough
- Track formula relating expressions to arrays
  - Undecidable for arbitrary formulas
- Track restricted formulas
  - Decent solution in practice
    - Presburger arithmetic

Analysis as an Approximation

- Analysis must approximate in practice
  - May report errors where there are really none
    - False positives
  - May not report errors that really exist
    - False negatives
  - All analysis tools have either false negatives or false positives
- Approximation strategy
  - Find a pattern P for correct code
    - which is feasible to check (analysis terminates quickly),
    - covers most correct code in practice (low false positives),
    - which implies no errors (no false negatives)
- Analysis can be pretty good in practice
  - Many tools have low false positive/negative rates
  - A sound tool has no false negatives
    - Never misses an error in a category that it checks

Attribute-Specific Analysis

- Analysis is specific to
  - A quality attribute
    - Race condition
    - Buffer overflow
    - Use after free
  - A strategy for verifying that attribute
    - Protect each shared piece of data with a lock
    - Presburger arithmetic decision procedure for array indexes
    - Only one variable points to each memory location
- Analysis is inappropriate for some attributes
  - Approach to assurance is ad-hoc and follows no clear pattern
  - No known decision procedure for checking an assurance pattern that is followed
  - ***Examples?***

Soundness Tradeoffs

- Sound Analysis
  - Assurance that no bugs are left
    - Of the target error class
  - Can focus other QA resources on other errors
  - May have more false positives
- Unsound Analysis
  - No assurance that bugs are gone
  - Must still apply other QA techniques
  - May have fewer false positives

Which to Choose?

- Cost/Benefit tradeoff
  - Benefit: How valuable is the bug?
    - How much does it cost if not found?
    - How expensive to find using testing/inspection?
  - Cost: How much did the analysis cost?
    - Effort spent running analysis, interpreting results – includes false positives
    - Effort spent finding remaining bugs (for unsound analysis)
- Rule of thumb
  - For critical bugs that testing/inspection can't find, a sound analysis is worth it
    - As long as false positive rate is acceptable
  - For other bugs, maximize engineer productivity

Outline

- Why static analysis?
- What is static analysis?
- How does static analysis work?
- What do practical tools look like?
  - FindBugs & Fortify: Simple Bug Finders
  - Microsoft's PreFAST: Design intent-driven analysis
- How does it fit into an organization?

Example Tool: FindBugs

- Origin: research project at U. Maryland
  - Now freely available as open source
  - Standalone tool, plugins for Eclipse, etc.
- Checks over 250 “bug patterns”
  - Over 100 correctness bugs
  - Many style issues as well
  - Includes the two examples just shown
- Focus on simple, local checks
  - Similar to the patterns we’ve seen
  - But checks bytecode, not AST
    - Harder to write, but more efficient and doesn’t require source
- http://findbugs.sourceforge.net/

Demonstration: FindBugs & Fortify

Example FindBugs Bug Patterns

- Correct equals()
- Use of ==
- Closing streams
- Illegal casts
- Null pointer dereference
- Infinite loops
- Encapsulation problems
- Inconsistent synchronization
- Inefficient String use
- Dead store to variable

FindBugs Experiences

- Useful for learning idioms of Java
  - Rules about libraries and interfaces
    - e.g. equals()
- Customization is important
  - Many warnings may be irrelevant, others may be important – depends on domain
    - e.g. embedded system vs. web application
- Useful for pointing out things to examine
  - Not all are real defects
  - Turn off false positive warnings for future analyses on codebase