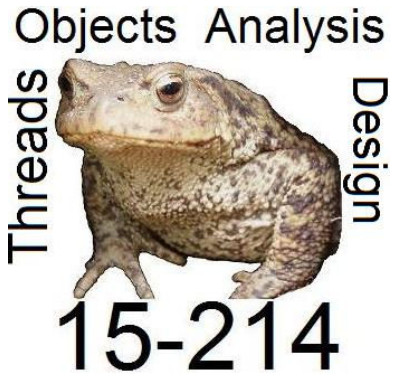
Static Analysis



Principles of Software System Construction

Jonathan Aldrich

Some slides from Ciera Jaspan

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

Limits of Inspection

- People
- …are very high cost
- …make mistakes
- …have a memory limit

So, let's automate inspection!

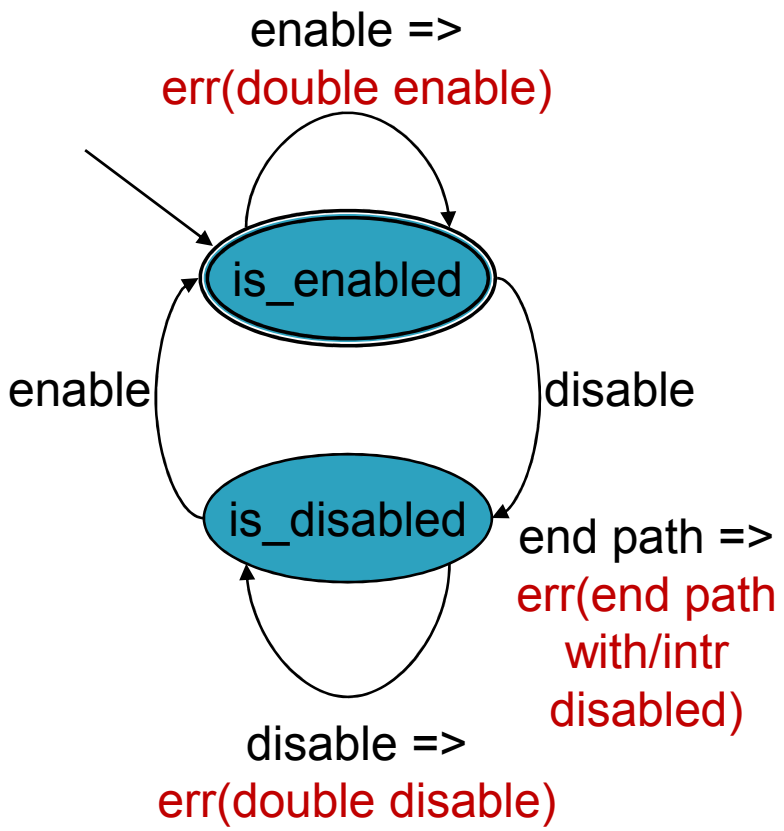
Metal Interrupt Analysis

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

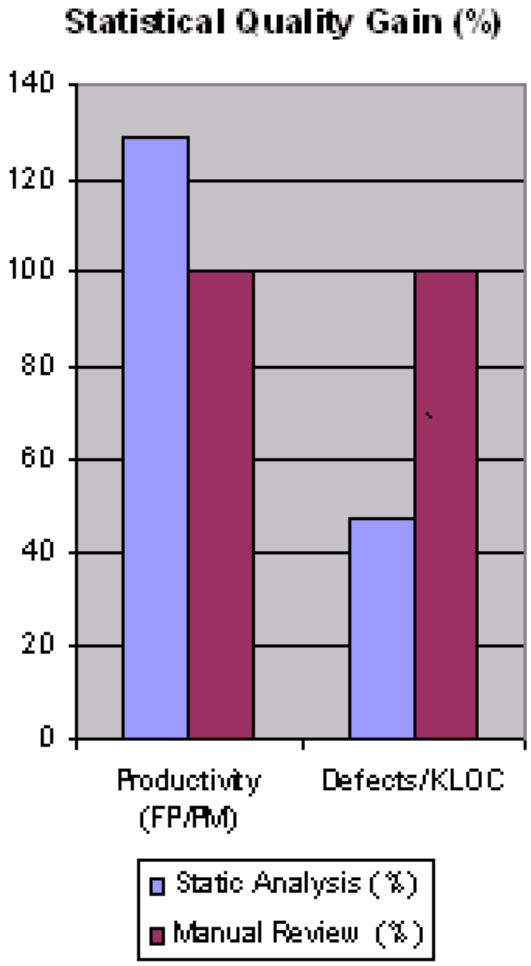
Source: Engler et al., *Checking System Rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '00.

```
/* 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
}
```

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]

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

Outline

- Why static analysis?
  - Automated
  - Can find some errors faster than people
  - Can provide guarantees that some errors are found
- How does it work?
- What are the hard problems?
- How do we use real tools in an organization?

Outline

- Why static analysis?
- How does it work?
  - Systematic exploration of program abstraction
  - Many kinds of analysis
    - AST walker
    - Control-flow and data-flow
    - Type systems
    - Model checking
  - Specifications frequently used for more information
- What are the hard problems?
- How do we use real tools in an organization?

Abstract Interpretation

- Static program analysis is the **systematic examination** of an **abstraction of a program's state space**
- Abstraction
  - Don't track everything! (That's normal interpretation)
  - Track an important abstraction
- Systematic
  - Ensure everything is checked in the same way
- Let's start small…

A Performance Analysis

What's the performance problem?

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

Seems minor…
but if this performance gain on 1000 servers means we need 1 less machine, we could be saving a a lot of money

A Performance Analysis

- Check that we don't create strings outside of a Logger.inDebug check
- Abstraction
  - Look for a call to Logger.debug()
  - Make sure it's surrounded by an if (Logger.inDebug())
- Systematic
  - Check all the code
- Known as an **Abstract Syntax Tree** (**AST) walker**
  - Treats the code as a structured tree
  - Ignores control flow, variable values, and the heap
  - Code style checkers work the same way
    - you should never be checking code style by hand
  - Simplest static analysis: grep

An interrupt checker

- Check for the interrupt problem
- Abstraction
  - 2 states: enabled and disabled
  - Program counter
- Systematic
  - Check all paths through a function
- Error when we hit the end of the function with interrupts disabled
- Known as a **control flow analysis**
  - More powerful than reading it as a raw text file
  - Considers the program state and paths

Adding branching

- When we get to a branch, what should we do?
  - 1: explore each path separately
    - Most exact information for each path
    - But—how many paths could there be?
    - Leads to an exponential state explosion
  - 2: join paths back together
    - Less exact
    - But no state explosion
- Not just conditionals!
  - Loops, switch, and exceptions too!

Example: Bad

```
1.   int foo() {
2.       unsigned long flags;
3.       int rv;
4.       save_flags(flags);
5.       cli();
6.       rv = dont_interrupt();
7.       if (rv > 0) {
8.           do_stuff();
9.           restore_flags();
10.      } else {
11.          handle_error_case();
12.      }
13.      return rv;
14.  }
```

Abstraction (before statement)

2-4: enabled
5: enabled
6: disabled
7: disabled
8: disabled
9: disabled
11: disabled
13: unknown

Error: did not reenable interrupts on some path

A null pointer checker

- Prevent accessing a null value
- Abstraction
  - Program counter
  - 3 states for each variable: null, not-null, and maybe-null
- Systematic
  - Explore all paths in the program (as opposed to all paths in the method)
- Known as a **data-flow** analysis
  - Tracking how data moves through the program
  - Very powerful, many analyses work this way
  - Compiler optimizations were the first

Example: Bad

```
1.    int foo() {
2.       Integer x = new Integer(6);
3.       Integer y = bar();
4.       int z;

5.       if (y != null)
6.          z = x.intVal() + y.intVal();
7.       else {
8.          z = x.intVal();
9.          y = x;
10.         x = null;
11.      }
12.      return z + x.intVal();
13.   }
```

Abstraction (before statement)

3: x → not-null

4: x → not-null, y → maybe-null

5: x → not-null, y → maybe-null

6: x → not-null, y → not-null

8: x → not-null, y → null

9: x → not-null, y → null

10: x → not-null, y → not-null

12: x → maybe-null, y → not-null

Error: may have null pointer on line 12

Example: Method calls

```
1.    int foo() {
2.       Integer x = bar();
3.       Integer y = baz();
4.       Integer z = noNullsAllowed(x, y);
5.       return z.intValue();
6.    }

7.    Integer noNullsAllowed(Integer x, Integer y) {
8.       int z;
9.       z = x.intValue() + y.intValue();
10.      return new Integer(z);
11.   }
```

Two options:
1. Global analysis
2. Modular analysis with specifications

Global Analysis

- Dive into every method call
  - Like branching, exponential without joins
  - Typically cubic (or worse) in program size even with joins
- Requires developer to determine which method has the fault
  - Who should check for null? The caller or the callee?

Modular Analysis w/ Specifications

- Analyze each module separately
- Piece them together with specifications
  - **Pre-condition** and **post-condition**
- When analyzing a method
  - Assume the method's precondition
  - Check that it generates the postcondition
- When the analysis hits a method call
  - Check that the precondition is satisfied
  - Assume the call results in the specified postcondition

Example: Method calls

```
1.   int foo() {
2.       Integer x = bar();
3.       Integer y = baz();
4.       Integer z = noNullsAllowed(x, y);
5.       return z.intValue();
6.   }

7.   @Nonnull Integer noNullsAllowed( @Nonnull Integer x, @Nonnull Integer y) {
8.       int z;
9.       z = x.intValue() + y.intValue();
10.      return new Integer(z);
11.  }

12.  @Nonnull Integer bar();

13.  @Nullable Integer baz();
```

Class invariants

- Is always true outside a class's methods
- Can be broken inside, but must always be put back together again

```
public class Buffer {
  boolean isOpen;
  int available;
  /*@ invariant isOpen <==> available > 0  @*/

  public void open() {
    isOpen = true;
    //invariant is broken
    available = loadBuffer();
  }
}
```

ESC/Java is a kind of static analysis tool

Other kinds of specifications

- Class invariants
  - What is always true when entering/leaving a class?
- Loop invariants
  - What is always true inside a loop?
- Lock invariant
  - What lock must you have to use this object?
- Protocols
  - What order can you call methods in?
    - Good: Open, Write, Read, Close
    - Bad: Open, Write, Close, Read

Typechecking

- Another static analysis!
- In Perl…
  - No typechecking at all!
- In ML, no annotations required
  - Global typechecking
- In Java, we annotate with types
  - Modular typechecking
  - Types are a specification!
- In C#, no annotations for local variables
  - Required for parameters and return values
  - Best of both

```
foo() {
   a = 5;
   b = 3;
   bar("A", "B");
   print(5 / 3);
}

bar(x, y) {
   print(x / y);
}
```

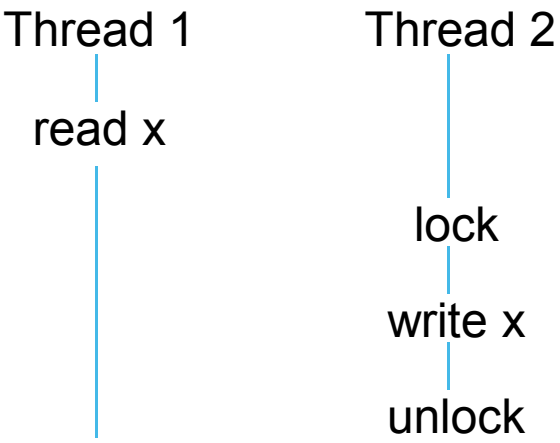
Static Analysis for Race Conditions

- ***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
- Known as *Model Checking*

Model Checking for Race Conditions

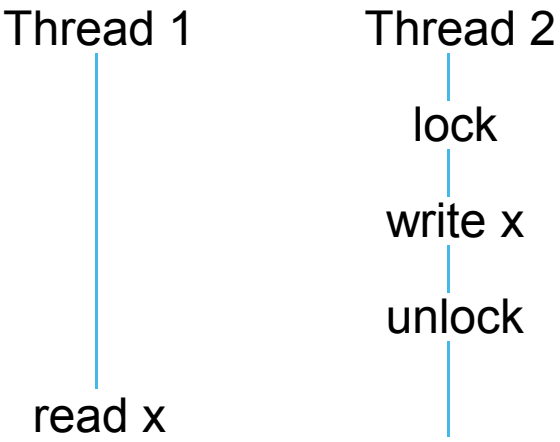
```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK

Model Checking for Race Conditions

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

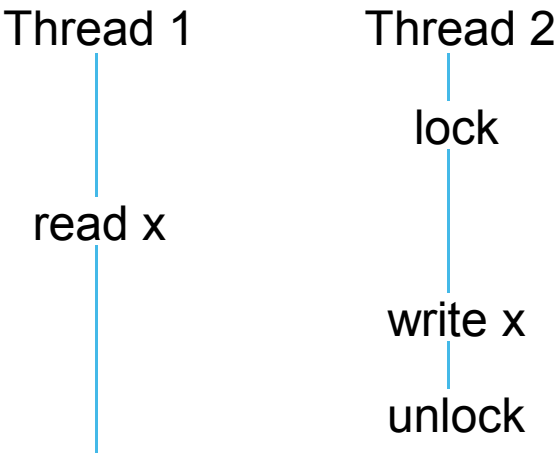


Interleaving 1: OK

Interleaving 2: OK

Model Checking for Race Conditions

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



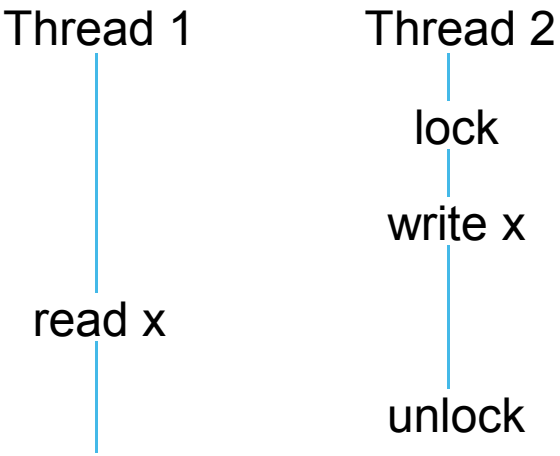
Interleaving 1: OK

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

Outline

- Why static analysis?
- How does it work?
- What are the important properties?
  - Side effects
  - Modularity
  - Aliases
  - Termination
  - Precision
- How do we use real tools in an organization?

Hard problems

- Side effects
  - Often difficult to specify precisely
    - In practice: ignore (unsafe) or approximate (loses accuracy)
- Modularity
  - Specifications
  - Not just performance issue
  - Don’t have to analyze all the code
  - Reduces interactions between people
- Aliasing and pointer arithmetic
- Termination
- Precision

Aliasing

- Two variables point to the same object
- A variable might change underneath you during a seemingly unrelated call
- Multi-threaded: change at any time!
- Makes analysis extremely hard

Aliasing solutions

- Can add more specifications
  - Unique, Immutable, Shared…
- Analysis can assume no aliases
  - Can miss issues from aliasing
- Analysis can assume the worst case
  - Can report issues that don't exist

Pointer arithmetic

- Very difficult to analyze
- Many tools will gladly report an issue, even if there is none
- May be a good idea to avoid
  - Rationale: It might be correct, but it's ugly and makes problems more difficult to find

Termination

- How many paths are in a program?
- Exponential # paths with if statements
- Infinite # paths with loops
- How could we possibly cover them all?

Termination Solution

- Use abstraction!
- Finite number of (abstract) states
- If you've already explored a state for a 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
  - Might analyze a loop several times, but will eventually reach a fixed point
- Worst case: lose precision, but terminate
- If the number of states isn't finite, too bad
  - Your analysis may not terminate

Example

```
1.  void foo(int x) {
2.    File f = null;
3.    if (x == 0)
4.      f = new File(bar());
5.    else
6.      f = new File(baz());
7.    while (x > 0) {
8.      do_work(f);
9.    }
10.   f.delete();
11. }
```

Path 1 (before stmt): else/no loop

3: f=null;

6: f=null;

10: f != null;

no errors

Example

```
1.  void foo(int x) {
2.    File f = null;
3.    if (x == 0)
4.      f = new File(bar());
5.    else
6.      f = new File(baz());
7.    while (x > 0) {
8.      do_work(f);
9.    }
10.   f.delete();
11. }
```

Path 2 (before stmt): else/1 loop

3: f = null
6: f = null
7: f != null
8: f != null
9: f != null
10: f != null

Example

```
1.  void foo(int x) {
2.    File f = null;
3.    if (x == 0)
4.      f = new File(bar());
5.    else
6.      f = new File(baz());
7.    while (x > 0) {
8.      do_work(f);
9.    }
10.   f.delete();
11. }
```

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

3: f = null

6: f = null

7: f != null

8: f != null

9: f != null

7: f != null

already been here

Example

```
1.  void foo(int x) {
2.    File f = null;
3.    if (x == 0)
4.      f = new File(bar());
5.    else
6.      f = new File(baz());
7.    while (x > 0) {
8.      do_work(f);
9.    }
10.   f.delete();
11. }
```

Path 4 (before stmt): then

3: f = null

4: f = null

7: f != null

already been here

all of state space has been explored

Precision

- Abstraction is an approximation
- And it can be wrong
- No tool reports all and only real issues

	Error exists	Error does not exist
Analysis reports error	**True Positive**	**False Positive** (annoying)
Analysis doesn't report error	**False Negative** (false confidence)	True Negative

Soundness and Completeness

- **Sound** tools have no false negatives
  - Can have false positives
  - Ideally, they are from “ugly” code anyway
  - Provides assurance that no defects (of that type) are left
- **Complete** tools have no false positives
  - All issues are “real” issues
  - Not many of these in practice
  - No confidence, but maybe good for smoke tests?
- Many tools try for low numbers of both

Methods to increase precision

- Ignore highly unusual cases
- Make abstraction less abstract
- Add specifications
- Make code more analyzable
  - Remove aliases
  - Remove pointer arithmetic
  - Clean up control flow

Tradeoffs

- You can't have it all
  1. No false positives
  2. No false negatives
  3. Perform well
  4. No specifications
  5. Modular
- You can't even get 4 of the 5
  - Halting problem means first 3 are incompatible
  - Modular analysis requires specifications
- Each tool makes different tradeoffs

Outline

- Why static analysis?
- How does it work?
- What are the important properties?
- How do we use real tools in an organization?
  - FindBugs @ eBay
  - SAL @ Microsoft (source: Manuvir Das)

"False" Positives

```
1.    int foo(Person person) {
2.      if (person != null) {
3.        person.foo();
4.      }
5.      return person.bar();
6.    }
```

Error on line 5:
Redundant comparison to null

- Is this a false positive?
- What if that branch is never run in practice?
- Do you fix it? And how?

“False” Positives

```
1.    public class Constants {
2.        static int myConstant = 1000;
3.    }
```

Error on line 3: field isn’t final but should be

- Is this a false positive?
- What if it’s in an open-source library you imported?
- What if there are 1000 of these?

True Positives

- Defn 1: Any issue that the developer does not intend to fix
- Defn 2: Any issue that the developer wants to see (regardless of whether it is fixed)
- Varies between projects and people
- Soundness and completeness are relative to the technical abstractions
- We hope the abstraction is what people want

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/

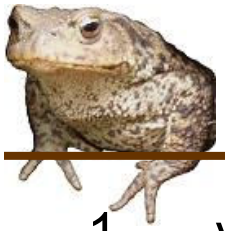
Example FindBugs Bug Patterns

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

Demonstration: FindBugs

FindBugs at eBay

- eBay wants to use static analysis
- Need off the shelf tools
- Focus on security and performance
- Had bad past experiences
  - Too many false positives
  - Tools used too late in process
- Help them choose a tool and add it to the process



How important is this issue?

```
1.    void foo(int x, int y)
2.        int z;
3.        z = x + y;
4.    }
```

Line 3: Dead store to local

How about this one?

```
void foo(int x, int y)
  List dataValues;
  dataValues = getDataFromDatabase(x, y);
}
```

Significant overhead, and not caught any other way!

Tool Customization

- Turn on all defect detectors
- Run on a single team's code
- Sort results by detector
- Assign each detector a priority
- Repeat until consensus (3 teams)

Priority = Enforcement

- Priority must mean something
  - (otherwise it's all "high priority")
- High Priority
  - High severity functional issues
  - Medium severity, but easy to fix
- Medium Priority
  - Medium severity functional issues
  - Indicators to refactor
  - Performance issues
- Low Priority
  - Only some domain teams care about them
  - Stylistic issues
- Toss
  - Not cost effective and lots of noise

Cost/Benefit Analysis

- Costs
  - Tool license
  - Engineers internally supporting tool
  - Peer reviews of defect reports
- Benefits
  - How many defects will it find?
  - What priority?
- Compare to cost equivalent of testing by QA Engineers
  - eBay's primary quality assurance mechanism
  - Back of the envelope calculation
  - FindBugs discovers significantly more defects
    - Order of magnitude difference
    - Not as high priority defects

Quality Assurance at Microsoft

- 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

PREFast at Microsoft

- Concerned with memory usage
- Major cause of security issues
- Manpower to developer custom tool

Standard Annotation Language (SAL)

- A language for specifying contracts between functions
  - Intended to be lightweight and practical
  - Preconditions and Postconditions
  - More powerful—but less practical—contracts supported in systems like JML or Spec#
- Initial focus: memory usage
  - buffer sizes
  - null pointers
  - memory allocation

SAL is checked using PREfast

- Lightweight analysis tool
  - Only finds bugs within a single procedure
  - Also checks SAL annotations for consistency with code
- To use it (for free!)
  - Download and install Microsoft Visual C++ 2005 Express Edition
    - http://msdn.microsoft.com/vstudio/express/visualc/
  - Download and install Microsoft Windows SDK for Vista
    - http://www.microsoft.com/downloads/details.aspx?familyid=c2b1e300-f358-4523-b479-f53d234cdccf
  - Use the SDK compiler in Visual C++
    - In Tools | Options | Projects and Solutions | VC++ Directories add C:\Program Files\Microsoft SDKs\Windows\v6.0\VC\Bin (or similar)
    - In project Properties | Configuration Properties | C/C++ | Command Line add /analyze as an additional option

Buffer/Pointer Annotations

_in	The function reads from the buffer. The caller provides the buffer and initializes it.
_inout	The function both reads from and writes to buffer. The caller provides the buffer and initializes it.
_out	The function writes to the buffer. If used on the return value, the function provides the buffer and initializes it. Otherwise, the caller provides the buffer and the function initializes it.
_bcount(size)	The buffer size is in bytes.
_ecount(size)	The buffer size is in elements.
_opt	This parameter can be NULL.

PREfast: Immediate Checks

- Library function usage
  - deprecated functions
    - e.g. gets() vulnerable to buffer overruns
  - correct use of printf
    - e.g. does the format string match the parameter types?
  - result types
    - e.g. using macros to test HRESULTs
- Coding errors
  - = instead of == inside an if statement
- Local memory errors
  - Assuming malloc returns non-zero
  - Array out of bounds

SAL: the Benefit of Annotations

- Annotations express **design intent**
  - How you intended to achieve a particular quality attribute
    - e.g. never writing more than N elements to this array
- As you add more annotations, you find more errors
  - Get checking of library users for free
  - Plus, those errors are less likely to be false positives
    - The analysis doesn't have to guess your intention
  - Instant Gratification Principle
- Annotations also improve **scalability** through modularity
  - PreFAST uses very sophisticated analysis techniques
  - These techniques can't be run on large programs
  - Annotations isolate functions so they can be analyzed one at a time

SAL: the Benefit of Annotations

- How to motivate developers?
  - Especially for millions of lines of unannotated code?
- Require annotations at checkin
  - Reject code that has a char* with no __ecount()
- Make annotations natural
  - Ideally what you would put in a comment anyway
    - But now machine checkable
    - Avoid formality with poor match to engineering practices
- Incrementality
  - Check code ↔ design consistency on every compile
  - Rewards programmers for each increment of effort
    - Provide benefit for annotating partial code
    - Can focus on most important parts of the code first
    - Avoid excuse: I'll do it after the deadline
- Build tools to infer annotations
  - Inference is approximate
  - Unfortunately not yet available outside Microsoft

Impact at Microsoft

- Thousands of bugs caught monthly
- Significant observed quality improvements
  - e.g. buffer overruns latent in codebaes
- Widespread developer acceptance
  - Tiered Check-in gates
  - Writing specifications

Static Analysis in Engineering Practice

- A tool with different tradeoffs
  - Soundness: can find all errors in a given class
  - Focus: mechanically following design rules
- Major impact at Microsoft and eBay
  - Tuned to address company-specific problems
  - Affects every part of the engineering process