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CSE 331

# Software Design & Implementation

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Debugging

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# A Bug's Life

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*defect* – mistake committed by a human

*error* – incorrect computation

*failure* – visible error: program violates its specification

Debugging starts when a failure is observed

- Unit testing

- Integration testing

- In the field

Goal of debugging is to go *from failure back to defect*

# Bug Removal

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## Tools, Inspection, & Testing

- increase confidence that the code is correct
- uncover problems by running the code

## Defensive programming

- lay traps as you code to catch bugs when run

## Debugging

- find out why a program is not functioning as intended

## Testing ≠ debugging

- *test*: reveals existence of problem
- *debug*: pinpoint location & cause of problem
- debugging is often painful, testing is not

# Defence in depth

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Levels of defence:

1. Make errors *impossible*
  - examples: Java prevents type errors, memory corruption  
Python prevents key mutation
2. Don't introduce defects
  - “get things right the first time” (by reasoning & unit testing)
3. Make errors *immediately visible* (often by defensive programming)
  - examples: assertions, **checkRep**
  - reduce *distance* from error to failure

(subtle bugs like key mutations are hard to find  
because of the distance between error and failure)

# First defense: Impossible by design

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## In the language

- Java prevents type mismatches, memory overwrite bugs; guaranteed sizes of numeric types, ...

## In the protocols/libraries/modules

- TCP/IP guarantees data is not reordered
- **BigInteger** guarantees there is no overflow

## In self-imposed conventions

- immutable data structure guarantees behavioral equality
- **finally** block can prevent a resource leak

Caution: You must maintain discipline

# Second defense: Correctness

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## Get things right the first time

- think before you code (don't code before you think!)
- if you're making **lots** of easy-to-find defects, you're probably **also** making hard-to-find defects

## Especially important when debugging is going to be hard

- concurrency, real-time environment, no access to customer environment, etc.
- (formalism gets more important as the problems get harder)

The key techniques are everything we have been learning:

- forward & backward reasoning
- clear and complete specs
- these techniques lead to *simpler software*

# Strive for simplicity

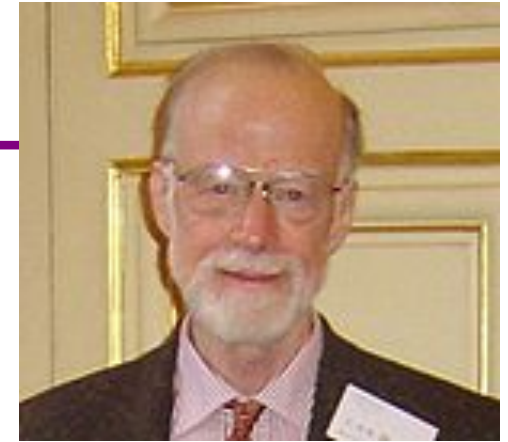
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“There are two ways of constructing a software design:

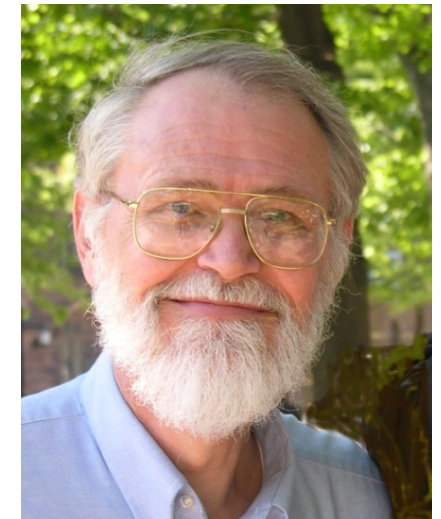
One way is to make it **so simple** that there are obviously no deficiencies, and the other way is to make it **so complicated** that there are no obvious deficiencies.

The first method is far more difficult.”

“Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, **not smart enough to debug it.**”



Sir Anthony Hoare



Brian Kernighan

# Second defence: Correctness

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Find errors by testing before you check in the code:

**Unit testing:** when you test a module in isolation, any failure is due to a defect in that unit (or the test driver)

**Regression testing:** run tests as often as possible when changing code. If there is a failure, chances are there's a mistake in the code you just changed (or the new code is triggering a bug that hadn't been observed before)

Test early and often. More tests is almost never a bad thing.



# Third defence: Immediate visibility

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If we can't prevent errors, we can try to spot them early

**Assertions** (e.g., `checkRep`): check at runtime that the program is in the state that we are expecting.

Assertions make more sense for server code

- Google policy (8+ years ago) on servers:
  - assertions always enabled
  - if any failure is detected, **crash** the program
- Microsoft policy (20+ years ago) on clients:
  - try to recover from failures. hide them from the user

# Benefits of immediate visibility

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Failure is likely to be closer to the defect

- failure can occur far from the mistake that caused it
- immediate visibility reduces the search time to find the defect

Defect is less likely to have infected other parts of the program

- the longer we wait, the more code we'll likely have to change

Don't program in ways that hide errors

- this lengthens distance between defect and failure
- (only exception is when running on the client's computer)

# Don't hide errors

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```
// requires: x must be present in A
int i = 0;
while (true) {
    if (A[i] == x) break;
    i++;
}
```

This code fragment searches an array **A** for a value **x**

- value is guaranteed to be in the array
- what if that guarantee is broken (by a defect)?

# Don't hide errors

---

```
// requires: x must be present in a
int i = 0;
while (i < A.length) {
    if (A[i] == x) break;
    i++;
}
```

Fixes the bug so the loop always exits

- but no longer guaranteed that  $A[i] == x$
- if other code relies on this, then problems arise later
  - this just hides the bug!

# Don't hide errors

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```
// requires: x must be present in a
int i = 0;
while (i < A.length) {
    if (A[i] == x) break;
    i++;
}
assert i != A.length : "key not found";
```

- Assertions let us document and check invariants at run time
- Abort/debug program as soon as problem is detected
  - turn an **error** into a **failure**
- Unfortunately, we may still be a long distance from the *defect*
  - the defect is what caused **x** not to be in the array

# Last resort: debugging

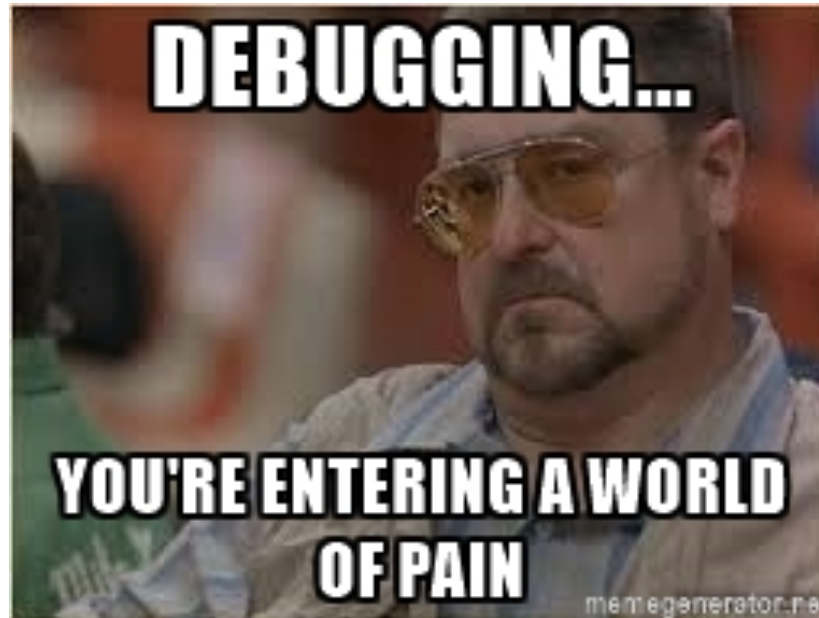
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Defects happen

- people are imperfect
- industry average (?): 10 defects per 1000 lines of code

Defects are often not immediately clear from the failure

That means...



# Basic Debugging

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Work through the following steps:

step 1 – Clarify symptom (simplify input), create “minimal” test

step 2 – Localize and understand cause

step 3 – Fix the defect

step 4 – Rerun *all* tests, old and new

# The debugging process

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**step 1:** *find (small) repeatable test case that produces the failure*

- smaller test case will make step 2 easier
- do *not* start step 2 until you have a repeatable test

**step 2:** *narrow down location and cause*

- *loop:* (a) study the data (b) hypothesize (c) experiment
- experiments often involve changing the code
- do *not* start step 3 until you understand the cause

**step 3:** *fix the defect*

- is it a simple typo or a design flaw?
- does it occur **elsewhere** in the code?

**step 4:** *run all the tests (including the new one)*

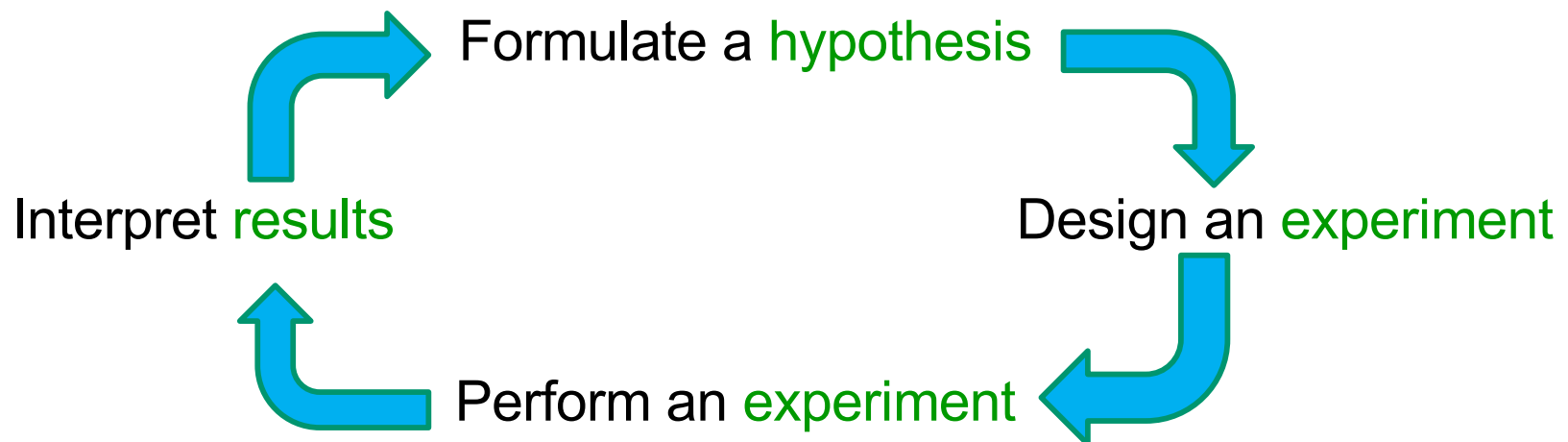
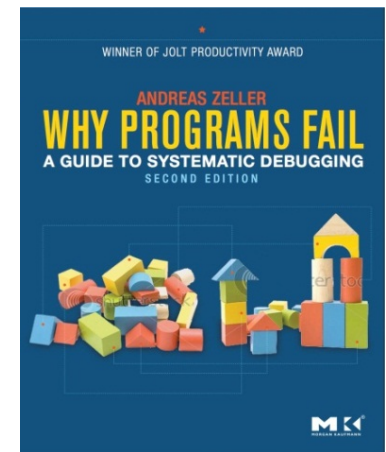
- is this failure fixed? are any other new failures introduced?



# Debugging and the scientific method

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- Debugging should be *systematic*
  - carefully *decide* what to do
    - don't flail about randomly!
  - may help to keep a *record* of what you tried
  - don't get sucked into fruitless avenues
- Use an iterative scientific process:



# Example

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```
// returns true iff sub is a substring of full
// (i.e. iff there exists A,B such that full=A+sub+B)
boolean contains(String full, String sub);
```

*User bug report:*

It can't find the string "very happy" within:

```
"Fáilte, you are very welcome! Hi Seán! I am
very very happy to see you all."
```

Poor responses:

- See accented characters, panic about not knowing about Unicode, begin unorganized web searches and inserting poorly understood library calls, ...
- Start tracing the execution of this example

Better response: simplify/clarify the symptom...

# Reducing input size

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Find a simple test case by divide-and-conquer

Pare test down:

*Can not* find "very happy" within

"Fáilte, you are very welcome! Hi Seán! I am very very happy to see you all."

"I am very very happy to see you all."

"very very happy"

*Can* find "very happy" within

"very happy"

*Can not* find "ab" within "aab"

# General strategy: simplify

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Find simplest input that will provoke failure

- usually not the input that revealed existence of the defect

Start with data that revealed the defect

- keep paring it down (binary search can help!)
- sometimes leads directly to an understanding of the cause

When not dealing with just one method call:

- “test input” is the set of steps that reliably trigger the failure
- same basic idea

# Localizing a defect

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Sometimes you can take advantage of modularity

- start with everything, take away pieces until failure goes away
- start with nothing, add pieces back in until failure appears

*Binary search* speeds up this process too

- error happens somewhere between first and last statement
- do binary search on that ordered set of statements
  - is the state correct after the middle statement?

# Binary search on buggy code

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```
public class MotionDetector {  
    private boolean first = true;  
    private Matrix prev = new Matrix();  
  
    public Point apply(Matrix current) {  
        if (first) {  
            prev = current;  
        }  
        Matrix motion = new Matrix();  
        getDifference(prev, current, motion);  
        applyThreshold(motion, motion, 10);  
        labelImage(motion, motion);  
        Hist hist = getHistogram(motion);  
        int top = hist.getMostFrequent();  
        applyThreshold(motion, motion, top, top);  
        Point result = getCentroid(motion);  
        prev.copy(current);  
        return result;  
    }  
}
```

no problem yet

*Check  
intermediate  
result  
at half-way point*

problem exists

# Binary search on buggy code

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```
public class MotionDetector {
    private boolean first = true;
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    public Point apply(Matrix current) {
        if (first) {
            prev = current;
        }
        Matrix motion = new Matrix();
        getDifference(prev, current, motion);
        applyThreshold(motion, motion, 10);
        labelImage(motion, motion);
        Hist hist = getHistogram(motion);
        int top = hist.getMostFrequent();
        applyThreshold(motion, motion, top, top);
        Point result = getCentroid(motion);
        prev.copy(current);
        return result;
    }
}
```

no problem yet

*Check  
intermediate  
result  
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problem exists

# Detecting Bugs in the Real World

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## Real systems

- large and complex
- collection of modules, written by multiple people
- complex input
- many external interactions
- non-deterministic

## Replication can be an issue

- infrequent failure (the worst)
- instrumentation eliminates the failure (the worst of the worst)

## Defects cross abstraction barriers

Large time lag from corruption (defect) to detection (failure)



# Debugging In Harsh Environments

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Failure is non-deterministic,  
difficult to reproduce

Can't print or use debugger

Can't change timing of  
program (or defect/failure  
depends on timing)

Such bugs are more  
common when users are  
your testers!



# Heisenbugs

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In a sequential, deterministic program, failure is repeatable

But the real world is not that nice...

- continuous input/environment changes
- concurrency and parallelism
- failure occurs randomly
  - literally depends on results of random-number generation

Common for debugging because...

- these are most likely bugs to **sneak past** reasoning & testing

Bugs hard to reproduce when:

- use of debugger or assertions makes failure goes away
  - due to timing or assertions having side-effects
- only happens when under heavy load
- only happens once in a while

# Logging Events

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Log (record) events during execution as program runs (at full speed)

Examine logs to help reconstruct the past

- particularly on failing runs
- and/or compare failing and non-failing runs

The log may be all you know about a customer's environment

- (some amount of logging is fairly standard)
- needs to tell you enough to reproduce the failure

# More Tricks for Hard Bugs

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Rebuild system from scratch

- bug could be in your build system or persistent data structures

Explain the problem to a friend (or to a rubber duck)

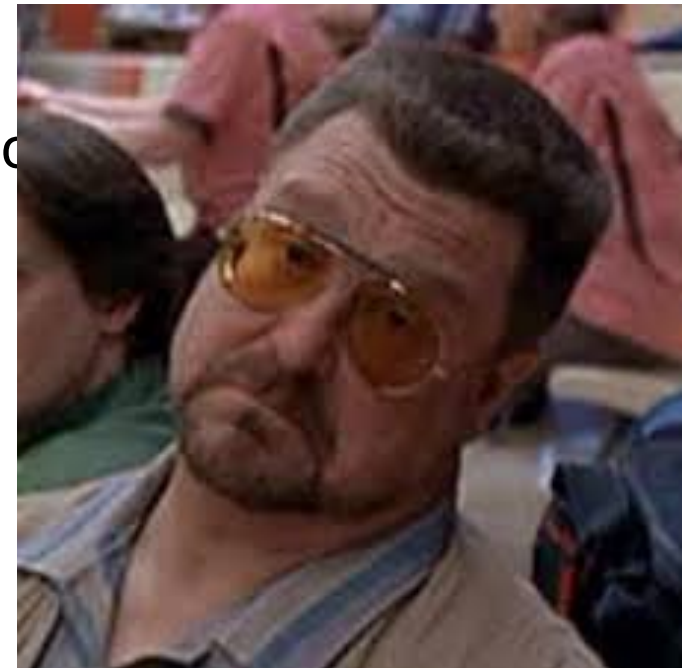
- The Pragmatic Programmer calls this “rubber ducking”

Make sure that you have correct source code

- check out fresh copy from repository; recompile

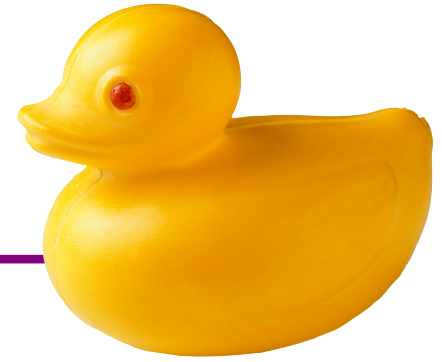
Make sure it is a bug

- program may be working correctly!



# More Tricks for Hard Bugs

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## Rebuild system from scratch

- bug could be in your build system or persistent data structures

## Explain the problem to a friend (or to a rubber duck)

- The Pragmatic Programmer calls this “rubber ducking”

## Make sure that you have correct source code

- check out fresh copy from repository; recompile everything

## Make sure it is a bug

- program may be working correctly!

## And things we already know:

- minimize input required to exercise bug (exhibit failure)
- add more checks to the program
- add more logging

# Where is the defect?

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The defect is **not** where you think it is (or else you'd have found it)

- ask yourself where it can not be; explain why

Look for simple easy-to-overlook mistakes first, e.g.,

- reversed order of arguments:  
`Collections.copy(src, dest);`
- spelling of identifiers: `int hashCode()`  
`@Override` can help catch method name typos
- same object vs. equal: `a == b` versus `a.equals(b)`
- deep vs. shallow copy

# When the going gets tough

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## Reconsider assumptions

- e.g., has the OS changed? Is there room on the hard drive? Is it a leap year? 2 full moons in the month?
- debug the code, *not* the comments
  - ensure that comments and specs describe the code

## Start documenting your system

- gives a fresh angle, and highlights area of confusion

## Get help

- we all develop blind spots
- explaining the problem often helps (even to rubber duck)

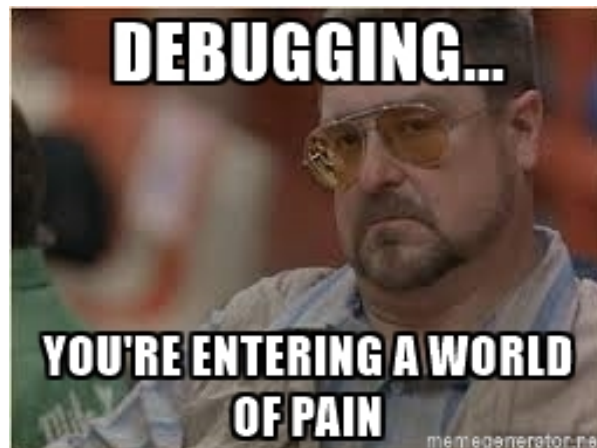
## Walk away

- sleep! often you can't see the problem because you're too tired
- one good reason to start early

# Summary

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- Debugging occurs when tools & inspection fail to catch a bug
- Debugging is the **search** from a **failure** back to the **defect**
  - defect = the actual bug, somewhere in the code
  - failure = bad effects from the bug becoming visible to users (crash, error message, incorrect result, etc.)
- Debugging can be *hours* (or even *days!*) of *frustrating* work
  - bugs that get past tools & inspection are usually the **most subtle**





# Advice

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Use assertions (& checkRep) to make failures **visible** ASAP

- reduces the work in debugging
- shortens the search from failure to defect

Debugging should be a systematic process

- use the *scientific method*

Understand the source of defects

- find similar ones and prevent them in the future