CSE 331
Software Design & Implementation

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Debugging
(Slides by Mike Ernst and David Notkin)
Ways to get your code right

Verification/quality assurance

Purpose is to uncover problems and increase confidence
Combination of reasoning and test

Debugging

Find out why a program is not functioning as intended

Defensive programming

Programming with validation and debugging in mind

Testing ≠ debugging

*test*: reveals existence of problem; test suite can also increase overall confidence
*debug*: pinpoint location + cause of problem
Relay #70 Panel F
(moth) in relay.

First actual case of 'bug' being found.

1700
Closed down.
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
Defense in depth (1)

Make errors impossible
  Java prevents type errors, memory overwrites
Don’t introduce defects
  Correctness: get things right the first time
Make errors immediately visible
  Local visibility of errors: best to fail immediately
Examples: assertions; checkRep() routine to check representation invariants
Defense in depth (2)

Last resort is debugging

Needed when failure (effect) is distant from cause (defect)

Scientific method: Design experiments to gain information about the defect

• Fairly easy in a program with good modularity, representation hiding, specs, unit tests etc.
• Much harder and more painstaking with a poor design, e.g., with rampant representation exposure
First defense: Impossible by design

In the language

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

In the protocols/libraries/modules

TCP/IP guarantees that data is not reordered

BigInteger guarantees that there is no overflow

In self-imposed conventions

Ban recursion to prevent infinite recursion/ insufficient stack – although it may just push the problem elsewhere

Immutable data structure guarantees behavioral equality

Caution: You must maintain the discipline
Second defense: Correctness

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 also making hard-to-find defects – don't use the compiler as crutch

Especially true, when debugging is going to be hard
Concurrency, real-time environment, no access to customer environment, etc.

Simplicity is key

Modularity
Divide program into chunks that are easy to understand
Use abstract data types/modules with well-defined interfaces
Use defensive programming; avoid rep exposure

Specification
Write specs for all modules, so that an explicit, well-defined contract exists between each module and its clients
Strive for simplicity

“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
Third defense: Immediate visibility

If we can't prevent errors, we can try to localize them to a small part of the program

**Assertions**: catch errors early, before they contaminate and are perhaps masked by further computation

**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

If you can localize problems to a single method or small module, defects can usually be found simply by studying the program text
Benefits of immediate visibility

The key difficulty of debugging is to find the defect: the code fragment responsible for an observed problem

A method may return an erroneous result, but be itself error-free if there is prior corruption of representation

The earlier a problem is observed, the easier it is to fix

This is why it helps to check the rep invariant frequently

General approach: fail-fast

Check invariants, don't just assume them
Don't (usually) try to recover from errors – it may just mask them
Don't hide errors

// k is guaranteed to be present in a
int i = 0;
while (true) {
    if (a[i]==k) break;
    i++;
}

This code fragment searches an array a for a value k
Value is guaranteed to be in the array
What if that guarantee is broken (by a defect)?
Temptation: make code more “robust” by not failing
Don't hide errors

```java
// k is guaranteed to be present in a
int i = 0;
while (i < a.length) {
    if (a[i] == k) break;
    i++;
}
```

Now at least the loop will always terminate
But it is no longer guaranteed that a[i] == k
If other code relies on this, then problems arise later

*Hiding the error makes it harder to see the link between the defect and the failure*
Don't hide errors

// k is guaranteed to be present in a
int i = 0;
while (i < a.length) {
    if (a[i] == k) break;
    i++;
}
assert (i != a.length) : "key not found";

Assertions let us document and check invariants
Abort/debug program as soon as problem is detected
    Turn an error into a failure
But the assertion is not checked until we use the data, which might be a long time after the original error
    “why isn’t the key in the array?”
Checks In Production Code

Should you include assertions and checks in production code?

Yes: stop program if check fails - don’t want to take chance program will do something wrong

No: may need program to keep going, maybe defect does not have such bad consequences (the failure is acceptable)

Correct answer depends on context!

Ariane 5 – overflow in unused value, exception thrown but not handled until top level, rocket crashes…

[full story is more complicated]
Regression testing

Whenever you find and fix a defect
  Add a test for it
  Re-run all your tests
Why is this a good idea?
  Often reintroduce old defects while fixing new ones
  Helps to populate test suite with good tests
  If a defect happened once, it could well happen again
Run regression tests as frequently as you can afford to
  Automate the process
  Make concise test suites, with few superfluous tests
Last resort: debugging

Defects happen – people are imperfect
   Industry average: 10 defects per 1000 lines of code (“kloc”)
Defects happen that are not immediately localizable
   Found during integration testing
   Or reported by user
The cost of an error increases by an order of magnitude for each lifecycle phase it passes through

step 1 – Clarify symptom (simplify input), create test
step 2 – Find and understand cause, create better test
step 3 – Fix
step 4 – Rerun all tests
The debugging process

step 1 – find a small, repeatable test case that produces the failure (may take effort, but helps clarify the defect, and also gives you something for regression)
  Don't move on to next step until you have a repeatable test

step 2 – narrow down location and proximate cause
  Study the data / hypothesize / experiment / repeat
  May change the code to get more information
  Don't move on to next step until you understand the cause

step 3 – fix the defect
  Is it a simple typo, or design flaw?
  Does it occur elsewhere?

step 4 – add test case to regression suite
  Is this failure fixed? Are any other new failures introduced?
Debugging and the scientific method

Debugging should be **systematic**
- Carefully decide what to do
- Don’t flail!
- Keep a record of everything that you do
- Don’t get sucked into fruitless avenues

Formulate a **hypothesis**
Design an **experiment**
Perform the experiment
Adjust your hypothesis and continue
Reducing input size example

// returns true iff sub is a substring of full
// (i.e. iff there exists A,B s.t.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, grab your Java texts to see how that is handled
Or google “unicode”, “funny characters”, etc.
Try to trace the execution of this example

Better response: simplify/clarify the symptom
Reducing *absolute* input size

Find a simple test case by divide-and-conquer
Pare test down – *can't* 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't* find "ab" within "aab"
Reducing relative input size

Can you find two almost identical test cases where one gives the correct answer and the other does not?

Can't find "very happy" within

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

Can find "very happy" within

"I am very happy to see you all."

General strategy: simplify

In general: 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)
  Often leads directly to an understanding of the cause
When not dealing with simple method calls:
  The “test input” is the set of steps that reliably trigger the failure
  Same basic idea
Localizing a defect

Take advantage of modularity
  Start with everything, take away pieces until failure goes away
  Start with nothing, add pieces back in until failure appears

Take advantage of modular reasoning
  Trace through program, viewing intermediate results

Binary search speeds up the process
  Error happens somewhere between first and last statement
  Do binary search on that ordered set of statements
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;
    }
}
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;
    }
}
Detecting Bugs in the Real World

Real Systems

- Large and complex (duh!)
- Collection of modules, written by multiple people
- Complex input
- Many external interactions
- Non-deterministic

Replication can be an issue

- Infrequent failure
- Instrumentation eliminates the failure

Defects cross abstraction barriers

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

Sequential, deterministic program – failure is repeatable
But the real world is not that nice…
  Continuous input/environment changes
  Timing dependencies
  Concurrency and parallelism
Failure occurs randomly
Hard to reproduce
  Use of debugger or assertions → failure goes away
Only happens when under heavy load
Only happens once in a while
Debugging In Harsh Environments

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)
Logging Events

Log (record) events during execution as program runs at (full) speed
When error is detected, stop program and examine logs to help reconstruct the past
The log may be all you know about a customer’s environment
   Needs to tell you enough to reproduce the failure
Performance / advanced issues:
   To reduce overhead, store in main memory, not on disk (performance vs stable storage)
   Circular logs avoid resource exhaustion and may be good enough
Tricks for Hard Bugs

Rebuild system from scratch, or restart/reboot
   Find the bug in your build system or persistent data structures

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

Make sure it is a bug
   Program may be working correctly and you don’t realize it!

Minimize input required to exercise bug (exhibit failure)

Add checks to the program
   Minimize distance between error and detection/failure
   Use binary search to narrow down possible locations

Use logs to record events in history
Where is the defect?

The defect is not where you think it is
   Ask yourself where it cannot be; explain why

Look for stupid 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)
   Failure to reinitialize a variable
   Deep vs. shallow copy

Make sure that you have correct source code!
   Check out fresh copy from repository
   Recompile everything
When the going gets tough

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
   Trade latency for efficiency – sleep!
   One good reason to start early
Key Concepts

Testing and debugging are different

**Testing** reveals existence of failures

**Debugging** pinpoints location of defects

Goal is to get program right

Debugging should be a systematic process

Use the scientific method

Understand the source of defects

To find similar ones and prevent them in the future