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
  Finding 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
Grace Hopper’s log book, Sep 9, 1947

Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.

1545
Relay #70 Panel F
(moth) in relay.

1100
Started Cosine Tape (Sine check)

1525
Started Multi Adder Test.

0700
Tested new card reader

1545
Relay #70 Panel F
(moth) in relay.

1300
Closed down.

Grace Hopper
A Bug’s Life

defect – mistake committed by a human as seen as a problem in the code

failure – visible error: program violates its specification

root cause – core issue that led to the defect

[One set of definitions – there are others]

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() 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 makes memory overwrite errors impossible
  Java/etc. won’t allow method argument type mismatch

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
"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."

― Sir Anthony Hoare

"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."

― 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.

Frequently checking the rep invariant helps.

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 (a[i] != k) {
    //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

```java
// 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 – program halted because of 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 that are not immediately localizable happen
   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

Sometimes it is helpful to 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 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;
    }
}
binary search on buggy code

```java
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 speed
When error 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 (trade 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
  Verify 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