CSE 331
Software Design & Implementation

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Debugging
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)
Ways to remove bugs

Inspection (reasoning)
- increase confidence that the code is correct

Testing
- uncover problems by running the code

Defensive programming
- lay traps to catch bugs as you code

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 sometimes very painful, testing is not
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*
Defense in depth

Levels of defense:

1. Make errors *impossible*
   - examples: Java prevents type errors, memory corruption

2. Don’t introduce defects
   - “get things right the first time” (by reasoning & testing)

3. Make errors *immediately visible* (often by defensive programming)
   - examples: assertions, `checkRep`
   - reduce distance from error to failure
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 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

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.

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

“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.”
Second defense: Correctness

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 defense: Immediate visibility

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 (5+ 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

More about this in next lecture…
Benefits of immediate visibility

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

// 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

```java
// 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 terminates
- but no longer guaranteed that A[i] == x
- if other code relies on this, then problems arise later
// 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 caused x not to be in the array
Last resort: debugging

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…
Last resort: debugging

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That means

![DEBUGGING... YOU'RE ENTERING A WORLD OF PAIN](meme.png)
Basic Debugging

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

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: 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 about randomly!
  - may help to keep a *record* of what you tried
  - don’t get sucked into fruitless avenues

- Use an iterative scientific process:
  1. Formulate a **hypothesis**
  2. **Design an experiment**
  3. Perform an **experiment**
  4. **Interpret results**

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Example

// 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 *absolute* input size

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"
Reducing relative input size

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

**Can not** 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

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

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?
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
- 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

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

In a 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
  – literally depends on results of random-number generation

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

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

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 it is a bug
  – program may be working correctly!
More Tricks for Hard Bugs

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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?

The defect is not where you think it is
   – ask yourself where it can not be; explain why

Look for simple easy-to-overlook mistakes first, e.g.,
   – reversed order of arguments:
     \[
     \text{Collections.copy(src, dest)};
     \]
   – spelling of identifiers: \text{int hashcode()}
     \@	ext{Override} can help catch method name typos
   – same object vs. equal: \text{a == b} versus \text{a.equals(b)}
   – 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*
  – debugging is much more **frustrating** than testing

Debugging should be a systematic process
  – use the *scientific method*

Understand the source of defects
  – find similar ones and prevent them in the future