CSE 331
Software Design & Implementation

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Debugging

(Slides by Mike Ernst and David Notkin)

Ways to get your code right

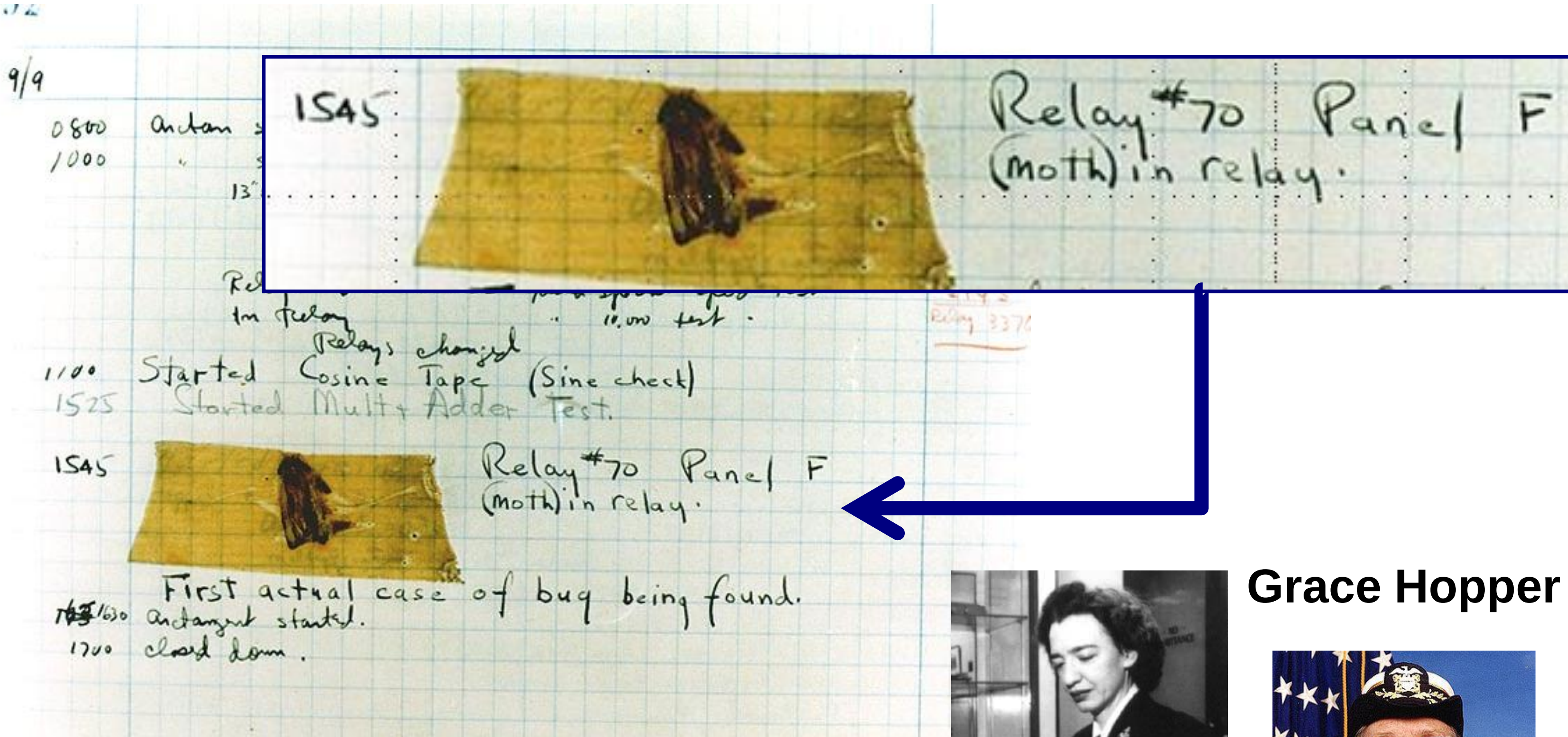
- Verification/quality assurance
  - Purpose is to uncover problems and increase confidence
  - Combination of reasoning and test
- Debugging
  - Finding out why a program is not functioning as intended
- Defensive programming
  - Programming with validation and debugging in mind
- Testing ≠ debugging
  - test: reveals existence of problem; test suite can also increase overall confidence
  - debug: pinpoint location + cause of problem

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
  - During any phase of testing or after ship: unit testing, integration testing, in the field

Whence “bug” – Sept. 9, 1947



Grace Hopper

Defense in depth (1)

- Make errors impossible
  - Java makes memory overwrite errors impossible
- Don't introduce defects
  - Correctness: get things right the first time
- Make errors immediately visible
  - Local visibility of errors: best to fail immediately
  - Example: assertions; **`checkRep()`**/**`repOK()`** 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 rep 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
  - Banning recursion prevents infinite recursion/ insufficient stack – although it may 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 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

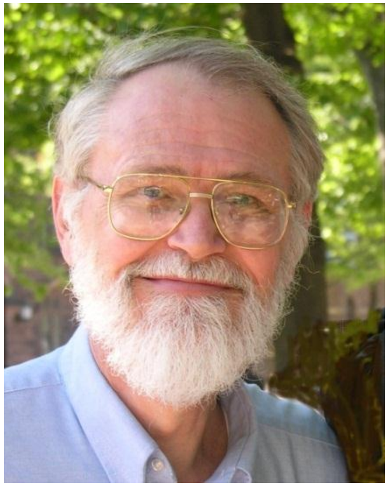
"There are two ways of constructing a software design:

- 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."

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, you can be confident that any error you find is due to a defect in that unit (unless it's in 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 (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

```
// 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
  – *This 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 – program halted because of overflow in unused value, exception thrown but not handled until top level, rocket crashes… [although the 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 finding and fixing an error usually goes up by an order of magnitude for each lifecycle phase it passes through

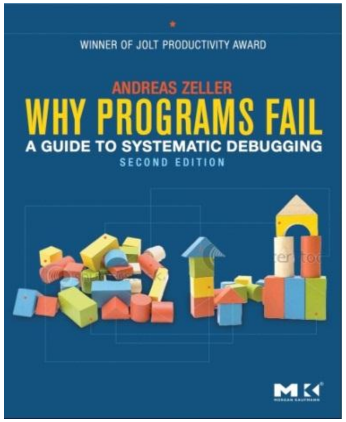
- step 1 – Clarify symptom (simplify input), create test
- step 2 – Find and understand cause, create better test
- step 3 – Fix
- step 4 – Rerun all tests

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."`**
- Less than ideal responses
  - See accented characters, panic about not having thought about unicode, and go diving for your Java texts to see how that is handled
  - 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 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 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

binary search on buggy code

```
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

```
public class MotionDetector {
    private boolean first = true;
    private Matrix prev = new Matrix();

    public Point apply(Matrix current) {
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        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

Quickly home in on defect in O(log n) time by repeated subdivision

Detecting Bugs in the Real World

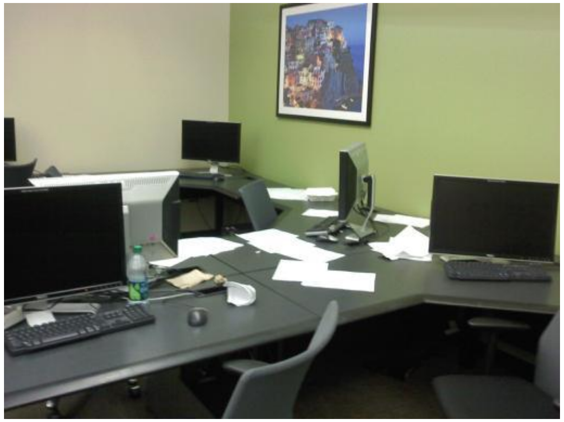
- Real Systems
  - Large and complex (duh!)
  - Collection of modules, written by multiple people
  - Complex input
  - Many external interactions
  - Non-deterministic
- Replication can be an issue
  - Infrequent failure
  - Instrumentation eliminates the failure
- Defects cross abstraction barriers
- 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

- Build an event log (circular buffer) and log (record) events during execution of program as it runs at speed
  - Maybe in main memory, maybe on disk or other non-volatile storage (performance vs permanent?)
- 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 – helps you to reproduce the failure

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?

- If 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?
  - Debug the code, *not* the comments – ensure the 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