

CS 520

Theory and Practice of Software Engineering
Fall 2026

Debugging

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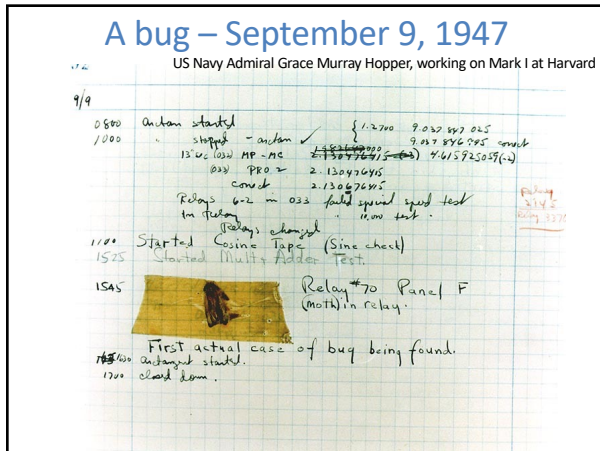
Ways to get your code right

- Validation
 - 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
 - debug: pinpoint location + cause of problem

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A bug – September 9, 1947

US Navy Admiral Grace Murray Hopper, working on Mark I at Harvard



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A Bug's Life



- 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

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Defense in depth

1. Make errors impossible
 - Java makes memory overwrite bugs impossible
2. Don't introduce defects
 - Correctness: get things right the first time
3. Make errors immediately visible
 - Local visibility of errors: best to fail immediately
 - Example: checkRep() routine to check representation invariants
4. Last resort is debugging
 - Needed when effect of bug is distant from cause
 - Design experiments to gain information about bug
 - 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

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First defense: Impossible by design

- In the language
 - Java makes memory overwrite bugs impossible
- In the protocols/libraries/modules
 - TCP/IP will guarantee that data is not reordered
 - BigInteger will guarantee that there will be no overflow
- In self-imposed conventions
 - Hierarchical locking makes deadlock bugs impossible
 - Banning the use of recursion will make infinite recursion/insufficient stack bugs go away
 - Immutable data structures will guarantee behavioral equality
 - Caution: You must maintain the discipline

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Second defense: correctness

- Get things right the first time
 - Don't code before you think! Think before you code.
 - If you're making lots of easy-to-find bugs, you're also making hard-to-find bugs
 - don't use compiler as crutch
- Especially true, when debugging is going to be hard
 - Concurrency
 - Difficult test and instrument environments
 - Program must meet timing deadlines
- 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

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Third defense: immediate visibility

- If we can't prevent bugs, we can try to localize them to a small part of the program
 - **Assertions**: catch bugs early, before failure has a chance to contaminate (and be obscured by) further computation
 - **Unit testing**: when you test a module in isolation, you can be confident that any bug you find is 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
- When localized to a single method or small module, bugs can be found simply by studying the program text

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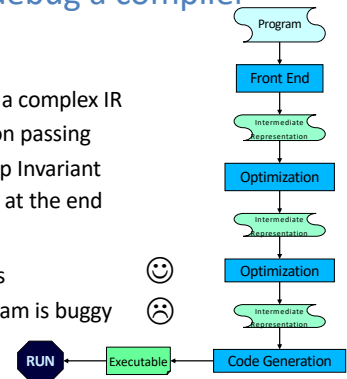
Benefits of immediate visibility

- Key difficulty of debugging is to find 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
 - For example, frequently checking the rep invariant helps the above problem
- General approach: fail-fast
 - Check invariants, don't just assume them
 - Don't try to recover from bugs – this just obscures them

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How to debug a compiler

- Multiple passes
 - Each operate on a complex IR
 - Lot of information passing
 - Very complex Rep Invariant
 - Code generation at the end
- Bug types:
 - Compiler crashes ☹️
 - Generated program is buggy ☹️



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Don't hide bugs

```

// k is guaranteed to be present in array 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
- If that guarantee is broken (by a bug), the code throws an exception and dies.
- Temptation: make code more “robust” by not failing

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Don't hide bugs

```

// 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 no longer guarantees that *a[i]==k*
 - If rest of code relies on this, then problems arise later
 - *All we've done is obscure the link between the bug's origin and the eventual erroneous behavior it causes.*

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Don't hide bugs

```
// 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 program as soon as problem is detected

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Inserting Checks

- Insert checks galore with an intelligent checking strategy
 - Precondition checks
 - Consistency checks
 - Bug-specific checks
- Goal: stop the program as close to bug as possible
Use debugger to see where you are, explore program a bit

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Checking For Preconditions

```
// 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";
```

Precondition violated? Get an assertion!

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Downside of Assertions

```
static int sum(Integer a[], List<Integer> index) {
    int s = 0;
    for (e: index) {
        assert (e < a.length, "Precondition violated");
        s = s + a[e];
    }
    return s;
}
```

Assertion not checked until we use the data
Fault occurs when bad index inserted into list
May be a long distance between fault activation and error detection

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checkRep: Data Structure Consistency Checks

```
static void checkRep(Integer a[], List<Integer> index) {
    for (e: index) {
        assert (e < a.length, "Inconsistent Data Structure");
    }
}
```

- Perform check after all updates to minimize distance between bug occurrence and bug detection
- Can also write a single procedure to check ALL data structures, then scatter calls to this procedure throughout code

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Bug-Specific Checks

```
static void check(Integer a[], List<Integer> index) {
    for (e: index) {
        assert (e != 1234, "Inconsistent Data Structure");
    }
}
```

Bug shows up as 1234 in list
Check for that specific condition

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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 bug does not have such bad consequences
 - 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...

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Ariane 5 rocket (1996)



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