Debugging

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

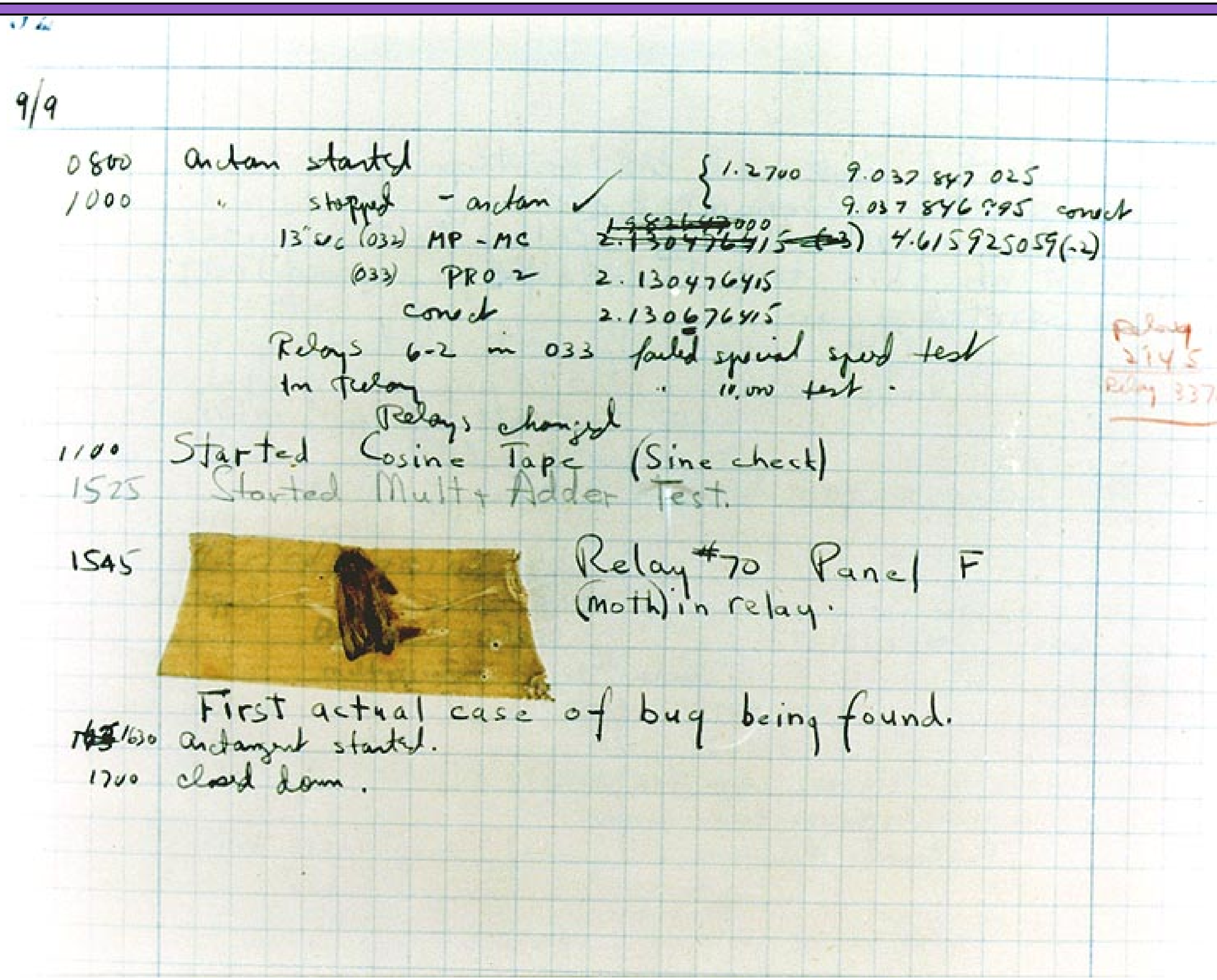
Programming with validation and debugging in mind

Testing ≠ debugging

test: reveals existence of problem

debug: pinpoint location+cause of problem

A bug – September 9, 1947



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

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

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

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

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

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

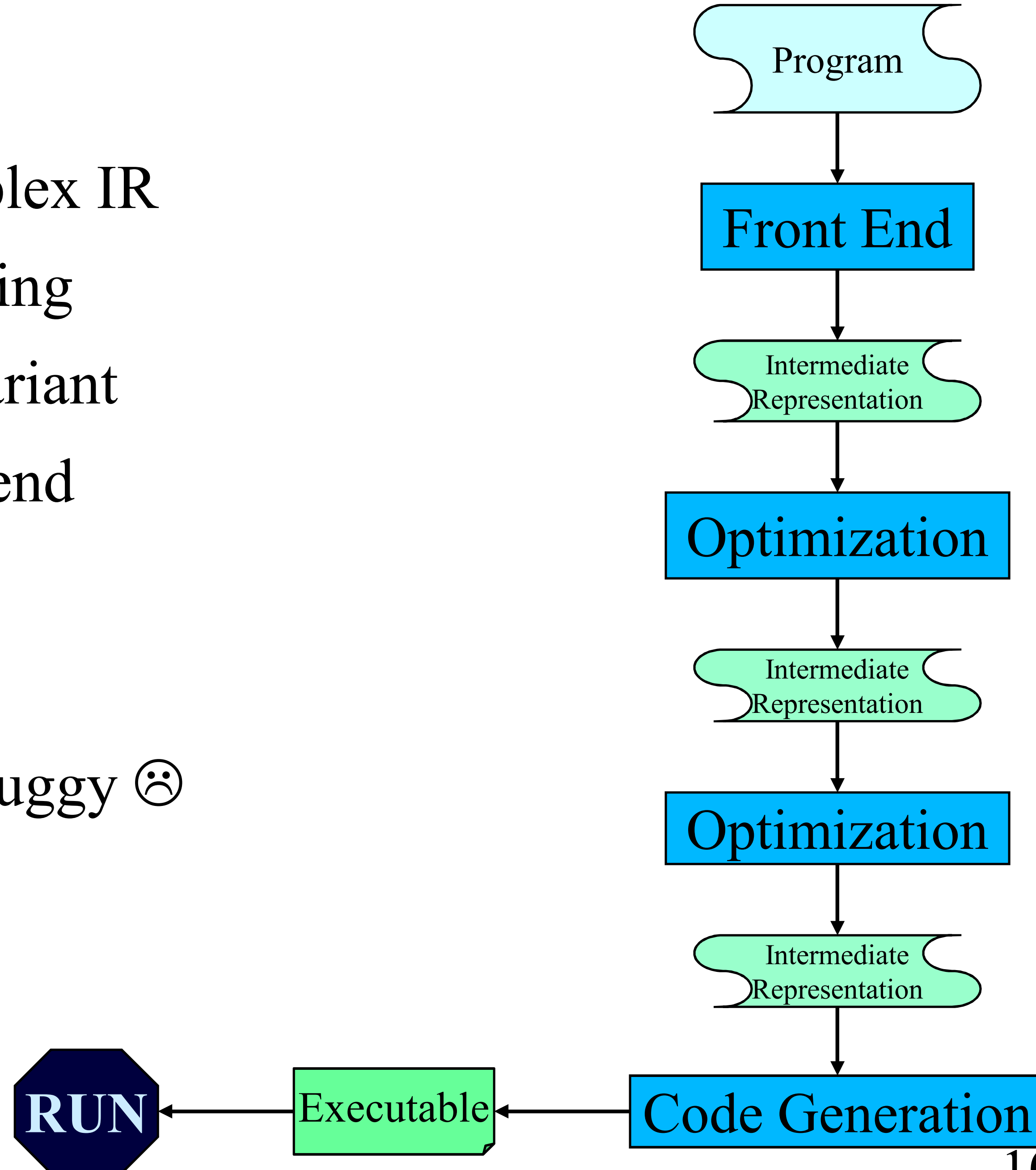
How to debug a compiler

Multiple passes

- Each operate on a complex IR
- Lot of information passing
- Very complex Rep Invariant
- Code generation at the end

Bugs

- Compiler crashes ☺
- Generated program is buggy ☹



Don't hide bugs

```
// 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.
- If that guarantee is broken (by a bug), the code throws an exception and dies.

Temptation: make code more “robust” by not failing

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 guaranteed 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.*

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

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

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!

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

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

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

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…

Regression testing

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

Logging Events

- Often you would like to have some indication of past when a check fails
- Design a logging infrastructure
  - Dump events to a file (strings)
  - Events have consistent format to enable efficient searches
  - Sometimes (usually for timing reasons) must keep lot in memory, not on disk
  - Circular logs to avoid resource exhaustion
- Important in debugging in customer environments
  - May not have access to the customer use
  - Only the log is available
  - Information on the log to help reproduce the bug

Last resort: debugging

Bugs happen
- Industry average: 10 bugs per 1000 lines of code ("kloc")

Bugs that are not immediately localizable happen
- Found during integration testing
- Or reported by user

step 1 – Clarify symptom

step 2 – Find and understand cause, create test

step 3 – Fix

step 4 – Rerun all tests

Kinds of Bugs

Quick, easy bugs (few minutes)

Medium bugs (hours)

Hard bugs (small number of days)

Really Bad bugs (many days to never)

Look for bugs in this order!

Different debugging strategies for each

Finding Easy Bugs

Hope for a quick bug, take a first quick shot

- Look at backtrace in the debugger
- Look at code where you think there might be a problem, maybe use a debugger or a few print statements in
- Try to get lucky

Make the first shot quick! Don’t get sucked in!

Look for medium bug with next shot

- Use print statements
- Design an organized print strategy
- Legible, easy to read error messages

Make the medium shot medium! Don’t get sucked in!

Tricks for Hard Bugs

Rebuild system from scratch and reboot

Explain bug to a friend

Make sure it is a bug – program may be working correctly and you don't realize it!

Minimize input required to exercise bug

Add checks to program

- Minimize distance between error and detection
- Use binary search to narrow down possible locations

Use logs to record events in history

Reducing Input Size Example

```
boolean substr(String s, String b)
```

returns false for

s = “The wworld is ggreat! Liffe is wwonderful! I am so vvery happy all of the ttime!”

b = “very happy”

even though “very happy” is a substring of s

Wrong approach: try to trace the execution of substr for this case

Right approach: try to reduce the size of the test case

Reducing Input Size

substr(“I am so vvery happy all of the ttime!”, “very happy”) == false

substr(“very happy all of the ttime!”, “very happy”) == true

substr(“I am so vvery happy”, “very happy”) == false

substr(“I am so vvery happy”, “happy”) == true

substr(“I am so vvery happy”, “very”) == false

substr(“I am so vvery happy”, “ve”) == false

substr(“vvery happy”, “ve”) == false

substr(“vvery happy”, “v”) == true

substr(“vvery”, “ve”) == false

substr(“vve”, “ve”) == false

substr(“ve”, “ve”) == true

General strategy: simplify

- In general: find simplest input that will provoke bug
  - Usually not the input that revealed existence of the bug
- Start with data that revealed bug
  - Keep paring it down (binary search can help)
  - Often leads directly to an understanding of the cause
- When not dealing with simple method calls
  - Think of "test input" as the set of steps needed to reliably trigger the bug
  - Same basic idea

Localizing a bug

- Take advantage of modularity
  - Start with everything, take away pieces until bug goes
  - Start with nothing, add pieces back in until bug appears
- Take advantage of modular reasoning
  - Trace through program, viewing intermediate results
- Can use binary search to speed things up
  - Bug happens somewhere between first and last statement
  - So can do binary search on that ordered set of statements

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;
    }
}
```

no problem yet

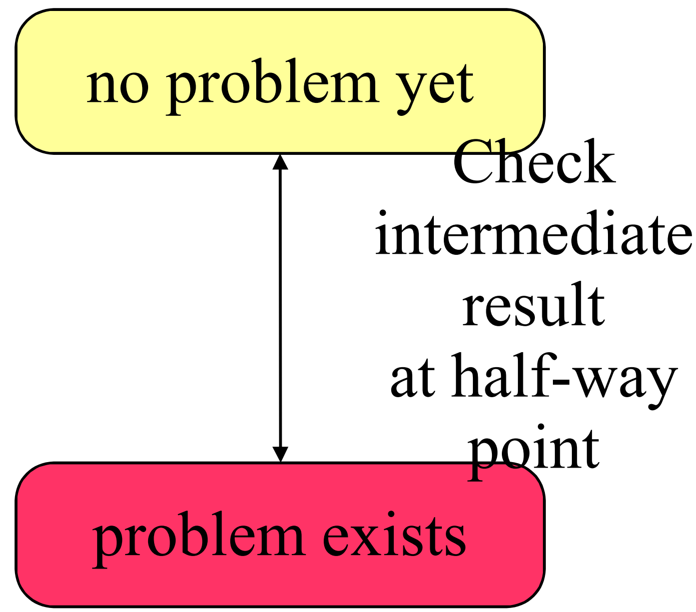
Check
intermediate
result
at half-way
point

problem exists

binary search on buggy code

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

    public Point apply(Matrix current) {
        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;
    }
}
```



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

Binary Search in a Compiler

	Class								
	A	B	C	D	E	F	G	H	I
Front end									
Optimization 1									
Optimization 2									
Optimization 3									
Optimization 4									
Optimization 5									
Optimization 6									
Code generation									
Link and Run									
Test									

Binary Search

Binary search

Binary Search in a Compiler

	Class								
	A	B	C	D	E	F	G	H	I
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Link and Run									
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Heisenbugs

Sequential, deterministic program – bug is repeatable

But the real world is not that nice…

- Continuous input/environment changes
- Timing dependencies
- Concurrency and Parallelism

Bug occurs randomly

Hard to reproduce

- Use of debugger or assertions → bug goes away
- Only happens when under heavy load
- Only happens once in a while

Debugging In Harsh Environments

- Harsh environments
  - Bug is nondeterministic, difficult to reproduce
  - Can’t print or use debugger
  - Can’t change timing of program (or bug has to do with timing)
- Build an event log (circular buffer)
- Log events during execution of program as it runs at speed
- When detect error, stop program and examine logs

Where is the bug?

- The bug is <u>not</u> 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
  - Recompile everything

When the going gets tough

Reconsider assumptions

- E.g., has the OS changed? Is there room on the hard drive?
- Debug the code, not the comments

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

Walk away

- Trade latency for efficiency – **sleep**!
- One good reason to start early

Detecting Bugs in the Real World

- Real Systems are…
  - Large and complex (duh!)
  - Collection of modules, written by multiple people
  - Complex input
  - Many external interactions
  - Non-deterministic
- Replication can be an issue
  - Infrequent bug
  - Instrumentation eliminates the bug
- Bugs cross abstraction barriers
- Large time lag from corruption to detection

Key Concepts in Review

- Testing and debugging are different
  - Testing reveals existence of bugs
  - Debugging pinpoints location of bugs
- Goal is to get program to work
  - Not to find bugs
- Debugging should be a systematic process
  - Use the "scientific method"
- It's important to understand source of bugs
  - To decide on appropriate repair