Testing, Debugging, Program Verification

Debugging Programs, Part II

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Today's Topic

— Last Week —

✔ Bug tracking

✔ Program control — Design for Debugging

✔ Input simplification

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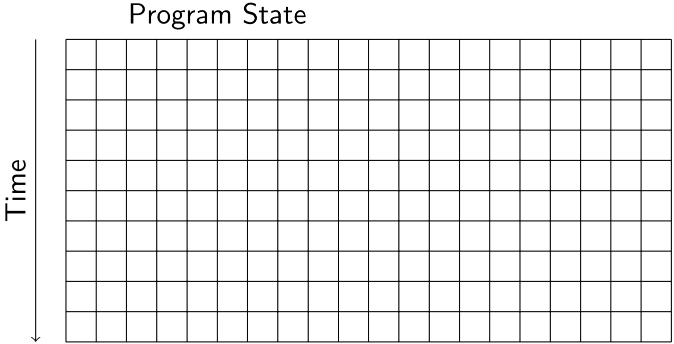
✔ Program control — Design for Debugging

✔ Input simplification

— Today —

- Execution observation
  - With logging
  - Using debuggers
- Tracking causes and effects

The Main Steps in Systematic Debugging



Reproduce failure with test input

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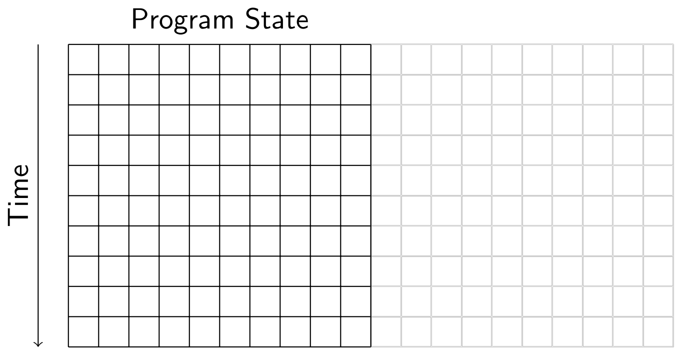

Reduction of failure-inducing problem

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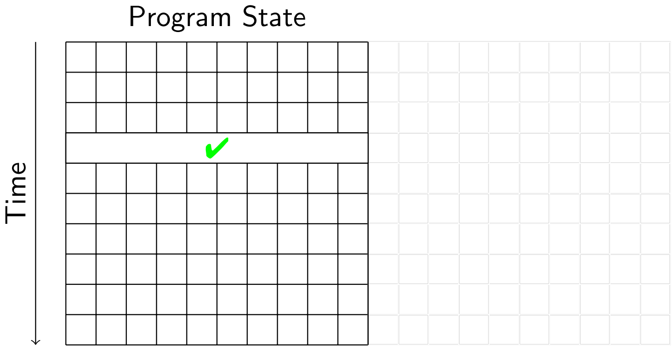

State known to be sane

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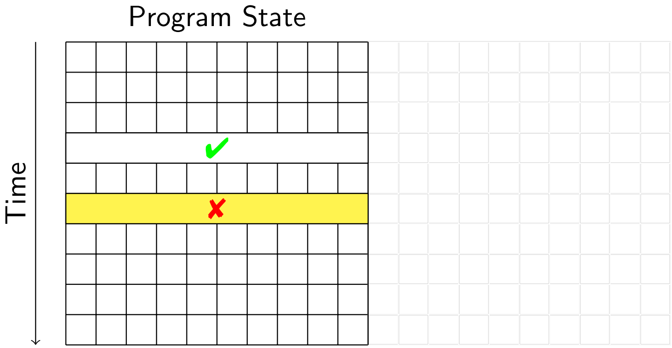

State known to be infected

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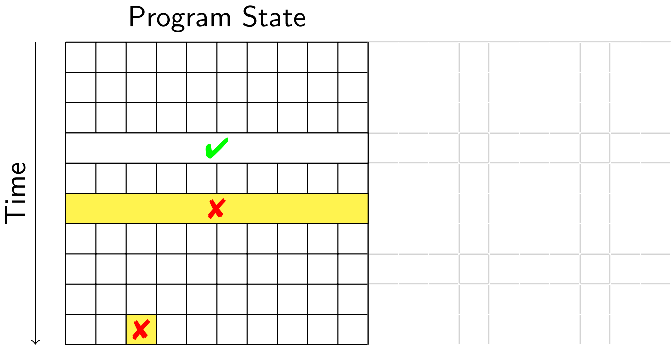

State where failure becomes observable

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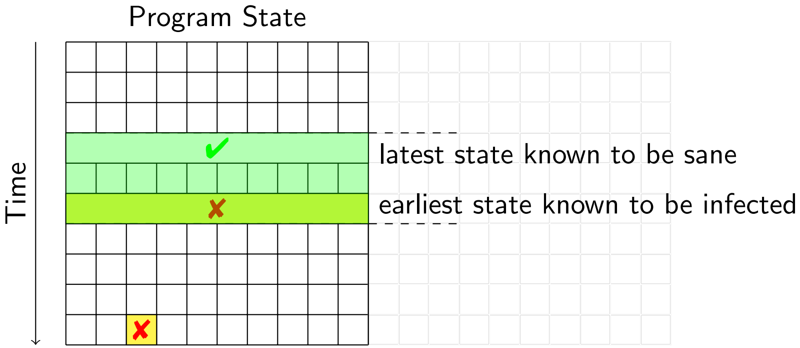

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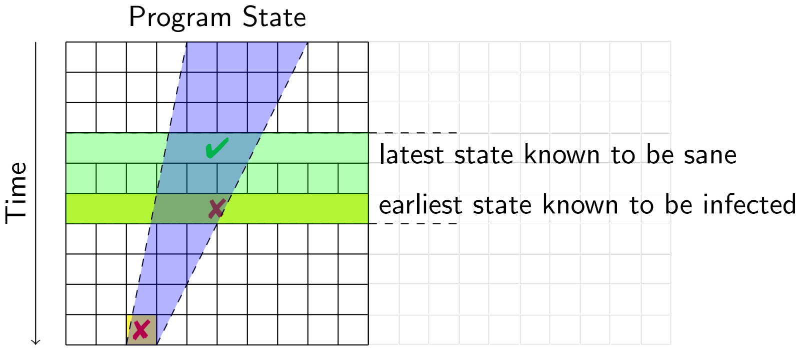

- Separate sane from infected states
- Separate relevant from irrelevant states

Central Problem

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Challenges/Obstacles

- Observation of intermediate state not part of functionality
  - Execution observation with logging and debuggers
- Narrowing down to relevant time/state sections
  - Tracking causes and effects

The Quick & Dirty Approach: Print Logging

Println Debugging

Manually add print statements at code locations to be observed

```
System.out.println("size␣=␣"+ size);
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Manually add print statements at code locations to be observed

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- ✔ Simple and easy
- ✔ Can use any output channel
- ✔ No tools or infrastructure needed, works on any platform

- ✘ Code cluttering
- ✘ Output cluttering (at least need to use debug channel)
- ✘ Performance penalty, possibly changed behaviour (real time apps)
- ✘ Buffered output lost on crash
- ✘ Source code access required, recompilation necessary

Logging Frameworks

Example (Logging Framework log4j for Java)

`logging.apache.org/log4j/`

Main principles of log4j

- Each class can have its own `logger` object
- Each logger has level: `DEBUG` < `INFO` < `WARN` < `ERROR` < `FATAL`
- Example: log `message` with `myLogger` and level `INFO`:
  `myLogger.info(Object message);`
- Logging is controlled by configuration file:
  which logger, level, layout, amount of information, channel, etc.
- No recompilation necessary for reconfiguration

log4j Demo

- Start ECLIPSE
  - Load project `logging` containing `Dubbel.java`
  - Add library `/usr/share/java/log4j-1.2.jar` to build path
- Show `Dubbel.java`
- Run `Dubbel.java`
- Show `SonOfDubbel.java`
- Show `logging-configuration.cf`
- Run `SonOfDubbel.java`
- Modify `logging-configuration.cf`: set `log4j.logger.log4fun=WARN`
- Refresh the project
- Show `SonOfDubbel.log`

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- Show `SonOfDubbel.log`

There are also tools for navigating log files

Output can be configured to be `mailto://` or database access

Evaluation of Logging Frameworks

- ✔ Output cluttering can be mastered
- ✔ Small performance overhead
  - Beware: string operations can be expensive! Protection:

    ```
    if (logger.isDebugEnabled()) { ... log ... };
    ```
- ✔ Exceptions are loggable
- ✔ Log complete up to crash
- ✔ Instrumented source code reconfigurable w/o recompilation

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- ✘ Code cluttering — don't try to log everything!

Code cluttering avoidable with aspects, but also with Debuggers

- post-mortem vs. interactive debugging

What is a Debugger?

Basic Functionality of a Debugger

Execution Control Stop execution at specific locations: breakpoints

Interpretation Step-wise execution of code

State Inspection Observe values of variables and stack

State Change Change state of stopped program

Historical term Debugger is misnomer as there are many debugging tools

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- Traditional debuggers (`gdb` for C) based on command line I/F
- We use the built-in GUI-based debugger of the ECLIPSE framework
  - Feel free to experiment with other debuggers!

Running Example

```java
public static int search( int array[], int target ) {

  int low = 0;
  int high = array.length;
  int mid;
  while ( low <= high ) {
    mid = (low + high)/2;
    if ( target < array[ mid ] ) {
        high = mid - 1;
    } else if ( target > array[ mid ] ) {
        low = mid + 1;
    } else {
        return mid;
    }
  }
  return -1;
}
```

Eclipse Debugger

- Load project `binary_search` from directory `example`
- Create/show run configuration `testBin`*i*`.run` present in directory
- Debug `testBin`*i* (the button with the bug)
- Open Debugging view of project `binary_search` (it should be automatic if you set a breakpoint)

Testing

Running a few test cases . . .

`search( {1,2,3}, 1 ) == 0` ✔

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search( {1,2,3}, 2 ) == 1 ✔
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search( {1,2,3}, 4 ) throws ArrayIndexOutOfBoundsException ✘
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`search( {1,2,3}, 4 )` throws `ArrayIndexOutOfBoundsException` ✘

Example taken from a published JAVA text book :-(

Halting Program Execution

Breakpoint

A program location that, when it is reached, halts execution

Example (Setting Breakpoint)

In `search()` at loop, right-click, toggle breakpoint

Some remarks on breakpoints

- Set breakpoint at last statement where state known to be sane
- This should be documented as an explicit hypothesis
- In ECLIPSE, not all lines can be breakpoints, because these are actually inserted into bytecode
- Don't forget to disable breakpoints when no longer needed

Resuming Program Execution

Example (Execution Control Commands)

- Start debugging of run configuration `testBin1`
- Resume halts when breakpoint is reached in next loop execution
- Disable breakpoint for this session
- Resume executes now until end
- Remove from debug log (Remove All Terminated)
- Enable breakpoint again in Breakpoints window
- Close debugging perspective

Step-Wise Execution of Programs

Step-Wise Execution Commands

Step Into Execute next statement, then halt

Step Over Consider method call as one statement

Some remarks on step-wise execution

- Usually JAVA library methods stepped over
  - They should not contain defects
  - You probably don't have the source code
- To step over bigger chunks, change breakpoints, then resume

Inspecting the Program State

Inspection of state while program is halted

- Variables window
  - Unfold reference types
  - Pretty-printed in lower half of window
- Tooltips for variables in focus in editor window
- Recently changed variables are highlighted

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Example (Tracking `search()`)

- Start debugging at beginning of loop (`testBin4`)
- Step through one execution of loop body
- After second execution of loop body `low==high==3`
- Therefore, `mid==3`, but `array[3]` doesn't exist!
- Whenever target is not in array, eventually `low==mid==array.length`

Changing the Program State

Hypothesis for Correct Value

Variable `high` should have value `array.length-1`

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Example (Fixing the defect in the current run)

At start of third round of loop, set `high` to correct value `2`

Resuming execution now yields correct result

Watching States with Debuggers

Halting Execution upon Specific Conditions

Use Boolean Watch expression in conditional breakpoint

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Example (Halting just before exception is thrown)

- From test run we know argument `mid` of `array` is 3 at this point
- Create breakpoint after assignment to `mid`
- Add watch expression `mid==3` to breakpoint properties
- Disable breakpoint at start of loop
- Execution halts exactly when `mid==3` becomes **true**

Watching States with Debuggers

Halting Execution upon Specific Conditions

Use Boolean Watch expression in conditional breakpoint

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Hints on watch expressions

- Make sure scope of variables in watch expressions is big enough

Evaluation of Debuggers

- ✔ Code cluttering completely avoided
- ✔ Prudent usage of breakpoints/watches reduces states to be inspected
- ✔ Full control over all execution aspects

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Important Lessons

- Both, logging and debuggers are necessary and complementary
- Need visualization tools to render complex data structures
- Minimal/small input, localisation of unit is important

Tracking Causes and Effects

Determine defect that is origin of failure

Fundamental problem

Programs executed forward, but need to reason backward from failure

Example

In `search()` the failure was caused by wrong value `mid`,
but the real culprit was the initialization of `high`

Example

```
public static int search( int array[], int target ) {

  int low = 0;
  int high = array.length ;
  int mid;
  while ( low <= high ) {
    mid = (low + high)/2;
    if ( target < array[ mid ] ) {
        high = mid - 1;
    } else if ( target > array[ mid ] ) {
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    } else {
        return mid;
    }
  }
  return -1;
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```

?

Effects of Statements

Fundamental ways how statements may affect each other

Write Change the program state
Assign a new value to a variable read by another statement

Control Change the program counter
Determine which statement is executed next

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Statements with Write Effect (in Java)

Quiz!

Effects of Statements

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Statements with Write Effect (in Java)

- Assignments
- I/O, because it affects buffer content
- new(), because object initialisation writes to fields

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Statements with Control Effect (in Java)

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Effects of Statements

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Statements with Control Effect (in Java)

- Conditionals, switches
- Loops: determine whether their body is executed
- Dynamic method calls: implicit case distinction on implementations
- Abrupt termination statements: **break**, **return**, **continue**, and...
- Exceptions: potentially at each object or array access!

Statement Dependencies

Definition (Data Dependency)

Statement `B` is data dependent on statement `A` iff

1. `A` writes to a variable `v` that is read by `B` and
2. There is at least one execution path between `A` and `B` in which `v` is not written to

"The outcome of `A` can directly influence a variable read in `B`"

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Definition (Control Dependency)

Statement B is control dependent on statement A iff

- B's execution is potentially controlled by A

"The outcome of A can influence whether B is executed"

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
  mid = (low + high)/2;
  if ( target < array[ mid ] ) {
      high = mid - 1;
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`mid` is data-dependent on this statement

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```

mid is control-dependent on the while statement

Computing Backward Dependencies

Definition (Backward Dependency)

Statement B is backward dependent on statement A iff

- There is a sequence of statements $A = A_1, A_2, \ldots, A_n = B$ such that:
  1. for all i, A_{i+1} is either control dependent or data dependent on A_i
  2. there is at least one i with A_{i+1} being data dependent on A_i

"The outcome of A can influence the program state in B"

Example

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mid is backward-dependent on data- and control- dependent statements

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Backward-dependent statements for first execution of loop body

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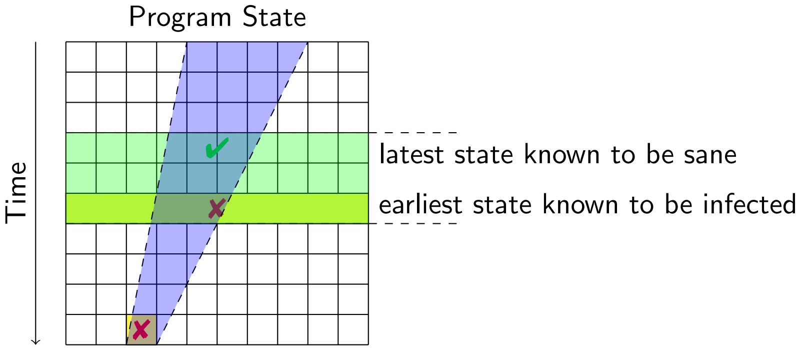
Backward-dependent statements for repeated execution of loop body

Systematic Localization of Defects



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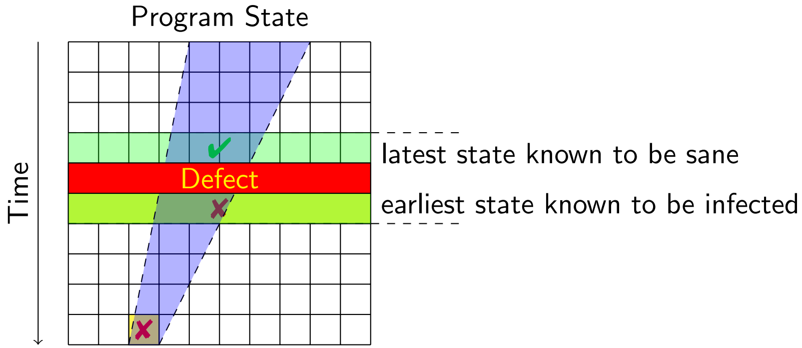

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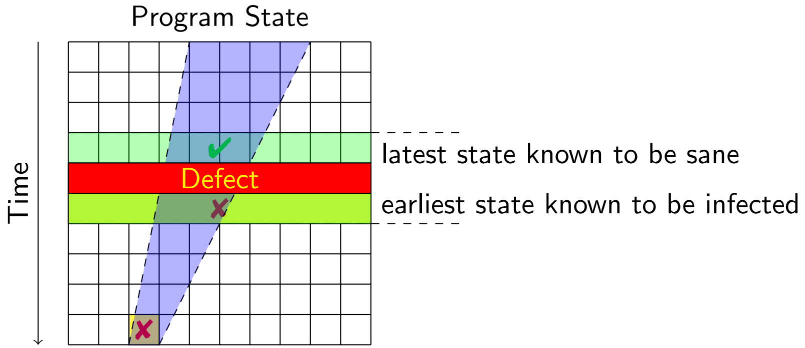

- Separate sane from infected states
- Separate relevant from irrelevant states
- Compute backward-dependent statements from infected locations

Tracking Down Infections

Algorithm for systematic localization of defects

Let $\mathcal{I}$ be a set of infected locations (variable+program counter)

Let L be the current location in a failed execution path

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   - 4.1 Let $\mathcal{I} := (\mathcal{I} \setminus \{L\}) \cup \mathcal{M}$ (replace L with the new candidates in $\mathcal{M}$)
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   - 4.3 Goto 2.

Tracking Down Infections

Algorithm for systematic localization of defects

Let $\mathcal{I}$ be a set of infected locations (variable+program counter)

Let L be the current location in a failed execution path

1. Let L be infected location reported by failure and set $\mathcal{I} := \{L\}$
2. Compute statements $\mathcal{S}$ that potentially contain origin of defect: one level of backward dependency from L in execution path
3. Inspect locations $L_1, \ldots, L_n$ written to in $\mathcal{S}$: check if they are infected, let $\mathcal{M} \subseteq \{L_1, \ldots, L_n\}$ be infected ones
4. If one of the L_i is infected, i.e., $\mathcal{M} \neq \emptyset$:
   - 4.1 Let $\mathcal{I} := (\mathcal{I} \setminus \{L\}) \cup \mathcal{M}$ (replace L with the new candidates in $\mathcal{M}$)
   - 4.2 Let new current location L be any location from $\mathcal{I}$
   - 4.3 Goto 2.
5. L depends only on sane locations, it must be the infection site!

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
  mid = (low + high)/2;
  if ( target < array[ mid ] ) {
      high = mid - 1;
  } else if ( target > array[ mid ] ) {
      low = mid + 1;
  } else {
      return mid;
  }
}
return -1;
```

Call `search( {1,2}, 3 )`, `mid` is infected, `mid==low==high==2`

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
  mid = (low + high)/2;
  if ( target < array[ mid ] ) {
      high = mid - 1;
  } else if ( target > array[ mid ] ) {
      low = mid + 1;
  } else {
      return mid;
  }
}
return -1;
```

Look for origins of `low` and `high`

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
   mid = (low + high)/2;
   if ( target < array[ mid ] ) {
      high = mid - 1;
   } else if ( target > array[ mid ] ) {
      low = mid + 1;
   } else {
      return mid;
   }
}
return -1;
```

`low` was changed in previous loop execution, value `low==1` seems sane

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
  mid = (low + high)/2;
  if ( target < array[ mid ] ) {
      high = mid - 1;
  } else if ( target > array[ mid ] ) {
      low = mid + 1;
  } else {
      return mid;
  }
}
return -1;
```

high==2 set at start (if-branch not taken when target not found), infected!

Example

```
int low = 0;
int high = array.length;
int mid;
while ( low <= high ) {
   mid = (low + high)/2;
   if ( target < array[ mid ] ) {
       high = mid - 1;
   } else if ( target > array[ mid ] ) {
       low = mid + 1;
   } else {
       return mid;
   }
}
return -1;
```

`high` does not depend on any other location—found infection site!

Example

```
int low = 0;
int high = array.length - 1;
int mid;
while ( low <= high ) {
  mid = (low + high)/2;
  if ( target < array[ mid ] ) {
      high = mid - 1;
  } else if ( target > array[ mid ] ) {
      low = mid + 1;
  } else {
      return mid;
  }
}
return -1;
```

Fixed defect

After Fixing the Defect: Testing!

- Failures that exhibited a defect become new test cases after the fix
  - used for regression testing
- During/after fixing the bug use existing unit test cases to
  - test a suspected method in isolation
  - make sure that your bug fix did not introduce new bugs
  - exclude wrong hypotheses about the defect

What Next?

Three unsolved problems

1. How is evaluation of test runs related to specification?
   So far: wrote oracle program or evaluated interactively
   How to check automatically whether test outcome conforms to spec?
2. It is tedious to write test cases by hand!
   Easy to forget cases
   JAVA: aliasing, run-time exceptions
3. When does a program have no more bugs?
   How to prove correctness without executing ∞ many paths?

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   How to prove correctness without executing ∞ many paths?

Three more topics in this course that give some answers

1. Formal Specification
2. Automated Test Case Generation
3. Verifying Program Correctness

Literature for this Lecture

Essential

Zeller Why Programs Fail: A Guide to Systematic Debugging
2nd edition, Elsevier, 2009
Chapters 7, 8, 9

Recommended

`log4j` Tutorial `logging.apache.org/log4j/1.2/manual.html`

See also

Java logging framework Package `java.util.logging` in JDK 6 Doc