Software Engineering
Testing and Debugging — Debugging

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09.07.2009

Motivation

Debugging is unavoidable and a major economical factor

- Software bugs cost the US economy ca. 60 billion US$/y (2002)
  In general estimated 0.6% of the GDP of industrial countries
- Ca. 80 percent of software development costs spent on identifying and correcting defects
- Software re-use is increasing and tends to introduce bugs due to changed specification in new context (Ariane 5)

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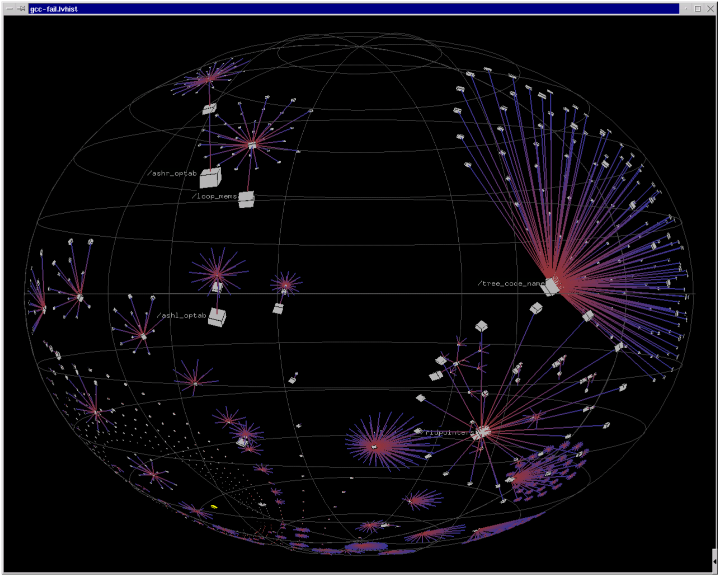
Debugging needs to be systematic

- Bug reports may involve large inputs
- Programs may have thousands of memory locations
- Programs may pass through millions of states before failure occurs

Example: memory graph of GCC 2.95.2



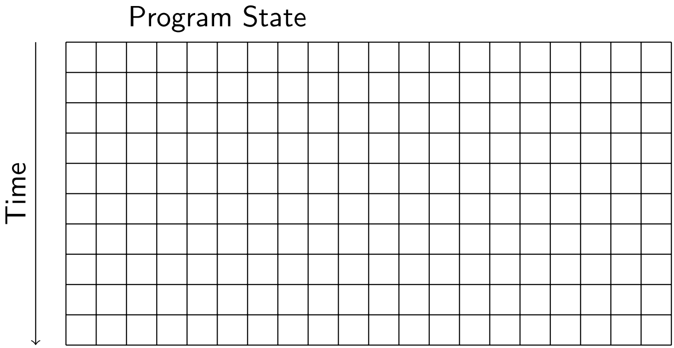
Reminder: Terminology

Bug-Related Terminology

1. Defect (aka bug, fault) introduced to the code by programmer
   Not always programmer's fault: changing/unforeseen requirements
2. Defect may cause infection of the program state during execution
   Not all defects cause an infection: e.g., Pentium bug
3. An infected state propagates during execution
   Infected parts of states may be overwritten, corrected, unused
4. An infection may cause a failure: an externally observable error
   This may include non-termination

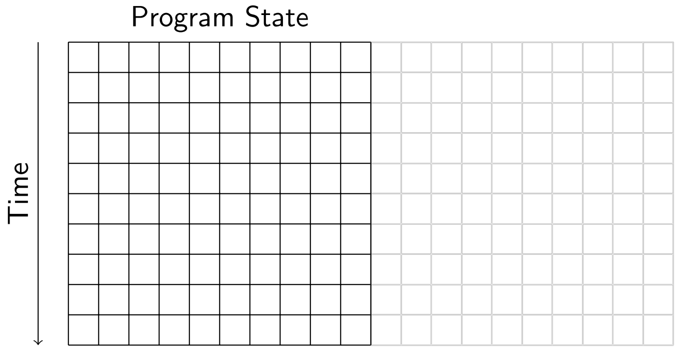
Defect — Infection — Propagation — Failure

The Main Steps in Systematic Debugging



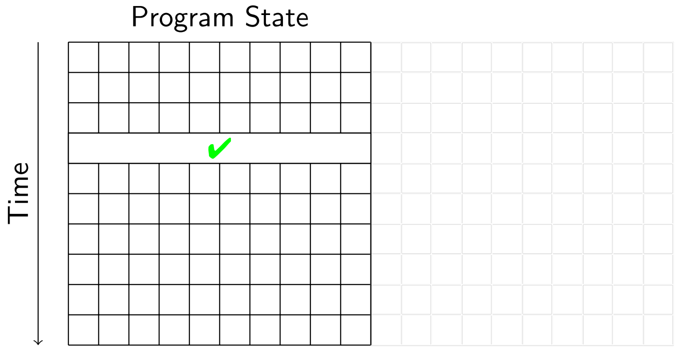
Reproduce failure with test input

The Main Steps in Systematic Debugging



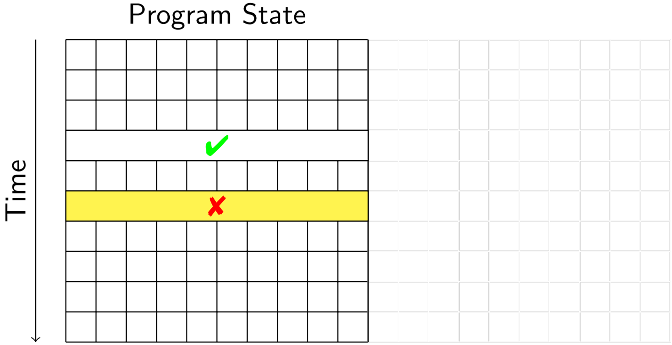
Reduction of failure-inducing problem

The Main Steps in Systematic Debugging



State known to be healthy

The Main Steps in Systematic Debugging



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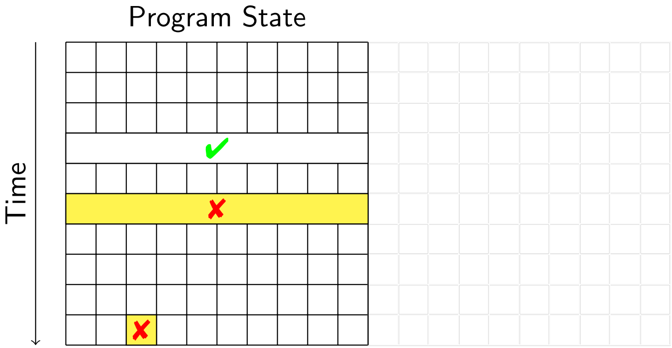

State where failure becomes observable

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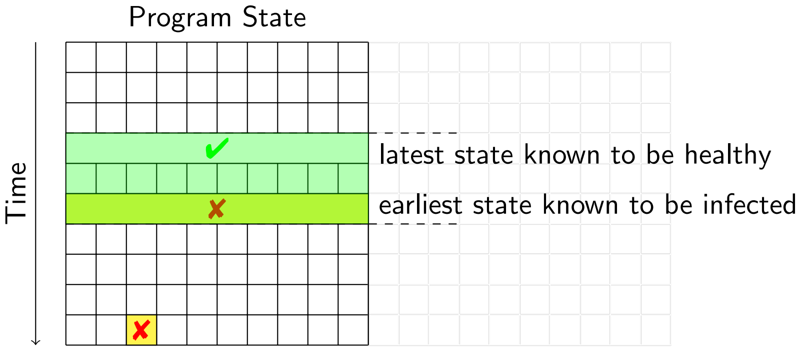

- Separate healthy from infected states

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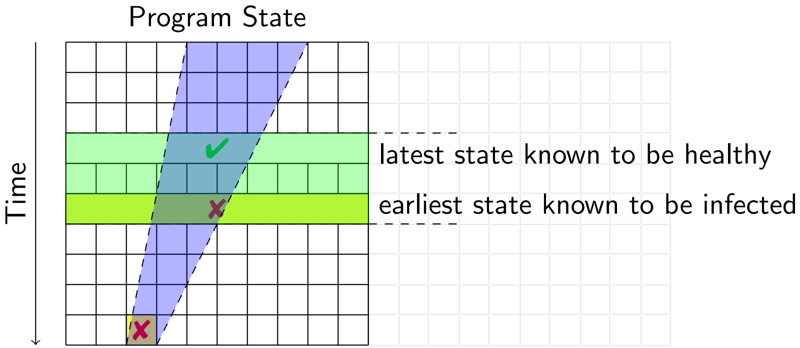

- Separate healthy from infected states
- Separate relevant from irrelevant states

Debugging Techniques

The analysis suggests main techniques used in systematic debugging:

- Bug tracking — Which start states cause failure?
- Program control — Design for Debugging
- Input simplification — Reduce state size
- State observation and watching using debuggers
- Tracking causes and effects — From failure to defect

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Common Themes

- Fighting combinatorial explosion: separate relevant from irrelevant
- Being systematic: avoid repetition, ensure progress, use tools

Bug Tracking Life Cycle

Unconfirmed

Raw problem report, often from end user

Bug Tracking Life Cycle

Unconfirmed ➜ New

Description complete, no duplicate of existing bug

Bug Tracking Life Cycle

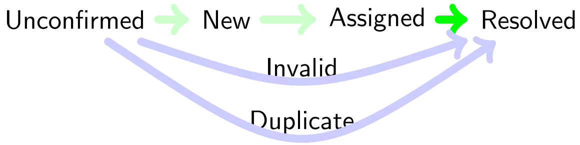
Unconfirmed → New → Assigned

Bug Tracking Life Cycle

Unconfirmed → New → Assigned → Resolved

Tag	Meaning
Fixed Problem	is fixed
WontFix	Impossible or undesirable (“feature”) to fix
WorksForMe	Can’t be reproduced
Invalid	Not a problem or insufficiently described
Duplicate	Refers to existing problem

Bug Tracking Life Cycle



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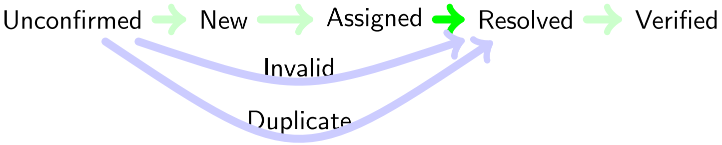
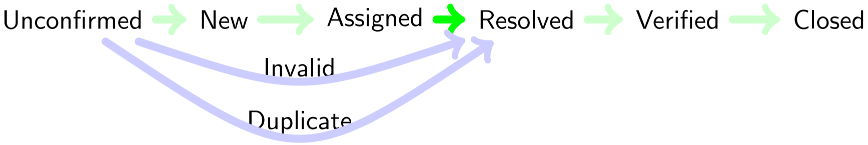


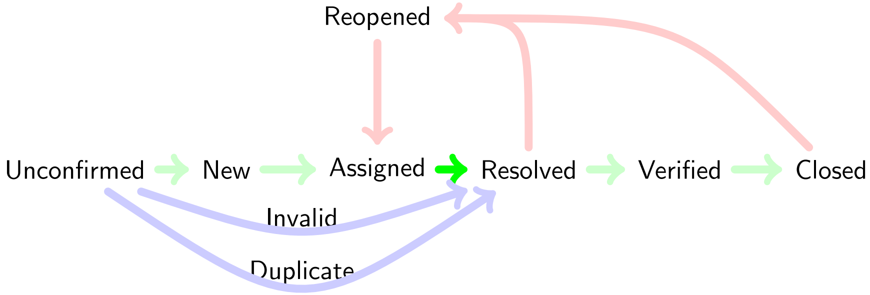
Only if Fixed

Bug Tracking Life Cycle



Important to avoid cluttering of bug database

Bug Tracking Life Cycle



The fix didn't work after all . . .

From Bug to Test Case

Scenario

Assume Firefox crashes while printing a certain URL to file

We need to turn the bug report into an automated test case!

From Bug to Test Case

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We need to turn the bug report into an automated test case!

Automated test case execution essential

- Reproduce the bug reliably (cf. scientific experiment)
- Repeated execution necessary during isolation of defect
- After successful fix, bug must become part of nightly run test suite

Prerequisites for automated execution

1. Program control (without manual interaction)
2. Isolating small program units that contain the bug

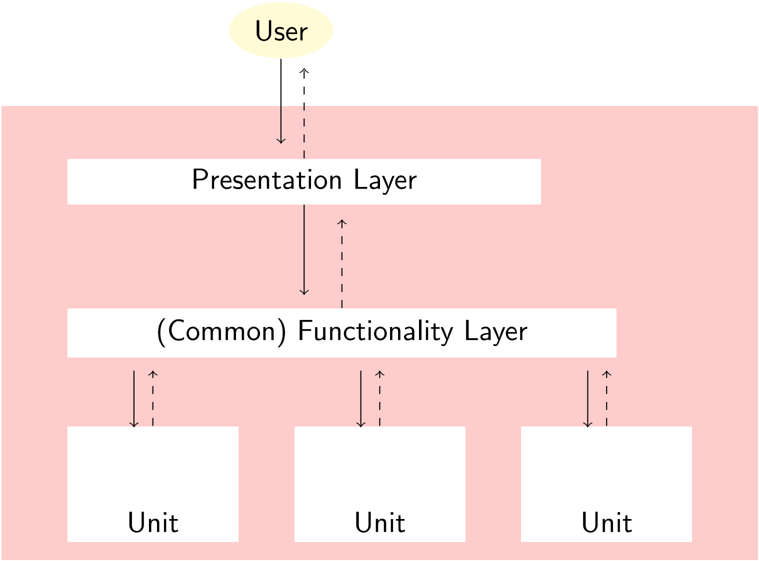
Program Control

Enable automated run of program that may involve user interaction

Example (Sequence of interaction that led to the crash)

1. Launch Firefox
2. Open URL location dialogue
3. Type in a location
4. Open Print dialogue
5. Enter printer settings
6. Initiate printing

Alternate Program Interfaces for Testing



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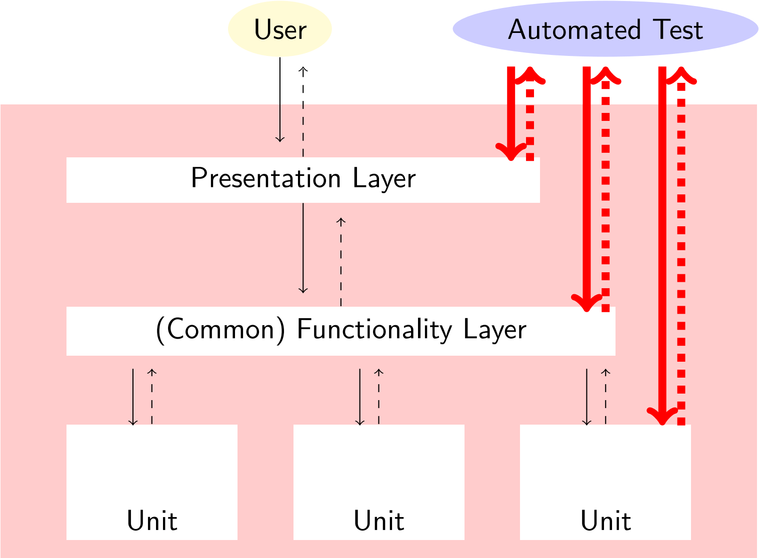

Automated Testing at Different Layers

Presentation: Scripting languages for capturing & replaying user I/O

- Specific to an OS/Window system/Hardware
- Scripts tend to be brittle

Functionality: Interface scripting languages

1. Implementation-specific scripting languages: VBScript
2. Universal scripting languages with application-specific extension: Python, Perl, Tcl

Unit: Unit testing frameworks (as in previous lecture)

- JUnit, CPPUnit, VBUnit, ...

Testing Layers: Discussion

The higher the layer, the more difficult becomes automated testing

- Scripting languages specific to OS/Window S./Progr. L.
- Test scripts depend on (for example):
  - application environment (printer driver)
  - hardware (screen size), work environment (paper size)

Testing Layers: Discussion

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Test at the unit layer whenever possible!

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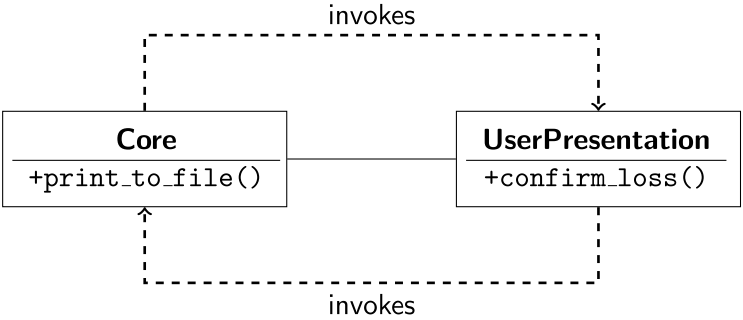
Test at the unit layer whenever possible!

Requires modular design with low coupling

- Good design is essential even for testing and debugging!
- We concentrate on decoupling rather than specific scripts

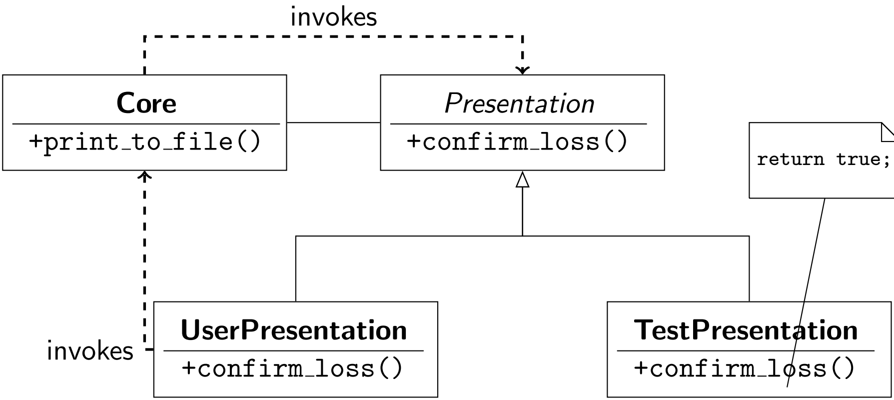
Disentangling Layers



Circular Dependency Example

- Print-to-file is core functionality
  calls `confirm_loss()` to prevent accidental file removal
- Override-if-file-exists question is in UI
  calls back `+print_to_file()` when override confirmed

Breaking Circular Dependencies by Refactoring



- Programming to interfaces important even for testability
- More general: Model-View-Controller Pattern

Isolating Units

Use test interfaces to isolate smallest unit containing the defect

- In the Firefox example, unit for file printing easily identified
- In general, use debugger (see next lecture) to trace execution

From Bug to Test Case, Part II

Scenario

Assume FIREFOX crashes while printing a loaded URL to file

We need to turn the bug report into an automated test case!

We managed to isolate the relevant program unit, but . . .

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We managed to isolate the relevant program unit, but ...

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD␣HTML␣4.01//EN
 ">
<html lang="en">

<head>
 <title>Mozilla.org</title>
 <meta http-equiv="Content-Type"
       content="text/html;␣charset=UTF-8">
... ca 200 lines more
```

Problem Simplification

We need a small failed test case

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Divide-and-Conquer

1. Cut away one half of the test input
2. Check, whether one of the halves still exhibits failure
3. Continue until minimal failing input is obtained

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Problems

- Tedious: rerun tests manually
- Boring: cut-and-paste, rerun
- What, if none of the halves exhibits a failure?

Automatic Input Simplification

- Automate cut-and-paste and re-running tests
- Increase granularity (size) of chunks when no failure occurs

In the exercises size of chunks is used for granularity: make consistent!

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Example

public static int `checkSum(`**int**`[] a)`

- is supposed to compute the checksum of an integer array
- gives wrong result, whenever `a` contains two identical consecutive numbers, but we don't know that yet
- we have a failed test case, eg, from protocol transmission:

  `{1,3,5,3,9,17,44,3,6,1,1,0,44,1,44,0}`

Input Simplification ($n =$ number of chunks)

1	3	5	3	9	17	44	3	6	1	1	0	44	1	44	0	✘

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1	3	5	3	9	17	44	3	✔

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								6	1	1	0					✘
								6	1							✔
										1	0					✔

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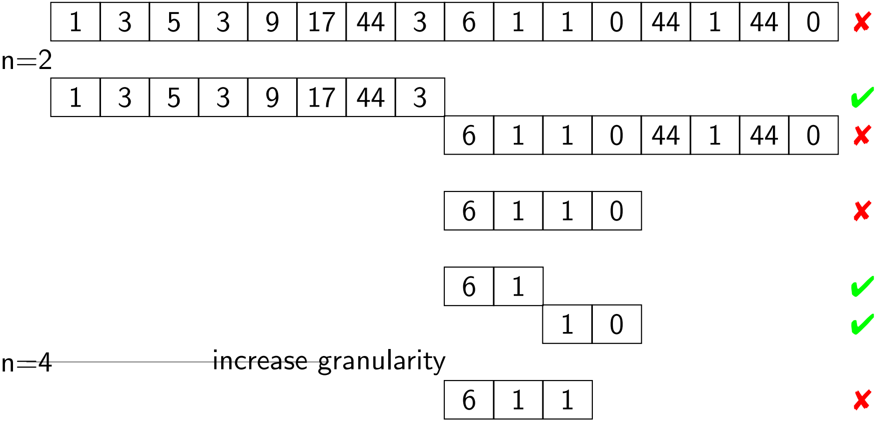

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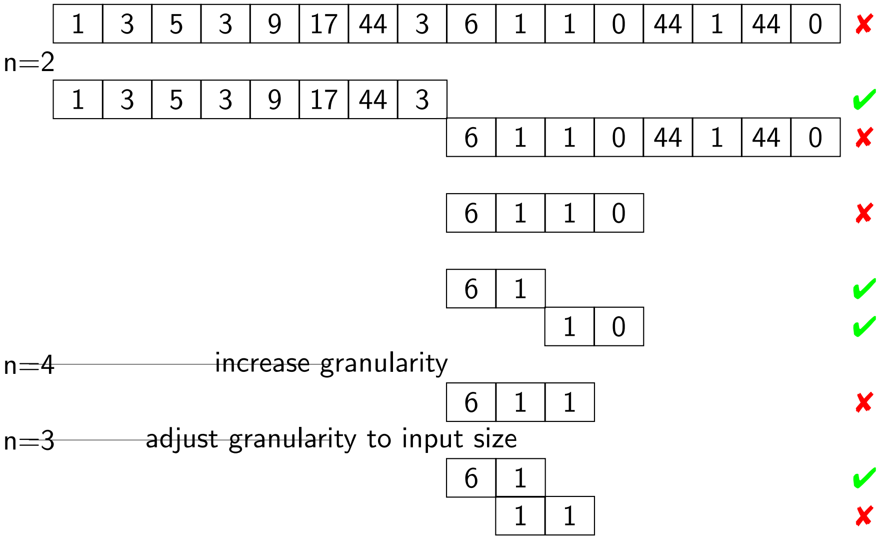

Simplification Algorithm

Prerequisites

- Let $c_{✘}$ be an input configuration with
  - granularity n, ie, $c_{✘} = \{c_1, \ldots, c_n\}$
  - length $|c_{✘}| = |c_1 \cup \cdots \cup c_n|$
- test(c) runs a test on c with possible outcome ✔, ✘, ?

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- $\text{test}(c)$ runs a test on c with possible outcome ✔, ✘, ?

Find minimal failing input: call $\text{ddMin}(c_0, 2)$ with $\text{test}(c_0) = ✘$

$$\text{ddMin}(c_{✘}, n) = \begin{cases} c_{✘} & |c_{✘}| = 1 \\ \text{ddMin}(c_{✘} \setminus c, \max(n-1, 2)) & c \in c_{✘} \text{ and } \text{test}(c_{✘} \setminus c) = ✘ \\ \text{ddMin}(c_{✘}, \min(2n, |c_{✘}|)) & n < |c_{✘}| \\ c_{✘} & \text{otherwise} \end{cases}$$

Example

Example

Faulty parser: failure for occurrence of array expression

```
char[] s = {'w','h','i','l','e','␣','b','␣',
            '{','a','[','i',']','=','0',';','}'
            };

javac -cp /usr/share/java/log4j-1.2.jar:. While.
java
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```

Minimal Failure Configuration

- Minimization algorithm is easy to implement
- Realizes input size minimization for failed run
- Implementation:
  - Small program in your favorite PL (Zeller: Python, Java)
  - Eclipse plugin DDInput at `www.st.cs.uni-sb.de/eclipse/`
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Demo: `DD.java`, `Dubbel.java`

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Consequences of Minimization

- Input small enough for observing, tracking, locating (next topics)
- Minimal input often provides important hint for source of defect

Principal Limitations of Input Minimization

Algorithm does not find all failure inputs with minimal size

Computes failure-inducing subsequence of the input that is minimal:

Taking away any chunk of any length removes the failure

1. The algorithm investigates only one failing input of smaller size

   There could be other minimal sequences with shorter length

2. Misses failure-inducing inputs created by taking away several chunks

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Failure occurs for integer array when frequency of occurrences of all numbers is even:

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Example (Incompleteness of minimization)

Failure occurs for integer array when frequency of occurrences of all numbers is even:

`{1,2,1,2}` fails

Taking away any chunk of size 1 or 2 passes

`{1,1}` fails, too, and is even smaller

Limitations of Linear Minimization

Minimization algorithm ignores any structure of input

Example (`.html` input configuration)

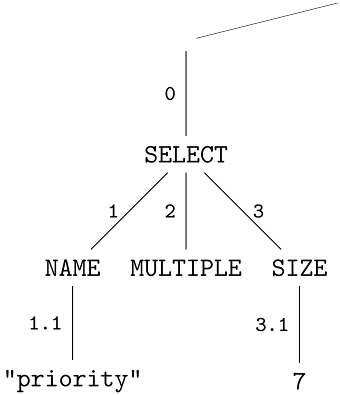
<SELECT NAME="priority"MULTIPLE SIZE=7> ✘

- Most substrings are not valid HTML: test result ? ("unresolved")
- There is no point to test beneath granularity of tokens

Minimization may require a very large number of steps

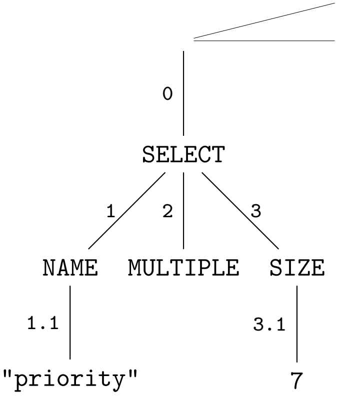
Structured Minimization

Linearization of $c_{✘}$:



Input configuration consists of nodes in ABS not characters

Structured Minimization



Linearization of $c_{\text{✘}}$:

`<SELECT NAME="priority" MULTIPLE SIZE=7>`

$$c_{\text{✘}} = \{0, 1, 1.1, 2, 3, 3.1\}$$

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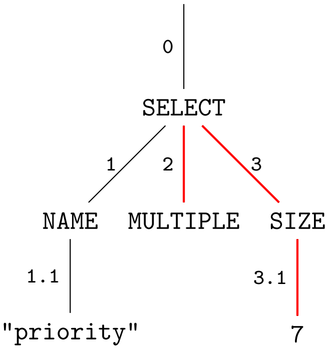

Linearization of $c_{\text{✘}}$:

<SELECT NAME="priority" MULTIPLE SIZE=7>

$c_{\text{✘}} = \{0, 1, 1.1, 2, 3, 3.1\}$ infeasible (not a tree) return ?

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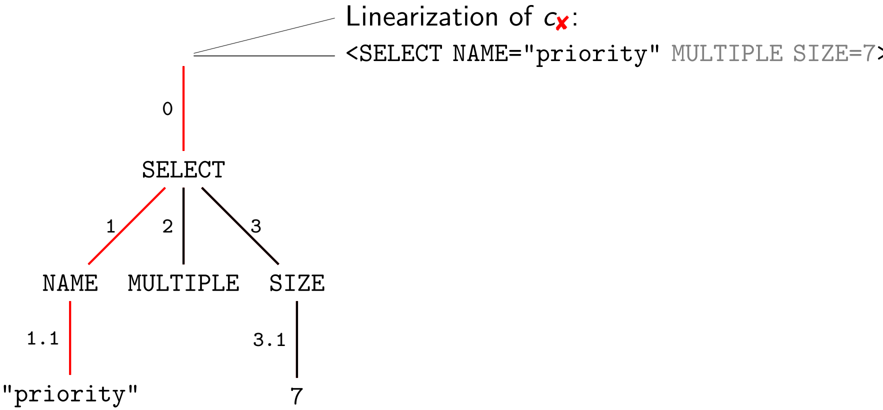
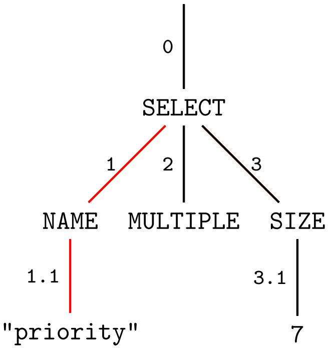


$c_{✘} = \{0, 1, 1.1, 2, 3, 3.1\}$ Failure occurs, reduce length

Structured Minimization

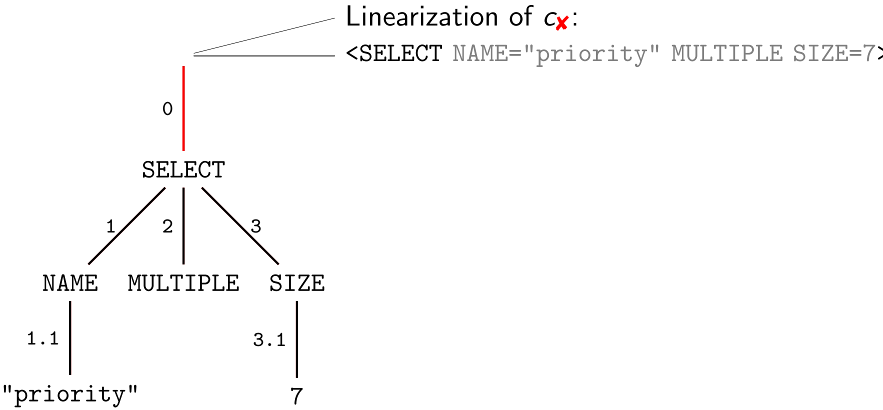


Linearization of $c_{✘}$:

`<SELECT NAME="priority" MULTIPLE SIZE=7>`

$c_{✘} = \{0, 1, 1.1, 2, 3, 3.1\}$ infeasible (not well-formed HMTL) return ?

Structured Minimization



$c_{✘} = \{0, 1, 1.1, 2, 3, 3.1\}$ Failure occurs, can't be minimized further

Delta Debugging, Adaptive Testing

The Bigger Picture

- Minimization of failure-inducing input is instance of delta debugging
- Delta debugging is instance of adaptive testing

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Definition (Delta Debugging)

Isolating failure causes by narrowing down differences (“δ”) between runs

This principle is used in various debugging activities

Delta Debugging, Adaptive Testing

The Bigger Picture

- Minimization of failure-inducing input is instance of delta debugging
- Delta debugging is instance of adaptive testing

Definition (Delta Debugging)

Isolating failure causes by narrowing down differences ("δ") between runs

This principle is used in various debugging activities

Definition (Adaptive Testing)

A test series where each test depends on the outcome of earlier tests

Some Tips

Logging

Log all debugging activities, particularly, test cases and outcomes

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Fix Time Limit for Quick-and-Dirty Debugging

Use "naive" debugging when bug seems obvious, but 10 mins max!

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Log all debugging activities, particularly, test cases and outcomes

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Avoids presentation layer scripts (brittle!) and interaction (tedious!)

Fix Time Limit for Quick-and-Dirty Debugging

Use “naive” debugging when bug seems obvious, but 10 mins max!

Test the Right Program

Is the path and filename correct? Did you compile?

What Next?

- ✔ Bug tracking
- ✔ Program control — Design for Debugging
- ✔ Input simplification

What Next?

- ✔ Bug tracking
- ✔ Program control — Design for Debugging
- ✔ Input simplification

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

Literature for this Lecture

Essential

Zeller Why Programs Fail: A Guide to Systematic Debugging, Morgan Kaufmann, 2005
Chapters 2, 3, 5

Background

McConnell Code Complete: A Practical Handbook for Software Construction, 2nd edition, Microsoft Press, 2004
Chapter 23