# 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 specifications in new context (Ariane 5)

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
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. Infection may cause a **failure**: externally observable error
   May include non-termination

**Defect — Infection — Propagation — Failure**
The Main Steps in Systematic Debugging

- The earliest state known to be infected
- The latest state known to be healthy
- Separate healthy from infected states
- Separate relevant parts from irrelevant ones
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

Common Themes

- Fighting combinatorial explosion: separate relevant from irrelevant
- Being systematic: avoid repetition, ensure progress, use tools
The fix didn’t work after all . . .
Bugzilla’s Bug Lifecycle

Bug is filed by a non-empowered user in a product where the UNCONFIRMED state is enabled.

Bug determined to be present

UNCONFIRMED

CONFIRMED

Developer is working on the bug

Developer stops work on bug

IN_PROGRESS

Fix checked in

RESOLVED

QA not satisfied with the solution

Possible resolutions:
- FIXED
- DUPLICATE
- WONTFIX
- WORKSFORME
- INVALID

VERIFIED

Fix turns out to be wrong

RESOLVED

Bug is not fixable (e.g., because it is invalid)

QA verifies that the solution works

Bug is reopened, was never confirmed
Scenario
Assume Firefox crashes while printing a certain URL to file

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, test case becomes part of test suite

Prerequisites for automated execution
1. Program control (without manual interaction)
2. Isolating small program units that contain the bug
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
Alternative Program Interfaces for Testing

User

Automated Test

Presentation Layer

(Common) Functionality Layer

Unit

Unit

Unit
### 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 testing frameworks (as in previous lecture)

**JUnit, CPPUnit, VBUnit, ...**
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*), working environment (*paper size*)

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 relies on core functionality to check file existence
Breaking Circular Dependencies by Refactoring

- Programming to interfaces is important even for testability
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 to trace execution
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 ...

```html
<!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** test case that fails!

**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

**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 of chunks when no failure occurs

Example

```java
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 transmission trace:

```plaintext
{1, 3, 5, 3, 9, 17, 44, 3, 6, 1, 1, 0, 44, 1, 44, 0}
```
Input Simplification \((n = \text{number of chunks})\)

- **n=2**
  - 1 3 5 3 9 17 44 3 6 1 1 0 44 1 44 0
  - 1 3 5 3 9 17 44 3 6 1 1 0 44 1 44 0

- **n=3**
  - 1 3 5 3 9 17 44 3 6 1 1 0 44 1 44 0
  - 6 1 1 0
  - 6 1
  - 6 1 1 0

- **n=4**
  - 1 3 5 3 9 17 44 3 6 1 1 0 44 1 44 0
  - 6 1 1 0
  - 6 1 1
  - 6 1
  - 6 1 1

- Increase granularity

- Adjust granularity to input size
Simplification Algorithm — Delta Debugging

Prerequisites

- \( \text{test}(c) \in \{\checkmark, \times, ?\} \) runs a test on configuration \( c \)
- Let \( c_{\times} \) be a failing input configuration with
  - \( \text{test}(c_{\times}) = \times \)
  - \( \text{length} \ l = |c_{\times}| \) if \( c_{\times} = \{x_1, \ldots, x_l\} \)
  - \( \text{view at granularity} \ n \leq l: \ c_{\times} = c_1 \cup \cdots \cup c_n, \ c_i \neq \emptyset \)
  - write \( c_i \in_n c \)

Find minimal failing input: call \( \text{dd}_{\text{Min}}(c_0, 2) \) with \( \text{test}(c_0) = \times \)

\[
\text{dd}_{\text{Min}}(c_{\times}, n) =
\begin{cases}
  c_{\times} & |c_{\times}| = 1 \\
  \text{dd}_{\text{Min}}(c_{\times} - c, \max(n-1, 2)) & c \in_n c_{\times} \land \text{test}(c_{\times} - c) = \times \\
  \text{dd}_{\text{Min}}(c_{\times}, \min(2n, |c_{\times}|)) & n < |c_{\times}| \\
  c_{\times} & \text{otherwise}
\end{cases}
\]
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/

Consequences of Minimization

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

Demo: DD.java, Dubbel.java
Principal Limitations of Input Minimization

- Algorithm computes minimal failure-inducting subsequence of the input:
  Taking away any chunk of any length removes the failure
- However, there might be failing inputs with smaller size!
  1. Algorithm investigates only one failing input of smaller size
  2. Misses failure-inducing inputs created by taking away several chunks

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 structure of input

Example (\texttt{.html} input configuration)
\[
\text{\textless SELECT NAME="priority"MULTIPLE SIZE=7> \times}
\]
- 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 $c_x$:

$<\text{SELECT NAME=}&\text{"priority" MULTIPLE SIZE=7}>$

$c_x = \{0, 1, 1.1, 2, 3, 3.1\}$ 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

Definition (Delta Debugging)

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

This principle is used in various debugging activities

Definition (Adaptive Testing)

Test series where each test depends on the outcome of earlier tests
Logging
Log all debugging activities, particularly, test cases and outcomes

Add Testing Interfaces
Avoids presentation layer scripts (brittle!) and interaction (tedious!)

Set Time Limit for Quick-and-Dirty Debugging
Use “naive” debugging when bug seems obvious, but 10 mins max!

Do not Test the Wrong Program
Is the path and filename correct? Did you compile?
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**

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