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Software Quality

Chapter 4

Debugging

4.1 Foundations

4.2 The Debugging Process

4.3 Reproducing Errors

4.4 Simplifying and Automating Test Cases

4.5 Techniques for Defect Localization

4.6 Defect Fixing

Terminology

Debugging – The process of finding and correcting a defect that causes an observed error

Defect (fault) – A faulty element in a program or other artifact

Error – A deviation of an observed result from the expected / correct result

- The term bug may denote a defect or an error
- An error may be caused by a combination of multiple defects
- The very same defect may manifest in more than one error
- „Program“ is meant in a comprehensive way: may be a single method or a component, or a complete system

Causes and Effects

- Typically, a defect
  - does not immediately lead to an error that can be observed,
  - but to faulty program states,
  - that propagate
  - and eventually manifest as observable errors
- The main task of debugging is identifying / reconstructing the cause-effect chain from a defect to an observable error

Where defects occur

- Classic: defect is a coding error, caused by a human mistake
- Alternatively:
  - Defects in other artifacts: requirements specification, system architecture, system design, user manual, ...
  - Defects in the data
  - Defects in processes
  - Human mistakes when using or operating a system
- Some defects are not local, but affect a complete system or sub-system

Example: A simple sorting problem [Zeller 2005]

Name: `sample`

Author: Andreas Zeller

Language: C

Call: `./sample` arg_1 arg_2 ... arg_n

Precondition: arg_1 arg_2 ... arg_n are integers, $n \in$ IN

Postcondition: The arguments appear in ascending order on the standard output device

Executing `sample` with test data:

```
$ ./sample -5 0 -9
Output: -9 -5 0   ✔
$ _
```

```
$ ./sample 11 14
Output: 0 11   ✘
$ _
```

Program `sample`: The code

```
/* sample.c -- Sample C program to be debugged */

#include <stdio.h>
#include <stdlib.h>

static void shell_sort(int a[], int size)
{
    int i, j;
    int h = 1;

do {
        h = h * 3 + 1;
    } while (h <= size);
    do {
        h /= 3;
        for (i = h; i < size; i++)
        {
            int v = a[i];
            for (j = i; j >= h && a[j - h] > v; j -= h)
                a[j] = a[j - h];
            if (i != j)
                a[j] = v;
        }
    } while (h != 1);
}
```

Program `sample`: The code – 2

```
int main(int argc, char *argv[])
{
    int *a;
    int i;

    a = (int *)malloc((argc - 1) * sizeof(int));
    for (i = 0; i < argc - 1; i++)
        a[i] = atoi(argv[i + 1]);

    shell_sort(a, argc);

    printf("Output: ");
    for (i = 0; i < argc - 1; i++)
        printf("%d ", a[i]);
    printf("\n");

    free(a);

    return 0;
}
```

What now?

Observation:

There are input data, for which `sample` computes a wrong result

Question:

- How do we find the defect in the code that causes this error?
- Is there a way of systematically searching for a defect?

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The main steps of the debugging process

- Describe the problem precisely
  - Sometimes this alone reveals the source of the problem
- Is the problem a software error?
  If yes:
  - Perform classic debugging

  If no:
  - Search and fix the problem elsewhere, e.g.
    - Defects in user manuals
    - Faulty business processes
    - Training deficits
- Check the effectiveness of the fix

The classic software debugging process

- Reproduce the error
- Simplify and (if possible) automate the test case that produces the error
- Localize the defect that causes the error
  - Create and test hypotheses
  - Observe program states
  - Check the validity of assertions in the program
  - Isolate cause-effect chains
- Fix the identified defect(s)

Checking the effectiveness of the fix

- Make sure that the defect has been fixed:
  - Re-run the test case(s) that resulted in errors
  - Everything ok now?
- Make sure that the fix did not create any new defects
  - Run your regression test suite
  - No new problems found?

Required infrastructure

- Problem reporting infrastructure
  - Process for handling problem reports
  - Tool for problem report administration and tracking
    For example, Bugzilla
- Configuration management system for software artifacts

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A sample bug report

Example: Mozilla bug report no. 24735 from 1999

-> Start mozilla

-> Go to bugzilla.mozilla.org

-> Select search for bug

-> Print to file setting the bottom and right margins to .50
(I use the file /var/tmp/netscape.ps)

-> Once it's done printing do the exact same thing again on
the same file (/var/tmp/netscape.ps)

-> This causes the browser to crash with a segfault

[Zeller 2005, p. 55]

Goal: Create an as simple as possible test case that reproduces the reported problem

Typical problems

- Reproducing the environment in which the problem occurs
- Reproducing the history trail may be necessary
- For software errors: reproduce a program run that causes the error; this may include
  - Input data
  - Initial persistent data
  - User interaction, interaction with neighboring systems
  - Time
  - Communication with other processes
  - Process threads
  - Random data

Time-dependent errors: a case

In early 1992 a company installed a new barrier gate control system in a couple of parking garages. In the morning of September 12, 1992, the operators of all these garages called the support line and reported the same problem: the exit barriers didn't open anymore.

What caused this problem?

Hint: The date had been coded with two integers, one for the year and one for the day of the year.

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Simplifying

- Given: a test case which reliably causes a reported error
- Goal:
  - Remove all irrelevant parts of the test case
  - Automate the simplified test case
- In an optimally simplified test case, all constituents are relevant, i.e. removing anything from the case no longer produces the reported error
- How to simplify?
  - Simplify environment
  - Reduce history trail
  - Simplify inputs / interactions

Automating

- The error-provoking test case must be executed frequently in the debugging process:
  - for finding simplifications
  - for testing hypotheses when systematically locating a defect

➪ Automation pays off

- Test automation techniques: → Chapter 4 of this course

Simplify the environment

- Determine which states or conditions in the system's environment are relevant and which ones aren't
  - Hardware and operating system
  - State of persistent data
  - Time
  - State of neighboring systems
- Irrelevant states and conditions can be safely ignored
- Goal: minimize the effort for setting up the test environment in which the a test case produces the reported error
- Means: systematic trying

Simplify the error history

- Can we reduce the number of steps, required for provoking the error?
- Means: systematic trying
- Example: Mozilla bug report no. 24735 (see above) reports the following error-provoking sequence of steps:
  Start mozilla; Go to bugzilla.mozilla.org; Select search for bug; Print to file setting the bottom and right margins to .50; Once it's done printing do the exact same thing again on the same file.

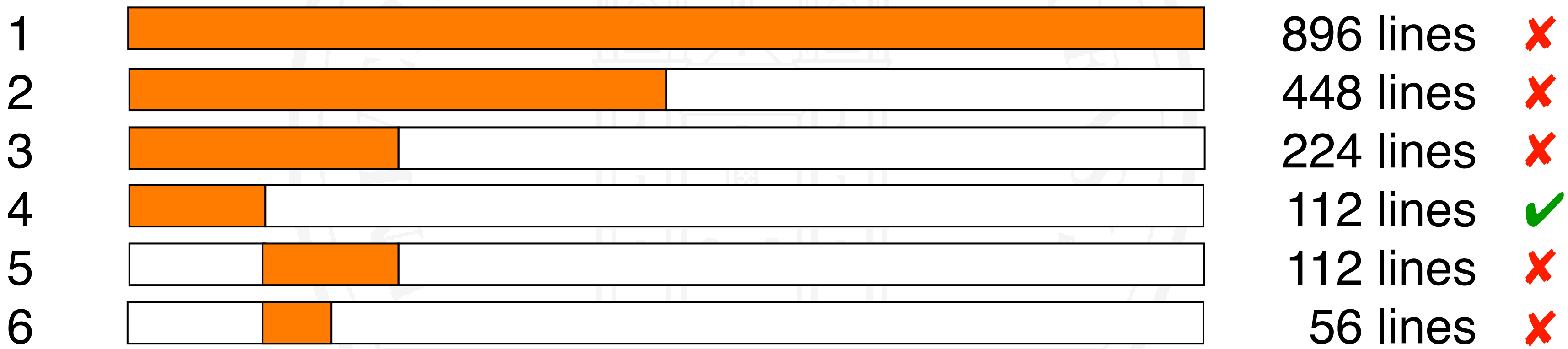
  Actually, the following steps suffice to provoke the error:
  Start mozilla; Go to bugzilla.mozilla.org; Select search for bug; Press Alt-P; Left-click on the Print button in the print dialog window.

Simplify inputs

- Example: Mozilla bug report no. 24735 (see above)
  - The erroneous printing function uses the currently displayed web page as input
  - This page consists of 896 lines of html code
- Which parts of this data cause the error and which ones are irrelevant?
- Means: binary search [Kernighan and Pike 1999]
  - Partition the set of input data into two halves
  - Test both halves individually
  - Recursively continue with that half which provokes the error

Simplify inputs – 2: An example [Zeller 2005]

- Example: Mozilla bug report no. 24735 (see above)
- Binary search yields a single fault-provoking line of html code in twelve steps:



...

12 <SELECT NAME="priority" MULTIPLE SIZE=7> 1 line ✗

Simplify inputs – 3

- What to do if both halves don't provoke the error while the whole does?

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

- Instead of halves use smaller portions, e.g., quarters

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

- Continue with eighths, etc.
- Result: <SELECT> ✘

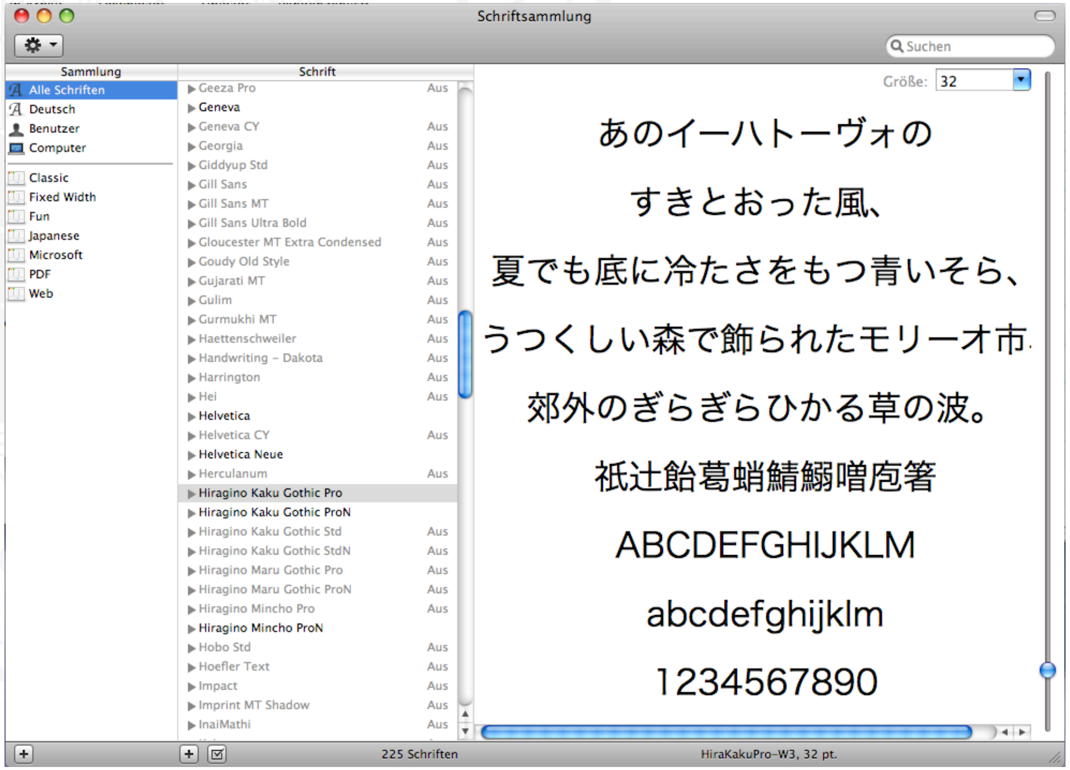
Automating the simplification

- Simplification can be automated partially
  - In particular, the technique of binary searching
  - Applicable for simplification of input data or interaction sequences
- Example: Zeller's ddmin delta debugging algorithm [Zeller 2005, Chapter 5.4-5.5]

Another example

Microsoft PowerPoint 2004 Version 11.0 on MacBook Pro with Mac OS 10.5.6 crashed during startup if the font *Hiragino Kaku Gothic Pro* was disabled in the font collection.

Using interval bisection on the set of all fonts we can find a minimal set of deactivated fonts that causes the error. This set only contains the font Hiragino Kaku Gothic Pro.



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Overview

- Create and test hypotheses
- Static and dynamic program analysis
  - Control flow
  - Data flow
- Analyze program states
- Observe program execution (stepping, breakpointing)
- Dynamically check program assertions
- Determine and isolate cause-effect chains
- Debugging by “gut feeling”

Creating and testing hypotheses

- The basis of systematic debugging
- Principle: Get insight through theory and experimentation
  1. Create a hypothesis
  2. Derive predictions from hypotheses
  3. Verify predictions experimentally
  4. If predictions and experiment results match
     - Correctness of hypothesis becomes more probable
     - Try to further confirm hypothesis

     } → Theory

     Otherwise:
     - Reject hypothesis
     - Create new or modified hypothesis; continue with step 2
- Important: record the track of all tested hypotheses

Finding hypotheses

Possible ways:

- Analysis of problem description
- Static analysis of the code
- Analysis of a erroneous execution run
- Comparison of correct and erroneous execution runs
- Building new hypotheses on the basis of previous ones:
  - Must be compatible with previously accepted
  - Must not use assumptions that stem from previously rejected hypotheses

Derive and check predictions

- Techniques
  - Static or dynamic analysis of the code
  - Observation of system states
  - Dynamic checking of assertions
- Deductive approach: draw logical conclusions from
  - existing knowledge
  - the source code
  - test cases and test results
- Experimental approach: observe
  - program execution
  - program state

Example: Program `sample` (cf. 4.1)

- First hypothesis

  Program runs correctly

  Prediction: Entering `11 14` yields `11 14` as result

  Experiment: `$ ./sample 11 14`

  `Output: 0 11` ✘

  ➥ Hypothesis is rejected

Example: Program `sample` (cf. 4.1)

- Second hypothesis

  Program prints wrong variables

  Prediction: `a[0]==11, a[1]==14`, but result is

  `Output: 0 11`

  Experiment: Replace code for input and sorting by

  ```
  a[0] = 11; a[1] = 14; argc = 3;
  ```

  Result: `Output: 11 14` ✔

  ➥ Hypothesis is rejected

Static and dynamic analysis

- Analyzing the control flow and the data flow of a program (see Chapter 3 on data flow testing and Chapter 11 on static analysis of my Software Engineering course)
- Static Analysis
  - Yields the potentially possible control and data flows
  - No program execution required
  - Independent of any concrete test cases
- Dynamic Analysis
  - Analyzes a concrete program run (based on a test case)
  - Yields actual control and data flows for this run

Example: static vs. dynamic program slicing

```
int main() {
int a, b, sum, mul;
sum = 0;
mul = 1;
a = read ();
b = read ();
while (a<=b) {
sum = sum + a;
mul = mul * a;
a = a +1;
}
write (sum);
write (mul);
}
```

Sample program

```
int main() {
int a, b, sum, mul;
sum = 0;
mul = 1;
a = read ();
b = read ();
while (a<=b) {
sum = sum + a;
mul = mul * a;
a = a +1;
}
write (sum);
write (mul);
}
```

Static slice of mul in line 13

```
int main() {
int a, b, sum, mul;
sum = 0;
mul = 1;
a = read ();
b = read ();
while (a<=b) {
sum = sum + a;
mul = mul * a;
a = a +1;
}
write (sum);
write (mul);
}
```

Dynamic slice of mul in line 13 with a=5, b=2

Analysis of program states

- The problem: a defect typically
  - leads to a sequence of erroneous states
  - that eventually manifest in observable errors
- Check suspicious program states
  - Instrumentation of the code:
    - Record variable values
    - Print or log variable values, maybe using a logging framework such as LOG4J [Logging Services]
  - Using a debugger
    - Compile program in debug mode
    - Halt execution at critical points (by setting breakpoints)
    - Inspect current variable values

Example: Program `sample` (cf. 4.1)

- Third hypothesis

  Sorting procedure called with wrong parameters

  Prediction: Values in array `a` and/or value of `argc` wrong

  Experiment: Prior to the call of shell_sort we instrument the source code with

```
printf("Parameters of shell_sort: ");
for (i = 0; i < argc; i++)
  printf("%d ", a[i]);
printf ("%d ", argc);
printf("\n");
```

  Result: `Parameters of shell_sort: 11 14 0 3` ✘

  ➥ Hypothesis is confirmed

- Alternatively, we could have used a debugger

Example: Program `sample` (continued)

- Theory: The input vector passed to shell_sort contains a non-allocated variable at the end, which is zero
- Prediction 1: Zero will always appear in the result
- Prediction 2: Any input vector containing only negative numbers and a zero will produce correct results
- Experiments:

```
$ ./sample 11 5 7
Output: 0 5 7
```
✘

```
$ ./sample 11 5 1
Output: 0 1 5
```
✘

```
$ ./sample -5 0 -9
Output: -9 -5 0
```
✔

```
$ ./sample 0 -21 -9
Output: -21 -9 0
```
✔

Example: Program `sample` (continued)

- All experiments confirm the theory

➥ Evidence that the passing of parameters to shell_sort is defective

Observe program execution

Using a debugger, we can

- Stepwise execute a program or halt it at breakpoints
  - Compare expected and actual control flow
  - Inspect parts of system state where appropriate
- Observe variable definition, modification and use

Checking assertions

- Specifying contracts for classes and methods with assertions:
  - Preconditions
  - Postconditions
  - Invariants

  Formally specified contracts can be checked dynamically by a suitable runtime system

- When an assertion is violated, analyze the program state

Causes and effects

- An observation:
  - In the decade of 1950 to1960 the decline of the population of storks in Europe is strongly correlated with the increasing number of tarmac roads
- Question:
  - Is the increasing number of tarmac roads the / a cause for the disappearance of storks?
- Testing for causality: a is a cause for b iff
  - b occurs if a has occurred previously
  - b does not occur if a has not occurred previously
  - All other variables are kept constant

Causes and effects – 2

- Experimental proof of (or evidence for) causality
  - Generally rather difficult: Problem of controlled experiments
  - For debugging, it is doable:
    - Controlled environment
    - Test case reproducible
- In debugging, a cause for an error f can be viewed as the difference between
  - a test case exhibiting the error f (1)
  - a test case that runs correctly (2)
- Again, we look for a minimal cause

➥ Search a minimal difference between (1) and (2)

Example: Program `sample` (cf. 4.1)

- Fourth hypothesis

  `shell_sort` *should be called with* `argc-1` *(instead of* `argc`*)*

  Prediction: Result is correct

  Experiment: Execute with modified source code (or modify state of running program with a debugger)

  Result: `Output: 11 14` ✔

  ➥ Hypothesis is confirmed

- From the first hypothesis we know that calling shell_sort with `argc` leads to an error
- The difference in the code is „`-1`“ in line 36
- This is a minimal cause of the error

Identifying and isolating cause-effect chains

- The immediate cause of an error normally is not a defect, but an erroneous program state, eventually caused by a defect
  - Identify cause-effect chains
  - and isolate them from the irrelevant rest of the program
- Time-consuming: Requires creation and test of many hypotheses
- Systematic procedure needed
- Automatable: Zeller's Delta Debugging algorithm [Zeller 2002]

Isolating causes with Delta Debugging

- Difference between isolation and simplification:
  - Simplification: Find a minimal error-provoking test case
  - Isolation: Find an error-provoking and an error-free test case with a minimal difference
- Example: Isolation of minimal error cause in this input:

Minimal difference = minimal cause

Error-provoking:	`5;6;2:1;`	✘	Reduce erroneous case ↓
	`5;6;2:1;`	✔	
	`5;6;2:1;`	✔	
	`5;6;2:1;`	✔	Extend error-free case ↑
Error-free:	∅ (empty input)	✔	

Debugging by gut feeling

- To some extent, experienced software engineers develop an ability to "smell" the cause of an error
- In many cases, debugging by intuition is faster than any systematic debugging procedure
- Problem:
  - We need to stop intuitive debugging at the right time when it does not succeed...
  - ...and then switch to systematic debugging
- Suggested procedure
  - For a strictly limited time, debug by intuition
  - If success: Eureka! else: stop and start systematic debugging

Fixing a localized defect

If a defect has been located

- Estimate severity of defect
- Determine what and how much has to be fixed
- Estimate impact on other parts of the system
- Make the required modifications to the code and/or the documentation carefully and systematically
- Avoid quick-and-dirty patching of code

Check effectiveness of problem resolution

- Make sure that the reported problem no longer exists
  In case of software errors:
  - Inspect the modified code and documentation
  - Test the modified units
    - using the error-provoking test case(s)
    - by writing more unit test cases
- Check for unexpected side effects
  - Adapt the regression test suite to the modified code
  - Perform a regression test
- Create a new configuration / release

Learning from the fixed defect

Defects are typically due to mistakes by humans

- Try to determine / guess the reasons why somebody made the mistake(s) that led to the defect
- Investigate if there are any similar defects in the source code that stem from the same kind of mistake
- Are there any constructive means to avoid such defects in the future, e.g., by
  - changing a process
  - training people

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