Lecture 18

Delta Debugging--
Yesterday my program worked, it does not. Why?

This Week - Fault Localization

- Debugging is a process of finding a defect during program execution.
- In other words, it is a process of localizing / pinpointing a defect (isolating a defect).
- It is often called as "Fault localization" as well.

This Week - Fault Localization

- Two seminal papers in the area of fault localization
  - Andreas Zeller, "Yesterday my program worked, today it does not. Why?" FSE 1999
  - Ben Liblit et al., "Bug isolation via remote program sampling," PLDI 2003
- Some slides are borrowed from Dr. Andreas Zeller at University of Saarland and Dr. Ben Liblit at the University of Wisconsin, Madison.
- If you don't know yet, Dr. Andreas Zeller is the famous author of DDD.

Today's Agenda

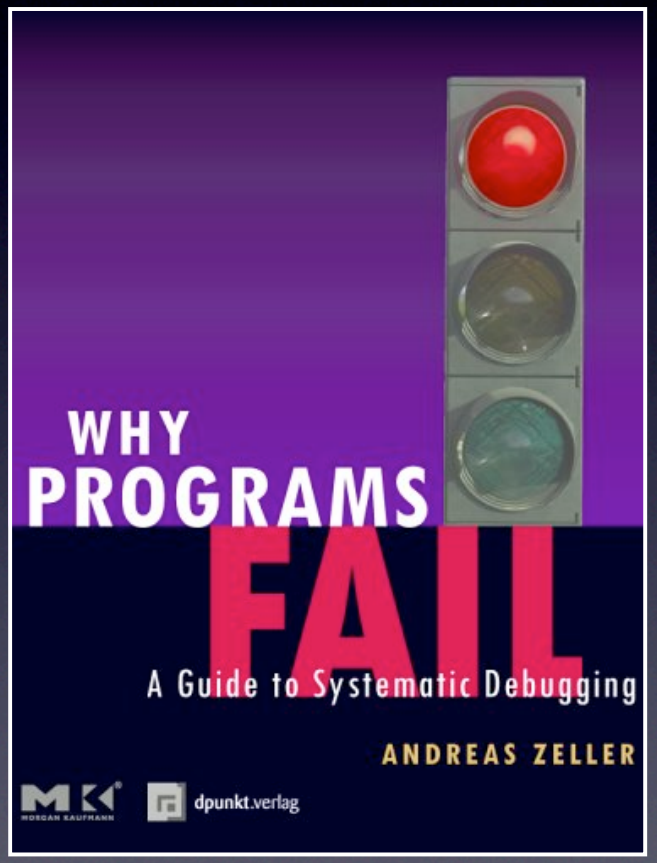
- Presentation:
  - Guarav Gutpa (Advocate)
  - Tileli Amimeur (Skeptic)
- Delta Debugging: Problem Space
  - Scenarios
  - Problem Characterization

Today's Agenda

- Delta Debugging: Solution Space
  - Simplifying and Isolating failure causes
  - Applications of Delta Debugging Algorithm

Highly recommend this book, "Why Programs Fail"

- How can I reproduce failures faithfully?
- How can I isolate automatically what's relevant for the failure?
- How does the failure come to be?
- How can I fix the program in the best possible way?



Although many programmers consider debugging as the most painful part of software development, few books are available for computer science students and practitioners to learn about scientific methods in debugging.

In this book, Andreas Zeller does an excellent job introducing useful debugging techniques and tools invented in both academia and industry. The book is easy to read and actually very fun as well—don't overlook all the bug stories included.
I strongly recommend this book to graduate and undergraduate students interested in software engineering research. It will not only help you discover a new perspective on debugging, but it will also teach you some fundamental static and dynamic program analysis techniques in plain language.
—MIRYUNG KIM, Graduate Student, University of Washington

Today's Presenters

- Guarav (Advocate)
- Tilelli (Skeptic)

Simplifying Problems

Andreas Zeller

Simplifying

- Once one has reproduced a problem, one must find out *what's relevant*:
  - Does the problem really depend on 10,000 lines of input?
  - Does the failure really require this exact schedule?
  - Do we need this sequence of calls?

Why simplify?

Simplifying

- For every circumstance of the problem, check whether it is relevant for the problem to occur.
- If it is not, remove it from the problem report or the test case in question.

Circumstances

- Any aspect that may influence a problem is a *circumstance:*
  - Aspects of the problem environment
  - Individual steps of the problem history

Experimentation

- By *experimentation*, one finds out whether a circumstance is relevant or not:
- Omit the circumstance and try to reproduce the problem.
- The circumstance is relevant if and only if the problem no longer occurs.

Mozilla Bug #24735

Ok the following operations cause mozilla to crash consistently on my machine

-> 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

bugzilla.mozilla.org

```
<SELECT NAME="op_sys" MULTIPLE SIZE=7>
<OPTION VALUE="All">All<OPTION VALUE="Windows 3.1">Windows 3.1<OPTION
VALUE="Windows 95">Windows 95<OPTION VALUE="Windows 98">Windows
98<OPTION VALUE="Windows ME">Windows ME<OPTION VALUE="Windows
2000">Windows 2000<OPTION VALUE="Windows NT">Windows NT<OPTION
VALUE="Mac System 7">Mac System 7<OPTION VALUE="Mac System 7.5">Mac
System 7.5<OPTION VALUE="Mac System 7.6.1">Mac System 7.6.1<OPTION
VALUE="Mac System 8.0">Mac System 8.0<OPTION VALUE="Mac System
8.5">Mac System 8.5<OPTION VALUE="Mac System 8.6">Mac System
8.6<OPTION VALUE="Mac System 9.x">Mac System 9.x<OPTION VALUE="MacOS
X">MacOS X<OPTION VALUE="Linux">Linux<OPTION VALUE="BSDI">BSDI<OPTION
VALUE="FreeBSD">FreeBSD<OPTION VALUE="NetBSD">NetBSD<OPTION
VALUE="OpenBSD">OpenBSD<OPTION VALUE="AIX">AIX<OPTION
VALUE="BeOS">BeOS<OPTION VALUE="HP-UX">HP-UX<OPTION
VALUE="IRIX">IRIX<OPTION VALUE="Neutrino">Neutrino<OPTION
VALUE="OpenVMS">OpenVMS<OPTION VALUE="OS/2">OS/2<OPTION VALUE="OSF/
1">OSF/1<OPTION VALUE="Solaris">Solaris<OPTION
VALUE="SunOS">SunOS<OPTION VALUE="other">other</SELECT>

</td>
<td align=left valign=top>
<SELECT NAME="priority" MULTIPLE SIZE=7>
<OPTION VALUE="--">--<OPTION VALUE="P1">P1<OPTION VALUE="P2">P2<OPTION
VALUE="P3">P3<OPTION VALUE="P4">P4<OPTION VALUE="P5">P5</SELECT>
```

What's relevant in here?

Why simplify?

- Ease of communication. A simplified test case is easier to communicate.
- Easier debugging. Smaller test cases result in smaller states and shorter executions.
- Identify duplicates. Simplified test cases *subsume* several duplicates.

The Gecko BugAThon

- Download the Web page to your machine.
- Using a text editor, start removing HTML from the page. Every few minutes, make sure it still reproduces the bug.
- Code not required to reproduce the bug can be safely removed.
- When you've cut away as much as you can, you're done.

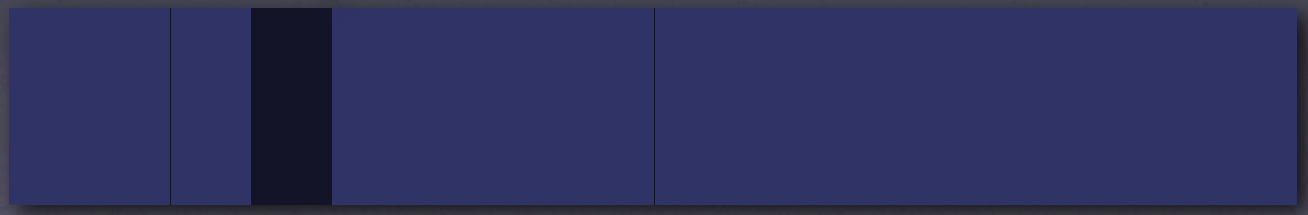
Rewards

5 bugs - invitation to the Gecko launch party
10 bugs - the invitation, plus an attractive Gecko stuffed animal
12 bugs - the invitation, plus an attractive Gecko stuffed animal autographed by Rick Gessner, the Father of Gecko
15 bugs - the invitation, plus a Gecko T-shirt
20 bugs - the invitation, plus a Gecko T-shirt signed by the whole raptor team

Binary Search

- Proceed by binary search. Throw away half the input and see if the output is still wrong.
- If not, go back to the previous state and discard the other half of the input.

HTML input



Simplified Input

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

- Simplified from 896 lines to one single line
- Required 12 tests only

Benefits

- Ease of communication. All one needs is "Printing <SELECT> crashes".
- Easier debugging. We can directly focus on the piece of code that prints <SELECT>.
- Identify duplicates. Check other test cases whether they're <SELECT>-related, too.

Why automate?

- Manual simplification is *tedious*.
- Manual simplification is *boring*.
- We have machines for tedious and boring tasks.

Basic Idea

- We set up an *automated test* that checks whether the failure occurs or not (= Mozilla crashes when printing or not)
- We implement a *strategy* that realizes the binary search.

Automated Test

1. Launch Mozilla
2. Replay (previously recorded) steps from problem report
3. Wait to see whether
   - Mozilla crashes (= the test *fails*)
   - Mozilla still runs (= the test *passes*)
4. If neither happens, the test is *unresolved*

Binary Search

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

What do we do if *both halves* pass?

Configuration

Circumstance

$$\delta$$

All circumstances

$$C = \{\delta_1, \delta_2, \ldots\}$$

Configuration $c \subseteq C$

$$c = \{\delta_1, \delta_2, \ldots \delta_n\}$$

Tests

Testing function

$$test(c) \in \{✔, ✘, ?\}$$

Failure-inducing configuration

$$test(c_{✘}) = ✘$$

Relevant configuration $c'_{✘} \subseteq c_{✘}$

$$\forall \delta_i \in c'_{✘} \cdot test(c'_{✘} \setminus \{\delta_i\}) \neq ✘$$

Binary Strategy

Split input

$$c_{\text{✗}} = c_1 \cup c_2$$

If removing first half fails…

$$test(c_{\text{✗}} \setminus c_1) = \text{✗} \implies c_{\text{✗}}' = c_{\text{✗}} \setminus c_1$$

If removing second half fails…

$$test(c_{\text{✗}} \setminus c_2) = \text{✗} \implies c_{\text{✗}}' = c_{\text{✗}} \setminus c_2$$

Otherwise, increase granularity:

$$c_{\text{✗}} = c_1 \cup c_2 \cup c_3 \cup c_4$$

$$c_{\text{✗}} = c_1 \cup c_2 \cup c_3 \cup c_4 \cup c_5 \cup c_6 \cup c_7 \cup c_8$$

General Strategy

Split input into *n* parts (initially 2)

$$c_{\text{✘}} = c_1 \cup c_2 \cup \cdots \cup c_n$$

If some removal fails…

$$\exists i \in \{1, \ldots, n\} \cdot test(c_{\text{✘}} \setminus c_i) = \text{✘} \implies \begin{array}{l} c_{\text{✘}}' = c_{\text{✘}} \setminus c_i \\ n' = \max(n-1, 2) \end{array}$$

Otherwise, increase granularity

$$c_{\text{✘}}' = c_{\text{✘}} \quad n' = 2n$$

ddmin in a Nutshell

$c'_{\text{✘}} = ddmin(c_{\text{✘}})$ is a relevant configuration

$ddmin(c_{\text{✘}}) = ddmin'(c'_{\text{✘}}, 2)$ with $ddmin'(c'_{\text{✘}}, n) =$

$$\begin{cases} c'_{\text{✘}} & \text{if } |c'_{\text{✘}}| = 1 \\ ddmin'(c'_{\text{✘}} \setminus c_i, \max(n-1, 2)) & \text{else if } \exists i \in \{1..n\} \cdot test(c'_{\text{✘}} \setminus c_i) = \text{✘} \\ & \text{(“some removal fails”)} \\ ddmin'(c'_{\text{✘}}, \min(2n, |c'_{\text{✘}}|)) & \text{else if } n < |c'_{\text{✘}}| \text{ (“increase granularity”)} \\ c'_{\text{✘}} & \text{otherwise} \end{cases}$$

where $c'_{\text{✘}} = c_1 \cup c_2 \cup \cdots \cup c_n$

$$\forall c_i, c_j \cdot c_i \cap c_j = \emptyset \wedge |c_i| \approx |c_j|$$

```
def _ddmin(circumstances, n):
    while len(circumstances) >= 2:
        subsets = split(circumstances, n)

        some_complement_is_failing = 0
        for subset in subsets:
            complement = listminus(circumstances, subset)
            if test(complement) == FAIL:
                circumstances = complement
                n = max(n - 1, 2)
                some_complement_is_failing = 1
                break

        if not some_complement_is_failing:
            if n == len(circumstances):
                break
            n = min(n * 2, len(circumstances))

    return circumstances
```

ddmin at Work

Input: <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨40 characters⟩ ✘
<SELECT NAME="priority" MULTIPLE SIZE=7> ⟨0 characters⟩ ✔

```
 1 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨20⟩ ✔
 2 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨20⟩ ✔
 3 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨30⟩ ✔
 4 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨30⟩ ✘
 5 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨20⟩ ✔
 6 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨20⟩ ✘
 7 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
 8 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
 9 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨15⟩ ✔
10 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨15⟩ ✔
11 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨15⟩ ✘
12 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
13 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
14 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
15 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨12⟩ ✔
16 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨13⟩ ✔
17 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨12⟩ ✔
18 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨13⟩ ✘
19 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
20 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✔
21 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨11⟩ ✔
22 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨10⟩ ✘
23 <SELECT NAME="priority" MULTIPLE SIZE=7>  ⟨7⟩ ✔
24 <SELECT NAME="priority" MULTIPLE SIZE=7>  ⟨8⟩ ✔
25 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
26 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨8⟩ ✔
27 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨9⟩ ✔
28 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨9⟩ ✔
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37 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
38 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
39 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨6⟩ ✔
40 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
41 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
42 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
43 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
44 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
45 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
46 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
47 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
48 <SELECT NAME="priority" MULTIPLE SIZE=7> ⟨7⟩ ✔
```

Result: <SELECT>

Complexity

- The maximal number of *ddmin* tests is

$$\frac{(|c_{\times}|^2 + 7|c_{\times}|)}{2}$$

Worst Case Details

First phase: every test is unresolved

$$t = 2 + 4 + 8 + \cdots + 2|c_{\times}|$$
$$= 2|c_{\times}| + |c_{\times}| + \frac{|c_{\times}|}{2} + \frac{|c_{\times}|}{4} + \cdots = 4|c_{\times}|$$

Second phase: testing *last* set always fails

$$t' = (|c_{\times}| - 1) + (|c_{\times}| - 2) + \cdots + 1$$
$$= 1 + 2 + 3 + \cdots + (|c_{\times}| - 1)$$
$$= \frac{|c_{\times}|(|c_{\times}| - 1)}{2} = \frac{|c_{\times}|^2 - |c_{\times}|}{2}$$

Binary Search

If

- there is only one failure-inducing circumstance, and
- all configurations that include this circumstance fail,

the number of tests is $t \leq \log_2(|c_{\times}|)$

Optimization

- Caching
- Stop Early
- Syntactic Simplification
- Isolate Differences, not Circumstances

Caching

- Basic idea: store the results of earlier test()
- Saves 8 out of 48 tests in <SELECT> example

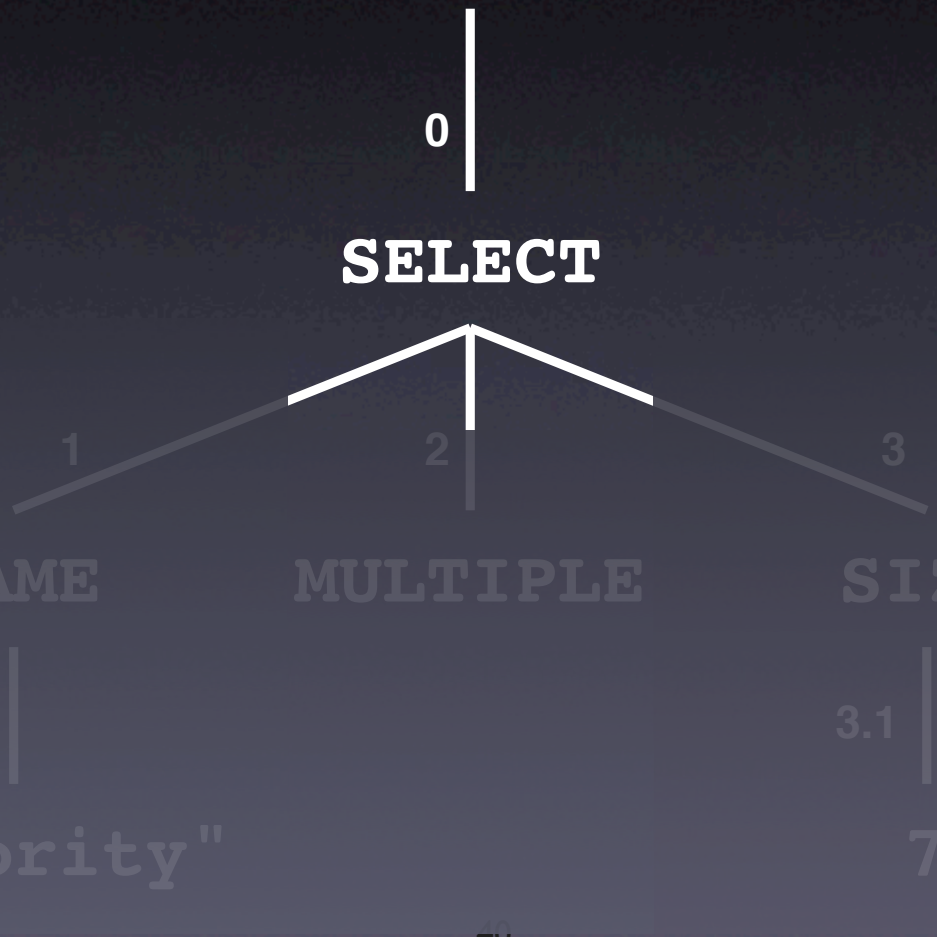
Stop Early

One may stop simplification when

- a certain *granularity* has been reached
- no *progress* has been made
- a certain *amount of time* has elapsed

Syntactic Simplification

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



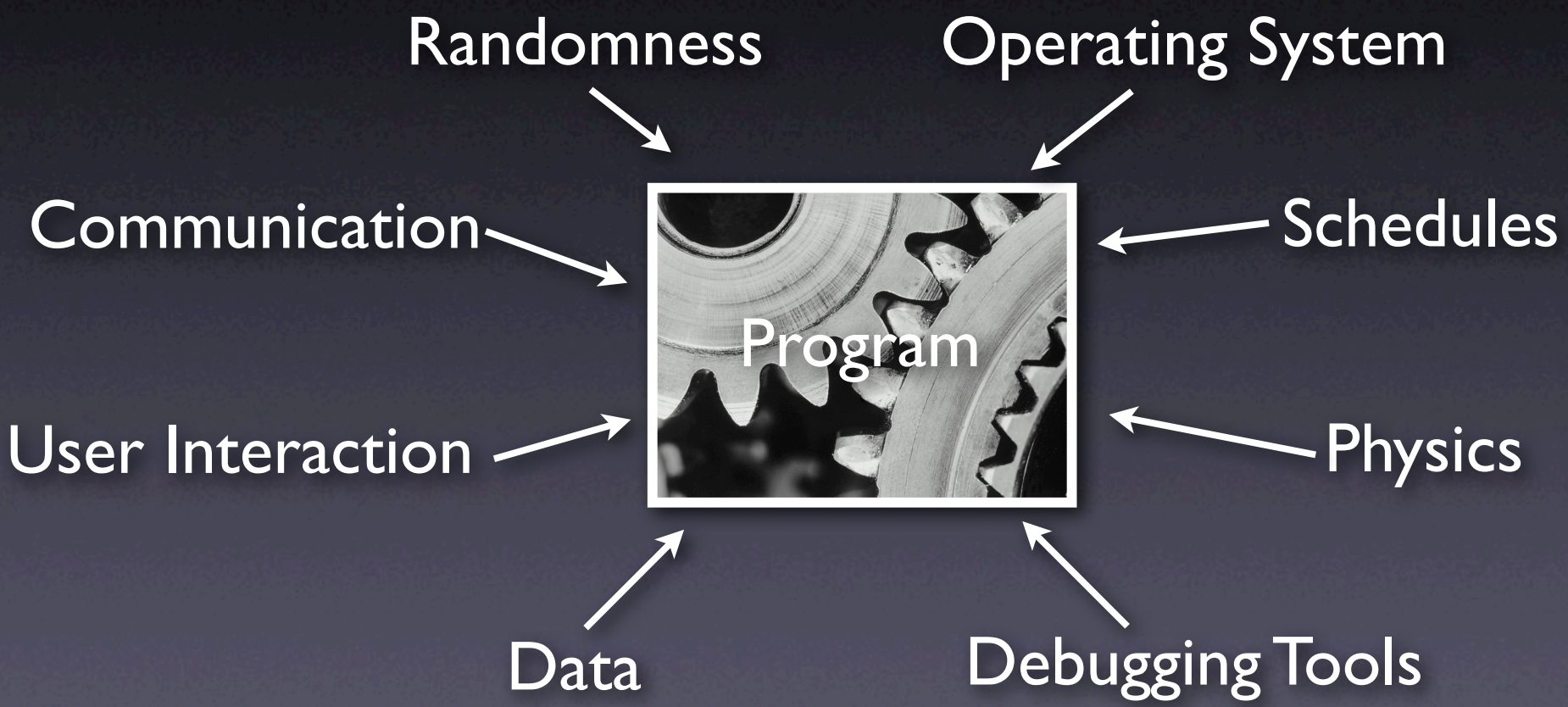
Differences

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

The extra “<” is failure-inducing!

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

More Circumstances



More Automation

- Failure-Inducing Input
- Failure-Inducing Code Changes
- Failure-Inducing Schedules
- Failure-Inducing Program States

Concepts

- The aim of simplification is to create a simple *test case* from a problem report.
- Simplified test cases…
  - are easier to communicate
  - facilitate debugging
  - identify duplicate problem reports

Concepts (2)

- To simplify a test case, remove all irrelevant circumstances.
- A circumstance is irrelevant if the problem occurs regardless of whether the circumstance is present or not.

Concepts (3)

- To automate simplification, set up
  - an *automated test*
  - a *strategy* to determine the relevant circumstances
- One such strategy is the *ddmin* delta debugging algorithm

Preview for Next Lecture

- Applications of Delta Debugging Algorithms
- Cooperative Bug Isolation by B. Liblit
- We may have a quiz on the delta debugging algorithm.
- Updated quiz solutions are posted.