Debugging
(with and without Debuggers)

Debuggers

- A very real interactive debugger: **gdb**
  - Widely used
  - Runs on everything
  - A classic implementation
    - Mostly standard debugger technology
- Design decisions
  - Runs and instruments object code
  - Must map accurately between source/object code
  - Must deal with many different machines
  - Must be well-integrated with the compiler

gdb Architecture

Three major pieces

1. User interface
2. Symbol piece
   - Mapping from source code to object code constructs
   - Dump the compile-time information into extra tables in the object code (at least when debugging is on)
   - Typically, most compiler optimizations are disabled
     - Otherwise, we lose track of the position of source lines
3. Execution piece
   - Run object code
   - Disassemble object code
   - Manipulate stack frames
   - Set breakpoints

Breakpoints

- The fundamental debugging primitive
- How does it work?
  - Via an object code rewriting hack
  - To stop at line 42, write an invalid opcode at line 42
    - Invalid opcode should be as small as possible
  - Trap resulting fault, recover, and switch to the UI

Single Stepping

- To single step:
  - Set breakpoint at next instruction
  - Resume execution
  - Trap exception, clear breakpoint, repeat
- Or:
  - Use hardware interpreter
  - Interpret instructions to the next source statement

Other Features

- Based on breakpoints
  - Skip over function call
  - Break on nth execution of a statement
- Based on exploiting compile-time information
  - Print the call stack
  - Etc.

Host/Target

- **gdb** can be used to debug a program on a remote machine
  - **gdb** runs on the host
  - Program runs on the target
- Introduces cross-architecture issues

A Big Problem with Debuggers

- Seemingly unavoidable lack of support for optimized code
- Makes it difficult to debug "the real thing"
  - Find compiler bugs
  - Find timing-dependent bugs
  - Find resource/performance bugs
- True for any known approach to debuggers

Debugger Advantages

- Works even if source is not available
  - Albeit crippled
- Responsive
  - Interactive experience is good
  - Scales well with object code size

Debugging without Debuggers

Debugging without Debuggers

- Debugging is more than debuggers
- In fact, debuggers are often the last resort
- Two other common problems:
  - Figuring out which program change caused a bug
  - Reducing a test case to a minimal example

A Generic Algorithm

- How do people solve these problems?
- Binary search
  - Cut the test case in half
  - Iterate
- Brilliant idea: *Why not automate this?*

Delta Debugging

- Find set of changes that cause a program to fail a test case
- Want to find a minimal set of changes that cause failure

Example

- Printing the following file causes Mozilla to crash:

```
<td align=left valign=top>
<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
```

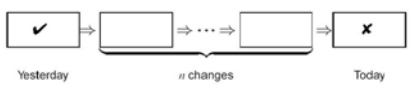


```
VALUE="BeOS">BeOS<OPTION VALUE="HP-UX">HP-UX<OPTION
VALUE="IRIX">IRIX<OPTION VALUE="Neutrino">Neutrino<OPTION
VALUE="OpenVMS">OpenVMS<OPTION VALUE="OS/2">OS/2<OPTION
VALUE="OSF/1">OSF/1<OPTION VALUE="Solaris">Solaris<OPTION
VALUE="SunOS">SunOS<OPTION VALUE="other">other</SELECT></td>
<td align=left 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>
</td>
<td align=left valign=top>
<SELECT NAME="bug severity" MULTIPLE SIZE=7>
<OPTION VALUE="blocker">blocker<OPTION
VALUE="critical">critical<OPTION VALUE="major">major<OPTION
VALUE="normal">normal<OPTION VALUE="minor">minor<OPTION
VALUE="trivial">trivial<OPTION
VALUE="enhancement">enhancement</SELECT>
</tr>
</table>
```


Example

- Now looking at that file it is hard to figure out what the real cause of the failure is
- It would be very helpful in finding the error if we can simplify the input file and still generate the same failure

Worked Yesterday, Not Today



- Yesterday, my program worked. Today, it does not. Why?
  - The new release 4.17 of GDB changed 178,000 lines
  - it no longer integrated properly with DDD (a graphical front-end)
  - How to isolate the change that caused the failure.

GCC-2.95.2 Crash

```
double bug(double z[], int n)
{
  int i , j ;
  i = 0;
  for (j = 0; j < n; j++) {
    i = i + j + 1;
    z[i] = z[i] *(z[0]+1.0);
  }
  return z[n];
}
$ gcc-2.95.2 -O bug.c
  gcc: Internal error:
   program cc1 got fatal
   signal 11
$ _
```

- What are the *causes* for GCC crashing?

Delta Debugging Version I

- Assume
  - There is a set of changes C
  - There is a single change that caused failure
  - Every set of changes is possible
    - Any subset produces a test case that either passes ✓ or fails ×

Algorithm for Version I

/* invariant: P with changes $c_1,\ldots,c_n$ fails */

DD(P, $\{c_1,\ldots,c_n\}$) =
  if n = 1 return $\{c_1\}$
  let $P_1 = P \oplus \{c_1 \ldots c_{n/2}\}$
  let $P_2 = P \oplus \{c_{n/2+1} \ldots c_n\}$
  if P_1 = ✓
    then DD(P, $\{c_{n/2+1} \ldots c_n\}$)
    else DD(P, $\{c_1 \ldots c_{n/2}\}$)

This is just binary search . . .

Extensions

- Let's get fancy. Assume:
- Any subset of changes may cause the bug
  - But no undetermined (?) tests, yet
- And the world is
  - *Monotonic:*
    $P \oplus C = \times \Rightarrow P \oplus (C \cup C') \neq \checkmark$
  - *Unambiguous:*
    $P \oplus C = \times \wedge P \oplus C' = \times \Rightarrow P \oplus (C \cap C') \neq \checkmark$
  - *Consistent*
    $P \oplus C \neq ?$

Scenarios

Try binary search:
- Divide changes C into C_1 and C_2
- If $P \oplus C_1$ = ×, recurse with C_1
- If $P \oplus C_2$ = ×, recurse with C_2

- Notes:
  - At most one case can apply, by unambiguity
  - By consistency, only other possibility is
    $P \oplus C_1 = \checkmark$ and $P \oplus C_2 = \checkmark$
  - What happens in this case?

Interference

By monotonicity, if $P \oplus C_1 = \checkmark$ and $P \oplus C_2 = \checkmark$
then no subset of C_1 or C_2 causes failure

So the failure must be a combination of elements from C_1 and C_2

This is called *interference*

Handling Interference

- The cute trick:
  - Consider $P \oplus C_1$
    - Find minimal $D_2 \subseteq C_2$ s.t. $P \oplus C_1 \cup D_2 = \times$
  - Consider $P \oplus C_2$
    - Find minimal $D_1 \subseteq C_1$ s.t. $P \oplus C_2 \cup D_1 = \times$
  - Then by unambiguity
    $P \oplus ((C_1 \cup D_2) \cap (C_2 \cup D_1)) = P \oplus (D_1 \cup D_2)$
  - This is also minimal

Example: 3 & 6 (of 8) Cause Failure

1	2	3	4	5	6	7	8	result	
1	2	3	4					✓	
				5	6	7	8	✓	*interference*
1	2			5	6	7	8	✓	
		3	4	5	6	7	8	×	
		(3)		5	6	7	8	×	
1	2	3	4	5	6			×	
1	2	3	4	5				✓	
1	2	3	4		(6)			×	

Algorithm

/* invariant: P with changes $c_1,\ldots,c_n$ fails */

DD(P, $\{c_1,\ldots,c_n\}$) =
  if n = 1 return $\{c_1\}$
  $P_1 \leftarrow P \oplus \{c_1 \ldots c_{n/2}\}$
  $P_2 \leftarrow P \oplus \{c_{n/2+1} \ldots c_n\}$
  if P_1 = × then DD(P,)
  elseif P_2 = × then DD(P,)
  else DD(P_2,) [DD(P_1,)

Algorithm

/* invariant: P with changes $c_1,\ldots,c_n$ fails */

DD(P, $\{c_1,\ldots,c_n\}$) =
  if n = 1 return $\{c_1\}$
  $P_1 \leftarrow P \oplus \{c_1 \ldots c_{n/2}\}$
  $P_2 \leftarrow P \oplus \{c_{n/2+1} \ldots c_n\}$
  if P_1 = × then DD(P, $\{c_1 \ldots c_{n/2}\}$)
  elseif P_2 = × then DD(P, $\{c_{n/2+1} \ldots c_n\}$)
  else DD(P_2,$\{c_1 \ldots c_{n/2}\}$) [DD(P_1,$\{c_{n/2+1} \ldots c_n\}$)

Complexity

- If a single change induces the failure, then logarithmic
  - Why?
- Otherwise, linear
  - Assumes constant time per invocation
  - Is this realistic?

Example

- Assume that we know that when Mozilla tries to print the following HTML input it crashes:

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

- How can we go about simplifying this input?
  - Remove parts of the input and see if it still causes the program to crash
- For the above example assume that we remove characters from the input file

Bold parts remain in the input, the rest is removed

1	**<SELECT NAME="priority" MULTIPLE SIZE=7>**	F
2	<SELECT NAME="priori**ty" MULTIPLE SIZE=7>**	P
3	**<SELECT NAME="priori**ty" MULTIPLE SIZE=7>	P
4	<SELECT NA**ME="priority" MULTIPLE SIZE=7>**	P
5	**<SELECT NA**ME="priori**ty" MULTIPLE SIZE=7>**	F
6	**<SELECT NA**ME="priority" MULTIP**LE SIZE=7>**	F
7	**<SELECT NA**ME="priority" MULTIPLE SIZE=7>	P
8	<SELE**CT NA**ME="priority" MULTIP**LE SIZE=7>**	P
9	**<SELE**CT NAME="priority" MULTIP**LE SIZE=7>**	P
10	**<SELECT NA**ME="priority" MULTIPLE SI**ZE=7>**	F
11	**<SELECT NA**ME="priority" MULTIPLE SIZE=7>	P
12	<S**ELECT NA**ME="priority" MULTIPLE SI**ZE=7>**	P
13	**<S**ELECT NAME="priority" MULTIPLE SI**ZE=7>**	P

F means input caused failure
P means input did not cause failure (input passed)

```
14    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
15    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
16    <SELECT NAME="priority" MULTIPLE SIZE=7>    F
17    <SELECT NAME="priority" MULTIPLE SIZE=7>    F
18    <SELECT NAME="priority" MULTIPLE SIZE=7>    F
19    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
20    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
21    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
22    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
23    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
24    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
25    <SELECT NAME="priority" MULTIPLE SIZE=7>    P
26    <SELECT NAME="priority" MULTIPLE SIZE=7>    F
```


Example

- After 26 tries we found that printing an HTML file which consists of:

<SELECT>

causes Mozilla to crash

- Delta debugging technique automates this approach of repeated trials for reducing the input

Delta Debugging ++: Revisit the Assumptions

- All three assumptions are suspect
  - *Monotonic:*
    $$P \oplus C = \times \Rightarrow P \oplus (C \cup C') \neq \checkmark$$
  - *Unambiguous:*
    $$P \oplus C = \times \wedge P \oplus C' = \times \Rightarrow P \oplus (C \cap C') \neq \checkmark$$
  - *Consistent*
    $$P \oplus C \neq ?$$

Delta Debugging ++

- Drop all of the assumptions
- What can we do?
- Problem formulation

  Find a set of changes that cause the problem, but removing any change causes the problem to go away
- This is *1-minimality*

Model

- A test either
  - Passes ✓
  - Fails ×
  - Is unresolved ?

Naïve Algorithm

- To find a 1-minimal subset of C, simply
- Remove one element c from C
- If $C - \{c\} = \times$, recurse with smaller set
- If $C - \{c\} \neq \times$, C is 1-minimal

Analysis

- In the worst case,
  - We remove one element from the set per iteration
  - After trying every other element
- Work is potentially

  $N + (N-1) + (N-2) + \ldots$
- This is $O(N^2)$

Work Smarter, Not Harder

- We can often do better
- Silly to start out removing 1 element at a time
  - Try dividing change set in 2 initially
  - Increase # of subsets if we can't make progress
  - If we get lucky, search will converge quickly

Algorithm

DD(P, C) =
  split C into $C_1 \ldots C_n$ (initially n=2)
  if $P \oplus C_i$ = ✗ then DD(P, C_i)
  if $P \oplus \neg C_i$ = ✗ then DD(P, $C_1 \cup \ldots \cup C_{i-1} \cup C_{i+1} \cup \ldots \cup C_n$})
  else double n and try again

Analysis

- Worst case is still quadratic
- Subdivide until each set is of size 1
  - Reduced to the naïve algorithm
- Good news
  - For single, monotone failure, converges in log N
  - Binary search again

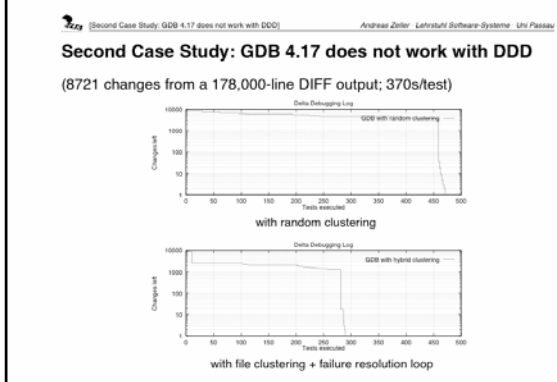
Case Studies

- Many in the papers
  - And convincing, too
- Isolating failure in modified **gdb**
  - 178,000 modified source lines
  - Symptom was that program simply crashed
  - What was the bug? Changing

    "Set arguments to give . . ."

    to

    "Set argument list to give . . ."



Failure Inducing Differences: Example

- Changing the input program for GCC from the one on the left to the one on the right removes the failure

This input causes failure

```
#define SIZE 20
double mult(double z[], int n)
{
  int i , j ;
  i = 0;
  for (j = 0; j < n; j++) {
    i = i + j + 1;
    z[i] = z[i] *(z[0]+1.0);
  return z[n];
}
```

This input does not cause failure

```
#define SIZE 20
double mult(double z[], int n)
{
  int i , j ;
  i = 0;
  for (j = 0; j < n; j++) {
    i + j + 1;
    z[i] = z[i] *(z[0]+1.0);
  return z[n];
}
```

Modified statement is shown in box

The Importance of Changes

- Basic to delta debugging is a *change*
  - We must be able to express the difference between the good and bad examples as a set of changes
- But notion of change is semantic
  - Not easy to capture in a general way in a tool
- And notion of change is algorithmic
  - Poor notion of change) many unresolved tests
  - Performance goes from linear (or sub-linear) to quadratic

Notion of Change

- We can see this in the experiments
  - Some **gdb** experiments took 48 hours
  - Improvements came from improving notion of changes
- Also important to exploit correlations between changes
  - Some subsets of changes require other changes
  - Again, can affect asymptotic performance

Opinion

- Delta Debugging is a technique, not a tool
- Bad News:
  - Probably must be reimplemented for each significant system
  - To exploit knowledge of changes
- Good News:
  - Relatively simple algorithm, significant payoff
  - It's worth reimplementing