Debugging

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Software Testing and Measurement

(Automated) Debugging: A Sorting Program

```
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]);
free(a);
return 0;
}
```

```
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);
}
```

(Automated) Debugging: A Sorting Program

Once upon a time, a tester found the following bug:

```
$ ./simple 5 4 3 2 1 666666
Output:  0 1 2 3 4 5
```

How do we find the fault?

Find and Focus

- Scientific method:
  1. assume,
  2. organize an experiment,
  3. if refuted, refine your assumption and repeat.

  possible formalization: invariants and assertions
- Observing: logging the value of infected variables

  e.g., `print` command in gdb
- Watching: keeping an eye on infected variables

  e.g., `break` and `watch` commands in gdb
- Slicing: find the slice responsible for infection

  see the lecture on slicing

Getting Our Hands Dirty...

We use gdb (any other debugger will do)

- Reproduce the test:
  `run 5 4 3 2 1 666666` Damn, the tester was right!
  (Not always that easy, try `55 4`.)
- Simplify the test-case
  `run 5 4 3 2`
- Find the possible the origins,
  focus on a problem area,
  e.g., `a[0]` and `shell_sort` (slicing...)
- Isolate the causes
  what makes `a[0]` wrong?
  compare it with the sane situation, what is different?
- Correct the problem

TRAFFIC

1. Track the problem
2. Reproduce the failure
3. Automate and simplify the test-case: minimal test-case $\Leftarrow$
4. Find possible origins: where it first went wrong
5. Focus on the most likely origins: what part of state is infected
6. Isolate the chain: what causes the state to be infected $\Leftarrow$
7. Correct the defect

Automated Debugging is about Perfection

Perfection

> *Perfection is achieved not when you have nothing more to add, but when there is nothing more left to take away.*
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> Antoine de Saint-Exupéry

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Automated Debugging

Take out all that has nothing to do with the failure...

Debugging: An Example

- My slides for today (in LaTeX) did not compile
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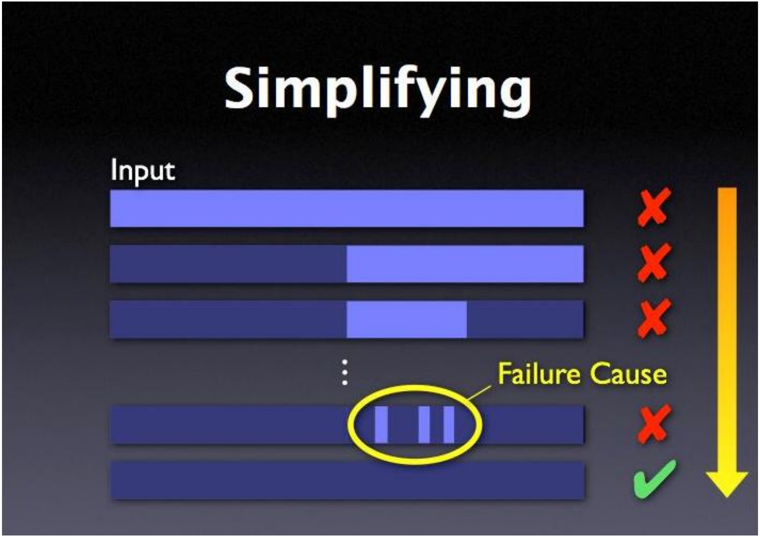
This is called delta debugging:
our order of business for today.

Outline



(Ack. figures are due to Andreas Zeller.)

Minimizing Delta Debugging: Basic Idea

Try to find the minimal environment causing the failure by:

- Divide the circumstances C in n parts C_i,
- remove a part C_i such that $C \setminus C_i$ causes failure, repeat the algorithm with $C \setminus C_i$,
- if no such part exists, choose a bigger $n <\mid C \mid$ and repeat.

Minimizing Delta Debugging: Formalization

- Circumstances: C (input but could be: program, environment, etc.)
- Test: $\mathit{test} : 2^C \rightarrow \{\times, \checkmark, ?\}$
- Starting state: $C_x \subseteq C$, such that $\mathit{test}(C_\times) = \times$
- Goal: find a minimal subset $C'_\times \subseteq C_x$ such that $\mathit{test}(C'_\times) = \times$

Minimizing Delta Debugging: Algorithm

$ddmin(C_\times, 2)$, where

$ddmin(C'_\times, n) =$

$$\begin{cases} C'_\times, & \text{if } \mid C'_\times \mid = 1, \\ ddmin(C'_\times \setminus C_i, max(n-1, 2)) & \text{else if } \exists_{i \leq n} test(C'_\times \setminus C_i) = \times \\ ddmin(C'_\times, max(2n, \mid C'_\times \mid)) & \text{else if } n < \mid C'_\times \mid \\ C'_\times & \text{otherwise} \end{cases}$$

where C_i's are partitions of $C'_\times$ of (almost) equal size.

Application in Random Testing

Idea

- feed huge inputs to the system
  (guaranteed crash on huge input)
- simplify input
- present the simplified result as a test-case

Application in Random Testing

Examples

- applied to command UNIX tools
- FLEX (lexical analyzer): crashed on a test-case of 2121 characters
- NROFF (document formatter): crashed on a single control character
- CRTPLOT (plotter output): crashed on single characters ‘t’ or ‘f’

Improvements

- caching: save the test outcomes,
  use the saved data
- stop early: define a criterion to stop the algorithm, e.g.,
  1. no progress
  2. reaching a certain granularity
  3. upper bound on time
- use structures, e.g., blocks instead of characters
- differences vs. circumstances
  (compare sane with insane)

What is a Cause?

- Effect: the failure
- Cause: an event preceding effect,
  without which effect would not have happened

Isolating the cause

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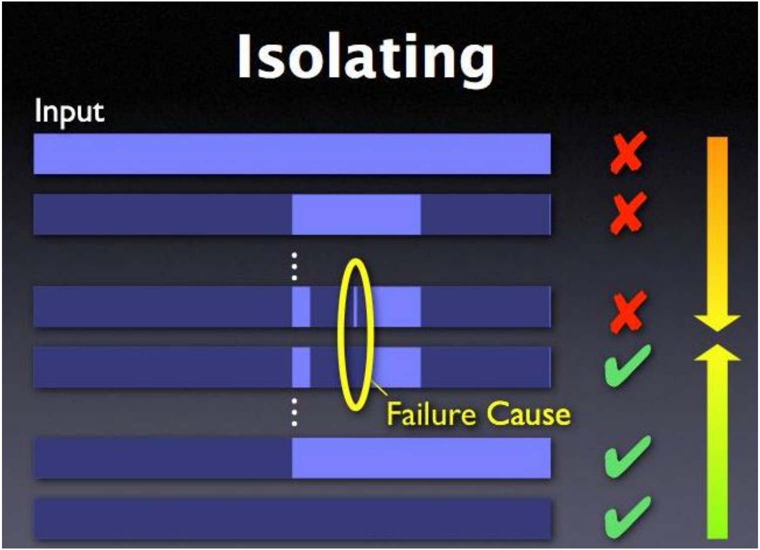
- Cause: the minimal difference between the worlds with and without the failure
- Challenge: the world without failure: the goal of debugging
- Two solutions:
  1. manipulate the world by a debugger: turn infected to sane
  2. use another test-case in which no fault appears

Isolating: The Sorting Program Case

1. `./sample` produces a failure on `5 4 3 666666`
2. works fine on `5 4 3`
3. find combinations of
   1. states of 1 with 2 such that the program passes
   2. states of 2 with 1 such that the program fails
4. the difference between the two leads to a cause


Isolating
Input
Failure Cause

Delta Debugging: The Algorithm

Start from:

- $C_{\checkmark} = \emptyset$: passing circumstances and
- $C_{\times}$: failing circumstances

1. compute the difference Δ between the failing and the passing circ., divide into n parts: Δ_i,

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5. remove Δ_i from the failing circ.; it is the new failing circ., if it fails
6. increase n if none of the above holds
7. repeat until the difference is a singleton

Delta Debugging: Algorithm

$dd(C_{\checkmark}, C_{\times}, 2)$,
where $ddmin(C'_{\checkmark}, C'_{\times}, n)$ is defined recursively as:

$$\begin{cases} (C'_{\checkmark}, C'_{\times}) & \text{if } \mid \Delta \mid = 1, \\ dd(C'_{\times} \setminus \Delta_i, C'_{\times}, 2) & \text{else if } \exists_{i \leq n} test(C'_{\times} \setminus \Delta_i) = \checkmark \\ dd(C'_{\checkmark}, C'_{\checkmark} \cup \Delta_i, 2) & \text{else if } \exists_{i \leq n} test(C'_{\checkmark} \cup \Delta_i) = \times \\ dd(C'_{\checkmark} \cup \Delta_i, C'_{\times}, max(n-1, 2)) & \text{else if } \exists_{i \leq n} test(C'_{\checkmark} \cup \Delta_i) = \checkmark \\ dd(C'_{\checkmark}, C'_{\times} \setminus \Delta_i, max(n-1, 2)) & \text{else if } \exists_{i \leq n} test(C'_{\times} \setminus \Delta_i) = \times \\ dd(C'_{\checkmark}, C'_{\times}, min(2n, \mid \Delta \mid)) & \text{else if } n < \mid \Delta \mid \\ (C'_{\checkmark}, C'_{\times}) & \text{otherwise} \end{cases}$$

where $\Delta = C'_{\times} \setminus C'_{\checkmark}$ and Δ_i's are n partitions of Δ of (almost) equal size.

Delta Debugging: Applied to Test-Case Simplification

Start from:

- $C_{\checkmark} = \emptyset$: the empty test-case
- $C_{\times}$: the test-case leading to failure
- Much more efficient than minimizing delta debugging

Delta Debugging: Applied to Regression Testing

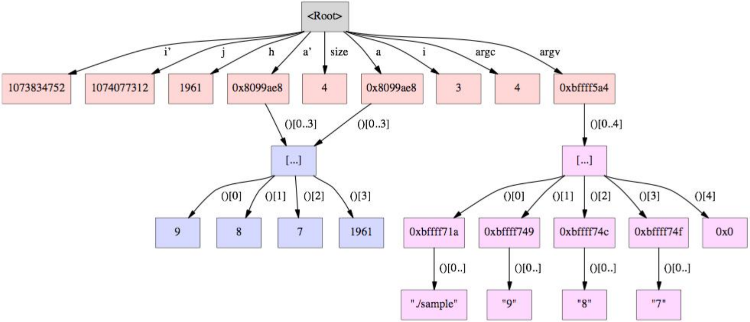
Start from:

- Goal: find out what went wrong in the new development (the old version worked well)
- $C_{\checkmark} = \emptyset$: basis is the old program, no changes needed
- $C_{\times}$: difference between the old and the new i.e., changes needed to obtain the new program from the old one

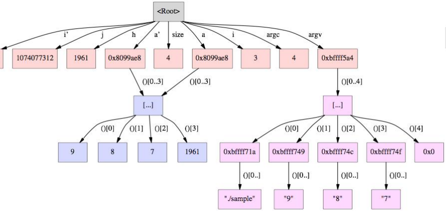
Isolating the Cause: Idea

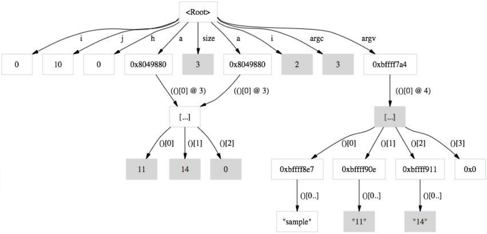
- Capture the state of the program
- Compare the states of a passes and a failed run
- The smallest difference Δ is the variable causing the problem
- Find out what influences this variable

Program State: Memory Graphs



Comparing the Differences





Implementable as debugger commands,
e.g., `set variable size = 2`.

Isolating the Cause: Implementation

- Compute the common subgraph of the passing and failing memory graphs. Let the difference be $C_\times$.
- Implement $C_\times$ as debugger commands.
- Apply delta-debugging to $C_\checkmark = \emptyset$ and $C_\times$
  1. Apply differences to the memory graphs and test.
  2. At each step of *dd* if the changed state is not a valid state (program does not run), return ?, if it is a valid state, return the result of the test,
- The result Δ leads to a cause.

Isolating the Cause: Sorting Case

Run the algorithm before calling `shell_sort` with the state of `./sample 7 8 9` as passing and `./sample 11 14` as failing.
If 0 at the state: test fails $\times$, passes $\checkmark$ otherwise.

1. $C_\times = \{$ `a[]`, `i`, `size`, `argc`, `argv[]` $\}$, $C_\checkmark = \emptyset$.
2. new failing state: `a[]`, `argv[1]` $\times$
3. new passing state: `argv[1]` $\checkmark$
4. new passing state: `a[0]` $\checkmark$
5. new passing state: `a[0]` and `a[1]` $\checkmark$
6. $\Delta = \{$ `a[2]` $\}$

Isolating the Cause: Illustrated Case

■ = δ is applied, □ = δ is *not* applied

#	$a'[0]$	$a[0]$	$a'[1]$	$a[1]$	$a'[2]$	$a[2]$	$argc$	$argv[1]$	$argv[2]$	$argv[3]$	i	$size$	Output	Test
1	□	□	□	□	□	□	□	□	□	□	□	□	7 8 9	✔
2	■	■	■	■	■	■	■	■	■	■	■	■	0 11	✘
3	■	■	■	■	■	■	□	□	□	□	□	□	0 11 14	✘
4	■	■	■	□	□	□	□	□	□	□	□	□	7 11 14	?
5	□	□	□	■	■	■	□	□	□	□	□	□	0 9 14	✘
6	□	□	□	■	□	□	□	□	□	□	□	□	7 9 14	?
7	□	□	□	□	■	■	□	□	□	□	□	□	0 8 9	✘
8	□	□	□	□	■	□	□	□	□	□	□	□	0 8 9	✘
Result					■									

Isolating the Chain of Causes

- Apply delta-debugging at the start, determine the minimal passing and running state
- Choose a common point (e.g., a function call) in the middle
- Apply delta-debugging on the states of the minimal passing and failing run
- Repeat the algorithm with the rest of the program and the new passing and failing states

Finding the Culprits

- The previous algorithm gives different Δ's (causes at different points)
- Track the change of causes
- A smelling point: a ceases to be a cause and b becomes a cause

Automated Debugging

- A natural mechanization of simple debugging principles
- Provides (partial) solutions to
  1. testing,
  2. simplifying the test-cases,
  3. isolating the causes and
  4. isolating the cause-effect chain.