Delta-Debugging

Wei Le

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Delta-debugging (dd) is an idea

The idea derives a set of tools and algorithms, that have different application settings:

- *Yesterday, my program worked, Today it does not, Why?*
- Simplifying and Isolating Failure-Inducing Input
- More here

The Problem

- GDB: GNU debugger for C
- DDD: graphical front-end of GDB
- Upgrade GDB from 4.16 to 4.17
- the integration of GDB and DDD no longer work

Goal

Determine the minimal set of failure inducing changes

Existing Work

regression containment (used at Cray research for compiler development): apply (the ordered) changes one a time until regression tests fail

- logical change can be large
- totally ordered changes are considered, no problems of interference, inconsistencies, granuality

Challenges

Challenges

- *Interference*: single change does not cause the problem, but multiple changes together produce the failure, e.g., merging the products of parallel development
- *Inconsistency*: the combinations of changes that do not result in a testable program, **you cannot just apply any changes and expect the program to run smoothly**
    1. Integration failure: a change cannot be applied, it may require earlier changes that are not included in the configuration, it may also be in conflict with another change, but the third conflict-resolving change is missing (Example 1)
    2. Construction failure: syntactic and semantic errors after applying the changes (Example 2)
    3. Execution failure: cannot run correctly, e.g., missing "create file" statement, so you cannot open a file
- *Granularity*: logical change can contain many lines
    - logical change: the developer commit a change
    - textual changes: you run a diff, you obtain a set of chunks

Formally define the problem

Background definitions: (sometimes, a paper defines a set of terms for easily presenting their work, these terms may not be applicable beyond the paper)

- configurations
- baseline
- test
- failure inducing, failure inducing change set, minimal failure-inducing change set

Formally define the problem

Assumptions: the configuration is

- monotony
- unambiguity
- consistency

Basic idea of dd: binary search

1. we partition c into two subsets c1 and c2 and test each of them.
2. Found in c1. The test of c1 fails—c1 contains a failure-inducing change.
3. Found in c2. The test of c2 fails—c2 contains a failure-inducing change.
4. Interference. Both tests pass. Since we know that testing $c = c1 \cup c2$ fails, the failure must be induced by combination of some change sets in c1 and some change sets in c2

Basic idea of dd: binary search

Step	c_i	Configuration								test	
1	c_1	1	2	3	4	.	.	.	.	✓	
2	c_2	.	.	.	.	5	6	7	8	✗	
3	c_1	.	.	.	.	5	6	.	.	✓	
4	c_2	.	.	.	.	.	.	7	8	✗	
5	c_1	.	.	.	.	.	.	7	.	✗	7 is found
Result		.	.	.	.	.	.	7	.		

Basic idea of dd: binary search

Interference: search both halves

Step	c_i	Configuration								*test*	
1	c_1	1	2	3	4	.	.	.	.	✓	
2	c_2	.	.	.	.	5	6	7	8	✓	
3	c_1	1	2	.	.	5	6	7	8	✓	
4	c_2	.	.	3	4	5	6	7	8	✗	
5	c_1	.	.	3	.	5	6	7	8	✗	3 is found
6	c_1	1	2	3	4	5	6	.	.	✗	
7	c_1	1	2	3	4	5	.	.	.	✓	6 is found
Result		.	.	3	.	.	6	.	.		

DD basic algorithm

$$dd(c) = dd_2(c, \emptyset) \quad \text{where}$$

$$dd_2(c, r) = \text{let } c_1, c_2 \subseteq c \text{ with } c_1 \cup c_2 = c,\ c_1 \cap c_2 = \emptyset,\ |c_1| \approx |c_2| \approx |c|/2$$

$$\text{in} \begin{cases} c & \text{if } |c| = 1 \text{ (“found”)} \\ dd_2(c_1, r) & \text{else if } \mathit{test}(c_1 \cup r) = \text{✘ (“in } c_1\text{”)} \\ dd_2(c_2, r) & \text{else if } \mathit{test}(c_2 \cup r) = \text{✘ (“in } c_2\text{”)} \\ dd_2(c_1, c_2 \cup r) \cup dd_2(c_2, c_1 \cup r) & \text{otherwise (“interference”)} \end{cases}$$

Return: the change set that contains the bug

Complexity

Step	c_i	Configuration								*test*	
1	c_1	1	2	3	4	.	.	.	.	✓	
2	c_2	.	.	.	.	5	6	7	8	✓	
3	c_1	1	2	.	.	5	6	7	8	✓	
4	c_2	.	.	3	4	5	6	7	8	✓	
5	c_1	1	.	3	4	5	6	7	8	✓	2 is found
6	c_2	.	2	3	4	5	6	7	8	✓	1 is found
7	c_1	1	2	3	.	5	6	7	8	✓	4 is found
8	c_2	1	2	.	4	5	6	7	8	✓	3 is found
9	c_1	1	2	3	4	5	6	.	.	✓	
10	c_2	1	2	3	4	.	.	7	8	✓	
11	c_1	1	2	3	4	5	.	7	8	✓	6 is found
12	c_2	1	2	3	4	.	6	7	8	✓	5 is found
13	c_1	1	2	3	4	5	6	7	.	✓	8 is found
14	c_2	1	2	3	4	5	6	.	8	✓	7 is found
Result		1	2	3	4	5	6	7	8		

Complexity

Worst case: all changes are failure inducing, still linear in terms of the

Step	c_i	Configuration								*test*	
1	c_1	1	2	3	4	.	.	.	.	✓	
2	c_2	.	.	.	.	5	6	7	8	✓	
3	c_1	1	2	.	.	5	6	7	8	✓	
4	c_2	.	.	3	4	5	6	7	8	✓	
5	c_1	1	.	3	4	5	6	7	8	✓	2 is found
6	c_2	.	2	3	4	5	6	7	8	✓	1 is found
7	c_1	1	2	3	.	5	6	7	8	✓	4 is found
8	c_2	1	2	.	4	5	6	7	8	✓	3 is found
9	c_1	1	2	3	4	5	6	.	.	✓	
10	c_2	1	2	3	4	.	.	7	8	✓	
11	c_1	1	2	3	4	5	.	7	8	✓	6 is found
12	c_2	1	2	3	4	.	6	7	8	✓	5 is found
13	c_1	1	2	3	4	5	6	7	.	✓	8 is found
14	c_2	1	2	3	4	5	6	.	8	✓	7 is found
Result		1	2	3	4	5	6	7	8		

number of changes

Handling inconsistencies

Review: reasons of inconsistencies:

1. Integration failure: a change cannot be applied, it may require earlier changes that are not included in the configuration, it may also be in conflict with another change, but the third conflict-resolving change is missing (Example 1)
2. Construction failure: syntactic and semantic errors after applying the changes (Example 2)
3. Execution failure: cannot run correctly, e.g., missing "create file" statement, so you cannot open a file

Testing output in presence of inconsistencies

- found: If testing any ci fails, then ci contains a failure-inducing subset.
- interference: If testing any ci passes and its complement $\overline{ci}$ passes as well, then the change sets ci and $\overline{ci}$ form an interference
- preference: If testing any ci is unresolved, and testing $\overline{ci}$ passes, then ci contains a failure-inducing subset and is preferred. In the following test cases, $\overline{ci}$ must remain applied to promote consistency.

Step	c_i	Configuration								*test*	
1	c_1	1	2	3	4	.	.	.	.	?	Testing c_1, c_2
2	c_2	.	.	.	.	5	6	7	8	✓	$\Rightarrow$ Prefer c_1
3	c_1	1	2	.	.	5	6	7	8	...	

Handling inconsistencies

Step	c_i	Configuration								test	
1	$c_1 = \bar{c}_2$	1	2	3	4	.	.	.	.	?	Testing c_1, c_2
2	$c_2 = \bar{c}_1$	.	.	.	.	5	6	7	8	?	$\Rightarrow$ Try again
3	c_1	1	2	.	.	.	.	.	.	?	Testing $c_1, \ldots, c_4$
4	c_2	.	.	3	4	.	.	.	.	?	
5	c_3	.	.	.	.	5	6	.	.	✓	
6	c_4	.	.	.	.	.	.	7	8	?	
7	$\bar{c}_1$	.	.	3	4	5	6	7	8	?	Testing complements
8	$\bar{c}_2$	1	2	.	.	5	6	7	8	?	
9	$\bar{c}_3$	1	2	3	4	.	.	7	8	✗	
10	$\bar{c}_4$	1	2	3	4	5	6	.	.	?	$\Rightarrow$ Try again

nodes 5 and 6 are not failure inducing, **What's next?**

Handling inconsistencies

should we just return nodes 1, 2, 3, 4, 7 and 8 as failure inducing? no,

we should try to minimize the change set some more: try again – re-partition!

- if ci pass, it is not failure inducing,=search for failure inducing sets from 6 changes,
- why changes 5 and 6 remain applied?

Handling inconsistencies

Step	c_i	Configuration								*test*	
11	c_1	1	.	.	.	5	6	.	.	✓	Testing $c_1, \ldots, c_6$
12	c_2	.	2	.	.	5	6	.	.	?	
13	c_3	.	.	3	.	5	6	.	.	?	
14	c_4	.	.	.	4	5	6	.	.	✓	
15	c_5	.	.	.	.	5	6	7	.	?	
16	c_6	.	.	.	.	5	6	.	8	✗	8 is found
Result		.	.	.	.	.	.	.	8		

- nodes 1, 4, 5, 6 are not failure inducing
- 8 is the cause
- changes 2, 3, 7 should always be applied together?
- if step 16 passes, then we know nodes 1, 4 and 8 are also not failure inducing, only nodes 2, 3 and 7 left, we just need to exclude all other changes?

dd+ algorithm

Output:

- find a minimal set of failure-inducing changes, and they are safe (remember we run them!)
- at least, exclude all changes that are safe (because we run them then we know they are not failure inducing) and not failure inducing

dd+ algorithm

$$
\begin{array}{l}
dd^{+}(c) = dd_3(c, \emptyset, 2) \quad \text{where} \\
dd_3(c, r, n) = \\
\quad \text{let } c_1, \ldots, c_n \subseteq c \text{ such that } \bigcup c_i = c, \text{ all } c_i \text{ are pairwise disjoint,} \\
\quad \text{and } \forall c_i \ (|c_i| \approx |c|/n); \\
\quad\quad \text{let } \bar{c}_i = c - (c_i \cup r),\ t_i = \mathit{test}(c_i \cup r),\ \bar{t}_i = \mathit{test}(\bar{c}_i \cup r), \\
\quad\quad c' = c \cap \bigcap \{\bar{c}_i \mid \bar{t}_i = \text{✗}\},\ r' = r \cup \bigcup \{c_i \mid t_i = \text{✓}\},\ n' = \min(|c'|, 2n), \\
\quad\quad d_i = dd_3(c_i, \bar{c}_i \cup r, 2), \text{ and } \bar{d}_i = dd_3(\bar{c}_i, c_i \cup r, 2) \\
\quad\quad\quad \text{in } \begin{cases}
c & \text{if } |c| = 1 \text{ (``found'')} \\
dd_3(c_i, r, 2) & \text{else if } t_i = \text{✗} \text{ for some } i \text{ (``found in } c_i\text{'')} \\
d_i \cup \bar{d}_i & \text{else if } t_i = \text{✓} \wedge \bar{t}_i = \text{✓} \text{ for some } i \text{ (``interference'')} \\
d_i & \text{else if } t_i = \text{?} \wedge \bar{t}_i = \text{✓} \text{ for some } i \text{ (``preference'')} \\
dd_3(c', r', n') & \text{else if } n < |c| \text{ (``try again'')} \\
c' & \text{otherwise (``nothing left'')}
\end{cases}
\end{array}
$$

Avoid inconsistencies

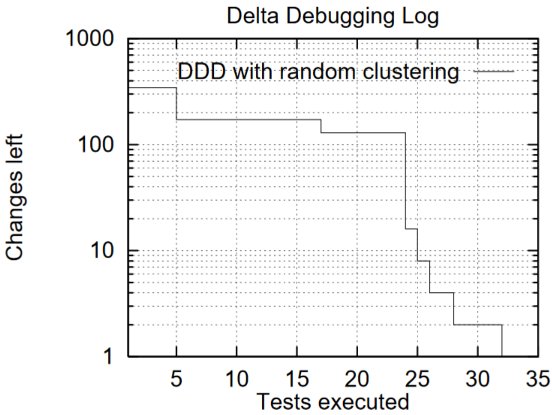
- group changes with additional information (location, lexical, syntactic, semantic, process)
- predicting test outcomes without running them (especially which change sets will lead to inconsistencies): only run ordered change sets

Study 1

Failure info:

- invoking a name of non-existing file, DDD 3.1.2 dumped core, DDD 3.1.1 prints an error message
- 116 logical changes, 344 textual changes

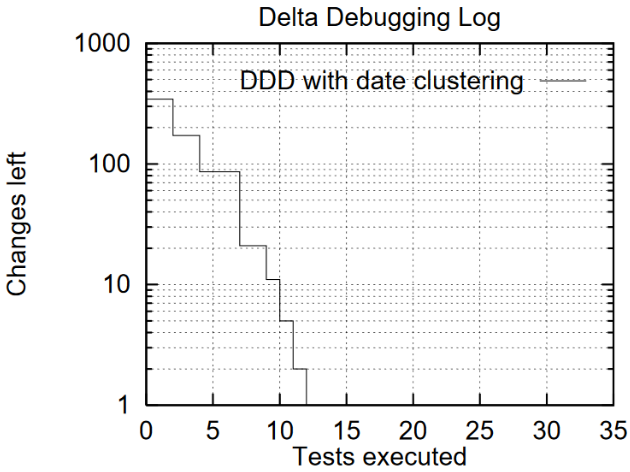
Study 1



(a) with random clustering

4: 172 changes, #31 find the failure inducing changes

Study 1



(b) with date clustering

each change implies its earlier changes, predicting any tests that do not have that property as unresolved

Study 1

12 test runs, 58 minutes

```
diff -r1.30 -r1.30.4.1 ddd/gdbinit.C
295,296c296
<   string classpath =
<       getenv("CLASSPATH") != 0 ? getenv("CLASSPATH") : "
---
>   string classpath = source_view->class_path();
```

source_view is an initialized pointer, lead to core dump

Study 2

Failure info:

- the integration of GDB and DDD no longer work when GDB upgraded from 4.16 to 4.17
- 178 k changed lines, 8721 textual changes
- 370 seconds a change, apply individual changes take about 37 days

Study 2

Random clustering:

- increase the number of subsets, reduce the changesets in each subset
- most of first 457 tests unresolved
- at test 458, find that one of subsets that contains 36 changes is failure inducing
- use the rest 12 tests to determine a single failure-inducing change
- run a total of 470 tests, took 48 hours

Study 2

An optimized approach:

- group changes based on the directory they are located
- group changes based on the common files
- within a file, changes are grouped according to the common usage of identifiers (keep changes together if they operated on common variables or functions)
- scan error messages of unresolved tests, find all changes that reference the identifies reported in the error messages, try again (to find a good construction)

Study 2

- ran 9 tests with various directory combinations, find failure inducing directory
- test 289, 20 hours, find the single line error inducing changes

Study 2

```
diff -r gdb-4.16/gdb/infcmd.c gdb-4.17/gdb/infcmd.c
1239c1278
< "Set arguments to give program being debugged when it is started.\n\
---
> "Set argument list to give program being debugged when it is started.\n\
```

GDB 4.16

```
Arguments to give program being debugged when it is started is "a b c"
```

GDB 4.17

```
Argument list to give program being debugged when it is started is "a b c"
```

DDD failed to parse the string in the new version

Thought Provoking Work

What are your comments and thoughts?

Conclusions and future work

- automatic approaches to isolate regression causes
- How to group changes? Using dependency information
- Using code coverage tools to select changes that have not executed

Further Reading

- a short tutorial for delta debugging
- more delta debugging