COMP5111 – Fundamentals of Software Testing and Analysis

Automated Fault Localization

Shing-Chi Cheung

Computer Science & Engineering

HKUST

https://hackthology.com/how-to-evaluate-statistical-fault-localization.html

Dream of a developer…

Software maintenance

- Testing
  - Detect a fault
- Fault localization
  - Locate the fault
- Patching
  - Fix the fault

Fault localization is tedious

- One of the most frustrated processes
- An article[1] in 2020 reported that engineers spend on average 13 hours to fix a single software failure
- Require high concentration
- Familiar with program logic

[1] https://devops.com/report-debugging-efforts-cost-companies-61b-annually/

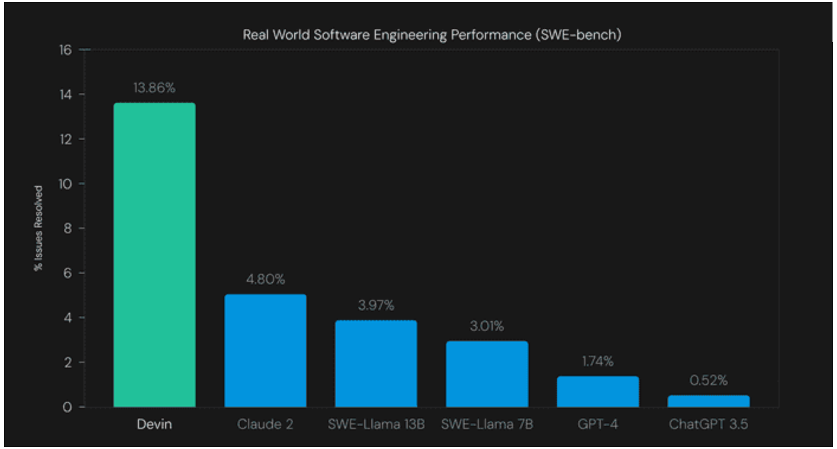
Traditional approaches

- Insert print statements
- Use debuggers and set breakpoints
- Add assertions
- Examine core dump or stack trace

Rely on thorough program understanding & expert knowledge

Dawn of AI Software Engineers

Devin AI - The First AI Software Engineer by Cognition Labs:



AutoDev: Automated AI-Driven Development

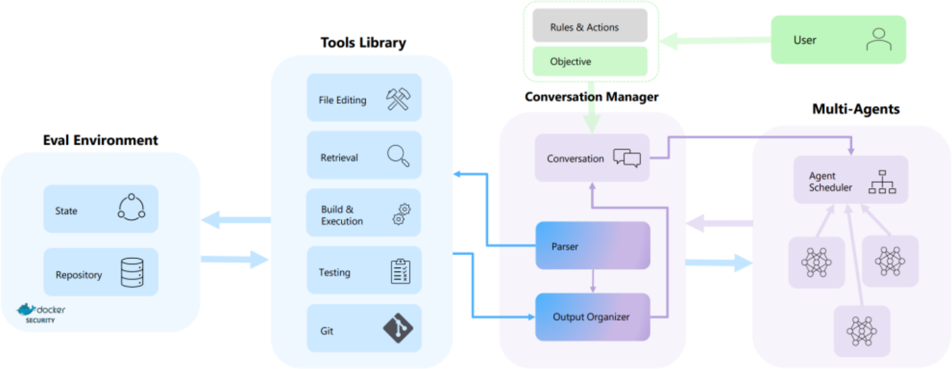
Michele Tufano
Microsoft
Redmond, USA

Anisha Agarwal
Microsoft
Redmond, USA

Jinu Jang
Microsoft
Redmond, USA

Roshanak Zilouchian Moghaddam
Microsoft
Redmond, USA

Neel Sundaresan
Microsoft
Redmond, USA



May we have program faults be automatically located?

http://www.youtube.com/watch?v=JkimgY0NGSc

- A demo of GZoltar

Fault Localization

func( ) {	Runs					
int x, y, z, m;	1	2	3	4	5	6
read(“Enter 3 numbers:”, x, y, z);						
m = z;						
if (y < z) {						
if (x < y)						
m = y;						
else if (x < z)						
m = y;						
} else {						
if (x > y)						
m = y;						
else if (x > z)						
m = x;						
}						
print(“Selected number is:”, m);						
}	✓	✓	✓	✓	✗	✓

- Runs
  - 1: (1,1,2)
  - 2: (0,1,2)
  - 3: (2,1,0)
  - 4: (0,2,1)
  - 5: (1,0,2)
  - 6: (2,0,1)

GZoltar

- Likely faults are colored in red.
- Less likely faults are colored in orange.
- More less likely faults are

```
4   public static int func(int x, int y, int z) {
5       int m = z;
6       if (y < z) {
7           if (x < y)
8               m = y;
9           else if (x < z)
10              m = y;
11      } else {
12          if (x > y)
13              m = y;
14          else if (x > z)
15              m = x;
16      }
17      return m;
18  }
```

Problems | Javadoc | Declaration | Coverage

0 errors, 7 warnings, 0 others

Description	Resource	Path	Location	Type
Warnings (7 items)				
Fault likelihood: 0.40824828	MyClass.java	/FaultLocalization/...	line 5	GZoltar Warni...
Fault likelihood: 0.40824828	MyClass.java	/FaultLocalization/...	line 6	GZoltar Warni...
Fault likelihood: 0.40824828	MyClass.java	/FaultLocalization/...	line 17	GZoltar Warni...
Fault likelihood: 0.5	MyClass.java	/FaultLocalization/...	line 7	GZoltar Orange
Fault likelihood: 0.57735026	MyClass.java	/FaultLocalization/...	line 9	GZoltar Orange
Fault likelihood: 0.70710677	MyClass.java	/FaultLocalization/...	line 10	GZoltar Error
Fault likelihood: 0.70710677	MyClass.java	/FaultLocalization/...	line 11	GZoltar Error

Fault Localization

func( ) {	Runs					
	1	2	3	4	5	6
int x, y, z, m;						
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●
m = z;	●	●	●	●	●	●
if (y < z) {	●	●	●	●	●	●
if (x < y)	●	●			●	●
m = y;		●				
else if (x < z)	●				●	●
m = y;	●				●	
} else {			●	●		
if (x > y)			●	●		
m = y;			●			
else if (x > z)				●		
m = x;						
}						
print("Selected number is:", m);	●	●	●	●	●	●
}	✓	✓	✓	✓	✗	✓

- Runs
  - 1: (1,1,2)
  - 2: (0,1,2)
  - 3: (2,1,0)
  - 4: (0,2,1)
  - 5: (1,0,2)
  - 6: (2,0,1)

Fault Localization

func( ) {	Runs					
	1	2	3	4	5	6
int x, y, z, m;						
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●
m = z;	●	●	●	●	●	●
if (y < z) {	●	●	●	●	●	●
if (x < y)	●	●			●	●
m = y;		●				
else if (x < z)	●				●	●
m = y; // *** BUG ***	●				●	
} else {			●	●		
if (x > y)			●	●		
m = y;			●			
else if (x > z)				●		
m = x;						
}						
print("Selected number is:", m);	●	●	●	●	●	●
}	✓	✓	✓	✓	✗	✓

- Runs
  - 1: (1,1,2)
  - 2: (0,1,2)
  - 3: (2,1,0)
  - 4: (0,2,1)
  - 5: (1,0,2)
  - 6: (2,0,1)

Fault Localization

func( ) {	Runs					
	1	2	3	4	5	6
int x, y, z, m;						
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●
m = z;	●	●	●	●	●	●
if (y < z) {	●	●	●	●	●	●
if (x < y)	●	●			●	●
m = y;		●				
else if (x < z)	●				●	●
m = y; // *** BUG ***	●				●	
} else {			●	●		
if (x > y)			●	●		
m = y;			●			
else if (x > z)				●		
m = x;						
}						
print("Selected number is:", m);	●	●	●	●	●	●
}	✓	✓	✓	✓	✗	✓

- Premise
  - Bugs participate more often in failing tests than passing tests
  - RIP model
    - Reachability
    - Infection
    - Propagation

Ranking function - Tarantula

- J. A. Jones and M. J. Harrold, "Empirical evaluation of the Tarantula automatic fault-localization technique," in *Proc. of the 20th IEEE/ACM Conference on Automated Software Engineering*, pp. 273-282, Long Beach, California, USA, December, 2005

$$X/X+Y,\ X=(N_{EF}/N_F)\ \&\ Y=(N_{ES}/N_S)$$

X: Participation in failing tests
Y: Participation in passing tests

N_{EF} : Number of failing tests executing the statement

N_{ES} : Number of passing tests executing the statement

N_F : Number of failing tests

N_S : Number of passing tests

Fault Localization

$X/X+Y$, $X=(N_{EF}/N_F)$ & $Y=(N_{ES}/N_S)$

$N_F: 1$, $N_S: 5$

func( ) {	Runs						Tarantula
int x, y, z, m;	1	2	3	4	5	6	
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●	0.5
m = z;	●	●	●	●	●	●	0.5
if (y < z) {	●	●	●	●	●	●	0.5
if (x < y)	●	●			●	●	0.625
m = y;		●					0.0
else if (x < z)	●				●	●	0.714
m = y; **// *** BUG *****	●				●		**0.833**
} else {			●	●			0.0
if (x > y)			●	●			0.0
m = y;			●				0.0
else if (x > z)				●			0.0
m = x;							0.0
}							0.0
print("Selected number is:", m);	●	●	●	●	●	●	0.5
}	✓	✓	✓	✓	✗	✓	

Can we further improve the accuracy?

Coincidental Correctness

func( ) {	Runs					
	1	2	3	4	5	6
int x, y, z, m;						
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●
m = z;	●	●	●	●	●	●
if (y < z) {	●	●	●	●	●	●
if (x < y)	●	●			●	●
m = y;		●				
else if (x < z)	●				●	●
m = y; // *** BUG ***	●				●	
} else {			●	●		
if (x > y)			●	●		
m = y;			●			
else if (x > z)				●		
m = x;						
}						
print("Selected number is:", m);	●	●	●	●	●	●
}	✓	✓	✓	✓	✗	✓

- Occurs when a faulty statement is executed but does not lead to a failure.

Fault Localization

$X/X+Y$, $X=(N_{EF}/N_F)$ & $Y=(N_{ES}/N_S)$

$N_F: 1$, $N_S: 4$

func( ) {	**Runs**					**Tarantula**	
int x, y, z, m;	2	3	4	5	6		
read(“Enter 3 numbers:”, x, y, z);	●	●	●	●	●	0.5	
m = z;	●	●	●	●	●	0.5	
if (y < z) {	●	●	●	●	●	0.5	
if (x < y)	●			●	●	0.625	
m = y;	●					0.0	
else if (x < z)				●	●	0.714	→ 0.8
m = y; // * BUG *****				●		**0.833**	→ **1.0**
} else {		●	●			0.0	
if (x > y)		●	●			0.0	
m = y;		●				0.0	
else if (x > z)			●			0.0	
m = x;						0.0	
}						0.0	
print(“Selected number is:”, m);	●	●	●	●	●	0.5	
}	✓	✓	✓	✗	✓		

- Ignore successful runs identical to failing tests

Fault Localization

$X/X+Y$, $X=(N_{EF}/N_F)$ & $Y=(N_{ES}/N_S)$

N_F : 1, N_S : 1

func( ) {	2	3	4	5	6	Tarantula	
int x, y, z, m;							
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	0.5	
m = z;	●	●	●	●	●	0.5	
if (y < z) {	●	●	●	●	●	0.5	
if (x < y)	●			●	●	0.625	
m = y;	●					0.0	
else if (x < z)				●	●	0.714	→ 0.5
m = y; // *** BUG ***				●		**0.833**	→ **1.0**
} else {		●	●			0.0	
if (x > y)		●	●			0.0	
m = y;		●				0.0	
else if (x > z)			●			0.0	
m = x;						0.0	
}						0.0	
print("Selected number is:", m);	●	●	●	●	●	0.5	
}	✓	✓	✓	✗	✓		

- Successful runs do not equally contribute to fault localization.
- Use successful runs most similar to the failing tests.

Use a better ranking function - Ochiai

- The formula consists of two components
  - N_{EF}/N_F: The chances that a statement E is executed in a failure
  - $N_{EF}/(N_{EF}+N_{ES})$: The chances of failure whenever E is executed
  - It ignores the total number of passing tests

$$\frac{N_{EF}}{\sqrt{N_F \times \underbrace{(N_{EF} + N_{ES})}_{\text{Total number of tests executing the statement E}}}}$$

N_{EF} : Number of failing tests executing the statement
N_{ES} : Number of passing tests executing the statement
N_F : Number of failing tests
N_S : Number of passing tests

ignore this factor?

Use a better ranking function - Ochiai

- A. Ochiai, “Zoogeographic studies on the soleoid fishes found in Japan and its neighboring regions,” *Bull. Japan Soc. Sci. Fish* 22, 526–530, 1957
- R. Abreu, P. Zoeteweij, R. Golsteijn, and A.J.C. van Gemund, “A Practical Evaluation of Spectrum-based Fault Localization,” *Journal of Systems and Software*, 82(11):1780 - 1792, 2009
- https://hackthology.com/how-to-evaluate-statistical-fault-localization.html

$$\frac{N_{EF}}{\sqrt{N_F \times \underbrace{(N_{EF} + N_{ES})}_{\text{Total number of runs executing the statement E}}}}$$

N_{EF} : Number of failing tests executing the statement
N_{ES} : Number of passing tests executing the statement
N_F : Number of failing tests
N_S : Number of passing tests

ignore this factor?

Fault Localization

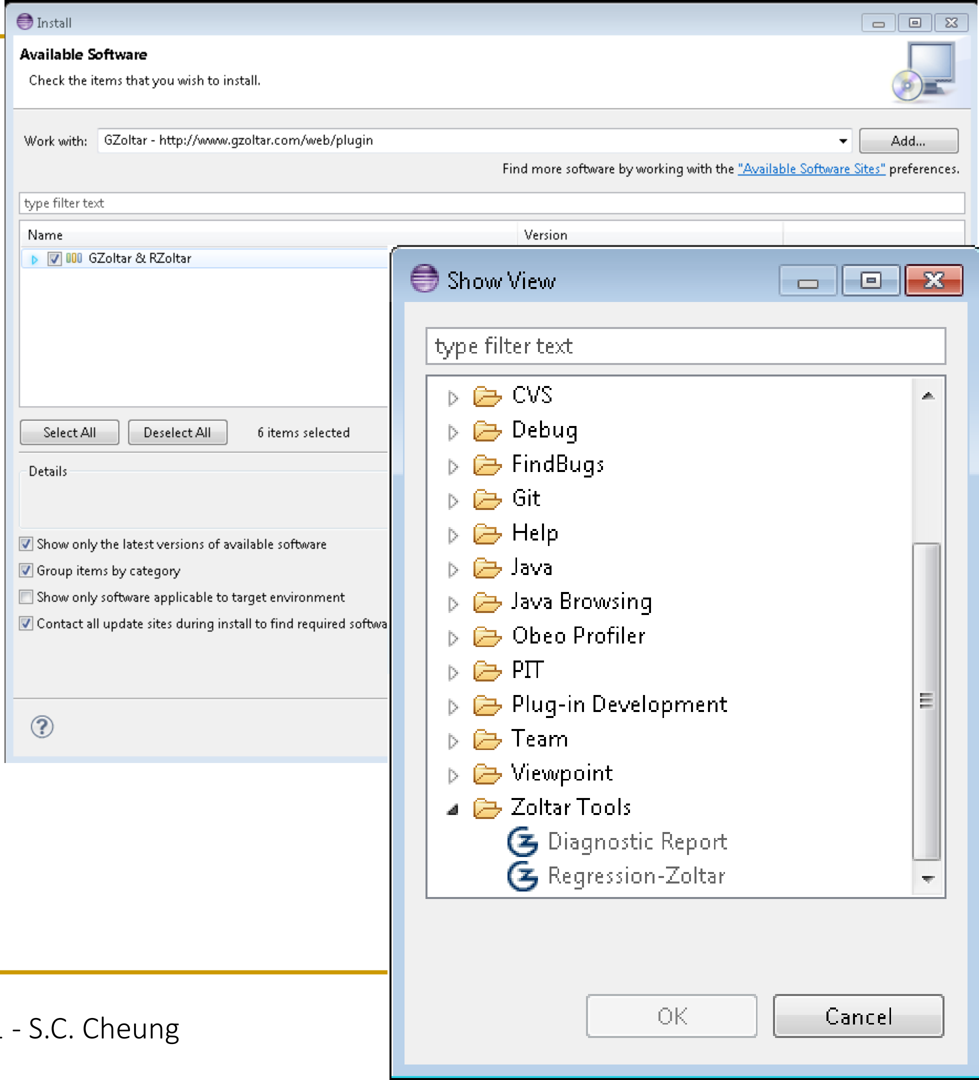
$$\frac{N_{EF}}{\sqrt{N_F \times (N_{EF} + N_{ES})}}$$

func( ) {	Runs						Tarantula	Ochiai
int x, y, z, m;	1	2	3	4	5	6		
read("Enter 3 numbers:", x, y, z);	●	●	●	●	●	●	0.5	0.408
m = z;	●	●	●	●	●	●	0.5	0.408
if (y < z) {	●	●	●	●	●	●	0.5	0.408
if (x < y)	●	●			●	●	0.625	0.5
m = y;		●					0.0	0.0
else if (x < z)	●				●	●	0.714	0.577
m = y; // *** BUG ***	●				●		**0.833**	**0.707**
} else {			●	●			0.0	0.0
if (x > y)			●	●			0.0	0.0
m = y;			●				0.0	0.0
else if (x > z)				●			0.0	0.0
m = x;							0.0	0.0
}							0.0	0.0
print("Selected number is:", m);	●	●	●	●	●	●	0.5	0.408
}	✓	✓	✓	✓	✗	✓		

Empirically, **Ochiai** outperforms **Tarantula** in ranking suspicious statements at the top

Gzoltar – Eclipse Plugin

- Ranking function
  - Ochiai
- Eclipse Plugin
  - http://www.gzoltar.com/web/eclipse-plugin
  - Window->Show View->Other…
  - The software has not been maintained for a couple of years, the plugin may not work on the latest Eclipse version. You may run GZoltar using its standalone library with Java 8 in command line mode. It generates a report.
- Select the Java Project -> CTL-F5
- Standalone library
  - http://gzoltar.com/lib/
- API Documentation
  - http://gzoltar.com/api/
- Video
  - http://www.youtube.com/user/GZoltarDebugging

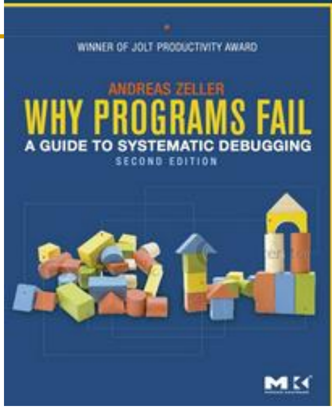


Generalizing the Concept

A test requirement is more suspicious if it participates in more failing than passing tests. The test requirement can be:

- Statement // *adopted so far in prior discussion*
- Statement sequence // *e.g., f.open() … f.close() … f.read()*
- Branch // *i.e., a specific evaluation of a predicate*
- Active boolean clause
- Prime path
- DU-path
- Mutants

Further readings



- Andreas Zeller, *Why Programs Fail: A Guide to Systematic Debugging (2nd Edition)*, Morgan Kaufmann, 2009.
  - https://www.udacity.com/course/cs259
  - https://www.st.cs.uni-saarland.de/whyprogramsfail/toc.php
- Xinming Wang, Shing-Chi Cheung, W.K. Chan, Zhenyu Zhang, Taming Coincidental Correctness: Coverage Refinement with Context Pattern to Improve Fault Localization, in *Proceedings of the 31st International Conference on Software Engineering (ICSE 2009)*, Vancouver, Canada, May 2009, pp. 45-55.
- Shay Artzi, Julian Dolby, Frank Tip, Marco Pistoia, Fault Localization for Dynamic Web Applications, *IEEE Transactions on Software Engineering 38(2)*, Mar/Apr 2012, pp. 314-335.
- Shin Yoo, Mark Harman, David Clark, Fault Localization Prioritization: Comparing Information-Theoretic and Coverage-Based Approaches, *ACM Transactions on Software Engineering and Methodology 22(3)*, July 2013.

Further readings

- Ming Wen, Rongxin Wu, Shing-Chi Cheung. How Well Do Change Sequences Predict Defects? Sequence Learning from Software Changes. In IEEE Transactions on Software Engineering 2018. To Appear.
- Ming Wen, Rongxin Wu, and Shing-Chi Cheung. Locus: Locating Bugs from Software Changes. In Proceedings of the 31st IEEE/ACM International Conference on Automated Software Engineering (ASE 2016), Singapore, Sept 2016, pp. 262-273.
- Rongxin Wu, Hongyu Zhang, Shing-Chi Cheung, and Sunghun Kim. CrashLocator: Locating Crashing Faults based on Crash Stacks . In Proceedings of the International Symposium on Software Testing and Analysis (ISSTA 2014), San Jose, California, USA, July 2014, pp. 204-214. **ACM SIGSOFT Distinguished Paper Award.**
- Daming Zou, Jingjing Liang, Yingfei Xiong, Michael Ernst, Lu Zhang. An Empirical Study of Fault Localization Families and Their Combinations. IEEE Transactions on Software Engineering, Online First, January 2019.