Advanced Software Testing and Debugging (CS598)

Intro

Spring 2022
Lingming Zhang
Course info

- Instructor: Lingming Zhang
  - Homepage: http://lingming.cs.illinois.edu/
  - Email: lingming@illinois.edu
  - Class Time: Tues/Thur 09:30am -- 10:45am (Central Time)
  - Office hours: Tues/Thur 10:45am – 11:45am (Central Time)

- Course:
  - Webpage: http://lingming.cs.illinois.edu/courses/cs598lmz-s22.html
  - Forum/notifications: https://campuswire.com/c/GC277F0D1
  - Zoom link: illinois.zoom.us/j/85217481800
  - Social events: ???
About me

Lingming Zhang
张令明
Associate Professor
Department of Computer Science
Grainger College of Engineering
University of Illinois at Urbana-Champaign
Office: Thomas M. Siebel Center
Email: lingming@illinois.edu

• Got my PhD in ECE from UT Austin in 2014
• Worked at UT Dallas for 6 years before joining Illinois in Fall’20
• Applied to Illinois for grad school
  • Obviously I failed:(

• Work on Software Engineering, as well as its synergy with Machine Learning, Formal Methods, and Programming Languages

• Enjoy building practical systems to help developers
  • Automatically detect, diagnose, and fix software bugs
  • Better understand, transform, and synthesize computer programs
About you

• Who are you (and where are you now)?
• What are you working on or interested in?
• Why are you taking this course?
• Anything else you’d like to share?
  • E.g., what’s your story with software bugs?😊
About the class
Textbook
Class organization

• Discuss two research papers each class
  • They usually belong to the same topic
  • The *primary* paper will be formally presented and discussed
  • The *optional* paper will usually be briefly discussed

• You are required to
  • **Read** both papers before each class
  • **Write** review for the primary paper before each class
    • **Due: 11:59pm before each class day** (starting from Feb. 1, submission info on course website)
  • **Participate** in the classroom discussions
    • I will randomly choose students to answer questions
  • **Lead** the discussion for one class
    • **Make your choice before 11:59pm Jan. 29**th (submission info on course website)
Goal of the course

• Get you exposed to real-world software testing and debugging problems
• Get you interested in SE/PL/FM research (if possible)
• Get your feet wet in SE/PL/FM research (through course project)
• Get you familiar with the typical research process (if you are junior PhD students)
Grading

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Paper review</td>
<td>20%</td>
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<tr>
<td>Paper presentation</td>
<td>10%</td>
</tr>
<tr>
<td>Class participation</td>
<td>10%</td>
</tr>
<tr>
<td>Course project</td>
<td>60%</td>
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</tbody>
</table>

• No exam!
Basic questions to ask on a research paper

• Why is the targeted problem important?
• What is the proposed technique and why does it work?
  • Does the proposed technique have enough technical contribution?
• How is the proposed technique evaluated?
  • Are the evaluation benchmarks/subjects real-world systems?
  • Are the used metrics reasonable?
  • Is the experimental procedure replicable?
  • Is it compared against state-of-the-art techniques?
• How are the experimental results?
  • Does it outperform prior work marginally or substantially?
• What are the impacts of this work?
  • Is it working on a rather specific problem or impacting a larger area?
• What are the strengths/limitations for this work?
• What are your suggestions/proposals to further advance this work?
Reading papers

• “How to Read a Research Paper”, by Michael Mitzenmacher
  • http://www.eecs.harvard.edu/~michaelm/postscripts/ReadPaper.pdf

• “How to Read an Engineering Research Paper”, by William Griswold
  • http://cseweb.ucsd.edu/~wgg/CSE210/howtoread.html

• Advice compiled by Tao Xie:
  • http://taoxie.cs.illinois.edu/advice.htm#review
Writing reviews

• “The Task of the Referee”, by Allan Smith
  • http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.177.3844

• “Constructive and Positive Reviewing” by Mark Hill and Kathryn McKinley
  • http://www.cs.utexas.edu/users/mckinley/notes/reviewing.html
Presenting papers

• “How to give strong technical presentations” by Markus Püschel
  • http://users.ece.cmu.edu/~pueschel/teaching/guides/guide-presentations.pdf

• Patrick Winston’s talk @ MIT:
  • https://www.youtube.com/playlist?list=PL9F536001A3C605FC

• Jean Luc Doumont’s talk
  • https://www.youtube.com/watch?v=meBXuTIPJQk
The way to **learn** software engineering is to go out there and **do** software engineering
Course project: group

• The course project will be group-based
  • 2 students in each group (recommended, working individually is also okay)
  • Feel free to post in Campuswire chat room (#find-teammates) if you need a teammate
    • Also let me know if you need help to find a teammate

• Suggestions for finding your teammate
  • Find someone with common interest but complementary expertise!
Course project: topic

• A list of example topics on software testing & debugging will be available for you to choose from on Campuswire
  • **Research-based ones:** recommended for PhD students
  • **Engineering-based ones:** recommended for MS/MCS students

• **You are encouraged to propose your own topics (subject to my approval)**
  • Especially the ones related to your own research/experience/interest

• Most research-based projects will fall into the following categories:
  • **Bug study:** study a specific (and interesting) type of bugs (>100), discuss the potentially implications for future bug detection, diagnosis, and fixing
  • **Technique study:** empirically study and improve state-of-the-art bug detection, diagnosis, and fixing techniques on new/larger datasets
  • **New technique:** design and build new techniques for better testing and/or debugging of certain types of bugs
Course project: topic selection

• Is this topic an impactful problem?
• Is this topic related to my own research?
• Am I really passionate about this topic?
• More importantly, can I finish this on time and in good shape?
  • Detect unknown bugs, or
  • Outperform state of the art on real-world benchmarks, or
  • Provide practical guidelines for future testing and debugging
• Don’t know what to work on yet?
  • Read the course project document and the papers in our schedule!
  • Read more related papers (e.g., ICSE, FSE, ISSTA, PLDI, SOSP/OSDI, Oakland)
  • Discuss with me!
Course project: deadlines

<table>
<thead>
<tr>
<th>Proposal (due 2/21)</th>
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<tbody>
<tr>
<td>What is the targeted problem</td>
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<tr>
<td>Why is it important</td>
</tr>
<tr>
<td>How you will do it</td>
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<tr>
<td>How you will evaluate it</td>
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<tr>
<td>What is your plan and expected outcome</td>
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<thead>
<tr>
<th>Deliverables</th>
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<tbody>
<tr>
<td>1-page .txt proposal</td>
</tr>
<tr>
<td>5min presentation (2/17)</td>
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<thead>
<tr>
<th>Midterm (due 04/07)</th>
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<tbody>
<tr>
<td>What have you done</td>
</tr>
<tr>
<td>Any challenges you have faced</td>
</tr>
<tr>
<td>Any changes you have made since proposal</td>
</tr>
<tr>
<td>Concrete plan for final report</td>
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<table>
<thead>
<tr>
<th>Deliverables</th>
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<tbody>
<tr>
<td>3-page PDF report</td>
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<tr>
<td>10min presentation (04/05)</td>
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<tr>
<th>Final (due 05/10)</th>
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<tbody>
<tr>
<td>What is the targeted problem</td>
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<tr>
<td>Why is it important</td>
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<tr>
<td>How you have done it</td>
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<tr>
<td>How you have evaluated it</td>
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<tr>
<td>What is your outcome</td>
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<tr>
<th>Deliverables</th>
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<tbody>
<tr>
<td>5-page PDF report</td>
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<tr>
<td>15min presentation (05/03)</td>
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The final report/presentation will be evaluated based on real research paper standards (e.g., the ones you are going to read)
Why this course?

• Software bugs are inevitable!
  • Programming still mainly a manual process
  • Software systems can be rather complicated
  • Software systems can be evolving
  • Interaction between software systems
  • Dependence on hardware supports
  • …
The first “bug”

“You were partly correct, I did find a ‘bug’ in my apparatus, but it was not in the telephone proper...

*Thomas Edison* (early 1800s)
The first computer “bug”

“First actual case of bug being found.”
Grace Hopper (1947)
Nowadays, software is everywhere!
So are software bugs...
Software testing and debugging cycle

Detect bugs!

Localize bugs!

Fix bugs!

• Build cycles per day:
  • Google: 17K*
  • Facebook: 60K
  • Microsoft: 30K

Facebook: https://bit.ly/2CAPvN9 (Android only)
Microsoft: https://bit.ly/2HgiUpw
Course topics (tentative)

**Bug detection**
- Guided Unit Test Gen
- Symbolic Execution
- Spec-based Test Gen
- Fuzz Testing
- Oracle Inference
- Human-assisted Bug Detection
- Regression Testing

**White-box testing**

**Black-box testing**

**Bug localization**
- Fault Diagnosis
- Fault Localization

**Program repair&synthesis**
- Search-based Program Repair
- Semantics-based Program Repair
- Revisiting Program Repair
- Syntax-Guided Program Synthesis (SyGuS)
- Learning-Based Program Synthesis

**Testing/debugging for more**
- Flaky Tests
- FM: SMT Solvers
- ML: Machine Learning Systems
- OS: Operating Systems
- DB: DB Engines

This is tentative, let me know your thoughts!
Guided unit test generation

*Program under test*

```java
public class HashSet extends Set{
    public boolean add(Object o){...
    public boolean remove(Object o){...
    public boolean isEmpty(){...
    public boolean equals(Object o){...
}
```

• Feedback guide:
  • Discarding illegal/redundant tests
  • Covering more object states
  • Closer to coverage targets
  • …

*Generated test t1*

```java
Set s = new HashSet();
s.add("hi");
```

*Generated test t2*

```java
Set s = new HashSet();
s.add("hi");
s.remove(null);
```

*Generated test t3*

```java
Set s = new HashSet();
s.isEmpty();
s.remove("no");
s.isEmpty();
s.add("no");
s.isEmpty();
s.isEmpty();
...
```
Symbolic execution

```c
void testme (int x, int y) {
    z = 4 * y;
    if (z == x) {
        if (x > y+4) {
            ERROR;
        }
    }
}
```

Program under test

Symbolic Execution

- $x: X_0$
- $y: Y_0$
- $z: \emptyset$

$4Y_0 = X_0$

$4Y_0 \neq X_0$

- $x: X_0$
- $y: Y_0$
- $z: 4Y_0$

$X_0 \geq Y_0 + 4$

- $x: X_0$
- $y: Y_0$
- $z: 4Y_0$

$X_0 \leq Y_0 + 4$

- $x: X_0$
- $y: Y_0$
- $z: 4Y_0$

ERROR!

SMT/SAT Solver

$4Y_0 = X_0 \land X_0 > Y_0 + 4$

- $x: X_0$
- $y: Y_0$
- $z: 4Y_0$

$x_0 = 8, y_0 = 2$

ERROR!
Spec-based testing

// specification for removing from binary tree
/*@ public normal_behavior
    @ requires has(n); // precondition
    @ ensures !has(n); // postcondition */
Fuzz testing

• Fuzzing strategies
  • Mutation-based
  • Grammar-based
  • Learning-based

• Feedback guide
  • New coverage?
  • Shorter execution?
  • Valid input?

• Targeted programs
  • Binaries
  • Compilers
  • Browsers
  • Operating systems
  • ML systems
  • ...
Test oracle problem!

Test oracle: a mechanism for determining whether software executed correctly for a test\(^1\).

One of the hardest problem in Software Engineering!

How to mitigate it?

\(^1\)https://en.wikipedia.org/wiki/Test_oracle
Differential testing

Provide the same input to similar applications, and observe output differences
Differential testing: browsers

Provide the same input to similar applications, and observe output differences
Metamorphic testing

\[
P(I+\Delta) = P(I)+\Delta
\]

For example:
\[
\sin(I+2\pi) = \sin(I)
\]
\[
\sin(-I) = -\sin(I)
\]

Provide the manipulated inputs to same application, and observe if output differences are as expected.
Oracle inference

• How to automatically obtain such predicates?
  • Manual summarization
  • Automated inference via analyzing the current project
  • Learning/mining from other projects

```java
public class HashSet extends Set{
    /*@ public normal_behavior
    @ requires !has(o); // precondition
    @ ensures has(o); // postcondition @*/
    public boolean add(Object o){...}
    /*@ public normal_behavior
    @ requires has(o); // precondition
    @ ensures !has(o); // postcondition @*/
    public boolean remove(Object o){...}
    ...
}
```

Program under test
Human-assisted bug detection

Historical bugs → Manual inspection → Derived techniques
• Regression testing is extremely costly in practice
  • Facebook has over 10,000 tests run per change
  • Google has over 150 million test executions per day
Fault diagnosis and localization

Delta debugging: Which page(s) caused Word to crash?

Fault localization: Which line(s) in the Word system is the root cause?
Program repair

- Search-based program repair
  - Transforms the repair problem to a search space exploration problem

- Semantics-based program repair
  - Leverages symbolic execution and constraint solving

How to further advance program repair?

12.27.0 Release Note (Joke): "We apologize to anyone who had problems with the app this week. We trained a neural net to eliminate all the bugs in the app and it deleted everything..."
Program synthesis

\[ \exists P. \forall x. \Phi(x, P(x)) \]

• Find a program \( P \) that satisfies the specification \( \Phi \) on any input \( x \)

• Synthesis improves
  • Productivity (when writing \( \Phi \) is easier than writing \( P \))
  • Correctness (when verifying \( \Phi \) is easier than verifying \( P \))

• Can be solved as:
  • A deductive theorem-proving problem: **deductive (classic) program synthesis**
  • A search problem: **inductive (syntax-guided) program synthesis**
  • A learning problem: **learning-based program synthesis**

may be a formula, a reference implementation, input/output pairs, traces, demonstrations, etc.
Testing and debugging for more

• Test the tests!
  • Flaky tests
• Test formal methods
  • SMT solvers
• Machine learning
  • Deep learning libs/compilers
• Operating systems
  • Linux kernel
• Database
  • Modern DB engines
• …
Any question for me?
Thanks and stay safe!