Natural language processing meets software testing

Michael Ernst

UW CSE

Joint work with Juan Caballero, Alberto Goffi, Alessandra Gorla, Mauro Pezze, Irfan Ul Haq, and Sai Zhang

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What is software?

What is software?

- A sequence of instructions that perform some task

What is software?

An engineered object amenable to formal analysis

- A sequence of instructions that perform some task

Formalizations

$$
\begin{array}{llll}
\mathtt{h} & \in & \mathtt{Heap} & = \mathtt{Addr} \rightarrow \mathtt{Obj} \\
\iota & \in & \mathtt{Addr} & = \text{Set of Addresses} \cup \{\mathtt{null}_a\} \\
\mathtt{o} & \in & \mathtt{Obj} & = {}^{r}\mathtt{Type},\ \mathtt{Fields} \\
{}^{r}\mathtt{T} & \in & {}^{r}\mathtt{Type} & = \mathtt{OwnerAddr}\ \mathtt{ClassId}\texttt{<}\overline{{}^{r}\mathtt{Type}}\texttt{>} \\
\mathtt{Fs} & \in & \mathtt{Fields} & = \mathtt{FieldId} \rightarrow \mathtt{Addr} \\
\iota & \in & \mathtt{OwnerAddr} & = \mathtt{Addr} \cup \{\mathtt{any}_a\} \\
{}^{r}\Gamma & \in & {}^{r}\mathtt{Env} & = \overline{\mathtt{TVarId}\ {}^{r}\mathtt{Type}};\ \overline{\mathtt{ParId}\ \mathtt{Addr}}
\end{array}
$$

$$
\begin{array}{llll}
\mathtt{P} & \in & \mathtt{Program} & ::= \overline{\mathtt{Class}},\ \mathtt{ClassId},\ \mathtt{Expr} \\
\mathtt{Cls} & \in & \mathtt{Class} & ::= \mathtt{class\ ClassId}\texttt{<}\overline{\mathtt{TVarI}} \\
 & & & \quad \mathtt{extends\ ClassId}\texttt{<}\overline{{}^{s}\mathtt{Ty}} \\
 & & & \quad \{\ \overline{\mathtt{FieldId}\ {}^{s}\mathtt{Type};}\ \mathtt{Met} \\
{}^{s}\mathtt{T} & \in & {}^{s}\mathtt{Type} & ::= {}^{s}\mathtt{NType}\ \mid\ \mathtt{TVarId} \\
{}^{s}\mathtt{N} & \in & {}^{s}\mathtt{NType} & ::= \mathtt{OM\ ClassId}\texttt{<}\overline{{}^{s}\mathtt{Type}}\texttt{>} \\
\mathtt{u} & \in & \mathtt{OM} & ::= \\
\mathtt{mt} & \in & \mathtt{Meth} & ::= \\
 & & \mathtt{MethSig} & ::= \\
\mathtt{w} & \in & \mathtt{Purity} & ::= \\
\mathtt{e} & \in & \mathtt{Expr} & ::= \\
 & & & \quad \mathtt{Expr.MethId}\texttt{<}{}^{s}\mathtt{Type}\texttt{>}(\mathtt{Expr})\ \mid \\
 & & & \quad \mathtt{new}\ {}^{s}\mathtt{Type}\ \mid\ ({}^{s}\mathtt{Type})\ \mathtt{Expr} \\
{}^{s}\Gamma & \in & {}^{s}\mathtt{Env} & ::= \overline{\mathtt{TVarId}\ {}^{s}\mathtt{NType}};\ \overline{\mathtt{ParId}\ {}^{s}\mathtt{Type}}
\end{array}
$$

$$
\text{OS-Upd}\ \frac{\begin{array}{c}\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}_0, \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \mathtt{h}_0, {}^{r}\Gamma, \mathtt{e}_2 \rightsquigarrow \mathtt{h}_2, \iota \\ \mathtt{h}' = \mathtt{h}_2[\iota_0.\mathtt{f} := \iota]\end{array}}{\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0.\mathtt{f}{=}\mathtt{e}_2 \rightsquigarrow \mathtt{h}',}
$$

$$
\text{OS-Read}\ \frac{\begin{array}{c}\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}', \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \iota = \mathtt{h}'(\iota_0)\downarrow_2(\mathtt{f})\end{array}}{\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0.\mathtt{f} \rightsquigarrow \mathtt{h}', \iota}
$$

$$
\text{GT-Upd}\ \frac{\begin{array}{c}\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \mathtt{u}_0\ \mathtt{C}_0\texttt{<\_>} \\ \mathtt{T}_1 = \mathit{fType}(\mathtt{C}_0, \mathtt{f}) \\ \Gamma \vdash \mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1 \\ \mathtt{u}_0 \neq \mathtt{any} \qquad \mathit{rp}(\mathtt{u}_0, \mathtt{T}_1)\end{array}}{\Gamma \vdash \mathtt{e}_0.\mathtt{f}{=}\mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1}
$$

$$
\text{GT-Read}\ \frac{\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \_\ (}{\Gamma \vdash \mathtt{e}_0.\mathtt{f} : \mathtt{N}_0 \rhd \mathit{fType}(\mathtt{C}_0, \mathtt{f})}
$$

$$
\left.\begin{array}{l}
\mathtt{h} \vdash {}^{r}\Gamma : {}^{s}\Gamma \\
\mathtt{h} \vdash \iota_1 : \mathit{dyn}({}^{s}\mathtt{N}, \mathtt{h}, {}^{r}\ldots) \\
\mathtt{h} \vdash \iota_2 : \mathit{dyn}({}^{s}\mathtt{T}, \iota_1, \mathtt{h}(\iota_1)\downarrow_1) \\
{}^{s}\mathtt{N} = \mathtt{u}_N\ \mathtt{C}_N\texttt{<>} \\
\mathtt{u}_N = \mathtt{this}_u \Rightarrow {}^{r}\Gamma(\mathtt{this}) \\
\mathit{free}({}^{s}\mathtt{T}) \subseteq \mathit{dom}(\mathtt{C}_N)
\end{array}\right\} \implies \mathtt{h} \vdash \iota_2 : \mathit{dyn}({}^{s}\mathtt{N} \rhd {}^{s}\mathtt{T}, \mathtt{h}, {}^{r}\Gamma)
$$

$$
\text{DYN}\ \frac{\begin{array}{c}{}^{r}\mathtt{T} = \iota'\ \_\texttt{<\_>} \qquad \iota \vdash {}^{r}\mathtt{T}\ {}^{r}\texttt{<:}\ \iota'\ \mathtt{C}\texttt{<}\overline{{}^{r}\mathtt{T}}\texttt{>} \qquad \iota \vdash {}^{r}\mathtt{T}\ {}^{r}\texttt{<:}\ \iota'\ \mathtt{C}\texttt{<}\overline{{}^{r}\mathtt{T}_a}\texttt{>} \Rightarrow \iota \vdash \overline{{}^{r}\mathtt{T}}\ {}^{r}\texttt{<:}\ \overline{{}^{r}\mathtt{T}_a} \\ \mathrm{dom}(\mathtt{C}) = \overline{\mathtt{X}} \qquad \mathrm{free}({}^{s}\mathtt{T}) \subseteq \overline{\mathtt{X}} \circ \overline{\mathtt{X}'}\end{array}}{\mathit{dyn}({}^{s}\mathtt{T}, \iota, {}^{r}\mathtt{T}, (\overline{\mathtt{X}'\ {}^{r}\mathtt{T}'};\_)) = {}^{s}\mathtt{T}[\iota'/\mathtt{this}, \iota'/\mathtt{peer}, \iota/\mathtt{rep}, \mathtt{any}_a/\mathtt{any}_u, \overline{{}^{r}\mathtt{T}/\mathtt{X}}, \overline{{}^{r}\mathtt{T}'/\mathtt{X}'}]}
$$

What is software?

- A sequence of instructions that perform some task

What is software?

- A sequence of instructions that perform some task

- Test cases
- Version control history
- Issue tracker
- Documentation
- …

How should it be analyzed?

Analysis of a natural object

- Machine learning over executions
- Version control history analysis
- Bug prediction
- Upgrade safety
- Prioritizing warnings
- Program repair

Natural language in programs

This talk:

1. Variable names:
   find undesired variable interactions
2. Error messages and user manuals:
   find inadequate diagnostic messages
3. Procedure documentation:
   generate test oracles

Undesired variable interactions

```
int totalPrice;
int itemPrice;
int shippingDistance;

totalPrice = itemPrice + shippingDistance;
```

Undesired variable interactions

```
int totalPrice;
int itemPrice;
int shippingDistance;
totalPrice = itemPrice + shippingDistance;
```

- The compiler issues no warning
- A human can tell the abstract types are different

Idea:

- Cluster variables based on usage in program operations
- Cluster variables based on words in variable names

Differences indicate bugs or poor variable names

Clustering based on operations

Abstract type inference [ISSTA 2006]

```
int totalCost(int miles, int price, int tax) {
  int year = 2016;
  if ((miles > 1000) && (year > 2000)) {
    int shippingFee = 10;
    return price + tax + shippingFee;
  } else {
    return price + tax;
  }
}
```

Clustering based on operations

Abstract type inference [ISSTA 2006]

```
int totalCost(int miles, int price, int tax) {
  int year = 2016;
  if ((miles > 1000) && (year > 2000)) {
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    return price + tax + shippingFee;
  } else {
    return price + tax;
  }
}
```

Clustering based on variable names

Compute variable name similarity

1. Tokenize each variable into dictionary words
   - **`in_authskey15`** ⇒ {"in", "authentications", "key"}
   - Expand abbreviations, best-effort tokenization
2. Compute word similarity
   - For all w1 ∈ var1 and w2 ∈ var2, use WordNet or edit distance
3. Combine word similarity into variable name similarity
   - maxwordsim(w1) = maximum wordsim(w1, w2) for w2 ∈ var2
   - varsim(var1) = average maxwordsim(w1) for w1 ∈ var1

Results

- Found an undesired variable interaction in grep

```
if (depth < delta[tree->label])
    delta[tree->label] = depth;
```

- Loses top 3 bytes of depth
- Not exploitable because of guards elsewhere in program, but not obvious here

Inadequate diagnostic messages

Scenario: user supplies a wrong configuration option
`--port_num=100.0`

Problem: software issues an unhelpful error message

- "… unexpected system failure …"
- "… unable to establish connection …"
- Better: "`--port_num` should be an integer"

Goal: detect such problems before shipping the code

Challenges for proactive detection of inadequate diagnostic messages

- How to *trigger a configuration error*?

- How to *determine the inadequacy* of a diagnostic message?

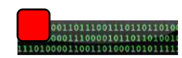
ConfDiagDetector's solutions

- How to *trigger a configuration error*?
  - Configuration mutation + run system tests

configuration

+

system tests



failed tests ≈ triggered errors

- How to *determine the inadequacy* of a diagnostic message?
  - Use a NLP technique to check its semantic meaning

Similar semantic meanings?

Diagnostic messages output by failed tests

User manual

Message analysis

- A message is adequate, if it
  - contains the mutated option name or value

  OR

  - has a similar semantic meaning with the manual description

Text similarity technique [Mihalcea’06]

A message

Manual description

Has similar semantic meanings, if many words in them have similar meanings

<u>Example:</u>

~~The~~ program goes wrong

~~The~~ software fails

- *Remove all stop words*
- *For each word in the diagnostic message, tries to find the similar words in the manual*
- *Two sentences are similar, if “many” words are similar between them.*

Results

- Reported 25 missing and 18 inadequate messages in Weka, JMeter, Jetty, Derby
- Validation by 3 programmers:
  - 0% false negative rate
  - 2% false positive rate

Test oracles for exceptional behavior

Exceptional behavior is a significant source of failures, but is under-tested (significantly less coverage)

Goal: create test oracles (= `assert` statements)

Although programmers may not write tests, the programmer does provide other indications: procedure documentation (e.g., Javadoc)

```
/**
 * Checks whether the comparator is now locked
 * against further changes.
 *
 * @throws UnsupportedOperationException if the
 * comparator is locked
 */
protected void checkLocked() {...}
```

Text to code

1. Parse the @throws expression using the Stanford Parser
    - Parse tree, grammatical relations, cross-references
    - Challenges:
        - Often not a well-formed sentence; code snippets as nouns/verbs
        - Referents are implicit, assumes coding knowledge
2. Match each subject to a Java element
    - Pattern matching
    - Semantic similarity
    - Lexical similarity to identifiers, types, documentation
3. Match each predicate to a Java element
4. Create assert statement from expressions and methods

Automatically generated tests

- A test generation tool outputs:
  - Passing tests – useful for regression testing
  - Failing tests – indicates a program bug
- Without a formal specification, tool guesses whether a given behavior is correct
  - False positives: report a failing test that was due to illegal inputs
  - False negatives: fail to report a failing test because it might have been due to illegal inputs
- Results: Reduced false positive test failures in EvoSuite by 1/3 or more

Machine learning + software engineering

- Software is more than source code
- Formal program analysis is useful, but insufficient
- Analyze and generate all software artifacts

A rich space for further exploration