Motivation

- Undetected errors which compromise the results of a computation can be dangerous
  - can lead to catastrophes (e.g. Therac-25, Ariane 5 Flight 501)

- Integration of many components often lead to rare bugs which can take days or weeks to debug (rare corner cases)

- Detecting bugs and hunting for root cause is important
Previous Work

- [Ernst et al] detects likely program invariants based on dynamic program behavior.
- It starts with a specific space of program invariants.
- The Daikon tool, is limited by the fixed set of invariants hypothesized and checked for.

DIDUCE (Dynamic Invariant Detection U Checking Engine)

- DIDUCE extracts invariants dynamically from program executions
- DIDUCE continually checks program behavior against the invariants hypothesized up to that point in the program's run and reports all detected violations.
- When a dynamic invariant violation is detected, the invariant is relaxed to allow for the new behavior and program execution is resumed.
Usage Models for DIDUCE

• Debugging programs that fail on some inputs:
  – DIDUCE can pinpoint differences in behavior between the successful and the failing runs
  – Extract invariants from test cases that pass
  – Check invariant violations for cases that fail (reduces debugging time)

• Debugging failures in long-running programs:
  – Some of the hardest bugs to track down are those that occur only after a program has executed for a long time.
  – DIDUCE blindly and continually monitors all the variables in the program

Usage Models for DIDUCE (continued)

• Debugging component-based software:
  – For component-based software, train DIDUCE on codes with same components working correctly, and apply it to check the behavior of a component in the context of the new software

• Testing programs with inputs for which the correct outputs are unknown:
  – Train DIDUCE on known tests cases, and use the invariants gathered to check the runs on inputs with no known outputs

• Assisting in program evolution:
  – Check the invariants collected before and after the update in a program
DIDUCE Invariants

- DIDUCE system instruments Java programs
  - Maintains invariants on the values of a set of *tracked expressions* at various program points
  - An invariant hypothesis on an expression is satisfied by all the values that have occurred in the history of the execution so far.
  - Invariant is relaxed on seeing a new violating value.

- DIDUCE operates in two modes
  - Training Mode:
    - DIDUCE silently learns invariants by relaxing invariant hypotheses as needed
  - Checking Mode:
    - DIDUCE emits messages about invariant relaxations which occur along the way
    - Training continues in checking mode as well

DIDUCE: Instrumented Program Points

- DIDUCE associates invariants with static program points

- DIDUCE allows tracked expressions to be attached to:
  - program points which read from or write to objects
  - program points which read from or write to a static variable
  - procedure call sites

- This design gives visibility to global state of computation

- User provides JAR files, DIDUCE will instrument all the static program points described above.
DIDUCE: Tracked Expressions

- At each instrumented program point
  - a set of expressions is maintained, each of which is a function of the object or variable being accessed.
  - An invariant is maintained for each expression in this set, starting with the strictest invariant assumption at the beginning.
  - Gradually relaxes the invariant to encompass the values observed for the expressions.

- Following expressions are tracked by default:
  - the value being read or written
  - parent object, in the case where a field of an object is accessed
  - the difference between the values of the location accessed before and after a write operation.

- For tracked expressions which are of reference type, map objects to their run-time types
- Null values are treated as a special run-time type of their own.
DIDUCE: Invariant Representation

- Values of all expressions of all types reduced to integers
- Reference type expressions are mapped to an integer which is the hashcode of the String object for their run-time type
- For each expression's value, the invariant maintains for each bit position two things.
  - 1) the value of that bit the first time the expression was evaluated,
  - 2) whether different values have been observed for that bit position
- A violation is reported if differences between the new value and previous ones are observed in new bit positions

With each expression a tuple of two integers, an initial value $V$ and a mask $M$ is associated
- The $i$th bit in $M$ is set to 1 iff the same bit value has always been observed for that position.

If the first value of an expression is $W$ then,
- $M := \neg 0$, $V := W$

Suppose subsequently an expression returns $W'$
- If $(W' \ XOR V) \ ^\wedge M \neq 0$
  - Then a violation is reported and invariant is relaxed by $M := M \ ^\wedge \neg (W' \ XOR V)$
DIDUCE: Invariant Representation

- DIDUCE keeps track of following properties
  - whether the values were only positive or only negative, only odd or only even
  - an approximate upper bound on the value
  - which of the bits have constant values

- With this representation, the number of violations detected for each expression can be no greater than the number of bits in a word

- The storage required for maintaining invariants is about three words per tracked expression

DIDUCE: Invariant confidence

- Confidence level of an invariant is defined as the ratio between the number of times the expression has been evaluated and the number of values the invariant accepts

- Every invariant violation is reported with the change in confidence levels between the old invariant and the newly relaxed invariant.
  - A large drop in confidence signals a noteworthy invariant violation.

- Code executed for the first time is reported with a fixed, user-specifiable invariant confidence change.
**DIDUCE Implementation**

- ByteCode Engineering Library (BCEL) is used to instrument Java class files and insert calls to the DIDUCE run time system at appropriate program points.

- Source code not required but useful in understanding the invariant violations reported.

- An instrumented program using the default settings currently runs one to two orders of magnitude slower.

**DIDUCE EXPERIENCES**

<table>
<thead>
<tr>
<th>Program name</th>
<th>Description</th>
<th># Lines of Source Code</th>
<th># Classes (instrumented/total)</th>
<th># Instrumented program points</th>
<th>Slowdown factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulator</td>
<td>Proprietary performance simulator for multiprocessor memory systems</td>
<td>3300</td>
<td>10/28</td>
<td>3204</td>
<td>8–12X (Using 10 machines)</td>
</tr>
<tr>
<td>Mailman</td>
<td>Open source mail management utility</td>
<td>1700 (+ ~ 20000 JavaMail library)</td>
<td>214/214 (203 classes in JavaMail library)</td>
<td>13014</td>
<td>6X</td>
</tr>
<tr>
<td>JSSE Library</td>
<td>Shipping reference implementation for Java Secure Sockets Layer Library</td>
<td>30000</td>
<td>384/384</td>
<td>34844</td>
<td>8X</td>
</tr>
<tr>
<td>Jooq</td>
<td>Research project to develop a Java Virtual Machine</td>
<td>31500</td>
<td>18/137</td>
<td>3371</td>
<td>20X</td>
</tr>
</tbody>
</table>

Table 1: Details of programs DIDUCE was tried on.

- DIDUCE was especially helpful in pinpointing late-stage bugs that occur after many test cases are run.
DIDUCE EXPERIENCES: Mailmanage

- Mailmanage crashed on a particular mail box throwing a cryptic IO Exception.

- Crash apparently occurred in the JavaMail library while trying to fetch a message from a mailbox

- Both Mailmanage and JavaMail library were instrumented

- DIDUCE was trained on a few mailboxes that worked correctly and then tested with the failing mailbox

**Fig. 6: Sample code from JavaMail library**

```java
do {
    switch (buffer[index]) {
        case 'E':
            index += ENVELOPE.name.length;
            // other processing for case E
            break;
        // similar handling of other cases
    }
} while (buffer[index++] != ')');
```

- Figure shows the relevant code identified by the invariant violation

- Invariant violation reported that buffer[index] contained a new value at the end of while loop.

- Prior to this violation, invariant accepted both a space character and a “)" character
DIDUCE EXPERIENCES: Mailmanage

• The bug in this case was not in either Mailmanage or JavaMail library. It was in IMAP server

• The response by the server contained extra CR-LF characters, which was an inconsistent with its RFC

• This confused the JavaMail parser, which eventually threw an exception.

DIDUCE EXPERIENCES: Mailmanage

• DIDUCE strengths from this case study
  – It detected an anomaly in the input
  – Helped the user debug unfamiliar code, isolating the problem down to the component which actually contained the bug
  – Helped in finding bugs in code that was not even instrumented by finding invariant violations at the interface between instrumented and uninstrumented domains.
**DIDUCE EXPERIENCES: Java SSE Library**

- On adding a proxy server to the library, an unseen failure in unrelated parts of the code was observed.

- Programmer tried to debug by working backwards from the point of failure through the rest of the library.

- After 2 days of manual debugging, she isolated the problem to a particular function.

- When asked to use DIDUCE, she trained it with correct runs and ran it on the failing runs in checking mode.

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**DIDUCE EXPERIENCES: Java SSE Library**

- DIDUCE reported a high confidence invariant on the return value of a call to `SocketInputStream.read()` method.

- This method does not guaranteed to fill the entire array and can return after it has filled 1 or more bytes.

- The programmer had fundamental misunderstanding of the `java.io` library.

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**Fig. 7: Excerpt from the SSL library**

```java
InputStream s = x; // x is instance of SocketInputStream
// .. various SSL protocol processing
if (...) {
    int len = ... // expression for length of header,
    // always 74 at this program point
    byte[] hdr = new byte[len];
    s.read(hdr);
}
```
DIDUCE EXPERIENCES: Java SSE Library

- DIDUCE was modified to include a simple static check for immediately discarding the return values from calls to various flavors of InputStream.read() with a byte array argument.

- Over 80 such examples in the Java 2 Standard Edition and Enterprise Edition v.1.3 libraries were found, most of which were likely to be errors.

- This shows the importance of automatic invariant discovery.

DIDUCE EXPERIENCES: Joeq

- DIDUCE was run in checking mode without training. Initial invariant violations were ignored.

- Joeq failed an assertion while compiling a particular version of the Java Runtime Library.

- Joeq read each entry in the library JAR file, processed it, and entered the name of the entry into its own hash table.

```java
JarInputStream in = ...;
Hashtable names = new Hashtable();...
for (<each entry in the jar file>) {
    JarEntry je = in.getNextJarEntry();
    // process entry ...
    names.put(je.getName());
}
assert (names.size() == jfile.size());
```

Fig. 8: Excerpt from joeq
DIDUCE EXPERIENCES: Joeq

• DIDUCE precisely pointed to the source of the problem
  – the return value of Hashtable.put() method indicates whether the object being inserted is already present in hash table
  – It returns the existing object if the key matches an element in the hash table, and NULL otherwise
  – The programmer implicitly assumed that the entries in a JAR file were unique, and ignored the return values
  – DEDUCE reported a warning on finding a duplicate entry thus finding the root cause of the problem

DIDUCE EXPERIENCES: MAJC Memory Simulator

• Ten classes were instrumented in the program separately, and these ten versions were run in parallel

• Invariant violations in the initial part were ignored as it was considered as the training phase

• DIDUCE discovered two bugs in the simulator that would otherwise be undetected and found the root causes of 3 other bugs

• All bugs were serious algorithmic errors
DIDUCE EXPERIENCES: MAJC Memory Simulator

- “New code” category
  - tracks when execution reaches a program point for the first time

- High confidence invariant violations refer only to the violations above the confidence change level of 100
  - Last stub in the figure is the only bug with a confidence change of over one million

Conclusions

- Finding program anomalies through online dynamic program invariant detection and checking engine

- DIDUCE is effective in detecting hidden errors and finding the root causes of complex programming errors.

- Finding bugs that result from algorithmic errors, errors in inputs, and developers’ misconceptions of the APIs.

- Helps programmers locate bugs in unfamiliar code and, sometimes even in codes that have not been instrumented.
QUESTIONS ????