GUICat: GUI Testing as a Service

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ABSTRACT

GUIs are event-driven applications where the flow of the program is determined by user actions such as mouse clicks and key presses. GUI testing is a challenging task not only because of the combinatorial explosion in the number of event sequences, but also because of the difficulty to cover the large number of data values. We propose GUICat, the first cloud-based GUI testing framework that simultaneously generates event sequences and data values. It is a white-box GUI testing tool that augments traditional sequence generation techniques with concolic execution. We also propose a cloud-based parallel algorithm for mitigating both event sequence explosion and data value explosion, by distributing the concolic execution tasks over public clouds such as Amazon EC2. We have evaluated the tool on standard GUI testing benchmarks and showed that GUICat significantly outperforms state-of-the-art GUI testing tools. The video demo URL is https://youtu.be/rfnnQOmZqj4.

CCS Concepts

•**Software and its engineering** → *Software verification and validation;* Software testing and debugging;

Keywords

Symbolic execution, Test generation, GUI testing, Cloud

1. INTRODUCTION

Graphical User Interfaces (GUIs) provide a convenient way for the user to interact with the computer. They are event-driven applications where the flow of the program is determined by user actions such as mouse clicks and key presses. In contrast to console applications whose only point of interaction is at the beginning, GUIs have a potentially large number of interaction points, each of which may be associated with a different state. These features often make traditional software testing techniques ineffective. Specifically, GUI testing has two significant challenges. First, covering all possible event sequences of a GUI application is difficult due to the combinatorial explosion, i.e., the number of possible ways of clicking k buttons can be as large as $k!$. Second, GUI behaviors depend not only on the event sequence but also on the data values of widgets such as text-boxes, edit-boxes, and combo-boxes, thus leading to an extremely large input space. For example, covering all possible values of a k-character input string requires 26^k test cases. Although existing GUI testing tools [9–11, 13] have addressed the challenge of generating high-quality event sequences, they have not addressed the challenge of simultaneously generating high-quality data values. As such, data-dependent GUI behaviors are often inadequately tested.

We propose GUICat, a cloud-based GUI testing framework that generates both high-quality event sequences and high-quality data values, by augmenting state-of-the-art event sequence generation techniques with concolic execution. The result is a white-box GUI testing tool that uniformly explores the event flow as well as the data flow. We also propose a parallel concolic execution algorithm for mitigating the data value explosion, by distributing the computation tasks over workers on private clusters as well as public clouds such as Amazon EC2 [3]. It provides an illusion of running GUICat on a powerful super computer and thus allows it to handle significantly larger applications than previously possible.

We have implemented GUICat based on a number of open-source tools, including *GUITAR* [10] for generating the initial event sequences, *ASM* [1] for Java bytecode instrumentation, *Catg* [12] for concolic execution, and *JaCoCo* [2] for computing code coverage. Unlike prior techniques, GUICat is fully automated in modeling GUI widgets. That is, it does not require developers to manually model these widgets. This is important because manual modeling is not only labor intensive and error prone but also hard to sustain in the long run due to frequent widget updates.

We have evaluated GUICat on Amazon EC2 for a set of GUI testing benchmarks. GUICat achieves scalability through the distribution of symbolic execution tasks

The remainder of the paper is organized as follows. We illustrate the main idea behind GUICat using motivating examples in Section 2. We present our algorithm in Section 3, which is followed by our experimental results in Section 4. We discuss the related work in Section 5. Finally, we give our conclusions in Section 6.

2. MOTIVATING EXAMPLES

Figure 1 shows a GUI example for computing ticket fare based on user inputs including Name, Age Level, Distance, and Coupons. Once the `Buy` button is clicked, the applica-

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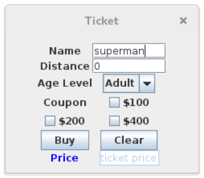

Ticket

Name superman

Distance 0

Age Level Adult

Coupon $100

$200 $400

Buy Clear

Price ticket price

```
name, JTextField, getText, String, superman

distance, JTextField, getText, int, 100

Age Level, JComboBox, getSelectedIndex, int, 0:1

$100, JComboBox, isSelected, int, 0:1

$200, JComboBox, isSelected, int, 0:1

$400, JComboBox, isSelected, int, 0:1
```

Figure 1: A GUI example and GUICat's configuration file.

```
OnClickComputePrice() {
  int coupon = 0;
  String age = (String)ageComboBox.getSelectedItem();
  String sdistance = distanceTextField.getText();
  int distance = Integer.parseInt(sdistance);
  if (d100CheckBox.isSelected())
    coupon += 100;
  if (d200CheckBox.isSelected())
    coupon += 200;
  if (d400CheckBox.isSelected())
    coupon += 400;
  if (age.equals(Child)) {
    coeffienct = 1;
  }else {
    coeffienct = 2;
  }
  if (distance < 60) {
    price = 500;
  }else if (distance < 80) {
    price = 11 * distance * coeffienct - coupon;
  }else if (distance < 100) {
    price = 10 * distance * coeffienct - coupon;
  }else if (distance < 120) {
    price = 9 * distance * coeffienct - coupon;
  }else {
    price = 8 * distance * coeffienct - coupon;
  }
  assert (price > 0);
  infoField.setText(price);
}
```

Figure 2: Code snippet for computing the ticket price.

tion computes and then displays ticket price, using a coefficient associated with the chosen age level. To allow GUICat to generate test cases, the user must provide a configuration file that specifies the name and type of the symbolic variables as shown in Figure 1 (right). Each entry (line) of the configuration file consists of the widget name, widget type, method for obtaining user input (e.g., *getText*), type of user input, and the default value (e.g., *superman*). Here, *0:1* means the default value is of *enum* type with two values *0* and *1*.

Figure 2 shows the code for computing the ticket price. It has a bug that can lead to negative ticket prices. For example, if a user has three coupons, then purchasing a child ticket for a distance of 60 miles would result in the price being -40 dollars. However, since a negative price requires a specific combination of widget values, such bug is difficult to detect using state-of-the-art GUI testing tools such as *GUITAR* [10]. This is because *GUITAR* focuses primarily on generating event sequences as opposed to generating a diverse set of widget values. Our new tool GUICat, in contrast, can quickly generate a combination of event sequences and widget values to expose this assertion failure.

GUICat generates the test cases as follows. First, it uses *GUITAR* to generate the initial set of event sequences up to a bounded length. Then, for each event sequence, it creates an instrumented GUI where some variables are marked as symbolic based on the configuration file. Next, it conducts symbolic execution of the instrumented GUI over the cloud. Finally, it uses JaCoCo to generate the coverage report. Now, we explain each step in more detail.

Step 1. We use *GUITAR* to generate event sequences of a bounded length. Assume the bound is 2, and events $e_1,\ldots,e_7$ denote *nameTextField*, *distanceTextField*, *AgeComboBox*, *100DollarCheckbox*, *200DollarCheckbox*, *400DollarCheckbox*, and *BuyButton*. After running *GUITAR*, we have the following seven length-2 event sequences: (e_1,e_7), (e_2,e_7), (e_3,e_7), (e_4,e_7), (e_5,e_7), (e_6,e_7), and (e_7,e_7). In this example all the bounded sequences end in e_7 because otherwise no action can be taken at the end of the user interaction. Consider (e_2,e_7) as an example. It means the user specifies a distance (e_2) before clicking the BuyButton (e_7). Although logically meaningless, this particular event sequence is feasible.

Step 2. For each event sequence produced by *GUITAR*, we generate more sequences by enumerate the values of widgets with *enum* types. For example, in (e_3,e_7), we know *JComboBox* is associated with e_3 and it has an *enum* type. Therefore, we enumerate all possible values of *JComboBox* to produce the new sequences (e_3^0,e_7) and (e_3^1,e_7), where e_3^i means the value i is chosen for event e_3. We also enumerate the values of other widgets with *enum* types, including *AgeComboBox*, *100DollarCheckBox*, *200DollarCheckBox*, *400DollarCheckBox*. Since these selectable widgets have a limited number of data values, enumerating them is often more efficient than generating the values using concolic execution.

Step 3. For each event sequence generated in Step 2, we instrument the GUI application by marking certain variables as symbolic. Consider the *guicat-conf* file in Figure 1 (right), where the last four widgets are of *enum* types but the first two are not. Thus, we mark the first two widgets as symbolic. That is, we use *CATG.readString("superman")* to create a symbolic string and use *CATG.readString(100)* to create a symbolic integer. Here *"superman"* and *100* are the default concrete values for the symbolic variables.

Step 4. We use *Catg* to execute each instrumented GUI application symbolically following the specific event sequence. Consider (e_3^1,e_7) again, where e_7 is associated with branches of an *if* statement. Symbolic execution will lead to the creation of new values for *name* and *distance*, e.g., *name=superman* and *distance=50*. Mapping the values back to the event sequence will result in $(e_1^{superman},e_2^{50},e_3^1,e_7)$, where the first two events are added to set the values of the widgets.

Step 5. After generating all the event sequences and data values using concolic execution, we use JaCoCo to compute the coverage report. JaCoCo is an open-source code coverage library for Java, whose output is formulated as an HTML page to show the coverage statistics.

3. ARCHITECTURE

Figure 3 shows the architecture of GUICat. Given a GUI program P as input, GUICat first invokes *GUITAR* to generate event sequences. Then, it instruments the program based on each sequence and the symbolic variables specified in *guicat-conf*. Next, it invokes the distributed algorithm to conduct symbolic execution of the instrumented program on a cloud node. Finally, the test cases generated by all instrumented programs are collected and then used by JaCoCo to compute the coverage report.

In the distributed symbolic execution algorithm, N_0 is the load balancer and $N_1\ldots N_k$ are the k workers on the cloud. N_0 distributes the set E of instrumented GUI programs, one per event sequence, over the k workers. The workers then conduct symbolic execution on their share of tasks. Initially, each worker receives roughly the same number of tasks. How-

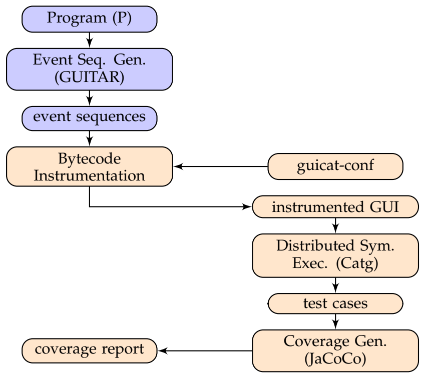


Figure 3: The architecture of our GUICat tool.

Algorithm 1 Symbolic Execution on a Worker.

```
1:  $E = T = \emptyset$;
2:  while true do
3:    if receiving task set $E'$ then
4:      $E = E \cup E'$;
5:      send($N_0, |E|$);
6:    else if requesting tasks on behalf of $N_i$ then
7:      send($N_i, E[0..|E|/2]$);
8:      send($N_0, |E|$);
9:    else if collecting test cases then
10:     send($N_0, T$);
11:     terminate;
12:   end if
13:   for all $e \in E$ do
14:     $P_e$ = instrument($P, e, cfg$)
15:     $T_e$ = Catg'.execute($P_e$);
16:     send($N_0, |E|$);
17:     $T = T \cup T_e$;
18:   end for
19: end while
```

ever, since the cost of symbolic execution varies for each event sequence, some workers may finish their symbolic execution tasks sooner than others. N_0 detects such imbalance and requests a worker with the largest workload to share its tasks with the idle worker. After all workers complete their tasks, the load balancer N_0 collects the test cases.

Algorithm 1 shows the symbolic execution procedure for each individual worker. Initially, the set E of tasks and test cases T are both empty. Then, the worker keeps checking messages from N_0 and conducting local symbolic execution. If it receives a set E' of tasks (from N_0 or another worker), the new tasks are added to the local set. Since the number of tasks is changed, it updates N_0 with its current number of tasks. This also occurs at Lines 8 and 16. With such updates, N_0 knows the number of tasks to be processed at the workers. If the worker receives a message from N_0 that requests more tasks on behalf of another worker N_i, it sends half of its tasks to N_i (Line 7). A signal of termination is received if N_0 asks for its test cases, and in such case, the current worker sends the locally generated test cases and then terminates.

Symbolic execution is conducted for each individual event sequence $e \in E$. Essentially, it allows us to execute the event-driven application as if it is a sequential Java program. We leverage the *Catg* concolic execution tool, which maintains two execution stacks: one for concrete execution and the other for symbolic execution. When *Catg* executes an unknown method, for example, *Integer.parseInt()* , the symbolic execution stack would not be updated, we have modified *Catg* to handle unknown methods.

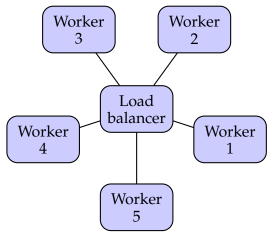


Figure 4: Architecture of GUICat's distributed algorithm.

```
for worker in $(workers); do
   scp -r ${AUTDIR}.tar.gz {worker}:~/gui/guicat/log/
done
...
for worker in $(workers); do
   scp ${worker}:~/gui/guicat/${AUTDIR}/report.tar.gz
     ./${AUTDIR}/${worker}.tar.gz
done
```

Figure 5: Communication from load balancer to workers.

The distributed algorithm in GUICat has been implemented on Amazon EC2 as a Cloud service. We divide EC2 instances into the load balancer and the workers. The load balancer is a multi-processor EC2 instance that generates event sequences, distributes tasks to the workers, and collects the test cases generated by the workers. Each worker is a single-processor EC2 instance that symbolically executes an event sequence to generate test cases. GUICat allows the user to customize the Cloud service, such as the number of workers and their computation capabilities, based on customer requirements such as whether a budget-first testing is preferred over a speed-first testing, or whether branch coverage is preferred over instruction coverage.

To allow easy customization, we implement GUICat by following the star topology shown in Figure 4, where the load balancer generates and distributes event sequences to the workers, and the workers conduct concolic execution with respect to the event sequence in isolation, before sending test cases back to the load balancer. Figure 5 illustrates how event sequences are distributed to the workers and how test cases are collected from the workers. For now, distributed file system libraries are used to implement the transfer of event sequences and test cases between the load balancer and workers. The main advantage of this architecture is efficiency since there is no communication between the workers.

4. EXPERIMENTAL EVALUATION

We have implemented GUICat using a number of open-source tools, including *GUITAR* for generating the initial event sequences, *ASM* for instrumenting the Java bytecode, *Catg* for implementing the distributed parallel concolic execution, and *JaCoCo* for computing the code coverage report.

We have evaluated GUICat on several GUI testing benchmarks. In all experiments, we have used the Amazon EC2 cloud computing infrastructure, where the load balancer is deployed as a multi-processor EC2 instance and each worker is deployed as a single-processor EC2 instance.

In the remainder of this section, we report the results of two case studies: a ticket seller and a workout generator. In each case study, our experiment consists of the following steps. First, we create a configuration file for the application under test. Then, we generate the event sequences using

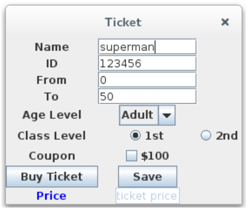


Figure 6: Ticket Seller

GUITAR [10]. Next, we distribute the event sequences from the load balancer to workers on Amazon EC2. The initial distribution is static and divides the tasks evenly to the EC2 instances. After receiving the event sequences, each worker conducts concolic execution using *Catg*; as a result, test cases are generated for these event sequences. When all workers finished, the load balancer collects their test cases and then uses *JaCoCo* to compute the coverage report.

4.1 The Ticket Seller

Figure 6 shows the user interface of a more sophisticated ticket seller than the one shown in Figure 1. It allows the user to provide passenger information such as the *Name*, *ID*, start distance (*From*), end distance (*To*), *Age Level*, *Class Level*, and the *Coupon*. When the user clicks the *Buy Ticket* button, the application stores the passenger information to an object named *TicketModel*, checks for consistency using the method *checkModel()*, and computes the price using the method *computePrice()*.

There are five different types of GUI widgets in Figure 6: four of *JTextField* type, one of *JComboBox* type, one of *JRadioButton* type, one of *JCheckBox* type, and two of *JButton* type.

The first two *JTextField* widgets collect the values of `Name` and `ID` by invoking *JTextField.getText()*, the combination of which may lead to buggy behaviors. We mark both fields as symbolic. That is, when loading the related Java class, we use the bytecode rewriting tool *ASM* to instrument the program on the fly, to replace invocations of *getText()* with invocations of *sGetText()*, a method that we develop to return a symbolic value. The symbolic values for `Name` and `ID` are used during the subsequent symbolic execution step.

The next two *JTextField* widgets collect the values of *From* and *To* by first invoking *JTextField.getText()* and then invoking *Integer.parseInt* to cast the strings into integers. Since the symbolic execution engine *Catg* does not support such casting, we have modified *Catg* to convert these strings into integers before using them in the subsequent logic.

As for the selectable widgets *JComboBox*, and *JCheckbox*, we enumerate all possible values of the *enum* types. We choose enumeration over symbolic execution for these selectable widgets due to efficiency and ease of implementation. First, selectable widgets do not have many different values. Second, the existing symbolic execution engine often has trouble handling them. For example, *JComboBox* has two methods *getSelectedIndex()* and *getSelectItem()* that return values of a customized *Object* type, which cannot be easily cast to strings or integers inside *Catg*.

To summarize, we used *GUITAR* to generate the initial event sequences together with the initial parameters/states. Then, we add the enumerated values for selectable widgets, before conducting symbolic execution to generate the values for widgets of other types. If the initial event sequence is too short to contain all widgets of *JTextField* type needed, we remove the stateless *JTextField* event and then append more stateful *JTextField* event to the beginning of the event sequence, thus increasing the length of the sequence.

Table 1: Results on the ticket seller (length = 2, node = 1).

Tool	Button	Branches	Coverage	Instructions	Coverage
GUITAR	checkModel	6	33.3%	56	53.5%
	computePrice	34	23.5%	172	30.8%
GUICat	checkModel	6	100%	56	100%
	computePrice	34	100%	172	100%

Table 2: Results on ticket seller: the test cases generated in addition to *GUITAR* and the unique paths covered.

Tool	length	Test Case (TC)	enum TC	concolic TC	paths covered
GUITAR	2	11	-	-	4
	3	110	-	-	7
GUICat	2	11	13	286	96
	3	110	156	3212	190

We analyzed the ticket seller with several configurations. Table 1 shows the results of generating the length-2 test cases. Columns 1-2 show the tool name and the name of the button clicked. Columns 3-4 show the total number of branches and the percentage of branches covered. Columns 5-6 show the total number of instructions and the percentage of instructions covered. The results show that GUICat can achieve full branch and instruction coverage even with length-2 test cases, whereas *GUITAR* can only achieve 33.3% branch coverage and 53.5% instruction coverage for *checkModel*, 23.5% branch coverage and 30.8% instruction coverage for *computePrice*.

Table 2 compares GUICat and *GUITAR* in terms of the number of paths covered. Column 1 shows the tool name. Column 2 shows the length of the test sequences. Column 3 shows the total number of test cases generated by *GUITAR*. Column 4 shows the number of additional test cases generated by GUICat after enumerating the values of selectable widgets. Column 5 shows the number of test cases generated by GUICat after concolic execution. Column 6 shows the path coverage.

To accurately compute the number of paths covered, we manually added code into the program. Specifically, we used a vector named *path*, where each element was mapped to an *if*-statement. For example, the *age* combo-box corresponds to an *if*-statement where we set *path[0]=0* in the *then* branch and *path[0]=1* in the *else* branch. Each time the program terminates, we will obtain a unique vector *path* that acts as the path identifier. These vectors are stored and then used to compute the path coverage after GUICat terminates.

Our result shows that, overall, GUICat achieved significantly higher path coverage than *GUITAR*. For length-2 test sequences, in particular, GUICat had 96/4=24 times higher path coverage, whereas for length-3 test sequences, GUICat had 190/7=27 times higher path coverage.

GUICat also successfully detected two bugs in ticket seller. One bug is a *NullPointerException* caused by the race condition between clicking of the *save* button and clicking of the *buy* button as shown in Figures 7 and 8. The other bug is the failure of an assertion due to the computed price being less than zero.

4.2 The Workout Generator

Figure 9 shows the user interface of the workout generator, which is taken from *Barad* [6]. It generates a workout plan based on the user input, including the *Gender*, *Metabolism*,

```
buyButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent e) {
    ticketModel.name = nameInput.getText();
    if(ticketModel.checkModel()) {
        ticketModel.computePrice();
        assert ticketModel.price>0 : @Bug: price<=0
   ! ;
}}});
saveButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent e) {
    ...
    ticketModel = null;
}});
```

Figure 7: The buggy code snippet in ticket seller.

```
[AWT-EventQueue-0] ERROR Uncaught exception
java.lang.NullPointerException
at examples.ticket.BaradTicket$1.actionPerformed(
   BaradTicket.java:177)
...

[AWT-EventQueue-0] ERROR Uncaught exception
java.lang.AssertionError: @ Bug: price <= 0!
at examples.ticket.BaradTicket$1.actionPerformed(
   BaradTicket.java:235)
```

Figure 8: The ticket seller bug detected by GUICat.

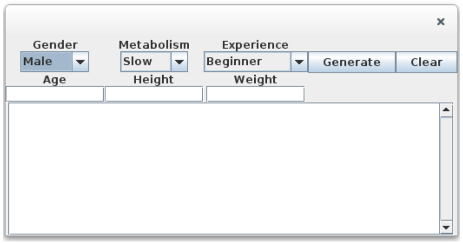


Figure 9: Workout Generator

Experience, *Age*, *Height*, and *Weight*. The computation starts when the user clicks the *Generate* button. Depending on the user information, the computation goes through different execution paths that use different cardio coefficients.

There are three *JTextField* widgets and three *JComboBox* widgets. The *JTextField* widgets return string values of *Age*, *Height*, and *Weight* using the method *JTextField.getText()*, before casting them to integers using *Integer.parseInt()*. Based on the configuration file provided by the user, GUICat creates three symbolic variables for these three widgets, and replaces *getText()* with *sGetText(Object)* so it can return symbolic values. The *JComboBox* widgets return values of *Gender*, *Metabolism*, and *Experience*. Since they are selectable widgets, we use enumeration to create the value combinations.

Table 3 shows the results of applying GUICat to workout generator with the length of test sequences set to 1 and 3. Columns 1-2 show the tool name and the length of the test sequences. Columns 3-4 show the number of branches covered and the percentage of branches covered. Columns 5-6 show the number of instructions covered and the percentage of instructions covered. Again, GUICat significantly outperformed *GUITAR* in terms of both path coverage and instruction coverage. Neither tool was able to reach full path and instruction coverage with length-2 test sequences, because there are three selectable widgets, which requires the length of test sequences being to be larger than 2.

With length-3 test sequences, GUICat was able to achieve 100% instruction coverage and 97.4% branch coverage. In contrast, *GUITAR* did not show significant improvement in

Table 3: Results on workout generator (node=1).

Tool	Length	Branches	Coverage	Instructions	Coverage
GUITAR	2	154	13.0%	2425	42.3%
	3	154	13.0%	2425	42.3%
GUICat	2	154	68.9%	2425	85.7%
	3	154	97.4%	2425	100%

Table 4: Results on workout generator: the test cases generated in addition to *GUITAR* and the unique paths covered.

Tool	length	Test Case (TC)	enum TC	concolic TC	paths covered
GUITAR	2	9	-	-	1
	3	72	-	-	2
GUICat	2	9	14	69	24
	3	72	182	909	56

branch/instruction coverage. The reason is that *GUITAR* only used the default values of the widgets, and thus cannot explore alternative paths even with a longer event sequence. In contrast, GUICat used both enumeration and symbolic execution to diversify the values of the widgets.

Table 4 compares GUICat and *GUITAR* in terms of the number of paths covered. Column 1 shows the tool name. Column 2 shows the length of the test sequences used in the experiments. Column 3 shows the number of test cases generated by *GUITAR*. Column 4 shows the number of additional test cases generated by GUICat after enumerating the values of selectable widgets. Column 5 shows the number of test cases generated by GUICat after concolic execution. Column 6 shows the number of paths covered. Our result demonstrates that, overall, GUICat can achieve significantly higher path coverage than *GUITAR*. For length-2 test sequences, in particular, GUICat reached 24/1=24 times higher path coverage, whereas for length-3 test sequences, GUICat reached 56/2=28 times higher path coverage.

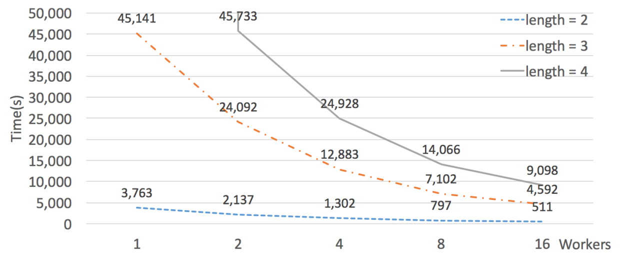
We also observed that GUICat generated many more test cases than the paths covered. For example, with the length set to 3, GUICat generated 909 test cases to cover 56 unique paths, which means some of these test cases have led to the same paths. If we could, for example, identify and eliminate these redundant test cases, the performance of GUICat would be further improved. However, we leave the pruning of these redundant test cases for future work.

4.3 Effect of Cloud Computing

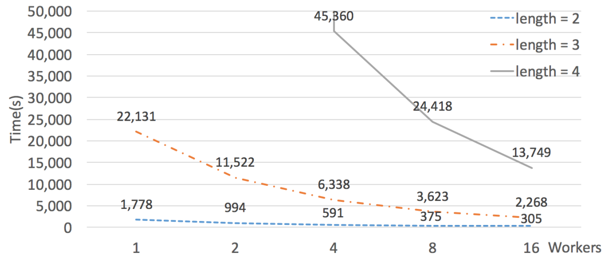
Figure 10 shows the effectiveness of distributing the testing of the ticket seller (a) and the workout generator (b) over Amazon EC2. The x-axis denote the number of workers, ranging from 1 to 16, and the y-axis denote the time usage in second. The solid, dashed and dotted lines represent the bounded length of 2, 3 and 4, respectively. Due to the inherent parallelism in symbolic execution of different event sequences, the speedup is almost linear.

5. RELATED WORK

GUITAR [10] is the first framework capable of performing the whole process of test generation, execution, and result assessment for GUIs. Since its first publication there have been multiple improvements (e.g. [14]). This framework generates tests as event sequences up to a given bound. For emulating user input a specification based approach is adopted, i.e., using values from a prefilled database. Since *GUITAR* does not provide a mechanism for reasoning about input values for data widgets, GUICat offers complementary and more comprehensive testing.



(a) ticket seller



(b) workout generator

Figure 10: Time reduction achieved by cloud computing.

The work closest to ours is `Barad` [6] that also exploits symbolic execution to compute input values for data widgets. It manually creates symbolic mirror of java GUI library, so its released source code contains a large symbolic java GUI library. Manual modeling is error prone and hard to sustain. In fact, we downloaded the tool but failed to make it work on our benchmarks. We employ a different test generation algorithm and symbolic analysis method for obtaining inputs. Another line of work is to apply model checking techniques. For example, `jfp-awt` [8] is an extension of the Java PathFinder for GUI applications.

Performance enhancement of GUI testing has traditionally focused on minimizing event sequences [9, 13]. `Barad` generates test cases as chains of event listener method invocations and maps these chains to event sequences that force the execution of these invocations. Such approach prunes the event input space because it does not need to consider events where there are no event listeners. More recent work starts to apply event dependency analysis [4], program slicing [5] or partial order reduction [7] to improve the performance. Our performance improvement is obtained by exploiting massive hardware resource available on cloud. Therefore our approach is orthogonal to the existing algorithmic approaches.

6. CONCLUSION

We have present GUICat, the first cloud-based GUI testing tool for simultaneously generating high-quality event sequences as well as high-quality data values. Internally, GUICat leverages *GUITAR* to generate the initial set of event sequences, and then uses a combination of value enumeration and symbolic execution to generate data values of the widgets. GUICat also leverages the cloud computation infrastructure to speed up the test generation, by distributing independent concolic execution tasks to EC2 nodes. We have implemented GUICat and evaluated it on a set of GUI testing benchmarks. Our experiments show that GUICat can significantly outperform *GUITAR* on standard GUI testing benchmarks in terms of both branch coverage and instruction coverage.

7. ACKNOWLEDGMENTS

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