Deadlocks as Runtime Exceptions

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Abstract. Deadlocks are a common type of concurrency bug. When a deadlock occurs, it is difficult to clearly determine whether there is an actual deadlock or if the application is slow or hanging due to a different reason. It is also difficult to establish the cause of the deadlock. In general, developers deal with deadlocks by using analysis tools, introducing application-specific deadlock detection mechanisms, or simply by using techniques to avoid the occurrence of deadlocks by construction. In this paper we propose a different approach. We believe that if deadlocks manifest at runtime, as exceptions, programmers will be able to identify these deadlocks in an accurate and timely manner. We leverage two insights to make this practical: (i) most deadlocks occurring in real systems involve only two threads acquiring two locks (TTTL deadlocks); and (ii) it's possible to detect TTTL deadlocks efficiently enough for most practical systems. We conducted a study on bug reports and found that more than 90% of identified deadlocks were indeed TTTL. We extended Java's `ReentrantLock` class to detect TTTL deadlocks and measured the performance overhead of this approach with a conservative benchmark. For applications whose execution time is not dominated by locking, the overhead is low. Empirical usability evaluation in two experiments showed that students finished tasks faster using the proposed approach and, in one of the experiments were also more accurate.

Keywords: deadlock, concurrency, exception handling, empirical studies

1 Introduction

Real-world applications use concurrency to do computation in parallel with multiple threads/processes taking more advantage of multicore processors. Unfortunately, concurrent code is difficult to write correctly, as it is well documented [1]. Deadlocks are a very common type of error in concurrent systems [1]. Deadlocks manifest when threads are waiting each other in a cycle, where each thread is waiting for another thread to release its desired lock. This produces a never-ending wait. Although there are two well-documented types of deadlocks, resource deadlocks and communication deadlocks [2][3], in this work our focus is

on resource deadlocks, e.g., deadlocks that stem from threads attempting to obtain exclusive access to resources, and whenever the term *deadlock* is used we implicitly mean resource deadlock.

In practice, developers employ a number of approaches to deal with deadlocks: (i) static program analyses [4][7][8][9]; (ii) dynamic program analyses [10][11][12][13][14][16]; (iii) application-specific deadlock detection infrastructures [19]; (iv) techniques to guarantee the absence of deadlocks by construction [4]; (v) model checking [17]. The first two approaches are known to be heavyweight. In addition, the former often produces many false positives. The third approach has limited applicability and often imposes a high runtime overhead. The fourth approach has a low cost but cannot be employed in cases where it is not feasible to order lock acquisitions nor use non-blocking locking primitives. Finally, model checking is a powerful solution but has limited scalability when applied in the context of real programs. It also has limited generality, since some programs with side effects simply cannot be model checked.

In this paper we advocate an approach that complements the aforementioned ones. In summary, we believe deadlocks should not fail silently but instead their occurrence should be signaled as exceptions at runtime. To make this vision possible, we leverage two insights: (i) the vast majority of existing deadlocks occur between two threads attempting to acquire two locks (as reported by other authors [1] and confirmed by us in Section 2); and (ii) it is possible to efficiently introduce deadlock detection for these two-thread, two-lock deadlocks (TTTL deadlocks) within the locking mechanism itself, incurring in an overhead that is low for applications whose execution time is not dominated by locking. We present a new type of lock that automatically checks for TTTL deadlocks at runtime and, if one is found, throws an exception indicating the problem. We have implemented this approach as an extension to Java's `ReentrantLock` class. Deadlock exceptions are already supported in programming languages such as Haskell [5] and Go [6] but they focus on different types of deadlocks. Similarly, runtime exceptions for data races have been proposed [15].

We present data from an empirical study showing that our assumption about the prevalence of TTTL deadlocks holds in practice. This confirms the findings of a previous study that focused on concurrency bugs in general [1]. To evaluate our approach, we conducted two controlled experiments. In both cases, subjects using these new locks were able to detect deadlocks significantly faster than subjects not using them. Furthermore, in one of the studies, this approach helped the subjects to more accurately identify the causes of the deadlock. We also show that our approach has an overhead that, while non-negligible, is low for applications whose execution time is not dominated by locking.

2 Bug Reports Study

Attempting to generalize deadlock detection at runtime does not seem feasible from a performance viewpoint, since existing dynamic analyses take considerable time [11]. But previous bug reports study [1] found that 30 out of 31 deadlock bug

reports involved at most two resources. We suspected TTTL deadlocks were more common in real world systems than more complex deadlocks, so we investigated this further. This section presents the results of this investigation.

2.1 Data Collection

We selected three open source projects to investigate: Lucene, Eclipse and OpenJDK. Lucene[1] is a text search engine library. Eclipse[2] is one of the most popular IDEs for java developers. OpenJDK[3] is an open-source implementation of the Java Platform. These three projects share some key similarities: they're mostly written in Java; they have immense bug report repositories with easy tools to search into them; and lastly, their bug reports were usually well discussed and contained enough context that allowed us to classify them with some confidence, which was very important in this study.

In total, we collected 541 bug reports containing the word *deadlock* on their titles or on their descriptions. In Lucene, we found 27 closed issues of type "bug" in module "lucene-core".[4] In Eclipse, we found 406 resolved issues with resolution "fixed".[5] In OpenJDK, we found 108 issues of type "bug" on module "JDK" with resolution "fixed" and status "resolved".[6] We then proceeded to calculate the sample size that would allow us to have 95% of confidence level and 5% sampling error, which resulted in 225 bugs. Thus we created a random sample of that size to analyze further [7].

2.2 Data Labeling

We defined a set of fields to classify for each bug analyzed in the sample. First, we define a category. Then complete other fields based on how much we could understand of each bug report, like the number of threads involved, number of resources involved, type of locking mechanism used, and so on.

We have four different values for the category field. Category *A* indicates that we are confident this is a resource deadlock. Thus, we should be able to describe the number of threads and locks that were involved. In contrast, category *B* represents the opposite: it is certainly not a resource deadlock. The reported bug is a communication deadlock, due to evidence of lost notify/signal in the bug context or anything else that supports it was not a resource deadlock. Category *C* refers to all the false-positive results: the term *deadlock* was used as a synonym of "hanging" or an "infinite loop", or to just mention another deadlock bug as a reference, not as a cause of the current bug. Lastly, category *D* is set for all bugs that we could not understand clearly, due to a lack of evidence or discussion.

[1] Lucene: http://lucene.apache.org/
[2] Eclipse: https://eclipse.org/
[3] OpenJDK: http://openjdk.java.net/
[4] Lucene bug reports list: http://goo.gl/DhVI3t
[5] Eclipse bug reports: http://goo.gl/qQnrEm
[6] OpenJDK bug reports: http://goo.gl/xYFfsO
[7] Bug reports sample: http://goo.gl/zNsIGz

2.3 Results Analysis

Initially we consider only bugs we clearly identified, that is, bugs that were not labeled as category D. In Table 1 (second column), we can see in that from all resource deadlocks, 92.07% of them are indeed TTTL deadlocks. Another interesting finding is that 75.93% of all deadlocks are indeed resource deadlocks.

Table 1: Labeled Categories and Estimations

Category	Number of Bugs	Estimated
A	101	146
A and TTTL	93	134
B	32	46
C	23	33
D	69	0

If we now consider bugs we could not clearly classify, we can make some estimations of how many of them would be resource deadlocks and TTTL deadlocks. The first estimate is the worse case scenario, that is, all bugs in category D should be in category A but none of them would be TTTL deadlocks. In this case, only 54.7% of resource deadlocks would be TTTL deadlocks. If we look at the best case scenario, that is, all bugs in D would be TTTL deadlocks, then it would be 95.29% instead. However none of these two scenarios seems realistic. We believe that a more realistic scenario would be to assume that bugs in category D are distributed roughly in the same way as those in categories A, B, and C. If that is the case (last column of Table 1), out of all resource deadlocks, we estimate that 91.7% of them would also be TTTL deadlocks. Thus TTTL deadlocks are certainly the most popular type of resource deadlocks, amounting to more than 9 out of every 10 resource deadlocks. This result makes it evident that an approach to automatically detect these deadlocks has practical value.

2.4 Threats to Validity

Only one of the authors labeled all bug reports due to constraints on time and lack of resources. In counterpart, having only one reviewer makes it easier to guarantee that all bug reports were reviewed following the exact same procedure, but we would have preferred to have at least one more reviewer to label each bug independently and use it as a way to double check the labels accuracy. Furthermore, one factor that might limit generalization of these findings is that all projects we looked were written in Java and different programming languages may have different distribution of deadlock bugs.

3 Deadlock Detection

In this section we present the proposed approach. We extend the notion of lock by making locks responsible for both detecting TTTL deadlocks and raising exceptions whenever such deadlocks occur. In this section we present an algorithm implementing this extended notion of lock and show that our algorithm guarantees that (i) every TTTL deadlock is detected; and (ii) if an exception reporting a deadlock is raised, it must stem from the occurrence of a TTTL deadlock.

We have modified the default implementation of Java's *ReentrantLock* to allow efficient runtime detection of TTTL deadlocks. It works as follows:

1. Each lock has a pointer to a thread, the owner of the lock, or `null` when no thread owns that lock.
2. Each lock has an integer to represent its current state: 0 means the lock is free and no thread owns it (the *unlocked* state), 1 means there is a thread that owns the lock (the *locked* state). For simplicity, we are only interested on these two states. Nonetheless, in the implementation of *ReentrantLock*, each time a thread owner acquires the same lock, this state would be incremented, and decremented each time the thread releases it.
3. Each thread has a thread-local list of pointers to locks it currently owns.
4. Each lock has a waiting queue of threads that are waiting to acquire it. Whenever a thread tries to obtain a lock when it's already acquired, the thread will add itself to the waiting queue before parking. Upon the event of releasing the lock, the owner of that lock will look for the first thread in the waiting queue and unpark it.
5. When a thread wants to acquire a lock, it will swap the current state to *locked* if the current state is *unlocked* atomically.
   (a) If the thread fails, it must be because the lock is already owned by some other thread, then it will add itself on the waiting queue for that lock. Finally, the thread will park.
   (b) Otherwise, the thread will set itself as the current owner of that lock and also add this lock to its thread-local list of pointers of locks it owns.
6. When a thread is about to release a lock, the current owner pointer of that lock is set to `null` and that lock is also removed from the thread-local list of owned locks. Finally, the lock state is changed to *unlocked*.
7. Before parking, a thread will check whether there is a deadlock. When the current thread is unable to acquire its desired lock, it must be because another thread already owns it. It is possible to know who is the owner of any lock, so the current thread identifies the owner of its desired lock as the conflicting thread. Then the current thread will search on each lock of its list of owned locks if the conflicting thread is waiting for it.
   (a) If positive, then we have a circular dependency (current thread is stuck waiting for its desired lock and the conflicting thread is stuck waiting for a lock the current thread owns) and thus a deadlock exception will be raised.
   (b) Otherwise, the thread parks.

We take advantage of the current algorithm employed by *ReentrantLock* and some of its guarantees listed below to avoid the need to introduce extra synchronization mechanisms or costly atomic operations during deadlock detection:

1. The operation of swapping the state of a lock from *unlocked* to *locked* must be done atomically by the thread, so only one thread can be successful at a time.
2. A thread will only park when it is guaranteed that some other thread can unpark it. Missing notifications will never happen and concurrent uses of park and unpark on the same thread will be resolved gracefully.
3. Inserts on each lock's waiting queue must be done atomically. If multiple threads concurrently attempt to insert themselves in the waiting queue on the same lock, they will both succeed eventually but the exact order of insertions is not important.
4. Once the last element in the waiting queue of a lock is read, it should be safe to read all threads in the waiting queue that arrived before the last element. Since the thread who reads the waiting queues is also the one who blocks every thread waiting on the queues, we can guarantee the only updates that could happen concurrently are new insertions at the end of each queue. However insertions in the end of the queue are not important once a last element pointer is obtained.

Lemma 1. *The proposed protocol can always detect TTTL deadlocks.*

Proof. By way of contradiction, suppose not and a TTTL deadlock occurred without it being detected. Lets assume that threads A and B have both acquired locks a and b respectively, as follows:

$$write_A(state_a = locked) \rightarrow write_A(owner_a = A) \tag{1}$$

$$write_B(state_b = locked) \rightarrow write_B(owner_b = B) \tag{2}$$

In the above expressions, '$x \rightarrow y$' indicates that event x happened before event y. Notation '$write_B(owner_b = B)$' indicates that thread B wrote to variable $owner_b$ the value B. And now each thread will attempt to acquire the opposing lock: thread A is trying to acquire lock b and thread B is trying to acquire lock a, as follows:

$$read_A(state_b == locked) \rightarrow write_A(waiting\_queue_b.insert(A)) \tag{3}$$

$$read_B(state_a == locked) \rightarrow write_B(waiting\_queue_a.insert(B)) \tag{4}$$

The notation '$read_A(state_b == locked)$' indicates that thread A read variable $state_b$ and obtained value *locked*. If a TTTL deadlock happened, then both threads are now parked and all previous equations should be correct. But before parking, each thread must check for deadlock by inspecting each lock it owns if the opposing thread is on its waiting queue. As we initially assumed no deadlock

exception has been raised, then both threads are parked and also the following equations must be correct:

$$read_A(owner_b == B) \rightarrow read_A(waiting\_queue_a.contains(B) == false) \quad (5)$$

$$read_B(owner_a == A) \rightarrow read_B(waiting\_queue_b.contains(A) == false) \quad (6)$$

The problem with the previous equations is that they both cannot be true simultaneously. Before checking for deadlock, each thread must add itself on the waiting queue of its desired lock. If it holds that the opposing thread is not in the waiting queue yet, then it must be because it did not start to check for deadlock yet, thus a contradiction. □

Lemma 2. *The proposed protocol never raises a deadlock exception for a non-existent TTTL deadlock.*

Proof. By way of contradiction, assume the opposite: a deadlock exception was raised and there is no real TTTL deadlock. Exactly one of the following equations must be true in order to raise a deadlock exception (if both were true at the same time, an actual deadlock would have occurred):

$$read_A(owner_b == B) \rightarrow read_A(waiting\_queue_a.contains(B) == true) \quad (7)$$

$$read_B(owner_a == A) \rightarrow read_B(waiting\_queue_b.contains(A) == true) \quad (8)$$

Suppose without loss of generality that the first equation is true. It means that thread B is waiting for lock a and it is also the owner of lock b. If it is on the waiting queue, that thread is either parked already or about to park and in both cases thread B is going to depend on the release of lock a to proceed. However, as we have seem previously, thread A at this point is also about to park and is checking for a deadlock. If this condition holds, we have a circular dependency between threads A and B, a real TTTL deadlock, thus we have a contradiction. □

3.1 Extension: raising exceptions in all threads

The protocol we presented guarantees that an exception is raised in at least one of the threads involved in a deadlock. A safer approach, however, would be to have exceptions raised in both threads involved in the deadlock. In this section we describe an extension to the protocol that provides this guarantee. This does not affect how deadlock is detected but what should be done after a deadlock is detected. Thus, does not impact the correctness of the protocol. The proposed extension comprises the following:

1. Each lock has a list of tainted threads. This list should only be read or updated by the owner of that lock, allowing immunity from interference without any extra synchronization cost.

2. Once a deadlock is detected and the current thread is about to raise a deadlock exception, it already knows which thread is conflicting with itself and which lock that thread desires. The current thread (the owner of the desired lock) will add this conflicting thread to the tainted threads list for that lock. After that, the deadlock exception is raised.
3. When the conflicting thread is unparked and finally acquires its desired lock (it becomes the owner of that lock), then it is allowed to read the list of tainted threads. If this thread identifies itself in this list, then it must be because it was part of a deadlock before, so it removes its reference from the list and also raises a deadlock exception.
4. Every operation on the list of tainted threads of any lock (either reading or inserting values) should be followed up by some cleanup on all references to threads that are no longer running.

That is sufficient to force both threads to raise exceptions when only one of them would raise an exception in the initial protocol. The latter only raises exception on both threads if they simultaneously reach the point where they check for deadlocks. However, for this particular case, this change introduces a different problem: dangling references. If each thread adds their conflicting thread to the lists of tainted threads of the locks they own, but none of them is able to acquire their respective desired locks (as in *item 3*), both threads will leave their references behind for others to cleanup (as in *item 4*). We minimize this issue by cleaning these references as soon as any thread acquires the lock.

3.2 Implementation

The modified OpenJDK *ReentrantLock* version to implement this algorithm is available in our code repository [18]. Further implementation details were omitted here for brevity.

4 Evaluation

In this section we present an evaluation of our approach. Our evaluation comprises two parts: (i) a usability evaluation involving two experiments with two groups of students (Section 4.1); and (ii) a preliminary analysis of the performance overhead of our approach (Section 4.2). The exact input, instructions, and any additional document we have used in this section are available at [18].

4.1 Usability Evaluation

We ran empirical evaluation to measure the efficiency of deadlock exceptions with regard to problem solving speed and accuracy. We defined two research questions for this evaluation: **RQ1.** Is the time spent to identify the bug reduced using our implementation? **RQ2.** Is the accuracy in the identification of the causes of a deadlock bug improved for developers using our approach? For the

second question, each answer was evaluated based on three criteria with three possible values each: 0 for absence, 0.5 for partially present and 1 for fully present. First criteria, A, stands for "correctly classified problem as deadlock"; second criteria, B, means "classified problem as different from deadlock"; and lastly, C means "correctly identified method calls involved in the deadlock". Whenever $(A - B) + C \geq 1.5$ is true, we defined it as a correct answer (that is, whenever the bug was described as deadlock and at least one of the methods involved in the deadlock were identified correctly).

We wrote two programs with different levels of complexity which were presented in the same order for all subjects. The first program, known as *Bank*, contained 4 classes spread among 4 files, 3 threads, 3 explicit locks, and a mean of 82 lines of code per file. The second program, known as *Eclipse*, had 15 classes spread in 11 files, 4 threads, 5 explicit locks, and a mean of 40 lines of code per file. Each program could use either *LockA* or *LockB*, where *LockA* was our implementation with deadlock detection on at least one thread involved in a deadlock, while *LockB* was just the default *ReentrantLock* implementation. Each student was assigned to either group A or B randomly. In group A, students would start with *LockA* in the first program but use *LockB* on the second program; meanwhile, in group B students would have the locks in opposite order.

The two experiments had similar setups but differed in terms of the subjects. For the first experiment, the subjects comprised a group of third-year undergraduate students who underwent an 18-hour concurrent programming course. The course included a number of programming assignments. The experiment was conducted as a test for the course. The subjects of the second experiment were graduate students enrolled in master's degree or PhD program attending a 40-hour Parallel Programming course with a focus on algorithms and data structures. They had classes about advanced concepts of parallel programming and had practical exercises, including implementing a number of different locking approaches. The participants in the second experiment were all volunteers and were not required to take part in it. Also, for both experiments, the assignments were the same. It asked students to identify any problems they could with the provided programs. All students started the experiment with program *Bank*. When they finished, they received the second program, *Eclipse*. When a student finished one of the programs, we set a timestamp on it. The timestamp was written based on a chronometer visible to everyone in the laboratory. For the first group (undergraduate students), we allowed 90 minutes per program. For the second group (graduate students), we allowed 60 minutes per program.

Time Analysis. We defined the following hypothesis to answer **RQ1**:

$$H_0 : \mu_{TimeLockA} \geq \mu_{TimeLockB} \tag{9}$$

$$H_1 : \mu_{TimeLockA} < \mu_{TimeLockB} \tag{10}$$

We used Latin Square Design [24] to control two factors that might affect the metrics: subjects and program complexity. Programs *Bank* and *Eclipse* had

complexity easy and difficult respectively, while *LockA* and *LockB* were the two possible treatments we wanted to compare. Since we had N subjects, 2 programs and 2 possible treatments, we disposed subjects in rows and programs in columns of latin squares, randomly assigning in each cell of the square a treatment that could be *LockA* or *LockB*, but also guaranteeing that for any given row or column in this square, each treatment appeared only once. Consequently, we have replication, local control and randomization which are the three principles of experiment design [24]. Time analysis was conducted with R Statistical Software using the inputs extracted from each day. We used the linear model described in Figure 1 that considers the effect of different factors on the response variable similarly to Accioly's work[21], adding the effect between each replica and treatment [20].

$$Y_{lijk} = \mu + \tau_l + \tau\alpha_{li} + \beta_j + \gamma_k + \tau\gamma_{lk} + \epsilon_{lijk}$$

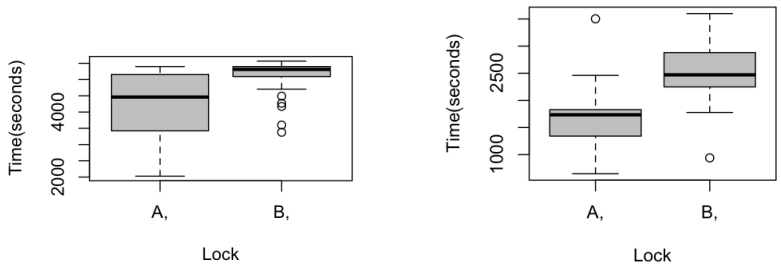
Y_{lijk} - response of l_{th} replica, i_{th} student, j_{th} program, k_{th} lock
τ_l - effect of l_{th} replica
$\tau\alpha_{li}$ - effect of interaction between l_{th} replica and i_{th} student
β_j - effect of j_{th} program
γ_k - effect of k_{th} lock
$\tau\gamma_{lk}$ - effect of interaction between l_{th} replica and k_{th} lock
ϵ_{lijk} - random error

Fig. 1: Regression model.

Initially, we plotted box-plot graphics shown in Figure 2 for both experiments. Then we ran Box-Cox transformation to reduce anomalies such as non-additivity and non-normality. The value of λ at the maximum point in the curve drawn by box-cox function in R was not approximately 1 ($\lambda = 5$), thus we should apply the transformation: on our regression model, Y_{lijk} should be powered to λ. We did the same on the second experiment as $\lambda = 1.3636$.

After applying Box-Cox transformation, we ran Tukey Test of Additivity that checks whether effect model is additive. If the model was additive, then rows and columns of each latin square wouldn't affect significantly the response [24]. Now consider the hypothesis where the null hypothesis (H_0) says the model is additive and alternative hypothesis (H_1) says the opposite. In the first experiment, model was additive as we obtained p-value of 0.514 which is not lower than 0.05 and we couldn't reject H_0; similarly for the second experiment, the model was also additive as p-value found was 0.914.

Finally, we ran the ANOVA (ANalysis Of VAriance) test which compares the effect of treatments on the response variable, providing an approximated p-value for every associated factor. When a variable has $p\text{-}value < 0.05$, it means that factor was significant to the response. Table 2 and Table 3 shows **the most important factor as the type of *Lock* for both experiments**, allowing us



(a) First experiment (b) Second experiment

Fig. 2: Box-plot on both experiment days

to reject our null hypothesis defined for **RQ1**. Thus, considering this result and the box plots in Figure 2, we can say that the use of our locks promoted faster identification of deadlocks.

Table 2: First experiment ANOVA results.

	Df	Sum Sq	Mean Sq	F value	*p-value*
Replica	14	3.8633e+37	2.7595e+36	1.6553	0.1784197
Program	1	4.1460e+36	4.1460e+36	2.4869	0.1371197
Lock	1	3.9489e+37	3.9489e+37	23.6873	0.0002492 ***
Replica:Student	15	4.1013e+37	2.7342e+36	1.6401	0.1808595
Replica:Lock	14	2.4033e+37	1.7166e+36	1.0297	0.4785520
Residuals	14	2.3340e+37	1.6671e+36		

Accuracy Analysis. We used the number of correct answers using each lock to measure accuracy, so we defined the following hypothesis to answer **RQ2**.

$$H_0 : \mu_{CorrectAnswersLockA} \leq \mu_{CorrectAnswersLockB} \tag{11}$$

$$H_1 : \mu_{CorrectAnswersLockA} > \mu_{CorrectAnswersLockB} \tag{12}$$

To compare the accuracy of the subjects using Java's regular `ReentrantLock` and our modified implementation, we employed Fisher's exact test [25]. We could not use ANOVA because the data for accuracy is categorical (Correct vs. Incorrect) instead of numerical. Applying Fisher's exact test on data from Table 4 and Table 5, we can see that undergraduate students results presented a two-tailed P value equals 0.0004: the association between rows (groups) and columns (outcomes) was considered to be extremely statistically significant; consequently, it suggests that an improvement on accuracy occurred due to the use of the proposed approach. However graduate students results presented a two-tailed P value equals 0.3259, which does not represent statistically significant evidence.

Table 3: Second experiment ANOVA results.

	Df	Sum Sq	Mean Sq	F value	Pr(¿F)
replica	6	2576883250	429480542	14.1891	0.0025793 **
program	1	6875586	6875586	0.2272	0.6505035
lock	1	1958179433	1958179433	64.6938	0.0001975 ***
replica:student	7	2328154077	332593440	10.9881	0.0047601 **
replica:lock	6	823830276	137305046	4.5362	0.0441188 *
Residuals	6	181610625	30268438		

	Correct	Incorrect
LockA	29	2
LockB	16	15

Table 4: First group accuracy

	Correct	Incorrect
LockA	13	1
LockB	10	4

Table 5: Second group accuracy

Although we cannot draw strong conclusions regarding improved accuracy, we found some interesting behavior. Some students in the second group were greatly experienced on concurrent programming and they knew how to efficiently find a deadlock using the tools available in their IDE of choice, thus being able to finish the tasks really quickly for both problems. This observation allows us to hypothetize that deadlock exceptions are more helpful for less experienced programmers, but we leave investigation of this matter for future work.

Threats to Validity We must consider a few remarks regarding the validity of our results. First remark: we could have used automated process to handle timestamps rather than manually writing their name with it on the whiteboard once they finished a question to keep track of time limit per subject later; this could potentially reduce overhead and increase timestamp precision. Secondly, the first group did this experiment in replacement of their actual exam might have impacted the time we measured. We noticed some students spent more time on each question by purpose. We believe that they were reluctant to ask for the next question because they still had plenty of time left and they wanted to make sure it was correct. We did not notice such behavior with the second group of students and we believe it is because they did not have the same pressure to deliver correct results as the first group had. Third remark is related to programs' complexity: the ones we used to evaluate the students are considerably easier to understand than most programs in real world, but unfortunately we could not use any real world scenario as students would not be able to finish each assignment in time; with that in mind, we created two questions based on real world bugs we found on our bug report studies. Last remark is about whether we are able to draw conclusions based on students data: some studies suggest that using students as subjects is as good as using industry professionals [23]; Runes ran an experiment which shows that there's not much significant differences

between undergraduate, graduate and industry professionals, with the exception that undergraduate students often take more time to complete the tasks [22].

4.2 Performance Overhead

We conducted a preliminary set of experiments to analyze the overhead of our approach. We compared our deadlock-safe implementation with the original `ReentrantLock` implementation available in the JDK and with Eclipse's deadlock-safe `OrderedLock` [19]. `OrderedLock` is similar our approach in the sense that it attempts to detect deadlocks at runtime. However, it aims to be general, detecting N-thread deadlocks without much concern for performance. OrderedLock deeply relies on Eclipse's code architecture. So, in order to use it in our evaluation, we had to perform some small code changes, removing only Eclipse-specific bits that did not affect the core functionality of `OrderedLock`. The source code for these lock implementations is available elsewhere[18].

We developed a synthetic benchmark that creates N threads that perform additions to ten integer counters where each increment in a counter is protected by explicit locks. Each thread would have to increment its corresponding counter 1000 times before finishing its execution and the counters were evenly distributed across the threads. Therefore, each counter will have exactly *(N / 10)* threads doing increments on it and higher values of N result in higher contention, that is, more threads will compete against each other for a particular counter. In this preliminary evaluation, we have conducted measurements for values of N equal to 10, 50, 100, and 200. Since each thread in the benchmark never acquires more than one lock at the same time, deadlocks cannot occur. We emphasize that this setup is very conservative, since every operation that each thread performs requires locking. Thus, the obtained overhead will be a worst-case estimate and thus much higher than one would encounter in a real-world application [26]. The measurements were made on an Intel CoreTM i7 3632QM Processor (6Mb Cache, 2.2GHz) running Ubuntu 12.04.4 LTS and each cell in Table 6 is the average of 50 executions (preceded by 20 executions that served as a warm-up).

Table 6: Benchmark time measurements (in seconds)

# Threads	ReentrantLock	ReentrantLock Modified	OrderedLock
10	0.084184	0.105729	0.159503
50	0.089094	0.136507	1.094718
100	0.090978	0.159541	3.395974
200	0.131739	0.194075	11.258714

The difference of results between our implementation and the original ReentrantLock gives a range of increased time from about 50% to 90%. Meanwhile, OrderedLock performed a lot worse, reaching a 8446.3% increase in time for the worst case. To get a rough estimate of the impact that this overhead would have

on actual application execution time, we analyzed the results obtained by Lozi et al. [26]. The authors profiled 19 real-world applications and small benchmarks in order to measure the time these systems spend on their critical sections. Worst-case results ranged between 0.3% and 92.7%. If we consider the average time spent on the critical sections of 12 of these systems, the impact of our approach on the overall execution time would be **less than 6% in the worst case**. The remaining cases are extreme, in the sense that these systems spend more time in their critical sections than out of them [26].

5 Conclusion

In this work, we investigated deadlock bug reports in open source projects and confirmed a previous study claim that TTTL deadlocks are the most frequent case of deadlock (92.07% of all resource deadlocks we identified). We modified Java's *ReentrantLock* and provided a lightweight version of it that detects TTTL deadlock in runtime. We measured its performance overhead with a very conservative benchmark and we estimate our cost to be less than 6% for worse case on real world applications. Finally, we did an empirical evaluation to measure its usability and we found that deadlock exceptions speeds up finding deadlock bugs in code, and we also found some non-conclusive evidence showing that it may also improve accuracy of deadlock bug reports, but we leave for future work to verify whether this last observation is actually true.

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