

Correct Refactoring of Concurrent Java Code

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Abstract. Automated refactorings as implemented in modern IDEs for Java usually make no special provisions for concurrent code. Thus, refactored programs may exhibit unexpected new concurrent behaviors. We analyze the types of such behavioral changes caused by current refactoring engines and develop techniques to make them behavior-preserving, ranging from simple techniques to deal with concurrency-related language constructs to a framework that computes and tracks synchronization dependencies. By basing our development directly on the Java Memory Model, we can state and prove precise correctness results about refactoring concurrent programs. We show that a broad range of refactorings are not influenced by concurrency at all, whereas other important refactorings can be made behavior-preserving for correctly synchronized programs by using our framework. Experience with a prototype implementation shows that our techniques are easy to implement and require only minimal changes to existing refactoring engines.

1 Introduction

Ever since its inception, Java has offered strong support for writing concurrent code, and with the increasing prevalence of multicore processors in recent years, concurrent programming has become crucial to exploiting these architectures. It may, then, come as a surprise that many of the most frequently used refactorings as implemented in modern Java IDEs are not concurrency-aware. When applied to concurrent programs, even refactorings that work reliably for sequential code may introduce concurrency bugs in the form of unexpected new behaviors, race conditions, deadlocks, or livelocks.

For sequential programs, the refactoring community has generally downplayed the importance of ensuring that refactoring engines handle all corner cases correctly [11], instead encouraging developers to use regression tests to ensure that refactorings do not change program behavior. But this approach is likely to be much less effective in a concurrent setting; concurrency bugs like race conditions may only occur on particular hardware or with a very rare thread schedule, making it much more difficult to gain confidence in a refactoring via regression testing.

While there has been some work on new refactorings designed specifically to improve the concurrent behavior of existing code [7, 8, 23, 34], the correctness of

traditional refactorings on concurrent code is not well studied. In his classic guide to refactorings, Fowler cautions that “these refactorings . . . are described with single-process software in mind” and anticipates that refactorings for concurrent software will be quite different [11].

This paper presents what is to the best of our knowledge the first systematic approach to ensuring the correctness of commonly used refactorings on concurrent code. We propose to extend the concept of dependence edge preservation, previously used by Schäfer et al. to ensure correctness of refactorings on sequential code [27, 28], to the realm of concurrent programs. The newly introduced dependence edges relate language constructs significant to the underlying memory model, based on the reordering constraints it imposes. A refactoring implementation then builds on this framework and ensures that the appropriate edges are preserved under the transformation, which guarantees that certain behavior changes are not introduced.

By firmly grounding our dependence edges in the specification of the memory model, we can formulate and prove precise behavior preservation results for refactorings that adopt them. For concurrent code, the notion of “behavior preservation” has to account for the non-deterministic behavior that can easily arise in concurrent settings. We say that a refactored program preserves the behavior of the original one if *all* behaviors it can exhibit can also be exhibited by the original program, and vice versa. We investigate a number of commonly-used refactorings in terms of the Java Memory Model (JMM) [22] and show that the majority of them always preserve behavior in this sense, assuming they are behavior-preserving for sequential code. For some other important refactorings, we can prove that they preserve the behavior of concurrent programs without data races when enhanced with our techniques. Even for programs with races, we guarantee not to introduce any new races or deadlocks between actions from the original code (further discussed in §4.3).

We have implemented our proposed techniques as an extension to an existing refactoring engine [27, 28] with very moderate effort. We show that the use of synchronization constructs that would impede refactoring is rare in real-world Java programs, hence the additional constraints imposed by our framework are unlikely to prevent common refactoring operations.

The main contributions of our paper are as follows:

- We show that many existing refactoring implementations can introduce concurrency bugs related to altering possible inter-thread orderings (see §2).
- We present the first comprehensive approach for avoiding such bugs in Java refactoring engines based on desugaring of the **synchronized** method modifier and on preservation of *synchronization dependence edges* (see §3).
- We relate our techniques to the Java memory model and prove that they yield a strong behavior preservation guarantee (see §4).
- We describe an implementation of our techniques in an existing refactoring engine, showing that only moderate implementation effort is required to obtain behavior preservation for concurrent code (see §5).

Finally, we discuss some related work in §6, before concluding in §7.

<pre> class C1 implements TM { static class Super { static int x, y; } static class Sub extends Super { static synchronized void m() { ++x; ++y; } static synchronized void n() { if (x != y) { print("bug"); } } } public void m1() { Sub.m(); } public void m2() { Sub.n(); } } </pre> <p style="text-align: center;">(a)</p>	<pre> class C1 implements TM { static class Super { static int x, y; static synchronized void m() { ++x; ++y; } } static class Sub extends Super { static synchronized void n() { if (x != y) { print("bug"); } } } public void m1() { Super.m(); } public void m2() { Sub.n(); } } </pre> <p style="text-align: center;">(b)</p>
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Fig. 1. Example showing how the PULL UP MEMBERS refactoring can change program behavior; here, the `Sub.m()` method is pulled up to class `Super`.

2 Motivating Examples

In this section, we present a number of examples where existing refactorings do not preserve program behavior in the presence of concurrency. The examples show that a variety of concurrency bugs may be introduced via existing refactorings, and that in some cases the introduced bugs are quite subtle, indicating the need for a principled approach to refactoring concurrent code.

Example Structure Each example contains a class implementing an interface `TM` (for “Two Methods”) with methods `m1()` and `m2()`. A harness provided in Appendix A executes `m1()` and `m2()` in parallel, exposing the concurrency bugs introduced by the refactorings. In all the example figures, part (a) shows the original program and part (b) shows the refactored program. The code targeted by the refactoring is highlighted in dark gray in part (a) of each figure, and code changed by the refactoring is highlighted in light gray in part (b).

In every example, we will argue that the refactored program can exhibit some behavior that was not possible in the original program. We have verified the possibility of these behaviors using the MemSAT tool [32].

Pull Up Members The PULL UP MEMBERS refactoring [11] can introduce concurrency bugs when it mishandles the **synchronized** method modifier. Consider the example program of Figure 1(a). The program includes a class `Super` that declares two fields `x` and `y`. Its subclass `Sub` declares two static methods `m()` and `n()` that are respectively invoked by the methods `m1()` and `m2()`, and hence may be run in parallel. Note that `m()` and `n()` are both **synchronized**, which implies that

```

class C2 implements TM {
    static class A {
        synchronized static void m() {}
        synchronized static void n() {}
    }
    static class B {}
    public void m1() {
        synchronized (B.class) { A.m(); }
    }
    public void m2() {
        synchronized (A.class) { A.n(); }
    }
}

```

(a)

```

class C2 implements TM {
    static class A {
        synchronized static void m() {}
    }
    static class B {
        synchronized static void n() {}
    }
    public void m1() {
        synchronized (B.class) { A.m(); }
    }
    public void m2() {
        synchronized (A.class) { B.n(); }
    }
}

```

(b)

Fig. 2. Example showing how the MOVE refactoring may change program behavior. Here, the `A.m()` method is moved to class `B`.

the code in the body of each method is protected by the same lock, `Sub.class`.³ As a result, the updates to fields `x` and `y` by `m()` are executed atomically from method `n()`'s point of view, and the print statement in `n()` can never execute.

Now suppose that the PULL UP MEMBERS refactoring is applied to move method `Sub.m()` into its superclass `Super`. We are not aware of any preconditions imposed on the PULL UP MEMBERS refactoring in the literature that would prevent this refactoring, and current IDEs such as Eclipse and IDEA allow it, producing the code of Figure 1(b).

However, this transformation is not behavior-preserving: the `synchronized` method `m()` is now located in class `Super`, which means that it is now protected by the lock `Super.class`. Method `n()` is still protected by the lock `Sub.class`, and since these locks are different, the methods `n()` and `m()` can now be interleaved in arbitrary ways. In particular, `n()` may execute in between the field writes in `m()`, leading to “bug” being printed, an impossibility in the original program.

Note, incidentally, that pulling up `synchronized` instance methods does not suffer from this problem: such methods synchronize on the receiver object, which is not changed by the refactoring.

Move Method Figure 2 gives an example where the MOVE METHOD refactoring can introduce a deadlock. In the original program, method `m1()` first acquires the `B.class` lock and then calls `A.m()`, which in turn acquires the `A.class` lock (since it is `synchronized`). Method `m2()` acquires the `A.class` lock and then calls `A.n()`, which again acquires lock `A.class` (this second lock-acquire trivially suc-

³ In Java, a `static synchronized` method is protected by a lock on the `Class`-object associated with the class in which the method is declared.

```

class C3 implements TM {
    int f;
    public void m1() {
        int g = 0;
        synchronized (this) {
            g = f;
        }
        if (g % 2 != 0) { print("bug"); }
        synchronized (this) { g = f; }
    }
    public synchronized void m2() {
        ++f; ++f;
    }
}

```

(a)

```

class C3 implements TM {
    int f;
    public void m1() {
        int g = 0;
        int n = f;
        synchronized (this) {
            g = n;
        }
        if (g % 2 != 0) { print("bug"); }
        synchronized (this) { g = n; }
    }
    public synchronized void m2() {
        ++f; ++f;
    }
}

```

(b)

Fig. 3. Example showing how the EXTRACT LOCAL refactoring may change program behavior. Here, the first read of `f` in method `m1()` is extracted.

ceeds because Java monitors are reentrant). Deadlock is impossible in the original version of the program, because the only lock that is required by both threads, `A.class`, is never held indefinitely by either thread.

Now suppose that we apply the MOVE METHOD refactoring to move method `n()` from class `A` to class `B`, resulting in the code of Figure 2(b). As with PULL UP MEMBERS, this refactoring is allowed by both the Eclipse and IDEA IDEs. However, the refactored program may deadlock. Moving the `synchronized` method `A.n()` to class `B` causes the method to synchronize on `B.class`. Hence, method `m2()` now first attempts to acquire lock `A.class` and then lock `B.class`. Since method `m1()` still attempts to acquire lock `B.class` and then lock `A.class`, we have the classic scenario where deadlock may occur due to a lack of a consistent locking order.

Extract Local Here we show that the EXTRACT LOCAL refactoring can introduce an atomicity bug. For Figure 3(a), consider applying EXTRACT LOCAL to the first read of the `f` field in method `m1()`. The EXTRACT LOCAL refactoring as implemented in Eclipse and IDEA will introduce a new local variable (with a name interactively chosen by the programmer; we chose `n` in the example), initialize it to the selected expression, and replace *all* occurrences of that expression with a reference to the variable.⁴ Since `m1()` contains another occurrence of the expression `f`, the refactoring produces the code shown in Figure 3(b), declaring `n` outside the `synchronized` block.

⁴ Eclipse replaces all occurrences by default, with an option to only extract the selected occurrence, whereas IDEA's default is to only extract the selected occurrence.

```

class C4 implements TM {
    static volatile boolean a = false;
    static volatile boolean b = false;
    public void m1() {
        boolean x = (a = true);
        while (!b);
        if (x);
        print("m1_finished");
    }
    public void m2() {
        while (!a);
        b = true;
        print("m2_finished");
    }
}

```

(a)

```

class C4 implements TM {
    static volatile boolean a = false;
    static volatile boolean b = false;
    public void m1() {
        while (!b);
        if ((a = true));
        print("m1_finished");
    }
    public void m2() {
        while (!a);
        b = true;
        print("m2_finished");
    }
}

```

(b)

Fig. 4. Example showing how the `INLINE LOCAL` refactoring may change program behavior. Here, the local `x` in `m1()` is inlined.

Unfortunately, this transformation can change program behavior. Note that, in the original program, accesses to field `f` in methods `m1()` and `m2()` are protected by a lock on **this**. Consequently, the two increments of `f` in method `m2()` are performed atomically from the point of view of the references to `f` in `m1()`, and hence `m1()` will only see even values in `f`. After the refactoring, the reference to `f` has been hoisted outside the **synchronized** blocks in `m1()`. As a result, the reads of `f` in method `m1()` may occur between the two writes in `m2()`, making it possible for `m1()` to print “bug” (an impossibility in the original program).

Inline Local Figure 4(a) shows an example program that relies only on two **volatile** fields `a` and `b` to synchronize between threads—the program does not contain any **synchronized** blocks or methods. In Java, a write of a **volatile** field by one thread guarantees that any other thread that subsequently reads this field sees all memory updates the former thread has performed, up to and including the volatile write.⁵ Thus a volatile field can be used as a flag by which one thread notifies another about the completion of a task or the availability of data.

The execution of the program in Figure 4(a) takes place in the following order. First, the fields `a` and `b` are both initialized to **false**. Then, the thread executing `m1()` sets `a` to **true** and then spins until `b` becomes **true**. The only assignment to `b` is in the thread that executes method `m2()`, meaning the spin-loop in `m1()` will continue to be executed until the other thread executes this assignment. Meanwhile, the thread executing `m2()` begins by spinning until `a`

⁵ In contrast, writes to non-volatile fields without other synchronization may appear to happen out-of-order from the perspective of other threads.

<pre> class C5 implements TM { int x = 0; int y = 0; int z = 0; public void m1() { int r1 = x; synchronized (this) {} y = 1; print(r1); } public void m2() { int r2 = y; synchronized (this) { z++; } x = 1; print(r2); } } </pre>	<pre> class C5 implements TM { int x = 0; int y = 0; AtomicInteger z = new AtomicInteger(0); public void m1() { int r1 = x; synchronized (this) {} y = 1; print(r1); } public void m2() { int r2 = y; z.getAndIncrement(); x = 1; print(r2); } } </pre>
(a)	(b)

Fig. 5. Example showing how the CONVERT INT TO ATOMICINTEGER refactoring [7] may change program behavior. Here, the refactoring is applied to the `z` field.

becomes **true**, which happens when the other thread assigns **true** to `a`. At that point, `b` is set to **true**, and the thread terminates after printing “m2 finished”. After `b` becomes **true**, the **if**-statement in `m1()` is executed and the thread terminates after printing “m1 finished”. In summary, the execution of the actions by the two threads proceeds in a fixed order and always terminates normally.⁶

Figure 4(b) shows the example program after applying **INLINE LOCAL** to the variable `x`. Note that refactoring has moved the write of the **volatile** field `a` after the spin-loop in method `m1()`. This means that both threads are now executing their spin-loop until the other sets the **volatile** field used in its condition to **true**. Neither thread can make progress, resulting in a livelock, which was not possible in the original version of the program.

Convert Int to AtomicInteger The **CONCURRENCER** tool of Dig et al. [7] provides refactorings aimed to help migrate code to the `java.util.concurrent` libraries introduced in Java 1.5. One such refactoring is **CONVERT INT TO ATOMICINTEGER**, which converts a field of type `int` and its accesses to the appropriate operations on an `AtomicInteger`. The transformation can improve both thread safety and scalability [7].

Surprisingly, in some corner cases it is possible for **CONVERT INT TO ATOMICINTEGER** to change program behavior. To explain how, we must introduce some terminology. The Java Memory Model relates reads, writes, and lock acquire and release events (among others) by the *happens-before* relation [20]. In-

⁶ The order in which the two print statements are executed is not constrained.

formally, an operation a happens-before b , written $a \leq_{\text{hb}} b$, if (1) a is performed before b by the same thread, or (2) $a \leq_{\text{hb}} r$ and $q \leq_{\text{hb}} b$, where r is a release of a lock that is later acquired by q . Given \leq_{hb} , we can define a *data race*:

Definition 1. *Two accesses to the same field or array element form a data race iff they are unrelated by \leq_{hb} and at least one of them is a write.*

Now, consider the program in Fig. 5(a). The key thing to notice about this program is that either `m1()` or `m2()` will always print 0, due to the following reasoning. The placement of the **synchronized** blocks in `m1()` and `m2()` ensures that the program cannot have a data race on both `x` and `y` simultaneously. If `m1()` acquires and releases the **this** monitor before `m2()`, then the read of `x` in `m1()` happens-before the write of `x` in `m2()`, and therefore `m1()` must print 0. (In this case, there is no data race on `x`, but there may be a race on `y`.) By similar reasoning, if `m2()` synchronizes on **this** before `m1()`, then `m2()` must print 0.

Now suppose that the CONVERT INT TO ATOMICINTEGER refactoring is applied to the field `z`, yielding the program in Figure 5(b). The refactoring removes the **synchronized** block from `m2()` and, with it, the happens-before edges between the operations on `x` and `y`.⁷ That is, the refactored program, unlike the original one, may race on both `x` and `y`. According to the JMM, these races could cause the refactored program to print two 1's to the console, which was impossible in the original program.

This counter-intuitive outcome may be more easily understood in terms of the compiler transformations allowed by the JMM. In theory, a compiler could transform the `m1()` method from the refactored program in Figure 5(b) to the following:

```
public void m1() { y = 1; int r1 = x; print(r1); }
```

In this scenario, the compiler removes the **synchronized** block from `m1()` after discovering that no other thread synchronizes on the same object.⁸ Once the block is removed, the compiler can then reorder the read of `x` and the write of `y`, since they are independent accesses to different memory locations [16]. After these compiler transformations, there is an interleaving of the refactored program in which both `m1()` and `m2()` print 1.

No Java compiler we know of performs the kind of global reasoning that is required for the transformations described above. As a result, we have not observed an execution of the program in Figure 5(b) that prints two 1's to the console. In general, we suspect that this sort of bug is very unlikely to arise in practice for typical hardware and JVMs. Nonetheless, the example illustrates the difficulty of ensuring the correctness of refactorings with respect to the JMM, which allows various compiler and hardware optimizations that result in out-of-order reads and writes of shared memory.

⁷ While the `getAndIncrement()` method can be thought of as atomically performing a volatile read and a write of `z`, the atomicity and volatility of this operation do not induce any inter-thread happens-before edges because `z` is accessed only in `m2()`.

⁸ This assumes the program is run with the harness as described in Appendix A.

3 Techniques for Preserving Concurrent Behaviors

Section 2 showed that it is all too easy for a refactoring that rearranges or moves code to introduce concurrency bugs by enabling new interactions between parallel threads. Here, we describe two relatively simple techniques that can enable a refactoring engine to avoid introducing a wide variety of concurrency bugs, including all of those presented in §2. First, §3.1 shows that a simple desugaring of the **synchronized** method modifier simplifies the preservation of its semantics during refactoring. Then, §3.2 describes how the approach of preserving dependence edges to ensure refactoring correctness [28] can easily be extended to prevent problematic reordering of concurrent code.

3.1 Handling **synchronized** methods

In the examples of Figures 1 and 2, a refactoring changed program behavior because moving a **synchronized** method to another class can result in the method acquiring a different lock when executed. A straightforward solution to this problem is to perform a desugaring step before refactoring that transforms a **synchronized** method into a method containing a **synchronized** block that explicitly refers to the appropriate lock. For example, the desugaring would transform the **synchronized** method `A.n()` of Fig. 2 into the following form:

```
static void n() { synchronized(A.class) { } }
```

In this form, the method can safely be moved to class `B` without changing program behavior. In the same vein, method `Sub.m()` from Fig. 1 would be desugared by introducing synchronization on `Sub.class` around its body, so it can be pulled up to class `Super` without further ado. After the refactoring, a “re-sugaring” step then tries to eliminate the introduced **synchronized** blocks in favor of **synchronized** modifiers, which is, however, not possible in these two examples.

The desugaring and resugaring steps are similar to the micro-refactorings advocated by Schäfer et al. [28], although interestingly here the focus is on *simplifying* the language to facilitate refactoring, whereas the latter work put its emphasis on *enriching* the language for the same purpose.

3.2 Dependence Edges

In past work [28], Schäfer et al. employed the concept of *dependence edge preservation* to rule out the possibility of behavior change for sequential refactorings. For example, the `INLINE LOCAL` refactoring, in its simplest form, takes a declaration `T x = e`; of a local variable, and replaces every reference to `x` with a copy of `e`. To ensure correctness, the refactoring engine computes all data and control dependencies of `e`, in particular all the reaching definitions of read accesses in `e` before and after the refactoring, and ensures that dependencies are neither acquired nor lost.

This approach is appealing since it enables us to apply well-understood concepts and techniques from the compiler construction literature in a refactoring

context. For example, a framework for computing control flow graphs and determining data dependencies is part of many compiler frontends, and can perhaps be reused. This contrasts sharply with precondition-based approaches, where sufficient preconditions for behavior preservation have to be invented from scratch.

However, preserving data and control dependencies is not sufficient for concurrent code, as illustrated by the example in Figure 4. There, the expression `a=true` has no (intraprocedural) control or data dependencies either before or after the refactoring, and yet the refactoring causes a behavior change due to interference with another thread. While in principle it might be possible to avoid this problem by adding inter-thread control and data dependencies, such an approach does not seem practical for real-world Java programs.

Looking more closely at the examples, we see that one of the main reasons for behavior change is the reordering of concurrency-related code by the refactoring. For example, in Fig. 3, a read of field `f` is moved out of a **synchronized** block, and in Fig. 4, a write and a read of two volatile fields are permuted; such reorderings enable new concurrent behaviors. We will now introduce *synchronization dependencies*, which capture this kind of constraint and will prevent such reorderings from happening.

For example, an access to a field is synchronization dependent on every **synchronized** block in which it is nested or which precedes it, so it will lose a dependence when it is moved out of one of these blocks. Analogous to control and data dependencies, the refactoring engine will compute all synchronization dependencies of expressions it moves and checks that dependencies are preserved, thereby avoiding bugs like those in Figures 3 and 4.

Determining what synchronization dependencies must be modelled and how exactly they must be preserved requires consulting the memory model defining possible concurrent behaviors, in our case the JMM. While the detailed specification of the model is very technical, its main consequences in terms of permissible instruction reorderings are neatly summarized in Doug Lea’s “JSR-133 Cookbook” [21], from which we take the matrix in Fig. 6. The JMM classifies instructions into several categories, five of which figure in the reordering matrix:

1. A *normal access* is a read or write of a non-volatile shared memory location, i.e., a field that is not declared **volatile**, or an array element.
2. A *volatile read* is a read of, and a *volatile write* a write of, a field declared **volatile**.⁹
3. A *monitor enter* is an instruction that acquires a lock; it corresponds to the beginning of a **synchronized** block or method.
4. A *monitor exit* is an instruction that releases a lock; it corresponds to the end of a **synchronized** block or method.

An instruction from any of these categories that occurs in a particular execution of the program is called a (memory) *action*. Many other instructions, such as reads or writes of local variables or arithmetic operations, are not relevant to the memory model and do not give rise to actions.

⁹ Array elements cannot be declared **volatile** in Java.

	Normal Access	Volatile Read, Monitor Enter	Volatile Write Monitor Exit
Normal Access			×
Volatile Read, Monitor Enter	×	×	×
Volatile Write, Monitor Exit		×	×

Fig. 6. JMM Reordering Matrix from [21]

The matrix specifies under which conditions an action can be reordered with an action that follows it in some execution. Each cell corresponds to a situation where an action of the kind indicated by the row label is followed (not necessarily immediately) by an action of the kind indicated by the column label. If the cell is labelled \times , these two instructions cannot in general be reordered.¹⁰

For example, the \times in the first column of the second row indicates that a volatile read or monitor enter cannot be permuted with a subsequent normal access, which at source level would correspond to moving a normal access before a volatile read or out of a **synchronized** block. On the other hand, the blank cell in the upper left corner indicates that normal accesses can be reordered, provided that no other constraints such as data dependencies prohibit it.

Figure 6 shows that as far as reordering is concerned, volatile reads behave the same as monitor enters, and volatile writes the same as monitor exits. The former two kinds of actions are collectively referred to as *acquire actions*, and the latter two as *release actions*. Both acquire actions and release actions are termed *synchronization actions* (but normal accesses are not). Hence, the matrix can be summarized by saying that (1) synchronization actions are not to be reordered; (2) a normal access cannot be moved past a release action; and (3) a normal access cannot be moved before an acquire action.

We define two kinds of synchronization dependencies in terms of the program’s control flow graph:

- A CFG node b has an *acquire dependence* on a node a if a corresponds to an acquire action and there is a path from a to b in the CFG. We then say that there is an *acquire edge* between a and b .
- A CFG node a has a *release dependence* on a node b if b corresponds to a release action and there is a path from a to b in the CFG. We then say that there is a *release edge* between a and b .

In terms of these dependencies, Figure 6 implies that during the reorderings performed by a refactoring,

¹⁰ These restrictions are chosen from a pragmatic perspective, presupposing only moderate analysis capabilities, and hence are slightly conservative. For instance, a very sophisticated global analysis may be able to prove that a volatile field is only accessible from a single thread, and can hence be treated like a normal field [21].

1. a normal access may never lose acquire dependencies,
2. a normal access may never lose release dependencies,
3. a node corresponding to a synchronization action may never gain acquire or release dependencies.

The matrix does not mention two other kinds of actions defined by the JMM: external actions and thread management actions. The former category comprises any action that interacts with the program’s environment (such as input/output), whereas the latter represents the thread management methods from the Java standard library’s `Thread` class. External actions do not require any special treatment. To ensure that no action is ever reordered with a thread management action, we introduce a third kind of synchronization dependence: a node a has a *thread management dependence* on any node b that corresponds to a thread management action and is reachable from it in the CFG. We require that

4. a node corresponding to an action may never gain or lose a thread management dependence.

Synchronization dependencies are easy to compute once we have a control flow graph of the program to be refactored, in particular since they do not require any form of alias analysis. For example, a normal access has an acquire dependence on *any* preceding volatile read, no matter which field the read refers to.

In principle, any sequential refactoring can be made safe for concurrent programs as follows: (1) compute synchronization dependencies on the initial CFG, (2) perform the refactoring as in the sequential case, yielding an updated CFG, and (3) recompute synchronization dependencies on the updated CFG and ensure that they have been preserved as described above. An implementation of EXTRACT LOCAL updated in this way will reject the refactoring in Fig. 3 since `f` loses its acquire dependence on `synchronized(this) { ... }`, and an implementation of INLINE LOCAL will reject the refactoring in Fig. 4, since the volatile read of `b` gains a release dependence on the volatile write of `a`.

While the reordering matrix of Figure 6 succinctly represents the implications of the JMM for code reorderings, some refactorings from our examples can do more than just reorder code. For example, the EXTRACT LOCAL refactoring is able to replace multiple identical expressions with the same new local, thereby possibly replacing multiple field accesses with one access (see Figure 3). Similarly, applying INLINE LOCAL may duplicate an expression, thereby replacing one field access with many. The next section examines the implications of our dependence preservation framework more formally, proving a strong correctness guarantee even for some refactorings that go beyond code permutations.

4 Correctness of Refactorings in the Presence of Concurrency

In this section, we formalize the synchronization dependence preservation technique of §3.2 and show that for many refactorings, it yields a strong guarantee

that *the exact concurrent behaviors of input programs are preserved*. In §4.1 we give some background on the Java Memory Model, and in §4.2 we present our formalization based on the memory model. Finally, §4.3 discusses our handling of programs with data races.

4.1 Java Memory Model Basics

Before formalizing our refactorings, we first describe some necessary concepts from the Java Memory Model [13, Chapter 17]. The JMM abstracts away from the concrete syntactic structure of programs, instead considering a program to be given as the (possibly infinite) set of its threads, and each thread as a set of memory traces representing possible executions. A memory trace is a list of actions (introduced in §3.2) paired up with their value, i.e., the value read or written by a normal or volatile access. These traces are required to obey *intra-thread semantics* in the sense that they correspond to executions of threads in isolation, except that reads of shared locations (fields or array elements) may yield arbitrary values to account for interaction between threads.

The set of memory traces for a thread is an overapproximation of the behavior it may actually exhibit when run in parallel with other threads. The JMM defines the notion of an *execution*, which chooses a particular trace for every thread and relates their actions in three ways. The first and simplest relation is the *program order* \leq_{po} , which reflects the intra-thread ordering of actions, and is hence determined by the choice of traces. The program order never relates actions from different threads. Second, the execution defines a global total order \leq_{so} on all synchronization actions in the traces, known as the *synchronization order*. For synchronization actions occurring within the same thread, this order has to be consistent with \leq_{po} . Finally, the execution assigns to every read action r a corresponding write action $W(r)$ on the same field or array element, requiring that the value seen by read r is the value written by write $W(r)$.

Based on the program order \leq_{po} and the synchronization order \leq_{so} of an execution, two additional orders are defined. The *synchronizes-with* order \leq_{sw} relates a release action r to an acquire action q if they correspond (i.e., either r is a write of a volatile field v which is read in q , or r exits a monitor m which q enters) and $r \leq_{\text{so}} q$. The *happens-before* order \leq_{hb} (described informally in §2) is defined as the transitive closure of $\leq_{\text{po}} \cup \leq_{\text{sw}}$. This means that $a \leq_{\text{hb}} b$ if either (1) $a \leq_{\text{po}} b$, or (2) there is a release action r and an acquire action q such that $a \leq_{\text{po}} r \leq_{\text{sw}} q \leq_{\text{hb}} b$. As in Defn. 1, a *data race* is then a pair of accesses to the same variable, at least one of which is a write, such that these accesses are not ordered by \leq_{hb} .

Finally, the JMM defines a set of *legal executions* for a program, i.e., those behaviors that may actually occur when executing the program. To determine these legal executions, the JMM starts with *well-behaved executions*, which are executions in which every read r sees a most recent write $W(r)$ to the same variable in the happens-before order. To derive a legal execution from a well-behaved execution, one then proceeds to commit data races, i.e., one decides whether a read sees a value through such a race or not. (This process can proceed one race

at a time or can involve multiple races, and may even be restarted, although committed choices cannot be undone.) In a *correctly synchronized* program, i.e., a program with no data races, all legal executions are well-behaved, and the most recent write occurring before a given read is always uniquely defined.

It is perhaps worth pointing out that correctly synchronized programs in this terminology are only required to be free of the low-level data races defined by the JMM. They may still contain higher-level races.

4.2 Correctness Proofs

The JMM deals with programs in a very abstract and low-level representation that is quite far removed from the Java source code a refactoring actually manipulates. Yet it is this high level of abstraction that allows us to easily establish our first correctness result:

Theorem 1. *Any refactoring that is trace-preserving, i.e., does not alter the set of memory traces of a program, preserves the behavior of arbitrary concurrent programs: every possible behavior of the original program is a behavior of the refactored program and vice versa. This holds even in the presence of data races.*

Proof. This is just a reformulation of a result in [16].

Perhaps surprisingly, a great many refactorings (and in particular the majority of all refactorings implemented in Eclipse) are trace-preserving, since many source-code constructs do not correspond to JMM actions. For example, the memory model has no concept of classes or methods, so refactorings that reorganize the program at this level are trace-preserving, among them PULL UP METHOD, PUSH DOWN METHOD, MOVE METHOD, and type-based refactorings such as INFER GENERIC TYPE ARGUMENTS. (This assumes the **synchronized** method modifier is handled correctly; see §3.1.) The model does not deal with names either, so RENAME does not become any more complicated in a concurrent setting.

The JMM also does not model method calls (in a sense, method calls are always inlined in traces), so the refactorings EXTRACT METHOD, INLINE METHOD, and ENCAPSULATE FIELD are all trace-preserving (again assuming correct handling of the **synchronized** keyword).

Two important refactorings that are not trace-preserving in general are INLINE LOCAL and EXTRACT LOCAL, since they may reorder field accesses. Note, however, that if these two refactorings are applied to expressions that do not involve field accesses or method calls (e.g., arithmetic expressions on local variables), they again become “invisible” to the memory model, and Thm. 1 guarantees their correctness on all programs.

Thus the JMM concept of traces and memory actions gives us a convenient criterion to decide whether a refactoring is affected by concurrency at all.

For non-trace-preserving refactorings, we can pursue two directions: we can identify further subclasses of refactorings for which general results can be proved,

or we can tackle the refactorings one by one to prove that their sequential implementation can be updated to preserve behavior on concurrent programs.

Exploring the former approach first, we note that among those refactorings that do in fact alter the set of memory traces a program yields, most do not actually remove any code from the refactored program (at least not code that corresponds to memory actions), but merely rearrange it. This might entail re-ordering statements or expressions, or merging pieces of code that do the same thing.

On the level of the JMM, we describe such transformations as follows:

Definition 2. *A restructuring transformation is a partial function ρ on programs such that for every program $P \in \text{dom}(\rho)$ and every execution E' of $\rho(P)$ there is an execution E of P and a mapping f from actions in E to actions of the same kind in E' . Also, this mapping does not map actions belonging to the same thread in E to different threads in E' .*

Intuitively, for every execution of the transformed program $\rho(P)$ we can find a corresponding execution of the original program P . We do not require that this execution has the same behavior in any sense, but just that there is a mapping between their actions which shows that no actions of the old program have been lost, even though new actions may have been introduced.

Most importantly, however, the kinds of all actions need to be preserved. That means, in particular, that field accesses have to refer to the same fields and read or write the same values, and monitor operations have to handle the same locks.

Given this very liberal specification, it is impossible to prove that such a transformation preserves behavior. Instead, we will show that a restructuring transformation cannot introduce new data races or new deadlocks between existing actions if it respects the synchronization dependencies introduced in the previous section.

Definition 3. *A restructuring transformation is said to respect synchronization dependencies if its mapping f fulfills the following three conditions for all actions a, b .*

1. *If $a \leq_{\text{so}} b$, then also $f(a) \leq'_{\text{so}} f(b)$.*
2. *If a is an acquire action and $a \leq_{\text{po}} b$, then also $f(a) \leq'_{\text{po}} f(b)$.*
3. *If b is a release action and $a \leq_{\text{po}} b$, then also $f(a) \leq'_{\text{po}} f(b)$.*

Since \leq_{so} is a total order, the first requirement says that f cannot swap the order of synchronization actions, whereas the second and third requirements prohibit reordering normal accesses to appear before acquire actions or after release actions. Note that this is just a formalization of the synchronization dependencies introduced in §3.2.¹¹

We first establish a slightly technical result.

¹¹ For brevity, we mostly ignore thread management actions in this section, but all results can easily be extended to cover them as well.

Lemma 1. *Let a synchronization dependence respecting restructuring be given, and let a and b be actions. If $a \leq_{\text{hb}} b$, then either $f(b) \leq'_{\text{hb}} f(a)$ or $f(a) \leq'_{\text{hb}} f(b)$.*

Proof. We first treat the case where a is an acquire action. In this case, we can actually prove that $a \leq_{\text{hb}} b$ implies $f(a) \leq'_{\text{hb}} f(b)$ by induction on \leq_{hb} :

If $a \leq_{\text{po}} b$, then $f(a) \leq'_{\text{po}} f(b)$, and hence $f(a) \leq'_{\text{hb}} f(b)$, by Defn. 3. Otherwise we have a release action l and an acquire action q such that $a \leq_{\text{po}} l \leq_{\text{sw}} q \leq_{\text{hb}} b$. As before, this means that $f(a) \leq'_{\text{po}} f(l)$; since f preserves action kinds and \leq_{so} we have $f(l) \leq'_{\text{sw}} f(q)$, and finally $f(q) \leq'_{\text{hb}} f(b)$ by induction hypothesis. Together this again shows $f(a) \leq'_{\text{hb}} f(b)$.

Now consider the general case where a is not necessarily an acquire action. If $a \leq_{\text{po}} b$, then $f(a) \leq'_{\text{po}} f(b)$ or $f(b) \leq'_{\text{po}} f(a)$, since f does not map actions across threads. Otherwise, $a \leq_{\text{po}} l \leq_{\text{sw}} q \leq_{\text{hb}} b$ for some release action l and an acquire action q . But by Defn. 3 this gives $f(a) \leq'_{\text{po}} f(l)$. As above we see $f(l) \leq'_{\text{sw}} f(q)$, and $f(q) \leq'_{\text{hb}} f(b)$ follows since q is an acquire action. In summary, we get $f(a) \leq'_{\text{hb}} f(b)$, establishing the claim.

Now our first result follows effortlessly:

Theorem 2. *If there is a data race between two actions $f(a)$ and $f(b)$ in execution E' , then there is already a data race between a and b in E .*

Proof. Follows directly from the previous lemma and the definition of a data race.

This result ensures that a synchronization respecting restructuring can never introduce a new data race between two actions carried over from the original program, although there may well be a data race involving actions introduced by the transformation.

We immediately gain an important corollary:

Corollary 1. *A restructuring transformation that does not introduce any new actions will map correctly synchronized (i.e., data race free) programs to correctly synchronized programs.*

A similar result can be established for deadlocks.

Lemma 2. *If there is a deadlock in an execution E' of $\rho(P)$ caused by locking actions in $\text{rng}(f)$, then the same deadlock occurs in E .*

Proof. We sketch the proof for the case of two deadlocking threads. In that case, there are threads ϑ and ϑ' and monitor enter actions l_1, l'_1, l_2, l'_2 . Writing $L(l_1)$ for the lock acquired by action l_1 and similarly for the others, we require $L(l_1) = L(l'_1)$ and $L(l_2) = L(l'_2)$; actions l_1 and l_2 belong to ϑ , whereas l'_1 and l'_2 belong to ϑ' .

By the definition of f , the same must be true of $f(l_1), f(l'_1), f(l_2), f(l'_2)$. In order for ϑ and ϑ' to deadlock, we must have $f(l_1) \leq_{\text{po}} f(l_2)$, $f(l'_2) \leq_{\text{po}} f(l'_1)$, $f(l_1) \leq_{\text{so}} f(l'_1)$, and $f(l'_2) \leq_{\text{so}} f(l_2)$. By definition of f , the same is true of l_1, l'_1, l_2, l'_2 due to the totality of \leq_{so} over all synchronization actions, the fact that \leq_{po} and \leq_{so} are consistent, and the first point of Def. 3.

Again, this proves that the transformation cannot introduce a deadlock only involving actions from the original program, but does not preclude the existence of deadlocks involving newly introduced actions.

The above two results establish a certain baseline. They apply to a wide range of refactorings (and indeed non-behavior-preserving transformations), but only guarantee very basic properties.

We conclude this section by establishing the correctness of two very important refactorings on correctly synchronized programs (we discuss programs with races in §4.3):

Theorem 3. *The refactorings EXTRACT LOCAL and INLINE LOCAL preserve the behavior of correctly synchronized programs if they preserve the behavior of sequential programs and respect synchronization dependencies.*

Proof (Outline). For EXTRACT LOCAL, note that if we extract copies e_1, \dots, e_n of an expression e into a local variable, there cannot be any acquire or thread management actions between the individual copies, since the refactoring needs to preserve synchronization dependencies. In a well-behaved execution this means that the read actions in all copies see the same values, hence correctness for sequential programs ensures behavior preservation.

For INLINE LOCAL, the refactoring may move field reads over acquire actions, which would seem to make it possible for them to see values written by different field writes than before the refactoring. For correctly synchronized programs, however, this is not possible, since the read must already have been preceded by corresponding acquire actions in the original program to prevent data races. So again read actions will see the same values as in the original program, and sequential correctness ensures behavior preservation.

The above argument can be made somewhat more precise, but a rigorous proof would need a formalization of the correspondence between source-level Java programs and programs as they are viewed by the JMM. Such an undertaking is beyond the scope of this work, so we content ourselves with this intuitive argument.

Apart from pragmatic considerations described in the following subsection, there are some technical details of the JMM specification that make it unlikely that the above correctness result can be extended to hold on programs with data races. Concretely, our definition of dependence edges allows INLINE LOCAL to perform a so-called “roach motel reordering”, in which an access is moved inside a **synchronized** block [22], and EXTRACT LOCAL to perform a redundant read elimination. While the authors of the JMM originally claimed that these transformations are formally behavior-preserving [22], later research has shown that this is not the case [5, 16]. Arguably this indicates a fault with the specification of the JMM, but it remains an open problem whether the model can be changed to accommodate these and similar transformations.

<pre> class C6 implements TM { int x = 0, y = 0; public void m1() { int tmp = x; y = tmp+tmp; } public void m2() { x = 1; } } </pre> <p style="text-align: center;">(a)</p>	<pre> class C6 implements TM { int x = 0, y = 0; public void m1() { y = x+x; } public void m2() { x = 1; } } </pre> <p style="text-align: center;">(b)</p>
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Fig. 7. INLINE LOCAL applied to `tmp` in `m1()` in the presence of a possible data race.

4.3 Handling Programs with Races

Theorem 3 only states that EXTRACT LOCAL and INLINE LOCAL are correct for programs without data races. For programs with data races, it is possible for these refactorings to remove or introduce concurrent behaviors. For example, consider Figure 7, where INLINE LOCAL is applied to `tmp` in `m1()`. If `m1()` and `m2()` can run concurrently, there is a possible data race on the `x` field. In the original program, `m1()` can assign either 0 or 2 to field `y`, depending on when `m2()` executes. In the modified program, `x` is read twice, enabling the new behavior of `m1()` assigning 1.

It is impractical to require refactorings to preserve the concurrent behaviors of programs with races while still enabling standard transformations. Note that the refactoring in Figure 7 is behavior-preserving if the program is sequential; hence, its correctness depends on whether `m1()` and `m2()` can execute in parallel. Unfortunately, for Java programs, determining what code can execute in parallel requires expensive whole-program analysis [24], and may even be impossible when refactoring library code with unknown clients. Hence, to enable standard refactorings on sequential code to proceed (the common case), we allow refactorings like that of Figure 7 even when programs may have data races.

We expect that issues involving refactorings and data races will arise very rarely in practice. Java best practices generally discourage the use of data races, and hence most races encountered in practice are likely to be unintentional. A similar situation arises with the practice of ignoring Java reflection in refactoring engines—while in principle the use of reflection could cause many refactorings to be incorrect, in practice it rarely causes a problem.

5 Implementation

In this section, we describe our experience implementing the techniques described in §3 for correctly refactoring concurrent code. We first present an implementation that is purely intraprocedural, handling procedure calls pessimistically.

Then, we discuss a technique that handles procedure calls more precisely while remaining amenable to implementation in a refactoring tool.

Intraprocedural implementation Our intraprocedural implementation operates on a control-flow graph, as described in §3.2. In addition to the dependencies described earlier, method calls are handled conservatively by treating them as thread management actions, preventing any reordering across them. To approximate calling contexts, the start node of every method also counts as an acquire action, and the end node as a release action. Recall that this dependence computation is only required for refactorings like `INLINE LOCAL` and `EXTRACT LOCAL` that alter memory traces; the many refactorings that do not affect memory traces require no changes (see Theorem 1).

We implemented the computation of synchronization dependence edges using the control flow analysis of Nilsson-Nyman *et al.* [25]. Their analysis is implemented in the attribute grammar system JastAdd [10] as an extension of the JastAddJ Java compiler [9]. These new dependence edges were then integrated into the refactoring engine developed by the first author [27, 28], which is likewise based on JastAddJ. Since that engine already uses dependence edges to ensure preservation of control and data flow dependencies, we simply introduced three new kinds of edges (acquire, release, and thread management dependence edges) and implemented the checks to ensure their preservation. In particular, we extended the implementations of `EXTRACT LOCAL` and `INLINE LOCAL` to preserve synchronization dependencies, and we ensured that they correctly identify the problematic examples presented earlier in this paper, while passing all existing regression tests [28].¹²

To ensure correct handling of the `synchronized` keyword, we implemented the desugaring step described in §3.1 that replaces `synchronized` modifiers with `synchronized` blocks before the refactoring, and performs the reverse transformation afterwards where possible. The existing name binding machinery in the refactoring engine then ensures that `synchronized` blocks are handled correctly.

The amount of code required to add the above features was quite modest. The analysis for computing synchronization dependence edges was implemented in about 70 lines of JastAdd, and the sugaring/desugaring of `synchronized` in less than 50 lines. Updating existing refactorings to make use of these new techniques was a matter of adding only two lines of code.

Better Handling of Procedure Calls The main limitation of the intraprocedural implementation is its coarse treatment of method calls, which in particular prevents extracting and inlining most expressions involving such calls. Fortunately, we found that a simple and practical analysis could prove that 70–90% of calls have no synchronization dependencies in practice, enabling many more refactorings to proceed.

Note that procedure calls already present a significant challenge for refactoring tools in the case of sequential code, due to unknown data dependencies,

¹² Note that our implementation of `EXTRACT LOCAL` does not do any clone detection, and hence only ever extracts a single copy of an expression.

possible side effects, etc. Detecting these effects can be very expensive, as it requires a precise call graph and reasoning about pointer aliasing. The real-world refactoring engines we are aware of currently do not even attempt to detect these issues, leaving reasoning about the correctness of refactoring procedure calls to the user. In what follows, we concentrate solely on how to analyze procedure calls to determine synchronization dependencies; to preserve behavior, a refactoring tool would have to combine this analysis with other techniques to handle issues pertinent to sequential code.

To construct synchronization dependence edges for method calls, we must know if the invoked method may perform monitor operations, accesses to volatile fields, or thread management operations. Given the relative rarity of such operations, one would expect that an analysis with a very coarse call graph could still provide much better information than the pessimistic approach described before.

More precisely, we want to find out how many methods in a typical Java program involve synchronization, where we say that a method m *involves synchronization* if

1. m is declared **synchronized** or contains a **synchronized** block, or
2. m contains an access to a volatile field, or
3. m calls a thread management method from the standard library, or
4. m calls a method m' which involves synchronization.

We implemented a simple stand-alone analysis in WALA [33] that examines all methods in a given program to see whether they involve synchronization. To make the analysis cheap, the call graph used is based solely on a class hierarchy (required by many refactorings) and declared types of variables, and the call graph of any method is pruned to 200 methods. If a method has more than 200 transitive callees, we conservatively assume that it involves synchronization.

We ran this analysis on the DaCapo 2006-10-MR2 benchmarks [3] and Apache Ant 1.7.1 [1], another large Java program.¹³ For each benchmark, Table 1 gives the total number of methods examined, the number of methods that may involve synchronization, the number of methods proved not to involve synchronization, and the number of methods for which the analysis exceeded the threshold. The last two columns give the mean number of callees that need to be analyzed per method and the percentage of methods proved to not involve synchronization.

In summary, the results show that a simple and cheap analysis can establish for 70–90% of methods in real world programs that they never involve synchronization, and hence cannot give rise to synchronization dependence edges. The analysis does not require a precise call graph, and the work it does can easily be bounded, thus it is certainly feasible to integrate such an analysis into a refactoring engine.¹⁴ Note also that for code that does not involve synchronization,

¹³ The `lusearch` benchmark is excluded from the table since the results were identical to `luindex`.

¹⁴ The analysis as described here does not consider native methods. A conservative handling could always treat native methods as thread management actions that pro-

benchmark	number of methods					
	total	synch	no synch	aborted	mean analyzed	% no synch
antlr	2680	617	2063	2	4.2	76.98%
bloat	4094	740	3354	156	13.0	81.92%
chart	6607	694	5913	85	8.5	89.50%
eclipse	3726	924	2802	30	6.4	75.20%
fop	5653	706	4947	26	5.0	87.51%
hsqldb	5457	1212	4254	62	6.4	77.79%
jython	8755	1543	7212	334	14.3	82.38%
luindex	2737	511	2226	16	6.2	81.33%
pmd	4121	530	3591	105	9.2	87.14%
xalan	5821	858	4963	31	7.7	85.26%
apache-ant	10486	2876	7610	96	6.1	72.57%

Table 1. Analysis results for finding methods that do not involve synchronization

tracking synchronization dependencies does not change the behavior of a refactoring tool; hence, these data indicate that refactoring tools enhanced with our techniques will behave as before for most code.

6 Related Work

6.1 Correctness of Refactorings

Correctness of refactorings has long been a primary concern in the literature. Opdyke [26] champions a pre- and post-condition based approach, specifying global conditions a program has to meet for the refactoring to be correct. Griswold [14] views refactorings in terms of their effects on the program dependence graph, which gives rise to a treatment of refactoring correctness in terms of dependence preservation as espoused in earlier work by the first author [27, 28].

Tip et al. [30, 31] develop an approach based on type constraints to reason about the correctness of refactorings related to generalization such as EXTRACT INTERFACE. This work was later extended to support refactorings that introduce generics [12, 18], and a refactoring that assists programmers with the transition from legacy classes to functionally equivalent ones that replace them [2].

In recent work by Steimann and Thies [29], the correctness of refactorings in the face of access modifiers such as `public` and `private` is considered. Like our work, theirs is concerned with situations where the application of existing refactorings such as MOVE CLASS unexpectedly change a program’s behavior without appropriate changes to access modifiers. To avoid such problems, Steimann et al. propose a constraint-based approach similar in spirit to that of [30, 31].

hibit reordering; we verified that this treatment does not significantly impact the numbers in Table 1. For the Java standard library, the API documentation provides more precise information about what synchronization actions a native method entails.

All the above approaches explicitly or implicitly restrict their attention to sequential programs. Papers that do deal with concurrency related issues, like [17], usually strengthen their preconditions to prevent refactoring code that looks like it might be run in a concurrent setting.

6.2 Java Compilers

Java compilers are generally very cautious about optimizing concurrent code. While we could not find any published work on the optimizations performed by recent systems, it appears that previous versions of the Jikes virtual machine’s just-in-time compiler utilized a notion of synchronization dependence edges not unlike the one we use in this paper to prevent code motion of memory operations across synchronization points [4]. Their dependencies would appear to be more restrictive than ours (forbidding, for instance, roach motel reordering), and they are based on the pre-Java 5 memory model. Also recall that for practicality, we allow some non-behavior-preserving transformations for programs with data races (see §4.3), which clearly must be disallowed in a compiler.

6.3 Dependencies for Concurrent Programs

There has been some work in the slicing community on slicing concurrent programs. For this purpose, several authors have proposed new dependencies to complement the classic control and data dependencies in analysing concurrent programs. Cheng [6] proposes three new kinds of dependencies: selection dependence to model control dependencies arising from non-deterministic selection, synchronization dependence to model synchronization between processes¹⁵, and communication dependence to model inter-process communication.

Krinke [19] instead introduces interference dependencies that model the interaction between threads due to the use of shared variables; no synchronization constructs are considered. In particular, it seems that such dependencies would have to take data races and all their possible outcomes into account, which would make them unsuitable for our purposes.

Both authors treat the problem at a fairly abstract level. Zhao [35] considers the problem of computing the dependencies proposed by Cheng for Java programs. His approach does not seem to be directly based on the pre-Java 5 memory model, though, and in particular does not handle volatile accesses.

6.4 Refactoring and Concurrency

Recently, there has been a lot of interest in refactoring programs to enhance their concurrent behavior. The REENTRANCER tool transforms programs to be reentrant, enabling safe parallel execution [34]. The CONCURRENCER tool of Dig et al. [7] (discussed in §2) aims to adapt sequential Java code to use concurrent

¹⁵ Despite the name, this is a very different concept from the synchronization dependencies introduced in this work.

libraries, and the RELOOPER tool [8] reorganizes loops to execute in parallel. Note that while our techniques would prevent the potentially problematic CONCURRENCER transformation described in §2, devising conditions under which such a transformation is safe under the JMM remains as future work.

Finally, several researchers have tackled the problem of implementing refactorings for X10, a Java-based language with sophisticated concurrency support, and have reported promising first results [23].

7 Conclusions

We have investigated the problem of making existing sequential refactoring implementations concurrency-aware so that they do not change the behavior of concurrent code. We have shown examples of how basic refactorings can break concurrent programs, even if they work correctly for sequential code. Some problems can be solved simply by improved handling of concurrency-related language constructs such as the **synchronized** keyword. A more subtle problem is the reordering of memory actions by refactorings, which calls for a principled solution.

We have tackled this problem by introducing synchronization dependencies that model ordering constraints imposed by the memory model. A refactoring has to respect them in the same way it has to respect control and data dependencies, avoiding problematic code reordering that could change the behavior.

We have related these dependencies to the specification of the Java memory model, and proved that respecting them makes some key refactorings behavior-preserving on correctly synchronized programs. For a broad class of transformations we can also prove that they do not inadvertently introduce new data races or deadlocks. But perhaps the most reassuring result is that the majority of refactorings do not need any special treatment to work on concurrent programs.

This work has laid the foundations on adapting basic refactorings to a concurrent setting. While our discussion has been focused on Java and its current memory model, adapting the techniques to other high-level languages, such as C#, and their memory models [15] should be straightforward, as they are based on similar concepts.

One possible area of future work would be to consider more complex refactorings that do more than just moving code around. For instance, some advanced refactorings like CONVERT LOCAL VARIABLE TO FIELD introduce new shared state, which is challenging to handle correctly in a concurrent environment. While synchronization dependencies alone are not enough to solve this kind of problem, the concepts and techniques developed in this work can hopefully serve as a basis for addressing new challenges.

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```

interface TM { void m1(); void m2(); }
class Harness {
    public static void runInParallel(final TM tm) {
        Thread t1 = new Thread(new Runnable() {
            public void run() { tm.m1(); } });
        Thread t2 = new Thread(new Runnable() {
            public void run() { tm.m2(); } });
        t1.start(); t2.start();
    }
}

```

Fig. 8. Harness for executing two methods in parallel.

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A Execution harness

The examples presented in §2 can all be executed in a common harness, shown in Figure 8. The method `Harness.runInParallel()` takes an argument of interface type `TM`, which defines methods `m1()` and `m2()`. To use the harness, the programmer must (i) create a subtype `T` of `TM` that provides methods `m1()` and `m2()` and (ii) invoke `runInParallel()` with an instance `t` of `T`, resulting in the concurrent execution of `t.m1()` and `t.m2()`. For instance, the example of Figure 1 could be run by calling `Harness.runInParallel(new C1())`.