Chapter 1

Threads and Locks

1.1 Introduction

Java virtual machines support multiple *threads* of execution. Threads are represented in Java by the `Thread` class. The only way for a user to create a thread is to create an object of this class; each Java thread is associated with such an object. A thread will start when the `start()` method is invoked on the corresponding `Thread` object.

The behavior of threads, particularly when not correctly synchronized, can be confusing and counterintuitive. This specification describes the semantics of multithreaded Java programs; it includes rules for which values may be seen by a read of shared memory that is updated by multiple threads. As the specification is similar to the *memory models* for different hardware architectures, these semantics are referred to as the *Java memory model*.

These semantics do not describe how a multithreaded program should be executed. Rather, they describe the behaviors that multithreaded programs are allowed to exhibit. Any execution strategy that generates only allowed behaviors is an acceptable execution strategy.

1.1.1 Locks

Java provides multiple mechanisms for communicating between threads. The most basic of these methods is *synchronization*, which is implemented using *monitors*. Each object in Java is associated with a monitor, which a thread can *lock* or *unlock*. Only one thread at a time may hold a lock on a monitor. Any other threads attempting to lock that monitor are blocked until they can obtain a lock on that monitor.

A thread t may lock a particular monitor multiple times; each unlock reverses the effect of one lock operation.

The `synchronized` statement computes a reference to an object; it then attempts to perform a lock action on that object's monitor and does not proceed further until the lock action has successfully completed. After the lock action has been performed, the body of the `synchronized` statement is executed. If execution of the body is ever completed, either normally or abruptly, an unlock action is automatically performed on that same monitor.

A `synchronized` method automatically performs a lock action when it is invoked; its body is not executed until the lock action has successfully completed. If the method is an instance method, it locks the monitor associated with the instance for which it was invoked (that is, the object that will be known as `this` during execution of the body of the method). If the method is static, it locks the monitor associated with the Class object that represents the class in which the method is defined. If execution of the method's body is ever completed, either normally or abruptly, an unlock action is automatically performed on that same monitor.

The Java programming language neither prevents nor requires detection of deadlock conditions. Programs where threads hold (directly or indirectly) locks on multiple objects should use conventional techniques for deadlock avoidance, creating higher-level locking primitives that don't deadlock, if necessary.

Other mechanisms, such as reads and writes of volatile variables and classes provided in the `java.util.concurrent` package, provide alternative mechanisms for synchronization.

1.1.2 Notation in Examples

The Java memory model is not fundamentally based in the object oriented nature of the Java programming language. For conciseness and simplicity in our examples, we often exhibit code fragments without class or method definitions, or explicit dereferencing. Most examples consist of two or more threads containing statements with access to local variables, shared global variables or instance fields of an object. We typically use variables names such as `r1` or `r2` to indicate variables local to a method or thread. Such variables are not accessible by other threads.

Original code
Initially, A == B == 0

Thread 1	Thread 2
`1: r2 = A;`	`3: r1 = B`
`2: B = 1;`	`4: A = 2`

May observe `r2 == 2`, `r1 == 1`

Valid compiler transformation
Initially, `A == B == 0`

Thread 1	Thread 2
`B = 1;`	`r1 = B`
`r2 = A;`	`A = 2`

May observe `r2 == 2`, `r1 == 1`

Figure 1.1: Surprising results caused by statement reordering

1.2 Incorrectly Synchronized Programs Exhibit Surprising Behaviors

The semantics of the Java programming language allow compilers and microprocessors to perform optimizations that can interact with incorrectly synchronized code in ways that can produce behaviors that seem paradoxical.

Consider, for example, Figure 1.1. This program uses local variables `r1` and `r2` and shared variables `A` and `B`. It may appear that the result `r2 == 2, r1 == 1` is impossible. Intuitively, either instruction 1 or instruction 3 should first in an execution. If instruction 1 comes first, it should not be able to see the write at instruction 4. If instruction 3 comes first, it should not be able to see the write at instruction 2.

If some execution exhibited this behavior, then we would know that instruction 4 came before instruction 1, which came before instruction 2, which came before instruction 3, which came before instruction 4. This is, on the face of it, absurd.

However, compilers are allowed to reorder the instructions in either thread, when this does not affect the execution of that thread in isolation. If instruction 1 is reordered with instruction 2, then it is easy to see how the result `r2 == 2` and `r1 == 1` might occur.

To some programmers, this behavior may seem "broken". However, it should be noted that this code is improperly synchronized:

- there is a write in one thread,
- a read of the same variable by another thread,
- and the write and read are not ordered by synchronization.

When this occurs, it is called a *data race*. When code contains a data race, counterintuitive results are often possible.

Several mechanisms can produce the reordering in Figure 1.1. The just-in-time compiler and the processor may rearrange code. In addition, the

Original code

Initially: `p == q`, `p.x == 0`

Thread 1	Thread 2
`r1 = p;`	`r6 = p;`
`r2 = r1.x;`	`r6.x = 3`
`r3 = q;`	
`r4 = r3.x;`	
`r5 = r1.x;`	

May observe `r2 == r5 == 0, r4 == 3`?

Valid compiler transformation

Initially: `p == q`, `p.x == 0`

Thread 1	Thread 2
`r1 = p;`	`r6 = p;`
`r2 = r1.x;`	`r6.x = 3`
`r3 = q;`	
`r4 = r3.x;`	
`r5 = r2;`	

May observe `r2 == r5 == 0, r4 == 3`

Figure 1.2: Surprising results caused by forward substitution

memory hierarchy of the architecture on which a virtual machine is run may make it appear as if code is being reordered. For the purposes of simplicity, we shall simply refer to anything that can reorder code as being a compiler. Source code to bytecode transformation can reorder and transform programs, but must do so only in the ways allowed by this specification.

Another example of surprising results can be seen in Figure 1.2. This program is also incorrectly synchronized; it accesses shared memory without enforcing any ordering between those accesses.

One common compiler optimization involves having the value read for `r2` reused for `r5`: they are both reads of `r1.x` with no intervening write.

Now consider the case where the assignment to `r6.x` in Thread 2 happens between the first read of `r1.x` and the read of `r3.x` in Thread 1. If the compiler decides to reuse the value of `r2` for the `r5`, then `r2` and `r5` will have the value 0, and `r4` will have the value 3. From the perspective of the programmer, the value stored at `p.x` has changed from 0 to 3 and then changed back.

1.3 Informal Semantics

A program must be *correctly synchronized* to avoid the kinds of counterintuitive behaviors that can be observed when code is reordered. The use of correct synchronization does not ensure that the overall behavior of a program is correct. However, its use does allow a programmer to reason about the possible behaviors of a program in a simple way; the behavior of a correctly synchronized program is much less dependent on possible reorderings. Without correct synchronization, *very* strange, confusing and counterintuitive behaviors are possible.

There are three key ideas to understanding whether a program is correctly synchronized:

Conflicting Accesses Two accesses (reads of or writes to) the same shared field or array element are said to be *conflicting* if at least one of the accesses is a write.

Happens-Before Relationship Two actions can be ordered by a *happens-before* relationship. If one action happens-before another, then the first is visible to and ordered before the second. It should be stressed that a happens-before relationship between two actions does not imply that those actions must occur in that order in a Java implementation. The happens-before relation mostly stresses orderings between two actions that conflict with each other, and defines when data races take place. There are a number of ways to induce a happens-before ordering in a Java program, including:

- Each action in a thread happens-before every subsequent action in that thread.
- An unlock on a monitor happens-before every subsequent lock on that monitor.
- A write to a volatile field happens-before every subsequent read of that volatile.
- A call to `start()` on a thread happens-before any actions in the started thread.
- All actions in a thread happen-before any other thread successfully returns from a `join()` on that thread.
- If an action a happens-before an action b, and b happens before an action c, then a happens-before c.

Happens-before is defined more thoroughly in Section 1.5.

Sequential Consistency *Sequential consistency* is a very strong guarantee that is made about visibility and ordering in an execution of a program. Within a sequentially consistent execution, there is a total order over all individual actions (such as a read or a write) which is consistent with the order they occur in the program. Each individual action is atomic and is immediately visible to every thread.

When a program contains two conflicting accesses that are not ordered by a happens-before relationship, it is said to contain a *data race*. A correctly synchronized program is one that has no data races when it is executed with the guarantee of sequential consistency. Programmers therefore do not need to reason about potential reorderings when determining whether their code is correctly synchronized.

A more subtle example of incorrectly synchronized code can be seen in Figure 1.3, which shows two different executions of the same program, both of which contain conflicting accesses to shared variables `X` and `Y`. The two threads in the program lock and unlock a monitor `M1`. In the execution shown in Figure 1.3a, there is a happens-before relationship between all pairs of conflicting accesses. However, in the execution shown in Figure 1.3b, there is no happens-before ordering between the conflicting accesses to `X`. Because of this, the program is not correctly synchronized.

If a program is correctly synchronized, then all executions of the program will appear to be sequentially consistent. This is an extremely strong guarantee for programmers. Programmers do not need to reason about reorderings to determine that their code contains data races. If this determination can be made, the programmer does not need to worry that reorderings will affect their code.

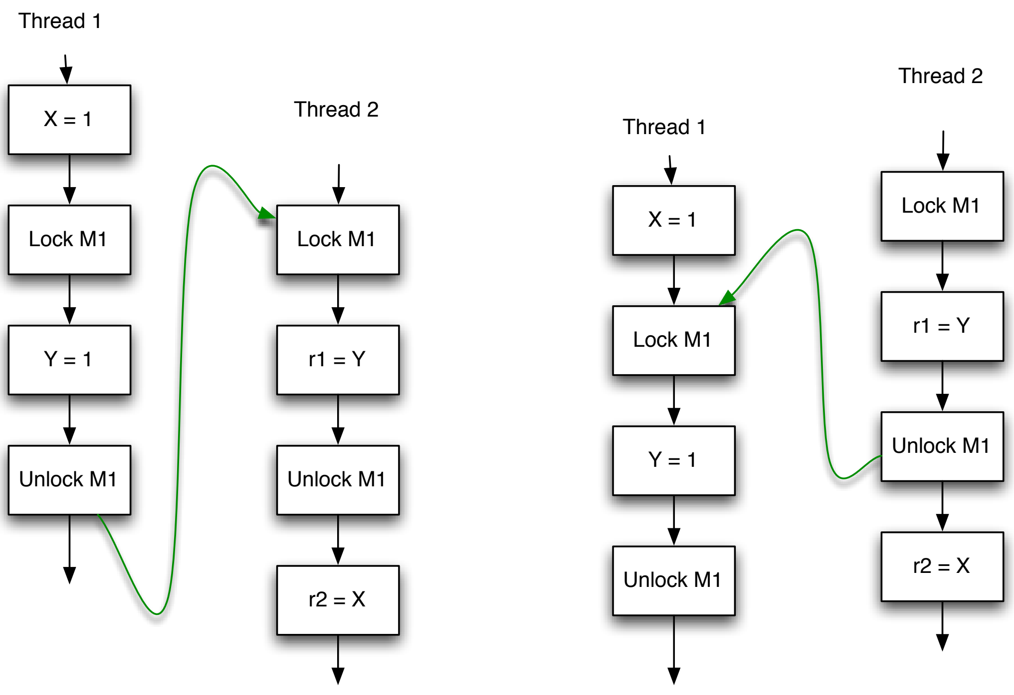
1.3.1 Sequential Consistency

Sequential consistency is a very strong guarantee that is made about visibility and ordering in an execution of a program. Within a sequentially consistent execution, there is a total order over all individual actions (such as reads and writes) which is consistent with the order of the program.

Each individual action is atomic and is immediately visible to every thread. If a program has no data races, then all executions of the program will appear to be sequentially consistent. As noted before, sequential consistency and/or freedom from data races still allows errors arising from groups of operations that need to be perceived atomically and are not.

If we were to use sequential consistency as our memory model, many of the compiler and processor optimizations that we have discussed would be illegal. For example, in Figure 1.2, as soon as the write of 3 to `p.x` occurred, subsequent reads of that location would be required to see that value.

Having discussed sequential consistency, we can use it to provide an important clarification regarding data races and correctly synchronized programs. A data race occurs in an execution of a program if there are conflicting actions in that execution that are not ordered by synchronization.



(a) Thread 1 acquires lock first;
Accesses to X are ordered by happens-before

(b) Thread 2 acquires lock first;
Accesses to X not ordered by happens-before

Figure 1.3: Ordering by a happens-before relationship

A program is correctly synchronized if and only if all sequentially consistent executions are free of data races. Programmers therefore only need to reason about sequentially consistent executions to determine if their programs are correctly synchronized.

A more full and formal treatment of memory model issues for normal fields is given in Sections 1.4–1.6.

1.3.2 Final Fields

Fields declared `final` are initialized once, but never changed under normal circumstances. The detailed semantics of final fields are somewhat different from those of normal fields. In particular, compilers have a great deal of freedom to move reads of final fields across synchronization barriers and calls to arbitrary or unknown methods. Correspondingly, compilers are allowed to keep the value of a final field cached in a register and not reload it from memory in situations where a non-final field would have to be reloaded.

Final fields also allow programmers to implement thread-safe immutable objects without synchronization. A thread-safe immutable object is seen as immutable by all threads, even if a data race is used to pass references to the immutable object between threads. This can provide safety guarantees against misuse of an immutable class by incorrect or malicious code.

Final fields must be used correctly to provide a guarantee of immutability. An object is considered to be *completely initialized* when its constructor finishes. A thread that can only see a reference to an object after that object has been completely initialized is guaranteed to see the correctly initialized values for that object's final fields.

The usage model for final fields is a simple one. Set the final fields for an object in that object's constructor. Do not write a reference to the object being constructed in a place where another thread can see it before the object's constructor is finished. If this is followed, then when the object is seen by another thread, that thread will always see the correctly constructed version of that object's final fields. It will also see versions of any object or array referenced by those final fields that are at least as up-to-date as the final fields are.

Figure 1.4 gives an example that demonstrates how final fields compare to normal fields. The class `FinalFieldExample` has a final int field `x` and a non-final int field `y`. One thread might execute the method `writer()`, and another might execute the method `reader()`. Because `writer()` writes `f` *after* the object's constructor finishes, the `reader()` will be guaranteed to see the properly initialized value for `f.x`: it will read the value 3. However,

```
class FinalFieldExample {

  final int x;
  int y;
  static FinalFieldExample f;

  public FinalFieldExample() {
    x = 3;
    y = 4;
  }

  static void writer() {
    f = new FinalFieldExample();
  }

  static void reader() {
    if (f != null) {
      int i = f.x; // guaranteed to see 3
      int j = f.y; // could see 0
    }
  }
}
```

Figure 1.4: Example illustrating final field semantics

```
Thread 1                                  Thread 2
Global.s = "/tmp/usr".substring(4);       String myS = Global.s;
                                          if (myS.equals("/tmp"))
                                            System.out.println(myS);
```

Figure 1.5: Without final fields or synchronization, it is possible for this code to print `/usr`

`f.y` is not final; the `reader()` method is therefore not guaranteed to see the value 4 for it.

Final fields are designed to allow for necessary security guarantees. Consider the code in Figure 1.5. `String` objects are intended to be immutable and string operations do not perform synchronization. While the `String` implementation does not have any data races, other code could have data races involving the use of `String`s, and the memory model makes weak guarantees for programs that have data races. In particular, if the fields of the `String` class were not final, then it would be possible (although unlikely) that Thread 2 could initially see the default value of 0 for the offset of the string object, allowing it to compare as equal to `"/tmp"`. A later operation on the `String` object might see the correct offset of 4, so that the `String` object is perceived as being `"/usr"`. Many security features of the Java programming language depend upon `String`s being perceived as truly immutable, even if malicious code is using data races to pass String references between threads.

This is only an overview of the semantics of final fields. For a more detailed discussion, which includes several cases not mentioned here, consult Section 1.9.

1.4 What is a Memory Model?

A *memory model* describes, given a program and an execution trace of that program, whether the execution trace is a legal execution of the program. Java's memory model works by examining each read in an execution trace and checking that the write observed by that read is valid according to certain rules.

The memory model describes possible behaviors of a program. An implementation is free to produce any code it likes, as long as all resulting executions of a program produce a result that can be predicted by the memory model. This provides a great deal of freedom for the Java implementor to perform a myriad of code transformations, including the reordering of actions and removal of unnecessary synchronization.

A high level, informal overview of the memory model shows it to be a set of rules for when writes by one thread are visible to another thread. Informally, a read r can usually see the value of any write w such that w does not happen-after r and w is not seen to be overwritten by another write w' (from r's perspective).

When we use the term "read" in this memory model, we are only referring to actions that read fields or array elements. The semantics of other operations, such as reads of array lengths, executions of checked casts, and invocations of virtual methods, are not directly affected by data races. The JVM implementation is responsible for ensuring that a data race cannot cause incorrect behavior such as returning the wrong length for an array or having a virtual method invocation cause a segmentation fault.

The memory semantics determine what values can be read at every point in the program. The actions of each thread in isolation must behave as governed by the semantics of that thread, with the exception that the values seen by each read are determined by the memory model. When we refer to this, we say that the program obeys *intra-thread semantics*.

1.5 Definitions

In this section we define in more detail some of the informal concepts we have presented.

Shared variables/Heap memory Memory that can be shared between threads is called *shared* or *heap* memory. All instance fields, static fields and array elements are stored in heap memory. We use the term *variable* to refer to both fields and array elements. Variables local to a method are never shared between threads and are unaffected by the memory model.

Inter-thread Actions An inter-thread action is an action performed by one thread that can be detected or directly influenced by another thread. Inter-thread actions include reads and writes of shared variables and synchronization actions, such as locking or unlocking a monitor, reading or writing a volatile variable, or starting a thread. Also included are actions that interact with the external world (*external* actions), and actions that cause a thread to go into an infinite loop (*thread divergence* actions). For more information on these actions, consult Section 1.7.1.

We do not need to concern ourselves with intra-thread actions (e.g., adding two local variables and storing the result in a third local variable).

As previously mentioned, all threads need to obey the correct intra-thread semantics for Java programs.

Every inter-thread action is associated with information about the execution of that action. All actions are associated with the thread in which they occur and the program order in which they occur within that thread. Additional information associated with an action include:

write	The variable written to and the value written.
read	The variable read and the write seen (from this, we can determine the value seen).
lock	The monitor which is locked.
unlock	The monitor which is unlocked.

For brevity's sake, we usually refer to inter-thread actions as simply *actions*.

Program Order Among all the inter-thread actions performed by each thread t, the program order of t is a total order that reflects the order in which these actions would be performed according to the intra-thread semantics of t.

Intra-thread semantics *Intra-thread semantics* are the standard semantics for single threaded programs, and allow the complete prediction of the behavior of a thread based on the values seen by read actions within the thread. To determine if the actions of thread t in an execution are legal, we simply evaluate the implementation of thread t as it would be performed in a single threaded context, as defined in the rest of the Java Language Specification.

Each time the evaluation of thread t generates an inter-thread action, it must match the inter-thread action a of t that comes next in program order. If a is a read, then further evaluation of t uses the value seen by a as determined by the memory model.

Simply put, intra-thread semantics are what determine the execution of a thread in isolation; when values are read from the heap, they are determined by the memory model.

Synchronization Actions Synchronization actions include locks, unlocks, reads of and writes to volatile variables, actions that start a thread, and actions that detect that a thread is done.

Synchronization Order Every execution has a *synchronization order*. A synchronization order is a total order over all of the synchronization actions of an execution. For each thread t, the synchronization order of the synchronization actions in t is consistent with the program order of t.

Happens-Before Edges If we have two actions x and y, we use $x \xrightarrow{hb} y$ to mean that x *happens-before* y. If x and y are actions of the same thread and x comes before y in program order, then $x \xrightarrow{hb} y$.

Synchronization actions also induce happens-before edges. We call the resulting directed edges *synchronized-with* edges. They are defined as follows:

- An unlock action on monitor m synchronizes-with all subsequent lock actions on m (where subsequent is defined according to the synchronization order).
- A write to a volatile variable v synchronizes-with all subsequent reads of v by any thread (where subsequent is defined according to the synchronization order).
- An action that starts a thread synchronizes-with the first action in the thread it starts.
- The final action in a thread T1 synchronizes-with any action in another thread T2 that detects that T1 has terminated. T2 may accomplish this by calling `T1.isAlive()` or doing a join action on T1.
- If thread T1 interrupts thread T2, the interrupt by T1 synchronizes-with any point where any other thread (including T2) determines that T2 has been interrupted (by having an `InterruptedException` thrown or by invoking `Thread.interrupted` or `Thread.isInterrupted`).
- The write of the default value (zero, false or null) to each variable synchronizes-with to the first action in every thread.

  Although it may seem a little strange to write a default value to a variable before the object containing the variable is allocated, conceptually every object is created at the start of the program with its default initialized values. Consequently the default initialization of any object happens-before any other actions (other than default-writes) of a program.
- There is a happens-before edge from the end of a constructor of an object to the start of a finalizer for that object.

If an action x synchronizes-with a following action y, then we also have $x \overset{hb}{\rightarrow} y$. Further more, Happens-before is transitively closed. In other words, if $x \overset{hb}{\rightarrow} y$ and $y \overset{hb}{\rightarrow} z$, then $x \overset{hb}{\rightarrow} z$.

It should be noted that the presence of a happens-before relationship between two actions does not necessarily imply that they have to take place in that order in an implementation. If the reordering produces results consistent with a legal execution, it is not illegal. For example, the write of a default value to every field of an object constructed by a thread need not happen before the beginning of that thread, as long as no read ever observes that fact.

More specifically, if two actions share a happens-before relationship, they do not necessarily have to appear to have happened in that order to any code with which they do not share a happens-before relationship. Writes in one thread that are in a data race with reads in another thread may, for example, appear to occur out of order to those reads.

The `wait` methods of class `Object` have lock and unlock actions associated with them; their happens-before relationships are defined by these associated actions. These methods are described further in Section 1.12.

1.6 Approximations to a Memory Model for Java

We have already described sequential consistency. It is too strict for use as the Java memory model, because it forbids standard compiler and processor optimizations.

This section reviews sequential consistency, which is too strong to be usable as a memory model for Java. It also presents another model, called happens-before consistency. This model is closer to fulfilling the needs of the Java memory model, but it is too weak; it allows unacceptable violations of causality. The problems with causality are described in Section 1.6.3.

In Section 1.7, we present the Java memory model, a formal model that strengthens happens-before consistency to provide adequate guarantees of causality.

1.6.1 Sequential Consistency

Formally, in sequential consistency, all actions occur in a total order (the execution order) that is consistent with program order; furthermore, each read r of a variable `v` sees the value written by the write w to `v` such that:

- w comes before r in the execution order, and

Initially, `A == B == 0`

Thread 1	Thread 2
`1: B = 1;`	`3: A = 2`
`2: r2 = A;`	`4: r1 = B`

May observe `r2 == 0`, `r1 == 0`

Figure 1.6: Behavior allowed by happens-before consistency, but not sequential consistency

- there is no other write w' such that w comes before w' and w' comes before r in the execution order.

1.6.2 Happens-Before Consistency

Before presenting the Java model in full, we will present a simpler model, called *happens-before consistency.*

We retain from sequential consistency the idea that there is a total order over all actions that is consistent with the program order. Using this order, we can relax the rules by which writes can be seen by a read. We compute a partial order called the *happens-before order*, as described in Section 1.5.

We say that a read r of a variable v is *allowed* to observe a write w to v if, in the happens-before partial order of the execution trace:

- r is not ordered before w (i.e., it is not the case that $r \xrightarrow{hb} w$), and
- there is no intervening write w' to v (i.e., no write w' to v such that $w \xrightarrow{hb} w' \xrightarrow{hb} r$).

Informally, a read r is allowed to see the result of a write w if there is no happens-before ordering to prevent that read.

An execution is *happens-before consistent* if each read sees a write that it is allowed to see by the happens-before ordering. For example, the behavior shown in Figure 1.6 is happens-before consistent, since there are execution orders that allow each read to see the appropriate write. In this case, since there is no synchronization, each read can see either the write of the initial value or the write by the other thread. One such execution order is

```
1: B = 1
3: A = 2
2: r2 = A; // sees initial write of 0
4: r1 = B // sees initial write of 0
```

Initially, `x == y == 0`

Thread 1	Thread 2
`r1 = x;`	`r2 = y;`
`if (r1 != 0)`	`if (r2 != 0)`
`    y = 1;`	`    x = 1;`

Correctly synchronized, so `r1 == r2 == 0` is the only legal behavior

Figure 1.7: Happens-Before consistency is not sufficient

Similarly, the behavior shown in Figure 1.1 is happens-before consistent, since there is an execution order that allows each read to see the appropriate write. An execution order that displays that behavior is:

```
1: r2 = A; // sees write of A = 2
3: r1 = B // sees write of B = 1
2: B = 1
4: A = 2
```

In this execution, the reads see writes that occur later in the execution order. This may seem counterintuitive, but is allowed by happens-before consistency. It turns out that allowing reads to see later writes can sometimes produce unacceptable behaviors.

1.6.3 Causality

Happens-Before consistency is a necessary, but not sufficient, set of constraints. Merely enforcing happens-before consistency would allow for *unacceptable* behaviors – those that violate the requirements we have established for Java programs. For example, happens-before consistency allows values to appear “out of thin air”. This can be seen by a detailed examination of Figure 1.7.

The code shown in Figure 1.7 is correctly synchronized. This may seem surprising, since it doesn't perform any synchronization actions. Remember, however, that a program is correctly synchronized if, when it is executed in a sequentially consistent manner, there are no data races. If this code is executed in a sequentially consistent way, each action will occur in program order, and neither of the writes will occur. Since no writes occur, there can be no data races: the program is correctly synchronized.

Since this program is correctly synchronized, the only behaviors we can allow are sequentially consistent behaviors. However, there is an execution of this program that is happens-before consistent, but not sequentially consistent:

```
r1 = x; // sees write of x = 1
y = 1;
r2 = y; // sees write of y = 1
x = 1;
```

This result is happens-before consistent: there is no happens-before relationship that prevents it from occurring. However, it is clearly not acceptable: there is no sequentially consistent execution that would result in this behavior. The fact that we allow a read to see a write that comes later in the execution order can sometimes thus result in unacceptable behaviors.

Although allowing reads to see writes that come later in the execution order is sometimes undesirable, it is also sometimes necessary. As we saw above, Figure 1.1 requires some reads to see writes that occur later in the execution order. Since the reads come first in each thread, the very first action in the execution order must be a read. If that read can't see a write that occurs later, then it can't see any value other than the initial value for the variable it reads. This is clearly not reflective of all behaviors.

We refer to the issue of when reads can see future writes as *causality*, because of issues that arise in cases like the one found in Figure 1.7. In that case, the reads cause the writes to occur, and the writes cause the reads to occur. There is no "first cause" for the actions. Our memory model therefore needs a consistent way of determining which reads can see writes early.

Examples such as the one found in Figure 1.7 demonstrate that the specification must be careful when stating whether a read can see a write that occurs later in the execution (bearing in mind that if a read sees a write that occurs later in the execution, it represents the fact that the write is actually performed early).

The Java memory model takes as input a given execution, and a program, and determines whether that execution is a legal execution of the program. It does this by gradually building a set of "committed" actions that reflect which actions were executed by the program. Usually, the next action to be committed will reflect the next action that can be performed by a sequentially consistent execution. However, to reflect reads that need to see later writes, we allow some actions to be committed earlier than other actions that happen-before them.

Obviously, some actions may be committed early and some may not. If, for example, one of the writes in Figure 1.7 were committed before the read of that variable, the read could see the write, and the "out-of-thin-air" result could occur. Informally, we allow an action to be committed early if we know that the action can occur without assuming some data race occurs. In

Figure 1.7, we cannot perform either write early, because the writes cannot occur unless the reads see the result of a data race.

1.7 Specification of the Java Memory Model

This section provides the formal specification of the Java memory model (excluding issues dealing with final fields, which are described in Section 1.9).

1.7.1 Actions and Executions

An action a is described by a tuple $\langle t, k, v, u \rangle$, comprising:

t - the thread performing the action

k - the kind of action: volatile read, volatile write, (normal or non-volatile) read, (normal or non-volatile) write, lock or unlock. Volatile reads, volatile writes, locks and unlocks are synchronization actions. There are also external actions, and thread divergence actions.

v - the variable or monitor involved in the action

u - an arbitrary unique identifier for the action

An execution E is described by a tuple $\langle P, A, \overset{po}{\rightarrow}, \overset{so}{\rightarrow}, W, V, \overset{sw}{\rightarrow}, \overset{hb}{\rightarrow}, \overset{ob}{\rightarrow} \rangle$, comprising:

P - a program

A - a set of actions

$\overset{po}{\rightarrow}$ - program order, which for each thread t, is a total order all actions performed by t in A

$\overset{so}{\rightarrow}$ - synchronization order, which is a total order over all synchronization actions in A

W - a write-seen function, which for each read r in A, gives $W(r)$, the write action seen by r in E.

V - a value-written function, which for each write w in A, gives $V(w)$, the value written by w in E.

$\overset{sw}{\rightarrow}$ - synchronizes-with, a partial order over synchronization actions.

$\overset{hb}{\rightarrow}$ - happens-before, a partial order over actions

$\xrightarrow{ob}$ - observable order, a total order over all actions that is consistent with the happens-before order and synchronization order.

Note that the synchronizes-with and happens-before are uniquely determined by the other components of an execution and the rules for well-formed executions.

Two of these kinds of actions need special descriptions.

external actions - An external action is an action that is observable outside of an execution, and has a result based on an environment external to the execution. An external action tuple contains an additional component, which contains the results of the external action as perceived by the thread performing the action. This may be information as to the success or failure of the action, and any values read by the action.

Parameters to the external action (e.g., which bytes are written to which socket) are not part of the external action tuple. These parameters are set up by other actions within the thread and can be determined by examining the intra-thread semantics. They are not explicitly discussed in the memory model.

The primary impact of observable actions comes from the fact that if an external action is observed, it can be inferred that other actions occur in a finite prefix of the observable order.

thread divergence action - A thread divergence action is only performed by a thread that is in an infinite loop in which no memory or observable actions are performed. If a thread performs a thread divergence action, it will be followed by an infinite number of thread divergence actions. These actions are introduced so that we can explain why such a thread may cause all other threads to stall and fail to make progress.

1.7.2 Definitions

1. **Definition of synchronizes-with**. Section 1.5 defines synchronizes-with edges. The source of a synchronizes-with edge is called a *release*, and the destination is called an *acquire*.

2. **Definition of happens-before**. The happens-before order is given by the transitive closure of the synchronizes-with and program order orders. This is discussed in detail in Section 1.5.

3. **Definition of sufficient synchronization edges**. A set of synchronization edges is *sufficient* if it is the minimal set such that you can

take the transitive closure of those edges with program order edges, and determine all of the happens-before edges in the execution. This set is unique.

4. **Restrictions of partial orders and functions**. We use $f|_d$ to denote the function given by restricting the domain of f to d: for all $x \in d$, $f(x) = f|_d(x)$ and for all $x \notin d$, $f|_d(x)$ is undefined. Similarly, we use $\xrightarrow{e} |_d$ to represent the restriction of the partial order $\xrightarrow{e}$ to the elements in d: for all $x, y \in d$, $x \xrightarrow{e} y$ if and only if $x \xrightarrow{e} |_d\, y$. If either $x \notin d$ or $y \notin d$, then it is not the case that $x \xrightarrow{e} |_d\, y$.

1.7.3 Well-Formed Executions

We only consider well-formed executions. An execution $E = \langle P, A, \xrightarrow{po}, \xrightarrow{so}, W, V, \xrightarrow{sw}, \xrightarrow{hb}, \xrightarrow{ob}\rangle$ is well formed if the following conditions are true:

1. **Each read sees a write to the same variable in the execution. All reads and writes of volatile variables are volatile actions.** For all reads $r \in A$, we have $W(r) \in A$ and $W(r).v = r.v$. The variable $r.v$ is volatile if and only if r is a volatile read, and the variable $w.v$ is volatile if and only if w is a volatile write.

2. **Happens-before order is acyclic**. The transitive closure of synchronizes-with edges and program order is acyclic.

3. **The execution obeys intra-thread consistency.** For each thread t, the actions performed by t in A are the same as would be generated by that thread in program-order in isolation, with each write w writing the value $V(w)$, given that each read r sees the value $V(W(r))$. Values seen by each read are determined by the memory model. The program order given must reflect the program order in which the actions would be performed according to the intrathread semantics of P.

4. **The execution obeys happens-before consistency.** For all reads $r \in A$, it is not the case that either $r \xrightarrow{hb} W(r)$ or that there exists a write $w \in A$ such that $w.v = r.v$ and $W(r) \xrightarrow{hb} w \xrightarrow{hb} r$.

5. **The execution obeys synchronization-order consistency.** For all volatile reads $r \in A$, it is not the case that either $r \xrightarrow{so} W(r)$ or that there exists a write $w \in A$ such that $w.v = r.v$ and $W(r) \xrightarrow{so} w \xrightarrow{so} r$.

1.7.4 Observable Order and Observable External Actions

An execution may have an infinite number of actions. This models a non-terminating execution. Using the total order given by $\xrightarrow{ob}$, the actions may have a ordinality greater than omega. This means that there may exist an action x such that an infinite number of actions occur before x in the observable order. In an infinite execution, the only external actions that can be observed are those such that only a finite number of actions occur before them in the observable order. For finite executions, the observable order doesn't have any impact or significance.

1.7.5 Executions and Causality Requirements

A well-formed execution $E = \langle P, A, \xrightarrow{po}, \xrightarrow{so}, W, V, \xrightarrow{sw}, \xrightarrow{hb}, \xrightarrow{ob} \rangle$ is validated by *committing* actions from A. If all of the actions in A can be committed, then the execution satisfies the causality requirements of the Java memory model.

Starting with the empty set as C_0, we perform a sequence of steps where we take actions from the set of actions A and add them to a set of committed actions C_i to get a new set of committed actions C_{i+1}. To demonstrate that this is reasonable, for each C_i we need to demonstrate an execution E_i containing C_i that meets certain conditions.

Formally, there must exist

- Sets of actions $C_0, C_1, \ldots$ such that
  - $C_0 = \emptyset$
  - $i < j$ implies $C_i \subset C_j$
  - $A = \cup(C_0, C_1, C_2, \ldots)$

  If A is finite, then the sequence $C_0, C_1, \ldots$ will be finite, ending in a set $C_n = A$. However, if A is infinite, then the sequence $C_0, C_1, \ldots$ may be infinite with an ordinality greater than omega, and it must be the case that the union of all elements of this infinite sequence is equal to A.

- Well-formed executions $E_1, \ldots,$ where $E_i = \langle P, A_i, \xrightarrow{po_i}, \xrightarrow{so_i}, W_i, V_i, \xrightarrow{sw_i}, \xrightarrow{hb_i}, \xrightarrow{ob_i} \rangle$.

Given these, we also define F_i to be the set of fully committed actions in E_i: the union of all C_j where $0 \leq j < i$.

Given these sets of actions $C_0, \ldots$ and executions $E_1, \ldots$, every action in C_i must be one of the actions in E_i. All actions in C_i must share the same relative happens-before order and synchronization order in both E_i and E. Formally,

1. $F_i \subset C_i \subseteq A_i$
2. $\overset{hb_i}{\rightarrow}|_{C_i} = \overset{hb}{\rightarrow}|_{C_i}$
3. $\overset{so_i}{\rightarrow}|_{C_i} = \overset{so}{\rightarrow}|_{C_i}$

The values written by the writes in C_i must be the same in both E_i and E. Only the reads in F_i need to see the same writes in E_i as in E. Formally,

4. $V_i|_{C_i} = V|_{C_i}$
5. $W_i|_{F_i} = W|_{F_i}$

All reads in E_i that are not in F_i must see writes that happen-before them. Each read r in $C_i - F_i$ must see writes in F_i in both E_i and E, but may see a different write in E_i from the one it sees in E. Formally,

6. For any read $r \in A_i - F_i$, we have $W_i(r) \overset{hb_i}{\rightarrow} r$
7. For any read $r \in C_i - F_i$, we have $W_i(r) \in F_i$ and $W(r) \in F_i$

Given a set of sufficient synchronizes-with edges for E_i, if there is a release-acquire pair that happens-before an action you are committing, then that pair must be present in all E_j, where $j \geq i$. Formally,

8. Let $\overset{ssw_i}{\rightarrow}$ be the $\overset{sw_i}{\rightarrow}$ edges that are also in the transitive reduction of $\overset{hb_i}{\rightarrow}$ but not in $\overset{po_i}{\rightarrow}$. We call $\overset{ssw_i}{\rightarrow}$ the sufficient synchronizes-with edges for E_i. If $x \overset{ssw_i}{\rightarrow} y \overset{hb_i}{\rightarrow} z$ and $z \in C_i$, then $x \overset{sw_j}{\rightarrow} y$ for all $j \geq i$.

If an action y is committed, all external actions that happen-before y are also committed.

9. If y is an external action, $x \overset{hb_i}{\rightarrow} y$ and $y \in C_i$, then $x \in C_i$.

Initially, `x = y = 0`

Thread 1	Thread 2
`r1 = x;`	`r2 = y;`
`y = 1;`	`x = r2;`

`r1 == r2 == 1` is a legal behavior

Figure 1.8: A standard reordering

1.8 Illustrative Test Cases and Behaviors

1.8.1 An Example of a Simple Reordering

As an example of how the memory model works, consider Figure 1.8. Note that there are initially two writes of the default values to `x` and `y`. We wish to get the result `r1 == r2 == 1`, which can be obtained if a processor reorders the statements in Thread 1.

The set of actions C_0 is the empty set, and there is no execution E_0.

Execution E_1 will therefore be an execution where all reads see writes that happen-before them, as per rule 6. For this program, both reads must see the value 0 in E_1. We first commit the initial writes of 0 to `x` and `y` as well as the write of 1 to `y` by Thread 1; these writes are contained in the set C_1.

We wish to add `r2 = y` seeing 1. C_1 could not contain this action, regardless of what write it saw: neither write to `y` had been committed. C_2 may contain this action; however, the read of `y` must return 0 in E_2, because of rule 6. Execution E_2 is therefore identical to E_1.

In E_3, `r2 = y` can see any conflicting write that occurs in C_2 which is happens-before consistent for it to see (by rule 7, and our happens-before consistency criterion). The write this read sees is the write of 1 to `y` in Thread 1, which was committed in C_1. We commit one additional action in C_3: a write of 1 to `x` by `x = r2`.

C_4 contains `r1 = x`, but it still sees 0 in E_4, because of rule 6. In our final execution E, however, rule 7 allows `r1 = x` to see the write of 1 to `x` that was committed in C_3.

For a table showing when given actions are committed, consult Figure 1.9.

1.8.2 An Example of a More Complicated Reordering

Figure 1.10 shows another unusual behavior. In order for `r1 == r2 == r3 == 1`, Thread 1 would seemingly need to write 1 to `y` before reading `x`.

Action	Final Value	First Committed In	First Sees Final Value In
`x = 0`	0	C_1	E_1
`y = 0`	0	C_1	E_1
`y = 1`	1	C_1	E_1
`r2 = y`	1	C_2	E_3
`x = r2`	1	C_3	E_3
`r1 = x`	1	C_4	E

Figure 1.9: Table of commit sets for Figure 1.8

Initially, `x == y == 0`

Thread 1	Thread 2
`r1 = x;`	`r2 = y;`
`r3 = 1 + r1*r1 - r1;`	`x = r2;`
`y = r3;`	

`r1 == r2 == r3 == 1` is a legal behavior

Figure 1.10: Compilers can think hard about when actions are guaranteed to occur

However, the dependencies in this program make it appear as if Thread 1 does not know what value `r3` will be until after `x` is read.

In fact, the compiler can perform an analysis that shows that `x` and `y` are guaranteed to be either 0 or 1. Knowing that, the compiler can determine that the quadratic equation always returns 1, resulting in Thread 1's always writing 1 to `y`. Thread 1 may, therefore, write 1 to `y` before reading `x`.

The memory model validates this execution in exactly the same way it validates the execution in Figure 1.8. Since the program writes the same value to y regardless of whether it reads 0 or 1 for x, the write is allowed to be committed before the read of x.

1.9 Final Field Semantics

Fields marked `final` are initialized once and not changed. This is useful for passing immutable objects between threads without synchronization.

Final field semantics are based around several competing goals:

- The value of a final field is not intended to change. The compiler should not have to reload a final field because a lock was obtained, a volatile variable was read, or an unknown method was invoked. In fact, the compiler is allowed to hoist reads within thread t of a final field f of an object X to immediately after the very first read of a reference to X by t; the thread never need reload that field.

- Objects that have only final fields and are not made visible to other threads during construction should be perceived as immutable even if references to those objects are passed between threads via data races.
  - Storing a reference to an object X into the heap during construction of X does not necessarily violate this requirement. For example, synchronization could ensure that no other thread could load the reference to X during construction. Alternatively, during construction of X, a reference to X could be stored into another object Y; if no references to Y are made visible to other threads until after construction of X is complete, then final field guarantees still hold.
- Making a field f final should impose minimal compiler/architectural cost when reading f.
- Must allow for situations such as deserialization, in which final fields of an object are modified after construction of the object is complete.

The use of final fields adds constraints on which writes are considered ordered before which reads, for the purposes of determining if an execution is legal.

Other techniques, such as deserialization, may cause a final field to be modified after the end of the enclosing object's constructor. There must be a freeze of the final field after each such write. Setting a final field in this way is meaningful only during deserialization or reconstruction of instances of classes with blank final fields, before they are made available for access by other parts of a program.

If a reference to an object is shared with other threads between the initial construction of an object and when deserialization changes the final fields of the object, most of the guarantees for final fields of that object can go kerflooey; this includes cases in which other parts of a program continue to use the original value of this field.

It should be noted that reflection may be used to set final fields. Specifically, the `set(...)` method of the `Field` class in `java.lang.reflect` may be used to this effect. If the underlying field is final, this method throws an `IllegalAccessException` unless `setAccessible(true)` has succeeded for this field and this field is non-static.

1.9.1 Formal Semantics of Final Fields

The semantics for final fields are as follows. Assume a *freeze* action on a final field f of an object o takes place when the constructor for o in which f is written exits normally. Note that if one constructor invokes another constructor, and the invoked constructor sets a final field, the freeze for the final field takes place at the end of the invoked constructor.

For each execution, the behavior of reads is influenced by two additional partial orders, dereference chain ($\overset{dc}{\rightarrow}$) and memory chain ($\overset{mc}{\rightarrow}$), which are considered to be part of the execution (and thus, fixed for any particular execution). These partial orders must satisfy the following constraints (which need not have a unique solution):

- **Dereference Chain** If an action a is a read or write of a field or element of an object o by a thread t that did not initialize o, then there must exist some read r by thread t that sees the address of o such that $r \overset{dc}{\rightarrow} a$.

- **Memory Chain** There are several constraints on the memory chain ordering:

  a) If r is a read that sees a write w, then it must be the case that $w \overset{mc}{\rightarrow} r$.

  b) If r and a are actions such that $r \overset{dc}{\rightarrow} a$, then it must be the case that $r \overset{mc}{\rightarrow} a$.

  c) If w is a write of the address of an object o by a thread t that did not initialize o, then there must exist some read r by thread t that sees the address of o such that $r \overset{mc}{\rightarrow} w$.

Given a write w, a freeze f, an action a (that is not a read of a final field), a read r_1 of the final field frozen by f and a read r_2 such that $w \overset{hb}{\rightarrow} f \overset{hb}{\rightarrow} a \overset{mc}{\rightarrow} r_1 \overset{dc}{\rightarrow} r_2$, then when determining which values can be seen by r_2, we consider $w \overset{hb}{\rightarrow} r_2$ (but these orderings do not transitively close with other $\overset{hb}{\rightarrow}$ orderings). Note that the $\overset{dc}{\rightarrow}$ order is reflexive, and r_1 can be the same as r_2.

For reads of final fields, the only writes that are deemed to come before the read of the final field are the ones derived through the final field semantics.

1.9.2 Reading Final Fields During Construction

A read of a final field of an object within the thread that constructs that object is ordered with respect to the initialization of that field within the constructor by the usual happens-before rules. If the read occurs after the field is set in the constructor, it sees the value the final field is assigned, otherwise it sees the default value.

1.9.3 Subsequent Modification of Final Fields

In some cases, such as deserialization, the system will need to change the final fields of an object after construction. Final fields can be changed via reflection and other implementation dependent means. The only pattern in which this has reasonable semantics is one in which an object is constructed and then the final fields of the object are updated. The object should not be made visible to other threads, nor should the final fields be read, until all updates to the final fields of the object are complete. Freezes of a final field occur both at the end of the constructor in which the final field is set, and immediately after each modification of a final field via reflection or other special mechanism.

Even then, there are a number of complications. If a final field is initialized to a compile-time constant in the field declaration, changes to the final field may not be observed, since uses of that final field are replaced at compile time with the compile-time constant.

Another problem is that the specification allows aggressive optimization of final fields. Within a thread, it is permissible to reorder reads of a final field with those modifications of a final field that do not take place in the constructor.

For example, consider the code fragment in Figure 1.11. In the `d()` method, the compiler is allowed to reorder the reads of `x` and the call to `g()` freely. Thus, `A().f()` could return -1, 0 or 1.

To ensure that this problem cannot arise, an implementation may provide a way to execute a block of code in a *final field safe context*. If an object is constructed within a final field safe context, the reads of a final field of that object will not be reordered with modifications of final field that occur within that final field safe context.

A final field safe context has additional protections. If a thread has seen an incorrectly published reference to an object that allows the thread to see the default value of a final field, and then, within a final-field safe context, reads a properly published reference to the object, it will be guaranteed to see the correct value of the final field. In the formalism, code executed within

```
class A {
  final int x;
  A() {
    x = 1;
  }
  int f() {
    return d(this,this);
  }
  int d(A a1, A a2) {
    int i = a1.x;
    g(a1);
    int j = a2.x;
    return j - i;
  }
  static void g(A a) {
    // uses reflection to change a.x to 2
  }
}
```

Figure 1.11: Example of reordering of final field reads and reflective change

a final-field safe context is treated as a separate thread (for the purposes of final field semantics only).

In an implementation, a compiler should not move an access to a final field into or out of a final-field safe context (although it can be moved around the execution of such a context, so long as the object is not constructed within that context).

One place where use of a final-field safe context would be appropriate is in an executor or thread pool. By executing each `Runnable` in a separate final field safe context, the executor could guarantee that incorrect access by one `Runnable` to a object o won't remove final field guarantees for other `Runnable`s handled by the same executor.

1.9.4 Examples of Final Field Semantics

In order to determine if a read of a final field is guaranteed to see the initialized value of that field, you must determine that there is no way to construct a partial order $\overset{mc}{\rightarrow}$ without providing the chain $f \overset{hb}{\rightarrow} a \overset{mc}{\rightarrow} r_1$ from the freeze f of that field to the read r_1 of that field.

An example of where this can go wrong can be seen in Figure 1.12. An object o is constructed in Thread 1 and read by Threads 2 and 3. Dereference `f` is a final field; its default value is 0

Thread 1	Thread 2	Thread 3
`r1.f = 42;`	`r2 = p;`	`r6 = q;`
`p = r1;`	`r3 = r2.f;`	`r7 = r6.f;`
`freeze r1.f;`	`r4 = q;`	
`q = r1;`	`if (r2 == r4)`	
	`    r5 = r4.f;`	

We assume `r2`, `r4` and `r6` do not see the value null. `r3` and `r5` can be 0 or 42, and `r7` must be 42.

Figure 1.12: Final field example where reference to object is read twice

and memory chains for the read of `r4.f` in Thread 2 can pass through any reads by Thread 2 of a reference to *o*. On the chain that goes through the global variable `p`, there is no action that is ordered after the freeze operation. If this chain is used, the read of `r4.f` will not be correctly ordered with regards to the freeze operation. Therefore, `r5` is not guaranteed to see the correctly constructed value for the final field.

The fact that `r5` does not get this guarantee reflects legal transformations by the compiler. A compiler can analyze this code and determine that `r2.f` and `r4.f` are reads of the same final field. Since final fields are not supposed to change, it could replace `r5 = r4.f` with `r5 = r3` in Thread 2.

Formally, this is reflected by the dereference chain ordering (`r2 = p`) $\xrightarrow{dc}$ (`r5 = r4.f`), but *not* ordering (`r4 = q`) $\xrightarrow{dc}$ (`r5 = r4.f`). An alternate partial order, where the dereference chain does order (`r4 = q`) $\xrightarrow{dc}$ (`r5 = r4.f`) is also valid. However, in order to get a guarantee that a final field read will see the correct value, you must ensure the proper ordering for all possible dereference and memory chains.

In Thread 3, unlike Thread 2, all possible chains for the read of `r6.f` include the write to `q` in Thread 1. The read is therefore correctly ordered with respect to the freeze operation, and guaranteed to see the correct value.

In general, if a read R of a final field x in thread t_2 is correctly ordered with respect to a freeze F in thread t_1 via memory chains, dereference chains, and happens-before, then the read is guaranteed to see the value of x set before the freeze F. Furthermore any reads of elements of objects that were only reached in thread t_2 by following a reference loaded from x are guaranteed to occur after all writes w such that $w \xrightarrow{hb} F$.

Figures 1.14 and 1.15 show an example of the transitive guarantees provided by final fields. For this example, there is no dereference chain in

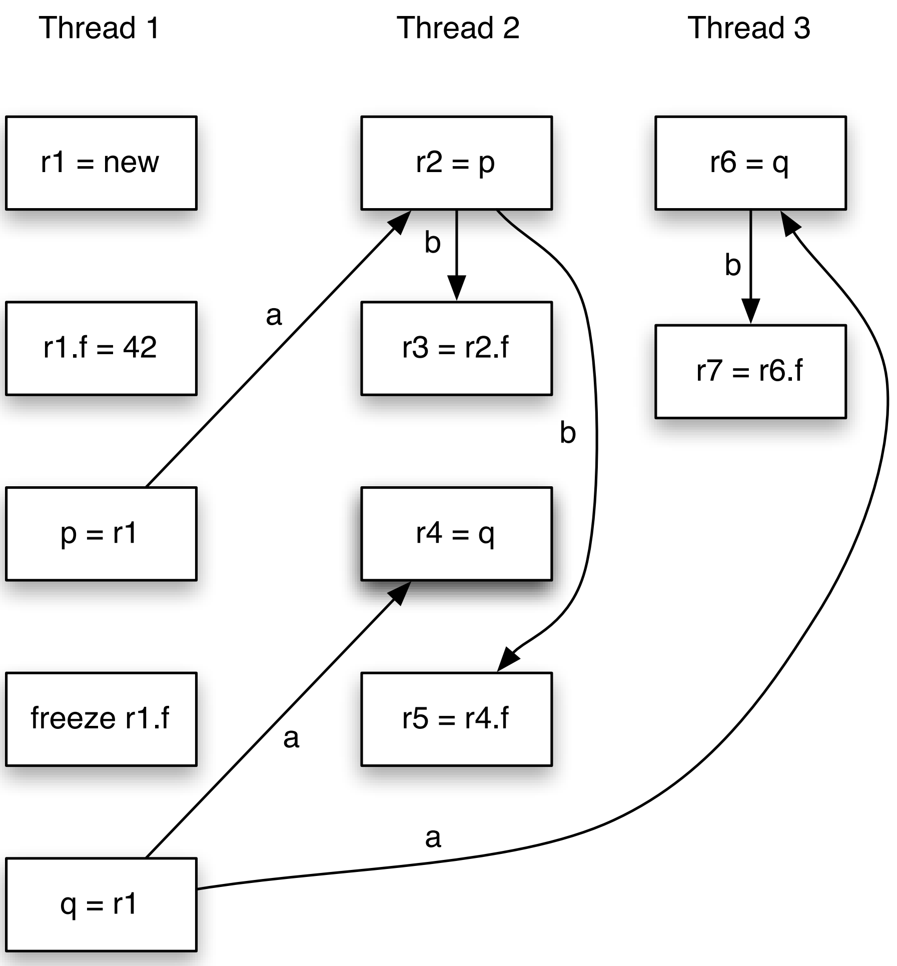


Figure 1.13: Memory chains in an execution of Figure 1.12

`a` is a final field of a class A

Thread 1	Thread 2
`r1 = new A;`	`r3 = p;`
`r2 = new int[1];`	`r4 = r3.a;`
`r1.a = r2;`	`r5 = r4[0]`
`r2[0] = 42`	
`freeze r1.a;`	
`p = r1;`	

Assuming Thread 2 read of `p` sees the write by Thread 1, Thread 2 reads of `r3.a` and `r4[0]` are guaranteed to see the writes to Thread 1.

Figure 1.14: Transitive guarantees from final fields

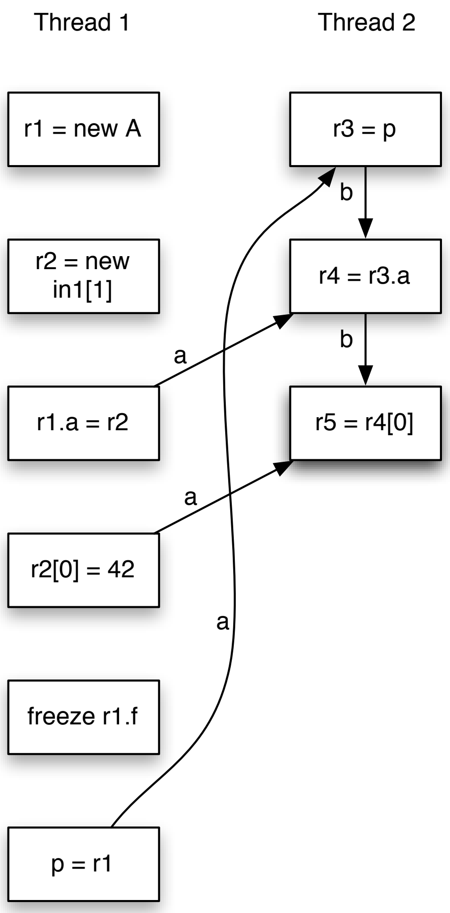


Figure 1.15: Memory chains in an execution of Figure 1.14

`f` is a final field; x is non-final

Thread 1	Thread 2	Thread 3
`r1 = new ;`	`r3 = p;`	`r5 = q;`
`r2 = new ;`	`r4 = r3.x;`	`r6 = r5.f;`
`r2.x = r1;`	`q = r4;`	
`r1.f = 42;`		
`freeze r1.f;`		
`p = r2;`		

Assuming that Thread 2 sees the writes by Thread 1, and Thread 3's read of `q` sees the write by Thread 2, `r6` is guaranteed to see 42.

Figure 1.16: Yet another final field example

Thread 2 that would permit the reads through `a` to be traced back to an incorrect publication of `p`. Since the final field `a` must be read correctly, the program is not only guaranteed to see the correct value for `a`, but also guaranteed to see the correct value for contents of the array.

Figures 1.16 and 1.17 show two interesting characteristics of one example. First, a reference to an object with a final field is stored (by `r2.x = r1`) into the heap before the final field is frozen. Since the object referenced by `r2` isn't reachable until the store `p = r2`, which comes after the freeze, the object is correctly published, and guarantees for its final fields apply.

This example also shows the use of rule (c) for memory chains. The memory chain that guarantees that Thread 3 sees the correctly initialized value for `f` passes through Thread 2. In general, this allows for immutability to be guaranteed for an object regardless of which thread writes out the reference to that object.

1.10 Word Tearing

One implementation consideration for Java virtual machines is that every field and array element is considered distinct; updates to one field or element must not interact with reads or updates of any other field or element. In particular, two threads that update adjacent elements of a byte array separately must not interfere or interact and do not need synchronization to ensure sequential consistency.

Some processors (notably early Alphas) do not provide the ability to write to a single byte. It would be illegal to implement byte array updates on such a processor by simply reading an entire word, updating the appropriate byte, and then writing the entire word back to memory. This problem

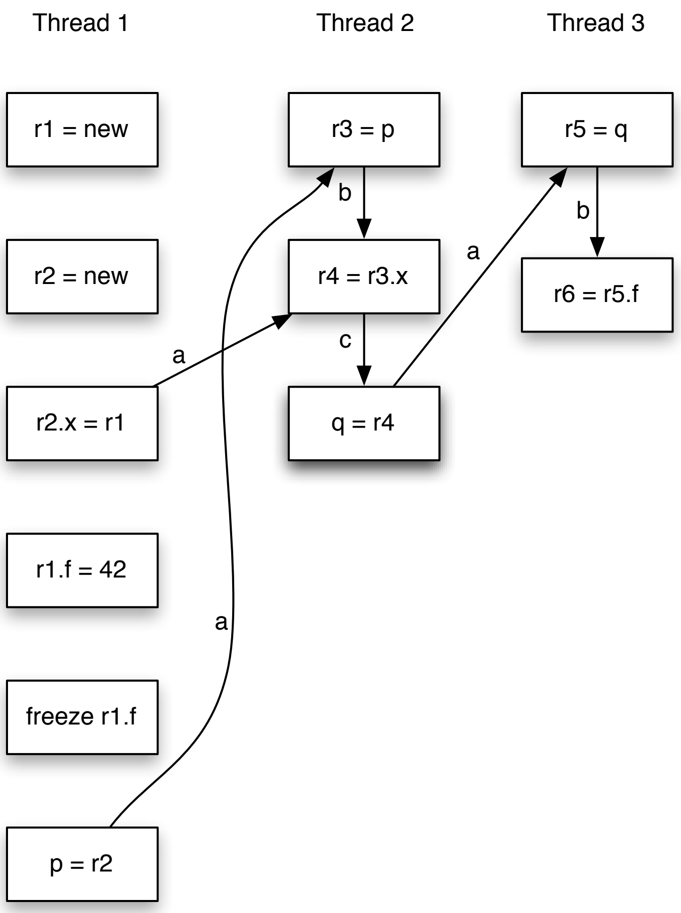


Figure 1.17: Memory chains in an execution of Figure 1.16

```
public class WordTearing extends Thread {
    static final int LENGTH = 8;
    static final int ITERS = 1000000;
    static byte[] counts = new byte[LENGTH];
    static Thread[] threads = new Thread[LENGTH];
    final int id;
    WordTearing(int i) {
        id = i;
    }
    public void run() {
        byte v = 0;
        for (int i = 0; i < ITERS; i++) {
            byte v2 = counts[id];
            if (v != v2) {
                System.err.println("Word-Tearing found: " + "counts[" + id
                        + "] = " + v2 + ", should be " + v);
                return;
            }
            v++;
            counts[id] = v;
        }
    }
    public static void main(String[] args) {
        for (int i = 0; i < LENGTH; ++i)
            (threads[i] = new WordTearing(i)).start();
    }
}
```

Figure 1.18: Bytes must not be overwritten by writes to adjacent bytes

is sometimes known as *word tearing*, and on processors that cannot easily update a single byte in isolation some other approach will be required. Figure 1.18 shows a test case to detect word tearing.

1.11 Non-atomic Treatment of `double` and `long`

Some Java implementations may find it convenient to divide a single write action on a 64-bit long or double value into two write actions on adjacent 32 bit values. For efficiency's sake, this behavior is implementation specific; Java virtual machines are free to perform writes to long and double values atomically or in two parts.

For the purposes of this memory model, a single write to a non-volatile long or double value is treated as two separate writes: one to each 32-bit half. This can result in a situation where a thread sees the first 32 bits of a 64 bit value from one write, and the second 32 bits from another write. Write and reads of volatile long and double values are always atomic. Writes to and reads of references are always atomic, regardless of whether they are implemented as 32 or 64 bit values.

VM implementors are encouraged to avoid splitting their 64-bit values where possible. Programmers are encouraged to declare shared 64-bit values as volatile or synchronize their programs correctly to avoid possible complications.

1.12 Wait Sets and Notification

Every object, in addition to having an associated lock, has an associated wait set. A wait set is a set of threads. When an object is first created, its wait set is empty. Elementary actions that add threads to and remove threads from wait sets are atomic. Wait sets are manipulated in Java solely through the methods `Object.wait`, `Object.notify` , and `Object.notifyAll`.

Wait set manipulations can also be affected by the interruption status of a thread, and by the `Thread` class methods dealing with interruption. Additionally, `Thread` class methods for sleeping and joining other threads have properties derived from those of wait and notification actions.

1.12.1 Wait

Wait actions occur upon invocation of `wait()`, or the timed forms `wait(long millisecs)` and `wait(long millisecs, int nanosecs)`. A call of `wait(long millisecs)` with a parameter of zero, or a call of `wait(long millisecs,` `int nanosecs)` with two zero parameters, is equivalent to an invocation of `wait()`.

Let thread t be the thread executing the wait method on object m, and let n be the number of lock actions by t on m that have not been matched by unlock actions. One of the following actions occurs.

- If n is zero (i.e., thread t does not already possess the lock for target m) an `IllegalMonitorStateException` is thrown.
- If this is a timed wait and the nanosecs argument is not in the range of 0-999999 or the millisecs argument is negative, an `IllegalArgumentException` is thrown.
- If thread t is interrupted, an `InterruptedException` is thrown and t's interruption status is set to false.
- Otherwise, the following sequence occurs:
  1. Thread t is added to the wait set of object m, and performs n unlock actions on m.
  2. Thread t does not execute any further Java instructions until it has been removed from m's wait set. The thread may be removed from the wait set due to any one of the following actions, and will resume sometime afterward.
     - A notify action being performed on m in which t is selected for removal from the wait set.
     - A notifyAll action being performed on m.
     - An interrupt action being performed on t.
     - If this is a timed wait, an internal action removing t from m's wait set that occurs after at least `millisecs` milliseconds plus `nanosecs` nanoseconds elapse since the beginning of this wait action.
     - An internal action by the Java JVM implementation. Implementations are permitted, although not encouraged, to perform "spurious wake-ups" – to remove threads from wait sets and thus enable resumption without explicit Java instructions to do so. Notice that this provision necessitates the Java coding practice of using `wait` only within loops that terminate only when some logical condition that the thread is waiting for holds.

Each thread must determine an order over the events that could cause it to be removed from a wait set. That order does not have to be consistent with other orderings, but the thread must behave as though those events occurred in that order. For example, if a thread t is in the wait set for m, and then both an interrupt of t and a notification of m occur, there must be an order over these events.

If the interrupt is deemed to have occurred first, then t will eventually return from `wait` by throwing `InterruptedException`, and some other thread in the wait set for m (if any exist at the time of the notification) must receive the notification. If the notification is deemed to have occurred first, then t will eventually return normally from `wait` with an interrupt still pending.

3. Thread t performs n lock actions on m.
4. If thread t was removed from m's wait set in step 2 due to an interrupt, t's interruption status is set to false and the wait method throws `InterruptedException`.

1.12.2 Notification

Notification actions occur upon invocation of methods `notify` and `notifyAll`. Let thread t be the thread executing either of these methods on Object m, and let n be the number of lock actions by t on m that have not been matched by unlock actions. One of the following actions occurs.

- If n is zero an `IllegalMonitorStateException` is thrown. This is the case where thread t does not already possess the lock for target m.

- If n is greater than zero and this is a `notify` action, then, if m's wait set is not empty, a thread u that is a member of m's current wait set is selected and removed from the wait set. (There is no guarantee about which thread in the wait set is selected.) This removal from the wait set enables u's resumption in a wait action. Notice however, that u's lock actions upon resumption cannot succeed until some time after t fully unlocks the monitor for m.

- If n is greater than zero and this is a `notifyAll` action, then all threads are removed from m's wait set, and thus resume. Notice however, that only one of them at a time will lock the monitor required during the resumption of wait.

1.12.3 Interruptions

Interruption actions occur upon invocation of method `Thread.interrupt`, as well as methods defined to invoke it in turn, such as `ThreadGroup.interrupt`. Let t be the thread invoking `U.interrupt`, for some thread u, where t and u may be the same. This action causes u's interruption status to be set to true.

Additionally, if there exists some object m whose wait set contains u, u is removed from m's wait set. This enables u to resume in a wait action, in which case this wait will, after re-locking m's monitor, throw `InterruptedException`.

Invocations of `Thread.isInterrupted` can determine a thread's interruption status. The static method `Thread.interrupted` may be invoked by a thread to observe and clear its own interruption status.

1.12.4 Interactions of Waits, Notification and Interruption

The above specifications allow us to determine several properties having to do with the interaction of waits, notification and interruption. If a thread is both notified and interrupted while waiting, it may either:

- return normally from `wait`, while still having a pending interrupt (in other works, a call to `Thread.interrupted` would return true)
- return from `wait` by throwing an `InterruptedException`

The thread may not reset its interrupt status and return normally from the call to `wait`.

Similarly, notifications cannot be lost due to interrupts. Assume that a set s of threads is in the wait set of an object m, and another thread performs a `notify` on m. Then either

- at least one thread in s must return normally from `wait`. By "return normally", we mean it must return without throwing `InterruptedException`, or
- all of the threads in s must exit `wait` by throwing `InterruptedException`

Note that if a thread is both interrupted and woken via `notify`, and that thread returns from `wait` by throwing an `InterruptedException`, then some other thread in the wait set must be notified.

1.13 Sleep and Yield

`Thread.sleep` causes the currently executing thread to sleep (temporarily cease execution) for the specified duration, subject to the precision and accuracy of system timers and schedulers. The thread does not lose ownership of any monitors, and resumption of execution will depend on scheduling and the availability of processors on which to execute the thread.

Neither a sleep for a period of zero time nor a yield operation need have observable effects.

It is important to note that neither `Thread.sleep` nor `Thread.yield` have any synchronization semantics. In particular, the compiler does not have to flush writes cached in registers out to shared memory before a call to sleep or yield, nor does the compiler have to reload values cached in registers after a call to sleep or yield. For example, in the following (broken) code fragment, assume that `this.done` is a non-volatile boolean field:

```
while (!this.done)
   Thread.sleep(1000);
```

The compiler is free to read the field `this.done` just once, and reuse the cached value in each execution of the loop. This would mean that the loop would never terminate, even if another thread changed the value of `this.done`.

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Chapter 2

Finalization

This section details changes to Section 12.6 of the Java language specification, which deals with finalization. The relevant portions are reproduced here.

The class `Object` has a protected method called `finalize`; this method can be overridden by other classes. The particular definition of `finalize` that can be invoked for an object is called the *finalizer* of that object. Before the storage for an object is reclaimed by the garbage collector, the Java virtual machine will invoke the finalizer of that object.

Finalizers provide a chance to free up resources that cannot be freed automatically by an automatic storage manager. In such situations, simply reclaiming the memory used by an object would not guarantee that the resources it held would be reclaimed.

The Java programming language does not specify how soon a finalizer will be invoked, except to say that it will occur before the storage for the object is reused. Also, the language does not specify which thread will invoke the finalizer for any given object. It is guaranteed, however, that the thread that invokes the finalizer will not be holding any user-visible synchronization locks when the finalizer is invoked. If an uncaught exception is thrown during the finalization, the exception is ignored and finalization of that object terminates.

It should also be noted that the completion of an object's constructor happens-before the execution of its `finalize` method (in the formal sense of happens-before).

It is important to note that many finalizer threads may be active (this is sometimes needed on large SMPs), and that if a large connected data structure becomes garbage, all of the finalize methods for every object in that data structure could be invoked at the same time, each finalizer invocation running in a different thread.

The `finalize` method declared in class Object takes no action.

The fact that class `Object` declares a `finalize` method means that the `finalize` method for any class can always invoke the `finalize` method for its superclass. This should always be done, unless it is the programmer's intent to nullify the actions of the finalizer in the superclass. Unlike constructors, finalizers do not automatically invoke the finalizer for the superclass; such an invocation must be coded explicitly.)

For efficiency, an implementation may keep track of classes that do not override the `finalize` method of class Object, or override it in a trivial way, such as:

```
protected void finalize() throws Throwable {
   super.finalize();
}
```

We encourage implementations to treat such objects as having a finalizer that is not overridden, and to finalize them more efficiently, as described in Section 2.0.1.

A finalizer may be invoked explicitly, just like any other method.

The package `java.lang.ref` describes weak references, which interact with garbage collection and finalization. As with any API that has special interactions with the language, implementors must be cognizant of any requirements imposed by the java.lang.ref API. This specification does not discuss weak references in any way. Readers are referred to the API documentation for details.

2.0.1 Implementing Finalization

Every object can be characterized by two attributes: it may be *reachable*, *finalizer-reachable*, or *unreachable*, and it may also be *unfinalized*, *finalizable*, or *finalized*.

A *reachable* object is any object that can be accessed in any potential continuing computation from any live thread. Any object that may be referenced from a field or array element of a reachable object is reachable. Finally, if a reference to an object is passed to a JNI method, then the object must be considered reachable until that method completes.

A class loader is considered reachable if any instance of a class loaded by that loader is reachable. A class object is considered reachable if the class loader that loaded it is reachable.

Optimizing transformations of a program can be designed that reduce the number of objects that are reachable to be less than those which would naïvely be considered reachable. For example, a compiler or code generator may choose to set a variable or parameter that will no longer be used to null to cause the storage for such an object to be potentially reclaimable sooner.

Another example of this occurs if the values in an object's fields are stored in registers. The program then may access the registers instead of the object, and never access the object again. This would imply that the object is garbage.

Note that this sort of optimization is only allowed if references are on the stack, not stored in the heap. For example, consider the *Finalizer Guardian* pattern:

```
class Foo {
  private final Object finalizerGuardian = new Object() {
    protected void finalize() throws Throwable {
      /* finalize outer Foo object */
    }
  }
}
```

The finalizer guardian forces a `super.finalize` to be called if a subclass overrides finalize and does not explicitly call `super.finalize`.

If these optimizations are allowed for references that are stored on the heap, then the compiler can detect that the *finalizerGuardian* field is never read, null it out, collect the object immediately, and call the finalizer early. This runs counter to the intent: the programmer probably wanted to call the `Foo` finalizer when the `Foo` instance became unreachable. This sort of transformation is therefore not legal: the inner class object should be reachable for as long as the outer class object is reachable.

Transformations of this sort may result in invocations of the `finalize` method occurring earlier than might be otherwise expected. In order to allow the user to prevent this, we enforce the notion that synchronization may keep the object alive. *If an object's finalizer can result in synchronization on that object, then that object must be alive and considered reachable whenever a lock is held on it.*

Note that this does not prevent synchronization elimination: synchronization only keeps an object alive if a finalizer might synchronize on it. Since the finalizer occurs in another thread, in many cases the synchronization could not be removed anyway.

A *finalizer-reachable* object can be reached from some finalizable object through some chain of references, but not from any live thread. An *unreachable* object cannot be reached by either means.

An *unfinalized* object has never had its finalizer automatically invoked; a *finalized* object has had its finalizer automatically invoked. A *finalizable* object has never had its finalizer automatically invoked, but the Java virtual machine may eventually automatically invoke its finalizer. An object cannot be considered finalizable until its constructor has finished. Every pre-finalization write to a field of an object must be visible to the finalization of that object. Furthermore, none of the pre-finalization reads of fields of that object may see writes that occur after finalization of that object is initiated.

2.0.2 Interaction with the Memory Model

It must be possible for the memory model to decide when it can commit actions that take place in a finalizer. This section describes the interaction of finalization with the memory model.

Each execution has a number of *reachability decision points*, labeled d_i. Each action either *comes-before* d_i or *comes-after* d_i. Other than as explicitly mentioned, *comes before* in this section is unrelated to all other orderings in the memory model.

If r is a read that sees a write w and r comes-before d_i, then w must come-before d_i. If x and y are synchronization actions on the same variable or monitor such that $x \overset{so}{\rightarrow} y$ and y comes-before d_i, then x must come-before d_i.

At each reachability decision point, some set of objects are marked as unreachable, and some subset of those objects are marked as finalizable. These reachability decision points are also the points at which References are checked, enqueued and cleared according to the rules provided in the JavaDocs for `java.lang.ref`.

Reachability

The only objects that are considered definitely reachable at a point d_i are those that can be shown to be reachable by the application of these rules:

- An object B is definitely reachable at d_i from static fields if there exists there is a write w_1 to an static field v of a class C such that the value written by w_1 is a reference to B, the class C is loaded by a reachable classloader and there does not exist a write w_2 to v s.t. $\neg(w_2 \overset{hb}{\to} w_1)$, and both w_1 and w_2 come-before d_i.

- An object B is definitely reachable from A at d_i if there is a write w_1 to an element v of A such that the value written by w_1 is a reference to B and there does not exist a write w_2 to v s.t. $\neg(w_2 \overset{hb}{\to} w_1)$, and both w_1 and w_2 come-before d_i.
- If an object C is definitely reachable from an object B, object B is definitely reachable from an object A, then C is definitely reachable from A.

An action a is an active use of X if and only if

- it reads or writes an element of X
- it locks or unlocks X and there is a lock action on X that happens-after the invocation of the finalizer for X.
- it writes a reference to X
- it is an active use of an object Y, and X is definitely reachable from Y

If an object X is marked as unreachable at d_i,

- X must not be definitely reachable at d_i from static fields,
- All active uses of X in thread t that come-after d_i must occur in the finalizer invocation for X or as a result of thread t performing a read that comes-after d_i of a reference to X.
- All reads that come-after d_i that see a reference to X must see writes to elements of objects that were unreachable at d_i, or see writes that came after d_i.

If an object X marked as finalizable at d_i, then

- X must be marked as unreachable at d_i,
- d_i must be the only place where X is marked as finalizable,
- actions that happen-after the finalizer invocation must come-after d_i

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