Threading in C#, by Joe Albahari

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PART 2: BASIC SYNCHRONIZATION

Synchronization Essentials

So far, we've described how to start a task on a thread, configure a thread, and pass data in both directions. We've also described how local variables are private to a thread and how references can be shared among threads, allowing them to communicate via common fields.

The next step is *synchronization*: coordinating the actions of threads for a predictable outcome. Synchronization is particularly important when threads access the same data; it's surprisingly easy to run aground in this area.

Synchronization constructs can be divided into four categories:

Simple blocking methods

These wait for another thread to finish or for a period of time to elapse. **Sleep**, **Join**, and **Task.Wait** are simple blocking methods.

Locking constructs

These limit the number of threads that can perform some activity or execute a section of code at a time. *Exclusive* locking constructs are most common — these allow just one thread in at a time, and allow competing threads to access common data without interfering with each other. The standard exclusive locking constructs are **lock** (**Monitor.Enter**/**Monitor.Exit**), **Mutex**, and SpinLock. The nonexclusive locking constructs are **Semaphore**, **SemaphoreSlim**, and the reader/writer locks.

Signaling constructs

These allow a thread to pause until receiving a notification from another, avoiding the need for inefficient polling. There are two commonly used signaling devices: event wait handles and **Monitor**'s **Wait/Pulse** methods. Framework 4.0 introduces the **CountdownEvent** and **Barrier** classes.

Nonblocking synchronization constructs

These protect access to a common field by calling upon processor primitives. The CLR and C# provide the following nonblocking constructs: **Thread.MemoryBarrier, Thread.VolatileRead, Thread.VolatileWrite**, the **volatile** keyword, and the **Interlocked** class.

Blocking is essential to all but the last category. Let's briefly examine this concept.

Blocking

A thread is deemed *blocked* when its execution is paused for some reason, such as when **Sleep**ing or waiting for another to end via **Join** or **EndInvoke**. A blocked thread immediately *yields* its processor time slice, and from then on consumes no processor time until its blocking condition is satisfied. You can test for a thread being blocked via its **ThreadState** property:

```
bool blocked = (someThread.ThreadState & ThreadState.WaitSleepJoin) != 0;
```

(Given that a thread's state may change in between testing its state and then acting upon that information, this code is useful only in diagnostic scenarios.)

When a thread blocks or unblocks, the operating system performs a *context switch*. This incurs an overhead of a few microseconds.

Unblocking happens in one of four ways (the computer's power button doesn't count!):

- by the blocking condition being satisfied

- by the operation timing out (if a timeout is specified)
- by being interrupted via Thread.Interrupt
- by being aborted via Thread.Abort

A thread is not deemed blocked if its execution is paused via the (deprecated) Suspend method.

Blocking Versus Spinning

Sometimes a thread must pause until a certain condition is met. Signaling and locking constructs achieve this efficiently by *blocking* until a condition is satisfied. However, there is a simpler alternative: a thread can await a condition by *spinning* in a polling loop. For example:

```
while (!proceed);
```

or:

```
while (DateTime.Now < nextStartTime);
```

In general, this is very wasteful on processor time: as far as the CLR and operating system are concerned, the thread is performing an important calculation, and so gets allocated resources accordingly!

Sometimes a hybrid between blocking and spinning is used:

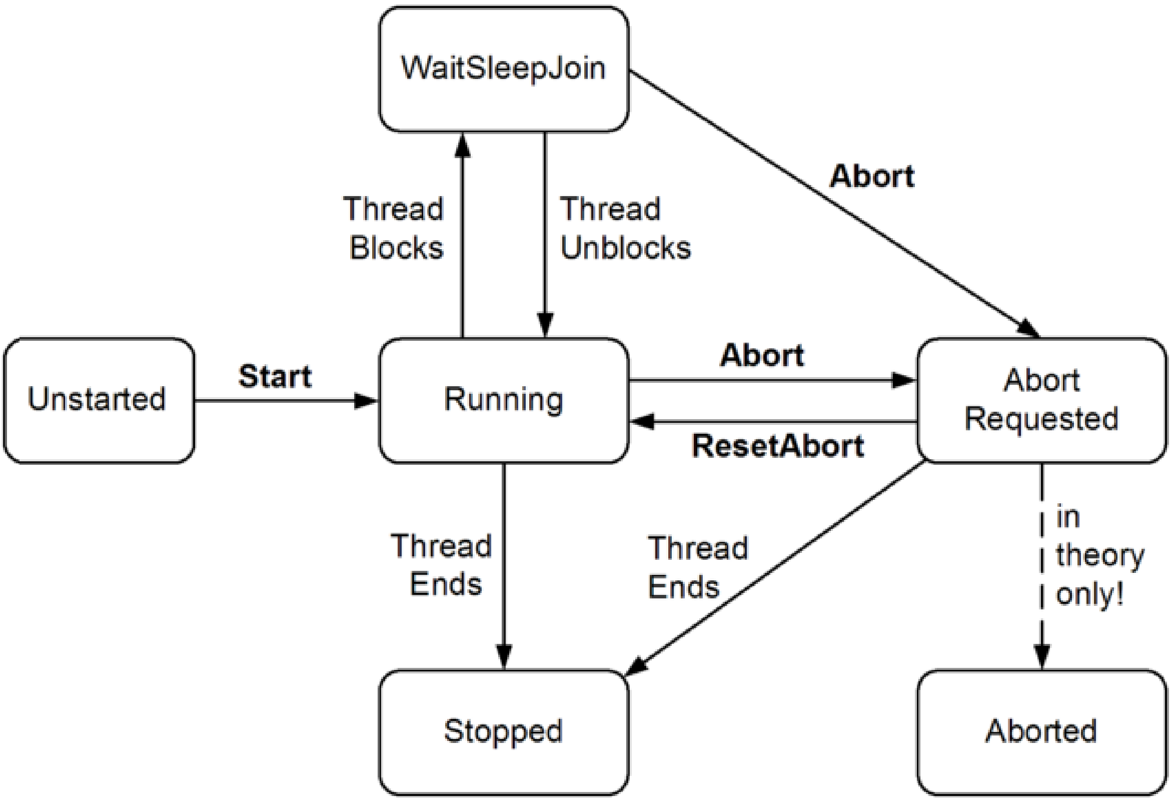
```
while (!proceed) Thread.Sleep (10);
```

Although inelegant, this is (in general) far more efficient than outright spinning. Problems can arise, though, due to concurrency issues on the **proceed** flag. Proper use of locking and signaling avoids this.

> Spinning *very briefly* can be effective when you expect a condition to be satisfied soon (perhaps within a few microseconds) because it avoids the overhead and latency of a context switch. The .NET Framework provides special methods and classes to assist — these are covered in the parallel programming section.

ThreadState

You can query a thread's execution status via its **ThreadState** property. This returns a flags enum of type **ThreadState**, which combines three “layers” of data in a bitwise fashion. Most values, however, are redundant, unused, or deprecated. The following diagram shows one “layer”:



The following code strips a **ThreadState** to one of the four most useful values: **Unstarted**, **Running**, **WaitSleepJoin**, and **Stopped**:

```
public static ThreadState SimpleThreadState (ThreadState ts)
{
  return ts & (ThreadState.Unstarted |
               ThreadState.WaitSleepJoin |
               ThreadState.Stopped);
}
```

The **ThreadState** property is useful for diagnostic purposes, but unsuitable for synchronization, because a thread's state may change in between testing **ThreadState** and acting on that information.

Locking

Exclusive locking is used to ensure that only one thread can enter particular sections of code at a time. The two main exclusive locking constructs are **lock** and **Mutex**. Of the two, the **lock** construct is faster and more convenient. **Mutex**, though, has a niche in that its lock can span applications in different processes on the computer.

In this section, we'll start with the **lock** construct and then move on to **Mutex** and semaphores (for nonexclusive locking). Later, we'll cover reader/writer locks.

> From Framework 4.0, there is also the SpinLock struct for high-concurrency scenarios.

Let's start with the following class:

```
class ThreadUnsafe
{
  static int _val1 = 1, _val2 = 1;

  static void Go()
  {
    if (_val2 != 0) Console.WriteLine (_val1 / _val2);
    _val2 = 0;
  }
}
```

This class is not thread-safe: if **Go** was called by two threads simultaneously, it would be possible to get a division-by-zero error, because **_val2** could be set to zero in one thread right as the other thread was in between executing the **if** statement and **Console.WriteLine**.

Here's how **lock** can fix the problem:

```
class ThreadSafe
{
  static readonly object _locker = new object();
  static int _val1, _val2;

  static void Go()
  {
    lock (_locker)
    {
      if (_val2 != 0) Console.WriteLine (_val1 / _val2);
      _val2 = 0;
    }
  }
}
```

Only one thread can lock the synchronizing object (in this case, **_locker**) at a time, and any contending threads are blocked until the lock is released. If more than one thread contends the lock, they are queued on a "ready queue" and granted the lock on a first-come, first-served basis (a caveat is that nuances in the behavior of Windows and the CLR mean that the fairness of the queue can sometimes be violated). Exclusive locks are sometimes said to enforce *serialized* access to whatever's protected by the lock, because one thread's access cannot overlap with that of another. In this case, we're protecting the logic inside the **Go** method, as well as the fields **_val1** and **_val2**.

A thread blocked while awaiting a contended lock has a **ThreadState** of **WaitSleepJoin**. In Interrupt and Abort, we describe how a blocked thread can be forcibly released via another thread. This is a fairly heavy-duty technique that might be used in ending a thread.

A Comparison of Locking Constructs

Construct	Purpose	Cross-process?	Overhead*
lock (**Monitor.Enter** / **Monitor.Exit**)	Ensures just one thread can access a resource, or section of code at a time	-	20ns
Mutex		Yes	1000ns
SemaphoreSlim (introduced in Framework 4.0)	Ensures not more than a specified number of concurrent threads can access a resource, or section of code	-	200ns
Semaphore		Yes	1000ns
ReaderWriterLockSlim (introduced in Framework 3.5)	Allows multiple readers to coexist with a single writer	-	40ns
ReaderWriterLock (effectively deprecated)		-	100ns

*Time taken to lock and unlock the construct once on the same thread (assuming no blocking), as measured on an Intel Core i7 860.

Monitor.Enter and Monitor.Exit

C#'s **lock** statement is in fact a syntactic shortcut for a call to the methods **Monitor.Enter** and **Monitor.Exit**, with a **try**/**finally** block. Here's (a simplified version of) what's actually happening within the **Go** method of the preceding example:

```
Monitor.Enter (_locker);
try
{
  if (_val2 != 0) Console.WriteLine (_val1 / _val2);
  _val2 = 0;
}
finally { Monitor.Exit (_locker); }
```

Calling **Monitor.Exit** without first calling **Monitor.Enter** on the same object throws an exception.

The lockTaken overloads

The code that we just demonstrated is exactly what the C# 1.0, 2.0, and 3.0 compilers produce in translating a **lock** statement.

There's a subtle vulnerability in this code, however. Consider the (unlikely) event of an exception being thrown within the implementation of **Monitor.Enter**, or between the call to **Monitor.Enter** and the **try** block (due, perhaps, to **Abort** being called on that thread — or an **OutOfMemoryException** being thrown). In such a scenario, the lock may or may not be taken. If the lock *is* taken, it won't be released — because we'll never enter the **try**/**finally** block. This will result in a leaked lock.

To avoid this danger, CLR 4.0's designers added the following overload to **Monitor.Enter**:

```
public static void Enter (object obj, ref bool lockTaken);
```

lockTaken is false after this method if (and only if) the **Enter** method throws an exception and the lock was not taken.

Here's the correct pattern of use (which is exactly how C# 4.0 translates a **lock** statement):

```
bool lockTaken = false;
try
{
  Monitor.Enter (_locker, ref lockTaken);
  // Do your stuff...
}
finally { if (lockTaken) Monitor.Exit (_locker); }
```

TryEnter

Monitor also provides a **TryEnter** method that allows a timeout to be specified, either in milliseconds or as a **TimeSpan**. The method then returns **true** if a lock was obtained, or **false** if no lock was obtained because the method timed out. **TryEnter** can also be called with no argument, which "tests" the lock, timing out immediately if the lock can't be obtained right away.

As with the **Enter** method, it's overloaded in CLR 4.0 to accept a **lockTaken** argument.

Choosing the Synchronization Object

Any object visible to each of the partaking threads can be used as a synchronizing object, subject to one hard rule: it must be a reference type. The synchronizing object is typically private (because this helps to encapsulate the locking logic) and is typically an instance or static field. The synchronizing object can double as the object it's protecting, as the **_list** field does in the following example:

```
class ThreadSafe
{
  List <string> _list = new List <string>();

  void Test()
  {
    lock (_list)
    {
      _list.Add ("Item 1");
      ...
```

A field dedicated for the purpose of locking (such as **_locker**, in the example prior) allows precise control over the scope and granularity of the lock. The containing object (**this**) — or even its type — can also be used as a synchronization object:

```
lock (this) { ... }
```

or:

```
lock (typeof (Widget)) { ... }    // For protecting access to statics
```

The disadvantage of locking in this way is that you're not encapsulating the locking logic, so it becomes harder to prevent deadlocking and excessive blocking. A lock on a type may also seep through application domain boundaries (within the same process).

You can also lock on local variables captured by lambda expressions or anonymous methods.

Locking doesn't restrict access to the synchronizing object itself in any way. In other words, **x.ToString()** will not block because another thread has called **lock(x)**; both threads must call **lock(x)** in order for blocking to occur.

When to Lock

As a basic rule, you need to lock around accessing *any writable shared field*. Even in the simplest case — an assignment operation on a single field — you must consider synchronization. In the following class, neither the **Increment** nor the **Assign** method is thread-safe:

```
class ThreadUnsafe
{
  static int _x;
  static void Increment() { _x++; }
  static void Assign()    { _x = 123; }
}
```

Here are thread-safe versions of **Increment** and **Assign**:

```
class ThreadSafe
{
  static readonly object _locker = new object();
  static int _x;

  static void Increment() { lock (_locker) _x++; }
  static void Assign()    { lock (_locker) _x = 123; }
}
```

In Nonblocking Synchronization, we explain how this need arises, and how the memory barriers and the **Interlocked** class can provide alternatives to locking in these situations.

Locking and Atomicity

If a group of variables are always read and written within the same lock, you can say the variables are read and written *atomically*. Let's suppose fields **x** and **y** are always read and assigned within a **lock** on object **locker**:

```
lock (locker) { if (x != 0) y /= x; }
```

One can say **x** and **y** are accessed atomically, because the code block cannot be divided or preempted by the actions of another thread in such a way that it will change **x** or **y** and *invalidate its outcome*. You'll never get a division-by-zero error, providing **x** and **y** are always accessed within this same exclusive lock.

The atomicity provided by a lock is violated if an exception is thrown within a **lock** block. For example, consider the following:

```
decimal _savingsBalance, _checkBalance;

void Transfer (decimal amount)
{
  lock (_locker)
  {
    _savingsBalance += amount;
    _checkBalance -= amount + GetBankFee();
  }
}
```

If an exception was thrown by **GetBankFee()**, the bank would lose money. In this case, we could avoid the problem by calling **GetBankFee** earlier. A solution for more complex cases is to implement "rollback" logic within a **catch** or **finally** block.

Instruction atomicity is a different, although analogous concept: an instruction is atomic if it executes indivisibly on the underlying processor (see Nonblocking Synchronization).

Nested Locking

A thread can repeatedly lock the same object in a nested (*reentrant*) fashion:

```
lock (locker)
  lock (locker)
    lock (locker)
    {
       // Do something...
    }
```

or:

```
Monitor.Enter (locker); Monitor.Enter (locker);  Monitor.Enter (locker);
// Do something...
Monitor.Exit (locker);  Monitor.Exit (locker);   Monitor.Exit (locker);
```

In these scenarios, the object is unlocked only when the outermost **lock** statement has exited — or a matching number of **Monitor.Exit** statements have executed.

Nested locking is useful when one method calls another within a lock:

```
static readonly object _locker = new object();

static void Main()
{
  lock (_locker)
  {
     AnotherMethod();
     // We still have the lock - because locks are reentrant.
  }
}

static void AnotherMethod()
{
  lock (_locker) { Console.WriteLine ("Another method"); }
}
```

A thread can block on only the first (outermost) lock.

Deadlocks

A deadlock happens when two threads each wait for a resource held by the other, so neither can proceed. The easiest way to illustrate this is with two locks:

```
object locker1 = new object();
object locker2 = new object();

new Thread (() => {
                    lock (locker1)
                    {
                      Thread.Sleep (1000);
                      lock (locker2);      // Deadlock
                    }
                  }).Start();
lock (locker2)
{
  Thread.Sleep (1000);
  lock (locker1);                          // Deadlock
}
```

More elaborate deadlocking chains can be created with three or more threads.

> The CLR, in a standard hosting environment, is not like SQL Server and does not automatically detect and resolve deadlocks by terminating one of the offenders. A threading deadlock causes participating threads to block indefinitely, unless you've specified a locking timeout. (Under the SQL CLR integration host, however, deadlocks *are* automatically detected and a [catchable] exception is thrown on one of the threads.)

Deadlocking is one of the hardest problems in multithreading — especially when there are many interrelated objects. Fundamentally, the hard problem is that you can't be sure what locks your *caller* has taken out.

So, you might innocently lock private field **a** within your class **x**, unaware that your caller (or caller's caller) has already locked field **b** within class **y**. Meanwhile, another thread is doing the reverse — creating a deadlock. Ironically, the problem is exacerbated by (good) object-oriented design patterns, because such patterns create call chains that are not determined until runtime.

The popular advice, “lock objects in a consistent order to avoid deadlocks,” although helpful in our initial example, is hard to apply to the scenario just described. A better strategy is to be wary of locking around calling methods in objects that may have references back to your own object. Also, consider whether you really need to lock around calling methods in other classes (often you do — as we’ll see later — but sometimes there are other options). Relying more on declarative and data parallelism, immutable types, and nonblocking synchronization constructs, can lessen the need for locking.

> Here is an alternative way to perceive the problem: when you call out to other code while holding a lock, the encapsulation of that lock subtly *leaks*. This is not a fault in the CLR or .NET Framework, but a fundamental limitation of locking in general. The problems of locking are being addressed in various research projects, including *Software Transactional Memory*.

Another deadlocking scenario arises when calling **Dispatcher.Invoke** (in a WPF application) or **Control.Invoke** (in a Windows Forms application) while in possession of a lock. If the UI happens to be running another method that’s waiting on the same lock, a deadlock will happen right there. This can often be fixed simply by calling **BeginInvoke** instead of **Invoke**. Alternatively, you can release your lock before calling **Invoke**, although this won't work if your *caller* took out the lock. We explain **Invoke** and **BeginInvoke** in Rich Client Applications and Thread Affinity.

Performance

Locking is fast: you can expect to acquire and release a lock in as little as 20 nanoseconds on a 2010-era computer if the lock is uncontended. If it is contended, the consequential context switch moves the overhead closer to the microsecond region, although it may be longer before the thread is actually rescheduled. You can avoid the cost of a context switch with the SpinLock class — if you’re locking very briefly.

Locking can degrade concurrency if locks are held for too long. This can also increase the chance of deadlock.

Mutex

A **Mutex** is like a C# **lock**, but it can work across multiple processes. In other words, **Mutex** can be *computer-wide* as well as *application-wide*.

> Acquiring and releasing an uncontended **Mutex** takes a few microseconds — about 50 times slower than a **lock**.

With a **Mutex** class, you call the **WaitOne** method to lock and **ReleaseMutex** to unlock. Closing or disposing a **Mutex** automatically releases it. Just as with the **lock** statement, a **Mutex** can be released only from the same thread that obtained it.

A common use for a cross-process **Mutex** is to ensure that only one instance of a program can run at a time. Here’s how it’s done:

```
class OneAtATimePlease
{
  static void Main()
  {
    // Naming a Mutex makes it available computer-wide. Use a name that's
    // unique to your company and application (e.g., include your URL).

    using (var mutex = new Mutex (false, "oreilly.com OneAtATimeDemo"))
    {
      // Wait a few seconds if contended, in case another instance
      // of the program is still in the process of shutting down.

      if (!mutex.WaitOne (TimeSpan.FromSeconds (3), false))
      {
        Console.WriteLine ("Another app instance is running. Bye!");
        return;
      }
      RunProgram();
    }
  }

  static void RunProgram()
```

```
  {
    Console.WriteLine ("Running. Press Enter to exit");
    Console.ReadLine();
  }
}
```

> If running under Terminal Services, a computer-wide **Mutex** is ordinarily visible only to applications in the same terminal server session. To make it visible to all terminal server sessions, prefix its name with *Global*.

Semaphore

A semaphore is like a nightclub: it has a certain capacity, enforced by a bouncer. Once it's full, no more people can enter, and a queue builds up outside. Then, for each person that leaves, one person enters from the head of the queue. The constructor requires a minimum of two arguments: the number of places currently available in the nightclub and the club's total capacity.

A semaphore with a capacity of one is similar to a **Mutex** or **lock**, except that the semaphore has no "owner" — it's *thread-agnostic*. Any thread can call **Release** on a **Semaphore**, whereas with **Mutex** and **lock**, only the thread that obtained the lock can release it.

> There are two functionally similar versions of this class: **Semaphore** and **SemaphoreSlim**. The latter was introduced in Framework 4.0 and has been optimized to meet the low-latency demands of [parallel programming](). It's also useful in traditional multithreading because it lets you specify a [cancellation token]() when waiting. It cannot, however, be used for interprocess signaling.
>
> **Semaphore** incurs about 1 microsecond in calling **WaitOne** or **Release**; **SemaphoreSlim** incurs about a quarter of that.

Semaphores can be useful in limiting concurrency — preventing too many threads from executing a particular piece of code at once. In the following example, five threads try to enter a nightclub that allows only three threads in at once:

```
class TheClub      // No door lists!
{
  static SemaphoreSlim _sem = new SemaphoreSlim (3);    // Capacity of 3

  static void Main()
  {
    for (int i = 1; i <= 5; i++) new Thread (Enter).Start (i);
  }

  static void Enter (object id)
  {
    Console.WriteLine (id + " wants to enter");
    _sem.Wait();
    Console.WriteLine (id + " is in!");           // Only three threads
    Thread.Sleep (1000 * (int) id);               // can be here at
    Console.WriteLine (id + " is leaving");       // a time.
    _sem.Release();
  }
}
```

```
1 wants to enter
1 is in!
2 wants to enter
2 is in!
3 wants to enter
3 is in!
4 wants to enter
5 wants to enter
1 is leaving
4 is in!
2 is leaving
5 is in!
```

If the **Sleep** statement was instead performing intensive disk I/O, the **Semaphore** would improve overall performance by limiting excessive concurrent hard-drive activity.

A **Semaphore**, if named, can span processes in the same way as a **Mutex**.

Thread Safety

A program or method is thread-safe if it has no indeterminacy in the face of any multithreading scenario. Thread safety is achieved primarily with locking and by reducing the possibilities for thread interaction.

General-purpose types are rarely thread-safe in their entirety, for the following reasons:

- The development burden in full thread safety can be significant, particularly if a type has many fields (each field is a potential for interaction in an arbitrarily multithreaded context).
- Thread safety can entail a performance cost (payable, in part, whether or not the type is actually used by multiple threads).
- A thread-safe type does not necessarily make the program using it thread-safe, and often the work involved in the latter makes the former redundant.

Thread safety is hence usually implemented just where it needs to be, in order to handle a specific multithreading scenario.

There are, however, a few ways to "cheat" and have large and complex classes run safely in a multithreaded environment. One is to sacrifice granularity by wrapping large sections of code — even access to an entire object — within a single exclusive lock, enforcing serialized access at a high level. This tactic is, in fact, essential if you want to use thread-unsafe third-party code (or most Framework types, for that matter) in a multithreaded context. The trick is simply to use the same exclusive lock to protect access to all properties, methods, and fields on the thread-unsafe object. The solution works well if the object's methods all execute quickly (otherwise, there will be a lot of blocking).

> Primitive types aside, few .NET Framework types, when instantiated, are thread-safe for anything more than concurrent read-only access. The onus is on the developer to superimpose thread safety, typically with exclusive locks. (The collections in **System.Collections.Concurrent** are an exception.)

Another way to cheat is to minimize thread interaction by minimizing shared data. This is an excellent approach and is used implicitly in "stateless" middle-tier application and web page servers. Since multiple client requests can arrive simultaneously, the server methods they call must be thread-safe. A stateless design (popular for reasons of scalability) intrinsically limits the possibility of interaction, since classes do not persist data between requests. Thread interaction is then limited just to the static fields one may choose to create, for such purposes as caching commonly used data in memory and in providing infrastructure services such as authentication and auditing.

The final approach in implementing thread safety is to use an automatic locking regime. The .NET Framework does exactly this, if you subclass **ContextBoundObject and apply the Synchronization attribute** to the class. Whenever a method or property on such an object is then called, an object-wide lock is automatically taken for the whole execution of the method or property. Although this reduces the thread-safety burden, it creates problems of its own: deadlocks that would not otherwise occur, impoverished concurrency, and unintended reentrancy. For these reasons, manual locking is generally a better option — at least until a less simplistic automatic locking regime becomes available.

Thread Safety and .NET Framework Types

Locking can be used to convert thread-unsafe code into thread-safe code. A good application of this is the .NET Framework: nearly all of its nonprimitive types are not thread-safe (for anything more than read-only access) when instantiated, and yet they can be used in multithreaded code if all access to any given object is protected via a lock. Here's an example, where two threads simultaneously add an item to the same **List** collection, then enumerate the list:

```
class ThreadSafe
{
  static List <string> _list = new List <string>();

  static void Main()
  {
    new Thread (AddItem).Start();
    new Thread (AddItem).Start();
  }

  static void AddItem()
  {
    lock (_list) _list.Add ("Item " + _list.Count);

    string[] items;
    lock (_list) items = _list.ToArray();
    foreach (string s in items) Console.WriteLine (s);
  }
}
```

In this case, we're locking on the **_list** object itself. If we had two interrelated lists, we would have to choose a common object upon which to lock (we could nominate one of the lists, or better: use an independent field).

Enumerating .NET collections is also thread-unsafe in the sense that an exception is thrown if the list is modified during enumeration. Rather than locking for the duration of enumeration, in this example we first copy the items to an array. This avoids holding the lock excessively if what we're doing during enumeration is potentially time-consuming. (Another solution is to use a reader/writer lock.)

Locking around thread-safe objects

Sometimes you also need to lock around accessing thread-safe objects. To illustrate, imagine that the Framework's **List** class was, indeed, thread-safe, and we want to add an item to a list:

```
if (!_list.Contains (newItem)) _list.Add (newItem);
```

Whether or not the list was thread-safe, this statement is certainly not! The whole **if** statement would have to be wrapped in a lock in order to prevent preemption in between testing for containership and adding the new item. This same lock would then need to be used everywhere we modified that list. For instance, the following statement would also need to be wrapped in the identical lock:

```
_list.Clear();
```

to ensure that it did not preempt the former statement. In other words, we would have to lock exactly as with our thread-unsafe collection classes (making the **List** class's hypothetical thread safety redundant).

> Locking around accessing a collection can cause excessive blocking in highly concurrent environments. To this end, Framework 4.0 provides a thread-safe queue, stack, and dictionary.

Static members

Wrapping access to an object around a custom lock works only if all concurrent threads are aware of — and use — the lock. This may not be the case if the object is widely scoped. The worst case is with static members in a public type. For instance, imagine if the static property on the **DateTime** struct, **DateTime.Now**, was not thread-safe, and that two concurrent calls could result in garbled output or an exception. The only way to remedy this with external locking might be to lock the type itself — **lock(typeof(DateTime))** — before calling **DateTime.Now**. This would work only if all programmers agreed to do this (which is unlikely). Furthermore, locking a type creates problems of its own.

For this reason, static members on the **DateTime** struct have been carefully programmed to be thread-safe. This is a common pattern throughout the .NET Framework: *static members are thread-safe; instance members are not.* Following this pattern also makes sense when writing types for public consumption, so as not to create impossible thread-safety conundrums. In other words, by making static methods thread-safe, you're programming so as not to *preclude* thread safety for consumers of that type.

> Thread safety in static methods is something that you must explicitly code: it doesn't happen automatically by virtue of the method being static!

Read-only thread safety

Making types thread-safe for concurrent read-only access (where possible) is advantageous because it means that consumers can avoid excessive locking. Many of the .NET Framework types follow this principle: collections, for instance, are thread-safe for concurrent readers.

Following this principle yourself is simple: if you document a type as being thread-safe for concurrent read-only access, don't write to fields within methods that a consumer would expect to be read-only (or lock around doing so). For instance, in implementing a **ToArray()** method in a collection, you might start by compacting the collection's internal structure. However, this would make it thread-unsafe for consumers that expected this to be read-only.

Read-only thread safety is one of the reasons that enumerators are separate from "enumerables": two threads can simultaneously enumerate over a collection because each gets a separate enumerator object.

> In the absence of documentation, it pays to be cautious in assuming whether a method is read-only in nature. A good example is the **Random** class: when you call **Random.Next()**, its internal implementation requires that it update private seed values. Therefore, you must either lock around using the **Random** class, or maintain a separate instance per thread.

Thread Safety in Application Servers

Application servers need to be multithreaded to handle simultaneous client requests. WCF, ASP.NET, and Web Services applications are implicitly multithreaded; the same holds true for Remoting server applications that use a network channel such as TCP or HTTP. This means that when writing code on the server side, you must consider thread safety if there's any possibility of interaction among the threads processing client requests. Fortunately, such a possibility is rare; a typical server class is either stateless (no fields) or has an activation model that creates a separate object instance for each client or each request. Interaction usually arises only through static fields, sometimes used for caching in memory parts of a database to improve performance.

For example, suppose you have a **RetrieveUser** method that queries a database:

```
// User is a custom class with fields for user data
internal User RetrieveUser (int id) { ... }
```

If this method was called frequently, you could improve performance by caching the results in a static **Dictionary**. Here's a solution that takes thread safety into account:

```
static class UserCache
{
  static Dictionary <int, User> _users = new Dictionary <int, User>();

  internal static User GetUser (int id)
  {
    User u = null;

    lock (_users)
      if (_users.TryGetValue (id, out u))
        return u;

    u = RetrieveUser (id);   // Method to retrieve user from database
    lock (_users) _users [id] = u;
    return u;
  }
}
```

We must, at a minimum, lock around reading and updating the dictionary to ensure thread safety. In this example, we choose a practical compromise between simplicity and performance in locking. Our design actually creates a very small potential for inefficiency: if two threads simultaneously called this method with the same previously unretrieved **id**, the **RetrieveUser** method would be called twice — and the dictionary would be updated unnecessarily. Locking once across the whole method would prevent this, but would create a worse inefficiency: the entire cache would be locked up for the duration of calling **RetrieveUser**, during which time other threads would be blocked in retrieving *any* user.

Rich Client Applications and Thread Affinity

Both the Windows Presentation Foundation (WPF) and Windows Forms libraries follow models based on thread affinity. Although each has a separate implementation, they are both very similar in how they function.

The objects that make up a rich client are based primarily on **DependencyObject** in the case of WPF, or **Control** in the case of Windows Forms. These objects have *thread affinity*, which means that only the thread that instantiates them can subsequently access their members. Violating this causes either unpredictable behavior, or an exception to be thrown.

On the positive side, this means you don't need to lock around accessing a UI object. On the negative side, if you want to call a member on object X created on another thread Y, you must marshal the request to thread Y. You can do this explicitly as follows:

- In WPF, call **Invoke** or **BeginInvoke** on the element's **Dispatcher** object.
- In Windows Forms, call **Invoke** or **BeginInvoke** on the control.

Invoke and **BeginInvoke** both accept a delegate, which references the method on the target control that you want to run. **Invoke** works *synchronously*: the caller blocks until the marshal is complete. **BeginInvoke** works *asynchronously*: the caller returns immediately and the marshaled request is queued up (using the same message queue that handles keyboard, mouse, and timer events).

Assuming we have a window that contains a text box called **txtMessage**, whose content we wish a worker thread to update, here's an example for WPF:

```
public partial class MyWindow : Window
{
  public MyWindow()
  {
    InitializeComponent();
    new Thread (Work).Start();
  }

  void Work()
  {
    Thread.Sleep (5000);           // Simulate time-consuming task
    UpdateMessage ("The answer");
  }

  void UpdateMessage (string message)
  {
    Action action = () => txtMessage.Text = message;
    Dispatcher.Invoke (action);
  }
}
```

The code is similar for Windows Forms, except that we call the (**Form**'s) **Invoke** method instead:

```
  void UpdateMessage (string message)
  {
    Action action = () => txtMessage.Text = message;
    this.Invoke (action);
  }
```

The Framework provides two constructs to simplify this process:

- **BackgroundWorker**
- **Task continuations**

Worker threads versus UI threads

It's helpful to think of a rich client application as having two distinct categories of threads: UI threads and worker threads. UI threads instantiate (and subsequently "own") UI elements; worker threads do not. Worker threads typically execute long-running tasks such as fetching data.

Most rich client applications have a single UI thread (which is also the main application thread) and periodically spawn worker threads — either directly or using **BackgroundWorker**. These workers then marshal back to the main UI thread in order to update controls or report on progress.

So, when would an application have multiple UI threads? The main scenario is when you have an application with multiple top-level windows, often called a *Single Document Interface* (SDI) application, such as Microsoft Word. Each SDI window typically shows itself as a separate "application" on the taskbar and is mostly isolated, functionally, from other SDI windows. By giving each such window its own UI thread, the application can be made more responsive.

Immutable Objects

An immutable object is one whose state cannot be altered — externally or internally. The fields in an immutable object are typically declared read-only and are fully initialized during construction.

Immutability is a hallmark of functional programming — where instead of *mutating* an object, you create a new object with different properties. LINQ follows this paradigm. Immutability is also valuable in multithreading in that it avoids the problem of shared writable state — by eliminating (or minimizing) the writable.

One pattern is to use immutable objects to encapsulate a group of related fields, to minimize lock durations. To take a very simple example, suppose we had two fields as follows:

```
int _percentComplete;
string _statusMessage;
```

and we wanted to read/write them atomically. Rather than locking around these fields, we could define the following immutable class:

```
class ProgressStatus    // Represents progress of some activity
{
  public readonly int PercentComplete;
  public readonly string StatusMessage;

  // This class might have many more fields...

  public ProgressStatus (int percentComplete, string statusMessage)
  {
    PercentComplete = percentComplete;
    StatusMessage = statusMessage;
  }
}
```

Then we could define a single field of that type, along with a locking object:

```
readonly object _statusLocker = new object();
ProgressStatus _status;
```

We can now read/write values of that type without holding a lock for more than a single assignment:

```
var status = new ProgressStatus (50, "Working on it");
// Imagine we were assigning many more fields...
// ...
lock (_statusLocker) _status = status;    // Very brief lock
```

To read the object, we first obtain a copy of the object (within a lock). Then we can read its values without needing to hold on to the lock:

```
ProgressStatus statusCopy;
lock (_locker ProgressStatus) statusCopy = _status;   // Again, a brief lock
int pc = statusCopy.PercentComplete;
string msg = statusCopy.StatusMessage;
...
```

> Technically, the last two lines of code are thread-safe by virtue of the preceding lock performing an implicit *memory barrier (see part 4)*.

Note that this lock-free approach prevents inconsistency within a group of related fields. But it doesn't prevent data from changing while you subsequently act on it — for this, you usually need a lock. In Part 5, we'll see more examples of using immutability to simplify multithreading — including PLINQ.

> It's also possible to safely assign a new **ProgressStatus** object based on its preceding value (e.g., it's possible to "increment" the **PercentComplete** value) — without locking over more than one line of code. In fact, we can do this without using a single lock, through the use of explicit memory barriers, **Interlocked.CompareExchange**, and spin-waits. This is an advanced technique which we describe in later in the parallel programming section.

Signaling with Event Wait Handles

Event wait handles are used for *signaling*. Signaling is when one thread waits until it receives notification from another. Event wait handles are the simplest of the signaling constructs, and they are unrelated to C# events. They come in three flavors: **AutoResetEvent**, **ManualResetEvent**, and (from Framework 4.0) **CountdownEvent**. The former two are based on the common **EventWaitHandle** class, where they derive all their functionality.

A Comparison of Signaling Constructs

Construct	Purpose	Cross-process?	Overhead*
AutoResetEvent	Allows a thread to unblock once when it receives a signal from another	Yes	1000ns
ManualResetEvent	Allows a thread to unblock indefinitely when it receives a signal from another (until reset)	Yes	1000ns
ManualResetEventSlim (introduced in Framework 4.0)		-	40ns
CountdownEvent (introduced in Framework 4.0)	Allows a thread to unblock when it receives a predetermined number of signals	-	40ns
Barrier (introduced in Framework 4.0)	Implements a thread execution barrier	-	80ns
Wait and Pulse	Allows a thread to block until a custom condition is met	-	120ns for a **Pulse**

*Time taken to signal and wait on the construct once on the same thread (assuming no blocking), as measured on an Intel Core i7 860.

AutoResetEvent

An **AutoResetEvent** is like a ticket turnstile: inserting a ticket lets exactly one person through. The "auto" in the class's name refers to the fact that an open turnstile automatically closes or "resets" after someone steps through. A thread waits, or blocks, at the turnstile by calling **WaitOne** (wait at this "one" turnstile until it opens), and a ticket is inserted by calling the **Set** method. If a number of threads call **WaitOne**, a queue builds up behind the turnstile. (As with locks, the fairness of the queue can sometimes be violated due to nuances in the operating system). A ticket can come from any thread; in other words, any (unblocked) thread with access to the **AutoResetEvent** object can call **Set** on it to release one blocked thread.

You can create an **AutoResetEvent** in two ways. The first is via its constructor:

```
var auto = new AutoResetEvent (false);
```

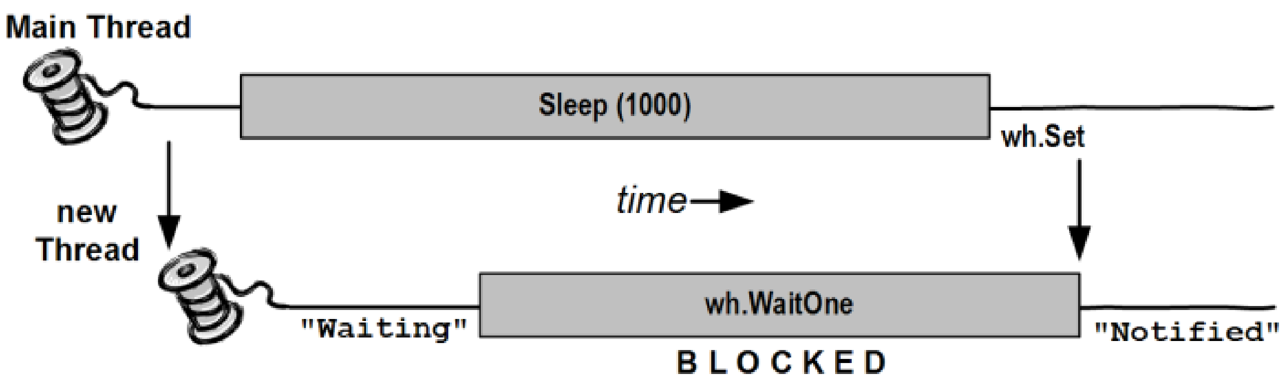
(Passing **true** into the constructor is equivalent to immediately calling **Set** upon it.) The second way to create an **AutoResetEvent** is as follows:

```
var auto = new EventWaitHandle (false, EventResetMode.AutoReset);
```

In the following example, a thread is started whose job is simply to wait until signaled by another thread:

```
class BasicWaitHandle
{
  static EventWaitHandle _waitHandle = new AutoResetEvent (false);

  static void Main()
  {
    new Thread (Waiter).Start();
    Thread.Sleep (1000);                  // Pause for a second...
    _waitHandle.Set();                    // Wake up the Waiter.
  }

  static void Waiter()
  {
    Console.WriteLine ("Waiting...");
    _waitHandle.WaitOne();                // Wait for notification
    Console.WriteLine ("Notified");
  }
}
```

```
Waiting... (pause) Notified.
```



If **Set** is called when no thread is waiting, the handle stays open for as long as it takes until some thread calls **WaitOne**. This behavior helps avoid a race between a thread heading for the turnstile, and a thread inserting a ticket ("Oops, inserted the ticket a microsecond too soon, bad luck, now you'll have to wait indefinitely!"). However, calling **Set** repeatedly on a turnstile at which no one is waiting doesn't allow a whole party through when they arrive: only the next single person is let through and the extra tickets are "wasted."

Calling **Reset** on an **AutoResetEvent** closes the turnstile (should it be open) without waiting or [blocking](#).

WaitOne accepts an optional timeout parameter, returning **false** if the wait ended because of a timeout rather than obtaining the signal.

> Calling **WaitOne** with a timeout of **0** tests whether a wait handle is "open," without blocking the caller. Bear in mind, though, that doing this resets the **AutoResetEvent** if it's open.

Disposing Wait Handles

Once you've finished with a wait handle, you can call its **Close** method to release the operating system resource. Alternatively, you can simply drop all references to the wait handle and allow the garbage collector to do the job for you sometime later (wait handles implement the disposal pattern whereby the finalizer calls **Close**). This is one of the few scenarios where relying on this backup is (arguably) acceptable, because wait handles have a light OS burden ([asynchronous delegates](#) rely on exactly this mechanism to release their **IAsyncResult**'s wait handle).

Wait handles are released automatically when an application domain unloads.

Two-way signaling

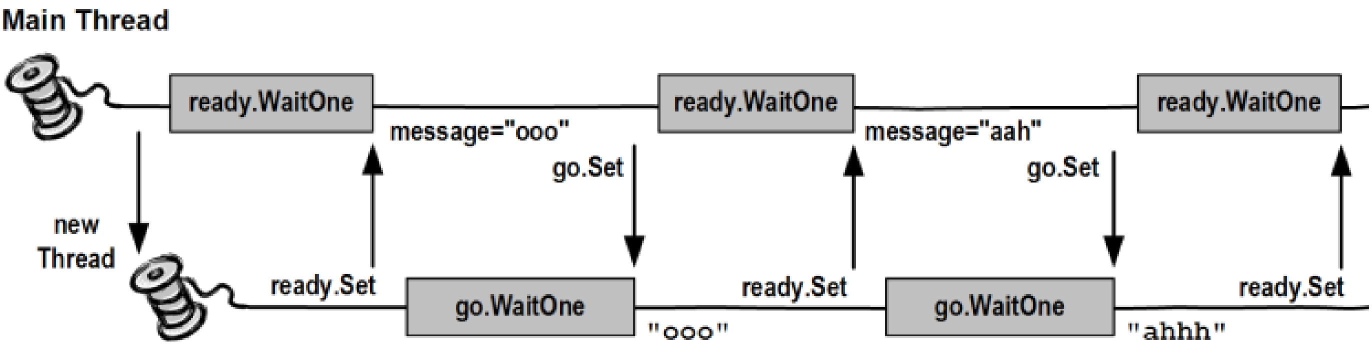
Let's say we want the main thread to signal a worker thread three times in a row. If the main thread simply calls **Set** on a wait handle several times in rapid succession, the second or third signal may get lost, since the worker may take time to process each signal.

The solution is for the main thread to wait until the worker's ready before signaling it. This can be done with another **AutoResetEvent**, as follows:

```
class TwoWaySignaling
{
  static EventWaitHandle _ready = new AutoResetEvent (false);
  static EventWaitHandle _go = new AutoResetEvent (false);
  static readonly object _locker = new object();
  static string _message;

  static void Main()
  {
    new Thread (Work).Start();

    _ready.WaitOne();                  // First wait until worker is ready
    lock (_locker) _message = "ooo";
    _go.Set();                         // Tell worker to go
```

```
    _ready.WaitOne();
    lock (_locker) _message = "ahhh";  // Give the worker another message
    _go.Set();
    _ready.WaitOne();
    lock (_locker) _message = null;    // Signal the worker to exit
    _go.Set();
  }

  static void Work()
  {
    while (true)
    {
      _ready.Set();                          // Indicate that we're ready
      _go.WaitOne();                         // Wait to be kicked off...
      lock (_locker)
      {
        if (_message == null) return;        // Gracefully exit
        Console.WriteLine (_message);
      }
    }
  }
}
```

```
ooo
ahhh
```



Here, we're using a null message to indicate that the worker should end. With threads that run indefinitely, it's important to have an exit strategy!

Producer/consumer queue

A producer/consumer queue is a common requirement in threading. Here's how it works:

- A queue is set up to describe work items — or data upon which work is performed.
- When a task needs executing, it's enqueued, allowing the caller to get on with other things.
- One or more worker threads plug away in the background, picking off and executing queued items.

The advantage of this model is that you have precise control over how many worker threads execute at once. This can allow you to limit consumption of not only CPU time, but other resources as well. If the tasks perform intensive disk I/O, for instance, you might have just one worker thread to avoid starving the operating system and other applications. Another type of application may have 20. You can also dynamically add and remove workers throughout the queue's life. The CLR's thread pool itself is a kind of producer/consumer queue.

A producer/consumer queue typically holds items of data upon which (the same) task is performed. For example, the items of data may be filenames, and the task might be to encrypt those files.

In the example below, we use a single **AutoResetEvent** to signal a worker, which waits when it runs out of tasks (in other words, when the queue is empty). We end the worker by enqueing a null task:

```
using System;
using System.Threading;
using System.Collections.Generic;

class ProducerConsumerQueue : IDisposable
{
  EventWaitHandle _wh = new AutoResetEvent (false);
  Thread _worker;
```

```
  readonly object _locker = new object();
  Queue<string> _tasks = new Queue<string>();

  public ProducerConsumerQueue()
  {
    _worker = new Thread (Work);
    _worker.Start();
  }

  public void EnqueueTask (string task)
  {
    lock (_locker) _tasks.Enqueue (task);
    _wh.Set();
  }

  public void Dispose()
  {
    EnqueueTask (null);     // Signal the consumer to exit.
    _worker.Join();         // Wait for the consumer's thread to finish.
    _wh.Close();            // Release any OS resources.
  }

  void Work()
  {
    while (true)
    {
      string task = null;
      lock (_locker)
        if (_tasks.Count > 0)
        {
          task = _tasks.Dequeue();
          if (task == null) return;
        }
      if (task != null)
      {
        Console.WriteLine ("Performing task: " + task);
        Thread.Sleep (1000);  // simulate work...
      }
      else
        _wh.WaitOne();         // No more tasks - wait for a signal
    }
  }
}
```

To ensure thread safety, we used a lock to protect access to the **Queue<string>** collection. We also explicitly closed the wait handle in our **Dispose** method, since we could potentially create and destroy many instances of this class within the life of the application.

Here's a main method to test the queue:

```
static void Main()
{
  using (ProducerConsumerQueue q = new ProducerConsumerQueue())
  {
    q.EnqueueTask ("Hello");
    for (int i = 0; i < 10; i++) q.EnqueueTask ("Say " + i);
    q.EnqueueTask ("Goodbye!");
  }

  // Exiting the using statement calls q's Dispose method, which
  // enqueues a null task and waits until the consumer finishes.
}
```

```
Performing task: Hello
Performing task: Say 1
Performing task: Say 2
Performing task: Say 3
...
...
Performing task: Say 9
Goodbye!
```

Framework 4.0 provides a new class called BlockingCollection<T> that implements the functionality of a producer/consumer queue.

Our manually written producer/consumer queue is still valuable — not only to illustrate **AutoResetEvent** and thread safety, but also as a basis for more sophisticated structures. For instance, if we wanted a *bounded blocking queue* (limiting the number of enqueued tasks) and also wanted to support cancellation (and removal) of enqueued work items, our code would provide an excellent starting point. We'll take the producer/consume queue example further in our discussion of Wait and Pulse.

ManualResetEvent

A **ManualResetEvent** functions like an ordinary gate. Calling **Set** opens the gate, allowing *any* number of threads calling **WaitOne** to be let through. Calling **Reset** closes the gate. Threads that call **WaitOne** on a closed gate will block; when the gate is next opened, they will be released all at once. Apart from these differences, a **ManualResetEvent** functions like an **AutoResetEvent**.

As with **AutoResetEvent**, you can construct a **ManualResetEvent** in two ways:

```
var manual1 = new ManualResetEvent (false);
var manual2 = new EventWaitHandle (false, EventResetMode.ManualReset);
```

From Framework 4.0, there's another version of **ManualResetEvent** called **ManualResetEventSlim**. The latter is optimized for short waiting times — with the ability to opt into spinning for a set number of iterations. It also has a more efficient managed implementation and allows a **Wait** to be canceled via a **CancellationToken**. It cannot, however, be used for interprocess signaling. **ManualResetEventSlim** doesn't subclass **WaitHandle**; however, it exposes a **WaitHandle** property that returns a **WaitHandle**-based object when called (with the performance profile of a traditional wait handle).

Signaling Constructs and Performance

Waiting or signaling an **AutoResetEvent** or **ManualResetEvent** takes about one microsecond (assuming no blocking).

ManualResetEventSlim and **CountdownEvent** can be up to 50 times faster in short-wait scenarios, because of their nonreliance on the operating system and judicious use of spinning constructs.

In most scenarios, however, the overhead of the signaling classes themselves doesn't create a bottleneck, and so is rarely a consideration. An exception is with highly concurrent code, which we'll discuss in Part 5.

A **ManualResetEvent** is useful in allowing one thread to unblock many other threads. The reverse scenario is covered by **CountdownEvent**.

CountdownEvent

CountdownEvent lets you wait on more than one thread. The class is new to Framework 4.0 and has an efficient fully managed implementation.

If you're running on an earlier version of the .NET Framework, all is not lost! Later on, we show how to write a **CountdownEvent** using Wait and Pulse.

To use **CountdownEvent**, instantiate the class with the number of threads or "counts" that you want to wait on:

```
var countdown = new CountdownEvent (3);  // Initialize with "count" of 3.
```

Calling **Signal** decrements the "count"; calling **Wait** blocks until the count goes down to zero. For example:

```
static CountdownEvent _countdown = new CountdownEvent (3);
```

```
static void Main()
{
  new Thread (SaySomething).Start ("I am thread 1");
  new Thread (SaySomething).Start ("I am thread 2");
  new Thread (SaySomething).Start ("I am thread 3");

  _countdown.Wait();   // Blocks until Signal has been called 3 times
  Console.WriteLine ("All threads have finished speaking!");
}

static void SaySomething (object thing)
{
  Thread.Sleep (1000);
  Console.WriteLine (thing);
  _countdown.Signal();
}
```

> Problems for which **CountdownEvent** is effective can sometimes be solved more easily using the *structured parallelism* constructs that we'll cover in Part 5 (PLINQ and the **Parallel** class).

You can reincrement a **CountdownEvent**'s count by calling **AddCount**. However, if it has already reached zero, this throws an exception: you can't "unsignal" a **CountdownEvent** by calling **AddCount**. To avoid the possibility of an exception being thrown, you can instead call **TryAddCount**, which returns **false** if the countdown is zero.

To unsignal a countdown event, call **Reset**: this both unsignals the construct and resets its count to the original value.

Like **ManualResetEventSlim**, **CountdownEvent** exposes a **WaitHandle** property for scenarios where some other class or method expects an object based on **WaitHandle**.

Creating a Cross-Process EventWaitHandle

EventWaitHandle's constructor allows a "named" **EventWaitHandle** to be created, capable of operating across multiple processes. The name is simply a string, and it can be any value that doesn't unintentionally conflict with someone else's! If the name is already in use on the computer, you get a reference to the same underlying **EventWaitHandle**; otherwise, the operating system creates a new one. Here's an example:

```
EventWaitHandle wh = new EventWaitHandle (false, EventResetMode.AutoReset,
                                          "MyCompany.MyApp.SomeName");
```

If two applications each ran this code, they would be able to signal each other: the wait handle would work across all threads in both processes.

Wait Handles and the Thread Pool

If your application has lots of threads that spend most of their time blocked on a wait handle, you can reduce the resource burden by calling **ThreadPool.RegisterWaitForSingleObject**. This method accepts a delegate that is executed when a wait handle is signaled. While it's waiting, it doesn't tie up a thread:

```
static ManualResetEvent _starter = new ManualResetEvent (false);

public static void Main()
{
  RegisteredWaitHandle reg = ThreadPool.RegisterWaitForSingleObject
                             (_starter, Go, "Some Data", -1, true);
  Thread.Sleep (5000);
  Console.WriteLine ("Signaling worker...");
  _starter.Set();
  Console.ReadLine();
  reg.Unregister (_starter);    // Clean up when we're done.
}

public static void Go (object data, bool timedOut)
{
  Console.WriteLine ("Started - " + data);
  // Perform task...
}
```

```
(5 second delay)
Signaling worker...
Started - Some Data
```

When the wait handle is signaled (or a timeout elapses), the delegate runs on a pooled thread.

In addition to the wait handle and delegate, **RegisterWaitForSingleObject** accepts a "black box" object that it passes to your delegate method (rather like **ParameterizedThreadStart**), as well as a timeout in milliseconds (–1 meaning no timeout) and a boolean flag indicating whether the request is one-off rather than recurring.

RegisterWaitForSingleObject is particularly valuable in an application server that must handle many concurrent requests. Suppose you need to block on a **ManualResetEvent** and simply call **WaitOne**:

```
void AppServerMethod()
{
  _wh.WaitOne();
  // ... continue execution
}
```

If 100 clients called this method, 100 server threads would be tied up for the duration of the blockage. Replacing **_wh.WaitOne** with **RegisterWaitForSingleObject** allows the method to return immediately, wasting no threads:

```
void AppServerMethod
{
  RegisteredWaitHandle reg = ThreadPool.RegisterWaitForSingleObject
   (_wh, Resume, null, -1, true);
  ...
}

static void Resume (object data, bool timedOut)
{
  // ... continue execution
}
```

The data object passed to **Resume** allows continuance of any transient data.

WaitAny, WaitAll, and SignalAndWait

In addition to the **Set**, **WaitOne**, and **Reset** methods, there are static methods on the **WaitHandle** class to crack more complex synchronization nuts. The **WaitAny**, **WaitAll**, and **SignalAndWait** methods perform signaling and waiting operations on multiple handles. The wait handles can be of differing types (including **Mutex** and **Semphore**, since these also derive from the abstract **WaitHandle** class). **ManualResetEventSlim** and **CountdownEvent** can also partake in these methods via their **WaitHandle** properties.

> **WaitAll** and **SignalAndWait** have a weird connection to the legacy COM architecture: these methods require that the caller be in a multithreaded apartment, the model least suitable for interoperability. The main thread of a WPF or Windows application, for example, is unable to interact with the clipboard in this mode. We'll discuss alternatives shortly.

WaitHandle.WaitAny waits for any one of an array of wait handles; **WaitHandle.WaitAll** waits on all of the given handles, atomically. This means that if you wait on two **AutoResetEvents**:

- **WaitAny** will never end up "latching" both events.
- **WaitAll** will never end up "latching" only one event.

SignalAndWait calls **Set** on one **WaitHandle**, and then calls **WaitOne** on another **WaitHandle**. After signaling the first handle, it will jump to the head of the queue in waiting on the second handle; this helps it succeed (although the operation is not truly atomic). You can think of this method as "swapping" one signal for another, and use it on a pair of **EventWaitHandles** to set up two threads to rendezvous or "meet" at the same point in time. Either **AutoResetEvent** or **ManualResetEvent** will do the trick. The first thread executes the following:

```
WaitHandle.SignalAndWait (wh1, wh2);
```

whereas the second thread does the opposite:

```
WaitHandle.SignalAndWait (wh2, wh1);
```

Alternatives to WaitAll and SignalAndWait

WaitAll and **SignalAndWait** won't run in a single-threaded apartment. Fortunately, there are alternatives. In the case of **SignalAndWait**, it's rare that you need its queue-jumping semantics: in our rendezvous example, for instance, it would be valid simply to call **Set** on the first wait handle, and then **WaitOne** on the other, if the wait handles were used solely for that rendezvous. In The Barrier Class, we'll explore yet another option for implementing a thread rendezvous.

In the case of **WaitAll**, an alternative in some situations is to use the **Parallel class's Invoke method**, which we'll cover in Part 5. (We'll also cover **Task**s and continuations, and see how **TaskFactory**'s **ContinueWhenAny** provides an alternative to **WaitAny**.)

In all other scenarios, the answer is to take the low-level approach that solves all signaling problems: **Wait and Pulse**.

Synchronization Contexts

An alternative to locking manually is to lock *declaratively*. By deriving from **ContextBoundObject** and applying the **Synchronization** attribute, you instruct the CLR to apply locking automatically. For example:

```
using System;
using System.Threading;
using System.Runtime.Remoting.Contexts;

[Synchronization]
public class AutoLock : ContextBoundObject
{
  public void Demo()
  {
    Console.Write ("Start...");
    Thread.Sleep (1000);           // We can't be preempted here
    Console.WriteLine ("end");     // thanks to automatic locking!
  }
}

public class Test
{
  public static void Main()
  {
    AutoLock safeInstance = new AutoLock();
    new Thread (safeInstance.Demo).Start();     // Call the Demo
    new Thread (safeInstance.Demo).Start();     // method 3 times
    safeInstance.Demo();                        // concurrently.
  }
}
```

```
Start... end
Start... end
Start... end
```

The CLR ensures that only one thread can execute code in **safeInstance** at a time. It does this by creating a single synchronizing object — and locking it around every call to each of **safeInstance**'s methods or properties. The scope of the lock — in this case, the **safeInstance** object — is called a *synchronization context*.

So, how does this work? A clue is in the **Synchronization** attribute's namespace: **System.Runtime.Remoting.Contexts**. A **ContextBoundObject** can be thought of as a "remote" object, meaning all method calls are intercepted. To make this interception possible, when we instantiate **AutoLock**, the CLR actually returns a proxy — an object with the same methods and properties of an **AutoLock** object, which acts as an intermediary. It's via this intermediary that the automatic locking takes place. Overall, the interception adds around a microsecond to each method call.

> Automatic synchronization cannot be used to protect static type members, nor classes not derived from **ContextBoundObject** (for instance, a Windows Form).

The locking is applied internally in the same way. You might expect that the following example will yield the same result as the last:

```
[Synchronization]
public class AutoLock : ContextBoundObject
{
  public void Demo()
  {
    Console.Write ("Start...");
    Thread.Sleep (1000);
    Console.WriteLine ("end");
  }

  public void Test()
  {
    new Thread (Demo).Start();
    new Thread (Demo).Start();
    new Thread (Demo).Start();
    Console.ReadLine();
  }

  public static void Main()
  {
    new AutoLock().Test();
  }
}
```

(Notice that we've sneaked in a **Console.ReadLine** statement). Because only one thread can execute code at a time in an object of this class, the three new threads will remain blocked at the **Demo** method until the **Test** method finishes — which requires the **ReadLine** to complete. Hence we end up with the same result as before, but only after pressing the Enter key. This is a thread-safety hammer almost big enough to preclude any useful multithreading within a class!

Further, we haven't solved a problem described earlier: if **AutoLock** were a collection class, for instance, we'd still require a lock around a statement such as the following, assuming it ran from another class:

```
if (safeInstance.Count > 0) safeInstance.RemoveAt (0);
```

unless this code's class was itself a synchronized **ContextBoundObject**!

A synchronization context can extend beyond the scope of a single object. By default, if a synchronized object is instantiated from within the code of another, both share the same context (in other words, one big lock!) This behavior can be changed by specifying an integer flag in **Synchronization attribute**'s constructor, using one of the constants defined in the **SynchronizationAttribute** class:

Constant	Meaning
NOT_SUPPORTED	Equivalent to not using the Synchronized attribute
SUPPORTED	Joins the existing synchronization context if instantiated from another synchronized object, otherwise remains unsynchronized
REQUIRED (default)	Joins the existing synchronization context if instantiated from another synchronized object, otherwise creates a new context
REQUIRES_NEW	Always creates a new synchronization context

So, if object of class **SynchronizedA** instantiates an object of class **SynchronizedB**, they'll be given separate synchronization contexts if **SynchronizedB** is declared as follows:

```
[Synchronization (SynchronizationAttribute.REQUIRES_NEW)]
public class SynchronizedB : ContextBoundObject { ...
```

The bigger the scope of a synchronization context, the easier it is to manage, but the less the opportunity for useful concurrency. At the other end of the scale, separate synchronization contexts invite deadlocks. For example:

```
[Synchronization]
public class Deadlock : ContextBoundObject
{
  public DeadLock Other;
  public void Demo() { Thread.Sleep (1000); Other.Hello(); }
  void Hello()       { Console.WriteLine ("hello");        }
}

public class Test
{
  static void Main()
  {
    Deadlock dead1 = new Deadlock();
```

```
    Deadlock dead2 = new Deadlock();
    dead1.Other = dead2;
    dead2.Other = dead1;
    new Thread (dead1.Demo).Start();
    dead2.Demo();
  }
}
```

Because each instance of **Deadlock** is created within **Test** — an unsynchronized class — each instance will get its own synchronization context, and hence, its own lock. When the two objects call upon each other, it doesn't take long for the deadlock to occur (one second, to be precise!) The problem would be particularly insidious if the **Deadlock** and **Test** classes were written by different programming teams. It may be unreasonable to expect those responsible for the **Test** class to be even aware of their transgression, let alone know how to go about resolving it. This is in contrast to explicit locks, where deadlocks are usually more obvious.

Reentrancy

A thread-safe method is sometimes called reentrant, because it can be preempted part way through its execution, and then called again on another thread without ill effect. In a general sense, the terms thread-safe and reentrant are considered either synonymous or closely related.

Reentrancy, however, has another more sinister connotation in automatic locking regimes. If the **Synchronization** attribute is applied with the **reentrant** argument true:

```
[Synchronization(true)]
```

then the synchronization context's lock will be temporarily released when execution leaves the context. In the previous example, this would prevent the deadlock from occurring; obviously desirable. However, a side effect is that during this interim, any thread is free to call any method on the original object ("re-entering" the synchronization context) and unleashing the very complications of multithreading one is trying to avoid in the first place. This is the problem of reentrancy.

> Because **[Synchronization(true)]** is applied at a class-level, this attribute turns every out-of-context method call made by the class into a Trojan for reentrancy.

While reentrancy can be dangerous, there are sometimes few other options. For instance, suppose one was to implement multithreading internally within a synchronized class, by delegating the logic to workers running objects in separate contexts. These workers may be unreasonably hindered in communicating with each other or the original object without reentrancy.

This highlights a fundamental weakness with automatic synchronization: the extensive scope over which locking is applied can actually manufacture difficulties that may never have otherwise arisen. These difficulties — deadlocking, reentrancy, and emasculated concurrency — can make manual locking more palatable in anything other than simple scenarios.

<< Part 1   Part 3 >>

***Threading in C#* is from Chapters 21 and 22 of C# 4.0 in a Nutshell.**