ETH Zürich
Chair of Software Engineering

Java and C# in depth

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C#: concurrency

Outline

- C# threads
  - thread implementation
  - sleep and join
  - threads that return values
- Thread synchronization
  - implicit locks and synchronized blocks
  - producer/consumer example
- More efficient concurrency
  - thread pools
  - atomic integers
- Other concurrency models
  - asynchronous programming
  - polyphonic C#

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C# threads

C# threads

C#’ s concurrency model is based on threads

Threads are created by instantiating class **`Thread`**

- The constructor takes a **`ThreadStart delegate`** that wraps the method which the thread will execute

Any method can be called with the delegate mechanism

- Unlike Java, any existing class can be used for multi-threaded execution without modifications

In all the examples, assume

```
using System; using System.Threading;
```

A simple class (to be threaded)

```
public class DumbClass {

    private String id;

    public DumbClass(String id) {
          this.id = id;
    }

    public void print_id() {
        // do something
        Console.WriteLine("This is " + id);
    }
}
```

Creating and starting a thread

Create the object with the method the thread will execute

```
DumbClass db = new DumbClass("db");
```

Create a `Thread` object and pass method `print_id` to is using a `ThreadStart` delegate

```
Thread mt = new Thread(
                new ThreadStart(db.print_id));
```

Start the thread

```
mt.Start();
```

Optionally, wait for it to terminate

```
mt.Join();  // wait until mt terminates
    Console.WriteLine(
                "The thread has terminated");
```

Putting a thread to sleep

The `Sleep(int t)` `static` method suspends the thread in which it is invoked for `t` milliseconds

```
Thread.Sleep(2000); // suspend for 2 seconds
```

- the timing may be more or less precise according to the real-time guarantees of the executing environment

Threads that return values

Threads can return values using additional delegates

- E.g., to have threads that return strings declare a delegate type:

```
public delegate void delForStrings(String s);
```

- A class stores a reference to the delegate and activates it when appropriate (to pass values to the caller)

```
public class DullClass {
  private String id;
  // delegate used to return a value when terminating
  private delForStrings d;
  // the constructor must bind the actual method
  public DullClass(String id, delForStrings d)
       { this.id = id;  this.d = d; }
  public void give_id() {
       // call the delegate to return the value id
       if (d != null) { d(id); }
  }}
```

Creating threads that return values

Define a method to process the information returned by the thread (its signature matches the delegate's)

- for simplicity, we make it static

```
public static void printValueSent(String
s)  {
    Console.WriteLine("The thread sent: " + s);
 }
```

Create the object with the method the thread will execute and pass the delegate to it

```
DullClass d1 = new DullClass("d1",
        new delForString(printValueSent));
```

Creating threads that return values

Create a **`Thread`** object and pass method **`give_id`** to is using a **`ThreadStart`** delegate

```
Thread t = new Thread(
                new ThreadStart(dl.give_id));
```

Start the thread

```
t.Start();
```

After executing, it will invoke **`printValueSent`** through the delegate, which will print the given **`id`**

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Thread synchronization

Synchronization with locks

The `lock` statement supports synchronization based on locks

- blocks of statements guarded by `lock(o)`
- the lock `o` itself can be any object (including `this`)
- locking/unlocking is implicit when entering/exiting the block
- useful to define critical regions and fine-grained synchronization
- monitors are implemented by locking the whole method body on `this`

Synchronization with locks

The `lock` statement supports synchronization based on locks

```
// s must be accessed in mutual exclusion
private int s;

// dict is a read-only object, no concurrency problems
private List<String> dict;

public String decrement_and_lookup() {
      // critical region
  lock(this) { if (s > 0) { s = s - 1; } }
      // non-critical region
  return dict.Item(s);
}
```

Coordination with signals

Locked threads can communicate with signals, implemented as static methods of class **`Monitor`**:

- **`Monitor.Wait(o)`**: suspend and release the lock on **`o`** until some thread does a **`Pulse(o)`** or **`PulseAll(o)`**
- **`Monitor.Pulse(o)`**: resume one suspended thread (chosen nondeterministically) waiting on object **`o`**, which becomes ready for execution when possible
- **`Monitor.PulseAll(o)`**: resume all suspended threads waiting on object **`o`**, which become ready for execution when possible

- Analogues of Java's **`wait`**, **`notify`**, **`notifyAll`**

Coordination with events

A more fine-grained (and possibly efficient) coordination uses services of the **`WaitHandle`** class to coordinate threads

Coordination events are in one of two states: signaled and unsignaled

- Method **`Set`** puts an event in the signaled state
  - that is, it issues the signal
- Method **`Reset`** puts an event in the unsignaled state
  - that is, it cancels the signal

Coordination with events

A more fine-grained (and possibly efficient) coordination uses services of the **`WaitHandle`** class to coordinate threads

Two main classes implement coordination events

- **`AutoResetEvent`**
  - automatically resets to unsignaled after being received by one of the waiting threads
- **`ManualResetEvent`**
  - does not automatically reset, hence it can be received by more than one waiting thread
  - can be reset with method **`Reset()`**

Coordination with events

Use services of the **`WaitHandle`** class to coordinate threads

A thread can block waiting for an event using some methods of the class

- **`WaitHandle.WaitOne()`** waits for the event to be signaled (and blocks until then)
- **`static WaitHandle.WaitAny(WaitHandle[] e)`** waits for any of the events in array **`e`**.
  - The method returns when an event is received
  - It returns an integer **`i`**, which is an index within array **`e`**
  - **`e[i]`** is the event that has been received
- **`static WaitHandle.WaitAll(WaitHandle[] e)`** waits for all the events in array **`e`** to be signaled.

Unlike **`Monitor.Wait`**, if these wait primitives occur in a **`lock`** block they do not release the lock while waiting.

The producer-consumer problem

Two threads, the Producer and the Consumer, work concurrently on a shared Buffer of bounded size

The Producer puts new messages in the buffer

- if the buffer is full, the Producer must wait until the Consumer takes some messages
- the Producer also signals the last message

The Consumer takes messages from the buffer

- if the buffer is empty, the Consumer must wait until the Producer puts some new messages
- the Consumer terminates after the last message

Consistent access to the Buffer requires locks and synchronization

One way is to define critical regions when accessing the buffer data structure (with `lock`) and signal events

The main class

```
public class ProducerConsumer {

    public static void main(String[] args) {
        // create a synchronizer object
        Synchronizer s = new Synchronizer();
        // create a buffer of size 3
        Buffer b = new Buffer(3, s);
        // create producer and consumer
        Producer p = new Producer(b, s);
        Consumer c = new Consumer(b, s);
        // instantiate threads
        Thread pT = new Thread(p.produce);
        Thread cT = new Thread(c.consume);
        // start them
        pT.Start();  cT.Start();
}
```

Events for synchronization (1/2)

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

public class Synchronizer {
   private EventWaitHandle takeEvent;
   public EventWaitHandle TakeEvent
                  { get { return takeEvent; } }

   private EventWaitHandle giveEvent;
   public EventWaitHandle GiveEvent
                  { get { return giveEvent; } }

   private EventWaitHandle endEvent;
   public EventWaitHandle EndEvent
                  { get { return endEvent; } }
```

Events for synchronization (2/2)

```
  public Synchronizer() {
              // events initialized to unsignaled state
    takeEvent = new AutoResetEvent(false);
    giveEvent = new AutoResetEvent(false);
    endEvent = new ManualResetEvent(false);
  }
}
```

- **`takeEvent`** is an **`AutoResetEvent`** so it is received by exactly one waiting thread among all those waiting for a take to happen.
- **`giveEvent`** is an **`AutoResetEvent`** so it is received by exactly one waiting thread among all those waiting for a give to happen.
- **`endEvent`** is a **`ManualResetEvent`** so it is received by all waiting threads: they will all be notified that they can terminate.

The shared Buffer (1/3)

```
public class Buffer {

    public Buffer(int max_size, Synchronizer s) {
        this.max_size = max_size;
        this.messages = new Queue<String>();
        this.s = s;
    }
    // buffer of messages, managed as a queue
    private Queue<String> messages;
    // maximum number of elements in the buffer
    private int max_size;
    // reference to events for synchronization
    private Synchronizer s;
```

The shared Buffer (2/3)

```
public String take() {
    if (messages.Count == 0) {
        // only one thread receives the event
        WaitHandle.WaitAny(
            // wait until a give occurs
            new WaitHandle[] {s.GiveEvent});
    }
    // now the buffer is not empty
    lock(this) {
        m = messages.Dequeue();
    }
    // signal that a take has occurred
    s.TakeEvent.Set();
    return m;
}
```

The shared Buffer (3/3)

```
public void give(String msg) {
    if (messages.Count == max_size) {
        // only one thread receives the event
        WaitHandle.WaitAny(
            // wait until a take occurs
            new WaitHandle[] {s.TakeEvent});
    }
    // now the buffer has at least an available slot
    lock(this) {
        messages.Enqueue(msg);
    }
    // signal that a give has occurred
    s.GiveEvent.Set();
}
}
```

The Producer (1/2)

```
public class Producer {

  // a reference to the shared buffer
  private Buffer b;

  // events to synchronize on
  private Synchronizer s;

  // set the reference to the buffer and synchronizer
  public Producer(Buffer b, Synchronizer s) {
   this.b = b;
   this.s = s;
  }
```

The Producer (2/2)

```
public void produce() {

    // work for 20 turns
    for (int i = 0; i < 20; i++) {
        // put a message in the buffer
        b.give(i.ToString());
    }
    // signal that production has ended
    s.EndEvent.Set();
}

}
```

The Consumer (1/2)

```
public class Consumer {

  // a reference to the shared buffer
  private Buffer b;

  // events to synchronize on
  private Synchronizer s;

  // set the reference to the buffer and synchronizer
  public Producer(Buffer b, Synchronizer s) {
      this.b = b;
      this.s = s;
  }
```

The Consumer (2/2)

```
    public void consume() {
        // loop as new events arrive, until:
        //          EndEvent is signaled AND b is empty
        while ( WaitHandle.WaitAny( new WaitHandle[]
                    {s.GiveEvent, s.EndEvent}) != 1
                  || !b.Empty ) {
               string m = b.take();
               Console.WriteLine(
                 "Consumer has consumed message " + m );
        }
    }

}
```

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More efficient concurrency

Concurrency and performance

Thread creation is time-consuming

- massive thread creation can annihilate responsiveness
- C#' s solution: thread pools

Lower-level primitives are available

- `Mutex` class for mutexes
  - less efficient than monitors and `lock` (unlike Java)
- `Interlocked` `static` class
  - atomic operations on integers

Tip: don' t forget the efficiency/abstraction trade-off

Thread pools

Thread pools are an efficient way of running multi-threaded applications

- maintain a pool of worker threads
- when a client requests a new task to run, preempt one of the available worker threads and assign it to the task
- no creation overhead upon task invocation

C#'s static class **`System.Threading.ThreadPool`**

- **`QueueUserWorkItem(WaitCallback w,Object o)`**: schedule delegate **`w`** for execution by a worker thread, when possible; **`o`** is passed as argument to **`w`**.

Thread pool thread creation

Create a wrapper delegate for each method to be threaded

- In the Producer/Consumer example:

```
public static void Main(string[] args) {
        Producer p = new Producer(b, s);
        Consumer c = new Consumer(b, s);
        ThreadPool.QueueUserWorkItem(new
                        WaitCallback(consuming), c);
        ThreadPool.QueueUserWorkItem(new
                        WaitCallback(producing), p);
 }
public static void consuming(object o)
{ ((Consumer) o).consume(); }
public static void producing(object o)
{ ((Producer) o).produce(); }
```

There's an undesirable side-effect with this code as is. What is it?

Thread pool thread creation

Create a wrapper delegate for each method to be threaded

- In the Producer/Consumer example:

```
public static void Main(string[] args) {
        Producer p = new Producer(b, s);
        Consumer c = new Consumer(b, s);
        ThreadPool.QueueUserWorkItem(new
                        WaitCallback(consuming), c);
        ThreadPool.QueueUserWorkItem(new
                        WaitCallback(producing), p);
}
```

There's an undesirable side-effect with this code as is. What is it?

- `Main` terminates after invoking `QueueUserWorkItem`; hence the `ThreadPool` object is deallocated and the worker threads forcefully terminated!

`Interlocked` class

C#' s implementation of atomic operations on integers

```
// shared variable
int s;

...
// this is equivalent to an atomic s++
Interlocked.Increment(ref s);
...
// this is equivalent to an atomic s--
Interlocked.Decrement(ref s);
```

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Other concurrency models: Asynchronous programming

Concurrency and correctness

Programming thread-safe data structures is error-prone

- Thread-safe collections are available since C# 4.0
- Current collections provide a `SyncRoot` object for synchronization

Threads and monitors are too general for straightforward parallel computation

- C#'s solution: asynchronous methods

Tip: don't forget the efficiency/abstraction trade-off

Asynchronous programming

C# 5.0 introduced simple mechanisms to have methods execute asynchronously and wait for one another.

The model is based on asynchronous methods:

```
async Task<T> DoAsync()
```

- `DoAsync` may execute asynchronously from its clients
- In turn, its clients can wait for `DoAsync`'s to complete (and only then access its result).

(The class `Task` can also be used independent of asynchronous methods, mostly to introduce forms of data-bound parallelism.)

Asynchronous methods

```
async Task<T> DoAsync()
```

Asynchronous methods:

- Are declared as such with the keyword `async`
- Can have only specific return types:
  - `Task<T>` for methods returning values of type `T`
  - `Task` for methods returning no values
  - `void` for methods returning no values used as event handlers
- Cannot have `ref` or `out` arguments (there's no way to "wait" for those)
- By convention, have name ending in "`Async`"
- Can wait for other asynchronous methods to complete using the `await` instruction in their bodies.

Waiting

```
async Task<T> DoAsync()
```

When an asynchronous method `DoAsync` executes an `await`:

- Control may return to the caller (the compiler/runtime decides if a context switch is worth the cost)
- The caller will be able to retrieve the result later when available, after `await`ing
- No new thread is created: the asynchronous computation uses the thread executing `DoAsync`

The result obtained when `await`ing for an asynchronous method with return type `Task<T>` has type `T`.

Asynchronous programming: example

Write a method **`AvgAgesAsync`** that computes the average age of the population of several cities.

The data for each city is accessible remotely using a library method:

```
async Task<List<int>> GetAgesAsync(String city)
```

A call return a list of ages, one for each person of the city.

Calls to **`AvgAgesAsync`** may take time, but can be executed asynchronously:

1. First, the client start the asynchronous computation:

   ```
   Task<double> t = AvgAgesAsync(listOfCities);
   ```

2. Now, the client can do other stuff while **`AvgAgesAsync`** executes in parallel.
3. Eventually, the client will get the final results with a call:

   ```
   double avg = await t;
   ```

Asynchronous programming: example

```
async Task<double> AvgAgesAsync (List<String> cities)
{
   int i = 0, pop = 0; double avg = 0;
   foreach (String c in cities) {
      // wait for results from GetAgesAsync
      // (but AvgAgesAsync's caller needn't block)
      List<int> v = await GetAgesAsync(c);
      avg =     // new average, from old one
         ((avg*pop) + v.Sum()) / (pop + v.Count);
      pop += v.Count; // new total population
      i++; // one more city done
      Console.WriteLine(
        "Done {0}% of cities. Current average: {1}",
             (i/cities.Count*100), avg);
   } return avg;
}
```

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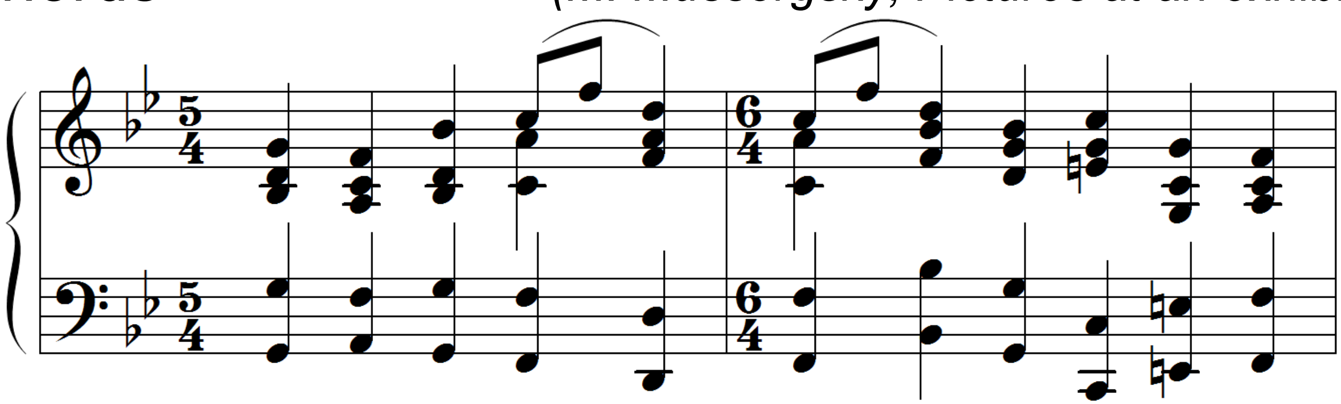
Other concurrency models: Polyphonic C#

Introducing Polyphonic C#

- Polyphonic C# is an extension of C# with a few high-level primitives for concurrency
  - not part of .NET framework
  - based on join calculus (Fournet & Gonthier, 1996)
  - taken up by Microsoft's Cω project
  - JoinJava is a similar extension for Java
- Based on two basic notions
  - Asynchronous methods
  - Chords

(M. Mussorgsky, Pictures at an exhibition)



Polyphonic asynchronous methods

Calls to asynchronous methods return immediately without returning any result

- The callee is scheduled for execution in a different thread
- similar to sending a message or raising an event
- declared using **`async`** keyword instead of **`void`**

```
public async startComputation () {
  // computation
}
```

- asynchronous methods do not return any value and cannot have **`ref`** or **`out`** arguments

Chords: syntax

A chord is an extension of the notion of method definition

- The signature of a chord is a collection of (traditional) method declarations joined by **&**
- The body of a chord is all similar to the body of a traditional method

```
public int get() & public async put(int i) {
    return i;
}
```

- Within a chord:
  - at most one method can be non-asynchronous
- Within a class:
  - the same method can appear in more than one chord
- (We do not discuss additional rules for inheritance and overloading)

Chords: semantics

A chord is only executed once all the methods in its signature have been called

- Calls are buffered until there is a matching chord
  - the implicit buffer supports complex synchronization patterns with little code (see Producer/Consumer later)

- If multiple matches are possible, nondeterminism applies

- Execution returns a value to the only non-asynchronous method in the chord (if any)

Chords semantics: example

```
public class Buffer() {
   public int get() & public async put(int i)
       { return i; }
}
...
Buffer b = new Buffer();
b.put(“okey”)
Console.WriteLine(b.get());     // prints “okey”
b.put(“okey”); b.put(“dokey”);
   // prints “okeydokey” or “dokeyokey”
Console.WriteLine(b.get() + b.get());
b.get();    // blocks until some other thread calls put
```

Producer/Consumer with chords (1/3)

```
public class Buffer {

  public void give(String s) & async available(int a) {
      if (a == 1) {
  // just one slot available and giving: become full
          full();
      } else {
  // more than one slot available and giving:
  // enable more giving
          available(a - 1);
      }
  // buffer message for takes
      inBuffer(s);
  }
```

Producer/Consumer with chords (2/3)

```
public String take() & async inBuffer(String s) &
                      async full() {
    // full and taking: one slot becomes available
    available(1);
    // return message in queue
    return s;
}

public String take() & async inBuffer(String s) &
                      async available(int a) {
    // not full: one more slot becomes available
    available(a + 1);
    // return message in queue
    return s;
}
```

Producer/Consumer with chords (3/3)

```
    // constructor
    public Buffer(int capacity) {
        available(capacity);
    }

}
```

Note: unlike in the examples we developed with locks, here there is no guarantee of ordered retrieval because any message in the implicit buffer can be retrieved at any time