Parallel Programming in C#

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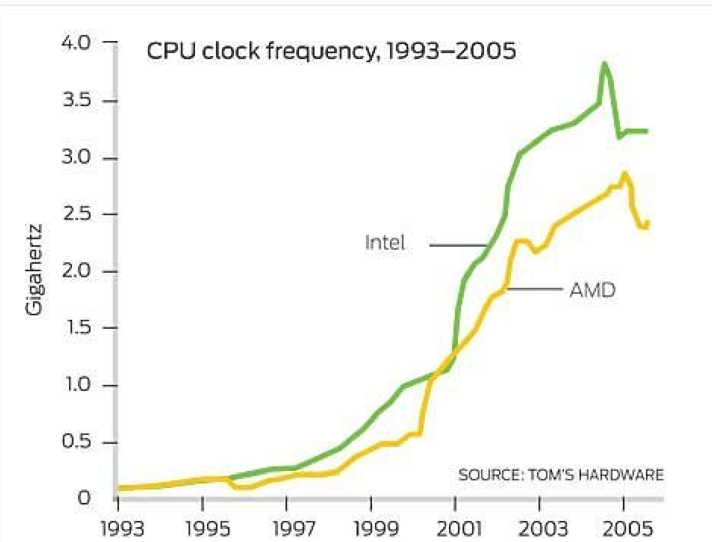
Computers are always too slow!

Clock Rates



The Free Lunch is over!

- **Don't expect your sequential program to run faster on new processors**
- **Still, processor technology advances**
- **BUT the focus now is on *multiple cores per chip***
- **Today's desktops typically have 4 cores.**
- **Latest experimental multi-core chips have up to 1,000 cores[1].**

[1] See *"World's First 1,000-Processor Chip"*, University of California, Davis, June 2016

Options for Parallel Programming in C#

C# provides several mechanisms for par. programming:
Explicit threads with synchronisation via locks, critical regions etc.

- The user gets full control over the parallel code.
- *BUT* orchestrating the parallel threads is tricky and error prone (race conditions, deadlocks etc)
- This technique requires a *shared-memory model*.

Explicit threads with a message-passing library:

- Threads communicate by explicitly sending messages, with data required/produced, between workstations.
- Parallel code can run on a *distributed-memory architecture*, eg. a network of workstations.
- The programmer has to write code for (un-)serialising the data that is sent between machines.
- *BUT* threads are still explicit, and the difficulties in orchestrating the threads are the same.
- A common configuration is C+MPI.

OpenMP provides a standardised set of program annotations

Types of Parallelism in C#

C# supports two main models of parallelism:

- *Data parallelism:* where an operation is applied to each element in a collection.
- *Task parallelism:* where independent computations are executed in parallel.

Parallel Loops in C#

A sequential `for` loop in C#:

```
int n = ...
for (int i = 0; i<=n; i++)
{
  // ...
});
```


parallel performance.

Parallel Loops in C#

A parallel `for` loop in C#:

```
int n = ...
Parallel.For(0, n, i =>
{
  // ...
});
```

- The *language construct* `for` is translated into a (higher-order) function *Parallel.For*.
- The argument to Parallel.For is an *anonymous method*, specifying the code to be performed in each loop iteration.
- The arguments to this anonymous method are the start value, the end value and the iteration variable.

A Simple Example

We can limit the degree of parallelism like this:

```
var options = new ParallelOptions() {
               MaxDegreeOfParallelism = 2 };
Parallel.For(0, n, options, i =>
 {
  fibs[i] = Fib(i);
 });
```


Terminating a Parallel Loop

Parallel loops have two ways to break or stop a loop instead of just one.

- Parallel break, *loopState.Break()*, allows all steps with indices lower than the break index to run before terminating the loop.
- Parallel stop, *loopState.Stop()*, terminates the loop without allowing any new steps to begin.

Parallel Aggregates

- The *parallel aggregate* pattern combines data parallelism over a collection, with the aggregation of the result values to an overall result.
- It is parameterised both over the operation on each element as well as the combination (aggregation) of the partial results to an overall results.
- This is a very powerful pattern, and it has become famous as the *Google MapReduce* pattern.

An Example of Parallel Aggregates

```
var options = new ParallelOptions() {
                MaxDegreeOfParallelism = k};
Parallel.ForEach(seq /* sequence */, options,
                () => 0,  // The local initial partial result
                // The loop body
                (x, loopState, partialResult) =>  {
                   return Fib(x) + partialResult; },
                // The final step of each local context
                (localPartialSum) => {
                   // Protect access to shared result
                   lock (lockObject)
                     {
                       sum += localPartialSum;
                     }
                });
```

Discussion

- The *ForEach* loop iterates over all elements of a sequence *in parallel*.
- Its arguments are:
  - A *sequence* to iterate over;
  - *options* to control the parallelism (optional);
  - a delegate initialising the result value;
  - a delegate specifying the operation on each element of the sequence;
  - a delegate specifying how to combine the partial results;
- To protect access to the variable holding the overall result, a *lock* has to be used.

Another Example of Parallel Aggregates

```
int size = seq.Count / k;  // make a partition large enough to feed k cor
var rangePartitioner = Partitioner.Create(0, seq.Count, size);
Parallel.ForEach(
  rangePartitioner, () => 0, // The local initial partial result
  // The loop body for each interval
  (range, loopState, initialValue) => {
    // a *sequential* loop to increas the granularity of the parallelism
    int partialSum = initialValue;
    for (int i = range.Item1; i < range.Item2; i++) {
      partialSum += Fib(seq[i]);
    }
    return partialSum; },
  // The final step of each local context
  (localPartialSum) => {
    // Use lock to enforce serial access to shared result
    lock (lockObject) {
      sum += localPartialSum;
    }
   });
```


Discussion

- A *Partitioner* (`System.Collections.Concurrent`) is used to split the entire range into sub-ranges.
- Each call to the partitioner returns an index-pair, specifying a sub-range.
- Each task now works on such a sub-range, using a sequential `for` loop.
- This reduces the overhead of parallelism and can improve performance.

Task Parallelism in C#

- When independent computations are started in different tasks, we use a model of *task parallelism*.
- This model is more general than data parallelism, but requires more detailed control of synchronisation and communication.
- The most basic construct for task parallelism is:

  `Parallel.Invoke(DoLeft, DoRight);`
- It executes the methods `DoLeft` and `DoRight` in parallel, and waits for both of them to finish.

Example of Task Parallelism

The following code sorts 2 lists in parallel, providing a comparison operation as an argument:

```
Parallel.Invoke( // generate two parallel threads
                 () => ic1.Sort(cmp_int_lt),
                 () => ic2.Sort(cmp_int_gt));
```


Implementation of Task Parallelism

- The implementation of *Invoke* uses the more basic constructs
  - *StartNew*, for starting a computation;
  - *Wait*, *WaitAll*, *WaitAny*, for synchronising several computations.
- Any shared data structure needs to be protected with locks, semaphores or such.
- Programming on this level is similar to explicitly managing threads:
  - it can be more efficient but
  - it is error-prone.

Task Parallelism in C#

- Sometimes we want to start several computations, but need only one result value.
- As soon as the first computation finishes, all other computations can be aborted.
- This is a case of *speculative parallelism*.
- The following construct executes the methods `DoLeft` and `DoRight` in parallel, waits for *the first task* to finish, and cancels the other, still running, task:

  ```
  Parallel.SpeculativeInvoke(DoLeft, DoRight);
  ```


Futures

- A *future* is variable, whose result may be evaluated by a parallel thread.
- Synchronisation on a future is implicit, depending on the evaluation state of the future upon read:
  - If it has been evaluated, its value is returned;
  - if it is under evaluation by another task, the reader task blocks on the future;
  - if evaluation has not started, yet, the reader task will evaluate the future itself
- The main benefits of futures are:
  - Implicit synchronisation;
  - automatic inlining of unnecessary parallelism;
  - asynchronous evaluation
- Continuation tasks can be used to build a chain of tasks, controlled by futures.

Example: Sequential Code

```
private static int seq_code(int a) {
 int b = F1(a);
 int c = F2(a);
 int d = F3(c);
 int f = F4(b, d);
 return f;
}
```


Example: Parallel Code with Futures

```
private static int par_code(int a) {
 // constructing a future generates potential parallelism
 Task<int> futureB = Task.Factory.StartNew<int>(() => F1(a));
 int c = F2(a);
 int d = F3(c);
 int f = F4(futureB.Result, d);
 return f;
}
```


Divide-and-Conquer Parallelism

- **Divide-and-Conquer is a common (sequential) pattern:**
  - **If the problem is atomic, solve it directly;**
  - **otherwise the problem is *divided* into a sequence of sub-problems;**
  - **each sub-problem is solved recursively by the pattern;**
  - **the results are *combined* into an overall solution.**

Recall: Binary Search Trees

```
public class Node<T> where T:IComparable {
     // private member fields
     private T data;
     private Node<T> left;
     private Node<T> right;

     // properties accessing fields
     public T Value { get { return data;  }
                      set { data = value; } }
     public Node<T> Left { get { return this.left;  }
                           set { this.left = value; } }
     public Node<T> Right { get { return this.right;  }
                            set { this.right = value; } }
```

Example: Parallel Tree Mapper

```
public delegate T TreeMapperDelegate(T t);

public static void ParMapTree(TreeMapperDelegate f,
                              Node<T> node) {
if (node==null) { return ; }

node.Value = f(node.Value);
var t1 = Task.Factory.StartNew(() =>
               ParMapTree(f, node.Left));
var t2 = Task.Factory.StartNew(() =>
               ParMapTree(f, node.Right));
Task.WaitAll(t1, t2);
}
```


Example: Sorting

```
static void SequentialQuickSort(int[] array, int from, int to) {
   if (to - from <= Threshold)   {
     InsertionSort(array, from, to);
   } else {
     int pivot = from + (to - from) / 2;
     pivot = Partition(array, from, to, pivot);
     SequentialQuickSort(array, from, pivot - 1);
     SequentialQuickSort(array, pivot + 1, to);
   }
 }
```


Example: Parallel Quicksort

```
static void ParallelQuickSort(int[] array, int from,
                              int to, int depthRemaining) {
  if (to - from <= Threshold) {
    InsertionSort(array, from, to);
  } else {
    int pivot = from + (to - from) / 2;
    pivot = Partition(array, from, to, pivot);
    if (depthRemaining > 0) {
      Parallel.Invoke(
        () => ParallelQuickSort(array, from, pivot - 1,
                                depthRemaining - 1),
        () => ParallelQuickSort(array, pivot + 1, to,
                                depthRemaining - 1));
    } else {
      ParallelQuickSort(array, from, pivot - 1, 0);
      ParallelQuickSort(array, pivot + 1, to, 0);
    }
  }
}
```


Example: Partition (Argh)

```
private static int Partition(int[] array, int from, int to, int pivot) {
 // requires: 0 <= from <= pivot <= to <= array.Length-1
 int last_pivot = -1;
 int pivot_val = array[pivot];
 if (from<0 || to>array.Length-1) {
   throw new System.Exception(String.Format("Partition: indices out of bounds: from={0}, to={1}, Length={2}",
                                            from, to, array.Length));
 }
 while (from<to) {
  if (array[from] > pivot_val) {
    Swap(array, from, to);
    to--;
  } else {
    if (array[from]==pivot_val) {
      last_pivot = from;
    }
    from++;
  }
 }
 if (last_pivot == -1) {
   if (array[from]==pivot_val) {
     return from;
   } else {
     throw new System.Exception(String.Format("Partition: pivot element not found in array"));
   }
 }
 if (array[from]>pivot_val) {
   // bring pivot element to end of lower half
   Swap(array, last_pivot, from-1);
   return from-1;
 } else {
  // done, bring pivot element to end of lower half
  Swap(array, last_pivot, from);
```

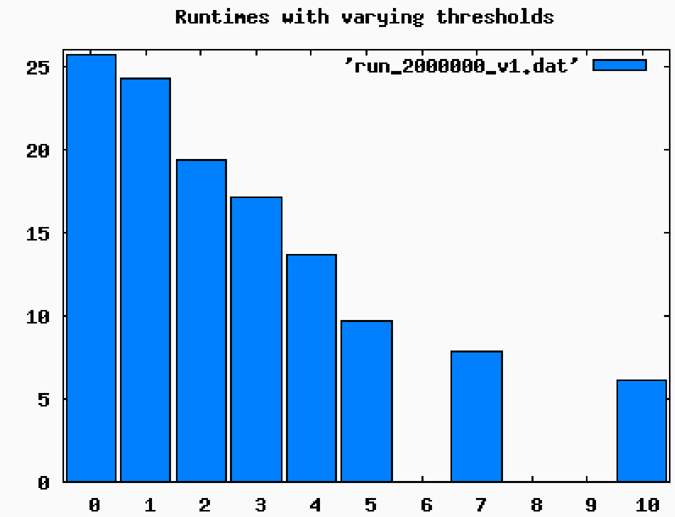


```
 }
```

Discussion

- **An explicit threshold is used to limit the amount of parallelism that is generated (*throttling*).**
- **This parallelism threshold is not to be confused with the sequential threshold to pick the appropriate sorting algorithm.**
- **Here the divide step is cheap, but the combine step is expensive; don't expect good parallelism from this implementation!**

Performance of Parallel QuickSort



A Comparison: QuickSort in Haskell

```
quicksort :: (Ord a, NFData a) => [a] -> [a]
quicksort [] = []
quicksort [x] = [x]
quicksort (x:xs) = (left ++ (x:right))
        where
        left = quicksort [ y | y <- xs, y < x]
        right = quicksort [ y | y <- xs, y >= x]
```


A Comparison: QuickSort in Haskell

```
quicksort :: (Ord a, NFData a) => [a] -> [a]
quicksort [] = []
quicksort [x] = [x]
quicksort (x:xs) = (left ++ (x:right)) `using` strategy
        where
        left = quicksort [ y | y <- xs, y < x]
        right = quicksort [ y | y <- xs, y >= x]
        strategy result = rnf left `par`
                          rnf right `par`
                          rnf result
```

More on high-level parallel programming next term in F21DP2 "Distributed and Parallel Systems"

Pipelines

- A *pipeline* is a sequence of operations, where the output of the n-th stage becomes input to the $n + 1$-st stage.
- Each stage is typically a large, sequential computation.
- Parallelism is achieved by overlapping the computations of all stages.
- To communicate data between the stages a `BlockingCollection<T>` is used.
- This pattern is useful, if large computations work on many data items.

Pipelines

```
var buffer1 = new BlockingCollection<int>(limit);
var buffer2 = new BlockingCollection<int>(limit);

var f = new TaskFactory(TaskCreationOptions.LongRunning,
                        TaskContinuationOptions.None);
var task1 = f.StartNew(() =>
               Pipeline<int>.Producer(buffer1, m, n, inc));
var task2 = f.StartNew(() =>
               Pipeline<int>.Consumer(
                buffer1,
                new Pipeline<int>.ConsumerDelegate(x => x*x),
                buffer2));
var task3 = f.StartNew(() =>
                { result_str =
                   Pipeline<int>.LastConsumer(buffer2, str);
                });
Task.WaitAll(task1, task2, task3);
```


Pipelines: Producer Code

```
public static void Producer(BlockingCollection<T> output, ... ) {
  ...
  try {
    foreach (T item in ...) {
      output.Add(item);
    }
  } finally {
    output.CompleteAdding();
  }
}
```


Pipelines: Consumer Code

```
public static void Consumer(BlockingCollection<T> input,
                            ConsumerDelegate worker,
                            BlockingCollection<T> output) {
 try {
   foreach (var item in input.GetConsumingEnumerable()) {
      var result = worker(item);
      output.Add(result);
   }
  } finally {
      output.CompleteAdding();
  }
}
```

Selecting the Right Parallel Pattern

Application characteristic	Relevant pattern
Do you have *sequential loops* where there's no communication among the steps of each iteration?	The *Parallel Loop pattern*. Parallel loops apply an independent operation to multiple inputs simultaneously.
Do you need to *summarize data* by applying some kind of combination operator? Do you have loops with steps that are not fully independent?	The *Parallel Aggregation pattern*. Parallel aggregation introduces special steps in the algorithm for merging partial results. This pattern expresses a reduction operation and includes map/reduce as one of its variations.
Do you have *distinct op-*	The *Parallel Task pattern*.

Summary

- The preferred, high-level way of coding parallel computation in C# is through *parallel patterns*, an instance of design patterns.
- Parallel patterns capture common patterns of parallel computation.
- Two main classes of parallelism exist:
  - Data parallelism, which is implemented through parallel For/Foreach loops.
  - Task parallelism, which is implemented through parallel method invocation.
- Tuning the parallel performance often requires code restructuring (eg. thresholding).

Further Reading

Further reading:

- "Parallel Programming with Microsoft .NET — Design Patterns for Decomposition and Coordination on Multicore Architectures", by C. Campbell, R. Johnson, A. Miller, S. Toub. Microsoft Press. August 2010. `http://msdn.microsoft.com/en-us/library/ff963553.aspx`
- "Patterns for Parallel Programming", by T. G. Mattson, B. A. Sanders, and B. L. Massingill. Addison-Wesley, 2004.
- "MapReduce: Simplified Data Processing on Large Clusters", J. Dean and S. Ghemawat. In *OSDI '04 — Symp. on Operating System Design and Implementation*, pages 137–150, 2004. `http://labs.google.com/papers/mapreduce.html`

Does your application	The *Pipelines pattern*.

Advertisment

Next term: F21DP2 "Distributed and Parallel Systems"

In this course we will cover parallel programming in

- C+MPI: threads with explicit message passing
- OpenMP: data and (limited) task parallelism
- parallel Haskell: semi-explicit parallelism in a declarative language

Exercise

Produce a parallel implementation, testing the *"Goldbach conjecture"*:

> *Every even integer greater than 2 can be expressed as the sum of two primes.*

For details see:
`http://en.wikipedia.org/wiki/Goldbach%27s_conjecture`
A sample solution is available from the Sample C# source section of the course page.