Asynchronous and parallel F# 3
&
Asynchronous and parallel C# 4.5

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Agenda

- Why is parallel programming important?
- CPU-bound parallelism in F# 3.0
- I/O-bound parallelism in F# 3.0

- Tasks in .NET 4.0, illustrated with C#
- Asynchronous programming in C# 4.5

Why parallel programming?

- Until 2004, CPUs became faster every year
  - So sequential software became faster every year
- Today, CPUs are still 2-4 GHz as in 2004
  - So sequential software has not become much faster
- Instead, we get
  - Multicore: 2, 4, 8, ... CPUs on a chip
  - Vector instructions (4 x MAC) built into CPUs
  - Superfast Graphics Processing Units (GPU)
    - 96 simple CUDA codes in this 2009 laptop
    - 448 simple but fast CUDA cores in Nvidia Tesla co-processor
    - 1536 simple (single-precision) CUDA cores in Nvidia Kepler
- Herb Sutter: *The free lunch is over (2005)*
- More speed requires **parallel programming**
  - But parallel programming is **difficult** and **errorprone**
  - ... with existing means: threads, synchronization, ...

Why *functional* parallel programming?

- What is the purpose of synchronization?
  - To avoid conflicting **updates** of **shared data**
- Functional programming
  - **No** updates to shared data
  - Instead: copying, partial sharing, intermediate data structures, message passing, agents, ...
- Some consensus this is the way forward
  - Even in the press: Economist, 2 June 2011 http://www.economist.com/node/18750706
  - Hiperfit project, www.hiperfit.dk
  - Actulus project, www.actulus.dk

Nvidia's chief scientist says...

Making it easy to program a machine that requires 10 billion threads to use at full capacity is also a challenge.

While a backward compatible path will be provided to allow existing MPI codes to run, MPI plus C++ or Fortran is not a productive programming environment for a machine of this scale.

We need to move toward **higher-level programming models** where the programmer **describes the algorithm with all available parallelism and locality exposed**, and tools automate much of the process of efficiently mapping and tuning the program to a particular target machine.

Bill Dally in HPC Wire, 15 April 2013

CPU-bound parallel programming in F#

- A slow, CPU-consuming operation:

```
let rec slowfib n =
    if n<2 then 1.0 else slowfib(n-1) + slowfib(n-2);;
```

```
let fib40 = slowfib(40);;
// Real: 00:00:02.634, CPU: 00:00:02.634
```

F# 3.0.0.0
Mono 3.2.7
MacOS 10.6.8
Core 2 Duo

- Computing two Fibonacci numbers:

```
let fibs = [ slowfib(39); slowfib(40) ];;
// Real: 00:00:04.263, CPU: 00:00:04.264
```

- Doing it in parallel, F# 3.0

Two CPUs

```
let fibs =
    let tasks = [ async { return slowfib(39) };
                  async { return slowfib(40) } ]
    Async.RunSynchronously (Async.Parallel tasks);;
// Real: 00:00:02.657, CPU: 00:00:04.260
```

More CPU-bound parallel programming in F#

- Computing 41 Fibonacci numbers:

```
let fibs = [ for i in 0..40 -> slowfib(i) ];;
// Real: 00:00:06.908, CPU: 00:00:06.908
```

Same as "do yield"

- Doing it in parallel:

```
let fibs =
    let tasks = [ for i in 0..40 -> async { return slowfib(i) } ]
    Async.RunSynchronously (Async.Parallel tasks);;
// Real: 00:00:03.665, CPU: 00:00:06.887
```

Dissecting the example

```
let tasks = [ for i in 0..40 -> async { return slowfib(i) } ]
Async.RunSynchronously (Async.Parallel tasks);;
```

```
async { return slowfib(i) }
```

`Async<float>`

An asynchronous task that will produce a **`float`**

```
let tasks =
    [ for i in 0..40 -> async { return slowfib(i) } ]
```

`Async<float> list`

List of asynchronous tasks that each will produce a **`float`**

```
Async.Parallel tasks
```

`Async<float []>`

An asynchronous task that will produce a **`float`** array

```
Async.RunSynchronously (Async.Parallel tasks)
```

`float []`

A **`float`** array

Asynchronous operations in F#

- An **`async { ... }`** expression produces an asynchronous task, Async<t>
- When **`return e`** inside where **`e`** has type t
- **`let! res = e`** will run **`e`** and bind the result to **`res`** of type u, when **`e`** has type Async<u>
- Async.RunSynchronously(**`asy`**) will run computation **`asy`** and wait for its completion
- Async.Parallel(**`asys`**) creates a new asynchronous task that will run all **`asys`** and return an array of their results

Finding prime factors

- Prime factors of a number

```
factors 973475;;
val it : int list = [5; 5; 23; 1693]
```

```
Array.init : int -> (int -> 'a) -> 'a []
```

- Prime factors of 0..100000

```
Array.init 100000 factors;;
Real: 00:00:03.036, CPU: 00:00:03.035, GC gen0: 1, gen1: 0
val it : int list [] =
  [|[]; []; [2]; [3]; [2; 2]; [5]; [2; 3]; [7]; ... |]
```

- Same, in parallel

```
let factors100000 = Array.Parallel.init 100000 factors;;
Real: 00:00:01.550, CPU: 00:00:03.048, GC gen0: 1, gen1: 0
val factors100000 : int list [] =
  [|[]; []; [2]; [3]; [2; 2]; [5]; [2; 3]; [7]; ... |]
```

The number of prime factors

```
let histogram = Array.init 100000 (fun i -> 0)
let incr i = histogram.[i] <- histogram.[i] + 1
Array.iter (fun fs -> List.iter incr fs) factors100000;;

Real: 00:00:00.054, CPU: 00:00:00.054, GC gen0: 0, gen1: 0

val histogram : int [] =
  [|0; 0; 99989; 49995; 0; 24994; 0; 16662; 0; 0; 0;
    9997; 0; 8331; 0; 0; 0; 6249; 0; 5554; 0; 0; 0;
    4544; 0; 0; 0; 0; 0; 3570; 0; 3332; 0; 0; 0; ... |]
```

- The heavy task, factorization, is parallelized
- The easy task, counting, is sequential
- Compare C# version cs/FactorsParallel.cs
  - Exactly same performance
  - Easy to forget synchronization => wrong results!!

More concurrency: I/O-bound parallel programming in F#

- Let us find the sizes of some homepages

```
let urls = ["http://www.itu.dk"; "http://www.diku.dk";
            ...];;
```

```
let lengthSync (url : string) =

    let wc = new WebClient()
    let html = wc.DownloadString(Uri(url))

    html.Length;;
```

```
lengthSync("http://www.diku.dk");;
```

```
[ for url in urls -> lengthSync url];;
```

Doing it in parallel, even with just 1 CPU

Not optimal

- Because *the webservers* work in parallel

```
let lens =
    let tasks = [ for url in urls -> async { return lengthSync url } ]
    Async.RunSynchronously(Async.Parallel tasks);;
```

- Better: Let IO system deal with responses:

```
let lengthAsync (url : string) =
    async {
        printf ">>>%s>>>\n" url
        let wc = new WebClient()
        let! html = wc.AsyncDownloadString(Uri(url))
        printf "<<<%s<<<\n" url
        return html.Length
        };;
```

```
let lens =
    let tasks = [ for url in urls -> lengthAsync url])
    Async.RunSynchronously(Async.Parallel tasks);;
```

Why not async { ... lengthSync ... }?

- The thread will block while waiting for synchronous call wc.DownloadString(...)
- The new wc.AsyncDownloadString(...) is asynchronous
  - Will send a web request
  - Will release the calling thread
  - When a response arrives, it will continue computation (maybe on a different thread)
- So can have many more active requests than there are threads
  - Very bad to have more than 1,000 threads
  - But 50,000 async concurrent requests is fine

Parallel and asynchronous C#

- The async { ... } concept arose in F# 2.0
- The C# and .NET people adopted it
  - And changed it somewhat
- It is part of .NET 4.5 and C# 4.5

Reminder: C# delegates, lambdas

Types

```
delegate R Func<R>();
delegate R Func<A1,R>(A1 x1);
...
delegate void Action();
delegate void Action<A1>(A1 x1);
...
```

=

```
unit -> R
A1 -> R
```

=

```
unit -> unit
A1 -> unit
```

Expressions

```
Func<int> fun1 = delegate() { return 42; };
Func<int> fun2 = () => 42;
Func<int,double> fun3 = x => x*Math.PI;
int r1 = fun1() + fun2();
double r2 = fun3(2);

Action act1 = delegate() { Console.Write("Hello!"); };
Action act2 = () => { Console.Write("Hello!"); };
Action<int> act3 = x => { r1 += x; };
act1(); act2(); act3(42);
```

Parallel.For in .NET via C#

- Example: 50x50 matrix multiplication

```
for (int r=0; r<rRows; r++)
  for (int c=0; c<rCols; c++) {
    double sum = 0.0;
    for (int k=0; k<aCols; k++)
      sum += A[r,k]*B[k,c];
    R[r,c] = sum;
  }
```

Sequential,
5575 ms/mult

```
Parallel.For(0, rRows, r => {
  for (int c=0; c<rCols; c++) {
    double sum = 0.0;
    for (int k=0; k<aCols; k++)
      sum += A[r,k]*B[k,c];
    R[r,c] = sum;
  }
});
```

Parallel,
1800 ms/mult

4-core Xeon

What does Parallel.For do

```
Parallel.For(0, rRows, r => {
  for (int c=0; c<rCols; c++) {
    double sum = 0.0;
    for (int k=0; k<aCols; k++)
      sum += A[r,k]*B[k,c];
    R[r,c] = sum;
  }
});
```

Delegate of type **`Action<int>`**

`Parallel.For(m, n, body)`

executes **`body(m)`**, **`body(m+1)`**, ..., **`body(n-1)`**

in some order, possibly concurrently

Parallel.Invoke

```
static double SlowFib(int n) { ... heavy job ... }
```

- Assume we need to compute this:

```
double result = SlowFib(40) * 3 + SlowFib(43);
```

- Use Invoke to compute in parallel:

```
double fib40 = 0.0, fib43 = 0.0;
Parallel.Invoke(delegate { fib40 = SlowFib(40); },
                delegate { fib43 = SlowFib(43); });
double result = fib40 * 3 + fib43;
```

- Sanity check: What is the best speed-up this can give?

Parallel.For for web access

- Get a protein's amino acid sequence from NCBI:

```
static String NcbiEntrez(String query) {
  byte[] bytes = new WebClient().DownloadData(new Uri(...));
  return ASCIIEncoding.ASCII.GetString(bytes);
}
static String NcbiProtein(String id) {
  return NcbiEntrez("efetch.fcgi?db=protein&id=" + id);
}
```

- Get many proteins in parallel:

```
static String[] NcbiProteinParallel(params String[] ids) {
  String[] res = new String[ids.Length];
  Parallel.For(0, ids.Length,
               i => { res[i] = NcbiProtein(ids[i]); });
  return results;
}
```

This is thread-safe. Why?

Locking

- Try to put results into an array list (wrong):

```
IList<String> results = new List<String>();
Parallel.For(0, ids.Length,
             i => { String res = NcbiProtein(ids[i]);
                    results.Add(res);
             });
```

Multiple concurrent updates, so wrong results

- Need to lock on the array list:

```
IList<String> results = new List<String>();
Parallel.For(0, ids.Length,
             i => { String res = NcbiProtein(ids[i]);
                    lock (results)
                      results.Add(res);
             });
```

Why not inline `res` in the call: `results.Add(NcbiProtein(ids[i]))`?

Asynchronous actions; GUI example

- Actions may block the GUI thread
  - Eg long-running computations
  - Eg access to network, disk, remote server
- Asynchronous actions avoid this problem

```
b1.Click +=       delegate(Object sender, EventArgs e)
  {
    b1.Enabled = false;
    b1.Text = "(Computing)";
    Console.Write("\nComputing SlowFib({0}) = ", n);
    double result =       SlowFib     (n++);
    Console.WriteLine(result);
    b1.Text = "Next Fib";
    b1.Enabled = true;
  };
```

General tasks for asynchrony

- Class Task
  - Asynchronous activity that returns no result
  - Typically created from an Action delegate
  - Executes on a *task scheduler*
  - ... which can execute many tasks on few threads
  - A *task* is not a *thread*

- Class Task<T> subclass of Task
  - Asynchronous activity that returns result of type T
  - Typically created from a Func<T> delegate
  - Called a "Future" by Lisp and Java people

Operations on Task and Task<T>

- Task.Run(Action act)
  - started Task that executes **`act()`**
- Task.Run(Func<T> fun)
  - started Task<T> that executes **`fun()`**, gives its result
- Task.Delay(ms)
  - started task that delays for ms milliseconds

- t.Wait()
  - block until t is complete
- t.Result (when t is Task<T>)
  - block until t is complete and then return its result
- t.ContinueWith(Action<Task> cont)
  - task that executes cont(t) when t completes
- t.ContinueWith<U>(Func<Task,U> cont)
  - task that executes cont(t) when t completes

A task to compute SlowFib

- Create Task<double> from delegate:

```
static Task<double> SlowFibTask(int n) {
  return Task.Run(() => SlowFib(n));
}
```

type Func<double>

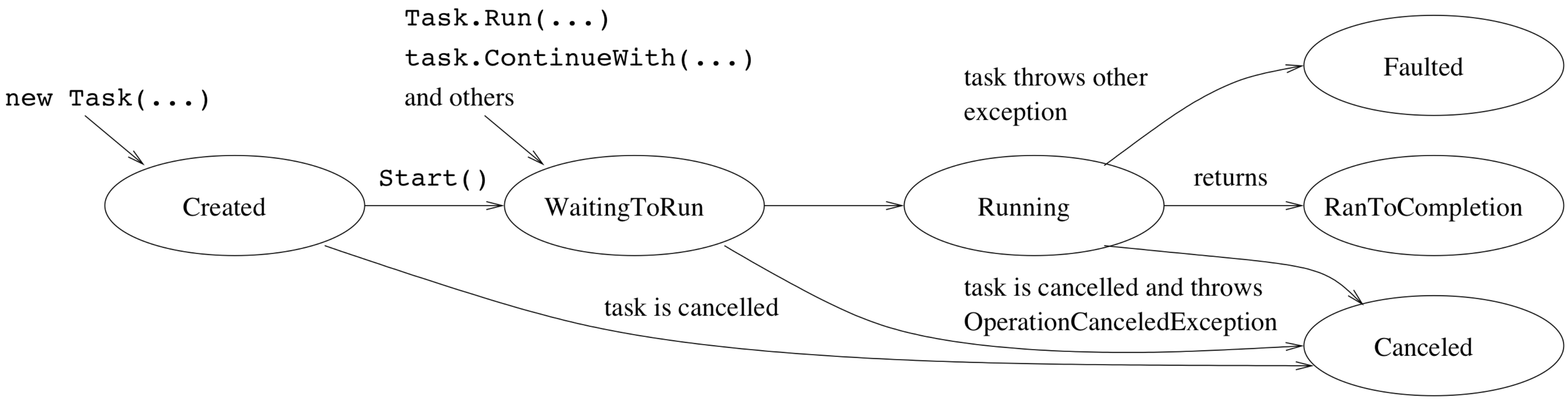
- Returns a task, that when run, will compute SlowFib(n)

- How to use the task:

```
Task<double> task = SlowFibTask(n);
... task may now be running ...
Console.WriteLine(task.Result);
```

Task states (task.Status)

- RanToCompletion = terminated successfully
- Faulted = task threw exception
- Canceled = was cancelled, acknowledged it
- Completed = any of the above



Tasks for web access

- Read bytes, then convert to String:

```
static Task<String> NcbiEntrezTask(String query) {
  return new WebClient().DownloadDataAsync(new Uri(...))
   .ContinueWith((Task<byte[]> task) =>
                 ASCIIEncoding.ASCII.GetString(task.Result));
}
```

New (4.5)

Much neater on slide 35

- The result of the method is a started task t
- The task performs the download asynchronously
- When the download completes,
  - the download task is bound to **`task`**
  - the **`task.Result`** byte array is transformed to a String and becomes the result of the task t

```
static Task<String> NcbiProteinTask(String id) {
  return NcbiEntrezTask("efetch.fcgi?...&db=protein&id="+id);
}
```

Aggregate task operations (C# 4.5)

- Task.WhenAll(params Task[] ts)
  - task that completes when *all* of tasks ts complete (aka concurrency "barrier")
- Task.WhenAll(params Task<T>[] ts)
  - task that completes when all of ts complete, returning a T[] containing their results

- Task.WhenAny(params Task[] ts)
- Task.WhenAny(params Task<T>[] ts)
  - task that completes when *any* of the ts complete, returning one of the ts that completed

Tasks for parallel web access

- Get many proteins in parallel

```
static Task<String[]> NcbiProteinParallelTasks(String[] ids) {
  IEnumerable<Task<String>> tasks
                 = from id in ids select NcbiProteinTask(id);
  return Task.WhenAll(tasks);
}
```

- How to use it:

```
ShowResult(NcbiProteinParallelTasks("P01308", ...).Result);
```

```
>gi|124617|sp|P01308.1|INS_HUMAN RecName: Full=Insulin; ...
MALWMRLLPLLALLALWGPDPAAAFVNQHLCGSHLVEALYLVCGERGFFYTPKTRREAEDLQVGQVELGG
GPGAGSLQPLALEGSLQKRGIVEQCCTSICSLYQLENYCN

>gi|12643972|sp|P01315.2|INS_PIG RecName: Full=Insulin; ...
MALWTRLLPLL...
```

Implementing task timeouts

- Use WhenAny to await task or a Delay:

```
static Task<double> SlowFibTimeout1Task(int n) {
  Task<double> slow = SlowFibTask(n);
  return Task.WhenAny(slow, TaskEx.Delay(1000))
    .ContinueWith<double>((Task<Task> task) =>
                                 task.Result==slow ? slow.Result : -1
                                );
}
```

- When the **`slow`** task or the **`Delay`** completes so does the **`WhenAny`** task
- The **`WhenAny`** task gets bound to variabl
- The **`task.Result`** is the completed task
  - If the **`slow`** task completed, return its result
  - Otherwise the **`slow`** task timed out, return -1

Much neater on slide 36

Task cancellation

- One cannot "kill", "stop" or "suspend" a task
- But one can *request* cancellation, and the task can check for and *acknowledge* (or not)

```
public static void ComputeTask(CancellationToken token) {
  for (int i=0; i<100000000; i++)
    token.ThrowIfCancellationRequested();
}
```

Check and acknowledge

```
CancellationTokenSource cts = new CancellationTokenSource();
CancellationToken token = cts.Token;
Task task = Task.Run(() => ComputeTask(token), token);

cts.Cancel();
// task.Wait();
```

Running

Canceled

Would throw AggregateException containing TaskCanceledException

Exceptions in tasks

- An exception **`exn`** thrown by a task is not propagated to the task's creator
- Instead
  - the task is moved to state Faulted
  - **`t.Wait()`** and **`t.Result`** will throw an AggregateException containing **`exn`**
  - WaitAll collects thrown exceptions from subtasks

Tasks versus threads

- A task is executed on a *task scheduler*
  - Typically many tasks run on a few threads
  - Because tasks may be blocked not on CPU work but input/output, GUI, net, GPU, ...
  - A task typically takes up few resources (just a representation of what to do when resumed)
- A *thread* might be used to represent a task
  - But a thread takes up many more resources
  - Eg each thread has a method call stack in the VM
  - Eg many threads slow down garbage collection (certainly in IBM JVM, not sure about .NET)
- The default task scheduler is based on the ThreadPool (in .NET 4.0 and 4.5)

Asynchronous methods (C# 4.5)

- Tasks allow compositional asynchrony
- But using ContinueWith gets rather hairy

- C# 4.5 has asynchronous methods
  - Declared using **`async`** keyword
  - Must return Task or Task<T> or **`void`**
  - May contain **`await e`** where **`e`** is a task
  - The rest of the method is the continuation of **`e`**

- Implementation of asynchronous method:
  - the compiler rewrites it to a state machine
  - much like **`yield return`** in iterator methods

Asynchronous web download

- Declare the method **`async`**
- Use **`await`** instead of ContinueWith(...)

```
static async Task<String> NcbiEntrezAsync(String query) {
  byte[] bytes = await new WebClient().DownloadDataAsync(...));
  return ASCIIEncoding.ASCII.GetString(bytes);
}
```

- Use as before, or from other **`async`** methods:

```
static async Task<String> NcbiProteinAsync(String id) {
  return await NcbiEntrezAsync("efetch.fcgi?...&id=" + id);
}
```

```
static async Task<String[]> NcbiProteinParallelAsync(... ids) {
  var tasks = from id in ids select NcbiProteinAsync(id);
  return await Task.WhenAll(tasks);
}
```

Timeout rewritten with async/await

- Much clearer than the ContinueWith version:

```
static async Task<double> SlowFibTimeoutAsync(int n) {
  Task<double> slow = SlowFibTask(n);
  Task completed = await Task.WhenAny(slow, Task.Delay(1000));
  return completed == slow ? slow.Result : -1;
}
```

- Use as before ...

Composing asynchronous methods

- An NCBI PubMed query is done in two phases
  - First do an **`esearch`** to get a WebKey in XML
  - Then use **`efetch`** and the WebKey to get results
- To do this asynchronously using Task and ContinueWith would be quite convoluted
- Rather easy with asynchronous methods:

```
static async Task<String> NcbiPubmedAsync(String term) {
  String search = String.Format("esearch.fcgi?...", term);
  XmlDocument xml = new XmlDocument();
  xml.LoadXml(await NcbiEntrezAsync(search));
  XmlNode node = xml["eSearchResult"];
  String fetch = String.Format("...&db=Pubmed&WebEnv={1}", ...
                                 node["WebEnv"].InnerText);
  return await NcbiEntrezAsync("efetch.fcgi?...&" + fetch);
}
```

Composability, general timeout

- Async methods can be further composed, eg
  - do all tasks asynchronously using WhenAll
  - do some task asynchronously using WhenAny
  - do task, subject to timeout
  - etc

- A general timeout task combinator

```
static async Task<T> Timeout<T>(Task<T> task, int ms, T alt) {
  if (task == await Task.WhenAny(task, Task.Delay(ms)))
    return task.Result;
  else
    return alt;
}
```

Rules for C# asynchronous methods

- Cannot have out and ref parameters
- If the method's return type is Task
  - it can have no value-returning **`return e;`** stmts.
- If the method's return type is Task<T>
  - then all paths must have a **`return e;`** stmt. where **`e`** has type T
- In an **`await e`** expression,
  - if **`e`** has type Task then **`await e`** has no value
  - if **`e`** has type Task<T> then **`await e`** has type T

References

- The importance of "popular parallel programming"
  - Free Lunch is Over: http://www.gotw.ca/publications/concurrency-ddj.htm
  - http://www.cra.org/uploads/documents/resources/rissues/computer.architecture_.pdf
  - http://www.nitrd.gov/subcommittee/hec/materials/ACAR1_REPORT.pdf
  - http://www.scala-lang.org/sites/default/files/pdfs/esynopsis.pdf
- F# 3.0 asynchronous programming
  - http://msdn.microsoft.com/en-us/library/dd233250.aspx (Asynch Workfl)
  - http://msdn.microsoft.com/en-us/library/ee353679.aspx (WebClient)
  - http://tomasp.net/blog/csharp-fsharp-async-intro.aspx
  - http://en.wikibooks.org/wiki/F_Sharp_Programming/Async_Workflows
- F# parallel programming
  - http://tomasp.net/blog/fsharp-parallel-samples.aspx
  - http://tomasp.net/blog/fsharp-parallel-plinq.aspx
  - http://tomasp.net/blog/fsharp-parallel-aggregate.aspx
  - http://tomasp.net/blog/fsharp-parallel-adash.aspx
- C# parallel (4.0) and asynchronous (5.0) programming
  - Sestoft: C# Precisely 2nd ed chapters 22 and 23
  - Microsoft technical notes, see refs. in C# Precisely chapter 34