Everyday Parallel Programming in C# and .NET

NPRG042: Programming in Parallel Environment

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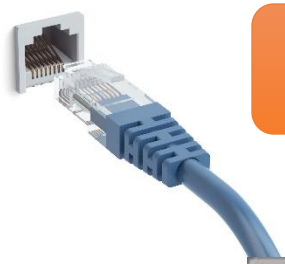
Everyday Parallel Programming

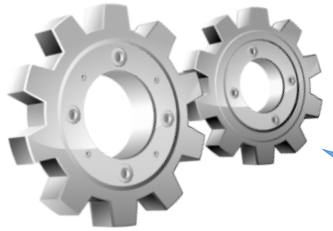
- Modern applications need to perform many tasks simultaneously

Handling network I/O



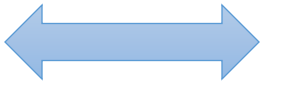
Main thread, event loop

Intensive computations (rendering, data preprocessing, data analysis, ML tasks, …)



Rest of the course will focus on this

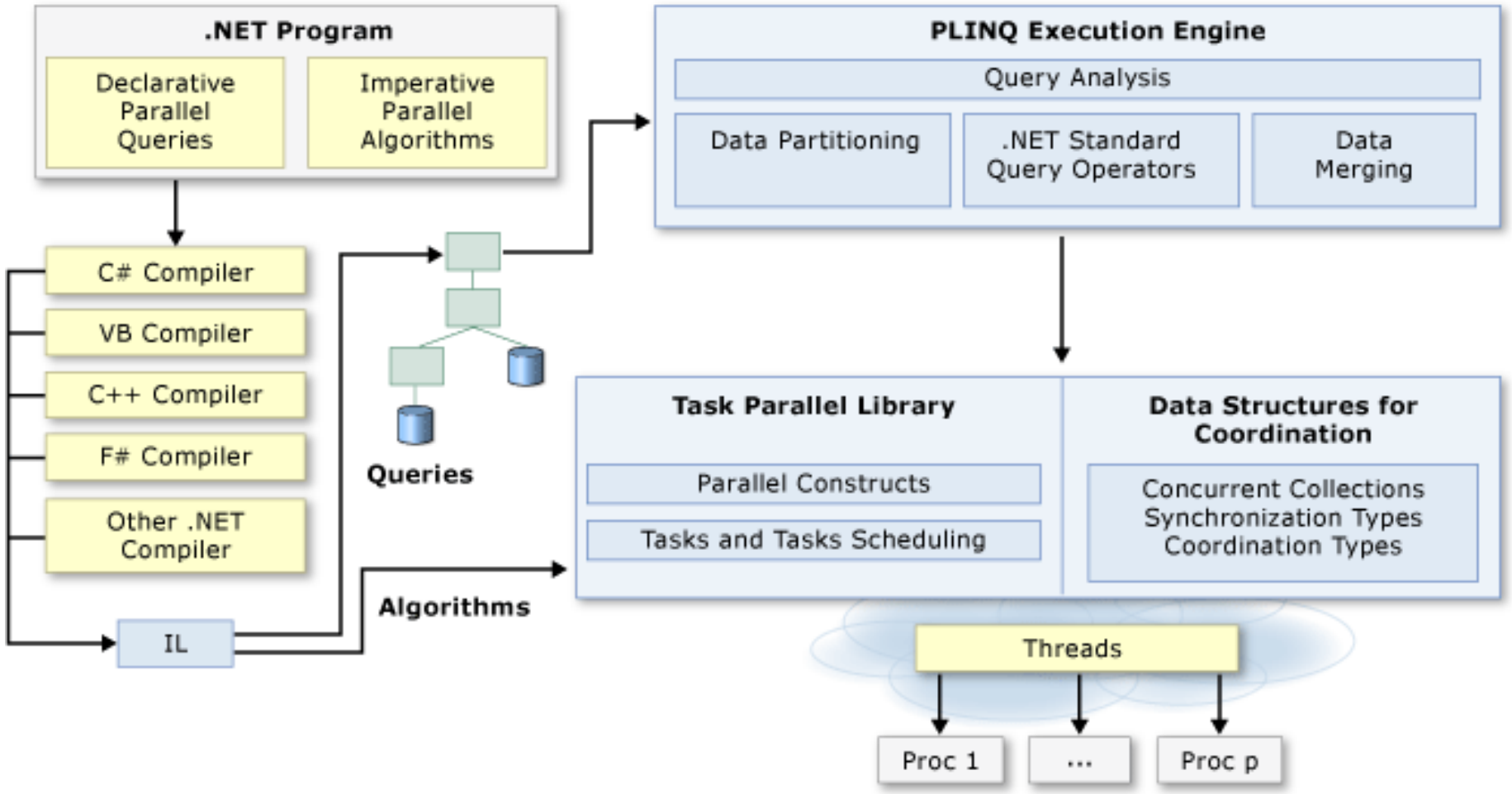
User interface



Files (I/O)

Database (heavy I/O)

Parallel Programing in .NET



Common Threads

- **`Thread`** class
  - Constructor expects a delegate to execute
  - Has to be explicitly started (**`Start()`** method)
  - Foreground vs background threads
    - **`IsBackground`** property
    - Applications ends when all foreground threads end
    - Background threads are killed when app terminates
  - Waiting for termination
    - **`Join()`** – optionally with timeout
    - **`Abort()`** – throws aborting exception inside threads
  - **`Thread.CurrentThread`**

Deprecated! Use cancelation token...

Common Threads

- **`Thread`** class
  - **`Priority`**
  - **`Suspend()`**, **`Resume()`**
  - **`Sleep()`**, **`Interrupt()`**
  - **`Yield()`**
  - **`VolatileRead()`**, **`VolatileWrite()`**, **`volatile`**

Deprecated! Not safe.

- Basic synchronization

```
lock (object) {
    // critical section bound to object
}
```

Synchronization Primitives

- **`System.Threading`** namespace
  - **`Monitor`**, **`Mutex`**, **`ReaderWriterLock`**, **`Semaphore`**
  - **`ReaderWriterLockSlim`**, **`SemaphoreSlim`**
  - **`Barrier`**
  - **`AutoResetEvent`**, **`ManualResetEvent`**, **`EventWaitHandle`**, **`CountdownEvent`**
    - Thread can wait on event until it is signaled
  - **`Interlocked`** – provides atomic operations
  - **`ThreadLocal<T>`**
  - **`CancelationToken`**

Slim versions are better

Thread Pool

- **`ThreadPool`** class
  - Often better alternative to individual threads
    - Especially for non-blocking tasks
    - Only uses background threads
  - Used automatically in many situations
    - **`Task`** execution
    - Asynchronous timers
    - Registered wait handlers' callbacks
  - Can be used manually
    - **`ThreadPool.QueueUserWorkItem(proc)`**
    - Passing a **`WaitCallback`** delegate

Parallel Constructs

- **`Parallel`** class
  - **`Parallel.For(0, N, methodOrDelegate);`**
  - **`Parallel.For(0, N, i => { ... });`**
    - Parallel equivalent of for construct
  - **`Parallel.ForEach(enum, x => { ... });`**
    - Parallel equivalent of foreach construct
  - **`Parallel.Invoke(actions)`**
    - Invokes an array of delegates concurrently

Tasks

- **`Task`**, **`Task<Result>`** classes
  - Independent encapsulated jobs executed by a thread pool in the background
  - Separate creation and execution

```
Task t = new Task(action, …);
t.Start();
```

  - Other ways how to create/start a task
    - **`Task.Run(action)`** – creates and executes a task
    - **`Task.Factory.StartNew()`** – also creates and executes
    - **`t.RunSynchronously()`** – run a task in the current thread immediately

Tasks

- Synchronization
  - **`Wait()`**
    - Optionally with timeout and/or cancelation token
  - **`Task.WaitAny(tasks)`**, **`Task.WaitAll(tasks)`**

- Dependencies
  - **`var t2 = t1.ContinueWith(action)`**
    - Create new task which is a continuation of given task
  - **`Task.WhenAny(tasks)`**, **`Task.WhenAll(tasks)`**
    - Create a task which is executed when any of/all given tasks terminate

Tasks

- Task Scheduling
  - Global queue + Local Queues (similar to TBB)
  - Employs work stealing for load balancing
  - Task inlining (sync. execution in waiting thread)
  - **`TaskScheduler`** class
    - Some actions may be given a scheduler object
      - **`Start()`**, **`ContinueWith()`**, …
    - **`TaskScheduler.FromCurrentSynchronizationContext`**
      - Returns scheduler related to sync. context of the current thread
      - Very useful for UI (WinForms, WPF) – allows a specific task to be executed in the main thread (to operate UI controls)

Oops, lectures causality violation!

Concurrent Data Structures

- **`System.Collections.Concurrent`** namespace
  - **`ConcurrentBag<T>`**
    - Unordered collection
  - **`ConcurrentDictionary<K,V>`**
  - **`ConcurrentQueue<T>`**
  - **`ConcurrentStack<T>`**
  - **`BlockingCollection<T>`**
    - Collection for producer/consumer problems

Asynchronous Programming

- Asynchronous functions
  - `public async Task<Res> foo() { ... }`
  - Can be suspended in the middle (see await)
  - Note that instead of result, it yields a task
- Waiting for tasks

```
var t = somethingThatReturnsTask();
var res = await t;
```

  - Suspends the code until a result of a task become available
    - Does not block the physical thread (core)
  - Only available in **`async`** functions

Similar (or even the same) constructs can be found in other languages (JavaScript, Python, Rust, C++, Scala, Swift…)

Unlike `Wait()`

Dataflow

- **`Dataflow`** class
  - Data-passing pipeline-like parallel model
  - Data are passed through the flow in *messages*
  - *Dataflow blocks* – buffer and process the data
    - **`ISourceBlock<TOut>`** - read-only
    - **`ITargetBlock<TIn>`** - write-only
    - **`IPropagatorBlock<TIn, TOut>`** - source & target
  - Blocks can be linked into pipelines or even graphs

    `ISourceBlock<TOut>.LinkTo(target)`
    - Arbitrary number of links (0:N)
    - Optionally may receive a filtering predicate

Installed as a separate NuGet package

Dataflow

- Programming Model
  - Source block calls **`OfferMessage()`** of target
    - Message can be accepted, rejected, or postponed
    - Postponed messages can be reserved for later

    `ISourceBlock.ReserveMessage()`
    - Reserved messages should be later processed

    `ISourceBlock.ConsumeMessage()`, **`ReleaseReservation()`**
  - Sending messages externally (outside the dataflow)
    - **`Post()`**, **`SendAsync()`**
    - **`Receive()`**, **`ReceiveAsync()`**, **`TryReceive()`**
  - Support for the completion concept
    - Completion may propagate and can be waited for

Dataflow

- Predefined blocks
  - Buffering
    - **`BufferBlock<T>`** - generic buffer
    - **`BroadcastBlock<T>`** - holds only the most recent value
    - **`WriteOnceBlock<T>`** - holds the first written value
  - Execution
    - **`ActionBlock<TIn>`** - calls a delegate on receive
    - **`TransformBlock<TIn, TOut>`** - gets a delegate which acts as map() function
    - **`TransformManyBlock<TIn, TOut>`** - similar to **`TransformBlock`**, but produces zero or more outputs per each input value

Dataflow

- Predefined grouping blocks
  - **`BatchBlock<T>`**
    - Reads a given number of messages and returns them as an array
  - **`JoinBlock<T1, T2>`**, **`JoinBlock<T1, T2, T3>`**
    - Does not implement **`ITargetInput`**, but provides **`Target1`**, **`Target2`** (and **`Target3`**) properties with this interface
    - Zips given messages in tuples
  - **`BatchedJoinBlock<T1, T2>`** (or **`<T1, T2, T3>`**)
    - Combination of batch and join block
    - Produces an array of tuples

PLINQ

- Parallel Language-Integrated Queries
  - LINQ – SQL-like in-memory lazy-evaluated queries conducted on enumerable containers
  - Parallel LINQ can resolve the queries concurrently
    - ```
      var res = from x in data.AsParallel()
                where x > 10 select x;
      ```
    - PLINQ may choose seq. evaluation based on heuristics, but we can override by selecting the execution mode or even selecting the degree of parallelism
  - Enforcing ordering
    - `.AsParallel().AsOrdered()`
  - **`query.ForAll()`** instead of using **`foreach`**
      ```

Discussion