Intel Thread Building Blocks, Part II

SPD course 2015-16
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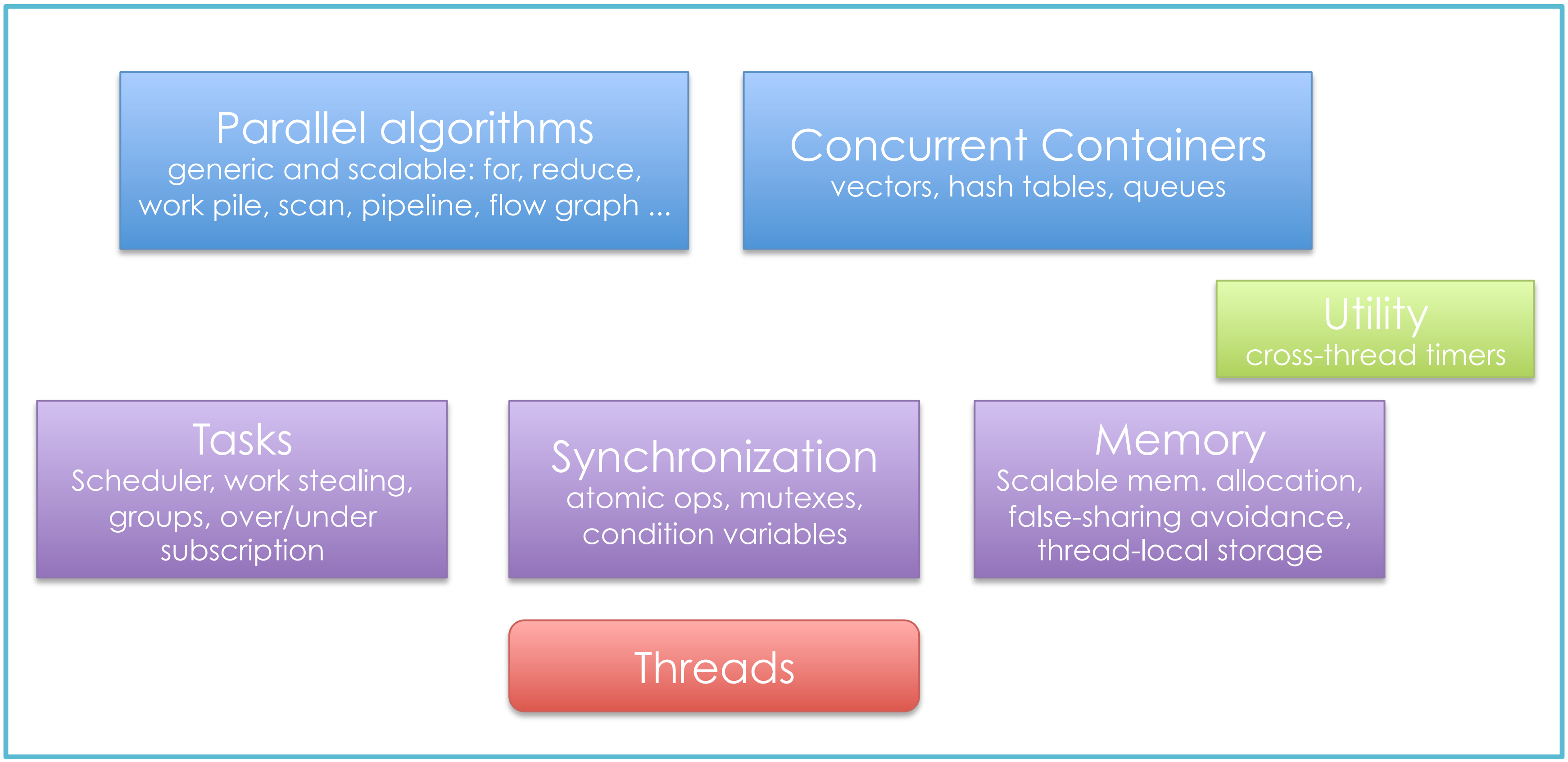
TBB Recap

- Portable environment
  - Based on C++11 standard compilers
  - Extensive use of templates
- No vectorization support (portability)
  - use vector support from your specific compiler
- Full environment: compile time + runtime
- Runtime includes
  - memory allocation
  - synchronization
  - task management
- TBB supports patterns as well as other features
  - algorithms, containers, mutexes, tasks...
  - mix of high and low level mechanisms
  - programmer must choose wisely

TBB “layers”

- All TBB architectural elements are present in the user API, **except** the actual threads



Threads and composability

- Composing parallel patterns
  - a pipeline of farms of maps of farms
  - a parallel for nested in a parallel loop within a pipeline
  - each construct can express more potential parallelism
  - deep nesting → too many threads → overhead
- Potential parallelism should be expressed
  - difficult or impossible to extract for the compiler
- Actual parallelism should be flexibly tuned
  - messy to define and optimize for the programmer, performance hardly portable
- TBB solution
  - Potential parallelism = tasks
  - Actual parallelism = threads
  - Mapping tasks over threads is largely automated and performed at run-time

Tasks vs threads

- Task is a unit of computation in TBB
  - can be executed in parallel with other tasks
  - the computation is carried on by a thread
  - task mapping onto threads is a choice of the runtime
    - the TBB user can provide hints on mapping
- Effects
  - Allow **Hierarchical Pattern Composability**
  - raise the level of abstraction
    - avoid dealing with different thread semantics
  - increase run-time portability across different architectures
    - adapt to different number of cores/threads per core

Summary

- A quick tour of TBB abstractions used to express parallelism
  - A few **C++ Concepts**, i.e. sets of template requirements that allow to combine C++ data container classes with parallel patterns
    - Splittable
    - Range
  - TBB Algorithms, i.e. the templates actually expressing thread (task) parallel computation
  - Data container classes that are specific to TBB
  - Lower-level mechanisms (thread storage, Mutexes) that allow the compentent programmers to implement new abstractions and solve special cases

Splittable Concept

- A type is splittable if it has a so-called *split constructor* that allows splitting an instance in two parts
  - X::X(X& x,   split)
    Split X into X and newly constructed object
  - First argument is a reference to the original object
  - Second argument is a dummy placeholder
- Split concept is used to express
  - Range concepts, to allow recursive decomposition
  - Forking a body (a function object) to allow concurrent execution (see the reduce algorithm)
- The binary split is usually in almost equal halves
  - Range classes can have a further split method that also specifies the split proportion

TBB Range classes

- Range classes express intervals of parameter values and their decomposability
  - **recursively** splitting intervals to produce parallel work for many patterns (e.g. for, reduce, scan…)

- The Range concept relies on five mandatory and two optional methods
  - copy constructor
  - destructor
  - is_divisible() true if range is not too small
  - empty() true if range empty
  - split() split the range in two parts
  - *two more methods allow proportional split*

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The Range concept

Class R implementing the concept of range must define:

```
R::R( const R& );
R::~R();
bool R::is_divisible() const;
bool R::empty() const;
R::R( R& r, split );
```

Split range R into two subranges. One is returned via the parameter, the other one is the range itself, accordingly reduced

Blocked Range

- TBB 4 has implementations of the range concept as templates for 1D, 2D and 3D blocked ranges
  – 3 nested parallel for are functionally equivalent to a simple parallel for over a 3D range
  – the 2D and 3D range will likely exploit the caches better, due to the explicit 2D/3D tiling

```
tbb::blocked_range< Value > Class
tbb::blocked_range2d< RowValue, ColValue > Class
tbb::blocked_range3d< PageValue,
                     RowValue, ColValue > Class
```

Proportional split

- Class defining methods that allow control over the size of two split halves
- Passed as argument to methods performing a proportional split
  - `proportional_split( size_t _left = 1,`
    `size_t _right = 1 )`
    define a split object using the coefficients to compute the split ratio
  - `size_t left() const`
    `size_t right() const`
    return the size of the two halves
  - `operator split() const`
    backward compatibility with simpler split (allows implicit conversion)

Range with proportional split

- Optional methods allowing proportional splits
  - R::R(R& r, proportional_split proportion) optional costructor using a proportional split object to define the split ratio
  - static const bool R::is_splittable_in_proportion true iff the range implementation has a constructor allowing the proportional split

TBB 4 Algorithms (1)

Over time, the distinction between parallel patterns and algorithms may become blurred
TBB calls all of them just "algorithms"

- **parallel_for_each**
  - iteration via simple iterator, no partitioner choice
- **parallel_for**
  - iteration over a range, can choose partitioner
- **parallel_do**
  - iteration over a set, may add items
- **parallel_reduce**
  - reduction over a range, can choose partitioner, has deterministic variant
- **parallel_scan**
  - parallel prefix over a range, can choose partitioner

TBB 4 Algorithms (2)

- *parallel_while* (deprecated, see parallel_do)
  - iteration over a stream, may add items
- **parallel_sort**
  - sort over a set (via a RandomAccessIterator and compare function)

- **pipeline** and **filter**
  - runs a pipeline of filter stages, tasks in = tasks out
- **parallel_invoke**
  - execute a group of tasks in parallel
- **thread_bound_filter**
  - a filter explicitly bound to a serving thread

Parallel For each

```
void      tbb::parallel_for_each (InputIterator first,
                InputIterator last, const Function &f)
```

- simple case, employs iterators
- drop-in replacement for std for_each with parallel execution
  - Easy-case parallelization of existing C++ code
- it was a special case of for in previous TBB
- Serially equivalent to:

```
for (auto i=first; i<last; ++i) f(i);
```

- There is also the variant specifying the context (task group) in which the tasks are run

Passing args to parallel patterns

- Beside the range of values we need to compute over, we nee to specify the inner code of C++ templates implementing parallel patterns
- Most patterns have two separate forms
  - Args are a function reference (computation to perform to perform) and a series of parameters (to the parallel pattern)
  - Args contain a user-define class "*Body*" to specify the pattern body,
    - *Body* is a concrete class instantiating a virtual class specified by TBB as a model for that pattern
    - TBB docs calls "requirements" the methods that the *Body* class provides and will be called by the pattern implementation
- Example: for_each uses the first method

Passing args to parallel patterns

- Advantages and disadvantages
- Using functions (TBB documentation calls it the "functional form"…)
  - Easier to use lambda functions
  - We are passing around function references
  - Static (compilation-time) type checking is in some cases limited as the template needs to be general enough
- Using Body classes (TBB calls it "imperative")
  - Slightly more lengthy code
  - Better static type-checking
  - Body classes can more easily contain data/ references – they can have state that simplifies some optimization (ex. see the parallel_reduce pattern)

Optional args to parallel patterns

- A partitioner
  - A user-chosen partitioner used to split the range to provide parallelism
  - see later on the properties of auto_partitioner, (default in any recent TBB) simple_partitioner, affinity_partitioner
- task_group_context
  - Allows the user to control in which task group the pattern is executed
  - By default a new, separate task group is created for each pattern

Parallel For

```
parallel_for (
  tbb::blocked_range<size_t> (begin, end,
  GRAIN_SIZE), tbb_parallel_task());
```

- Loops over integral tipes, positive step, no wrap-around
- one way of specifying it, where tbb_parallel_task is a *Body* user-defined class
- uses a class for parallel loop implementations.
  - The actual loop "chunks" are performed using the () operator of the class
  - the computing function (operator ()) will receive a range as parameter
  - data are passed via the class and the range
- The computing function can also be defined in-place via lambda expressions

Parallel For

```
parallel_for (
  tbb::blocked_range<size_t> (begin, end,
  GRAIN_SIZE), tbb_parallel_task(), partitioner);
```

- Extended version
- the partitioner is one of those specified by TBB (simple, auto, affinity)
- no real choice usually, just allocate a const partitioner and pass it to the parallel loops:

```
tbb::affinity_partitioner ap;
```

  – (unless you want to define your own partitioner)

Parallel_for, 1D alternate syntax

- template<typename Index, typename Func>
  Func parallel_for(Index first, Index_type last,
  const Func& f
  [, partitioner
  [, task_group_context& group]]);
- template<typename Index, typename Func>
  Func parallel_for(Index first, Index_type last,
  Index step, const Func& f
  [, partitioner
  [, task_group_context& group]]);
- Implicit 1D range definition, employs a function reference (e.g. lambda function) to specify the body

partitioners

- simple
  - generate tasks by dividing the range as much as possible (remember about the grain size!)
- auto
  - divide into large chunks, divide further if more tasks are required
- affinity
  - carries state inside, will assign the tasks according to range locality to better exploit caches

Combining the elements

- Apply a range template to your elementary data type
- Define a class computing the proper for-body over elements of a range
- Call the parallel_for passing at least the range and the function
- specify a partitioner and/or a grain size to tune task creation for load balancing

Example (with lambda)

```
void relax(  double *a, double *b,
             size_t n, int iterations)
{
   tbb::affinity_partitioner ap;
   for (size_t t=0; t<iterations; ++t) {
      tbb::parallel_for(
         tbb::blocked_range<size_t>(1,n-1),
         [=]( tbb::blocked_range<size_t> r) {
            size_t e = r.end();
            for (size_t i=r.begin(), i<e; ++i)
               /*do work on a[i], b[i] */;
         },
         ap);
      std:swap(a,b); // always read from a, write to b
   }
}
```

Intel Thread Building Blocks, Part III

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Temporary slides - to be revised

reduce

- Reduce has also two forms
  - "*Functional*" from, nice with lambda function definitions
  - "*Imperative*" form, minimizes data copying
  - *Please remember this is just TBB terminology*

```
template<typename Range, typename Value, typename
         Func, typename Reduction>

Value parallel_reduce( const Range& range,
         const Value& identity, const Func& func,
         const Reduction& reduction,
         [, partitioner[, task_group_context& group]] );


template<typename Range, typename Body>

void parallel_reduce( const Range& range,
         const Body& body
         [, partitioner[, task_group_context& group]] );
```

“Functional” form

- Beside the function, several other objects have to be passed to the reduce

- Value Identity
  – left identity for the operator
- Value Func::operator()(const Range& range,
  const Value& x)
  – must accumulate a whole subrange of values starting from x (“sequential reduction”)
- Value Reduction::operator()(const Value& x,
  const Value& y);
  – Combines two values (“parallel” reduction)

Object-oriented form

- Computes the reduction on its Body object together with the associated Range
  - Data (reference) is held within the Body
  - The reduce can split() the body parameter, and will split() the range accordingly
  - Can also split only the range, and compute over a range that is smaller than the Body's data
    - This may allow saving some data copy operation when we exploit parallel slackness together with affinity
  - Results form each side will the be combined
- Body object's state contains the reduced value
  - Final result is accumulated in initial Body object

Reduce

- Both the function-based form and the OO one can specify a custom partitioner
- Both forms can specify a task group that will be used for the execution

Reduce – deterministic variant

- parallel_deterministic_reduce
- Performs a deterministically chosen sets of splits, joins and computations
- Exploits the simple_partitioner → no partitioner argument allowed
- Computes the same regardless of the number of threads in execution
  - no adaptive work assignment is ever performed
  - grain size must be carefully chosen in order to achieve ideal parallelism
- Has both the functional form and the OO one

pipeline

- Pipeline pattern
  - pipeline class — not strongly typed
  - parallel_pipeline — strongly typed interface
- Implements the pipeline pattern
  - A series of filter applied to a stream
    - You need to subclass the abstract filter class
  - Each filter can work in one of three modes
    - Parallel
    - Serial in order
    - Serial out of order

Pipeline class

- Pipeline is dynamically constructed
  - pipeline() create an empty pipeline
  - ~pipeline() destructor
  - void add_filter(filter& f) add a filter
  - clear() remove all filters
  - void run(size_t max_number_of_live_tokens [, task_group_context& group])
- Run until the first filter returns NULL
- Actual parallelism depends on pipeline structure, and on parameter
  - max_number_of_live_tokens
- Pipelines can be reused, but NOT concurrently
- Stages can be added in between runs
- Can have all tasks belong in a specified optional group, by default a new group is created

filter

- Abstract class implementing filters for pipelines
- Three modes, specified in the constructor
  - Parallel can process/produce any number of item in any order (e.g. nested parallelism)
  - Serial out of order filter processes items one at a time, and in no particular order
  - Serial in order filter processes items one at a time, in the received order
- Computation is specified by overriding the operator ()
  - virtual void* operator()(void * item)
  - Process one item and return result, via pointers
  - First stage signals with NULL the end of the stream
  - Result of last stage is ignored

Parallel_pipeline

- void parallel_pipeline(
  size_t max_number_of_live_tokens,
  const filter_t<void,void>& filter_chain
  [, task_group_context& group]);
- Strongly typed, can use lambdas
  - parallel_pipeline(max_number_of_live_tokens,
    make_filter<void,I1>(mode0,g0) &
    make_filter<I1,I2>(mode1,g1) & ...
    make_filter<In,void>(moden,gn));
- Employ the make_filter template to build filters on the spot from their operator() function
- Types are checked at compilation time
  - First stage must invoke fc.stop() and return a dummy value to terminate the stream

Notes

- Check that you compiler properly supports lambdas
- Installing TBB from sources and binary do not result in the same configuration
  - environment variables (paths, options) affect compilation
  - identify proper switches in compilation
- tbbvars.sh can set proper variables for you (but it is buggy in some TBB versions)
- Makefiles to compile examples tend to work reliably, but they rebuild their configuration each time