Advanced Tools For Parallel Programming

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C++ requirements

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We will now study TBB a C++ lib

Some notions are required:

- Inheritance, composition, namespace ...
- Template and STL
- `const` and references usage
- Object Functors
- C++11’s lambdas (optional)

TBB will work with usual compilers: g++, clang, Intel’s cc and MS Visual.
Object Functor

- An Object Functor in C++ is a kind of closure.
- It relies on overloading of `operator()`.
- As a closure (since it's an object) it embeds its needed environment.

Example:

```cpp
class SimpleFunctor {
    int count;

public:
    int operator() (void) {
        return count++;
    }
    SimpleFunctor(int c) : count(c) {}  
};
```
Relation To Closure

Example:

The following OCaml’s code:

```ocaml
let build_counter step init =
  let cpt = ref init in
  fun () -> let x = !cpt in cpt := !cpt + step; x
```

Can be translated into:

```cpp
class Build_counter {
  int cpt, step;
public:
  int operator() (void) {
    int x = cpt;
    cpt += step;
    return x;
  }
  Build_counter(int step_, int init) :
    cpt(init), step(step_) {}
};
```
Example:

**Usual syntax of C++11’s Lambdas:**

```cpp
int q = 42;
AFunctionUsingLambda(
    [=](int x)
    {
    return q + x*x;
    }
);
```

*In this example, q is added to the environment of the lambda as value.*

*If you use [&] it will be added as reference.*
Threading Building Blocks

Threading Building Blocks

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TBB is a library designed to provide high level constructions for parallel programming.

Initially TBB was an Intel project to demonstrate gains of multi-core processors.

It provides algorithms (such as parallel for), containers, tools and underlying framework for parallel computing.

It is a pure C++ library with templates classes. No additional support is required from the compiler (unlike OpenMP.)
Bounded Parallel Iterators: \textit{parallel for and parallel reduce}

Dynamic Parallel Loop: \textit{parallel do}

Pipeline

Spawing and continuation based tasks system

Containers: \textit{queues, vectors and hash tables}

Atomic Types

Various locks

Threading API \textit{compatible with requirements for C++11}

Various utilities: \textit{wall clock, memory allocators . . .}
Looping in parallel

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Parallel for and reduce provides the simplest but probably the most useful tools of TBB.

They provide a simple way to achieve a good data-driven decomposition.

Optimal data decomposition can be achieved almost automatically through the concept of range and partitioner.

Using C++11’s lambda (anonymous functions) writing a simple parallel for can be as simple as writing a for loop.
Ranges
What are ranges?

- A range a is a concept derived from iterator;
- It is used by parallel loops to *describe* inner step of linear blocks in the parallel iterations.
- It is also used to define partitions in data-set.
- The way it divides data (and the minimal grain of its division) drives the scheduling of the parallel iterations.
As an iterator, a range provides the usual iteration operations:

- `begin()` and `end()` (returning `const iterator`)
- `size()`

In order to divide the data-set, the range provides the following operations:

- `grainsize()` (minimal size of a sub-range)
- `is_divisible()` (whether we can split the actual range or not)
- And `split` constructor (almost like a copy constructor but with a dummy split argument to differentiate it from a copy constructor.)
A Basic Integer Range

Example:

```cpp
struct IntRange {
    int lower; int upper;
    bool empty() const { return lower==upper; }

    bool is_divisible() const
    { return upper>lower+1; }

    IntRange(IntRange& r, split) {
        int m = (r.lower+r.upper)/2;
        lower = m;
        upper = r.upper;
        r.upper = m;
    }
};
```
**Provided Ranges**

- TBB provides *blocked range* templates useful for most cases.
- The templates can be used with any integral type convertible to `size_t`.
- *Blocked ranges* comes in 3 flavors:
  - `blocked_range` for half-open interval;
  - `blocked_range2d` for two dimensional ranges;
  - `blocked_range3d` for three dimensional ranges.
Data Partitioner

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A partitioner specifies how a parallel loop should partition its works among threads.

Parallel loops try to recursively split a range in order to keep processors busy.

Partitioners control the *split politics*

TBB provides three partitioners:

- `auto_partitioner`: the default behavior
- `affinity_partitioner`: similar to auto but tries to be nice with cache
- `simple_partitioner`: divides ranges until `is_divisible` return false.
Choosing a partitioner

- In most cases, the automatic partitioner provides the best behavior.
- The affinity partitioner is used when data-set fits in cache and loop may be executed on the same data.
- The affinity partitioner may improve performances in some cases but need careful adjustment.
- The simple partitioner give you the full control over partitioning.
- You should use simple partitioner only if you have a clear idea on how data should be split.
Parallel For
Bounded Parallel Iterations

- A *parallel for* loop is a traditional *for* loop that TBB will execute in parallel.
- The loop iterate on a range and use the *splittable* concept of range to divide tasks on physical threads.
- A *parallel for* loop performs independent tasks on a set of data with result recollection at the end.
- The template provides by TBB can be used with functor objects or C++11’s lambdas.
We will suppose we have an operation $F(e)$ operating on a single data (double in our example.) Our data-set is an array. The linear version will look like:

```cpp
void Serial(double data[], size_t n) {
    for (size_t i=0; i != n; ++i)
        F(data[i]);
}
```
Using A Parallel For (simple functor)

Example:

```cpp
class Parallel {
    double *const my_data;
public:
    void operator() (const blocked_range<size_t>& r) const {
        double *a = my_data; // local copy
        for (size_t i=r.begin(); i!=r.end(); ++i)
            F(a[i]);
    }
    Parallel (double a[]) : my_data(a) {}
};

void ParallelRun(double data[], size_t n) {
    parallel_for(blocked_range<size_t>(0, n),
                 Parallel(data));
}
```
More possibilities

- You can use a lambda rather than a functor (more compact solution)
- If you only plans to iterate on an integer range you can just provide the range bound rather than a range object (when using lambda.)
- You can also provide a partitioner.
- You can use parallel for to iterate on STL containers quite easily.
The parallel for template algorithm relies on a smart scheduling of sub-ranges.

When starting the parallel for, the initial range is divided among threads.

Each thread will then split the work depending on partitioner politics.

When a thread has finished its own sub-range, it can steal work from other threads.

Depending on the chosen partitioner and the time spent in each blocks, TBB will try to keep each available threads occupied.
Parallel Reduce
Parallel Reduce

- *Parallel reduce* is a variation of the *parallel for* used when data recollection is needed.
- Globally it provides an efficient way to share a kind of accumulator to the loop.
- As for *parallel for*, operations on data should be reflexive.
- The way *parallel reduce* works avoid the need of a locked and shared accumulator.
- The functor provided to the loop must offer a split constructor and join operations.
Using Parallel Reduce

In this example we will compute the sum of a vector, the sequential version look like:

Example:

```c++
double Sum(double data[], size_t n) {
    double res = 0;
    for (size_t i=0; i != n; ++i)
        res += data[i];
    return res;
}
```
Using Parallel Reduce

Example:

```cpp
class SumWorker {
   double* my_data;

public:
   double* my_sum;

   void operator() (const blocked_range<size_t>& r) {
      double *a = my_data; double sum = my_sum;
      for (size_t i=r.begin(); i!=r.end; ++i)
         sum += a[i];
      my_sum = sum;
   }

   void join(const SumWorker& y) {
      my_sum += y.my_sum;
   }

   SumWorker(SumWorker x, split) :
      my_data(x.my_data), my_sum(0) {}
   SumWorker(double data[]) :
      my_data(data), my_sum(0) {}
};
```
Using Parallel Reduce

Example:

```cpp
double ParallelSum(double data[], size_t n) {
    SumWorker sw(data);
    parallel_reduce(
        blocked_range<size_t>(0, n), sw);
    return sw.my_sum;
}
```
You have no control over operations order, thus operations must be reflexive.

The `join` operation is only performed when a range was split in order to transfer works to another thread.

Using local copy of variable is strongly advised: local variables will probably be moved to register will object attributes should require indirect access and address computations.

Like the `parallel_for`, you can control data-partitioning with range definitions and partitioners.
How Parallel Reduce Works
Other kinds of loops
More loops

- `parallel_do`: unbounded loops, where new items can be added dynamically during iterations.
- `parallel_scan`: a complex for of loop with inner sequential dependencies.
Pipeline

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The assembly line

- TBB provides a framework to build pipeline of tasks.
- A pipeline is composed by a set of sequential tasks and flow of data that traverse these tasks.
- Each task will receive chunks of data from the previous task and send the resulting chunks to the next task.
- When a task receive several chunks, it can process them in parallel or sequentially.
- When a task process chunks in parallel, results can be emitted in FIFO order or asynchronously as processing ends.
- Pipeline provides a simple and efficient way of doing data-flow driven partitioning.
Filters

- Filters are tasks that can be added to a pipeline
- A filter is basically a functor providing information for the pipeline organisation (sequential or parallel computation, FIFO outputs . . . )
- TBB provides a template to build a filter out of simple functor.
- Filters can build and added in the pipeline rather at pipeline creation (using `operator&` to concatenate filters) or added afterward by using the `add_filter` method.
Once filters are designed, you can construct your pipeline and add filters in order.

When using parallel filter, you must take care of the number of tokens sends to filter: each token triggers invocation of an instance of the filters, if the next filter in line is serial, the parallel filter may start to much tasks. Constructor for pipeline provide a control over the maximum of living tokens in the pipeline.

A pipeline does not provides a non-linear structures: each filter as exactly one input (or none if first) and one output (or none if last.)
Building A Pipeline

1. Build your filters by derivating class `filter`;
2. Override `operator()` to perform operation on item. You must take a pointer to the current item and return a pointer for the next filter. Last filter’s output is ignored;
3. The first filter is a special case: it generates the stream for the chain and returns `NULL` to indicate the end of the stream;
4. Create an instance of class `pipeline`;
5. Create instances of your filters and add them to the pipeline in order from first to last. Each instance can be added at most once to a pipeline and should never be a member of more than one pipeline at a time.
6. Call method `pipeline::run` and set carefully the maximum live tokens to avoid too much memory usage.
• TBB tutorial provides a good example of pipeline.
• The purpose of this example is to process a file and change to upper case all first letters of words in a text.
• The pipeline is composed of three filters:
  • the input filter read a file and output chunks of text, it is obviously sequential;
  • the middle filter performs the action and is parallel;
  • the output filter write result to a file and is also sequential.
Containers

Containers

Containers

Containers

Containers

Containers

Containers

Containers

Containers
Concurrent Containers

- TBB provides some containers *parallel friendly*
- All containers are safe to be used in multi-threaded context (even when using system threads.)
- All TBB’s containers are not only safe, but also aim to have finest grain locking or (when possible) non-blocking policy.
- Latest TBB version include containers similar to C++11 concurrent containers.
Concurrent Hash Map
Concurrent Hash Map

- The template class `concurrent_hash_map` provides associative maps (backed with hash table.)
- Concurrent Hash Map provides a Readers/Writer policy at element level
- Operations can be performed concurrently (even element removal)
- The map stores `std::pair<const Key, T>` and use a notion of accessor to indicate access for reading or for writing.
- The Key template parameter must respect the HashCompare concept.
HashCompare concept defines in the same object the hash function and equality predicate.

It must satisfies usual constraints:
- Two equals key must have the same hash code
- Hash code of keys must not change when keys are in used.

You should also verify that hash function and equality predicate must not raise exceptions.
Usage

- When retrieve a pair you should provide an accessor.
- The item is locked (for reading or writing) until the accessor is deleted.
- The type of the accessor indicate the kind of operation you want (reading or writing): accessor or const_accessor

Example:

```cpp
{
    MyTable::accessor a; // lock for writing
    table.insert(a,key); // add or find if key exists
    a->second = new_val;
    // when leaving the block, a is destroyed
}
```
Concurrent Queue
Concurrent Queues

- TBB provide non-blocking queues (lock free) and blocking queues (locked and possibly bounded.)
- The class template `concurrent_queue<T, Alloc>` provides unbounded lock-free concurrent FIFO queues of elements of type `T`.
- The class template `concurrent_bounded_queue<T, Alloc>` provides blocking FIFO queues, possibly bounded.
- All queues behave like STL queues.
TBB provides a wide variety of locks

Locks in TBB are C++ friendly:
- You instantiate a local special object (from the shared lock)
- Once you acquire the lock, it will remain until the object exists
- The lock is released when you destroy the object
Atomic Types

- TBB provides template types for atomic values
- Atomic types in TBB is very similar to C++11 atomic types
- Atomic types provides a set of operations that are safe to use concurrently
- Since atomic types are bounded to integer like types, TBB override usual operators:
  - ++ and --
  - += and other op-assign operators
  - = assign operations
• TBB provides a working wall clock for performances measures
• Wall clocks are safe to use in concurrent environments and offer some guarantee on the time information they deliver.
• Precision is as accurate as system clock (often few milliseconds.)
TBB uses as its core a tasks system.
You can use it directly.
Task are single small computation.
Each task can spawn new tasks and wait (or not) for it.
You can also describe your tasks in continuation style: each task can return a new task to be performed.
Building a simple tasks based program:
  - You describe your tasks with class derived from the class task
  - Your first task will spawn other tasks
  - You launch it (using task::spawn_root_and_wait)
  - That’s (almost) all!
TBB provides efficient allocator to be used instead of standard allocators.

Exceptions and correct cancellation operations.

Read the docs!