Advanced Tools For Parallel Programming

Marwan Burelle

Threading Building Blocks

Looping in parallel

Pipeline

Containers

Other tools

Advanced Tools For Parallel Programming

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Outline

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   - Data Partitioner
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3. Pipeline
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Threading Building Blocks

TBB ?

- TBB is a librairy designed to provide high level constructions for parallel programming.
- Initialy 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++ librairy with templates classes. No additional support is required from the compiler (unlike OpenMP.)

Contents

- Bounded Parallel Iterators: *parallel for* and *parallel reduce*
- Dynamic Parallel Loop: *parallel do*
- Pipeline
- Spawing and continuation based tasks system
- Containers: *queues*, *vectors* and *hash tables*
- Atomic Types
- Various locks
- Threading API *compatible* with requirements for C++11
- Various utilities: *wall clock*, *memory allocators* . . .

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- Parallel for and reduce provides the simplest but probably the most usefull 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.

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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.

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What a range provides ?

- 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 opertations:
  - `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 differenciate it from a copy constructor.)

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A Basic Integer Range

```
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;
  }
};
```


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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 dimesional ranges.

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Data Partitioner

Partitioner concept

- 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.

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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 adjustement.
- 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.

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- 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.

Using A Parallel For

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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:

```
void Serial(double data[], size_t n)
{
  for (size_t i=0; i != n; ++i)
    F(data[i]);
}
```

Using A Parallel For (simple functor)

```
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));
}
```


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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.

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How parallel for works

- 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 choosen partitioner and the time spent in each blocks, TBB will try to keep each available threads occupied.

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- *Parallel reduce* is a variation of the *parallel for* used when data recollection is needed.
- Globaly 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

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

```
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

```
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) {}
};
```


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Using Parallel Reduce

```
double ParallelSum(double data[], size_t n)
{
  SumWorker sw(data);
  parallel_reduce(
    blocked_range<size_t>(0,n),sw
  );
  return sw.my_sum;
}
```

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Parallel Reduce Hints

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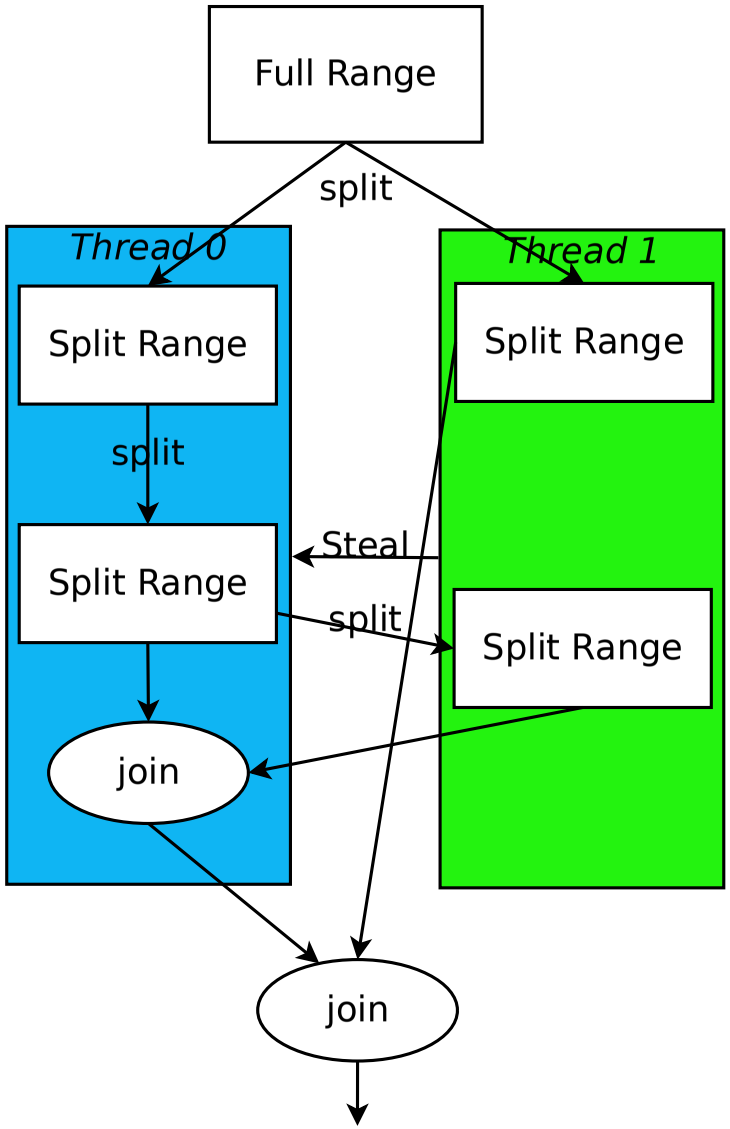
- You have no control over operations order, thus operations must be reflexive.
- The `join` operation is only performed when a range was split in order to transfer works to an other thread.
- Using local copy of variable is strongly advised: local variables will probably be moved to register will object 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



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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.

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Pipeline

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

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- 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.
- Filers 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.

Pipeline

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- 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 ouput (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 pipline in order from first to last. Each instance can be added at most once to a pipline and should never be a member of more than one pipline at a time.
6. Call method `pipeline::run` and set carefully the maximum live tokens to avoid too much memory usage.

Skeleton Example (Simple Interface)

```
struct StartFilter {
public:
  void* operator()(InType* x)
  { /* do the job here */ }
};
struct MiddleFilter {
public:
  Type2* operator()(Type1* x)
  { /* do the job here */ }
};
struct LastFilter {
public:
  void* operator()(Type2* x)
  { /* do the job here */ }
};
```

Skeleton Example

```
void MyPipeline(int maxToken, /* other data */)
{
  tbb::t_filter<void,Type1>
    fInput(tbb::serial_in_order,StartFilter());
  tbb::t_filter<Type1,Type2>
    fMiddle(tbb::parallel,MiddleFilter());
  tbb::t_filter<Type2,void>
    fOutput(tbb::serial_in_order,LastFilter());
  tbb::parallel_pipeline(maxToken,
       fInput & fMiddle & fOutput
  );
}
```

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Concurrent Containers

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Other tools

- 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 aime to have finest grain locking or (when possible) non-blocking policy.
- Latest TBB version include containers similar to C++11 concurrent containers.

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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

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- `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`

```
{
  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
}
```

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Concurrent Queues

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- 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.

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Locks

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Other tools

- 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 remains until the object exists
  - The lock is release 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

Wall clock

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New C++11 features in `std::chrono`

- TBB provides a working wall clock for performances measures
- Wall clocks are safe to use in concurrent environments and offer some garantee on the time information they deliver.
- Precision is as accurate as system clock (often few milliseconds.)

Tasks Based Programming

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- 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 !

Task Example

```
class FibTask: public task {
public:
 const long n; long* const sum;
 FibTask( long n_, long* sum_ ) :
   n(n_), sum(sum_) {}
 task* execute() {
   long x, y;
   FibTask& a =
     *new(allocate_child()) FibTask(n-1,&x);
   FibTask& b =
     *new(allocate_child()) FibTask(n-2,&y);
   set_ref_count(3);
   spawn( b );
   spawn_and_wait_for_all(a);
   *sum = x+y;
   return NULL;
 }
};
```

Task Example

```
long ParallelFib( long n ) {
  long sum;
  FibTask& a =
    *new(task::allocate_root()) FibTask(n,&sum);
  task::spawn_root_and_wait(a);
  return sum;
}
```

More . . .

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Other tools

- TBB provides efficient allocator to be used instead of standard allocators.
- Exceptions and correct cancellation operations.
- Read the docs !