CS 698L: Intel Threading Building Blocks

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Content influenced by many excellent references, see References slide for acknowledgements.

Approaches to Parallelism

- New languages
  - For example, Cilk, X10, Chapel
  - New concepts, but difficult to get widespread acceptance
- Language extensions/pragmas
  - For example, OpenMP
  - Easy to extend, but requires special compiler or preprocessor support
- Library
  - For example, C++ STL, Intel TBB, and MPI
  - Works with existing environments, usually no new compiler is needed

What is Intel TBB?

- A **library** to help leverage multicore performance using standard C++
  - Does not require programmers to be an expert
    - Writing a correct and scalable parallel loop is not straightforward
  - Does not require support for new languages and compilers
  - Does not directly support vectorization

- TBB was first available in 2006
  - Current release is 2019 Update 8
  - Open source and licensed versions available

What is Intel TBB?

- TBB works at the abstraction of **tasks** instead of low-level threads
  - **Specify tasks** that can run concurrently instead of threads
  - Specify work (i.e., tasks), instead of focusing on workers (i.e., threads)
    - Raw threads are like assembly language of parallel programming
  - Maps tasks onto physical threads, efficiently using cache and balancing load
  - Full support for nested parallelism

Advantages with Intel TBB

- Promotes scalable data-parallel programming
  - Data parallelism is more scalable than functional parallelism
  - Functional blocks are usually limited while data parallelism scales with more processors
  - Not tailored for I/O-bound or real-time processing
- Compatible with other threading packages and is portable
  - Can be used in concert with native threads and OpenMP
  - Relies on generic programming (e.g., C++ STL)

Key Features of Intel TBB

Generic Parallel algorithms
parallel_for, parallel_for_each,
parallel_reduce, parallel_scan,
parallel_do, pipeline, parallel_pipeline,
parallel_sort, parallel_invoke

Concurrent containers
concurrent_hash_map
concurrent_unordered_map
concurrent_queue
concurrent_bounded_queue
concurrent_vector

Task scheduler
task_group, structured_task_group,
task, task_scheduler_init

Synchronization primitives
atomic operations, condition_variable
various flavors of mutexes

Utilities
tick_count
tbb_thread

Memory allocators
tbb_allocator, cache_aligned_allocator, scalable_allocator, zero_allocator

Task-Based Programming

- Challenges with threads: oversubscription or undersubscription, scheduling policy, load imbalance, portability
  - For example, mapping of logical to physical threads is crucial
  - Mapping also depends on whether computation waits on external devices
  - Non-trivial impact of time slicing with context switches, cache cooling effects, and lock preemption
    - Time slicing allows more logical threads than physical threads

Task-Based Programming with Intel TBB

- Intel TBB parallel algorithms map tasks onto threads automatically
  - Task scheduler manages the thread pool
- Oversubscription and undersubscription of core resources is prevented by task-stealing technique of TBB scheduler
- Tasks are lighter-weight than threads

An Example: Hello World

```
#include <iostream>
#include <tbb/tbb.h>

using namespace std;
using namespace tbb;

class HelloWorld {
  const char* id;

public:
  HelloWorld(const char* s) : id(s) {}
  void operator()() const {
    cout << "Hello from task "
         << id << "\n"; }
};
```

```
int main() {
  task_group tg;

  tg.run(HelloWorld("1"));
  tg.run(HelloWorld("2"));

  tg.wait();

  return EXIT_SUCCESS;
}
```

An Example: Hello World

```
#include <iostream>
#include <tbb/tbb.h>

us
us

cl


pu
  HelloWorld(const char* s) : id(s) {}
  void operator()() const {
    cout << "Hello from task "
         << id << "\n"; }
};
```

```
int main() {
  task_group tg;

}
```

swarnendu@cse-BM1AF-BP1AF-BM6AF: ~/iitk-workspace/parallel-computing/src/tbb

```
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$ g++ -std=c++11 hello-world.cpp -o hello-world -ltbb
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$ ./hello-world
Hello from task 2
Hello from task 1
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$
```

Another Example: Parallel loop

```
#include <chrono>
#include <iostream>
#include <tbb/parallel_for.h>
#include <tbb/tbb.h>

using namespace std;
using namespace std::chrono;
using HRTimer = high_resolution_clock::time_point;

#define N (1 << 26)

void seq_incr(float* a) {
  for (int i = 0; i < N; i++) {
    a[i] += 10;
  }
}
```

```
void parallel_incr(float* a) {
  tbb::parallel_for(static_cast<size_t>(0),
 static_cast<size_t>(N),
  [&](size_t i) {
    a[i] += 10;
  });
}
```

Another Example: Parallel loop

```
int main() {
  float* a = new float[N];
  for (int i = 0; i < N; i++) {
    a[i] = static_cast<float>(i);
  }

  HRTimer start = high_resolution_clock:
:now();
  seq_incr(a);
  HRTimer end = high_resolution_clock::n
ow();
  auto duration = duration_cast<microsec
onds>(end - start).count();
  cout << "Sequential increment in " <<
duration << " us\n";
  start = high_resolution_clock::now();
  parallel_incr(a);
  end = high_resolution_clock::now();
  duration = duration_cast<microseconds>
(end - start).count();
  cout << "Intel TBB Parallel increment
in " << duration << " us\n";

  return EXIT_SUCCESS;
}
```

Another Example: Parallel loop

```
int main() {
  float* a = new float[N];
  for (int i = 0; i < N; i++) {
:
  seq_incr(a);
  HRTimer end = high_resolution_clock::now();
  auto duration = duration_cast<microseconds>(end - start).count();
  cout << "Sequential increment in " << duration << " us\n";
```

```
  start = high_resolution_clock::now();
  parallel_incr(a);
  end = high_resolution_clock::now();
  return EXIT_SUCCESS;
}
```

swarnendu@cse-BM1AF-BP1AF-BM6AF: ~/iitk-workspace/parallel-computing/src/tbb

```
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$ g++ -std=c++11 parallel_for.cpp -o parallel_for -ltbb
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$ ./parallel_for
Sequential increment in 139993 us
Intel TBB Parallel increment in 68843 us
swarnendu:~/iitk-workspace/parallel-computing/src/tbb$
```

Initializing the TBB Library

```
#include <tbb/task_scheduler_init.h>

using namespace tbb;

int main( ) {
  task_scheduler_init init;
  ...
  return 0;
}
```

Not required in recent versions, >= TBB 2.2

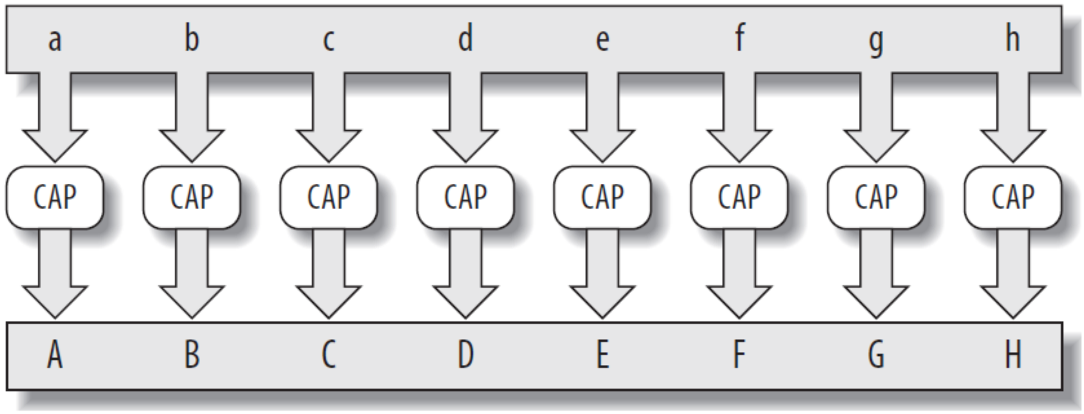
- Control when the task scheduler is constructed and destroyed.
- Specify the number of threads used by the task scheduler.
- Specify the stack size for worker threads

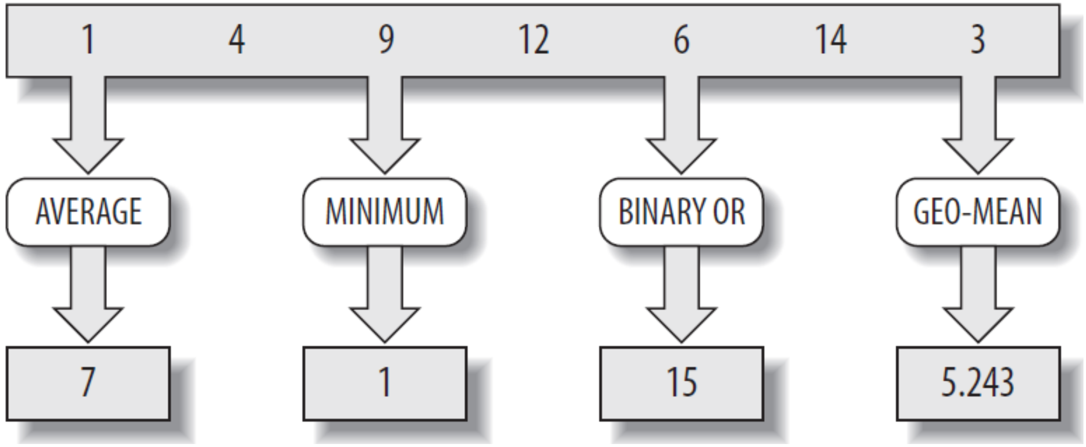
Thinking Parallel

- Decomposition
  - Decompose the problem into concurrent tasks
- Scaling
  - Identify concurrent tasks to keep processors busy
- Threads
  - Map tasks to threads
- Correctness
  - Ensure correct synchronization to shared resources

How to Decompose?

Data parallelism	**Task parallelism**





How to Decompose?

- Distinguishing just between data and task parallelism may not be perfect
  - Imagine TAs grading questions of varied difficulty
- Might need hybrid parallelism or pipelining or work stealing

OpenMP vs Intel TBB

OpenMP	**Intel TBB**
• Language extension consisting of pragmas, routines, and environment variables	• Library for task-based programming
• Supports C, C++, and Fortran	• Supports C++ with generics
• User can control scheduling policies	• Automated divide-and-conquer approach to scheduling, with work stealing
• OpenMP limited to specified types (for e.g., reduction)	• Generic programming is flexible with types

Generic Parallel Algorithms

Generic Programming

- Best known example is C++ Standard Template Library (STL)
- Enables distribution of useful high-quality algorithms and data structures
- Write best possible algorithm with fewest constraints (for e.g., `std::sort`)
- Instantiate algorithm to specific situation
  - C++ template instantiation, partial specialization, and inlining make resulting code efficient
- STL is not generally **thread-safe**

Generic Programming Example

- The compiler creates the needed versions

T must define a copy constructor and a destructor

```
template <typename T> T max (T x, T y) {
  if (x < y) return y;
  return x;
}

int main() {
  int i = max(20,5);
  double f = max(2.5, 5.2);
  MyClass m = max(MyClass("foo"), MyClass("bar"));
  return 0;
}
```

T must define operator <

Intel Threading Building Blocks Patterns

- High-level parallel and scalable patterns
  - `parallel_for`: load-balanced parallel execution of independent loop iterations
  - `parallel_reduce`: load-balanced parallel execution of independent loop iterations that perform reduction
  - `parallel_scan`: template function that computes parallel prefix

  - `parallel_while`: load-balanced parallel execution of independent loop iterations with unknown or dynamically changing bounds
  - `pipeline`: data-flow pipeline pattern
  - `parallel_sort`: parallel sort

Loop Parallelization

- `parallel_for` and `parallel_reduce`
    - Load-balanced, parallel execution of a fixed number of independent loop iterations
- `parallel_scan`
    - A template function that computes a prefix computation (also known as a scan) in parallel
    - `y[i] = y[i-1] op x[i]`

TBB parallel_for

```
void SerialApplyFoo(float a[], size_t n) {
  for (size_t i=0; i<n; ++i)
    foo(a[i]);
}
```

Class Definition for TBB parallel_for

```
#include "tbb/blocked_range.h"
class ApplyFoo {
  float *const m_a;
public:
  void operator()(const blocked_range<size_t>& r) const {
    float *a = m_a;
    for (size_t i=r.begin(); i!=r.end( ); ++i)
      foo(a[i]);
  }
  ApplyFoo(float a[]) : m_a(a) {}
};
```

Task

Body object

TBB parallel_for

```
#include "tbb/parallel_for.h"

void ParallelApplyFoo(float a[], size_t n) {
  parallel_for(blocked_range<size_t>(0,n,grainSize), ApplyFoo(a));
}
```

- parallel_for schedules tasks to operate in parallel on subranges of the original iteration space, using available threads so that:
  - Loads are balanced across the available processors
  - Available cache is used efficiently (similar to tiling)
  - Adding more processors improves performance of existing code

Requirements for parallel_for Body

- `Body::Body(const Body&)`
- Copy ctor
- `Body::~Body()`
- Dtor
- `void Body::operator() (Range& subrange) const`
- Apply the body to the subrange

Other Nuances

- The object has to have a copy constructor and destructor
- `operator()` should not modify the body
- `parallel_for` requires that the body object's `operator()` be declared as `const`
- Apply the body to a subrange

Splittable Concept

- A type is splittable if it has a splitting constructor that allows an instance to be split into two pieces
- `X::X(X& x, tbb::split)`
  - Split x into x and a newly constructed object
  - Attempt to split x roughly into two non-empty halves
  - Set x to be the first half, and the constructed object is the second half
  - Dummy argument distinguishes from a copy constructor
- Used in two contexts
  - Partition a range into two subranges that can be processed concurrently
  - Fork a body (function object) into two bodies that can run concurrently

Range is Generic

- `R::R(const R&)` — Copy constructor
- `R::~R()` — Destructor
- `bool R::is divisible() const` — True if splitting constructor can be called, false otherwise
- `bool R::empty() const` — True if range is empty, false otherwise
- `R::R(R& r, split)` — Splitting constructor. It splits range r into two subranges. One of the subranges is the newly constructed range. The other subrange is overwritten onto r.

More about Ranges

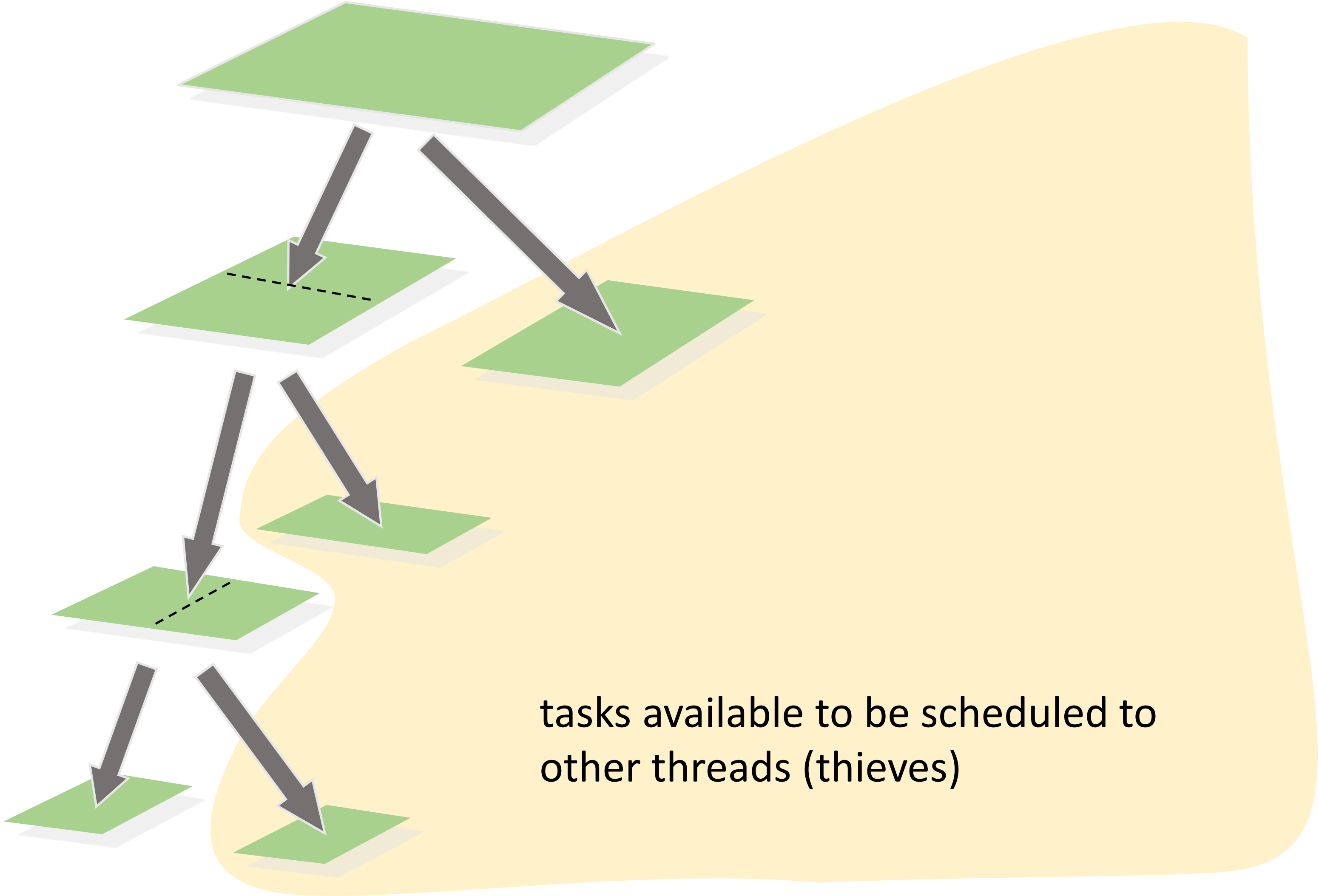
- `tbb::blocked_range<int>(0,8)` represents the index range {0,1,2,3,4,5,6,7}

```
// Construct half-open interval [0,30) with grainsize of 20
blocked_range<int> r(0,30,20);
assert(r.is_divisible());
// Call splitting constructor
blocked_range<int> s(r);
// Now r=[0,15) and s=[15,30) and both have a grainsize 20
// Inherited from the original value of r
assert(!r.is_divisible());
assert(!s.is_divisible());
```

More about Ranges

- A two-dimensional variant is `tbb::blocked_range2d`
  - Permits using a single parallel_for to iterate over two dimensions at once, which sometimes yields better cache behavior than nesting two one-dimensional instances of parallel_for

Splitting over 2D Range



Example 1

```
class ParallelAverage {
  const float* m_input;
  float* m_output;

public:
  ParallelAverage(float* a, float* b) : m_input(a), m_output(b) {}

  void operator()(const blocked_range<int>& range) const {
    for (int i = range.begin(); i != range.end(); ++i)
      m_output[i] = (m_input[i - 1] + m_input[i] + m_input[i + 1]) * (1 / 3.0f);
  }
};
…
ParallelAverage avg(a, par_out);
parallel_for(blocked_range<int>(1, N - 1), avg);
```

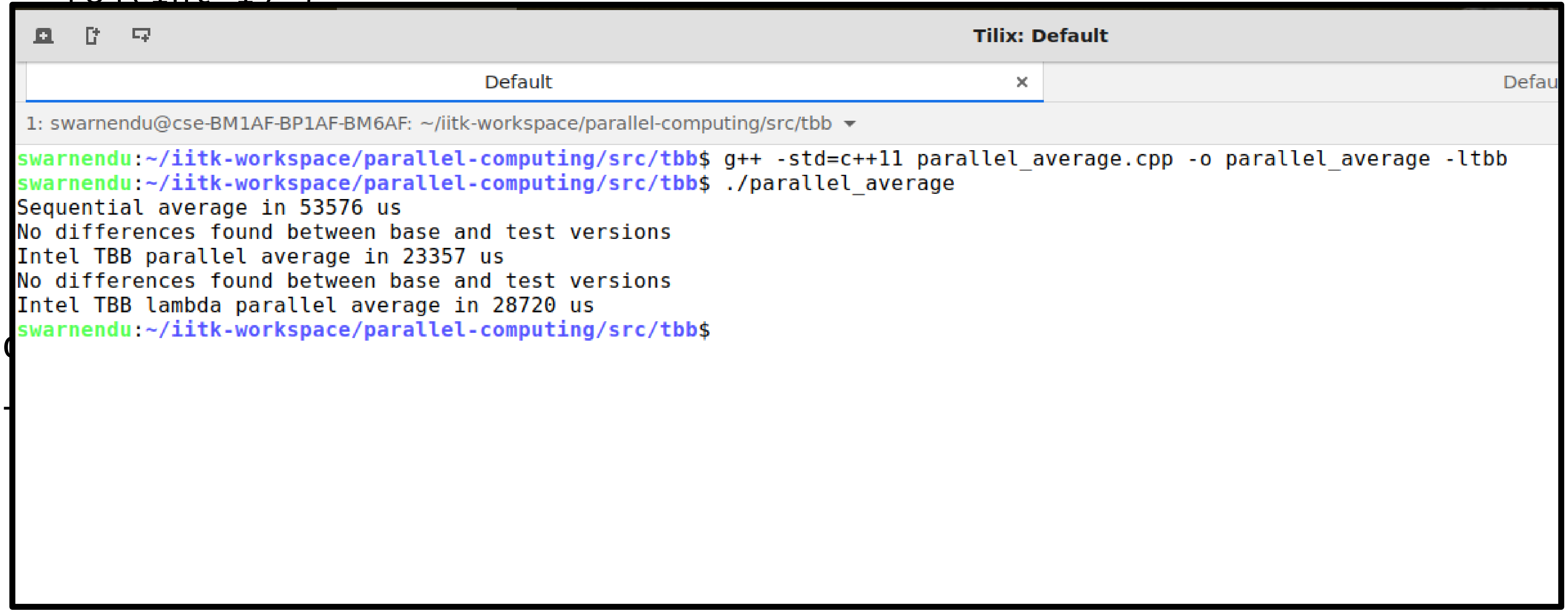
Example 1’

```
parallel_for(static_cast<int>(1), static_cast<int>(N - 1),
    [&](int i) {
      lamda_out[i] = (a[i - 1] + a[i] + a[i + 1]) * (1 / 3.0f);
    });
```

```
// Compile:
g++ -std=c++11 parallel_average.cpp -o parallel_average -ltbb
```

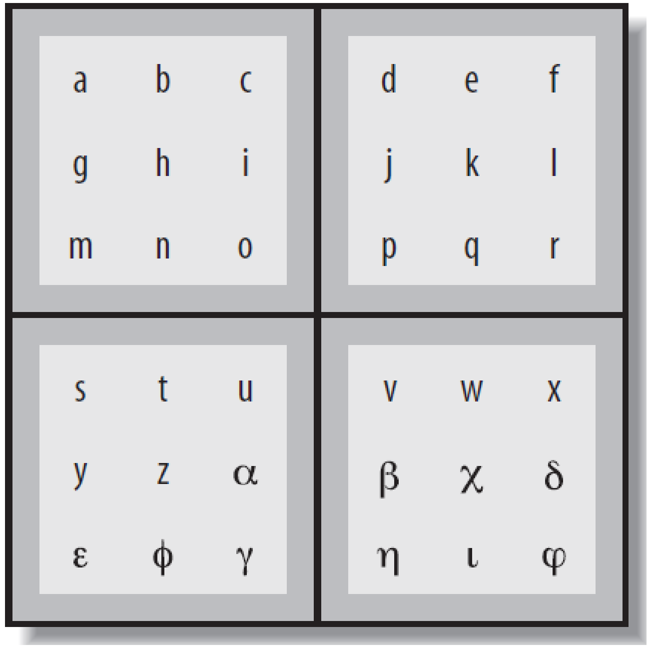
Example 1’

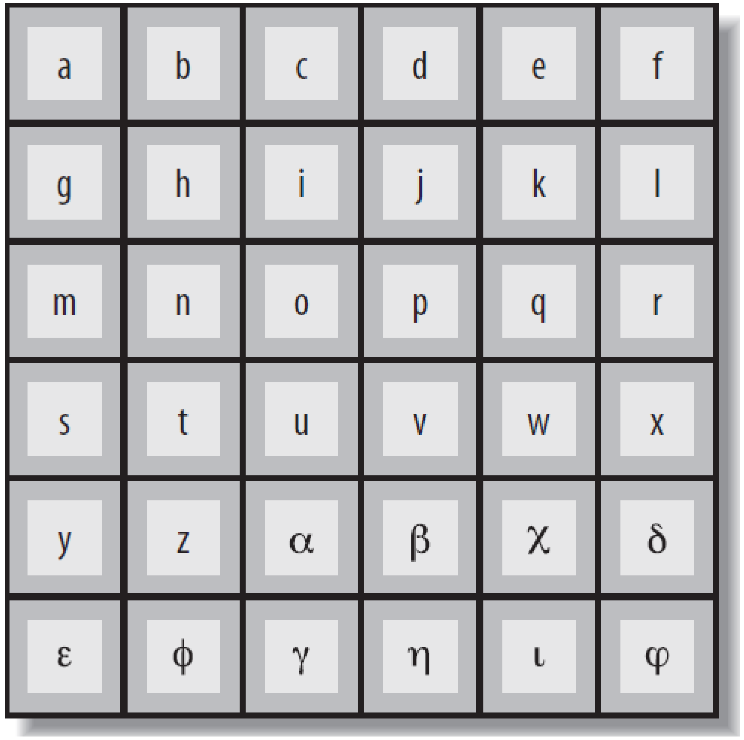
```
parallel_for(static_cast<int>(1), static_cast<int>(N - 1),
    [&](int i) {
```



Grain Size

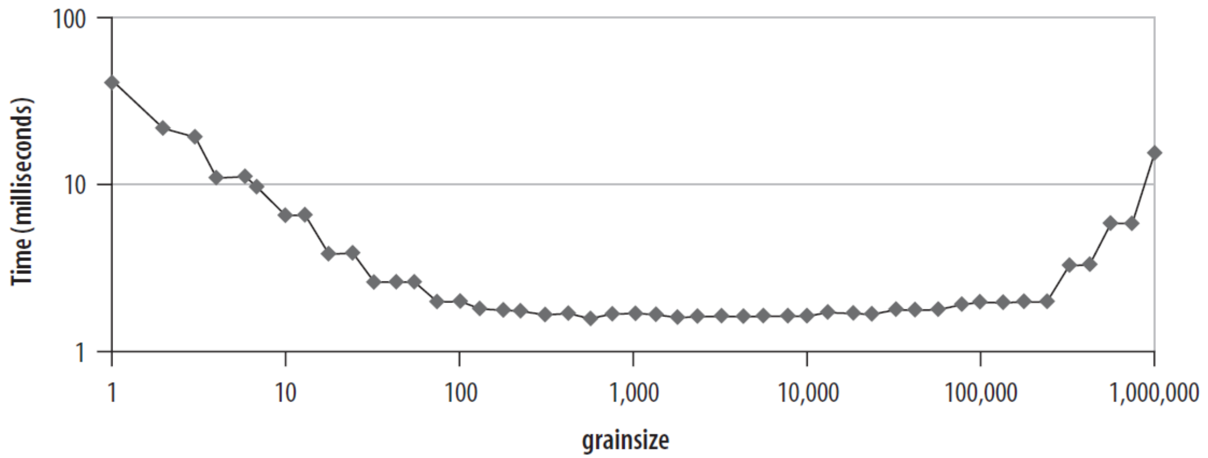
- Specifies the number of iterations for a chunk to give to a processor
- Impacts parallel scheduling overhead





Set the Right Grain Size

- Set the grainsize parameter higher than necessary
- Run your algorithm on one processor core
- Start halving the grainsize parameter
- See how much the algorithm slows down as the value decreases



Partitioner

- Range form of `parallel_for` takes an optional partitioner argument

```
parallel_for(r,f,simple_partitioner());
```

- `auto_partitioner`: Runtime will try to subdivide the range to balance load, this is the default
- `simple_partitioner`: Runtime will subdivide the range into subranges as finely as possible; method `is_divisible` will be false for the final subranges
- `affinity_partitioner`: Request that the assignment of subranges to underlying threads be similar to a previous invocation of `parallel_for` or parallel_reduce with the same `affinity_partitioner` object

Affinity Partitioner

- The computation does a few operations per data access
- The data acted upon by the loop fits in cache
- The loop, or a similar loop, is re-executed over the same data

```
void ParallelApplyFoo(float a[], size_t n) {
  static affinity_partitioner ap;
  parallel_for(blocked_range<size_t>(0,n), ApplyFoo(a), ap);
}
void TimeStepFoo(float a[], size_t n, int steps) {
  for (int t=0; t<steps; ++t)
    ParallelApplyFoo(a, n);
}
```

Partitioners

Partitioner	Description	Iteration Space
simple_partitioner	Chunk size bounded by grain size	$\lceil g/2 \rceil \leq chunksize \leq g$
auto_partitioner (default)	Automatic chunk size	$\lceil g/2 \rceil \leq chunksize$
affinity_partitioner	Automatic chunk size and cache affinity	

TBB parallel_reduce

- `#include <tbb/parallel_reduce.h>`

- `Value tbb::parallel_reduce(range, identity, func, reduction [, partitioner…]);`
  - Apply `func` to subranges in `range` and reduce the results suing the binary operator `reduction`
  - Parameters `func` and `reduction` can be lambda expressions

- `void parallel_reduce(range, body, [, partitioner…]`

Serial Reduction

```
float SerialSumFoo(float a[], size_t n) {
  float sum = 0;
  for (size_t i=0; i!=n; ++i)
    sum += Foo(a[i]);
  return sum;
}
```

Parallel Reduction

Assume iterations are independent

```
float ParallelSumFoo(const float *a, size_t n) {
  SumFoo sf(a);
  parallel_reduce(blocked_range<size_t>(0,n), sf);
  return sf.my_sum;
}
```

Parallel Reduction

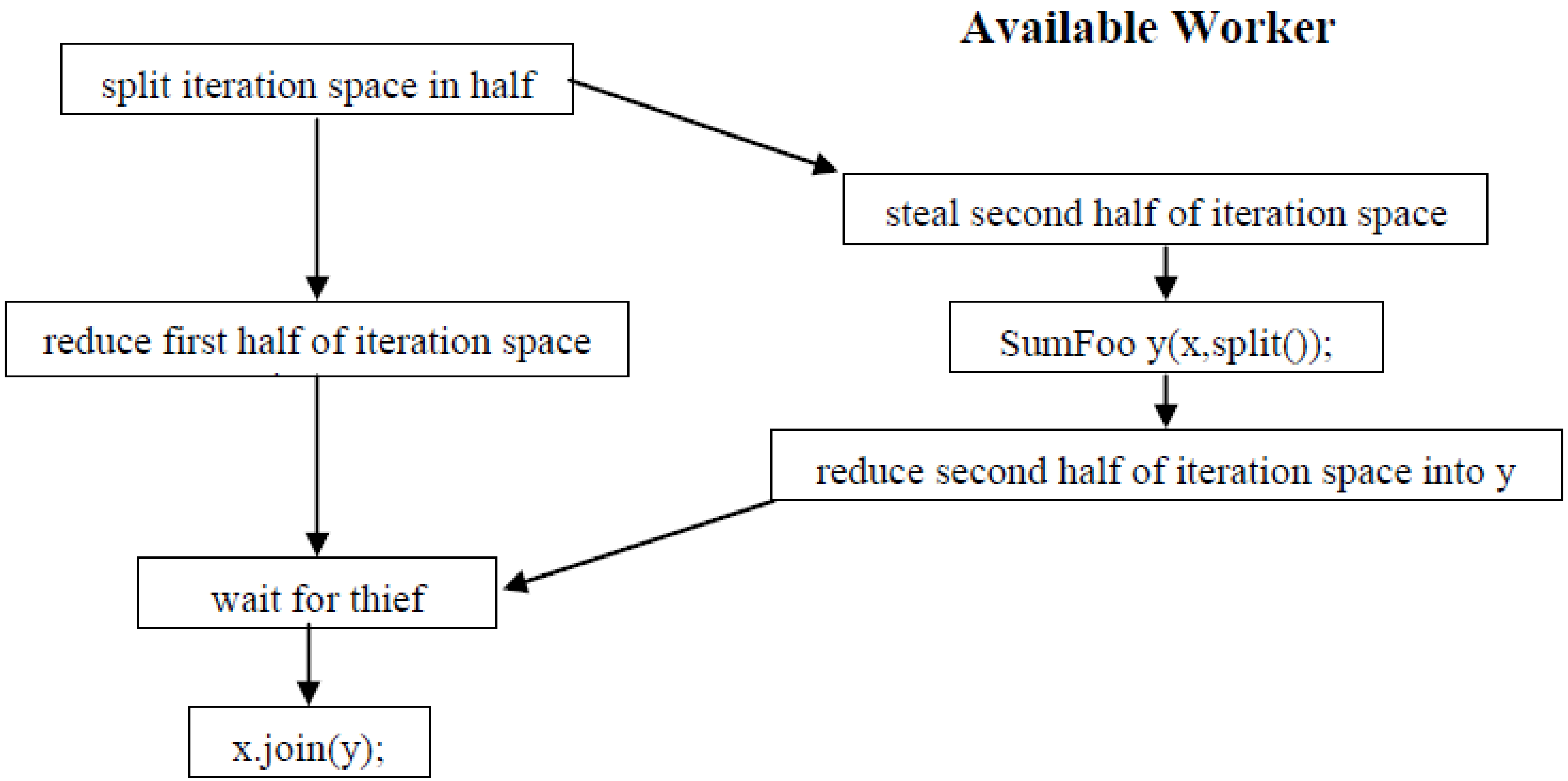
```
class SumFoo {
  float* my_a;
public:
  float my_sum;

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

```
  SumFoo(SumFoo& x, split) : my_a(x.my_a),
                             my_sum(0.0f)
{}

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

  SumFoo(float a[]) : my_a(a), my_sum(0.0f)
{}
};
```

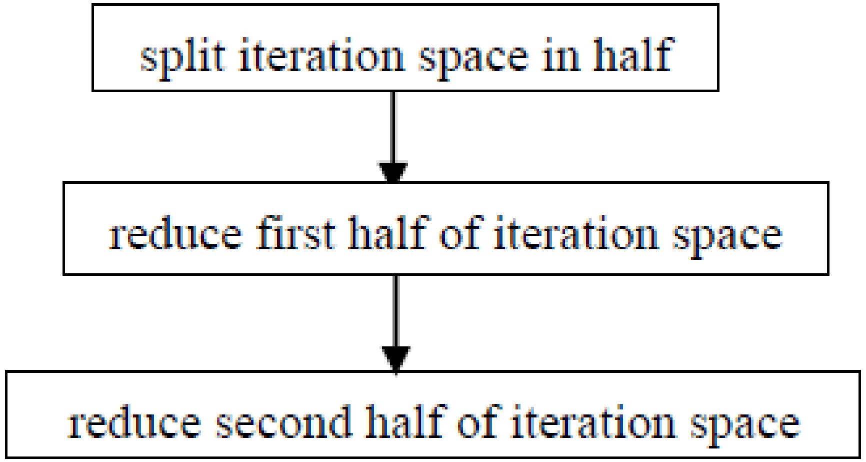
Differences between Parallel For and Reduce

parallel_for	**parallel_reduce**
• `operator()` is constant • Requires only a copy ctor	• `operator()` is not constant • Requires a splitting ctor for creating subtasks • Requires a `join()` function to accumulate the results of the subtasks

Graph of the Split-Join Sequence



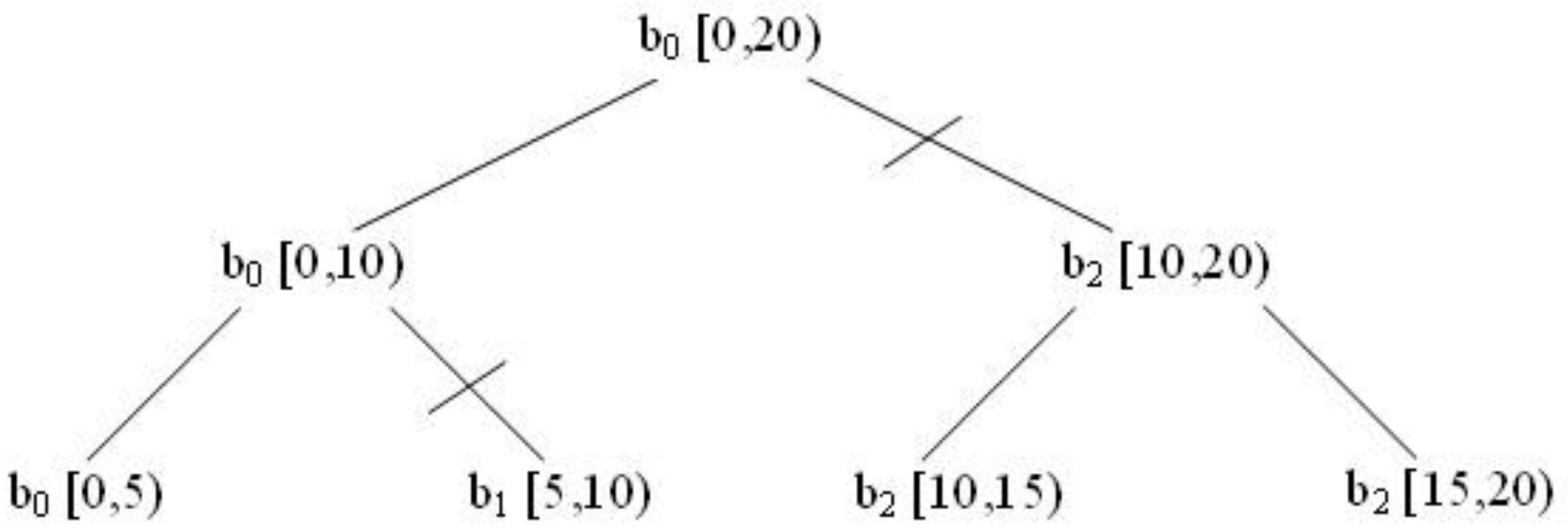
Graph of the Split-Join Sequence



No Available Worker

One Possible Execution of `parallel_reduce`

```
blocked_range<int>(0, 20, 5);
```



Incorrect Definition of Parallel Reduction

```
class SumFoo {
  float* my_a;
public:
  float my_sum;

  void operator()(const 
blocked_range<size_t>& r) {
    float *a = my_a;
    float sum = 0; // WRONG
    size_t end = r.end();
    for (size_t i=r.begin(); i!=end; ++i)
      sum += Foo(a[i]);
    my_sum = sum;
  }
```

```
  SumFoo(SumFoo& x, split) : my_a(x.my_a),
                             my_sum(0) {}

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

  SumFoo(float a[]) : my_a(a), my_sum(0) {}
};
```

TBB Task Scheduler

- Parallel algorithms make use of the task scheduler
  - TBB parallel algorithms map tasks onto threads automatically
  - Task scheduler manages the thread pool
    - Scheduler is *unfair* to favor tasks that have been most recent in the cache

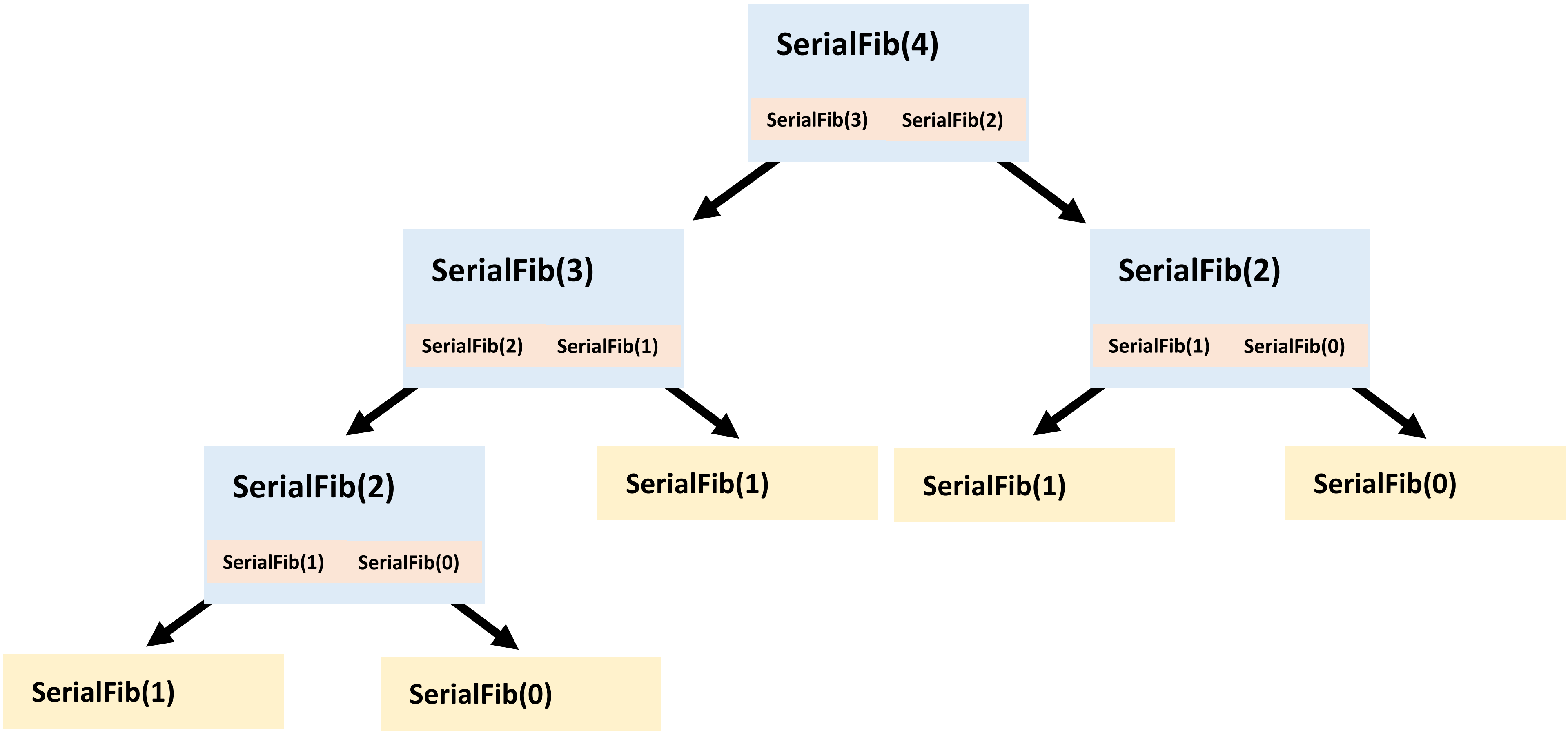
Problem	TBB Approach
Oversubscription	One scheduler thread per hardware thread
Fair scheduling	Non-preemptive unfair scheduling
High overhead	Programmer specifies tasks, not threads
Load imbalance	Work stealing balances load

Task-Based Programming

Serial Code

```
long SerialFib(long n) {
  if (n < 2)
    return n;
  else
    return SerialFib(n-1) + 
SerialFib(n-2);
}
```

Task Graph for Fibonacci Calculation



Task-Based Programming

Serial Code	TBB Code

Serial Code

```
long SerialFib(long n) {
  if (n < 2)
    return n;
  else
    return SerialFib(n-1) + SerialFib(n-2);
}
```

TBB Code

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

Description of FibTask Class

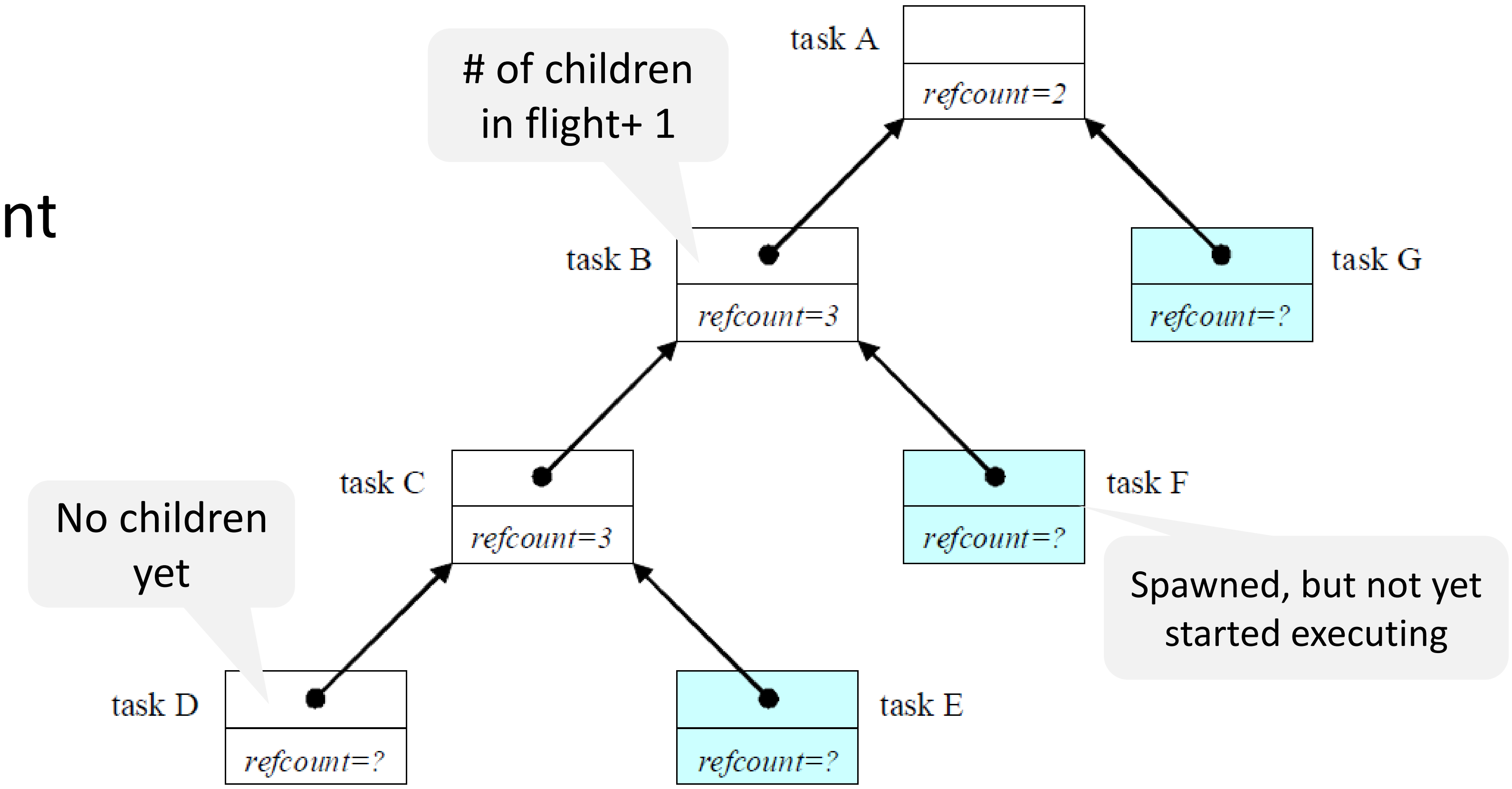
```
class FibTask: public task {
public:
  const long n;
  long* const sum;
  FibTask(long n_, long* sum_) :
n(n_), sum(sum_) {}

  task* execute() {
    if (n<CutOff) {
      *sum = SerialFib(n);
    }
    else {
      long x, y;
      FibTask& a = *new(
allocate_child()) FibTask(n-1,&x);
      FibTask& b = *new(
allocate_child()) FibTask(n-2,&y);
      // Convention: two children plus
      // one for the wait
      set_ref_count(3);
      spawn(b); // Return immediately
      spawn_and_wait_for_all(a);
      *sum = x+y;
    }
    return NULL;
  }};
```

Task Scheduler

- Engine that drives the parallel algorithms and task groups
- Each task has a method `execute()`
  - Definition should do the work of the task
  - Return either `NULL` or a pointer to the next task to run
- Once a thread starts running `execute()`, the task is bound to that thread until `execute()` returns
  - During that period, the thread serves other tasks only when it has to wait for some event

How Task Scheduling Works

- Scheduler evaluates a task graph
- Each task has a refcount
  - Number of tasks that have it as a successor

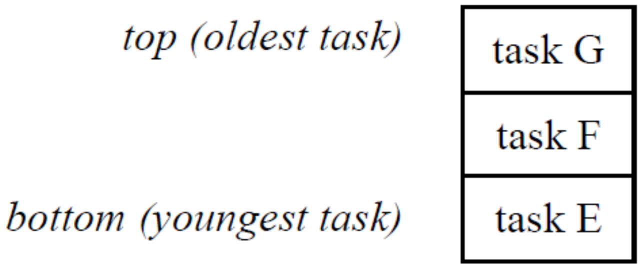


Task Scheduling

- Deeper tasks are more recently created, and will probably have better locality
- Breadth-first execution can have more parallelism if more physical threads are available
- TBB scheduler implements a hybrid of depth-first and breadth-first execution

Scheduling Algorithm

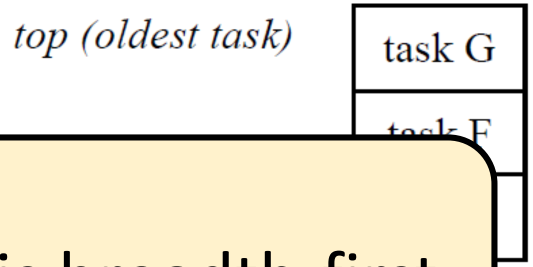
- There is a shared queue of tasks that were created
- Each thread has a “ready pool” of tasks it can run
    - The pool is basically a deque of task objects
- When a thread spawns a task, it pushes it to the end of its own deque



- Thread participates in task graph evaluation
    - Pops a task from the bottom of its deque
    - Steals a task from the top of another randomly deque

Scheduling Algorithm

- There is a shared queue of tasks that were created
- Each th… tasks i…
  - The… obj…
- When a thread spawns a task, it pushes it to the end of its own deque



Work done is depth-first and stealing is breadth-first

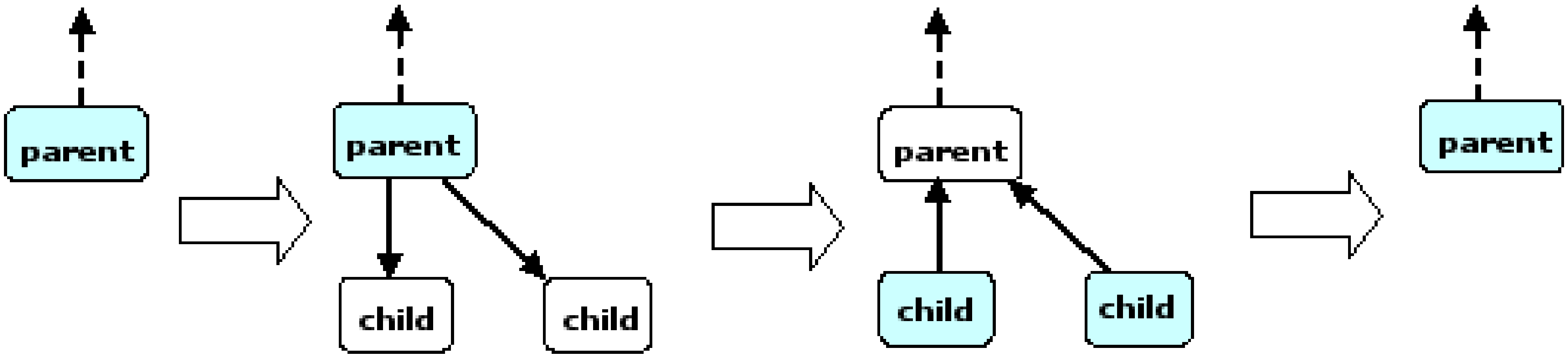
- Thread participates in task graph evaluation
  - Pops a task from the bottom of its deque
  - Steals a task from the top of another randomly deque

Parallelism in TBB

- Parallelism is generated by split/join pattern
  - Continuation-passing style and blocking style

Blocking Style

running tasks are shaded



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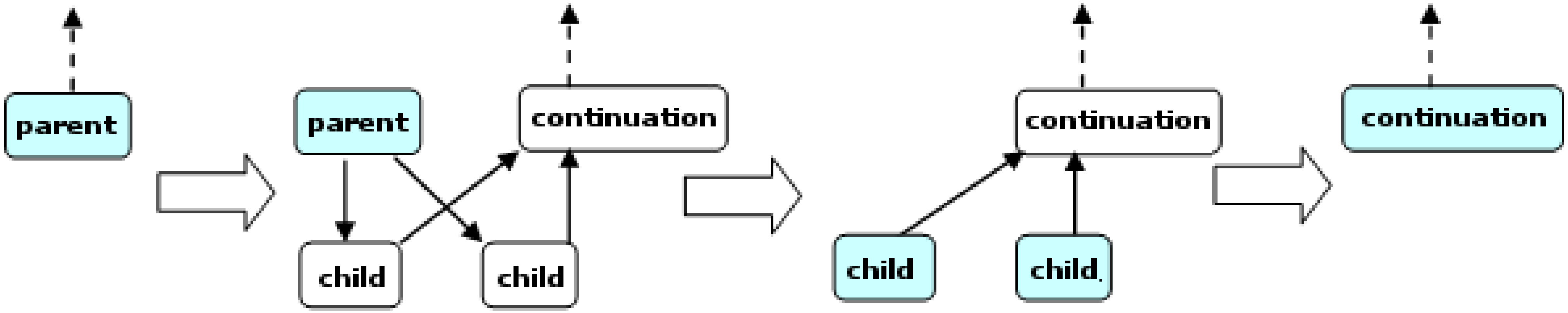
Disadvantages with Blocking Style

- The local variables of a blocked parent task live on the stack
  - Task is not destroyed until all its child are done, problematic for large workloads
- Worker thread that encounters `wait_for_all()` in parent task is doing no work

Continuation-passing Style

- Concept used in functional programming
- Parent task creates child tasks and specifies a continuation task to be executed when the children complete
  - Continuation inherits the parent's ancestor
- The parent task then exits; it does not block on its children
- The children subsequently run
- After the children (or their continuations) finish, the continuation task starts running
  - Any idle thread can run the continuation task

Continuation-passing Style



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Did Tasks Help?

```
class FibTask: public task {                    else {
public:
  const
  long*                                                                  ;
  FibTas                                                                 ;
n(n_), s                                                                 r the

  task*
    if (
      *s
    }
```

```
[ 76%] Built target tbb_parallel_incr
[ 80%] Built target tbb_parallel_change
[ 83%] Built target transformations_example2
[ 86%] Built target transformations_example1
[ 90%] Built target vectorization-sse
[ 93%] Built target vectorization-avx512
[100%] Built target vectorization1
[100%] Built target vectorization-avx
~/i/p/build (master|+2) $ ./bin/tbb_fibonacci
Sequential Fibonacci in 27970585 us
Task-based Fibonacci in 7554692 us
~/i/p/build (master|+2) $
```

Concurrent Containers

Concurrent Containers

- TBB Library provides highly concurrent containers
  - STL containers are not concurrency-friendly: attempt to modify them concurrently can corrupt container
  - Standard practice is to wrap a lock around STL containers
    - Turns container into serial bottleneck
- Library provides fine-grained locking or lockless implementations
  - Worse single-thread performance, but better scalability.
  - Can be used with the library, OpenMP, or native threads.

Concurrency-Friendly Interfaces

- Some STL interfaces are inherently not concurrency-friendly
- For example, suppose two threads each execute

```
extern std::queue q;
if(!q.empty()) {
    item=q.front();
    q.pop();
}
```

At this instant, another thread might pop last element.

- Solution: `concurrent_queue` has `try_pop()`

Concurrent TBB Containers

- TBB containers offer a high level of concurrency
  - Fine-grained locking
    - Multiple threads operate by locking only portions they really need to lock
    - As long as different threads access different portions, they can proceed concurrently
  - Lock-free techniques
    - Different threads account and correct for the effects of other interfering threads

Serial vs Concurrent Queue

std::queue	tbb::concurrent_queue

`extern std::queue<T> serialQ;`
`T item;`
`if (!serialQ.empty()) {`
`  item = serialQ.front();`
`  serialQ.pop_front();`
`  // process item`
`}`
	`extern concurrent_queue<T> myQ;`
	`T item;`
	`if (myQ.try_pop(item)) {`
	`  // process item`
	`}`

Concurrent Queue Container

- `concurrent_queue<T>`
  - FIFO data structure that permits multiple threads to concurrently push and pop items
  - Method `push(const T&)` places copy of item on back of queue. The method waits until it can succeed without exceeding the queue's capacity.
  - `try_push(item)` pushes `item` only if it would not exceed the queue's capacity
  - `pop(item)` waits until it can succeed
  - Method `try_pop(T&)` pops value if available, otherwise it does nothing
  - If a thread pushes values A and B in order, another thread B will see values A and B in order

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Concurrent Queue Container

- concurrent_queue<T>
  - Method size() returns signed integer
    - Number of push operations started minus the number of pop operations started
    - If size() returns –n, it means n pops await corresponding pushes on an empty queue
  - Method empty() returns size() == 0
    - May return true if queue is empty, but there are pending pop()

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Concurrent Queue Container Example

```
#include “tbb/concurrent_queue.h”
using namespace tbb;
int main () {
   concurrent_queue<int> queue;
   int j;
   for (int i = 0; i < 10; i++)
      queue.push(i);
   while (!queue.empty()) {
      queue.pop(&j);
      printf(“from queue: %d\n”, j);
   }
   return 0;
}
```

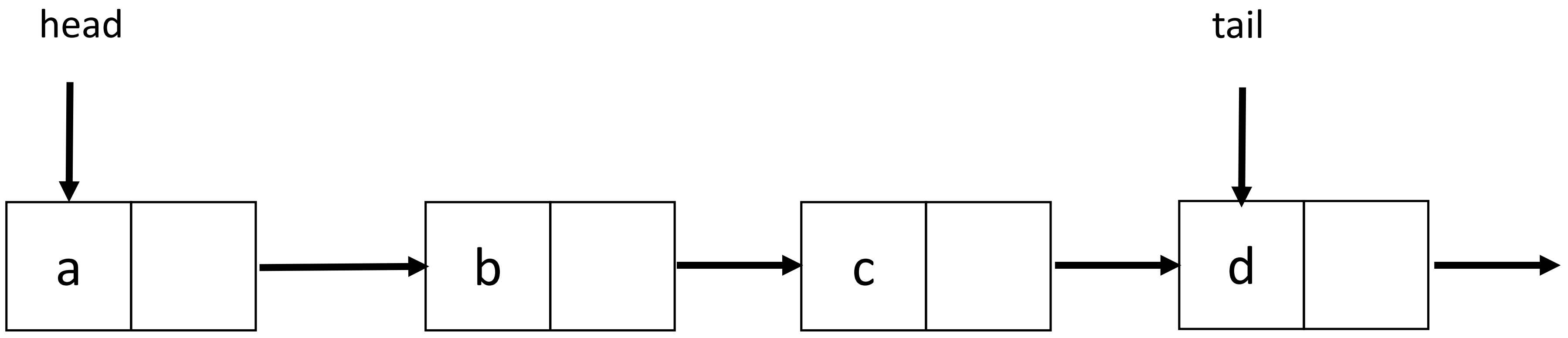
- Simple example to enqueue and print integers

ABA Problem

- A thread checks a location to be sure the value is *A* and proceeds with an update only if the value was *A*

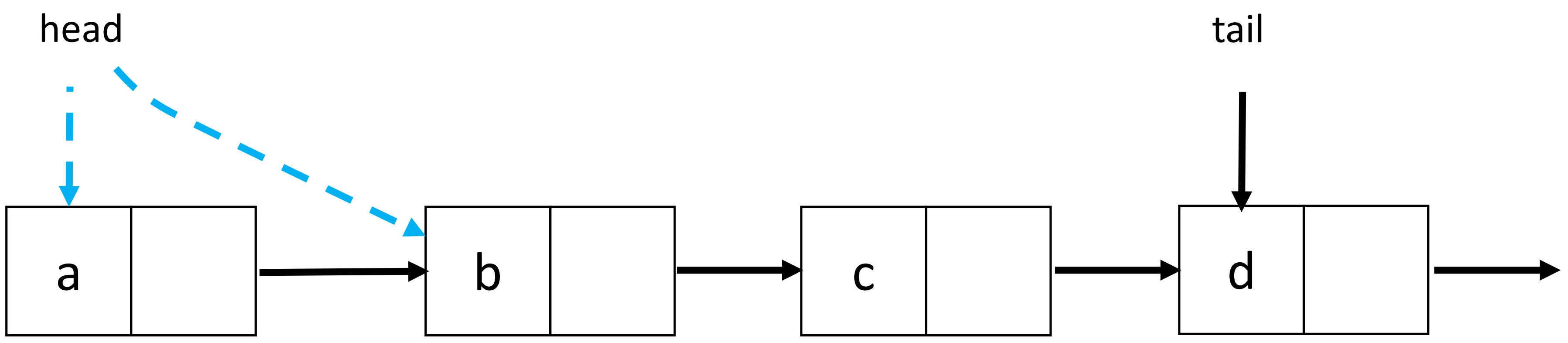
- Thread T1 reads value A from shared memory location
- Other threads update A to B, and then back to A
- T1 performs `compare_and_swap()` and succeeds

Example of ABA Problem



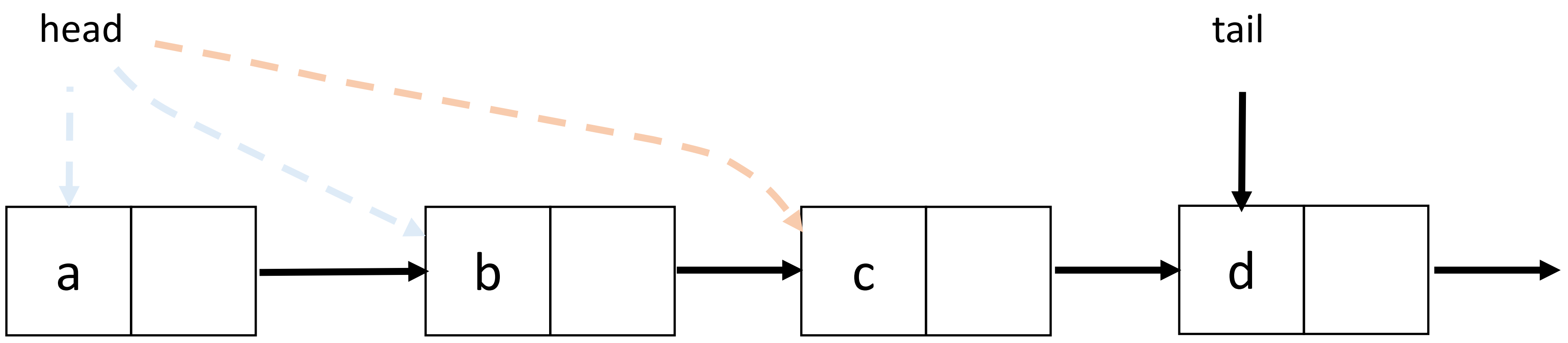
- Thread 1 will execute deq(a)

Example of ABA Problem



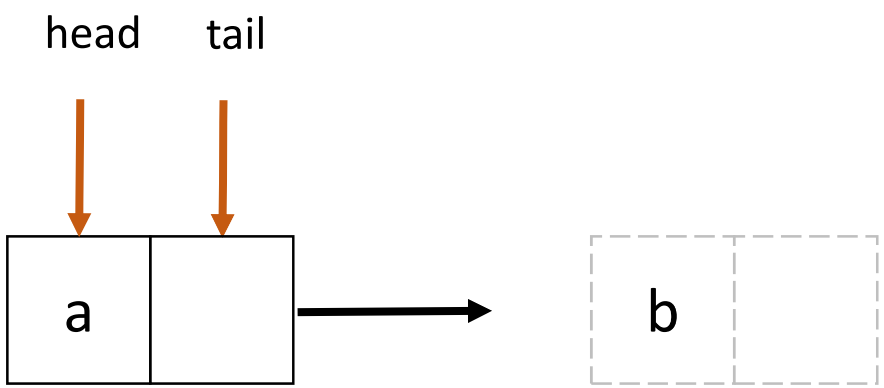
- Thread 1 is executing deq(a), gets delayed

Example of ABA Problem



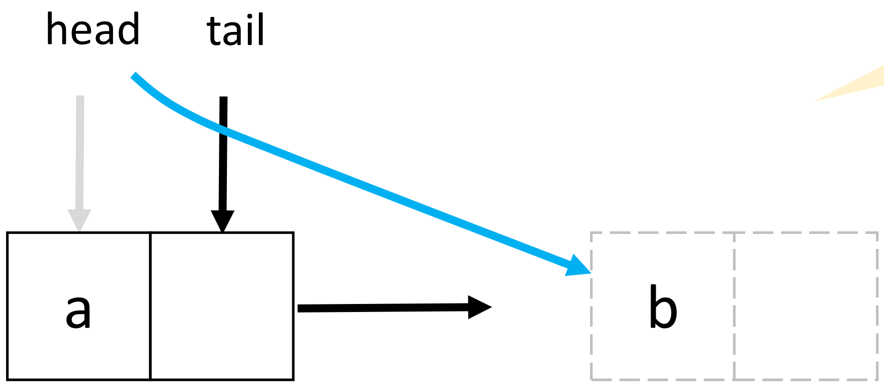
- Other threads execute deq(a, b, c, d), then execute enq(a)

Example of ABA Problem



- Other threads execute deq(a, b, c, d), then execute enq(a)

Example of ABA Problem



`head.compareAndSet(first, next)`

- Thread 1 is executes CAS for deq(a), CAS succeeds

Concurrent Vector Container

- `concurrent_vector<T>`
  - Dynamically growable array of T
    - Method `grow_by(size_type delta)` appends `delta` elements to end of vector
    - Method `grow_to_at_least(size_type n)` adds elements until vector has at least n elements
    - Method `push_back(x)` safely appends x to the array
    - Method `size()` returns the number of elements in the vector
    - Method `empty()` returns `size() == 0`
  - Never moves elements until cleared
    - Can concurrently access and grow
    - Method `clear()` is not thread-safe with respect to access/resizing

Concurrent Vector Container Example

- Append a string to the array of characters held in `concurrent_vector`
  - Grow the vector to accommodate new string
    - `grow_by()` returns old size of vector (first index of new element)
  - Copy string into vector

```
void Append(concurrent_vector<char>& V, const char* string) {
   size_type n = strlen(string)+1;
   memcpy(&V[V.grow_by(n)], string, n+1);
}
```

Concurrent HashMap Container

- `concurrent_hash_map<Key,T,HashCompare>`
  - Maps Key to element of type T
  - Define class HashCompare with two methods
    - `hash()` maps Key to hashcode of type size_t
    - `equal()` returns true if two Keys are equal
  - Enables concurrent `find()`, `insert()`, and `erase()` operations
    - An `accessor` grants read-write access
    - A `const_accessor` grants read-only access
    - Lock released when smart pointer is destroyed, or with explicit release()

Concurrent HashMap Container Example

```
// Structure that defines hashing and comparison operations for user's type
struct MyHashCompare {
  static size_t hash( const string& x ) {
    size_t h = 0;
    for (const char* s = x.c_str(); *s; ++s )
      h = (h*17)^*s;
    return h;
  }
  static bool equal( const string& x, const string& y ) {
    return x==y;
  }
};
```

Concurrent HashMap Container Example

```
// A concurrent hash table that maps strings to ints
typedef concurrent_hash_map<string,int,MyHashCompare> StringTable;
// Function object for counting occurrences of strings
struct Tally {
  StringTable& table;
  Tally(StringTable& table_) : table(table_) {}
  void operator()( const blocked_range<string*> range ) const {
    for (string* p=range.begin(); p!=range.end(); ++p) {
      StringTable::accessor a;
      table.insert(a, *p);
      a->second += 1;
    }
  }
};
```

Concurrent HashMap Container Example

```
const size_t N = 1000000;
string Data[N];

void CountOccurrences() {
  StringTable table;
  parallel_for(blocked_range<string*>(Data, Data+N, 1000), Tally(table));

  for (StringTable::iterator i=table.begin(); i!=table.end(); ++i)
    printf("%s %d\n",i->first.c_str(),i->second);
}
```

Scalable Memory Allocation

Scalable Memory Allocators

- Serial memory allocation can easily become a bottleneck in multithreaded applications
  - Threads require mutual exclusion into shared global heap
  - In the old days, a single-process lock was used for `malloc()` and `free()` in `libc`
  - Many `malloc()` alternatives are now available `(jemalloc(), tcmalloc())`
  - New C++ standards are trying to deal with this
    - Smart pointers, `std::aligned_alloc (C++17)`
- False sharing - threads accessing the same cache line
  - Even accessing distinct locations, cache line can ping-pong

Scalable Memory Allocators

- TBB offers two choices for scalable memory allocation
  - Similar to the STL template class `std::allocator`
  - `scalable_allocator`
    - Offers scalability, but not protection from false sharing
    - Memory is returned to each thread from a separate pool
  - `cache_aligned_allocator`
    - Two objects allocated by this allocator are guaranteed to not have false sharing
    - Always allocates on a cache line, increases space usage

```
std::vector<int, cache_aligned_allocator<int>>
```

Methods for `scalable_allocator`

- `#include <tbb/scalable_allocator.h>`

- Scalable versions of malloc, free, realloc, calloc
  - `void *scalable_malloc(size_t size);`
  - `void scalable_free(void *ptr);`
  - `void *scalable_realloc(void *ptr, size_t size);`
  - `void *scalable_calloc(size_t nobj, size_t size);`

Synchronization Primitives

Synchronization Primitives

- Critical regions of code are protected by scoped locks
  - The range of the lock is determined by its lifetime (scope)
  - Does not require the programmer to remember to release the lock
  - Leaving lock scope calls the destructor, making it exception safe
- Mutual exclusion is implemented with mutex objects and locks
  - Mutex is the object on which a thread can acquire a lock
- Several mutex variants are available

Mutex Example

```
spin_mutex mtx; // Construct unlocked mutex
{
  // Create scoped lock and acquire lock on mtx
  spin_mutex::scoped_lock lk(mtx);
  // Critical section
} // Lock goes out of scope, destructor releases the lock
```

```
spin_mutex::scoped_lock lk;
lk.acquire(mtx);
// Critical section
lk.release();
```

Atomic Execution

```
atomic<int> i;
. . .
int z = i.fetch_and_add(2);
```

- `atomic<T>`
  - T should be integral type or pointer type
  - Full type-safe support for 8, 16, 32, and 64-bit integers

Operations	Semantics
`“= x” and “x = “`	read/write value of x
`x.fetch_and_store(y)`	z = x, y = x, return z
`x.fetch_and_add(y)`	z = x, x += y, return z
`x.compare_and_swap(y, p)`	z = x, if (x == p) { x = y, return z; }

Summary

- Intel Threading Building Blocks is a data parallel programming model for C++ applications
  - Used for computationally intense code
  - Uses generic programming
- Intel Threading Building Blocks provides
  - Generic parallel algorithms
  - Highly concurrent containers
  - Low-level synchronization primitives
  - A task scheduler that can be used directly
- Learn when to use or mix Intel TBB, OpenMP or explicit threading

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