CS 610: Intel Threading Building Blocks

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

Parallel Programming Overview

Find parallelization opportunities in the problem

- Decompose the problem into parallel units

Create parallel units of execution

- Manage efficient execution of the parallel units

Problem may require inter-unit communication

- Communication between threads, cores, …

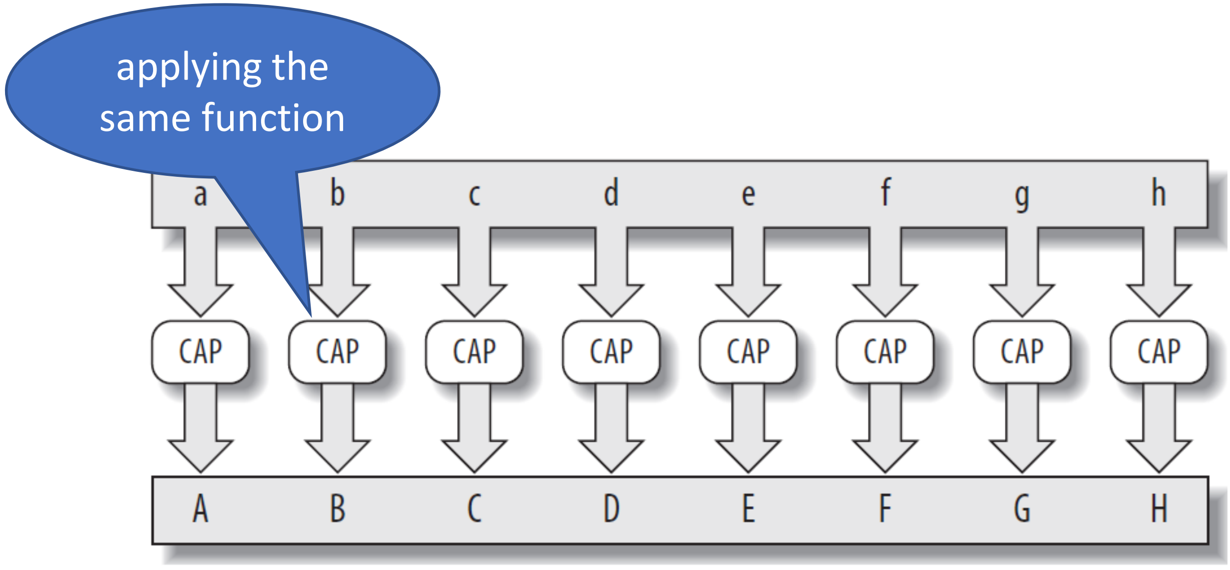
How to "Think Parallel"?

- Decomposition
  - Decompose the problem into concurrent logical tasks
- Scaling
  - Identify concurrent tasks to keep processors busy
- Choose and utilize appropriate algorithms
- Threads
  - Map tasks to threads
- Correctness
  - Ensure correct synchronization to shared resources

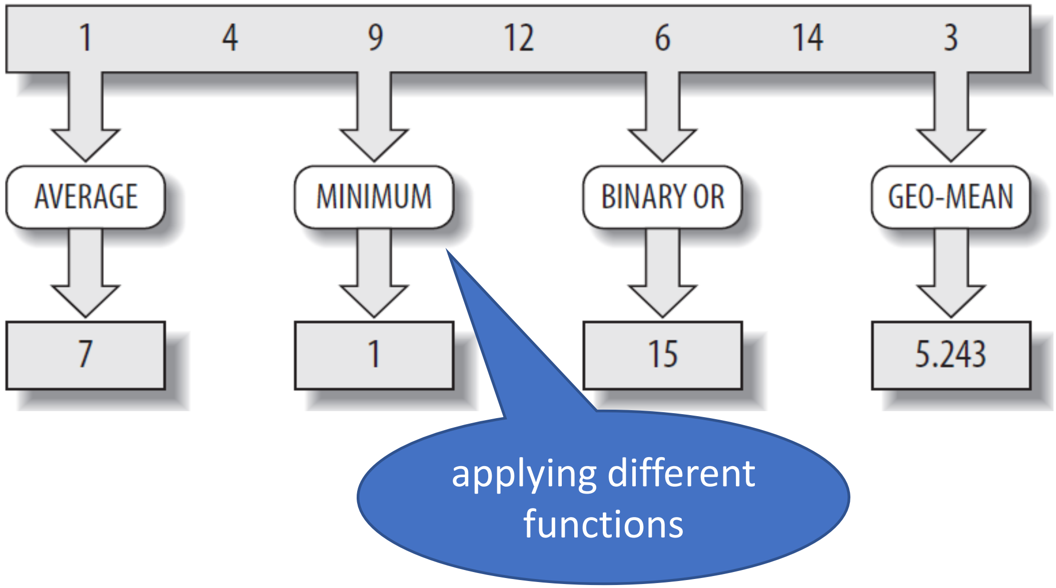
- How much parallelism is there in an application?
  - Depends on the size of the problem
  - Depends on whether the algorithm is easily parallelizable

How to Decompose?

Data parallelism



Task parallelism



Data Parallelism vs Task Parallelism

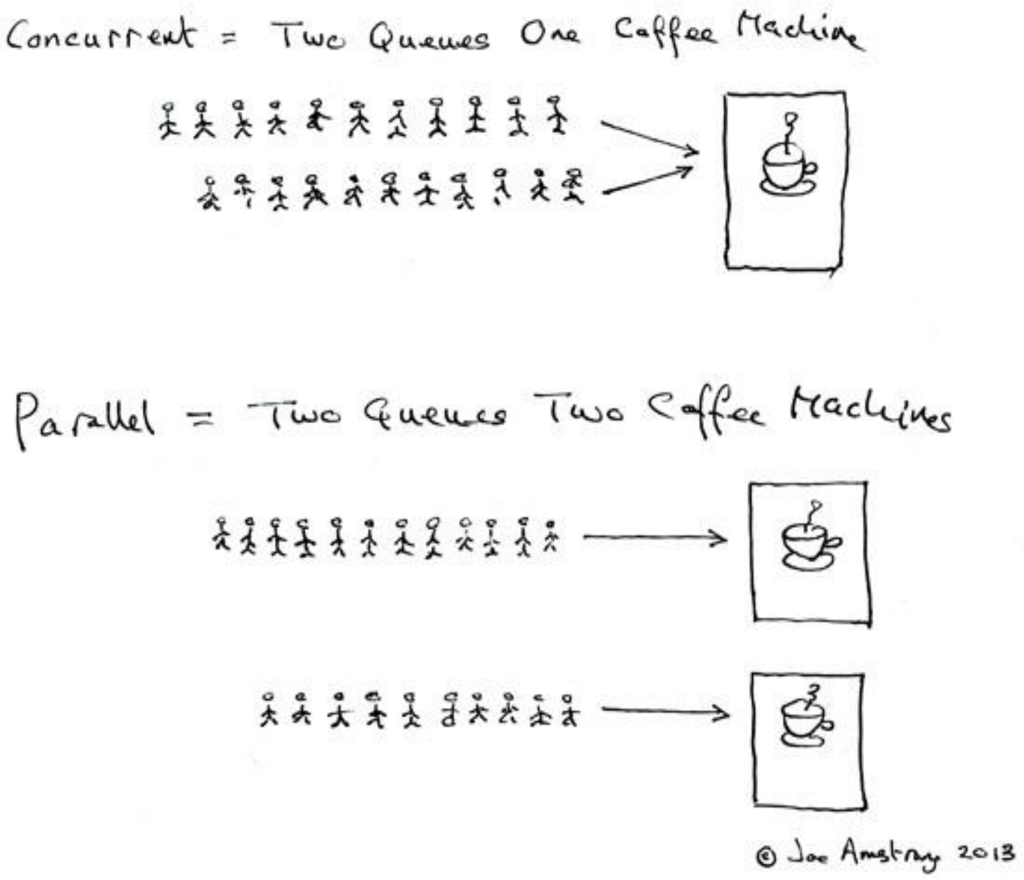
Data Parallelism	Task parallelism
• Same operations performed on different subsets of same data	• Different operations are performed on the same or different data
• Synchronous computation	• Asynchronous computation
• **Expected speedup is more** as there is only one execution thread operating on all sets of data	• **Expected speedup is less** as each processor will execute a different thread or process
• Amount of parallelization is proportional to the input data size	• Amount of parallelization is proportional to the number of independent tasks
• Designed for optimum load balance	• Load balancing depends on the availability of the hardware and scheduling algorithms like static and dynamic scheduling

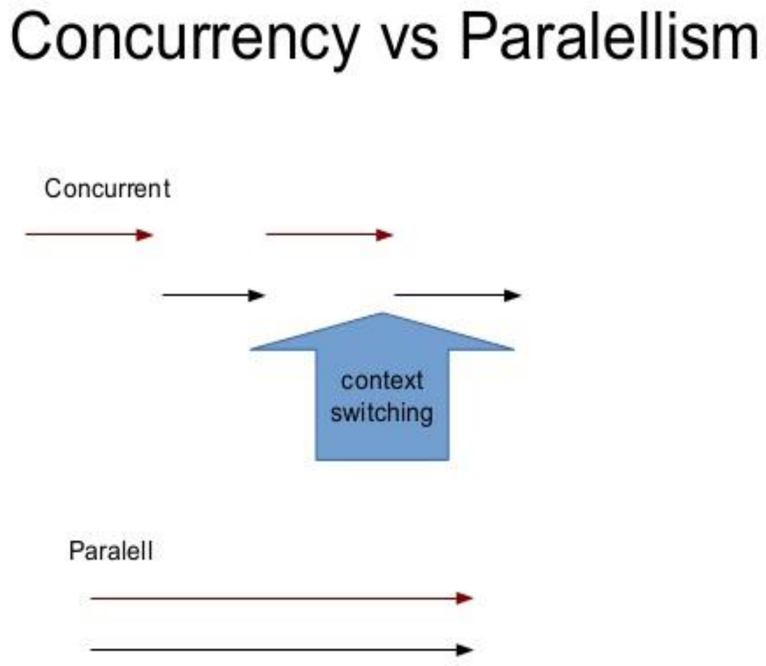
Data Parallelism vs Task Parallelism

- Distinguishing just between data and task parallelism may not be perfect
  - Imagine `p` TAs grading `m` questions of varied difficulty for a class with `n` students
  - Each TA grading `n/p` copies is data parallelism
  - Each TA grading one question for `n` students is task parallelism

- Might need hybrid parallelism or work stealing
  - Multiple TAs may grade a lengthy question

Parallelism vs Concurrency





Parallelism vs Concurrency

Parallel programming

- Use additional resources to speed up computation
- Performance perspective

Concurrent programming

- Correct and efficient control of access to shared resources
- Correctness perspective

Distinction is not absolute

Approaches to Parallelism

- Multithreading – “assembly language of parallel programming”
- New inherently-parallel languages (e.g., Cilk Plus, X10, and Chapel)
  - New concepts, may be difficult to get widespread acceptance
- Language extensions (e.g., OpenMP)
  - Easy to extend, but requires compiler or preprocessor support
- Library (e.g., C++ STL and Intel TBB)
  - Works with existing environments, usually no new compiler is needed

Challenges with a multithreaded implementation

- 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

- Programming at the abstraction of tasks is an appealing alternative
- A task is a sequence of instructions (logical unit of work) that can be processed concurrently with other tasks in the same program
  - Interleaving of tasks is constrained by control and data dependences
  - Tasks are lighter-weight compared to logical threads

Intel Threading Building Blocks

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 legacy release is 2020 Update 3, now packaged as oneTBB (part of oneAPI toolkit)

https://oneapi-src.github.io/oneTBB/

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 task 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

<u>Generic Parallel algorithms</u>

`parallel_for, parallel_for_each, parallel_reduce, parallel_scan, parallel_do, pipeline, parallel_pipeline, parallel_sort, parallel_invoke`

<u>Task scheduler</u>

`task_group, structured_task_group, task, task_scheduler_init`

<u>Concurrent containers</u>

`concurrent_hash_map`
`concurrent_unordered_map`
`concurrent_queue`
`concurrent_bounded_queue`
`concurrent_vector`

<u>Synchronization primitives</u>

atomic operations, condition_variable

various flavors of mutexes

<u>Utilities</u>

`tick_count`
`tbb_thread`

<u>Memory allocators</u>

`tbb_allocator, cache_aligned_allocator, scalable_allocator, zero_allocator`

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

An 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;
  });

}
```

An 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::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();
  duration = duration_cast<microseconds>(end - start).count();
  cout << "Intel TBB Parallel increment in " << duration << " us\n";

  return EXIT_SUCCESS;
}
```

An Example: Parallel loop

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

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

```
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$
```

```
:
  seq_incr(a);
  HRTimer end = high_resolution_clock::now();
  auto duration = duration_cast<microseconds>(end - start).count();
  cout << "Sequential increment in " << duration << " us\n";
```

```
  return EXIT_SUCCESS;
}
```

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

- 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

Pthreads vs Intel TBB

Pthreads	Intel TBB
• Low-level wrapper over OS support for threads	• Provides high-level constructs and parallel patterns

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

TBB Frontend

Generic Programming

- Enables distribution of useful high-quality algorithms and data structures
- Write the 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

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 prefix scan in parallel (`y[i] = y[i-1] op x[i]`)
`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

parallel_for

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

Class Definition for `parallel_for`

```
#include "tbb/blocked_range.h"
#include …

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

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
  - Work is load 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

- The object has to have a copy constructor and destructor if memory is dynamically allocated
  - `Body::Body(const Body&)`
  - `Body::~Body()`
- `operator()` should not modify the body
  - `void Body::operator() (Range& subrange) const`
  - `parallel_for` requires that the body object's `operator()` be declared as `const`
  - Apply the body to a subrange

Example of `parallel_for`

```
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);
```

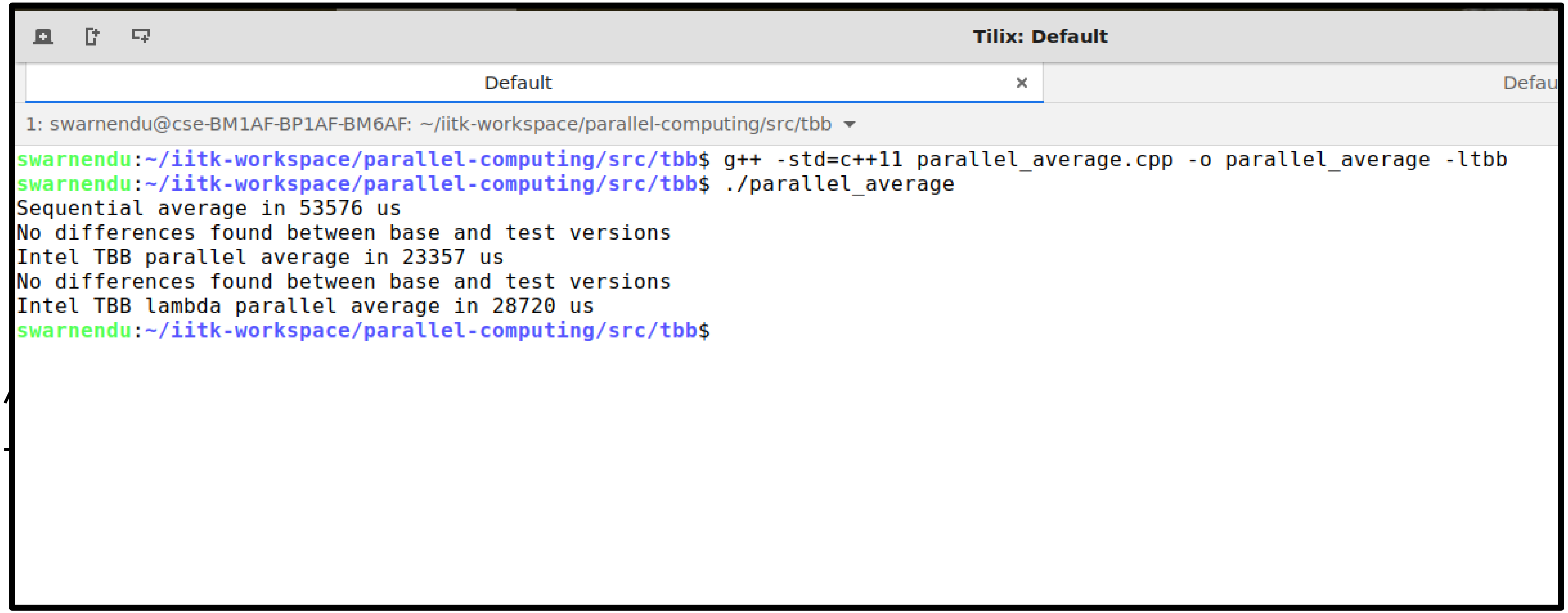
Example of `parallel_for` with Lambda

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

```
parallel_for(static_cast<int>(1), static_cast<int>(N - 1),
```




```
//
g
```

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

- Copy constructor
- Destructor
- True if splitting constructor can be called, false otherwise
- True if range is empty, false otherwise
- 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

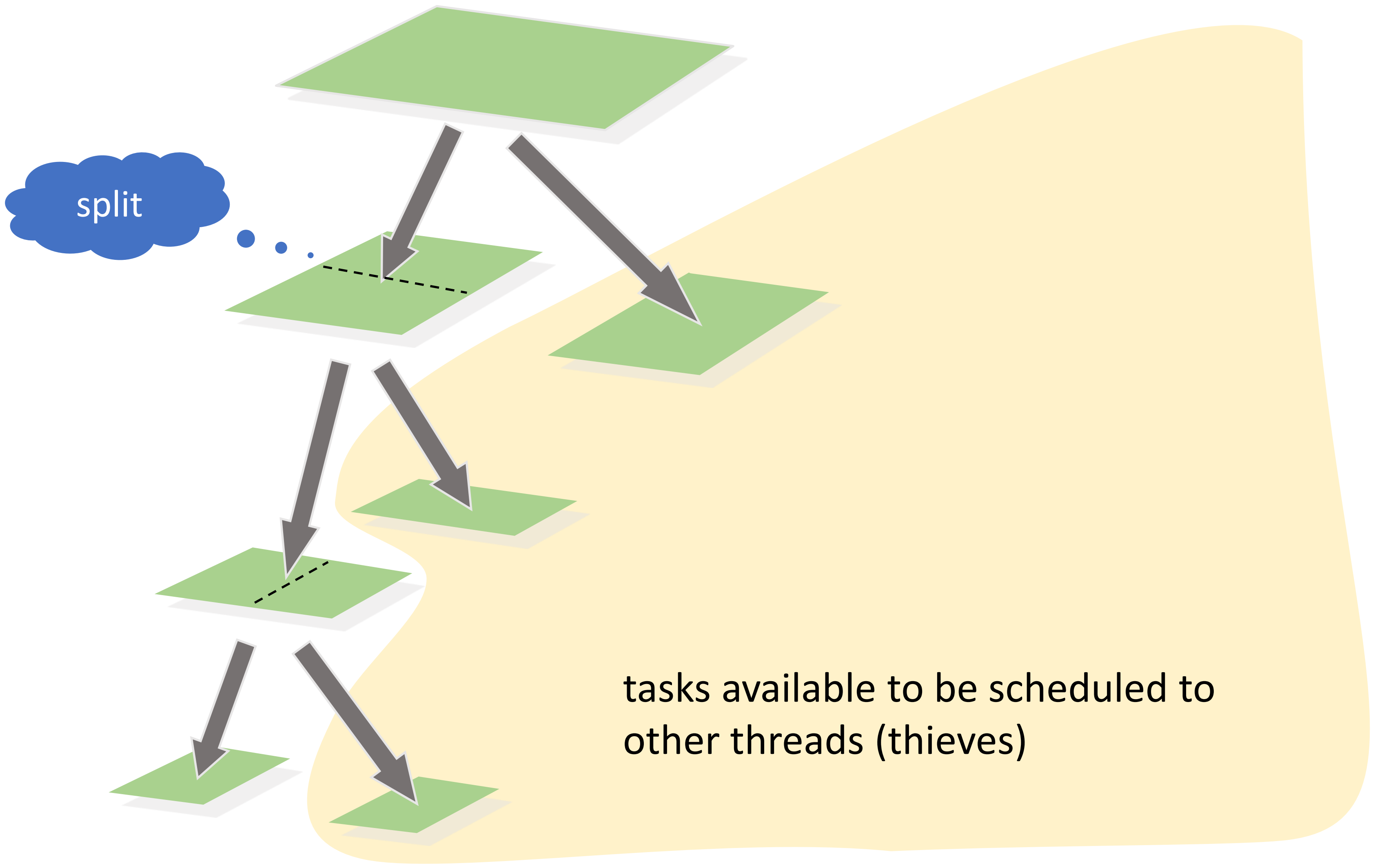
- `tbb::blocked_range<int>(0,8)` represents the index range {0,1,2,3,4,5,6,7}

```
// 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

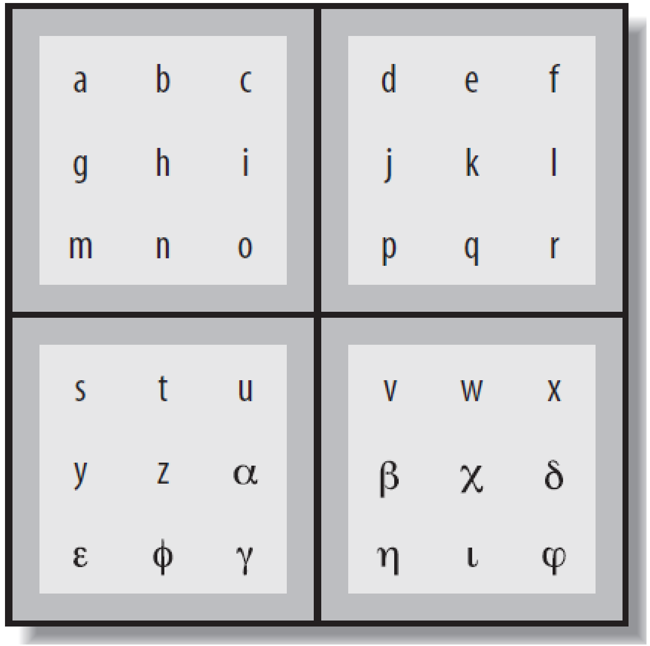
- A two-dimensional variant is `tbb::blocked_range2d`
- Permits using a single `parallel_for` to iterate over two dimensions at once
- Can yield better cache behavior than nesting two one-dimensional instances of `parallel_for`

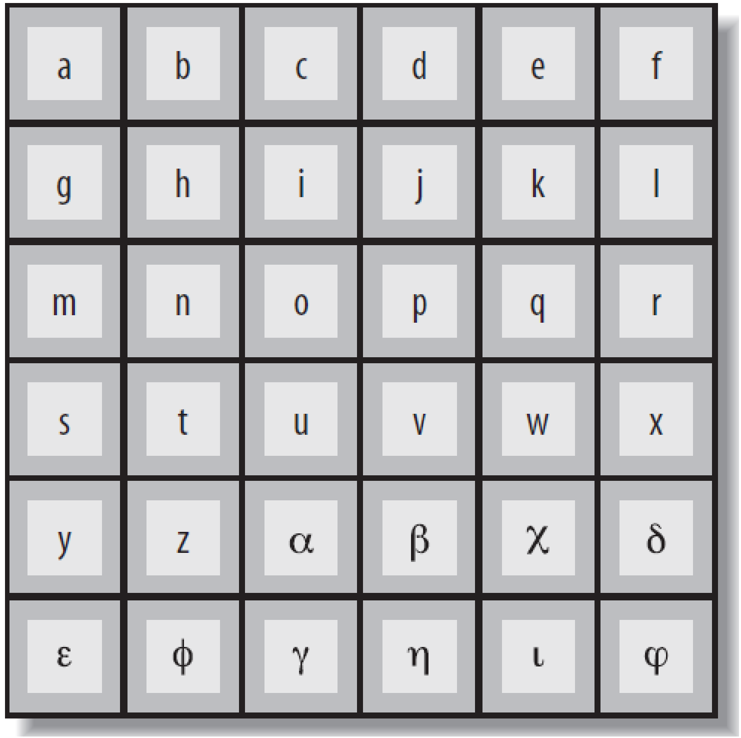
Splitting over 2D Range



Grain Size

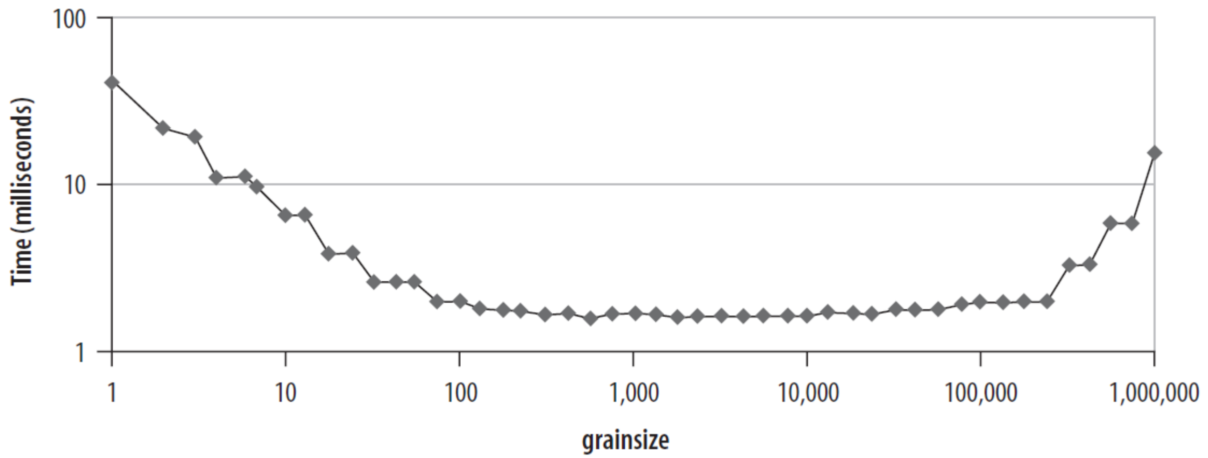
- Specifies the number of iterations for a chunk to give to a processor
- Impacts parallel scheduling overhead





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(range,bodyobject,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

- When can the affinity partitioner be useful?
  - 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; // Lives across loop iterations
  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	

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 using 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

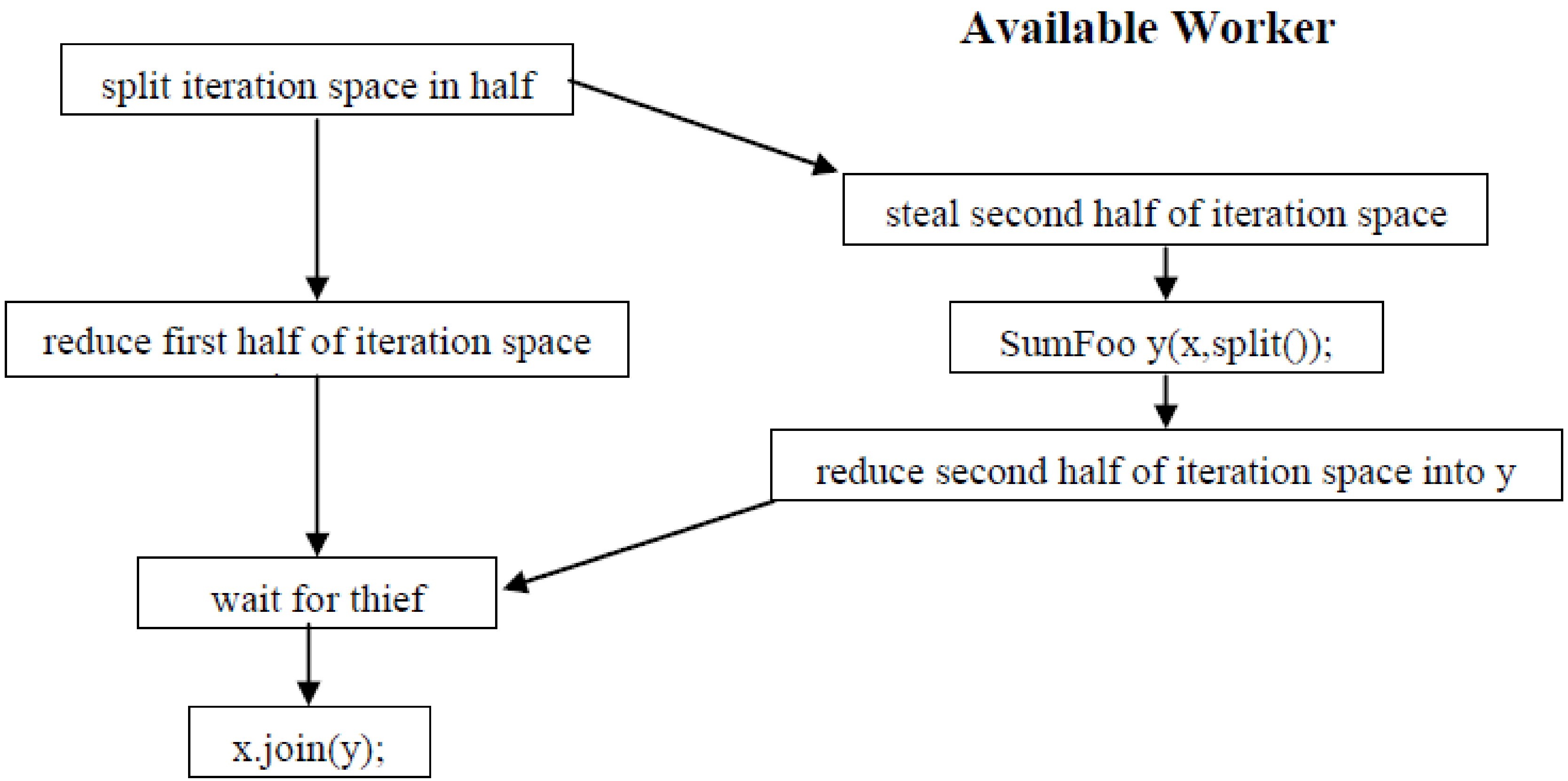
```
class SumFoo {
  float* my_a;
public:
  float my_sum;

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

```
  SumFoo(const 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

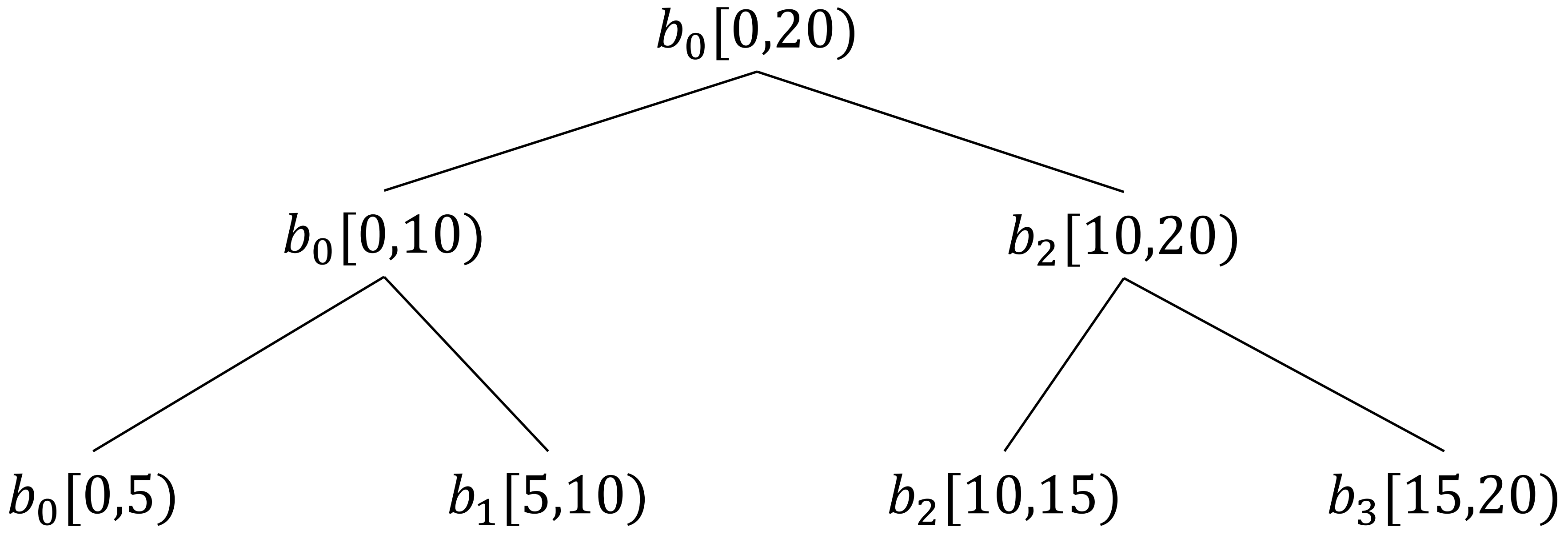
`parallel_for`	`parallel_reduce`
• `operator()` is constant • Requires only a copy ctor	• `operator()` is not constant • Requires a splitting ctor for creating subtasks • Requires a `join()` function to accumulate the results of the subtasks

Graph of the Split-Join Sequence



One Possible Execution of `parallel_reduce`

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



Another Possible Execution of `parallel_reduce`

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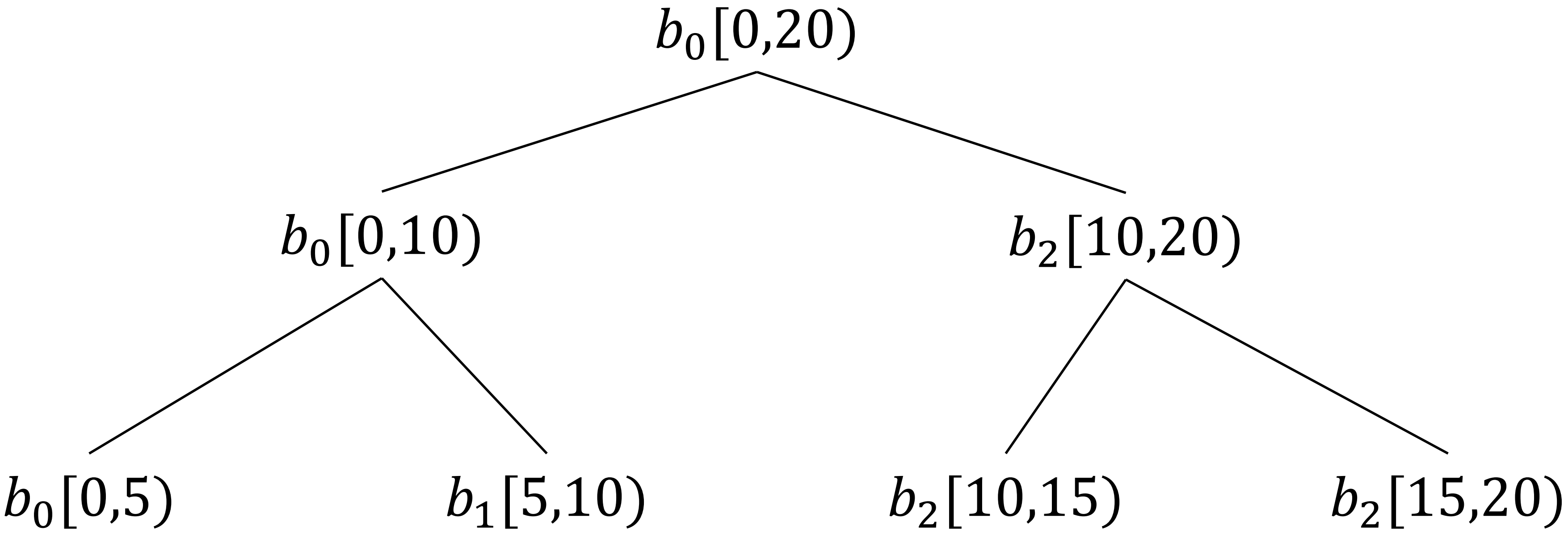
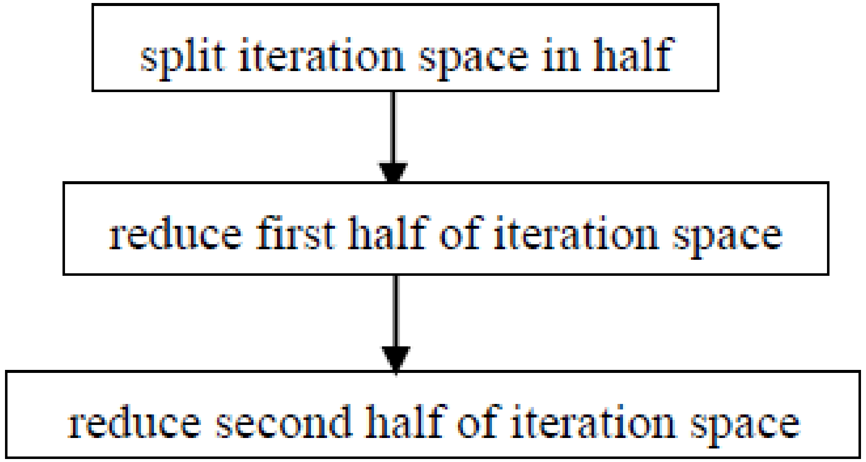


Graph of the Split-Join Sequence



No Available Worker

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) {}
};
```

Tasks and Task Scheduler

Behind the scenes in TBB

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

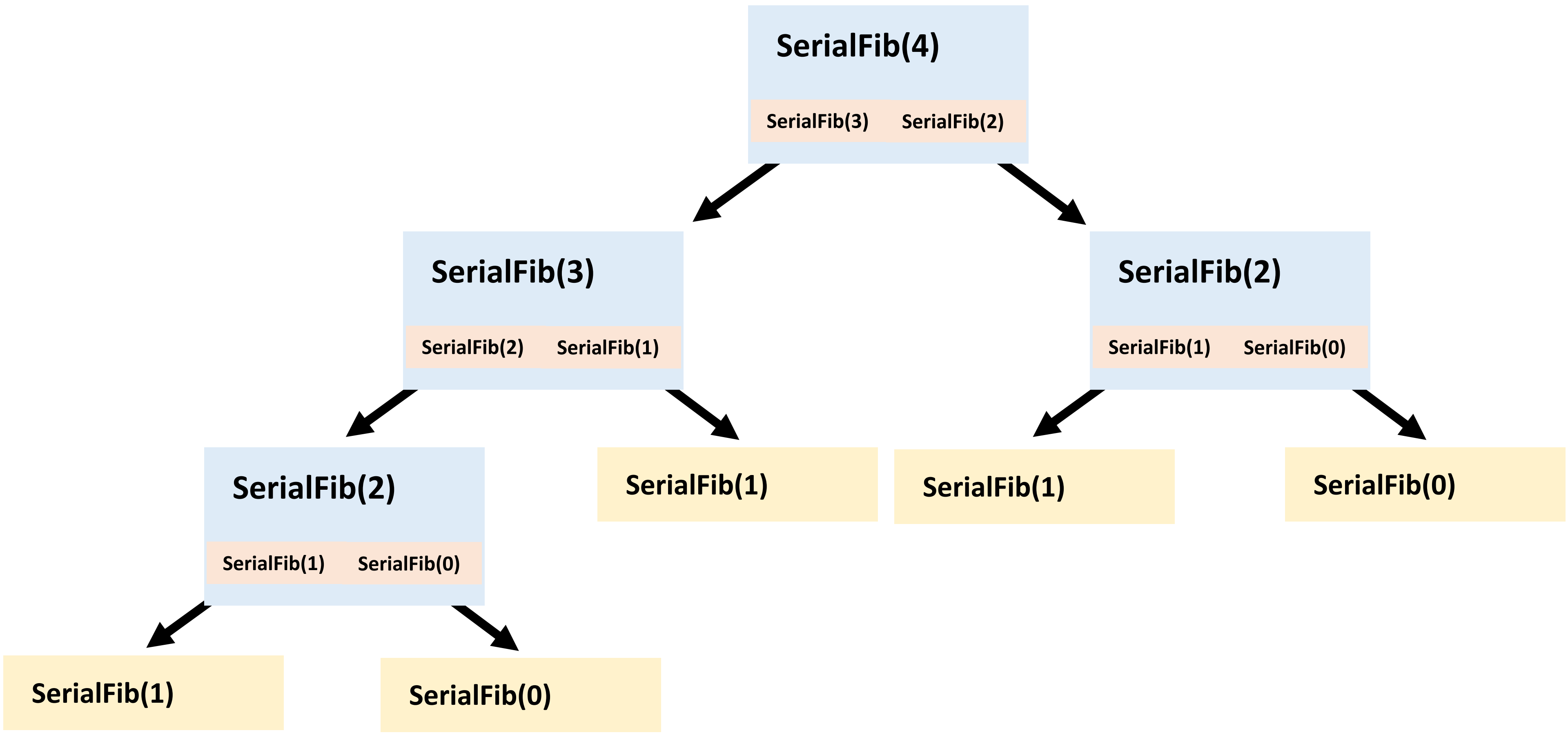
Problem	TBB Approach
Oversubscription	One scheduler thread per hardware thread
Fair scheduling	Non-preemptive unfair scheduling
High overhead	Programmer specifies tasks, not threads
Load imbalance	Work stealing balances load
Scalability	Specify tasks and how to create them, rather than threads

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 Fibonacci

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

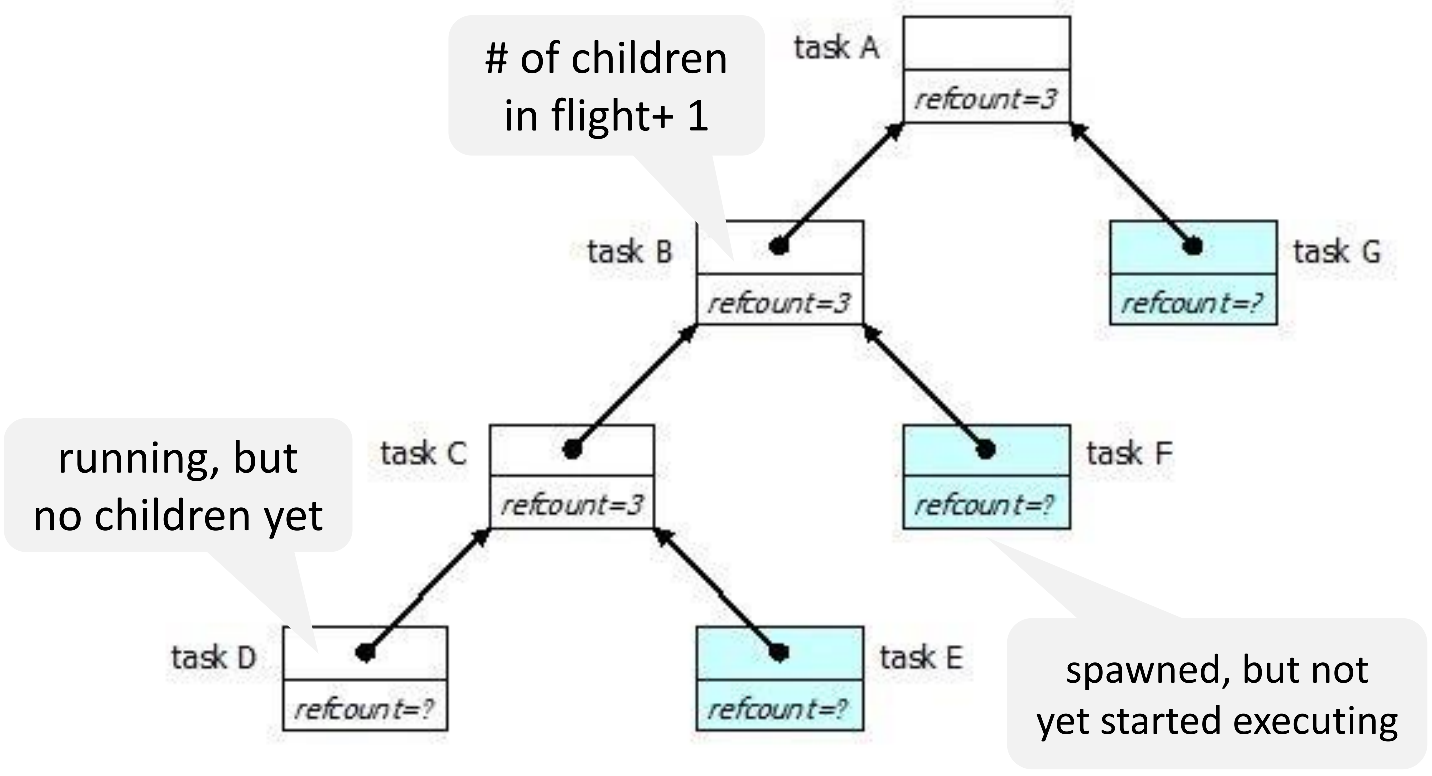
```
class FibTask: public task {
public:
  const long n;
  long* const sum;
  FibTask(long n_, long* sum_) :
n(n_), sum(sum_) {}

  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);
      // 2 children + 1 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

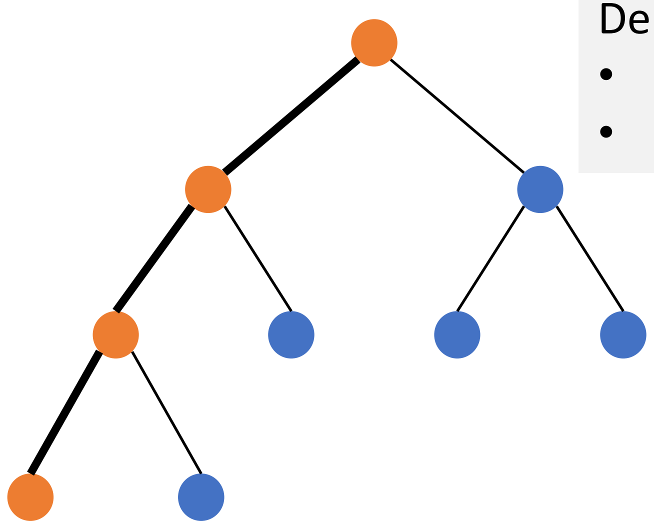
How Task Scheduling Works

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

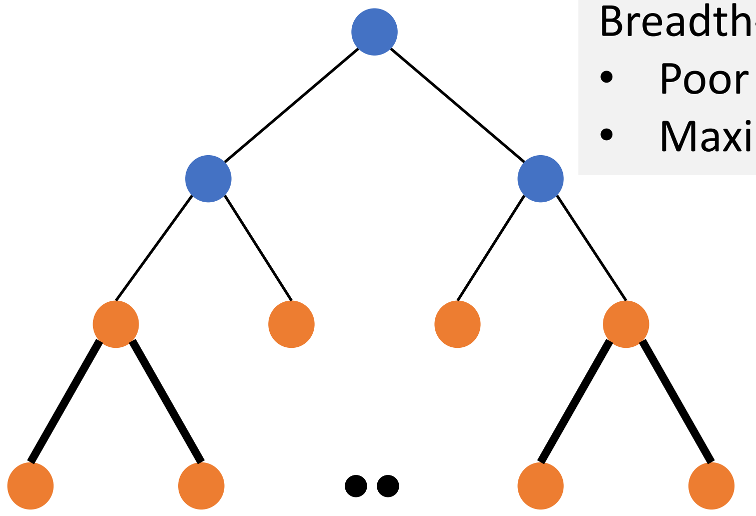


Task Scheduling

- Depth-first execution
  - Deeper tasks are more recently created, and will probably have better locality
  - Sequential execution of the task graph is more memory efficient
- 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



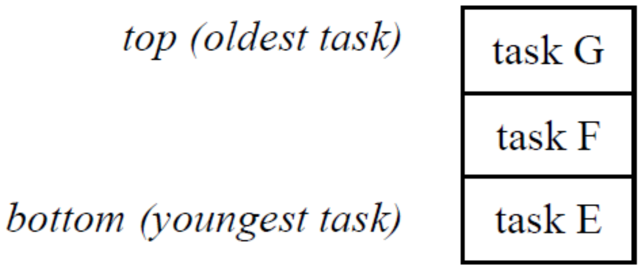
Depth-first execution
- Excellent cache locality
- No parallelism



Breadth-first execution
- Poor cache locality
- Maximum parallelism

Scheduling Algorithm

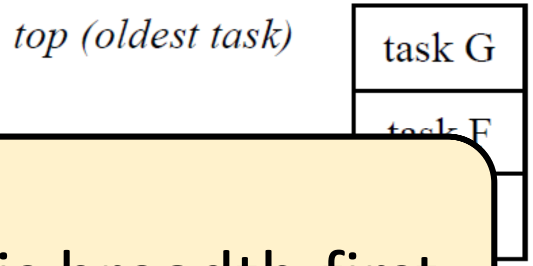
- Each thread has a "ready pool" of tasks it can run
  - The pool is basically a deque of task objects
- When a thread spawns a task, it pushes it to the end of its own deque



- A thread participates in task graph evaluation
  - Get the task returned by `execute()` for the previous task if any
  - 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

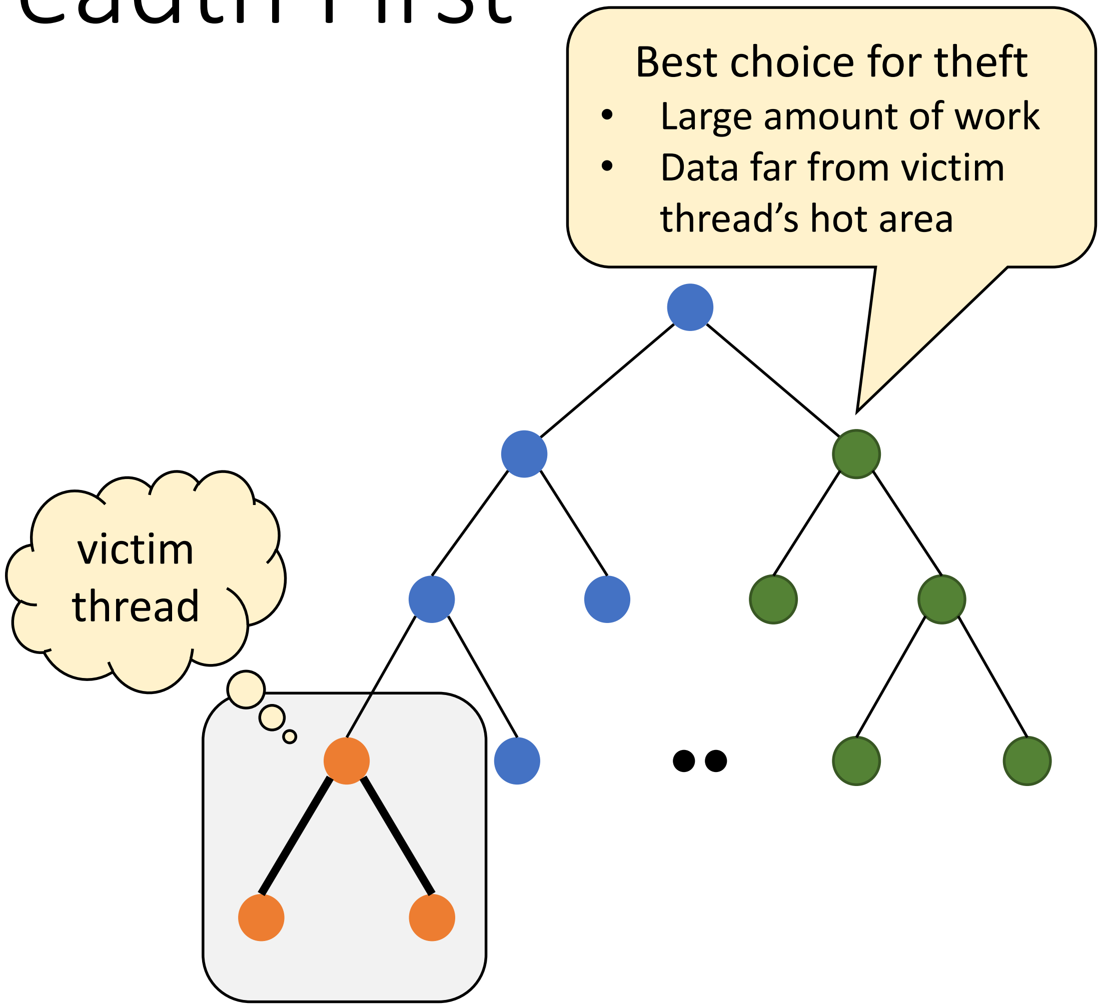


Work done is depth-first and stealing is breadth-first

- 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

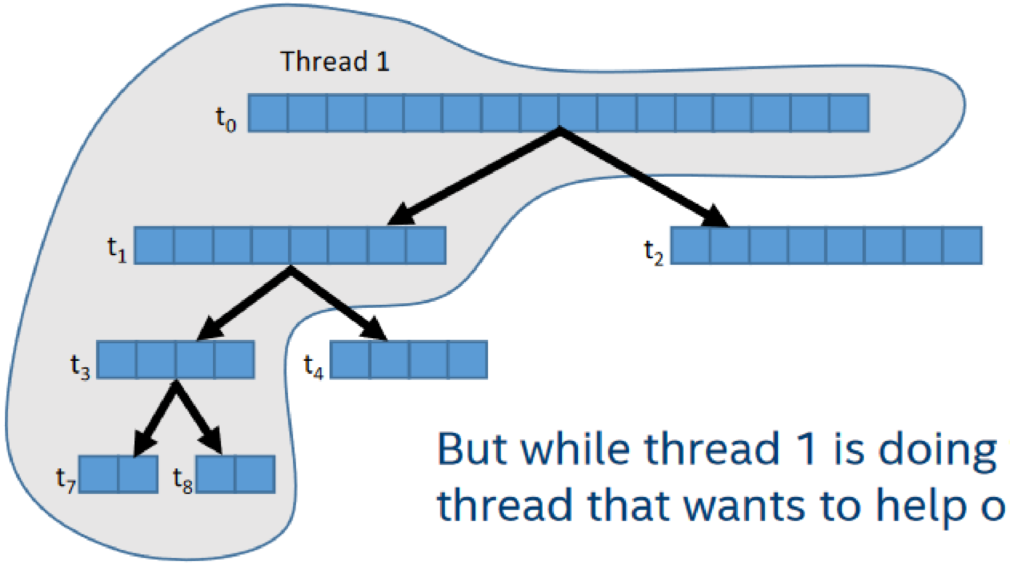
Work Depth First, Steal Breadth First

- Each thread maintains an (approximate) deque of tasks
- A thread performs depth-first execution
  - Uses own deque as a stack
  - Low space and good locality
- If a thread runs out of work, it steals tasks
  - Treats victim's deque as queue
  - Steals large tasks, and distant from the point of execution of the victim



A very nice distribution of a loop across 4 threads uses recursive splitting

```
tbb::parallel_for(0, N, 1, [a](int i) {
    f(a[i]);
});
```



But while thread 1 is doing this, along comes another thread that wants to help out...

https://www.cs.utexas.edu/~pingali/CS377P/2018sp/lectures/IntroductionToTBB-voss.pdf

A very nice distribution of a loop across 4 threads uses recursive splitting

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tbb::parallel_for(0, N, 1, [a](int i) {
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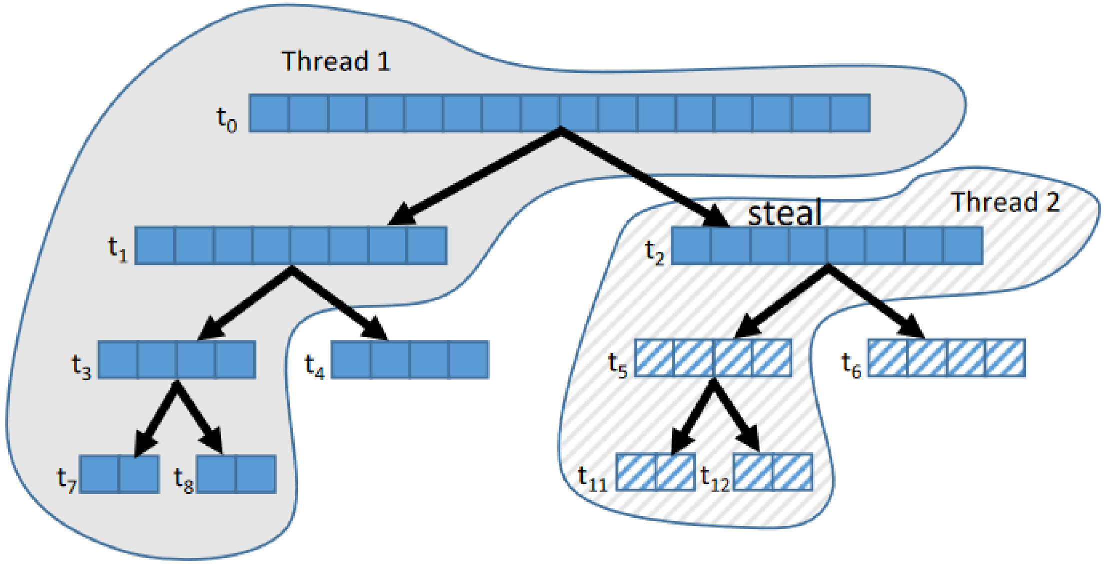

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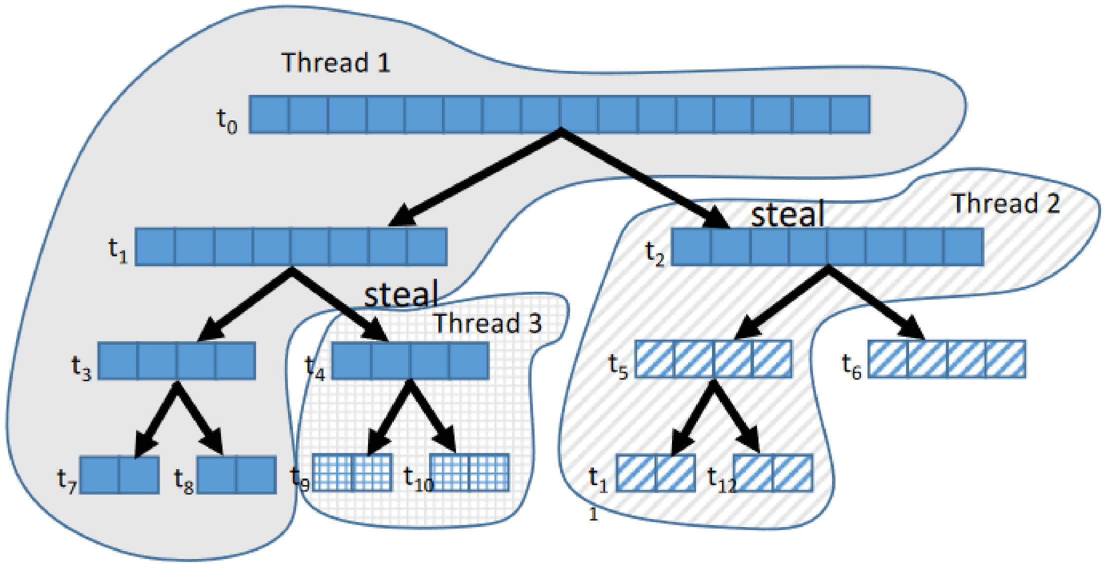

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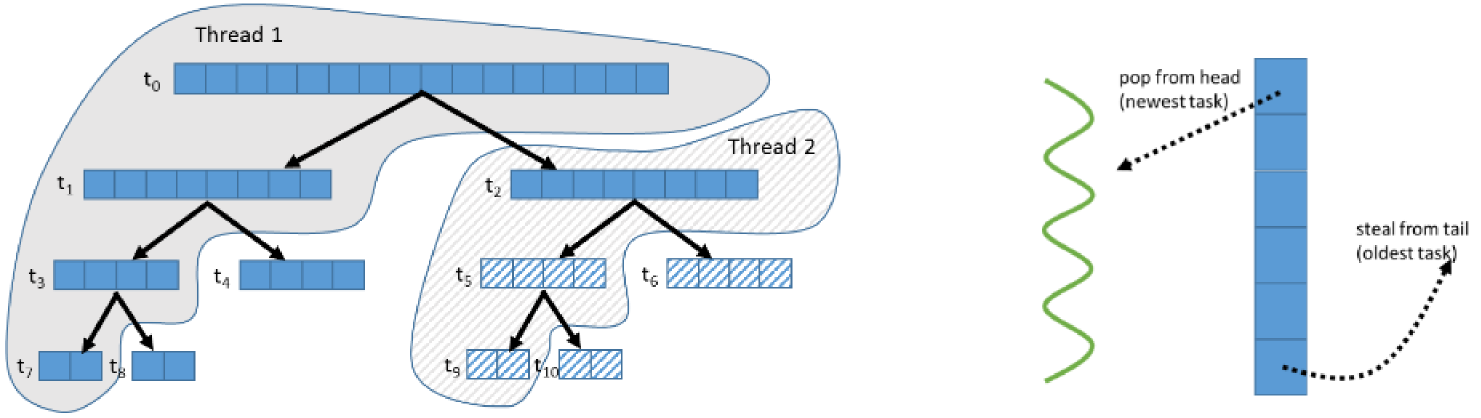
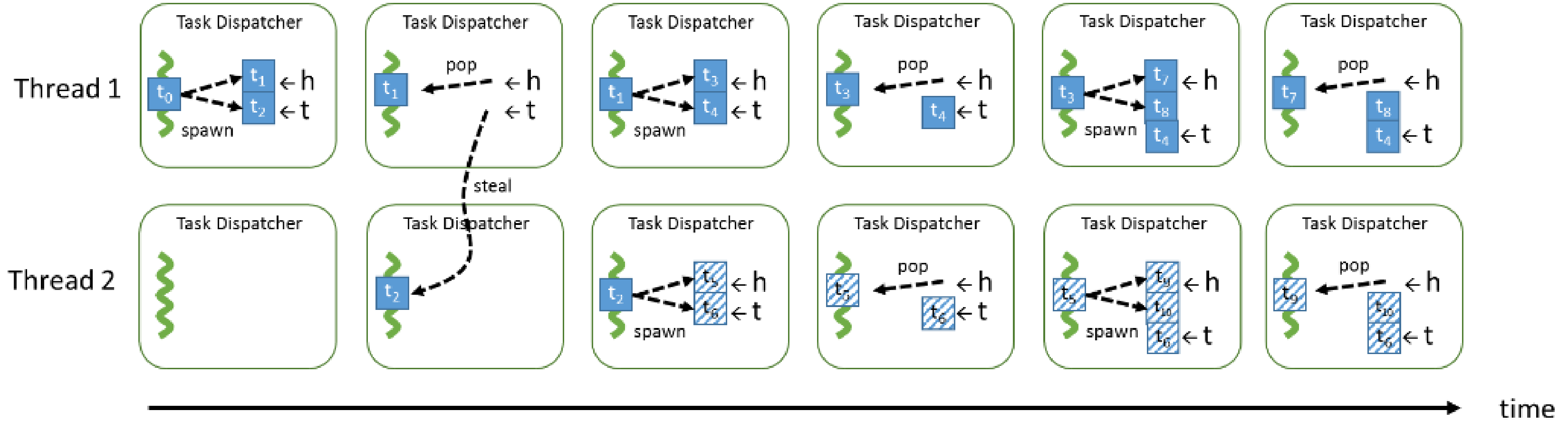


(a) tasks as distributed by work-stealing across two threads



(b) the Task Dispatcher actions that acquire the tasks

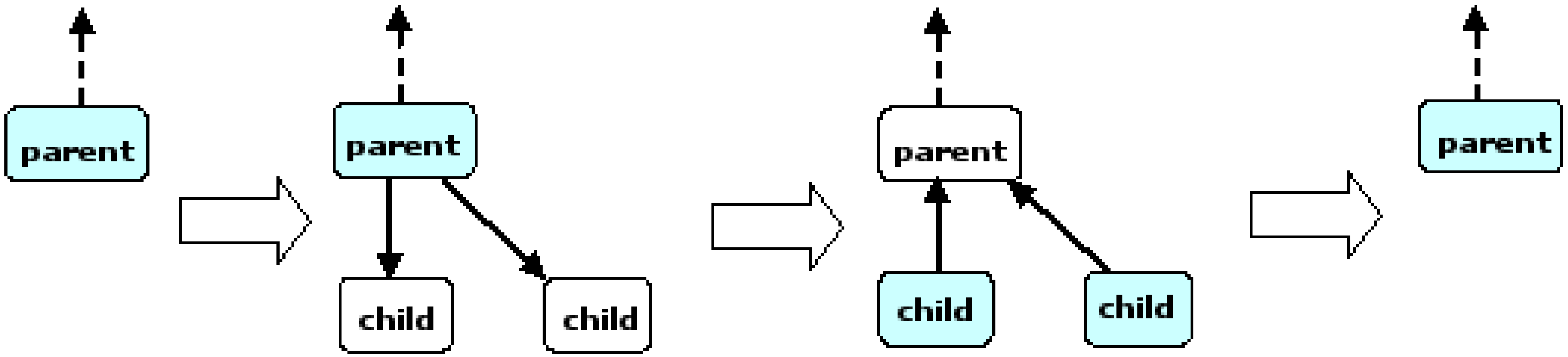
https://www.cs.utexas.edu/~pingali/CS377P/2018sp/lectures/IntroductionToTBB-voss.pdf

Parallelism in TBB

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

Blocking Style

running tasks
are shaded



https://www.threadingbuildingblocks.org/docs/help/reference/task_scheduler.html

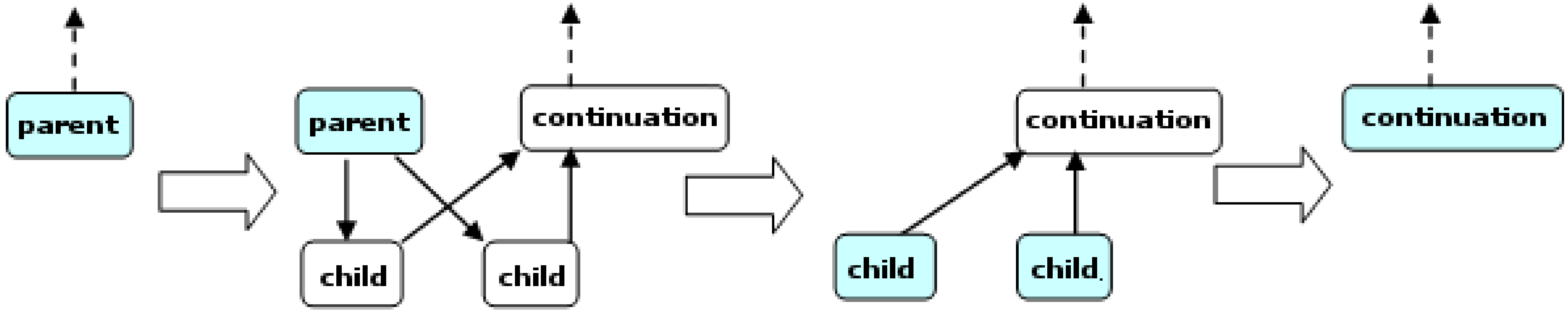
Disadvantages with Blocking Style

- Worker thread that encounters `wait_for_all()` in parent task is doing no work
- 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

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



https://www.threadingbuildingblocks.org/docs/help/reference/task_scheduler.html

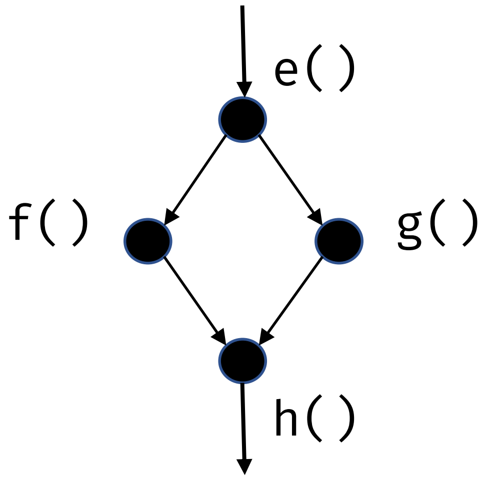
FibTask with Continuation Passing Style

```
struct FibC: public task {
  long* const sum;
  long x, y;
  F
  FibC(long* sum_) {
    sum = sum_;
  }
  task* execute() {
    *sum = x+y;
    return NULL;
  }
}
```

```
struct FibTask: public task {
  task* execute() {
    if (n < cutOff) { …
    } else {
      FibC& c = *new(allocate_continuation) FibC(sum);
      FibTask& a = *new(c.allocate_child()) FibTask(n-1,&c.x);
      FibTask& b = *new(c.allocate_child()) FibTask(n-2,&c.y);
      c.set_ref_count(2);
      spawn(b); // Return immediately
      spawn(a);
    }
    return NULL;
  }};
```

Scheduling Fork-Join Parallelism with Work Stealing

```
e();
spawn f();
g();
sync;
h();
```



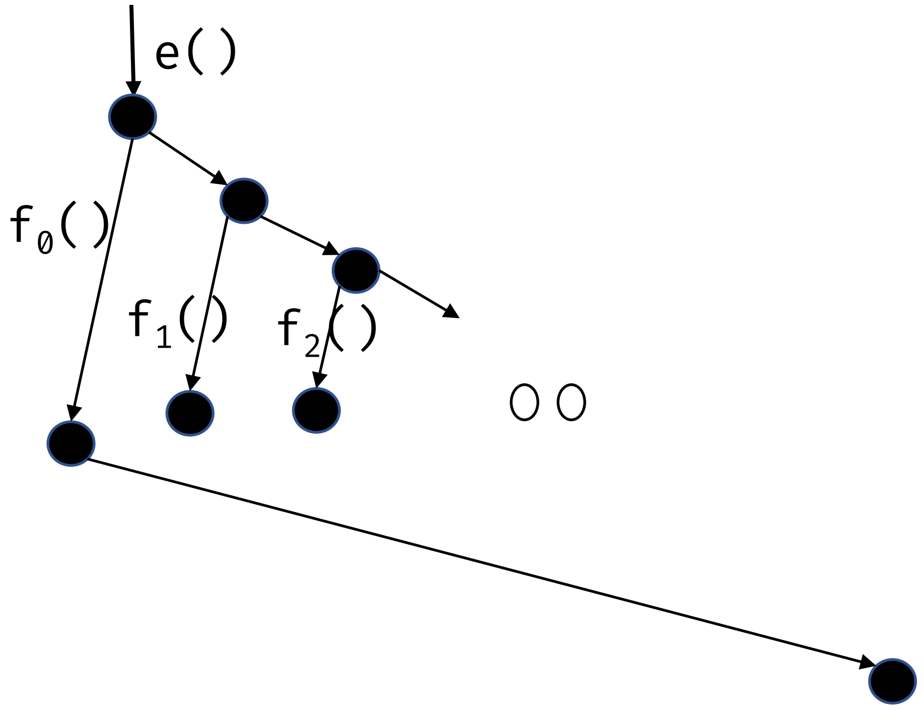
- Child stealing - thread that executed `e()` executes `g()`, `f()` is made available to thief threads
- Continuation stealing - thread that executed `e()` executes `f()`, the continuation (which will next call `g()`) becomes available to thief threads

- What threads should f() and g() run on?
- What thread should h() run on?

https://open-std.org/jtc1/sc22/wg21/docs/papers/2014/n3872.pdf

Child Stealing vs Continuation Stealing

```
e();
for (i in [0, N])
  spawn f();
sync;
```



https://open-std.org/jtc1/sc22/wg21/docs/papers/2014/n3872.pdf

Scheduler Bypass

```
struct FibTask: public task {
  task* execute() {
    if (n < cutOff) { …
    } else {
      FibC& c = *new(allocate_continuation) FibC(sum);
      FibTask& a = *new(c.allocate_child()) FibTask(n-1,&c.x);
      FibTask& b = *new(c.allocate_child()) FibTask(n-2,&c.y);
      c.set_ref_count(2);
      spawn(b); // Return immediately
      spawn(a);
    }
    return NULL;
  }};
```

```
struct FibTask: public task {
  task* execute() {
    if (n < cutOff) { …
    } else {
      FibC& c = *new(allocate_continuation) FibC(sum);
      FibTask& a = *new(c.allocate_child()) FibTask(n-1,&c.x);
      FibTask& b = *new(c.allocate_child()) FibTask(n-2,&c.y);
      c.set_ref_count(2);
      spawn(b); // Return immediately
      return &a;
    }
}};
```

Did Tasks Help?

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

  task*
    if (
      *s
    }
```

```
else {
  long x, y;
);
);
or the
```

```
[ 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
  - Can be used with the library, OpenMP, or native threads
  - Worse single-thread performance, but better scalability

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

Concurrency-Friendly Interfaces

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

```
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()`

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 will see values A and B in order

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()

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;
}
```

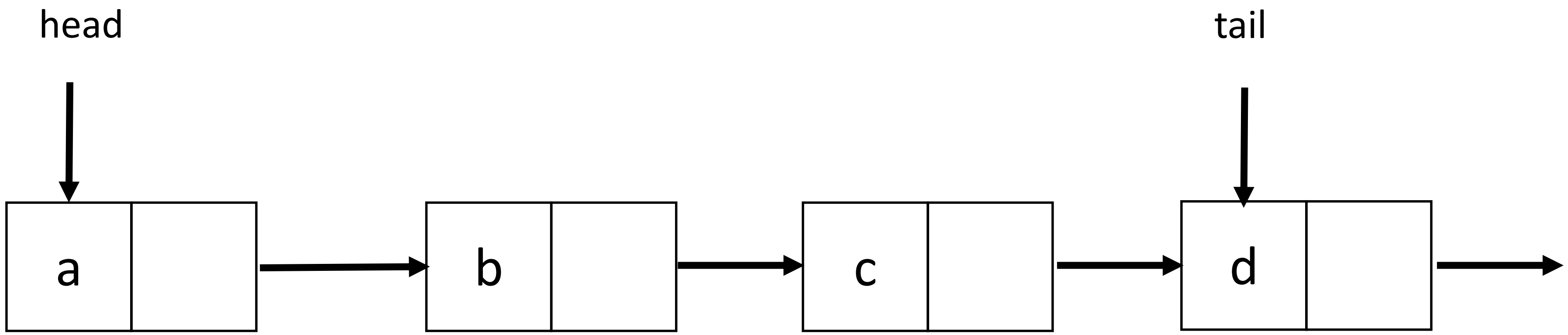
- Simple example to enqueue and print integers

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*

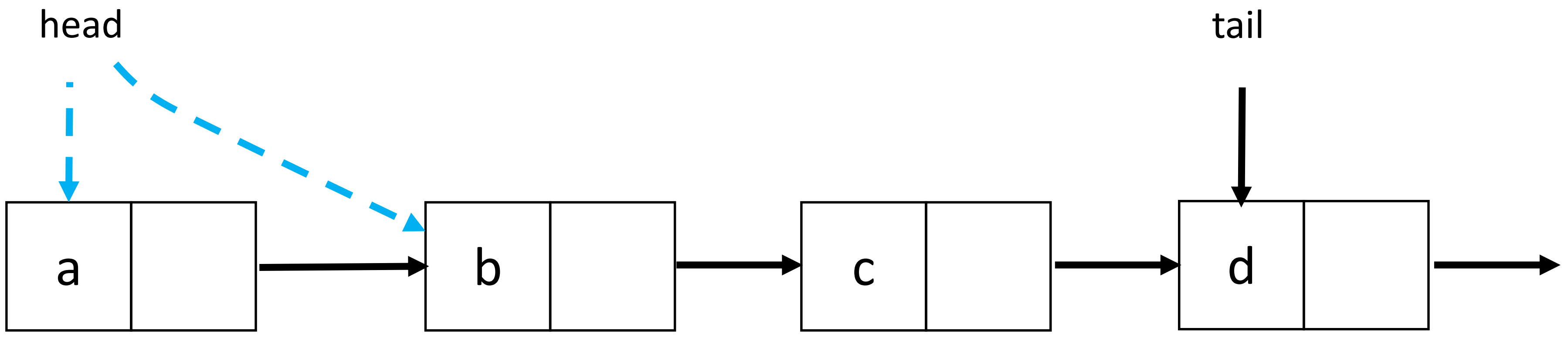
- Thread T1 reads value A from shared memory location
- Other threads update A to B, and then back to A
- T1 performs `compare_and_swap()` and succeeds

Example of ABA Problem



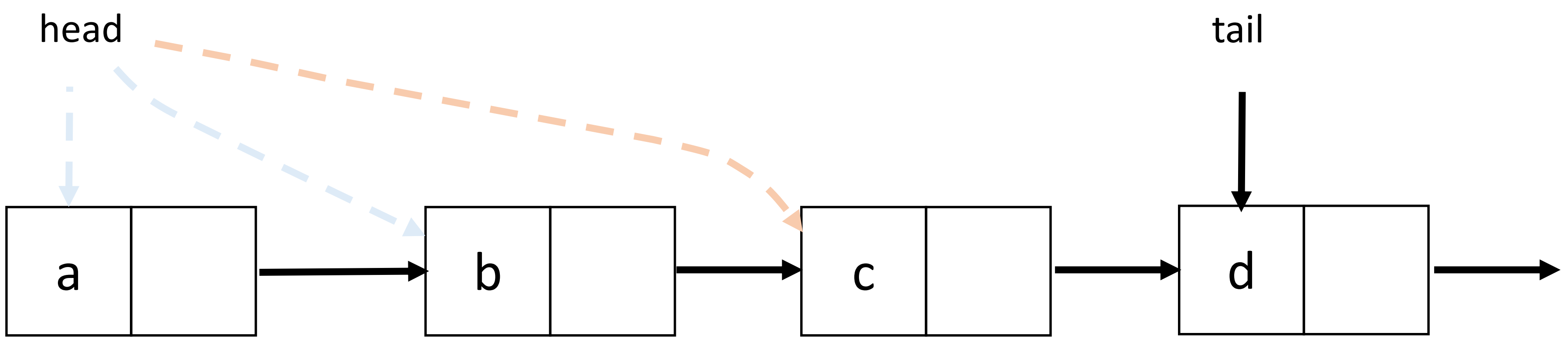
- Thread 1 will execute deq(a)

Example of ABA Problem



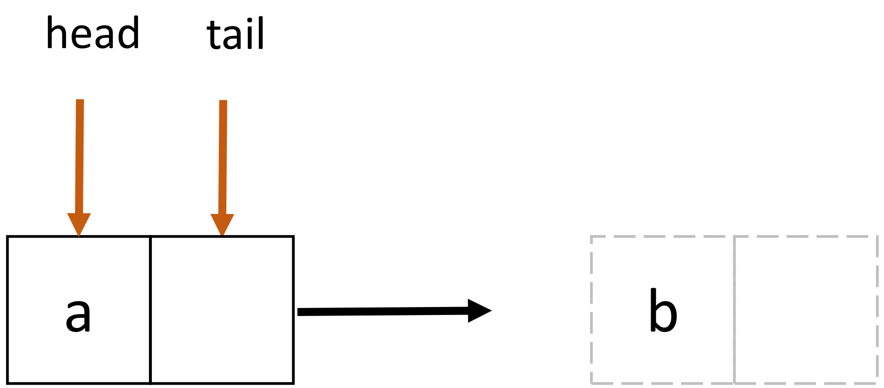
- Thread 1 is executing deq(a), gets delayed

Example of ABA Problem



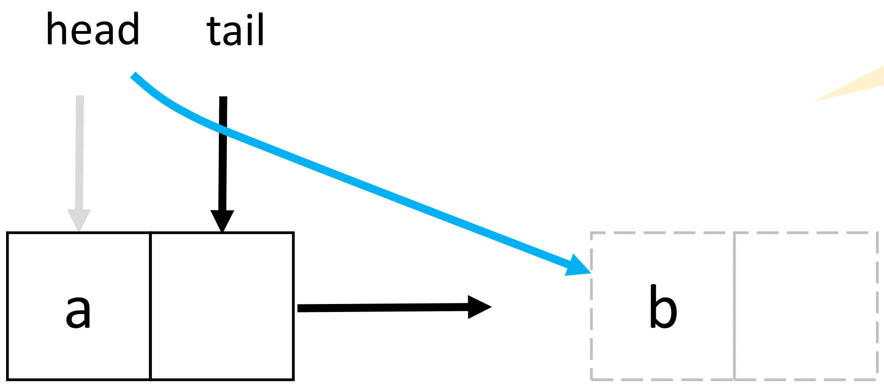
- Other threads execute deq(a, b, c, d), then execute enq(a)

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

- 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

- 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

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, x = y, return z
`x.fetch_and_add(y)`	z = x, x += y, return z
`x.compare_and_swap(y, z)`	w = x, if (x == z) { x = y, return w; }

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

References

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