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Software

AN INTRODUCTION TO THREADING IN C++ WITH THREADING BUILDING BLOCKS (TBB)

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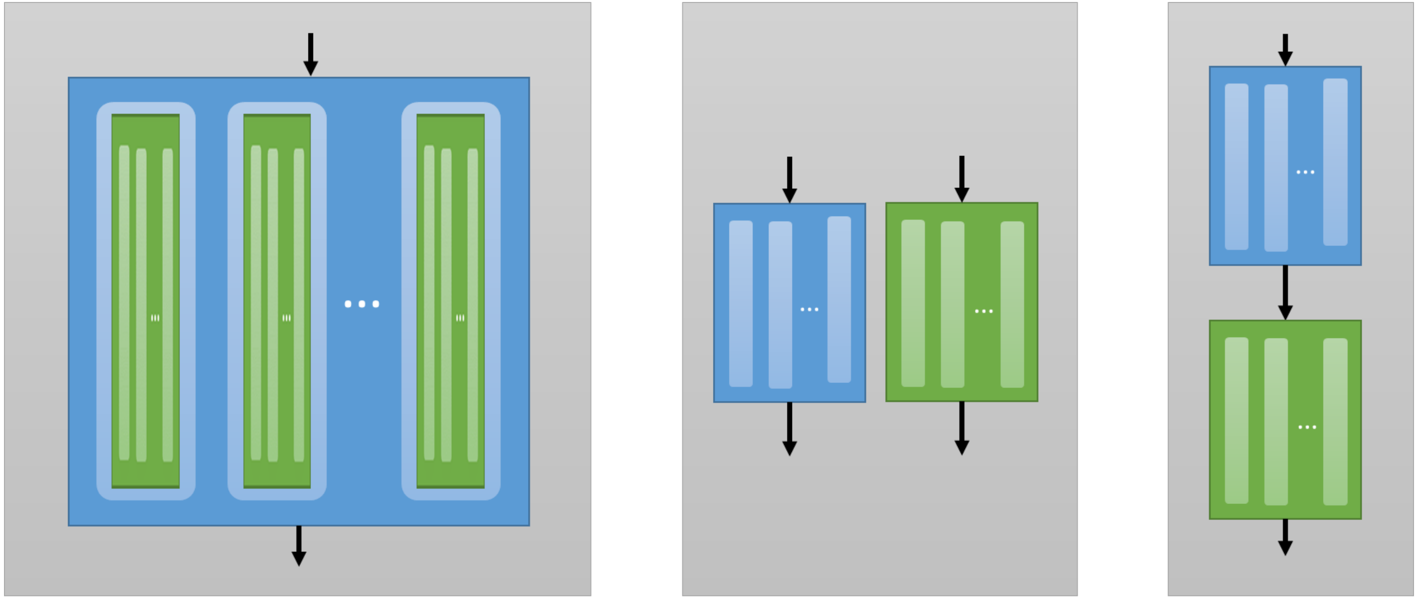
We've already talked about threading with pthreads and the OpenMP* API

- POSIX threads (pthreads) lets us express threading but makes us do a lot of the hard work
- OpenMP is higher-level model and is widely used in C/C++ and Fortran
  - It takes care of many of the low-level error prone details for us
- OpenMP has weaknesses, especially for C++ developers…
  - It uses #pragmas and so doesn't look like C++
  - It is not a *composable* parallelism model

Agenda

- What is composability and why is it important? ⬅
- An introduction to the Threading Building Blocks (TBB) library
  - What it is and what it contains
- TBB's high-level execution interfaces
  - The generic parallel algorithms, the flow graph and Parallel STL
- Synchronization primitives and concurrent containers
- The TBB scalable memory allocator

There are different ways parallel software components can be combined with other parallel software components



nested

concurrent

serial

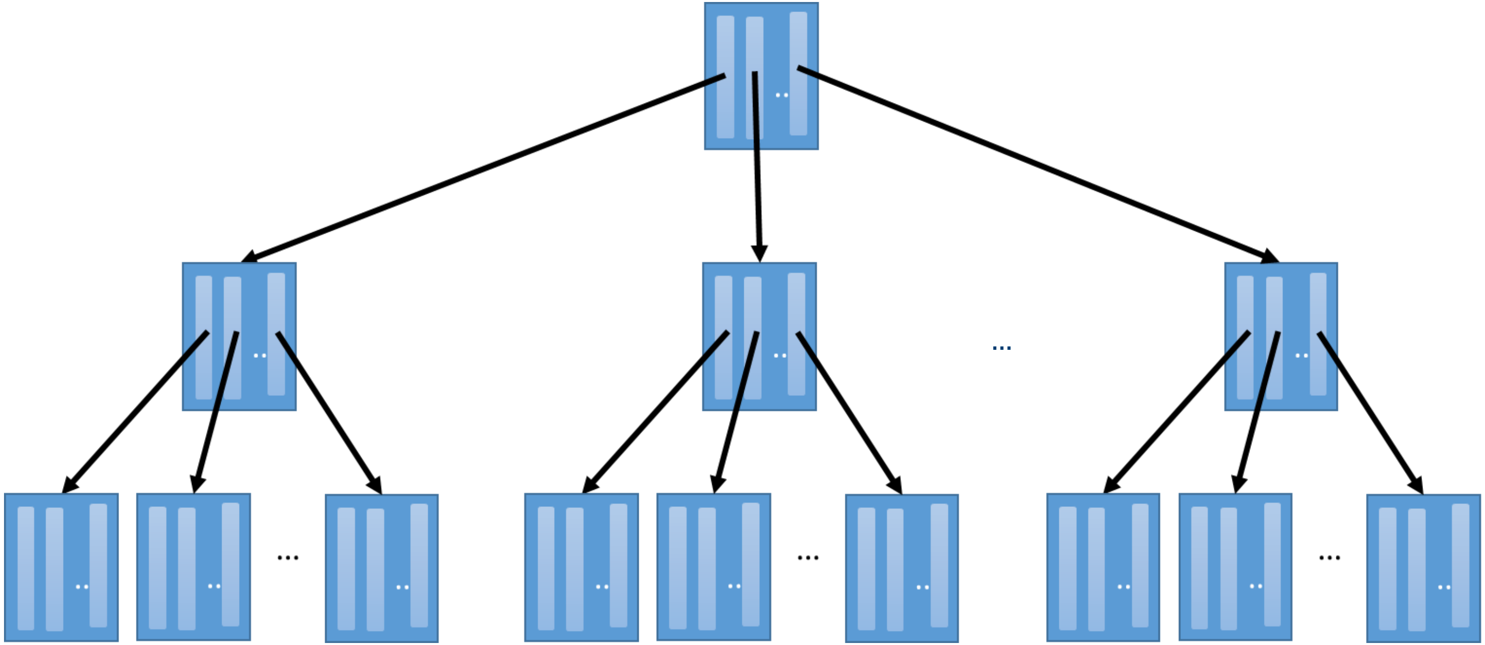
Nested composition

```
int main() {
    #pragma omp parallel
    f();
}

void f() {
    #pragma omp parallel
    g();
}

void g() {
    #pragma omp parallel
    h();
}
```

Nested composition

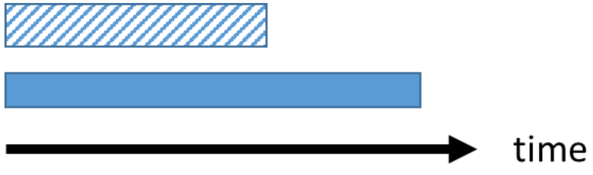


Nested parallelism can lead to an exponential growth in the available parallelism, great! Or the number of threads, very bad!

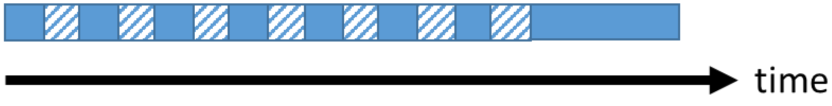
Concurrent Composition

```
#pragma omp parallel for
for (int i = 0; i < N; ++i) {
    b[i] = f( a[i] );
}
```

```
#pragma omp parallel for
for (int i = 0; i < M; ++i) {
    d[i] = g( c[i] );
}
```



parallel execution



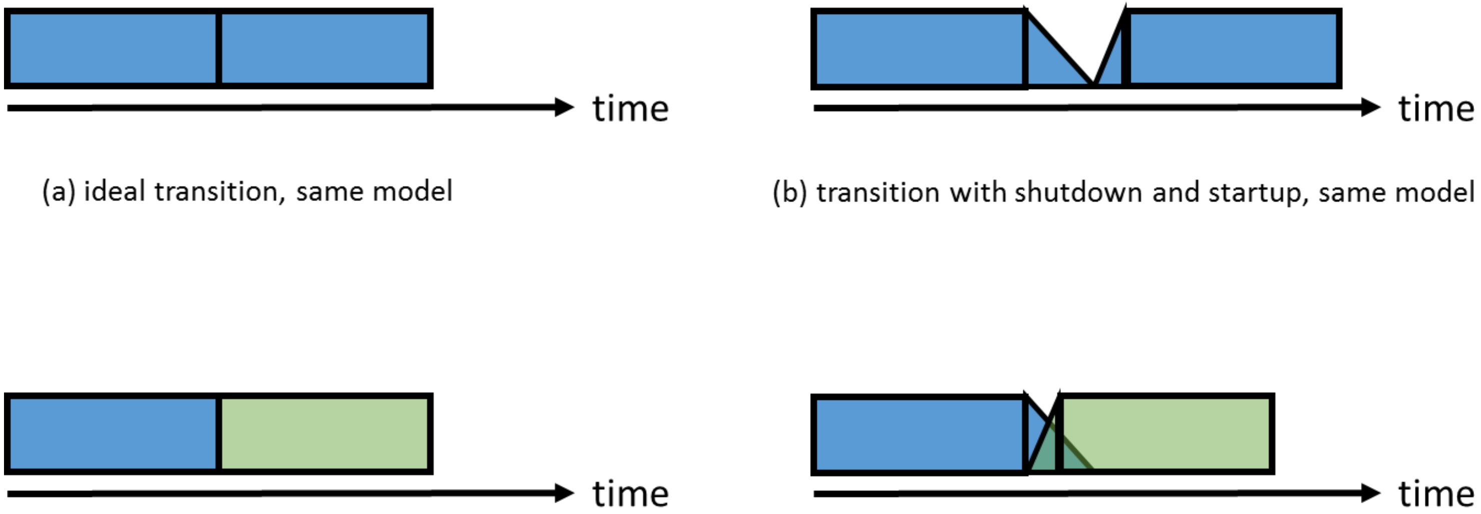
concurrent execution

Serial Composition

```
#pragma omp parallel for
for (int i = 0; i < N; ++i) {
    b[i] = f( a[i] );
}
```

```
#pragma some_other_kind_of_parallel_for
for (int i = 0; i < N; ++i) {
    c[i] = f( b[i] );
}
```

Serial Composition



(a) ideal transition, same model

(b) transition with shutdown and startup, same model

(c) ideal transition, different models

(d) transition with shutdown and startup, different models

A composable threading model

- Executes efficiently when its constructs are composed with other constructs from the same threading model
  - nested, concurrent and serial
- Doesn’t negatively impact other threading models too much when composed with constructs in the other threading model
  - nested, concurrent and serial
  - it can’t control the other model, but it can be a “good citizen”

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Threading Building Blocks (TBB)

Celebrated it's 10 year anniversary in 2016

A widely used C++ template library for shared-memory parallel programming

What

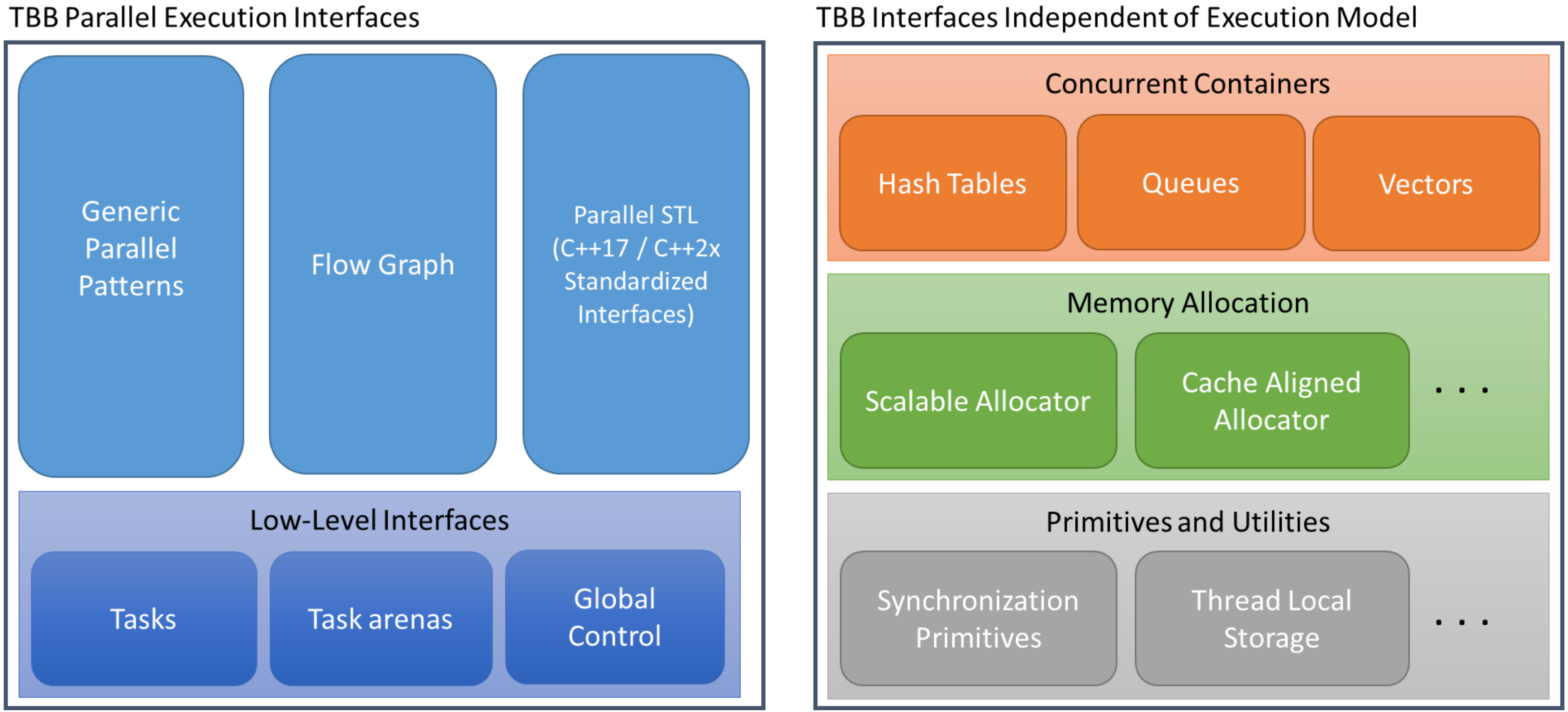
Parallel algorithms and data structures
Threads and synchronization primitives
Scalable memory allocation and task scheduling

Benefits

Is a library-only solution that does not depend on special compiler support
Is both a commercial product and an open-source project
Supports C++, Windows*, Linux*, OS X*, Android* and other OSes
Commercial support for Intel® Atom™, Core™, Xeon® processors and for Intel® Xeon Phi™ coprocessors

http://threadingbuildingblocks.org   http://software.intel.com/intel-tbb

The Components in Threading Building Blocks (TBB)



TBB Parallel Execution Interfaces

Generic Parallel Patterns

Flow Graph

Parallel STL (C++17 / C++2x Standardized Interfaces)

Low-Level Interfaces

Tasks

Task arenas

Global Control

TBB Interfaces Independent of Execution Model

Concurrent Containers

Hash Tables

Queues

Vectors

Memory Allocation

Scalable Allocator

Cache Aligned Allocator

. . .

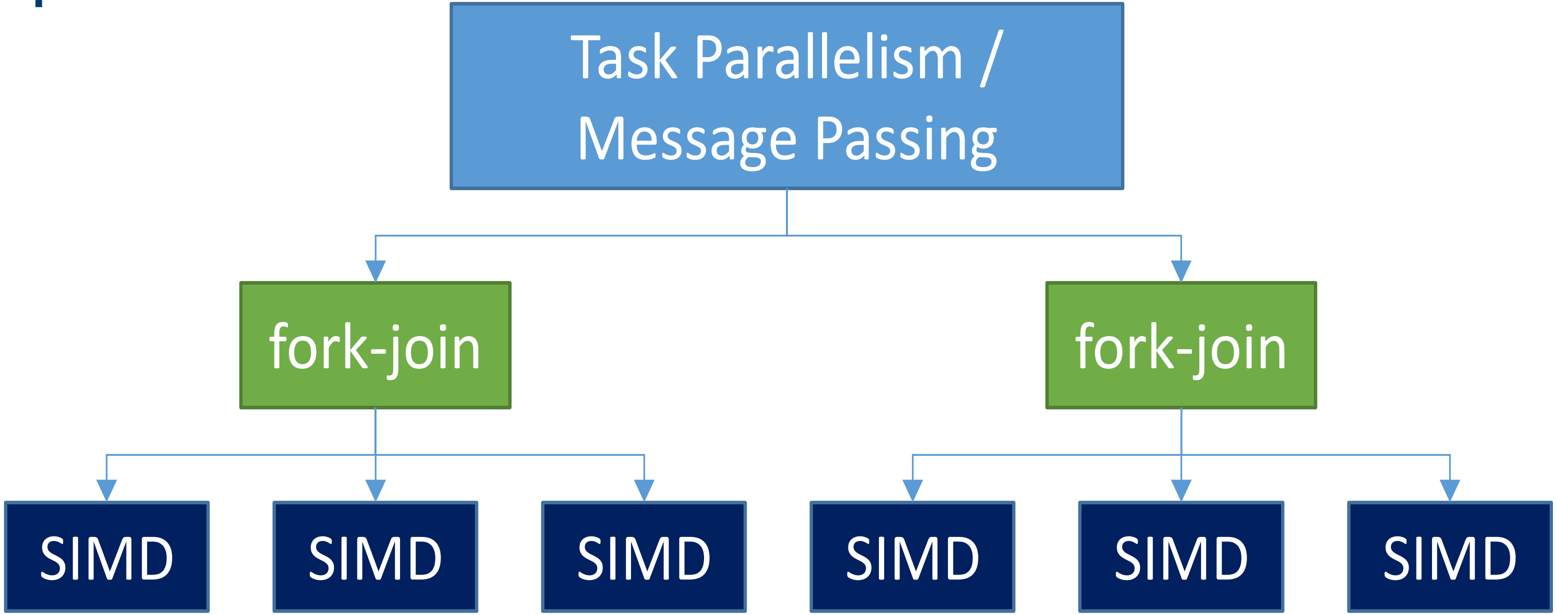
Primitives and Utilities

Synchronization Primitives

Thread Local Storage

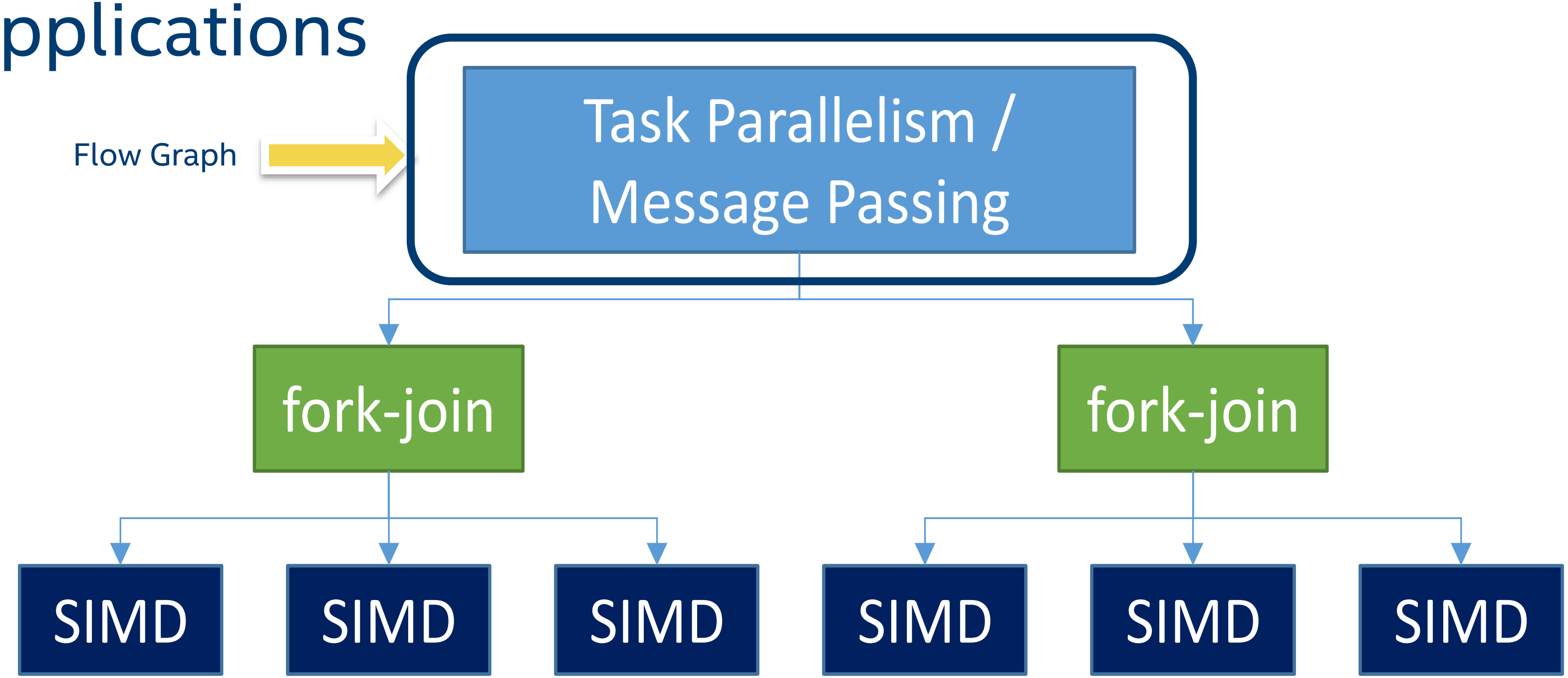
. . .

High-level execution interfaces map to parallelism in applications



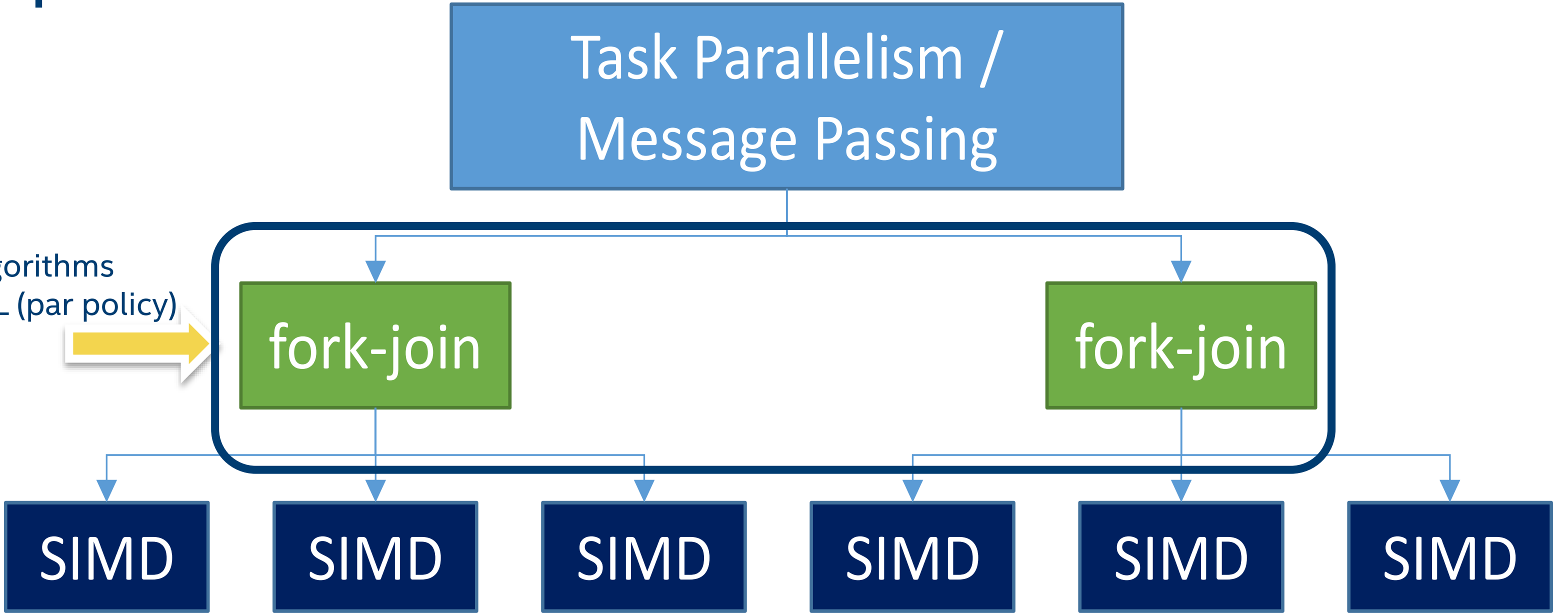
Intel TBB helps to develop composable levels

High-level execution interfaces map to parallelism in applications



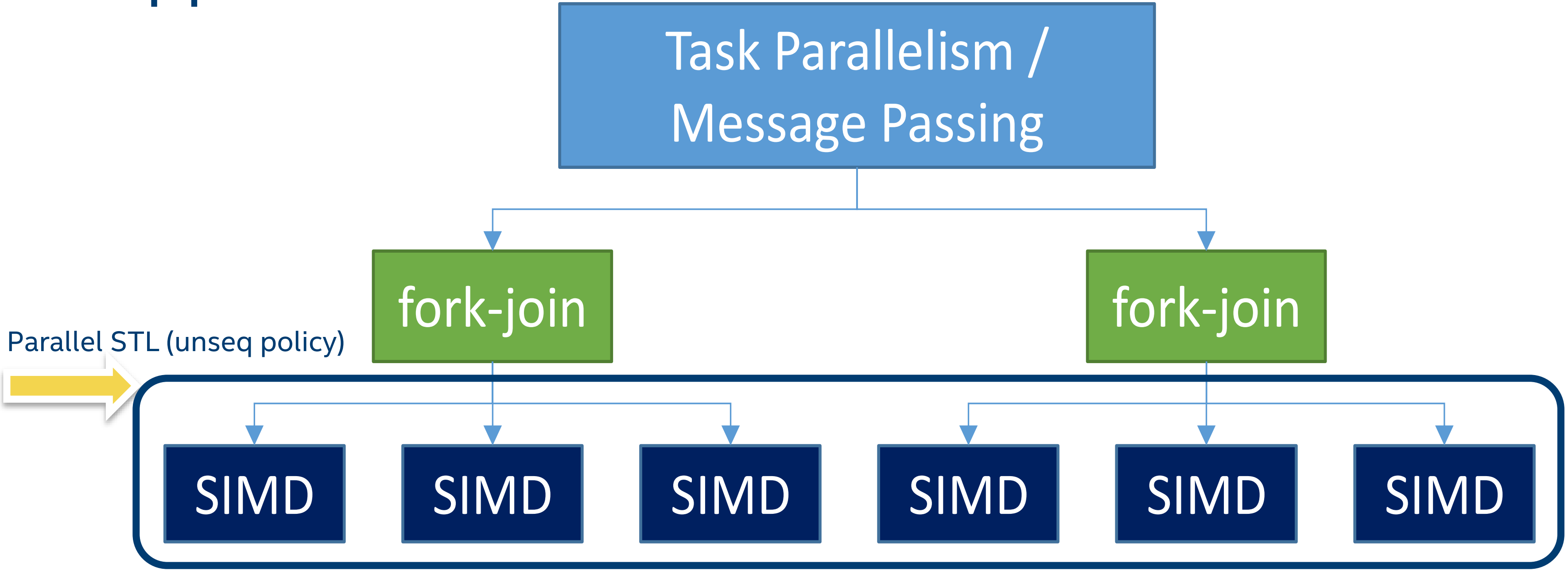
Intel TBB helps to develop composable levels

High-level execution interfaces map to parallelism in applications



Intel TBB helps to develop composable levels

High-level execution interfaces map to parallelism in applications


Task Parallelism / Message Passing
fork-join
fork-join
Parallel STL (unseq policy)
SIMD
SIMD
SIMD
SIMD
SIMD
SIMD

Intel TBB helps to develop composable levels

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But before we do that… a quick overview of C++ lambda expressions

- Lambda expressions are anonymous function objects

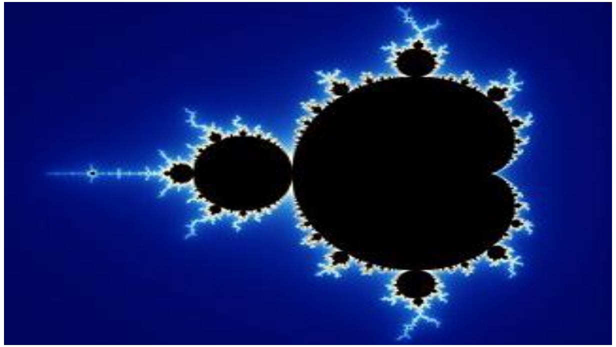
```
[ capture-list ] ( params ) -> ret { body }
```

- capture-list
  - a list of variables to capture from the enclosing scope
  - e.g. [x,y] or to capture a reference then [&x,y]
- params
  - The parameters of the function, just like for a named function
- ret is the return type
- body is the function body

Mandelbrot Example

Threading Building Blocks (TBB)

```
int mandel(Complex c, int max_count) {
  int count = 0; Complex z = 0;
  for (int i = 0; i < max_count; i++) {
    if (abs(z) >= 2.0) break;
    z = z*z + c; count++;
  }
  return count;
}
```



Task is a function object

Parallel algorithm

```
parallel_for( 0, max_row,
  [&](int i) {
    for (int j = 0; j < max_col; j++)
      p[i][j]=mandel(Complex(scale(i),scale(j)),depth);
  }
);
```

Use C++ lambda functions to define function object in-line

TBB Generic Parallel Algorithms

Loop parallelization

parallel_for

parallel_reduce

parallel_scan

Parallel sorting

parallel_sort

Parallel function invocation

parallel_invoke

Streaming

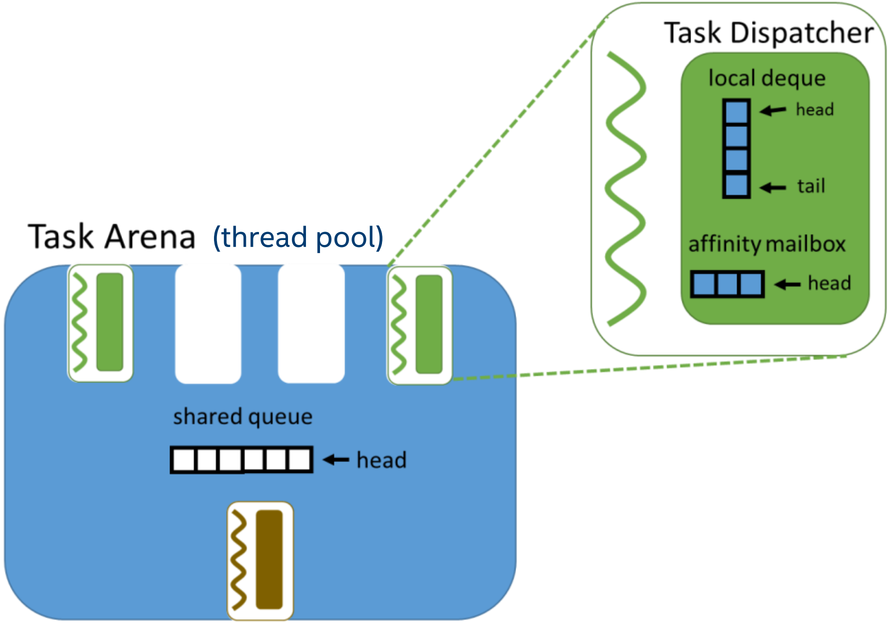
parallel_do

parallel_for_each

pipeline / parallel_pipeline

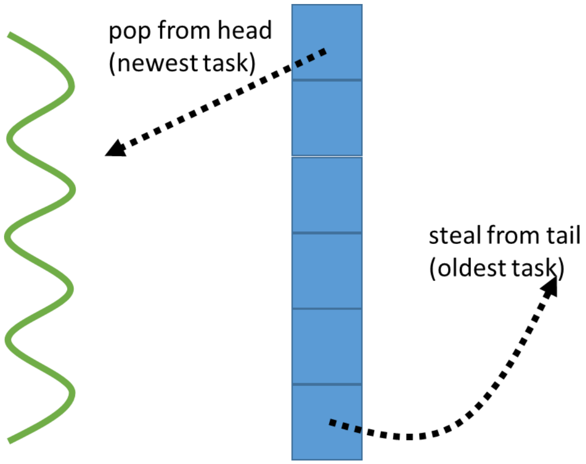
The most common patterns used in parallel programming

TBB is a composable library because it uses tasks, a thread pool and a work-stealing task scheduler



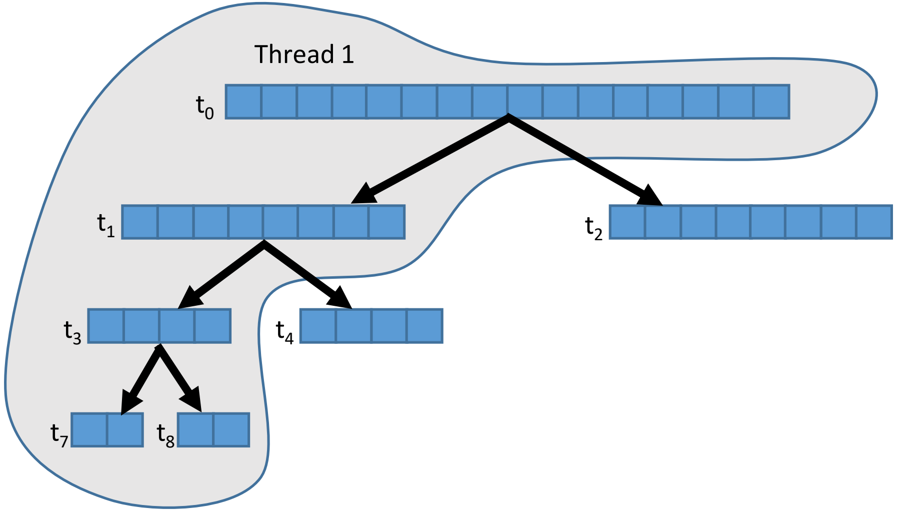
TBB is a composable library because it uses tasks, a thread pool and a work-stealing task scheduler

Simplified work-stealing task dispatcher used by each worker thread



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]);
});
```



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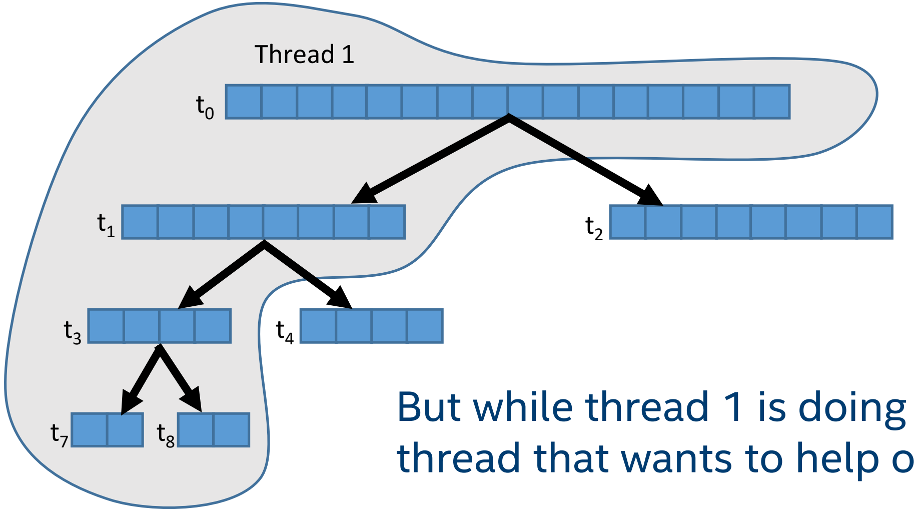
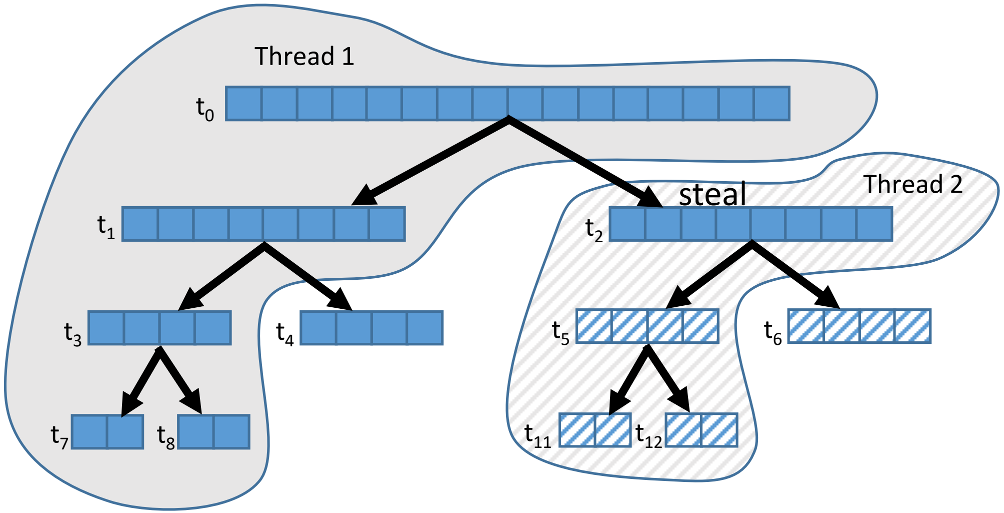


But while thread 1 is doing this, along comes another thread that wants to help out…

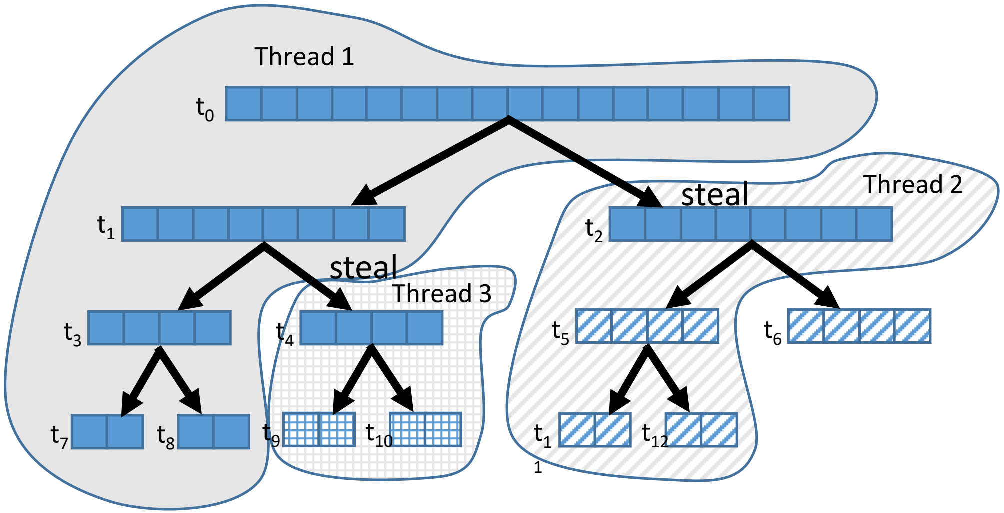
A very nice distribution of a loop across 4 threads uses recursive splitting

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



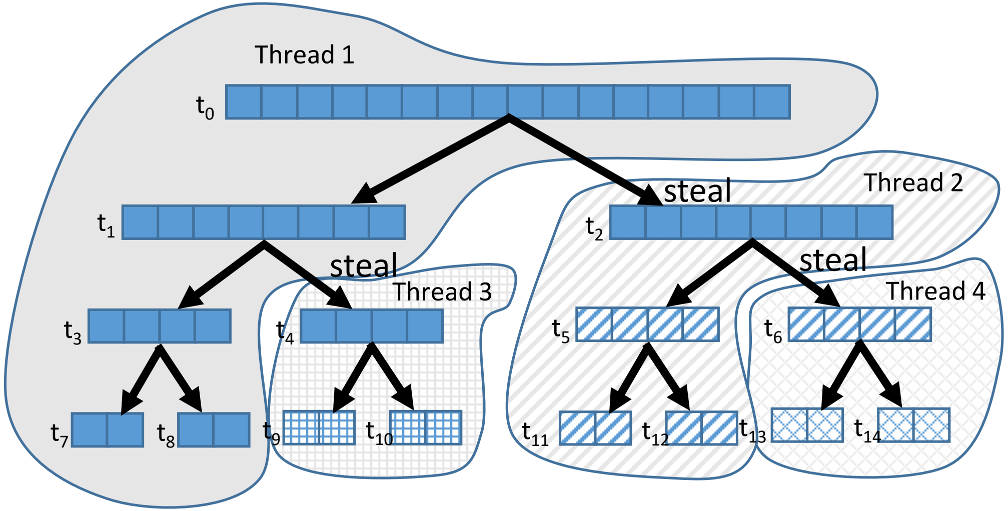
A very nice distribution of a loop across 4 threads uses recursive splitting

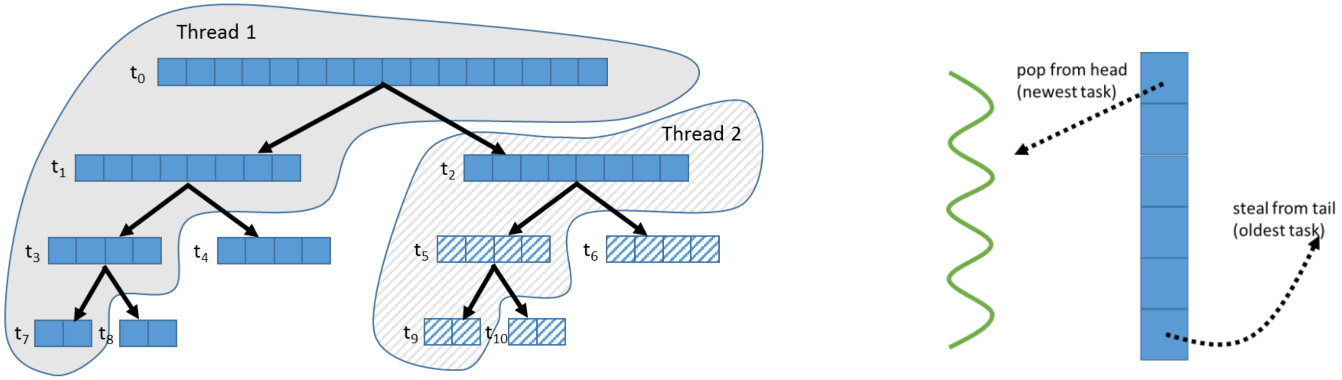
```
tbb::parallel_for(0, N, 1, [a](int i) {
    f(a[i]);
});
```



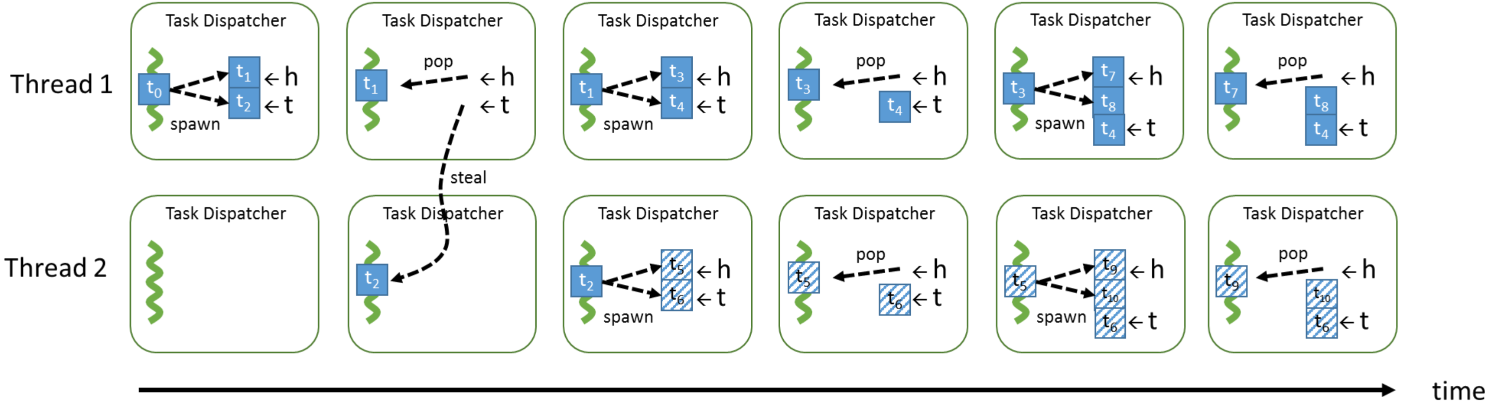
A very nice distribution of a loop across 4 threads uses recursive splitting

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





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



(b) the Task Dispatcher actions that acquire the tasks

TBB is a composable library because it uses tasks, a thread pool and a work-stealing task scheduler

- Nested parallelism just works
  - We create lots of small tasks but they execute on a the limited number of threads in the thread pools – no explosion of threads
- Concurrent composition just works
  - Tasks are scheduled to the same threads – no problem
- Serial composition just works
  - The thread pool stays alive and as work becomes available, idle worker threads steal it

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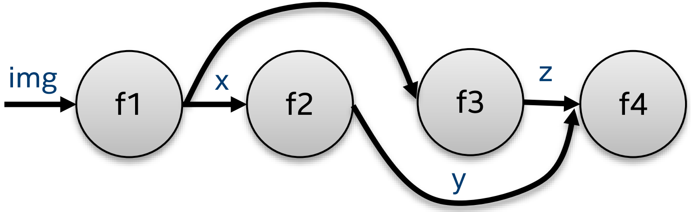
Graph-based parallelism

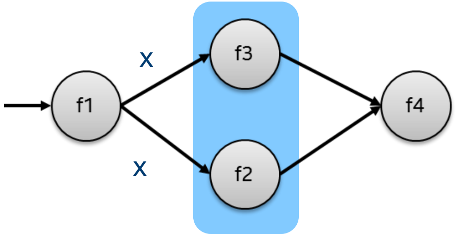
```
while ( img = get_image() ) {
    x = f1(img);
    y = f2(x);
    z = f3(x);
    f4(y,z);
}
```

Graphs express the operations and their input and output dependencies:

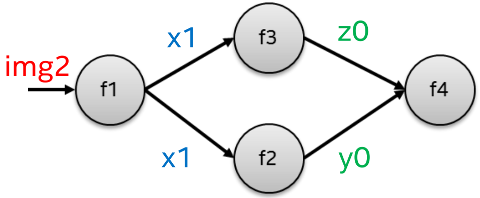


Given the operations and their input and output dependencies, a runtime scheduler:

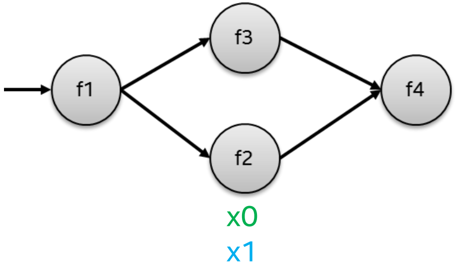
Can exploit functional parallelism:



Can exploit pipeline parallelism:



Can exploit data parallelism:

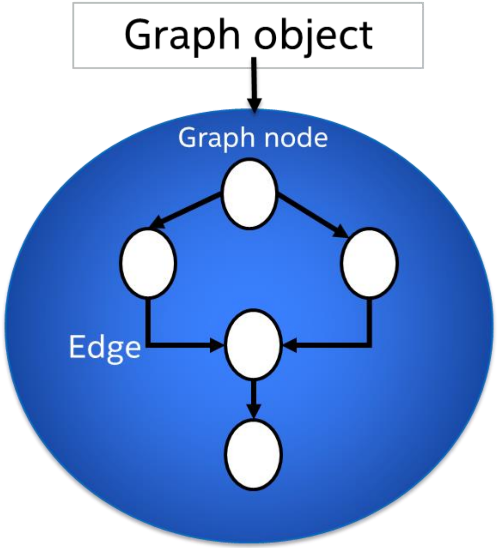


Threading Building Blocks flow graph

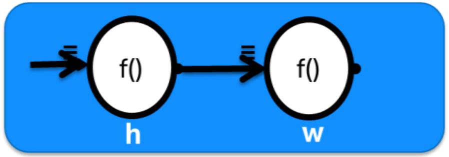
Efficient implementation of dependency graph and data flow algorithms

Enables developers to exploit parallelism at higher levels

Nodes execute as TBB tasks

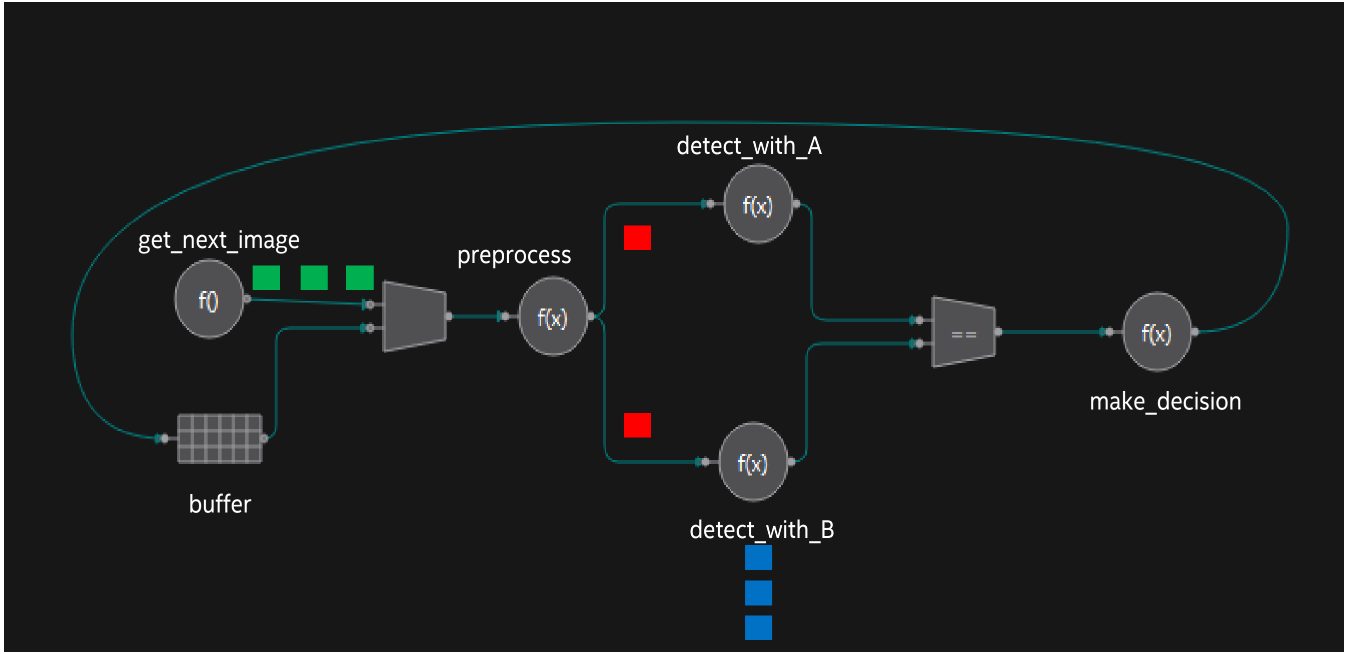


Hello World



```
graph g;
continue_node< continue_msg > h( g,
    []( const continue_msg & ) {
        cout << “Hello “;
    } );
continue_node< continue_msg > w( g,
    []( const continue_msg & ) {
        cout << “World\n“;
    } );
make_edge( h, w );
h.try_put(continue_msg());
g.wait_for_all();
```

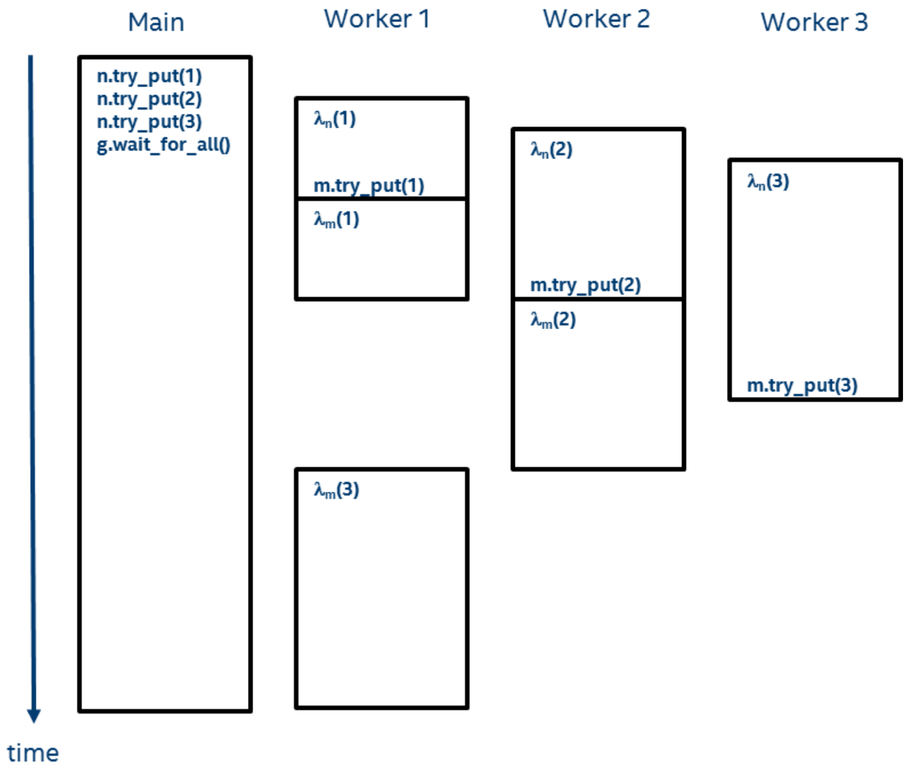
An example feature detection algorithm



Can express pipelining, task parallelism and data parallelism

How flow graph nodes map to TBB tasks

```
graph g;
function_node< int, int > n( g, unlimited, []( int v ) -> int {
   cout << v;
   spin_for( v );
   cout << v;
   return v;
} );
function_node< int, int > m( g, serial, []( int v ) -> int {
   v *= v;
   cout << v;
   spin_for( v );
   cout << v;
   return v;
} );
make_edge( n, m );
n.try_put( 1 );
n.try_put( 2 );
n.try_put( 3 );
g.wait_for_all();
```



One possible execution – stealing is random

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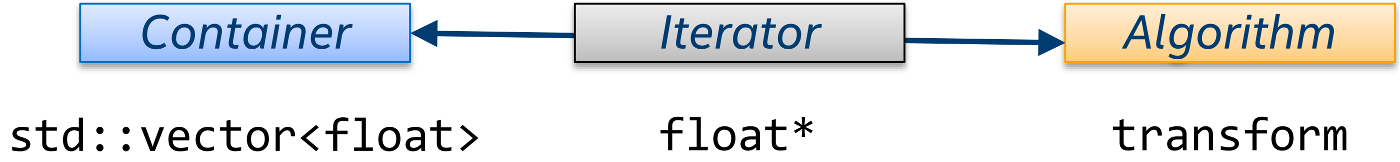
The C++ Standard Template Library



Container ← Iterator → Algorithm

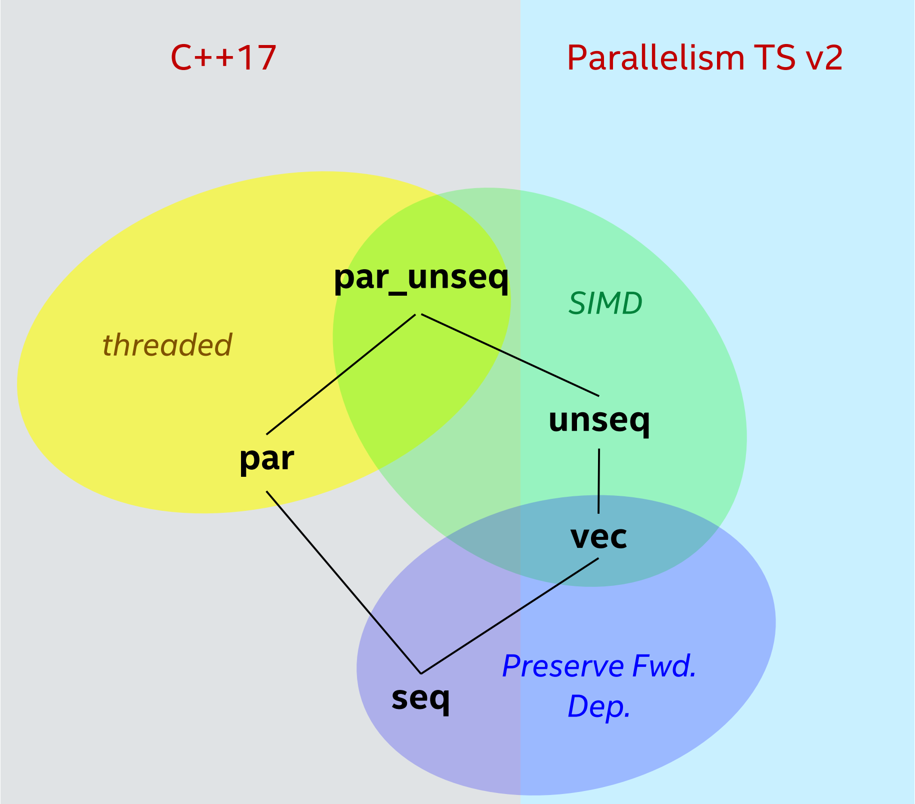
`std::vector<float>` `float*` `transform`

```
#include <algorithm>

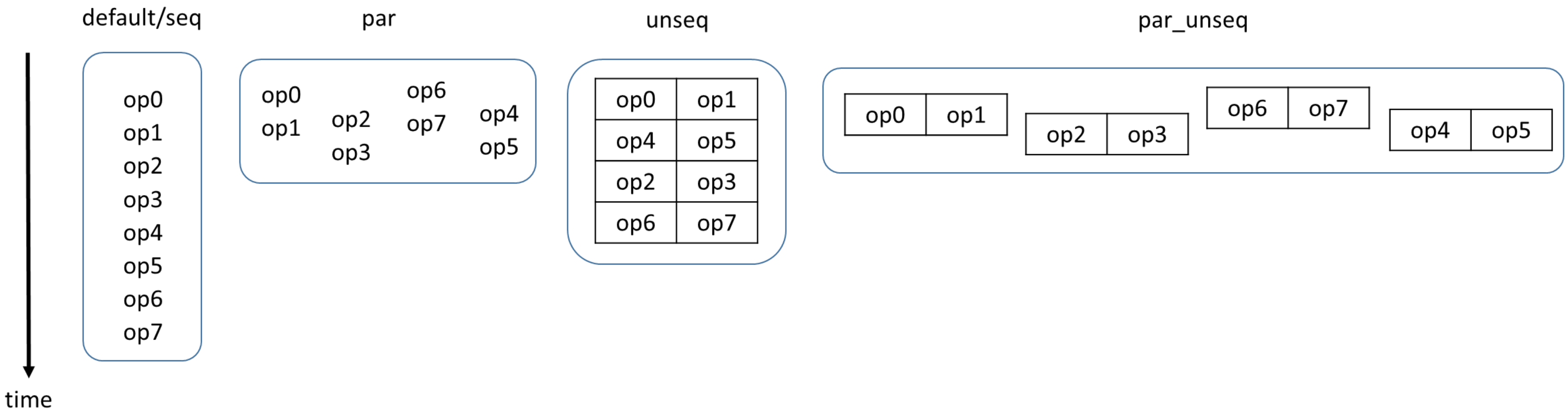
void increment( float *in, float *out, int N ) {
    using namespace std;
    transform( in, in + N, out, []( float f ) {
        return f+1;
    });
}
```

Enter Parallel STL

- Extension of C++ Standard Template Library algorithms with the “execution policy” argument
- Support for parallel execution policies is approved for C++17
- Support for vectorization policies is being developed in Parallelism Technical Specification (TS) v2



The different execution policies for Parallel STL



default/seq

op0
op1
op2
op3
op4
op5
op6
op7

par

op0
op1

op2
op3

op6
op7

op4
op5

unseq

op0	op1
op4	op5
op2	op3
op6	op7

par_unseq

op0	op1

op2	op3

op6	op7

op4	op5

time

Parallel STL Examples

```
// standard sequential sort
sort(v.begin(), v.end());

// explicitly sequential sort
sort(execution::seq,v.begin(), v.end());

// permitting parallel execution
sort(execution::par,v.begin(), v.end());

// permitting vectorization as well
sort(execution::par_unseq,v.begin(), v.end());

// Parallelism TS v2
// permitting vectorization only (no parallel execution)
sort(execution::unseq,v.begin(), v.end());
```

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```

Intel's Parallel STL executes using TBB tasks

Intel's Parallel STL uses OpenMP simd

Parallel STL includes many algorithms

- These are more specialized than the TBB generic algorithms
  - Like fill, find_if, etc…
- But contains some powerful functions
  - for_each, transform, reduce, transform_reduce, etc…
- Even so, they are less expressive than TBB since they work on sequences or containers
- But they have standardized C++ interfaces

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TBB includes C++ versions of many of the synchronization primitives we've learned about

- atomic variables
  - atomic<int> i;
  - supports compare_and_swap, fetch_and_add, etc…
- Mutexes & locks
  - spin_mutex, queuing_mutex, speculative_spin_mutex, etc…

But it also provides high-level thread friendly data structures

- maps, sets, queues and vectors

At this instant, another thread might pop the last element

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

TBB provides a try_pop function instead.

But it also provides high-level thread friendly data structures

- maps, sets, queues and vectors

```
extern concurrent_queue<T> MyQueue;
T item;
if( MyQueue.try_pop(item) ) {
        ...process item...
}
```

TBB provides a try_pop function instead.

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TBB provides useful memory allocators

- cache_aligned_allocator
  - Helps to prevent false sharing by doing the right padding
- scalable_allocator
  - Some OSes use a single global heap for memory allocator, that is protected by a lock
  - If many threads starting allocating in parallel there is contention on the lock
  - The TBB scalable memory allocator uses per-thread heaps to avoid locking

To Learn More:

See Intel’s The Parallel Universe Magazine

https://software.intel.com/en-us/intel-parallel-universe-magazine

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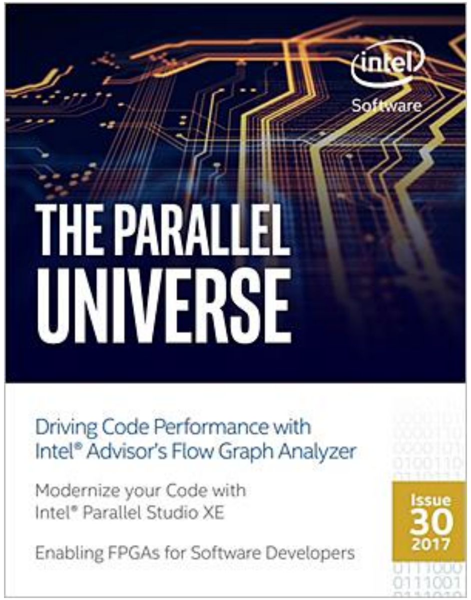

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