LINZ INSTITUTE OF TECHNOLOGY

PARALLEL COMPUTING
Parallel Computing with Modern C++

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Parallelism is Everywhere

- Servers
- Computers
- Smartphones

Why Parallel Computing?

- High performance (e.g., low execution time, high throughput, low latency)
- Scalability
- Quality of services
- Reduce the energy consumption?
  - Less cost
  - More sustainable

→ **How is this possible?**

Why Parallel Computing?

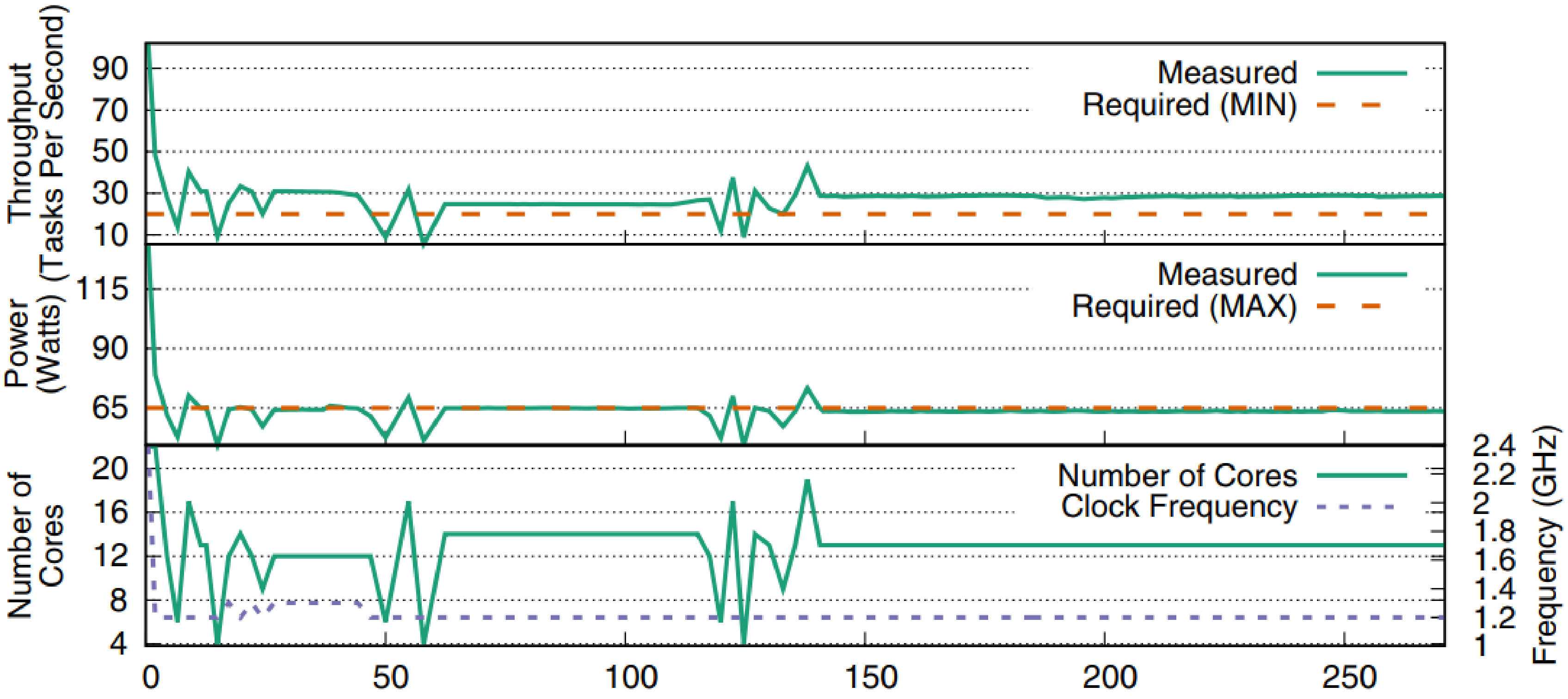
- Power consumption reduction obtained with parallel execution compared to the sequential ones [3]

	Pbzip2	Lane detection	Person recognition
Power consumption reduction (%)	– 9.43%	– 10.37%	– 7.39%

How is it possible?

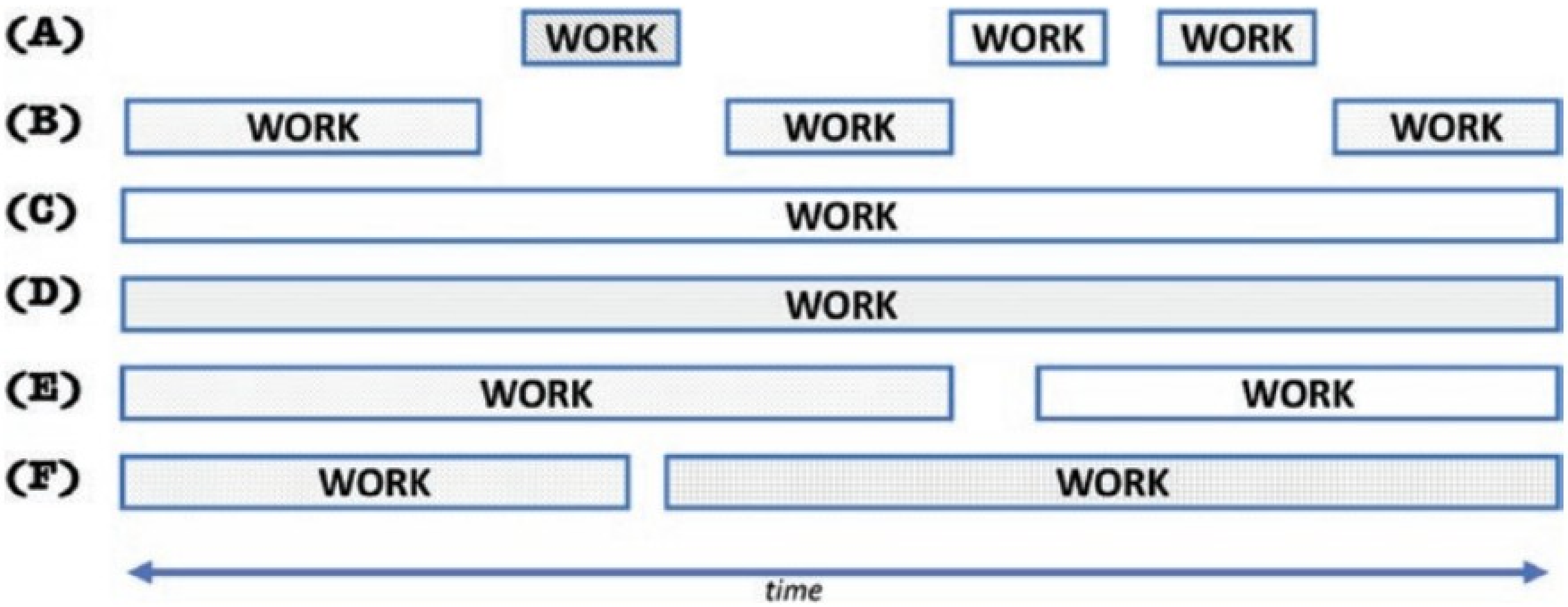
Why Parallel Computing?

- Power consumption reduction obtained with parallel execution compared to the sequential ones



Source [3]

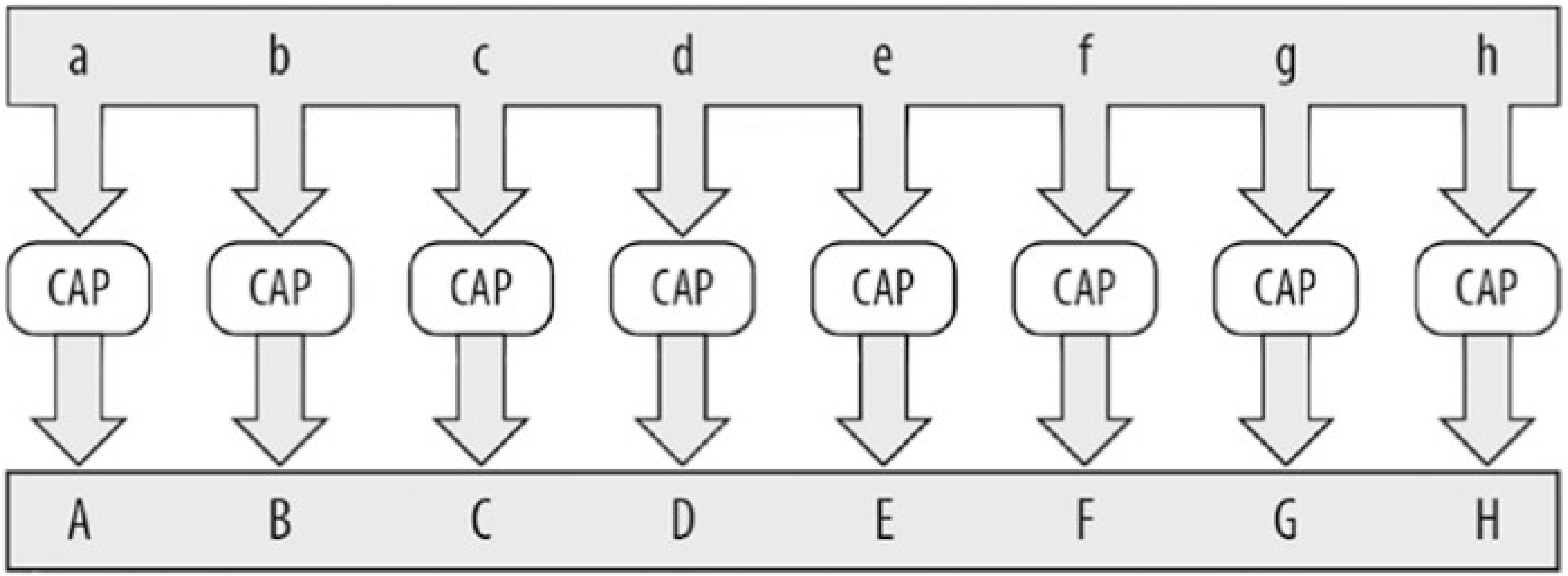
Concurrent vs. Parallel



- Tasks (A) and (B) are only concurrent
- The others are concurrent and parallel

Source [1]

Data Parallelism



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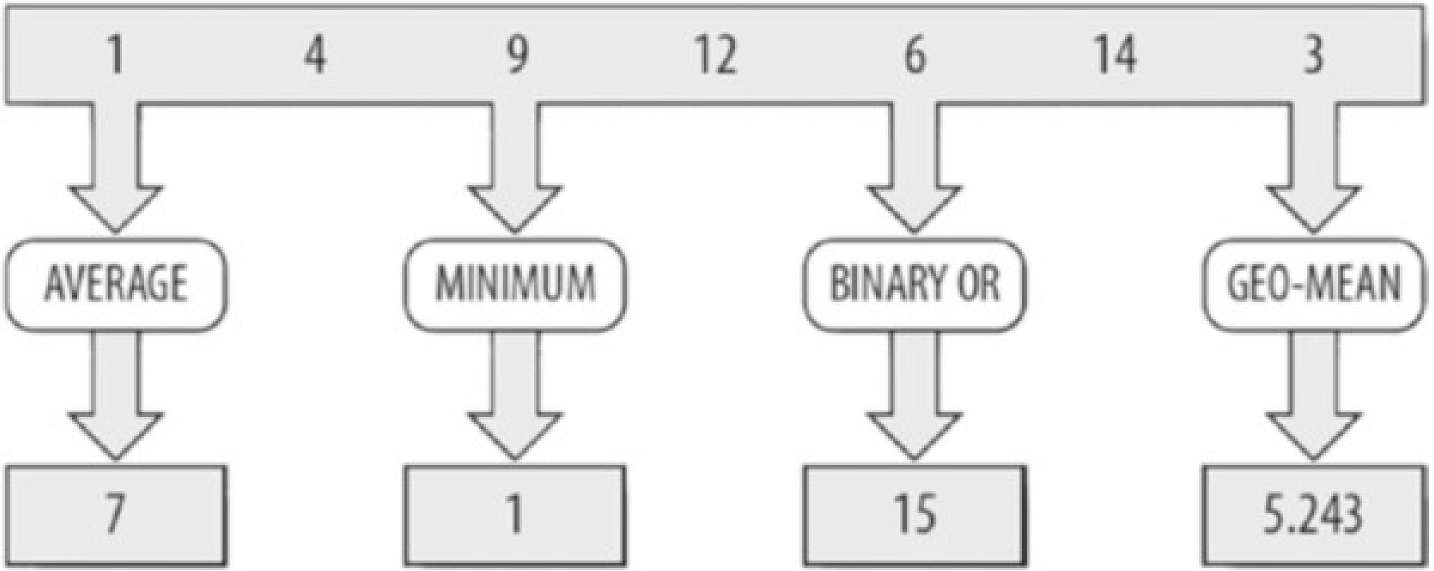
Task Parallelism



Source [1]

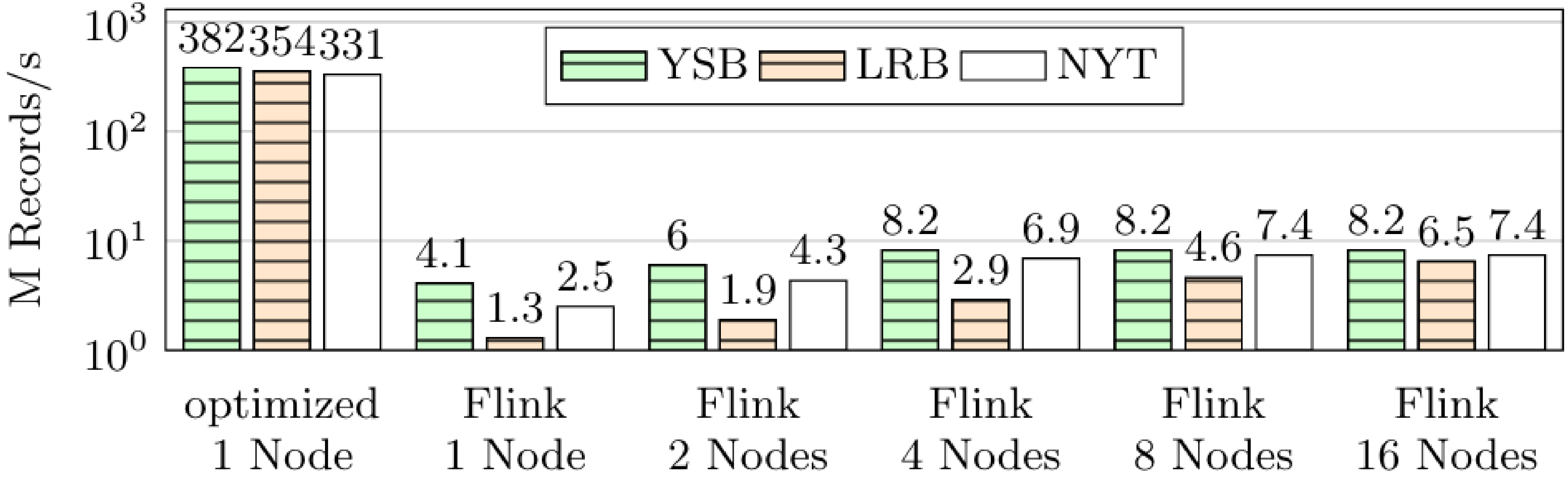
Parallel Computing

- How do we achieve parallelism in computing applications?
- We (still) need to model and program our applications to execute in parallel (in the vast majority of cases).
- Software must be designed to run in parallel: “The free lunch is over.” [Ref 5]
- Different ways were already presented in this course.
- Today we will see how to parallel computing works in **modern C++** using the **standard C++** threads
- Requirements:
  Familiarity with modern C++ features and access to C++17 compiler

Why C++?

Why C++?

It is efficient!



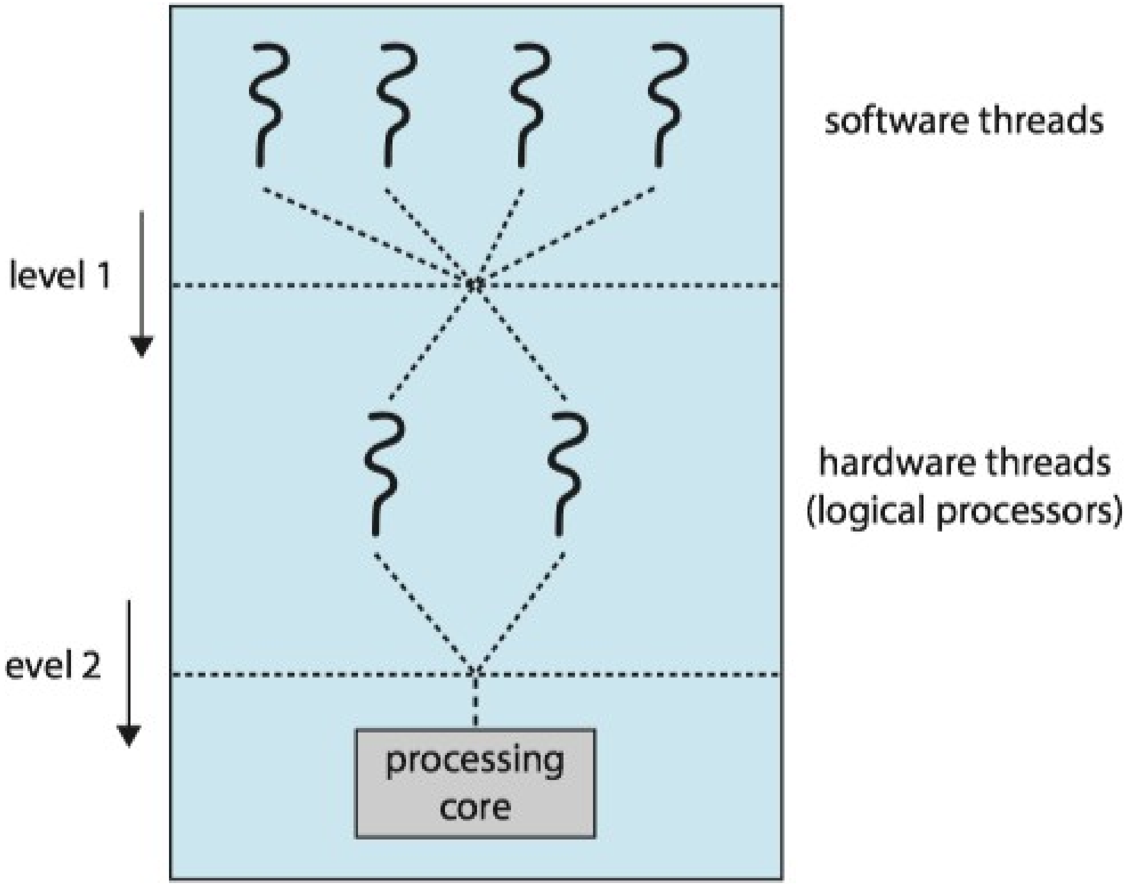
Read more on Zeuch *et al.* **Analyzing Efficient Stream Processing on Modern Hardware**

Concurrency in C++

- C++11 standard provided support for concurrency through multithreading: Standard C++ Thread Library
- Improved support with C++17 and C++20
- No major updates seen (until now) in C++23

What are threads?

- Hardware threads
- Software threads
- std::threads



Source: https://techlarry.github.io/OS

What if we create more threads than available hardware threads?

Standard C++ Threads

- Code examples using C++ thread class
- Implemented with RAII: Resource Acquisition Is Initialization

```cpp
#include <iostream>         // std::cout
#include <thread>           // std::thread
void foo() {
  // do stuff...
}
void bar(int x) {
  // do stuff...
}
int main() {
  std::thread first (foo);     // spawn new thread that calls foo()
  std::thread second (bar,0);  // spawn new thread that calls bar(0)
  std::cout << "main, foo and bar now execute concurrently...\n";
  // synchronize threads:
  first.join();                // pauses until first finishes
  second.join();               // pauses until second finishes
  std::cout << "foo and bar completed.\n";
  return 0;
}
```

Standard C++ Threads

- Many other features: https://cplusplus.com/reference/thread/thread/
  - Arguments
  - Change of ownership
  - Running in background
  - Identifying threads
  - System thread interface
    - Pause threads (this_thread::sleep_for(time))
    - Thread priority
    - Thread affinity “pinning”

Data Shared Between Threads

- There's mostly no problem if all shared data is read-only
- Modifying the shared data can cause problems
- Be careful when sharing data:
  - Problematic race conditions (the threads execution order affects the correctness) data races occur when the threads access the same memory location and one updates it.
  - We need to serialize to guarantee consistency and defined behavior.

Protecting Shared Data

- Critical sections
- Mutex
- Locks
- Deadlock

Why is this topic so relevant?

Parallelism Challenges

- Thinking in parallel
- Locks and mutexes
- Shared mutable state

```
timed_mutex the_mutex;
void task1() {
    cout << "Task1 trying to get lock" << endl;
    the_mutex.lock();
    cout << "Task1 has lock" << endl;
    this_thread::sleep_for(500ms);
    cout << "Task1 releasing lock" << endl;
    the_mutex.unlock();
}
```

Parallelism Challenges

- Locks and Mutexes
- “Locks, can’t live with them, can’t live without them.” [Ref 1]

Why locks are so problematic?

Thread Synchronization
Condition Variables

- From CPP reference:
  “*A condition variable is a synchronization primitive that allows multiple threads to communicate with each other. It allows some number of threads to wait (possibly with a timeout) for notification from another thread that they may proceed. A condition variable is always associated with a mutex.*”

Threads Synchronization
Condition variable example from cplusplus.com

```cpp
#include <iostream>
#include <string>
#include <thread>
#include <mutex>
#include <condition_variable>
std::mutex m;
std::condition_variable cv;
std::string data;
bool ready = false;
bool processed = false;
void worker_thread() {
    std::unique_lock lk(m);
    cv.wait(lk, []{return ready;}); // Wait until main() sends data,
                                       then we own the lock.
    std::cout << "Worker thread is processing data\n";
    data += " after processing";
    processed = true; // Send data back to main()
    std::cout << "Worker thread signals data processing completed\n";
    lk.unlock(); //Manual unlocking is done before notifying
    cv.notify_one();
}
```

```cpp
int main() {
    std::thread worker(worker_thread);
    data = "Example data";
    {
        std::lock_guard lk(m);
        ready = true;
        std::cout << "main() signals data ready\n";
    }
    cv.notify_one();
    {
        std::unique_lock lk(m);
        cv.wait(lk, []{return processed;});// wait for the
                                              worker
    }
    std::cout << "Back in main(), data = " << data << '\n';
    worker.join();
}
```

```
main() signals data ready
Worker thread is processing data
Worker thread signals data processing completed
Back in main(), data = Example data after processing
```

Threads Synchronization

Futures

Facility to obtain values that are returned and to catch exceptions that are thrown by asynchronous tasks

```cpp
#include <iostream>
#include <future>
int task() {
    std::cout << "Task started" << std::endl;
    std::cout << "Task completed" << std::endl;
    return 1;
}
int main() {
    //future that launches a task
    std::future<int> fut1 = std::async(std::launch::async, task);

    // Wait for the result of task
    int result = fut1.get();
    std::cout << "The result is : " << result << std::endl;
    return 0;
}
```

Standard C++ Tasks

- AKA Asynchronous programming
- Contrary of blocking and waiting, tasks can run in background
- Threads vs. tasks

Threads Synchronization
Promises

- std::promise provides means to set a value that can later be read with a std::future object:
  - The waiting thread could block on the future
  - The thread providing the data could use the promise to set the associated value and make the future ready [6].
- Promise: producer/writer
- Future: consumer/reader

Threads Synchronization

Promise Example (from https://cplusplus.com/reference/future/promise/)

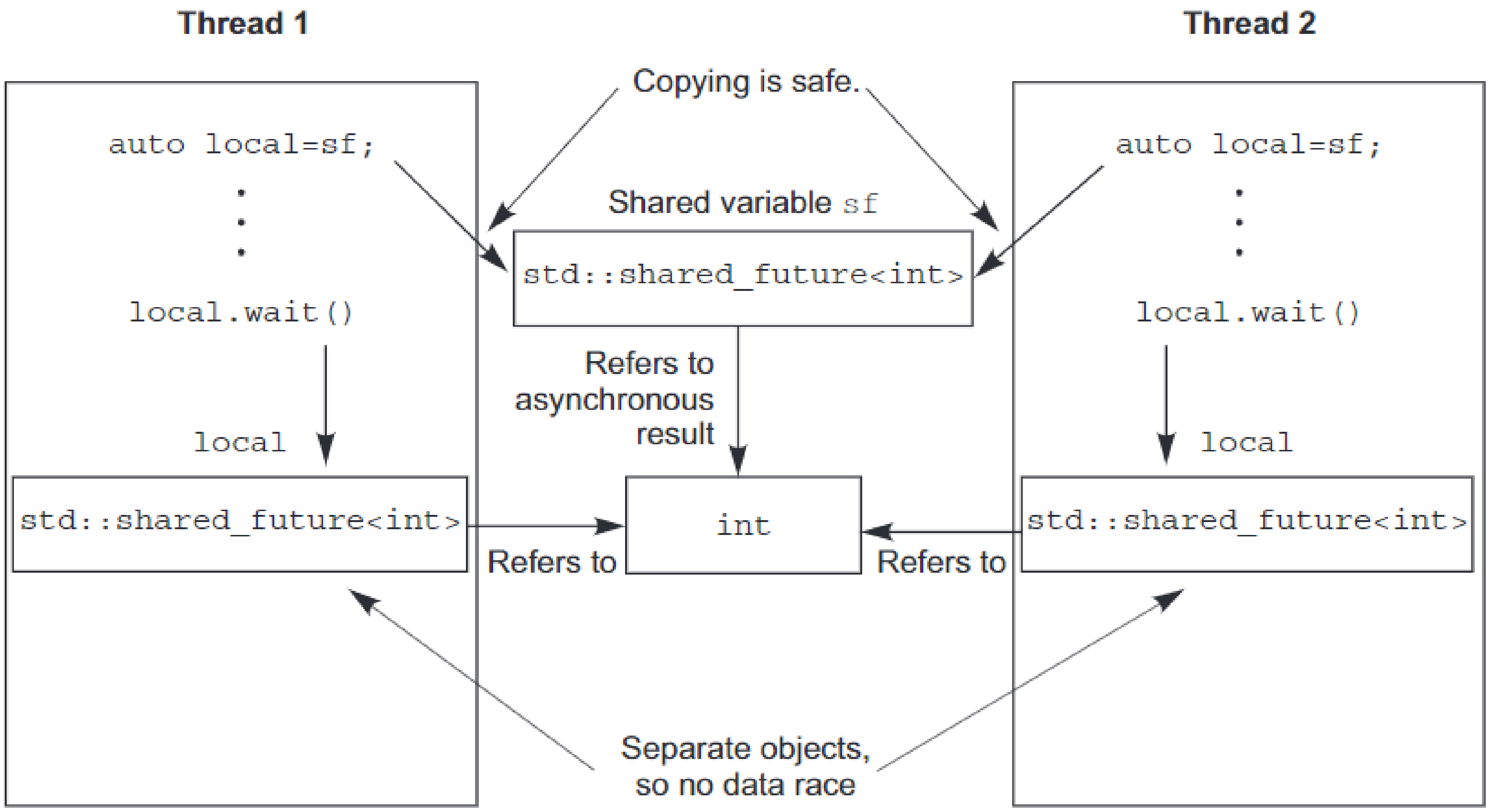
```
#include <iostream>        // std::cout
#include <functional>      // std::ref
#include <thread>          // std::thread
#include <future>          // std::promise, std::future
void print_int (std::future<int>& fut) {
  int x = fut.get();
  std::cout << "value: " << x << '\n';
}
int main () {
  std::promise<int> prom;                       // create promise
  std::future<int> fut = prom.get_future();     // engagement with future
  std::thread th1 (print_int, std::ref(fut));   // send future to new thread
  prom.set_value (10);                          // fulfill promise
                                                // (synchronizes with getting the future)
  th1.join();
  return 0;
}
```

Threads Synchronization

- A problem with futures:
  Data race and undefined behavior when accessing a std::future object from multiple threads (without additional synchronization)

Threads Synchronization

- Solution: shared_future
- Single producer multiple consumers
- Several threads can receive a “value”

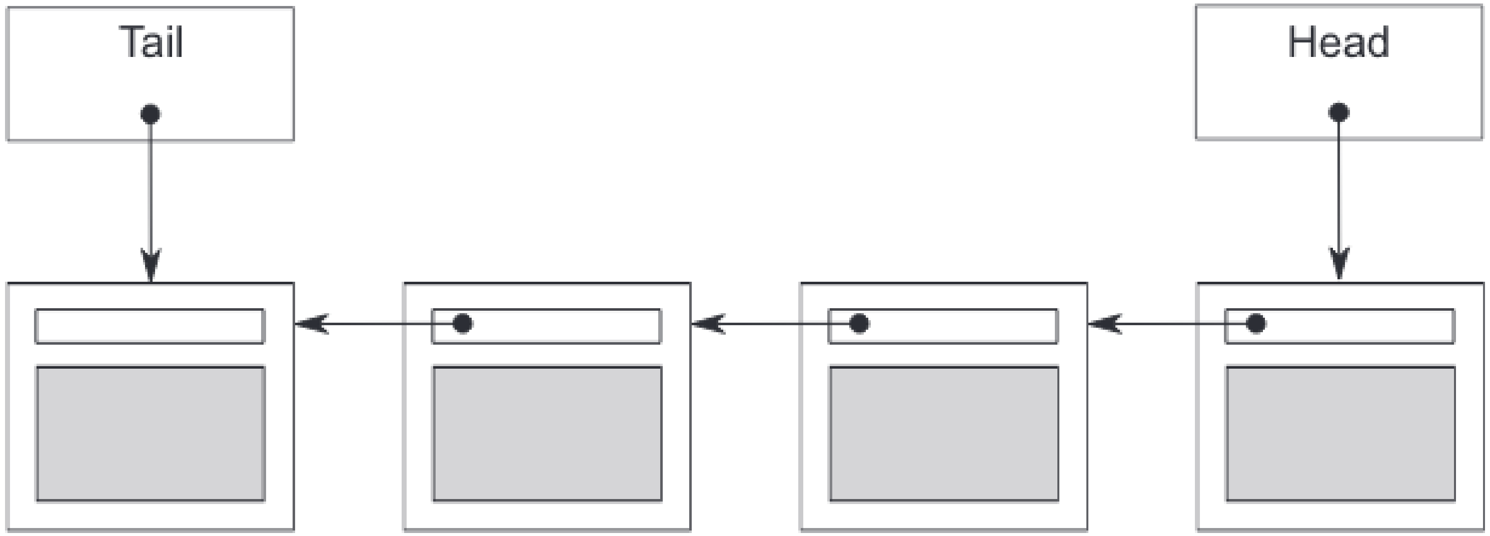


Source [6]

Communication Between Threads

- Thread safe concurrent data structures, such as:
  - Stacks
  - Queues
  - Lists
- (Potentially) Safe and (potentially) efficient threads communication

Queue: Represented as a Single-Linked List [6]



Source [6]

Requirement: Thread Safe Queues

- std::queue FIFO:
  - New data is pushed to end and the oldest data is popped at the “beginning”
  - front() return a reference to the value at the “beginning”
  - pop() no return, removes the element at the “beginning” (C++ constraint for exception safety)
- std::queue is not suitable to be used as a concurrent queue:
  - race conditions in concurrent function call
  - undefined behavior

C++ concurrent data structures

- Needed to share data and synchronize messages
- A queue between producers and consumer threads
- But, C++ does not provide a standard concurrent queue (why?)

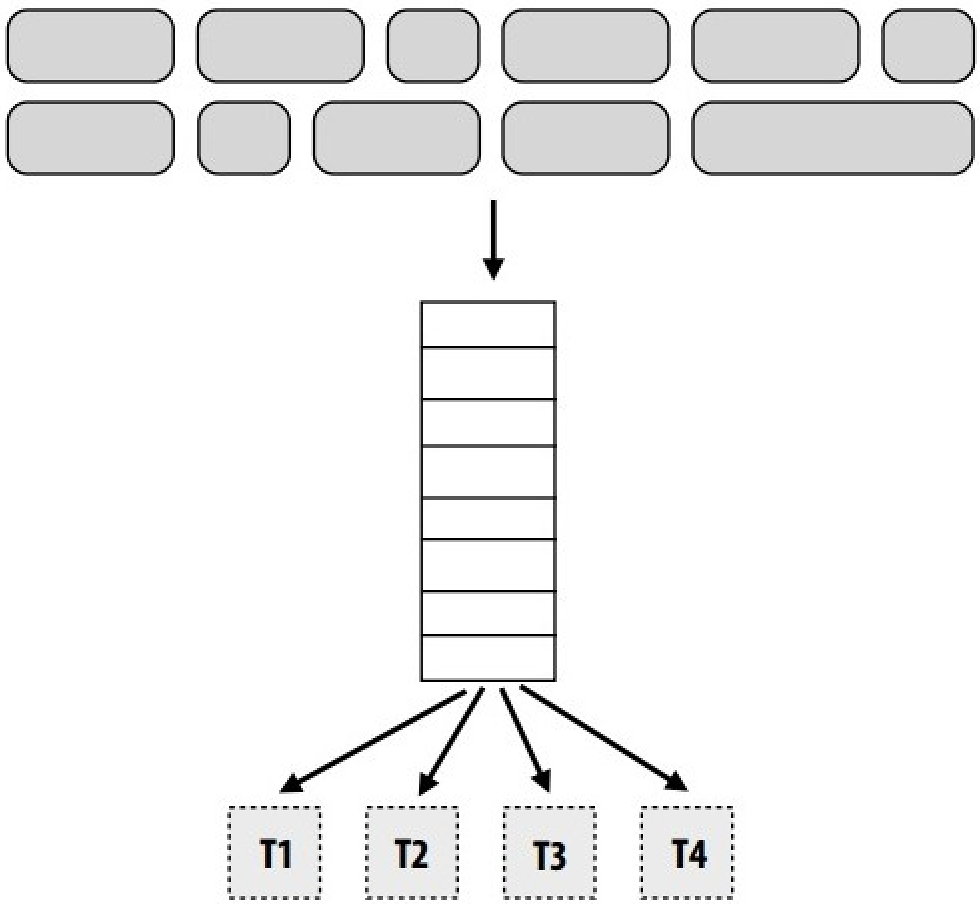
Thread Safe Concurrent Queues

- Simplest solution: Use a wrapper class that protects shared data with member instances:
  - std::queue
  - std::mutex
- Locking a mutex before calling a std::queue member function, then unlocks.
- Only one thread per time can access a given queue member function.

Thread Safe Concurrent Queues

```cpp
template <class T>
class threadSafeQueue {
    std::mutex m;
    std::queue<T> q;
    std::condition_variable cv;
public:
    threadSafeQueue() = default;
    void push(T value) {
        std::lock_guard<std::mutex> lg(m);
        q.push(value);
        cv.notify_one();
    }

    void pop(T& value) {
        std::unique_lock<std::mutex> lg(m);
        cv.wait(lg, [this] {return !q.empty();});
        value = q.front();
        q.pop();
    }
};
```



Code example from [7]
Representation from [8]

Using the Thread Safe Concurrent Queues

```
threadSafeQueue<int> myQueue;
void consumer() {
    int data;
    std::cout << "The consumer is running" << std::endl;
    myQueue.pop(data);                              // Get a value from the queue
    std::cout << "Consumer received: " << data << std::endl;
}
void producer() {
    std::cout << "The producer is running..." << std::endl;
    myQueue.push(10);                          // Push the data into the queue
    std::cout << "The producer has pushed some data" << std::endl;
}
int main() {
    auto cons = async(std::launch::async, consumer); //starting consumer
    auto prod = async(std::launch::async, producer); //starting producer
    cons.wait();
    prod.wait();
}
```

```
The consumer is running
The producer is running...
The producer has pushed some data
Consumer received: 10
```

```
The producer is running...
The consumer is runningThe producer has
pushed some data

Consumer received: 10
```

Standard C++ Parallelism

- Is it enough to achieve scalability?
- Not for the many use-cases!
- Why?

C++ Thread pools

- Scalability
- Use properly the CPU resources
- Manage the overhead of thread creation

```
#include <iostream>
#include <chrono>
#include <functional>
#include "concurrentQueue.h"
using namespace std;
// Example of a computation
void processTask(int taskId) {
  cout << "Processing task " << taskId << " in thread "
       << this_thread::get_id() << endl;
  this_thread::sleep_for (chrono::seconds(1)); // task processing
}
int main() {
  const int numTasks = 10;
  const int numThreads = 3 ;//std::thread::hardware_concurrency();
  cout << "Executing " << numTasks << " tasks in a thread pool of: "
       << numThreads << " threads" << endl;
  ThreadPool threadPool(numThreads);
  for (int i = 0; i < numTasks; ++i) {
     threadPool.enqueue(processTask, i);
  }
  return 0;
}
```

ThreadPool Class

```
class ThreadPool {
  public:
      ThreadPool(size_t num_threads) {
          for (size_t i = 0; i < num_threads; ++i) {
              threads_.emplace_back([this] {
                  while (true) {
                      std::function<void()> task;
                      {
                          std::unique_lock<std::mutex> lock(mutex_);
                          condition_.wait(lock, [this] {
                              return stop_ || !tasks_.empty();
                          });
                          if (stop_ && tasks_.empty()) {
                              return;
                          }
                          task = std::move(tasks_.front());
                          tasks_.pop();
                      }
                      task();
                  }
              });
          }
      }
```

```
      ~ThreadPool() {
          {
              std::unique_lock<std::mutex> lock(mutex_);
              stop_ = true;
          }
          condition_.notify_all();
          for (std::thread& thread : threads_) {
              thread.join();
          }
      }
      template<typename F, typename... Args>
      auto enqueue(F&& f, Args&&... args) -> std::future<typename
                std::result_of<F(Args...)>::type> {
          using return_type = typename std::result_of<F(Args...)>::type;
          auto task = std::make_shared<std::packaged_task<return_type()>>(
                  std::bind(std::forward<F>(f), std::forward<Args>(args)...)
          );
          std::future<return_type> result = task->get_future();
          {
              std::unique_lock<std::mutex> lock(mutex_);
              tasks_.emplace([task]() {
                  (*task)();
              });
          }
          condition_.notify_one();
          return result;
      }

  private:
      std::vector<std::thread> threads_;
      std::queue<std::function<void()>> tasks_;
      std::mutex mutex_;
      std::condition_variable condition_;
      bool stop_ = false;
};
```

Executing Thread Pools Example

```cpp
#include <iostream>
#include <chrono>
#include <functional>
#include "concurrentQueue.h"
using namespace std;
// Example of a computation
void processTask(int taskId) {
  cout << "Processing task " << taskId << " in thread "
       << this_thread::get_id() << endl;
  this_thread::sleep_for (chrono::seconds(1)); // task processing
}
int main() {
  const int numTasks = 10;
  const int numThreads = 3 ;//std::thread::hardware_concurrency();
  cout << "Executing " << numTasks << " tasks in a thread pool of: "
       << numThreads << " threads" << endl;
  ThreadPool threadPool(numThreads);
  for (int i = 0; i < numTasks; ++i) {
     threadPool.enqueue(processTask, i);
  }
  return 0;
}
```

```
Executing 10 tasks in a thread pool of: 3 threads
Processing task 0 in thread 140446390413056
Processing task 1 in thread 140446373627648
Processing task 2 in thread 140446382020352
Processing task 3 in thread 140446373627648
Processing task 4 in thread 140446390413056
Processing task 5 in thread 140446382020352
Processing task 6 in thread 140446373627648
Processing task 7 in thread Processing task
1404463904130568 in thread
140446382020352
Processing task 9 in thread 140446373627648
```

Practical Example

Parallelize the prime number calculation with C++ threads

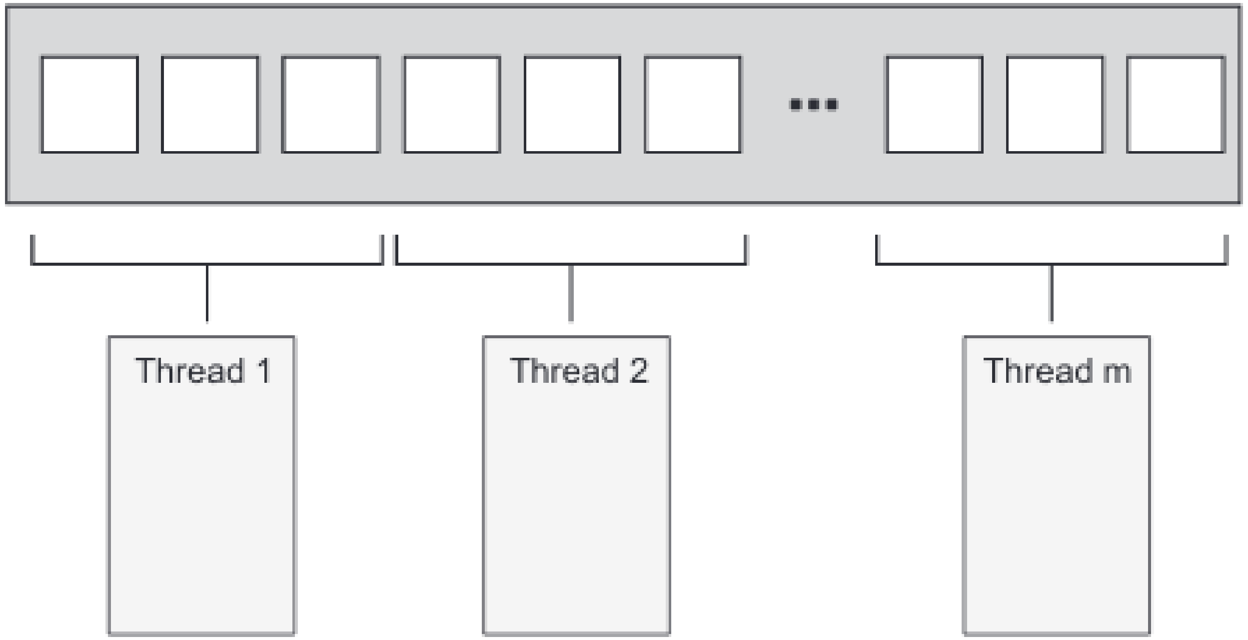
```cpp
// Function that checks if a number is prime
bool isPrime(int num) {
    if (num <= 1)
        return false;

    for (int i = 2; i < num; ++i) {
        if (num % i == 0)
            return false;
    }
    return true;
}
```

Practical Example

Naive thread pool with fixed chunks (AKA static assignment)

- Very low runtime overhead
- Works very well when the workload is fairly divided between the worker threads (balanced workload)



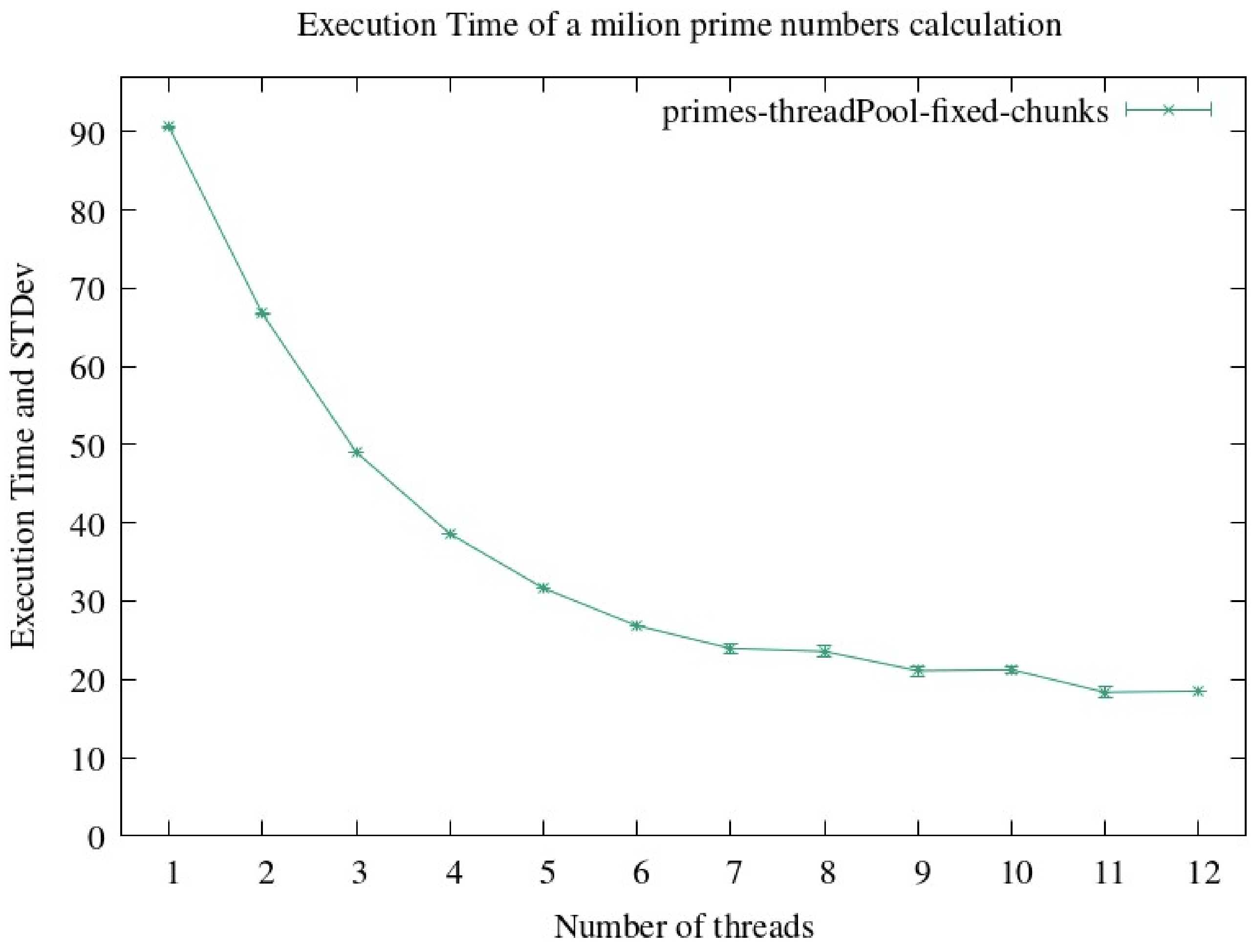
Source [6]

Parallel Prime Numbers

```
int main(int argc, char *argv[]){
   int interval=0, threadPoolSize=0;
   /* interval and threadPoolSize are argos code here and removed for visual clarity */
   const int rangeStart = 1;
   const int rangeEnd = interval;
   std::vector<std::thread> threads;
   std::vector<int> threadResults(threadPoolSize, 0);
   int chunkSize = (rangeEnd - rangeStart + 1) / threadPoolSize;
   int remaining = (rangeEnd - rangeStart + 1) % threadPoolSize;
   int start = rangeStart;
   for (int i = 0; i < threadPoolSize; ++i) {
       int end = start + chunkSize - 1;
       if (i < remaining)
           ++end;
       threads.emplace_back([start, end, i, &threadResults]() {
           threadResults[i] = countPrimesInRange(start, end);
       });
       start = end + 1;
   }
   for (auto& thread : threads) {
       thread.join();
   }
   int totalPrimes = 0;
   for (int result : threadResults) {
       totalPrimes += result;
   }
   /* Here we calculate the exec time */
   return 0;
}
```

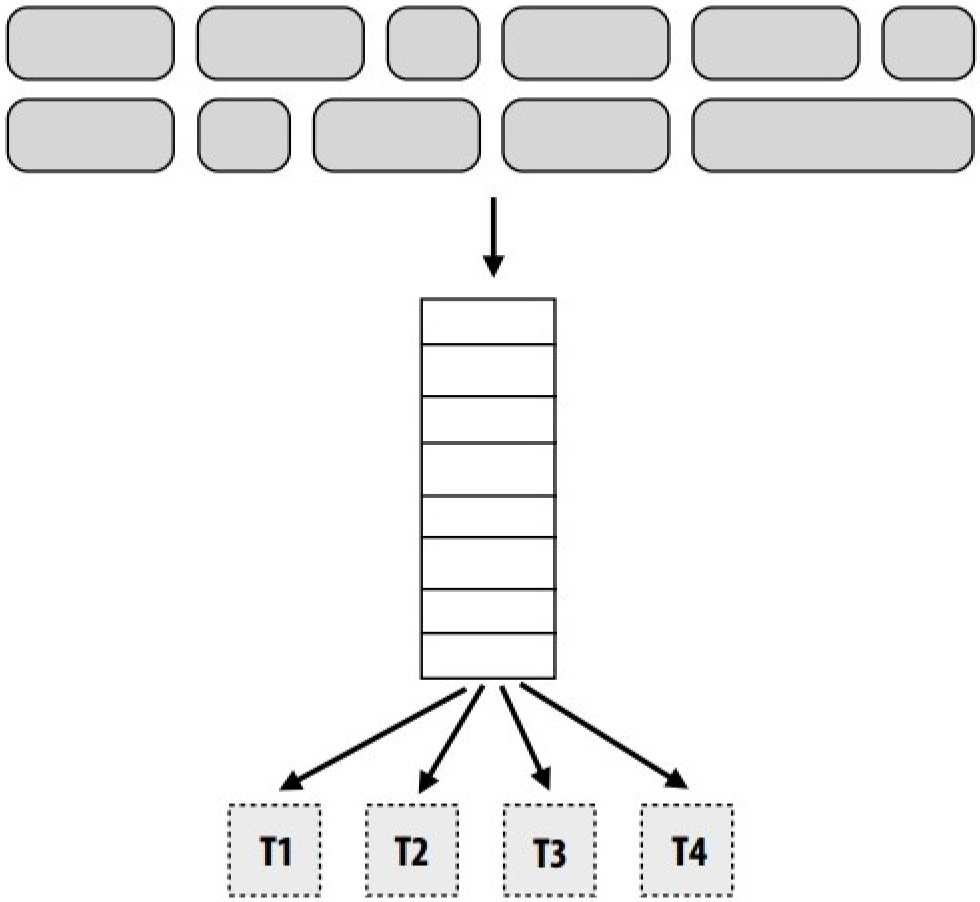
Parallel Prime Numbers

- Evaluation in a machine with 6 cores and 12 Hyperthreads
- Why this performance?
- Is it optimal?
- Remember: it works very well when the workload is fairly divided between the worker threads (balanced workload)



How can the performance be further improved?

What about using a concurrent queue?



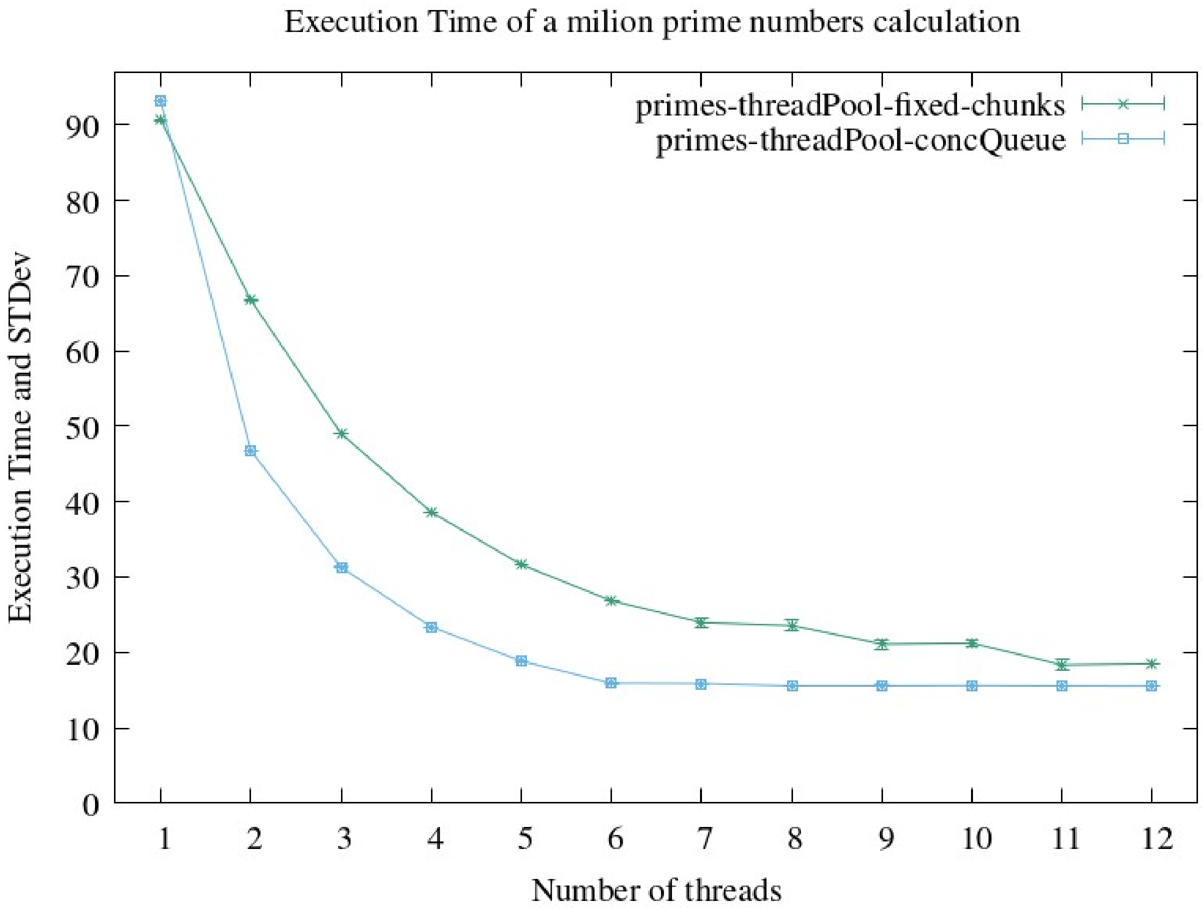
Parallel Prime Numbers with a Concurrent Queue

```
#include <iostream>
#include <vector>
#include <chrono>
#include "concurrentQueue.h"
int main(int argc, char *argv[]) {
   /* interval and threadPoolSize are argos code here and removed for visual clarity */
   ThreadPool pool(threadPoolSize);
   std::vector<std::future<bool>> results;
   for (int i = 0; i <  interval; ++i) {
       results.emplace_back(pool.enqueue([](int value) {
           if (value <= 1)
           return false;
           // Check from 2 to n-1
           for (int i = 2; i < value; i++){
           if (value % i == 0)
               return false;
           }
           return true;
       }, i));
   }
   int primerCount = 0;
   for (auto& result : results) {
       bool isPrime =  result.get();
       if (isPrime)
       {
          primerCount++;
       }
   }
   /* Here we calculate the exec time */
   return 0;
}
```

What performance can we expect?

Parallel Prime Numbers

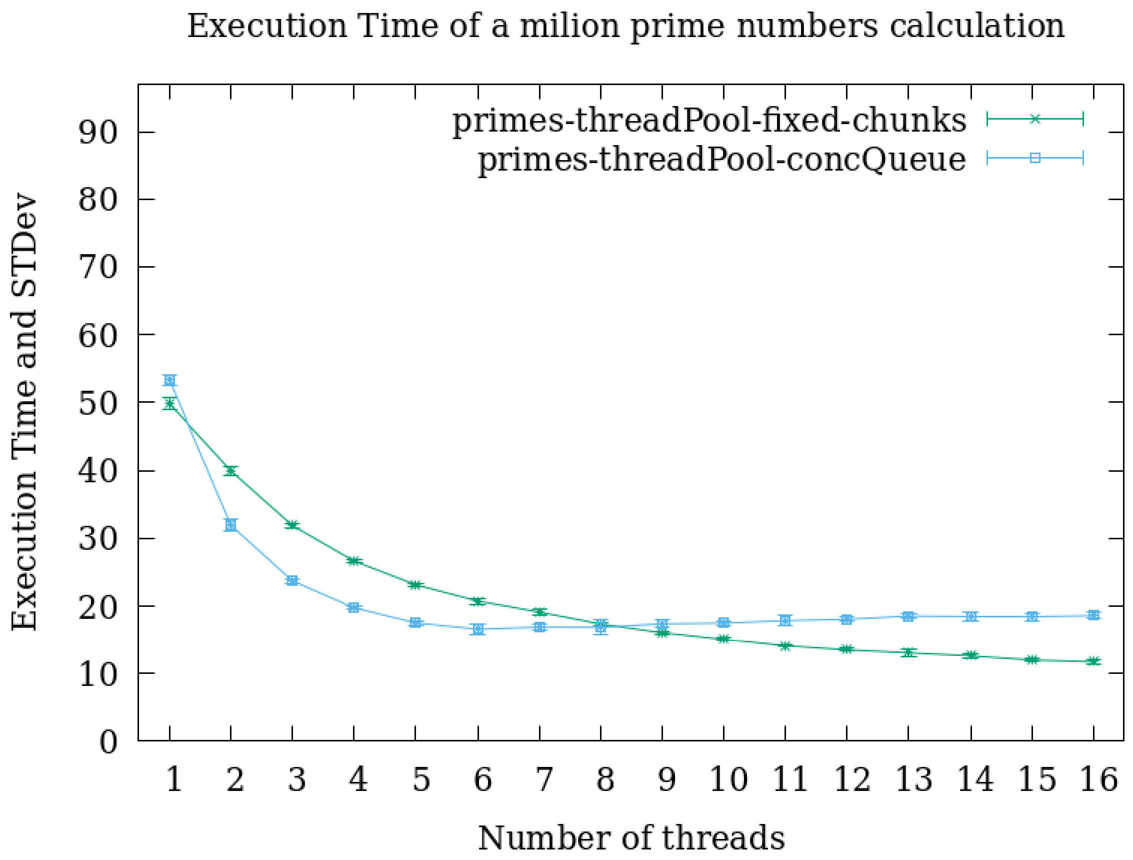
- Evaluation in a machine with 6 cores and 12 Hyperthreads
- Why this performance?



What if we run in a more powerful machine?

Parallel Prime Numbers

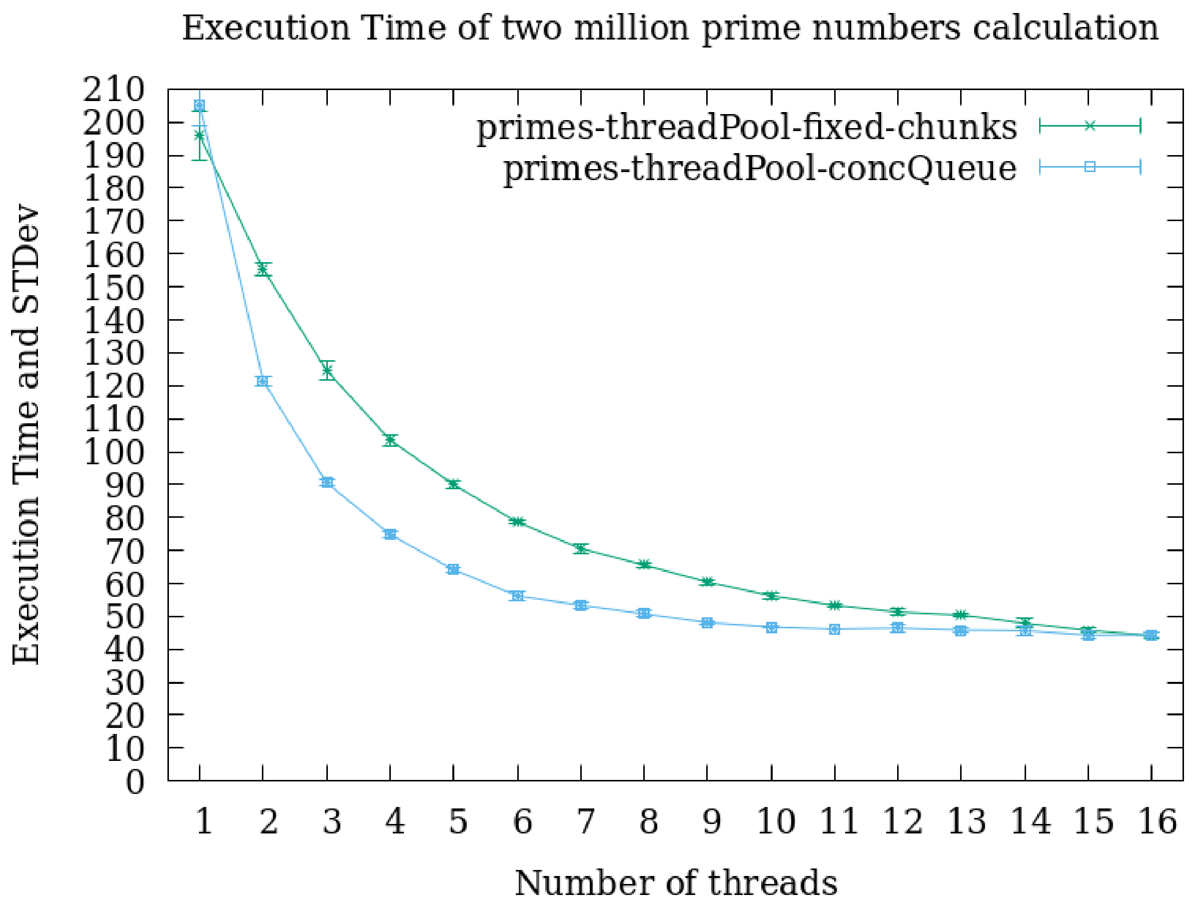
- Evaluation in a machine with 8 cores and 16 Hyperthreads
- Why this performance?



What if we increase the workload?

Parallel Prime Numbers

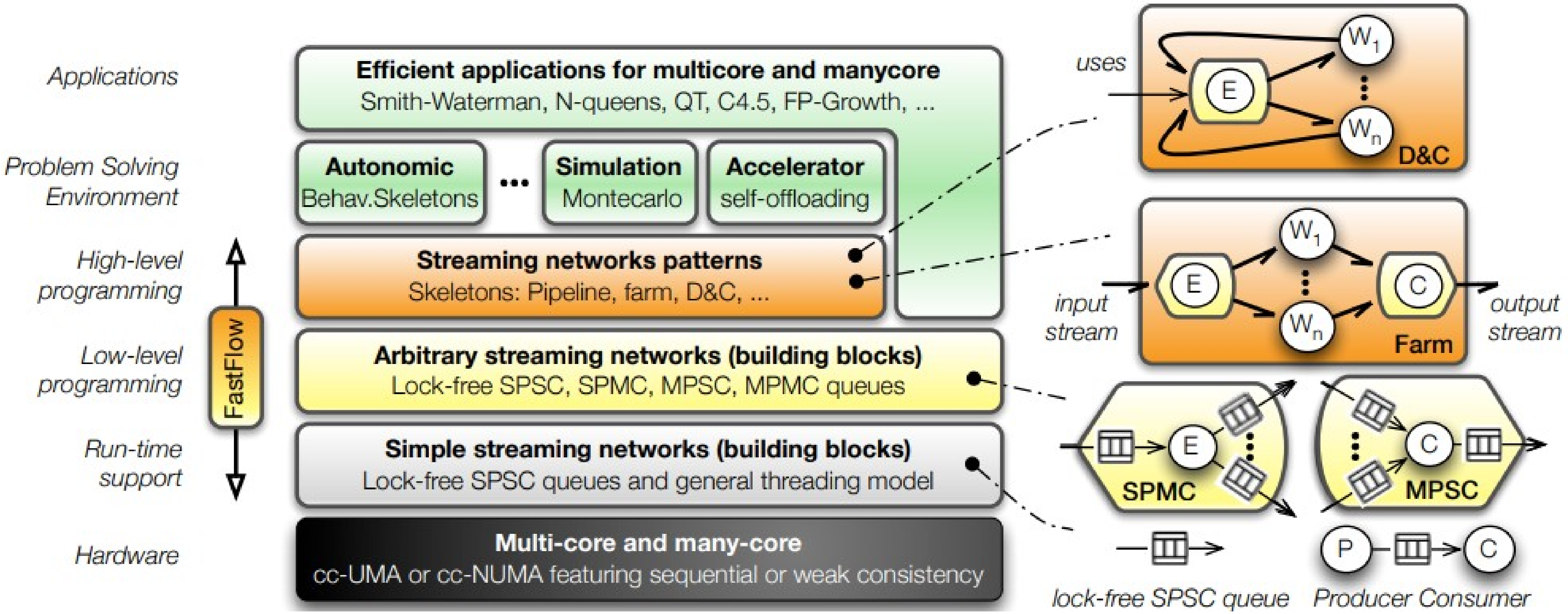
- Evaluation in a machine with 8 cores and 16 Hyperthreads
- Why this performance?



C++ concurrent data structures

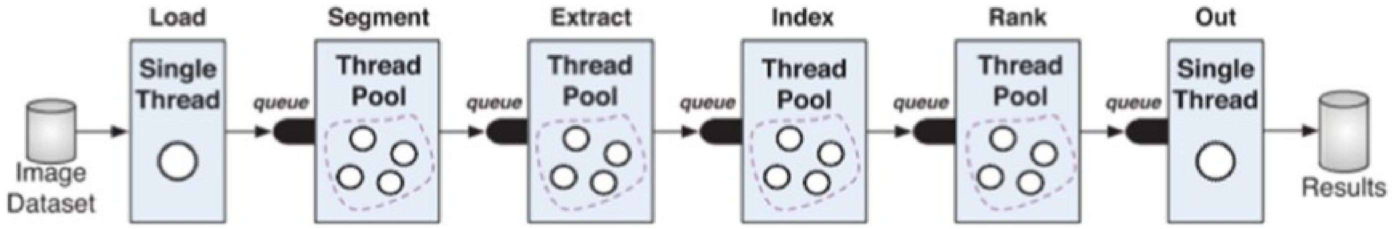
- Lock-free concurrent data structures?
- **A data structure where more than one thread can access the data structure concurrently**
- *“a lock-free queue might allow one thread to push and one to pop but break if two threads try to push new items at the same time”*
- *“A wait-free data structure is a lock-free data structure with the additional property that every thread accessing the data structure can complete its operation within a bounded number of steps, regardless of the behavior of other threads”*
- *“Writing wait-free data structures correctly is extremely hard”*
  memory **ordering** constraints, **atomic** operations, making **changes visible** to other threads in a **exact order**.
- Quotes from Williams [6]

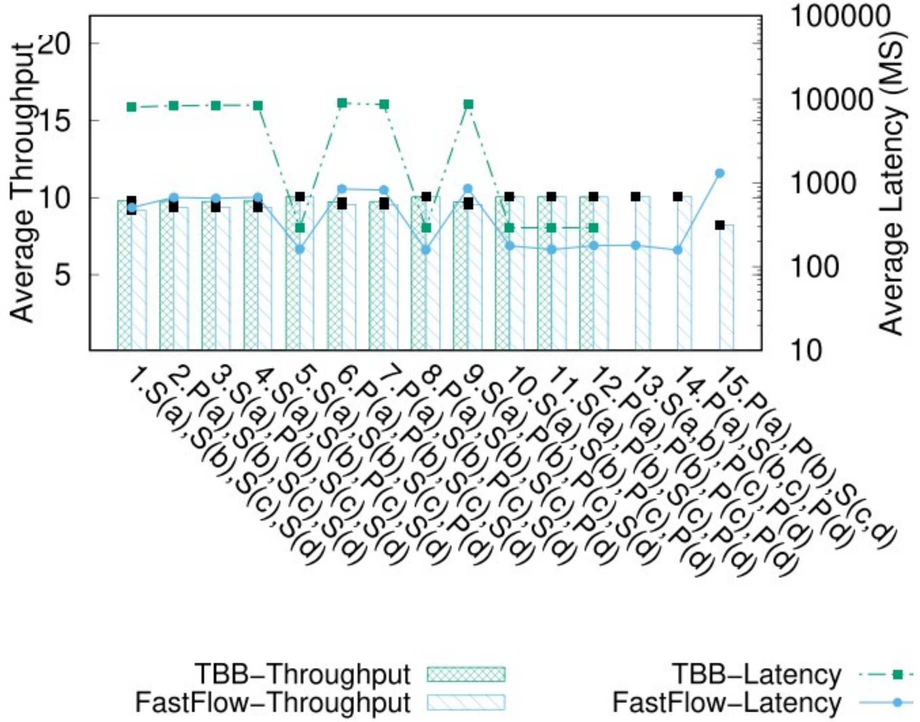
Lock-Free single producer single consumer (SPSC) Queues



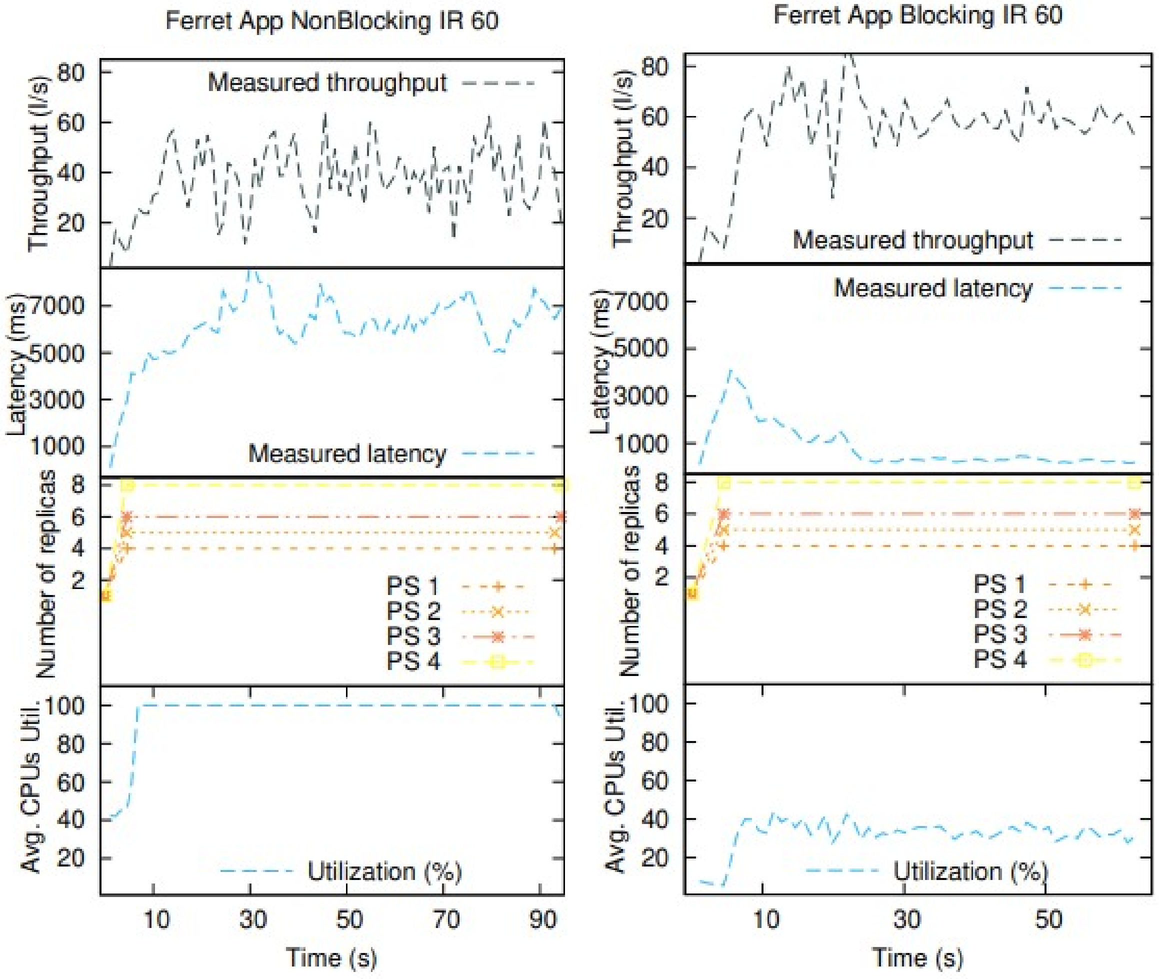
Read more about FastFlow in: https://doi.org/10.1007/978-3-642-32820-6_65

Lock-Free single producer single consumer (SPSC) Queues





Lock-Free single producer single consumer (SPSC) Queues



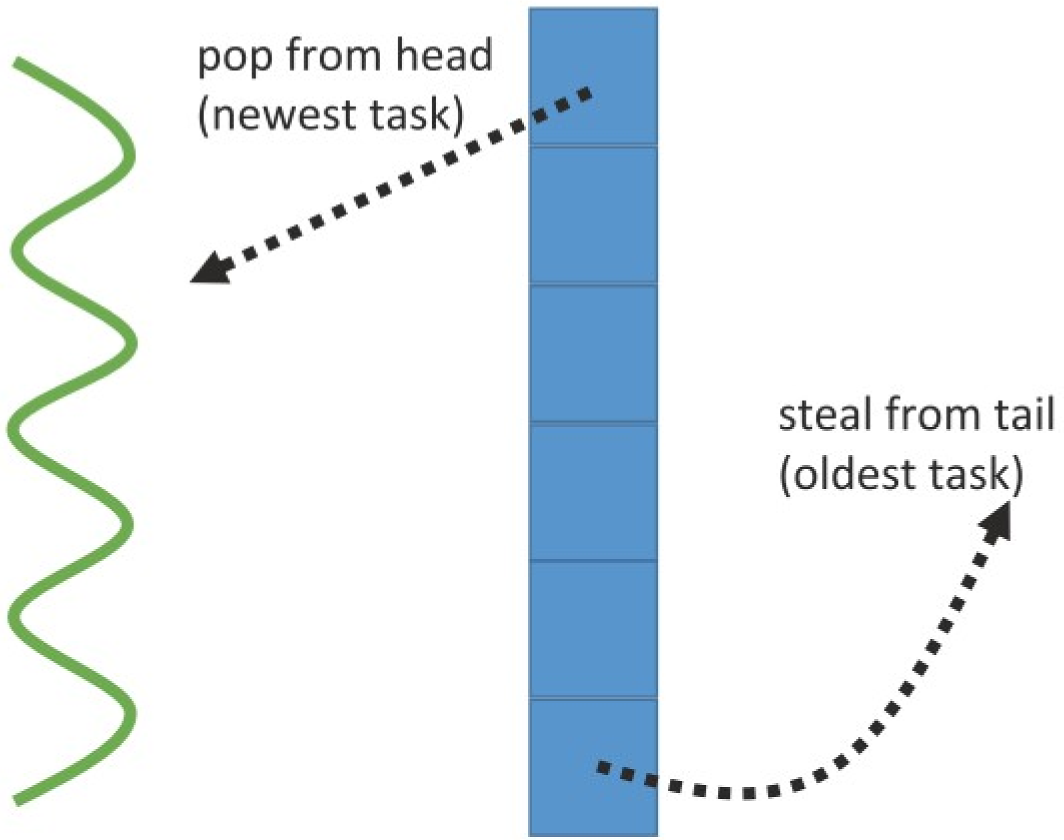
(a) Non-blocking Mode. (b) Blocking Mode.

Lock-free Concurrent Data Structures

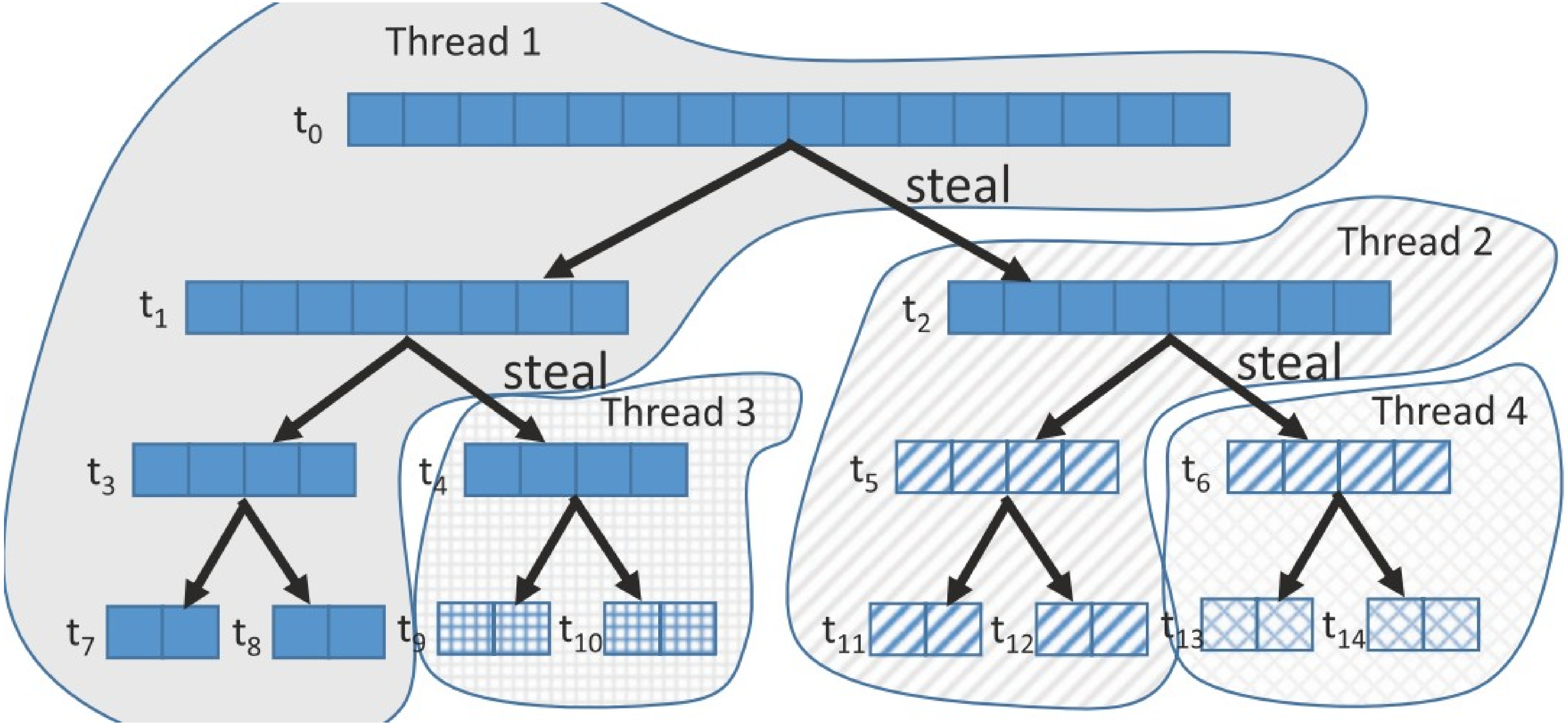
- Very strong reasons are needed to write one
- The benefits have to outweighs the costs
- **Advantages**
  - Every thread can progress no matter the status of others
  - Robustness: if a thread fails only its data is lost
- **Challenges**
  - "Although it can increase the potential for concurrency of operations on a data structure and reduce the time an individual thread spends waiting, **it may well decrease overall performance**" [6]
  - The needed atomic operations can be much slower than the non-atomic ones

Work-stealing?

- “work stealing is a rare event” [6]
- Work-stealing with intel Threading Building Blocks (One API) [1]



Work-stealing with intel Threading Building Blocks (One API) [1]



Standard C++ Parallel Algorithms

- C++17 added parallel algorithms to the standard library, with only a new first parameter for the execution policy. Example [6]:

```
std::vector<int> my_data;
std::sort(std::execution::par,my_data.begin(),my_data.end());
```

- Parallel algorithms require at least C++17 and ltbb (install libtbb-dev)

Standard C++ Parallel Algorithms

Parallel For

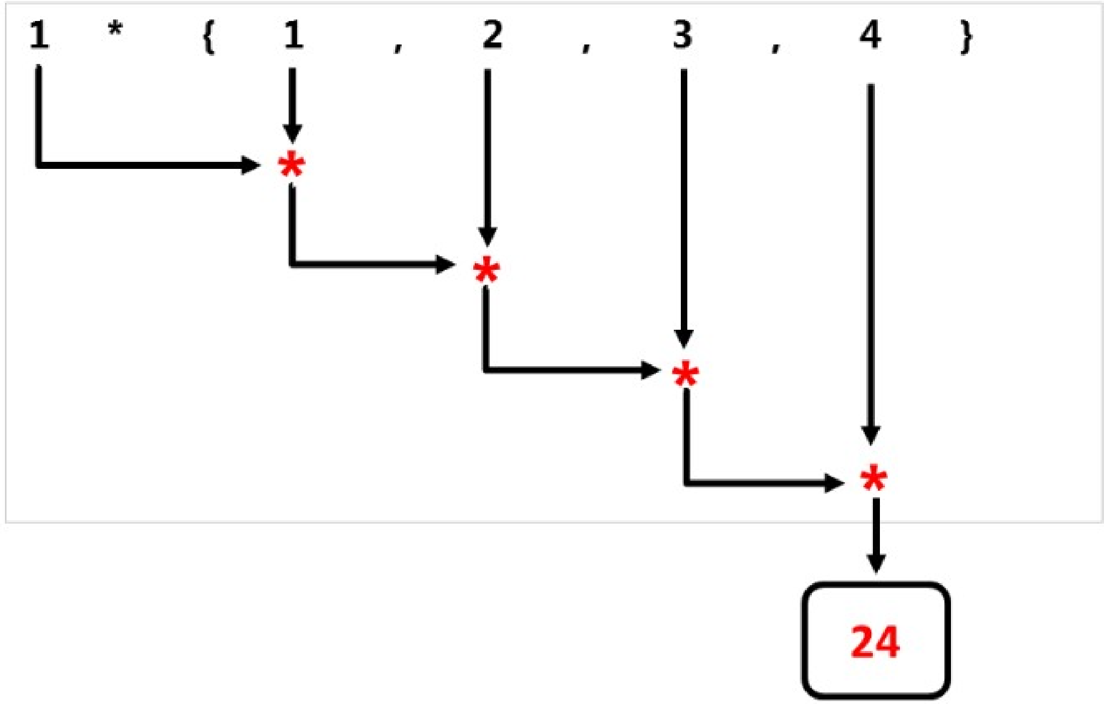
```
#include <future>
#pragma omp parallel for
for (unsigned i = 0; i < v.size(); ++i){
   do_stuff(v[i]);
}
```

```
std::sort(std::execution::par,
          v.begin(), v.end(), do_stuff);
```

Standard C++ Parallel Algorithms

std::accumulate (from left successively applying the operator)

```
std::vector<int> v{1, 2, 3, 4};
std::accumulate(v.begin(), v.end(), 1, [](int a, int b){ return a * b; });
```

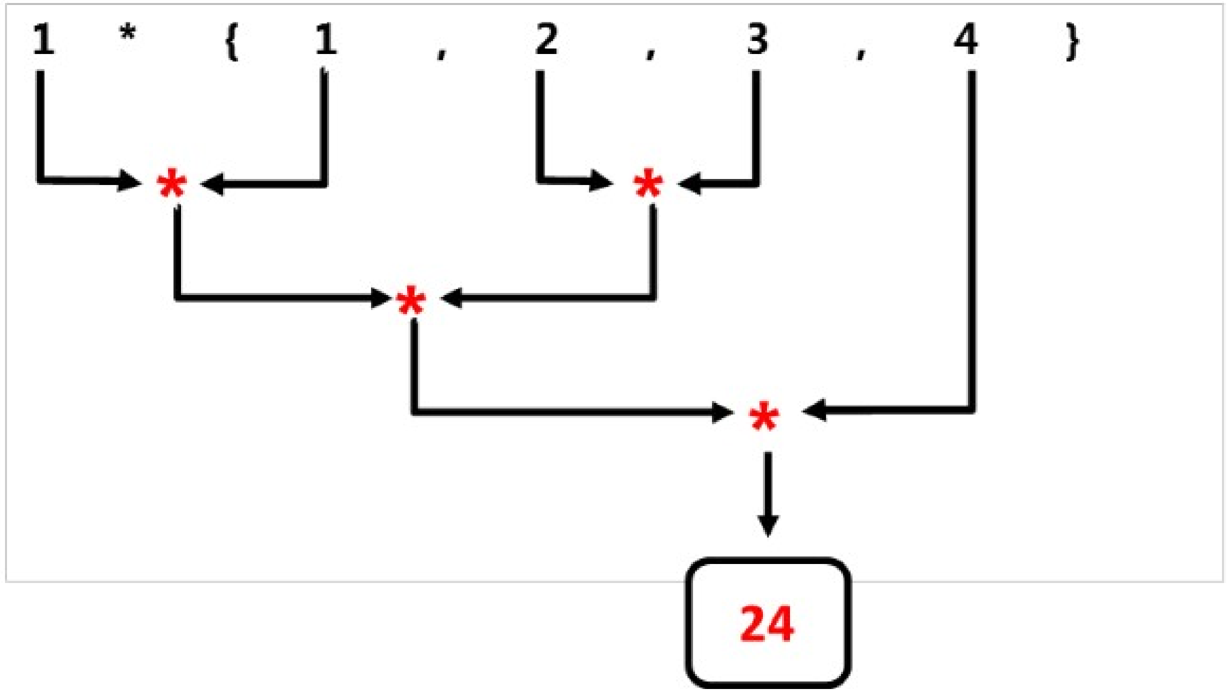


From www.modernescpp.com

Standard C++ Parallel Algorithms

std::reduce (applying the operator in a non-deterministic way)

```
std::vector<int> v{1, 2, 3, 4};
std::reduce(std::execution::par, v.begin(), v.end(), 1 , [](int a, int b){ return a * b; });
```



From www.modernescpp.com

Standard C++ Parallel Algorithms

std::transform_reduce

`first, last`	-	the range of elements to apply the algorithm to
`init`	-	the initial value of the generalized sum
`reduce`	-	binary *FunctionObject* that will be applied in unspecified order to the results of `transform`, the results of other `reduce` and `init`.
`transform`	-	unary or binary *FunctionObject* that will be applied to each element of the input range(s). The return type must be acceptable as input to `reduce`.

Standard C++ Parallel Algorithms

std::transform_reduce

```cpp
// Example modified from https://dev.to/sandordargo/the-big-stl-algorithms-tutorial-reduce-operations-3f1m
#include <iostream>
#include <numeric>
#include <vector>
int main() {
    std::vector v {1, 2, 3, 4, 5};
    int calc = std::transform_reduce(v.begin(), v.end(), 0,
                   [](int l, int r) {return l+r;},
                   [](int i) {return i*i;});
    std::cout << "The calculated result is: " << calc << std::endl;
}
```

std::transform_reduce

```
#include <iostream>
#include <numeric>
#include <vector>
int main() {
    using namespace std;
    std::vector v {1, 2, 3, 4, 5};
    int calc = std::transform_reduce(
        v.begin(),
        v.end(),
        0, //beginning of the vector
        [](int l, int r) {
            cout << "Reduce - L: " << l << " & R: " << r << " local: " << l+r << endl;
            return l+r;
            }, //reduce (sum transformed values)
        [](int i) {
            cout << "Transform - i:  " << i << " local: (" << i << "*" << i << "): " << i*i << endl;
            return i*i;
        } //transform: multiplies the values
    );
    std::cout << "The calculated result is: " << calc << std::endl;
}
```

```
Transform - i:  2 local: (2*2): 4
Transform - i:  1 local: (1*1): 1
Reduce - L: 1 & R: 4 local: 5
Transform - i:  4 local: (4*4): 16
Transform - i:  3 local: (3*3): 9
Reduce - L: 9 & R: 16 local: 25
Reduce - L: 5 & R: 25 local: 30
Reduce - L: 0 & R: 30 local: 30
Transform - i:  5 local: (5*5): 25
Reduce - L: 30 & R: 25 local: 55
The calculated result is: 55
```

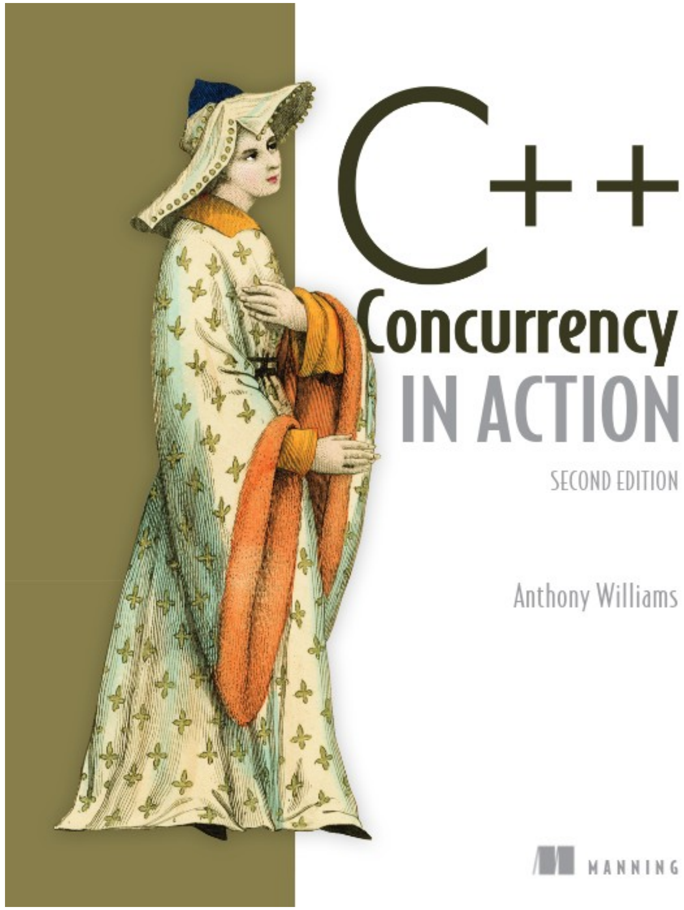
Standard C++ Parallel Algorithms

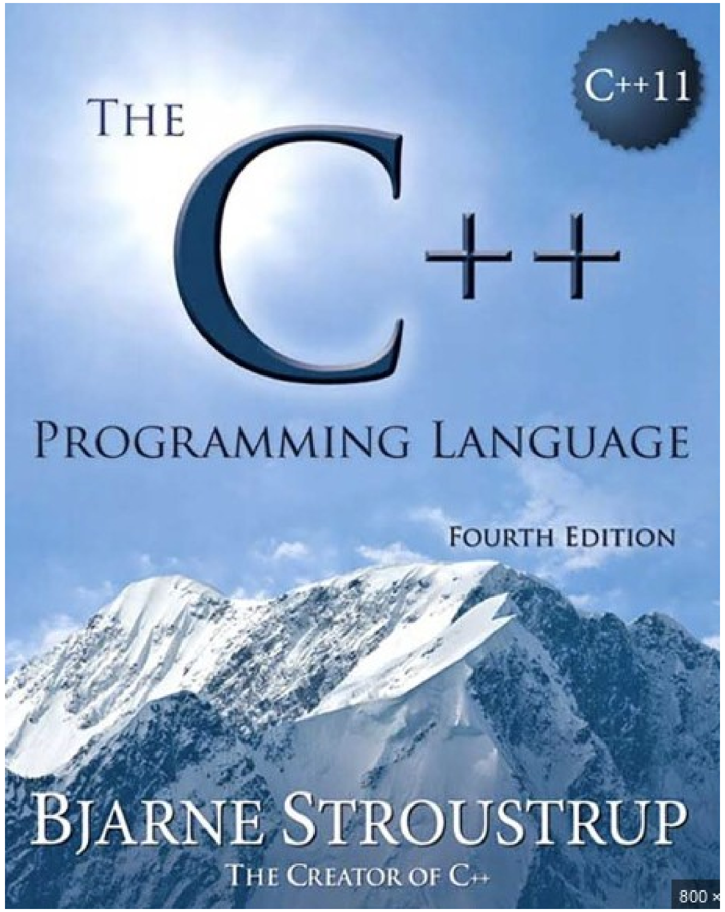
- See the list of parallelized algorithms: https://en.cppreference.com/w/cpp/algorithm

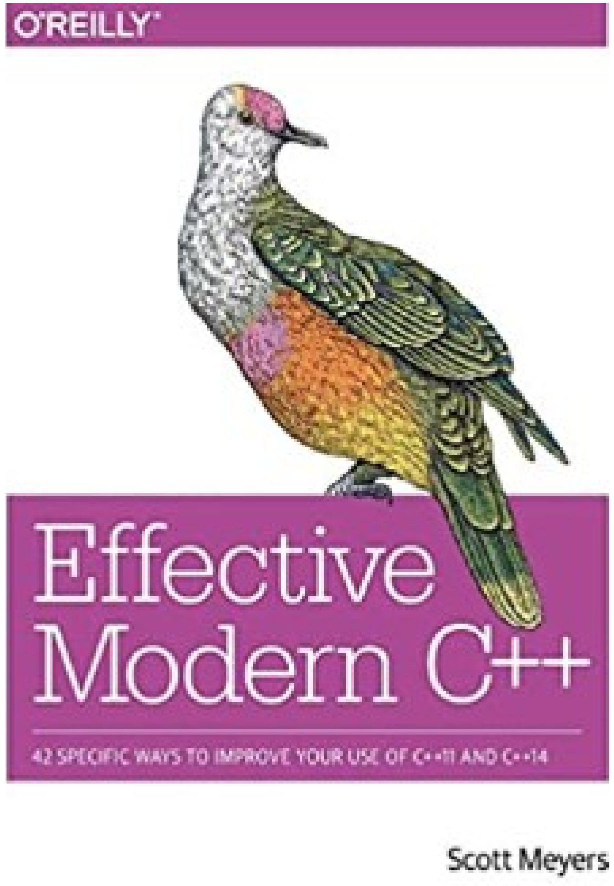
Standard C++ Parallel Algorithms

- **Is C++ STL scalable enough for all use cases?**
  - Probably not. That is why it can be extended to run in accelerators (e.g., GPGPUs, FPGAs) or multiple machines (distributed computing).
  - Other programming languages have a better support for distributed computing than C++

Further Resources







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Thank you!

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