Designing multithreaded code for scalability

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Designing multithreaded code for scalability

- Scalability
- Limitations
- Designing for Scalability

Scalability

Scalability

Modern C++ code runs across a wide variety of platforms:

- Embedded single-core microcontrollers
- Embedded multi-core systems
- Multi-core desktop computers
- Multi-core / multi-socket servers
- Many-core / many-socket HPC systems

Scalability

Modern C++ code runs across a wide variety of platforms:

- 1 CPU / 1 core
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Scalability

Modern C++ code runs across a wide variety of platforms:

- 1 CPU / 1 core
- 1 CPU / 4 cores
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Scalability

Modern C++ code runs across a wide variety of platforms:

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- 1 CPU / 4 cores
- 1 CPU / 8 cores
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Modern C++ code runs across a wide variety of platforms:

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- 1 CPU / 4 cores
- 1 CPU / 8 cores
- 4 CPUs / 32 cores per CPU
- Many-core / many-socket HPC systems

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- 10000 CPUs / 12 cores per CPU
- Plus GPUs — up to 65536 cores

Scalability

Communicating between threads has different constraints across these systems.

Your code is **scalable** if it can run on any of these systems without penalty.

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Our software needs to be scalable

Limitations

Limitations: Mutex contention

Mutex: **Mut**ual **Ex**clusion

A mutex is a means of **preventing** concurrent execution.

> *instead of picking up Djikstra's cute acronym we should have called the basic synchronization object "the bottleneck" (David Butenhof)*

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A mutex is a means of **preventing** concurrent execution.

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⟹ For scalable solutions, we need to **avoid** mutex contention.

Limitations: Atomic contention

Atomic operations can suffer from contention too:

Read-**M**odify-**W**rite operations always affect the **latest** values

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Read-**M**odify-**W**rite operations always affect the **latest** values

$\Longrightarrow$ RMW operations on a single location need to be serialized by the CPUs

$\Longrightarrow$ For scalable solutions, we need to be sparing with RMW operations

Limitations: False Sharing

CPUs synchronize memory at the granularity of a cache line.

Cache lines are typically 16-128 bytes

$\implies$ objects that are on the same cache line are essentially the same object for contention purposes

Limitations: Cache Ping-Pong

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Cache Ping-Pong is where a cacheline is continuously shuttled back and forth between two processors. This occurs when two threads are accessing either:

- **the same** atomic variable
- **different** variables on **the same cache line**

This can have a **big** performance impact, because transferring cache lines is **slow**.

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$\Longrightarrow$ There is a hard upper limit on communication speed for multi-socket systems

Limitations: Memory bandwidth

Intel Xeon Phi 7295:

- 115.2Gb/s Memory bandwidth
- 1.5Ghz Clock speed
- 72 Cores

$\Longrightarrow$ 76.8 bytes per clock
$\Longrightarrow$ 1.1 bytes per clock per core

Designing for Scalability

Strategies: Batch Communications

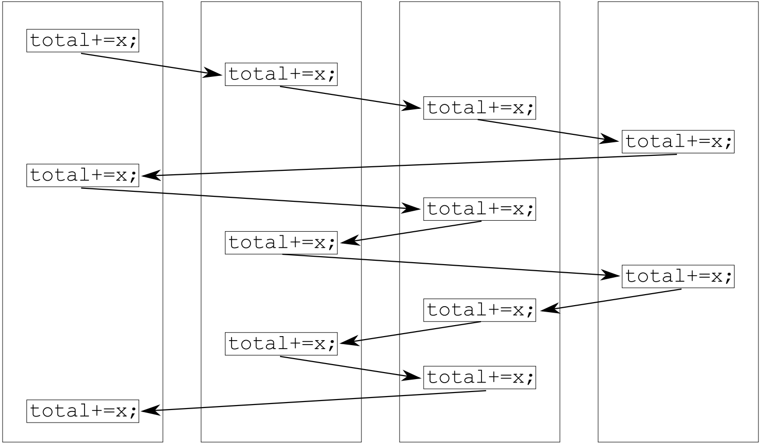
Can you avoid intermediate synchronization?

Each thread works on its own data, and only modifies shared data at the end

Batch Communication Example

```
std::vector<unsigned> const values=get_values();
std::atomic<unsigned long long> total{0};
unsigned const num_threads=...;
std::vector<joining_thread> threads(num_threads);
for(unsigned t=0;t<num_threads;++t){
  threads[t]=joining_thread([&,t]{
    auto start=...;
    auto end=...;
    std::for_each(start,end,[&](auto x){
      total+=x;
    });
  });
}
```

Batch Communication Costs



`total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;` `total+=x;`

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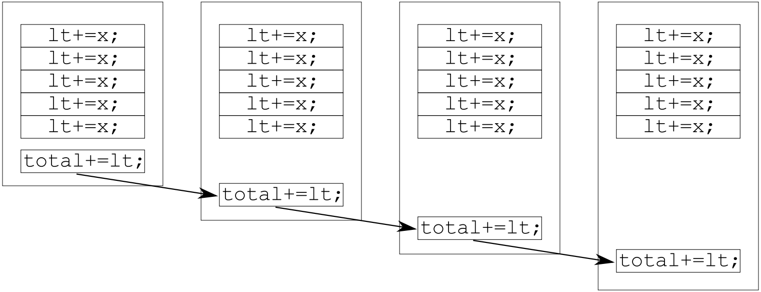
unsigned const num_threads=...;
std::vector<joining_thread> threads(num_threads);
for(unsigned t=0;t<num_threads;++t){
  threads[t]=joining_thread([&,t]{
    auto start=...;
    auto end=...;
    auto local_total=std::accumulate(start,end,0ull);
    total+=local_total;
  });
}
```

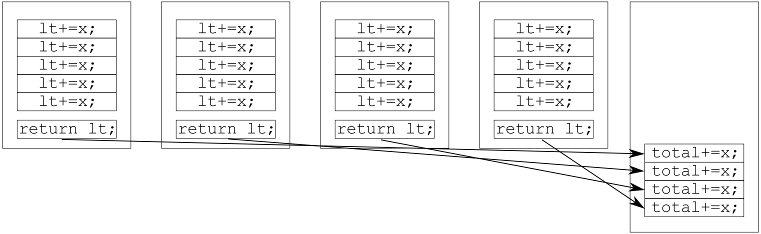
Batch Communication Costs



Batch Communication Example

```
std::vector<unsigned> const values=get_values();
unsigned const num_threads=...;
std::vector<std::future<unsigned long long>> futures(
  num_threads);
for(unsigned t=0;t<num_threads;++t){
  futures[t]=std::async(std::launch::async,[&,t]{
    auto start=...;
    auto end=...;
    return std::accumulate(start,end,0ull);
  });
}
unsigned long long total=0;
for(auto& f:futures) total+=f.get();
```

Batch Communication Costs



Batch Communication Costs

Sum of 100000000 elements on 4 threads:

Run	**Time**	**Ratio to serial**
Serial	0.081s	1
All atomic	9.74s	**120x slower!**
End atomic	0.052s	**1.6x faster**
Futures	0.052s	**1.6x faster**

Contended Lists

Suppose we have a linked list, accessible by multiple threads, and we might need to add or remove elements. What can we do?

- Use a mutex for the whole list
- Use a mutex for each link in the list
- Use `std::atomic<std::shared_ptr<Node*> >` for the node links
- Use `std::atomic<Node*>` for the node links, and a **Safe Reclamation** scheme to ensure `Node`s can be removed safely

Contended Lists: Costs

- Whole list mutex $\Longrightarrow$ **big bottleneck**
- Node mutex $\Longrightarrow$ lots of small bottlenecks
- `std::atomic<std::shared_ptr<Node*> >` $\Longrightarrow$ spin-locks, or RMW operations
- `std::atomic<Node*>` $\Longrightarrow$ low-cost for readers, **big cost** for writers

Safe Reclamation Options

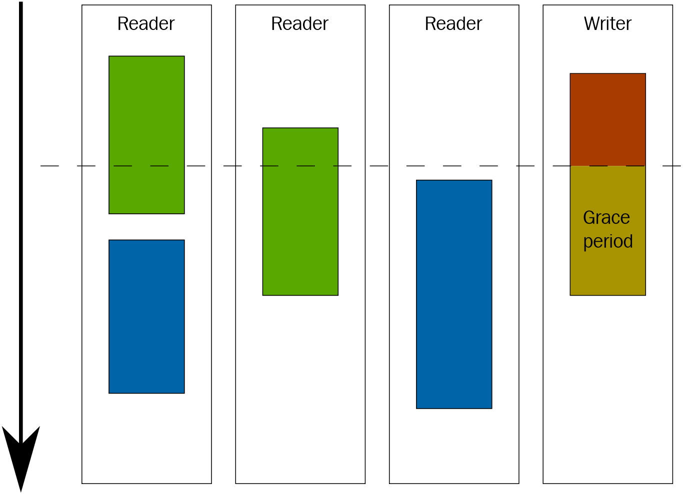
- Garbage Collection
- RCU
- Hazard Pointers

Safe Reclamation: RCU

Readers just record entry/exit to the read function.

Writers make atomic changes, then wait for a **grace period** before deleting removed objects.

Safe Reclamation: RCU



RCU costs

In user space:

- Read side:
    - Atomic read of global marker
    - Two atomic writes to a per-thread location
- Write side:
    - Atomic write of global marker
    - Multiple atomic reads of **all** per-thread locations for readers
    - Mutex locks, delays and spin-loops until all readers ready

In kernel space:

- Read side: **no overhead!**
- Write side:
    - Blocking wait until all processors have cycled a time slice

Safe Reclamation: Hazard Pointers

Readers store **hazard pointers** referring to objects being accessed

Writers make atomic changes, then check the **hazard pointers** to see if it is safe to delete an object.

Hazard Pointers Costs

- Read side:
  - Two (or more) atomic writes to a per-thread hazard pointer
  - Spin-loop ensuring value hasn't changed while updating hazard pointer
- Write side:
  - Atomic RMW operation adding to reclamation list
  - Objects not immediately destroyed
  - Period reclamation checks: when **N** objects are queued for reclamation
    - N depends on configuration parameters and number of threads
    - Each reclamation does atomic reads of **all** per-thread hazard pointers for readers
    - Cost of retiring objects varies by orders of magnitude

Standard Support for Safe Reclamation

There is a proposal under discussion for both RCU and Hazard Pointers, with a sample implementation:

P0566R4: Proposed Wording for Concurrent Data Structures: Hazard Pointer and Read-Copy-Update (RCU)
`http://wg21.link/p0566`

RCU implementation:
`https://github.com/paulmckrcu/RCUCPPbindings`

Hazard Pointer implementation:
`https://github.com/facebook/folly/tree/master/folly/experimental/hazptr`

Sequential Consistency vs Eventual Consistency

Sequential Consistency:

- All threads see the same view of shared state
- Single Total Order of operations
- This requires serialization, or extensive communication

Eventual Consistency:

- Threads may see different views of shared state
  Provided each thread has a **self-consistent** view all is well
- All changes propagate to all threads **eventually**
- Cannot write a Single Total Order of operations
- Much less communication required

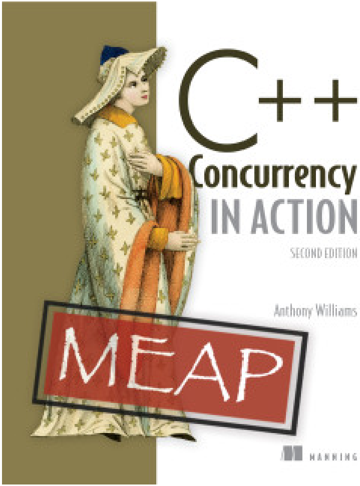
Sequential Consistency vs Eventual Consistency

Sequential Consistency is easier to reason about.
Eventual Consistency is more scalable.

Summary

- Multithreaded code needs to be scalable
- Avoid contention
- Avoid cache ping-pong
- Use Safe Reclamation schemes
- Use Eventual Consistency

My Book



C++ Concurrency in Action:
Practical Multithreading,
Second Edition

Covers C++17 and the
Concurrency TS

Early Access Edition now
available

`http://stdthread.com/book`

Just::Thread Pro

just::thread
Complete C++ Standard Thread Library

Just Software Solutions

`just::thread` Pro provides an actor framework, a concurrent hash map, a concurrent queue, synchronized values and a complete implementation of the C++ Concurrency TS, including a lock-free implementation of `atomic_shared_ptr`.

`http://stdthread.co.uk`

Questions?