Optimizing existing large codebase

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Outline

1. Measuring Performance
   - What is performance ?
   - Tools available
   - Finding bottlenecks
2. Code modernization
3. Improving Memory Handling
   - Context
   - Containers and memory
   - Container reservation
   - Detecting offending code
4. The nightmare of thread safety
   - Context and constraints
   - Identifying problems
   - Solving problems
   - Thread contention
5. Low level optimizations
   - Scope and target
   - How to measure ?
   - Improving
6. Conclusion

Goal of this course

- make the theory explained so far more concrete
- and adapt it to the special case of
  - dealing with large projects
  - dealing with legacy code
- I'll only talk of C^{++} projects

Specificity of the exercise

- Dealing with large code base (Mloc)
  - most of them unknown to you
  - and (usually) not supported by anyone
- Dealing with old code
  - using old fashion coding style (e.g. FORTRAN like)
  - modified n times, grew organically
- Target latest hardware
  - many cores
  - hyperthreading / superscalar
  - vectorization

Overall strategy

First measure !

- understand where time is spent
- understand the main limitations

Then attack these limitations

- modernize the code
- optimizing memory handling
- optimizing parallelism
- optimizing low level code

Measuring Performance

1 Measuring Performance
- What is performance ?
- Tools available
- Finding bottlenecks

2 Code modernization

3 Improving Memory Handling

4 The nightmare of thread safety

5 Low level optimizations

6 Conclusion

Defining our performance

Key question is : what is performance

- simply going faster ?

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  - not at all costs (money, physics results)

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  - most of the time hardware is cheaper than people !

Defining our performance

Key question is : what is performance

- simply going faster ?
  - not at all costs (money, physics results)
- making better use of the hardware
  - most of the time hardware is cheaper than people !
- you need to define your "Key Performance Indicators"
  - e.g. nb Evts / s / $ with constant man power for a trigger
- and get a clear idea of your different costs
  - flops/$ of your machines
    - including network, cabling, cooling, buildings, ...
  - human costs
  - cost of transition
  - ...

Measuring our software

Many parameters can be measured

- overall timing
- memory usage and cache efficiency
- CPU efficiency (Cycles per instructions, vectorization level)
- level of parallelism, usage of the different cores
- I/O limitations if any

For each of them, you need

- both overall data and detailed split per code unit
- per item, per core and full machine measurement

How to measure

The counters approach

- use CPU counters to find out what happened during actual execution
- do not slow down execution, so only do sampling

The software instrumentation

- run your code in a "virtual" environment
- measure everything precisely
- at the cost of speed

Counters approach in practice

- give precise timing of a realistic execution on your CPU
  - using real cache prediction, actual vectorization, ...
  - using real CPU behavior (e.g. downclocking when overheating...)
- allows to measure CPI (**C**ycles **P**er **I**nstruction) and low level behavior in general (caching, pipelining)
- but data is only statistical
  - so you need sufficient statistics
  - also not always reproducible, so hard to compare
    - e.g. first test on cold processor, second on warm one
- Main tools available : perf and variants, Intel VTune

Software instrumentation in practice

- give precise measurements of where you spend instructions
  - including many details
  - reproducible, so your can compare stuff
- but not always realistic
  - no real timing, only instructions count
  - memory caching is only simulated, often far from real case
  - no clue on low level efficiency (CPI in particular)
  - and gives no clue on hardware / OS behavior
- Main tool available : valgrind family

Finding bottlenecks

Understand where we can improve

- analyze each part of the software
- in order to find out where most time is spent
- and understand whether it can be improved

Most usual bottlenecks

From biggest to lowest impact (usually)

- IO
- Memory
- Parallelization
- Low level behavior : vectorization, cache behavior, high CPI

Code modernization

1 Measuring Performance

2 Code modernization

3 Improving Memory Handling

4 The nightmare of thread safety

5 Low level optimizations

6 Conclusion

Make use of latest C++features

- C++has evolved dramatically between 2010 and now
- five new versions : C++11, C++14, C++17, C++20, C++23
- a LOT of new features targeting performance
  - move semantic
  - threading library
  - variadic templates
  - vectorization coming ?
- converting existing code may already bring speed
- see previous courses for technical details
- see HSF C++course if you're not at ease with the language

Cleanup your code

- While reviewing the code for converting to latest C++:
  - drop unused code
  - drop unnecessary code
    - e.g. do I really need to sort by hits here ?
  - drop too generic APIs if they are finally not needed
  - replace virtual inheritance with templating when possible
  - consider dropping use of unmaintained libraries
- It is very often surprising how much you gain there

Improving Memory Handling

1 Measuring Performance

2 Code modernization

3 Improving Memory Handling
- Context
- Containers and memory
- Container reservation
- Detecting offending code

4 The nightmare of thread safety

5 Low level optimizations

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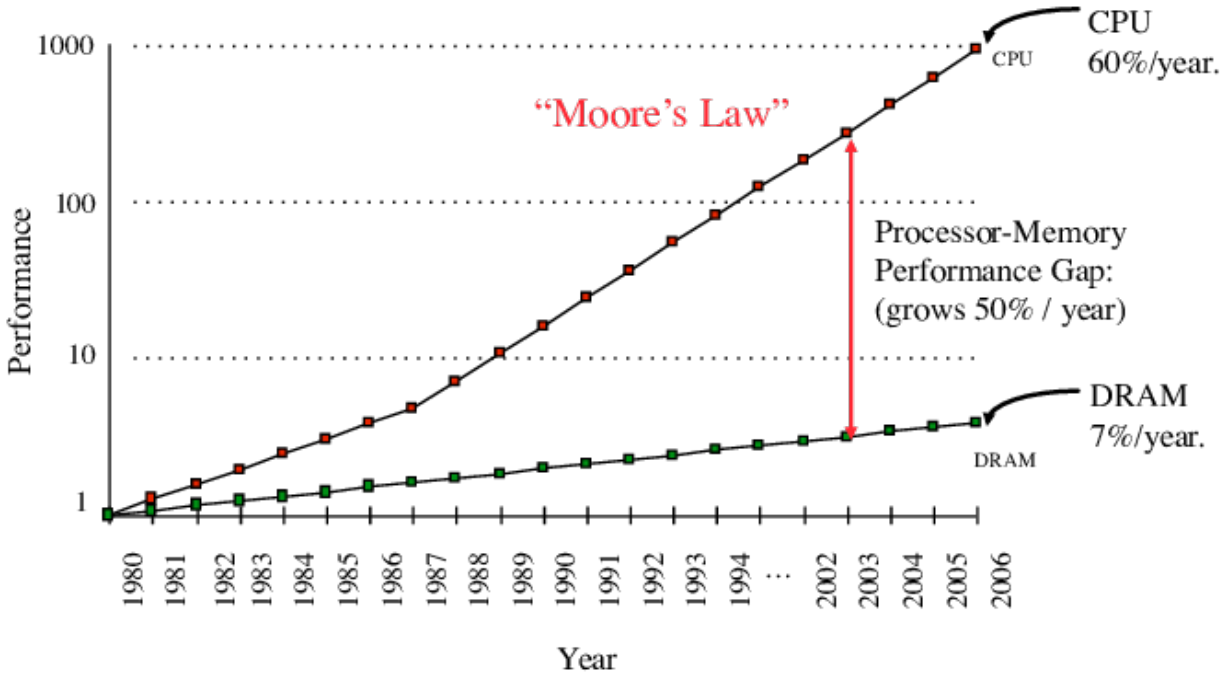
Evolution of memory in the past decades

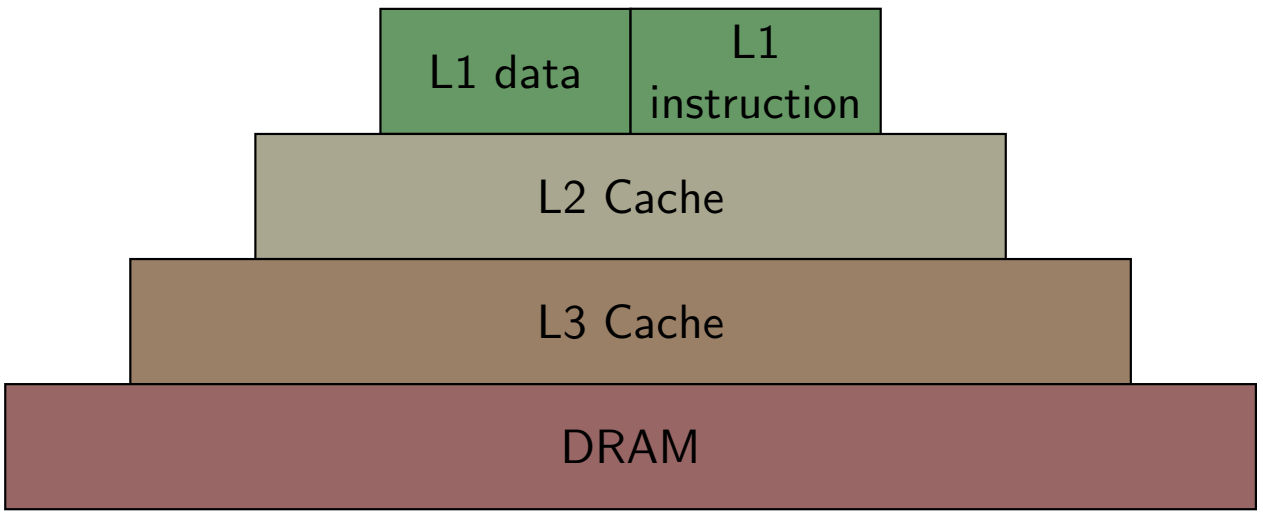


Due to Moore's law in the 80s and 90s, there is a gap between CPU and memory performances

Consequences :

- access to memory is now extremely slow (relatively)
- level of caches have been introduced to mitigate
- good usage of caches has become a key parameter

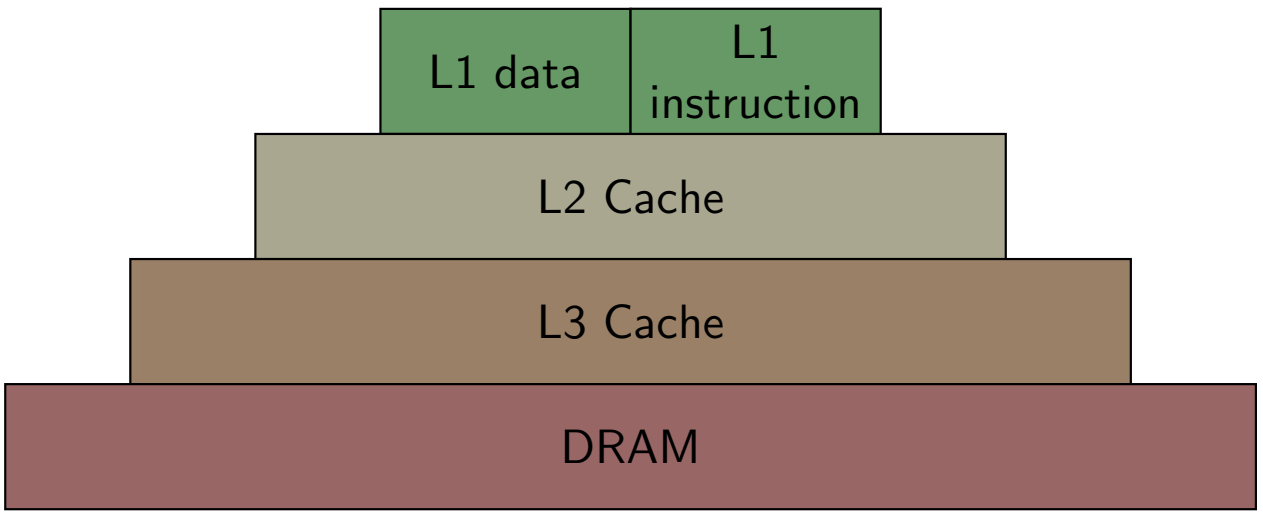
Typical cache structure



	size	latency
L1	64 kB	4 cycles
L2	256 kB	10 cycles
L3	10 MB	40 cycles
DRAM	64 GB	400 cycles

Typical data, on an Haswell architecture

Typical cache structure



	size	latency
L1 data / L1 instruction	64 kB	4 cycles
L2 Cache	256 kB	10 cycles
L3 Cache	10 MB	40 cycles
DRAM	64 GB	400 cycles

Typical data, on an Haswell architecture

Practical consequence in C++

Guidelines

- we want as few heap memory allocations as possible
  - stack usage is much better !
- we want continuous memory blocks, specially for containers
  - that means containers of objects, no pointers involved
  - e.g. `vector<Obj*>` or `array<vector<Obj>>` are banned !

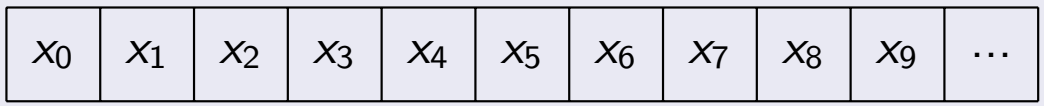
2 main rules

- use container of objects, not of pointers
  - use (const) references everywhere
  - avoid any unnecessary copy of data
    - including implicit ones
- use container reservation

Container of objects in memory

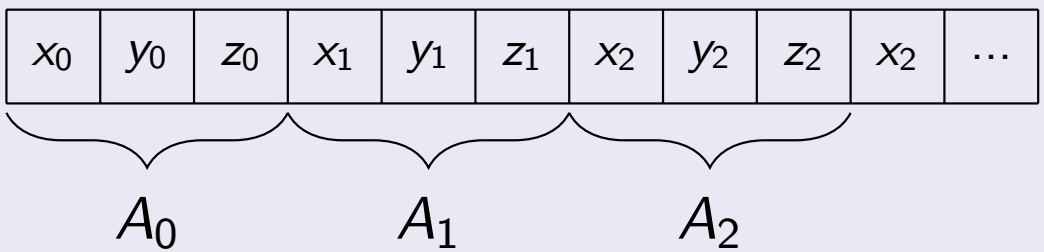
Simple vector case

```
std::vector<int> v;
```



Vector of objects

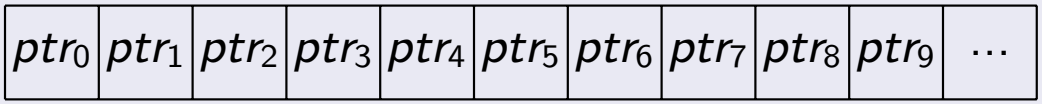
```
struct A { float x, y, z; };
std::vector<A> v;
```



Container of pointers in memory

Naïve view

```
struct A { float x, y, z; };
std::vector<A*> v;
```



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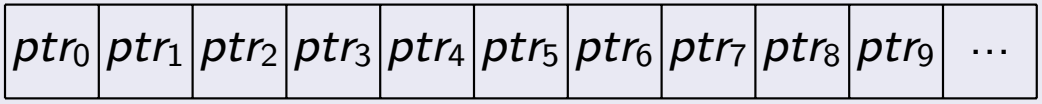
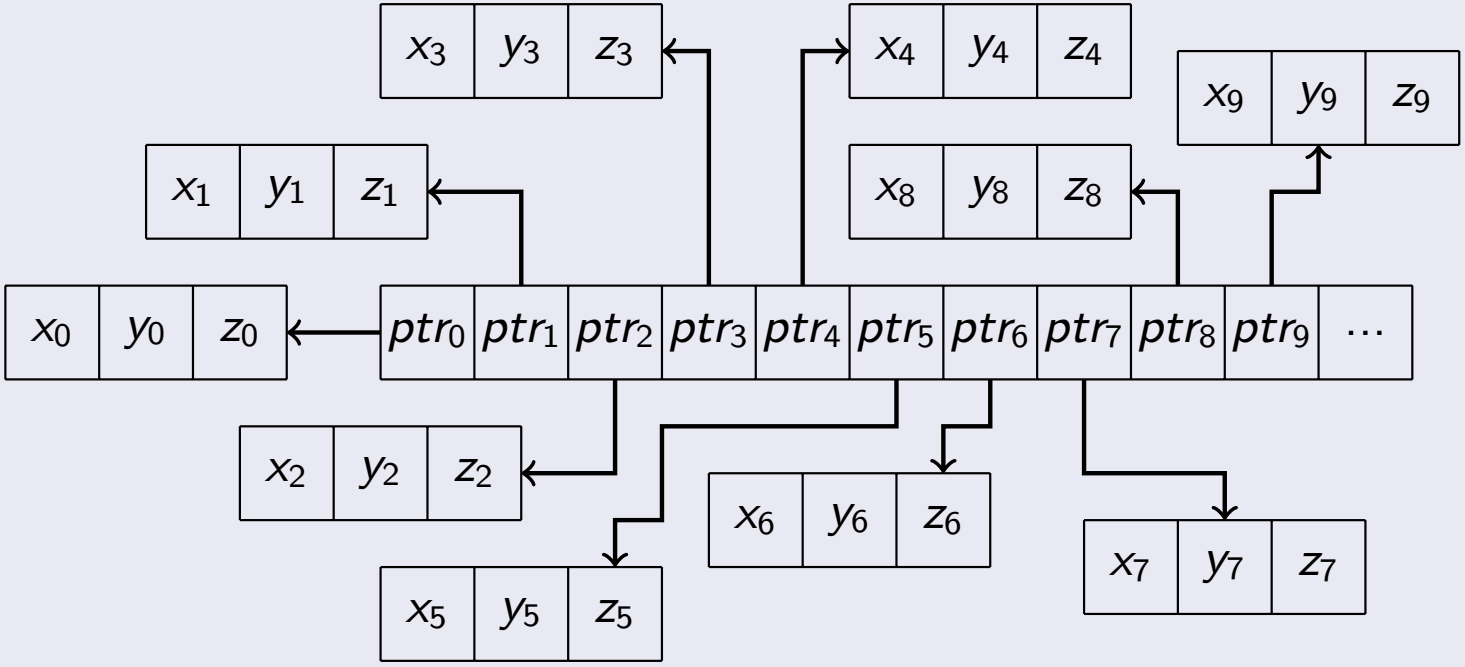


Realistic view



Container of objects in cache

Memory view for `vector<A>`

Each line corresponds to a cache line (64 bytes, 16 floats)

0x00C0	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
0x0080	x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3	x_4	y_4	z_4	x_5
0x0040	y_5	z_5	x_6	y_6	z_6	x_7	y_7	z_7	x_8	y_8	z_8	x_9	y_9	z_9	·	·
0x0000	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

All data are nicely collocated in cache

Container of pointers in cache

Memory view for `vector<A*>`

Each line corresponds to a cache line (64 bytes, 16 floats)

0x0240															
0x0200	x_8	y_8	z_8								x_9	y_9	z_9			
0x01C0						x_7	y_7	z_7								
0x0180								x_5	y_5	z_5				x_6	y_6	z_6
0x0140																
0x0100		x_3	y_3	z_3									x_4	y_4	z_4	
0x00C0						x_2	y_2	z_2								
0x0080					x_0	y_0	z_0	x_1	y_1	z_1						
0x0040	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9						
0x0000																

Cache nightmare : data is completely sparse

Note from Andrzej : this is already optimistic

Container with no reservation

```
struct A { float x, y, z; };
std::vector<A> v;
```

Container with no reservation

```
struct A { float x, y, z; };
std::vector<A> v;
```

Construction

Default constructor creates and empty vector, with no storage

start	0x0
finish	0x0
end_of_storage	0x0

Container with no reservation

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struct A { float x, y, z; };
std::vector<A> v;
```

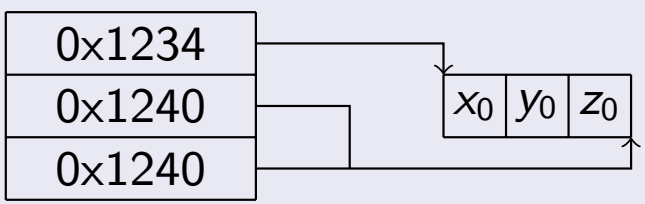
Construction

Default constructor creates and empty vector, with no storage

start	0x0
finish	0x0
end_of_storage	0x0

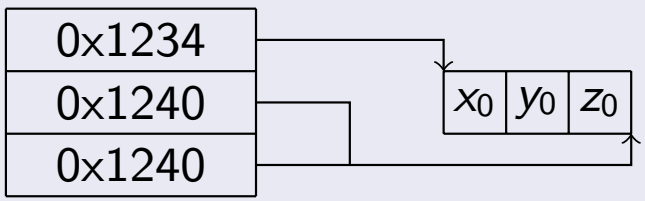
First push

allocates storage for the first element only !



Container with no reservation

Second push



Container with no reservation

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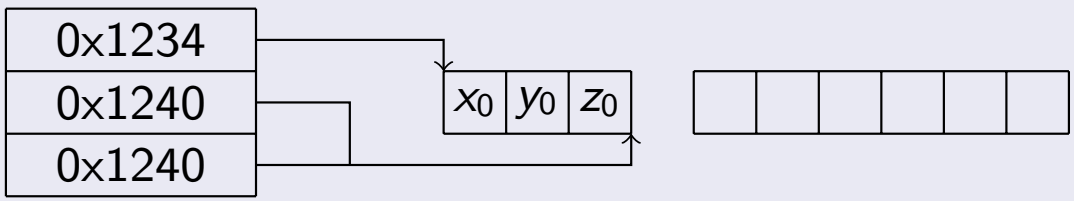
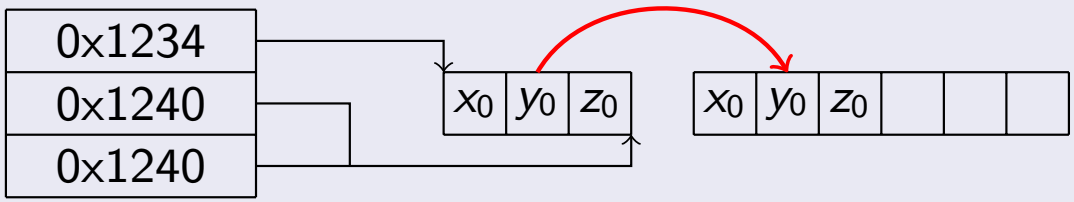


1. allocate new piece of memory for 2 items

Container with no reservation

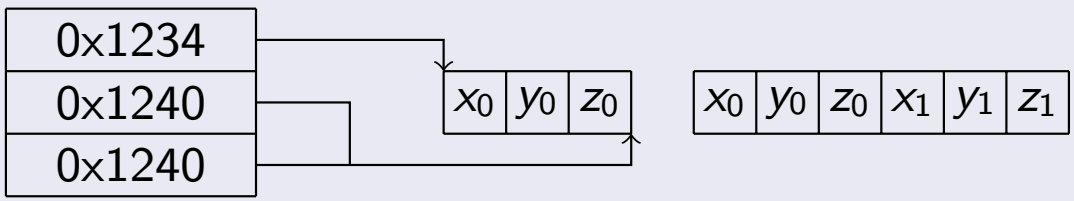
Second push



1. allocate new piece of memory for 2 items
2. copy existing content

Container with no reservation

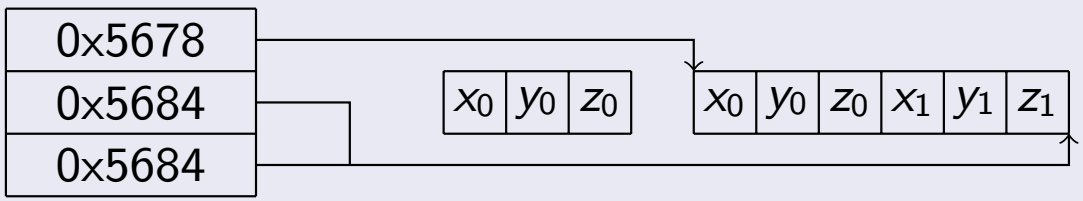
Second push



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content

Container with no reservation

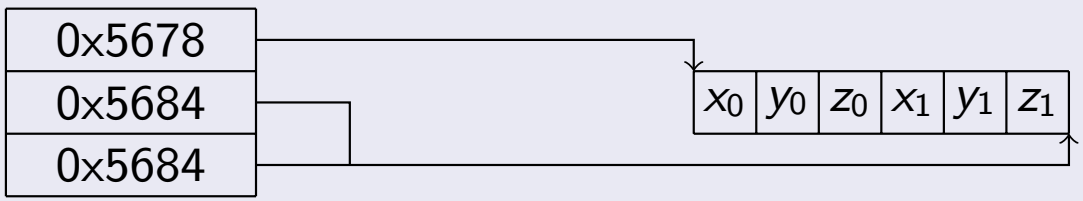
Second push



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content
4. update pointers

Container with no reservation

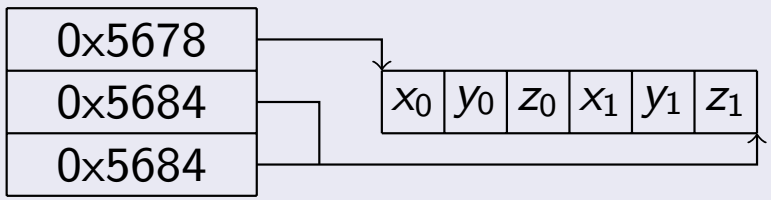
Second push



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content
4. update pointers
5. Deallocate original piece of memory

Container with no reservation

Third push



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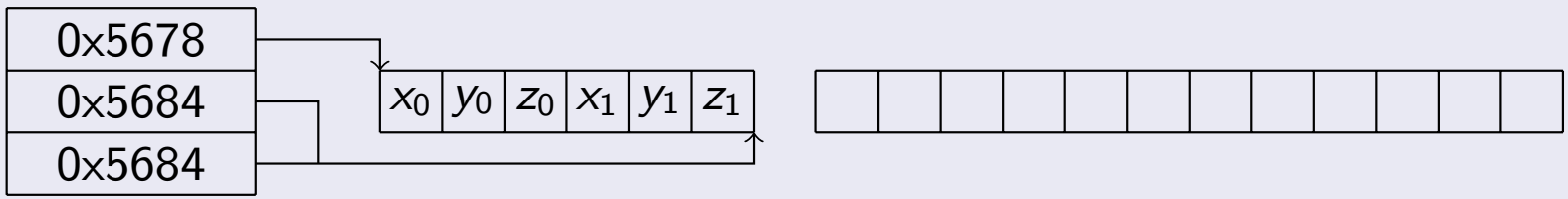
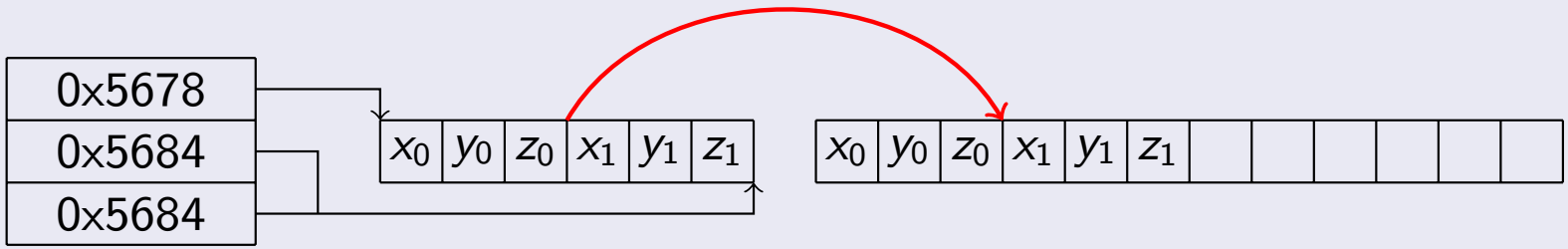


1. allocate new piece of memory for 4 items
   - double size at each iteration

Container with no reservation

Third push



1. allocate new piece of memory for 4 items
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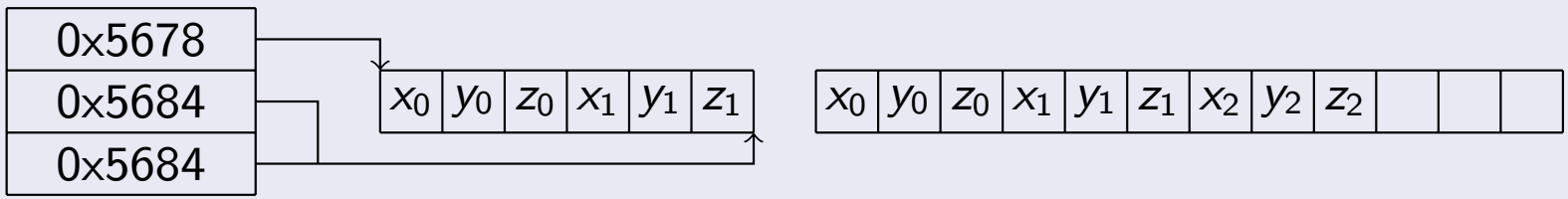
Container with no reservation

Third push



1. allocate new piece of memory for 4 items
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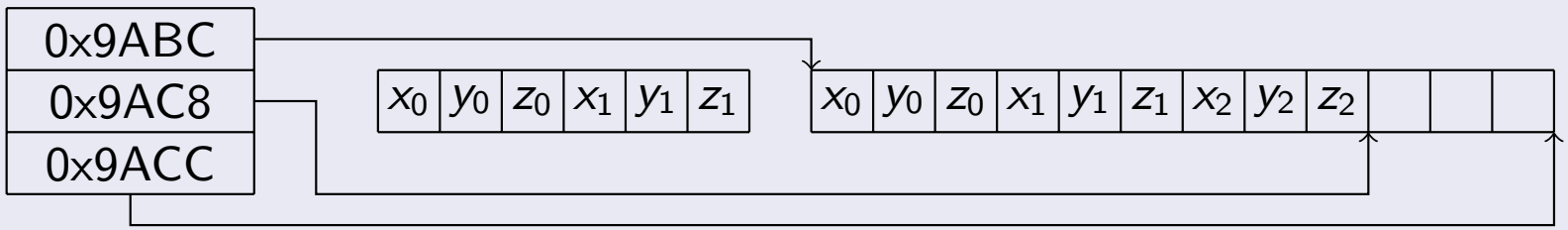
Container with no reservation

Third push



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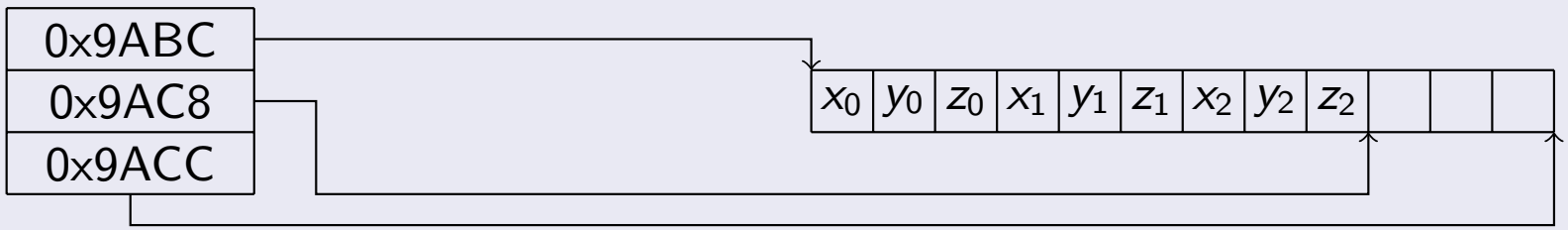

1. allocate new piece of memory for 4 items
   - double size at each iteration
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4. update pointers
5. Deallocate original piece of memory

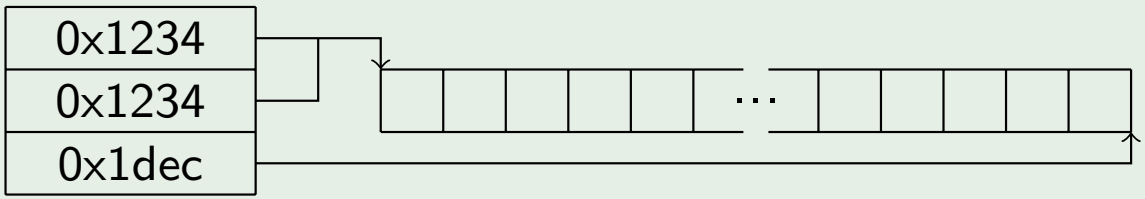
Container with proper reservation

Construction and reservation

- you can avoid all that thanks to reserve

```
std::vector<int> v;
v.reserve(1000);
```

- ensures single allocation, no copies, no reallocation



Without second line

- first item would have be copied 10 times !
- 1023 items would have been copied in total
- 11 pieces of memory allocated, 10 released

Avoiding copy when filling container

What should be avoided

```
1  std::vector<A> v;
2  v.reserve(10);
3  A tmp{args};
4  v.push_back(tmp);
```

Avoiding copy when filling container

What should be avoided

```
1  std::vector<A> v;
2  v.reserve(10);
3  A tmp{args};
4  v.push_back(tmp);
```

What actually happens :

- allocate space in the vector (line 2)
- allocate space for the temporary A object (line 3)
- call A constructor (line 3)
- call copy constructor for A (line 4)
- deallocate temporary A (end of scope)
- using `std::move(tmp)` on last line not necessarily better

Proper solution for vectors

In place construction

```
1  std::vector<A> v;
2  v.reserve(10);
3  v.emplace_back(args);
```

What actually happens :

- allocate space in the vector
- call constructor for A
  - using args as the constructor arguments
  - using the space allocated in the vector

For the record, this is using variadic templates, new in C++11

Proper solution for maps

In place construction + piecewise construct + forward_as_tuple

```
1  std::map<int,A> m;
2  m.emplace(piecewise_construct,
3            make_tuple(5),
4            forward_as_tuple(args));
```

- emplace_back now creates an std::pair
- piecewise_construct constructs the 2 items of the pair in place
- forward_as_tuple prevents a copy of args
  - by using a tuple of references

Detecting memory offending code

Look at your measurements !

- how much time do you spend in malloc/new/free/delete/... ?
  - more than a few % ? Room for improvement !
- what is your last level cache miss rate ?
  - 1 % or more ? Room for improvement !
- drill down to the method where the numbers are bad
- find the responsible container / data structure

Detecting memory offending code

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Function	Effective Time
operator new	16.7%
_int_free	8.3%
PrPixelTracking::bestHit	5.7%
PrForwardTool::collectAllXHits	5.7%
PVSeed3DTool::getSeeds	2.7%
PrStoreFTHit::storeHits	4.5%

The nightmare of thread safety

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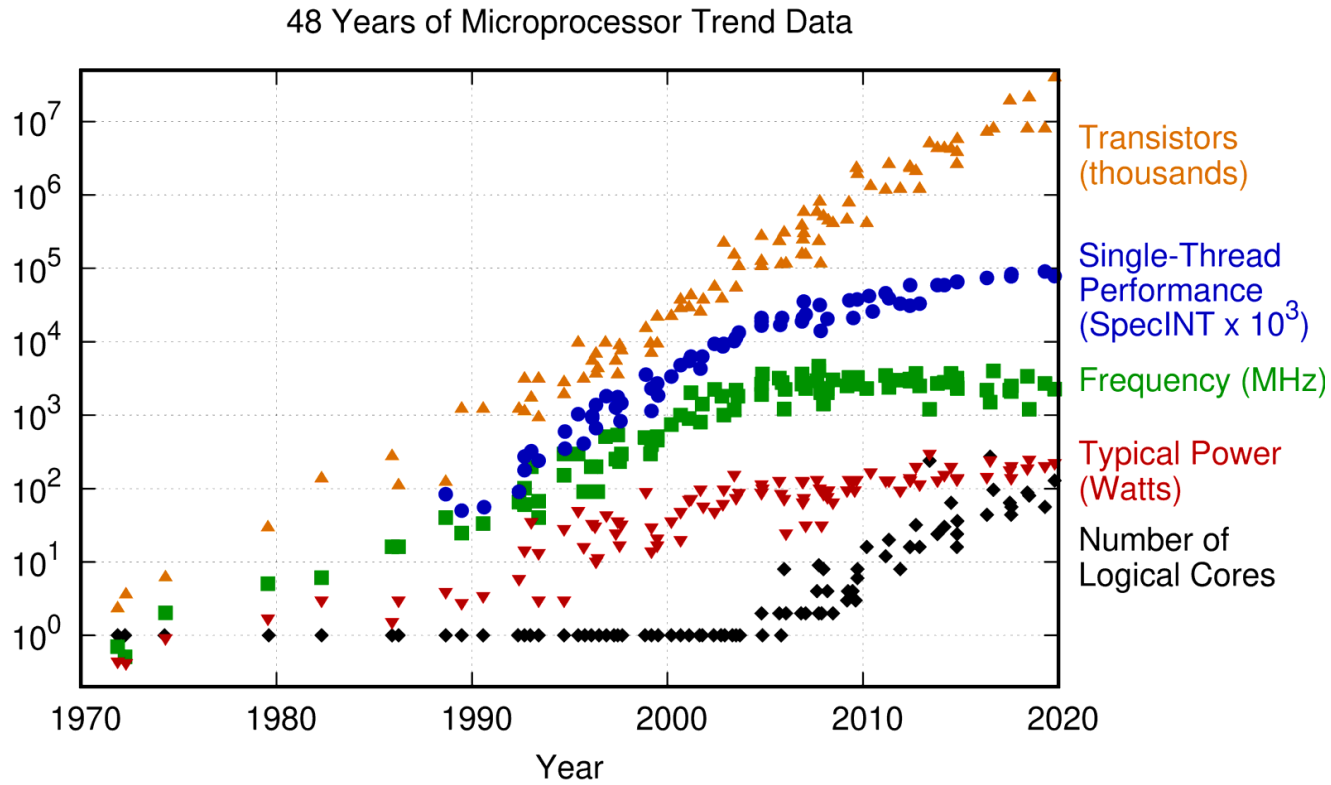
Evolution of CPUs in the past decades



source : `https://github.com/karlrupp/microprocessor-trend-data`

- clock speed is now fixed
- flops come now from parallel processing
- and especially from many cores

Adapting existing software : multiprocessing

Cheap and easy approach

- works when you can split your data
- just process the pieces in parallel
- launching your original application n times
  - where n is roughly the number of cores
- and glue the results together

Main problem

- the memory usage (amount and cache efficiency)

Adapting existing software : multithreading

Less easy but rewarding approach

- remember threads share their heap
- your memory is mainly "read only" during processing
  - all code and libraries
  - detector geometry, conditions
- threads share this common memory
  - 40 threads instead of 40 jobs means memory usage divided by 40 !

Main problem

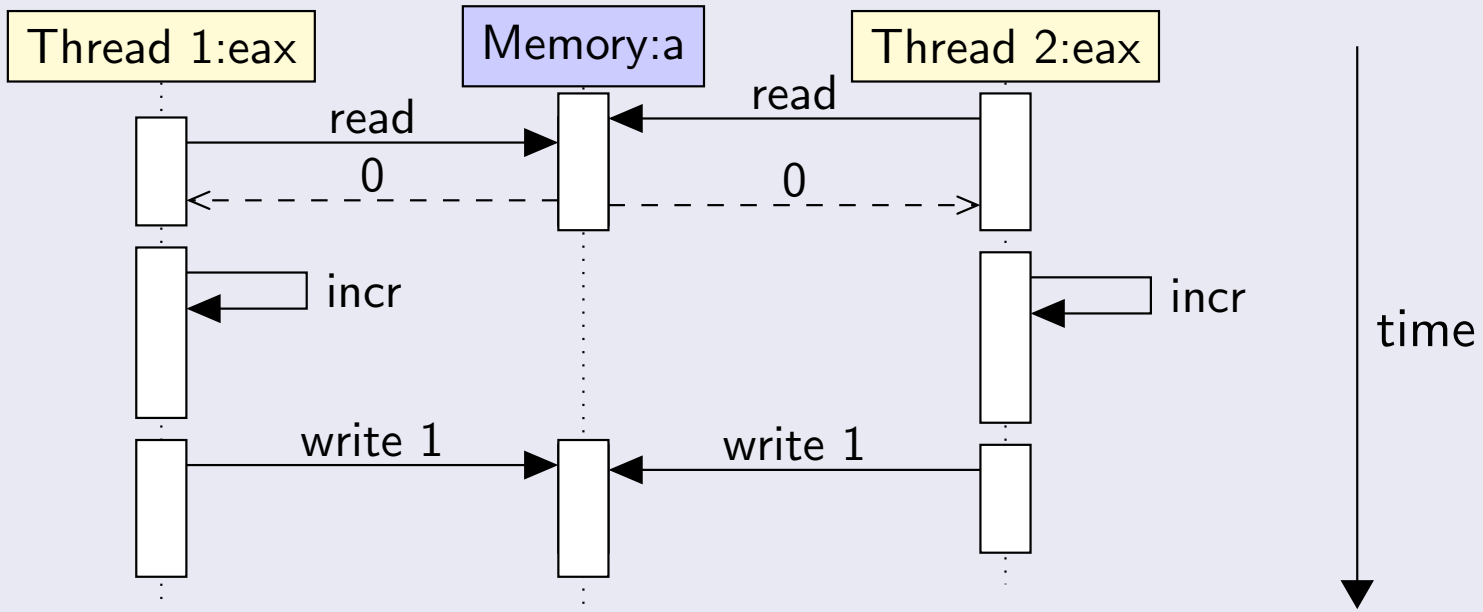
- race conditions on non read-only memory parts

Timing of ++ operation

Code

```
1  eax = a          // memory to register copy
2  increase eax     // increase (atomic CPU instruction)
3  a = eax          // copy back to memory
```

For 2 threads



What is not thread/safe ?

Everything ! unless explicitely stated

Non thread-safe code

- heap
- STL constainers
  - they use the heap !
  - some functions may be thread safe though
- global (non const) variables
- any member of a C^{++}class modified in a non const method
  - the method may be called concurrently by two threads
- `constcast`, singletons, caches, ...
- many C library calls (e.g. strtok, ctime, ...)
- external libearies
  - random number generators (most of them)

Converting to multithreading

Identify all shared state

and secure them

Identifying problematic shared states

A very hard topic !

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Level 0 : use gdb and debug crashes

- but race conditions do not happen at every run
- and crashes is the lucky case, wrong results is the other

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- but race conditions do not happen at every run
- and crashes is the lucky case, wrong results is the other

Level 0.5 : helgrind

- detects race conditions that did not happen
- but only in code that ran (coverage issue)
- and is very slow

Identifying problematic shared states

Actual (partial) solution : use the language

- C++11 constness is different from original one
- it now means "visibly const and race condition free"
- that is the "visible" state is not modified
- and internally thread safety is guaranteed if any thing changes

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Bottom line : proper use of constness can save us !

- especially constness of member functions
- it ensures they are reentrant
- it will tell us at compile time if not :-)

Practically identifying shared state

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  - mutables
  - const_cast, C casts

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- introduce constness everywhere
- look at compiler errors

- and look for globals, const does not apply here
- and do not forget special cases where constness is not respected...
  - mutables
  - const_cast, C casts
- better be fluent with grep...

Typical legacy code

```
1  /// hack to allow for tools with non-const interfaces
2  template <typename IFace>
3  IFace* fixup(const ToolHandle<IFace>& iface) {
4    return &const_cast<IFace&>(*iface);
5  }
6
7  void CaloHypoNtp::operator()(...) const {
8    ...
9    if( m_checker )
10     fixup(m_2MC)->from(hypo)->descriptor();
11   ...
12 }
```

Securing a shared state

non optimal way : locks and mutexes

- serializes access to given piece of code
- fine under low pressure
- but costly and leads to contention under high pressure
  - see later

Better way

- analyze the data race, extract the state
- can it be replicated/moved to higher level ?

State replication option

When to use it

- when the state can be replicated
- so not used as a synchronization point
- for heavily used, small state

Example : random number generator

- state is small, does not need to be shared
- so you can have one generator per thread
- or modify the random generator
  - and use thread local storage for the state
  - although may be more costful

Moving state to higher level

When to use it

- when the state can be replicated
- so not used as a synchronization point
- fine with small and large states
- typically for caches, when the state is data reused between calls

Principle

- simply make the state visible to the caller
- and initialize it one level higher on the stack
- so that you have local states per thread

Think of the state as hidden data passed magically to your calls, just make it explicit

State moving option example

Original class

```
1  class CachedAccessor {
2    mutable CachedObject m_myCache;
3    Item get(const KeyObject& key) const {
4      ...
5      m_myCache.update(...);
6      ...
7    }
8  };
```

Usage

```
1  CachedAccessor accessor{dataSource};
2  for(const auto& key: keyList) {
3    auto item = accessor.get(key);
4    ...
5  }
```

State extraction to higher level

Thread safe version of the class

```
1  class CachedAccessor {
2    Item get (const KeyObject& key, CachedObject& cache) const {
3      cache.update(... key ...);
4      ...
5    }
6  };
```

thread safe usage

```
1  CachedAccessor accessor{dataSource};
2  CachedObject cache;
3  for(const auto& key: keyList) {
4    auto item = accessor.get(key, cache);
5    ...
6  }
```

What do we call contention ?

- a situation where all hardware resources cannot be used efficiently
- because of one bottleneck in the chain
  - called point of contention
- can be anything
  - hardware : network, I/O, ...
  - lines of code, typically with a lock
  - architectural : one producer not fast enough blocking many consumers
- actually can be anything shared between threads

How to detect contention ?

- benchmark the code
- look at scalability
- look at thread usage

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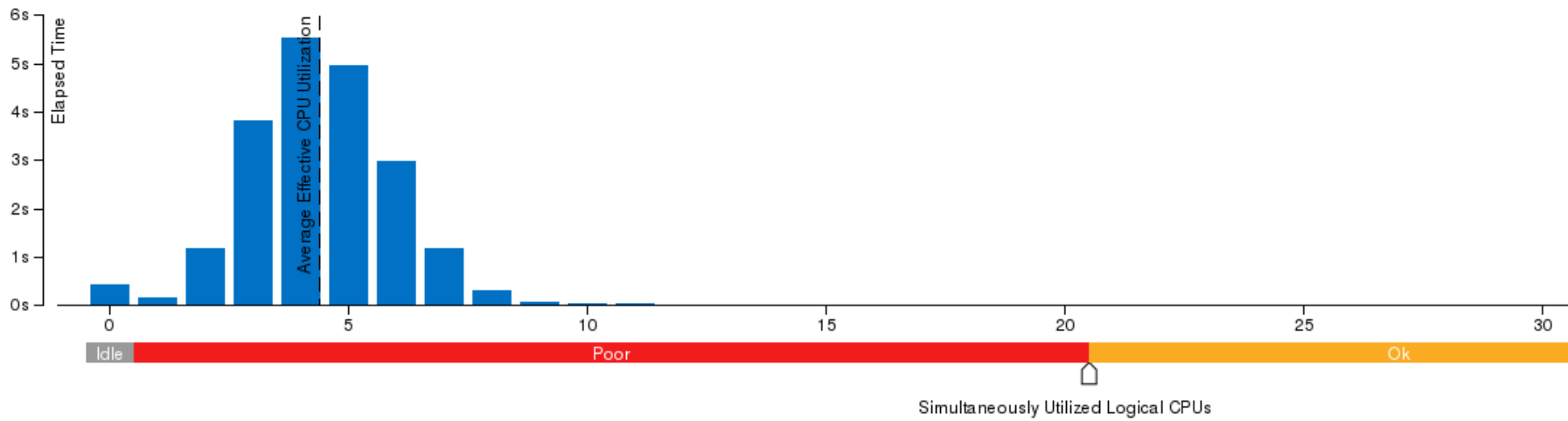
Example output of 40 threads on 20 physical cores' system

Effective CPU Utilization Histogram

This histogram displays a percentage of the wall time the specific number of CPUs were running simultaneously. Spin and Overhead time adds to the Idle CPU utilization value.



Where is the contention ?

Much more difficult question !

- you need to find the hotspot
- without any clue of its type
- look for
  - high CPU in a single thread
  - lengths of your queues (too full, too empty ?)
  - global state of your machine (I/O, network)

Example of memory based contention

Figure: Table of the main CPU consumers in the application

Function	Effective Time
operator new	16.7%
_int_free	8.3%
PrPixelTracking::bestHit	5.7%
PrForwardTool::collectAllXHits	5.7%
PVSeed3DTool::getSeeds	2.7%
PrStoreFTHit::storeHits	4.5%

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What was happening :

- too many small memory allocations across threads
- new has an internal locking for thread safety
- and cannot cope !

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- new has an internal locking for thread safety
- and cannot cope !

Another good reason to care about memory allocation !

Low level optimizations

1 Measuring Performance

2 Code modernization

3 Improving Memory Handling

4 The nightmare of thread safety

5 Low level optimizations
- Scope and target
- How to measure ?
- Improving

6 Conclusion

Scope and target

- improve usage of the hardware for a given code
- that includes in particular
  - better caching of memory accesses
  - better usage of pipelining and superscalar features
  - better vectorization
- in principle, the compiler does all that for you
- but you have better high level knowledge of the code !

Measuring low level efficiency

CPI

- **C**ycles **P**er **I**nstruction
- should be smaller when pipelining and superscalar features are used
- but typical values highly depend on the type of code

Cache misses

- should be really low (<1%)
- Andrzej used to say : "5% is catastrophic"

Vectorization

- look at specific counters in vtune/valgrind (extension)
- check the assembly code directly looking for SIMD instruction codes

How to improve

By acting mainly on 2 constraints that the compiler has to obey

your data dependencies

- you need close-by operations to be independent
- compiler code reordering is limited
- and pipelining/superscalar need that

your data structure

- especially true for caching and vectorization
- your data structures should group together what goes together
- Called SoA (**S**tructure **o**f **A**rrays) approach

In both cases : work more in parallel !

Conclusion

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Conclusion

Key messages of the day

- typical large old code can benefit a lot of optimizations
  - typically speedup of > 2 !
- main lines of optimizations is reworking the data structures
  - for optimizing memory allocation
  - for allowing more parallelism/vectorization
- handling multicores typically goes through threading
  - huge effort to be made to ensure thread safety
  - constness can greatly help