CERN

Efficiently exploit multicore architectures

The LHCb experience

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Outline

Context - LHCb and computing

Multi-threading and scheduling

Memory management

Results and lessons

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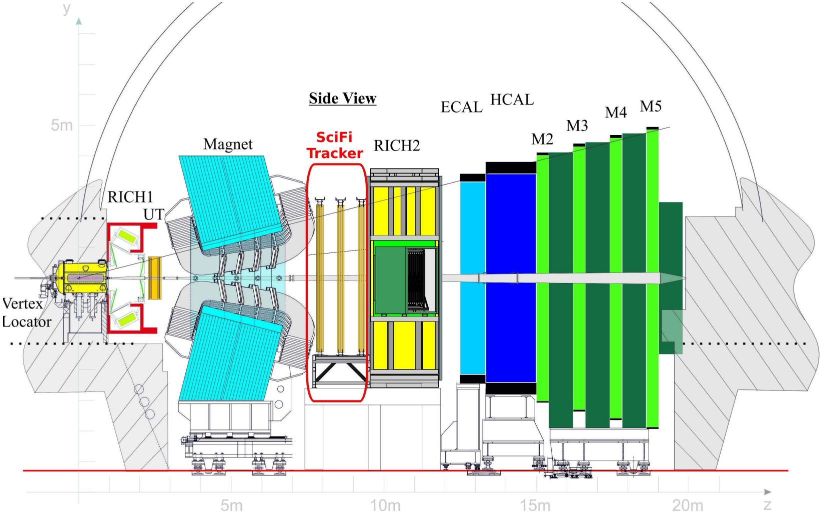
LHCb overview

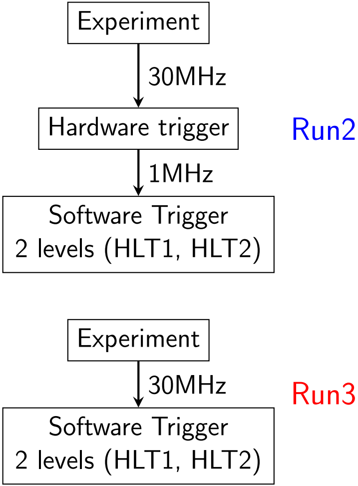


LHCb Run 3 landscape

- Upgrade of the detector itself to take more luminosity (x5)
  - still 30MHz collisions
  - more pile-up (now 5.5, was 1.1)

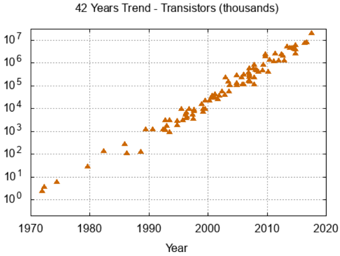
LHCb Run 3 landscape

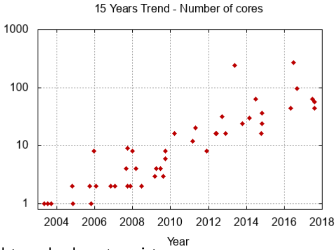
- Upgrade of the detector itself to take more luminosity (x5)
  - still 30MHz collisions
  - more pile-up (now 5.5, was 1.1)
- New trigger system
  - no hardware, fully software
  - input rate x30 !



Computer science landscape

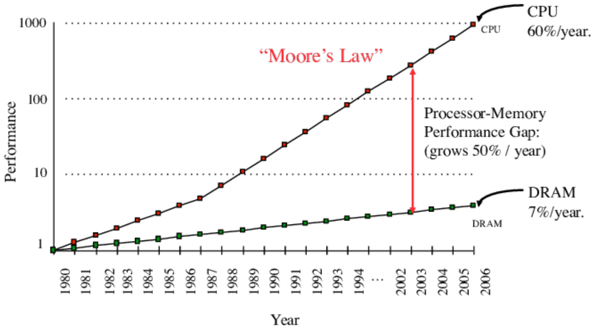
- Hardware evolution continues
  - Moore's law still holding
  - in numbers of transistors
- Hardware always more complex
  - more parallelization
  - pipelines, fuse multiple add, hyperthreads, vectors, ...
- Many-core area has started
  - easily 40, up to 100 logical CPU cores





Data source : https://github.com/karlrupp/microprocessor-trend-data, modified to only show transistors

More computer science landscape



CPU versus Memory improvements in last decades

- Memory is now extremely slow (relatively)
- Level of caches have been introduced to mitigate
- Good usage of caches has become a must

How to adapt ?

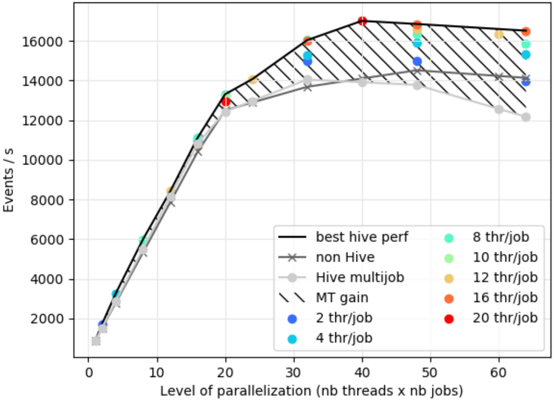
- Multi-core architecture asks for multi-threading
  - and careful scheduling
- Memory management is of utter importance
  - while it had been neglected in the past
  - and thus in our code bases
- Low level optimizations can make a difference
  - and in particular vectorization
  - this will be the topic of Arthur's talk

Multi-threading and scheduling

Why not multi-job ?

- Because it exhausts easily the memory
  - think of an application needing 10GB of memory
  - launch it 256 times on a KNL machine...
  - mitigation exists, but no more sufficient
- Because it harms the memory caches
  - jobs are competing for memory
  - while threads are cooperating, as they share most of it
  - resulting in performances gains (20% for LHCb)

Why not multi-job ?



Implications of multi-threading

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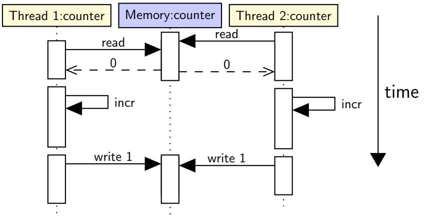
non-reentrant code

```
void MyClass::handleXYZ {
  ...
  m_xyzCounter++;
}
```



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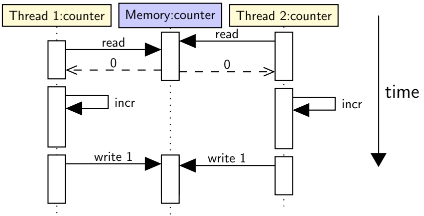


- Hard to identify non reentrant code !
- Need to review all the code
- Implies major changes in coding habits

A practical approach in LHCb

Use the framework of the experiment

- Users write algorithms
  - their entry point is the `operator()` method
  - which now has to be reentrant
- Which interact with a white board
  - items in the whiteboard are now immutable
  - so you can no more modify them once created

Use latest C++ features

- `const` means "bit-wise constant or thread-safe"
- Hence `const` methods of classes are reentrant
- Thread unsafe code leads to compile errors

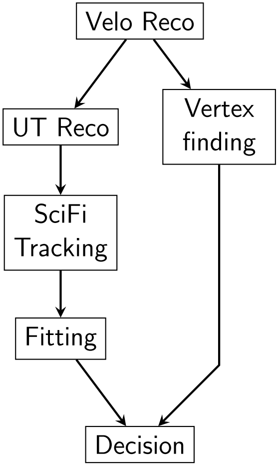
Make sure all cores are busy

Constraints

- Each thread needs to run independant tasks
  - avoid contention and false sharing
- Still some time dependencies

Consequences

- A directed acyclic graph of tasks
- “scheduling” needed



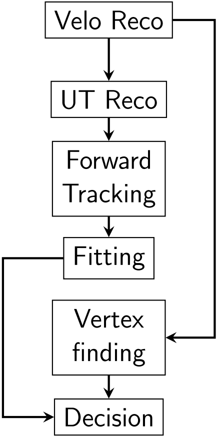
LHCb's HLT1 example

Tasks

- Only use event level parallelism
- No intra event multi-threading
- One event is only 1ms of CPU

Scheduling

- Static scheduling
- Graph solved at initialization time
  - and converted to linear sequence



Memory management

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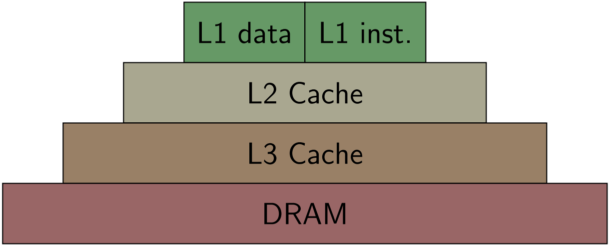
Results and lessons

Remember Memory is really slow



size	latency
64 kB	4 cycles
256 kB	10 cycles
10 MB	40 cycles
64 GB	400 cycles

Typical data, on an Haswell architecture

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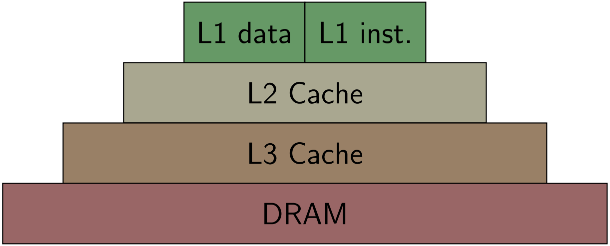

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Cost of an access to RAM

- 400 cycles, that is of the order of 10 Kflop !

Memory management strategy

- Limit seeks and jumps to the minimum
  - to load all in one single access
  - i.e. collocate what goes together
- Limit memory allocations to the minimum
  - the number of them, not the size
  - so group many allocations into one

Example of bad code (1)

```
std::vector<Track*> myTracks;
for (...) {
  myTracks.push(new Track(...));
}
```

- Each new track is an allocation
- Tracks are completely scattered in memory

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std::vector<Track*> myTracks;
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- Each new track is an allocation
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Rule 1 : no container of pointers !

at least when they own their content

Example of bad code (2)

```
std::vector<Track> myTracks;
for (...) {
  myTracks.push(Track(...));
}
```

- Vector will get reallocated many times
- And existing items copied over

Example of bad code (2)

```
std::vector<Track> myTracks;
for (...) {
  myTracks.push(Track(...));
}
```

- Vector will get reallocated many times
- And existing items copied over

Rule 2 : reserve space in your containers !

Example of bad code (3)

```
std::vector<Track> myTracks;
myTracks.reserve(100);
for (...) {
  myTracks.push(Track(...));
}
```

- Tracks get copied
- They should be created directly in place

Example of bad code (3)

```
std::vector<Track> myTracks;
myTracks.reserve(100);
for (...) {
  myTracks.push(Track(...));
}
```

- Tracks get copied
- They should be created directly in place

Rule 3 : use emplace !

Do you think this is optimal ?

```
std::vector<Track> myTracks;
myTracks.reserve(100);
for (...) {
  myTracks.emplace(...);
}
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```

Of course not !

- Use `std::array` or `boost::small_vector`
- And wait for Arthur's talk for more !

Memory management and threading

- Heap allocations are serialized
- Too many new/malloc/... will lead to contention
- Another good reason to reduce their usage

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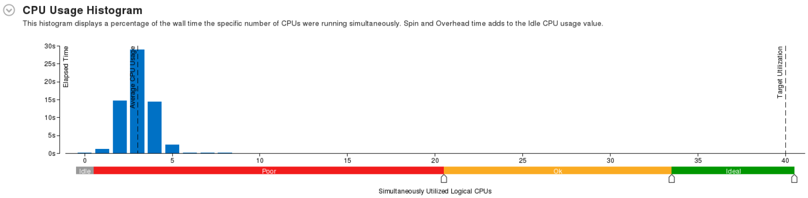
Example of a bad case on 40 virtual cores :



Detecting memory offending code

- Measure time spent in malloc/new/free/delete/... ?
  - more than a few % ? Room for improvement !
- What is your last level cache miss rate ?
  - above 1% ? Room for improvement !

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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%

Results and lessons

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3 years of LHCb HLT1 performances

Multithreading, from 500 evts/s to 3500 evts/s

- Make the HLT1 code thread safe and scalable

Vectorization, 2x to 3x speedup per algo

- Vectorize key algorithms

Change event model, from 24K evts/s to 33K evts/s

- Adopt SoA and plain old data – see Arthur's talk

Numbers measured on a "reference" machine, corresponding to 1‱ of the HLT1 farm capacity

Lessons

We can gain factors !

- Modern CPUs can be efficiently used
- And they are pretty good and fast actually

... not for free ...

- Deep changes in the code and data structures
- A change of paradigm, similar to the GPU

but it's rewarding

- New code is shorter, faster and more readable !

Advices, learnt the hard way...

- Start by cleaning up your code
  - will save you unecessary work
  - will already gain up to 2x in speed !
- Deal with memory before you go threaded
  - or the contention will be immediate
- Go to a simple event model
  - do not overdo object orientation
  - think structure of arrays from the beginning
- Only then vectorize
  - only if worth it, do not expect miracles
  - check expected gain with Amdahl's law in mind

Final remark

- Computing has become very complicated
- Huge need for disseminating the knowledge
- This is the key point to success for run 3 and 4 !