Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Introduction to Multi-Threading

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Overview

Who am I?

What is multi-threading?

Why use multi-threading

Multi-threading difficulties

Thread safety

Things to avoid

Who am I?

- I’m in charge of the CMS event processing framework
  - art was derived from an earlier version of the CMS framework

- I lead CMSes effort to switch to a multi-threaded framework
  - I designed the how the CMS framework uses threads
  - I lead the team that changed the framework
  - I implemented a large portion of the conversion
  - I provided instructions to the CMS developers on how to adapt their code

- This talk is based on that 6 years of experience

What is Multi-threading?

- A **thread** is the smallest unit of sequential processing
  - Each thread has its own call stack
    - Have own function local variables
    - Have own function callback stack

- All threads in a process share the same memory address space
  - If a thread changes a value in memory it affects other threads using the memory

- Contrast: multiple processes do not share the same memory address space
  - If a process changes a memory address it can NOT affect other processes

Why Use Multi-threading

Speed

Shared Resources

Speed

- Using multiple threads can make processing one event faster
  - There is always some point where threads are waiting for the last thread to complete
- Multi-threading does not decrease the time to process ALL events
  - Running multiple single-threaded jobs each processing events is usually faster
  - Many single-threaded jobs are usually the most CPU efficient
- Why bother with multi-threading?

Computing Hardware Trends

- CPU frequencies no longer increase
- Manufacturers are increasing number of CPU cores
- Cost of memory decrease at a slower rate than increase core count
  - Memory per Core is either flat or decreasing
- Intel Xeon we can afford 2 GB/core
- Intel Xeon Phi have 256 ‘cores’ but only afford 96GB total
  - If single threaded job takes 1.5 GB could only run 64 jobs on the machine
  - Would take 4x as many computers to use single-threading compared to multi-threading

Shared Resources

- Multi-threaded programs can share memory across many events
  - E.g. Geometry, Conditions, Configuration
  - CMS: 1.5GB can be shared and each event needs 0.2 to 0.5 GB

- Multi-threading help Batch and Workflow management systems scale
  - Do not have to have a batch slot per core
  - Systems only grow as the number of machines, not number of cores

- Multi-threading puts less pressure on computing sites
  - Database connections are shared across cores
  - File opens can be shared across cores

Multi-threading Difficulties

Race condition

Deadlock

Race Condition

A shared memory address where

- One thread is writing to the memory
- Another thread is reading or writing to the memory

There is no such thing as a ‘benign’ race condition

Race Condition Example

```
std::vector<double> values;
```

Thread 1

```
values.push_back(1.);
for(auto v:values) cout <<v;
```

Thread 2

```
values.push_back(2.);
for(auto v:values) cout <<v;
```

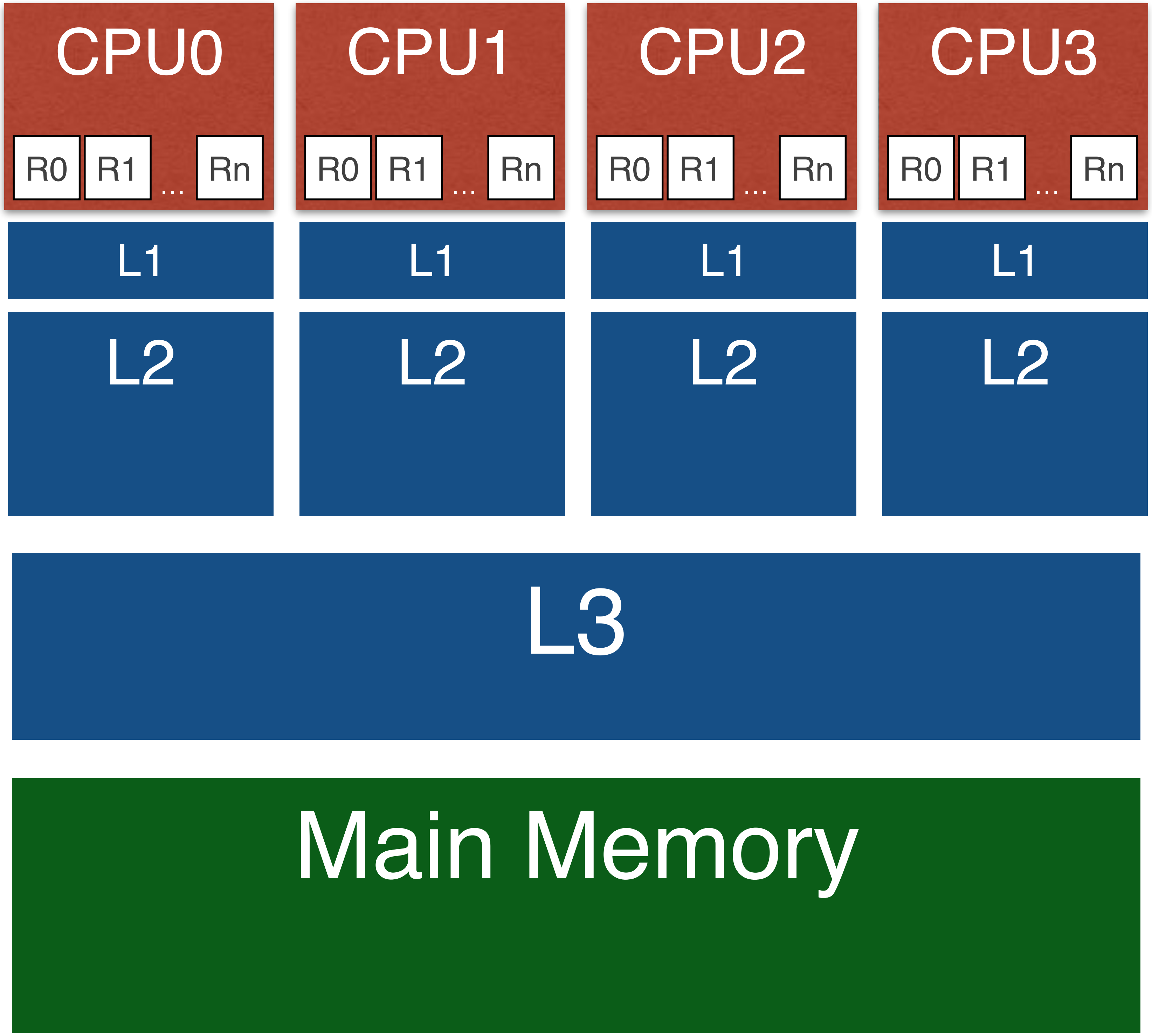
Results could be

- 1.0 1.0 2.0
- 2.0 2.0 1.0
- 1.0 2.0
- 2.0 1.0
- segmentation violation

Double-click to edit

Double-click to edit

CPU Memory Model



Double-click to edit

Race Condition Example

```
std::vector<bool> bools={false,false};
```

Thread 1

```
bools[0] = true;
cout <<“ 0 ”<<bools[0];
```

Thread 2

```
bools[1] = true;
cout <<“ 1 “<<bools[1];
```

Results could be

‘0 true’ and ‘1 true’

‘0 false’ and ‘1 true’

‘0 true’ and ‘1 false’

Deadlock

A deadlock is when two or more threads are waiting for other threads in the group to finish before continuing.

Thread 1

```
acquireGeometry();
acquireCalibration();
…
releaseCalibration();
releaseGeometry();
```

Thread 2

```
acquireCalibration();
acquireGeometry();
…
releaseGeometry();
releaseCalibration();
```

Thread Safety

The easiest way to be thread safe is to never have a thread write to memory that another thread will read.

For all other cases, C++ requires the use of synchronization mechanism

- E.g. mutex, semaphore, atomic
- These will not be covered in this talk
- *art* will automatically handle synchronization across modules
  - An object put into the Event by a module can safely be read by a module in another thread

Levels of Thread Safety for Objects

Thread-hostile

Thread friendly

const-thread safe

Thread safe

Thread Hostile

It is not safe for more than one thread at a time to call methods even for different class instances

E.g. with **static**

```
class Foo {
public:
  int convert(int iIn) const {
    static int s_oldIn{iIn};
    static int s_cache{ calculate(iIn) };
    if( iIn != s_oldIn) { s_cache = calculate(iIn);
                          s_oldIn = iIn; }
    return s_cache;
  }
  …
};
```

Thread Friendly

Different class instances can be used by different threads safely

- Sharing the same instance across multiple threads is not safe

E.g. with mutable cache

```
class Foo {
  mutable int cache_;
  mutable int oldIn_;
public:
  int convert(int iIn) const {
   if( iIn != oldIn_) { cache_ = calculate(iIn);
                        oldIn_ = iIn; }
    return cache_;
  }
  …
};
```

const Thread-Safe

Multiple threads can call const methods on the same class instance

Classes in the C++ standard library are const thread-safe

Classes put into the art::Event must be const thread-safe

```
class Foo {
  std::vector<int> values_;
public:
  Foo() : values_{calculateAllAllowedValues()} {}

  int convert(int iIn) const {
    return values_[iIn];
 }
  …
};
```

Thread Safe

Multiple threads can call non-const methods on the same class instance

Intel's Thread Building Block library has thread-safe containers

tbb::concurrent_vector, tbb::concurrent_hash_map, etc.

TBB is distributed with *art*

Thread 1

```
tbb::concurrent_vector<double> values;
startAndWaitForOtherThreadsToFinish( values );
for( auto v:values) { cout << v<<“ “; }
```

Thread 2

```
values.push_back(1.);
```

Thread 3

```
values.push_back(2.);
```

Results could be

1.0 2.0

2.0 1.0

Things to Avoid

non-const global memory

mutable data members in Event data products

art based Services with mutable state

Starting your own threads

Avoid: Non-const Global Memory

Global Memory: memory accessible from global C++ scope

Types of global memory

- File scope variables
- Function static variables
- Class static variables

No way to know if another thread is changing the values

Avoid: Mutable Data Members in Event Data Products

- Event data products are shared across threads
  - Multiple threads can be calling const functions on the same class instance

```
class Displacement {
  Cartesian3D vec_;
  mutable Polar3D polar_;
  mutable bool polarIsSet_;
public:
  Polar3D const& polar() const {
    if(not polarIsSet_) { polarIsSet_ = true;
                          polar_ = calculatePolar(); }
    return polar_;
  }
  …
};
```

Avoid: Services with Mutable State

Services are shared across threads

NOTE: storing event data in a Service is not considered best practice in *art*

```
class TrackFittingService {
  std::vector<Hit> hits_;
public:
  void setHits(std::vector<Hit> const& iHits) {
      hits_ = iHits; }
  Track fitToTrack() const;
  …
};
```

Avoid: Starting a Thread

Grid sites specify how many threads a process can use

art will start with the maximum allowed number of threads

Additional high CPU threads can lead to a site killing the process

art will provide facilities to allow you to do work concurrently within a module

- Calling TBB parallel algorithms within an art module is supported
- To start TBB add to configuration: `services.num_threads:` *<n>*

Conclusion

Multi-threading is coming to *art*

This will allow HEP processes to run on resource constrained systems

Need to prepare code now

- Remove use of ‘global’ variables
- Do not use mutable member data for Event data products
- Remove mutable state from Services

Advanced Resources

Useful book about C++ concurrency

“C++ Concurrency in Action” by Anthony Williams

Useful talk about C++ threading memory model

https://channel9.msdn.com/Shows/Going+Deep/Cpp-and-Beyond-2012-Herb-Sutter-atomic-Weapons-1-of-2