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Detector Simulation Multithreading

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CERN

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The following lecture is entirely based on Andrea Dotti's lecture given at the Geant4 tutorial at MIT in 2015.

I am fully reusing Andrea's slides in their original form.

Multithreading I

26-30 May, 2015
Geant4 tutorial @ MIT
Ray and Maria Stata Center - Room 32-124

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Important Note

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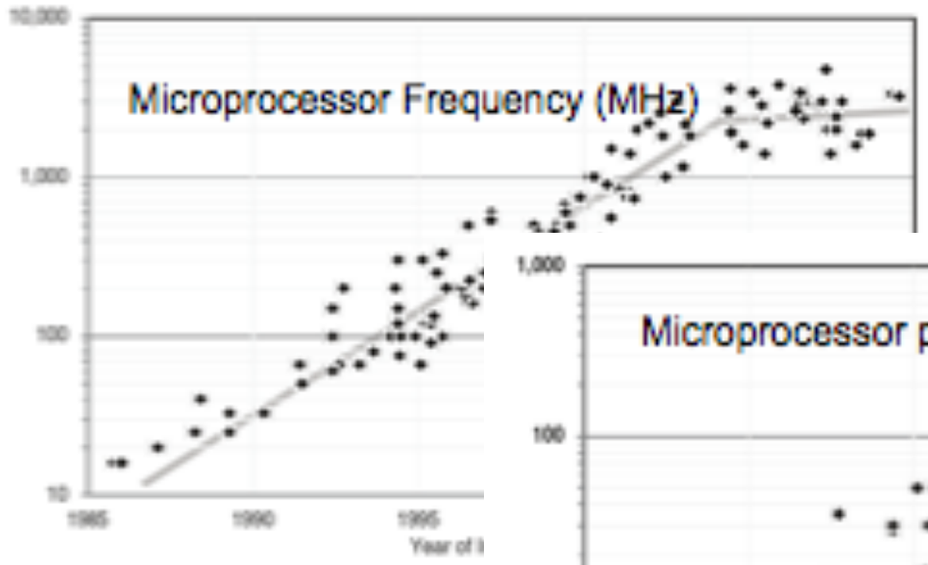
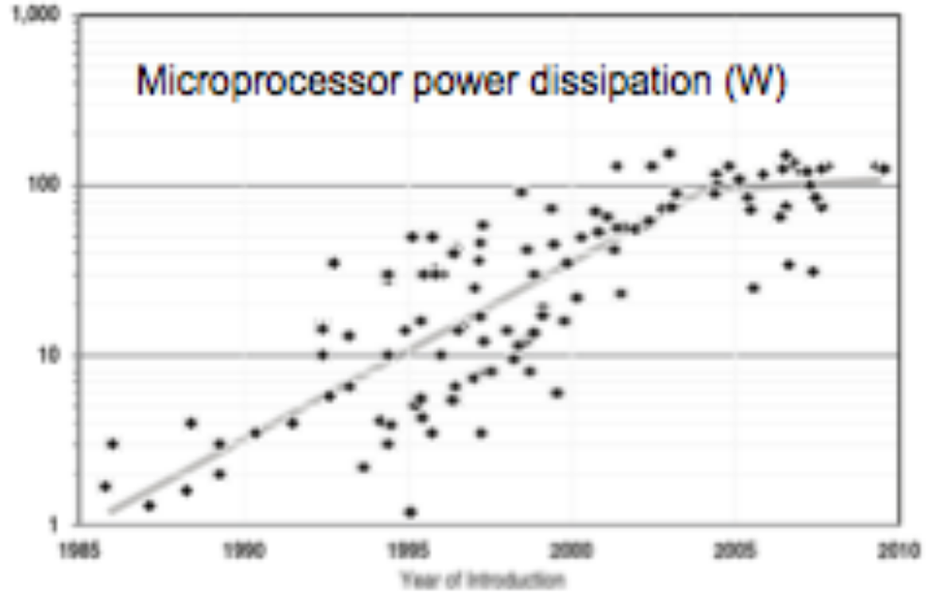
This is the first part of a 2- session

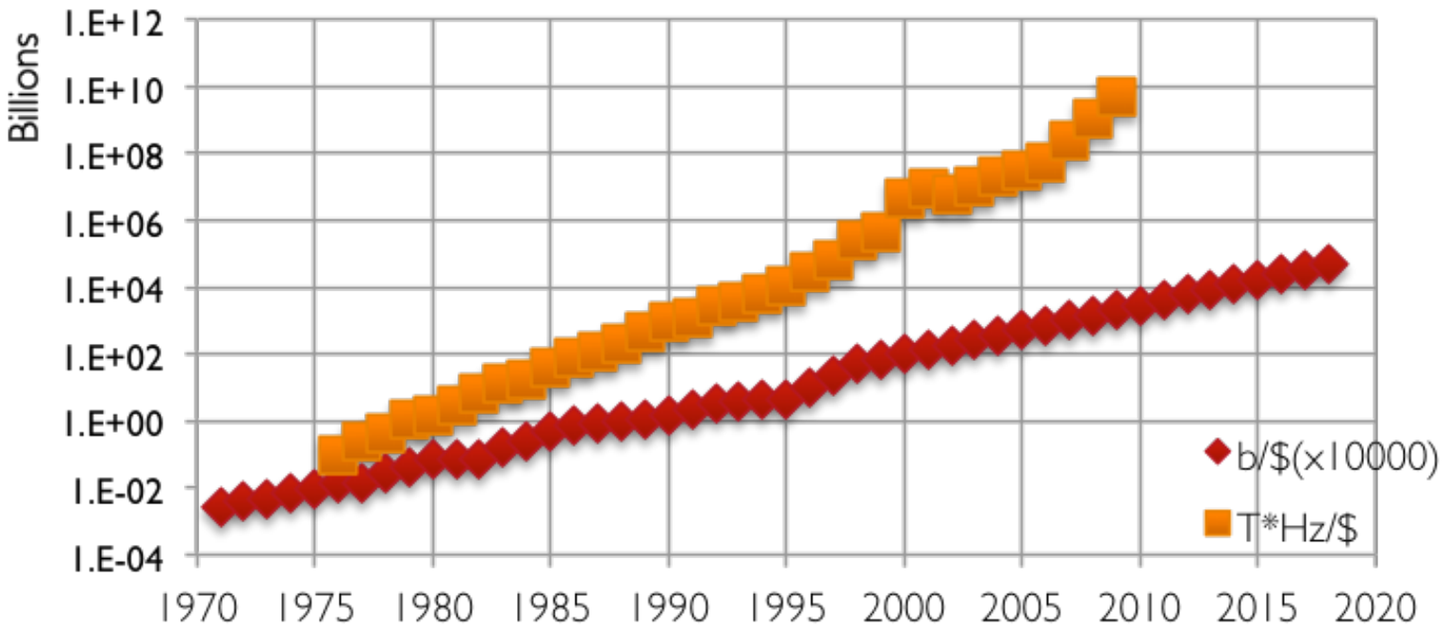
Only the **very minimum** will be introduced here

- What is multi-threading?
- How to activate MT
- How to migrate code (thread-safety in second talk)
- UI commands related to MT

The challenges of many-core era







- Increase frequency of CPU causes **increase of power needs**
- Reached plateau around 2005
- No more increase in CPU frequency
- However number of transistors /$ you can buy continues to grow
- Multi/May-core era
- Note: quantity memory you can buy with same $ scales slower
- **Expect:**
- Many core (double/2yrs?)
- Single core performance will not increase as we were used to
- Less memory/core
- New software models need to take these into account: increase parallelism

CPU Clock Frequecy 1and usage: The Future of Computing Performance: Game Over or Next Level?
DRAM cost: Data from 1971-2000:VLSI Research Inc. Data from 2001-2002: ITRS, 2002 Update, Table 7a, Cost-Near-Term Years, p. 172. Data from 2003-2018: ITRS, 2004 Update, Tables 7a and 7b, Cost-Near-Term Years, pp. 20-21.
CPU cost: Data from 1976-1999: E. R. Berndt, E. R. Dulberger, and N. J. Rappaport, "Price and Quality of Desktop and Mobile Personal Computers: A Quarter Century of History," July 17, 2000, ;Data from 2001-2016: ITRS, 2002 Update, On-Chip Local Clock in Table 4c: Performance and Package Chips: Frequency On-Chip Wiring Levels -- Near-Term Years, p. 167. ;
Average transistor price: Intel and Dataquest reports (December 2002), see Gordon E. Moore, "Our Revolution,"

In Brief

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- Modern CPU architectures: need to introduce **parallelism**
- Memory and its access will limit number of concurrent processes running on single chip
- Solution: add parallelism **in the application code**
- Geant4 needs back-compatibility with user code and **simple approach** (physicists != computer scientists)
- **Events are independent**: each event can be simulated separately
- Multi-threading for event level parallelism is the natural choice

Geant4 Multi Threading capabilities

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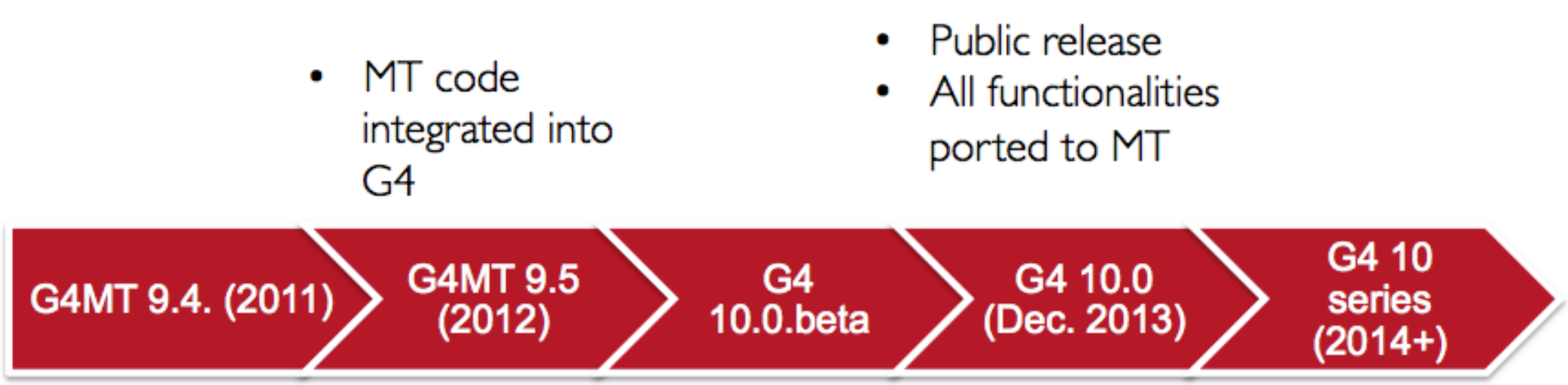
- Proof of principle
- Identify objects to be shared
- First testing

- MT code integrated into G4

- API re-design
- Example migration
- Further testing
- First optimizations

- Public release
- All functionalities ported to MT

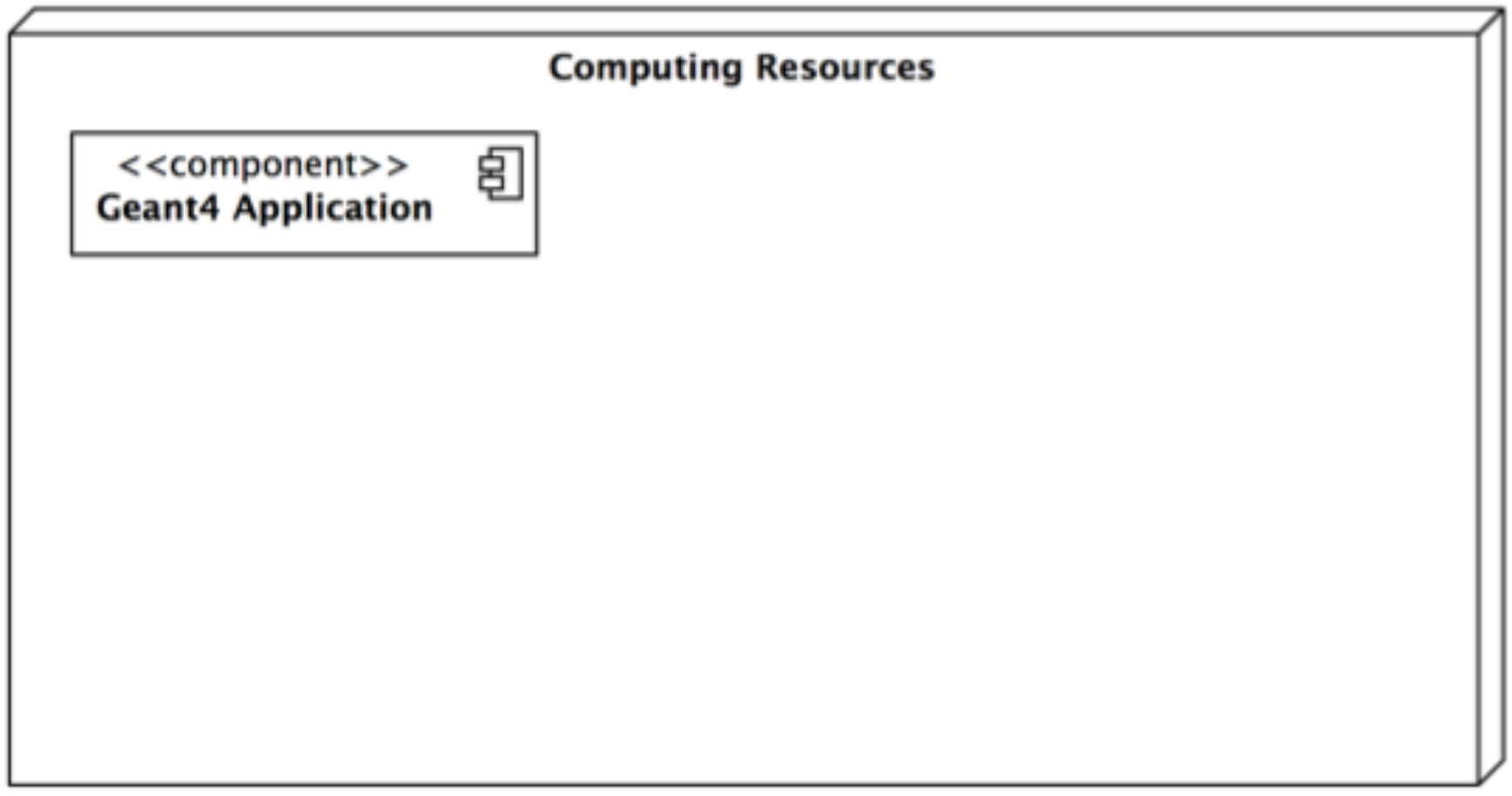
- Further Refinements
- Focus on further performance improvements



Threading 101

What is a thread?

Sequential application



What is a thread?

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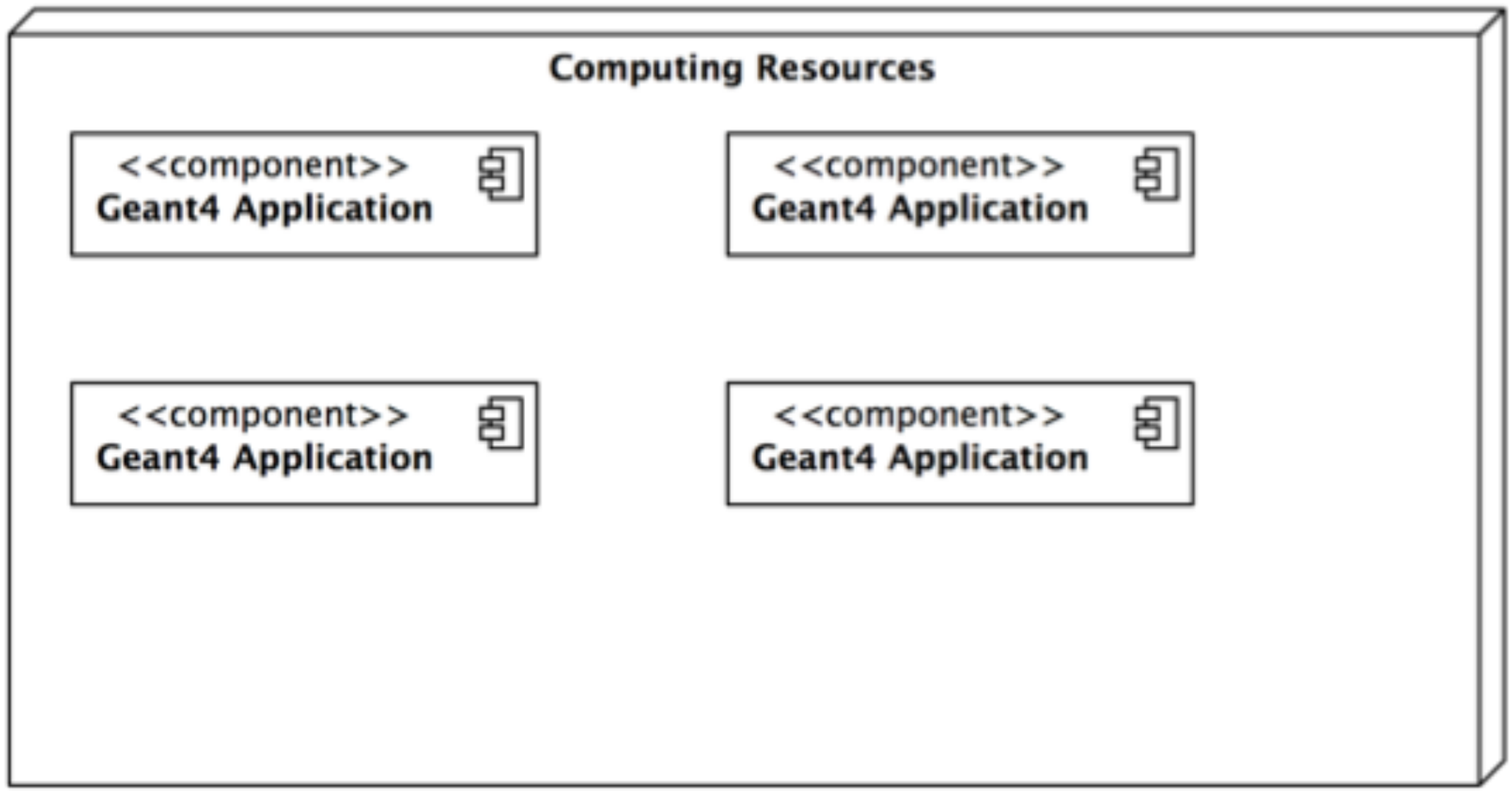
Sequential application: start N (cores/CPUs) copies of application if fits in memory



What is a thread?

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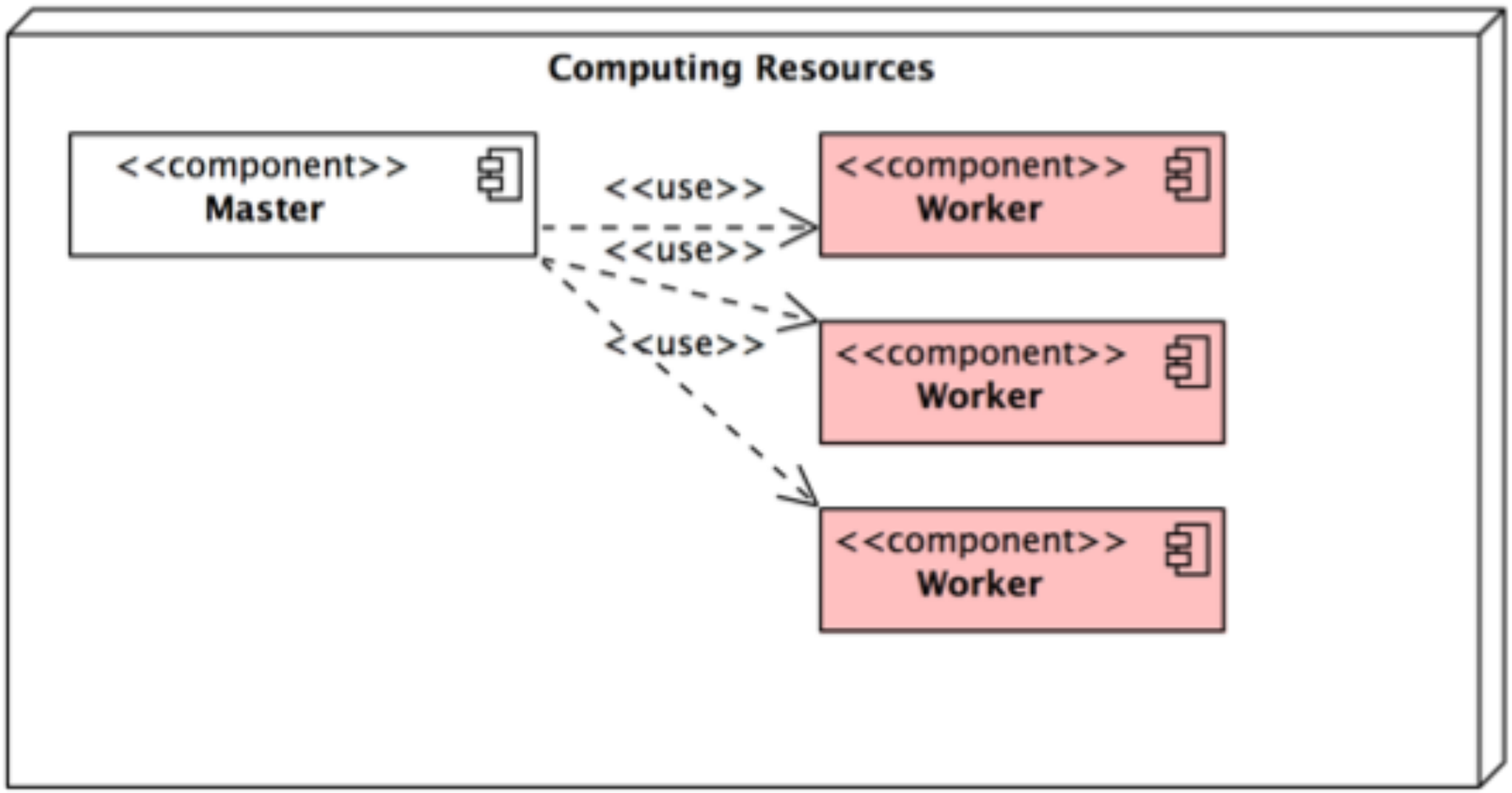
MT Application: single application starts threads. For G4: application (master) controls workers that do simulation, no memory sharing now, each worker is a copy of the application



What is a thread?

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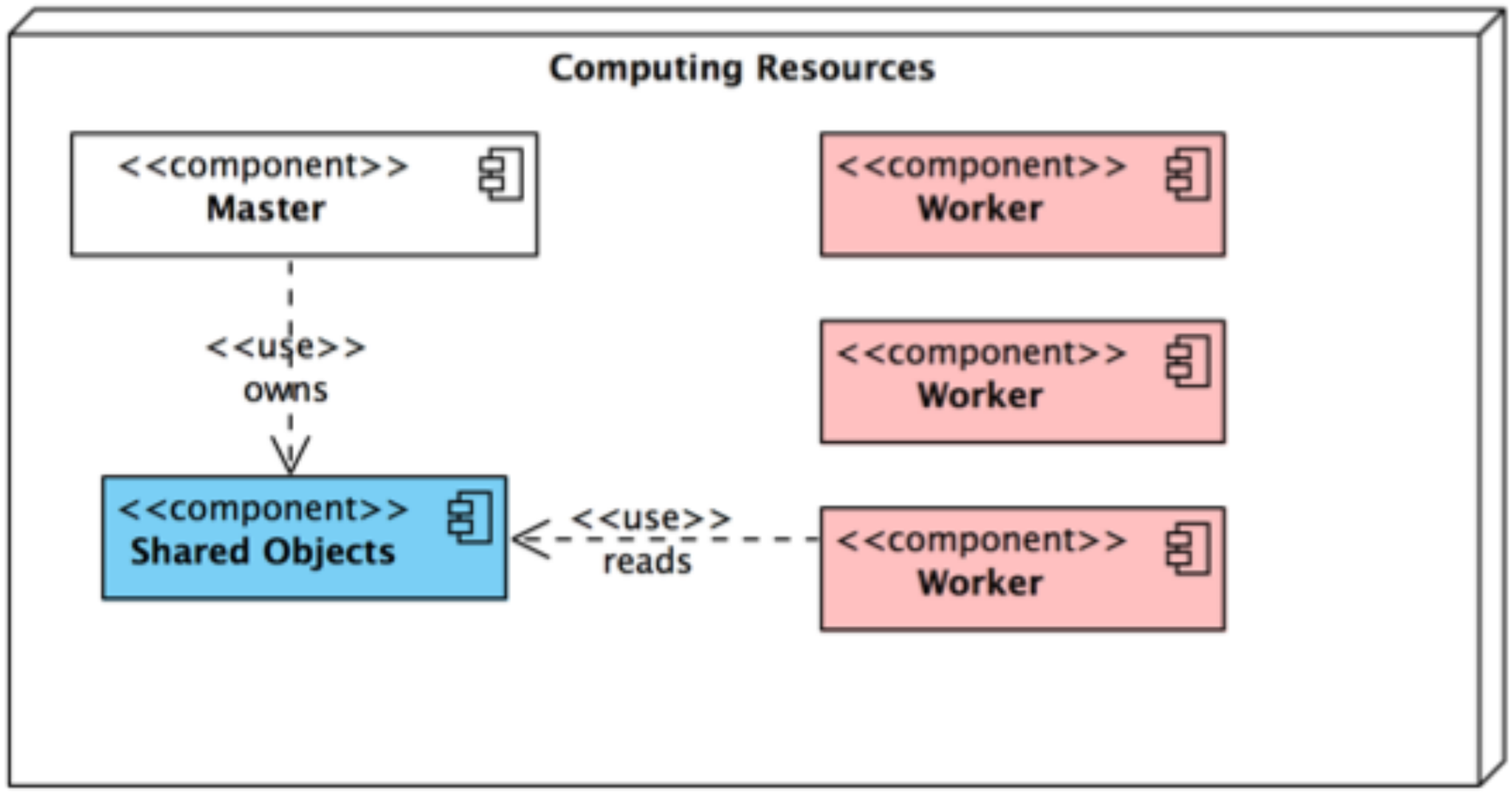
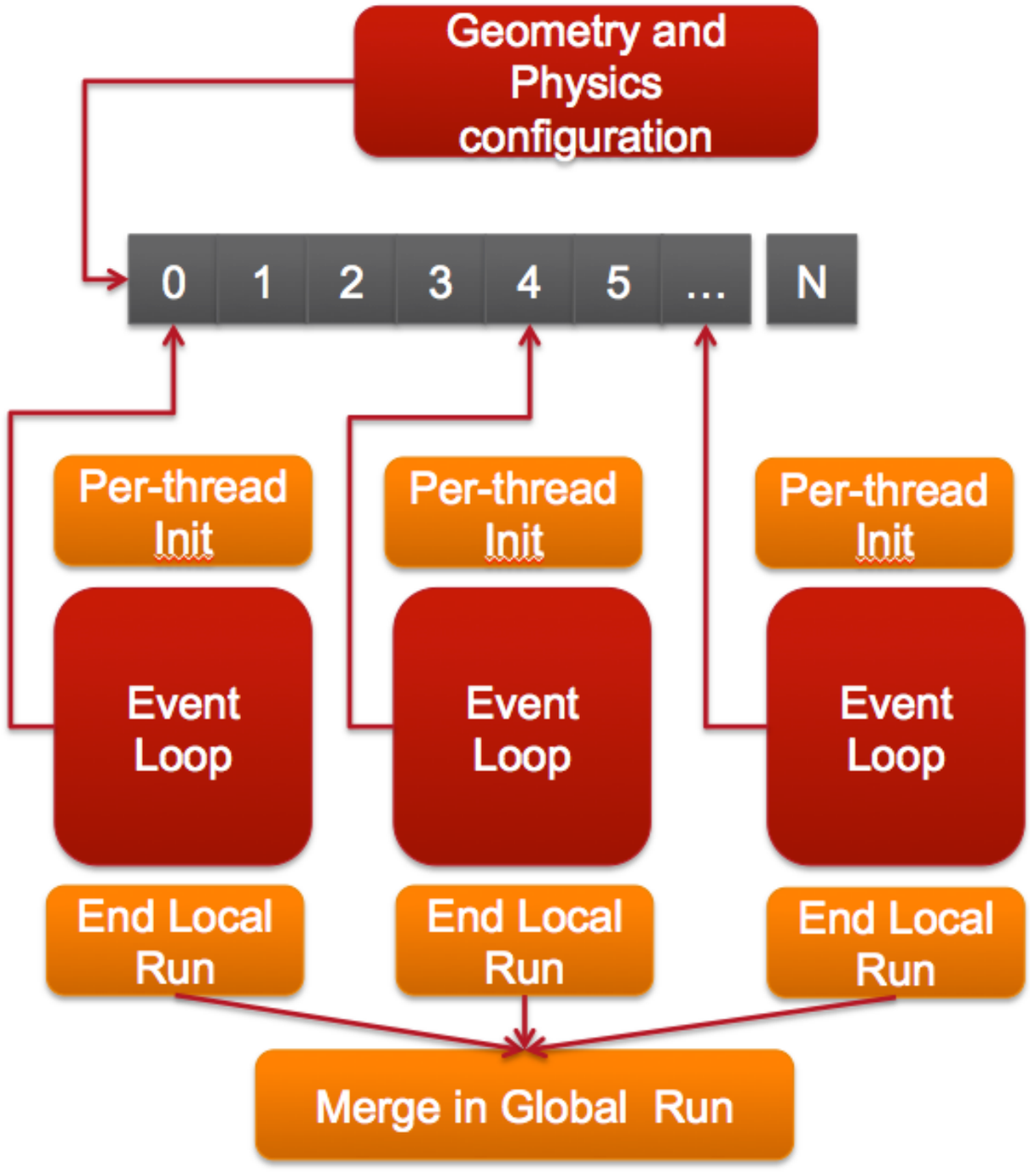
Memory reduction: introduce shared objects, memory of N threads is less than memory used by N copies of application



Multi-threading in Geant4: the basics

General Design



Per-event seeds pre-prepared in a "queue"

Threads compete for next event to be processes

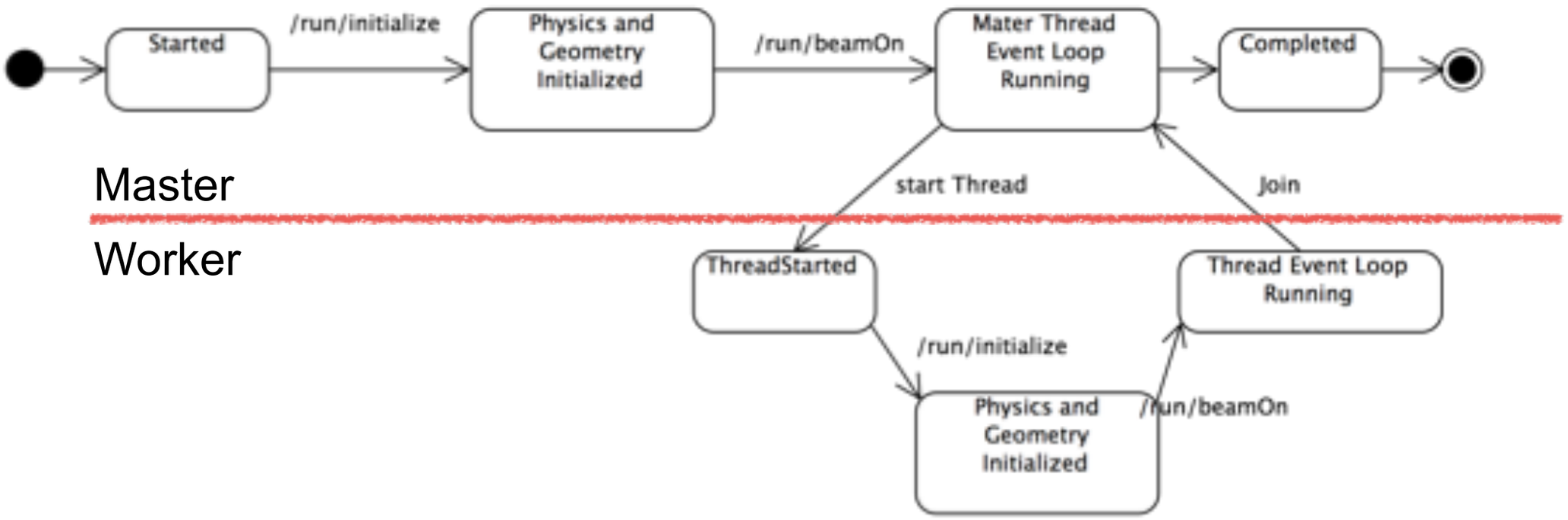
Command line scoring and G4tools automatically merge results from threads

Simplified Master / Worker Model

- A G4 (with MT) application can be seen as simple finite state machine

Simplified Master / Worker Model

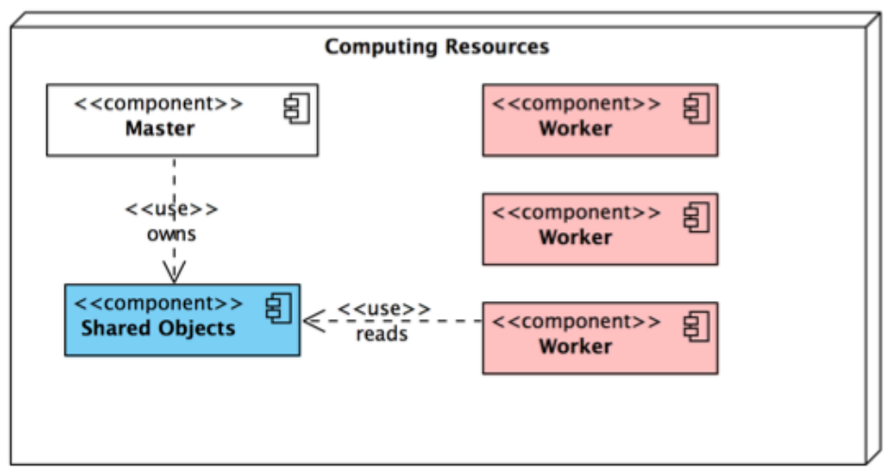
- A G4 (with MT) application can be seen as simple finite state machine
- Threads do not exists before first /run/beamOn
- When master starts the first run spawns threads and distribute work



Shared Vs Thread-local

- To reduce memory footprint threads must share at least part of the objects
- General rule in G4: threads can share whatever is invariant during the event loop (e.g. threads do not change these objects while processing events, these are used "read-only")

- Geometry definition
- Electromagnetic physics tables
- The reason for this is discussed in second part



Shared ? Private?

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- In the multi-threaded mode, generally saying, data that are stable during the event loop are shared among threads while data that are transient during the event loop are thread-local.

Shared by all threads

: stable during the event loop

- Geometry
- Particle definition
- Cross-section tables
- User-initialization classes

Thread-local

: dynamically changing for every event/ track/step

- All transient objects such as run, event, track, step, trajectory, hit, etc.
- Physics processes
- Sensitive detectors
- User-action classes

Without MT

Detector geometry & cross-section tables

MEMORY SPACE

Transient per event data (tracks, hits, etc.)

AVAILABLE CORES

Active cores

Unused cores

With MT

MEMORY SPACE

AVAILABLE CORES

Active cores

Shared ? Thread-local?

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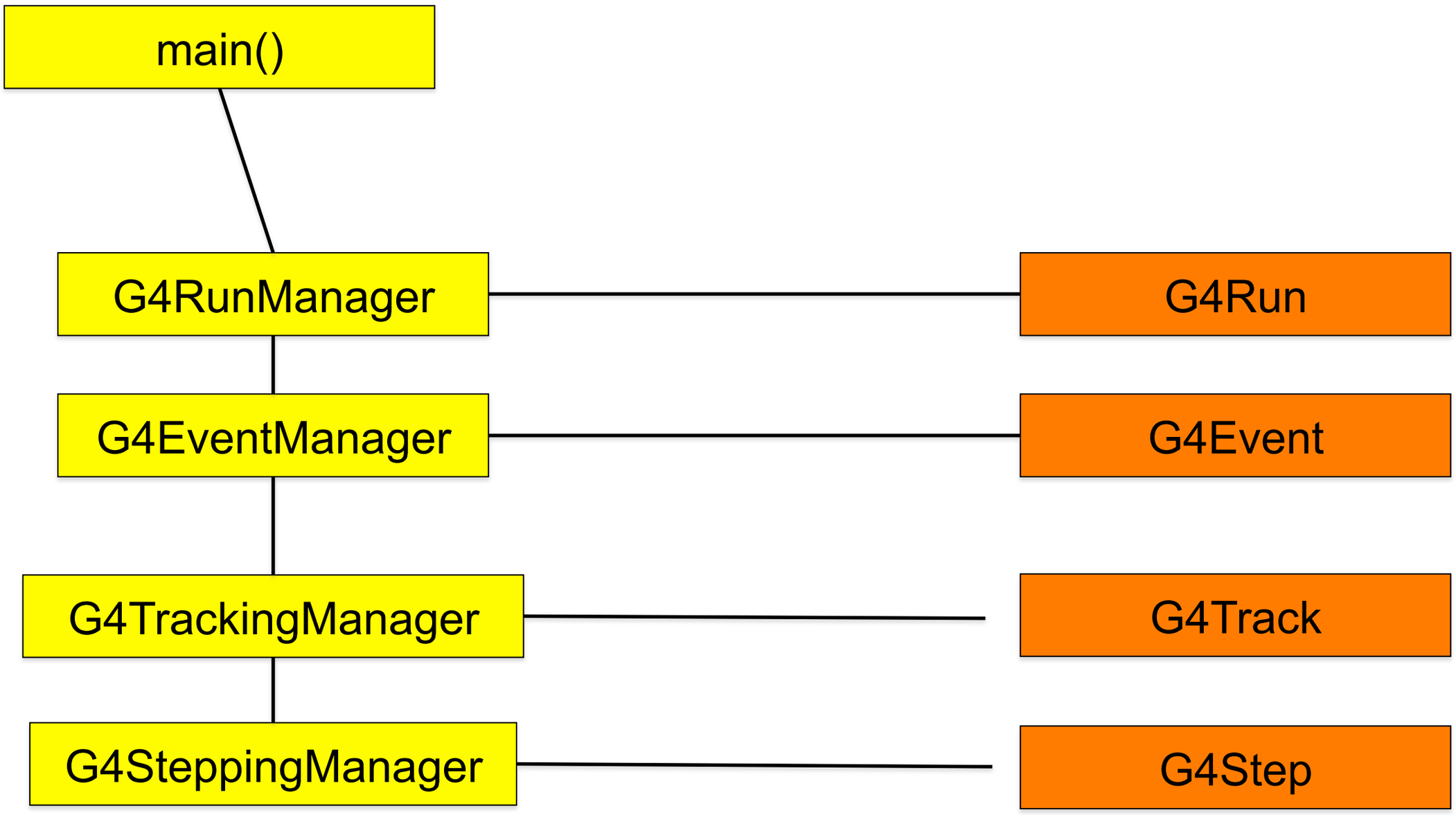
In general, geometry and physics tables are shared, while event, track, step, trajectory, hits, etc., as well as several Geant4 manager classes such as EevntManager, TrackingManager, SteppingManager, TransportationManager, FieldManager, Navigator, SensitiveDetectorManager, etc. are thread-local.

Among the user classes, user initialization classes (G4VUserDetectorConstruction, G4VUserPhysicsList and newly introduced G4VUserActionInitialization) are shared, while all user action classes and sensitive detector classes are thread-local.

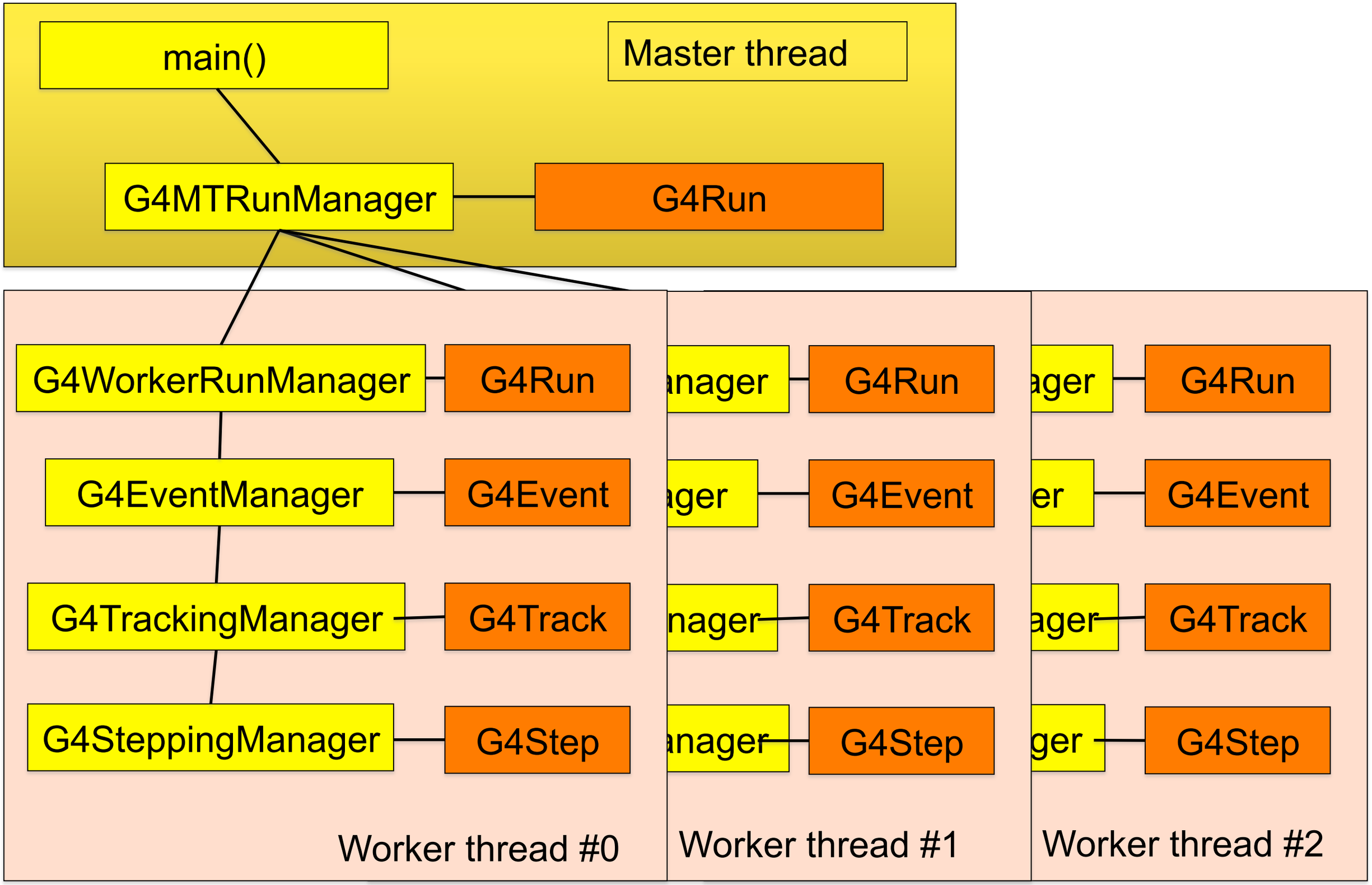
- It is not straightforward (and thus not recommended) to access from a shared class object to a thread-local object, e.g. from detector construction to stepping action.
- Please note that thread-local objects are instantiated and initialized at the first *BeamOn*.

To avoid potential errors, it is advised to always keep in mind which class is shared and which class is thread-local.

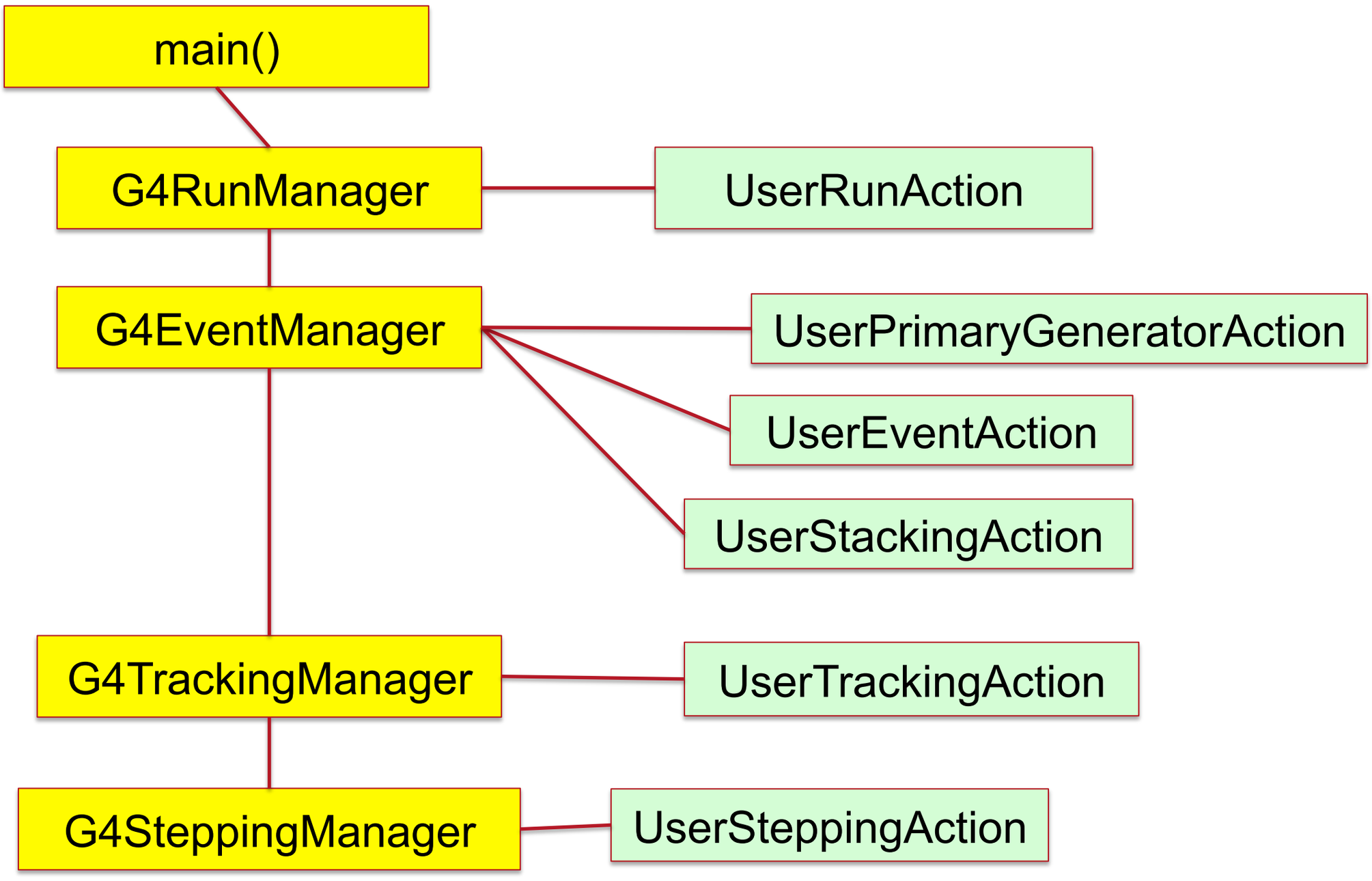
Sequential mode



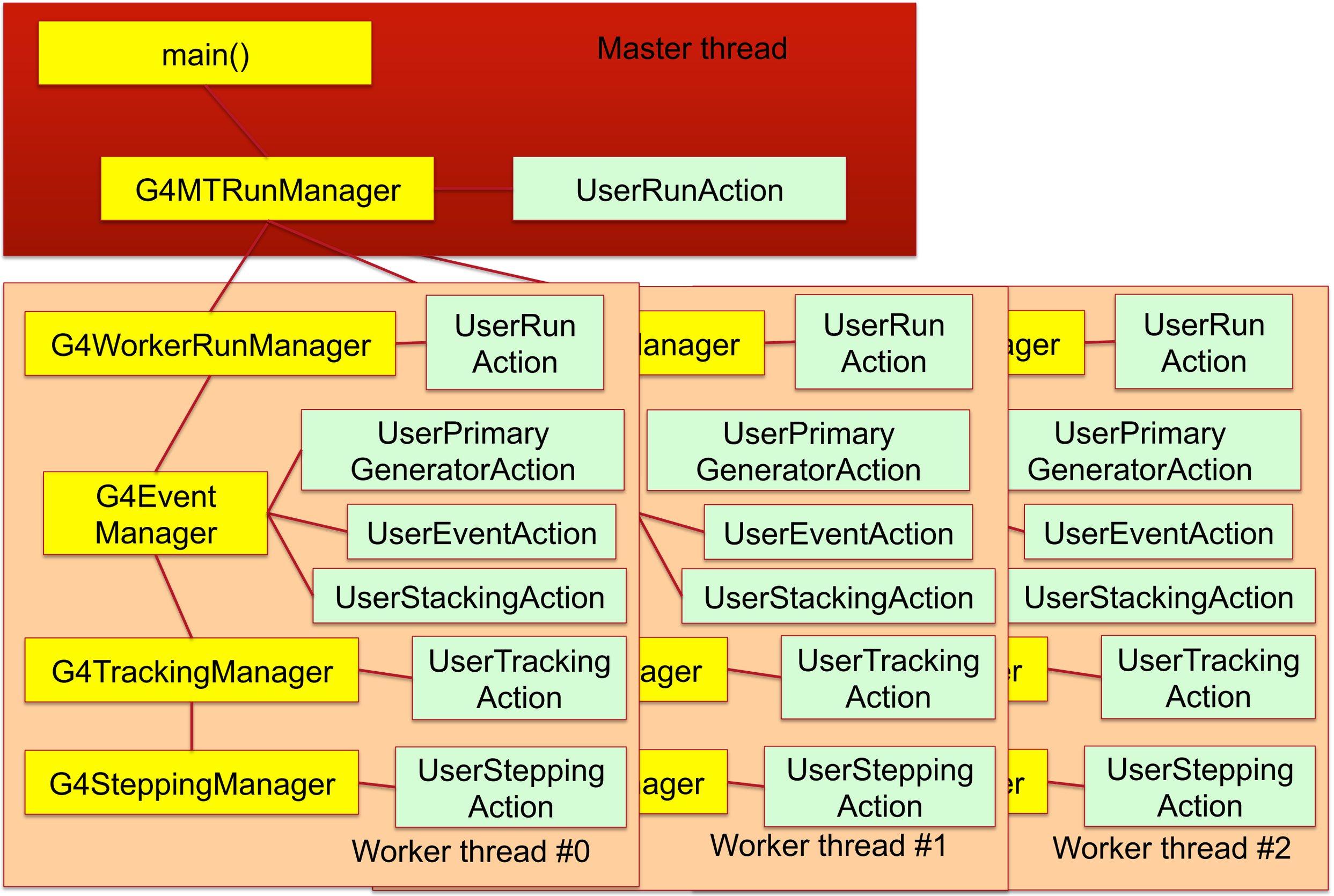
Multi-threaded mode



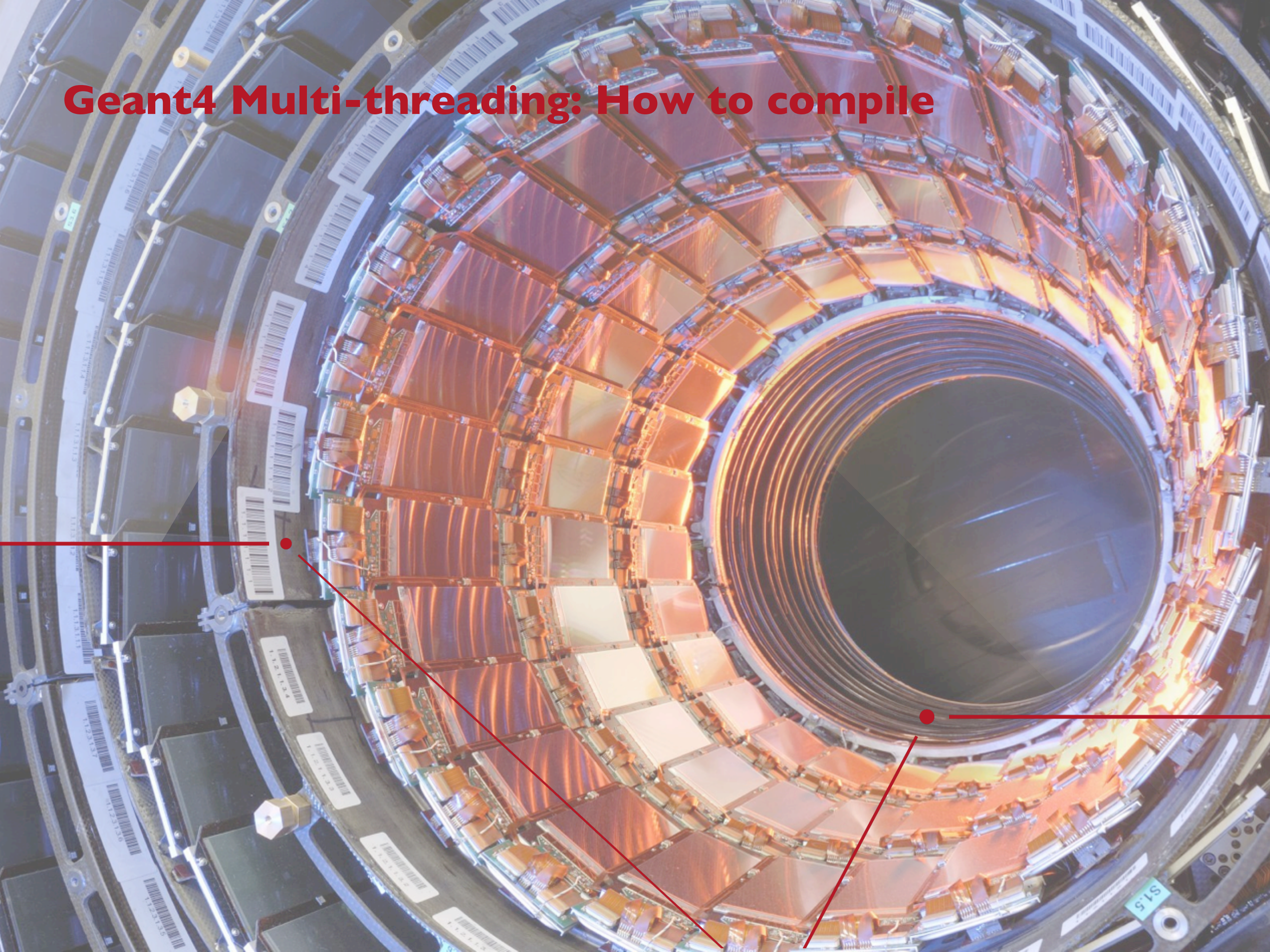
Sequential mode



Multi-threaded mode



Geant4 Multi-threading: How to compile



How to configure Geant4 for MT

- `cmake -DGEANT4_BUILD_MULTITHREADED=ON […]`
- Requires "recent" compiler that supports ThreadLocalStorage technology (to be discussed Thursday) and pthread library installed (usually pre-installed on POSIX systems)
- Check cmake output for:

```
-- Performing Test HAVE_TLS
-- Performing Test HAVE_TLS - Success
```

- If it complains then your compiler is too old, sorry…
- Mac OS X, you need to use clang>=3.0 (not gcc!). On Mac OS X 10.7:

```
cmake -DCMAKE_CXX_COMPILER=clang++ -DCMAKE_C_COMPILER=clang \
      -DGEANT4_BUILD_MULTITHREADED=ON […]
```

- Sorry no WIN support!
- Compile as usual

Code Compatibility

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- Some API have changed to enable MT (this is why this is a major release)
  - The exercises of this tutorial will show how to implement these correctly for MT

- You can use an application developed for G4 Ver 9.6 without changing your code in sequential mode (except for other mandatory modifications not MT-related)

- An MT-ready application, can also run in sequential mode without changing your code (but not vice-versa)

Application Changes: How to 1/2

- **Detector Construction** two functions to implement:
  - `G4VPhysicalVolume* G4VUserDetectorConstruction::Construct();`
    - Build here your detector geometry except Sensitive Detectors and magnetic filed (called by master thread once)
  - `void G4VUserDetectorConstruction::ConstructSDandField();`
    - Build here SDs and B-Fields (called by each thread)
- **Create a new class** that inherits from `G4VUserActionInitialization` and implement:
  - `void G4VUserActionInitialization::Build()`
    - Instantiate here user-actions for worker threads (called by each thread)
  - `void G4VUserActionInitialization::BuildForMaster()`
    - Instantiate here user-actions for master (optional) (called bu master)

If you are new to Geant4 this slide will become clear during the tutorial: you may want to review this presentation later in the week

Application Changes: How to 2/2

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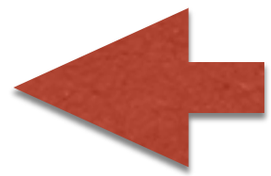
- In the main() function instantiate a `G4MTRunManager` and (if you want) set the default number of threads:

```
int main(int,char**) {
 #ifdef G4MULTITHREADED
    G4MTRunManager* runManager = new G4MTRunManager;
    runManager->SetNumberOfThreads(G4Threading::G4GetNumberOfCores());
#else
    G4RunManager* runManager = new G4RunManager;
#endif
```



Compiled if MT=ON

```
// Mandatory user initialization classes
runManager->SetUserInitialization(new DetectorConstruction);

G4VModularPhysicsList* physicsList = new FTFP_BERT;
runManager->SetUserInitialization(physicsList);

// User action initialization
runManager->SetUserInitialization(new ActionInitialization());
       //…
```

Application Changes: How to 2/2

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- In the main() function instantiate a G4MTRunManager and (if you want) set the default number of threads:

```
int main(int,char**) {
 #ifdef G4MULTITHREADED
    G4MTRunManager* runManager = new G4MTRunManager;
    runManager->SetNumberOfThreads(G4Threading::G4GetNumberOfCores());
#else
    G4RunManager* runManager = new G4RunManager;
#endif
```

Returns number of logical cores of machine

```
// Mandatory user initialization classes
runManager->SetUserInitialization(new DetectorConstruction);

G4VModularPhysicsList* physicsList = new FTFP_BERT;
runManager->SetUserInitialization(physicsList);

// User action initialization
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       //…
```

Application Changes: How to 2/2

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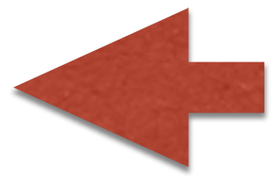
- In the main() function instantiate a G4MTRunManager and (if you want) set the default number of threads:

```
int main(int,char**) {
 #ifdef G4MULTITHREADED
    G4MTRunManager* runManager = new G4MTRunManager;
    runManager->SetNumberOfThreads(G4Threading::G4GetNumberOfCores());
#else
    G4RunManager* runManager = new G4RunManager;
#endif
```



Compiled if MT=OFF

```
    // Mandatory user initialization classes
    runManager->SetUserInitialization(new DetectorConstruction);

    G4VModularPhysicsList* physicsList = new FTFP_BERT;
    runManager->SetUserInitialization(physicsList);

    // User action initialization
    runManager->SetUserInitialization(new ActionInitialization());
          //…
```

https://twiki.cern.ch/twiki/bin/view/Geant4/QuickMigrationGuideForGeant4V10

UI Commands

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Photo Credit: Peter Ginter

MT related UI commands

`/run/numberOfThreads [n]` : Specify number of threads

or `/run/useMaximumLogicalCores` : Use the maximum number of cores

`/control/cout/setCoutFile [filename]` : Sends G4cout stream to a per-thread file. Use "***Screen***" to reset to screen

`/control/cout/setCerrFile [filename]` : As previous but for G4cerr

Advanced commands:

`/control/cout/useBuffer [true|false]` : Send G4cout/G4cerr to a per-thread buffer that will printed at the end of the job

`/control/cout/prefixString [string]` : Add an per-thread identifier to each output line from threads, the thread id is appended to this prefix (default: G4WTn)

`/control/cout/ignoreThreadsExcept [id]` : Show output only from thread "id"

`/run/pinAffinity [n]`: Set thread affinity (lock threads to core), may increase performances in some cases

`/run/eventModulo [n] [s]`: Set how many events to send to threads in one request and how often re-seed thread RNG engine, defaults work vast majority cases, in special cases (e.g. extremely small and fast events) tweaking this parameters can increase performances (warning: playing with seeding algorithm can break strong reproducibility)

Setting the number of threads

- Default the number of threads: 2
  - Use `/run/numberOfThreads` or `G4MTRunManager::SetNumberOfThreads()`
- `G4Threading::G4GetNumberOfCores()` returns the number of logical cores of your machine
- Currently number of threads **cannot be changed** after `/run/initialize` (C++ call to: `G4RunManager::Initialize()`)
- You can overwrite your application behavior and UI commands setting the (shell) environment variables `G4FORCENUMBEROFTHREADS=...` before starting the application (the special keyword `max` can be used to use all system cores)

User Defined UI commands

- User interacts with application typing UI commands
  - Master thread "accumulates" the commands and passes the commands stack to all the threads at the beginning of a run
  - Threads execute the same commands sequence as master thread
- However some commands **make sense only in master thread** (e.g. the one modifying the geometry)
- UI commands can be marked as "not to be broadcasted":

```
-G4UIcommand::SetToBeBroadcasted(false);
```

- Do not forget this step if you implement user-defined UI commands

Conclusions

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Parallelism is a tricky business:

- User code has to be thread-safe
- Race conditions may appear (better: they will very probably appear)
- Bugs may often seem "random" and difficult to reproduce
- Experience is needed for complex applications, but we believe for simple ones following these instructions is enough
- A new hyper news user forum has been created (Multithreading) to address all possible questions
- Ask an expert!