Version 11.1

Multithreading .. and tasking

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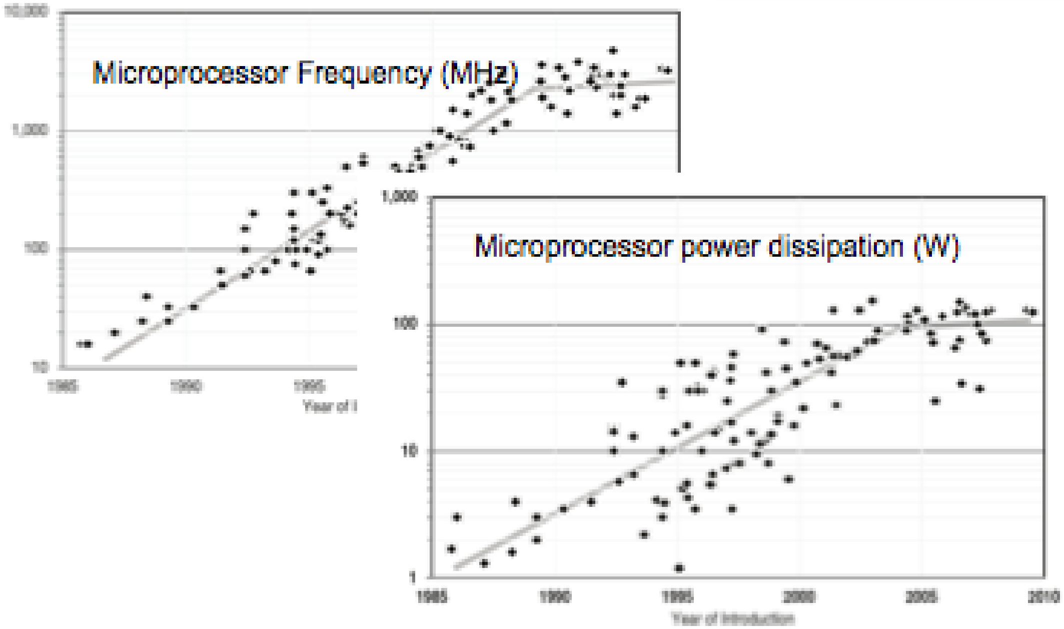
Slides from **Makoto Asai** (Jefferson Lab) – with small changes

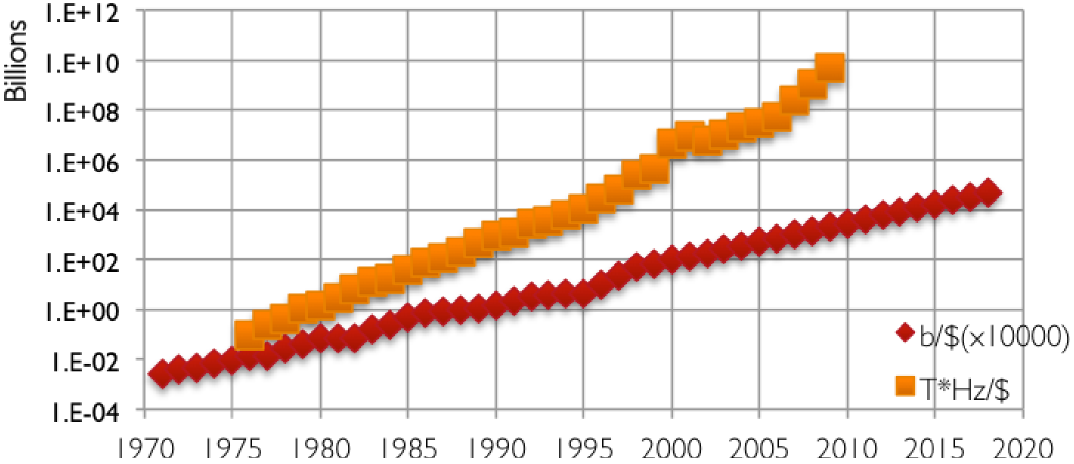
Outline:

- Introduction
- Multithreading in Geant4 : the basics
- UI commands for multithreading

INTRODUCTION

The challenges of many-core era





- Higher frequency of CPU **increase power consumption**
- Reached plateau around 2005
- No more increase in CPU frequency
- However number of transistors per chip continues to grow
- Multi/Many-core era
- Note: quantity memory you can buy with same $ scales slower
- **Expect:**
  - Many core (double/2yrs?)
  - Single core performance increases slowly
  - 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

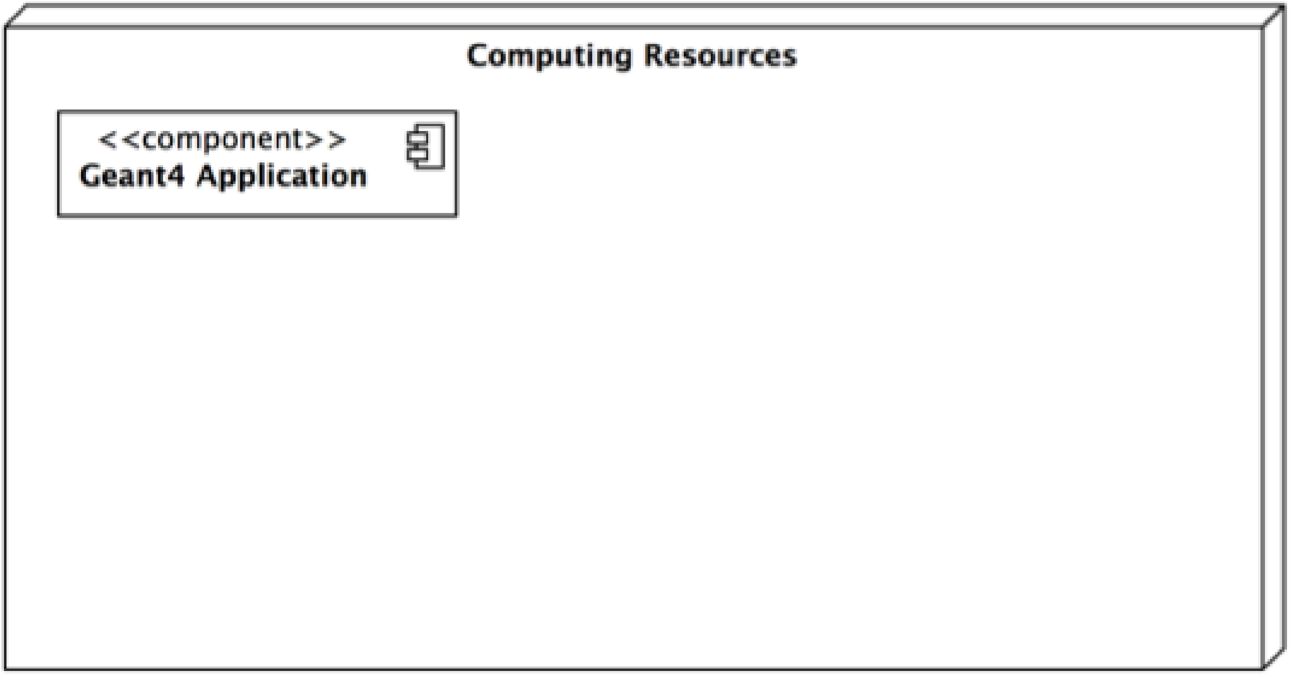
- Modern CPU architectures: need to introduce **parallelism**
- Memory and its access will limit number of concurrent processes running on single chip
- Solution: add parallelism **in the application code**

- 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 was the natural choice

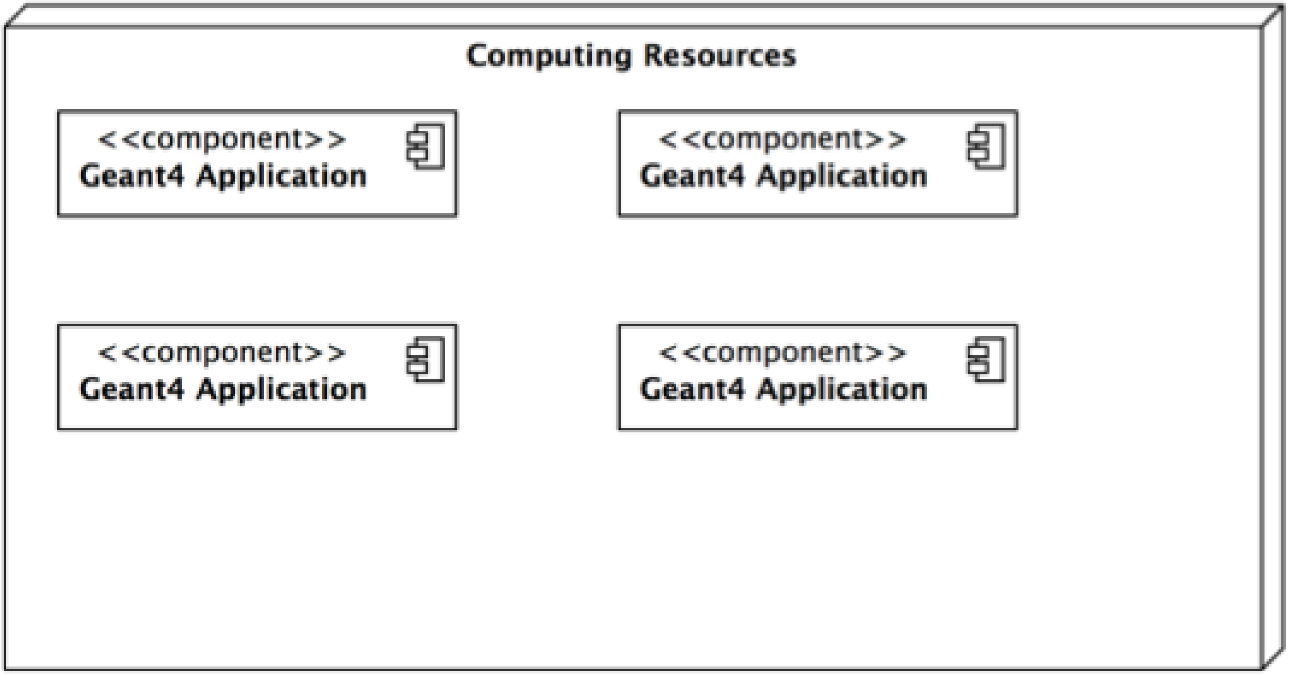
What is a thread?

Sequential application



What is a thread?

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



Computing Resources

<<component>>
Geant4 Application

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Geant4 Application

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Geant4 Application

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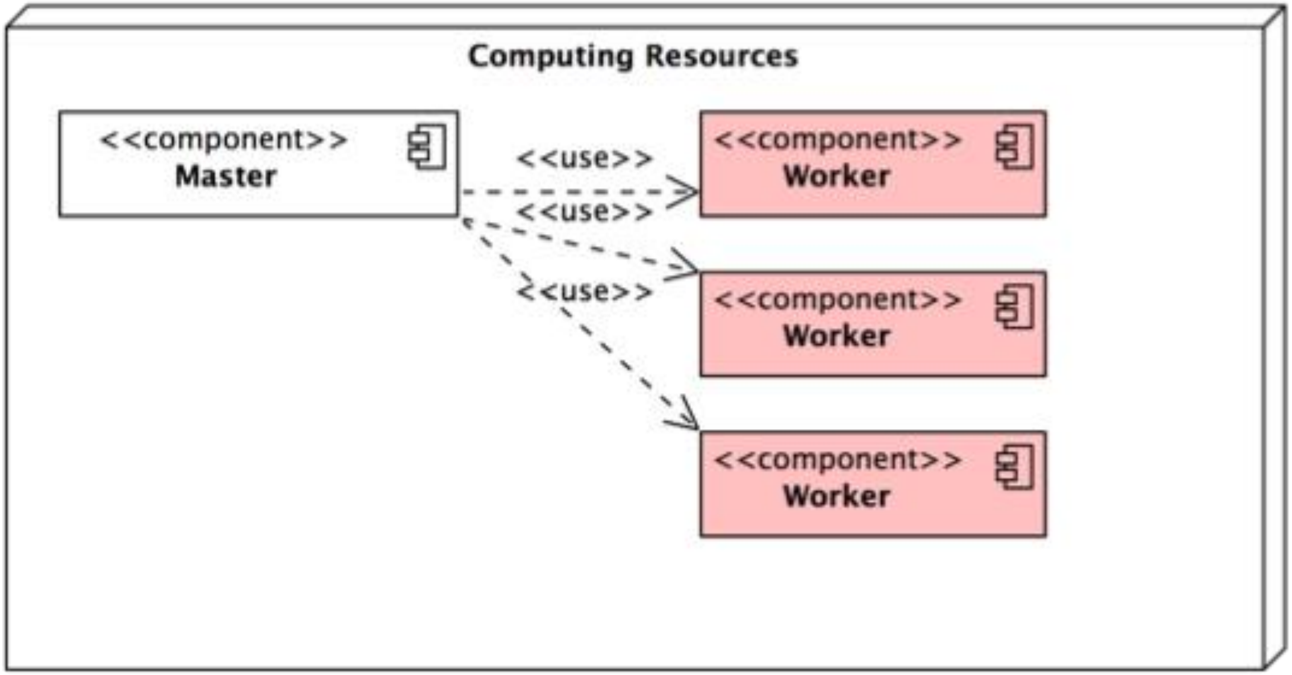
Geant4 Application

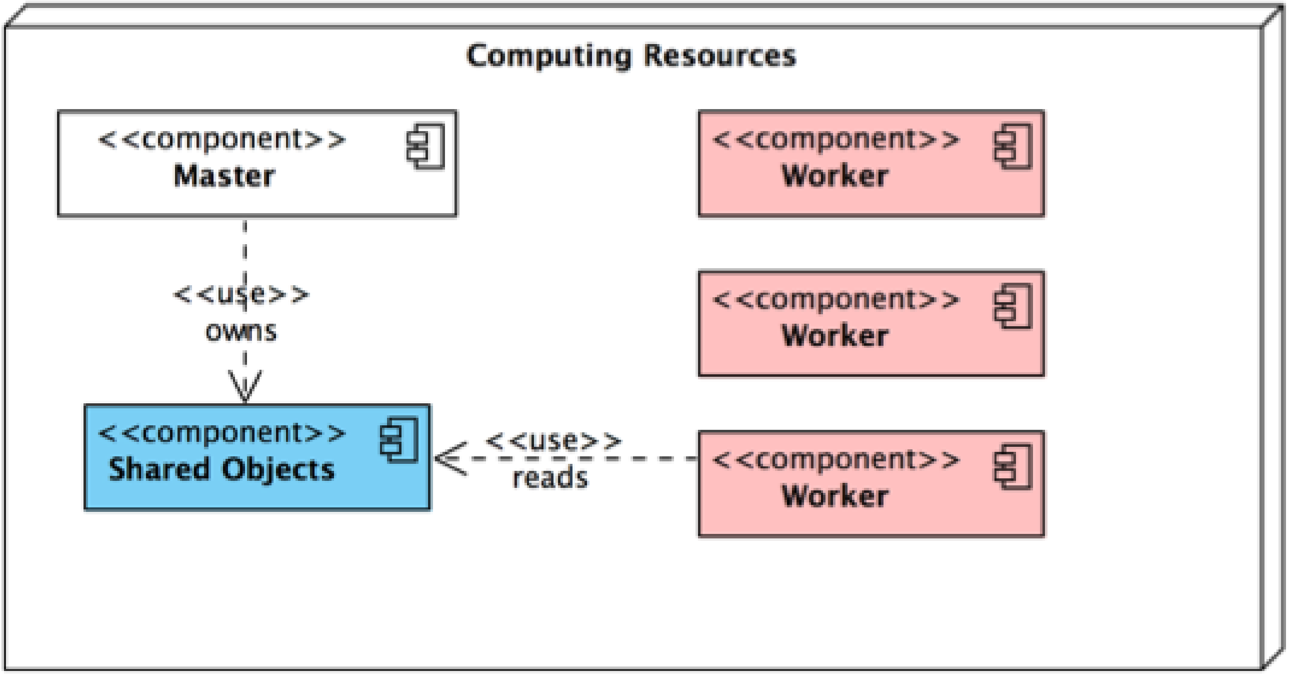
What is a thread?

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?

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

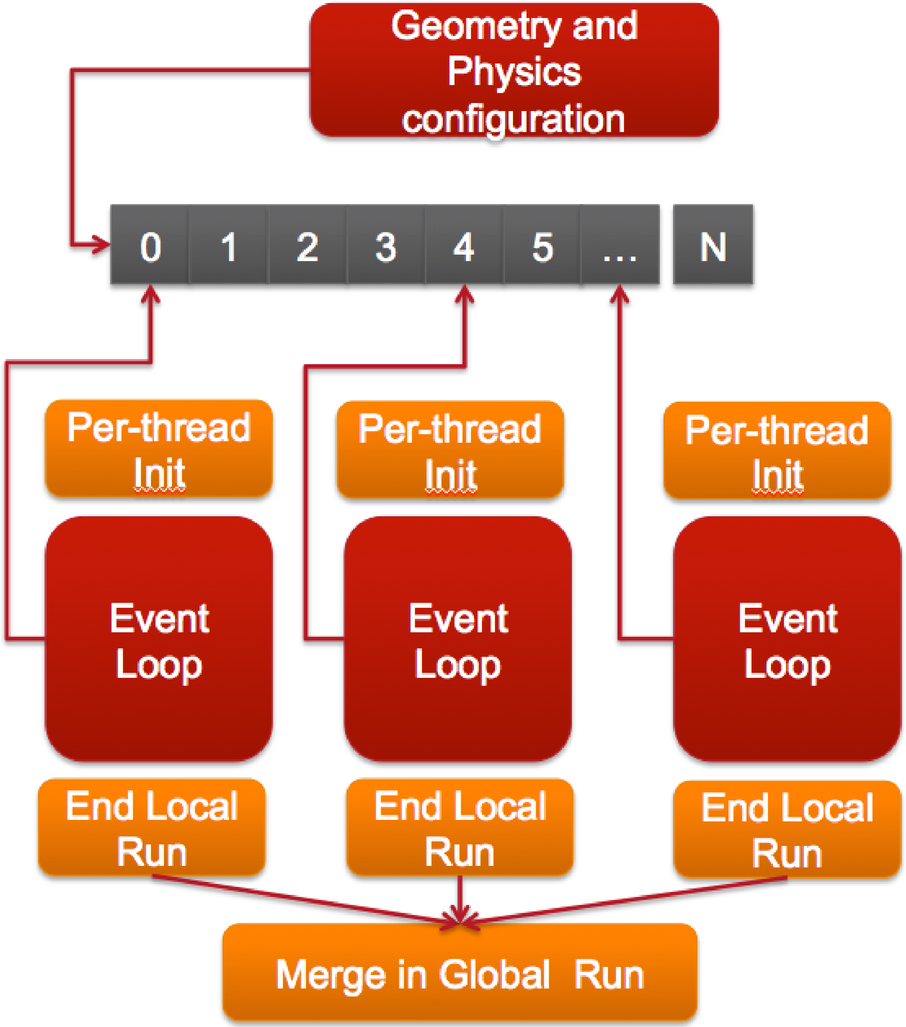


THE BASICS OF MULTI-THREADING IN GEANT4

How to think about a thread

- In a sequential program (or build of Geant4) the single CPU is executing one function / method at any time
- During initialisation, whether or not MT is enabled, Geant4 currently does the same things
  - Creates a detector
  - Initialises physics models
- Then when a run starts
  - In sequential mode one event is processed at a time
  - When Geant4 MT is enabled, we need each CPU (or CPU thread) to work on a different event
  - So in MT we copy all objects which that CPU (or thread) will access/change, and give it a fresh ‘blackboard’ and an event to simulate
- So long as all the changes created by a thread are made to objects which it owns, the event will have been simulated as though we had run it sequentially
- At the end of the event, its results must be pushed out (written or merged) using either MT capabilities of Geant4 or sometimes user code.

General Design



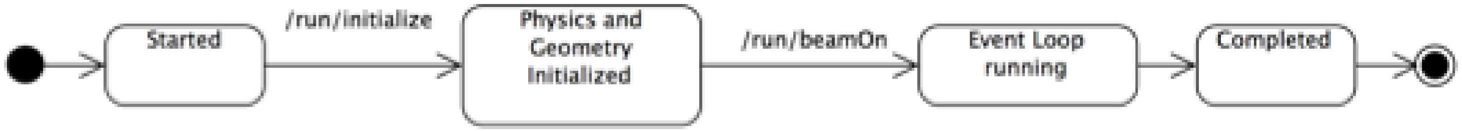
Per-event seeds pre-prepared in a "queue"

Threads compete for next event to be processes

Command line scoring and G4tools automatically merge results from threads

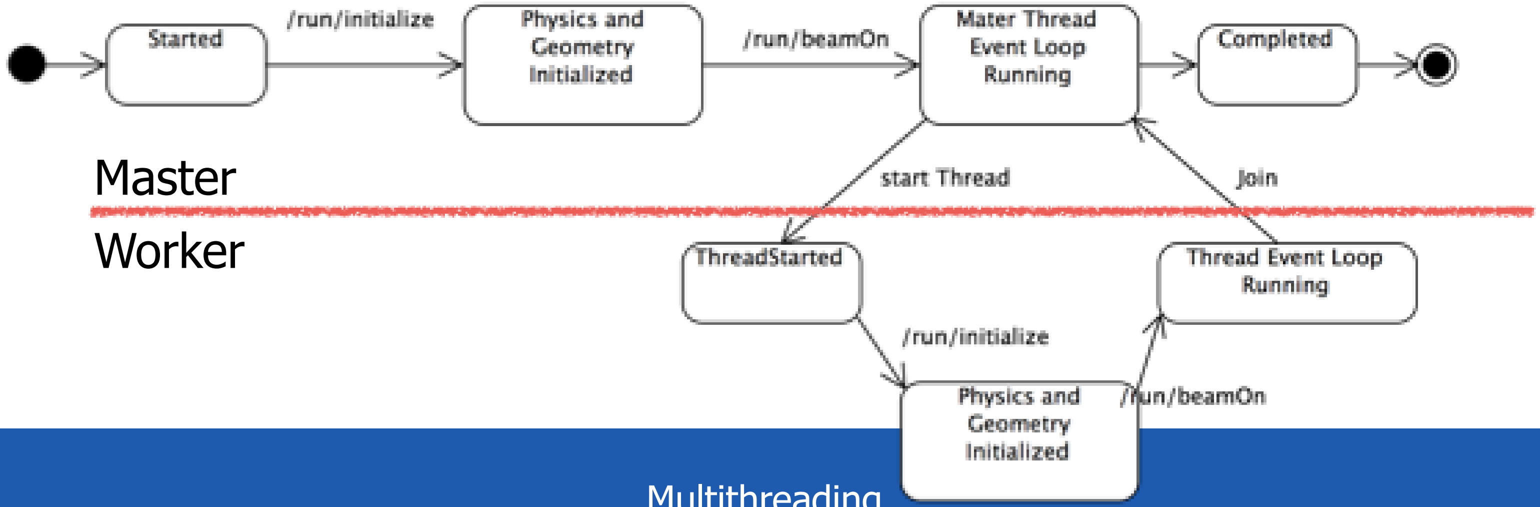
Simplified Master / Worker Model

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



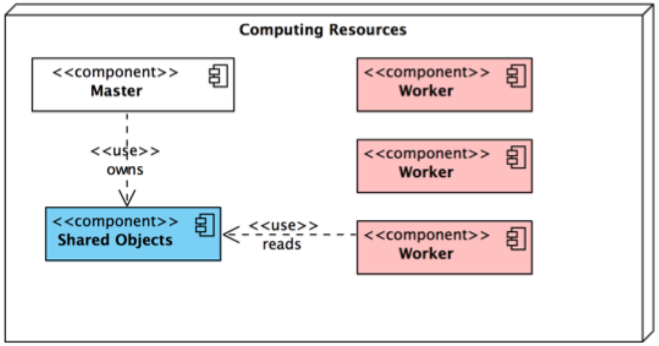
Simplified Master / Worker Model

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


Started
/run/initialize
Physics and Geometry Initialized
/run/beamOn
Mater Thread Event Loop Running
Completed
Master
start Thread
Join
Worker
ThreadStarted
Thread Event Loop Running
/run/initialize
Physics and Geometry Initialized
/run/beamOn

Shared Vs Thread-local

- To reduce memory footprint the threads must share some of the objects/data (as much as safely possible)
- **General rule in G4: threads 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

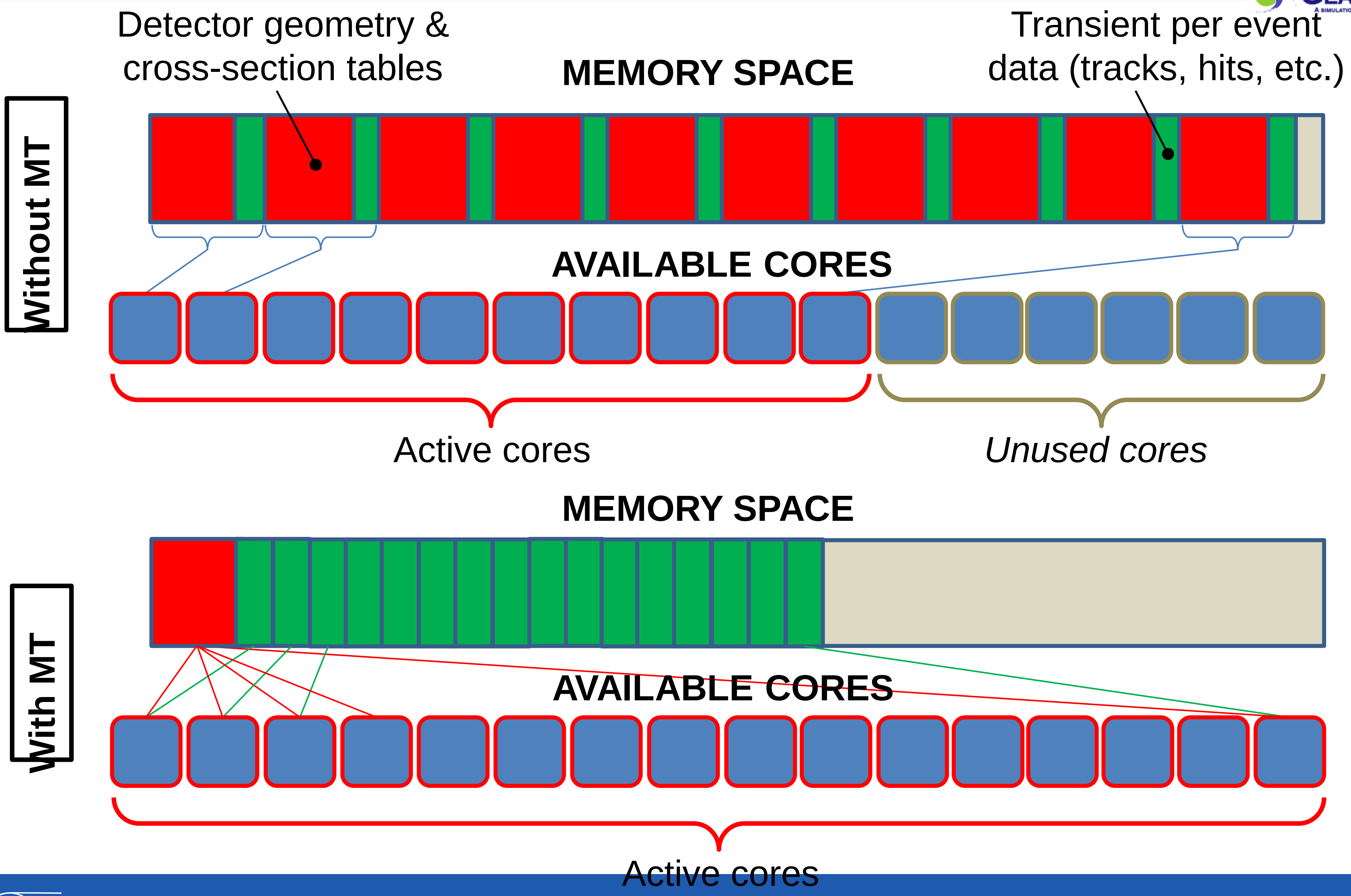


How we chose: Shared or Private?

- In multi-threaded mode the data/objects during the event loop
  - that are invariant (unchanged) are shared among threads
  - that are transient (changed) 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

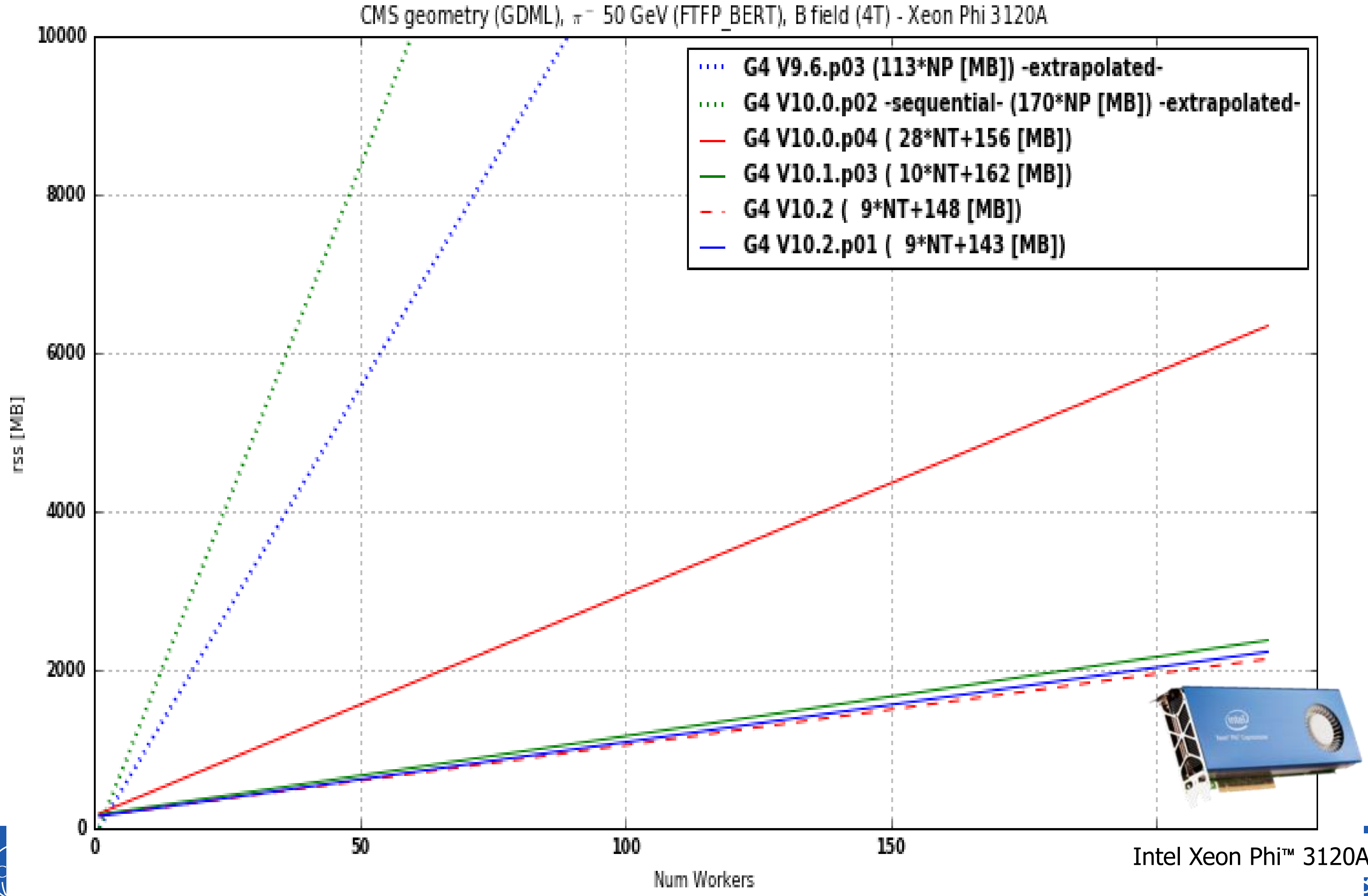
With MT

MEMORY SPACE

AVAILABLE CORES

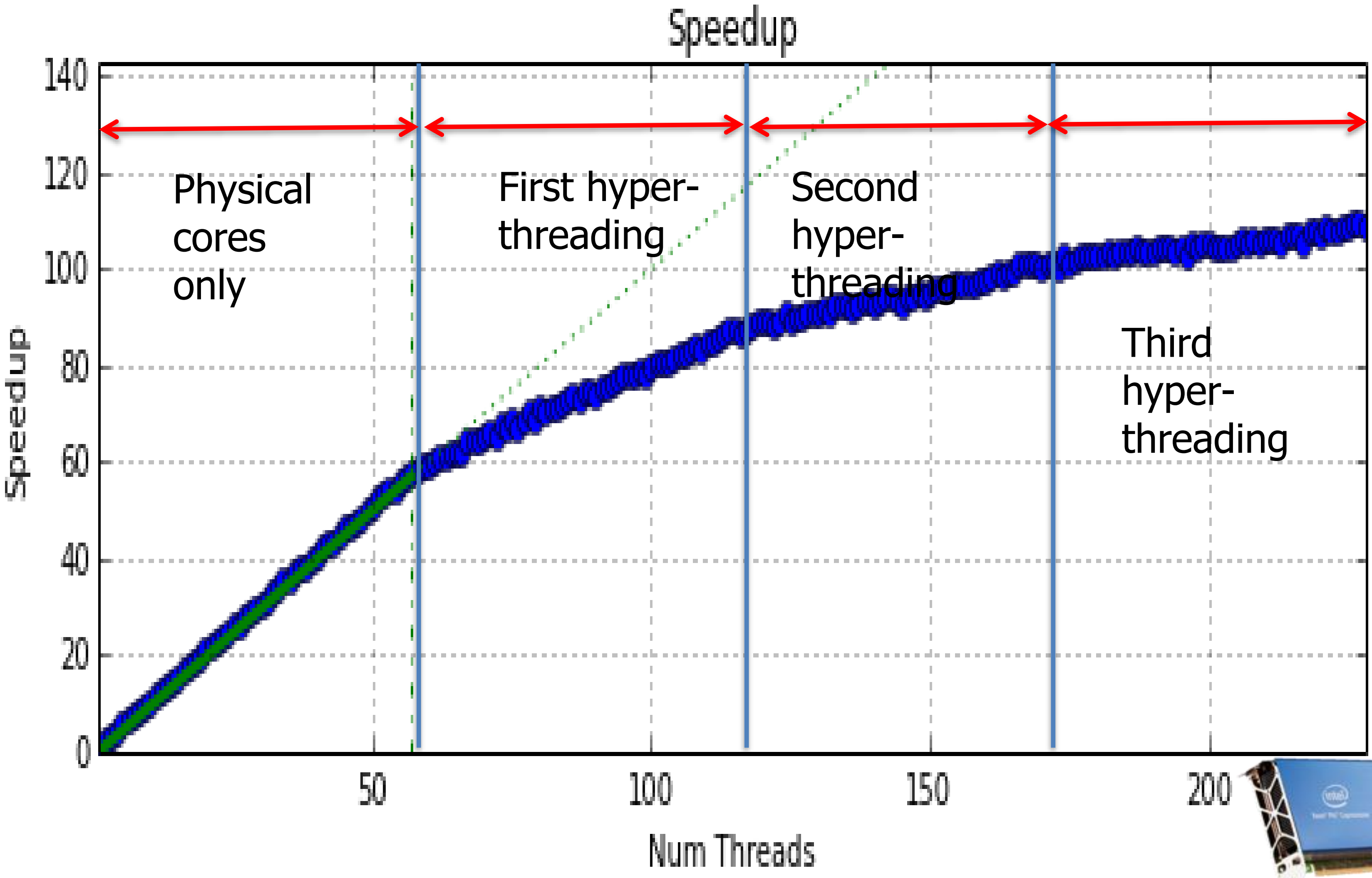
Active cores

Memory consumption on Intel Xeon Phi



Intel Xeon Phi™ 3120A

Scalability on Intel Xeon Phi



Intel Xeon Phi™ 3120A

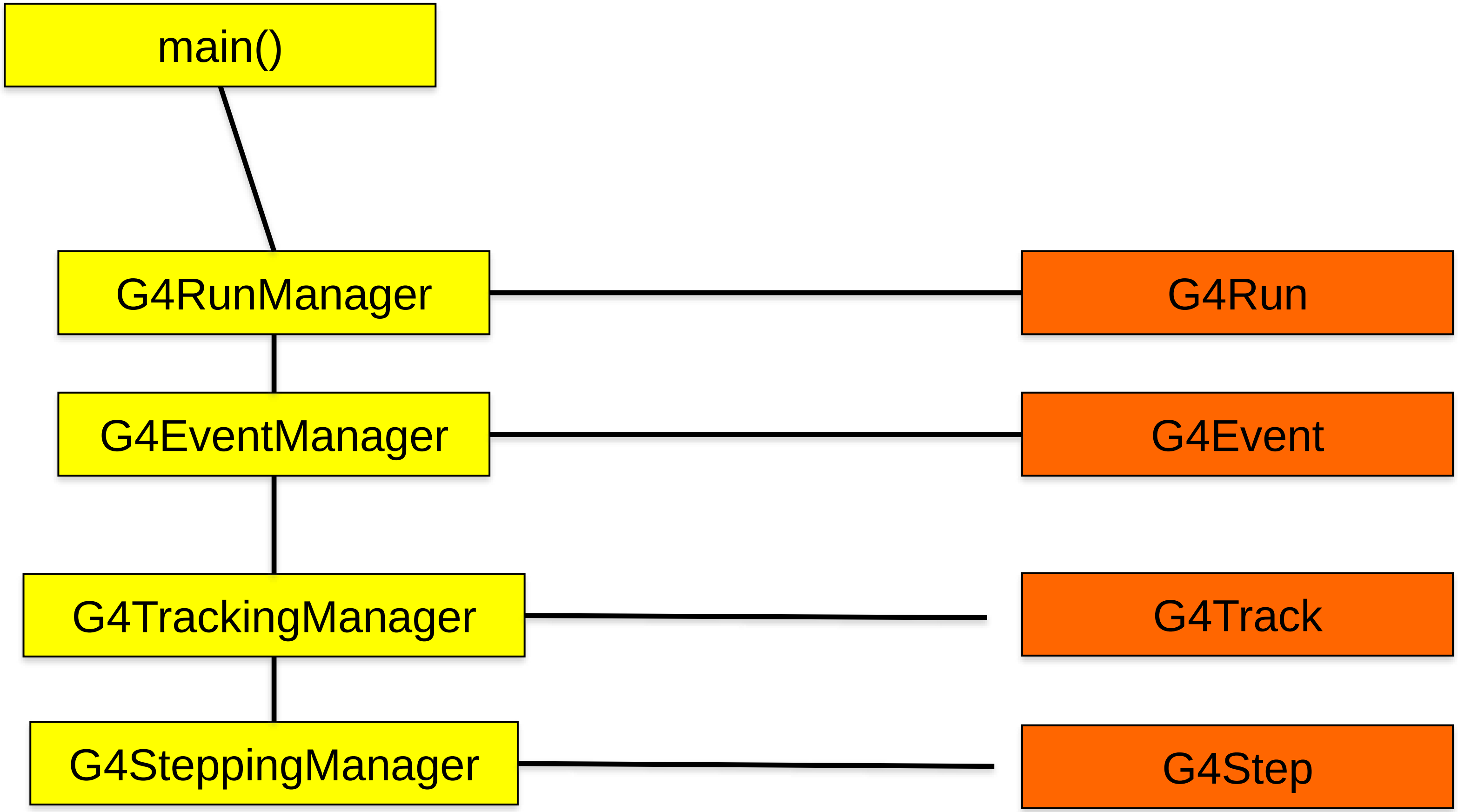
Shared ? Thread-local?

- In general, geometry and physics tables are shared
  - event, track, step, trajectory, hits, etc.,
  - Most Geant4 manager classes are thread-local, e.g. EventManager, TrackingManager, SteppingManager, TransportationManager, FieldManager, Navigator, SensitiveDetectorManager, ..
- Among the user classes, the initialization classes are **shared**:
  - G4VUserDetectorConstruction,
  - G4VUserPhysicsList,
  - G4VUserActionInitialization, ‘new’ and created for G4-MT
- All **user action** classes and sensitive detector classes are **thread-local**
  - Each is created when a thread calls UserActionInitialization::Build()
  - So the code of this method is called independently by each thread ”in parallel”

Shared ? Thread-local?

- It is not straightforward (and thus not recommended) to access a thread-local object from a shared class object,
  - e.g a stepping action from detector construction.
- Thread-local objects are instantiated and initialized in the first call to the run *BeamOn() method*.
- To avoid potential errors, please keep in mind which classes are shared (and thus need greater care) and which are thread-local.

Sequential mode


main()

G4RunManager

G4EventManager

G4TrackingManager

G4SteppingManager

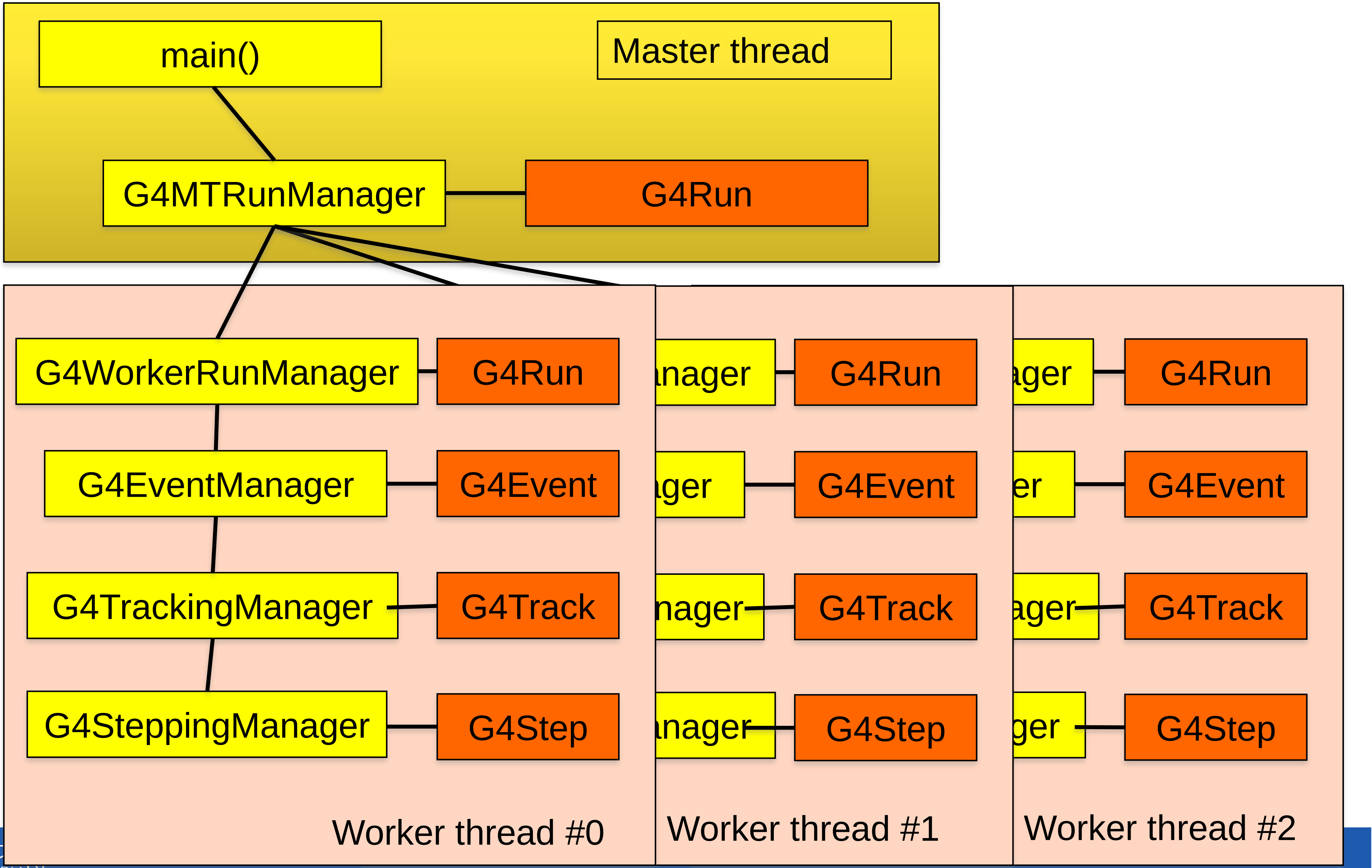
G4Run

G4Event

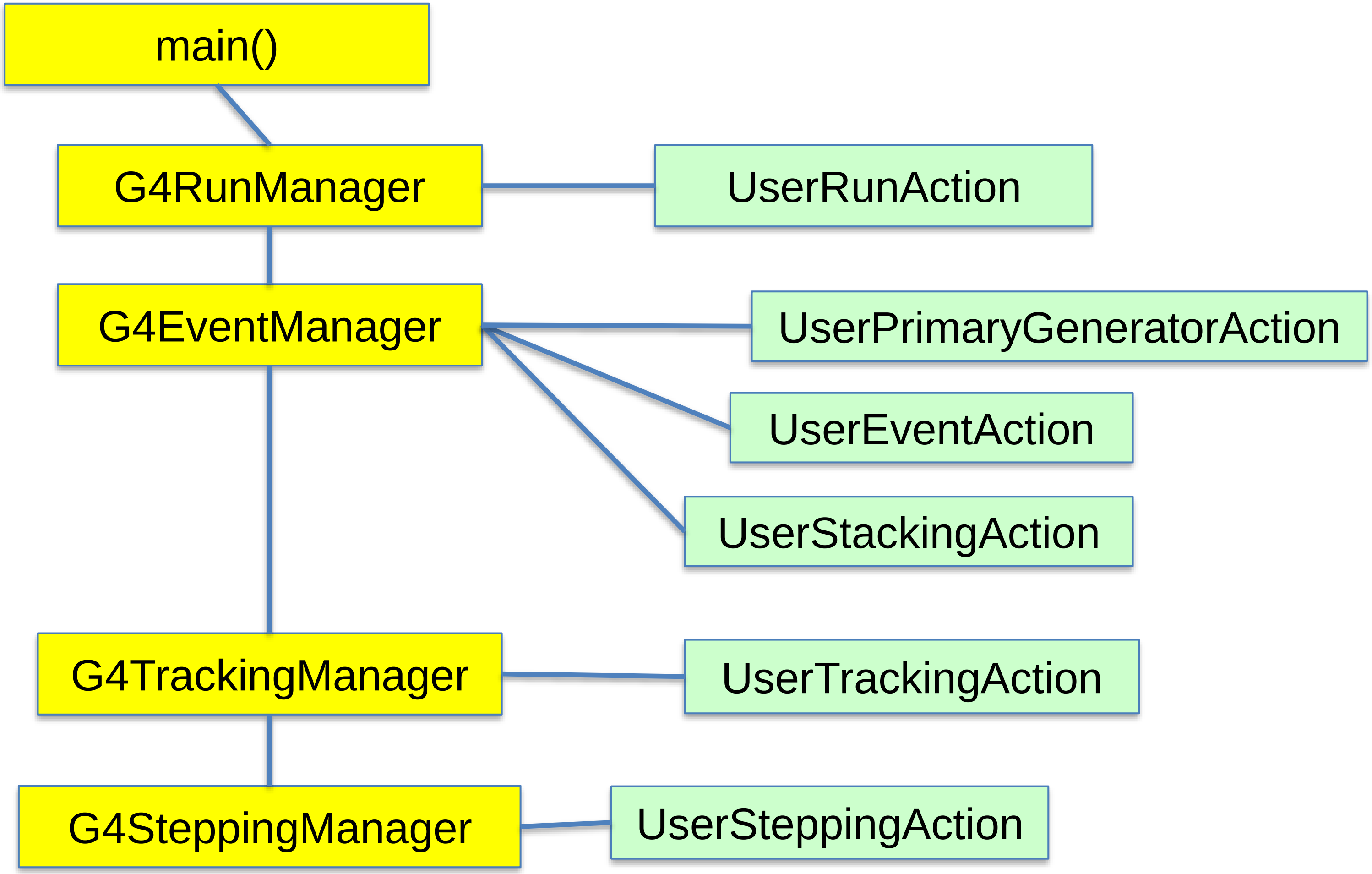
G4Track

G4Step

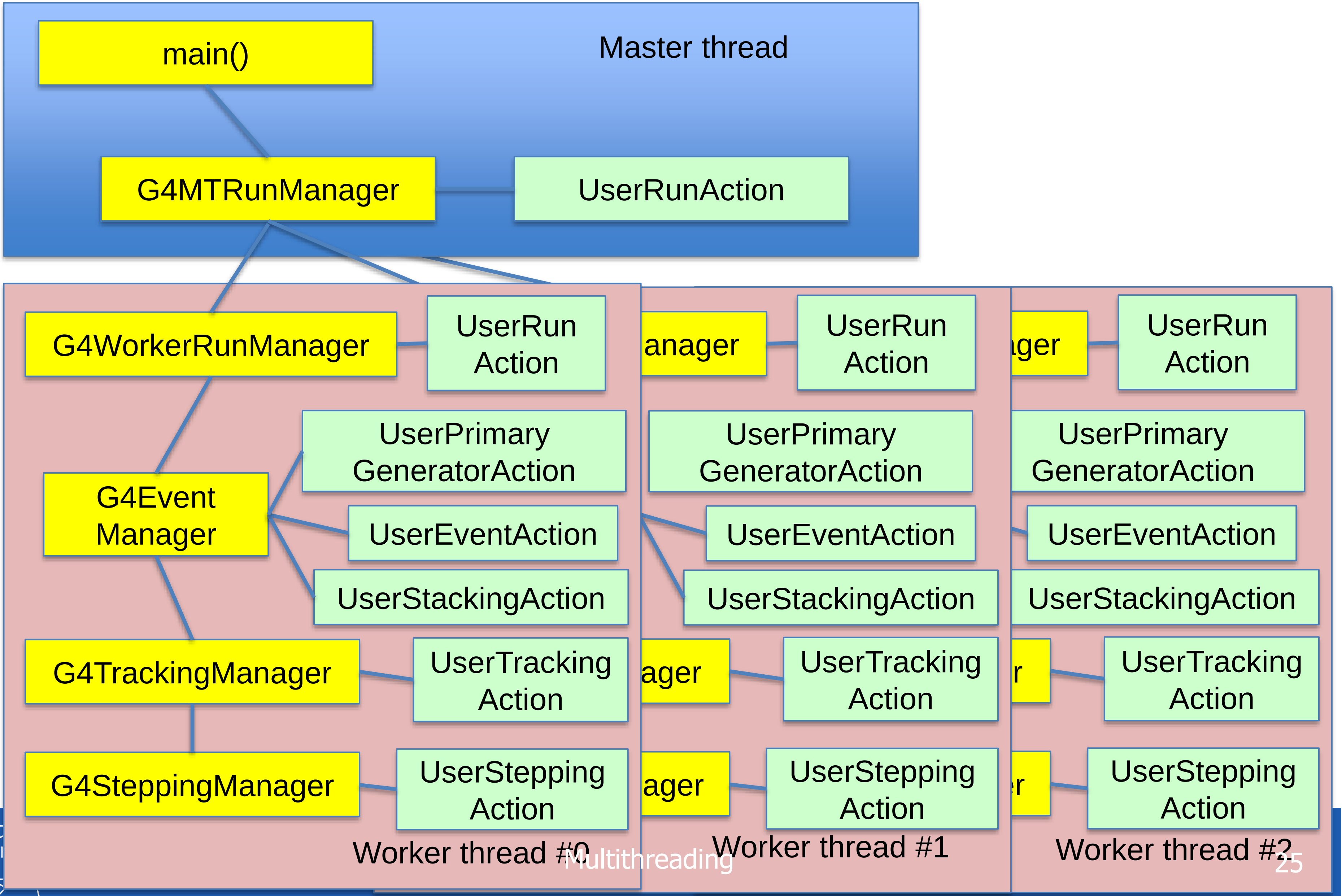
Multi-threaded mode



Sequential mode



Multi-threaded mode



UI COMMANDS FOR MULTITHREADING

Number of worker threads

- You can specify the number of worker threads.
  - They do not include master thread or visualization thread.
- Shell environment variable *G4FORCENUMBEROFTHREADS*. This will overwrite the following alternative settings. *G4FORCENUMBEROFTHREADS* can be an integer or a keyword "max". If "max" is specified, Geant4 uses all threads of the machine including all hyper threads.
- UI command */run/numberOfThreads, /run/useMaximumLogicalCores*
  - This UI command has to be issued at *PreInit>* state.
- *G4RunManager::SetNumberOfThreads(G4int)*
  - This method must be invoked prior to *G4RunManager::Initialize()*.
- UI command */run/pinAffinity*
  - Locks worker threads to specific logical cores.

/run/eventModulo <N> <seedOnce>

- Set the event modulo for dispatching events to worker threads
  - Each worker thread is tasked to simulate <N> events and then comes back to G4MTRunManager for next set.
- If it is set to zero (default value), N is roughly given by this.
  - N = int(sqrt(number_of_events / number_of_threads))
- The value N may affect on the computing performance in particular, if N is too small compared to the total number of events.
- The second parameter <seedOnce> specifies how frequent each worker thread is seeded by the random number sequence centrally managed by the master G4MTRunManager.
  - If <seedOnce> is set to 0 (default), seeds that are centrally managed by G4MTRunManager are set for every event of every worker thread. This option guarantees event reproducibility regardless of number of threads.
  - If <seedOnce> is set to 1, seeds are set only once for the first event of each run of each worker thread. Event reproducibility is guaranteed only if the same number of worker threads are used. On the other hand, this option offers better computing performance in particular for applications with relatively small primary particle energy and large number of events.

UI commands for cout/cerr

- /control/cout/useBuffer <*flag*>
  - Store G4cout and/or G4cerr stream to a buffer so that output of each thread is grouped.
  - The buffered text will be printed out on a screen for each thread at a time at the end of the job or at the time the user changes the destination to a file.
- /control/cout/ignoreThreadsExcept <*threadID*>
  - Omit output from threads except the one from the specified thread.
  - If *threadID* is greater than the actual number of threads, no output is shown from worker threads.
  - To reset, use -1 as *threadID*.
- /control/cout/prefixString <*prefix*>
  - In case G4cout and/or G4cerr are not buffered, output of all threads are displayed on the screen simultaneously.
  - With this command, the user may specify a prefix for each output line which is supplemented by the thread ID. By default it is “G4MT”
- /control/cout/setCoutFile <*fileName*> <*ifAppend*>
  /control/cout/setCerrFile <*fileName*> <*ifAppend*>
  - Send *G4cout/G4cerr* stream to a file dedicated to each thread. The file name has "G4W_n_" prefix where *n* represents the thread ID.
  - File name may be changes for each run. If *ifAppend* parameter is false, the file is overwritten when exactly the same file has already existed.
  - To change the *G4cout/G4cerr* destination back to the screen, specify the special keyword "**Screen**" as the file name.

LATEST DEVELOPMENTS

Tasking and developments in releases 10.7 and 11.0

- Tasking was introduced in Geant4 10.7 to adapt to frameworks of LHC experiments which are task oriented. It comes in two variants:
  - a native C++ implementation of the ‘task model’, and
  - (Intel) Thread Building Block based ‘TBB task mode’.
- The tasking system, based on PTL (Parallel Tasking Library) v2.0.0, is the default parallelism scheme for multi-threading starting in Geant4 11.0. To obtained either
  - use the dedicated run manager (G4TaskRunManager), or
  - Get it via the factory G4RunManagerFactory

  Both enabled use of tasks for the event loop.
- The default behaviour for tasking is to submit the tasks to an internal thread-pool and task-queue.

- Note: The tasking system with Intel TBB can be selected by specifying the option GEANT4_USE_TBB=ON is specified when configuring CMake.

Moving from threads to tasks – since release 10.7

- There are now several types of RunManagers provided in the Geant4 release:
  - Sequential (G4RunManager)
  - ‘Old-style’ Multi-threading (G4MTRunManager)
  - G4TaskRunManager in ‘native’ mode
  - G4TaskRunManager in TBB mode
- A new class **G4RunManagerFactory** can be used to create any of these:

```
#include “G4RunManagerFactory.hh”
// [Option #1]
// Select from enum class G4RunManagerType: Default, Serial, MT,
Tasking, TBB
auto* runMgr =
G4RunManagerFactory::CreateRunManager(G4RunManagerType::Default);
// [Option #2] choose by string:  “default”, “serial”, “mt”,
“task”, “tbb”
auto* runMgr = G4RunManagerFactory::CreateRunManager( "default");
```

- This was provided for the first time in release 10.7 (December 2020).