# Real-Time Linux and Open MPI -- An Introduction and Case Study

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- Introduction to Real-Time Linux
- Running an Open MPI benchmark on Real-Time Linux
  - (ok, not so much on this....)

# Real-Time and HPC have a lot in common....

- Somewhat poorly defined terms!
  - mean different things to different people
- Include a  broad range of solution space
- Known for being areas of challenging requirements
  - complex problems to solve
  - often tends not to be default path, require custom solutions
  - want low latency, reduced OS jitter
  - have critical applications that need a lot of processor time

So if not a marriage made in heaven....
we should at least be dating, right?

# Well, while not quite the Montagues and the Capulets...

- Opposite ends of the size spectrum, typically
  - HPC typically massive installations, larger systems
  - Real-Time at the smaller end typically, embedded
    - still in its infancy in terms of scaling...
- Complex programming models vs simpler, more general needs
- Real-Time is coming out of the embedded and/or custom solution space into general-purpose systems solving problems that would not have been called real-time even a decade ago

# So what is this Real-Time Linux?

- Enterprise Real-Time is “softer” real-time
  - The world is not going to explode should you miss a deadline or a latency guarantee
- Typically want “as fast as possible” but as/more importantly:
  - “deterministically”, “predictably”, “consistently”

# Normal Non-Real-Time Compute Model

- **Excellent throughput but with wide variability**
- **Average times may vary**
- **No prioritisation**
- **Favors raw throughput, latencies uncontrolled**
- **Acceptable non-real-time behavior:**
  - **100,000 transactions**
  - **99,999 at 5ms each and 1 at 2 *seconds***
  - **Unacceptable for real-time systems**
  - **(courtesy Paul McKenney)**

# What to expect from Real Time Linux?

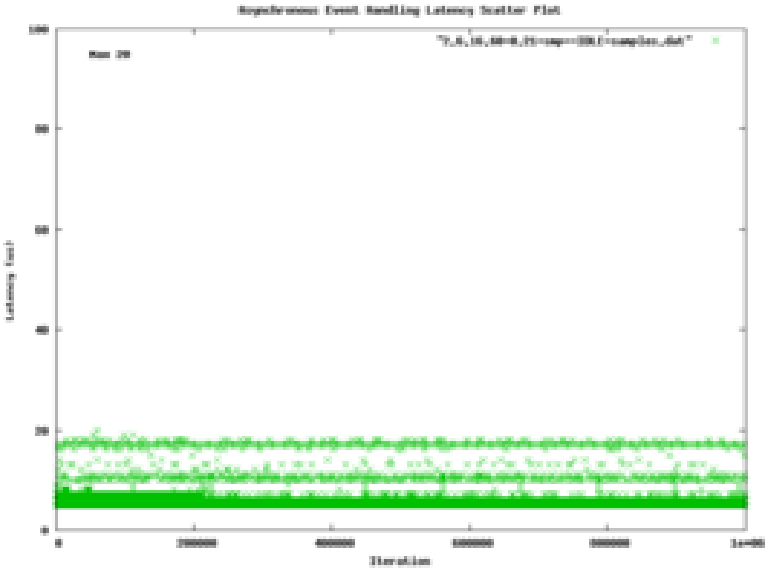
- Real Time Linux is not necessarily Real Fast Linux!!
- Determinism
  - sacrifice throughput to cap max latencies
- Highest priority real time tasks take precedence
  - they get system resources (*priority-driven environment*)
- The ability to shoot yourself in the foot!
  - “with great power comes great responsibility”

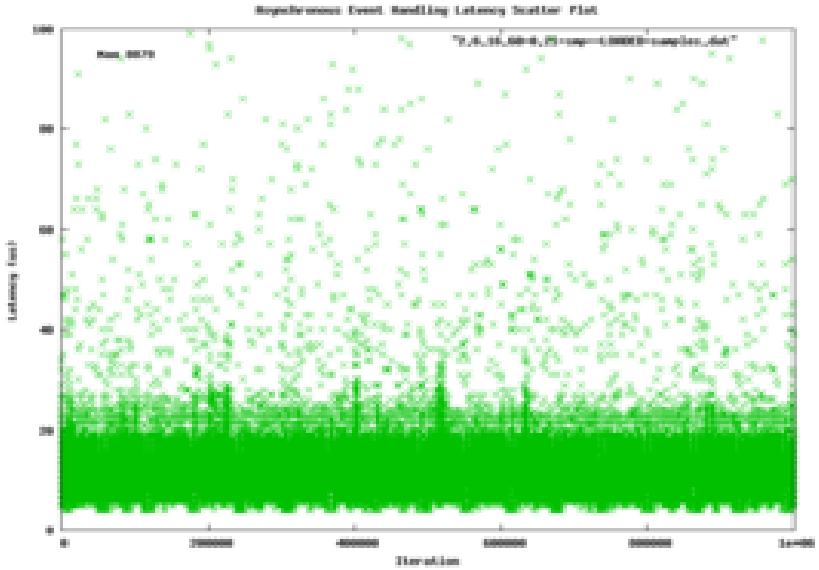
# Real-Time Kernel Goals - Determistic

- Deterministic
  - maximum latency bound
  - want to guarantee operations will take “at most 30 seconds”
  - no matter what happens (all paths)
  - Better to have 300 operations that take 20ms rather than 299 operations that take 15ms and 1 operation that takes 60ms.
  - ***Real-Time applications need bounded latencies***
  - Sacrifice throughput, performance for determinism
  - Trade-off benefits high priority tasks at the expense of low priority tasks

# Mainline idle/loaded - async-handler

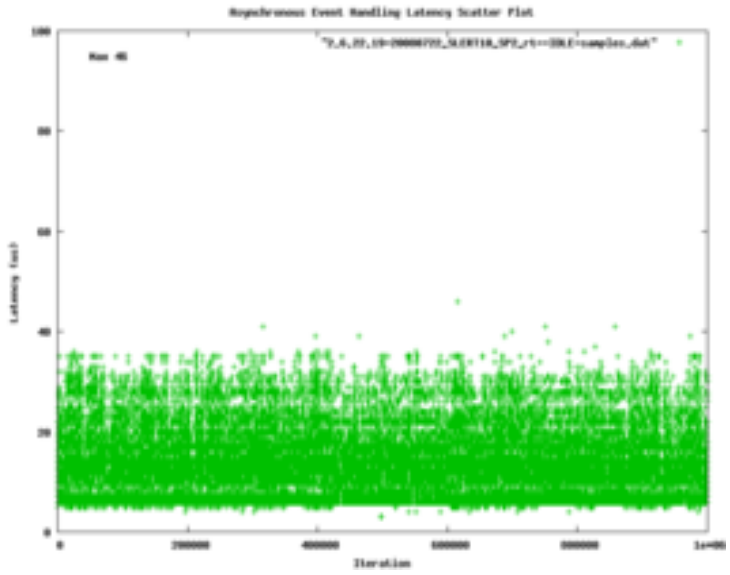
- Scatterplot

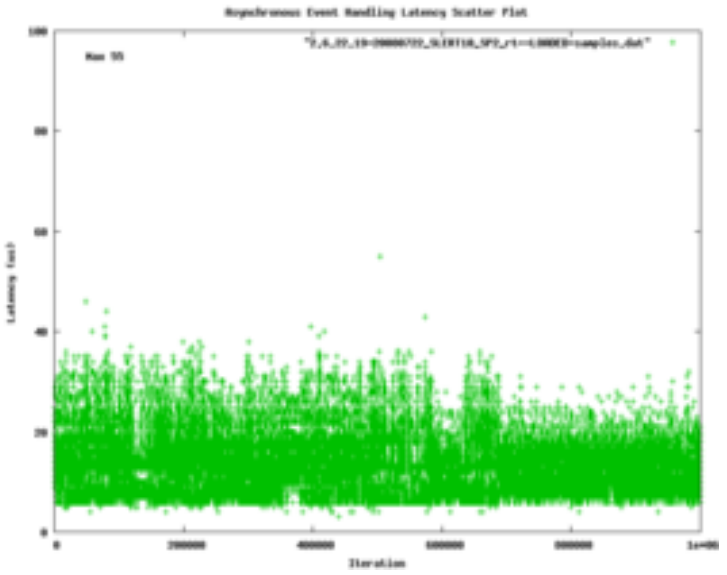




# RT idle/loaded - async-handler

- Scatterplot



# Real-Time Kernel Characteristics - Priority Driven

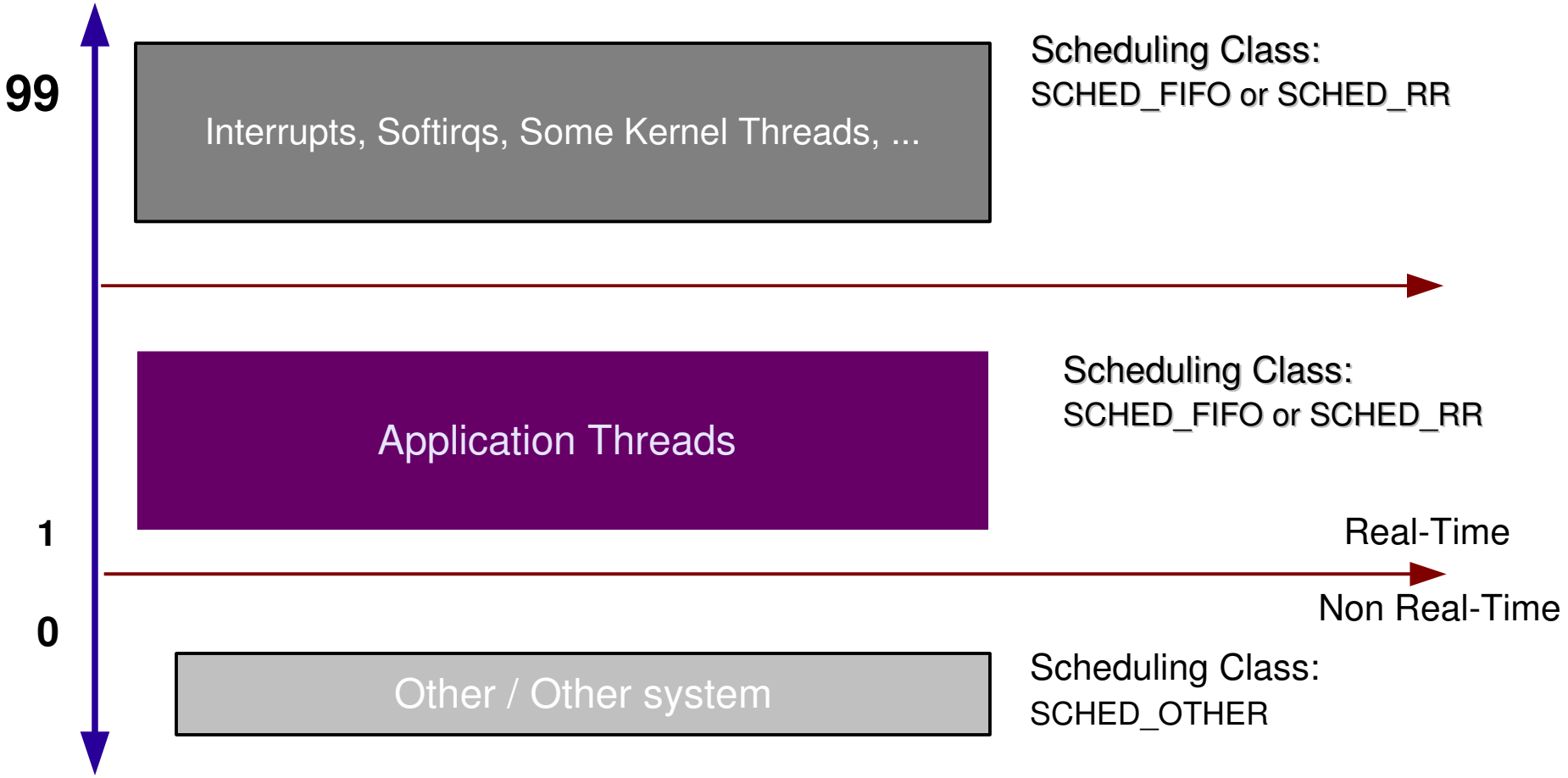
- Priority Driven
  - Traditional OSs are optimized for performance, overall throughput
  - BUT on RT we:
  - ***Always execute the N highest priority threads on an N-CPU box***
    - ***Latency guarantees can only be met if adequate resources!***
  - SCHED_FIFO not limited by timeslices (will not relinquish the CPU!)
  - if a higher priority thread becomes runnable, lower priority thread is migrated or suspended
    - this can cause some cache thrashing
    - inefficient overall (might yield almost immediately, ...)
    - potential deadlock, need care while programming, administering
  - Sacrifice system throughput for real-time priority ordered hierarchy
  - Trade-off benefits high priority tasks at the expense of low priority tasks

- Why do you need a Real-Time Linux kernel?
  - isn't mainline (POSIX 4) mostly there? (scheduler, timers, async I/O, ...)
- Mainline Linux
  - a real-time scheduler (CFS), high-resolution timers, tools - chrt, ftrace, perf, ...,
- Real-Time Linux (CONFIG_PREEMPT_RT)
  - more preemptive kernel (user space has greater control over kernel)
  - interrupt handling is different (irqs, softirqs are kernel threads)
  - locking is modified (rt mutexes replace spinlocks)
    - priority inheritance, preemptible
  - whole lot of other underlying infrastructure to support this
    - time, timer infrastructure; preemptive RCU, ....

# Real-Time Kernel Features - Scheduling

- CFS Scheduler - default scheduling algorithm
- **SCHEDULING POLICIES: SCHED_RR, SCHED_FIFO, SCHED_OTHER**
  - **SCHED_FIFO** not limited by timeslices
    - first highest priority task that's runnable gets CPU / keeps CPU
    - preempted only by higher priority task
    - real-time priority between 1-99
  - **SCHED_RR** has priority but is timesliced amongst same priority level
    - round robin : once timeslice completes, goes to back of runqueue
  - **SCHED_OTHER** does not have a real-time priority (time-sliced, priority 0)
- **SCHEDULING PRIORITIES:** SCHED_FIFO, SCHED_RR: 1 - 99

# Real Time Tuning of Applications



# Real-Time Kernel Features - Threaded Interrupts

- HW and SW Interrupts on RT are kernel threads
- Work deferred from HW interrupt to softirq (now a kernel thread)
  - except timer interrupt
- Their priorities fall somewhere between 30 - 99 (current default)
  - can be tricky if large number of high priority threads
  - manipulating these priorities is HIGH ART
  - need to ensure critical kernel activities not blocked
- Applications used to get interrupts which ran till they completed
  - caused a lot of variance in the time it took to run
  - now kernel activity competes for time with high priority real-time processes
  - allows high priority real-time tasks to run with fewer interrupts

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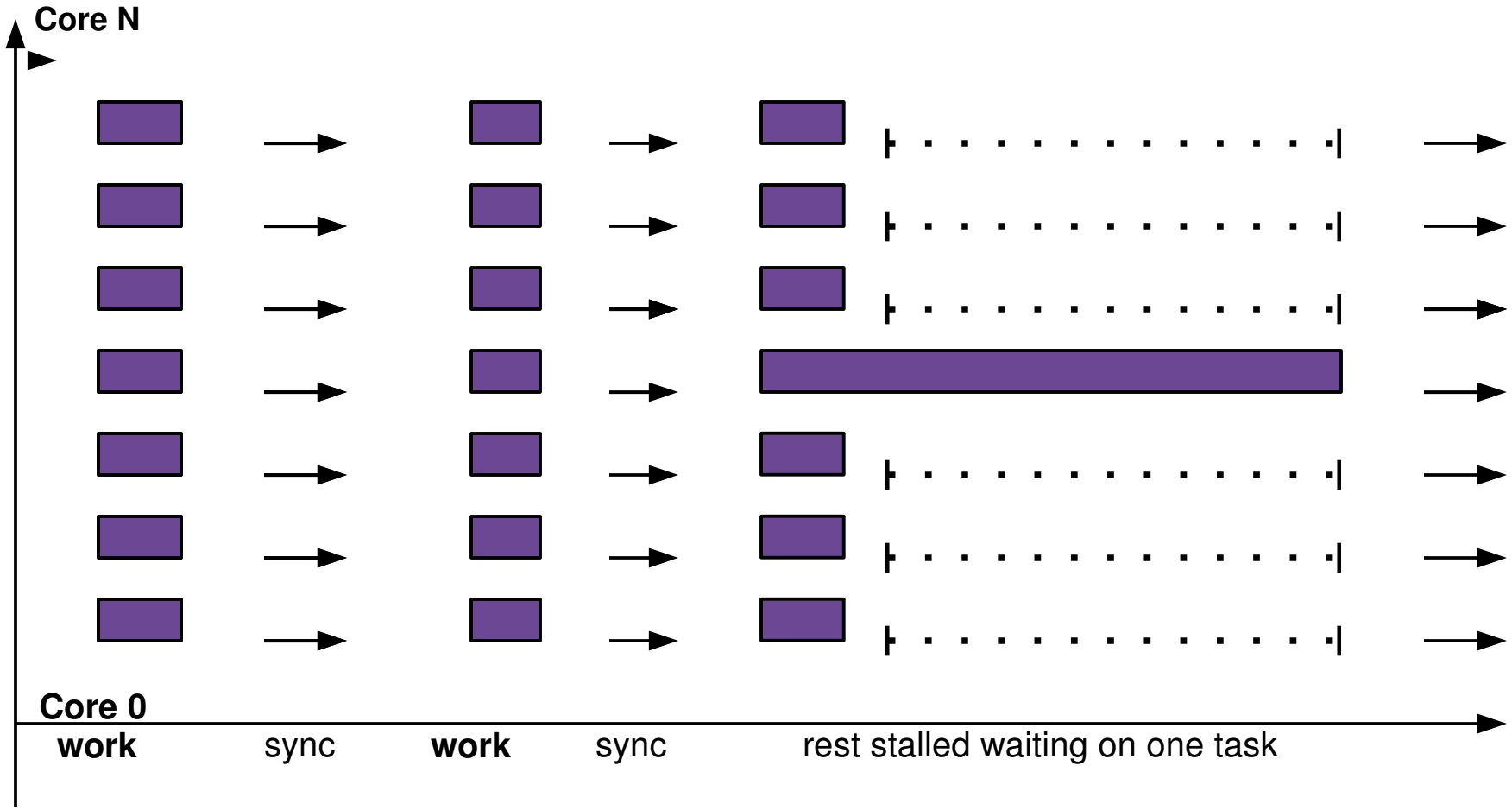
# Jitter is bad for lock-step applications (common in HPC)




**Improved determinism (max latencies capped) can improve throughput**

# Sources of Jitter

- Jitter - variation in execution times (also OS overhead)
  - lack of determinism
- Sources of jitter for application threads:
  - Scheduling - CPU contention
  - Lock contention
  - Interrupts - Hardware, Softirq (periodic, asynchronous)
  - Variance in memory allocation times, etc...
  - Device/Network/external  factors
  - system mgt events, throttling, ...

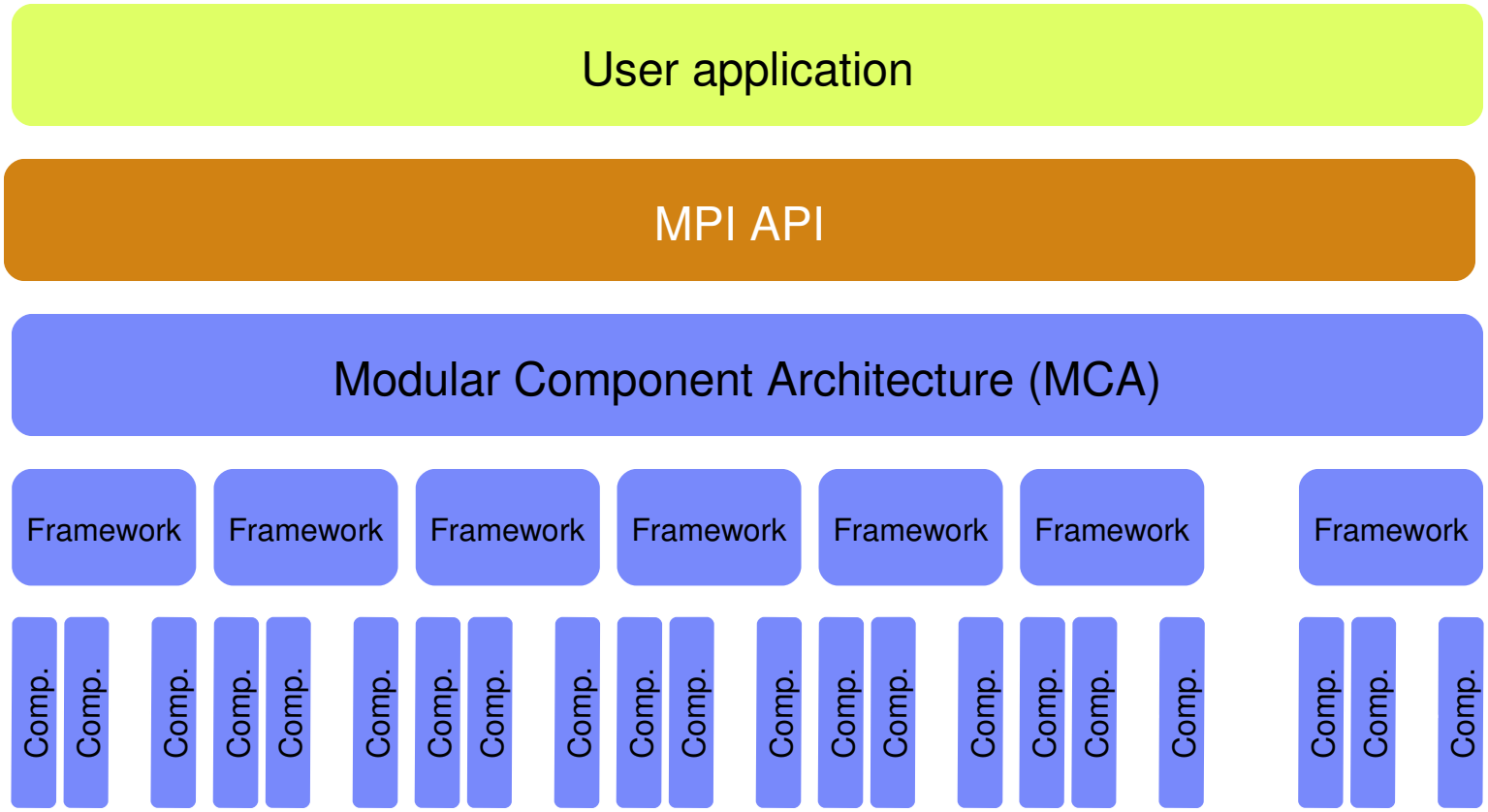
# What can users do?

- On mainline Linux (non-RT)
  - real-time priority scheduling
  - chrt to set scheduling class and priority (careful!)
  - taskset to pin interrupts, threads
- Run on RT  (tuning, priorities)
- Run on RT with application code changes
  - e.g. mlockall, etc to pin memory

# Typical....

# (don't do that)

# Plugin High-Level View



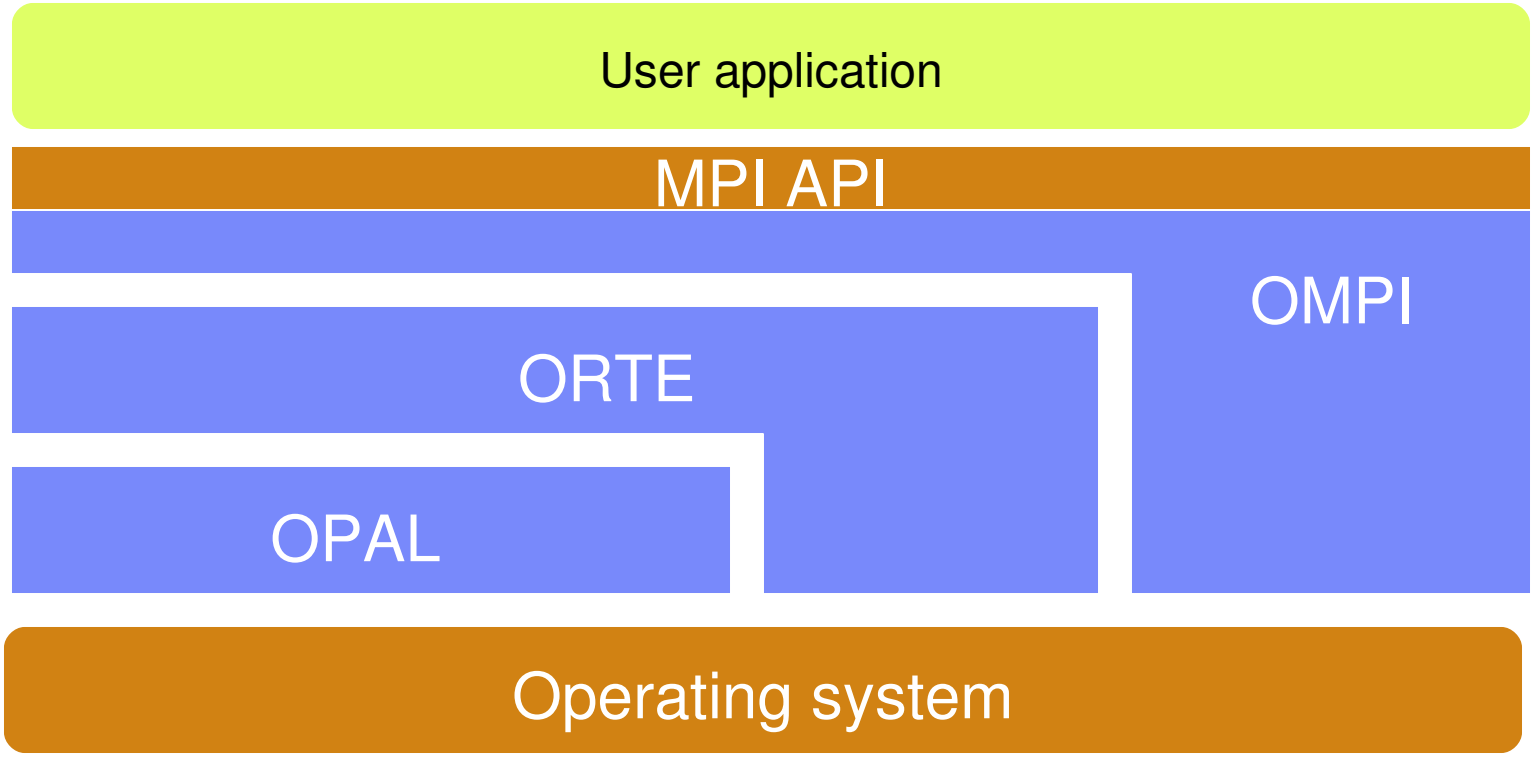

Courtesy: Jeff Squyres "What is MPI" 2008

# Three Main Code Sections

- Open MPI layer (OMPI)
  - Top-level MPI API and supporting logic
- Open Run-Time Environment (ORTE)
  - Interface to back-end run-time system
- Open Portability Access Layer (OPAL)
  - OS / utility code (lists, reference counting, etc.)
- Dependencies - not layers
  - OMPI → ORTE → OPAL

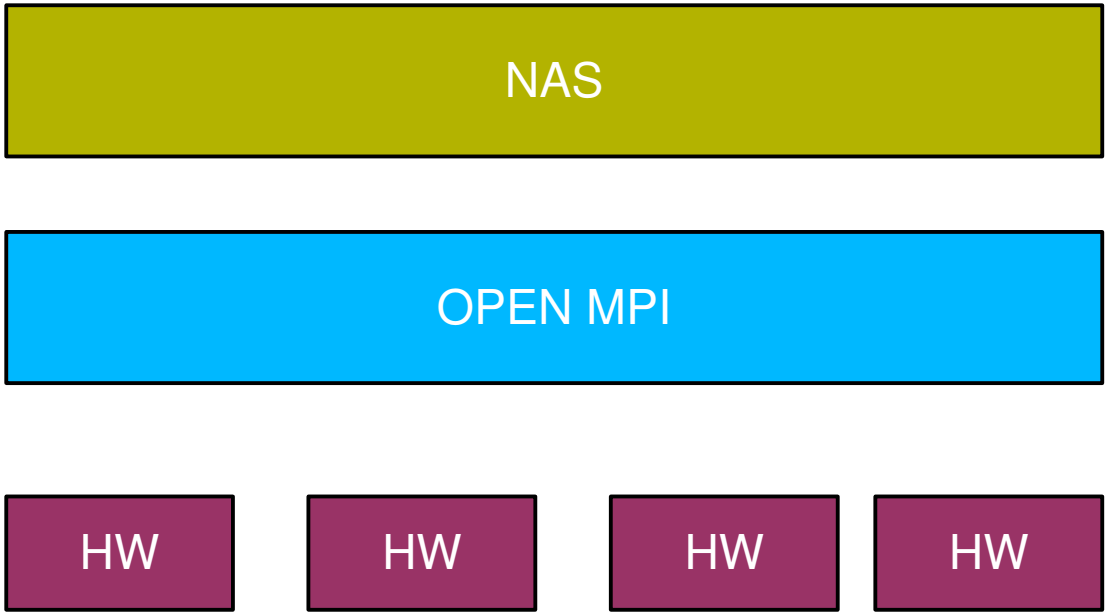
Courtesy Brad Benton

# Three Main Code Sections



## NASA's NAS Parallel Benchmark (NPB)

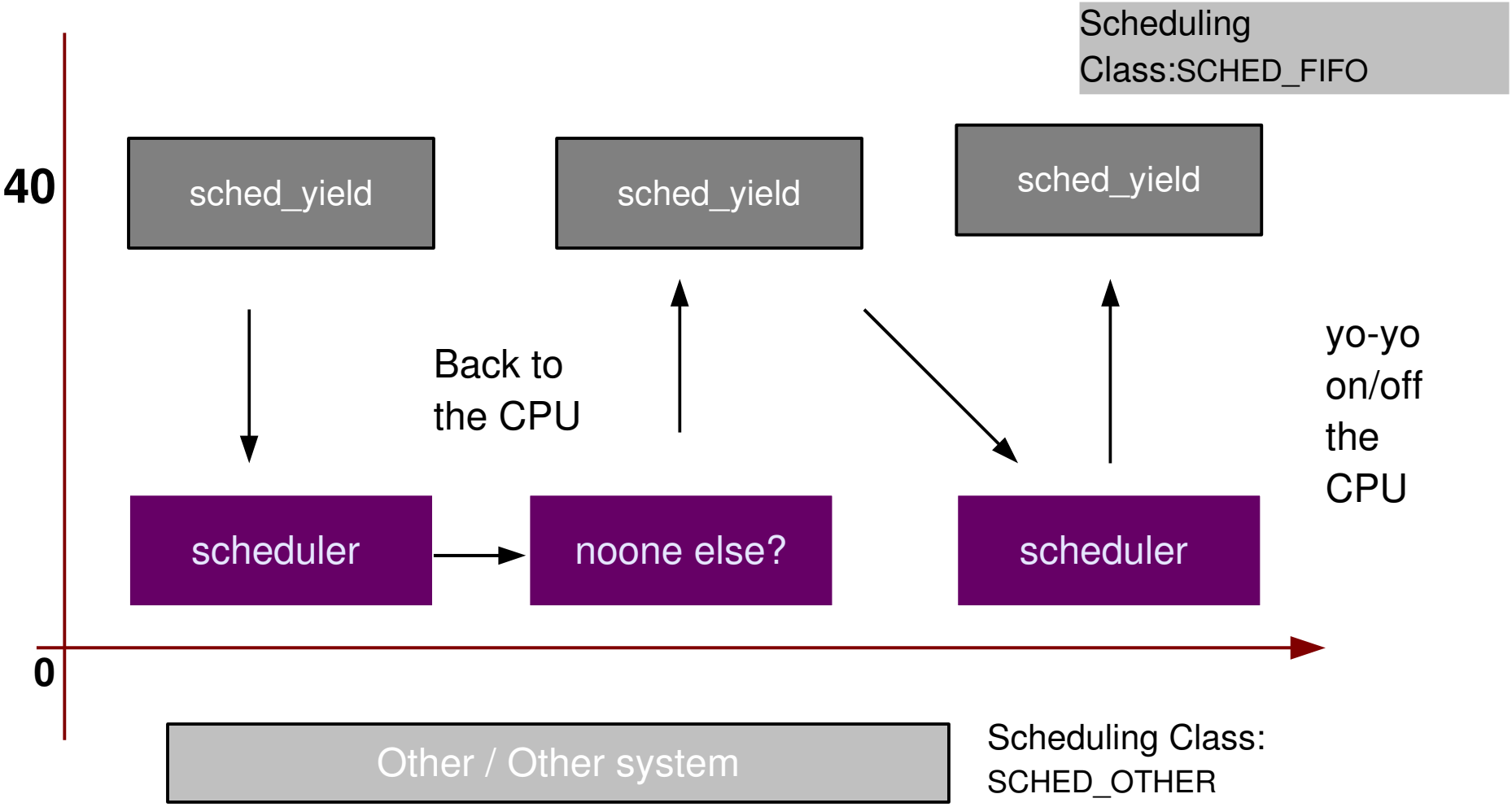
| | |
|---|---|
| BT | Block Tridiagonal |
| CG | Conjugate Gradient |
| EP | Embarrassingly Parallel |
| FT | Fast Fourier Transform |
| IS | Integer Sort |
| LU | Lower-Upper symmetric Gauss-Seidel |
| MG | MultiGrid |
| SP | Scalar Pentadiagonal |



# Shooting oneself in the foot...

- Immediate livelock
  - sched_yield() use
  - application believes it's yielding the CPU
    - just wants a delay
    - needs other activity to occur on the system for forward progress
    - depencies
    - asynchronous I/O from other nodes, ...
  - well, guess what...

# sched_yield() doesn't do what you think it does...



# So if there's one lesson - Real-Time Needs...

- Top down architecture design (**)
- Identified  dependencies
  - correctly prioritize in some sort of hierarchical sorting
  - ensure forward progress of your application

# Setting real-time attributes

- **rtctl** utility to manage threads, processes
  - /etc/rtgroups file
  - set system default scheduling priority/class for processes
  - note, rtctl utility default differs from kernel default
    - "ps -eLo pid,rtprio,policy,comm"
- command line using **chrt**

- Lots of jitter measurement and other tools available
  - resources on the web
  - cyclictest
  - ftrace, perf, kernelshark, trace-cmd, ...
- Lots of tuning help available
  - https://rt.wiki.kernel.org/index.php/Main_Page
  - https://www.ibm.com/developerworks/wikis/display/LinuxP/OS+Jitter+Mitigation+Techniques (IBM-specific)

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