Linux Realtime Response:

The CONFIG_PREEMPT Patch Set

Overview

- Production Systems and Realtime Response
- Isn't Realtime a Single-CPU Thing?
- What Does Realtime Entail?
- Linux Approaches to Realtime Response
- CONFIG_PREEMPT_RT Patch
- Priority Inversion and Reader-Writer Locking
- Administrative Tools
- Summary

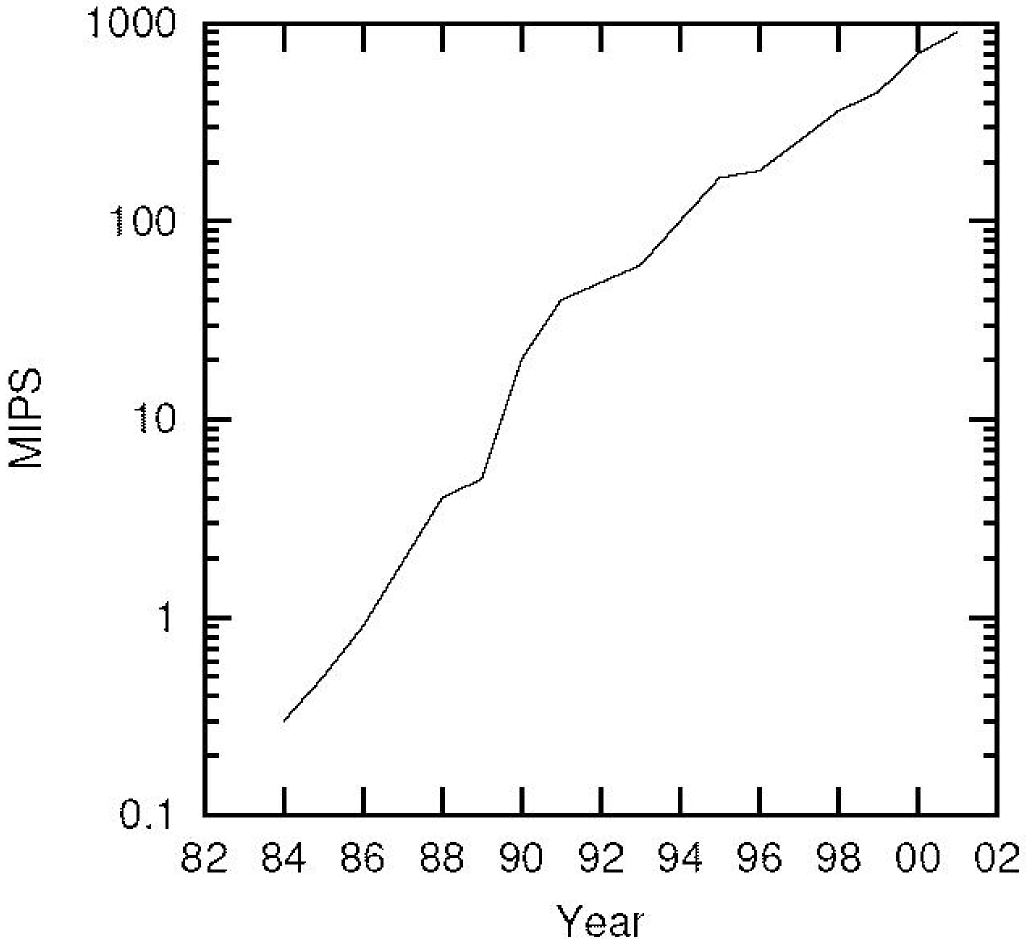
Production Systems and Realtime Response

- System Administrators Must:
  - 1960: Keep system running
  - 1970: Control user access to system
  - 1980: Keep network running
  - 1990: Keep system performing and scaling
  - 2000: Keep cluster/datacenter running
  - ***2010: Keep system responding in real time***
  - 2020: Keep Internet responding in real time?
    - Or maybe just cluster/datacenter...

Why Realtime Response???

- Moore's Law: AKA “because we can”
  - Cell phones are more powerful than 1970s mainframes, and therefore can support “real” operating systems (see next slide)
- Software “network effects”: common platform & software
- “Nintendo Generation”
  - Grew up with sub-reflex response time from computers
  - Now are entering jobs controlling computer purchases
- Human-computer interaction changes when response time drops below about 100 milliseconds
  - Much more natural and fluid, much more productive
  - And can developed countries afford to continue to pay their people to stare at hourglasses???
    - But this problem extends far above the operating system...
- Delays accumulate across networks of machines

Moore's Law as Illustrated by Sequent Computers



Isn't Realtime a Single-CPU Thing?

Today's Systems

Historical Realtime:
- ***Few CPUs***
- Latency Guarantees
- ***Non-Standard***

OR

Historical SMP:
- Many CPUs
- ***No Guarantees***
- Standard (and OSS)

But Not Both!!!

Convergence

Emerging Systems

SMP Realtime:
- Many CPUs
- Latency Guarantees
- Standard (and OSS)

- User Demand (DoD, Financial, Gaming, ...)
- Techological Changes Leading to Commodity SMP
  - Hardware Multithreading
  - Multi-Core Dies
  - Tens to Hundreds of CPUs per Die – Or More

What Does Realtime Entail?

- Quality of Service (Beyond “Hard”/“Soft”)
  - Services Supported
    - Probability of meeting deadline absent HW failure
    - Deadlines supported
  - Performance/Scalability for RT & non-RT Code
- Amount of Global Knowledge Required
- Fault Isolation
- HW/SW Configurations Supported

- “But Will People Use It?”

Linux Realtime Approaches (Violently Abbreviated)

Project	Quality of Service	Inspection	API	Complexity	Fault Isolation	HW/SW Configs
Vanilla Linux Kernel	10s of ms all services	All	POSIX + RT extensions	N/A	None	All
PREEMPT	100s of us Schd, Int	All spinlock critsect, preempt- & int-disable	POSIX + RT extensions	N/A	None	All
Nested OS	~10 us RTOS svs	RTOS + int-disable	RTOS	Dual environment	Good	All
Dual-OS / Dual-Core	<1 us RTOS svcs	All RTOS	RTOS	Dual environment	Excellent	Specialized
PREEMPT_RT	10s of us Schd, Int	All preempt- & int-disable (most ints in process ctxt)	POSIX + RT extensions	"Modest" patch	None	All (except some drivers)
Migration Between OSes	? us RTOS svcs	All RTOS + int-disable	RTOS (can be POSIX)	Dual env. (Fusion)	OK	All?
Migration Within OS	? us RTOS svcs	Scheduler + RT syscalls	POSIX + RT extensions	Small patch	None	All?

Examples of Linux Approaches

- Nested OS:
  - RTLinux, L4Linux, I-pipe (latency from RTLinux)
- Dual-OS/Dual-Core:
  - Huge numbers of real products, e.g., cell phones
- Migration Between OSes:
  - RTAI-Fusion
- Migration Within OS:
  - ARTiS (Asymmetric Real-Time Scheduling)

Related Patches & Components

- High-Resolution Timers (HRT)
  - Avoids “three-millisecond shuffle”
  - Additional code provides fine-grained timers
  - “ktimers” seems to be superseding HRT
- Variable idle Sleep Time (VST)
  - Suppress unneeded timer ticks, CONFIG_VST
  - Also helps virtualization/consolidation
- Robust Mutexes / “fusyn”
  - Priority inheritance for user-level mutexes
    - Such as pthread_mutex
- Isolcpus + interrupt-shielding patches & config options

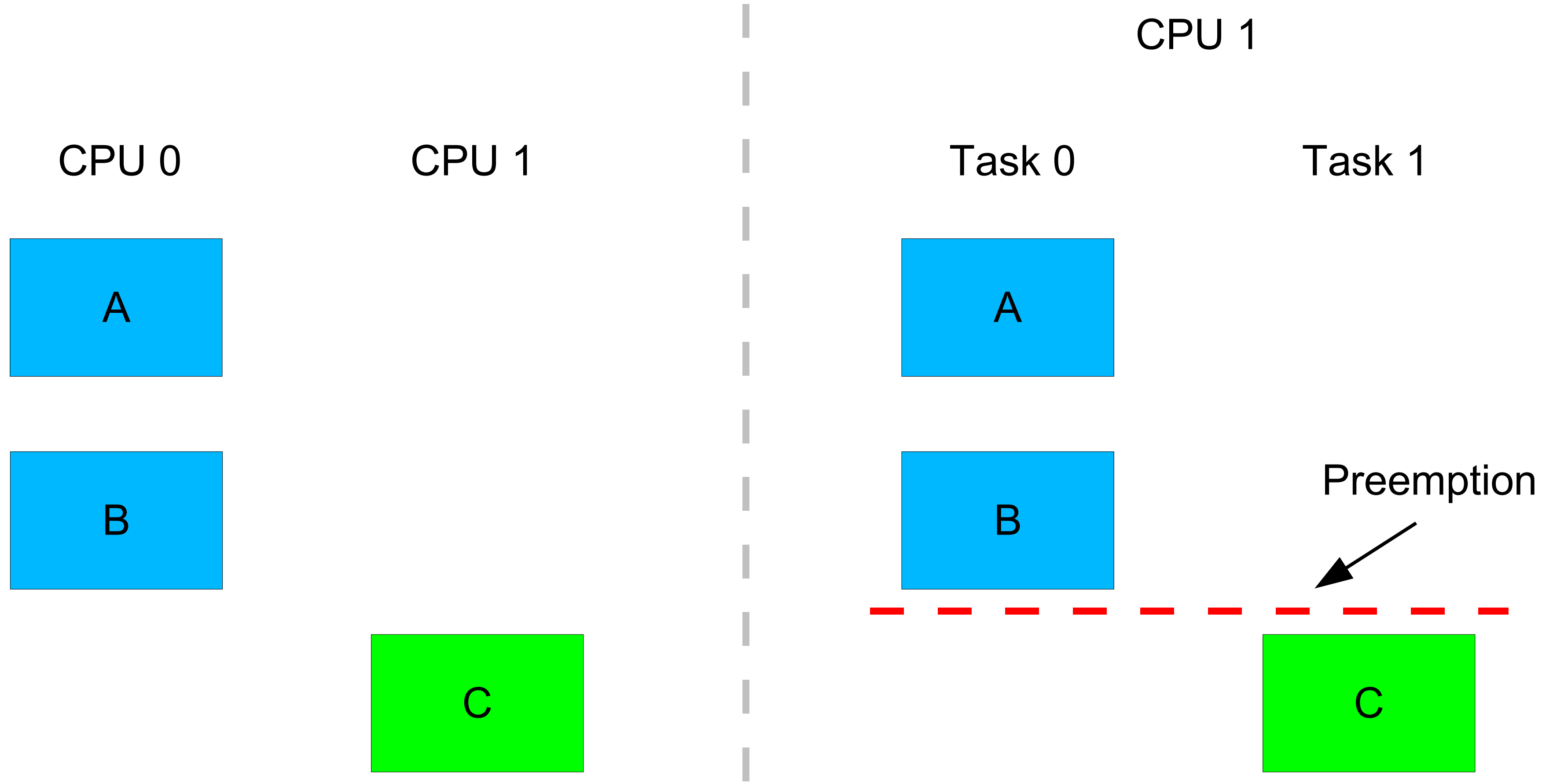
Other Patches That Might Appear. Someday.

- Deterministic I/O
  - Disk I/O – or, more likely, Flash memory
  - Network protocols
    - Datagram protocols (UDP) relatively straightforward
    - “Reliable” protocols (TCP, SCTP) more difficult
    - Maintaining low network utilization is key workaround
- Other Priority Inheritance
  - Across memory allocation
    - Boost priority of someone who is about to free...
  - Reader-writer locks with concurrent readers
    - Writer-to-reader boosting problematic
  - Across networks (automated cattle prod for users???)
  - Across RCU when OOM (this one is straightforward!)

CONFIG_PREEMPT_RT Patch: Philosophy

- Leverage Linux Kernel's SMP Capability
  - Any code segment must be able to tolerate interference from some other CPU
    - That is what SMP locking is all about, after all!!!
  - This property can be leveraged to support "macho preemption"
- But no need to actually remove a CPU
  - No high-overhead CPU-hotplug events, please!

CONFIG_PREEMPT_RT Patch: Philosophy

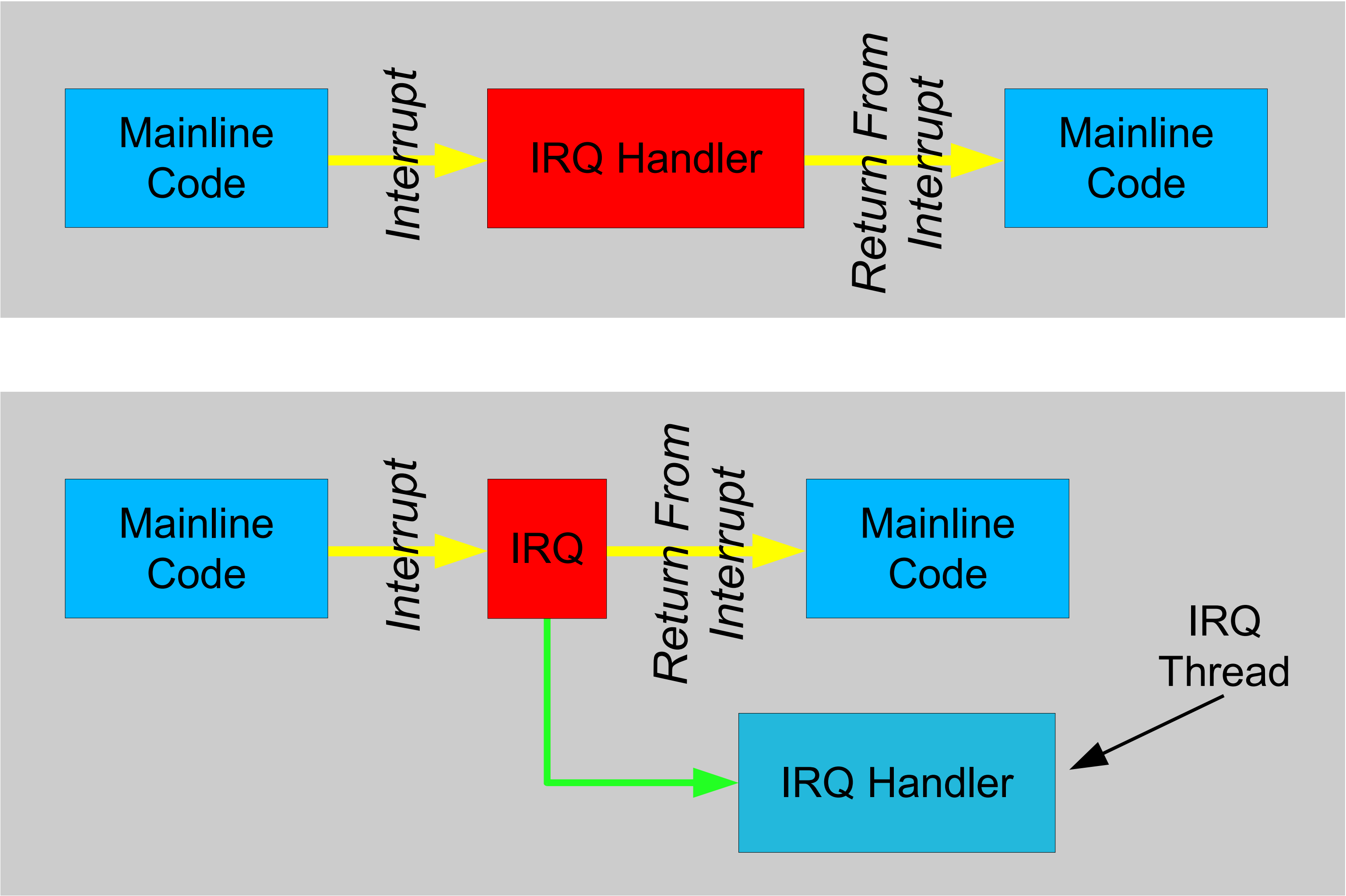


Happy coincidence: that which helps scalability usually also helps realtime latency!!!

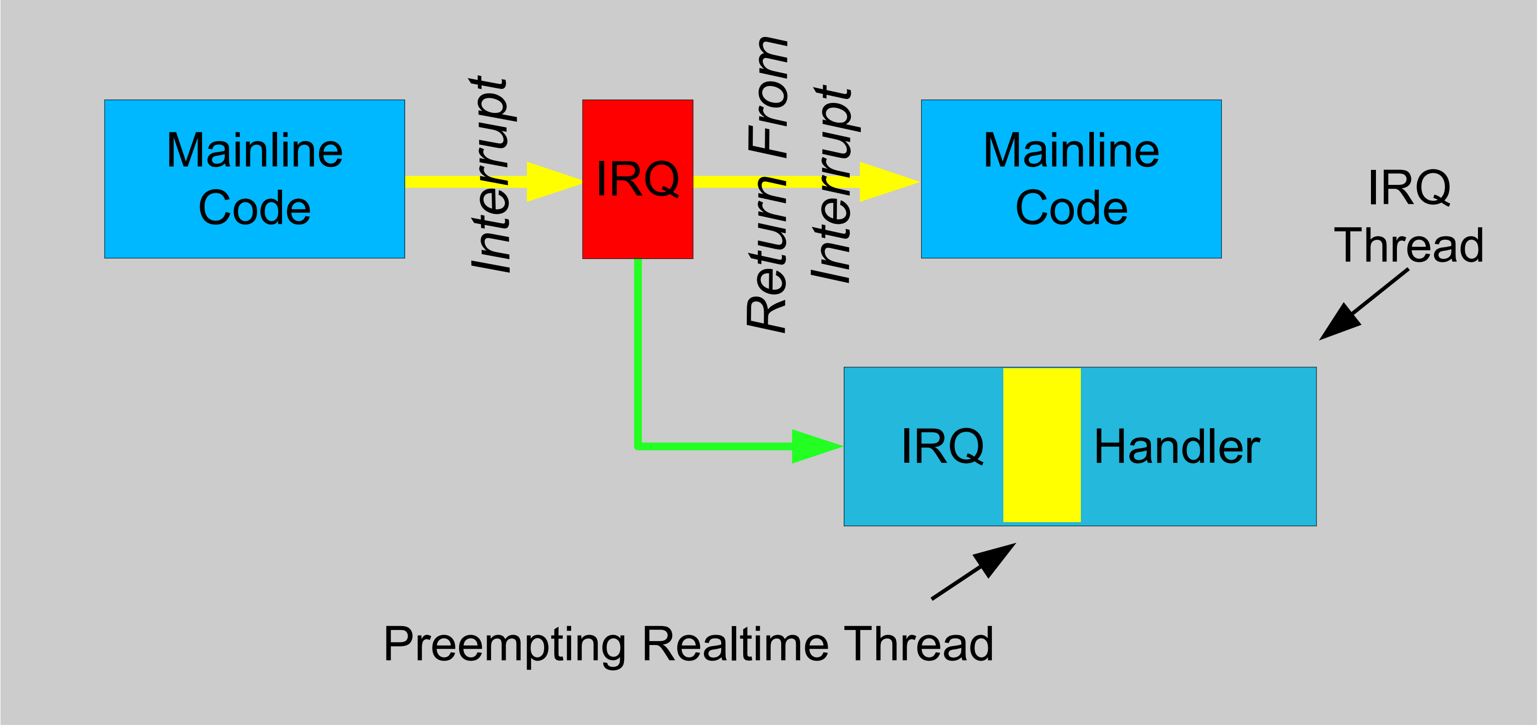
CONFIG_PREEMPT_RT Patch: Caveats

- Some Changes Were Required
  - Spinlocks can now sleep
    - “Raw” spinlock facility for the few locks that cannot tolerate sleeping (e.g., scheduler locks)
  - Must now explicitly protect per-CPU variables
    - Explicitly disable preemption or interrupts
    - Use get_cpu_var() API
    - Use DEFINE_PER_CPU_LOCKED() facility
      - Avoids realtime latency degradation
  - Interrupt handlers can now be preempted
    - As can “interrupt disable” code sequences
- But Numerous SMP Bugs Were Located!

Preempting Interrupt Handlers: IRQ Threads



Preempting Interrupt Handlers: IRQ Threads



In-Kernel Primitives

- So what does it mean to disable interrupts???
  - Disabling preemption will do the trick
    - And so local_irq_disable() and friends disable preemption
  - But disabling preemption degrades latency, so use of locks is usually preferable
  - Except that the scheduling-clock interrupt is still a “real” interrupt
    - Marked with SA_NODELAY
  - So raw_local_irq_disable() and friends disable “real” interrupts
- Per-CPU variables prone to preemption, so “locked” per-CPU variables
  - DEFINE_PER_CPU_LOCKED, DECLARE_PER_CPU_LOCKED, get_per_cpu_locked, put_per_cpu_locked, per_cpu_lock, per_cpu_locked

More In-Kernel Primitives

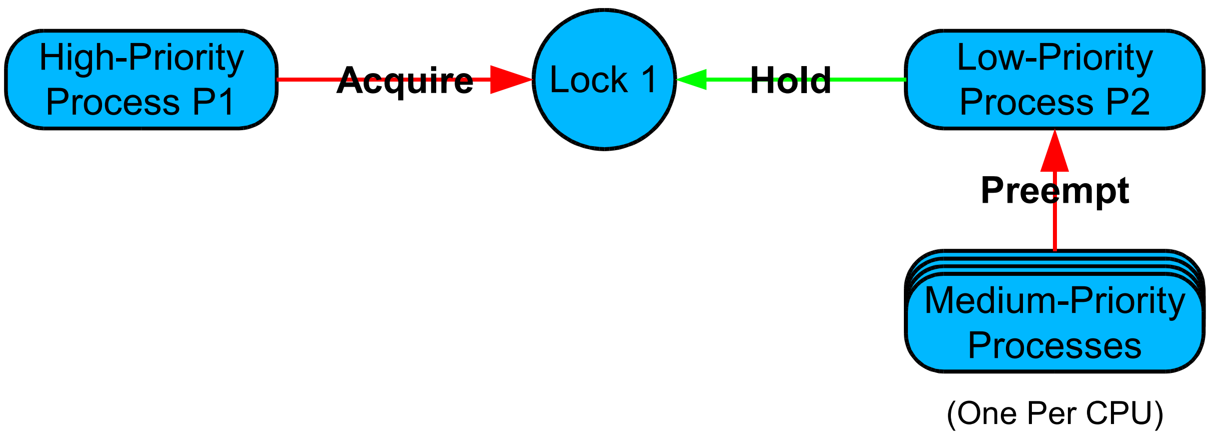
- spinlock_t is preemptible and participates in priority inheritance
  - But the runqueue spinlocks cannot be preempted (why?)
  - So there is raw_spinlock_t for “pure spinlock”
- Ditto for rwlock_t and raw_rwlock_t
- seqlock_t is preemptible, and participates in priority inheritance on the update side
- struct semaphore participates in priority inheritance
  - But priority inheritance does not make sense in event mechanisms (why?)
  - So there is a struct compat_semaphore with no inheritance
- Ditto for struct rw_semaphore and struct compat_rw_semaphore

Semaphores as Event Mechanisms

- Semaphores have associated “count”, initialize to “1” for sleeplock
  - First task's “down()” proceeds
  - Second task's “down()” blocks until first task does “up()”
  - Any task doing a “down()” must eventually do an “up()”
  - So if blocked on down(), give priority to whoever succeeded on last “down()” so that they get to their “up()” more quickly
- Initialize count to “0” for event
  - First task's “down()” blocks: wait for event
  - Task that detects event does “up()”
  - How to tell which task will detect event?
  - And why would raising that task's priority make the event happen more quickly???
    - “Are we there yet?”
- Thus: priority-inheritance-immune compat_semaphore for events

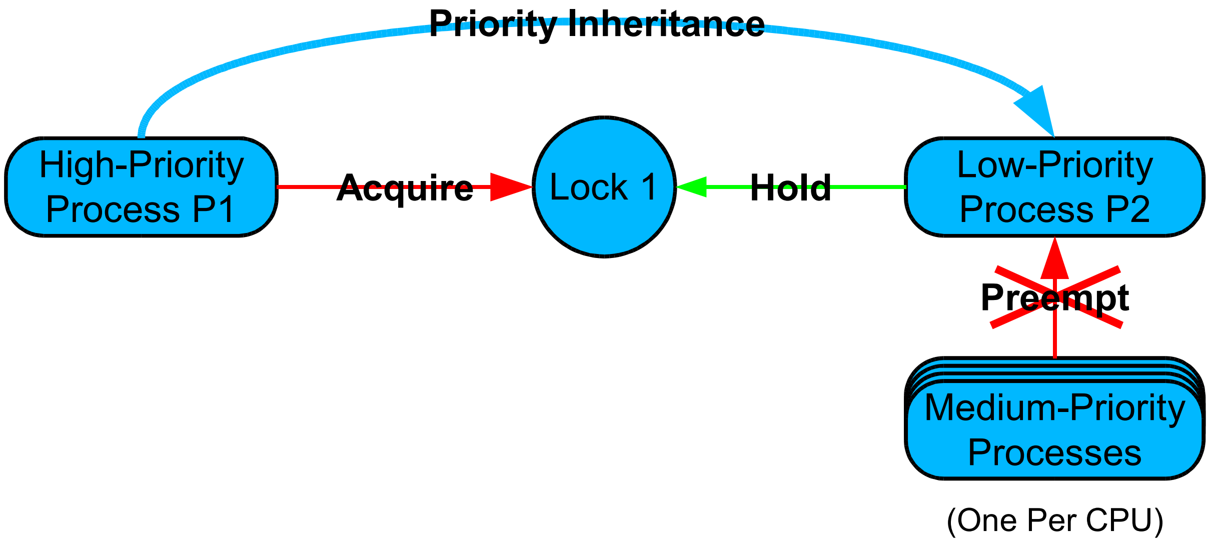
Priority Inversion

- Process P1 needs Lock L1, held by P2
- Process P2 has been preempted by medium-priority processes
  - Consuming all available CPUs
- Process P1 is blocked by lower-priority processes



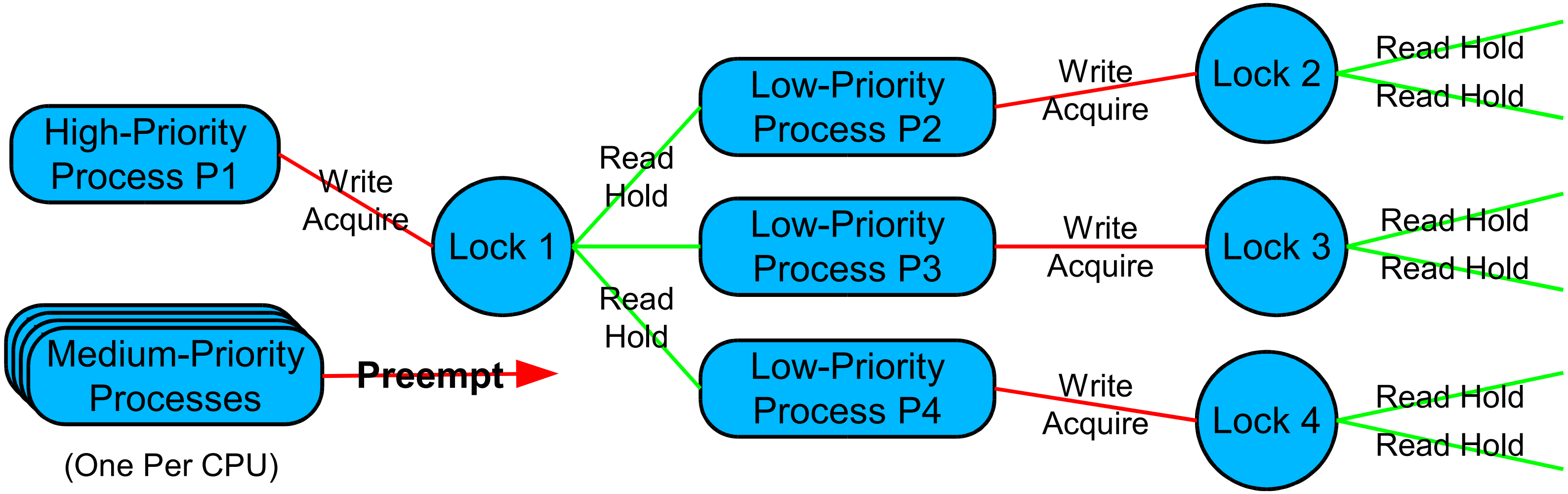
Preventing Priority Inversion

- Trivial solution: Prohibit preemption while holding locks
  - But degrades latency!!! Especially for sleeplocks!!!!
- Simple solution: “Priority Inheritance”: P2 “inherits” P1's priority
  - But only while holding a lock that P1 is attempting to acquire
  - Standard solution, very heavily used
- Either way, prevent the low-priority process from being preempted



Priority Inversion and Reader-Writer Locking

- Process P1 needs Lock L1, held by P2, P3, and P4
  - Each of which is waiting on yet another lock
    - read-held by yet more low-priority processes
    - preempted by medium-priority processes
- Process P1 will have a long wait, despite its high priority
  - ***Even given priority inheritance: many processes to boost!***
- And a great many processes might need to be priority-boosted
  - Further degrading P1's realtime response latency



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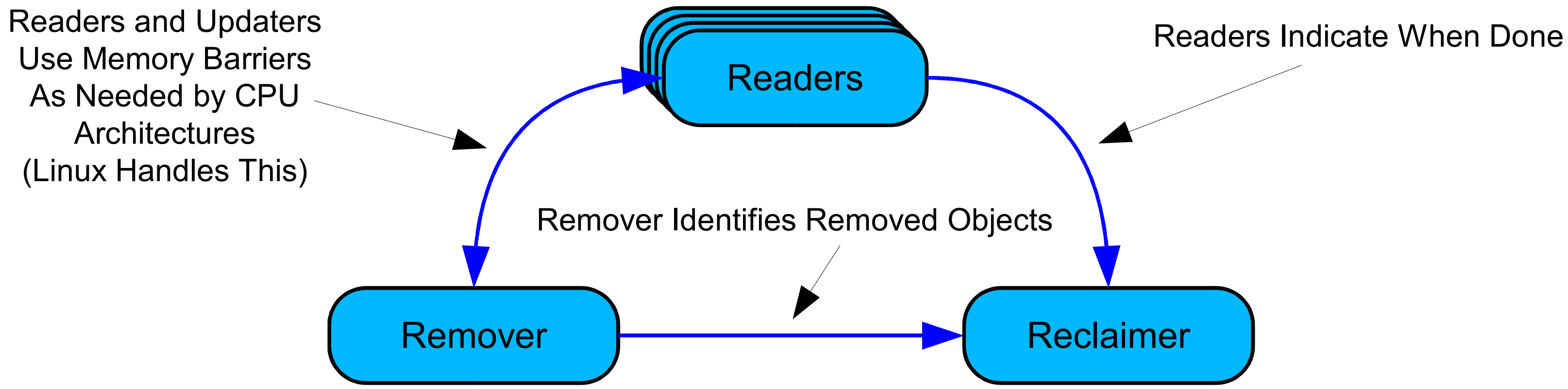
Priority Inheritance and Reader-Writer Lock

- Real-time operating systems have taken the following approaches to writer-to-reader priority boosting:
  - Boost only one reader at a time
    - Reasonable on a single-CPU machine, except in presence of readers that can block for other reasons.
    - Extremely ineffective on an SMP machine, as the writer must wait for readers to complete serially rather than in parallel
  - Boost a number of readers equal to the number of CPUs
    - Works well even on SMP, except in presence of readers that can block for other reasons (e.g., acquiring other locks)
  - Permit only one task at a time to read-hold a lock (PREEMPT_RT)
    - Very fast priority boosting, but severe read-side locking bottlenecks
- All of these approaches have heavy bookkeeping costs
  - Priority boost propagates transitively through multiple locks
  - Processes holding multiple locks may receive multiple priority boosts to different priority levels, actual boost must be to maximum level
  - Priority boost reduced (perhaps to intermediate level) when locks released
- Need something better...
  - Linux provides RCU!

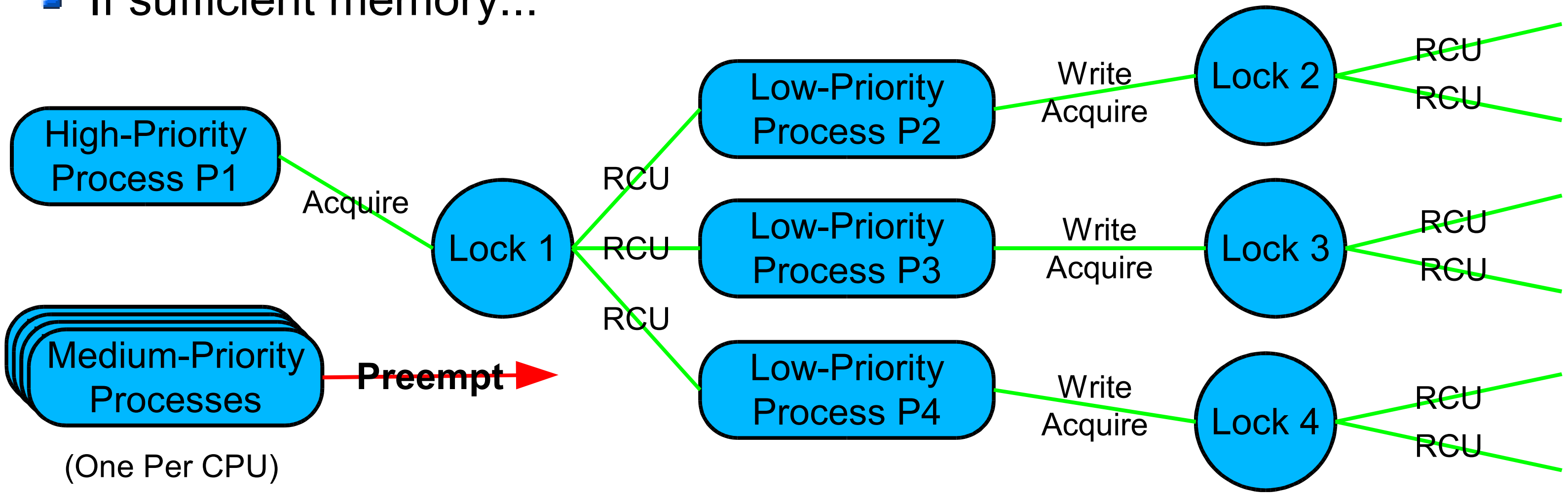
Priority Inversion and RCU: What is RCU?

- Analogous to reader-writer lock, but readers acquire no locks
  - Readers therefore cannot block writers
  - Reader-to-writer priority inversion is therefore impossible
- Writers break updates into “removal” and “reclamation” phases
  - Removals do not interfere with readers
  - Reclamations deferred until all readers drop references
    - Readers cannot obtain references to removed items
- RCU used in production for over a decade by IBM (and Sequent)
- IBM recently adapted RCU for realtime use in Linux



Priority Inversion and RCU

- Process P1 needs Lock L1, but P2, P3, and P4 now use RCU
  - P2, P3, and P4 therefore need not hold L1
  - Process P1 thus immediately acquires this lock
  - Even though P2, P3, and P4 are preempted by the per-CPU medium-priority processes
- No priority inheritance required
  - Except if low on memory: permit reclaimer to free up memory
- Excellent realtime latencies: medium-priority processes can run
  - High-priority process proceeds despite low-priority process preemption
  - If sufficient memory...



Realtime and RCU

- RCU exploited in PREEMPT_RT patchset to reduce latencies
  - “kill()” system-call RCU prototype provided large reduction in latency
  - Expect similar benefits for pthread_cond_broadcast() and pthread_cond_signal()
- Current PREEMPT_RT realtime Linux provides relatively few realtime services
  - Process scheduling, interrupts, some signals
- Increasing the number of realtime services will likely require additional exploitation of RCU
  - And will likely require that RCU readers be priority-boosted when low on memory

Provable Realtime Guarantees

- Linux approaches to realtime reduce amount of code that must be inspected in order to derive realtime guarantees
  - In PREEMPT_RT patchset, only need to inspect code with:
    - Interrupts disabled
    - Preemption disabled
    - High-latency hardware interactions
- However, commercial market is primarily soft realtime rather than hard realtime
  - Needed soft-realtime guarantees established via testing

Tools and Systems Administration

- Linux has plenty of fault-isolation tools
  - “ps”, “top”, network monitoring, memory consumption, resource limits, error logging, ...
  - Intent: find functional and performance problems
- Linux will need latency-isolation tools
  - Determine what is imposing poor latency
    - Report and/or fix problem
    - Avoid using problematic part of system
- These are starting to appear...

Tools & Systems Administration: CONFIG Options

- CRITICAL_PREEMPT_TIMING: measure maximum time that preemption is disabled
- CRITICAL_IRQSOFF_TIMING: measure maximum time that hardware interrupts are disabled
- DETECT_SOFTLOCKUP: dump stack of any process spending more than 10 seconds in kernel without rescheduling
- LATENCY_TRACE: record function-call traces of long-latency events
- RT_DETECT_DEADLOCK: find deadlock cycles
- RTC_HISTOGRAM: generate latency histograms
- WAKEUP_TIMING: measure maximum time from when high-priority task is awakened until it actually starts running

Summary

- Realtime requirements will start appearing more widely
- SMP systems starting to support realtime, courtesy of commodity realtime (multicore, multithreaded) SMP hardware
- Systems administrators will start needing to worry about realtime latency
  - Just as they started worrying about users, networks, performance, clustering, and so on...
- Tools to measure and manage latency are starting to appear, but are in their infancy

- Computing will continue to be exciting!!!