Real-Time OS Kernels

Advanced Real Time Operating Systems

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Latency

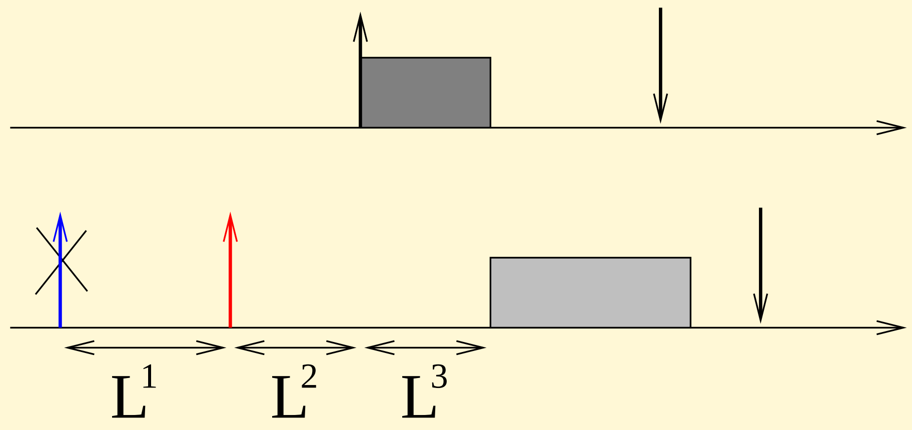
- Latency: measure of the difference between the theoretical and actual schedule
  - Task τ expects to be scheduled at time $t \ldots$
  - $\ldots$ but is actually scheduled at time t'
  - $\Rightarrow$ Latency $L = t' - t$
- The latency L can be modelled as a blocking time $\Rightarrow$ affects the guarantee test
  - Similar to what done for shared resources
  - Blocking time due to latency, not to priority inversion

Effects of the Latency

- Upper bound for L? If not known, no schedulability tests!!!
    - The latency must be *bounded*: $\exists L^{max} : L < L^{max}$
- If L^{max} is too high, only few task sets result to be schedulable
    - Large blocking time experienced by *all tasks*!
    - The worst-case latency L^{max} cannot be too high

Sources of Latency

- A task τ_i is a stream of jobs $J_{i,j}$ arriving at time $r_{i,j}$
- Job $J_{i,j}$ is scheduled at time $t' > r_{i,j}$
  - $t' - r_{i,j}$ is given by:
    1. $J_{i,j}$'s arrival is signalled at time $r_{i,j} + L^1$
    2. Such event is served at time $r_{i,j} + L^1 + L^2$
    3. $J_{i,j}$ is actually scheduled at $r_{i,j} + L^1 + L^2 + L^3$

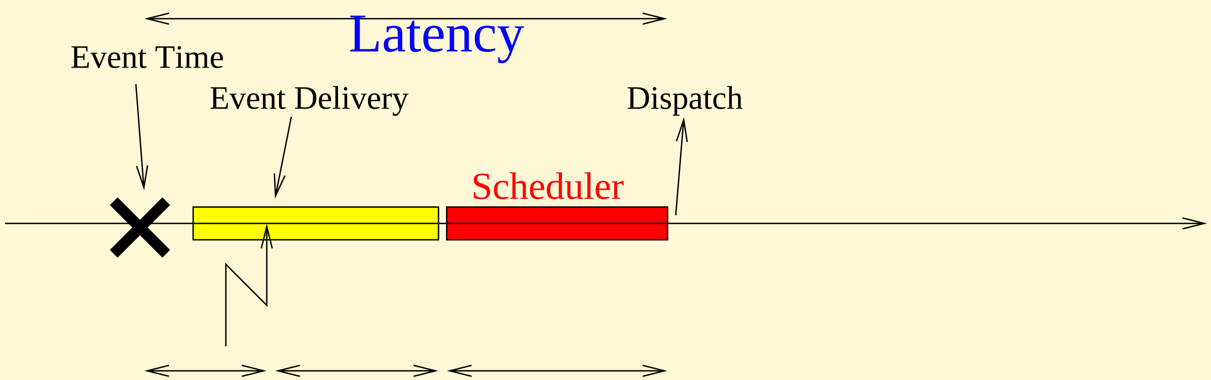


Analysis of the Various Sources

- $L = L^1 + L^2 + L^3$
- L^3 is sometimes called *scheduler latency*
  - But it is not really a latency!!!
  - Interference from higher priority tasks
  - Already accounted for by RTA / TDA or similar $\rightarrow$ let's not consider it
- L^2 is the *non-preemptable section latency* (L^{np})
- L^1 is due to the delayed interrupt generation

Non-Preemptable Section Latency

- Delay between time when an event is generated and when the kernel handles it
  - Due to non-preemptable sections in the kernel, which delay the response to hardware interrupts
  - Composed by various parts: *interrupt disabling*, *bottom halves delaying*, . . .
- Depends on how the kernel handles the various events...
- Will talk about it later!



Interrupt Generation Latency

- Hardware interrupts: generated by devices
- Sometimes, an interrupt should be generated at time $t \dots$
- $\dots$ but it si actually generated at time $t' = t + L^{int}$
- L^{int} is the *Interrupt Generation Latency*
  - It is due to hardware issues
  - It is *generally* small compared to L^{np}
  - Exception: if the device is a timer device, the interrupt generation latency can be quite high
    - *Timer Resolution Latency* L^{timer}

The Timer Resolution Latency

- Interrupt generation latency for a hw timer device
- L^{timer} can often be much larger than the non-preemptable section latency L^{np}
- Where does it come from?
  - Kernel timers are generally implemented by using a hardware device that produces periodic interrupts
- Can we do anything about it?

Example: Data Structures Consistency

- HW interrupt: *breaks* the regular execution flow
  - If the CPU is executing in US, switch to KS
- If execution is already in KS, possible problems:

1. The kernel is updating a linked list
2. IRQ While the list is in an inconsistent state
3. Jump to the ISR, that needs to access the list...

- Must *disable interrupts* while updating the list!
- Similar interrupt disabling is also used in spinlocks and mutex implementations...

Real-Time Executives

- Executive: Library code that can be directly linked to applications
- Implements functionalities generally provided by kernels
- Generally, no distinction between US and KS
  - No CPU privileged mode, or application executes in privileged mode
  - “kernel” functionalities are invoked by direct function call
  - Applications can execute privileged instructions

Real-Time Executives - 2

- Advantages:
  - Simple, small, low overhead
  - Only the needed code is linked in the final image
- Disadvantages:
  - No protection
  - Applications can even disable interrupts $\rightarrow L^{np}$ risks to be unpredictable

Real-Time Executives - 3

- Consistency of the internal structures is generally ensured by disabling interrupts
  - L^{np} is bounded by the maximum amount of time interrupts are disabled
  - ...Disabled by the executive or by applications!!!
- Generally used only when memory footprint is important, or when the CPU does not provide a privileged mode
  - Example: TinyOS `http://www.tinyos.net`

Monolithic Kernels

- Traditional Unix-like structure
- Protection: distinction between Kernel (running in KS) and User Applications (running in US)
- The kernel behaves as a single-threaded program
  - One single execution flow in KS at each time
  - Simplify consistency of internal kernel structures
- Execution enters the kernel in two ways:
  - Coming from upside (system calls)
  - Coming from below (hardware interrupts)

Single-Threaded Kernels

- Only one single execution flow (thread) can execute in the kernel
  - It is not possible to execute more than 1 system call at time
    - Non-preemptable system calls
    - In SMP systems, syscalls are critical sections (execute in mutual exclusion)
  - Interrupt handlers execute in the context of the interrupted task

Bottom Halves

- Interrupt handlers split in two parts
  - Short and fast ISR
  - “Soft IRQ handler”
- Soft IRQ hanlder: *deferred* handler
  - Traditionally known ass Bottom Half (BH)
  - AKA Deferred Procedure Call - DPC - in Windows
  - Linux: distinction between “traditional” BHs and Soft IRQ handlers

Synchronizing System Calls and BHs

- Synchronization with ISRs by disabling interrupts
- Synchronization with BHs: is almost automatic
  - BHs execute atomically (a BH cannot interrupt another BH)
  - BHs execute at the end of the system call, before invoking the scheduler for returning to US
- Easy synchronization, but large non-preemptable sections!
  - Achieved by reducing the kernel parallelism
  - Can be bad for real-time

Latency in Single-Threaded Kernels

- Kernels working in this way are often called *non-preemptable kernels*
- L^{np} is upper-bounded by the maximum amount of time spent in KS
  - Maximum system call length
  - Maximum amount of time spent serving interrupts

Evolution of the Monolithic Structure

- Monolithic kernels are single-threaded: how to run then on multiprocessor?
  - The kernel is a critical section: Big Kernel Lock protecting every system call
  - This solution does not scale well: a more fine-grained locking is needed!
- Tasks cannot block on these locks $\rightarrow$ not mutexes, but *spinlocks*!
  - Remember? When the CS is busy, a mutex blocks, a spinlock spins!
  - Busy waiting... Not that great idea...

Removing the Big Kernel Lock

- Big Kernel Lock $\rightarrow$ huge critical section for everyone
  - Bad for real-time...
  - ...But also bad for troughput!
- Let's split it in multiple locks...
- Fine-grained locking allows more execution flows in the kernel simultaneously
  - More parallelism in the kernel...
  - ...But tasks executing in kernel mode are still non-preemptable

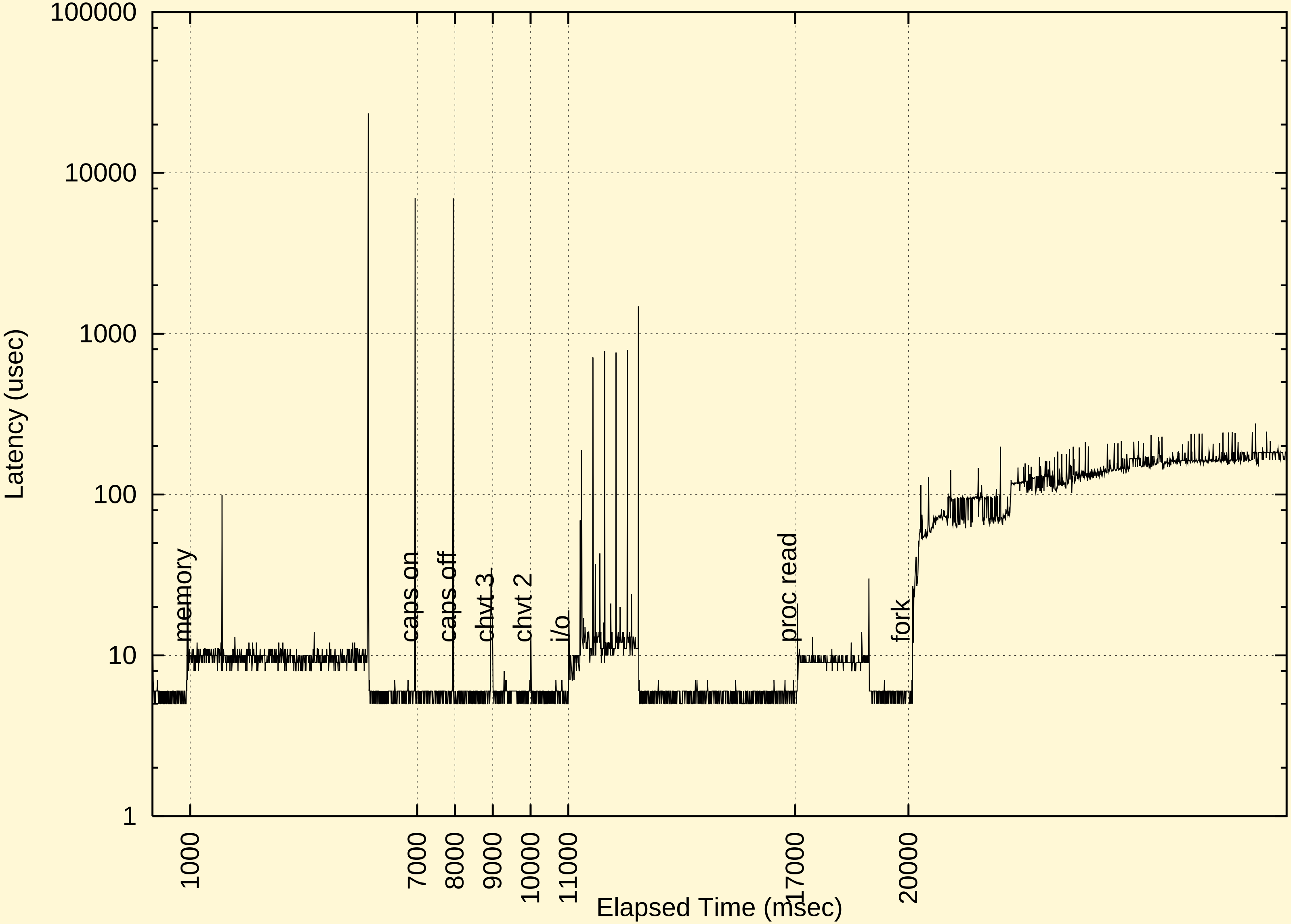
Preemptable Kernels

- Multithreaded kernel
  - Fine-grained critical sections inside the kernel
  - Kernel code is still non-preemptable
- Idea: When the kernel is not in critical section, preemptions can occurr
  - Check for preemptions when exiting kernel’s critical sections

Linux Kernel Preemptability

- Check for preemption when exiting a kernel critical section
  - Implemented by modifying spinlocks
  - Preemption counter: increased when locking, drecreased when unlocking
  - When preemption counter == 0, check for preemption
- In a preemptable kernel, L^{np} is upper bounded by the maximum size of a kernel critical section
- Critical section == non-preemptable... This is NPP!!!

Latency in a Preemptable Kernel



NPP Drawbacks

- Preemptable Kernel: use NPP for kernel critical sections
- NPP is known to have issues
  - Low-priority tasks with large critical sections can affect the schedulability of high-priority tasks not using resources!
  - In this context: low-priority (or NRT) tasks invoking system calls with long critical sections can compromise the schedulability of high priority real-time tasks
    - Even if they do not use those syscalls or critical sections!
- Can we do better???

Doing Better than NPP

- Possible alternatives: HLP and PI
- HLP: easy to implement, but requires to know which resources the tasks will use
  - Possible to avoid high latencies on tasks not using the “long critical sections”, but...
  - ...Those tasks must be identified somehow!
- PI: does not impose restrictions or require a-priori knowledge of the tasks behaviour, but requires more changes to the kernel!

Using HLP

- Simple idea: distinction between RT tasks (do not use the kernel!) and NRT tasks (can use the kernel)
  - Do not use the kernel: simple way to avoid long critical sections!
- How the hell can we execute a task without using the OS kernel???
- Some “lower level RT-kernel” is needed
  - Running below the kernel!
  - Two possibilities: μkernels or dual-kernel systems

μKernels - 1

- Basic idea: simplify the kernel
  - Reduce to the number of abstractions exported by the kernel
    - Address Spaces
    - Threads
    - IPC mechanisms (channels, ports, etc...)
  - Most of the “traditional” kernel functionalities implemented in user space
  - Even device drivers can be in user space!

μKernels - 2

- Interactions via IPC (IRQs to drivers as messages, ...)
- Servers: US processes implementing OS functionalities
  - OS kernel as a single user-space process: Single-server OSs
  - Multiple user-space processes (a server per driver, FS server, network server, ...): Multi-server OSs

μKernels vs Multithreaded Kernels

- μKernels are known to be “more modular” (servers can be stopped / started at run time)
- All the modern monolithic kernels provide a *module* mechanism
- Modules are linked into the kernel, servers are separate programs running in US
- Key difference between μKernels and traditional kernels: each server runs in its own address space
- In some “μKernel systems”, some servers share the same address space for some servers to avoid the IPC overhead

Latency in μKernel-Based Systems - 1

- Non-preemptable sections latency is similar to monolithic kernels
  - L^{np} is upper-bounded by the maximum amount of time spent in the μKernel...
  - ...But μKernels are simpler than monolithic kernels!
  - System calls and ISRs should be shorter $\Rightarrow$ the latency in a μKernel is generally smaller than in a monolithic kernel

Latency in μKernel-Based Systems - 2

- Unfortunately, the latency reduction achieved by the μKernel structure is often not sufficient for real-time systems
- Even μKernels have to be modified like monolithic kernels for obtaining good real-time performance
  - (μ)kernel preemptability, ...

2^{nd} Generation μKernels

- Problems with Mach-like "fat μKernels"
  - The kernel is too big $\rightarrow$ does not fit in cache memory
  - Inefficient IPC mechanisms
- Second generation of μKernels ("MicroKernels Can and Must be Small"): L4
  - Very simple kernel (only few syscalls)
  - Small (fits in cache memory)
  - Super-optimized IPC (designed to be efficient, not powerful)

2^{nd} Generation μKernels: Performance

- L4 μkernel: optimised for performance
  - Impact on global OS performance?
  - Real-Time performance?
- Linux ported to L4: `l4linux`
  - Single-Server OS
  - Only 10% performance penalty!
- Real-time performance: not so good. L4 heavily modified (introducing preemption points) to provide low latencies (Fiasco)

L4Linux

- l4linux: single-server OS, providing the Linux ABI
  - Linux applications run unmodified on it
  - Actually the server is the Linux kernel (ported to a new “l4” architecture)
- Idea: a μKernel is so simple and small that it does not need to be preemptable
  - False: Fiasco needed some special care to obtain good real-time performance

L4Linux and Real-Time

- Real-Time OS: DROPS
  - Non real-time applications run on l4linux (regular Linux applications)
  - Real-time applications directly run on L4
  - The l4linux server should not disable interrupts, or contain non-preemptable sections
- Use HLP instead of NPP
  - Easy to identify RT tasks: native L4 tasks!
  - The l4linux server must never have a priority higher than RT applications

“Tamed” L4Linux - 1

- The Linux kernel often disables interrupts (example: `spin_lock_irq()`) or preemption...
- ...So, l4linux risks to increase the latency for L4...
- Solution: in the “L4 architecture”, interrupt disabling can be remapped to a *soft interrupt disabling*
  - l4linux disables interrupts $\rightarrow$ no real `cli`
  - IPCs notifying interrupts to l4linux are disabled
  - When l4linux re-enables interrupts, pending interrupts can be notified to the l4linux server via IPC

“Tamed” L4Linux - 2

- l4linux does not really disable hw interrupts
  - L^{np} is high for the l4linux server (and for Linux applications)...
  - ...But is very low for L4 applications!
- l4linux cannot affect the latency experienced by L4 applications
  - HLP requires to know which applications use the resource...
  - ...In this context, it means “which applications use l4linux”

Dual Kernel Approach

- HLP idea: Linux applications are non real-time; real-time applications run at lower level
- Instead of using μkernels, mix the real-time executive approach with the monolithic approach
  - Low-level real-time kernel: directly handles interrupts and manage the hardware
  - Non real-time interrupts: forwarded to Linux only when they do not interfere with RT activities
  - Linux cannot disable interrupts (no `cli`)
  - can only disable (or delay) interrupt forwarding
- Real-time applications cannot use the Linux kernel

RTLinux

- Dual kernel approach: initially used by RTLinux
  - Patch for the Linux kernel to intercept the interrupts
  - Small kernel module implementing a real-time executive
    - Handle real-time interrupts (low latency)
    - Forward non real-time interrupts to Linux
    - Provide real-time functionalities (POSIX API)
  - Real-time applications are kernel modules
- There is a patent on interrupt forwarding ???

RTLinux & RTAI

- RTAI: "Free" implementation of a dual-kernel approach
- Better maintained than RTLinux
- Real-time applications are Linux modules: must have an (L)GPL compatible license
- No problem in Europe, maybe subject to RTLinux patent in the US
  - Big problem for adoption in the industry
  - Would you use something that might be infringing a patent?

RTAI & Friends

- I-Pipes: Interrupt Pipelines
  - A small *nanokernel* handles interrupts by sending them to pipelines of applications / kernels that actually manage them
  - Real-time application come first in the pipeline
  - Same functionalities as RTLinux interrupt forwarding, but different naming!
- Described in a paper that has been published before the RTLinux patent $\rightarrow$ patent free

I-Pipes Implementation

- Adeos nanokernel: implements interrupt pipelines
  - Same functionalities as RTLinux, but patent-free!
  - Can be optionally used by RTAI
- Xenomai: similar to RTAI; based on Adeos
  - Provides different real-time APIs
- Xenomai 3: both dual-kernel and user-space
- EVL (`https://evlproject.org`): next generation of dual-kernel/co-kernel systems (Xenomai 4)

Summing Up...

- Monolithic kernel: high latencies (no real-time)
- Preemptable kernel: kernel critical sections $\rightarrow$ Use NPP to protect them
  - Upper bound for L^{np}, but might be too high
- μkernel and dual-kernel: use HLP instead of NPP
  - HLP requires to know in advance which tasks will use a resource
  - Distinction between RT and NRT tasks!
- Can we do better? How to use PI???

Real-Time in Linux User Space

- HLP Idea: do not care about Linux kernel latencies, but make sure that they do not affect RT tasks
  - RT tasks: not Linux tasks!
- Real-Time performance to Linux processes $\Rightarrow$ need to reduce L^{np} for the Linux kernel, not for low-level applications running under it
- How to reduce L^{np}? Using PI directly is not easy...
  - There is a reason for using NPP
  - In some situations, the kernel cannot block!
  - But PI is a blocking protocol...

RT in User Space: Requirements

- Linux is a multithreaded kernel $\Rightarrow$ need:
  1. Fine-grained locking
  2. Preemptable kernel
  3. Schedulable ISRs and BHs $\Rightarrow$ threaded interrupt handling
  4. Replacing spinlocks with mutexes
  5. A real-time synchronisation protocol (PI) for these mutexes
- Remember Linux already provides high-resolution timers (since 2.6.21)

Using Threads for BHs and ISRs

- Using threads for serving BHs and ISRs, it is possible to schedule them
- The priority of interrupts not needed by real-time applications can be decreased, to reduce L^{np}
  - Non-threaded handlers: ISRs and BHs always preempt all tasks!!!
    - NRT tasks can trigger high latencies by just doing a lot of I/O!!!
  - Threaded handlers: if an interrupt is not needed by RT tasks, its priority can be lower than all the RT tasks priorities

Threaded Interrupt Handlers and PI

- Non-threaded ISRs $\Rightarrow$ use spinlocks to protect data structures accessed by the ISR
  - The ISR executes in the interrupted process context $\Rightarrow$ it cannot block
- Using threaded ISRs, spinlocks can be replaced with mutexes
- Spinlocks implicitly use NPP, mutexes can use PI!!!

The Preempt-RT Patch

- The features presented in the previous slides can surprisingly be implemented with a fairly small kernel patch
- Preempt-RT patch, started by Ingo Molnar and other Linux developers; now maintained by Thomas Gleixner
- `https://www.kernel.org/pub/linux/kernel/projects/rt`
  - Core RT patch: about 700KB of code
  - Larger patches because of added features (tracing, ...)
- Most of the code just changes spinlocks in mutexes
- Various real-time features can be enabled / disabled at kernel configuration time

Preempt-RT: Performance

- Continuous Integration and testing:

  `https://www.osadl.org/QA-Farm-Realtime.qa-farm-about.0.html`

- On a standard PC, **Worst Case** kernel latency less than $50\mu s$
  - Remember: it was more than $10ms$ on a vanilla kernel!
- Much more tested than many other “RT” kernels
  - Long (continuous!) runs
  - Multiple CPUs / architectures