# *Real-Time Kernels and Resource Sharing*

*Advanced Real Time Operating Systems*

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# Again on Preemptable Kernels

- Preemptable Linux kernel $\rightarrow$ reduces $L^N$
  - Is it just a hack?
- Theoretical foundation: spinlocks end up using NPP
  - Oh, no! Real-time jargon, once again!
  - So, what is NPP?
- Latencies can still be high... Why?
  - Once again, theory can explain...
- Two possible ways around: HLP and PI!
  - HLP? PI? WTH!!!
  - Recap on resource sharing protocols...

# Reconciliating Practice and (RT) Theory

- Latency: can be modelled as a blocking time
- RT Theory $\rightarrow$ lot of work on blocking times
  - Mainly seen as due to priority inversion
  - In OS kernels, blocking times due to someting different...
  - ...But to re-use RT theory, let's see them as priority inversion due to kernel critical sections!
- Non-preemptable (monolithic) kernels: the kernel is a critical section!
- Preemptable kernels: fine-grained critical sections inside the kernel
  - Issue: they affect even tasks not using syscalls / IRQs!

# Dealing with Priority Inversion

- Priority inversion can be reduced...
  - ...But how?
  - By introducing an appropriate *resource sharing protocol* (concurrency protocol)
- Provides an *upper bound for the blocking time*
  - Non Preemptive Protocol (NPP) / Highest Locking Priority (HLP)
  - Priority Inheritance Protocol (PI)
  - Priority Ceiling Protocol (PC)
  - Immediate Priority Ceiling Protocol (Part of the OSEK and POSIX standards)
- mutexes/spinlocks (not generic semaphores) must be used

# Non Preemptive Protocol (NPP)

- The idea is very simple *inhibit preemption when in a critical section*. How would you implement that?

- Advantages: *simplicity*
- Drawbacks: tasks which are not involved in a critical section suffer blocking

# Non Preemptive Protocol (NPP)

- The idea is very simple *inhibit preemption when in a critical section*. How would you implement that?
- Raise the task's priority to the maximum available priority when entering a critical section

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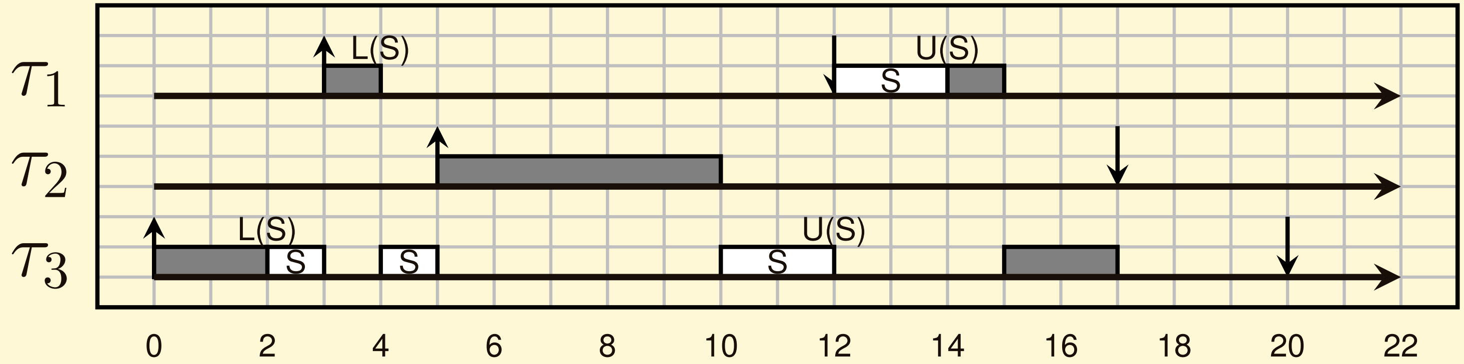
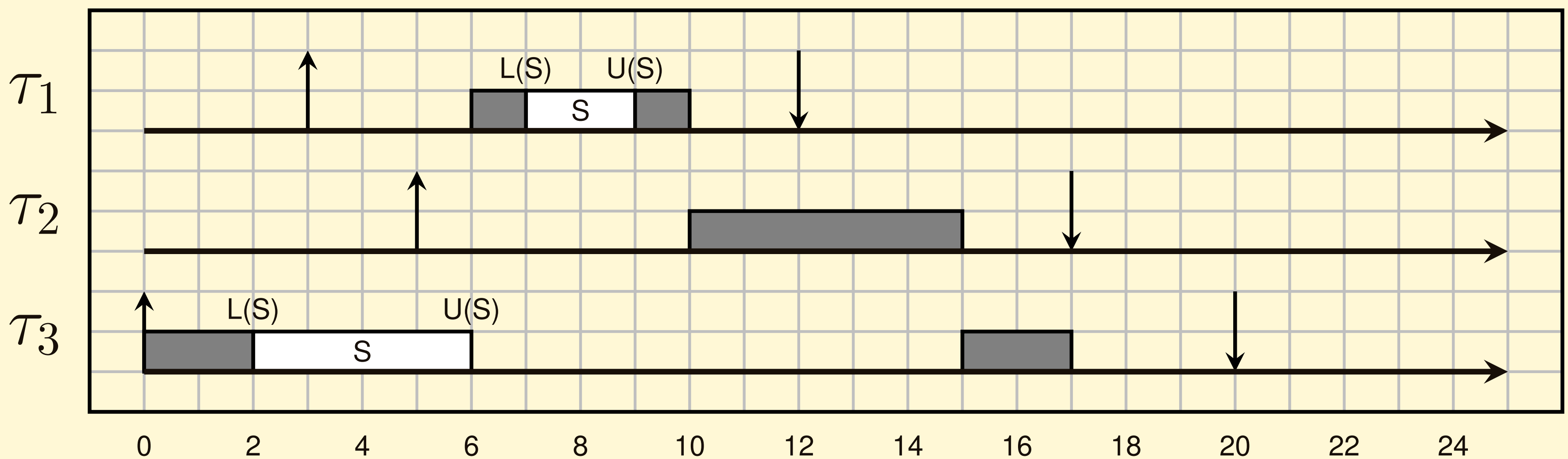
# NPP Example

- Remember the previous example...




- Using NPP, we have:

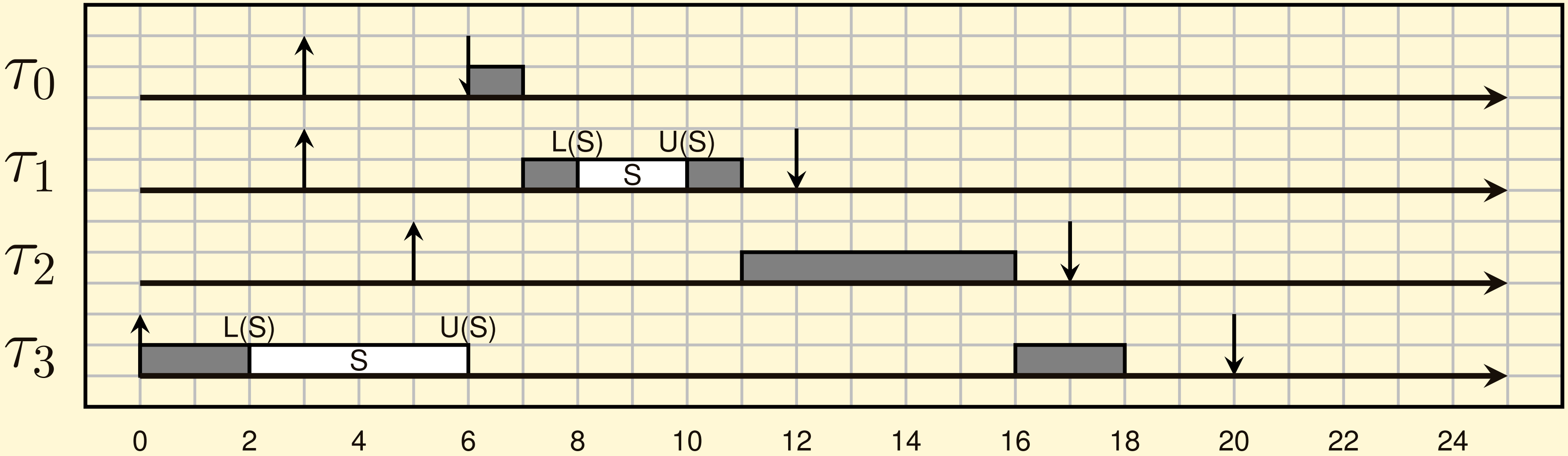


# Some Observations

- The blocking (priority inversion) is bounded by the length of the critical section of task $\tau_3$
- Medium priority tasks ($\tau_2$) cannot delay $\tau_1$
- $\tau_2$ experiences some blocking, but it does not use any resource
  - *Indirect blocking*: $\tau_2$ is *in the middle between* a higher priority task $\tau_1$ and a lower priority task $\tau_3$ which use the same resource
  - Must be computed and taken into account in the admission test as any other blocking time
- What's the maximum blocking time $B_i$ for $\tau_i$?

# A Problem with NPP

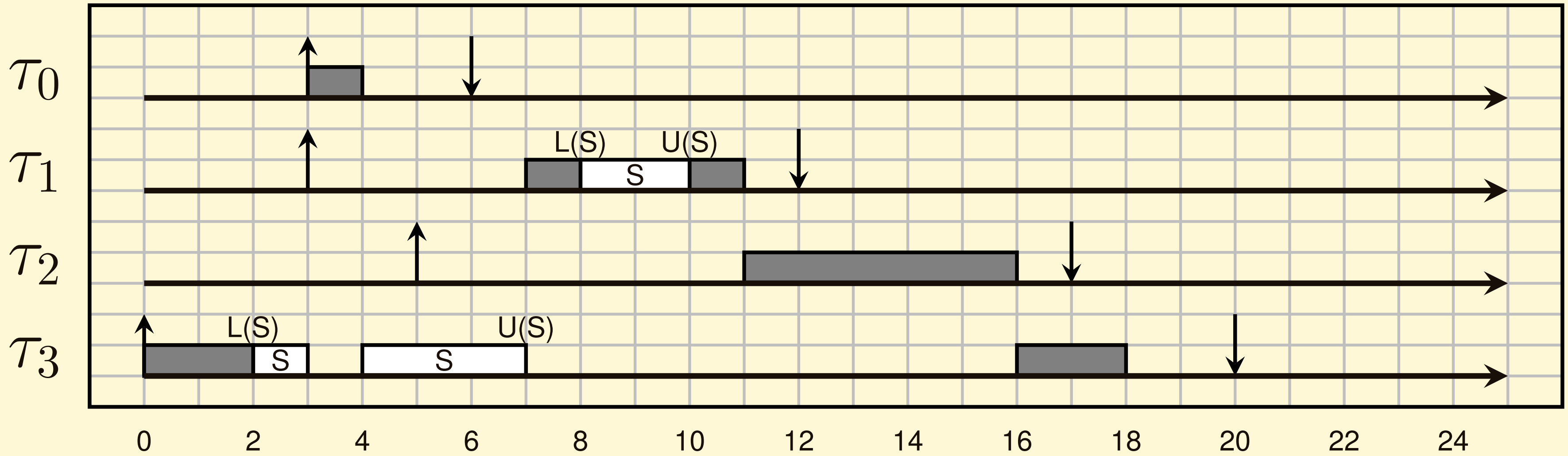
- Consider the following example, with $p_0 > p_1 > p_2 > p_3$.




- $\tau_0$ misses its deadline (suffers a blocking time equal to $3$) even though it does not use any resource!!
- Solution: raise $\tau_3$ priority to the maximum *between tasks accessing the shared resource* ($\tau_1$' priority)

# HLP

- So....




- This time, everyone is happy
- Problem: we must know in advance which task will access the resource

# Blocking Time and Response Time

- NPP introduces a blocking time on **all** tasks bounded by the *maximum lenght of a critical section used by lower priority tasks*
- How does blocking time affect the response times?
- Response Time Computation:

$$R_i = C_i + B_i + \sum_{j=1}^{i-1} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

  - $B_i$ is the blocking time from lower priority tasks
  - $\sum_{h=1}^{i-1} \left\lceil \frac{R_i}{T_h} \right\rceil C_h$ is the interference from higher priority tasks

# Response Time Computation - I

| Task | $C_i$ | $T_i$ | $\xi_{i,1}$ | $D_i$ |
|---|---|---|---|---|
| $\tau_1$ | 20 | 70 | 0 | 30 |
| $\tau_2$ | 20 | 80 | 1 | 45 |
| $\tau_3$ | 35 | 200 | 2 | 130 |

# Response Time Computation - II

| Task | $C_i$ | $T_i$ | $\xi_{i,1}$ | $D_i$ | $B_i$ |
|---|---|---|---|---|---|
| $\tau_1$ | 20 | 70 | 0 | 30 | 2 |
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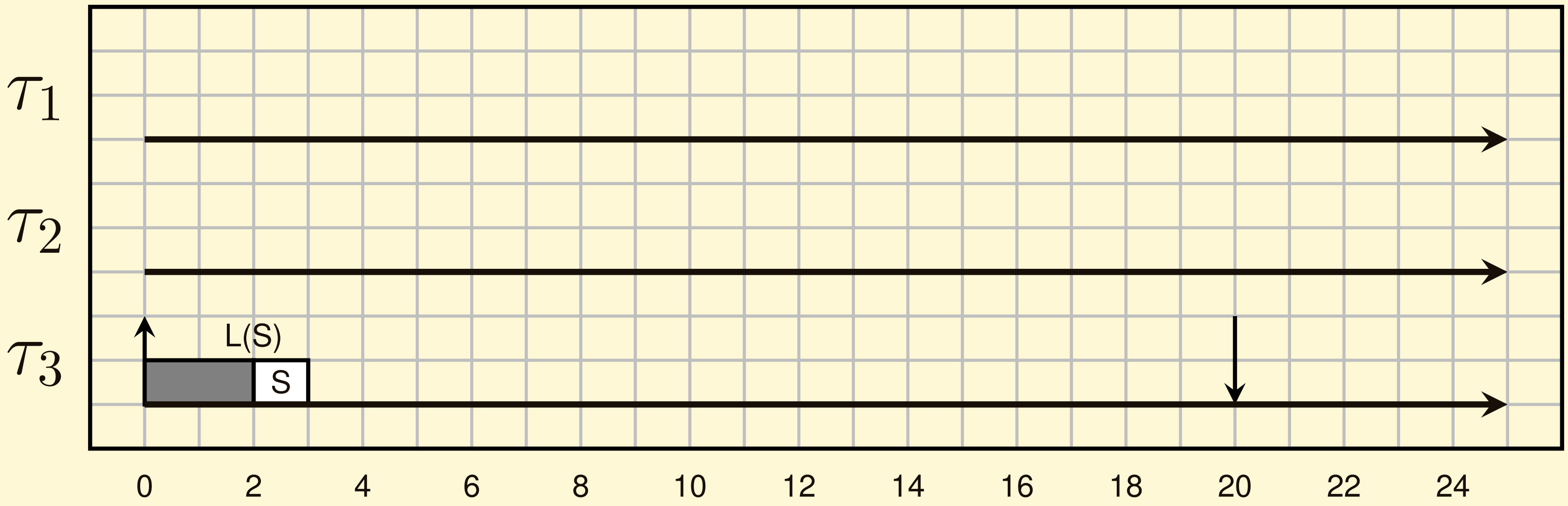
| $\tau_3$ | 35 | 200 | 2 | 130 | 0 |

# Response Time Computation - III

| Task | $C_i$ | $T_i$ | $\xi_{i,1}$ | $D_i$ | $B_i$ | $R_i$ |
|---|---|---|---|---|---|---|
| $\tau_1$ | 20 | 70 | 0 | 30 | 2 | 20+2=22 |
| $\tau_2$ | 20 | 80 | 1 | 45 | 2 | 20+20+2=42 |
| $\tau_3$ | 35 | 200 | 2 | 130 | 0 | 35+2*20+2*20=115 |

# The Priority Inheritance protocol

- Another possible solution to the priority inversion:
  - a low priority task $\tau_3$ blocking an higher priority task $\tau_1$ *inherits* its priority
  - $\rightarrow$ medium priority tasks cannot preempt $\tau_3$



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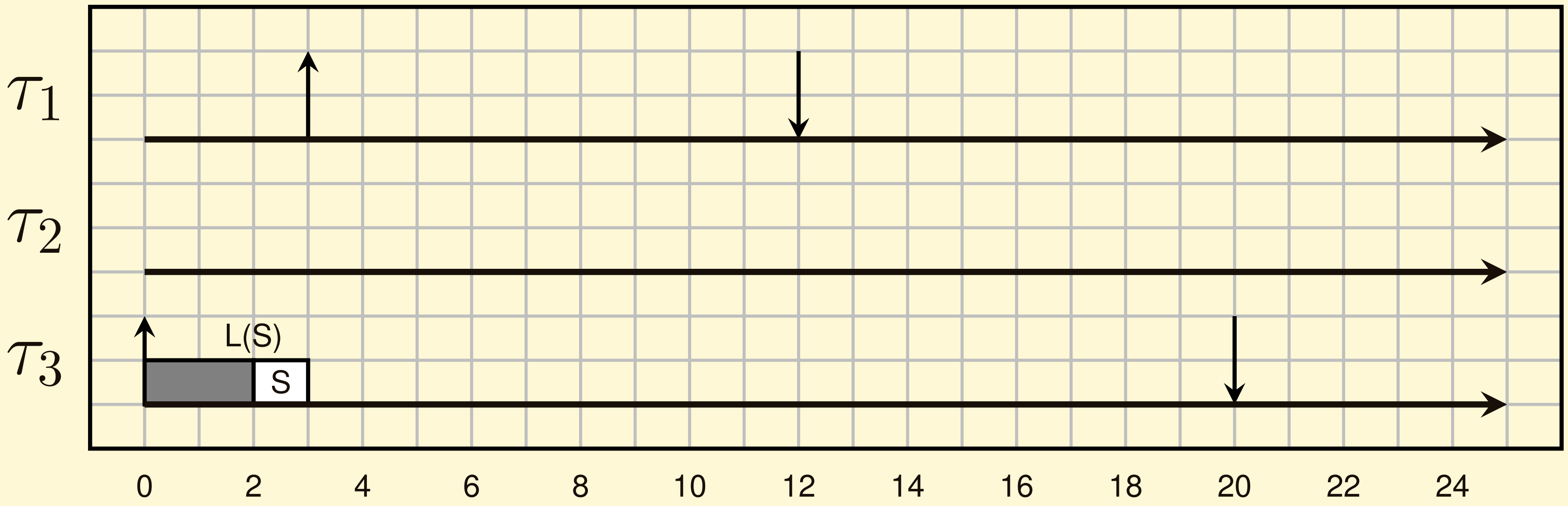

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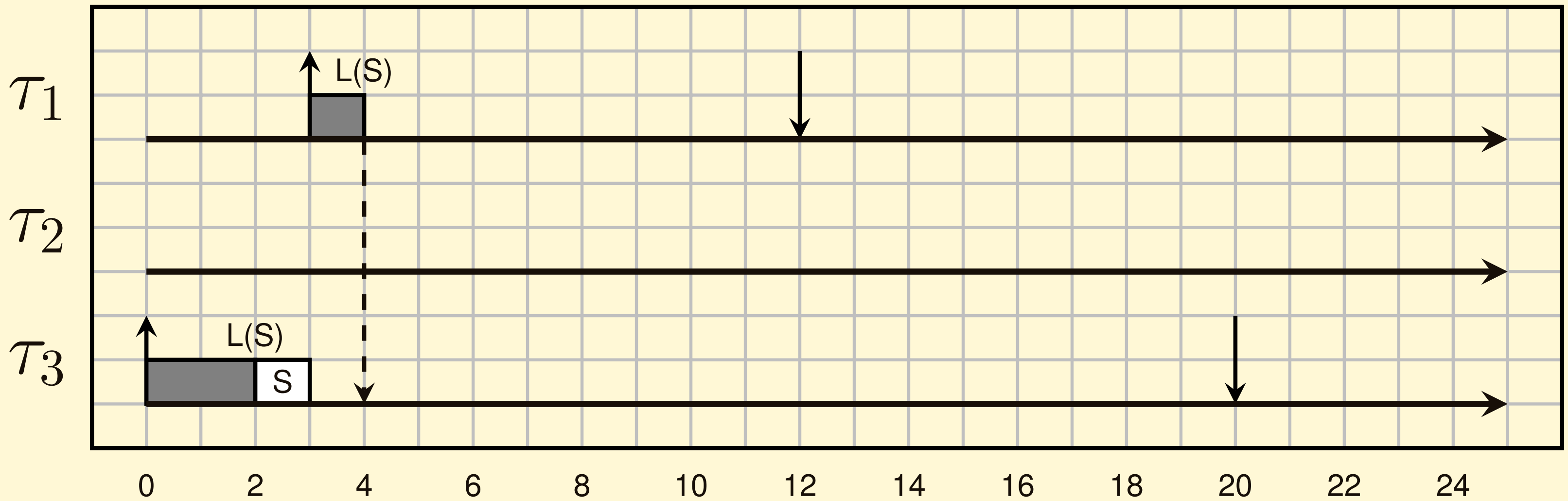

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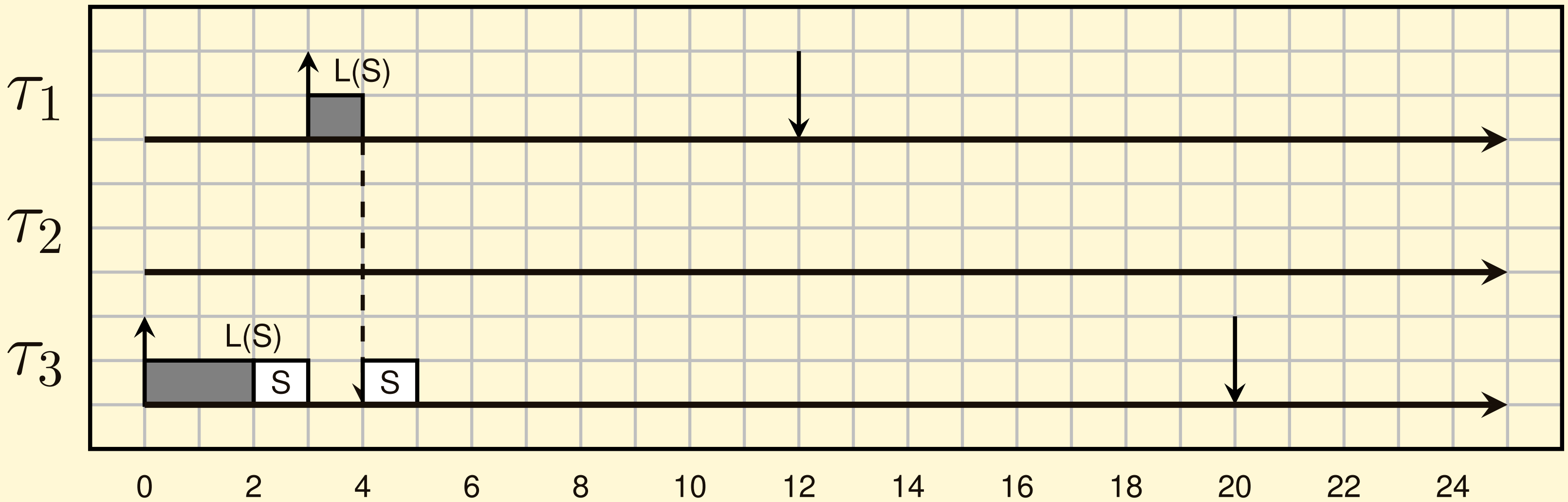


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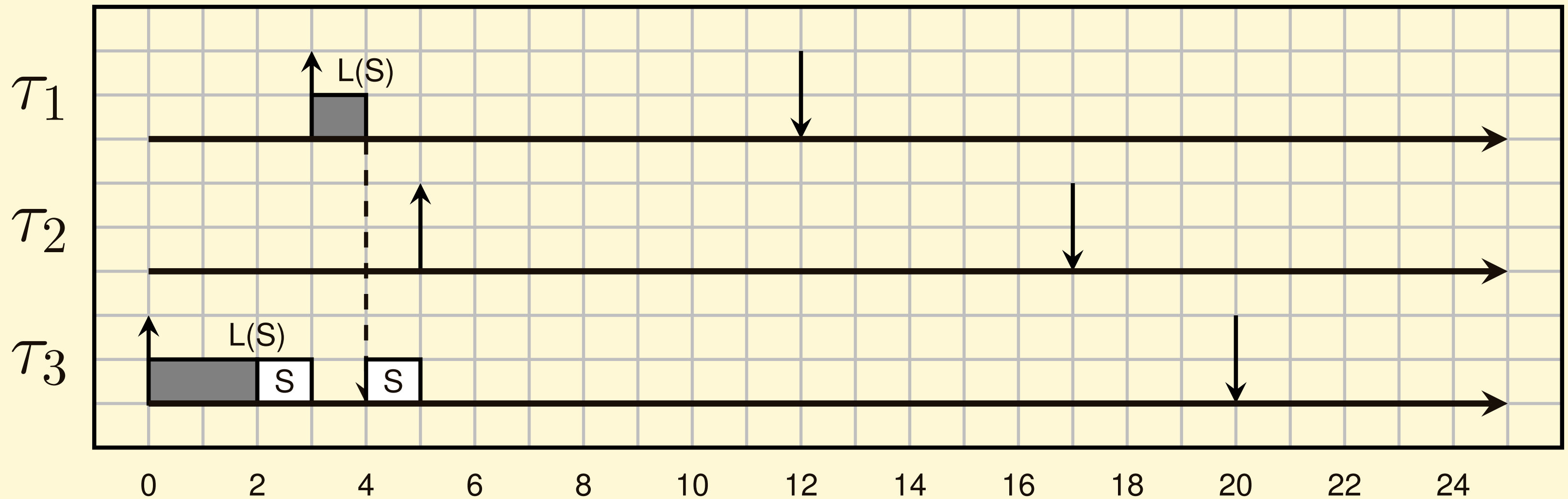


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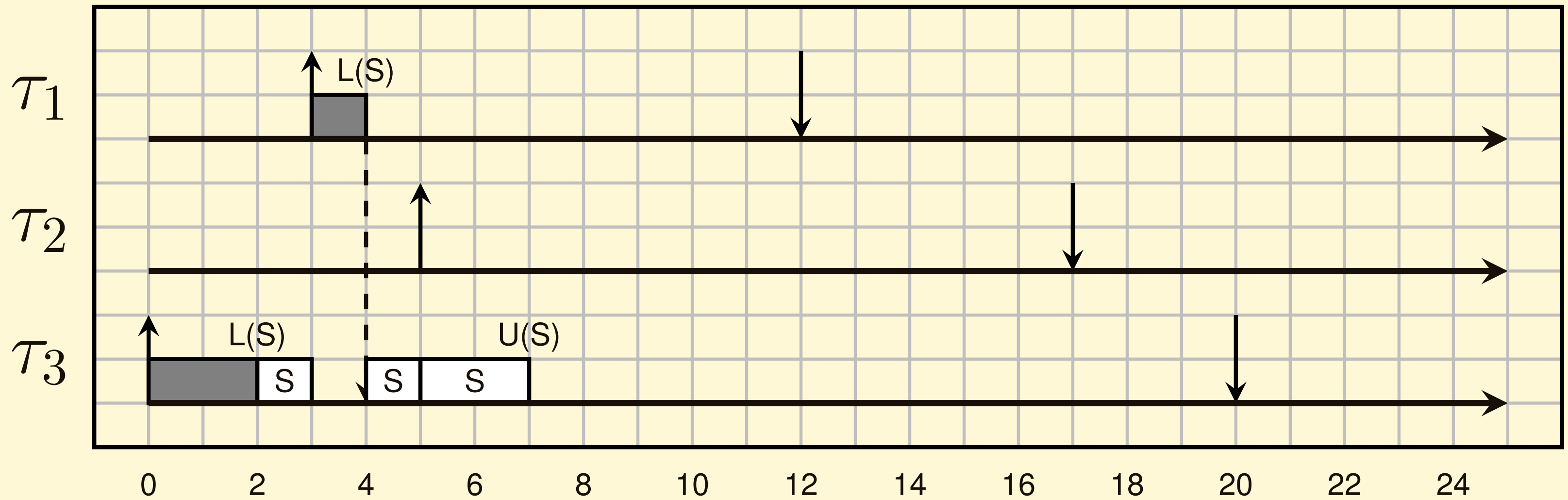


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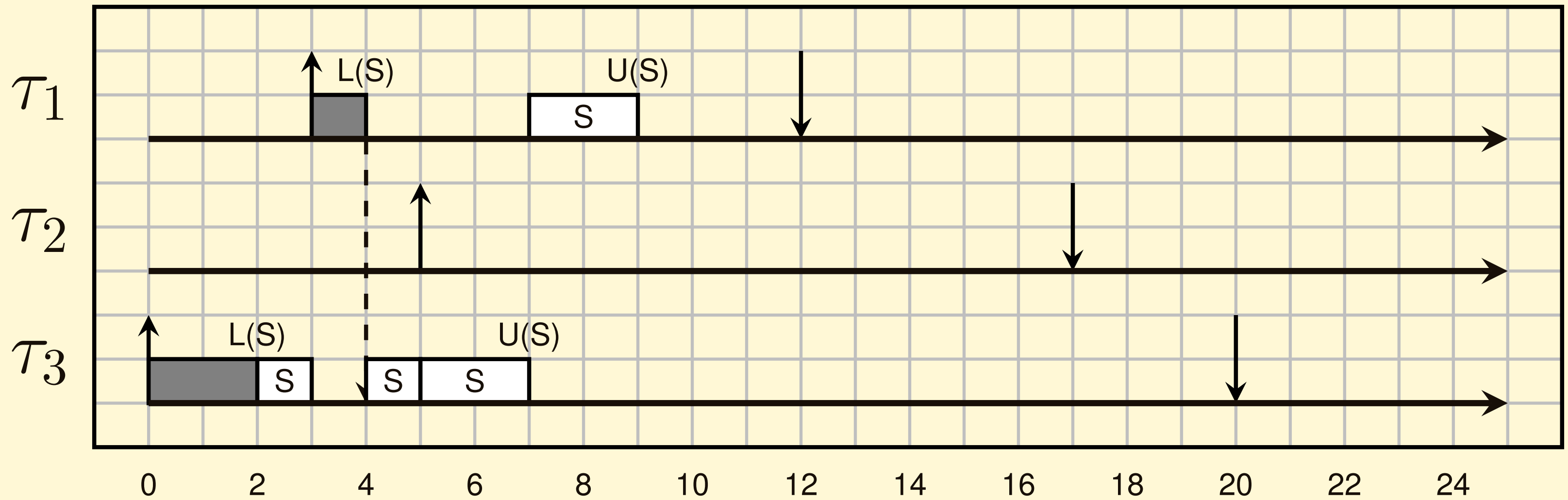


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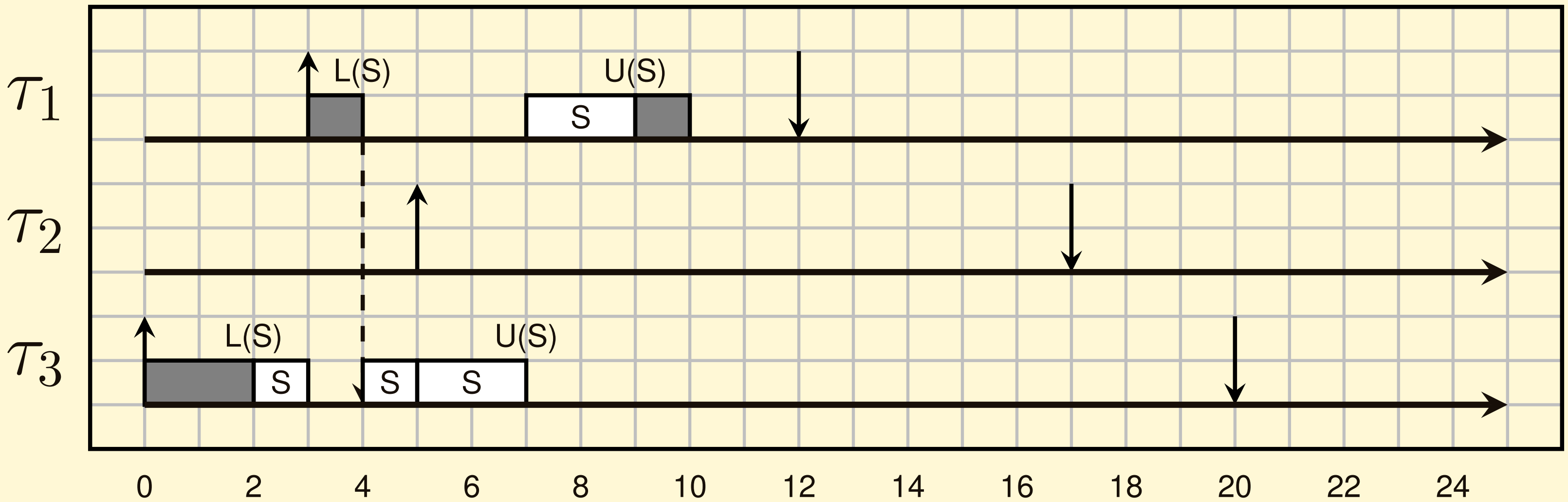


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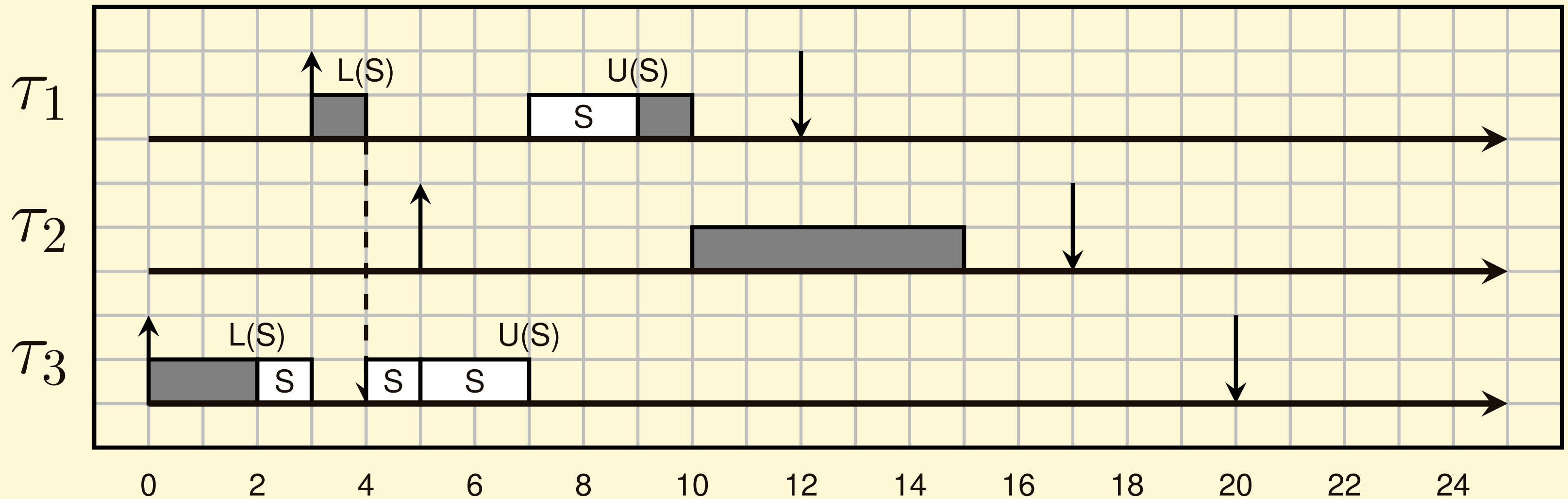


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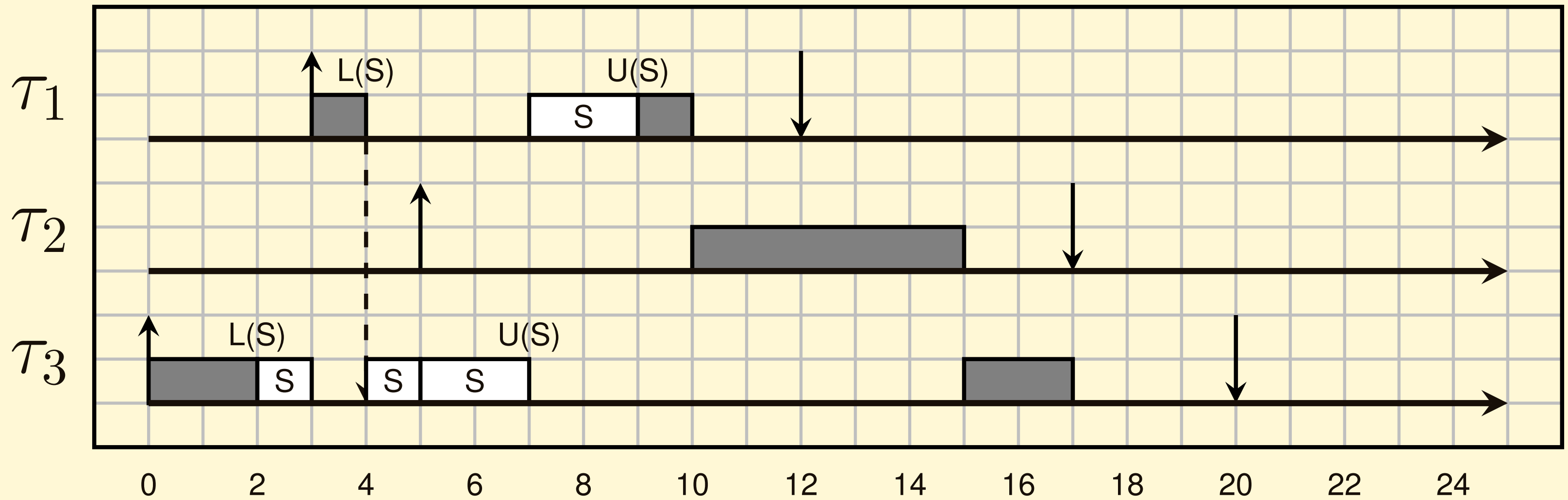


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# Some PI Properties

- Summarising, the main rules are the following:
  - If a task $\tau_i$ blocks on a resource protected by a mutex $S$, and the resource is locked by task $\tau_j$, then $\tau_j$ *inherits* the priority of $\tau_i$
  - If $\tau_j$ itself blocks on another mutex by a task $\tau_k$, then $\tau_k$ inherits the priority of $\tau_i$ (*multiple inheritance*)
  - If $\tau_k$ is blocked, the chain of blocked tasks is followed until a non-blocked task is found that inherits the priority of $\tau_i$
  - When a task unlocks a mutex, it returns to the priority it had when locking it

# Using HLP and PI

- Remember: Linux with kernel preemption uses NPP
  - Worst-case latency: maximum size of a kernel critical section
  - Latencies affect all the tasks (even tasks not using the kernel!)
  - Improvements: use PI or HLP
- Using HLP: $\mu$-kernel and dual-kernel (co-kernel) systems
  - NRT tasks using linux: only block Linux (NRT) tasks
  - RT tasks using a real-time co-kernel (or a $\mu$-kernel) $\leftarrow$ higher priority than NRT tasks
- Using PI: Preempt-RT (full kernel preemption!)