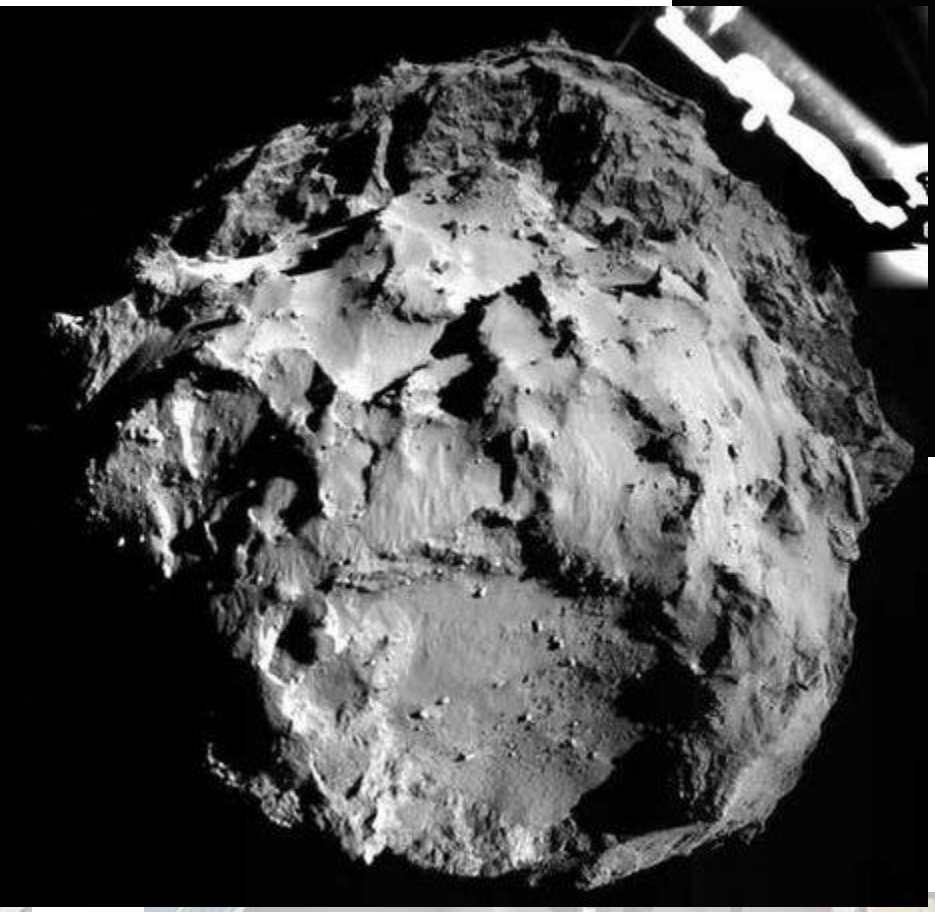
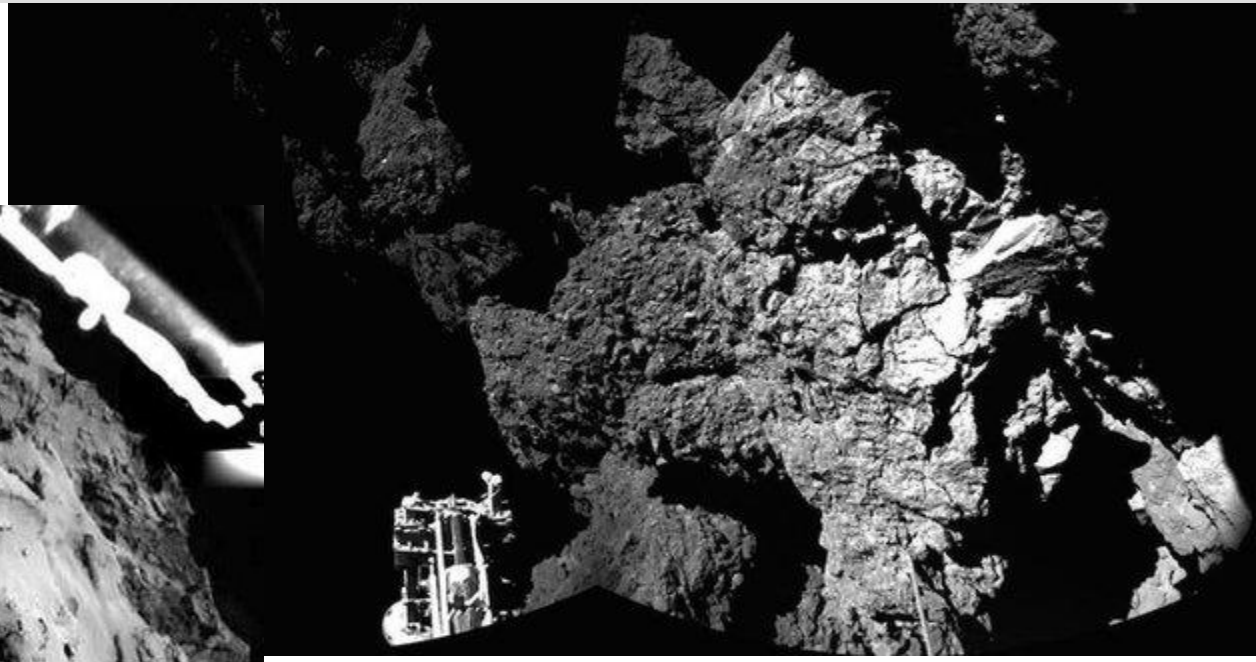
Embedded Software

Kai Huang

Rosetta: Comet probe Philae now stable

- **Latest pictures**



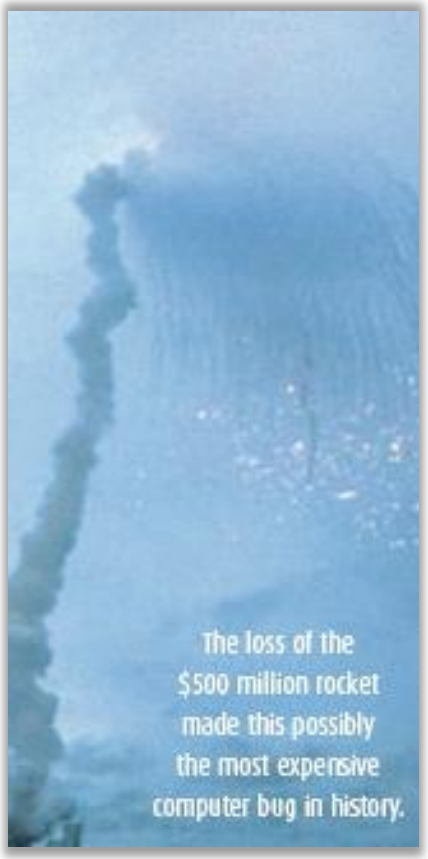


- **Mission facts:**
  - **Philae lander**
    - Travelled 6.4 billion km (four billion miles) to reach the comet
    - Journey took 10 years
    - Planning for the journey began 25 years ago
  - **Comet 67P**
    - More than four billion years old
    - Mass of 10 billion tonnes
    - Hurtling through space at 18km/s (40,000mph)
    - Shaped like a rubber duck

Antares rocket exploded. 30 Oct. 2014

Ariane 5 explosion

A data conversion from 64-bit floating point value to 16-bit signed integer value to be stored in a variable representing horizontal bias caused a processor trap (operand error) because the floating point value was too large to be represented by a 16-bit signed integer. The software was originally written for the Ariane 4 where efficiency considerations (the computer running the software had an 80% maximum workload requirement) led to four variables being protected with a handler while three others, including the horizontal bias variable, were left unprotected because it was thought that they were "physically limited or that there was a large margin of error". The software, written in Ada, was included in the Ariane 5 through the reuse of an entire Ariane 4 subsystem despite the fact that the particular software containing the bug, which was just a part of the subsystem, was not required by the Ariane 5 because it has a different preparation sequence than the Ariane 4.



- *Global Embedded Software Market To Grow At A CAGR Of 10.7 Percent Over The Period 2012-2016*

  - Embedded Software Market - 2013 Report

- According to the report, main driver being the increased demand for embedded software is in the Automotive segment. Embedded software is used in the development of in-vehicle infotainment systems, in-car navigation, and telematics. It provides users with additional entertainment and communication features that are now major requirements for vehicle buyers. One major challenge confronting the market is the safety and security issues associated with the use of embedded software. There are higher chances of the embedded software to malfunction as opposed to application software.

http://www.researchandmarkets.com/research/2x3m7b/global_embedded

Outline

- Embedded Operating System
- Resource Access Protocols

Why an OS at all?

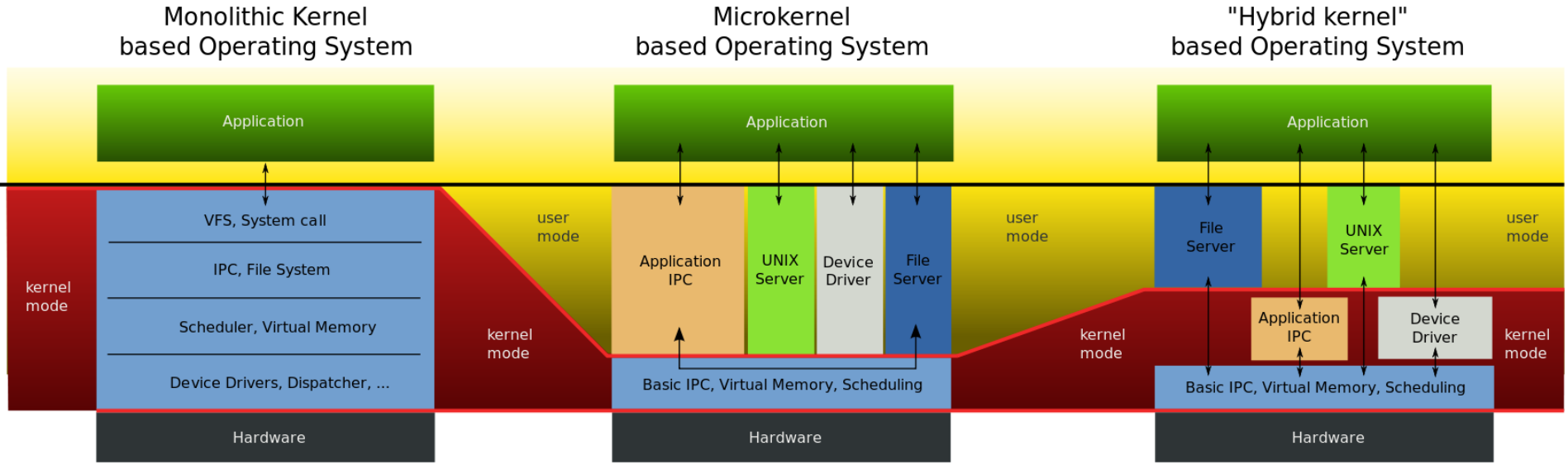
- Why not just bare-metal
  - Same reasons why we need one for a traditional computer.
  - Not all services are needed for any device.

- Large variety of requirements and environments:
  - Critical applications with high functionality (medical applications, space shuttle, ...).
  - Critical applications with small functionality (ABS, pace maker, ...)
- Not very critical applications with varying functionality (PDA, phone, smart card, microwave, oven, ...)

Why is a Desktop OS not Suited?

- Monolithic kernel is too feature reach.
- Monolithic kernel is not modular, fault-tolerant, configurable, modifiable, ...
- Takes too much space.
- Not power optimized.
- Not designed for mission-critical applications.

Operating System Architecture

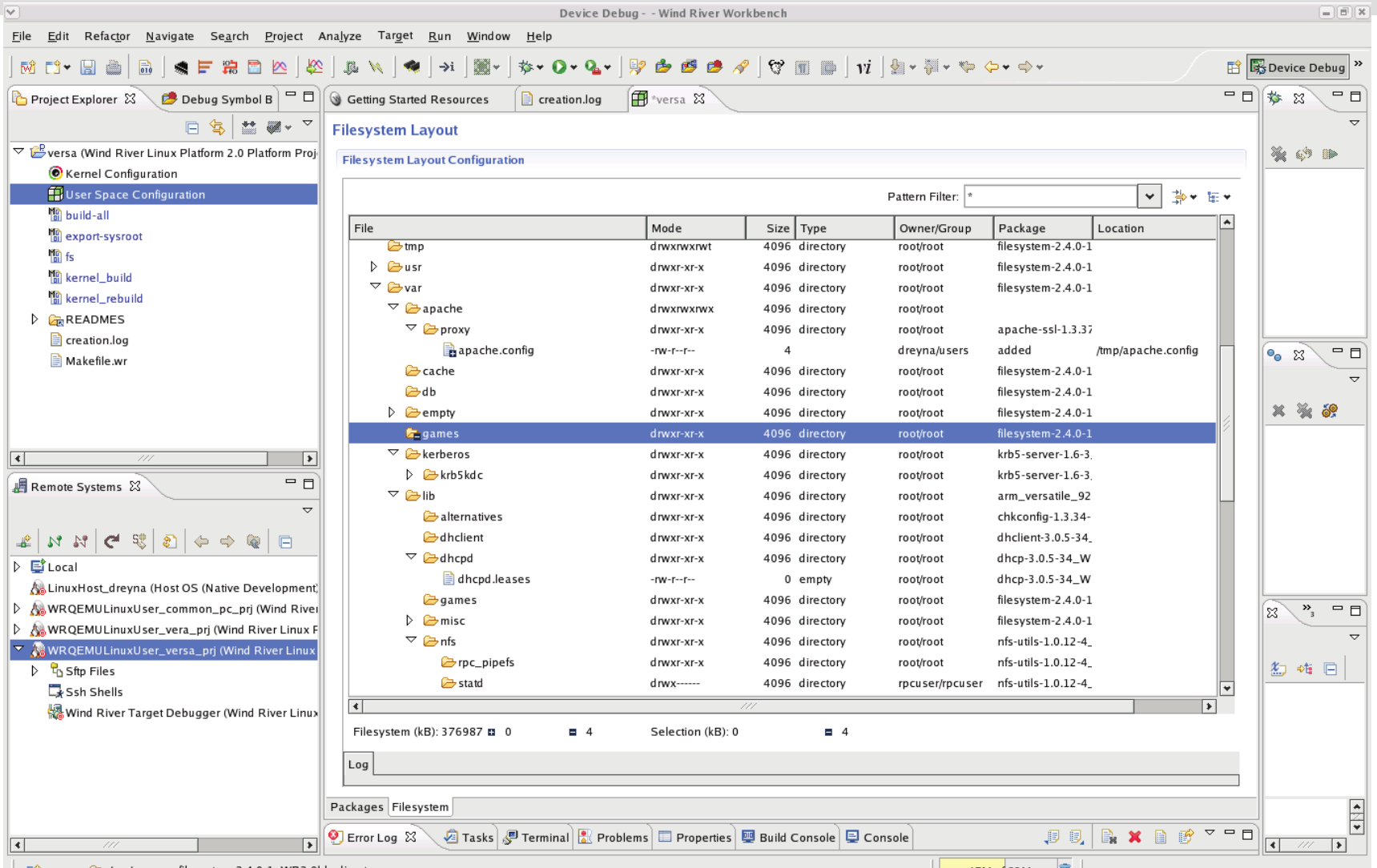


From wikipedia

Embedded OS - Configurability

- No single RTOS will fit all needs, no overhead for unused functions/data tolerated, configurability needed.
  - Simplest form: remove unused functions (by linker for example).
  - Conditional compilation (using #if and #ifdef commands).
  - Static data might be replaced by dynamic data (but then real-time behavior is in danger).

Example: Configuration of VxWorks

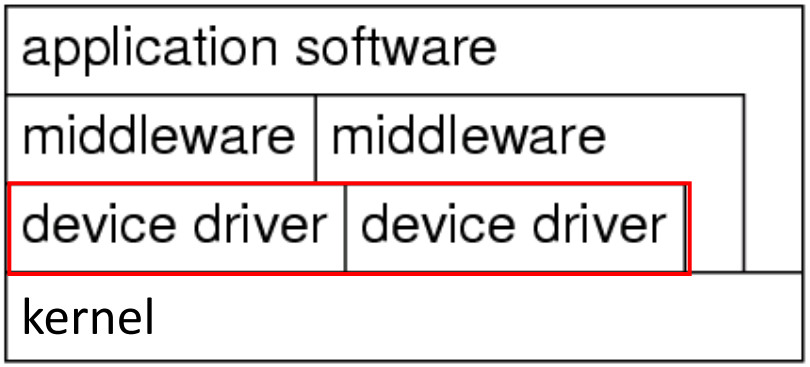


http://www.windriver.com/products/product-notes/PN_Workbench_0611.pdf

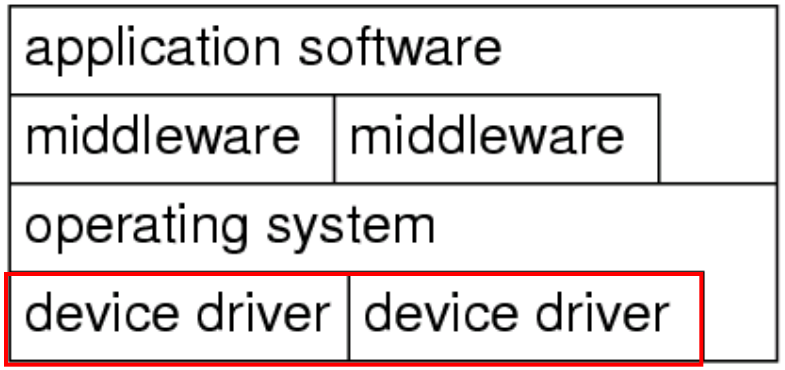
Embedded OS - Device Driver

- Device drivers handled by tasks instead of integrated drivers:
  - Improve predictability; everything goes through scheduler
  - Effectively no device that needs to be supported by all versions of the OS, except maybe the system timer.

Embedded OS



Standard OS



Embedded OS - Interrupt

- Interrupts can be employed by any process
  - For standard OS: would be serious source of unreliability.
  - Embedded programs can be considered to be tested … .
  - It is possible to let interrupts directly start or stop tasks (by storing the tasks start address in the interrupt table). More efficient and predictable than going through OS services.
  - However, composability suffers: if a specific task is connected to some interrupt, it may be difficult to add another task which also needs to be started by the same event.

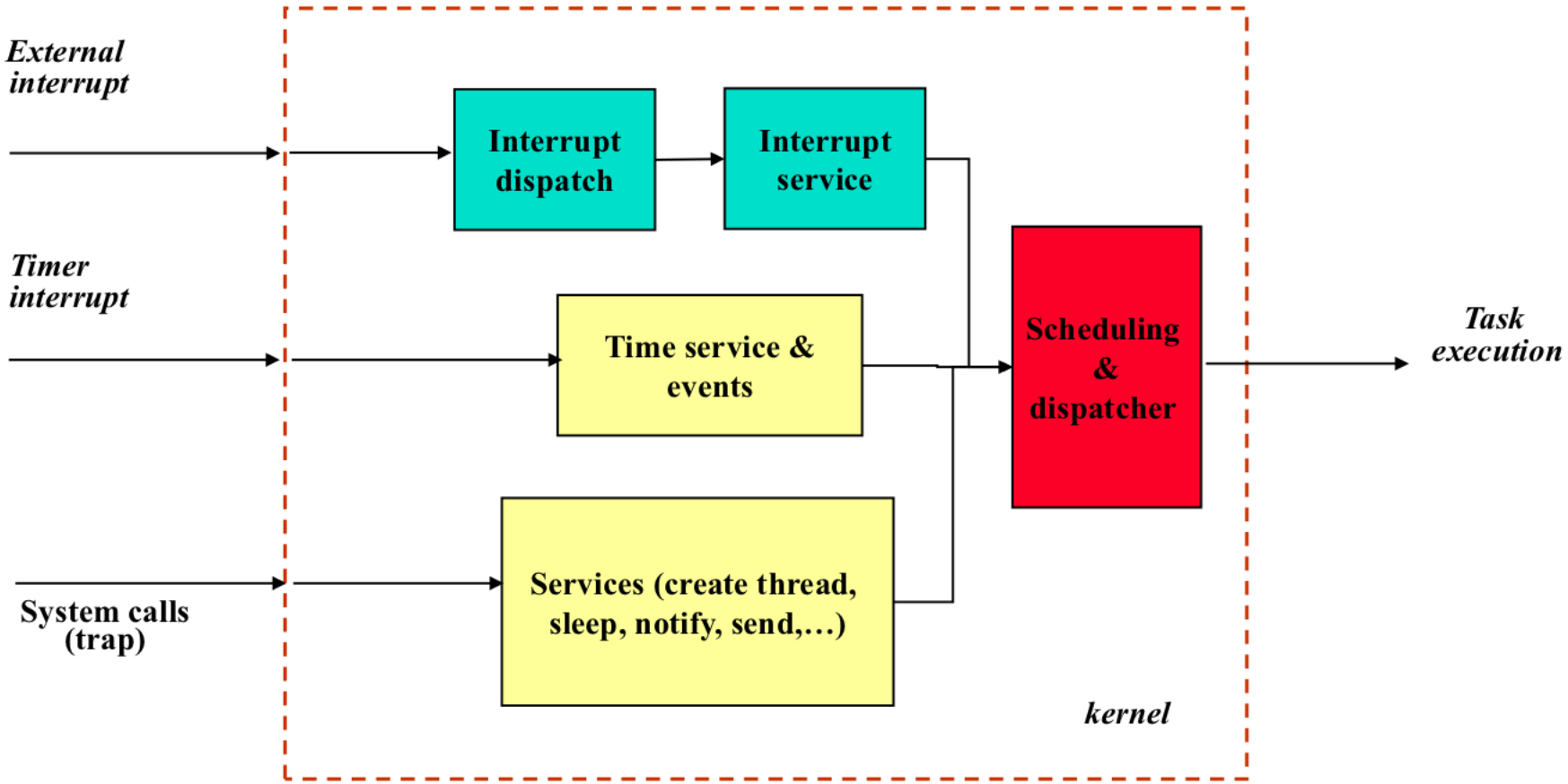
Real-Time OS

- Definition: A real-time operating system is an operating system that supports the construction of real-time systems.

- Three key requirements:

  1. The timing behavior of the OS must be predictable.
     - Every services of the OS: Upper bound on the execution time!
     - RTOSs must be deterministic:
       - unlike standard Java,
       - upper bound on times during which interrupts are disabled,
       - almost all activities are controlled by scheduler.
  2. OS must manage the timing and scheduling
     - OS possibly has to be aware of task deadlines; (unless scheduling is done off-line).
     - OS must provide precise time services with high resolution.
  3. The OS must be fast
     - Practically important.

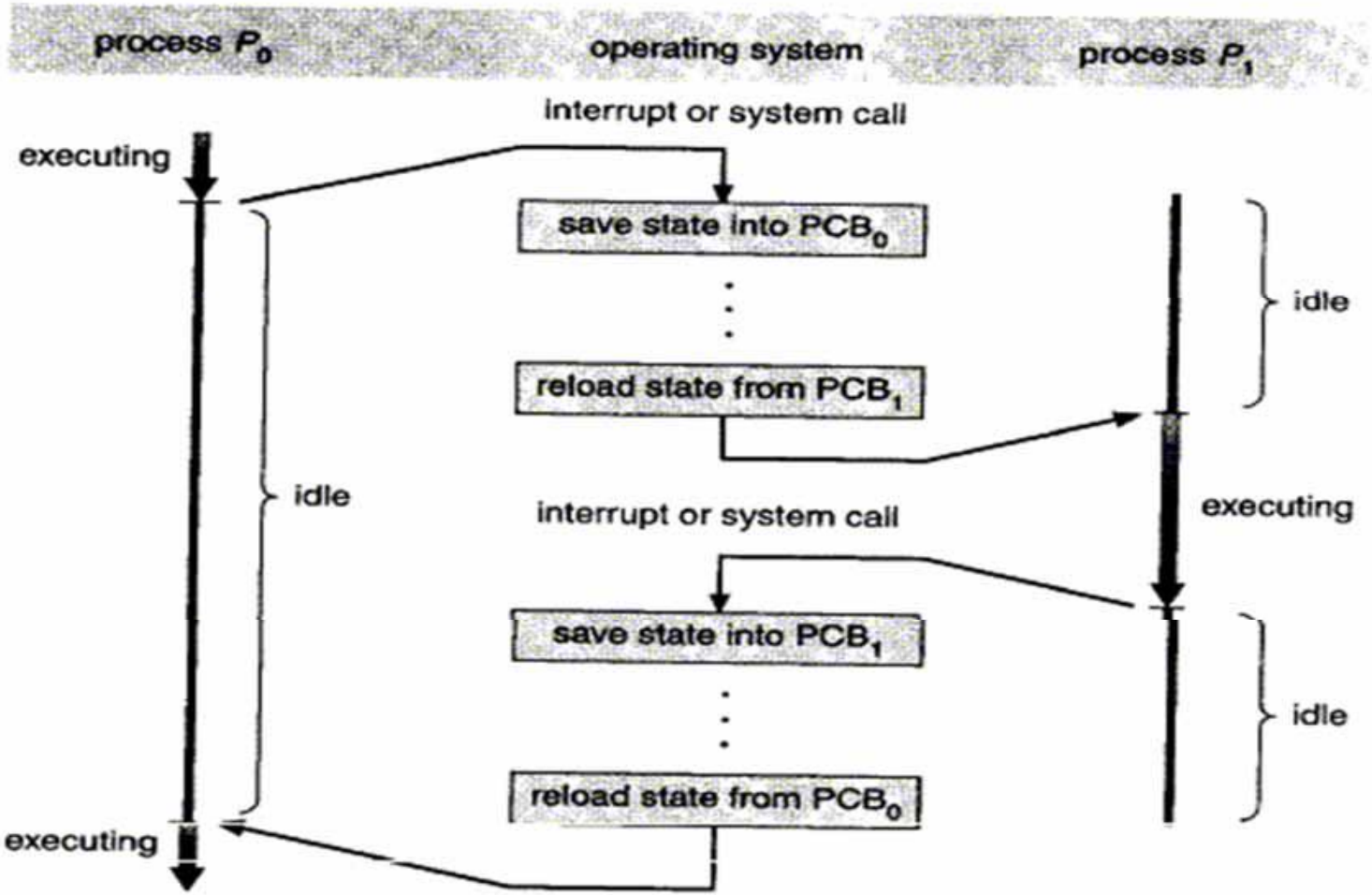
Process Management Services



Main Functionality of RTOS-Kernels

- Process management:
  - Execution of quasi-parallel tasks on a processor using processes or threads (lightweight process) by
    - maintaining process states, process queuing,
    - preemptive tasks (fast context switching) and quick interrupt handling
  - CPU scheduling (guaranteeing deadlines, minimizing process waiting times, fairness in granting resources such as computing power)
  - Process synchronization (critical sections, semaphores, monitors, mutual exclusion)
  - Inter-process communication (buffering)
  - Support of a real-time clock as an internal time reference

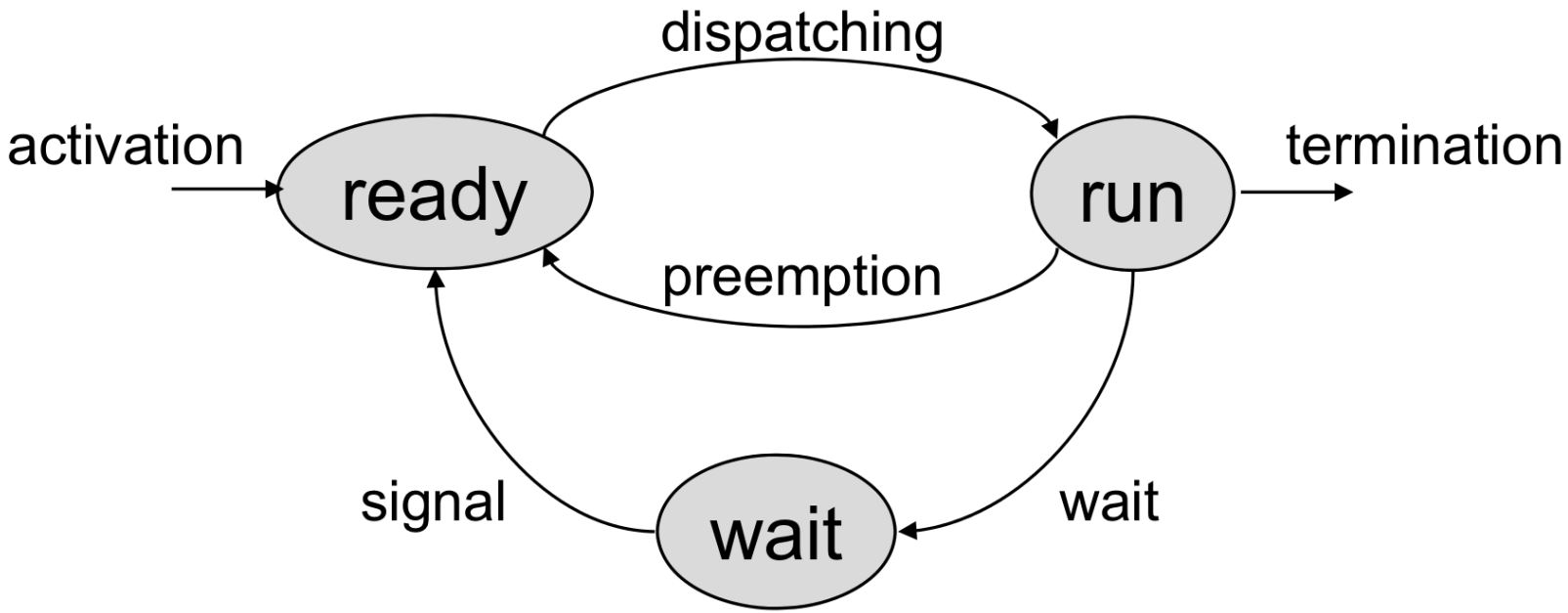
Context Switching



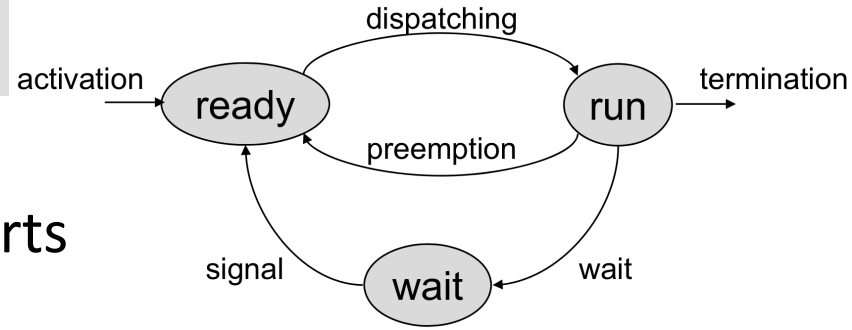
PCB: Process Control Block

Process States

- Minimal Set of Process States:



Process states

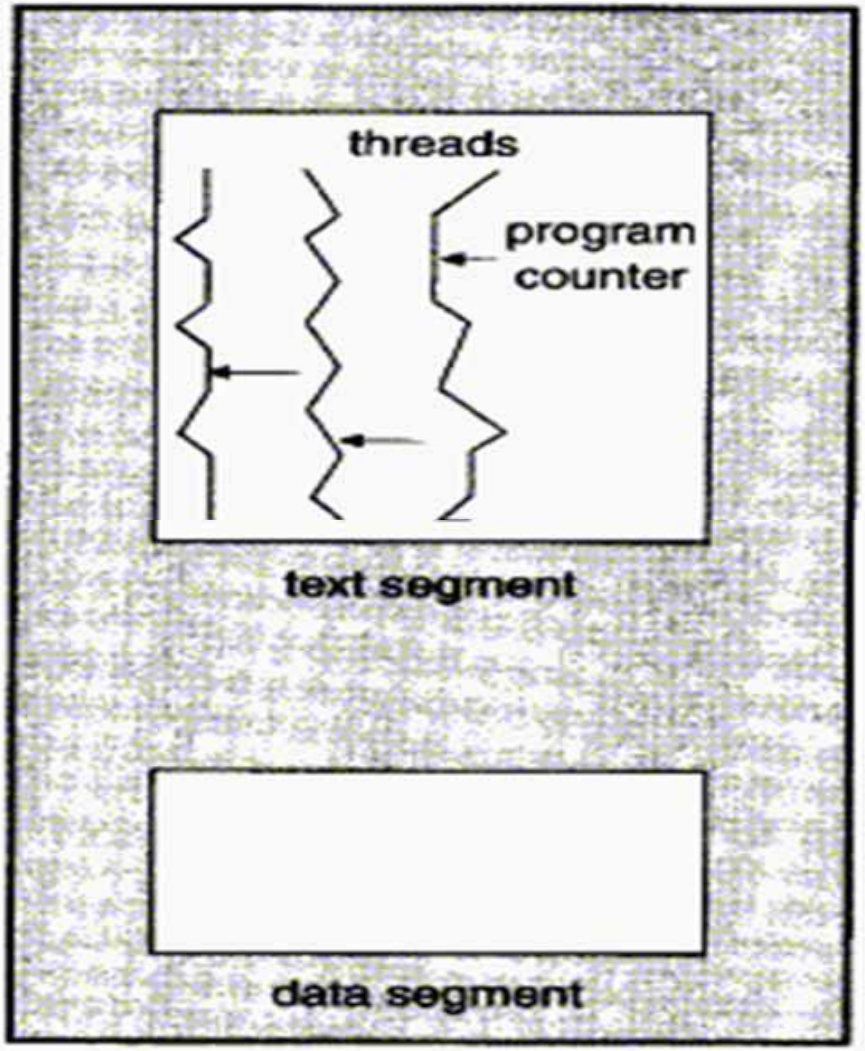


- Run:
  - A task enters this state as it starts executing on the processor
- Ready:
  - State of those tasks that are ready to execute but cannot be executed because the processor is assigned to another task.
- Wait:
  - A task enters this state when it executes a synchronization primitive to wait for an event, e.g., a wait primitive on a semaphore. In this case, the task is inserted in a queue associated with the semaphore. The task at the head is resumed when the semaphore is unlocked by a signal primitive. (Idle state can be a substate of wait)

Threads

- A thread is an execution stream within the context of a thread state; e.g., a thread is a basic unit of CPU utilization.
- The key difference between processes and threads: multiple threads share parts of their state.
  - Typically shared: memory.
  - Typically owned: registers, stack.
- Thread advantages and characteristics
  - Faster to switch between threads; switching between user-level threads requires no major intervention by operating system.
  - Typically, an application will have a separate thread for each distinct activity.
  - Thread Control Block (TCB) stores information needed to manage and schedule a thread
    - E.g., pointer to the PCB

Multiple Threads within a Process



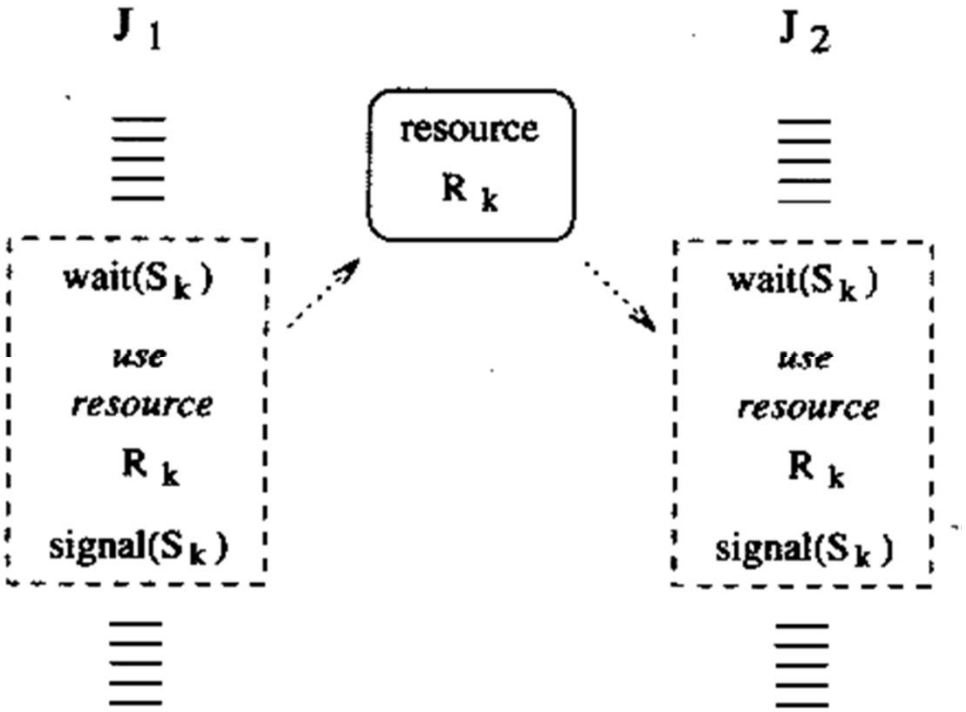
Process Management

- Process synchronization:
  - In classical operating systems, synchronization and mutual exclusion is performed via semaphores and monitors.
  - In real-time OS, special semaphores and a deep integration into scheduling is necessary (priority inheritance protocols, ...).

- Further responsibilities:
  - Initializations of internal data structures (tables, queues, task description blocks, semaphores, ...)

Communication Mechanisms

- Problem: the use of shared resources for implementing message passing schemes may cause priority inversion and blocking.

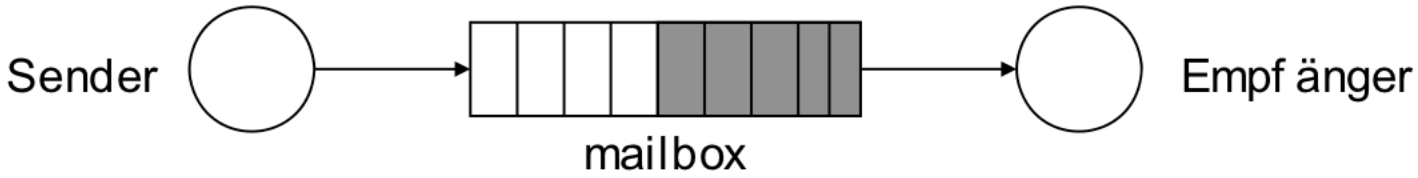


Communication mechanisms

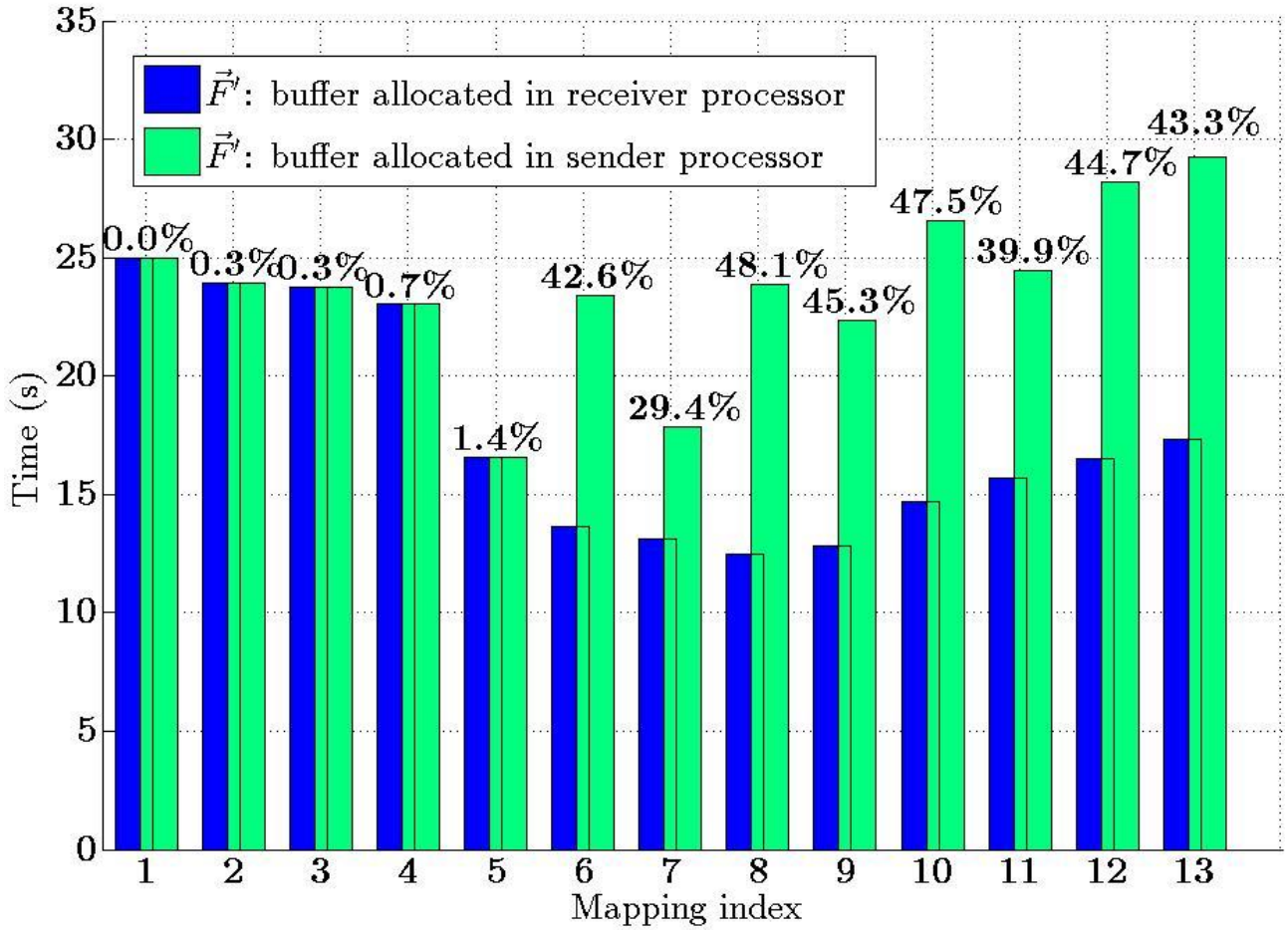
- Synchronous communication:
  - Whenever two tasks want to communicate they must be synchronized for a message transfer to take place (rendezvous)
  - They have to wait for each other.
  - Problem in case of dynamic real-time systems: Estimating the maximum blocking time for a process rendezvous.
  - In a static real-time environment, the problem can be solved off-line by transforming all synchronous interactions into precedence constraints.

Communication mechanisms

- Asynchronous communication:
  - Tasks do not have to wait for each other
  - The sender just deposits its message into a channel and continues its execution; similarly the receiver can directly access the message if at least a message has been deposited into the channel.
  - More suited for real-time systems than synchronous comm.
  - Mailbox: Shared memory buffer, FIFO-queue, basic operations are send and receive, usually has fixed capacity.
  - Problem: Blocking behavior if channel is full or empty; alternative approach is provided by cyclical asynchronous buffers.



Impact of Buffer Allocation



Class 1: Fast Proprietary Kernels

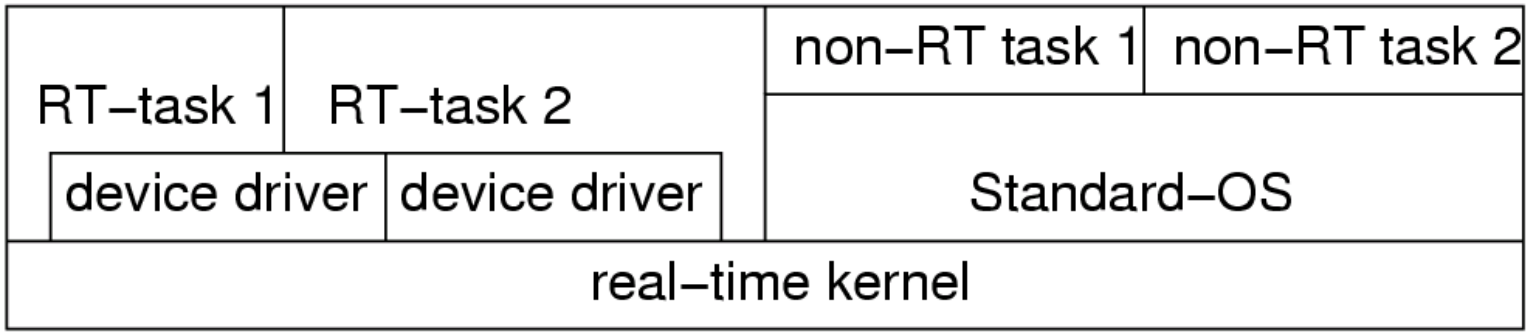
- Fast proprietary kernels

  For hard real-time systems, these kernels are questionable, because they are designed to be fast, rather than to be predictable in every respect

- Examples include
  - QNX, PDOS, VCOS, VTRX32, VxWORKS.

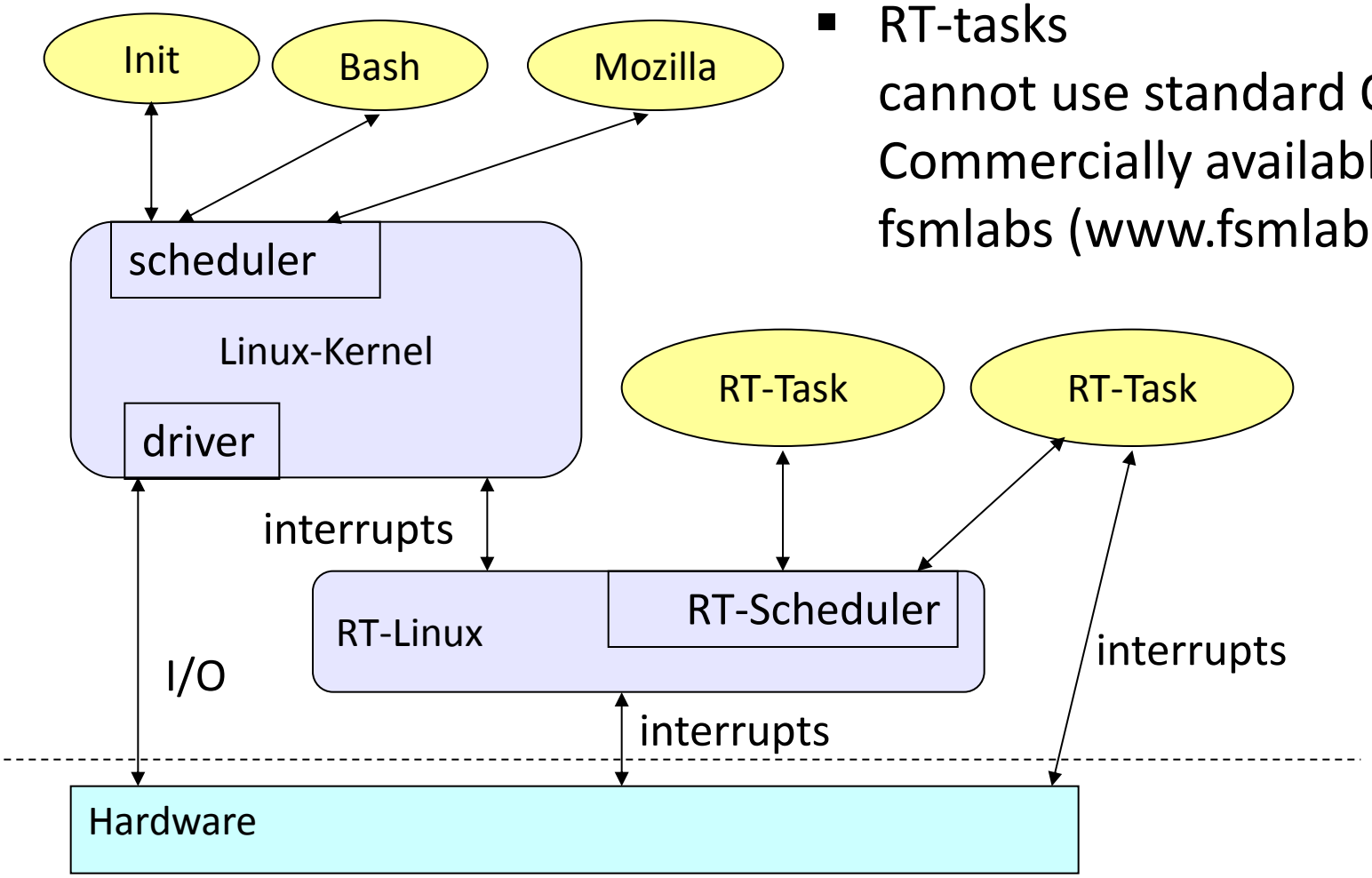
Class 2: Extensions to Standard OSs

- Real-time extensions to standard OS:
  - Attempt to exploit comfortable main stream OS.
  - RT-kernel running all RT-tasks.
  - Standard-OS executed as one task.



+ Crash of standard-OS does not affect RT-tasks;
- RT-tasks cannot use Standard-OS services;
  less comfortable than expected

Example RT Linux



- RT-tasks
  cannot use standard OS calls.
  Commercially available from fsmlabs (www.fsmlabs.com)

Class 3: Research Systems

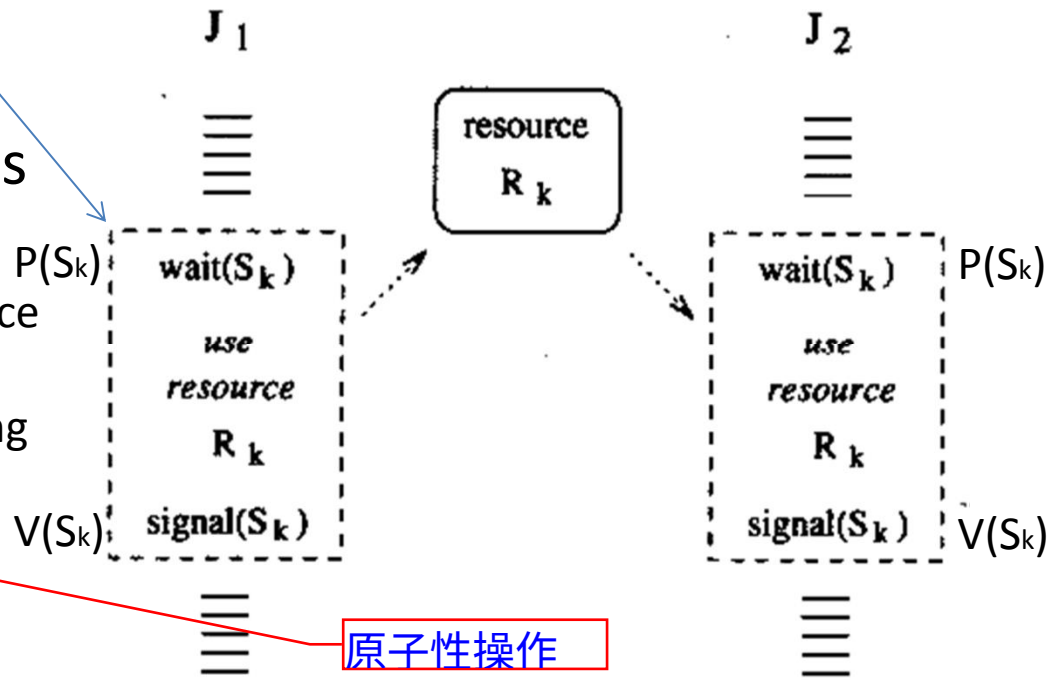
- Research systems trying to avoid limitations:
  - Include MARS, Spring, MARUTI, Arts, Hartos, DARK, and Melody
  - More latest: FreeRTOS, RTEMS, PikeOS, OKL4, uC/OS-II …
- Research issues:
  - low overhead memory protection,
  - temporal protection of computing resources
  - RTOSes for on-chip multiprocessors
  - quality of service (QoS) control (besides real-time constraints).

Outline

- Embedded Operating System
- Resource Access Protocols

Resource Sharing

- Examples of common resources: data structures, variables, main memory area, file, set of registers, I/O unit, ...
- Many shared resources do not allow simultaneous accesses but require mutual exclusion (exclusive resources). A piece of code executed under mutual exclusion constraints is called a critical section.
- Can be guaranteed with semaphores S or mutexes

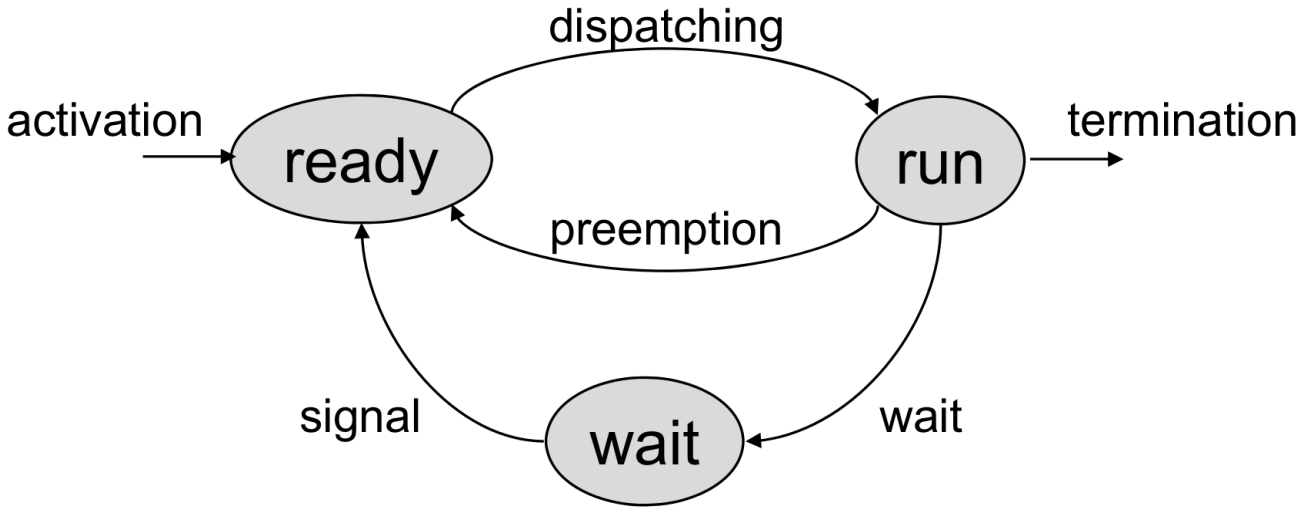


P(S) checks semaphore to see if resource is available and if yes, sets S to “used“. Uninterruptible operations! If no, calling task has to wait.

V(S): sets S to “unused“ and starts sleeping task (if any).

Terms

- A task waiting for an exclusive resource is said to be blocked on that resource. Otherwise, it proceeds by entering the critical section and holds the resource. When a task leaves a critical section, the associated resource becomes free.
- Waiting state caused by resource constraints:



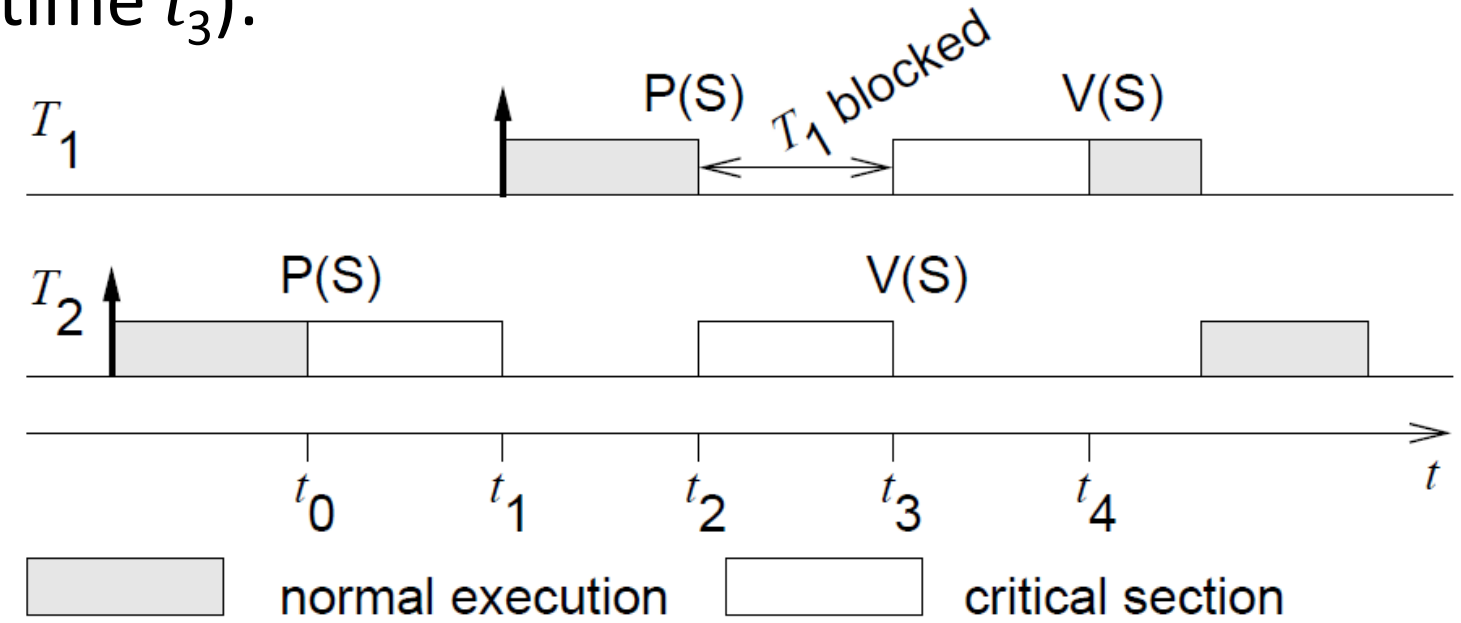
Terms

- Each exclusive resource R_i must be protected by a different semaphore S_i and each critical section operating on a resource must begin with a wait(S_i) primitive and end with a signal(S_i) primitive.

- All tasks blocked on the same resource are kept in a queue associated with the semaphore. When a running task executes a wait on a locked semaphore, it enters a waiting state, until another tasks executes a signal primitive that unlocks the semaphore.

Priority Inversion (1)

- Priority T_1 assumed to be > than priority of T_2.
- If T_2 requests exclusive access first (at t_0), T_1 has to wait until T_2 releases the resource (at time t_3):

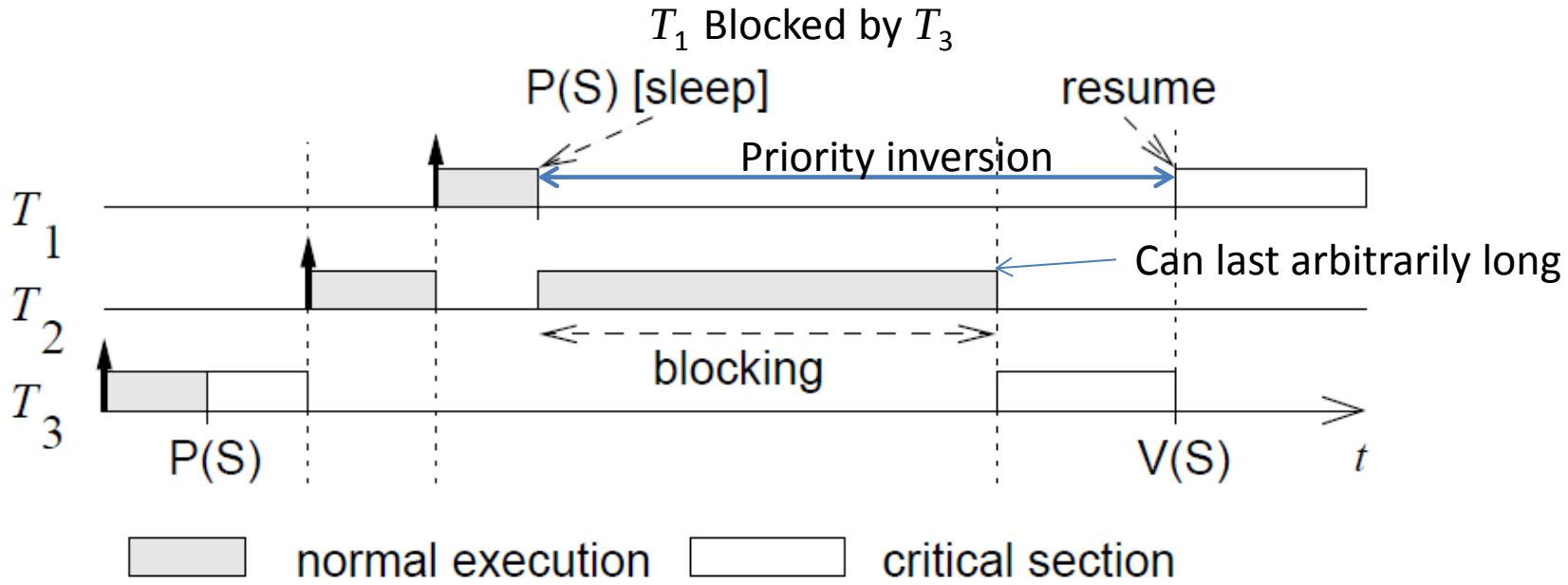


For 2 tasks: blocking is bounded by the length of the critical section

Priority Inversion (2)

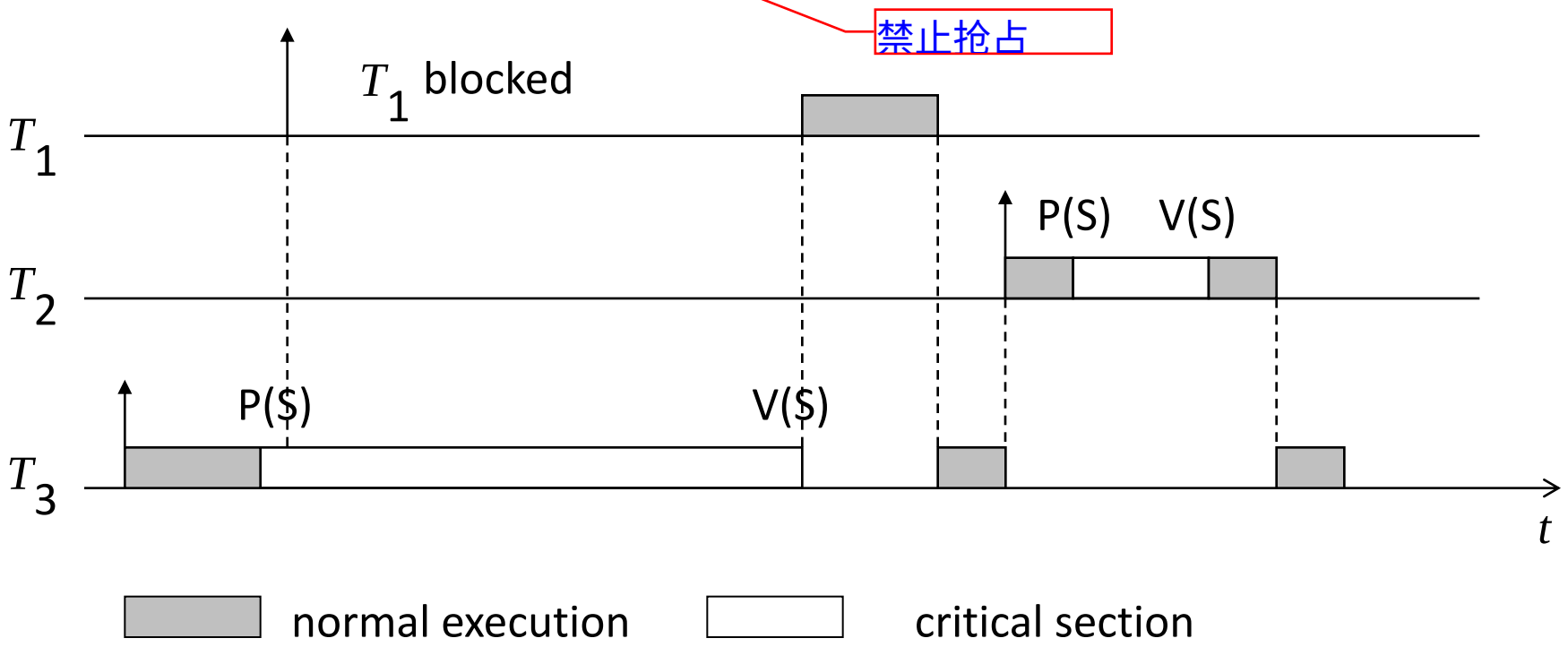
- Blocking with >2 tasks can exceed the length of any critical section
  - Priority of T_1 > priority of T_2 > priority of T_3.
  - T_2 preempts T_3: T_2 can prevent T_3 from releasing the resource.

等待一个优先级比自己低的进程结束



Solutions

- **Disallow preemption** during the execution of all critical sections. Simple, but creates unnecessary blocking as unrelated tasks may be blocked.



Resource Access Protocols

- Basic idea: Modify the priority of those tasks that cause blocking. When a task T_i blocks one or more higher priority tasks, it temporarily assumes a higher priority.

- Methods:
  - Priority Inheritance Protocol (PIP), for static priorities
  - Priority Ceiling Protocol (PCP), for static priorities
  - Stack Resource Policy (SRP),
    - For static and dynamic priorities
  - others ...

Priority Inheritance Protocol (PIP)

- Assumptions:
  - n tasks which cooperate through m shared resources; fixed priorities, all critical sections on a resource begin with a wait(S_i) and end with a signal(S_i) operation.

- Basic idea:
  - When a task T_i blocks one or more higher priority tasks, it temporarily assumes (inherits) the highest priority of the blocked tasks.

- Terms:
  - We distinguish a fixed nominal priority P_i and an active priority p_i larger or equal to P_i. Tasks T_i, ..., T_n are ordered with respect to nominal priority where T_1 has highest priority. Tasks do not suspend themselves.

PIP: Algorithm

- Tasks are scheduled according to their active priorities. Tasks with the same priorities are scheduled FCFS.
- When a task T_i tries to enter a critical section and the resource is blocked by a lower priority task, the task T_i is blocked. Otherwise it enters the critical section.
- When a task T_i is blocked, it transmits its active priority to the task T_k that holds the semaphore. T_k resumes and executes the rest of its critical section with a priority $p_k = p_i$ (it inherits the priority of the highest priority of the tasks blocked by it).
- When T_k exits a critical section, it unlocks the semaphore and the highest priority task blocked on that semaphore is awakened. If no other tasks are blocked by T_k, then p_k is set to P_k, otherwise it is set to the highest priority of the tasks blocked by T_k.

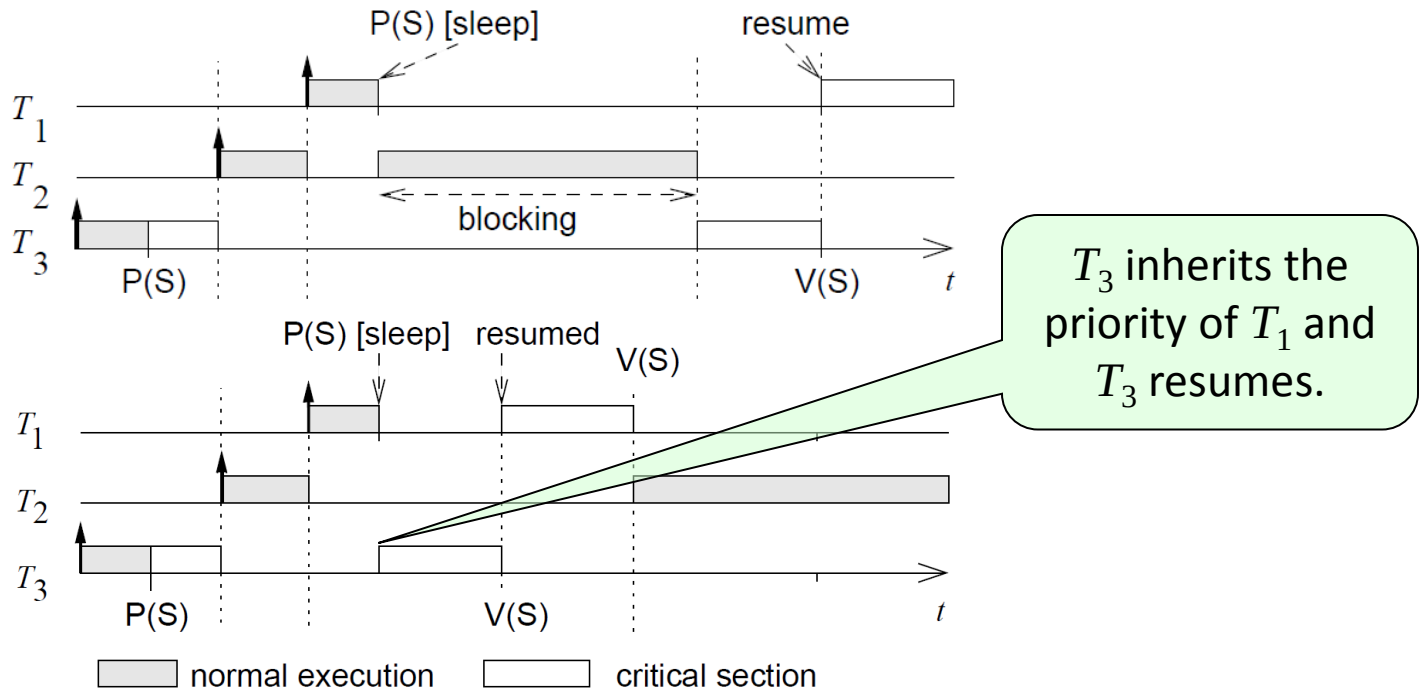
- Priority inheritance is transitive, i.e., if 1 is blocked by 2 and 2 is blocked by 3, then 3 inherits the priority of 1 via 2.

Example

- How would priority inheritance affect our example with 3 tasks?

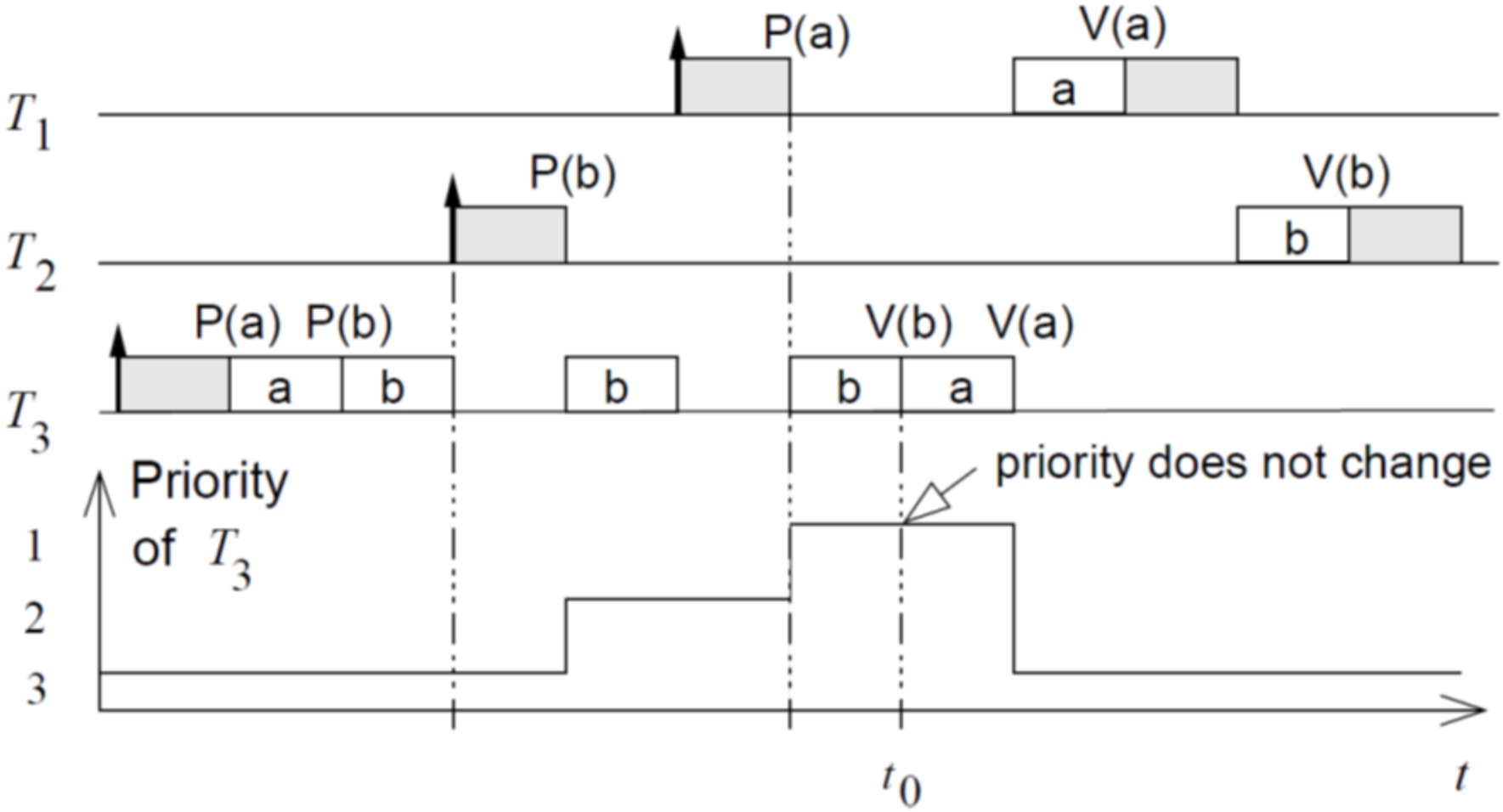
Before:

PIP:



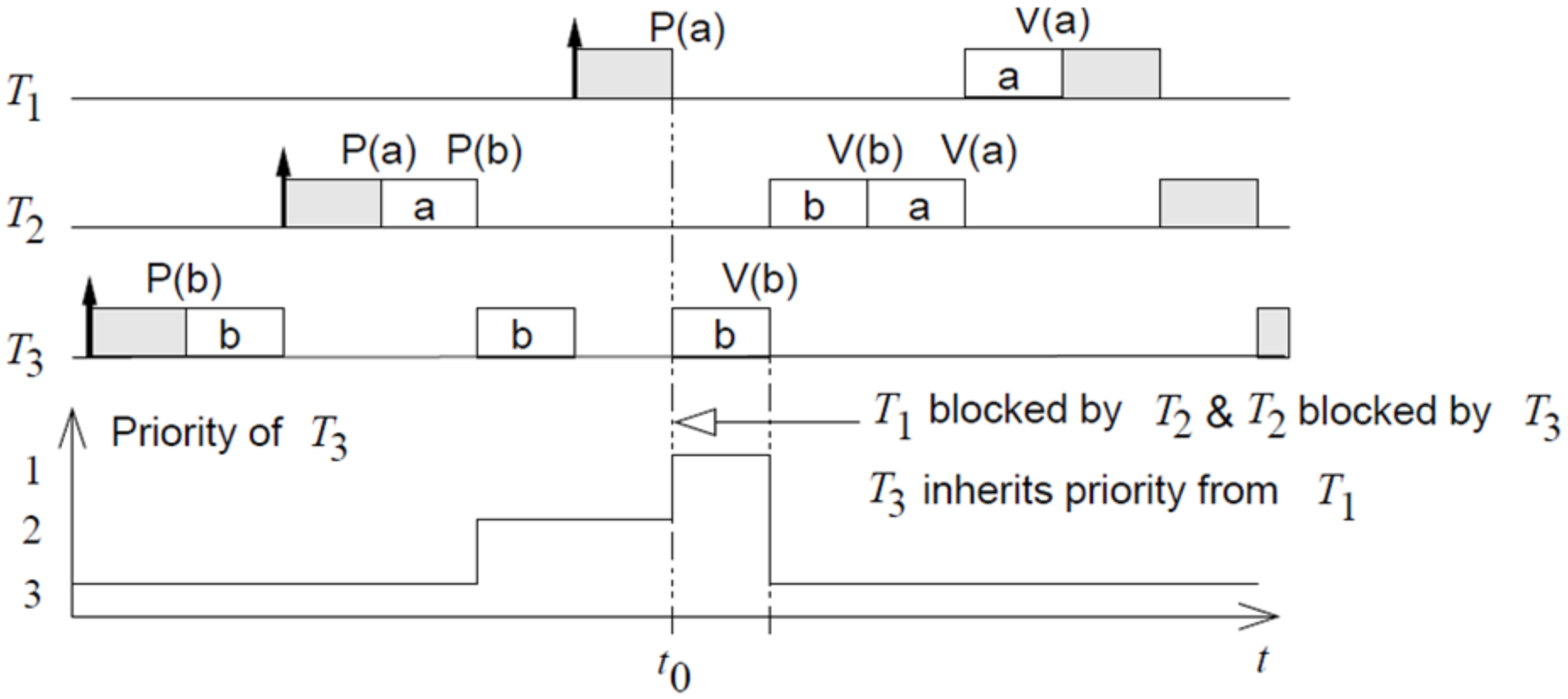
- Direct Blocking: higher-priority task tries to acquire a resource held by a lower-priority task
- Push-through Blocking: medium-priority task is blocked by a lower-priority. Task that has inherited a higher priority from a task it directly blocks

Nested Critical Sections



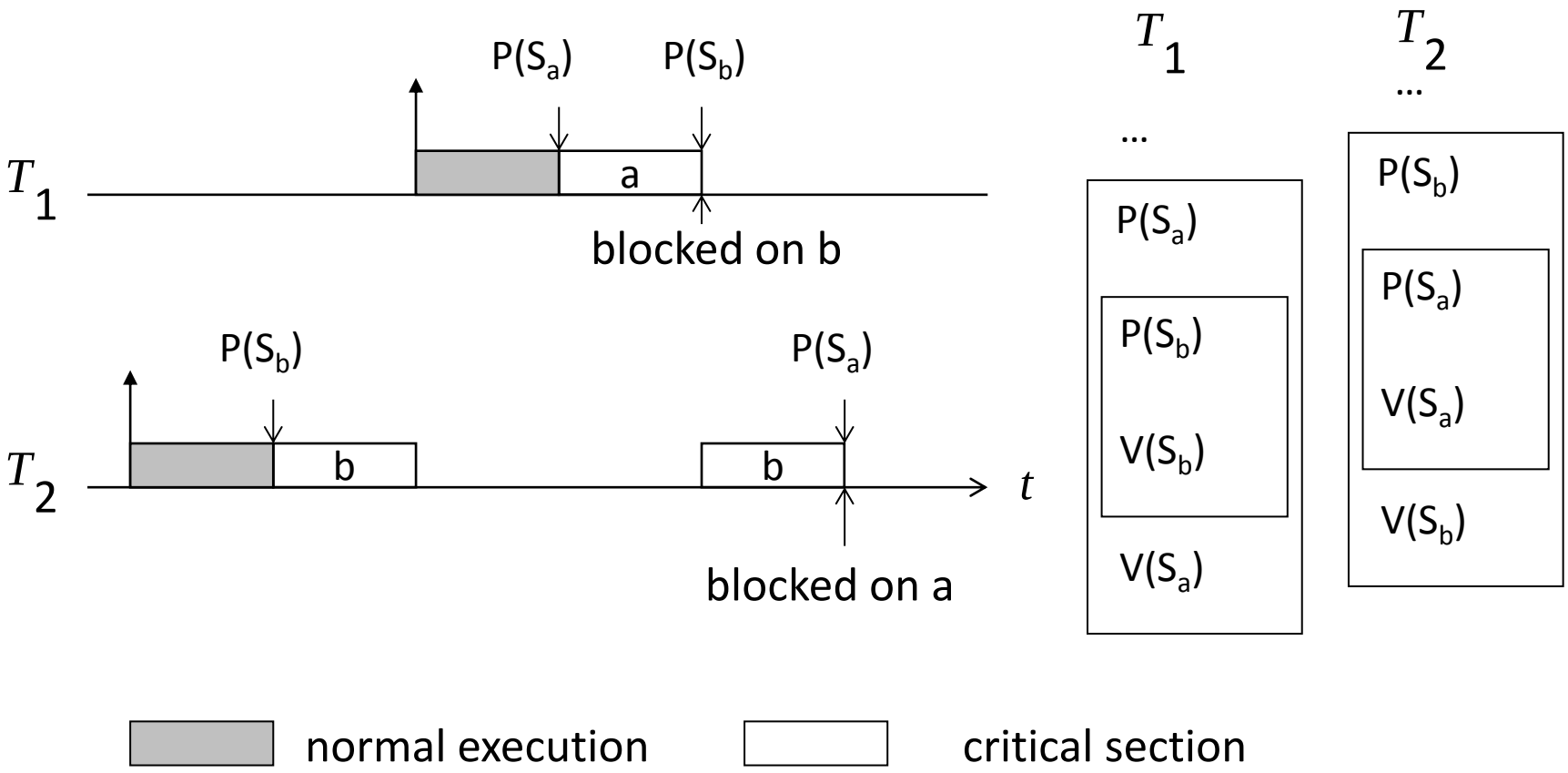
normal execution critical section

Transitiveness of Priority Inheritance



normal execution critical section

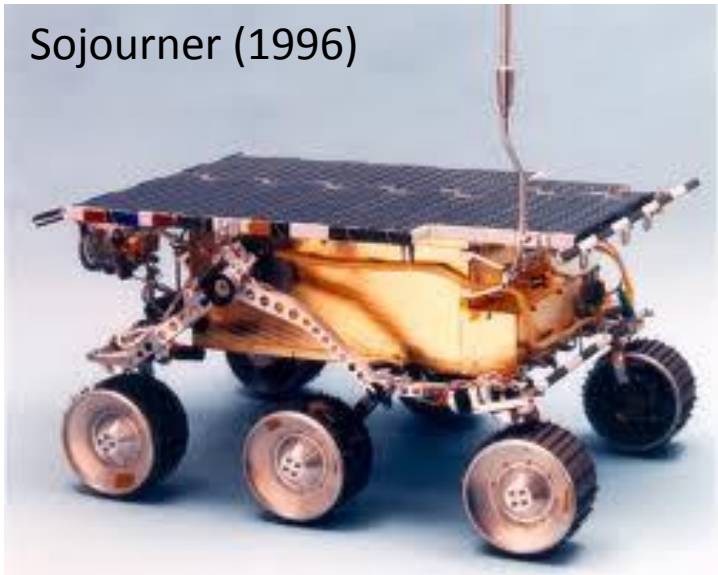
Deadlock is Possible



- Problem exists also when no priority inheritance is used

The MARS Pathfinder problem (1)

- “But a few days into the mission, not long after Pathfinder started gathering meteorological data, the spacecraft began experiencing total system resets, each resulting in losses of data. The press reported these failures in terms such as "software glitches" and "the computer was trying to do too many things at once".” …



http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html

The MARS Pathfinder problem (2)

- “VxWorks provides preemptive priority scheduling of threads. Tasks on the Pathfinder spacecraft were executed as threads with priorities that were assigned in the usual manner reflecting the relative urgency of these tasks.”
- “Pathfinder contained an "information bus", which you can think of as a shared memory area used for passing information between different components of the spacecraft.”

A bus management task ran frequently with high priority to move certain kinds of data in and out of the information bus. Access to the bus was synchronized with mutual exclusion locks (mutexes).”

http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html

The MARS Pathfinder problem (3)

- The meteorological data gathering task ran as an infrequent, low priority thread, … When publishing its data, it would acquire a mutex, do writes to the bus, and release the mutex. ..
- The spacecraft also contained a communications task that ran with medium priority.”

→
High priority: retrieval of data from shared memory
Medium priority: communications task
Low priority: thread collecting meteorological data

http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html

The MARS Pathfinder problem (4)

- "… However, very infrequently it was possible for an interrupt to occur that caused the (medium priority) communications task to be scheduled during the short interval while the (high priority) information bus thread was blocked waiting for the (low priority) meteorological data thread.

- In this case, the long-running communications task, having higher priority than the meteorological task, would prevent it from running, consequently preventing the blocked information bus task from running.

- After some time had passed, a watchdog timer would go off, notice that the data bus task had not been executed for some time, conclude that something had gone drastically wrong, and initiate a total system reset."

http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html

Priority inversion on Mars

- Priority inheritance also solved the Mars Pathfinder problem: the VxWorks operating system used in the pathfinder implements a flag for the calls to mutex primitives. This flag allows priority inheritance to be set to “on”. When the software was shipped, it was set to “off”.

The problem on Mars was corrected by using the debugging facilities of VxWorks to change the flag to “on”, while the Pathfinder was already on the Mars [Jones, 1997].

Remarks on PIP

- Possibly large number of tasks with high priority.
- Possible deadlocks.
- Ongoing debate about problems with the protocol:

  Victor Yodaiken: Against Priority Inheritance, Sept. 2004,
  http://www.fsmlabs.com/resources/white_papers/priority-inheritance/

- Finds application in ADA: During *rendez-vous*, task priority is set to the maximum.
- Protocol for fixed set of tasks: priority ceiling protocol.

PIP→PCP

- The Priority Inheritance Protocol (PIP)
  - does not prevent deadlocks
  - can lead to chained blocking ← 被连续的不同的进程抢占
    - (Several lower priority tasks can block a higher priority task)
  - and has inherent static priorities of tasks

→The Priority Ceiling Protocol (PCP)

  - avoids multiple blocking
  - guarantees that, once a task has entered a critical section, it cannot be blocked by lower priority tasks until its completion.

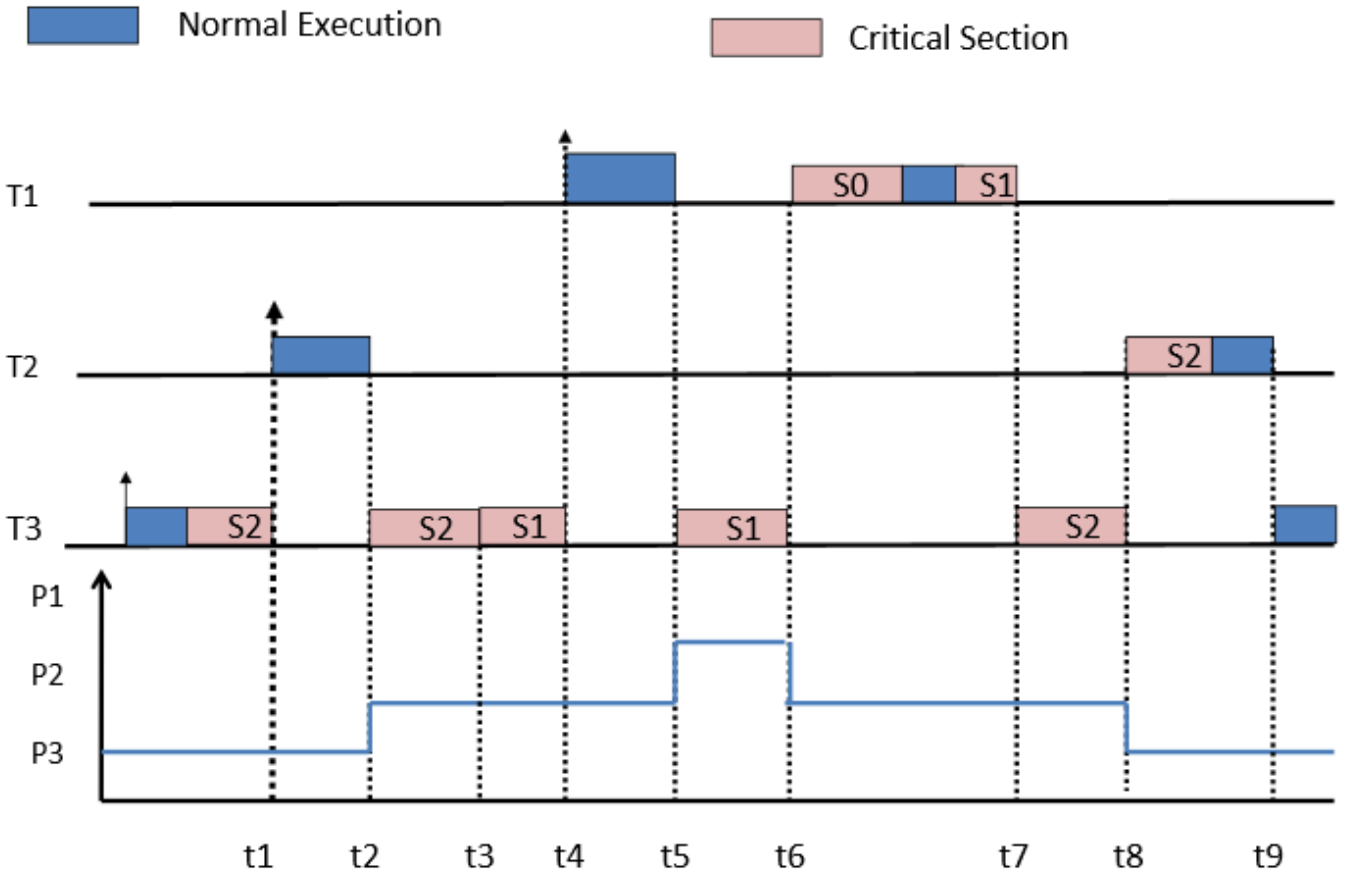
Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

PCP

- A task is not allowed to enter a critical section if there are already locked semaphores which could block it eventually
- Hence, once a task enters a critical section, it can not be blocked by lower priority tasks until its completion.
- This is achieved by assigning priority ceiling.
- Each semaphore S_k is assigned a priority ceiling $C(S_k)$. It is the priority of the highest priority task that can lock S_k.
  This is a static value.

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

Priority Ceiling: Example



C(S0=P1) C(S1=P1) C(S2=P2)

Source: http://www.ida.liu.se/ unmbo/RTS_CUGS_files/Lecture3.pdf

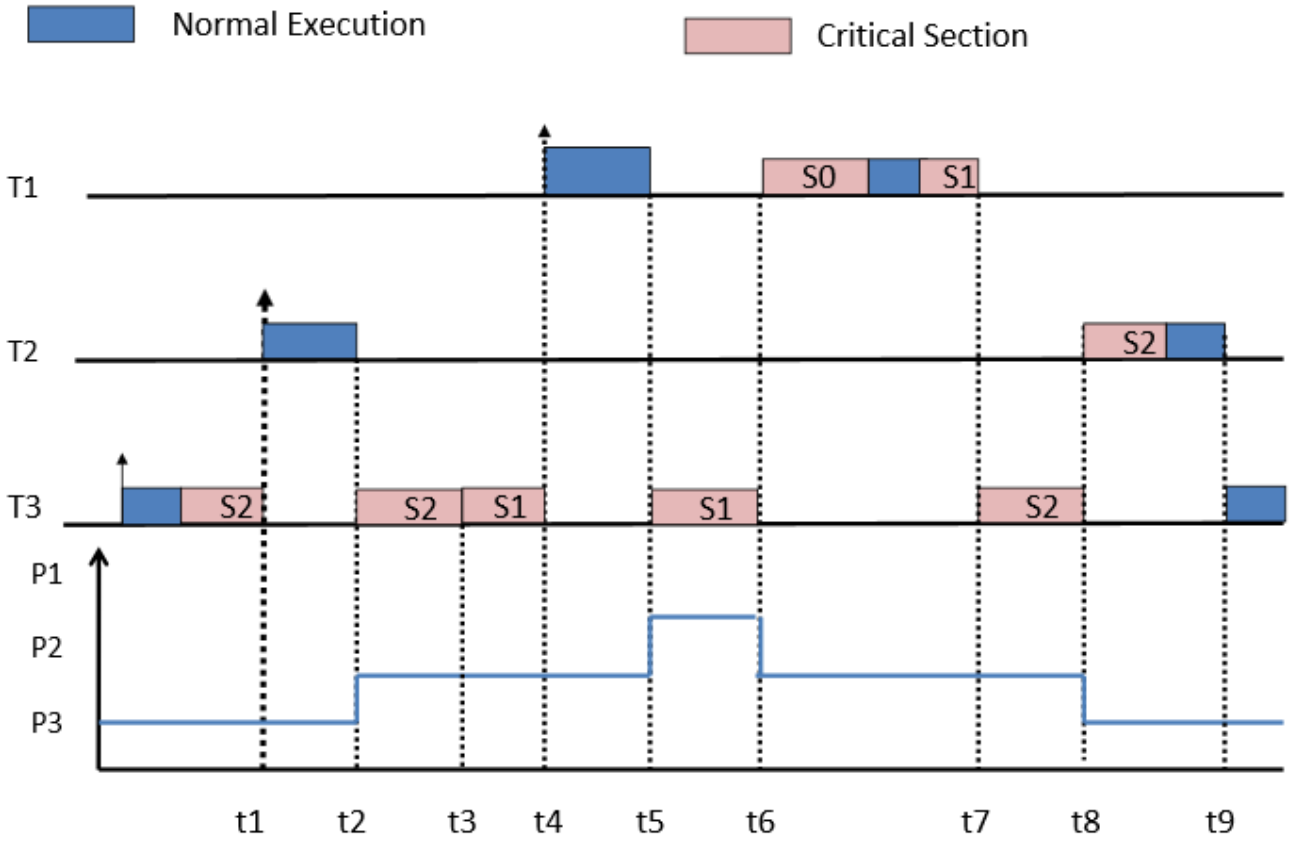
PCP

- Suppose T is running and wants to lock semaphore S_k.

- T is allowed to lock S_k only if
  priority of T > priority ceiling $C(S^*)$ of the semaphore S^* where:
  - S^* is the semaphore with the highest priority ceiling among all the semaphores which are currently locked by tasks other than T.
  - In this case, T is said to be blocked by the semaphore S^* (and the task currently holding S^*)
  - When T gets blocked by S^* then the priority of T is transmitted to the task that currently holds S^*

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

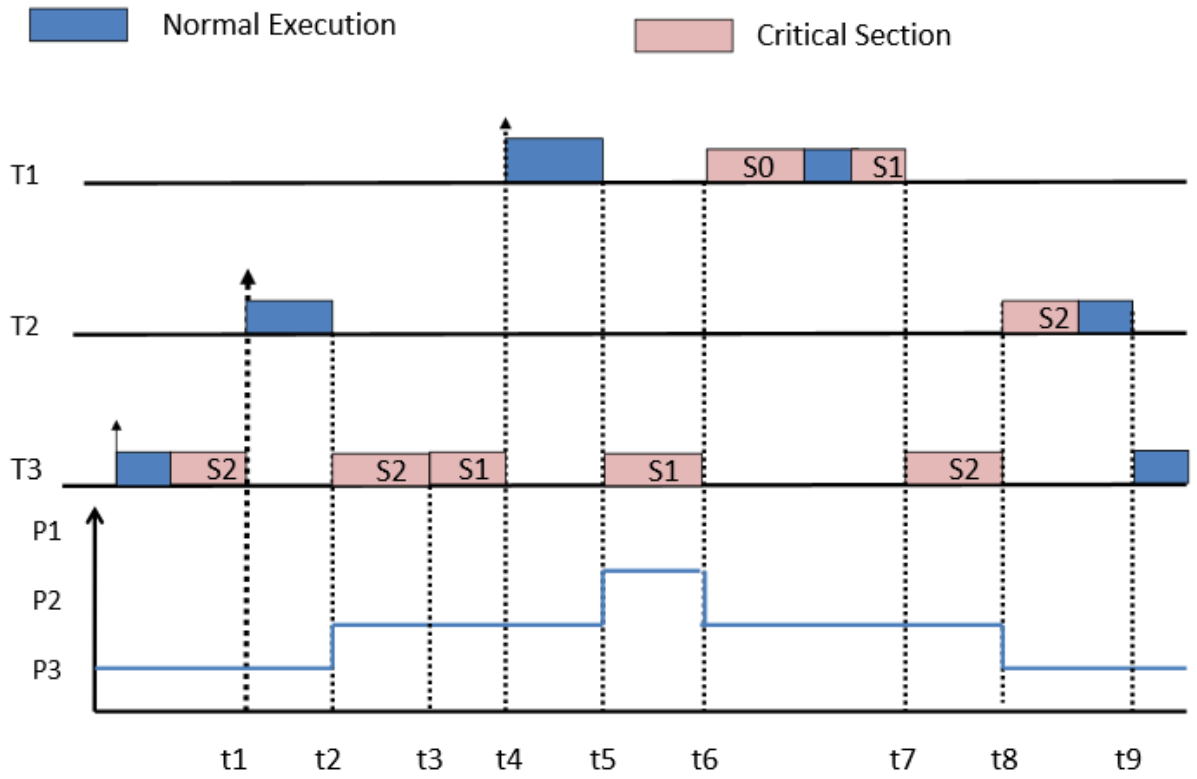
PCP: An Example



t2: T2 can not lock S2. Currently T3 is holding S2 and C(S2) = P2 and the current priority of T2 is also P2

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

PCP: An Example



t5 : T1 can not lock S0. Currently T3 is holding S2 and S1 and C(S1) = T1 and the current priority of T1 is also P1. The (inherited) priority of T3 is now P1

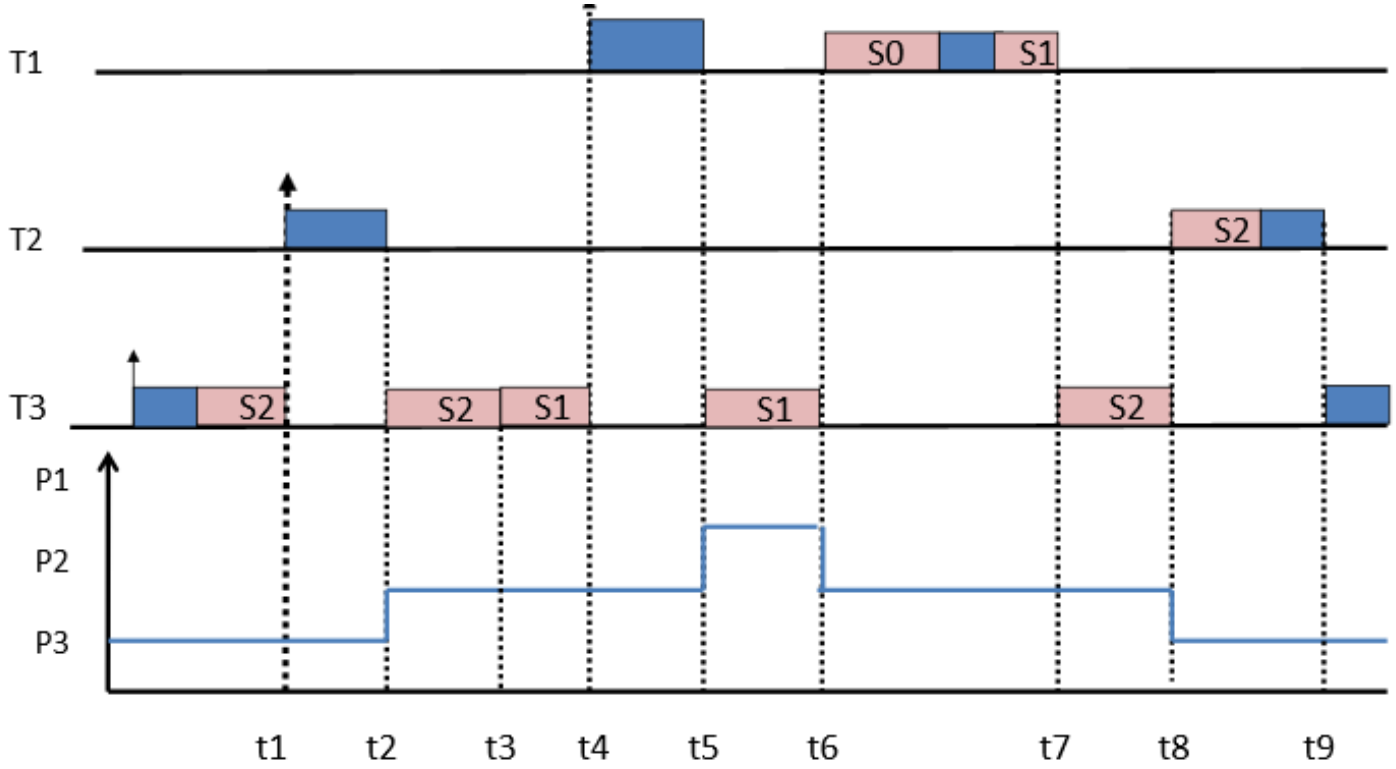
Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

PCP

- When T^* leaves a critical section guarded by S^* then it unlocks S^* and the highest priority task, if any, which is blocked by S^* is awakened
- The priority of T^* is set to the highest priority of the task that is blocked by some semaphore that T^* is still holding.
  If none, the priority of T^* is set to be its nominal one.

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

PCP: Example



Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

t6 : T3 unlocks S1. It awakens T1. But T3s (inherited) priority is now only P2 while P1>C(S2) =P2. So T1 preempts T3 and runs to completion.

t7: T3 resumes execution with priority P2

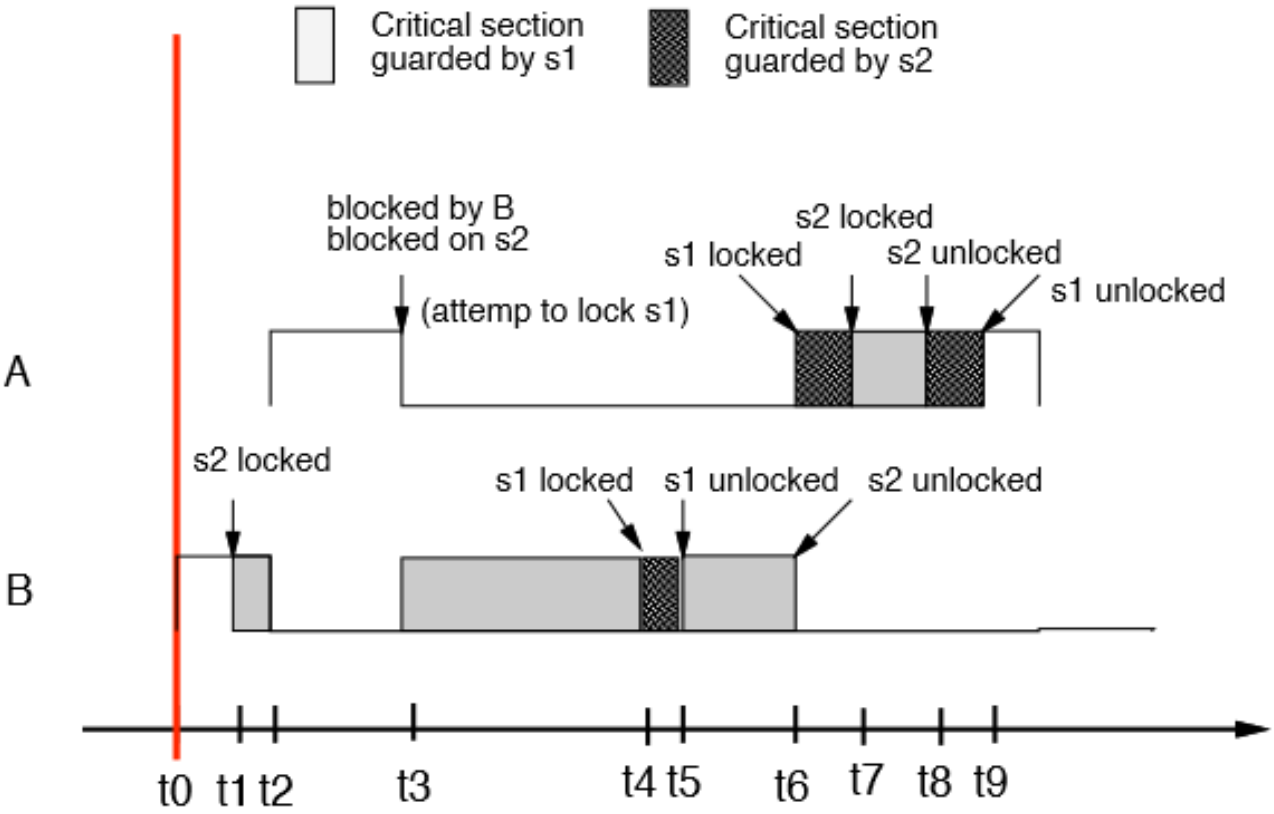
t8 : T3 unlocks S2, goes back to its priority P3. T2 preempts T3, runs to completion

PCP: Deadlock-Free Example

Task name	T	Priority
A	50	10
B	500	9

```
Task A          Task B

lock(s1)        lock(s2)
lock(s2)        lock(s1)
...             ...
unlock(s1)      unlock(s1)
unlock(s2)      unlock(s1)
```



$$ceil(s_1) = 10, ceil(s_2) = 10$$

Source: Lund University, course EDA 040, http://fileadmin.cs.lth.se/cs/Education/EDA040/lecture/RTP-F6b.pdf

PCP: Properties

- Deadlock free (only changing priorities)
- A given task i is delayed at most once by a lower priority task
- The delay is a function of the time taken to execute the critical section
- Certain variants as to when the priority is changed

Extending PCP: Stack Resource Policy (SRP)

- SRP supports dynamic priority scheduling
- SRP blocks the task at the time it attempts to preempt.
- **Preemption level** l_i of task i: decreasing function of deadline (larger deadline → easier to preempt) (Static)
- **Resource ceiling**: of a resource is the highest preemption level from among all tasks that may access that resource (Static)
- **System ceiling**: is the highest resource ceiling of all the resources which are currently blocked (dynamic, changes with resource accesses)

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

SRP Policy

抢占前保证优先级>当前system ceiling

- A task can preempt another task if
  - it has the highest priority
  - and its preemption level is higher than the system ceiling
- A task is not allowed to start until the resources currently available are sufficient to meet the maximum requirement of every task that could preempt it.

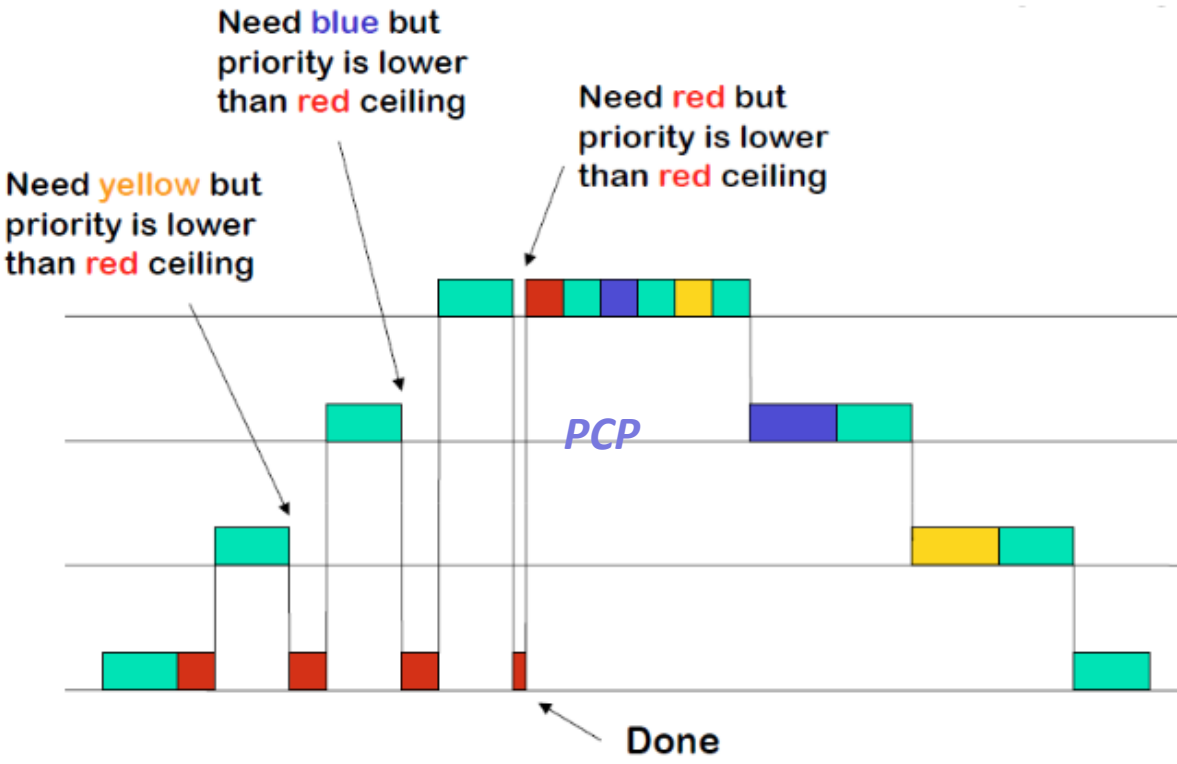
- Why ***Stack*** Resource Policy? Tasks cannot be blocked by tasks with lower l_i, can resume only when the task completes. Tasks on the same l_i can share stack space. More tasks on the same l_i → higher stack space saving.

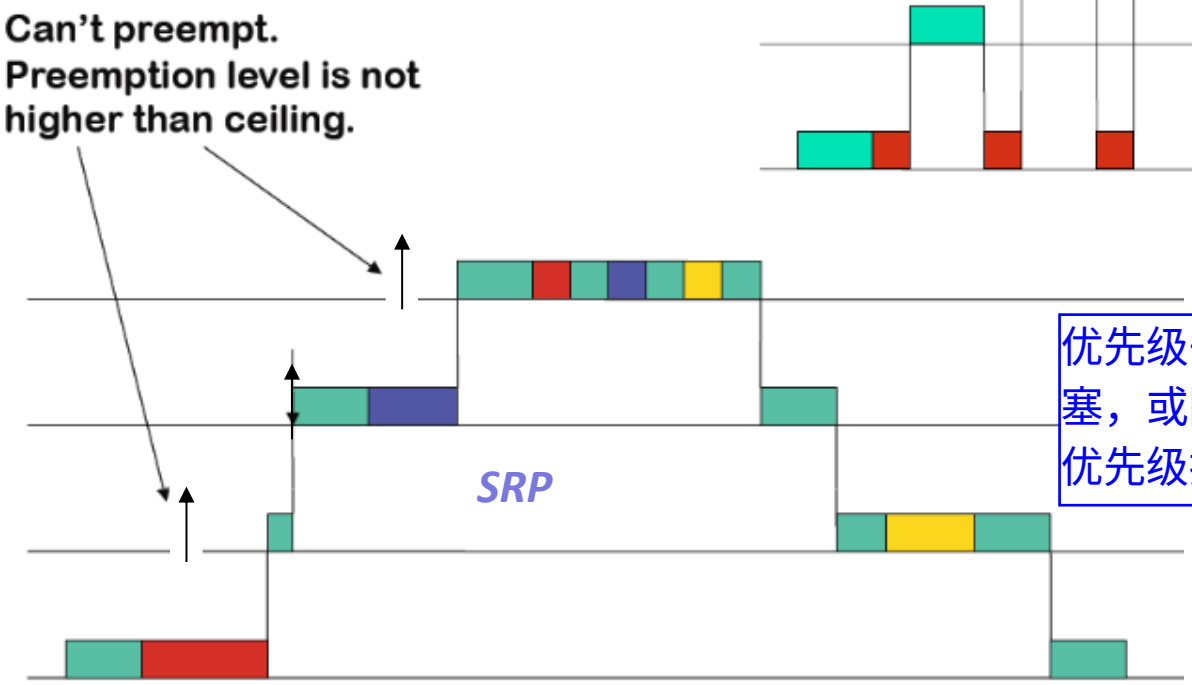
Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/Lecture3.pdf

SRP vs. PCP

- a

Less preemptions for SRP





优先级<SystemCeiling的进程最终会被阻塞，或因为请求访问临界区，或因为被高优先级抢占，从而减少Context Switch

Source: http://www.ida.liu.se/~unmbo/RTS_CUGS_files/ Lecture3.pdf