# Embedded Systems

# 6. Real-Time Operating Systems

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*Software and Programming*

*Processing and Communication*

*Hardware*

# Embedded OS

- ***Why an OS at all***?
  - 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, process automation, …).
  - Critical applications with small functionality (ABS, pace maker, …)
  - Not very critical applications with varying functionality (smart phone, smart card, microwave oven, …)

# Embedded OS

- 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 memory space.
  - It is often too ressource hungry in terms of computation time.
  - Not designed for mission-critical applications.
  - Timing uncertainty too large.

# Embedded Operating Systems

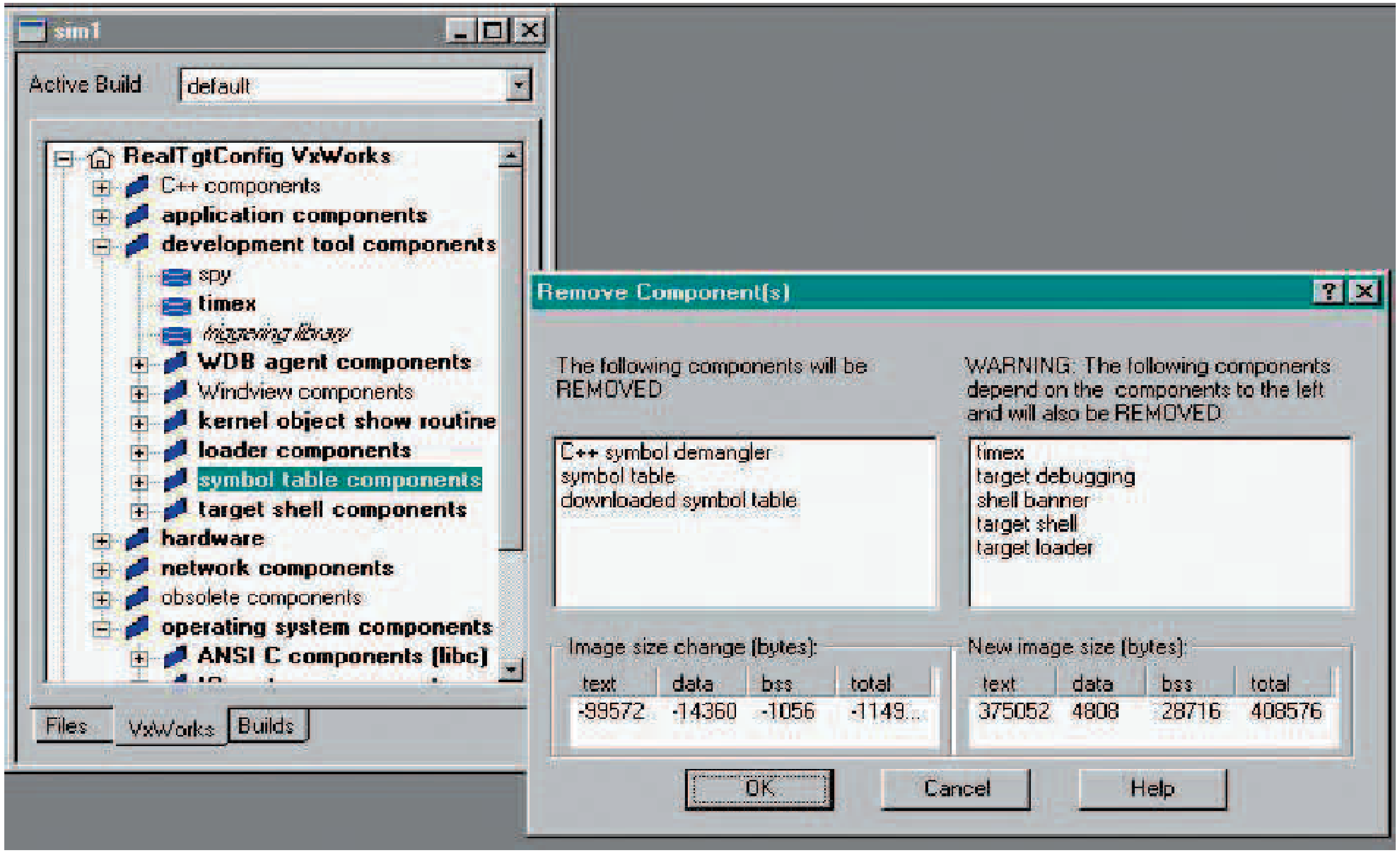
## *Configurability*

- No single RTOS will fit all needs, no overhead for unused functions/data tolerate: configurability is needed.
- For example, there are many embedded systems without external memory, a keyboard, a screen or a mouse.

*Configurability examples:*

- Simplest form: remove unused functions (by linker for example).
- Conditional compilation (using #if and #ifdef commands).
- Validation is a potential problem of systems with a large number of derived operating systems:
  - each derived operating system must be tested thoroughly;
  - for example, eCos (open source RTOS from Red Hat) includes 100 to 200 configuration points.

# Example: Configuration of VxWorks




http://www.windriver.com/products/development_tools/ide/tornado2/tornado_2_ds.pdf

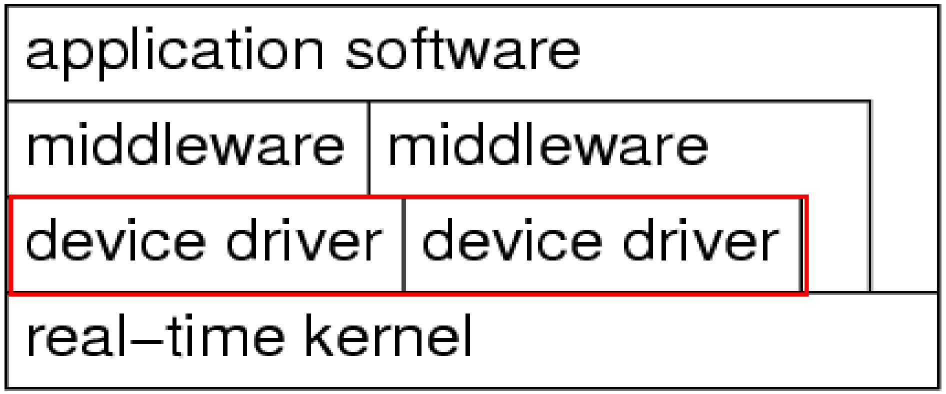
**Automatic dependency analysis and size calculations allow users to quickly custom-tailor the VxWORKS operating system.**

# Embedded operating systems

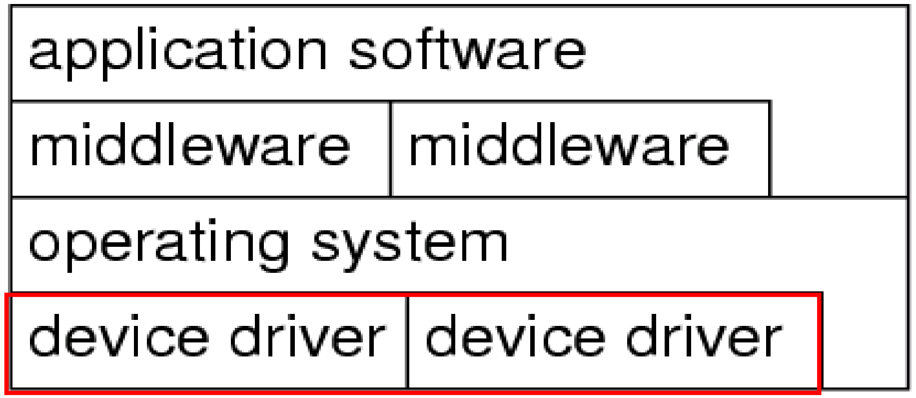
***Device drivers handled by tasks*** instead of hidden integrated drivers:

- 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.

RTOS




Standard OS



# Embedded Operating Systems

## *Interrupts can be employed by any process*

- For standard OS: this would be serious source of unreliability.
- But 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 interfaces and 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.
- If real-time processing is of concern, time to handle interrupts need to be considered. For example, interrupts may be handled by the scheduler.

# Embedded Operating Systems

***Protection mechanisms are not always necessary:***

- Embedded systems are typically designed for a single purpose, untested programs rarely loaded, software considered reliable.
- *Privileged* I/O instructions not necessary and tasks can do their own I/O.

  Example: Let **`switch`** be the address of some switch. Simply use

  ```
  load register,switch
  ```

  instead of a call to the underlying operating system.
- However, protection mechanisms may be needed for safety and security reasons.

# Real-time Operating Systems

- *A real-time operating system is an operating system that supports the construction of real-time systems.*
- ***Three key requirements:***

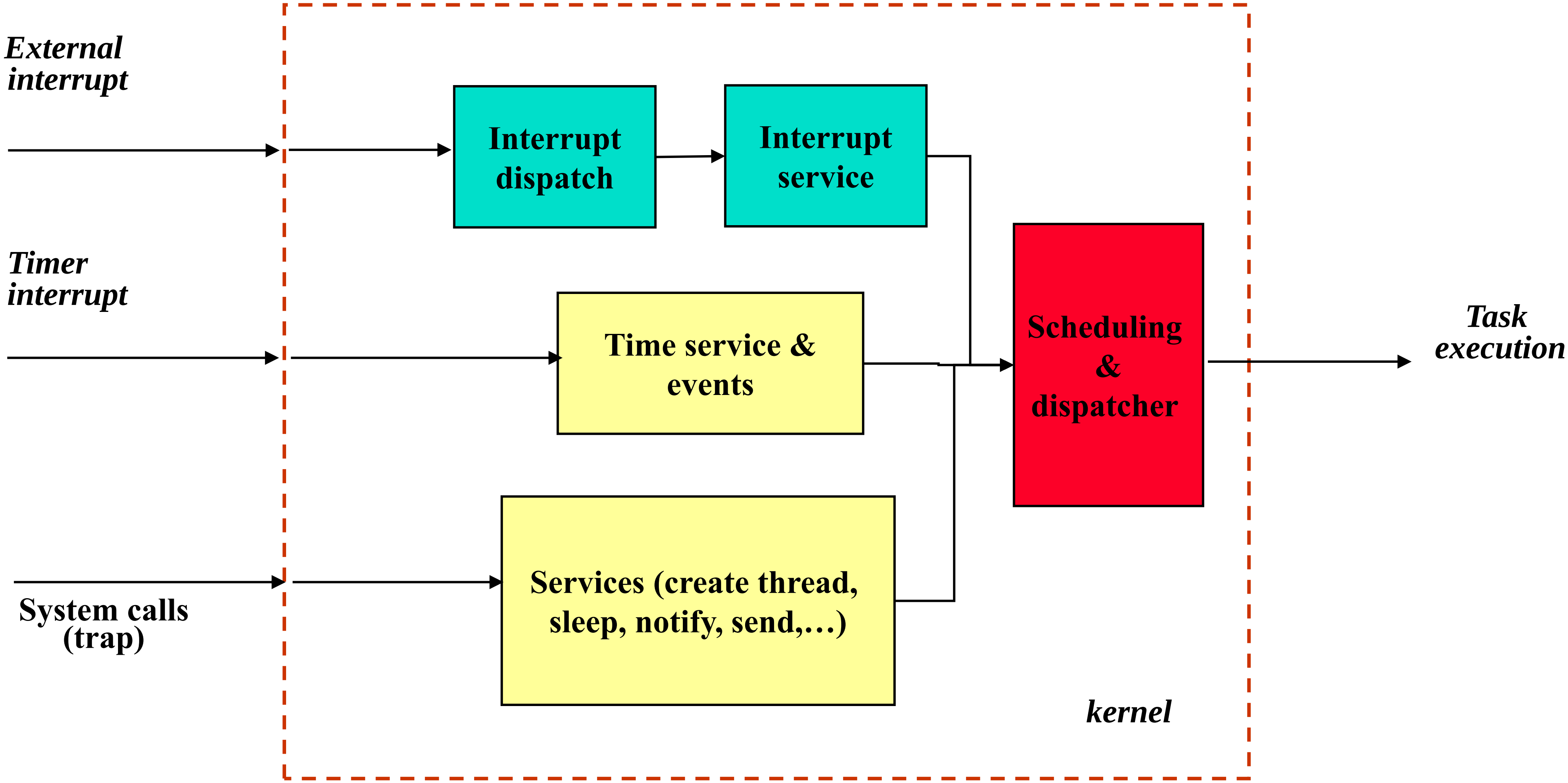
  **1. The timing behavior of the OS must be *predictable*.**

  $\forall$ services of the OS: Upper bound on the execution time!

  RTOSs must be deterministic (unlike standard Java for example):

  - upper bounds on blocking times need to be available, i.e. during which interrupts are disabled,
  - almost all activities are controlled by a real-time scheduler.

# Task Management Services



# Real-time Operating Systems

## 2. OS must *manage the timing and scheduling*

- OS possibly has to be aware of deadlines;
  (unless scheduling is done off-line).
- OS must provide precise time services with high resolution.

## 3. The OS must be *fast*

- Practically important.

# Main Functionality of RTOS-Kernels

- ***Task management***:
  - Execution of ***quasi-parallel tasks*** on a processor using processes or threads (lightweight process) by
    - maintaining process states, process queuing,
    - allowing for 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

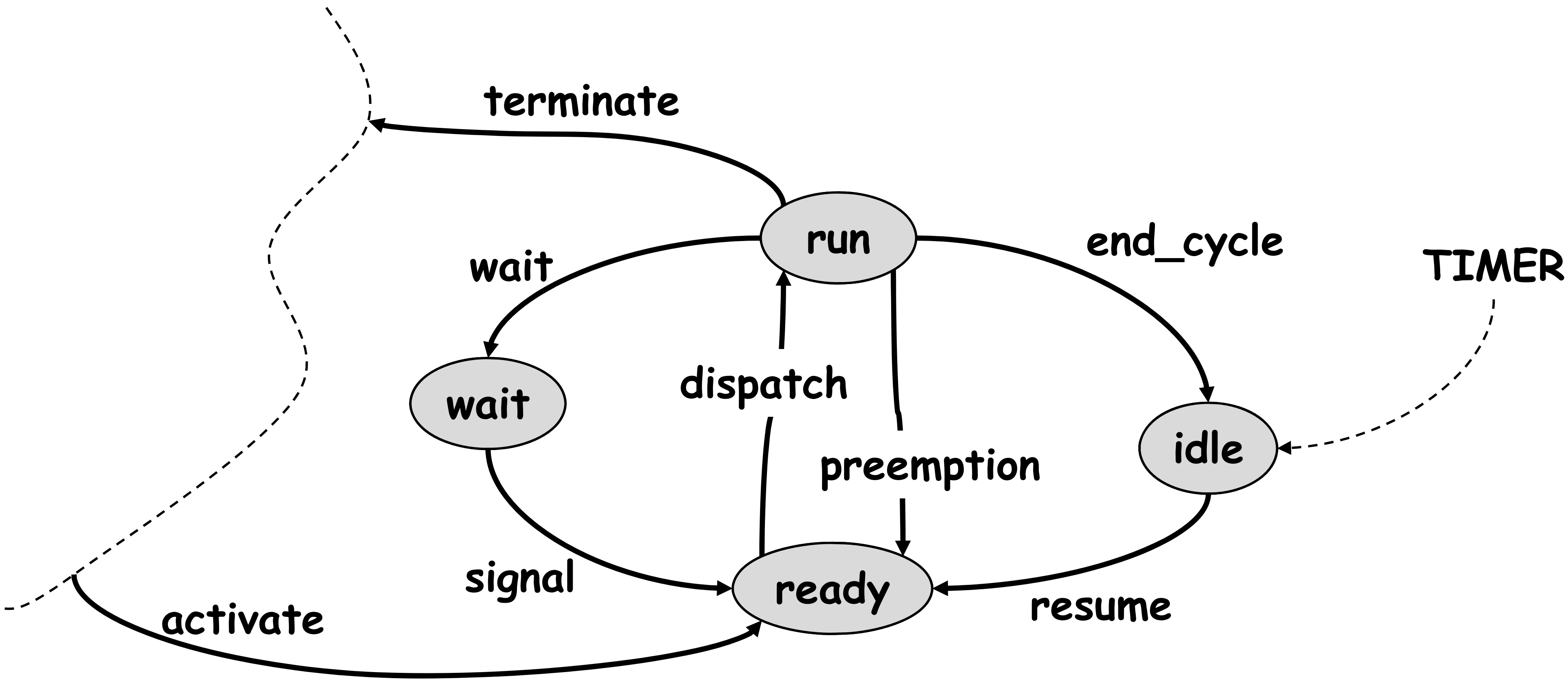
# Task Management

- ***Task 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, …)

# Task States

- ***Minimal Set of Task States***:



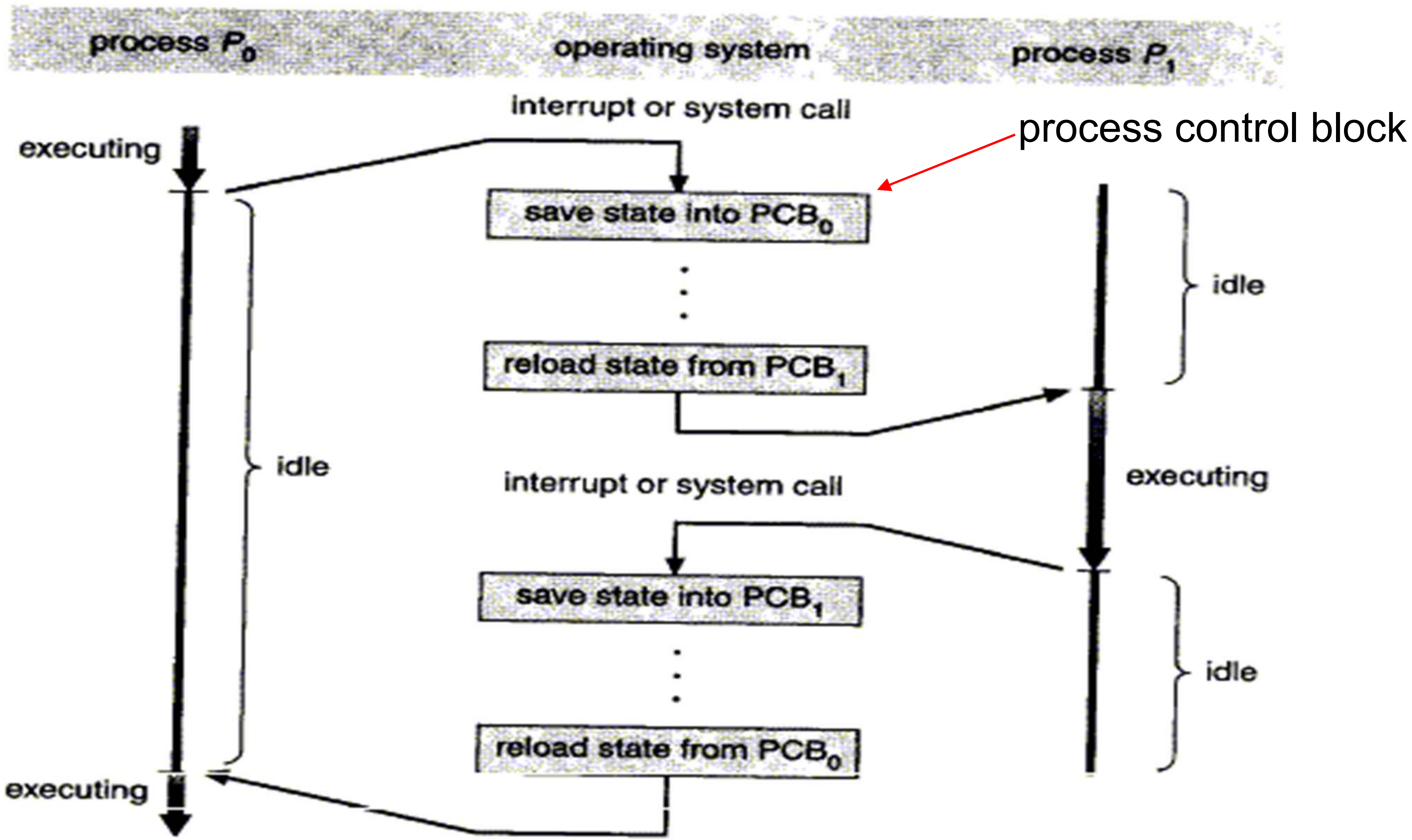
# Task states

- ***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***:
  - A periodic job enters this state when it completes its execution and has to wait for the beginning of the next period.

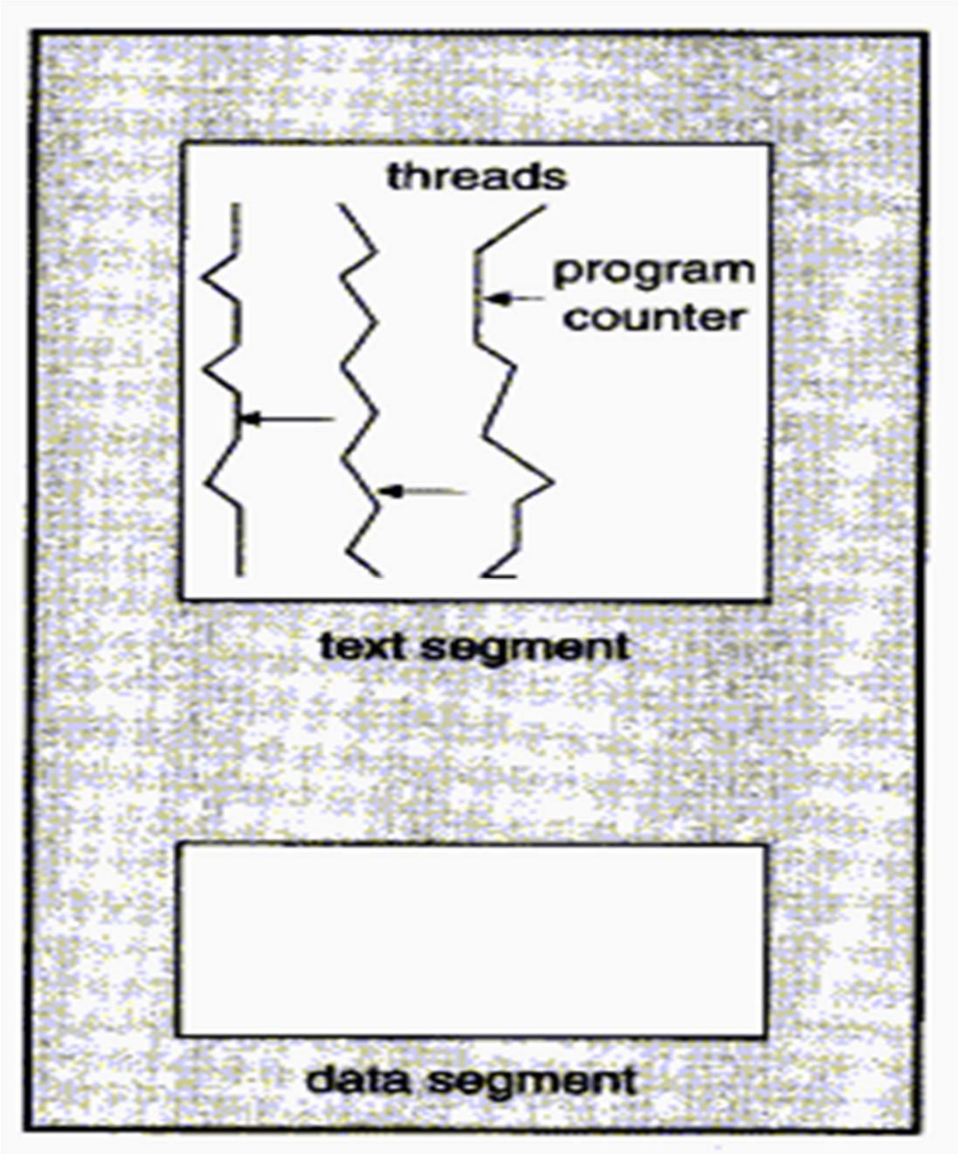
# Threads

- A ***thread*** is the smallest sequence of programmed instructions that can be managed independently by a scheduler; e.g., a thread is a basic unit of CPU utilization.
- Multiple threads can exist within the same process and share resources such as memory, while different processes do not share these resources:
  - Typically ***shared by threads***: memory.
  - Typically ***owned by threads***: registers, stack.
- ***Thread*** advantages and characteristics:
  - Faster to switch between threads; switching between user-level threads requires no major intervention by the 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

# Context Switching

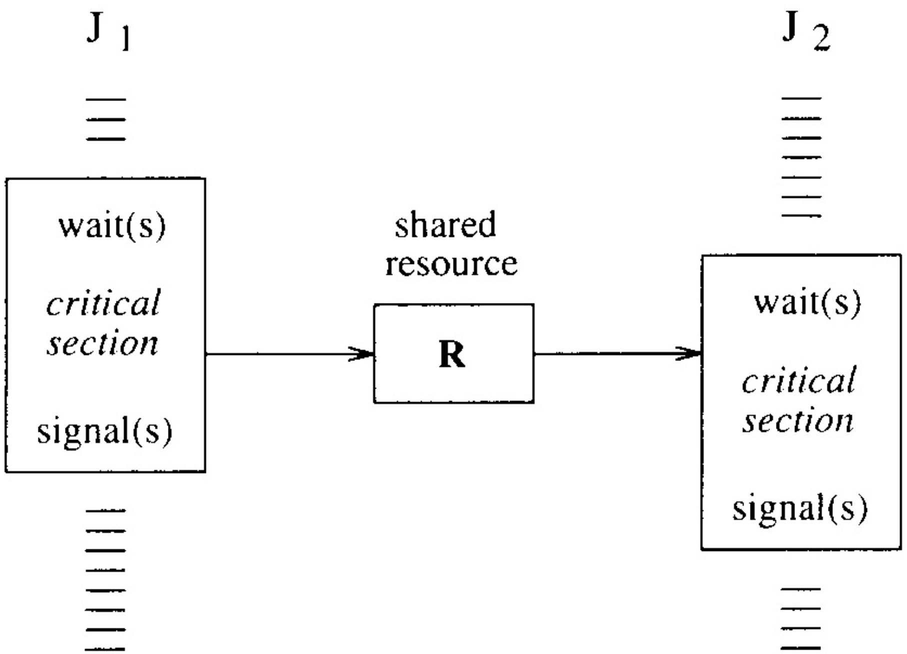


# Multiple Threads within a Process



# Communication Mechanisms

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

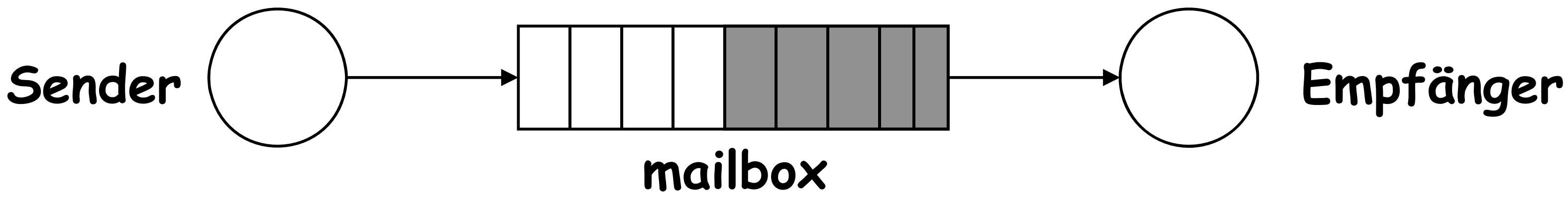


# Communication mechanisms

- ***Synchronous communication***:
  - Whenever two tasks want to communicate they must be synchronized for a message transfer to take place (***rendez-vous***)
  - They have to wait for each other.
  - ***Problem*** in case of dynamic real-time systems: Estimating the maximum blocking time for a process rendez-vous.
  - 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.



# Class 1: Fast Proprietary Kernels

***Fast proprietary kernels***

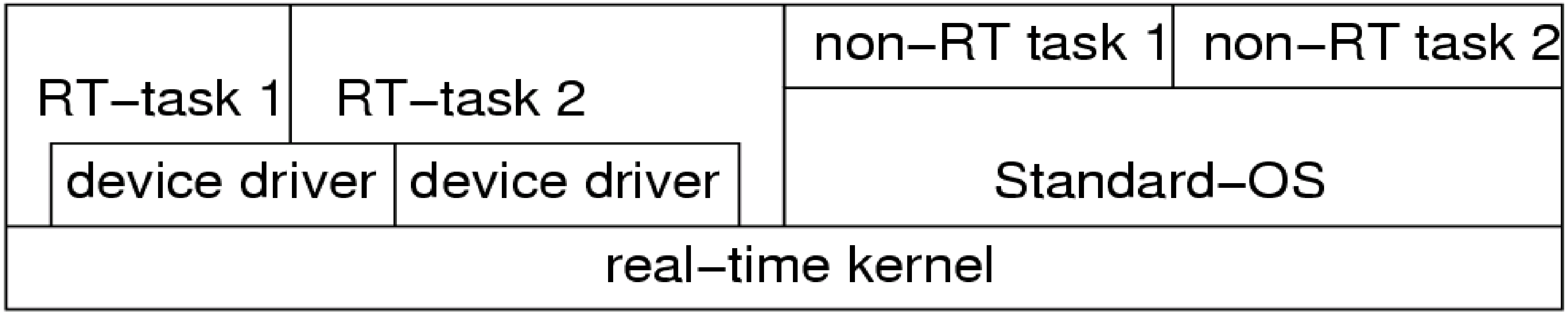
*For hard real-time systems, these kernels are questionable, because they are designed to be fast, rather than to be predictable in every respect*

Examples include

FreeRTOS, QNX, eCOS, RT-LINUX, VxWORKS, LynxOS.

# 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.

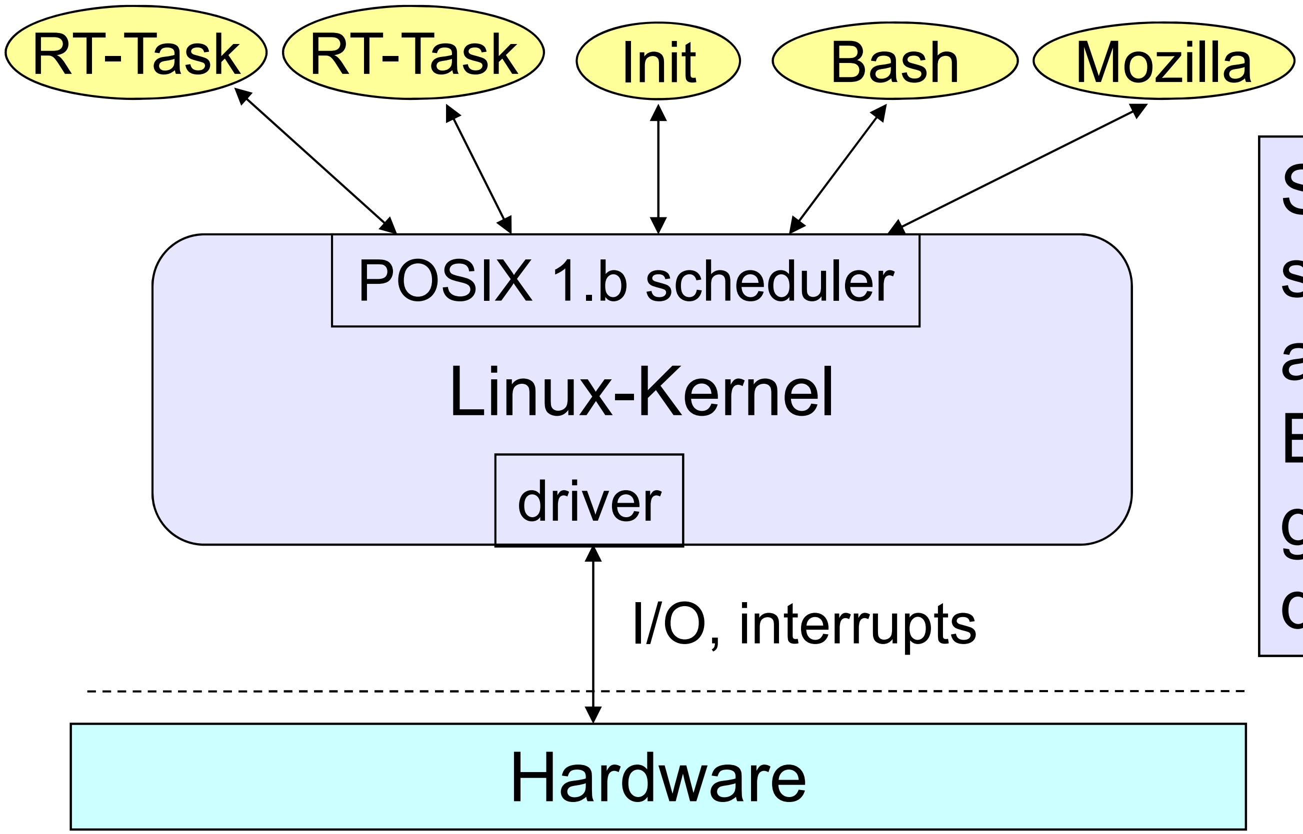



+ Crash of standard-OS does not affect RT-tasks;
- RT-tasks cannot use Standard-OS services;
  less comfortable than expected

revival of the concept:
hypervisor

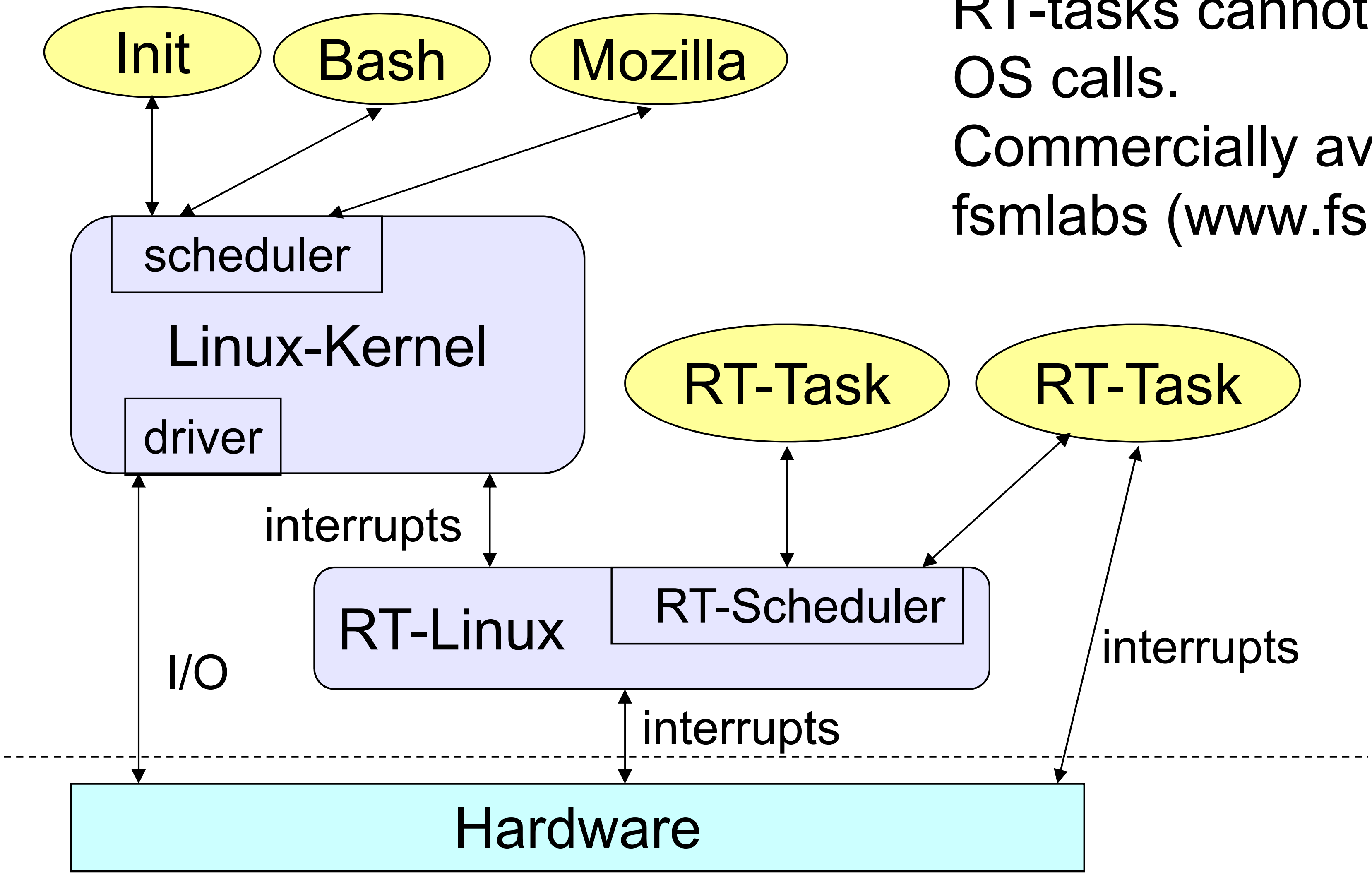
# Example: Posix 1.b RT-extensions to Linux

Standard scheduler can be replaced by POSIX scheduler implementing priorities for RT tasks




Special RT-calls and standard OS calls available.
Easy programming, no guarantee for meeting deadline

# 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 L4, seL4, NICTA, ERIKA, SHARK

***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)
- formally verified kernel properties

List of current real-time operating systems:
http://en.wikipedia.org/wiki/Comparison_of_real-time_operating_systems