Embedded Systems

5. Operating Systems

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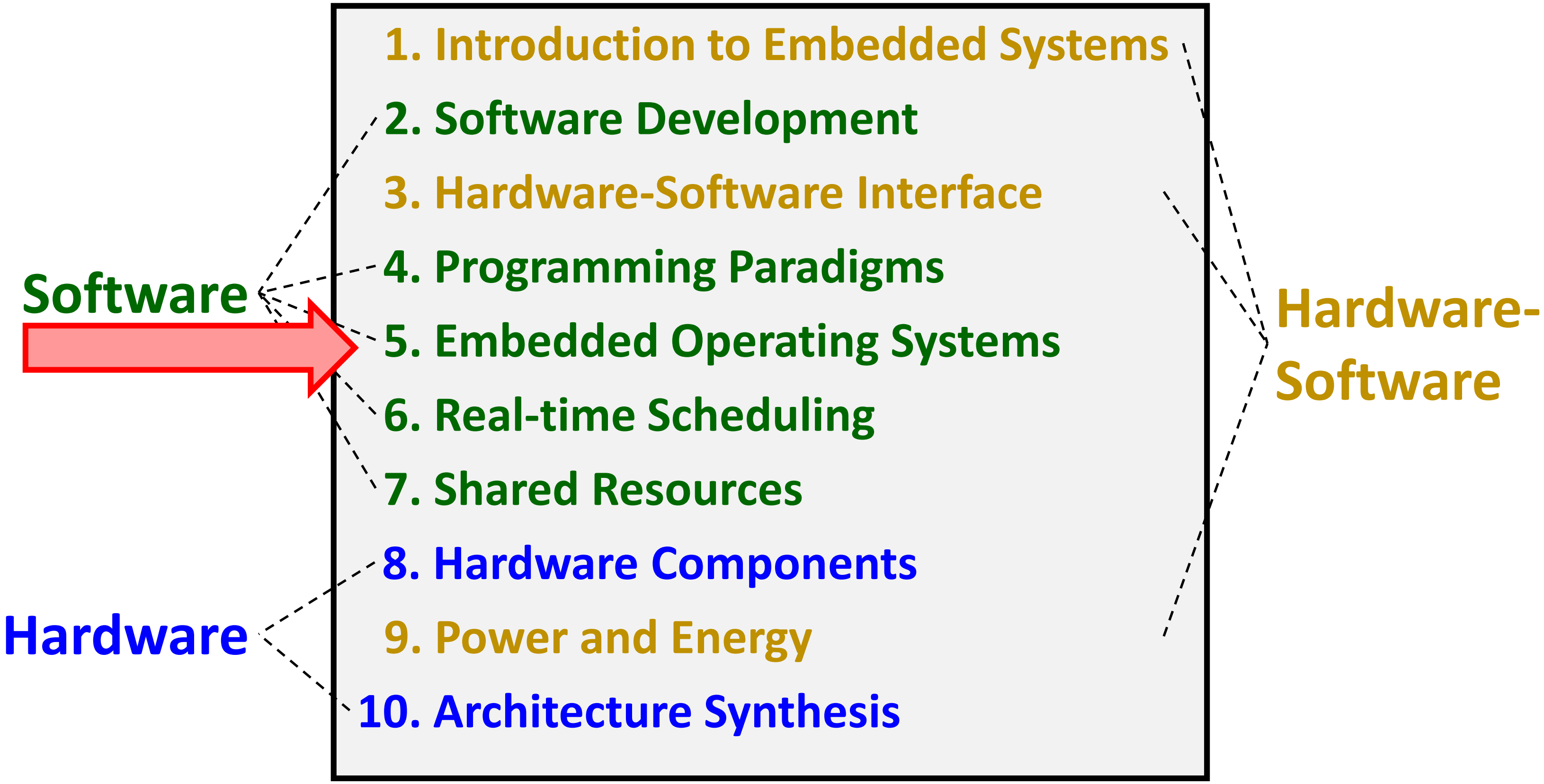
Embedded Operating Systems

Where we are …



Software

Hardware

1. Introduction to Embedded Systems
2. Software Development
3. Hardware-Software Interface
4. Programming Paradigms
5. Embedded Operating Systems
6. Real-time Scheduling
7. Shared Resources
8. Hardware Components
9. Power and Energy
10. Architecture Synthesis

Hardware-Software

Embedded Operating System (OS)

- *Why an operating system (OS) at all?*
  - Same reasons why we need one for a traditional computer.
  - Not every devices needs all services.

- In embedded systems we find a *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 broad range of functionality (smart phone, …).

Embedded Operating System

- *Why is a desktop OS not suited?*
  - The monolithic kernel of a desktop OS offers too many features that take space in memory and consume time.
  - Monolithic kernels are often not modular, fault-tolerant, configurable.
  - Requires too much memory space and is often too ressource hungry in terms of computation time.
  - Not designed for mission-critical applications.
  - The timing uncertainty may be too large for some applications.

Embedded Operating Systems

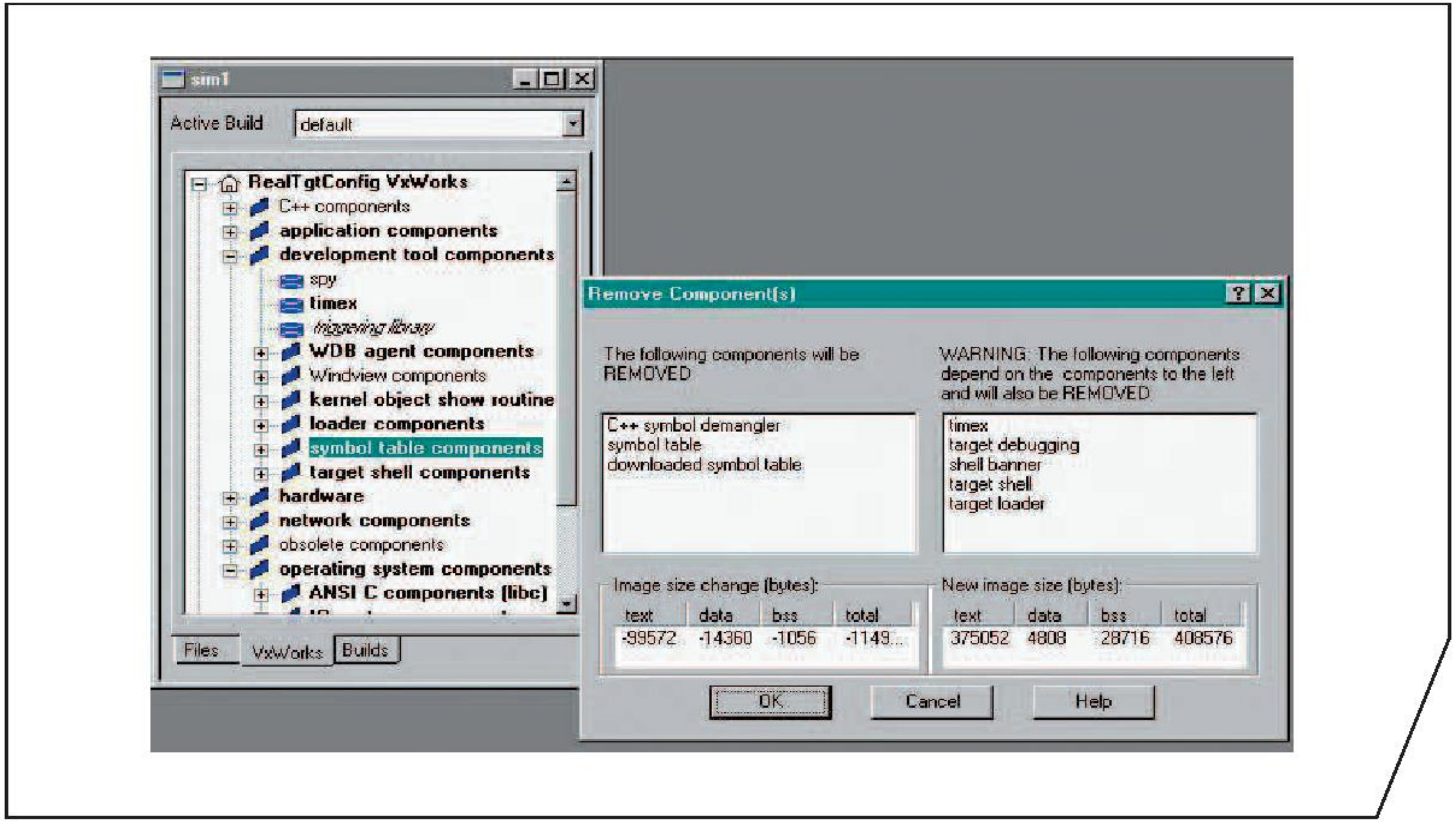
Essential characteristics of an embedded OS: Configurability

- *No single operating system will fit all needs*, but often no overhead for unused functions/data is tolerated. Therefore, configurability is needed.
- For example, there are many embedded systems without external memory, a keyboard, a screen or a mouse.

Configurability examples:

- *Remove unused functions*/libraries (for example by the linker).
- *Use conditional compilation* (using #if and #ifdef commands in C, for example).
- But deriving a consistent configuration is a potential problem of systems with a large number of derived operating systems. There is the danger of missing relevant components.

Example: Configuration of VxWorks



Active Build: default

Remove Component(s)

The following components will be REMOVED

C++ symbol demangler
symbol table
downloaded symbol table

WARNING: The following components depend on the components to the left and will also be REMOVED

timex
target debugging
shell banner
target shell
target loader

Image size change (bytes):

text	data	bss	total
-99572	-14360	-1056	-1149...

New image size (bytes):

text	data	bss	total
375052	4808	28716	408576

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

© Windriver

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

Real-time Operating Systems

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

Key requirements:

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

   For all services of the OS, an upper bound on the execution time is necessary. For example, for every service upper bounds on blocking times need to be available, i.e. for times during which interrupts are disabled. Moreover, almost all processor activities should be controlled by a real-time scheduler.

2. *OS must manage the timing and scheduling*

   - OS has to be aware of deadlines and should have mechanism to take them into account in the scheduling
   - OS must provide precise time services with a high resolution

Embedded Operating Systems

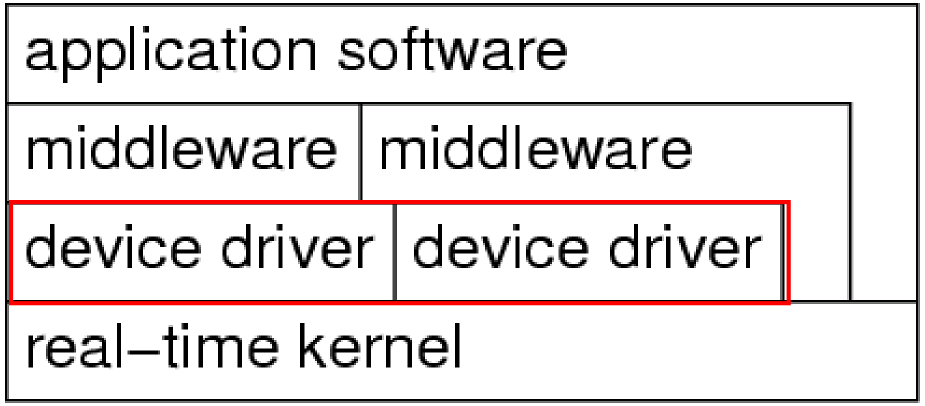
Features and Architecture

Embedded Operating System

Device drivers are typically handled directly by tasks instead of drivers that are managed by the operating system:

- This architecture *improves timing predictability* as access to devices is also handled by the scheduler
- If several tasks use the same external device and the associated driver, then the access must be carefully managed (shared critical resource, ensure fairness of access)

Embedded OS



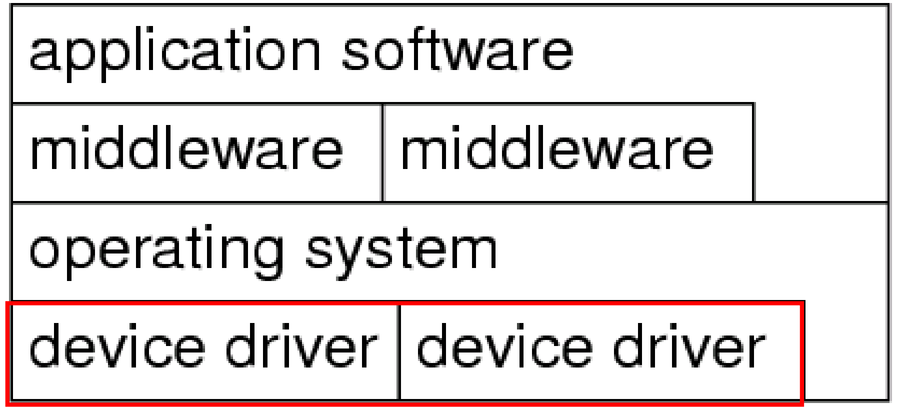
application software

middleware | middleware

device driver | device driver

real–time kernel

Standard OS



application software

middleware | middleware

operating system

device driver | device driver

Embedded Operating Systems

Every task can perform an interrupt:

- For *standard OS*, this would be *serious source of unreliability*. But embedded programs are typically programmed in a controlled environment.
- It is possible to let *interrupts directly start or stop tasks* (by storing the tasks start address in the interrupt table). This approach is more efficient and predictable than going through the operating system's interfaces and services.

Protection mechanisms are not always necessary in embedded operating systems:

- Embedded systems are typically designed for a single purpose, untested programs are rarely loaded, software can be considered to be reliable.
- However, protection mechanisms may be needed for *safety and security* reasons.

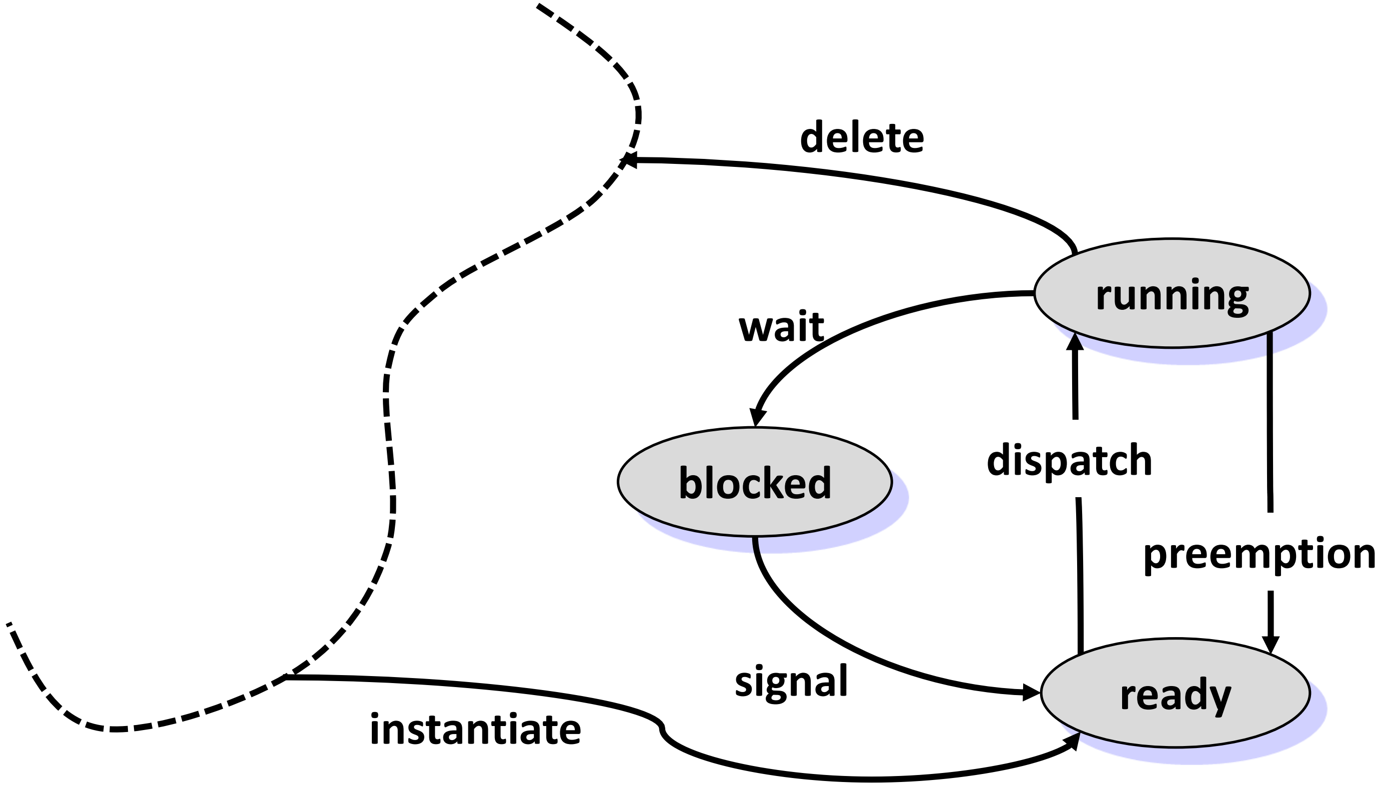
Main Functionality of RTOS-Kernels

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)
- *Inter-task communication* (buffering)
- *Support of real-time clocks*
- *Task synchronization* (critical sections, semaphores, monitors, mutual exclusion)
  - In classical operating systems, synchronization and mutual exclusion is performed via semaphores and monitors.
  - In real-time OS, special semaphores and a deep integration of them into scheduling is necessary (for example priority inheritance protocols as described in a later chapter).

Task States

Minimal Set of Task States:



Task states

Running:

- A task enters this state when it starts executing on the processor. There is as most one task with this state in the system.

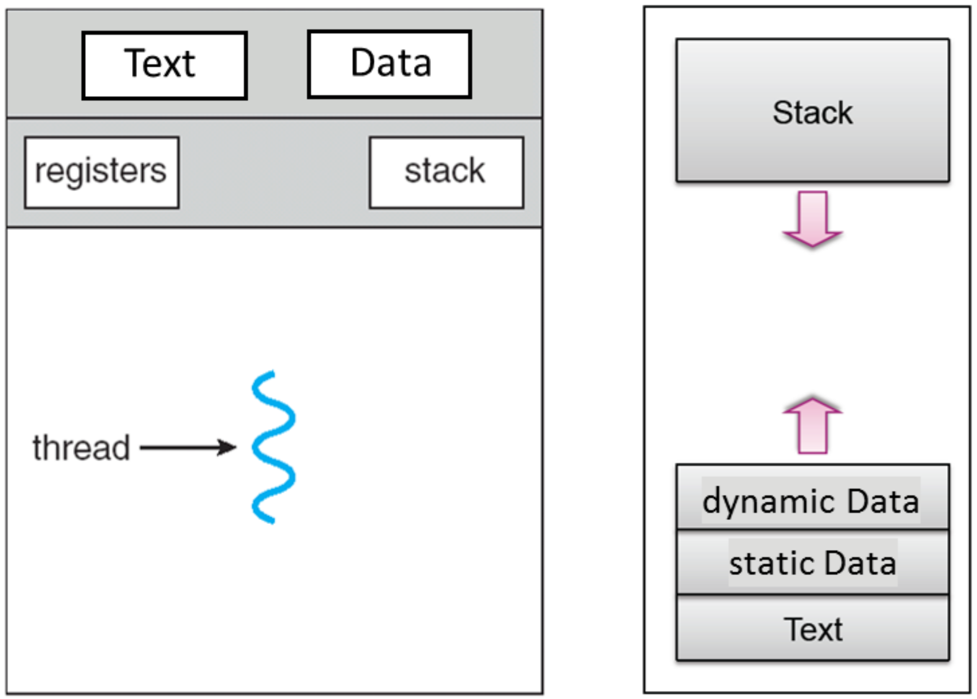
Ready:

- State of those tasks that are ready to execute but cannot be run because the processor is assigned to another task, i.e. another task has the state “running”.

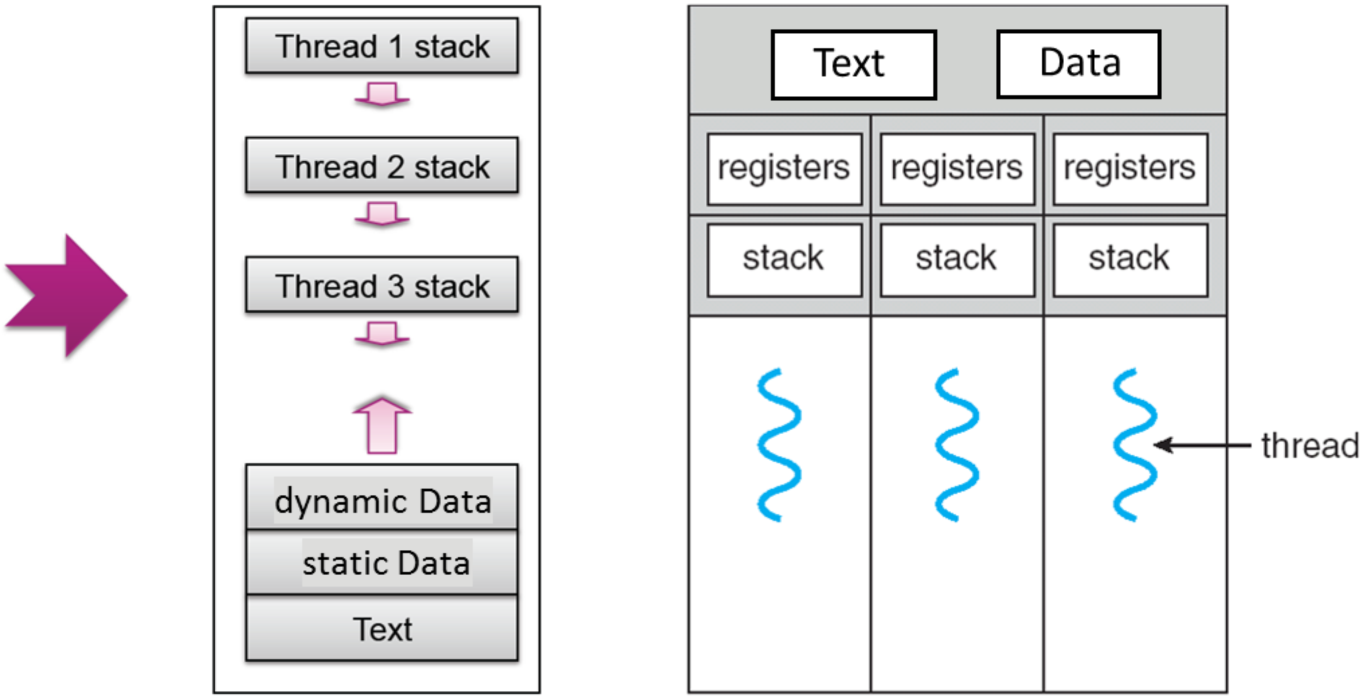
Blocked:

- A task enters the blocked state when it executes a synchronization primitive to wait for an event, e.g. a wait primitive on a semaphore or timer. In this case, the task is inserted in a queue associated with this semaphore. The task at the head is resumed when the semaphore is unlocked by an event.

Multiple Threads within a Process



process with a single thread



process with several threads

Threads

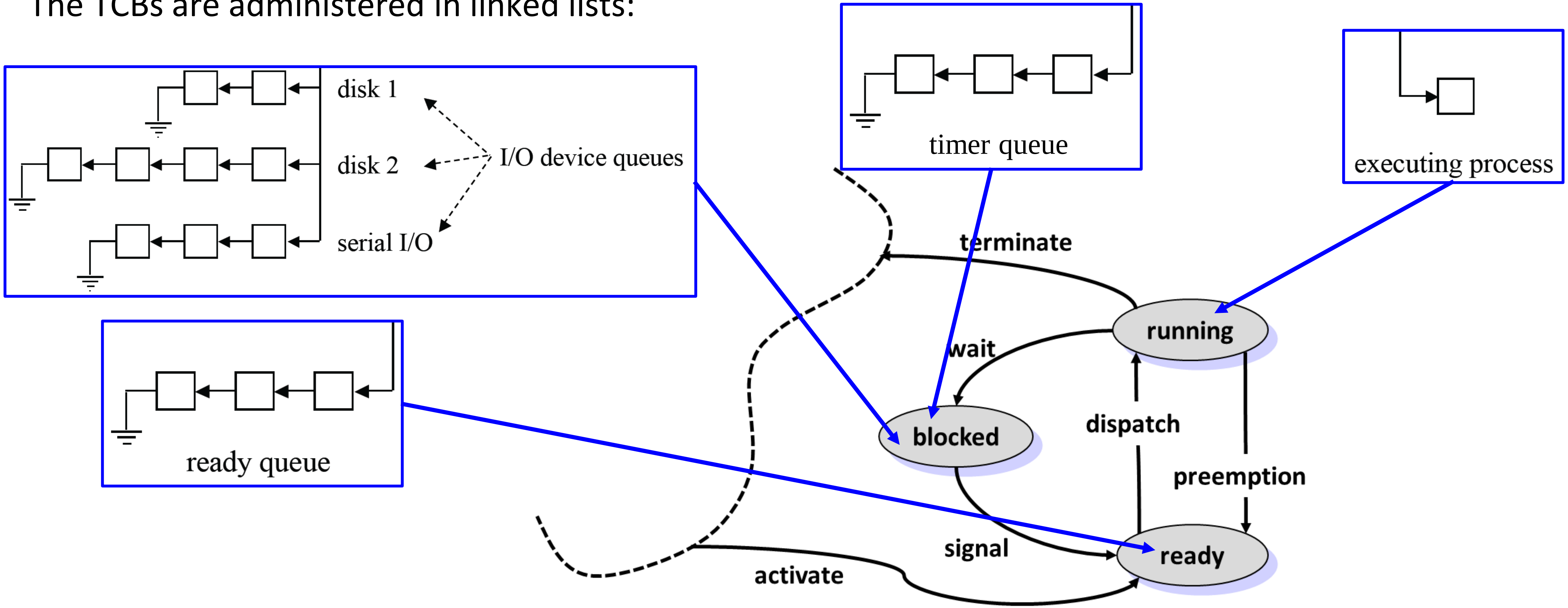
A thread is the smallest sequence of programmed instructions that can be managed independently by a scheduler; e.g., a thread is a basic unit of CPU utilization.

- *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.

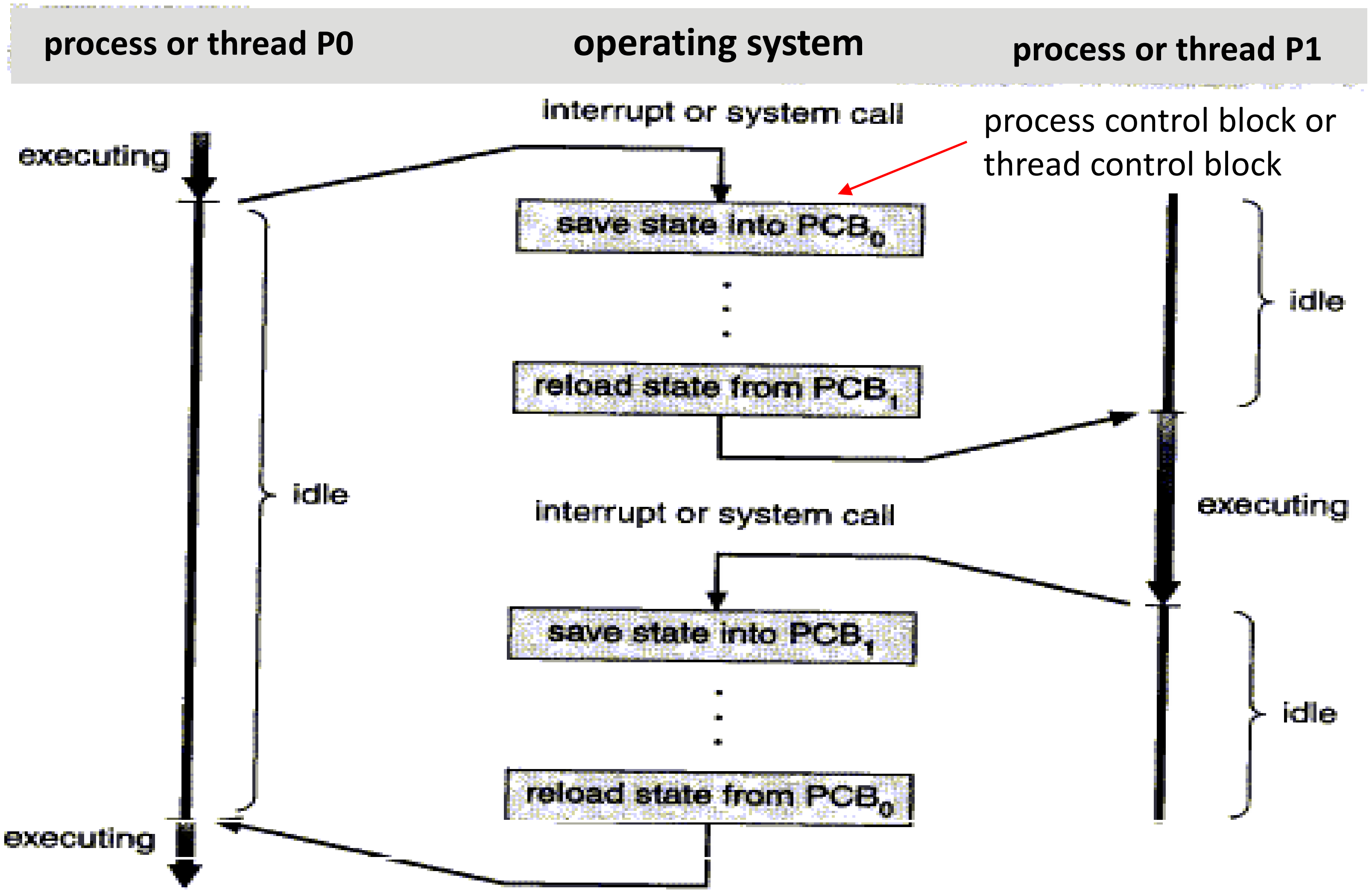
- *Thread advantages and characteristics*:
  - Faster to switch between threads; switching between user-level threads requires no major intervention by the operating system.
  - Typically, an application will have a separate thread for each distinct activity.
  - Thread Control Block (TCB) stores information needed to manage and schedule a thread

Threads

- The *operating system* maintains for each thread a *data structure (TCB – thread control block)* that contains its current status such as program counter, priority, state, scheduling information, thread name.
- The TCBs are administered in linked lists:



Context Switch: Processes or Threads



process control block or thread control block

Embedded Operating Systems

Classes of Operating Systems

Class 1: Fast and Efficient Kernels

Fast and efficient 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.

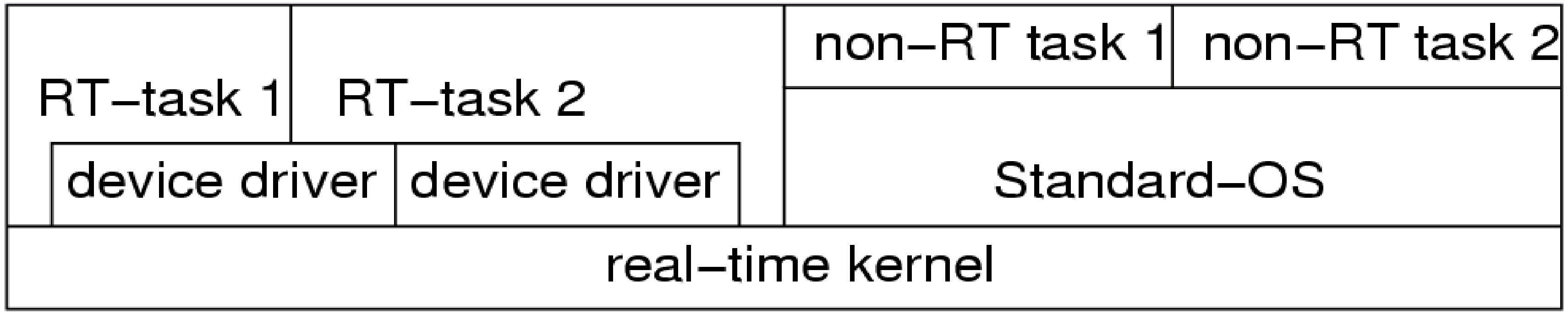
Examples include

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

Class 2: Extensions to Standard OSs

Real-time extensions to standard OS:

- Attempt to exploit existing and comfortable main stream operating systems.
- A real-time kernel runs all real-time tasks.
- The standard-OS is executed as one task.



RT–task 1

RT–task 2

device driver

device driver

non–RT task 1

non–RT task 2

Standard–OS

real–time kernel

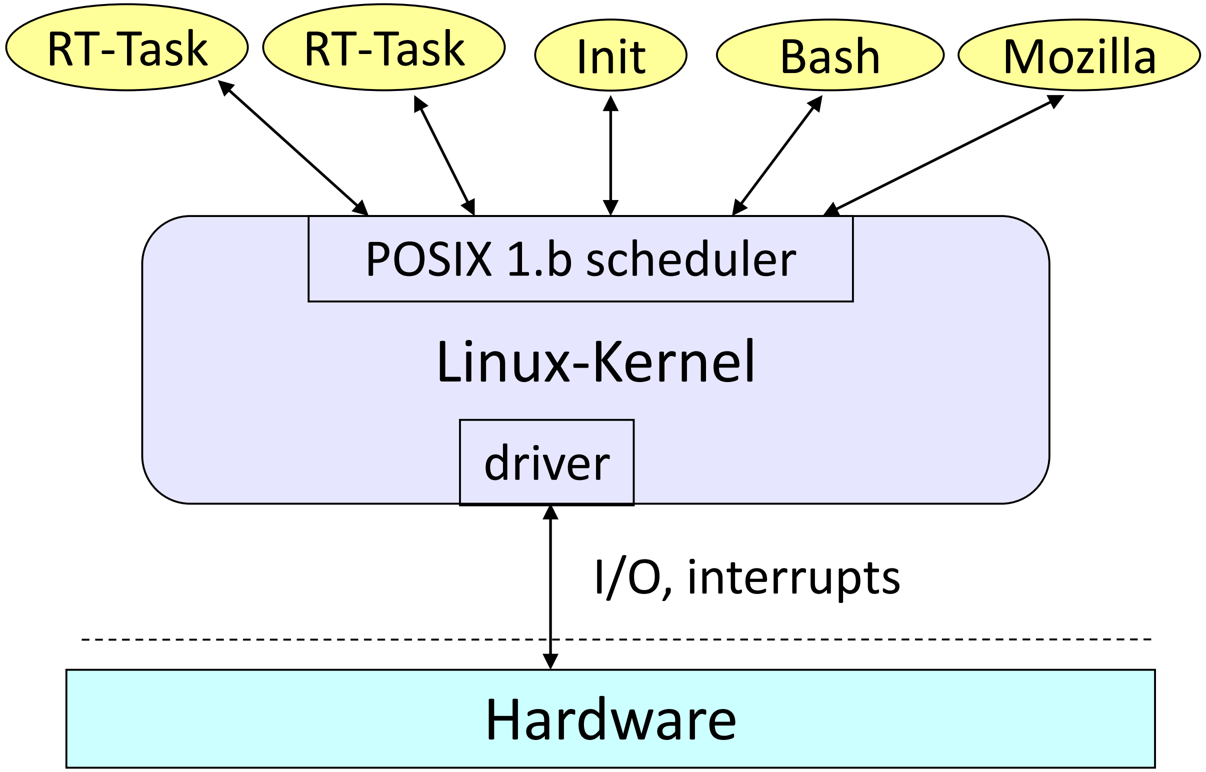
+ Crash of standard-OS does not affect RT-tasks;

- RT-tasks cannot use Standard-OS services; less comfortable than expected

revival of the concept: hypervisor

Example: Posix 1.b RT-extensions to Linux

The standard scheduler of a general purpose operating system can be replaced by a scheduler that exhibits *(soft) real-time properties*.



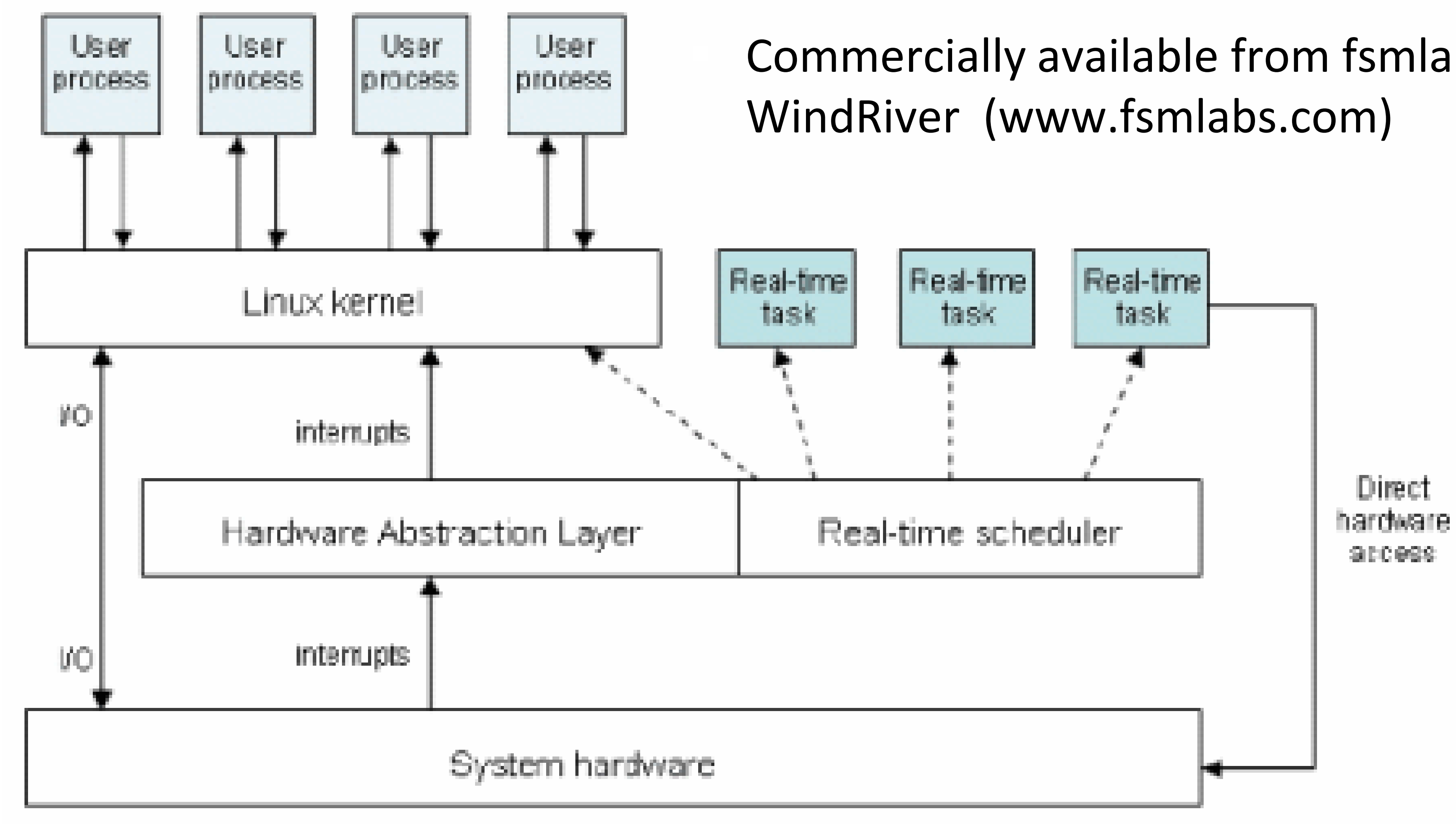
Special calls for real-time as well as standard operating system calls available.

Simplifies programming, but no guarantees for meeting deadlines are provided.

Example: RT Linux

RT-tasks cannot use standard OS calls.

Commercially available from fsmlabs and WindRiver (www.fsmlabs.com)



Class 3: Research Systems

Research systems try to avoid limitations of existing real-time and embedded operating systems.

- Examples include L4, seL4, NICTA, ERIKA, SHARK

Typical Research questions:

- low overhead memory protection,
- temporal protection of computing resources
- RTOS 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

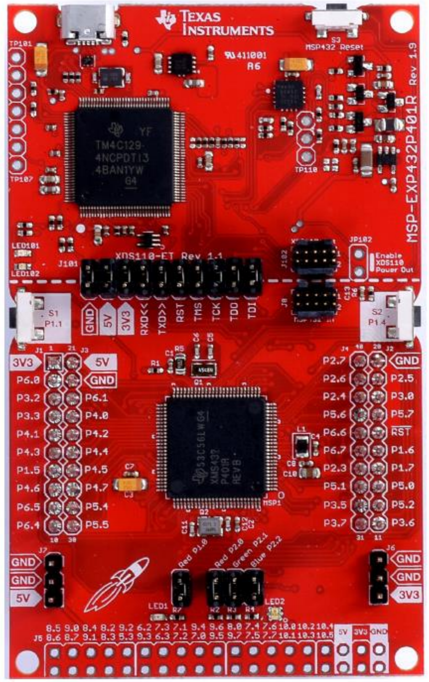
Embedded Operating Systems

FreeRTOS in the Embedded Systems Lab (ES-Lab)

Example: FreeRTOS (ES-Lab)

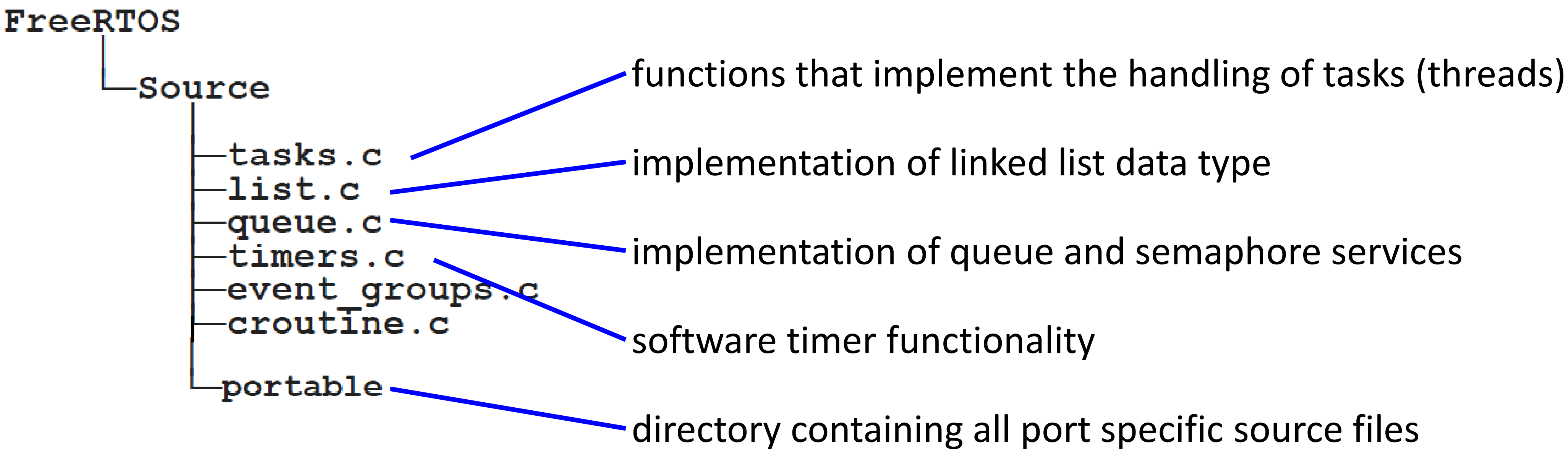
FreeRTOS (http://www.freertos.org/) is a typical embedded operating system. It is available for many hardware platforms, open source and widely used in industry. It is used in the ES-Lab.

- FreeRTOS is a *real-time kernel* (or real-time scheduler).
- Applications are organized as a *collection of independent threads* of execution.
- *Characteristics:* Pre-emptive or co-operative operation, queues, binary semaphores, counting semaphores, mutexes (mutual exclusion), software timers, stack overflow checking, trace recording, … .



Example: FreeRTOS (ES-Lab)

Typical directory structure (excerpts):



```
FreeRTOS
   └Source
       ├tasks.c
       ├list.c
       ├queue.c
       ├timers.c
       ├event_groups.c
       ├croutine.c
       │
       └portable
```

functions that implement the handling of tasks (threads)

implementation of linked list data type

implementation of queue and semaphore services

software timer functionality

directory containing all port specific source files

- *FreeRTOS is configured* by a header file called `FreeRTOSConfig.h` that determines almost all configurations (co-operative scheduling vs. preemptive, time-slicing, heap size, mutex, semaphores, priority levels, timers, …)

Embedded Operating Systems

FreeRTOS Task Management

Example FreeRTOS – Task Management

Tasks are implemented as threads.

- The *functionality of a thread* is implemented in form of a *function:*
  - Prototype: `void ATaskFunction( void *pvParameters );`

    some name of task function

    pointer to task arguments

  - Task functions are not allowed to return! They can be “killed” by a specific call to a FreeRTOS function, but usually run forever in an infinite loop.
  - Task functions can instantiate other tasks. Each created task is a separate execution instance, with its own stack.
  - *Example:*

```
void vTask1( void *pvParameters ) {
   volatile uint32_t ul; /* volatile to ensure ul is implemented. */
   for( ;; ) {
     ... /* do something repeatedly */
     for( ul = 0; ul < 10000; ul++ ) {  /* delay by busy loop */ }
   }
 }
```

Example FreeRTOS – Task Management

- *Thread instantiation:*

```
BaseType_t xTaskCreate( TaskFunction_t pvTaskCode,
                        const char * const pcName,
                        uint16_t usStackDepth,
                        void *pvParameters,
                        UBaseType_t uxPriority,
                        TaskHandle_t *pxCreatedTask );
```

a pointer to the function that implements the task

a descriptive name for the task

each task has its own unique stack that is allocated by the kernel to the task when the task is created; the usStackDepth value determines the size of the stack (in words)

returns pdPASS or pdFAIL depending on the success of the thread creation

the priority at which the task will execute; priority 0 is the lowest priority

pxCreatedTask can be used to pass out a handle to the task being created.

task functions accept a parameter of type pointer to void; the value assigned to pvParameters is the value passed into the task.

Example FreeRTOS – Task Management

***Examples** for changing properties of tasks:*

- Changing the *priority* of a task. In case of preemptive scheduling policy, the ready task with the highest priority is automatically assigned to the "running" state.

```
void vTaskPrioritySet( TaskHandle_t pxTask, UBaseType_t uxNewPriority );
```

handle of the task whose priority is being modified

new priority (0 is lowest priority)

- A task can *delete* itself or any other task. Deleted tasks no longer exist and cannot enter the "running" state again.

```
void vTaskDelete( TaskHandle_t pxTaskToDelete );
```

handle of the task who will be deleted; if NULL, then the caller will be deleted

Embedded Operating Systems

FreeRTOS Timers

Example FreeRTOS – Timers

- The operating system also provides *interfaces to **timers*** of the processor.
- As an example, we use the FreeRTOS timer interface to replace the busy loop by a delay. In this case, the task is put into the "blocked" state instead of continuously running.

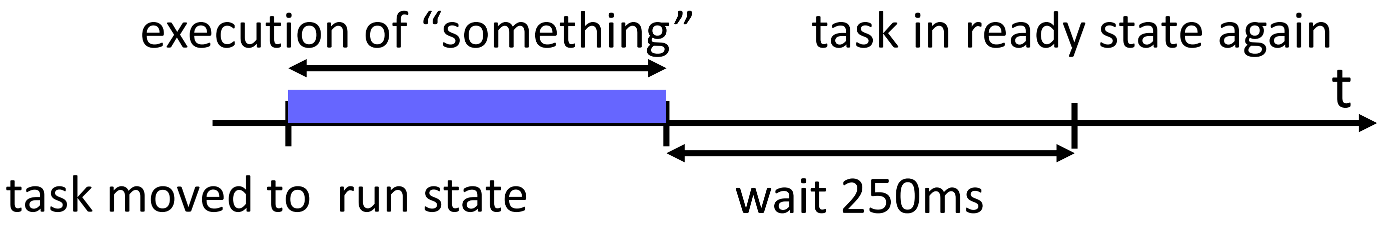
```
void vTaskDelay( TickType_t xTicksToDelay );
```

time is measured in "tick" units that are defined in the configuration of FreeRTOS (`FreeRTOSConfig.h`). The function `pdMS_TO_TICKS()` converts ms to "ticks".

```
void vTask1( void *pvParameters ) {
   for( ;; ) {
     ... /* do something repeatedly */
     vTaskDelay(pdMS_TO_TICKS(250));  /* delay by 250 ms */
   }
 }
```

Example FreeRTOS – Timers

- *Problem:* The task *does not execute* strictly *periodically*:



execution of “something”

task in ready state again

t

task moved to run state

wait 250ms

- The parameters to vTaskDelayUntil() specify the exact tick count value at which the calling task should be moved from the “blocked” state into the “ready” state. Therefore, the task is put into the “ready” state periodically.

```
void vTask1( void *pvParameters ) {
   TickType_t xLastWakeTime = xTaskGetTickCount();
   for( ;; ) {
     ... /* do something repeatedly */
     vTaskDelayUntil(&xLastWakeTime, pdMS_TO_TICKS(250));
   }
 }
```

The xLastWakeTime variable needs to be initialized with the current tick count. Note that this is the only time the variable is written to explicitly. After this xLastWakeTime is automatically updated within vTaskDelayUntil().

automatically updated when task is unblocked

time to next unblocking

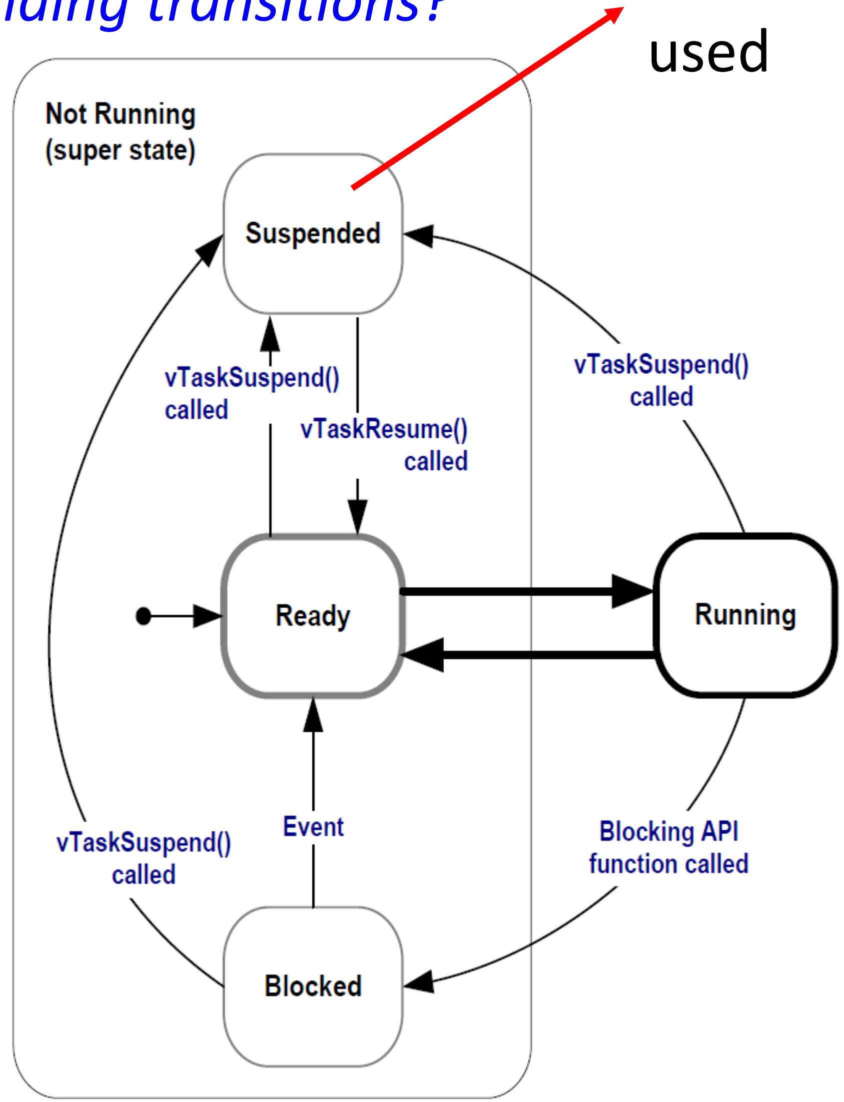
Embedded Operating Systems

FreeRTOS Task States

Example FreeRTOS – Task States

What are the task states in FreeRTOS and the corresponding transitions?

- A task that is waiting for an event is said to be in the *"Blocked" state*, which is a sub-state of the *"Not Running" state*.
- Tasks can enter the "Blocked" state to wait for two different types of event:
  - *Temporal (time-related) events*—the event being either a delay period expiring, or an absolute time being reached.
  - *Synchronization events*—where the events originate from another task or interrupt. For example, queues, semaphores, and mutexes, can be used to create synchronization events.



not much used

Example FreeRTOS – Task States

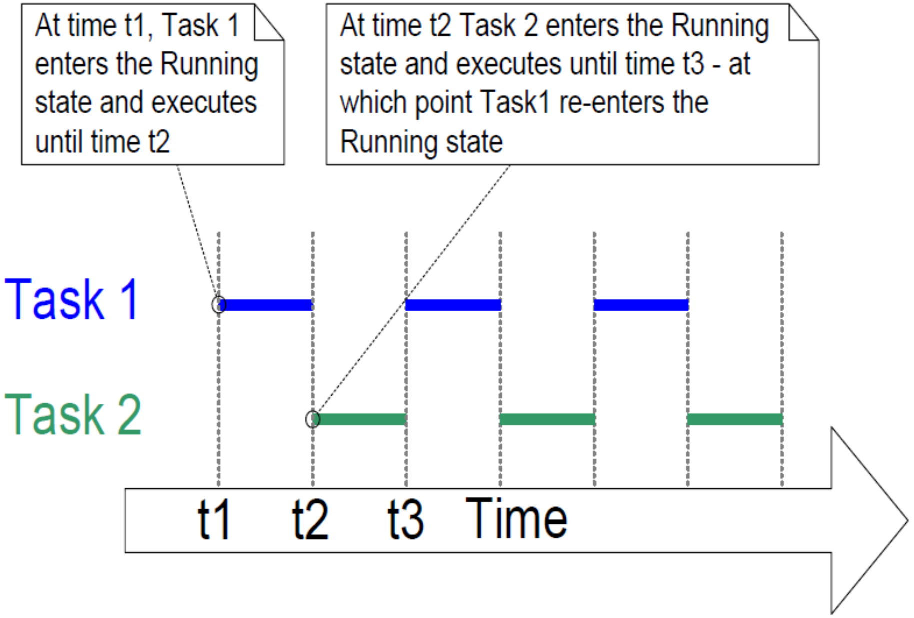
Example 1: *Two threads with equal priority.*

```
void vTask1( void *pvParameters ) {
   volatile uint32_t ul;
   for( ;; ) {
     ... /* do something repeatedly */
     for( ul = 0; ul < 10000; ul++ ) { }
   }
 }
```

```
void vTask2( void *pvParameters ) {
   volatile uint32_t u2;
   for( ;; ) {
     ... /* do something repeatedly */
     for( u2 = 0; u2 < 10000; u2++ ) { }
   }
 }
```

```
int main( void ) {
   xTaskCreate(vTask1, "Task 1", 1000, NULL, 1, NULL);
   xTaskCreate(vTask2, "Task 2", 1000, NULL, 1, NULL);
   vTaskStartScheduler();
   for( ;; );
 }
```

Both tasks have priority 1. In this case, FreeRTOS uses time slicing, i.e., every task is put into “running” state in turn.



At time t1, Task 1 enters the Running state and executes until time t2

At time t2 Task 2 enters the Running state and executes until time t3 - at which point Task1 re-enters the Running state

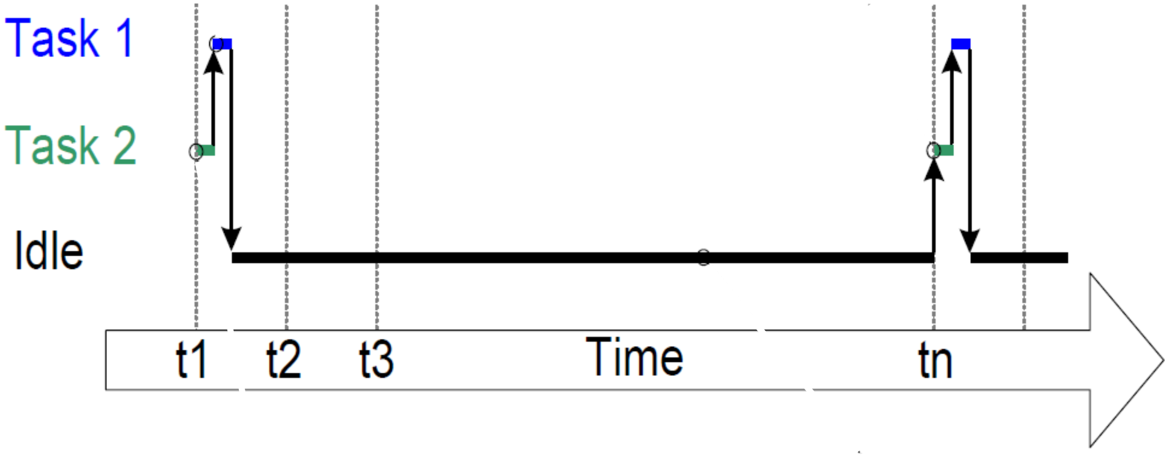
Example FreeRTOS – Task States

Example 2: *Two threads with delay timer.*

```
void vTask1( void *pvParameters ) {
   TickType_t xLastWakeTime = xTaskGetTickCount();
   for( ;; ) {
     ... /* do something repeatedly */
     vTaskDelayUntil(&xLastWakeTime,pdMS_TO_TICKS(250));
   }
}
```

```
void vTask2( void *pvParameters ) {
   TickType_t xLastWakeTime = xTaskGetTickCount();
   for( ;; ) {
     ... /* do something repeatedly */
     vTaskDelayUntil(&xLastWakeTime,pdMS_TO_TICKS(250));
   }
}
```

```
int main( void ) {
  xTaskCreate(vTask1,"Task 1",1000,NULL,1,NULL);
  xTaskCreate(vTask2,"Task 2",1000,NULL,2,NULL);
  vTaskStartScheduler();
  for( ;; );
}
```



If no user-defined task is in the running state, FreeRTOS chooses a built-in Idle task with priority 0. One can associate a function to this task, e.g., in order to go to low power processor state.

Embedded Operating Systems

FreeRTOS Interrupts

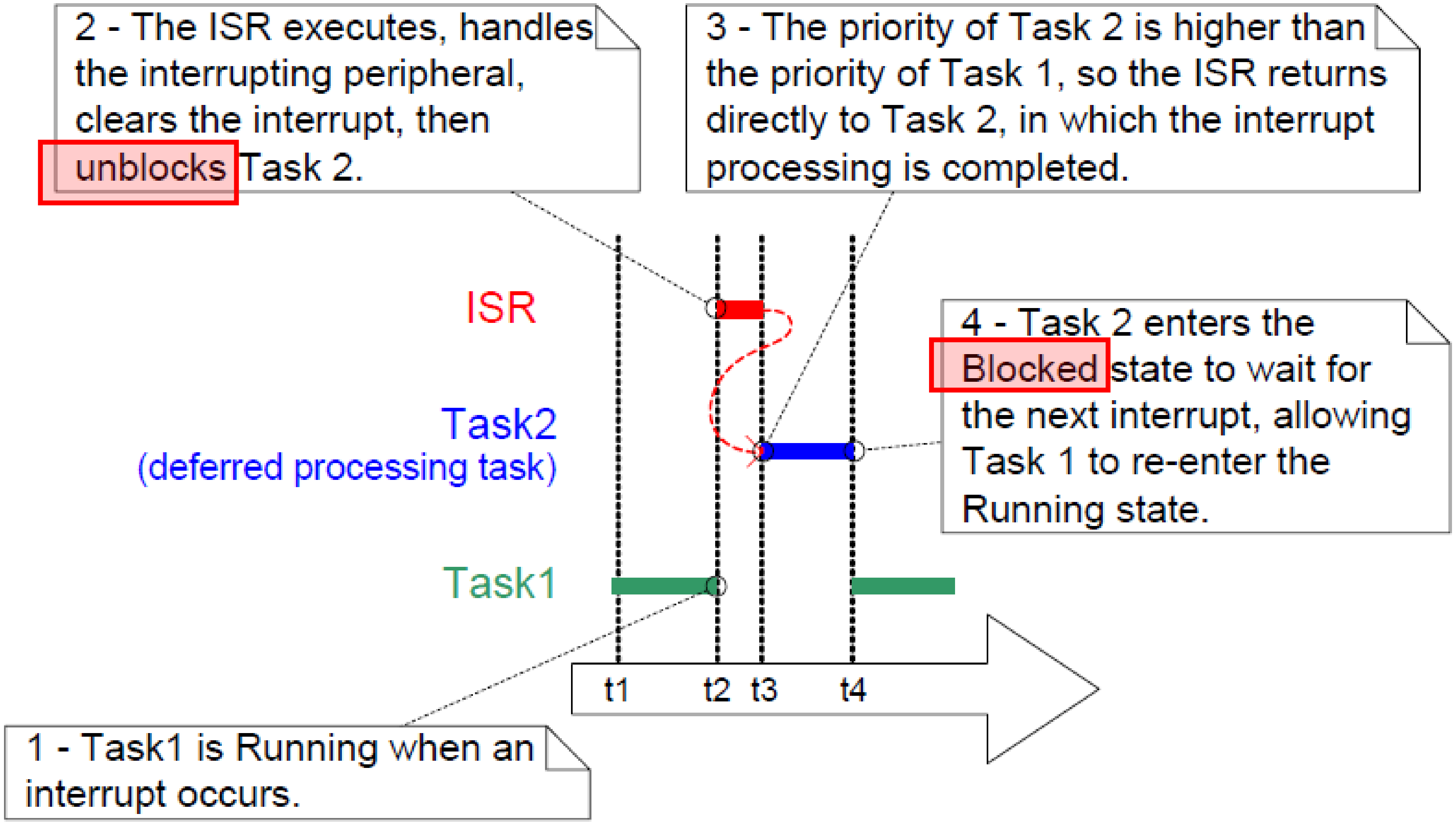
Example FreeRTOS – Interrupts

How are tasks (threads) and hardware interrupts scheduled jointly?

- Although written in software, an *interrupt service routine (ISR)* is a hardware feature because the hardware controls which interrupt service routine will run, and when it will run.
- *Tasks will only run when there are no ISRs running*, so the lowest priority interrupt will interrupt the highest priority task, and there is no way for a task to pre-empt an ISR. In other words, ISRs have always a higher priority than any other task.

- *Usual pattern:*
  - ISRs are usually very short. They find out the reason for the interrupt, clear the interrupt flag and determine what to do in order to handle the interrupt.
  - Then, they unblock a regular task (thread) that performs the necessary processing related to the interrupt.
  - For blocking and unblocking, usually semaphores are used.

Example FreeRTOS – Interrupts



1 - Task1 is Running when an interrupt occurs.

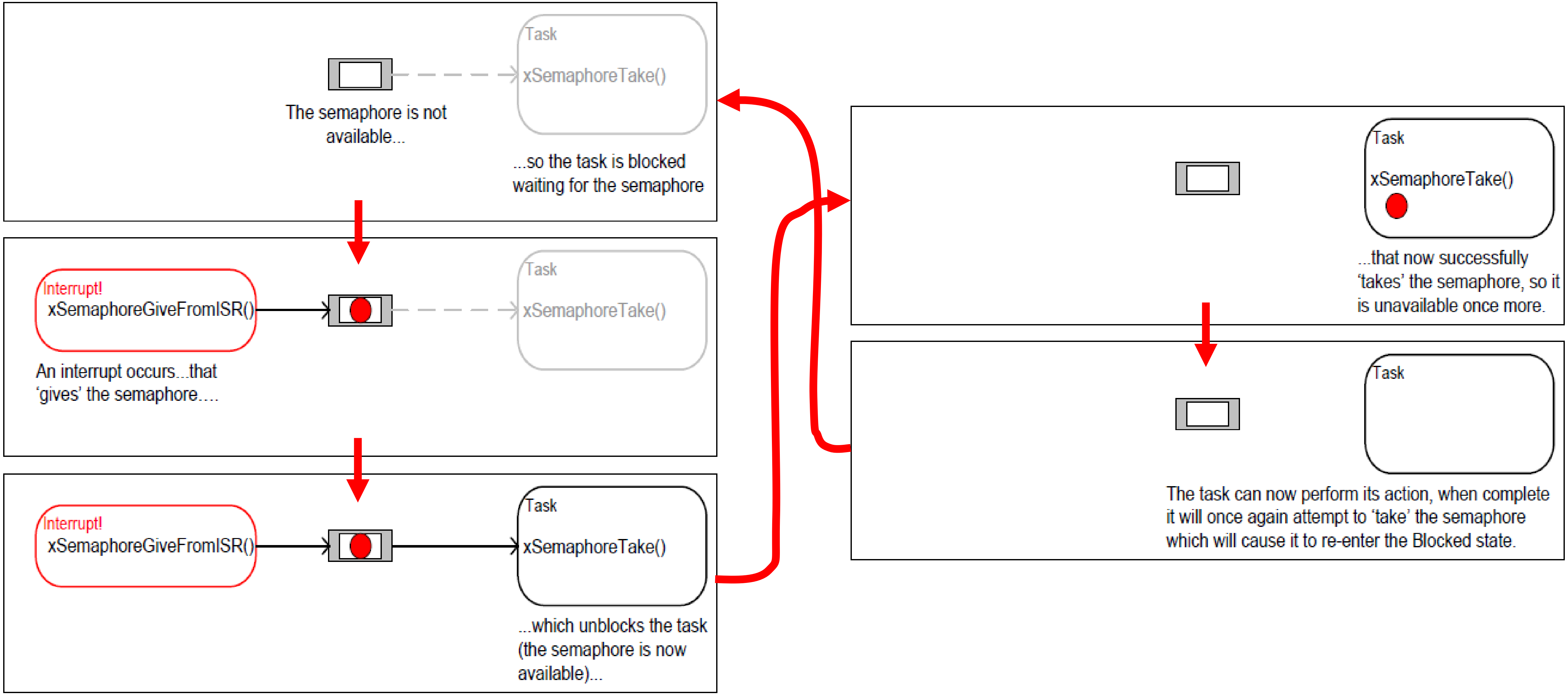
2 - The ISR executes, handles the interrupting peripheral, clears the interrupt, then unblocks Task 2.

3 - The priority of Task 2 is higher than the priority of Task 1, so the ISR returns directly to Task 2, in which the interrupt processing is completed.

4 - Task 2 enters the Blocked state to wait for the next interrupt, allowing Task 1 to re-enter the Running state.

blocking and unblocking is typically implemented via semaphores

Example FreeRTOS – Interrupts



The semaphore is not available...

...so the task is blocked waiting for the semaphore

An interrupt occurs...that 'gives' the semaphore....

...which unblocks the task (the semaphore is now available)...

...that now successfully 'takes' the semaphore, so it is unavailable once more.

The task can now perform its action, when complete it will once again attempt to 'take' the semaphore which will cause it to re-enter the Blocked state.