REAL TIME OPERATING SYSTEMS

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Why OS?

- To run a single program is easy
- What to do when several programs run in parallel?
  - Memory areas
  - Program counters
  - Scheduling (e.g. one instruction each)
  - Communication/synchronization/semaphors
  - Device drivers
- OS is a program offering the common services needed in all applications

Operating System Provides

- Environment for executing programs
- Support for multitasking/concurrency
- Hardware abstraction layer (device drivers)
- Mechanisms for Synchronization/Communication
- Filesystems/Stable storage

Batch Operating Systems

- Original computers ran in batch mode:
  - Submit job & its input
  - Job runs to completion
  - Collect output
  - Submit next job
- Processor cycles very expensive at the time
- Jobs involved reading, writing data to/from tapes
- Cycles were being spent waiting for the tape!

Timesharing Operating Systems

- Solution
  - Store multiple batch jobs in memory at once
  - When one is waiting for the tape, run the other one
- Basic idea of timesharing systems
- Fairness, primary goal of timesharing schedulers
  - Let no one process consume all the resources
  - Make sure every process gets “equal” running time

Real-Time Is Not Fair

- Main goal of an RTOS scheduler:
  - meeting timing constraints e.g. deadlines
- If you have five homework assignments and only one is due in an hour, you work on that one
- Fairness does not help you meet deadlines

Do We Need OS for RTS?

- Not always
- Simplest approach: cyclic executive

```
loop
do part of task 1 do part of task 2
do part of task 3
end loop
```

Cyclic Executive

- Advantages
  - Simple implementation
  - Low overhead
  - Very predictable
- Disadvantages
  - Can’t handle sporadic events (e.g. interrupt)
  - Everything must operate in lockstep
  - Code must be scheduled manually

Real-Time Systems and OS

- We need an OS
  - For convenience
  - Multitasking and threads
  - Cheaper to develop large RT systems
- But - don’t want to loose ability to meet deadlines (timing and resource constraints in general)
- This is why RTOS comes into the picture

Requirements on RTOS

- Determinism
- Responsiveness (quoted by vendors)
  - Fast process/thread switch
  - Fast interrupt response
- User control over OS policies
  - Mainly scheduling, many priority levels
  - Memory support (especially embedded)
- Reliability

Basic functions of OS kernel

- Process management
- Memory management
- Interrupt handling
- Exception handling
- Process Synchronization (IPC)
- Process scheduling

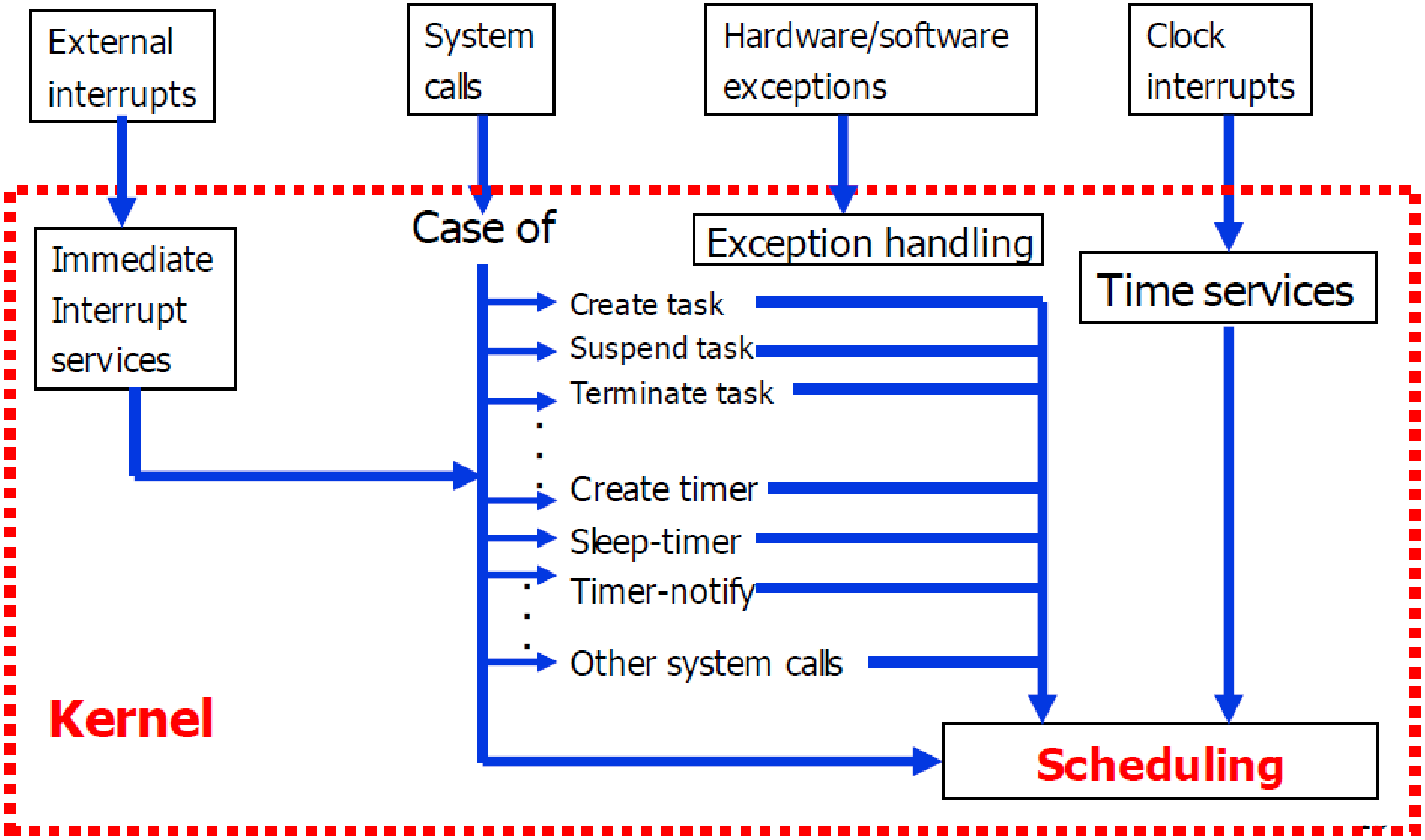
Process, Thread and Task

- A process is a program in execution.
- A thread is a “lightweight” process, in the sense that different threads share the same address space, with all code, data, process status in the main memory, which gives Shorter creation and context switch times, and faster IPC (Inter-process communication)
- Tasks are implemented as threads in RTOS.

Basic functions of RTOS kernel

- Task management
- Interrupt handling
- Memory management
  - no virtual memory for hard RT tasks
- Exception handling (important)
- Task synchronization
  - A void priority inversion
- Task scheduling
- Time management

Micro-kernel architecture

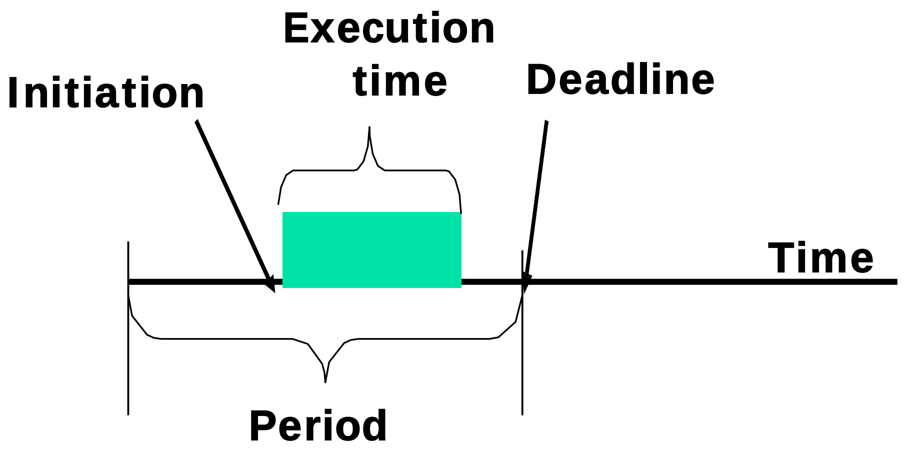


Task: basic notion in RTOS

- Task = thread (lightweight process)
  - A sequential program in execution
  - It may communicate with other tasks
  - It may use system resources such as memory blocks
- We may have timing constraints for tasks

Typical RTOS Task Model

- Each task a triplet: (execution time, period, deadline)
- Usually, deadline = period
- Can be initiated any time during the period

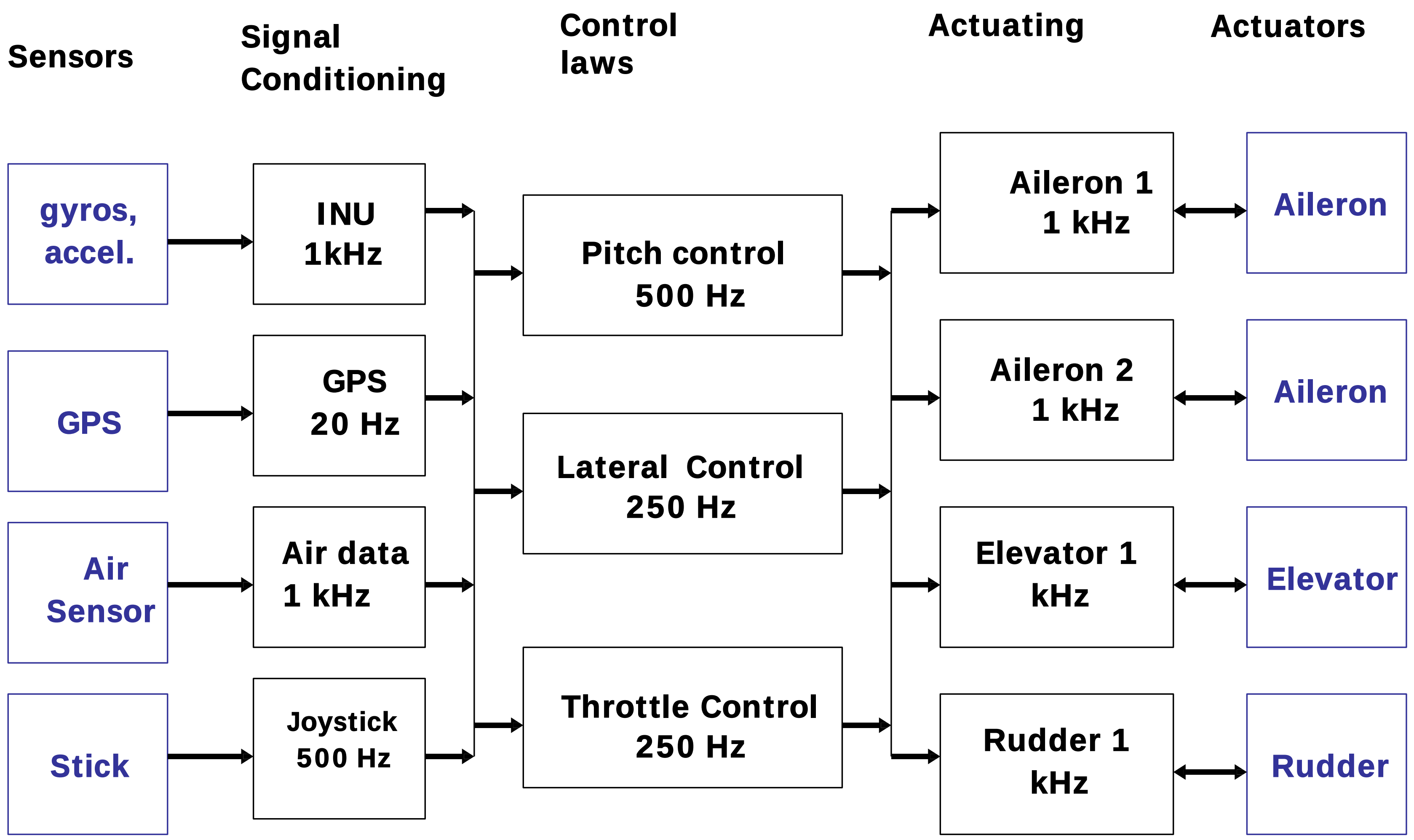


Task Classification (1)

- Periodic tasks: arriving at fixed frequency, can be characterized by 3 parameters (C,D,T) where
  - C = computing time
  - D = deadline
  - T = period (e.g. 20ms, or 50HZ) Often D=T, but it can be D<T or D>T
- Also called Time-driven tasks, their activations are generated by timers

Example: Fly-by-wire Avionics:

Hard real-time system with multi-rate tasks



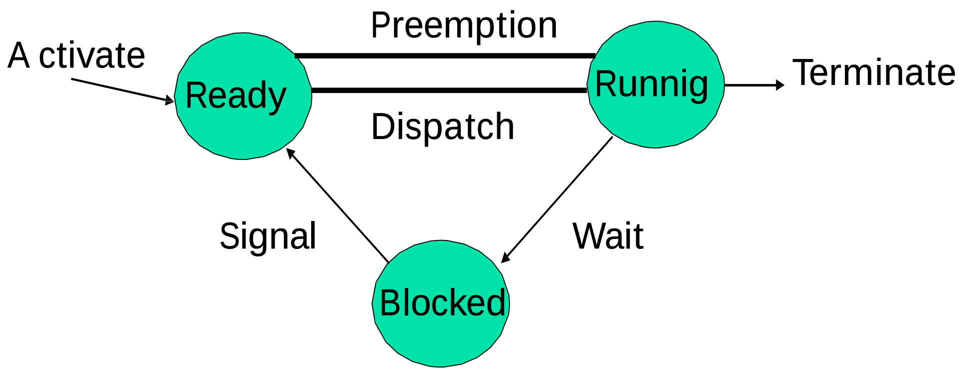
Task Classification (2)

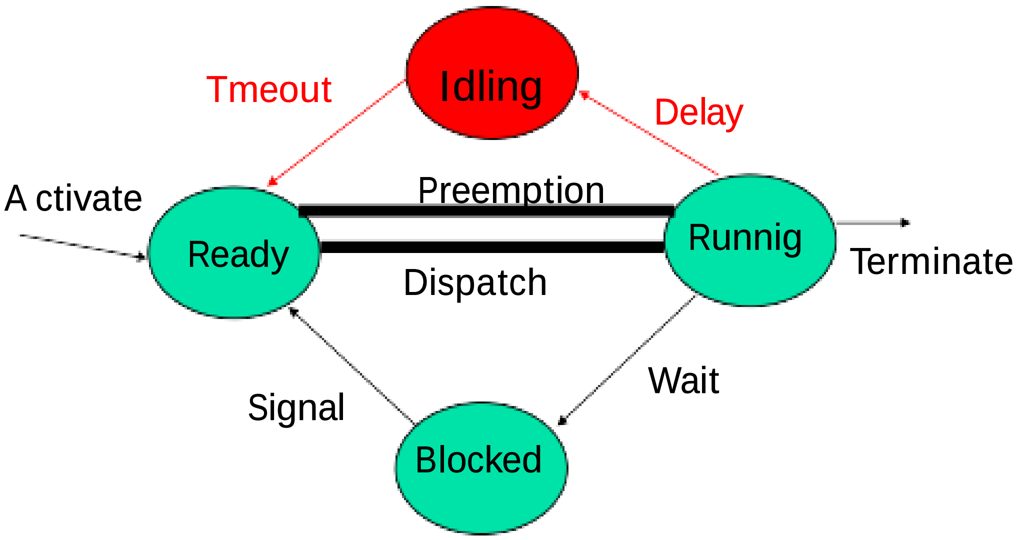
- Non-Periodic or aperiodic tasks = all tasks that are not periodic, also known as Event-driven, their activations may be generated by external interrupts
- Sporadic tasks = aperiodic tasks with minimum interarrival time T_{min} (often with hard deadline)
  - worst case = periodic tasks with period T_{min}

Task states

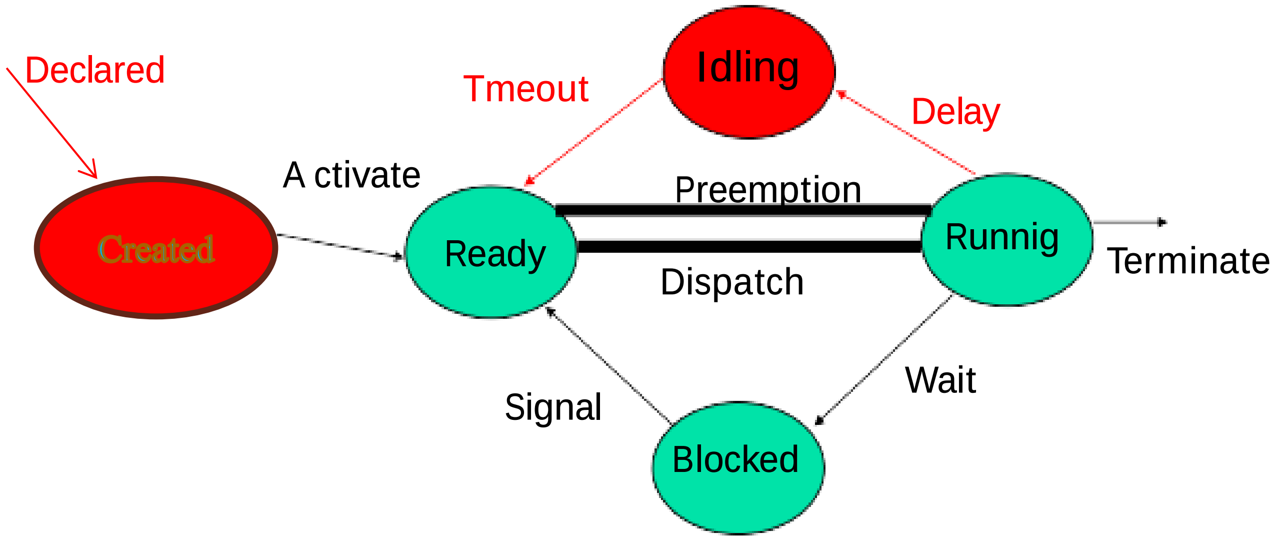
- Ready
- Running
- Waiting/blocked/suspended …
- Idling
- Terminated

Idling: Rölantide çalışma





Task states


Declared
Tmeout
Idling
Delay
A ctivate
Preemption
Created
Ready
Runnig
Terminate
Dispatch
Wait
Signal
Blocked

TCB (Task Control Block)

- Id
- Task state (e.g. Idling)
- Task type (hard, soft, background ...)
- Priority
- Other Task parameters
  - period
  - comuting time (if available)
  - Relative deadline
  - Absolute deadline
- Context pointer
- Pointer to program code, data area, stack
- Pointer to resources (semaphors etc)
- Pointer to other TCBs (preceding, next, waiting queues etc)

Basic functions of RT OS

- **Task mangement**
- Interrupt handling
- Memory management
- Exception handling
- Task synchronization
- Task scheduling
- Time management

Task mangement

- Task creation: create a new TCB
- Task termination: remove the TCB
- Change Priority: modify the TCB
- State-inquiry: read the TCB
- Challenges for an RTOS
  - The memory blocks for RT tasks must be locked in main memory to avoid access latencies due to swapping
  - Creating an RT task, it has to get the memory without delay: this is difficult because memory has to be allocated and a lot of data structures, code segment must be copied/initialized
  - Changing run-time priorities is dangerous: it may change the run-time behavior and predictability of the whole system

Basic functions of RT OS

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- **Interrupt handling**
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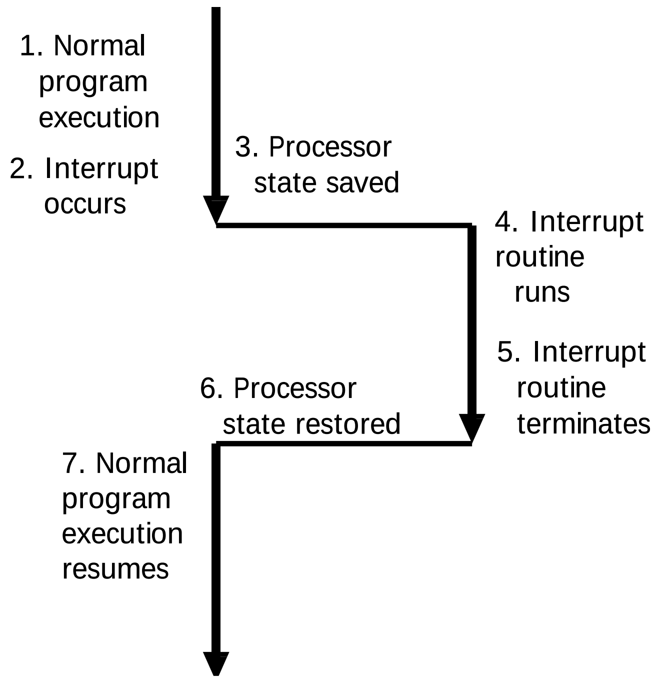
Interrupt and Interrupt Handling

- Interrupt: environmental event that demands attention.
  - Example: “byte arrived” interrupt on serial channel.
- Interrupt routine: piece of code executed in response to an interrupt.
- Most interrupt routines Copy peripheral data into a buffer.
  - Indicate to other code that data has arrived
  - Acknowledge the interrupt (tell hardware).
  - Longer reaction to interrupt performed outside interrupt routine.
- E.g., causes a process to start or resume running.


1. Normal program execution
2. Interrupt occurs
3. Processor state saved
4. Interrupt routine runs
5. Interrupt routine terminates
6. Processor state restored
7. Normal program execution resumes

Interrupt Handling

- Types of interrupts
  - Asynchronous (or hardware interrupt) by hardware event (timer, network card …) the interrupt handler as a separated task in a different context.
  - Synchronous (or software interrupt, or a trap) by software instruction (swi in ARM, int in Intel 80x86), a divide by zero, a memory segmentation fault, etc. The interrupt handler runs in the context of the interrupting task
- Interrupt latency
  - The time delay between the arrival of interrupt and the start of corresponding ISR.
  - Modern processors with multiple levels of caches and instruction pipelines that need to
  - Be reset before ISR can start might result in longer latency.
  - The ISR of a lower-priority interrupt may be blocked by the ISR of a high -priority

Basic functions of RT OS

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Memory Management

- Standard methods
  - Block-based, Paging, hardware mapping for protection
- No virtual memory for hard RT tasks
  - Lock all pages in main memory
- Many embedded RTS do not have memory protection – tasks may access any blocks – Hope that the whole design is proven correct and protection is unnecessary
  - to achieve predictable timing
  - to avoid time overheads
- Most commercial RTOS provide memory protection as an option
  - Run into ”fail-safe” mode if an illegal access trap (tuzak) occurs
  - Useful for complex reconfigurable systems

Basic functions of RT OS

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- Interrupt handling
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Exception handling

- Exceptions e.g missing deadline, running out of memory, timeouts, deadlocks
  - Error at system level, e.g. deadlock
  - Error at task level, e.g. timeout
- Standard techniques:
  - System calls with error code
  - Watch dog
  - Fault-tolerance (later)
- However, difficult to know all scenarios
  - Missing one possible case may result in disaster
  - This is one reason why we need Modelling and Verification

Watch-dog

- A task, that runs (with high priority) in parallel with all others
- If some condition becomes true, it should react ...

```
Loop begin
....
end
until condition
```

- The condition can be an external event, or some flags
- Normally it is a timeout
- Watch-dog (to monitor whether the application task is alive)

```
Loop
if flag==1 then
 {
 next :=system_time;
 flag :=0
 }
  else  if system_time> next+20s then WA RNING; sleep(100ms)
end loop
```

- A pplication-task
  - flag:=1 ... ... computing something ... ... flag:=1 ..... flag:=1 ....

Basic functions of RT OS

- Task management
- Interrupt handling
- Memory management
- Exception handling
- **Task synchronization**
- Task scheduling
- Time management

Task synchronization

- Synchronization primitives
  - ***Semaphore***: counting semaphore and binary semaphore
- A semaphore is created with *initial count,* which is the number of allowed *holders*
- of the semaphore lock. (initial count=1: binary sem)
- Sem_wait will decrease the count; while sem_signal will increase it.
- A task can get the semaphore when the count > 0; otherwise, block on it.
  - ***Mutex***: similar to a binary semaphore, but mutex has an *owner*.
- a semaphore can be "waited for" and "signaled" by *any* task,
- while only the task that has *taken* a mutex is allowed to release it.
  - ***Spinlock***: lock mechanism for multi-processor systems,
- A task wanting to get spinlock has to get a lock shared by *all* processors.
  - ***Read/write locks***: protect from concurrent write, while allow concurrent read
- *Many* tasks can get a *read* lock; but only *one* task can get a *write* lock.
- Before a task gets the write lock, all read locks have to be released.
  - ***Barrier***: to synchronize a lot of tasks,
- They should wait until *all* of them have reached a certain "barrier."

Task synchronization

- Challenges for RTOS
  - *Critical section* (data, service, code) protected by lock mechanism e.g. Semaphore etc. In a RTOS, the *maximum* time a task can be delayed because of locks held by other tasks should be less than its timing constraints.
  - *Race condition – deadlock, livelock, starvation* Some deadlock *avoidance/prevention* algorithms are too complicate and indeterministic for real-time execution. Simplicity is preferred, like
    - *all tasks* always take locks in the *same order*.
    - allow each task to hold only *one* resource.
  - *Priority inversion* using *priority*-based task scheduling and *locking* primitives should know the "*priority inversion*" danger: *a medium-priority job runs while a high priority task is ready to proceed.*

Data exchanging

- Semaphore
- Shared variables
- Bounded buffers
- FIFO
- Mailbox
- Message passing
- Signal
- Semaphore is the most primitive and widely used construct for Synchronization and communication in all operating systems

Semaphore

- A semaphore is a simple data structure with
  - a counter
    - the number of ”resources”
    - binary semaphore
  - a queue
    - Tasks waiting

and two operations:

- P(S): get or wait for semaphore
- V(S): release semaphore

SCB: Semaphores Control Block

Counter
Queue of TCBs (tasks waiting)
Pointer to next SCB

The queue should be sorted by priorities (Why not FIFO?)

Implementation of semaphores

- P(scb):
  - Disable-interrupt;
  - If scb.counter>0 then
    - scb.counter - -1;
  - end then else
    - save-context();
    - current-tcb.state := blocked; insert(current-tcb, scb.queue); dispatch();
    - load-context();
  - end else
  - Enable-interrupt
- V(scb):
  - Disable-interrupt;
  - If not-empty(scb.queue) then
    - tcb := get-first(scb.queue);
    - tcb.state := ready;
    - insert(tcb, ready-queue); save-context();
    - schedule(); /* dispatch invoked*/ load-context();
  - end then
  - else scb.counter ++1;
    - end else Enable-interrupt

Advantages & Disadvantages semaphores

Advantages with semaphores

- Simple (to implement and use)
- Exists in most (all?) operating systems
- It can be used to implement other synchronization tools
  - Monitors, protected data type, bounded buffers, mailbox etc

Disadvantages (problems) with semaphores

- Deadlocks
- Loss of mutual exclusion
- Blocking tasks with higher priorities (e.g. FIFO)
- Priority inversion !

Exercise/Questions

- Implement Mailbox by semaphore
  - Send(mbox, receiver, msg)
  - Get-msg(mbox,receiver,msg)
- How to implement hand-shaking communication?
  - V(S1)P(S2)
  - V(S2)P(S1)
- Solve the read-write problem
- (e.g max 10 readers, and at most 1 writer at a time)

Priority inversion problem

- Assume 3 tasks: A, B, C with priorities Ap<Bp<Cp
- Assume semaphore: S shared by A and C
- The following may happen:
  - A gets S by P(S)
  - C wants S by P(S) and blocked
  - B is released and preempts A
  - Now B can run for a long period .....
  - A is blocked by B, and C is blocked by A
  - So C is blocked by B
- The above scenario is called ’priority inversion’
- It can be much worse if there are more tasks with priorities in between Bp and Cp, that may block C as B does!