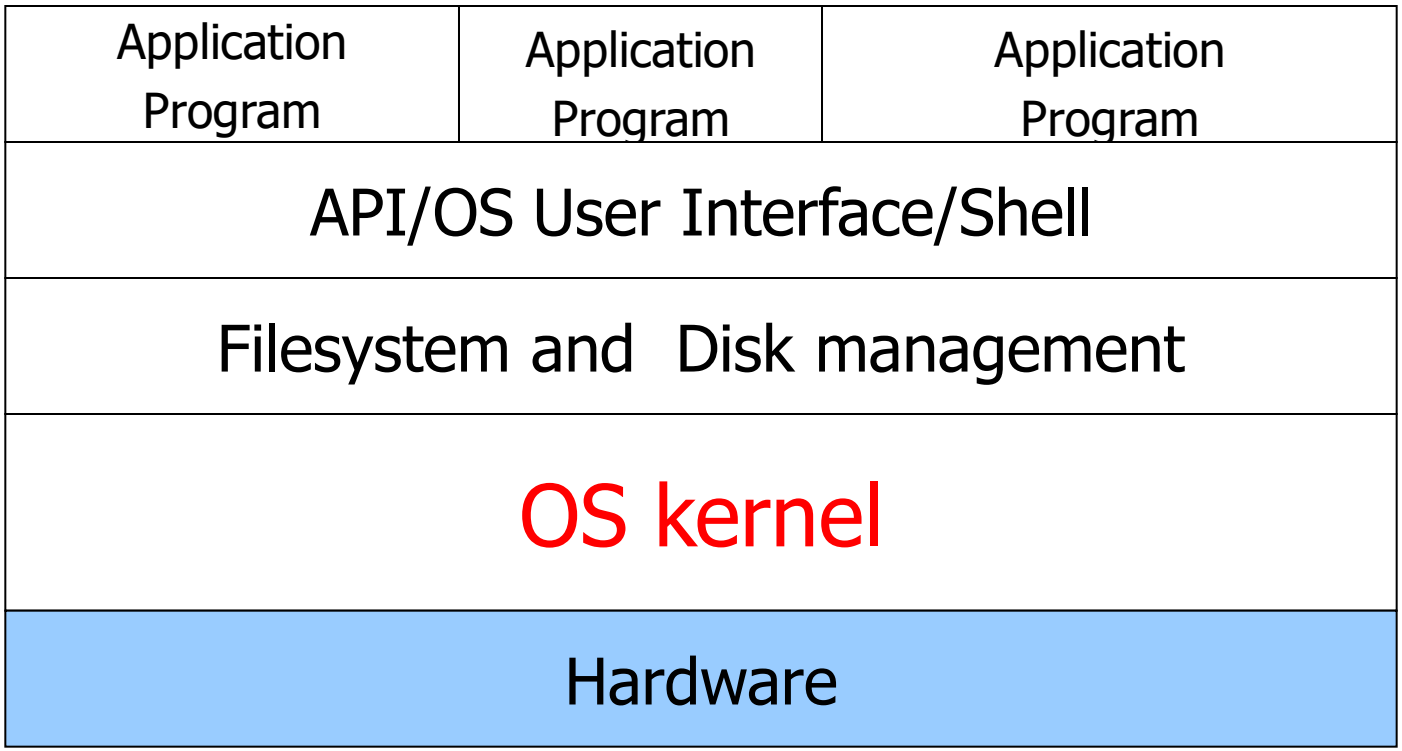
Today's topic: RTOS

(Real Time Operating Systems)

Operating System Provides

- Hardware abstraction layer
  - Interrupt processing
  - Device drivers: I/O Libraries - 10 times bigger than a minimal OS e.g. the firmware on an automotive ECU is 10% RTOS and 90% device drivers
  - API – Application Programming Interface -- System calls
- Environment for executing program(s)
  - Process/thread management, process communication
- Stable storage
  - Filesystems

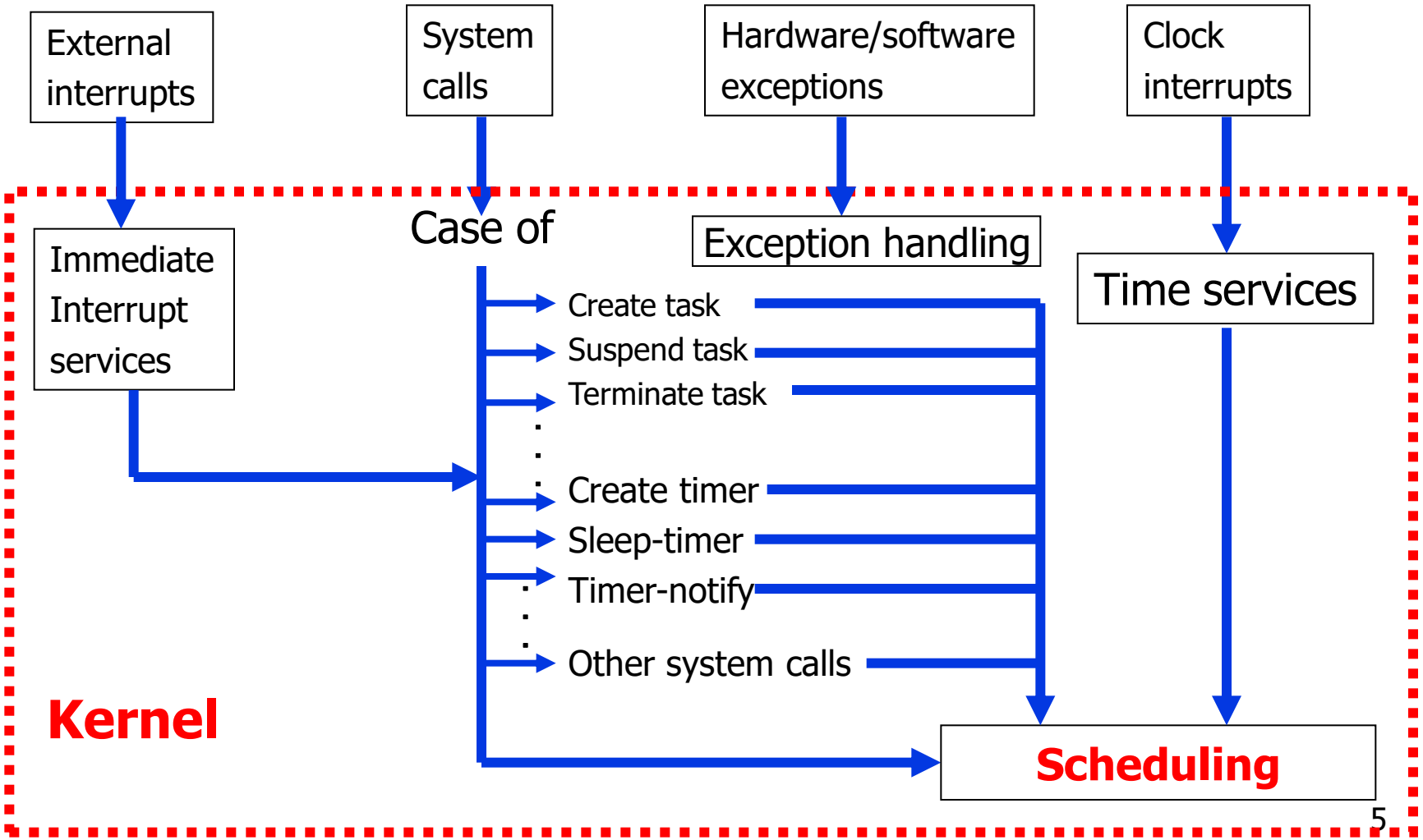
Overall Stucture of Computer Systems



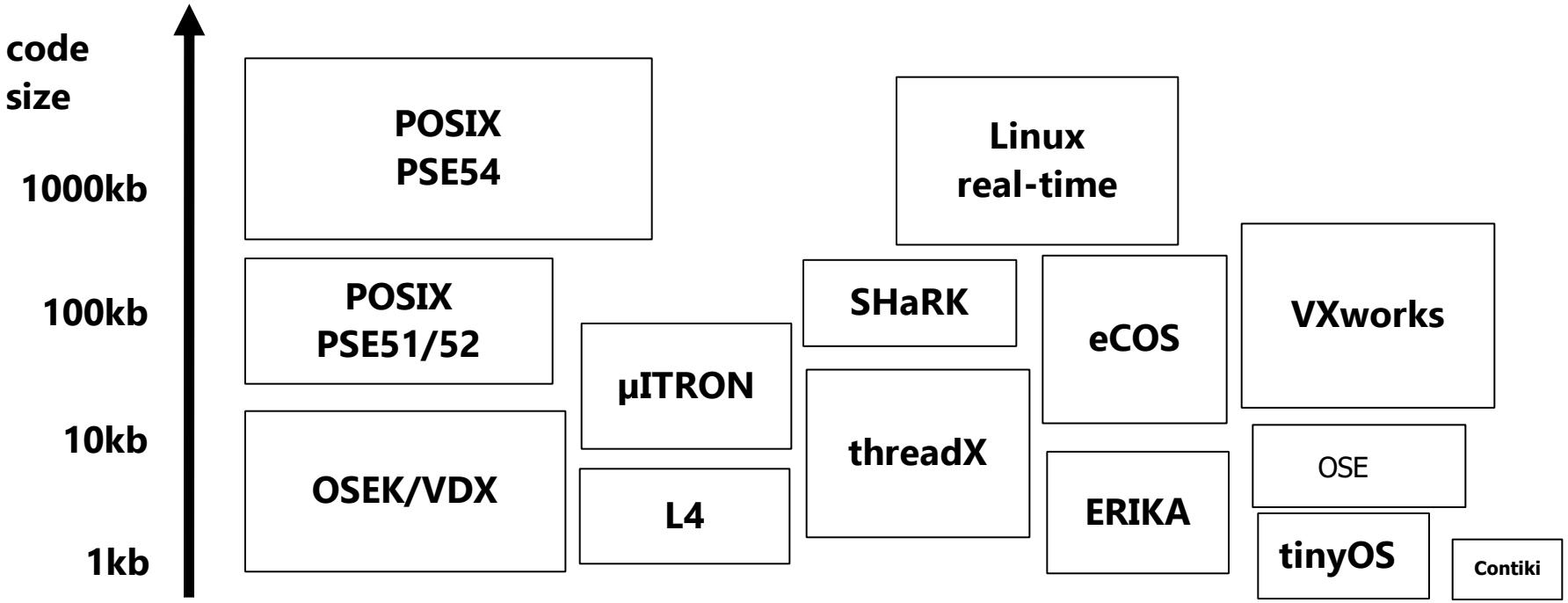
Requirements on RTOS

- Determinism
  - Deterministic system calls
- Responsiveness (quoted by vendors)
  - Fast context switch (#instructions)
  - Short interrupt latency (#CPU cycles)
- Support for timely concurrent processing
  - Real-time
  - Multi-tasking
  - synchronization
- User control over OS policies
  - CPU scheduling (e.g. many priority levels)
  - Support for memory management
    - E.g. pages locked in main memory
- Controlled code size (~1MB)
  - E.g. Micro kernel, Contiki, 1000 loc, OSE small kernel, 2k

Micro-kernel architecture



Typical footprints



Existing RTOS: 4 categories

- Priority based kernel for embbeded applications e.g. POSIX (IEEE standard 1003.1-1988, UNIX based), OSE (cell phone), VxWorks (space and robotics), OSEK/VDX (automotive), QNX (automotive and multimedia) .... Many of them are commercial kernels
  - Applications should be designed and programmed to suite priority-based scheduling e.g deadlines as priority etc
- Real Time Extensions of existing time-sharing OS e.g. Real time Linux, Real time NT by e.g locking RT tasks in main memory, assigning highest priorities etc
- Research RT Kernels e.g. L4 (some of the kernels are commercial), SHARK, TinyOS, …
- Run-time systems for RT programmingn languages e.g. Ada, Erlang, Real-Time Java ...

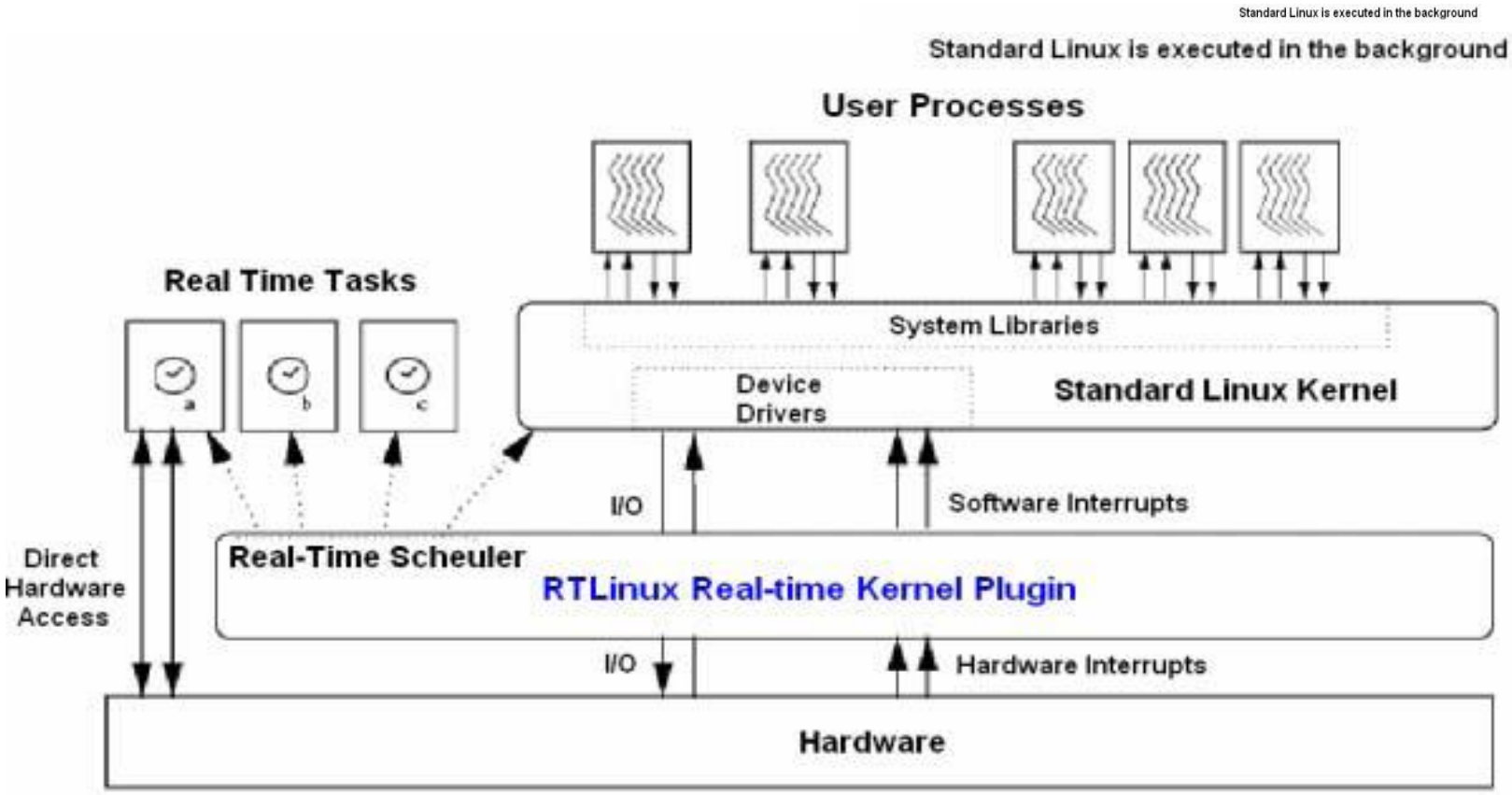
POSIX: an example RTOS

- POSIX: **P**ortable **O**perating **S**ystem **I**nterface for Uni**X**
  - IEEE standard 1003.1-1988
  - A typical footprint around 1M
- Use profiles to support subsets of the standard
- A profile lists a set of services typically used in a given environment
- POSIX real time profiles are specified by the ISO/IEEE standard 1003.13

POSIX 1003.13 profiles

- PSE51 minimal real-time system profile (around 50-150 Kbytes)
  - no file system
  - no memory protection
  - Mono-process multi-thread kernel
- PSE52 real-time controller system profile
  - PSE51 + file system + asynchronous I/O
- PSE53 dedicated real-time system profile
  - PSE51 + process support and memory protection
- PSE54 multi-purpose real-time system profile
  - PSE53 + file system + asynchronous I/O

RT Linux: an example RTOS



Linux v.s. RTLinux

- **Linux Non-real-time Features**
  - Dymanic scheduling, not designed for real-time tasks -- good *average* performance or throughput
  - Non-preemptible.
  - Un-predictable delays
    - Uninterruptible system calls, the use of interrupt disabling, virtual memory support (context switch may take hundreds of microsecond).
  - ”Coarse” timer resolution 1-10ms (e.g. 4ms)
- **RTLinux Real-time Features**
  - Real-time scheduling (EDF, RMS, FPS): guarantee *hard deadlines*
  - Pre-emptible kernel
  - Predictable delays (by its small size and limited operations)
  - ”Finer” timer resolution (can be nanos/too much overheads, 50micrs ...)

OSEK /VDX: an example RTOS (automotive applications)

- Founded in May 1993
  - Joint project of the German automotive industry
  - OSEK (German): Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug
  - Initial project partners: BMW, Bosch, DaimlerChrysler, Opel, Siemens, VW
- 1994 PSA & Renault joined OSEK
  - Similar project of the French automotive industry
  - VDX → Vehicle Distributed eXecutive
- OSEK/VDX resulted from the merge of the two projects
- `http://www.osek-vdx.org`

Basic functions of RTOS

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

Time mangement

- A high resolution hardware timer is programmed to interrupt the processor at fixed rate – Time interrupt
- Each time interrupt is called a system tick (time resolution)
  - Normally, the tick can vary in microseconds
    - The tick may be selected/configured by the user
    - All time parameters for tasks should be the multiple of the tick
    - OBS: too fine→ too much overheads, too coarse → too long latency
  - System time = 32 bits
    - One tick = 1ms: your system can run 50 days
    - One tick = 20ms: your system can run 1000 days = 2.5 years
    - One tick = 50ms: your system can run 2500 days= 7 years
  - The Lego processor/ARM-7: 48MHZ (automotive systems/Bosch, 200MHZ)
    - 48 000 000 CPU cycles (~12 000 000 instructions!) per second
    - ~12 000 instructions/1ms (per tick, if time resolution is 1ms)

Time interrupt routine

- Save the context of the task in execution
  - Increment the system time by 1, if current time > system lifetime, generate a timing error
  - Update timers (reduce each counter by 1)
    - A queue of timers
  - Activation of periodic tasks in idling state
  - Schedule again - call the scheduler
  - Other functions e.g.
    - (Remove all tasks terminated -- deallocate data structures e.g TCBs)
    - (Check if any deadline misses for hard tasks, monitoring)
- load context for the first task in ready queue

Basic functions of RTOS kernel

- Time management
- **Task mangement**
- Interrupt handling
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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

Periodic tasks

- Described with 3 parameters (C,D,T) where
  - C = resource budget
  - 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

Sporadic tasks

- Described with 3 parameters (C, D, T_{min}) where
  - C = resource budget
  - D = deadline
  - T_{min} = minimum interarrival time

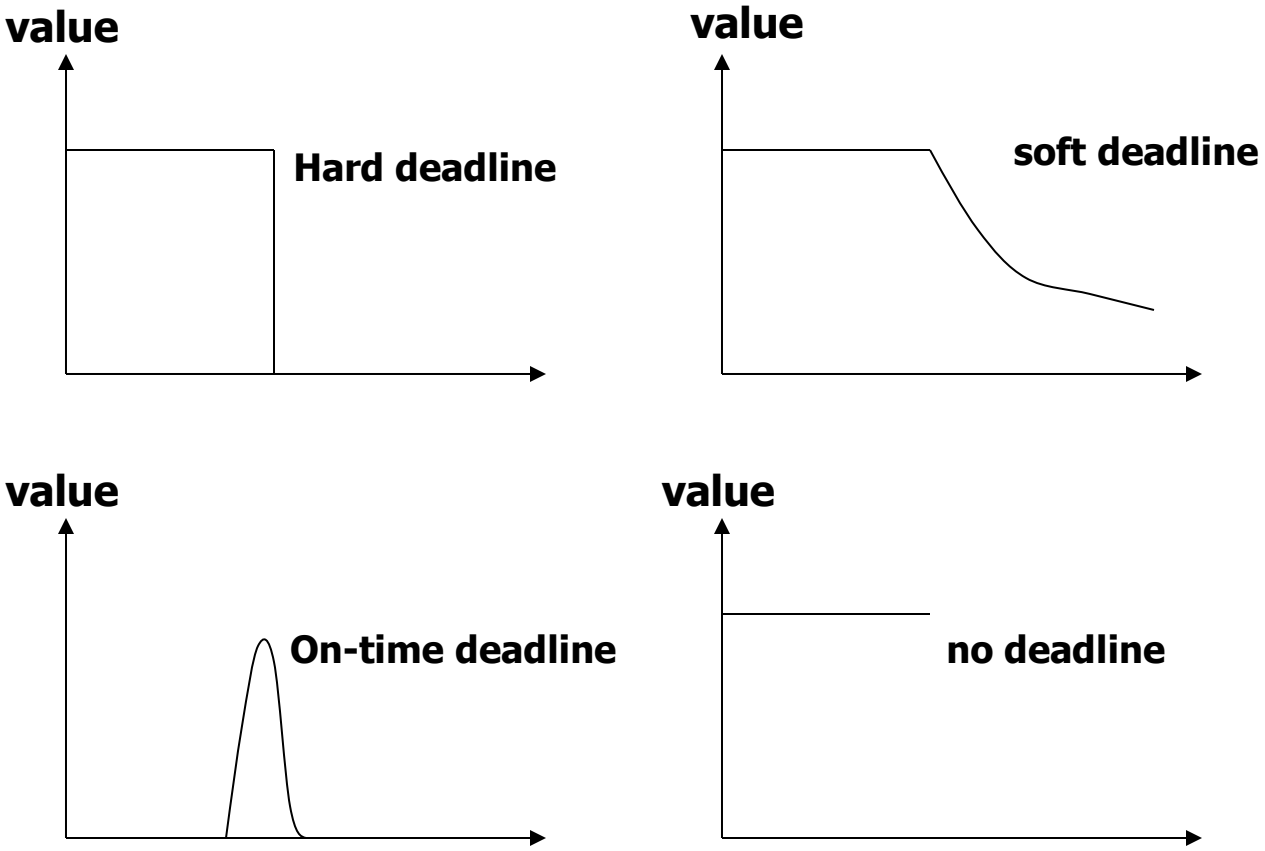
Olso known as Event-driven: their activations are generated by interrupts, but separated with minimum interarrival time T_{min}. In the worst case, it is the same as a periodic task with period T_{min}.

Timing Constraints

- Hard real-time — systems where it is absolutely imperative that responses occur within the required deadline. E.g. Flight control systems, automotive systems, robotics etc.
- Soft real-time — systems where deadlines are important but which will still function correctly if deadlines are occasionally missed. E.g. Banking system, multimedia etc.

A single system may have both hard and soft real-time tasks. In reality many systems will have a cost function associated with missing each deadline.

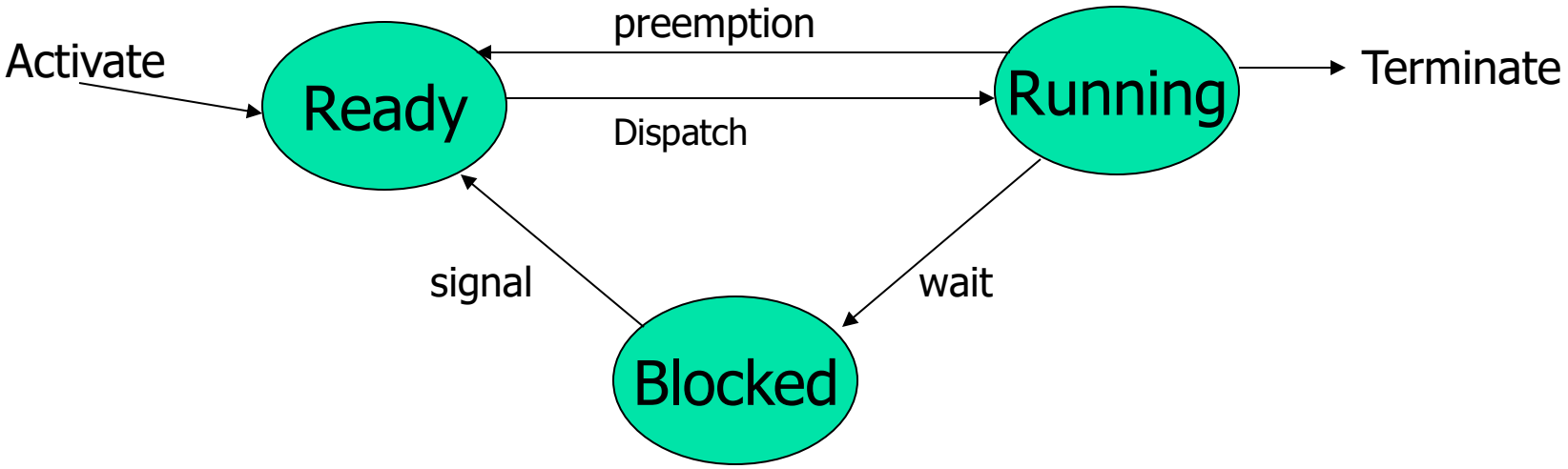
Timing Constraints



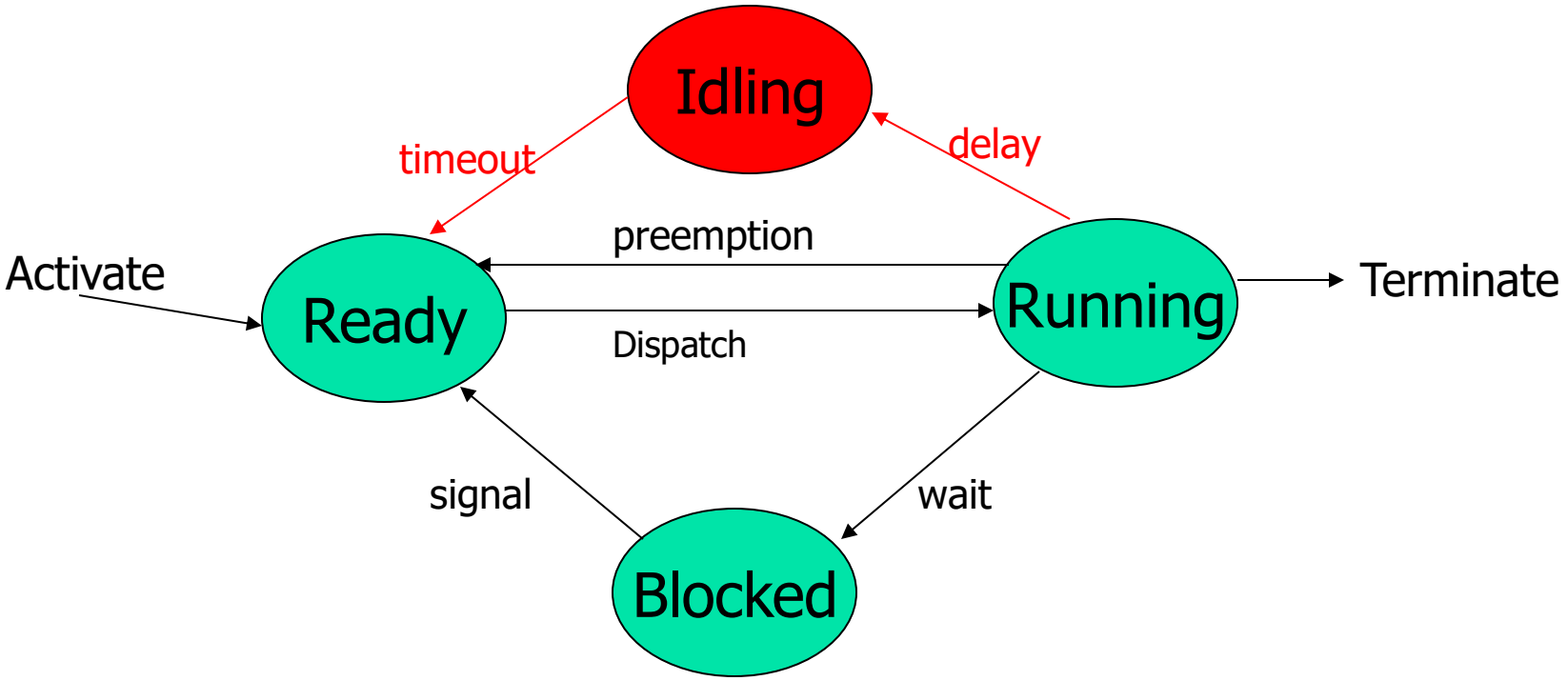
Task states (1)

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

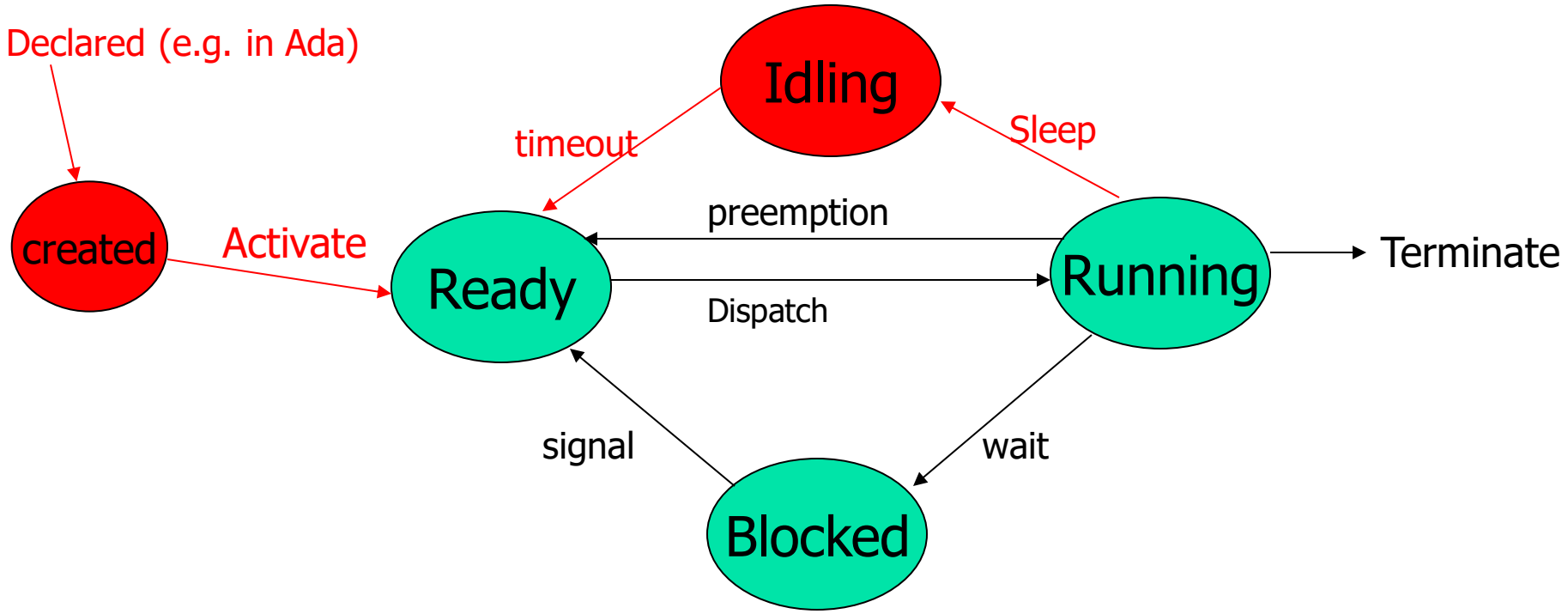
Task states (2)



Task states (Ada, delay)



Task states (Ada95)



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)

Task managment

- Task creation: create a newTCB
- Task termination: remove the TCB
- Change Priority: modify the TCB
- ...
- State-inquiry: read the TCB

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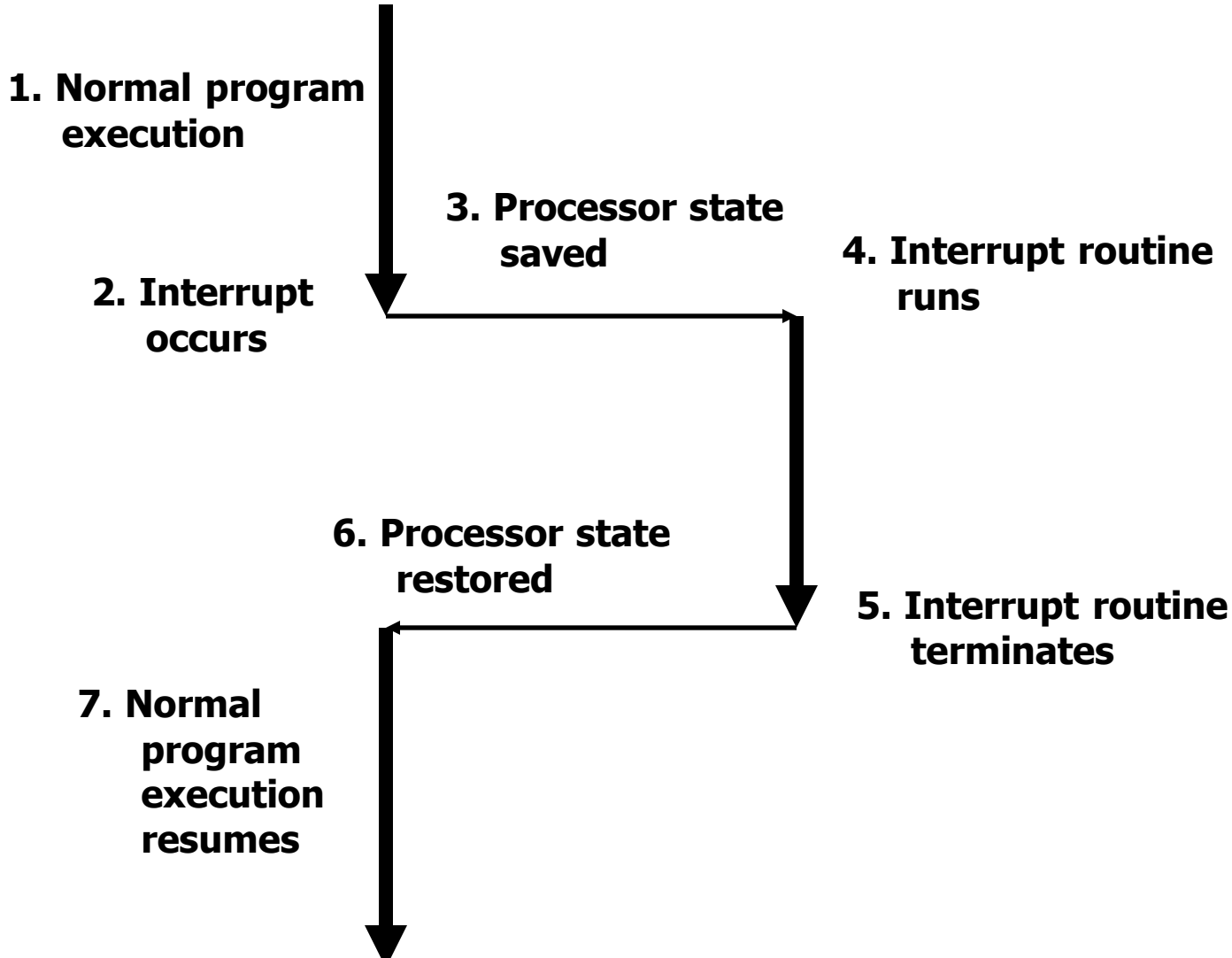
Handling an Interrupt



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Memory Management/Protection

- 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 block – Hope that the whole design is proven correct and protection is unneccessary
  - to achive 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 occurs
  - Useful for complex reconfigurable systems

Basic functions of RTOS

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Exception handling

- Exceptions e.g missing deadline, running out of memory, timeouts, deadlocks, divide by zero, etc.
  - Error at system level, e.g. deadlock
  - Error at task level, e.g. timeout
- Standard techniques:
  - System calls with error code
  - Watch dog

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

Example

- Watch-dog (to monitor whether the application task is alive)
  Every 100ms, it should check: if flag=1 then OK
  otherwise if flag has been 0 for 20s, send out a warning

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

- Application-task
  - flag:=1 … … computing something … … flag:=1 ….. flag:=1 ….

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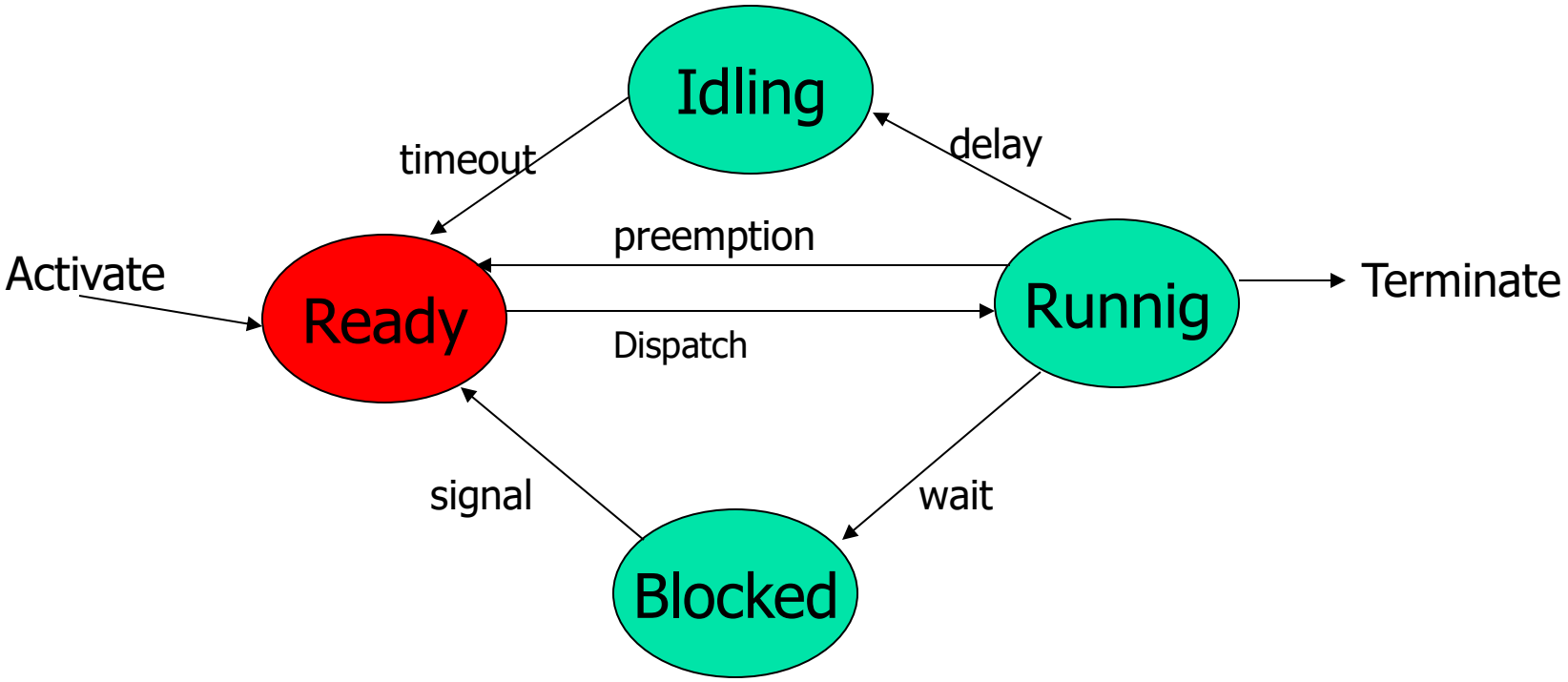
Task states


Idling
timeout
delay
preemption
Activate
Ready
Runnig
Terminate
Dispatch
signal
wait
Blocked

Scheduling algorithms

- Sort the READY queue acording to
  - Priorities (HPF)
  - Execution times (SCF)
  - Deadlines (EDF)
  - Arrival times (FIFO)
- Classes of scheduling algorithms
  - Preemptive vs non preemptive
  - Off-line vs on-line
    - Static vs dynamic

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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.
- Barrier: to synchronize a lot of tasks,
  - they should wait until all of them have reached a certain "barrier."

Potential problems in task synchronization

- **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.
- **Deadlock, livelock, starvation** Some deadlock avoidance/prevention algorithms are too complicate and indeterministic for real-time execution. Simplicity preferred, e..g.
  - all tasks always take locks in the same order.
- **Priority inversion** using priority-based task scheduling and locking primitives should know the "priority inversion" danger: a medium-priority job runs while a highpriority task is ready to proceed.