Real-Time systems

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Breve storia
informatica triste
"Sul mio
PC
funziona."
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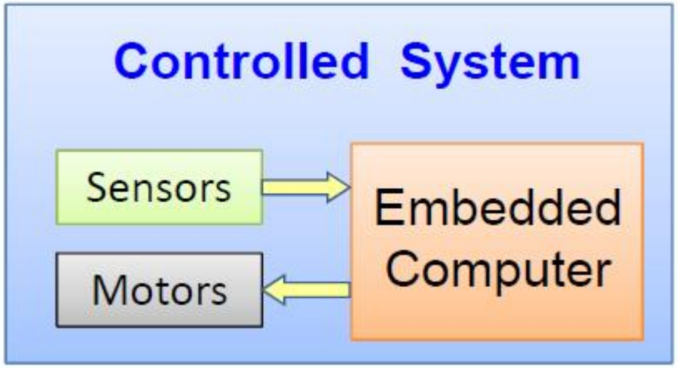
Definition

Real-Time Systems are computing systems that must perform computation within given timing constraints.

They are typically embedded in a larger system to control its functions:



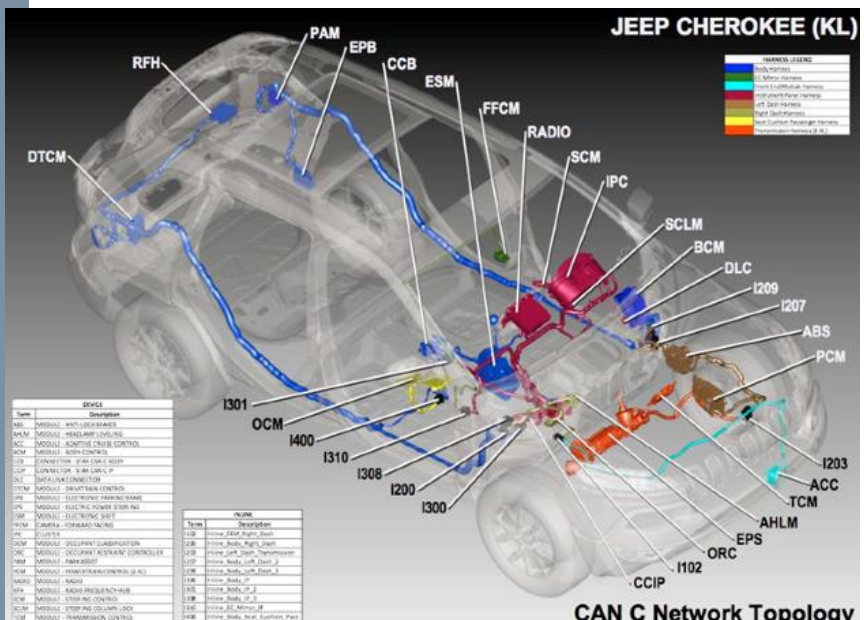
Real-Time Embedded Systems

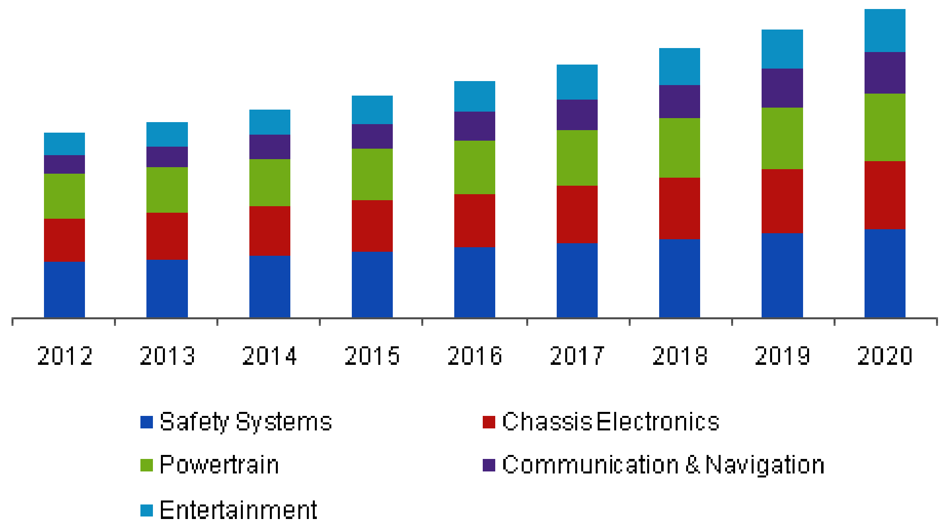
Computers Everywhere

Today, **98%** of all processors are **embedded** in other objects

Example: ECU Adoption in Automotive

* Electronic Control Unit





Example:

- 2010 [Range Rover] contained 41 ECUs
- 2014 Range Rover contains 98 ECUs

Increasing Complexity

The price to be paid is a higher software **complexity**

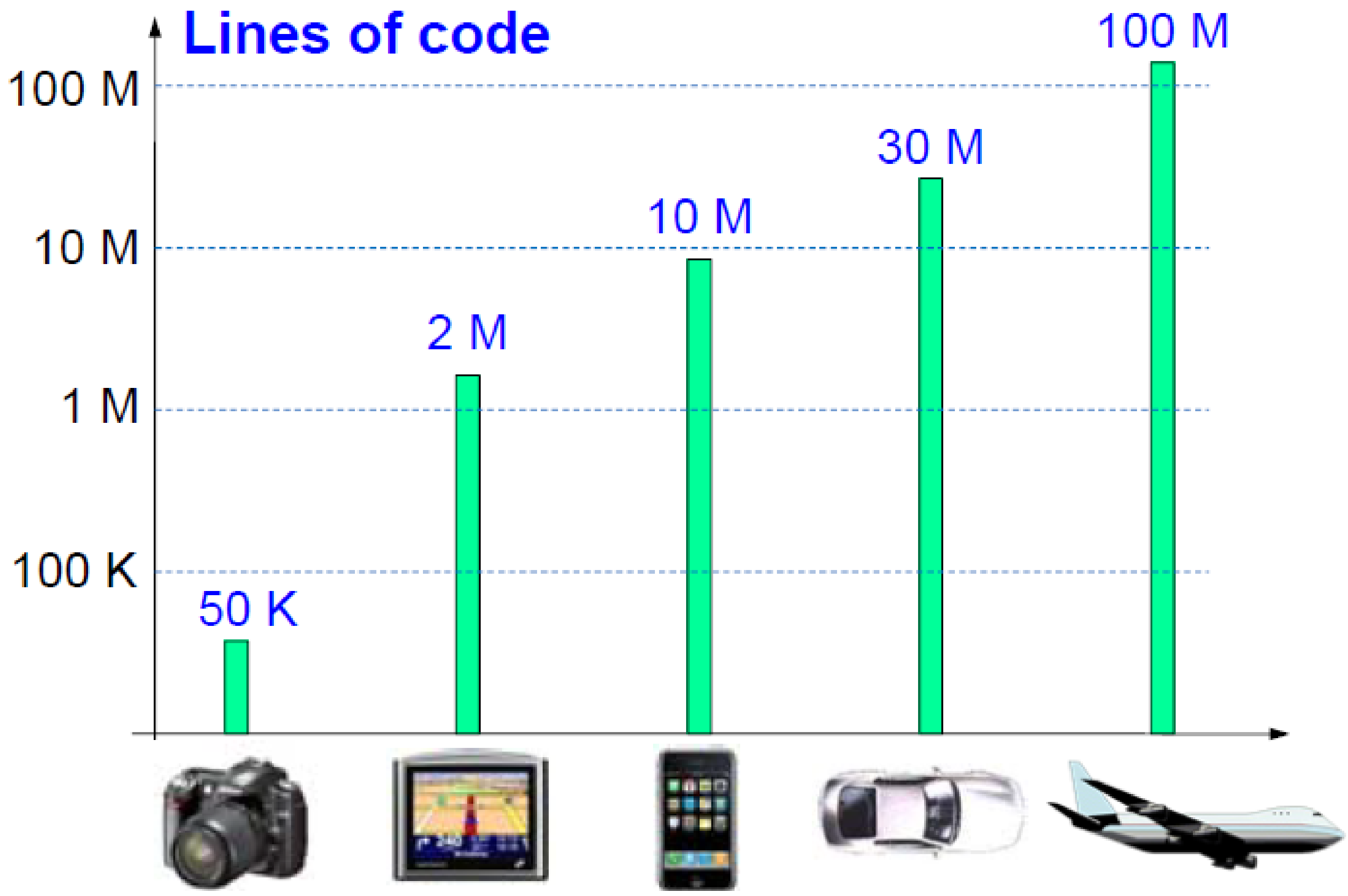
Related problems

- Difficult design
- Less predictability
- Less reliability

Novel solutions for

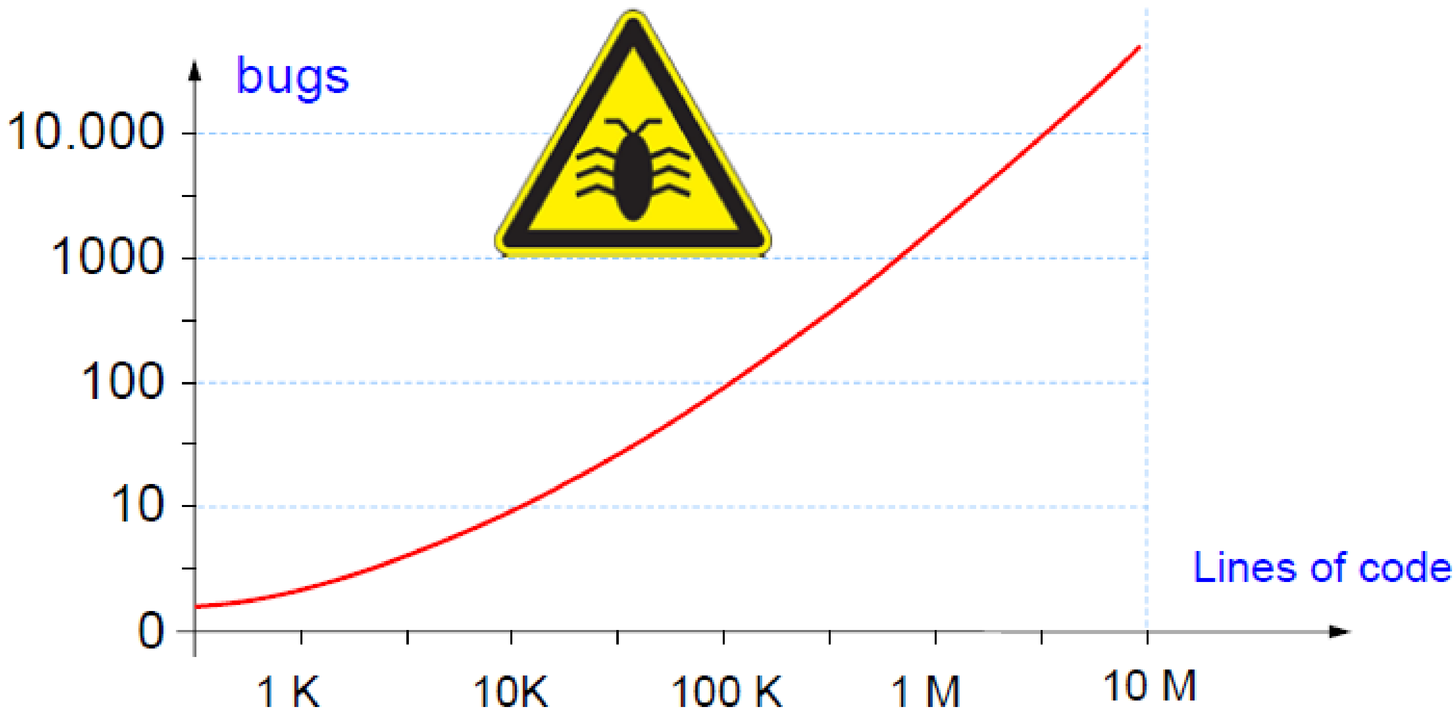
- Component-based software design
- Analysis for guaranteeing predictability and safety
- Testing

Comparing Software Complexity



Complexity and Bugs

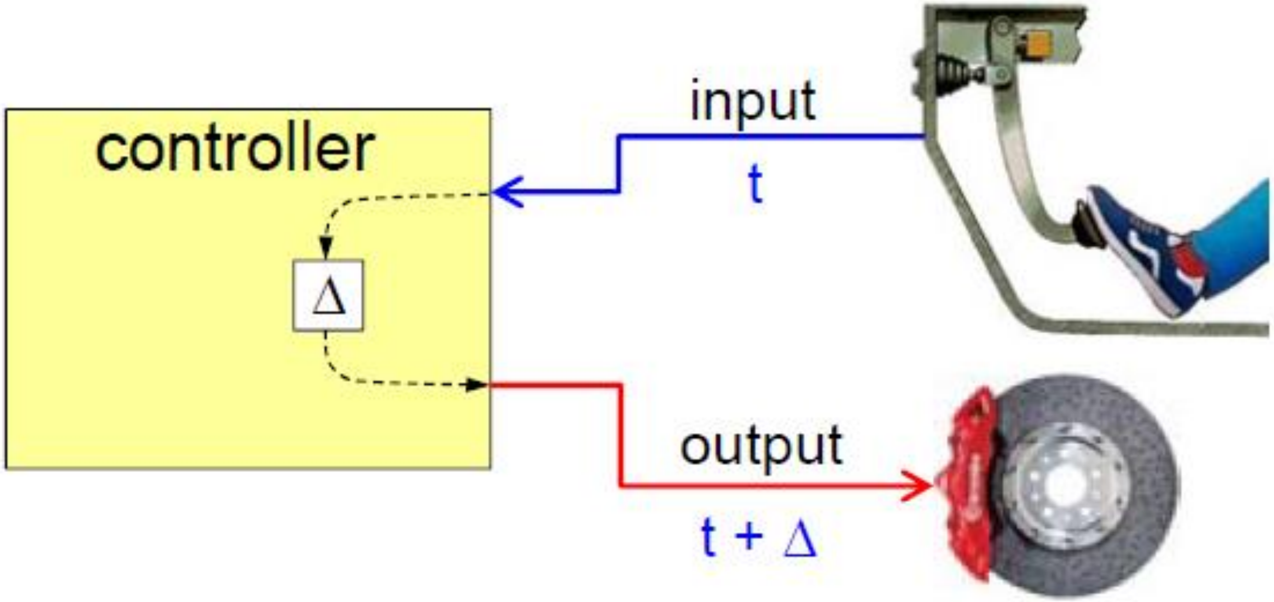
- Bugs increase with complexity



...and the situation is ever worse....

› Reliability does not only depend on the correctness of computation (bug-free)

› ....but also on having it **timely**



› A correct action executed **too late** is useless on even dangerous!

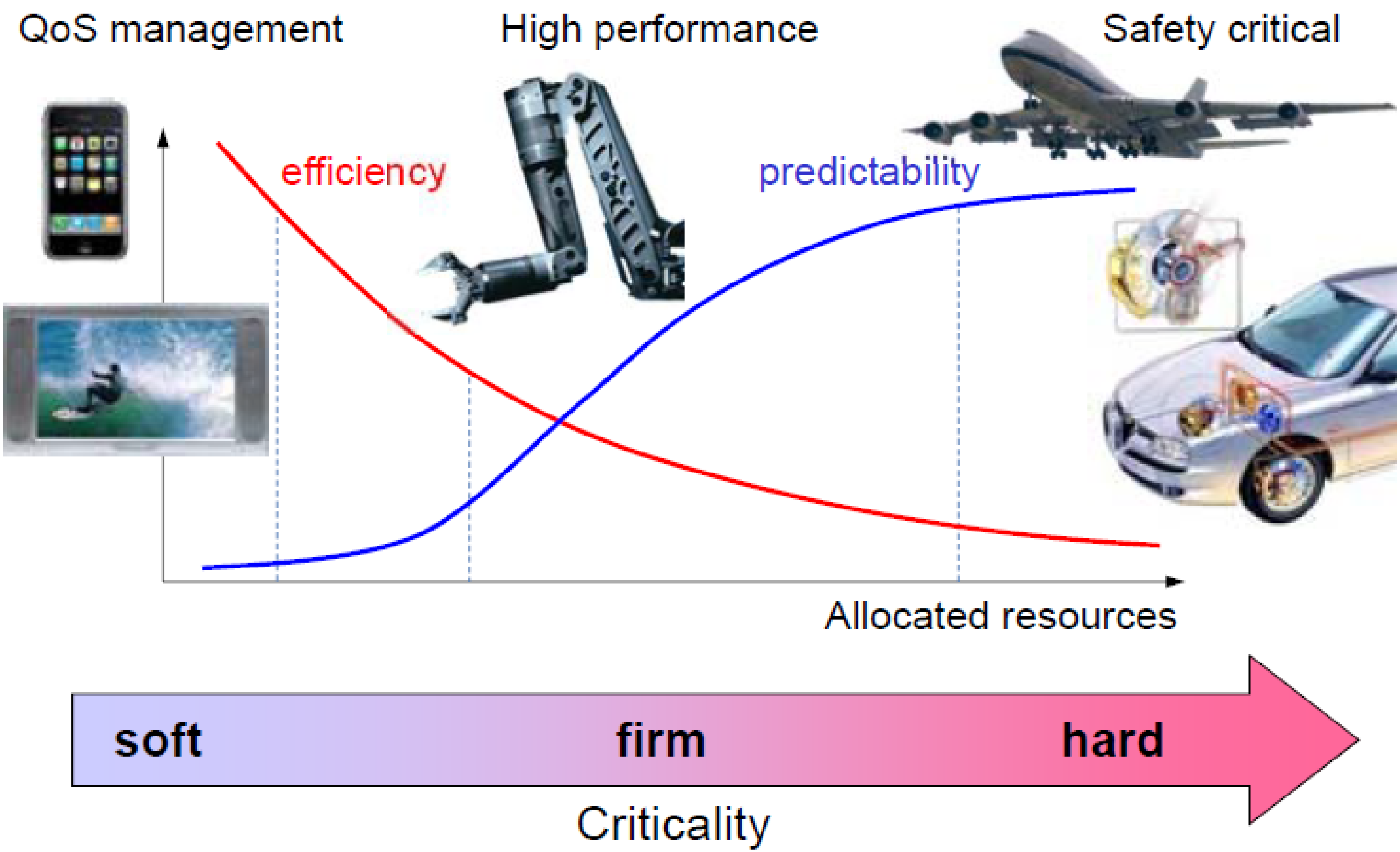
Real-Time Systems

"**Real-Time Systems** are computing systems that must guarantee <u>bounded</u> and <u>predictable</u> response times"

Predictability of response times must be **guaranteed**

- for each critical activity
- for all possible combination of events

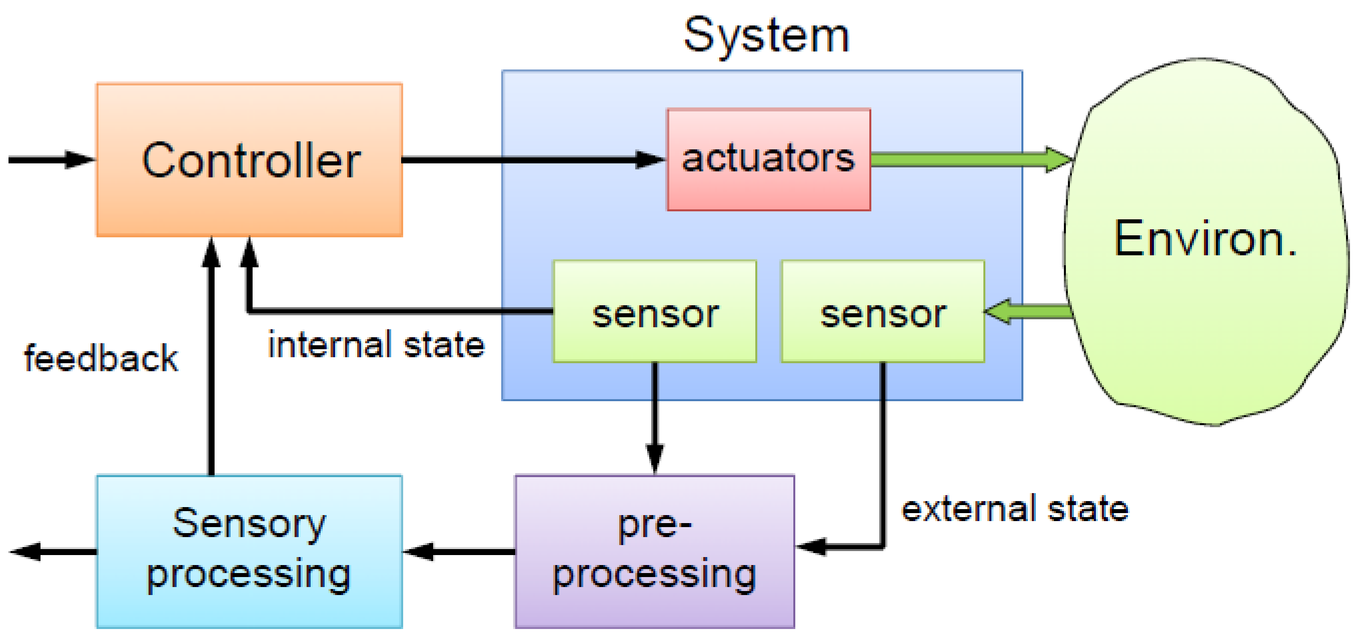
Predictability vs. Efficiency



Embedded System Characteristics

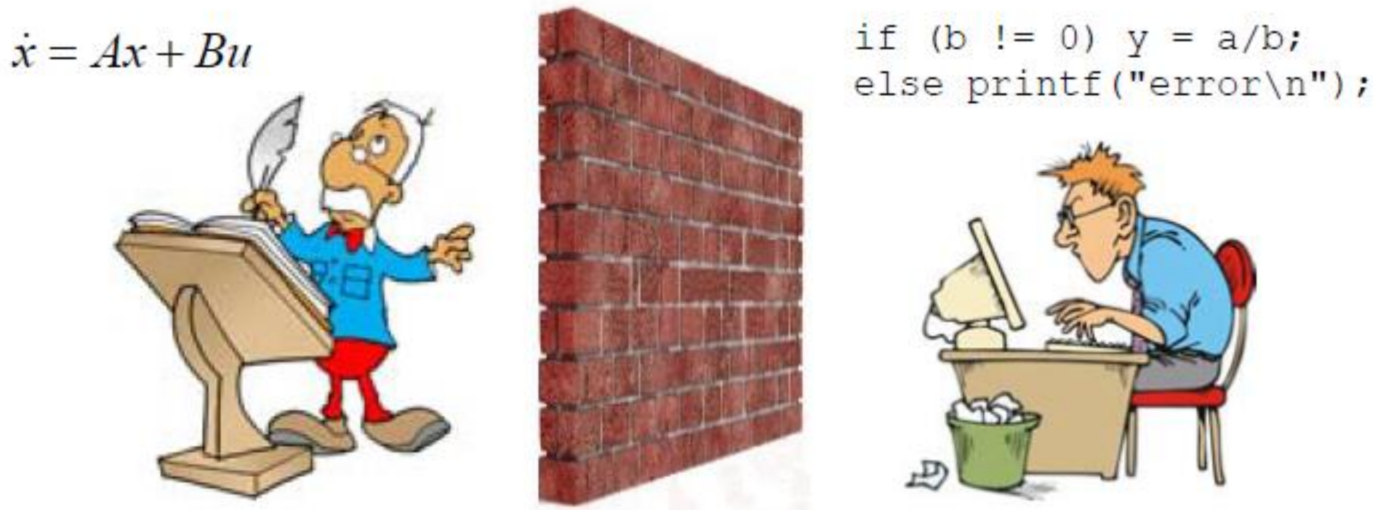
FEATURES (embedded)		REQUIREMENTS (RT)
Scarce resources (space, weight, time, memory, energy)	→	**High efficiency** in resource management
High concurrency and resource sharing (high task interference)	→	**Temporal isolation** to limit the interference
Interaction with the environment (causing timing constraints)	→	**High predictability** in the response time
High variability on workload and resource demand	→	**Adaptivity** to handle overload situations

Recap: a typical control system



Control and Implementation

Often, control and implementation are done by different people that do not talk to each other:



Control guys typically assume a computer with infinite resources and computational power

Example: Inverted Pendulum

A positive angle θ requires a positive control action u

$\theta > 0$ ➡ $u > 0$ $\theta < 0$ ➡ $u < 0$

A Control Task

```
task    control(float theta0, float k)
{
float   error;
float   u;
float   theta;

    while (1) {

        theta = read_sensor();

        error  = theta – theta0;
        u = k * error;

        output(u);

        wait_for_next_period();
    }
}
```

control gain

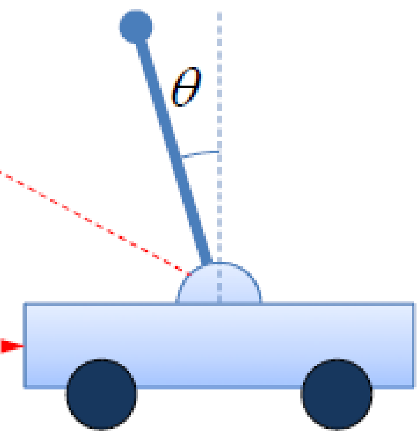
reference angle

sensing

computation

actuation

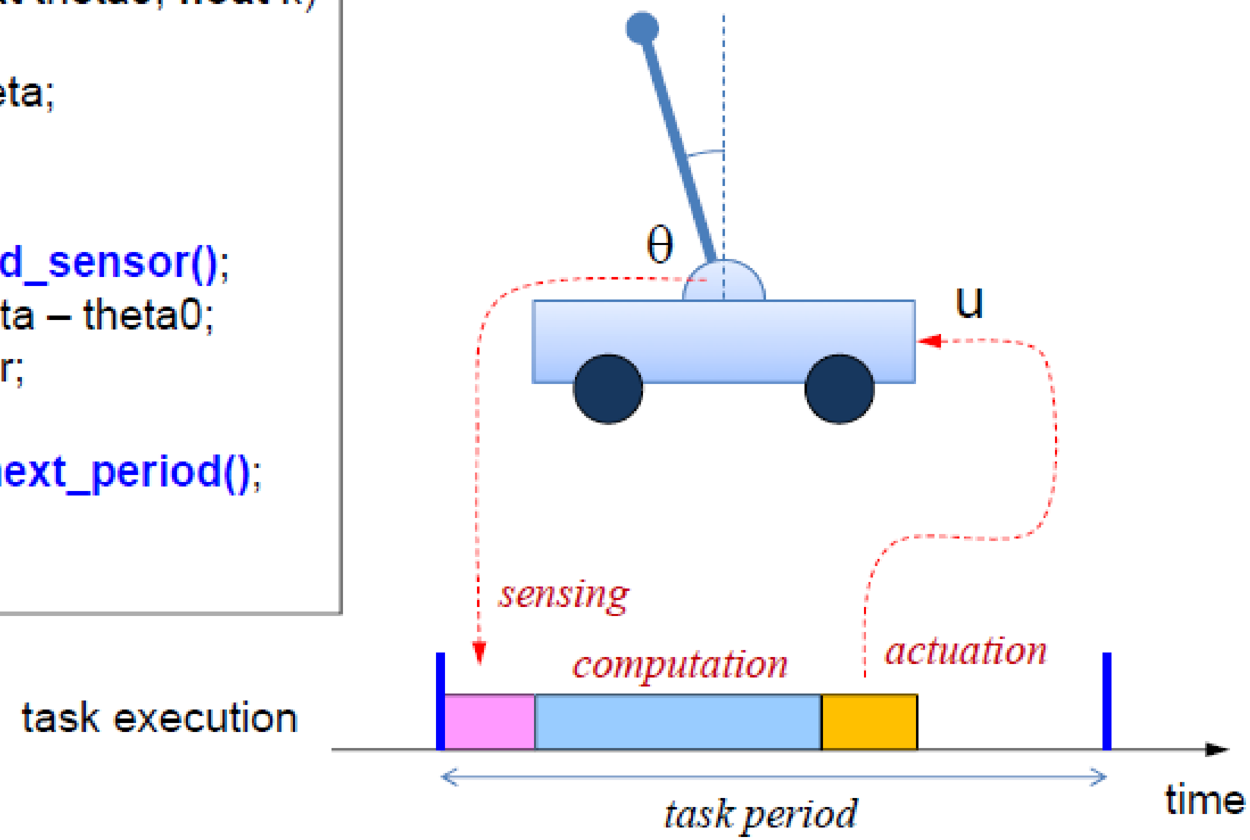
synchronization



A Control Task

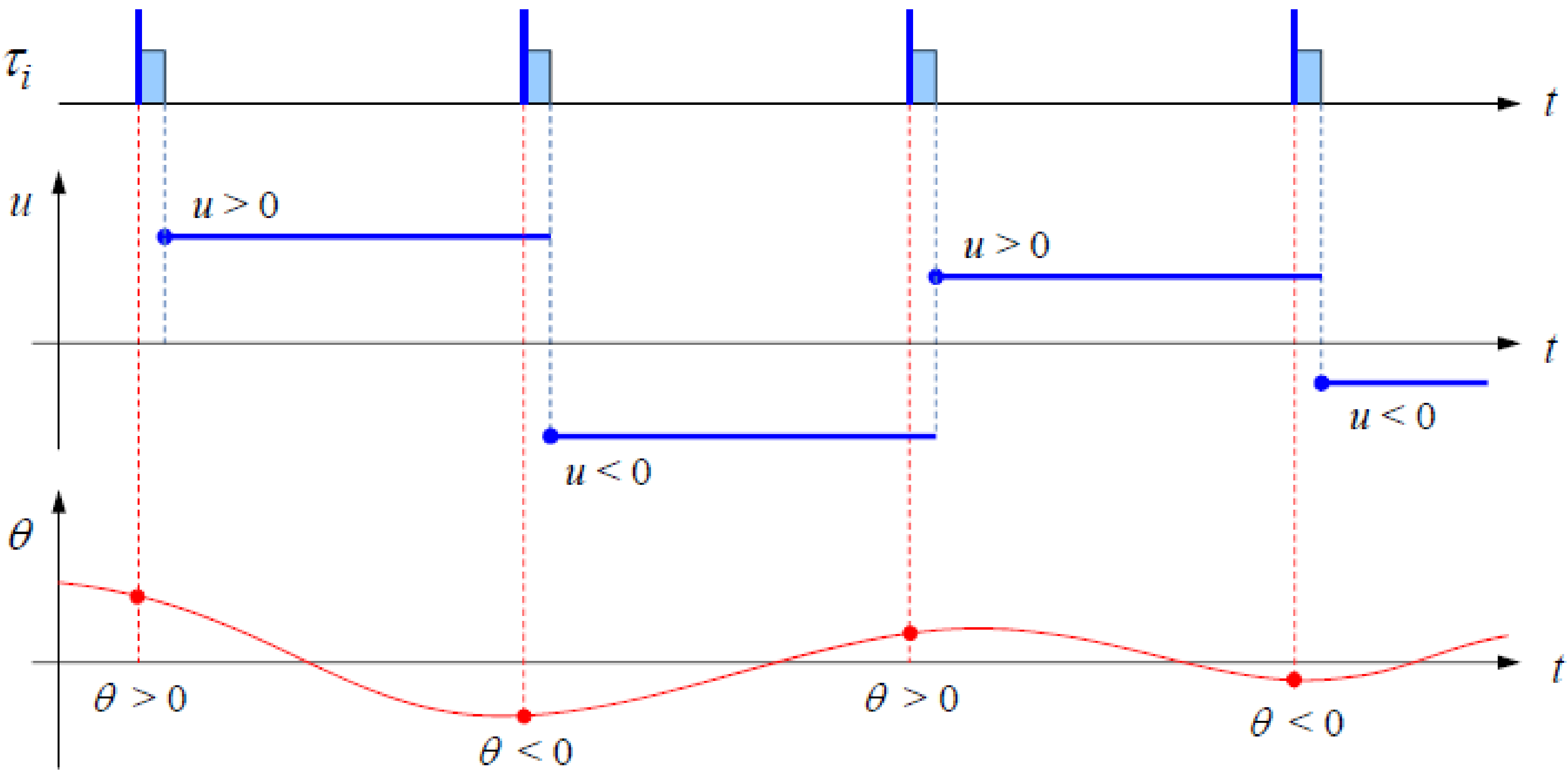
```
task    control(float theta0, float k)
{
float   error, u, theta;

    while (1) {
        theta = read_sensor();
        error  = theta – theta0;
        u = k * error;
        output(u);
        wait_for_next_period();
    }
}
```



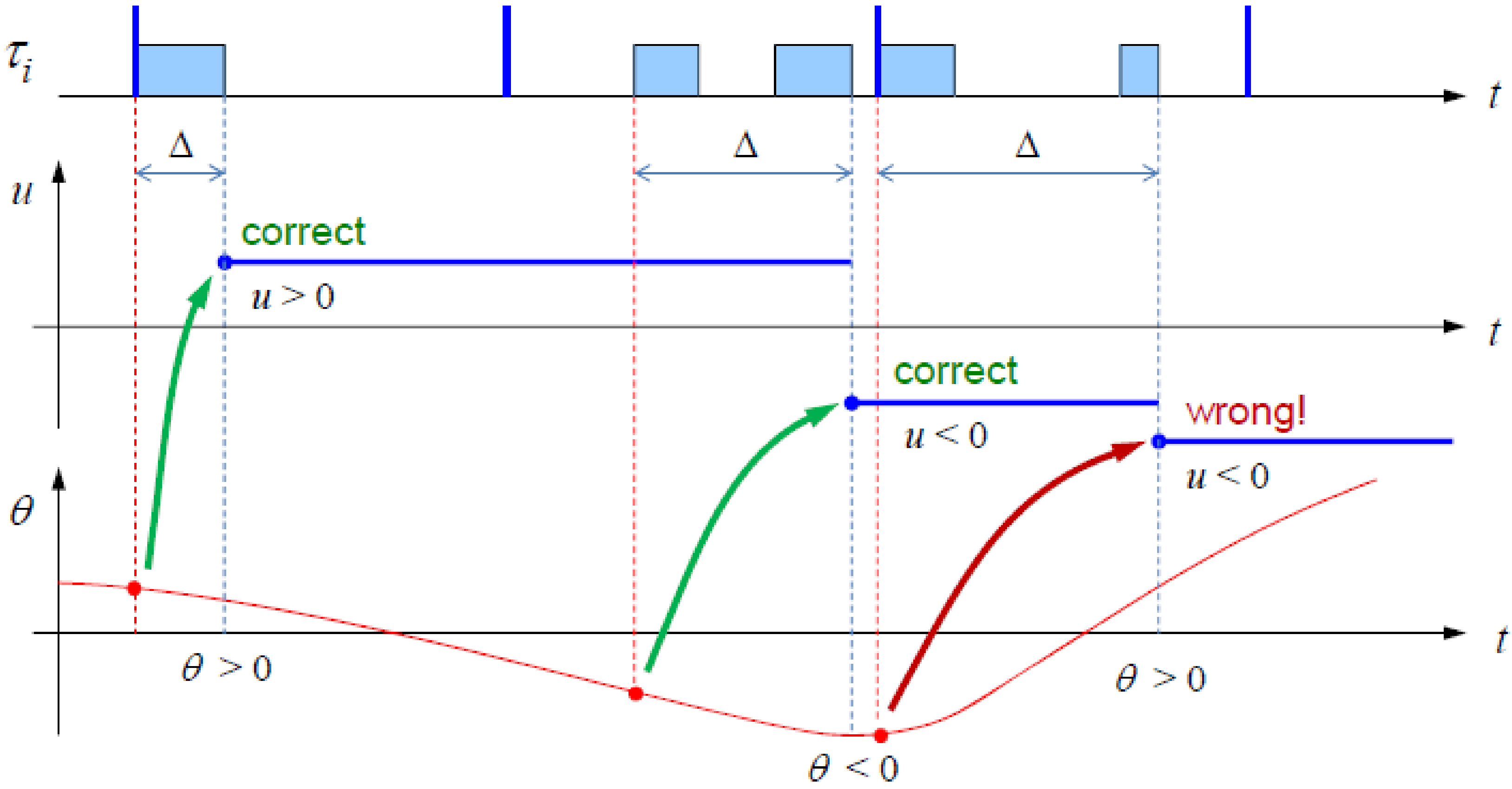
Traditional Control View

Negligible delay and jitter



Real Situation

Variable delay and jitter



Implications

- The tight interaction with the environment requires the system to react to events within **precise timing constraints**
- Timing constraints are imposed by the **performance** requirements and the **dynamics** of the system to be controlled

The operating system must be able
to execute tasks within timing constraints

Design Requirements

Modularity

› A subsystem must be developed without knowing the details of other subsystems (*system engineering and team work are essential*)

Configurability

› Software must be adapted to different situations (through the use of suitable parameters) without changing the source code

Portability

› Minimize code changes when porting the system to different hardware platforms

Predictability

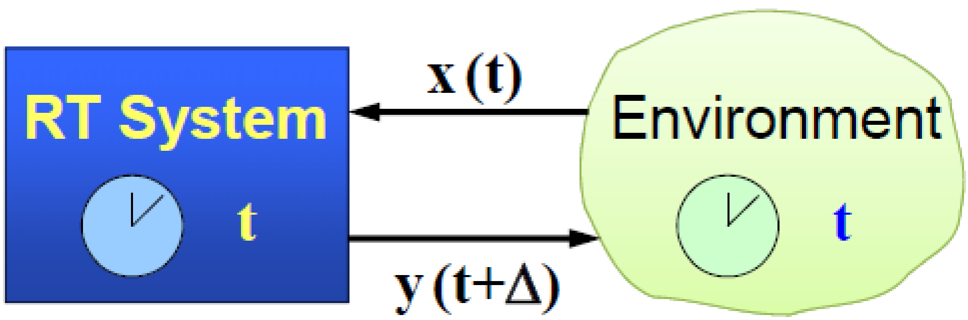
› Allow the estimation of maximum delays

Efficiency

› Optimize the use of available resources (computation time, memory, energy).

Cyber-Physical Real-Time Systems

It is a system in which the correctness depends not only on the output values, but also on the **time** at which results are produced



When we put the environment into the picture…

› REAL means that system time must be synchronized with the time flowing in the environment

Real-Time ≠ Fast

"To guarantee timing constraints it is sufficient to use faster and more powerful ECUs"

Real-Time ≠ Fast

“To guarantee timing constra sufficient to use faster and more
p ECUs”

A real-time system is <u>**not a fast system**</u>

The objective of a fast system is to minimize the <u>average response time</u>

But …

Real-time systems need to guarantee the <u>**WORST CASE RESPONSE TIME**</u>

Real-Time Requirements

Don't trust the average when you have to guarantee <u>worst-case performance</u>

"A guy once drowned crossing a river which was 10 inches deep on average"

A real-time system needs to guarantee that **multiple** critical tasks are **always** computed within well defined deadlines

› Testing is often NOT sufficient

› Timing behavior depends on actual situation **at runtime**

Worst case behavior **might never happen** in a lifetime!!!

› This doesn't mean you can't identify and bound it **analitically**

Sources of non determinism

Platform architecture

- Cache, pipelining, interrupts, DMA

Operating system

- Scheduling, synchronization, communication

Programming Language

- Lack of explicit support for time predictability

Design methodologies

- Lack of analysis and verification techniques

Traditional (wrong) approach

Traditional RT applications are typically designed using empirical techniques:

- Assembly programming
- Timing through dedicated timers
- Control through driver programming
- Priority manipulation

Disadvantages

- Tedious programming which heavily depends on programmer's ability
- Difficult code understanding
- Difficult maintainability
  - Millions LoC → understanding takes more than rewriting
- Difficult to verify timing constraints
- High risk of undetected failures
  - Low reliability

A new approach

Tests, although necessary, allow only a **partial verification** of system's behavior

- Analytical design
- Component by component
- Interaction between component is ~~also~~ modeled **first**

Predictability at the level of the **controller, operating system** and **ECUs**

- The are our "actuators"

Critical systems must be designed under **pessimistic assumptions**

- Think of **Worst case**

Real-Time Operating System (RTOS)

A real-time operating system is responsible for:

› Managing **concurrency**

› Activating periodic tasks at the beginning of each period (**time management**)

› Deciding the execution order of tasks (**scheduling**)

› Solving possible timing conflicts during the access of shared resources (**mutual exclusion**)

› Manage the timely execution of asynchronous events (**interrupt handling**)

Multi-process and multi-task management

What are processes?

A process is an executing program

(an OS can execute many processes at the same time → Concurrency)

A (sequential) process goes through **states**, which change over time

- what are the actual data values?
  - set of processor registers + vars
- what is processor doing?
  - running, waiting, ….

Example for (data) state: GCD

› Greatest common divisor

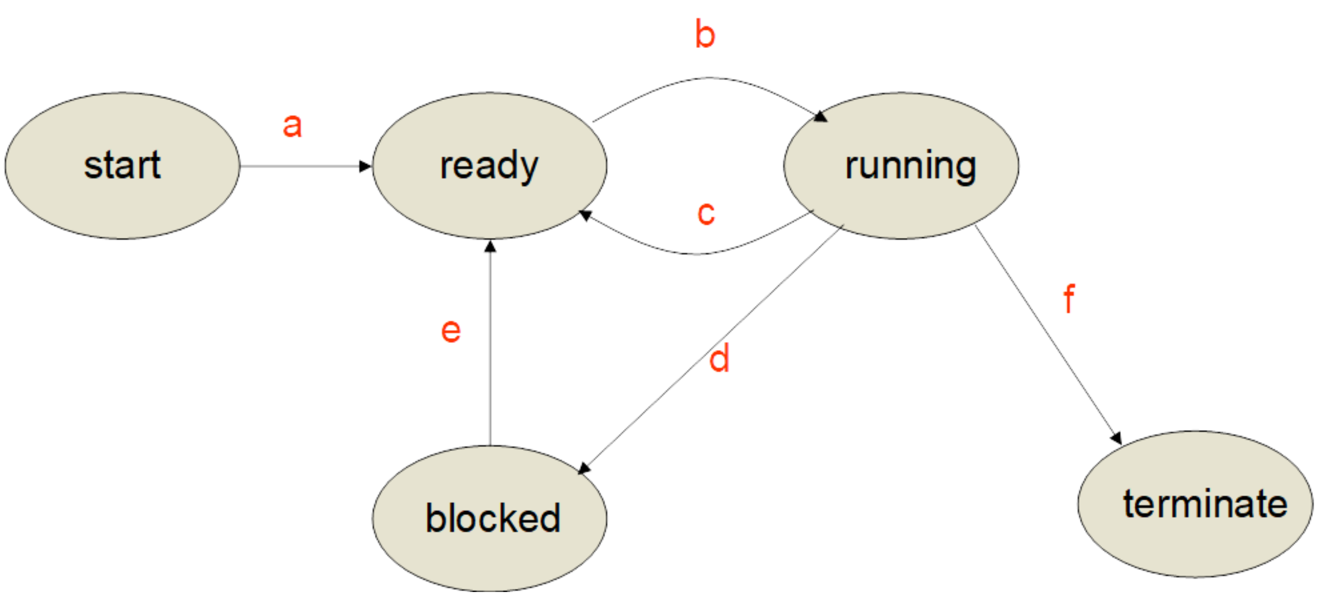
```
int gcd(int a, int b)
{
  while (a!=b)
  {
    if (a < b) b = b - a;
    else a = a - b;
  }
  return a;
}
```

Step	a	b
1	21	15
2	6	15
3	6	9
4	6	3
5	3	3

Process states

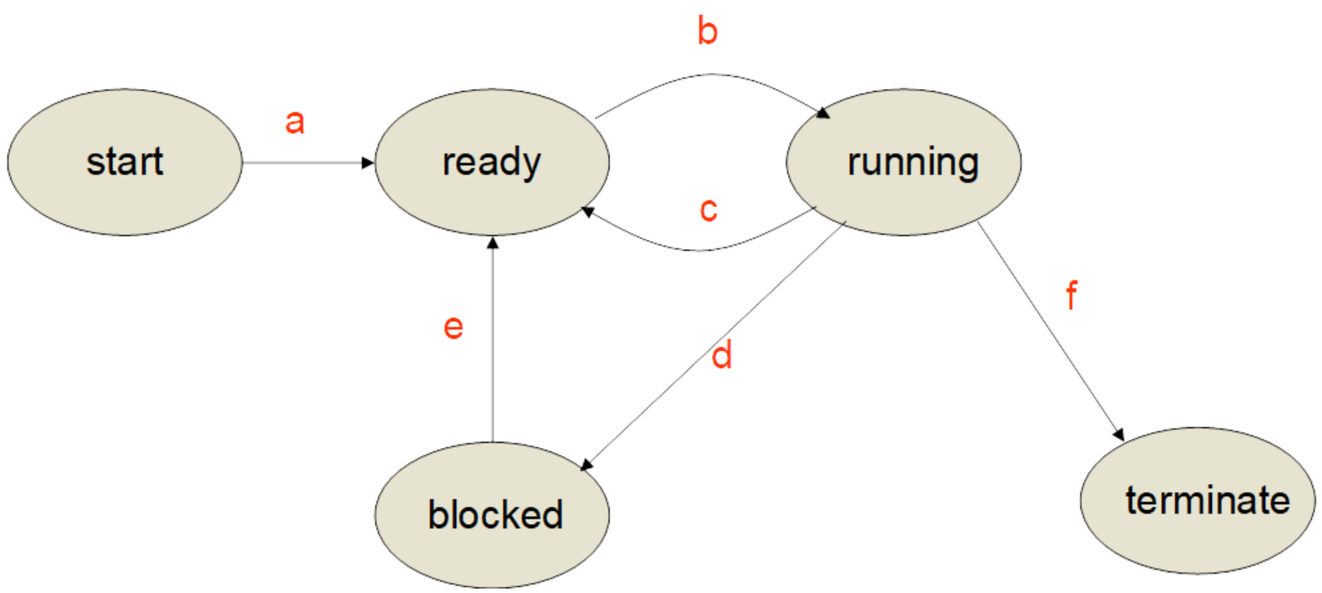
The OS executes many processes at the same time, each of them is either:

- starting (the process is being created)
- ready (the process is ready to be executed)
- executing (the process is executing)
- blocked (the process is waiting on a condition)
- terminating (the process is about to terminate)



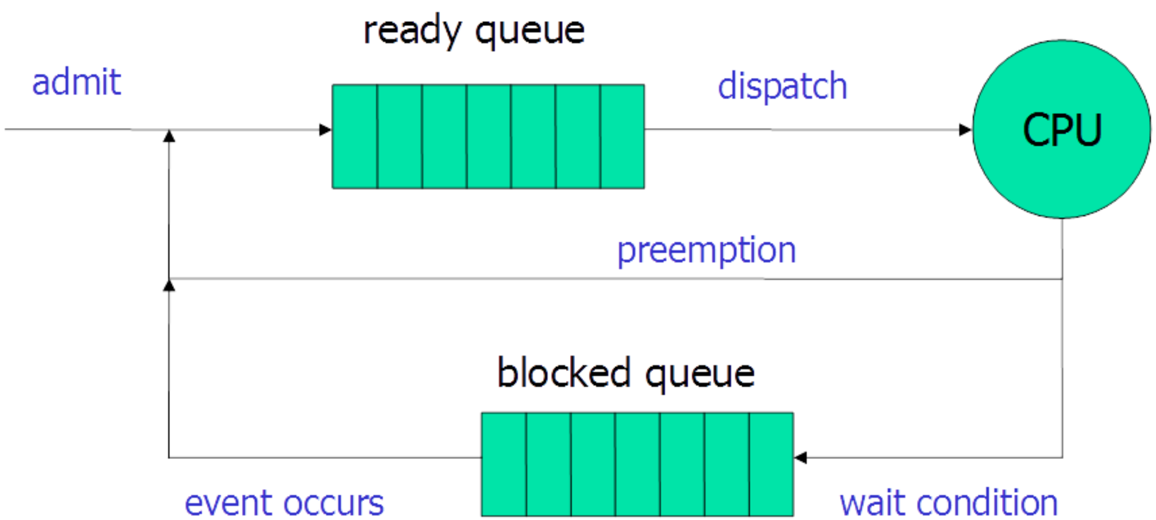
Process state events

a)	Creation	the process is created
b)	Dispatch	the process is selected to execute
c)	Preemption	the process leaves the processor
d)	Wait on condition	the process is blocked on a condition
e)	Condition true	the process is unblocked
f)	Exit	the process terminates



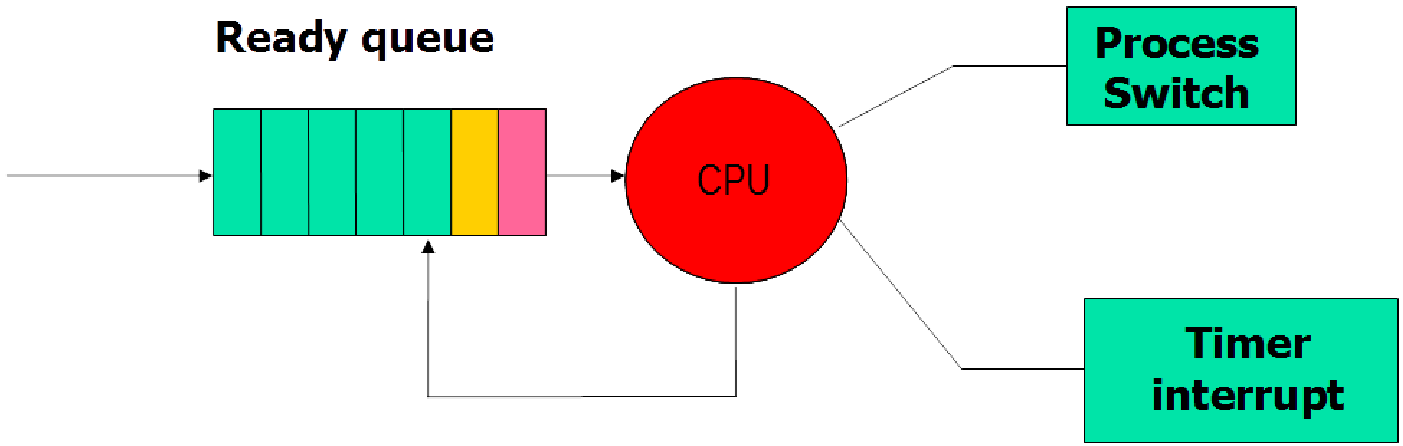
Scheduling– single processor

› The scheduling problem: choose which process goes first



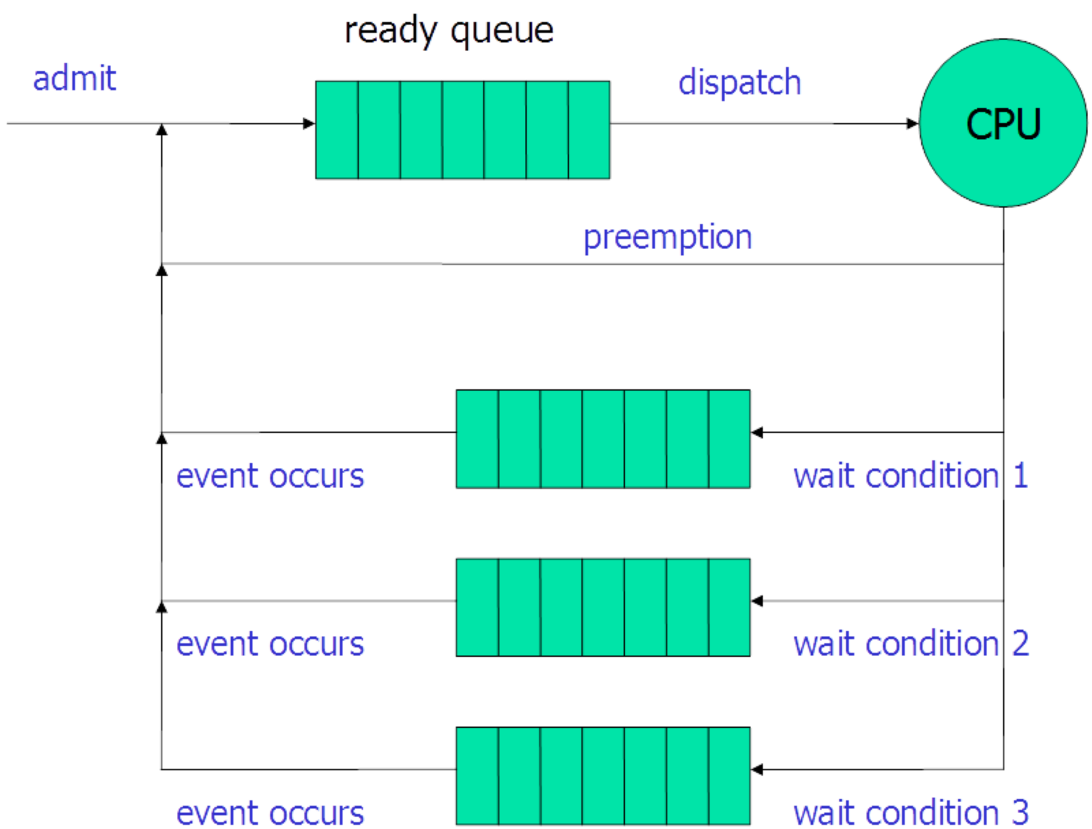
Time sharing - fairness

- Given a time T (e.g., 1 sec)
- be sure we allocate the CPU at least T/N, where N = #processes



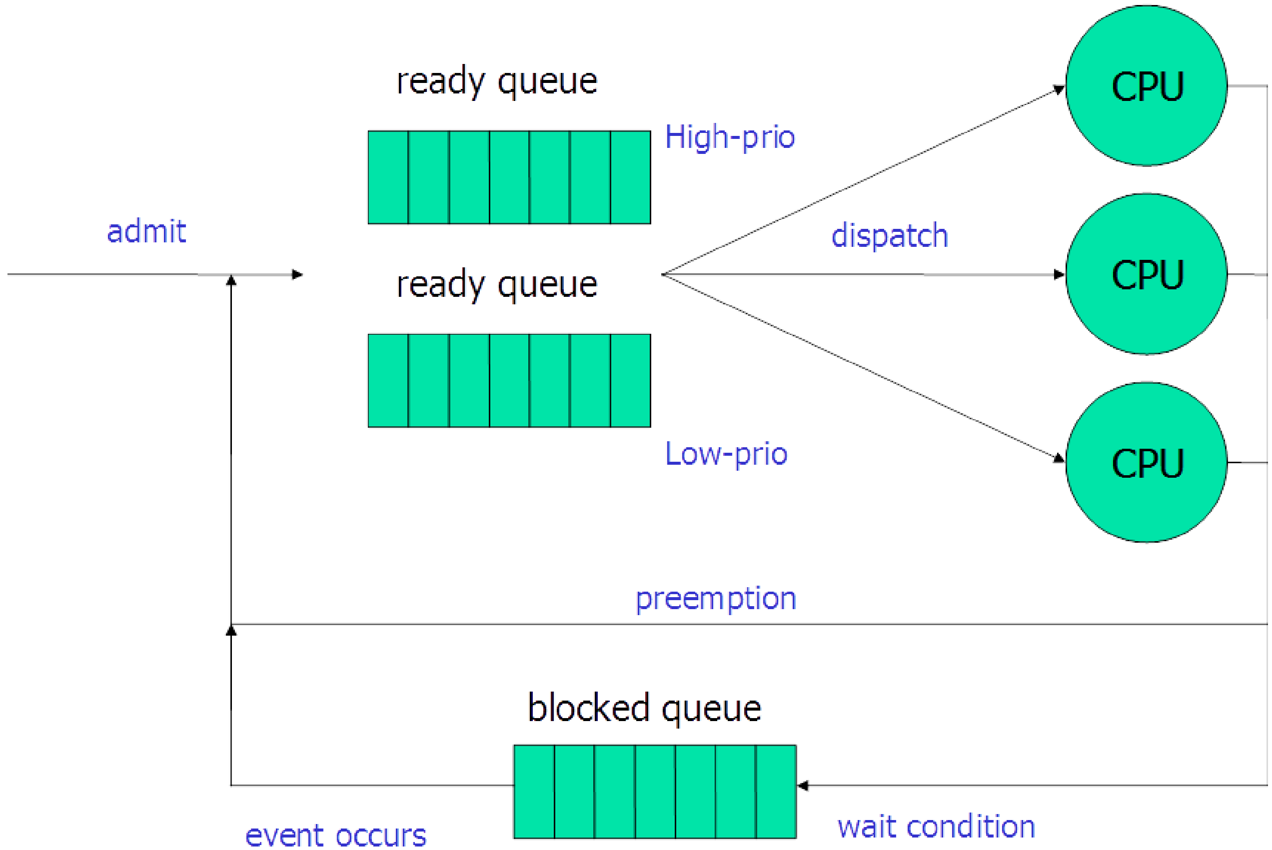
Scheduling – multi processor

- Multiple wait queues, a single ready queue



Priority scheduling

› Multiple ready queues associated with PRIORITY



Process switch

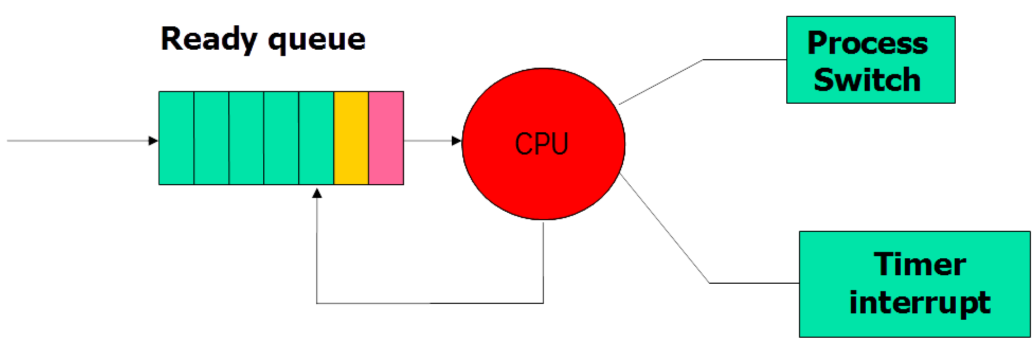
A process goes to the wait queue when it gives control to the OS

- Typically: system calls

...but we don't want a "bad" process might reserve 100% of processor!!

A switch can happen if:

- The process has been "**preempted**" by another higher priority process
- The process **blocks** on some condition, or syscall
- In **time-sharing** systems, the process has completed its "round" and it is the turn of some other process



Scheduling and resources

Scheduling/execution

- The execution of a process follows an execution path, and generates a trace (sequence of internal states)
- It has a state (ready, running, etc.) and scheduling parameters (priority, time left in the round, etc.)
- Already seen

Resource ownership

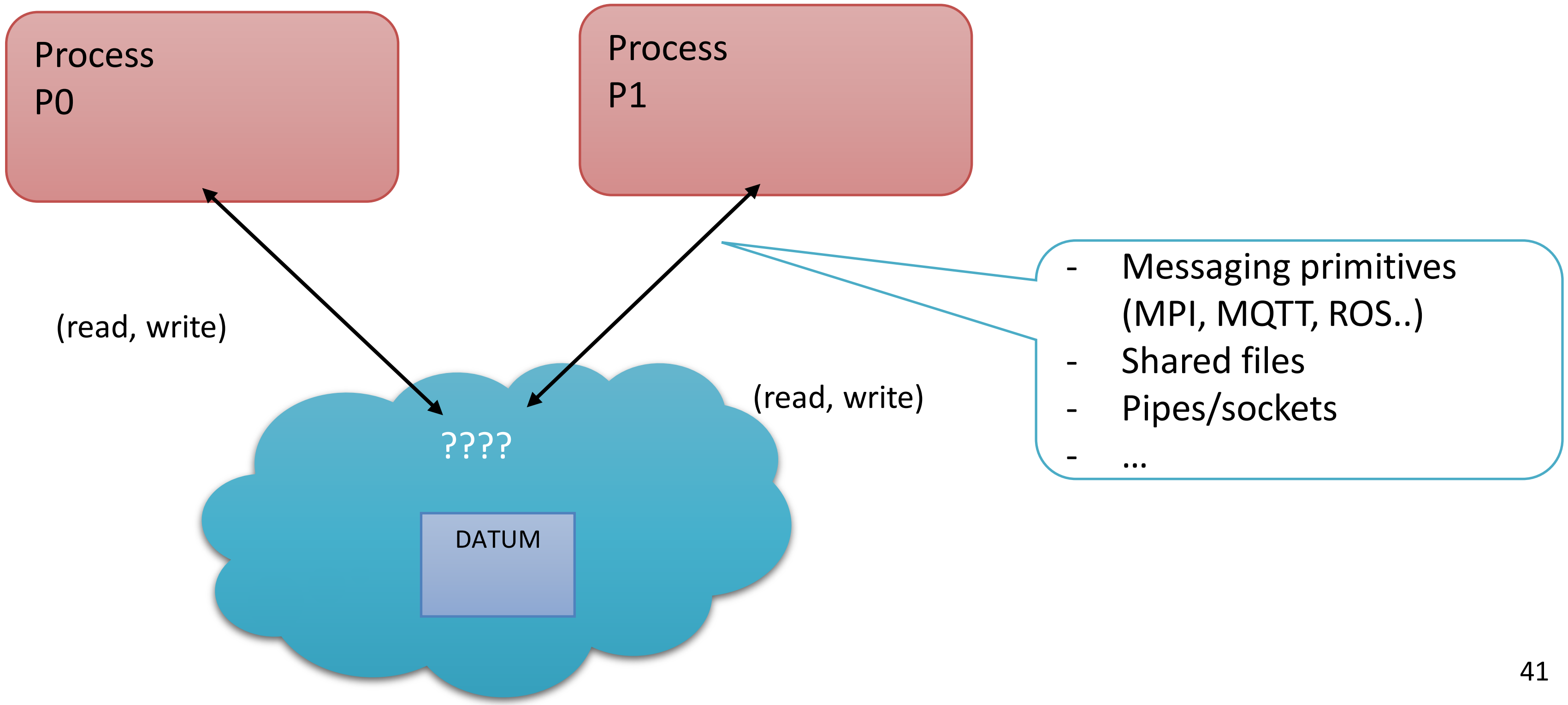
- A process includes a virtual address space, a process image (code + data)
- It is allocated a set of resources, like file descriptors, I/O channels, etc.
- We won’t see this (for the moment..)

Multi-threading

Multi-processing: limitations

Typically, processes do not share memory

- To communicate between process, it is necessary to use OS primitives: heavy and cumbersome
- Process switch is more complex because we must change address space

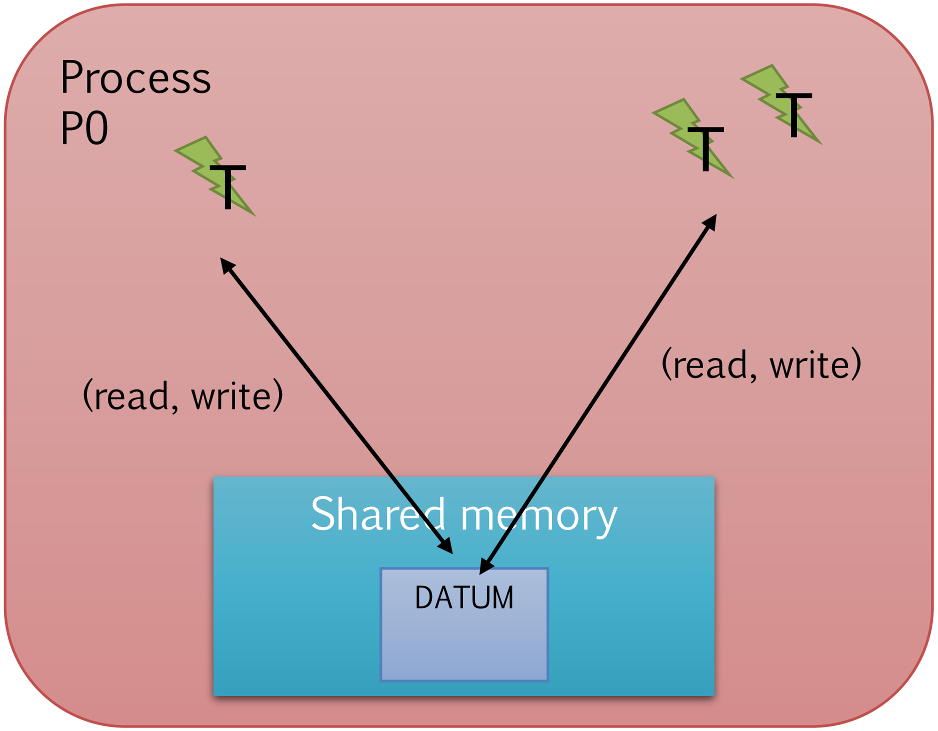


Multi-threading

Threads in the same process share the same address space

- They can access the same variables in memory
- Communication between threads is simpler
- Thread switch has less overhead

If possible, preferred for implementing concurrent applications



Processes vs. threads

Speed of creation

› Creating a thread takes far less time than a process

Speed of switching

› Thread switch is faster than process switch

Shared memory

› Threads of the same process run in same memory space

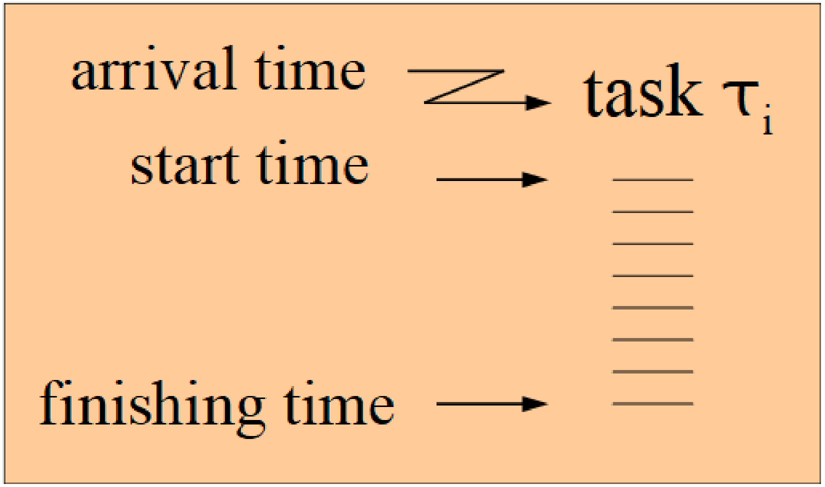
› You don’t need to use heavyweight primitives such as sockets, and message-passing

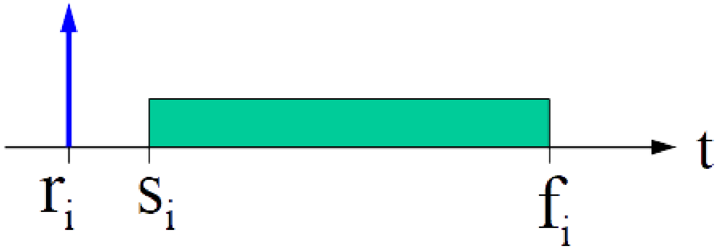
Scheduling theory from the OS perspective

Definitions: tasks

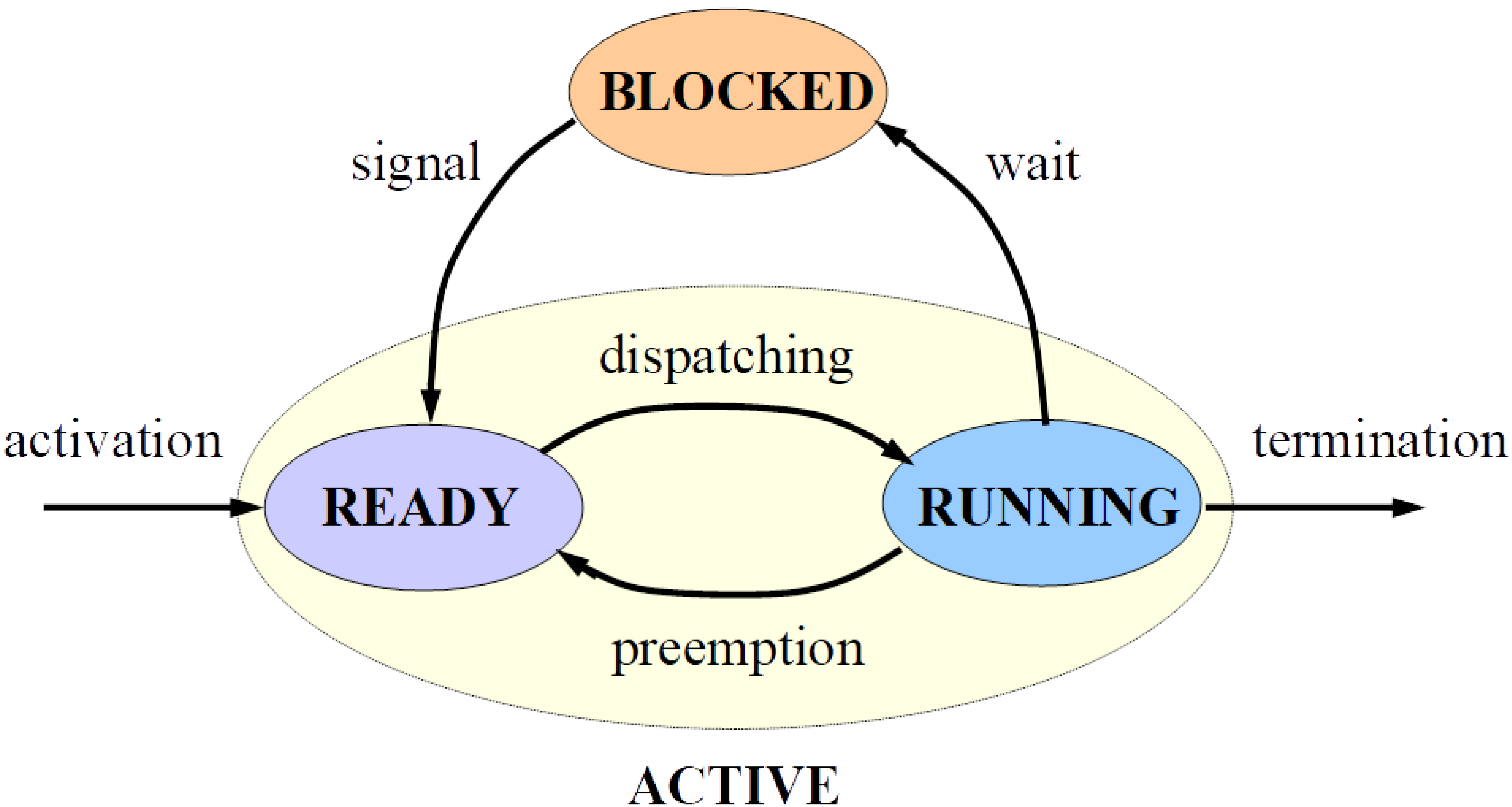
"A **task** is a sequence of instructions that in absence of other activities is continuously executed by the processor until completion"

- It can be a process or a thread depending on the operating system
- E.g., Linux does not distinguish between threads and processes
- Everything is **task!**





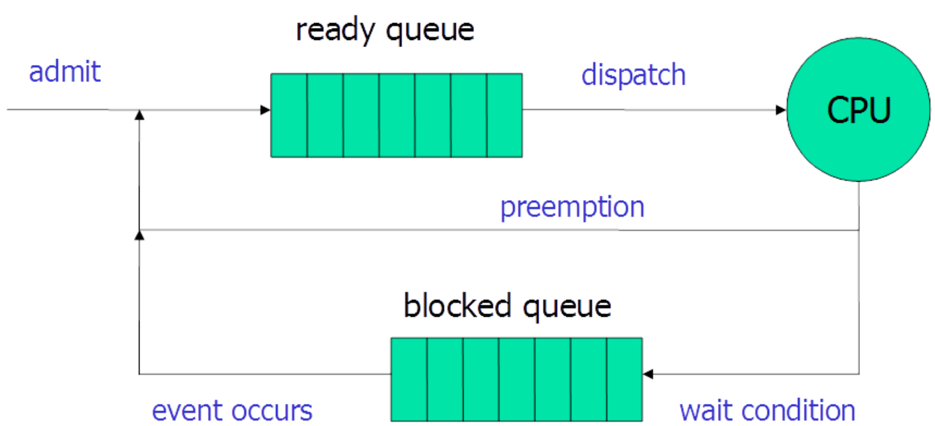
Task state transitions (steady cycle)



Task scheduling

› The ready tasks are kept in a waiting queue, called the ready queue;

› The strategy for choosing the ready task to be executed on the CPU is the **scheduling algorithm**



Can be

› **Preemptive** : if the running task can be temporarily suspended to execute a more important task.

› **Non-preemptive** : if the running task cannot be suspended until completion.

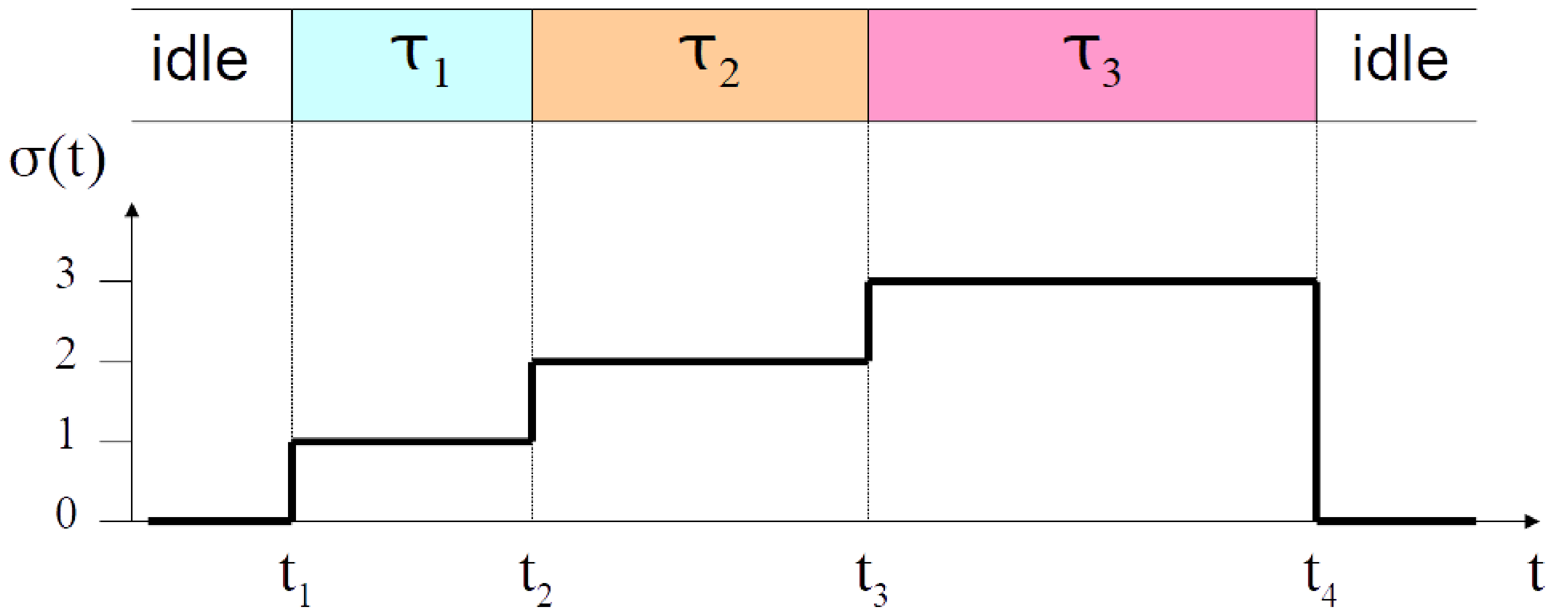
Schedule

A particular assignment to task(s) to processor(s)

- Given a task set $\Gamma = \{\tau_1, \ldots, \tau_n\}$, a schedule is a mapping σ : **R+ → N** such that **∀t ∈ R+**:

$$\sigma(t) = \begin{cases} k > 0 & \text{if } \tau_k \text{ is running} \\ 0 & \text{if the processor is idle} \end{cases}$$

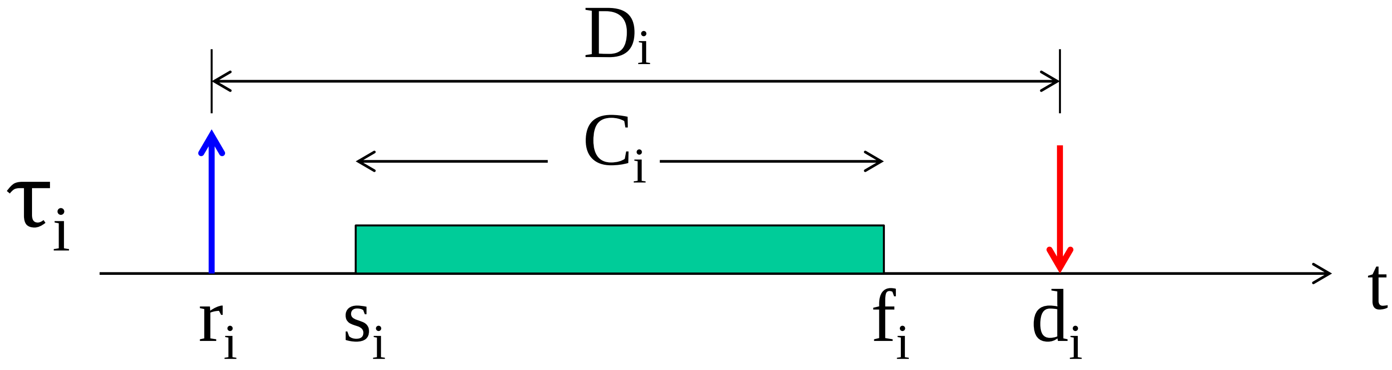
Schedule: example



- At time t_1, t_2, t_3, and t_4 a **context switch** is performed
- Each interval $[t_i, t_{i+1})$ is called a **time slice**

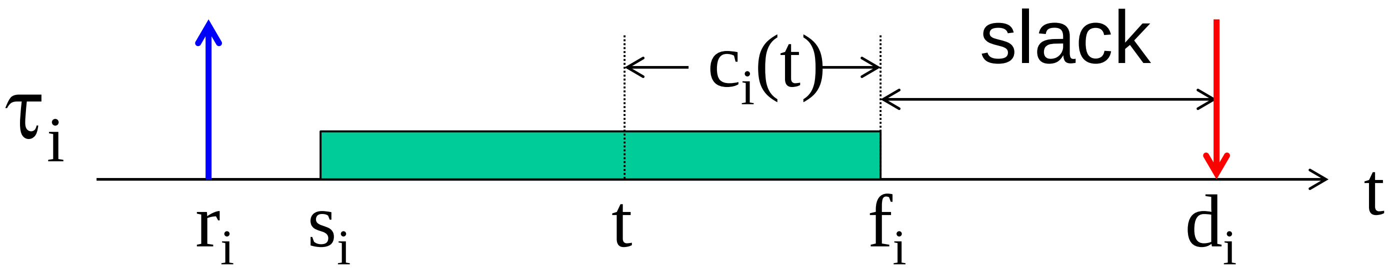
Real-time tasks

- r_i request time (arrival time ai)
- s_i start time
- C_i worst-case execution time (WCET)
- d_i absolute deadline
- D_i relative deadline
- f_i finishing time



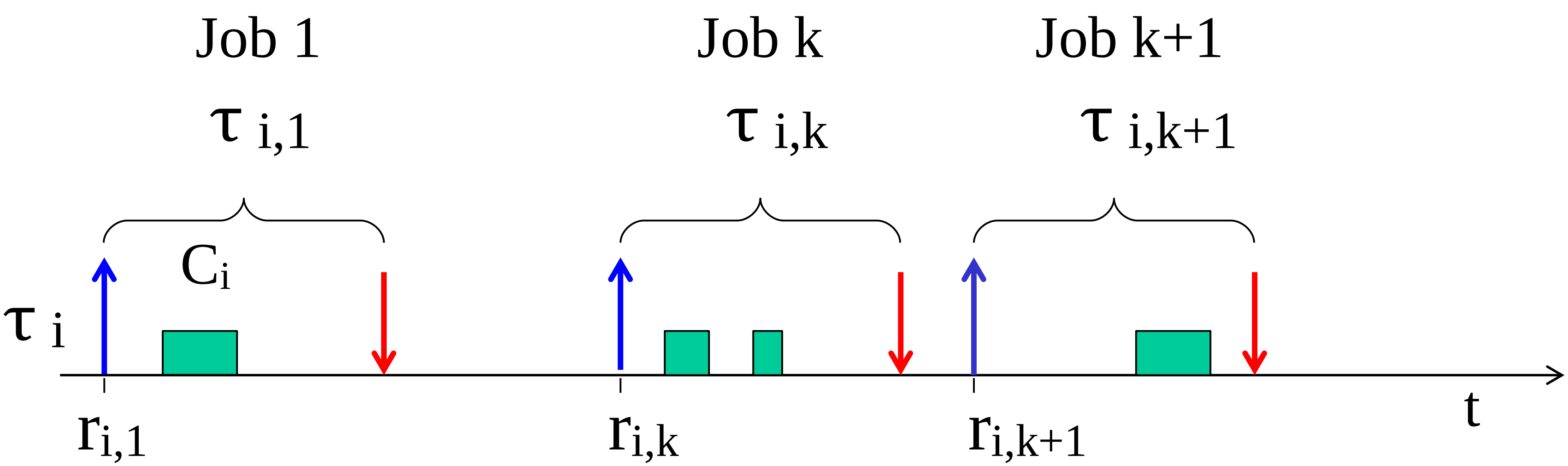
Other parameters

- **Lateness:** $L_i = f_i - d_i$
- **Tardiness:** $\max(0, L_i)$
- **Residual WCET:** $c_i(t)$ (at time r_i, it is $c_i(r_i) = C_i$)
- **Laxity (o slack):** $d_i - t - c_i(t)$



Tasks and Jobs

- a task is an infinite sequence of instances (jobs):



Task criticality

HARD tasks

- all jobs must meet their deadlines: missing a deadline may have serious consequences
  - sensory acquisition
  - low-level control
  - sensory-motor planning

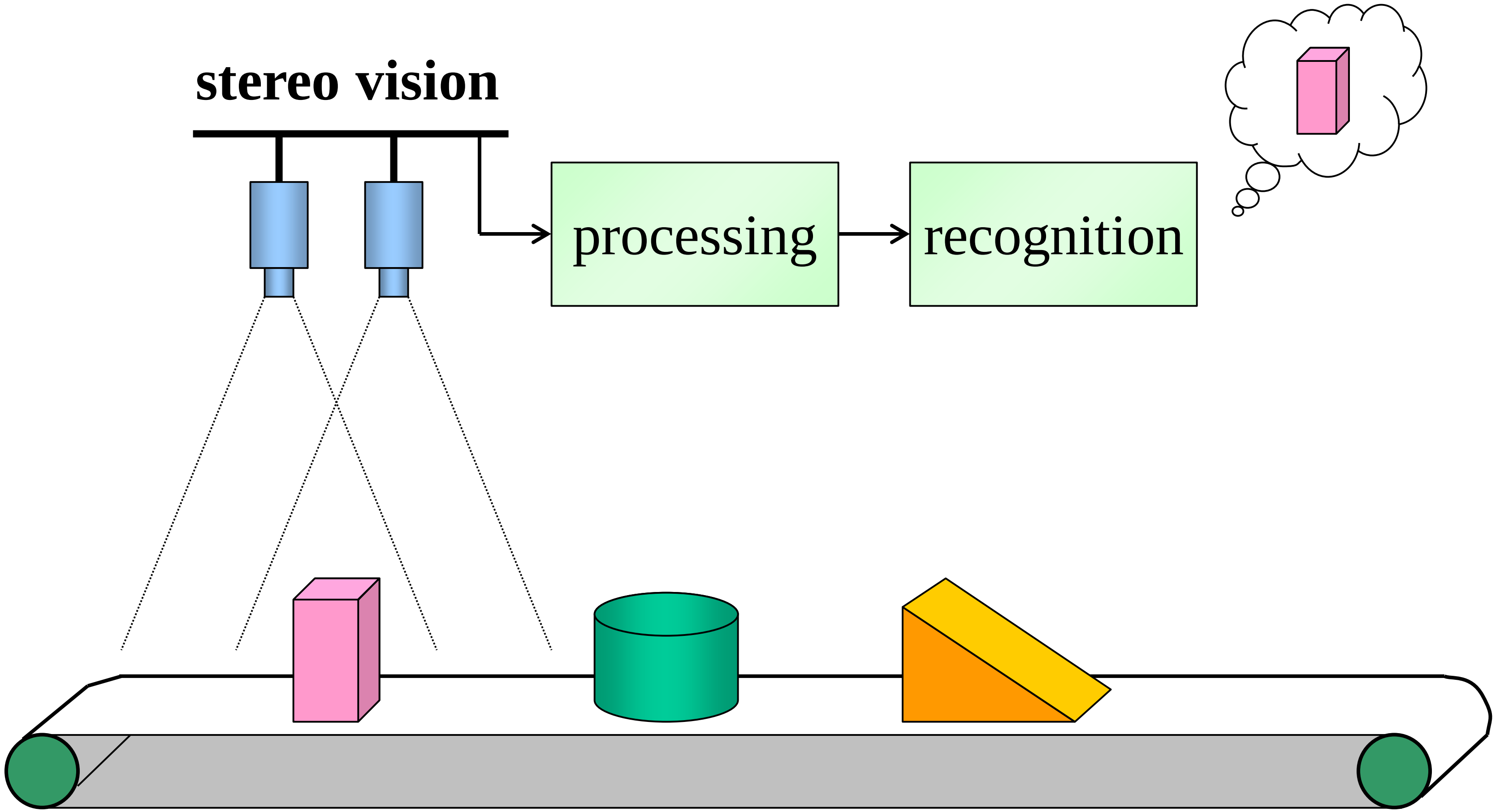
FIRM tasks

- only some jobs can miss their deadline

SOFT tasks

- jobs may miss deadlines: the goal is to minimize responsiveness
  - reading data from the keyboard
  - user command interpretation
  - message displaying
  - graphical activities

Sample application



Activation modes

time driven periodic tasks

- the task is automatically activated by the kernel at regular intervals.

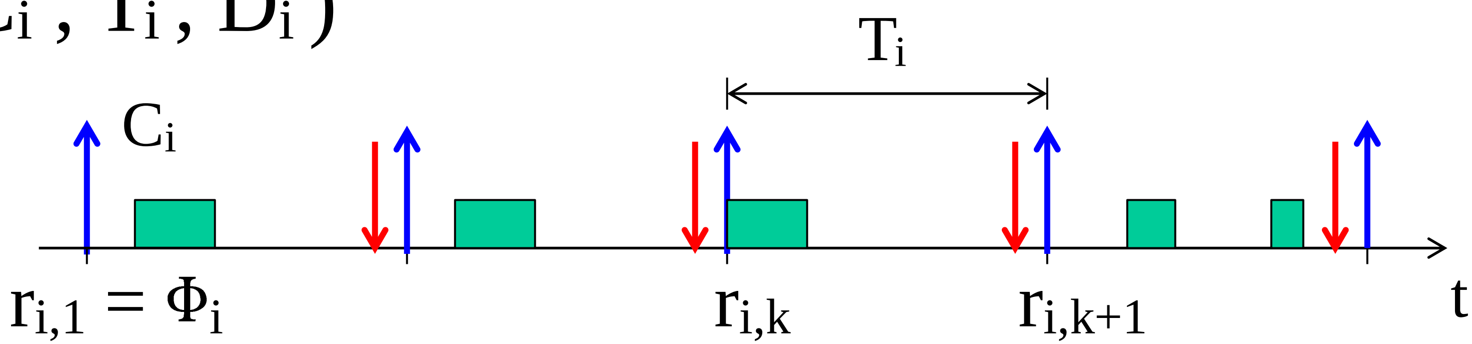
event driven aperiodic tasks

- the task is activated upon the arrival of an event or through an explicit invocation of the activation primitive.

Periodic task model

$$\begin{cases} r_{i1} = \Phi_i \\ r_{i,k+1} = r_{i,k} + T_i \end{cases}$$

$\tau_i\,(C_i\,,\,T_i\,,\,D_i\,)$



$$r_{i,k} = \Phi_i + (k-1)\,T_i$$

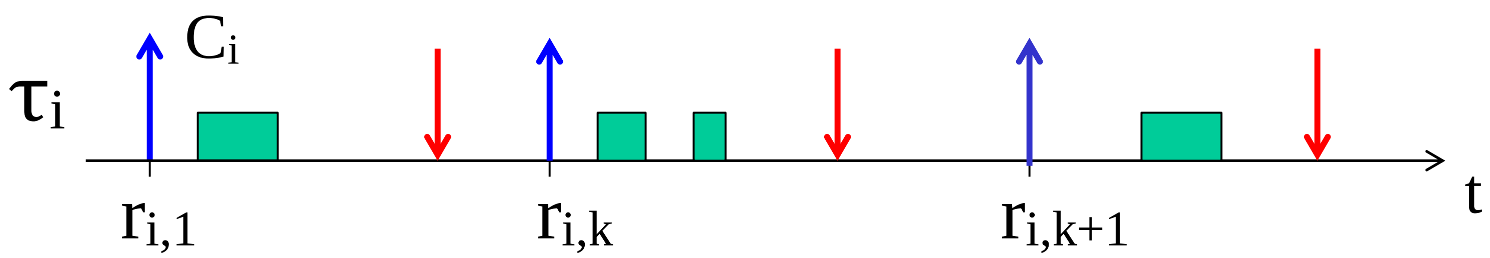
$$d_{i,k} = r_{i,k} + D_i$$

often $D_i = T_i$

Aperiodic task model

Aperiodic: $r_{i,k+1} > r_{i,k}$

Sporadic: $r_{i,k+1} \geq r_{i,k} + T_i$



Task constraints

Timing constraints

- deadline, activation, completion, jitter

Precedence constraints

- they impose an ordering in the execution

Resource constraints

- they enforce a synchronization in the access of mutually exclusive resources.

Timing constraints

Explicit

– Included in the specification of the system activities.

Examples

› open the valve in 10 seconds

› send the position within 40 ms

› read the altimeter every 200 ms

Implicit

– Do not appear in the system specification but must be respected to meet the requirements.

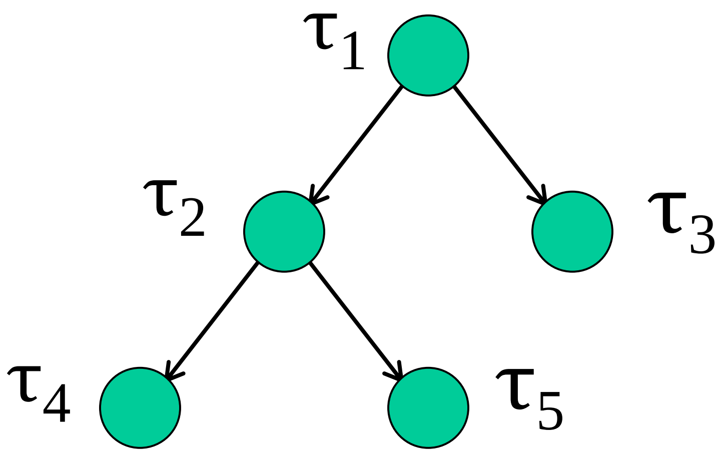
Examples

› avoid obstacles while running at speed *v*

› control an inverted pendulum of height *h* and weight *w*

Precedence constraints

Sometimes tasks must be executed with specific precedence relations, specified by a **Directed Acyclic Graph - DAG**



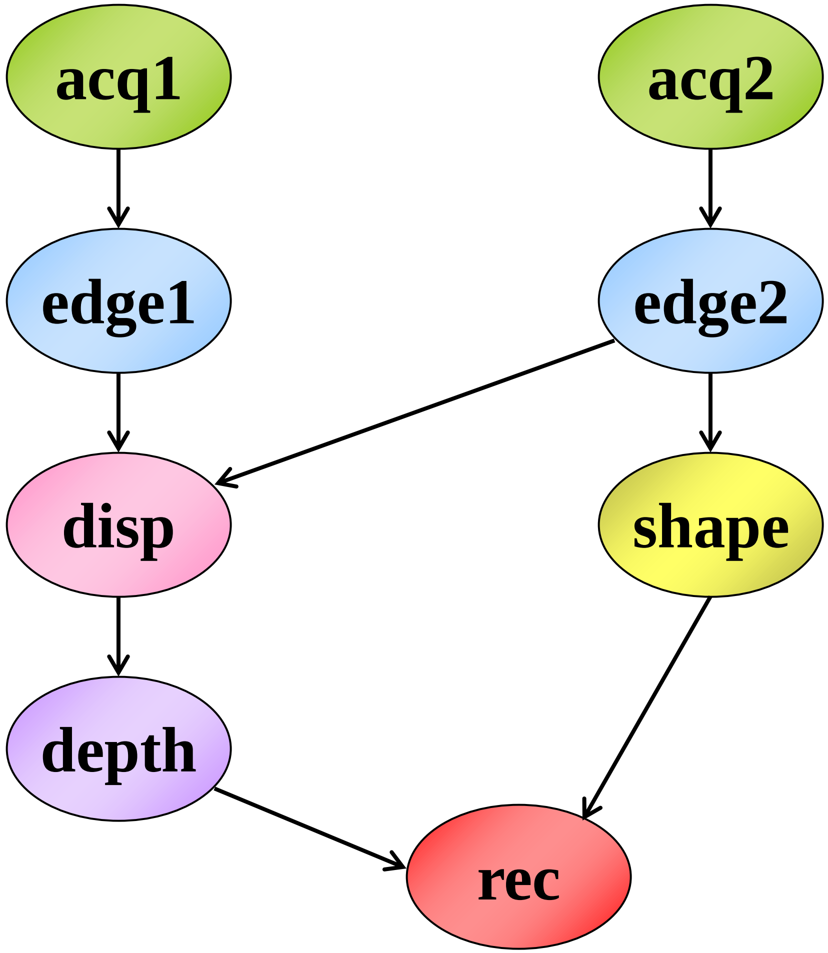
predecessor

$$\tau_1 \prec \tau_4$$

immediate predecessor

$$\tau_1 \rightarrow \tau_2$$

Precedence graph



References

Course website

- http://hipert.unimore.it/people/paolob/pub/Industrial_Informatics/index.html

My contacts

- paolo.burgio@unimore.it
- http://hipert.mat.unimore.it/people/paolob/

Resources

- Giorgio Buttazzo, “Hard Real-Time Computing Systems : Predictable Scheduling Algorithms and Applications“. 3rd Edition. 2011. Springer
- “Real-Time Embedded Systems” course by Prof. Bertogna @UNIMORE
- A "small blog"
  - http://www.google.com