# Execution Architecture for Real-Time Systems

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# Content

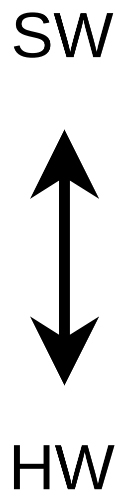
- Discussion on performance issues
- Introductory examples
- OS: process

  context switch, process-creation, thread, co-operative / preemptive multi-tasking, scheduling, EDF, RMS, RMA.
- How to design concur-rency / multi-tasking

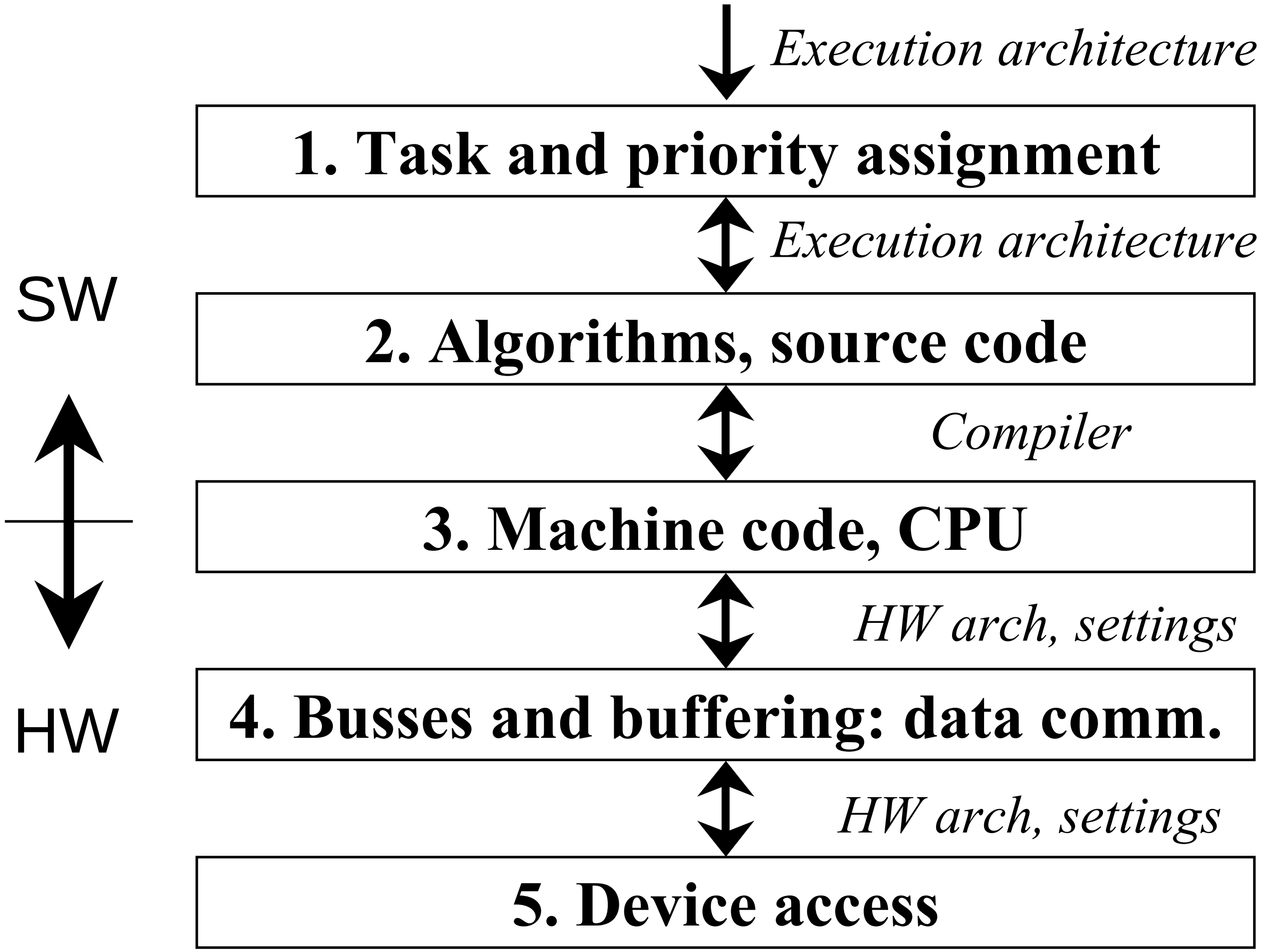
You:

- Discussion
- Various scheduling exercises
- RMA exercise

# Discussion on performance issues



# Model: Levels of execution



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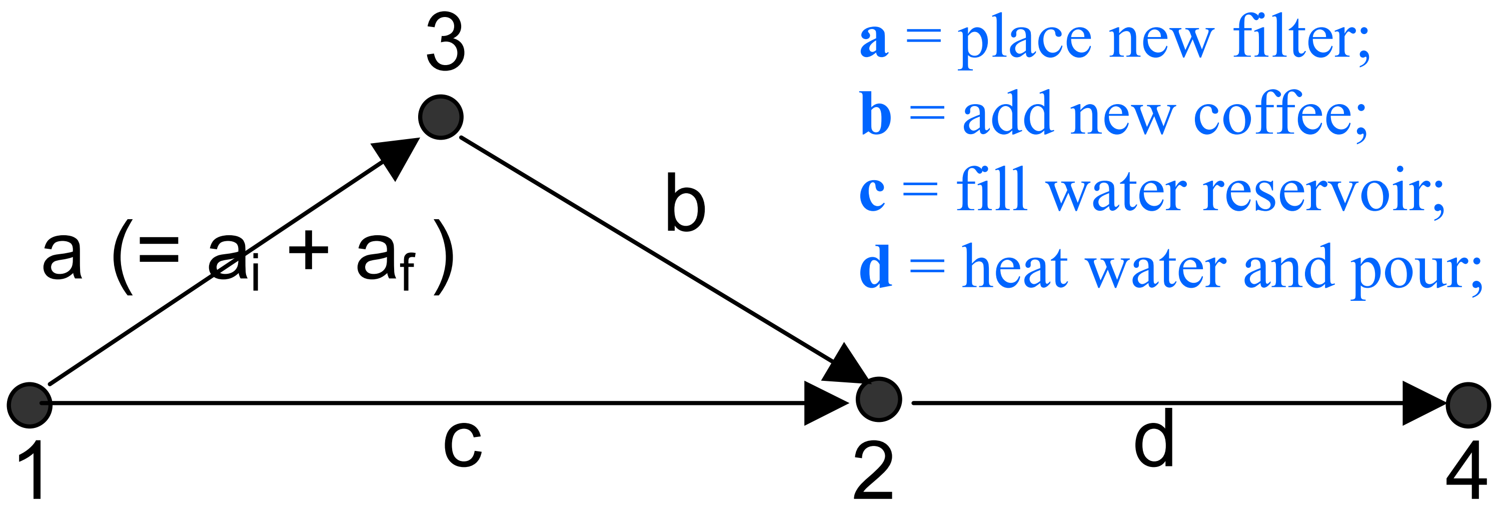
# Example 1: a coffee machine




**a** = place new filter; 1
**b** = add new coffee; 1
**c** = fill water reservoir; 2
**d** = heat water and pour; 2

main() { a(); b(); c(); d(); } t = 6

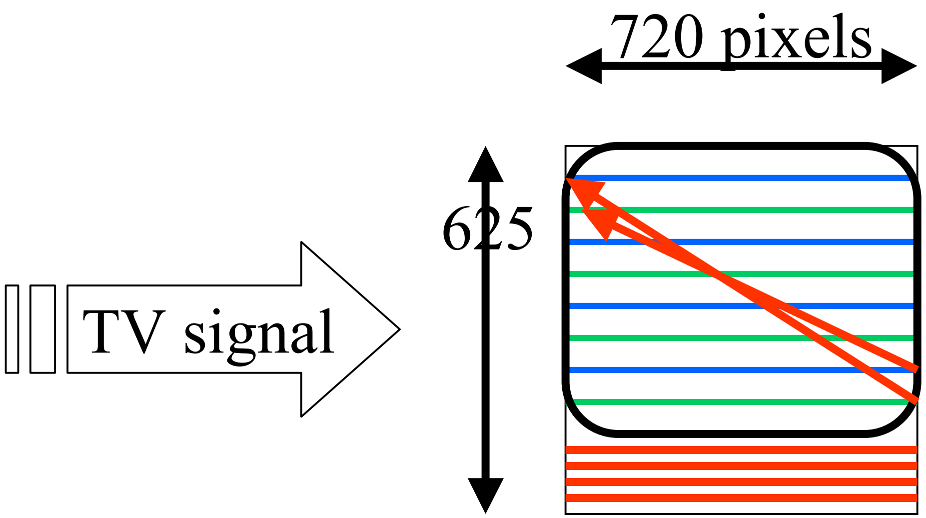
main() { c(); a(); b(); d(); } t = 6

main() { a_i(); c_i(); a_f(); b(); c_f(); d(); } t = 4

# Observations

- Timing requirements of actions are determined by dependency relations and deadlines.
- Hard-coded schedule of actions:
  - + Reliable, easy testable
  - + For small systems might be the best choice.

# Example 2: a TV system



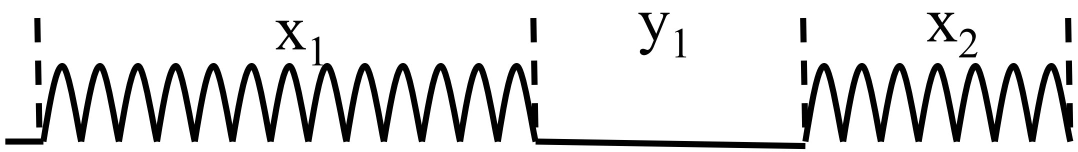

50 fields per second

Odd field

Even field

Txt lines in vertical blanking

Remote control




*Led flashing* *Led off* *Led flashing*

$x_i + y_i \approx 1$ ms

# Example 2: a TV system

- Simultaneous TV-system activities, e.g.,
  - 1) TXT processing and
  - 2) be able to respond to a Remote Cntrl key-press.
- One can include RC command checks in the TXT processing code. Mix unrelated things.
- RC-key press Timing Requirement is 0.5 s, TXT processing Timing Req. is 20 ms.

# Observations revised

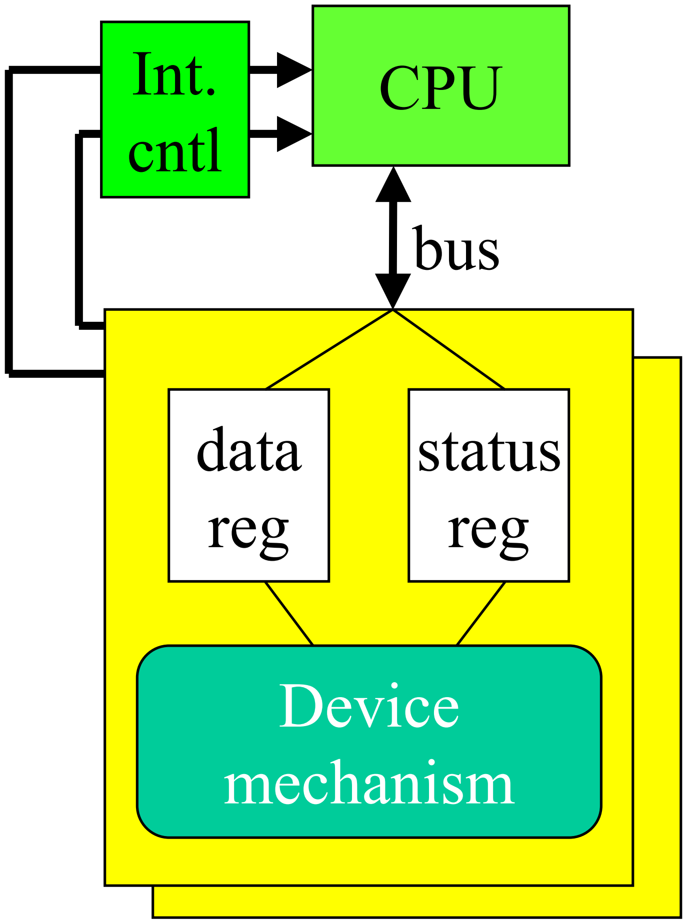
- Timing requirements of actions are determined by dependency relations and deadlines.
- Interrupts can be used for concurrency.
  - The RC-bit level is handled in this way.
- Hard-coded schedule:
  - it mixes unrelated functionality, and
  - lacks extendibility.
  - For small systems might be the best choice.

# Device - CPU Access

- Polling

```
Each x ms
  'check status';
```

- Interrupt
  - signal: handshake
  - forces next instruction to be a predetermined routine call



# Operating system, overview

- Supports concurrency, based on the concept of ‘process’, a virtual processor.
- Supports functions to handle problems caused by concurrency, e.g., mutual exclusion for a single-client resource.
- Auxiliary functions, like date/time, file system, networking, security, etc. etc.

# Why multiple processes?

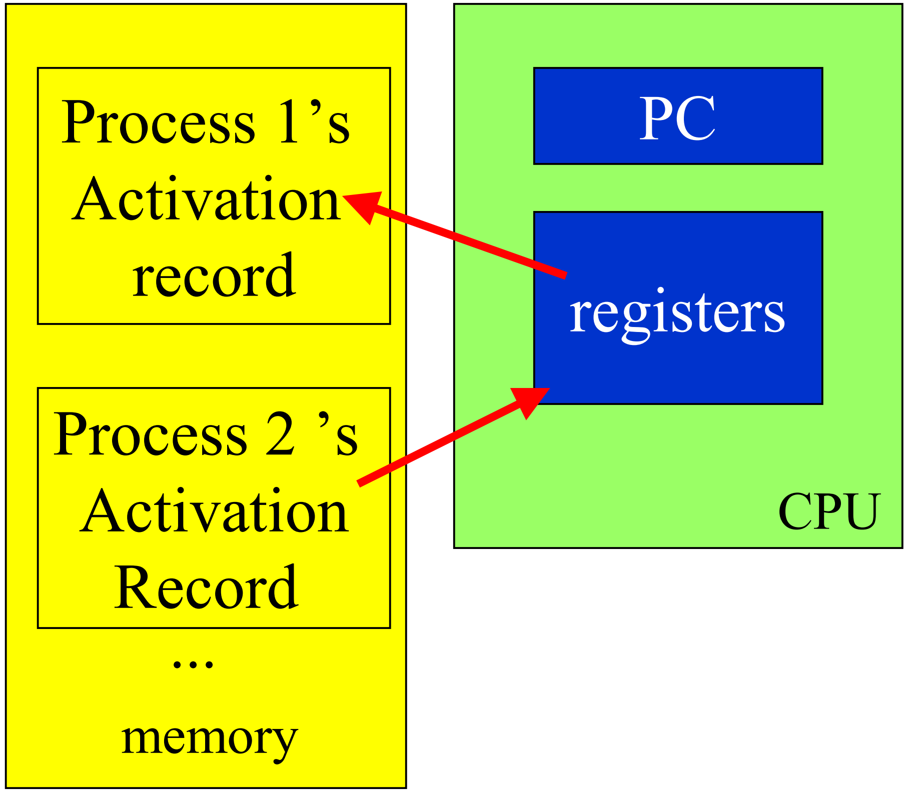
- Ease of programming: Separate programs execute quasi-parallel on a CPU.
- Handle urgency in particular for real-time activities.
- Utilisation of idle time. Continue with other processing when an activity is waiting for external response.

# Processes

- A process is a unique execution of a program or function, managed by the OS.
  - Several copies of a program may run simultaneously or at different times.
- A process has its own state:
  - processor status (registers, IR)
  - memory
    - stack, heap, process-status

# Processes and CPUs

- Activation record: copy of process state.
- Context switch:
  - current CPU context goes out;
  - new CPU context goes in.



# Threads

- Separate memory spaces per process require a Memory Management Unit (by using virtual memory).
- Thread = lightweight process: a process that shares memory space with other processes.
- Threads versus Processes: a reliability / safety and cost issue.

# Context switching

- Initiation?
- Switch to what other process?

- Answers = Characteristic of Operating System

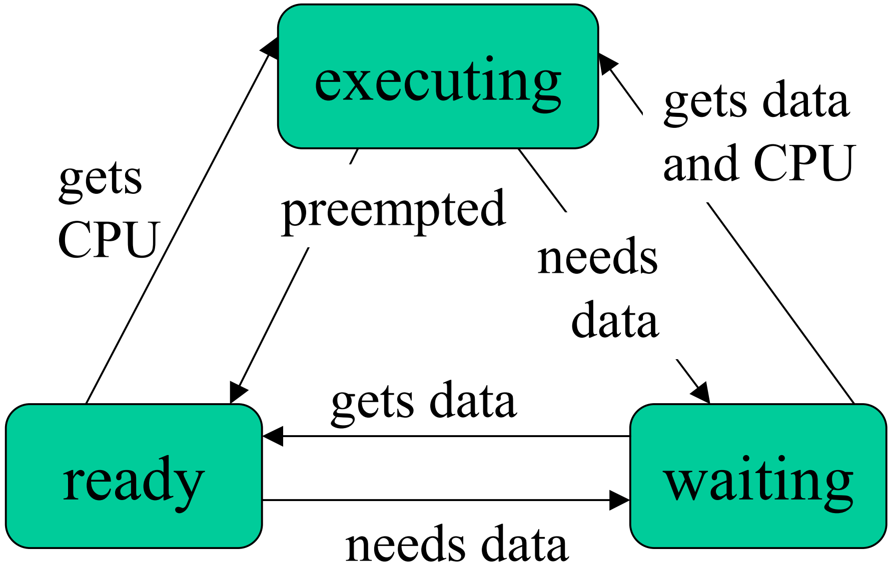
  – Preemptive multitasking

# Preemptive context switching

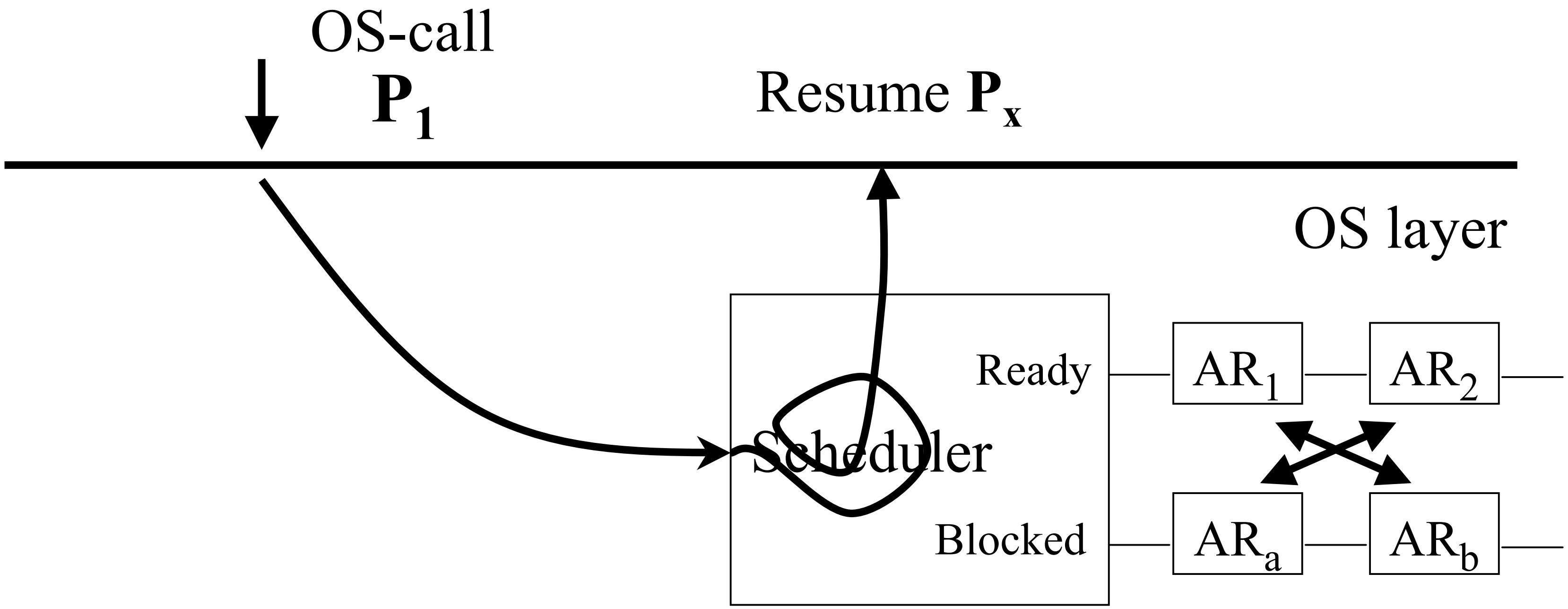
- OS saves current process's state in an activation record.
- OS chooses next process *p* to run (scheduling).
- OS installs activation record *p* as current CPU state, and the next process resumes.
- Do CPU caches improve context switching?

# Process state

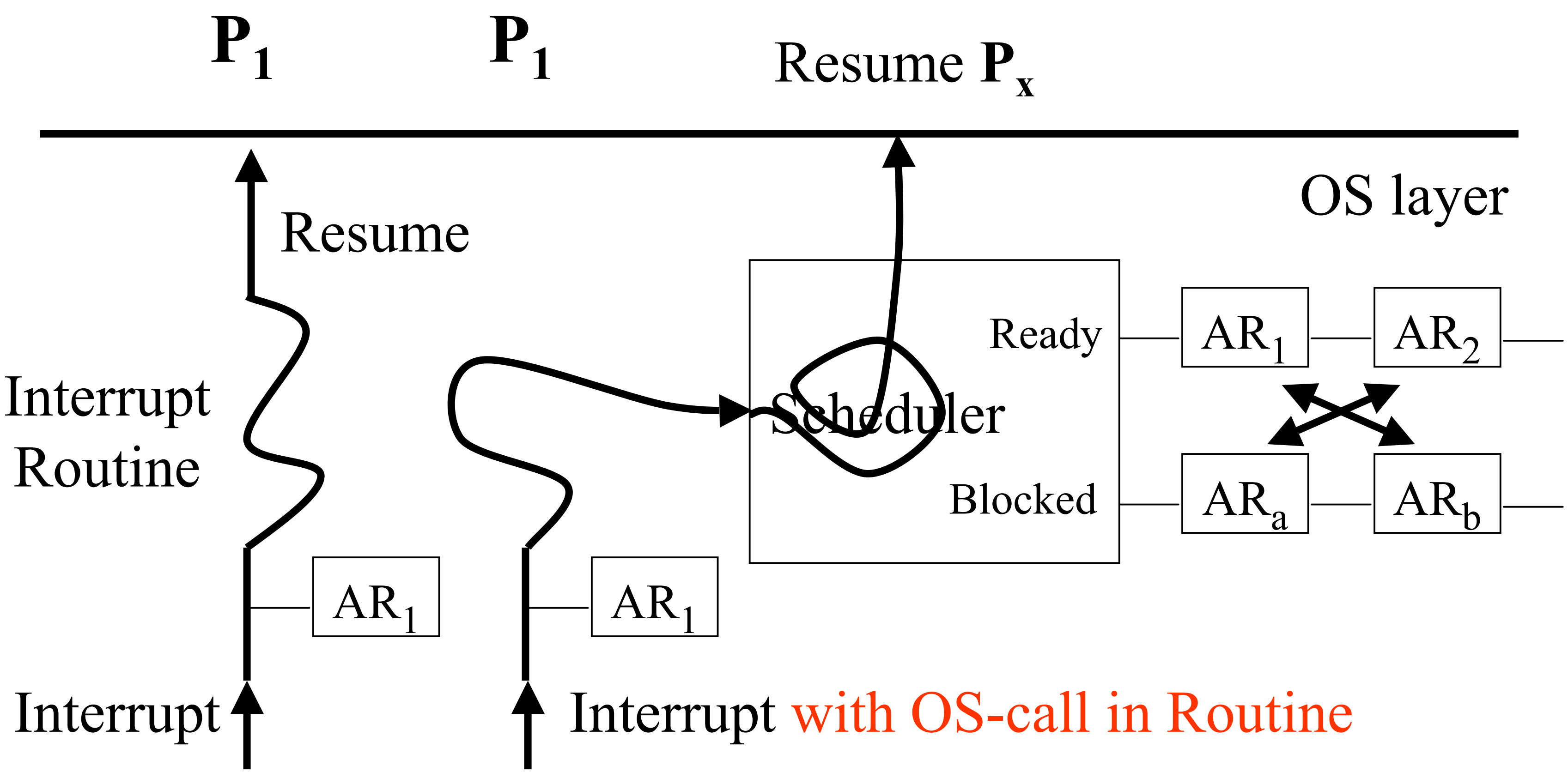
- A process can be in one of three states:
  - executing on the CPU;
  - ready to run;
  - blocking / waiting for data.
- Context switch caused when other process is made ready, like IPC, mutex, semaphores, etc.



# OS-call and scheduler



# Interrupts and scheduler

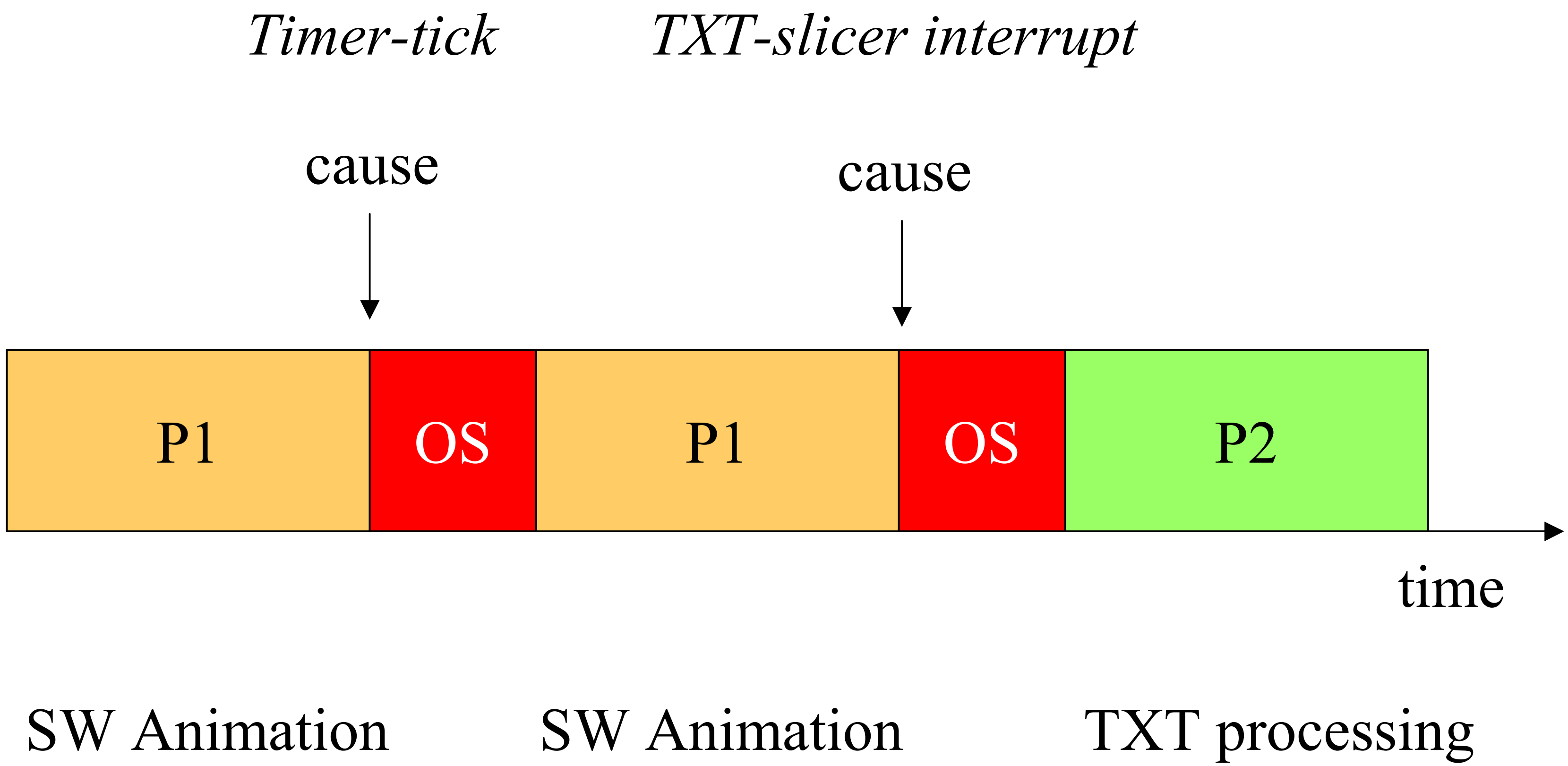


# Preemptive multitasking

- Most powerful form of multitasking:
  - OS controls when contexts switch; (cause)
  - OS determines what process runs next.
- Cause:
  - interrupts, e.g., a timer,
  - inter-process-calls, etc.

  → anything that can make a process ready to run

# Flow of control with preemption



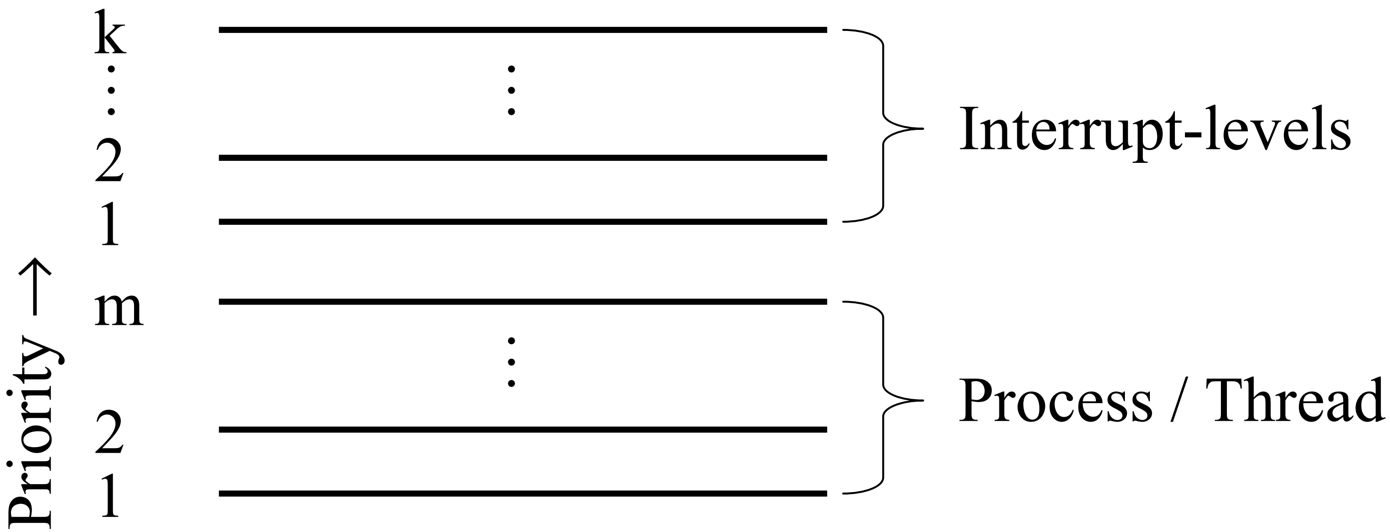
# Embedded vs. general-purpose scheduling

- Workstations try to avoid starving processes of CPU access.
  - Fairness = access to CPU.
- Embedded systems must meet deadlines.
  - Low-priority processes may not run for a long time. Risk of starvation.

# Priority-driven scheduling

- Each process has a priority.
- CPU goes to highest-priority process that is ready.
- Priorities determine scheduling policy:
  - fixed priority;
  - time-varying priorities.
  - round-robin scheduling in case of equal priorities

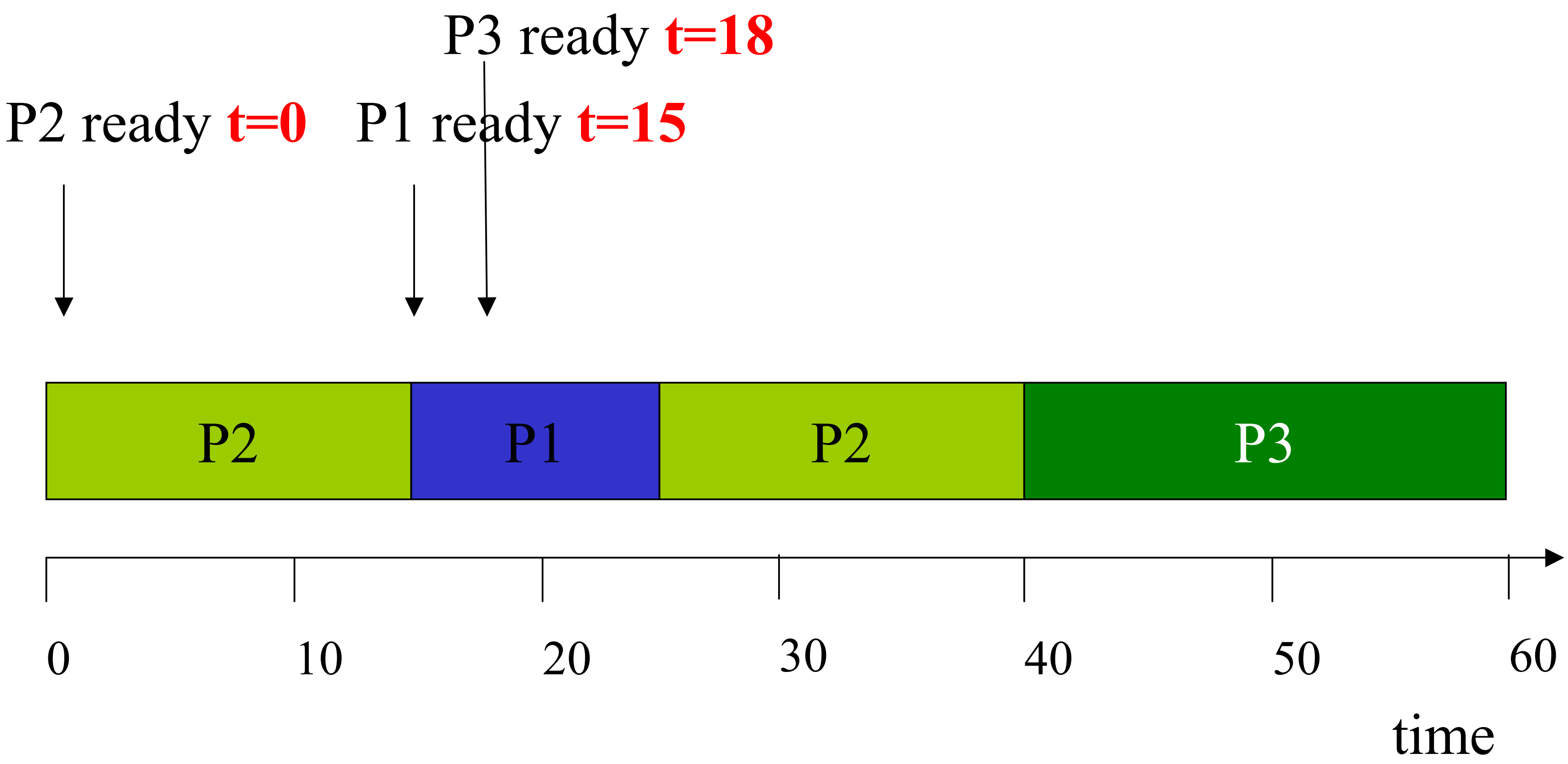
# Priority-based Tasks



# Priority-driven scheduling example

- Rules:
  - each process has a fixed priority (3 = highest);
  - highest-priority ready process gets CPU;
  - process continues until done.
- Processes
  - P1: priority 3, execution time 10
  - P2: priority 2, execution time 30
  - P3: priority 1, execution time 20

# Priority-driven scheduling example



# Simplified model

- Zero context switch time.
- No data dependencies between processes.
- Process execution time is constant.
- Deadline is at end of period.
- Highest-priority ready process runs.

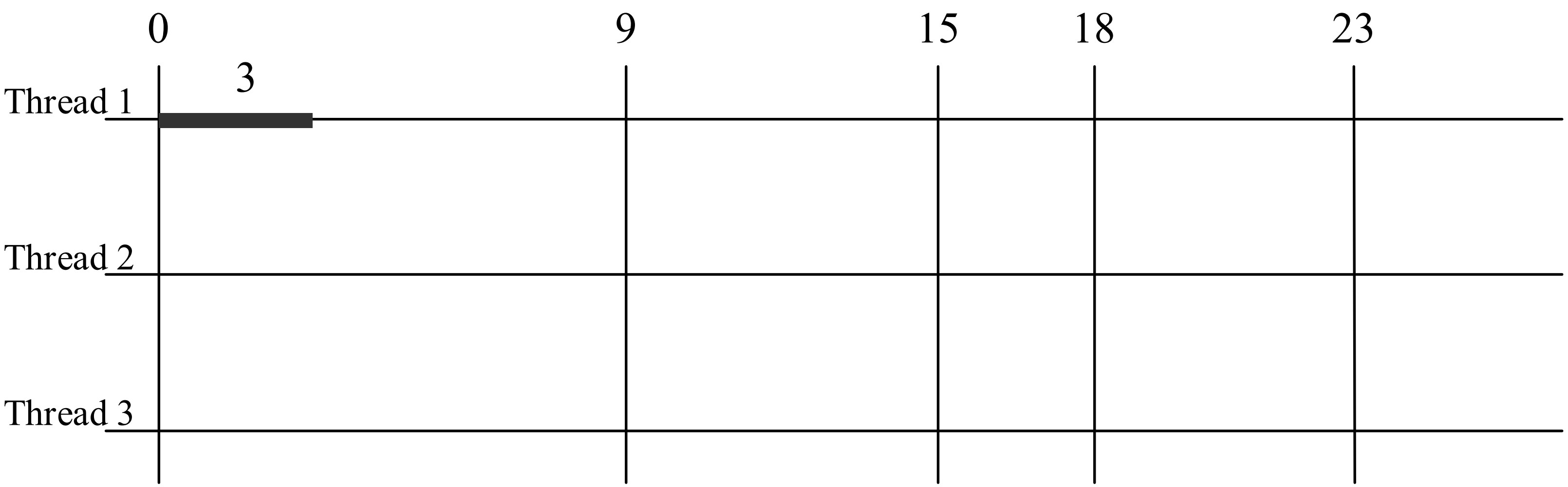
# Earliest-deadline-first scheduling

- EDF: dynamic priority scheduling scheme.
- Process closest to its deadline is given highest priority. In other words: the deadlines must be available.
- Requires recalculating process-priorities at every context switch-cause.

# Exercise: Earliest Deadline First

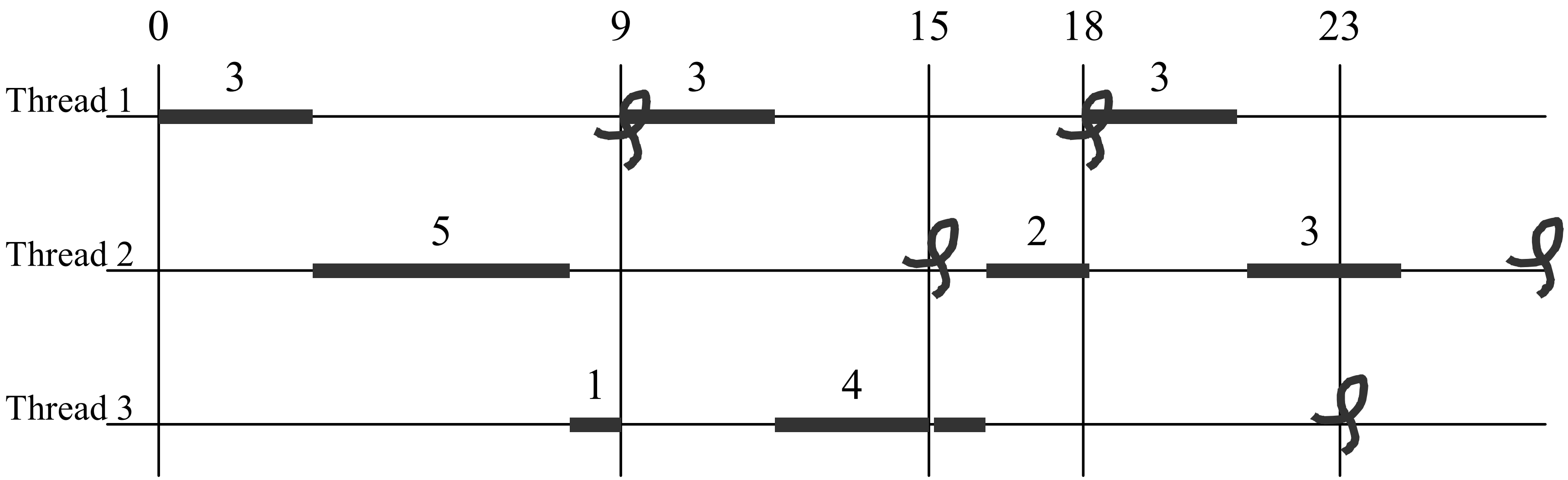
| Thread | Period = deadline | Processing | Load |
|---|---|---|---|
| Thread 1 | 9 | 3 | 33.3 % |
| Thread 2 | 15 | 5 | |
| Thread 3 | 23 | 5 | |
| | | | |

Suppose at t = 0, all threads are ready to process the arrived trigger.



# Answer to exercise: EDF

| Thread | Period = deadline | Processing | Load |
|---|---|---|---|
| Thread 1 | 9 | 3 | 33.3 % |
| Thread 2 | 15 | 5 | 33.3 % |
| Thread 3 | 23 | 5 | 21.7 % |
| | | | **88.3 %** |



# EDF evaluation

- EDF can utilize 100% of CPU.
- Overhead in context-switching is large.
- Deadlines (not only repetition rates) must explicitly be available in the system.

- Theoretically attractive, but hardly ever used.

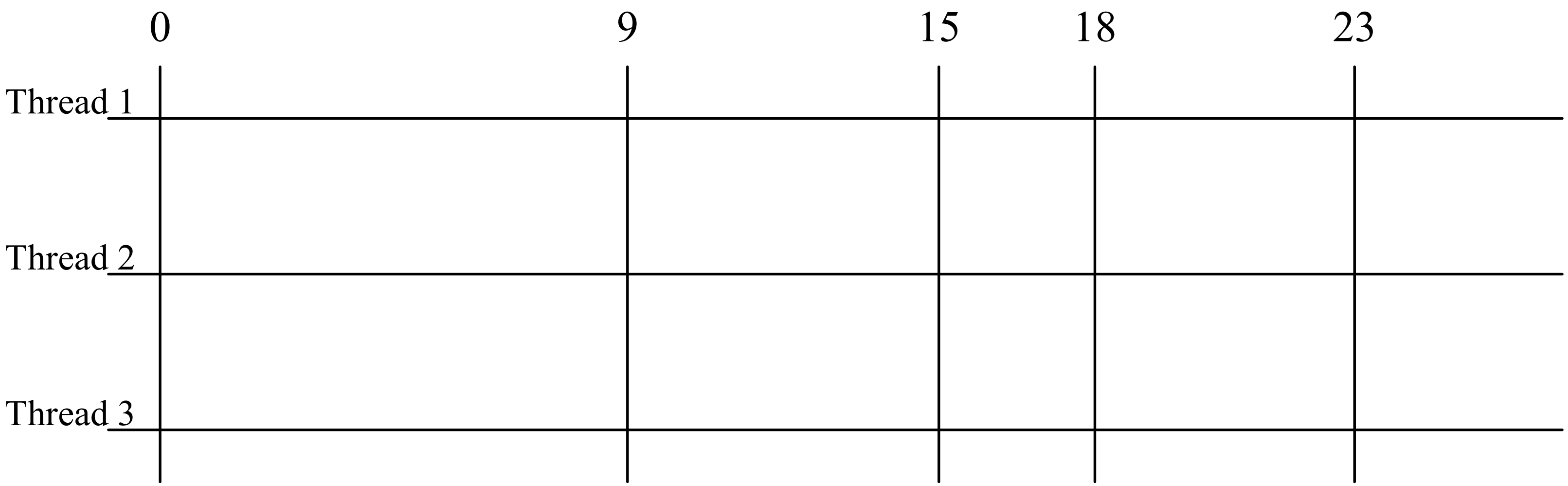
# Rate-Monotonic Scheduling

- RMS: static priority scheduling scheme.
- Priority assignment: the shorter deadline, the higher the priority.

# Exercise: Rate-Monotonic S

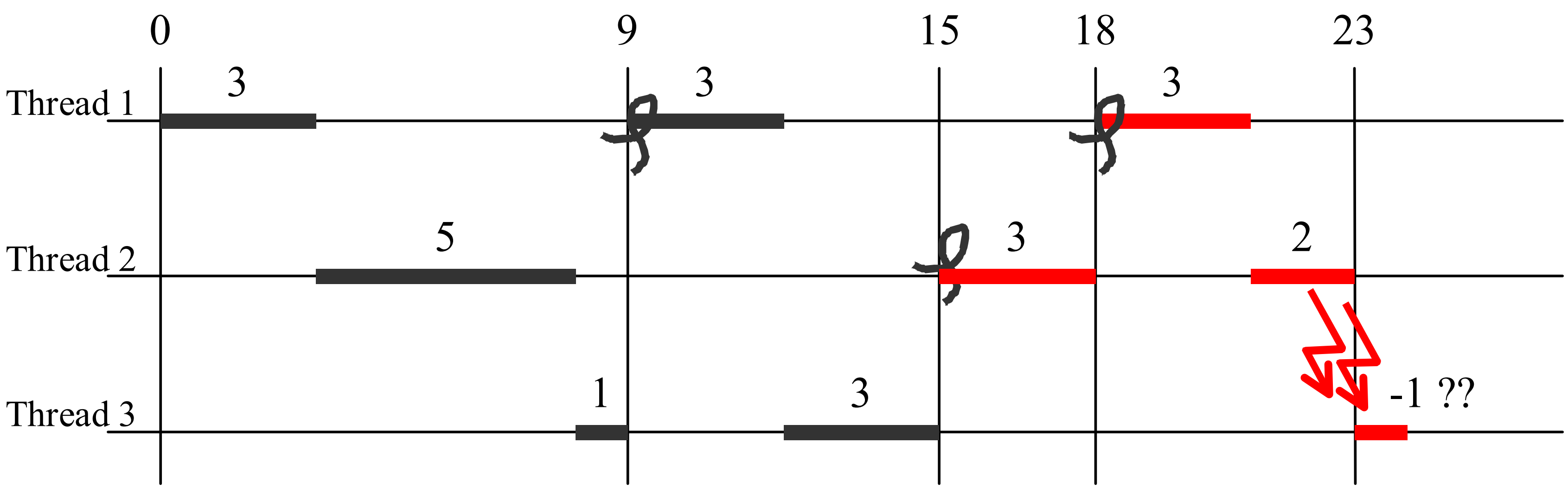
| Thread | Priority | Period = deadline | Processing | Load |
|---|---|---|---|---|
| Thread 1 | | 9 | 3 | 33.3 % |
| Thread 2 | | 15 | 5 | 33.3 % |
| Thread 3 | | 23 | 5 | 21.7 % |
| | | | | **88.3%** |

Suppose at t = 0, all threads are ready to process the arrived trigger.

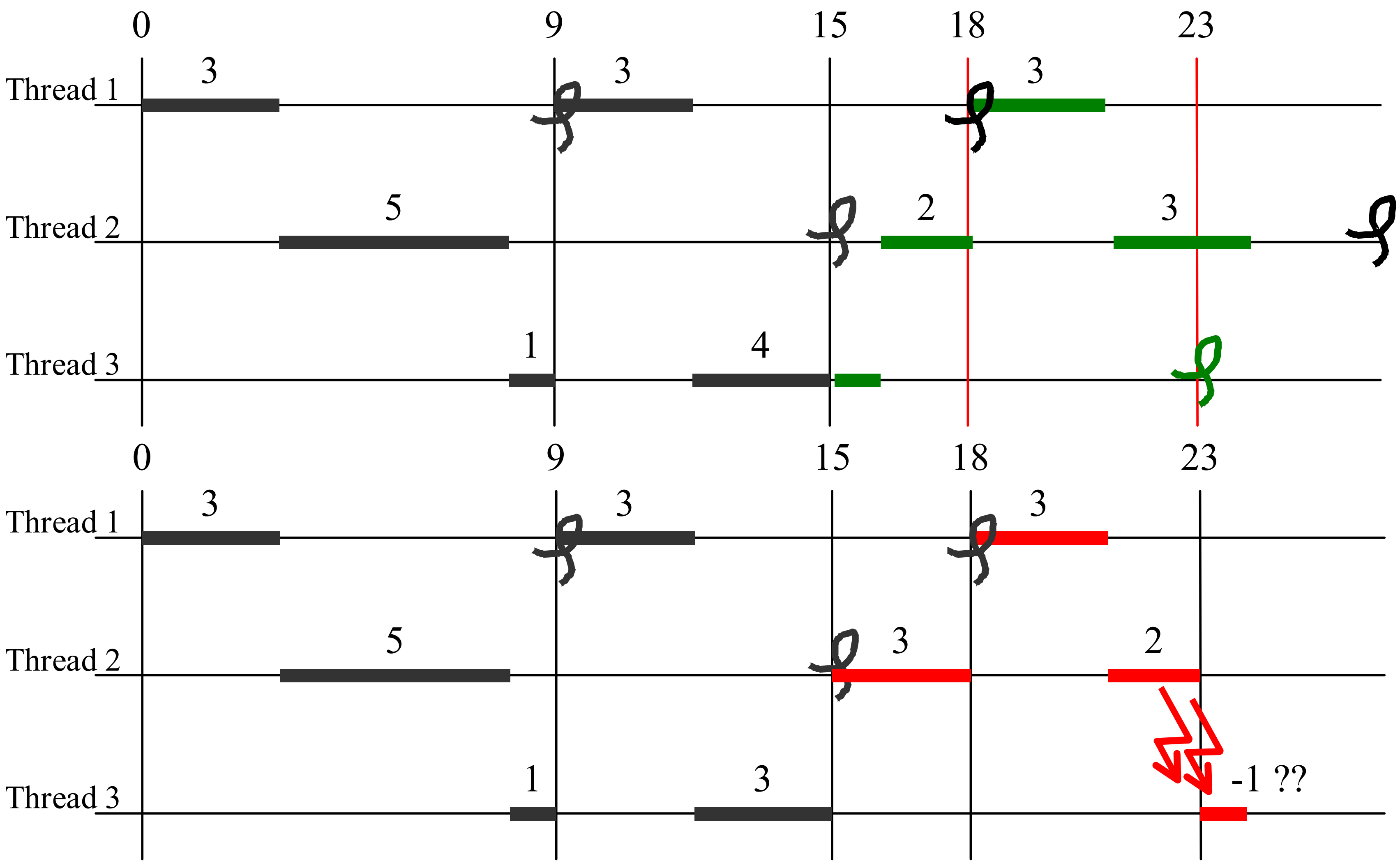


# Answer to exercise: RMS (vs EDF)

| Thread | Priority | Period = deadline | Processing | Load |
|---|---|---|---|---|
| Thread 1 | High | 9 | 3 | 33.3 % |
| Thread 2 | Medium | 15 | 5 | 33.3 % |
| Thread 3 | Low | 23 | 5 | 21.7 % |
| | | | | **88.3 %** |



# Answer to exercise: RMS (vs EDF)



# RMS evaluation

- RMS cannot utilize 100% = 1.0 of CPU, but for 1,2,3,4 … ∞ processes:

  1.00, 0.83, 0.78, 0.76, … *log 2 = 0.69.*
- RMS guarantees that all processes will always meet their deadlines, for any interleaving of processes.
- With fixed priorities, context switch overhead is limited.

# RMS evaluation (cont'd)

- For specific cases utilization bound higher, up to 0.88 load for large n.
- A processor running only hard-real-time processes is rare. For soft-RT less a problem.
- A lot of additional theory exists.
  - Meeting deadlines in hard-real-time systems, by L.P. Briand and D.M. Roy.

# Real-time scheduling theory, utilization bound

- Set of n tasks with periods T_i, and process time P_i, load u_i = P_i / T_i,
- Schedule is at least possible when tasks are independent and:

$$Load \equiv \sum_i u_i \leq n\left(2^{\frac{1}{n}} - 1\right)$$

- 1.00, 0.83, 0.78, 0.76, …. *log 2 = 0.69*.

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You:

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- RMA exercise

# How to design concurrency

- Introduction: Why? Grounds?
- Timing requirements
- Active versus passive
- Execution architecture steps
- Issues resulting from concurrency

# Multiple processes?

## Why?

- Handle urgency (meet various deadlines simultaneously)
- Ease of programming unrelated functionality
- Utilisation of idle time

## Why not?

- Ease of programming for strongly related functionality
  - Reduce unpredictability
- Context-switch overhead
  - and inter-process communication
- Memory cost (e.g. multiple stacks)

Design of concurrency is a crucial, non-trivial part of an architecture.

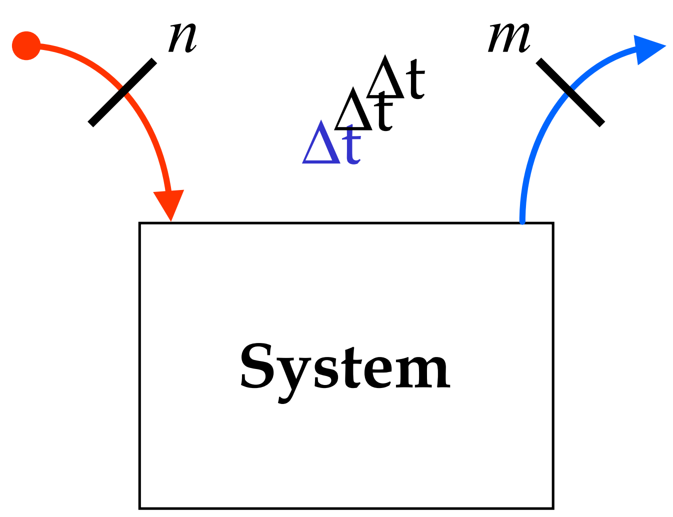
# Execution architecture design based on RMA.

Grounds:

- Function to Task mapping based on Gomaa's CODARTS rules.
- Scheduling of tasks based on RMS = rate-monotonic scheduling
- Deadline analysis is known as Rate Monotonic Analysis (RMA).

# Execution architecture: What are Timing Requirements?

Event / Trigger
Required deadline
Actual response




Multiple TRs:
concurrent responses.

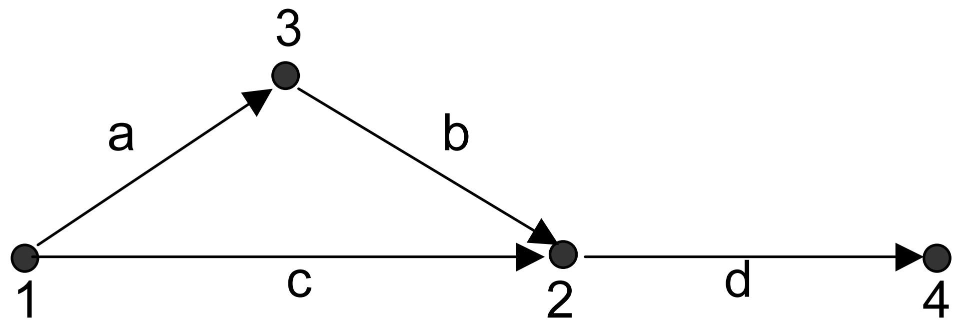
# What are Timing Requirements?

- What happens if a process doesn’t finish by its timing requirement?
  - Hard deadline: system fails if missed.
  - Soft deadline: user may notice, but system doesn’t necessarily fail.

  - Periodic events: cyclic.
  - Aperiod events, e.g. user-input.

# What are timing requirements?

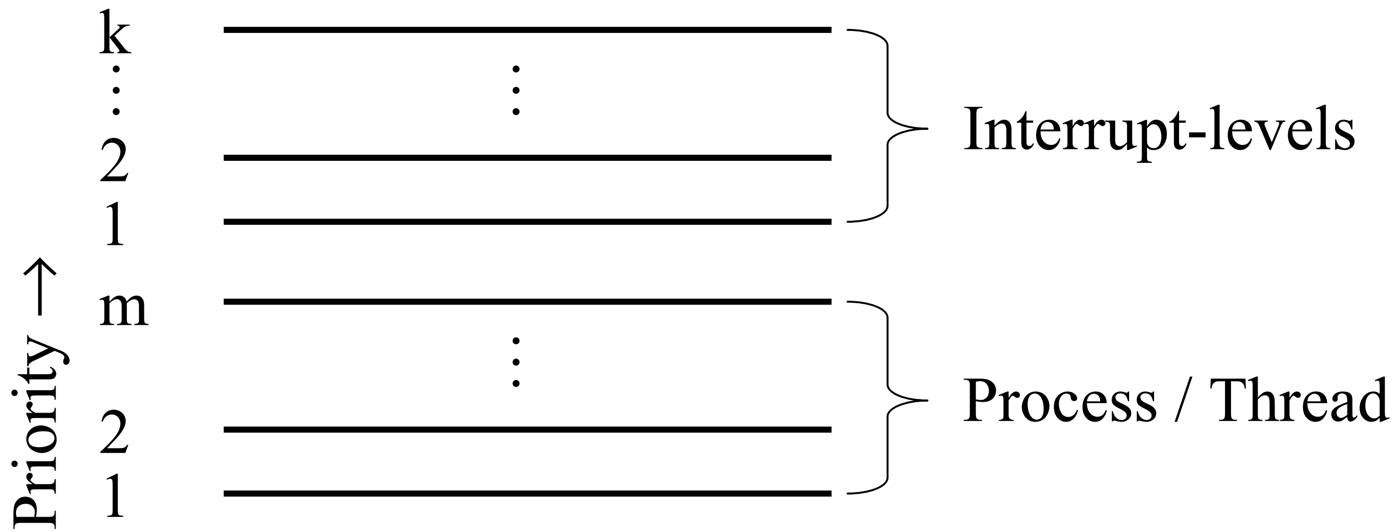
- Event
  - external: signal: e.g. device or timer
  - active or passive = interrupt or polling
  - internal: handover some datastructure
  - Dependency tree of actions = action flow



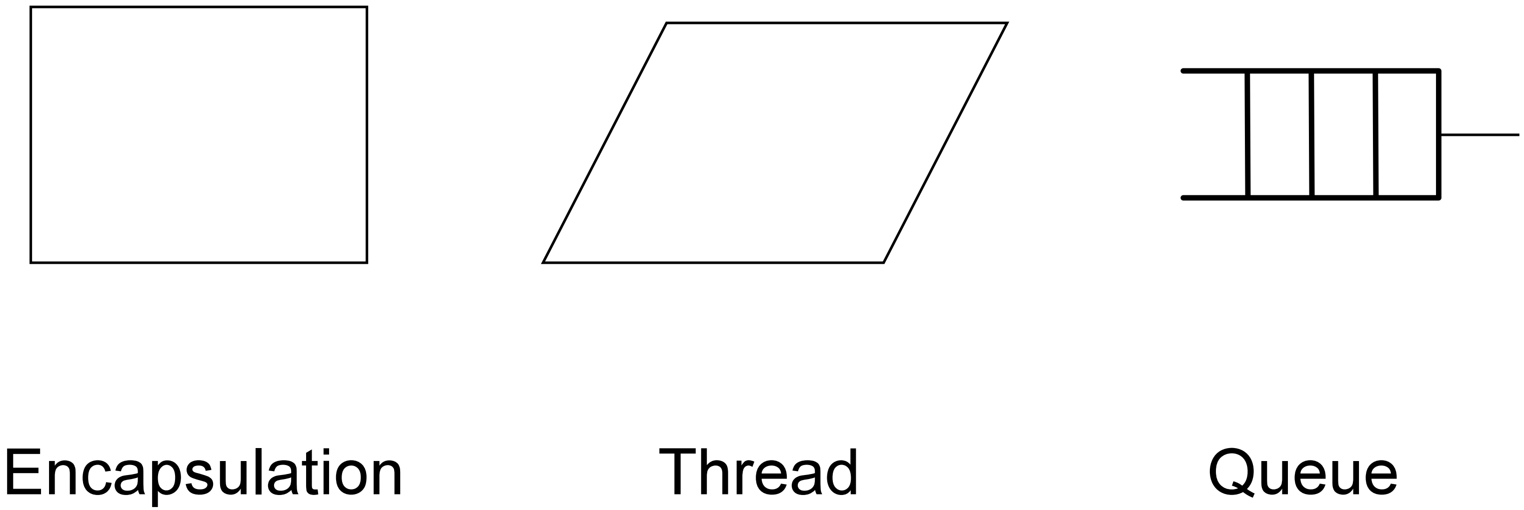
# Terminology

- Action = response function.
- Task is a virtual processor, executing a set of actions.
  - A process or thread is a sequential execution of a set of response functions, managed by the OS.
  - An interrupt routine is a function that may be triggered by an interrupt. Each interrupt-level can be regarded as a task, executing a set of interrupt routines.

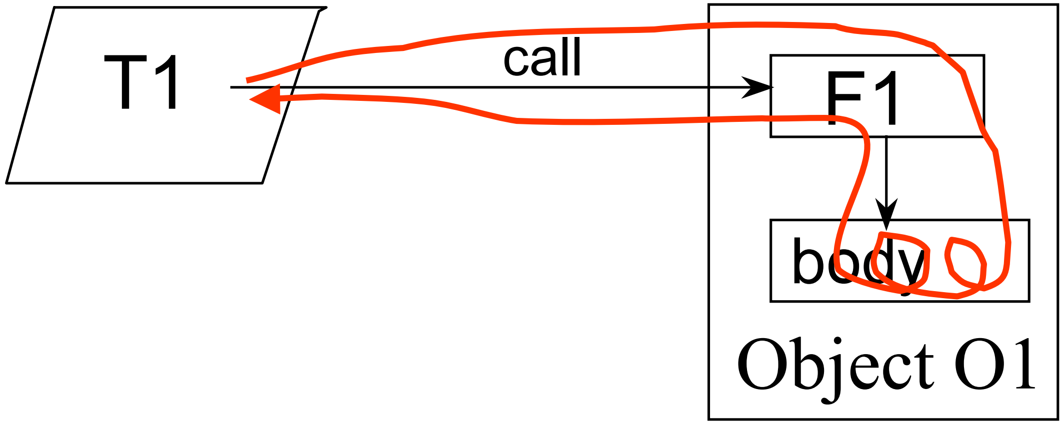
# Priority-based Tasks

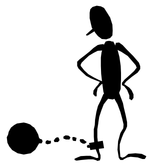


# Notation



# Passive versus Active

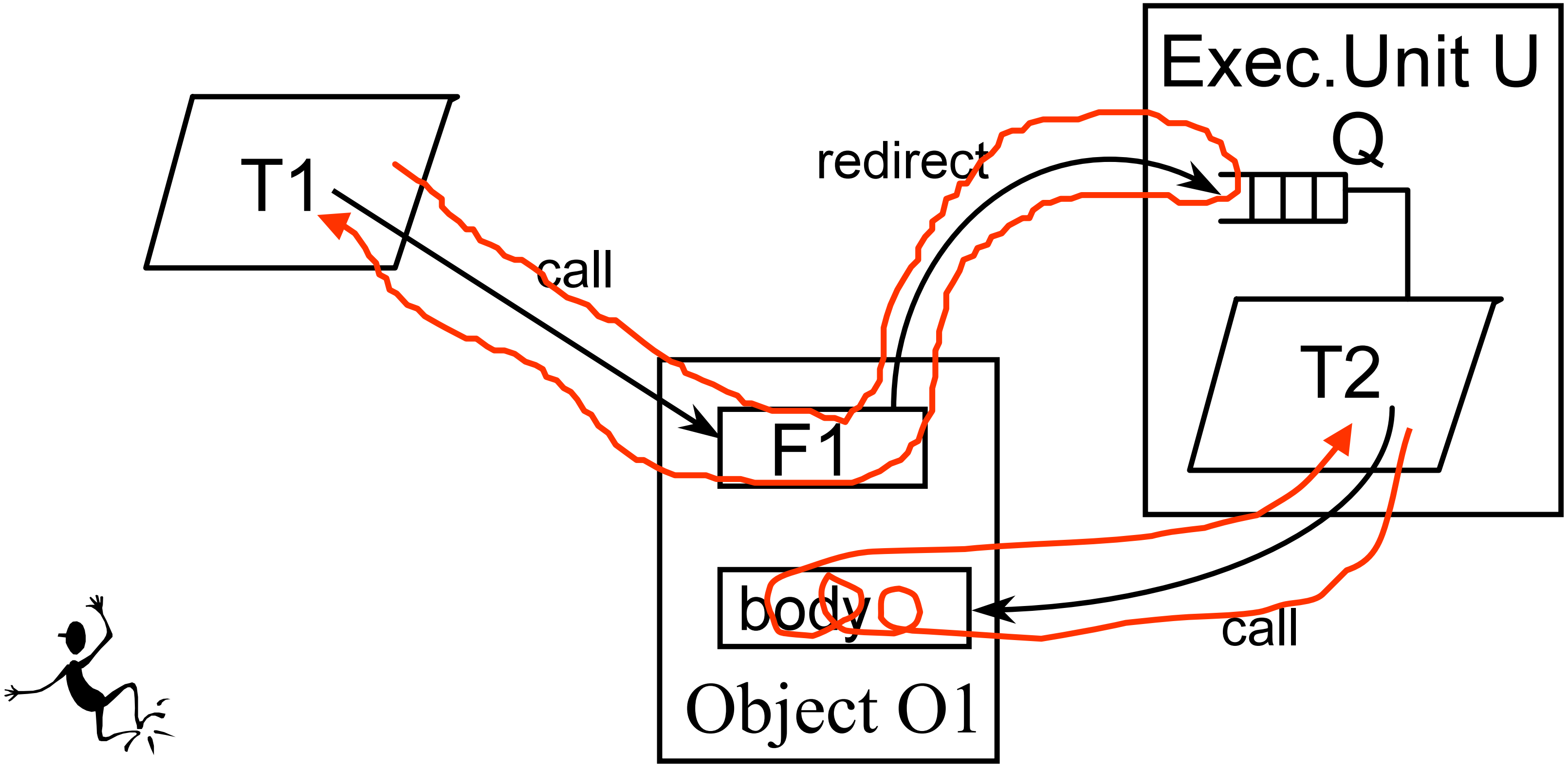


Objects / modules communicate via (member) functions

A passive module runs it’s functions on the task of a caller. The function is synchronous.

# Passive versus Active

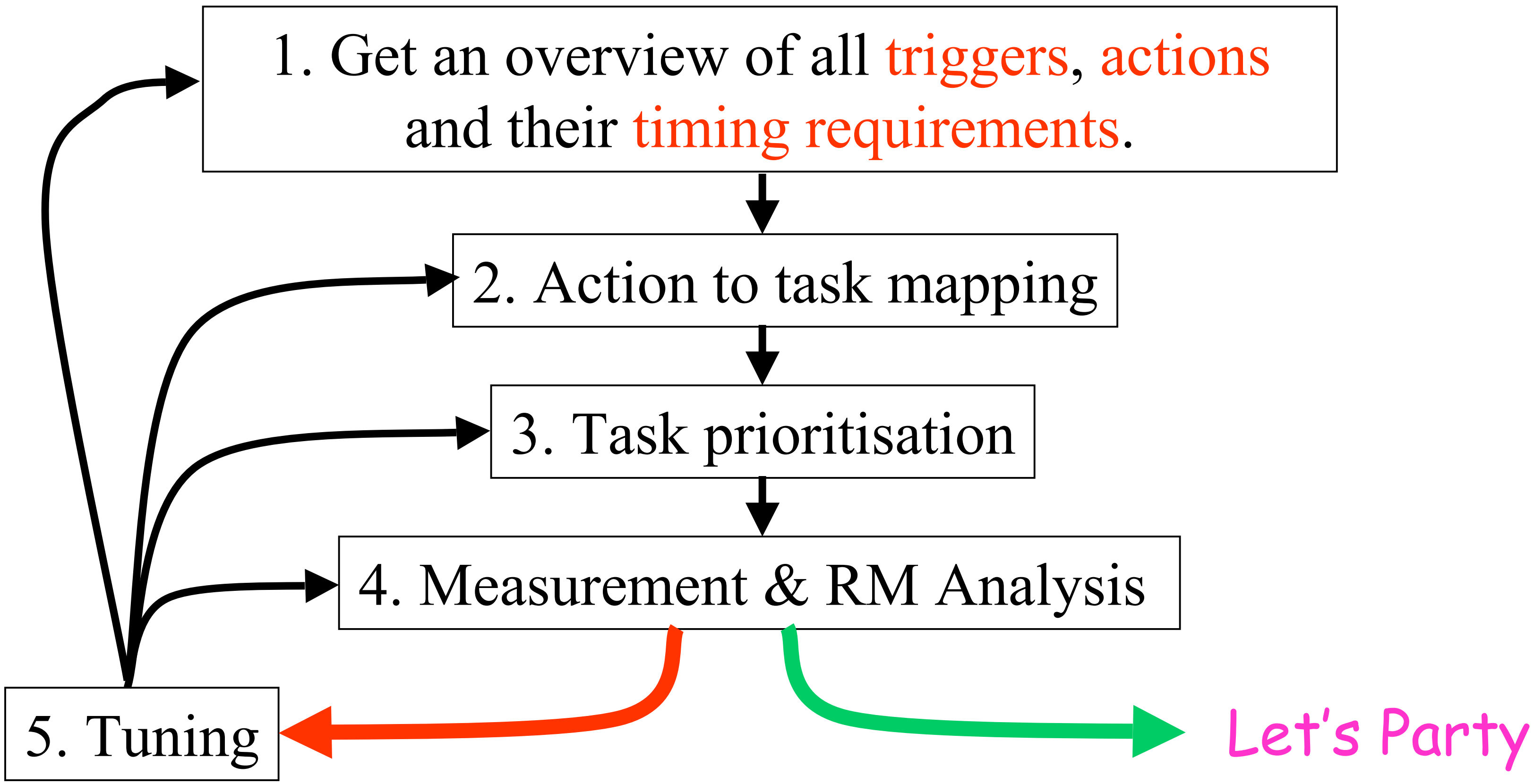



Active objects / functions defer execution to another task.
The function is asynchronous, or decoupled.

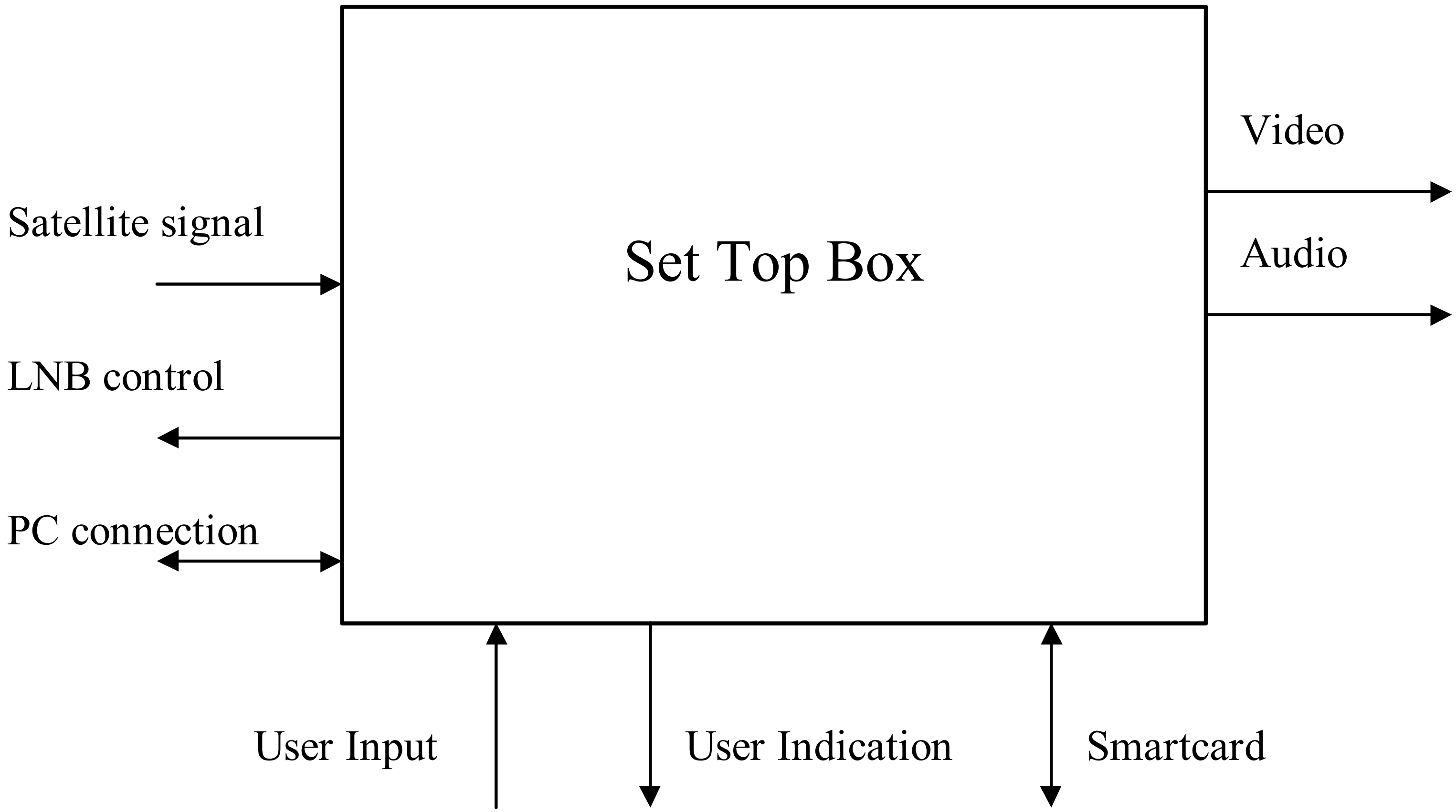
# Redirection

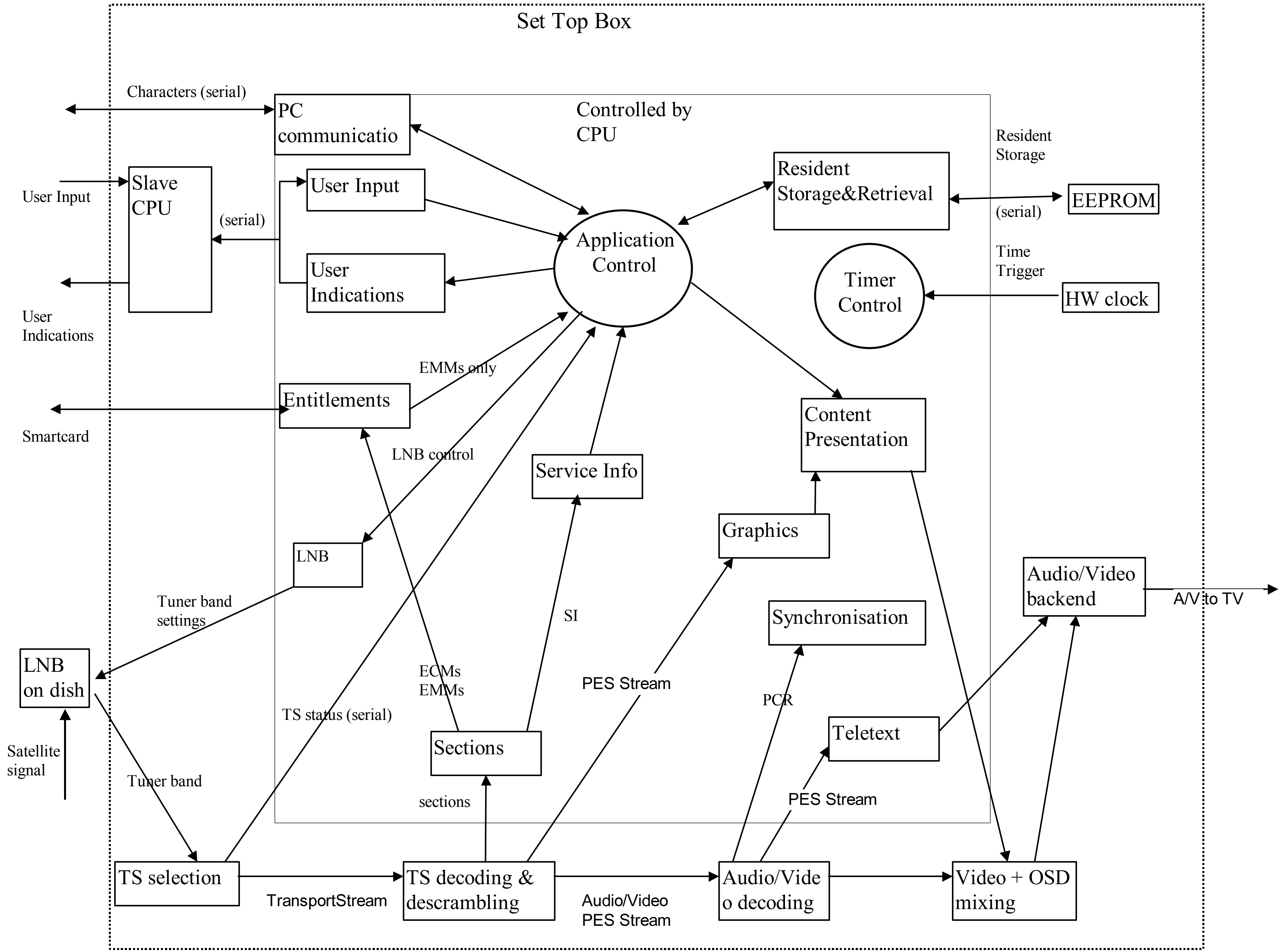
- Redirection data:
  - function pointer,
  - function arguments,
  - execution unit id.
- Can be generalized to a pattern to support simple change.
- Decouple functional and dynamical design.

# Overview of exec arch steps



# Step 1: Inventorize triggers, actions and timing requirements





Set Top Box
Characters (serial)
PC communicatio
Controlled by CPU
Resident Storage
User Input
Slave CPU
User Input
(serial)
Resident Storage&Retrieval
EEPROM
(serial)
Application Control
User Indications
Time Trigger
Timer Control
HW clock
User Indications
EMMs only
Entitlements
Smartcard
Content Presentation
LNB control
Service Info
Graphics
LNB
Audio/Video backend
A/V to TV
Tuner band settings
SI
Synchronisation
LNB on dish
ECMs EMMs
PES Stream
PCR
TS status (serial)
Teletext
Satellite signal
Sections
Tuner band
sections
PES Stream
TS selection
TS decoding & descrambling
Audio/Video decoding
Video + OSD mixing
TransportStream
Audio/Video PES Stream

# This is too complex ! ?

Yes, we have a problem and it's complex

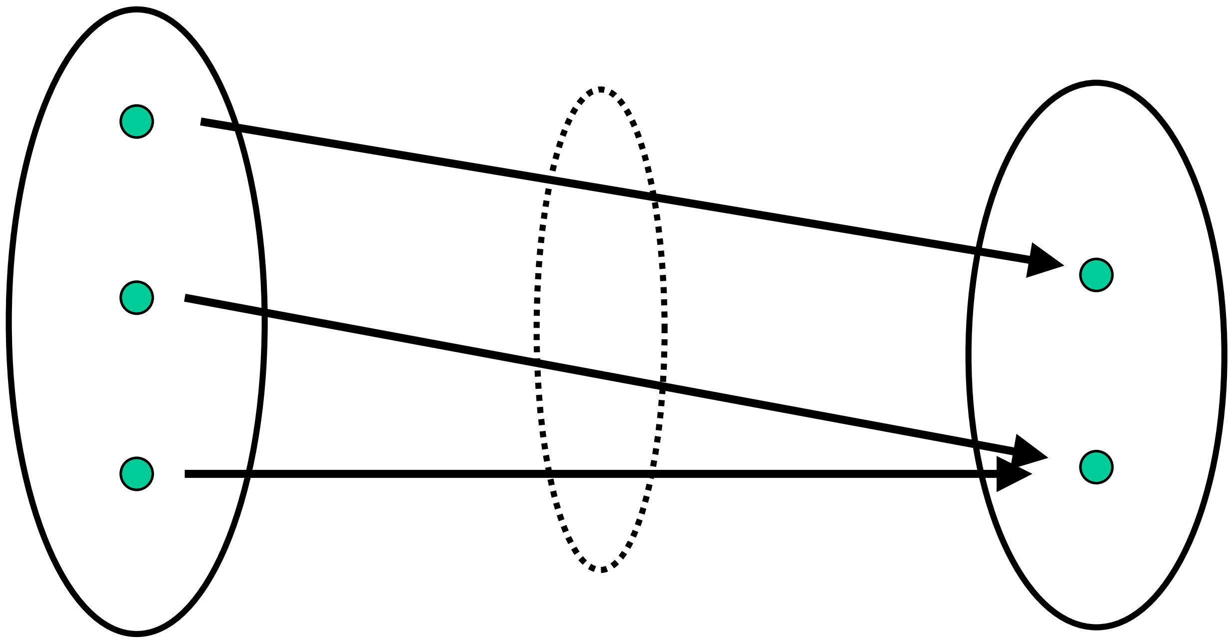
It's a matter of

- beginning and
- simplification

# 3 dimensions of simplification

- Highest priorities are independent of others.
  - do interrupt domain first. Reapply highest priority simplification in case it’s still difficult.
- Select critical scenario’s
  - for a TV: 1) play, 2) zap.
- Simplify by taking worst-case estimates. When it analyses to ‘trouble’, either you can relax in a more precise model, or you <u>are</u> in trouble.

# Step 2: Action to Task mapping



Action set =

Function set

Exec.
Params P

Exec.
Units U

# Action to Task Mapping

- 1: Task Structuring: Identify potential active functions / modules.
- 2: Task Cohesion: Some may share a task.
- Criteria: see next sheet.

- Example:
  - 1) SettopBox: 80 -> 20
  - 2) TV: 150 -> 6

# TM: Structuring criteria: active

- GOMAA - CODARTS structuring criteria:
  - asynchronous device I/O
  - resource monitors
  - periodic functions
  - control (object following a state-transition diagram)
  - user role (“sequential application”)

# TM: Cohesion step

- Characteristics:
  - also known as ‘task-merging’
  - global scope (architect)
  - consider mapping of active objects on the same execution unit (task)
  - aim: reduce task-switching overhead and memory requirements by reducing the number of execution units

# TM: Cohesion criteria

- GOMAA - CODARTS cohesion criteria:
  - temporal cohesion (= same priority)
    - different actions from the same event
    - actions with similar periods (when independent)
  - functional sequential cohesion (= no interference)
  - control cohesion (= no interference, exclusive calls)
  - Assign priorities according to deadlines.

# Step 3. Task prioritisation

- Rate-monotonic =
  shorter deadline <=> higher priority

# Step 4: Analysis

| *Specification* | | | *Design & Test* |
|---|---|---|---|
| System event | Period | Dead-line | |
| E1 | 20 | 5 | |
| E2 | 15 | 10 | |

- Situation table
- Measure processing times, and do RMA

# Step 4: RMA

## Situation table

| Requirements | Design and Test |
|---|---|
| • sys events<br>• period<br>• deadline | • action flow<br>• execution unit<br>• priority<br>• (shared resource)<br>• process time |

Calculated (< 70%, or more sophisticated)

• response time

compared

# Step 5: Tuning step

- Only when a deadline is **not** met:
  - either the processor is idle now and then, and you could benefit more from concurrency:
    - redo from cohesion onwards
  - or some bursts of context-switches appear
    - use more cohesion here, or priority-setting should be changed
  - otherwize: speed-up critical processing part ***(only now)***

# Exercise!

# Issues resulting from concurrency

***Issues***

- Reentrancy
- Synchronisation
- Shared resources
  - Large blocking time
  - Deadlocks
  - Starvation

***Means***

Among others

- semaphores
- separate execution unit (queue + task)

# Concurrency issue: Semaphores

- Semaphore: OS primitive for controlling access.
- Protocol:
  - Get access with P(s).
  - Perform critical region operations.
  - Release access with V(s).
- In general, initial value of *n* supports access to a resource of *n* items.

Choice of size is crucial !!

# Concurrency issue: Reentrancy

- Ability of a program or function to execute multiple times concurrently.
- This requires separate data  per call.
  - *Either use local data (I.e., no global data) or protect global data as being a shared resource.*

# Concurrency issue: Synchronisation

- Use semaphores, with initial value 0.
  - P(): probeer
  - V(): verhoog
- *When P(s) is called, it waits until a V(s) has happened.*

# Concurrency issue: Shared resources

- Example: shared date in memory, devices
- How to implement mutual exclusion:
  - disable interrupts (better: partly) or
  - disable task switching (even better: partly)
  - but what about real-time deadlines?
  - even better ...

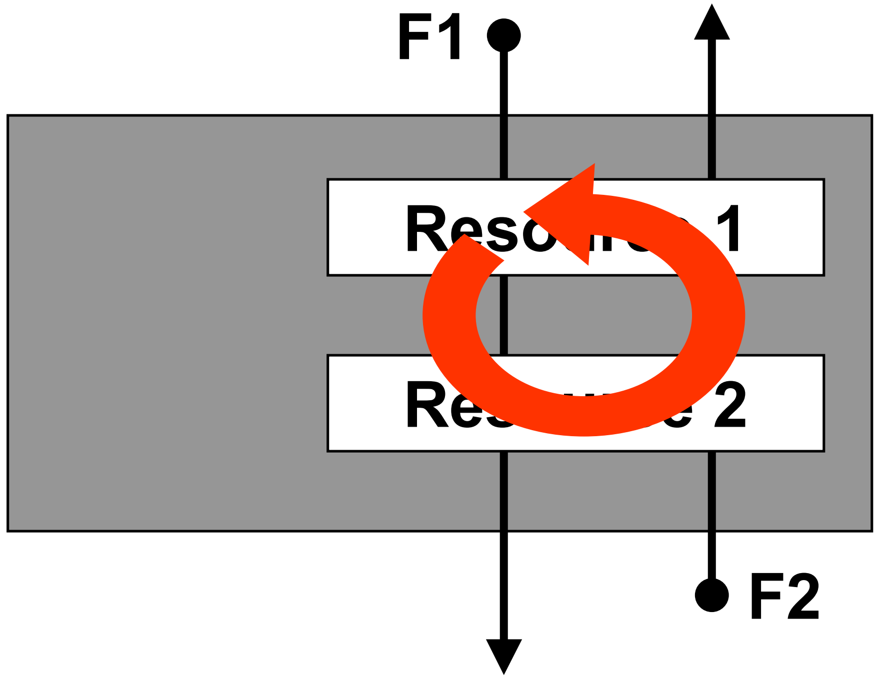
Concurrency issue:

# Shared resources (2)

- How to implement mutual exclusion (2)
  - semaphores
    - risk of priority inversion
      - ex: small kitchen, bad temper, dishwashing, a fridge
      - solution: priority inheritance / priority ceiling protocol
    - use extra "blocking time" in addition to processing time for the relevant events
    - Risk of deadlocks
  - thread decoupling: with "job queue" (e.g., I/O )

# Concurrency issue: Shared resources (3) deadlocks

- Result of mutual exclusion that contain each other. Mutex calls form a cyclic graph.
- Example:



# Concurrency issue: Shared resources (4) deadlocks prevention

- Exclude a cyclic order:
  - Order all modules based on their position in the entire system based on usage structure.
- Module of order N is only allowed to synchro-nously call methods from modules of order <N
- Example:
  - ‘down’ calls may be synchronous, but ‘up’ calls must be asynchronous (decoupled)
  - ‘down-stream calls’ are synchronous, up-stream decoupled.

# Concurrency issue: Shared resources (5) deadlocks prevention

- Absence of deadlocks is guaranteed because semaphores are always passed (locked, ‘P’) in the same order, i.e., the order given by the module ordering
- Now modules can implement their own (local) protection schemes while guaranteeing global absence of deadlocks.
- Yes, a specialized task (thread decoupling) works as well!
- Critical sections must be kept short.

# Concurrency issue: Priorities: starvation

- Actually this is impossible when applying RMA with hard deadlines.
- However, an example:
  - a monkey sitting on a keyboard

# Conclusion

- Design of execution architecture, by using concurrency is a crucial, non-trivial part of an architecture.
  - Requirements, function to taskmapping, analysis.
  - shared resources / synchronisation
- Upper part of the whole dynamic issue of a system ...

# Model: Levels of execution