Part 6: Real-Time OS & Virtualization

- **What is a Real-Time OS (RTOS)?**
- Real-Time Process Specification
- Real-Time CPU Scheduling
- Virtualization

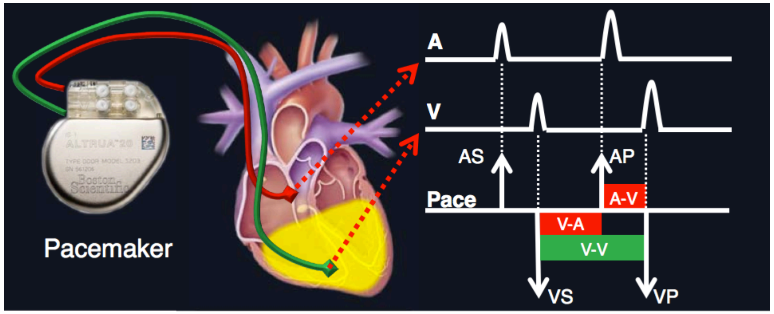
Cyber-Physical Systems

- Physical/Engineered systems whose operations are monitored, coordinated and controlled by a reliable computing and communication core
  - Automotive Systems (Autonomous driving, Parking assist, Airbag controls)
  - Avionics (Flight navigation & control)
  - Manufacturing Systems (Robotics, Process controls)
  - Medical Systems (Robotic surgery, devices)
  - …

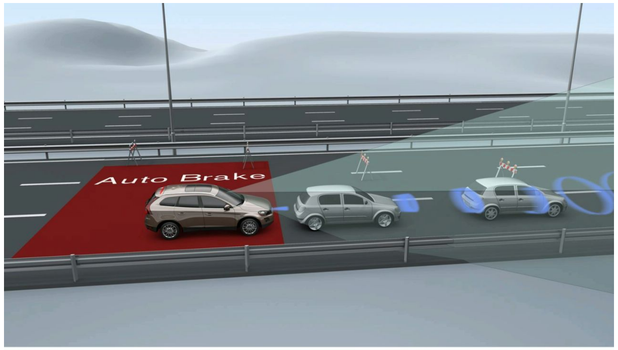
Relevance of Real-Time

- Common to many application examples we saw in the previous slide:
  - Collect data from various sensing devices
  - Execute control law(s) to determine response
  - Send actuator commands in a **reasonable amount of time**

Pacemaker timing diagram



Collision avoidance and braking



Collision Warning with Auto Brake

What is a Reasonable Time?

- What is the functionality?
  - Collision avoidance in automotive (milliseconds)
  - Pacemaker (up to a second)
  - Robotic surgery (varies greatly depending on the target)
- What are the environment constraints?
  - Available computing and communication resources
  - Timing characteristics of sensors/actuators/operations
- Failure-mitigation strategies?
  - Time to detect and recover from failures
  - Example: execution replication for redundancy

Common Misconception

- Real-Time ≠ Fast
- Real-Time = Predictable even in the worst-case

"Man drowned in a river with average depth 20 cms"

Real-Time CPS / Real-Time OS

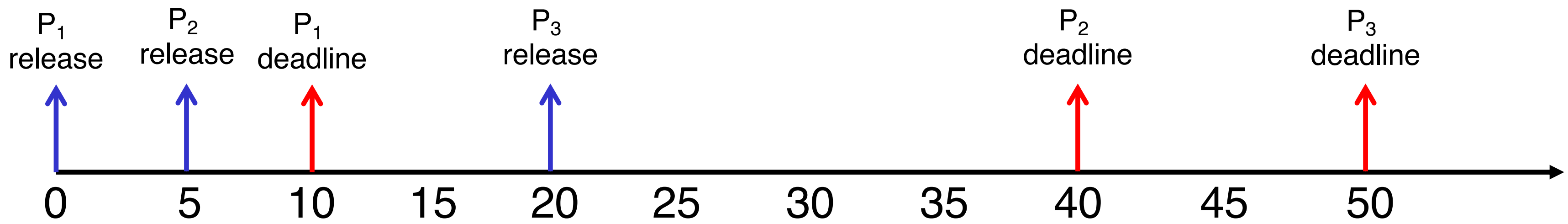
- Definition: System whose correctness depends not only on the logical/functional aspects, but also on the temporal aspects
  - Application has deadlines that must be met
  - **A real-time OS (RTOS) provides OS services to such systems (e.g., FreeRTOS, MicriumOS, …)**
- Key performance measure for RTOS
  - Timeliness/Predictability on timing constraints (deadlines)
  - Significance of worst-case over average-case
  - Deadlines are a function of application requirements

Part 5: Real-Time OS & Virtualization

- What is a Real-Time OS (RTOS)?
- **Real-Time Process Specification**
- Real-Time CPU Scheduling
- Virtualization

RTOS (Real-Time) Process

- Definition: A real-time process is specified as <R,C,D>, where R is process release time, C is execution requirement and D is relative deadline
  - Requires C time units of CPU in the interval [R, R+D)
  - **How does one determine these parameters?**
- Example: P_1<0,5,10>, P_2<5,10,35>, P_3<20,10,30>



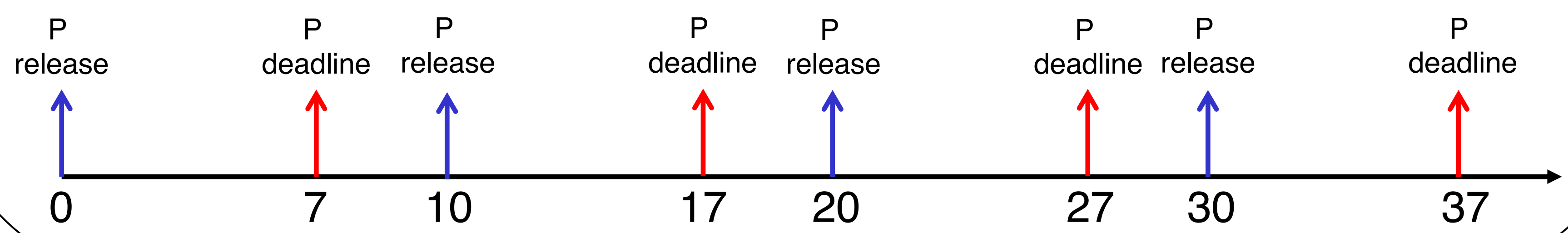
In this lecture, we assume processes only have a single CPU burst; C is the duration of this burst

Recurrent Real-Time Process

- Nature of real-time processes
  - Collect data from sensing devices, execute control laws to determine responses, and send actuator commands in reasonable time
  - **Repeat the above steps regularly**
    - ✳ Examples: airbag control, flight control, collision avoidance, pacemaker, etc.
- A recurrent real-time process
  - **Executes some function repeatedly over time**
  - Each instance of execution is a real-time process <R,C,D>

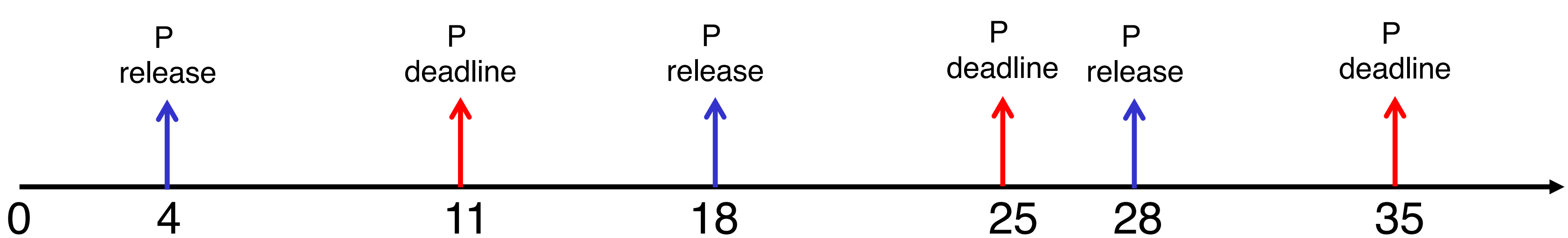
Periodic Real-Time Process

- Definition: A process that **repeats periodically**
  - Processes generated by a time-triggered phenomena (sensor sending data periodically)
  - Example: Perception function for collision detection
- A periodic process is specified as <T,C,D>, where T is process period, C & D are as defined earlier
  - Real-time processes are released at R=0, T, 2T, …
  - Example: Periodic process P<10, 5, 7>



Sporadic Real-Time Process

- Definition: A process that **repeats sporadically with a minimum gap between releases**
  - Processes generated by an event-triggered phenomena
  - Example: Anti-lock braking function in automotive
- A sporadic process is specified as <T,C,D>, where T is minimum release-separation time
  - Real-time processes are released with a min. gap of T
  - Example: Sporadic process P<10, 5, 7>

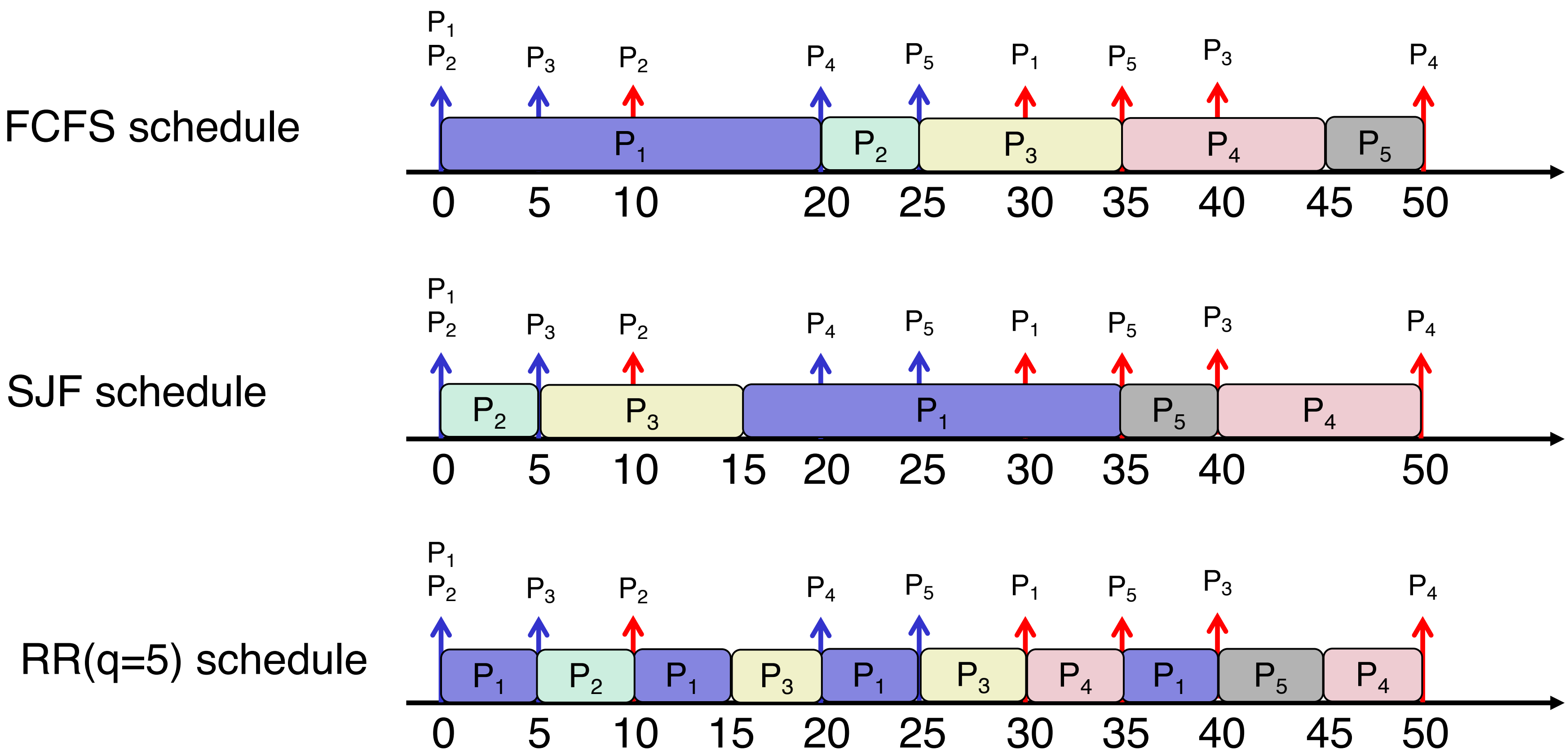


Part 5: Real-Time OS & Virtualization

- What is a Real-Time OS (RTOS)?
- Real-Time Process Specification
- **Real-Time CPU Scheduling (short-term scheduler)**
  - **Fixed-priority scheduling**
  - **Dynamic-priority scheduling**
- Virtualization

Why Classic Algorithms Fail?

- Consider real-time processes (non-recurring): P_1<0,20,30>, P_2<0,5,10>, P_3<5,10,35>, P_4<20,10,30>, P_5<25,5,10>

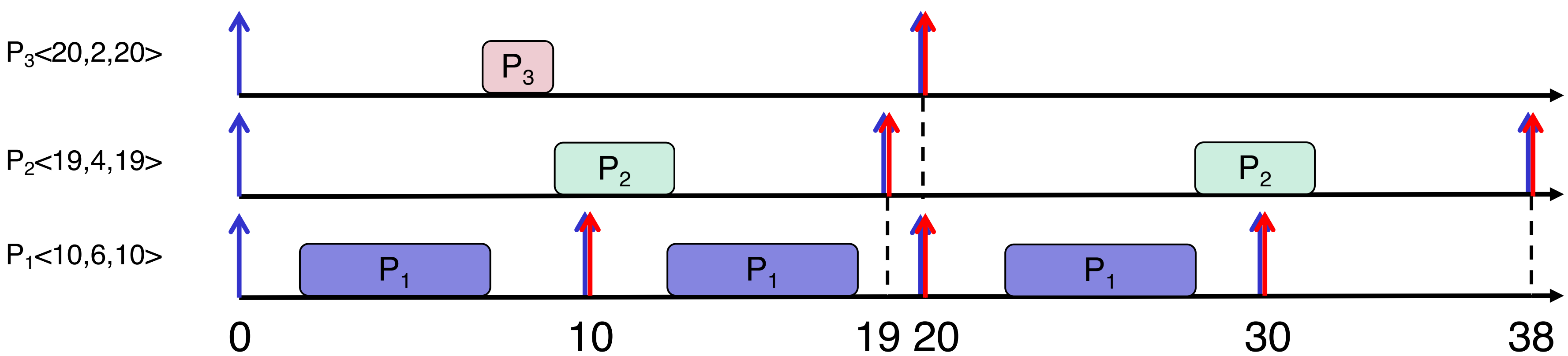


They don't prioritize deadlines and hence perform poorly

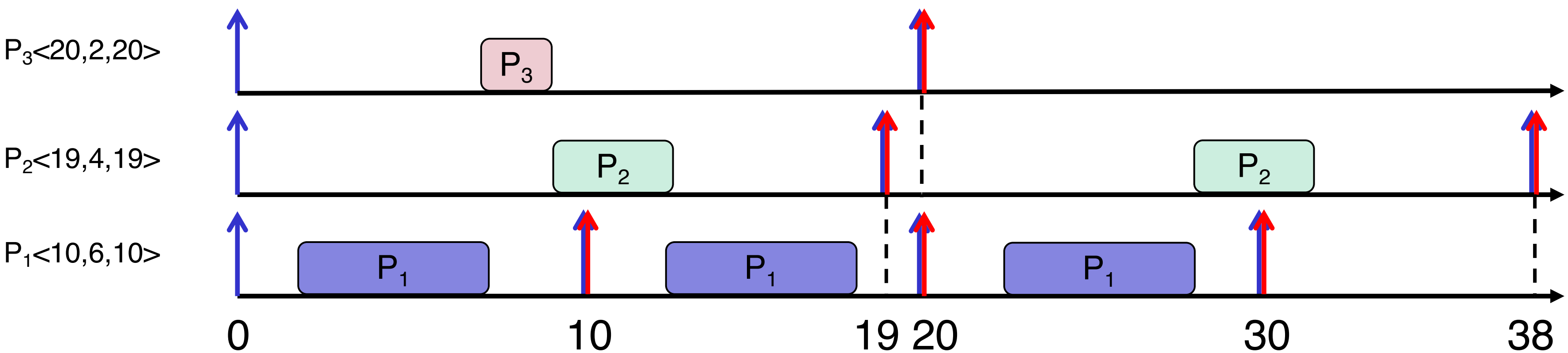
Real-Time CPU Scheduling Problem

Given a set of periodic/sporadic real-time processes, find a uni-processor CPU scheduling algorithm that can meet process deadlines

- We will use a running example (periodic real-time process set): P_1<10,6,10>, P_2<19,4,19>, P_3<20,2,20>



Fixed-Priority CPU Scheduling

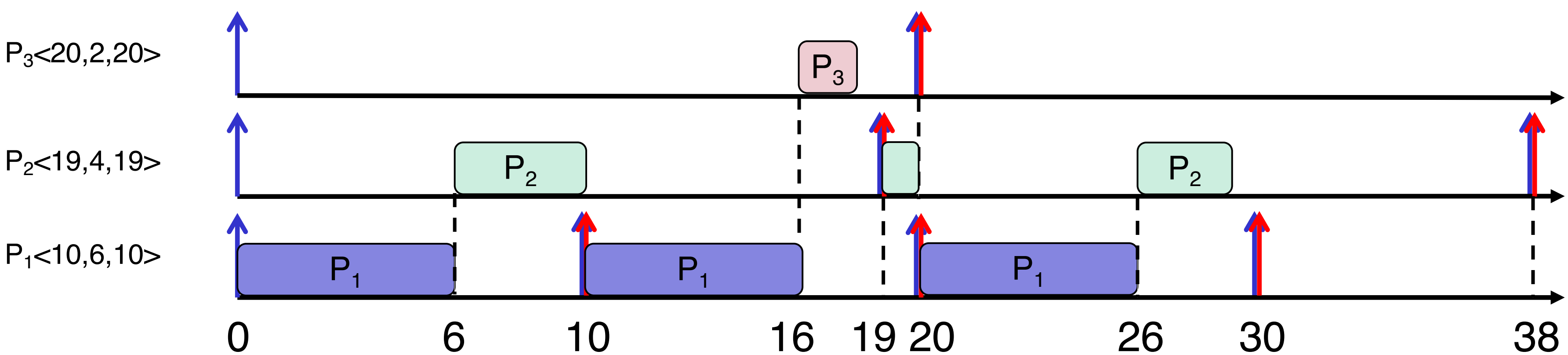


Priorities are fixed for each recurrent process

- **Priorities are fixed across instances of recurrent processes**
- Suppose instance of $P_1(R=0)$ has higher priority than instance of $P_2(R=0)$. Then,
  - $P_1(R=10)$ has higher priority than $P_2(R=0)$
  - $P_1(R=10)$ has higher priority than $P_2(R=19)$
  - $P_1(R=20)$ has higher priority than $P_2(R=19)$ …

Rate Monotonic (RM) Scheduler

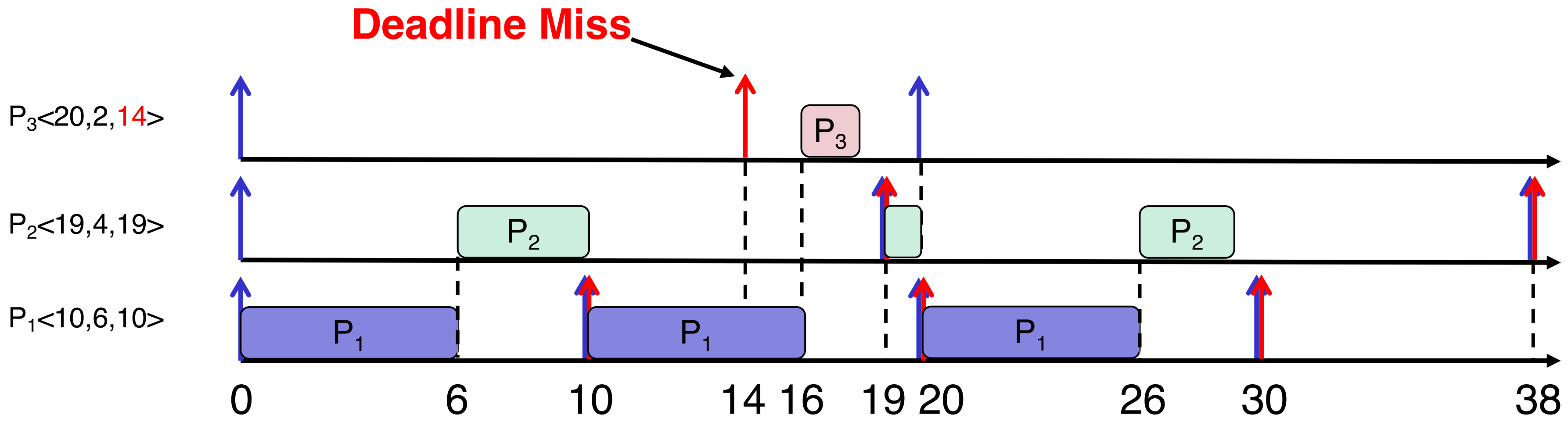
- Assign priorities based on process periods / minimum release-separation time (T)
  - Shorter T implies higher priority
  - Ties are broken arbitrarily



RM is a very popular short-term CPU scheduler in the real-time CPS industry. Why?

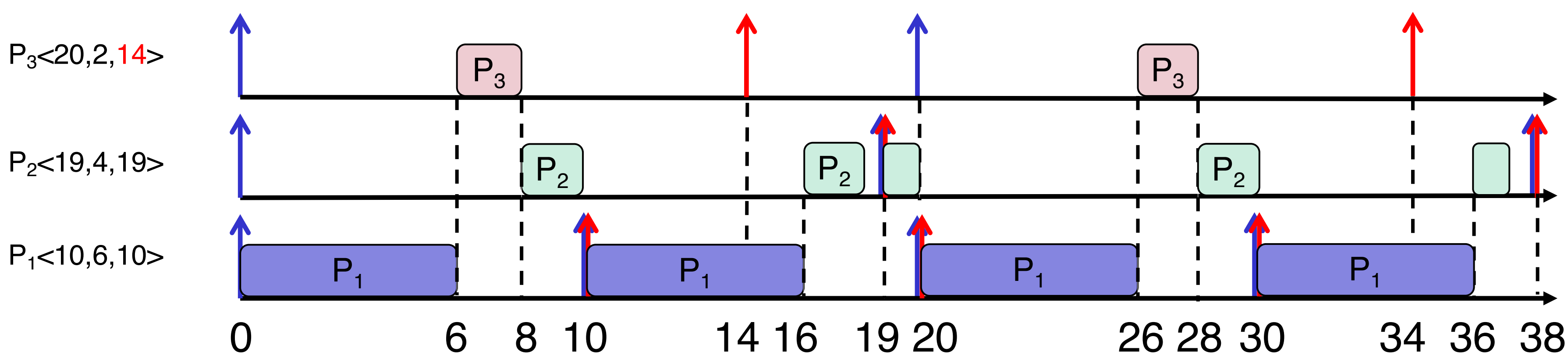
RM and Process Deadlines

- RM is good, but still does not always prioritize urgent processes
  - Suppose we modify the process set as follows: P_1<10,6,10>, P_2<19,4,19>, P_3<20,2,14>



Deadline Monotonic (DM) Scheduler

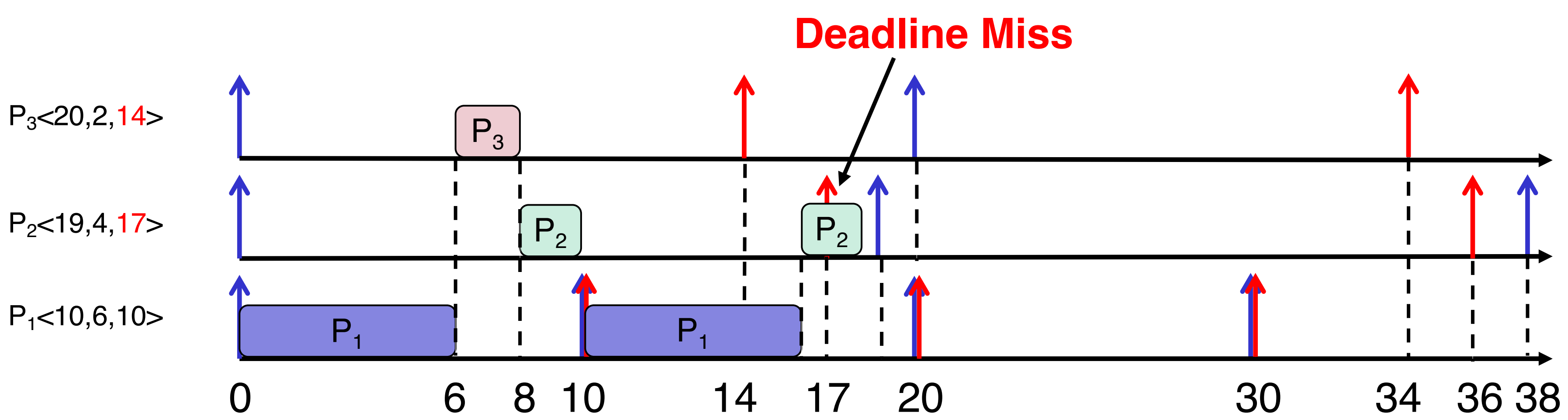
- Assign priorities based on process **deadlines (D)**
  - Shorter **D** implies higher priority
  - Ties are broken arbitrarily



Both RM and DM are fixed-priority schedulers

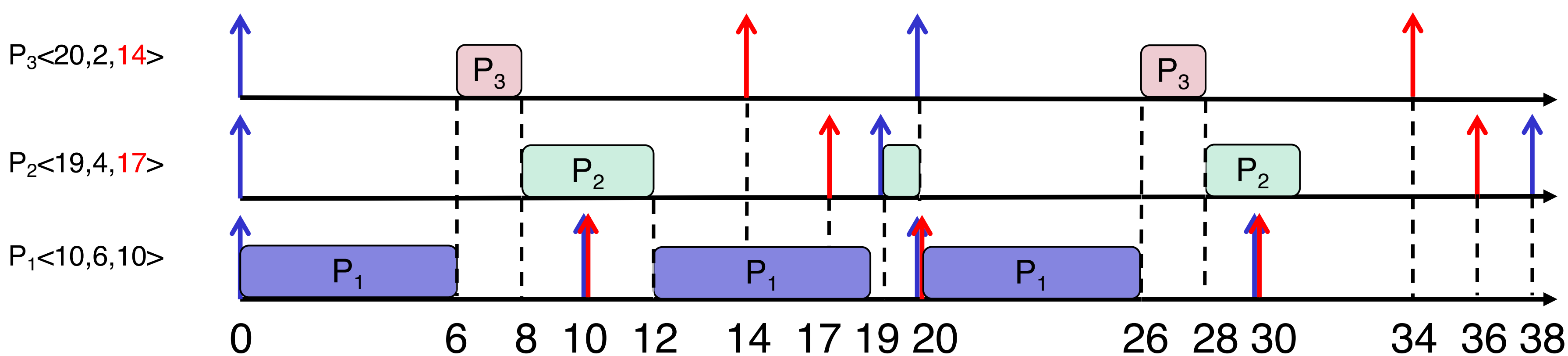
DM and Process Deadlines

- DM is better than RM, but it cannot change priorities across process instances
  - Suppose we further modify the process set as follows: P_1<10,6,10>, P_2<19,4,17>, P_3<20,2,14>



Earliest Deadline First (EDF) Scheduler

- Dynamic-priority scheduler that assigns priorities based on process **instance deadlines**
  - Instances with shorter deadline are given higher priority
    - ✳ **NOT the same as parameter D**
  - Ties are broken arbitrarily



EDF is a dynamic-priority scheduler, hence more powerful than RM and DM

RM/DM versus EDF

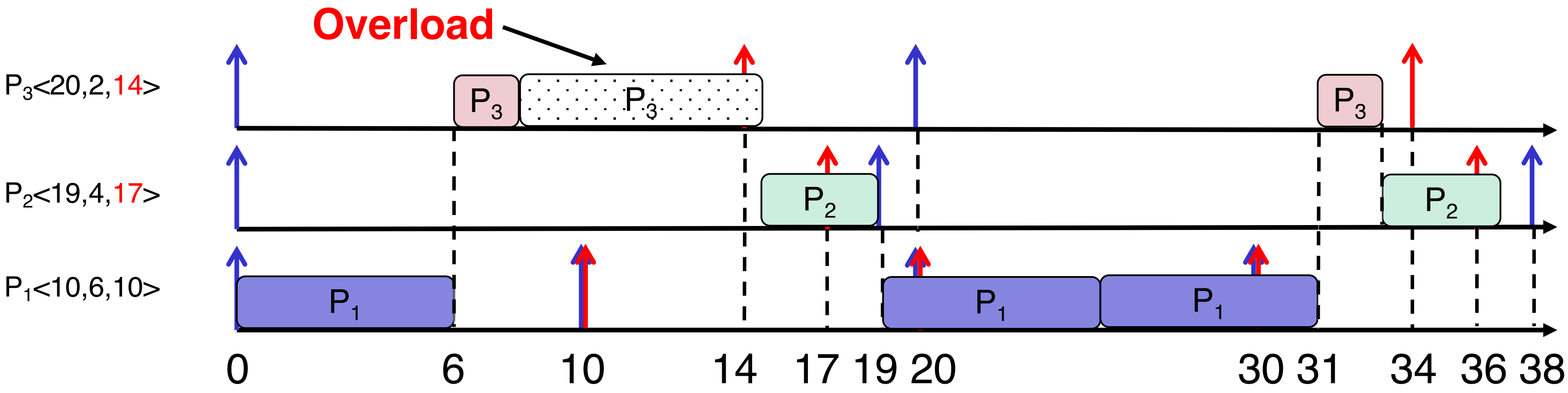
RM/DM

- Simpler implementation
  (separate queue for each recurrent process)
- Predictability for high priority processes, even under overload
  (next slide)

EDF

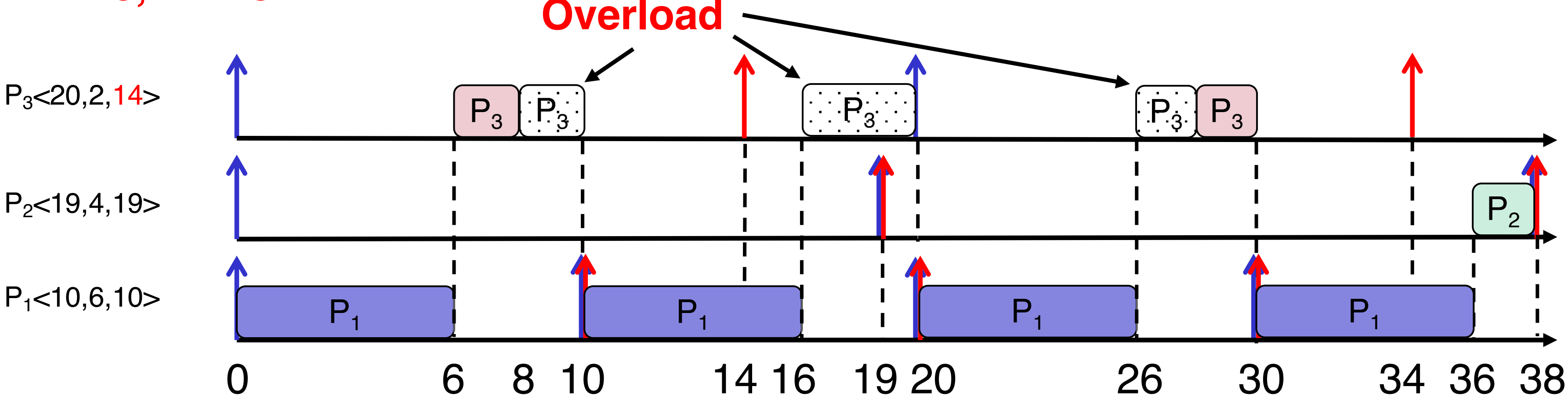
- Harder implementation
  (online sorting of queue based on instance deadlines)
- Misbehaviour during overload
  (next slide)

DM versus EDF during Overload



EDF Schedule

Deadline Misses
EDF=5, DM=3



DM Schedule

Part 5: Real-Time OS & Virtualization

- What is a Real-Time OS (RTOS)?
- Real-Time Process Specification
- Real-Time CPU Scheduling
- **Virtualization**

What is Virtualization?

- Definition: It is a technique that uses software, called Hypervisor (virtual machine manager or VMM), to create abstraction of hardware
  - Hardware is divided into multiple virtual computers, called Virtual Machines (VMs)
  - Each VM runs its own OS, called Guest OS, and behaves like an independent computer
    - Application processes can run on the guest OS as if it is an independent computer
  - Each VM is using only a portion of the actual hardware

Is a general OS also using virtualization?

Functions of a Hypervisor

- Creation and management of VMs
  - Allocating hardware resources for VMs
  - Executing instructions on the hardware on behalf of VMs (VMs may be using different guest OSes)
- Communication between VMs
  - Mechanisms for VMs hosted on the same hardware to be able to communicate securely with each other
- VM Migrations
  - Migrating VMs from one hypervisor/hardware to another, almost instantaneously (at runtime)
  - Gives a lot of flexibility and portability

Why do we need Virtualization?

- Allows for more efficient utilization of hardware
  - Cost-effective hardware deployment & sharing
  - Low latency and agile execution-environment deployments (VM creation and flexibility)
  - Failure mitigation (VM independence and migrations)
- Key technology that is driving cloud computing
  - Cloud providers can dynamically and cost-effectively scale hardware allocations based on user requirements
  - Enables the concept of platform as a service – rent hardware & services as and when needed

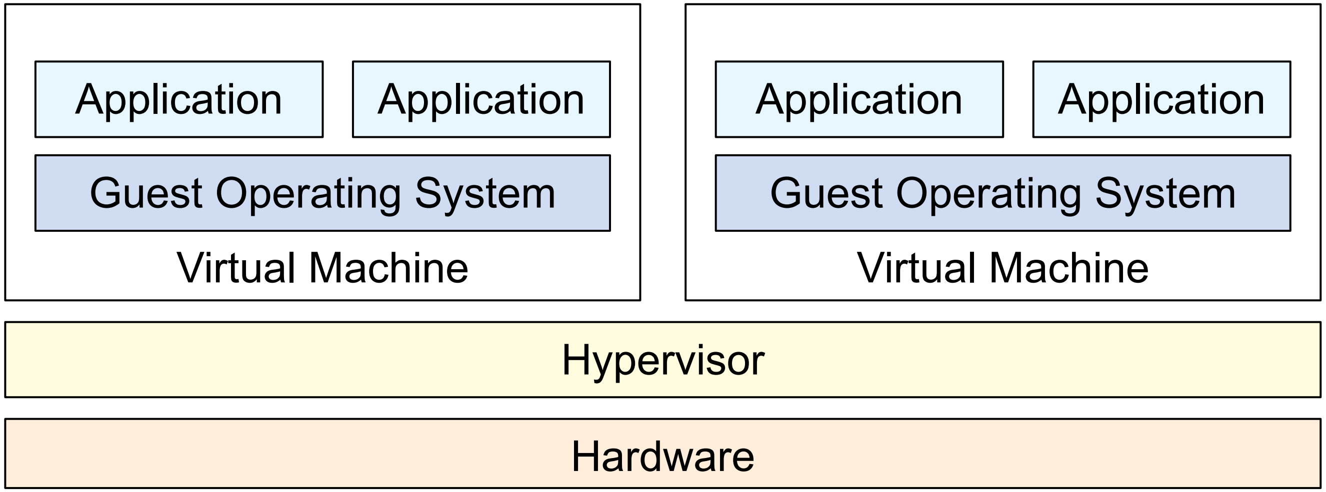
Virtualization Challenges

- Requires management layer: Hypervisor
  - Hypervisor is usually two orders of magnitude smaller than general purpose OS
  - Requires more disk space and RAM
  - Must ensure that instructions can be executed on H/W
- Real-Time CPS require different solutions than server virtualization
  - Real-time (worst-case timing predictability)
  - Minimal memory footprint & minimal overhead (highly resource constrained)

Type-1 Virtualization

Hypervisor interacts directly with hardware

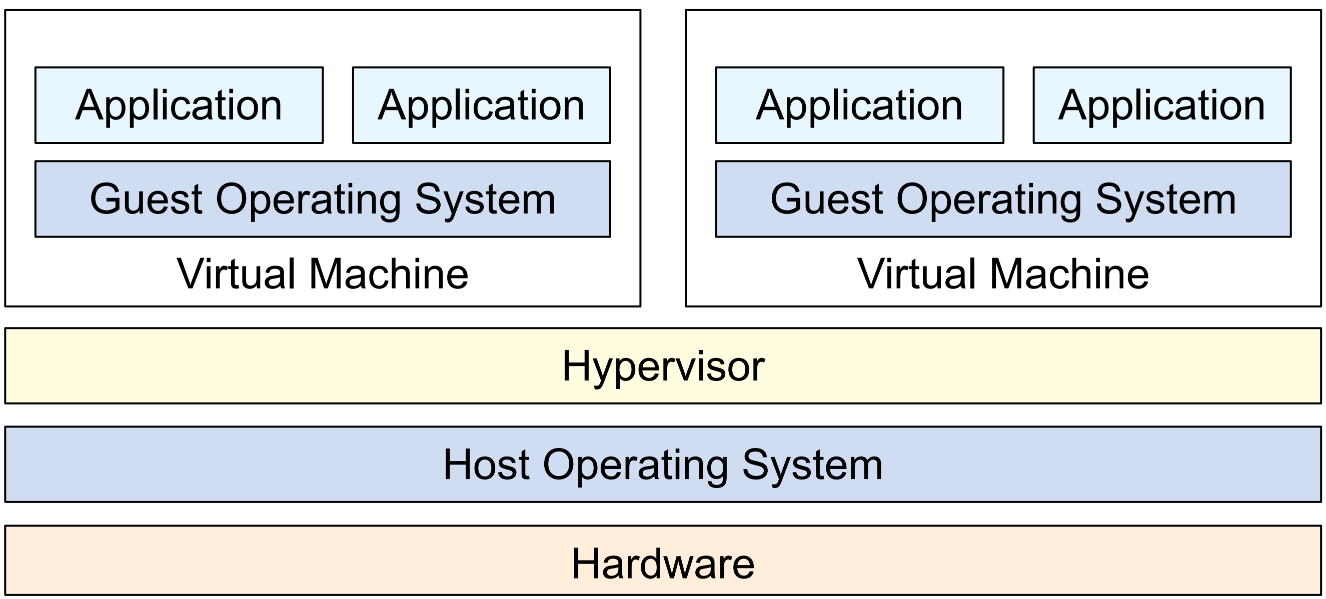
- Also called bare-metal hypervisor
- Highly secure and has low latency
- Popular in industry (KVM, Microsoft hyper-v, VMware esxi, Xen)



Type-2 Virtualization

Hypervisor interacts with a host OS, which in turn interacts with hardware

- Also called hosted hypervisor
- Higher latency, less popular, mostly for end-user virtualization (Oracle virtualbox, VMWare workstation)



Virtualization Levels

1. Full virtualization
   – Complete abstraction of the actual hardware
   – Guest OS runs unmodified on the hypervisor
     * It is unaware of hypervisor's existence
   – Examples: VMware esxi, Microsoft virtual server
2. Para-virtualization
   – Unique software interface (API) between guest OS - VM
   – Guest OS needs to be modified to adapt to the new API
   – **Advantage:** VM does not virtualize hard-to-implement parts of the H/W instruction set, hence more efficient
   – Examples: Xen, VMware, XtratuM