









# Real Time Systems & Real Time OS Concepts







# Agenda

- **Introduction to Real Time Systems (RTS)**
- **Introduction to Real Time Scheduling**
- **Introduction to Real Time Operating Systems (RTOS)**
- **How they differ: RTOS vs GPOS**
- **RTOS Building Blocks: Tasks, Services**
- **Overview of popular RTOS**

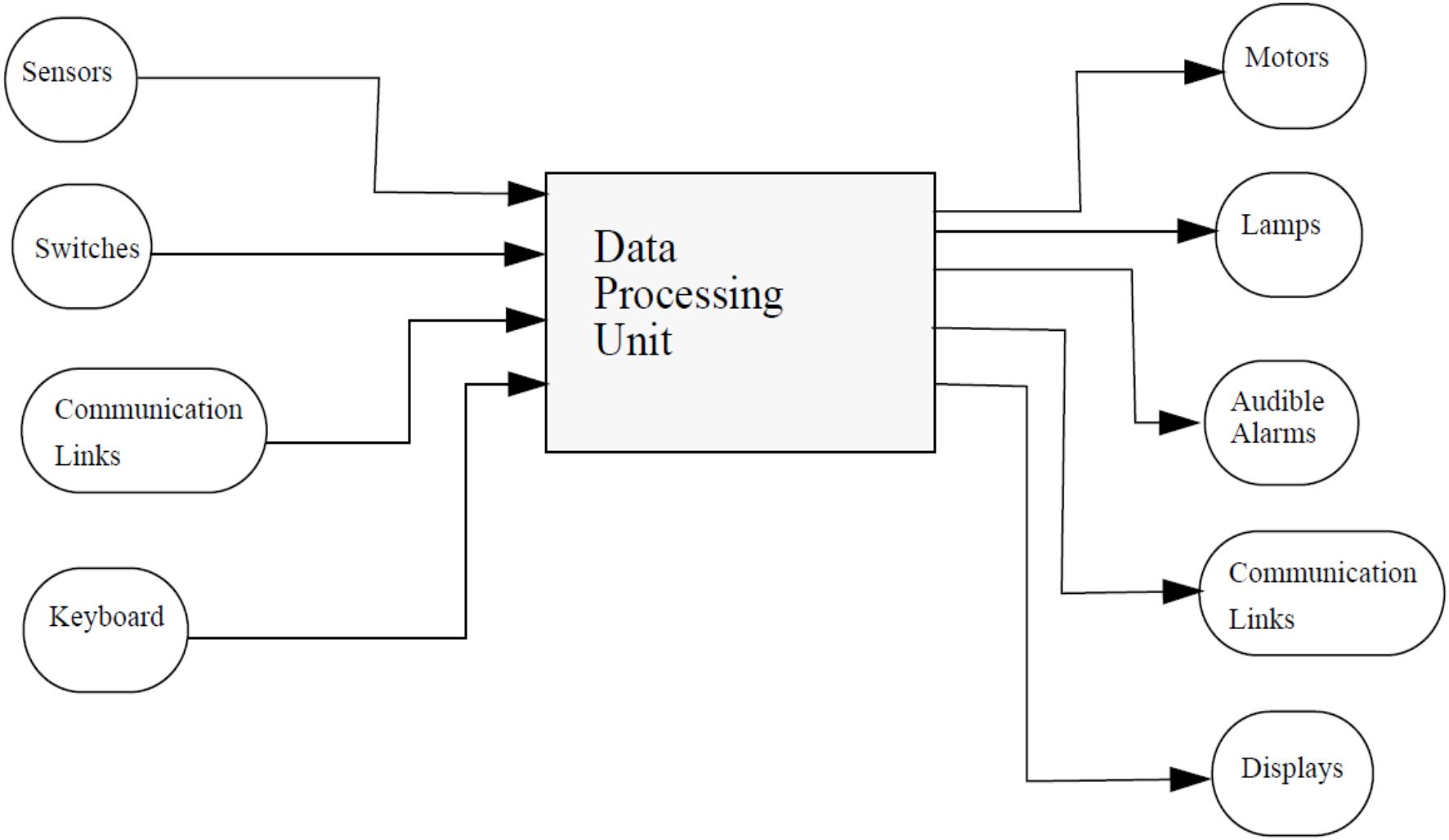
# Real-Time System definition

**Real-time systems have been defined as: "*those systems in which the correctness of the system depends not only on the logical result of the computation, but also on the time at which the results are produced*";**

# Real Time System Characteristics

- **Embedded Computer Systems**
  - Usually built around a micro-controller
  - Reads the input of various sensors, applies various filtering, calibration, and processing algorithms on the input data and produces output data to various actuators
- **Concurrent processing**
  - Involves processing of multiple inputs over the same time interval
  - Task scheduling is important for managing concurrency
  - Priority scheduling in which tasks with more stringent deadlines will be given a higher priority
- **Predictability**
  - Possible to show at “design time” that all the timing constraints of the application will be met. Systems require **determinism** to ensure predictable behavior

# Typical Real-Time System

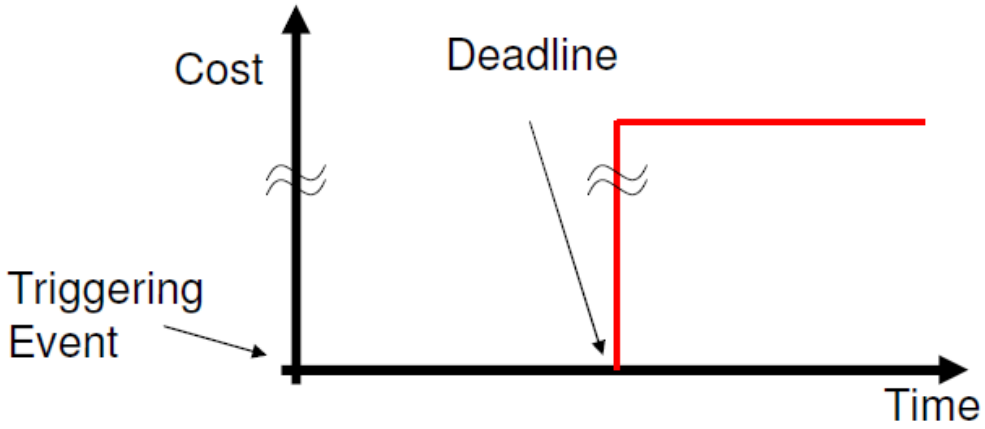


# Real Time Tasks

- **Periodic tasks**
  - Time-driven, characteristics are known a prior (pi, ci)
  - Eg: Task monitoring temperature of a patient in an ICU
- **Aperiodic tasks**
  - Event-driven, characteristics not known a prior (ai, ri, ci, di)
  - Task activated on detecting change in patient's condition
- **Sporadic Tasks**
  - Aperiodic tasks with known minimum inter-arrival time.
  - pi : task period  ai : arrival time ri : ready time  di : deadline ci : worst case exec time

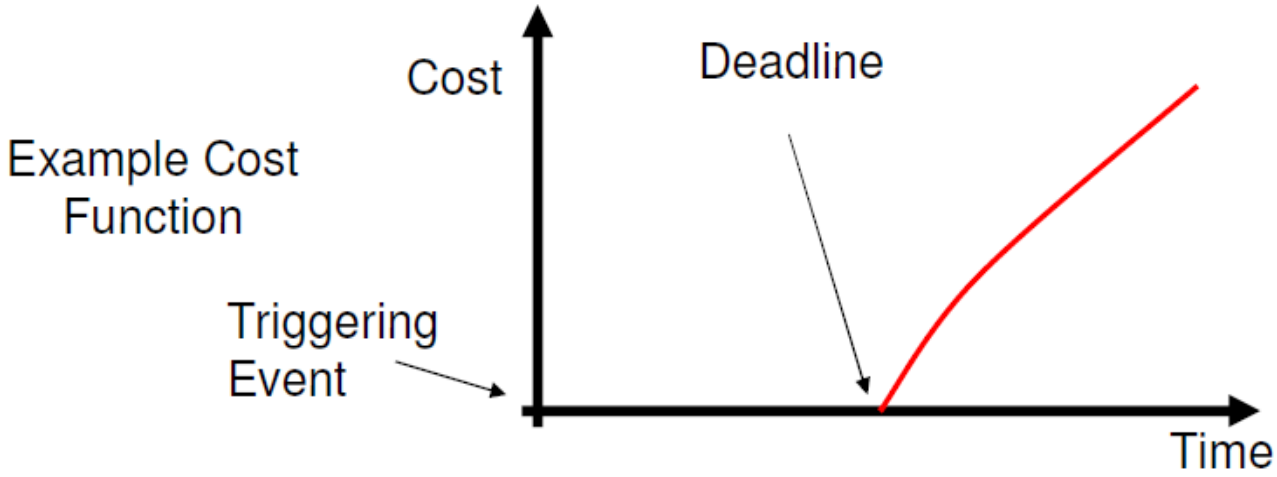
# Hard Real-Time Systems

- An overrun in response time leads to a catastrophe (potential loss of life and/or big financial damage)
- Many of these systems are considered to be safety critical.
- Sometimes they are “only” mission critical, with the mission being very expensive.
- In general there is a cost function associated with the system.
- Eg: Aircraft Control Systems, Nuclear Power Stations, Chemical Plants, Life support systems

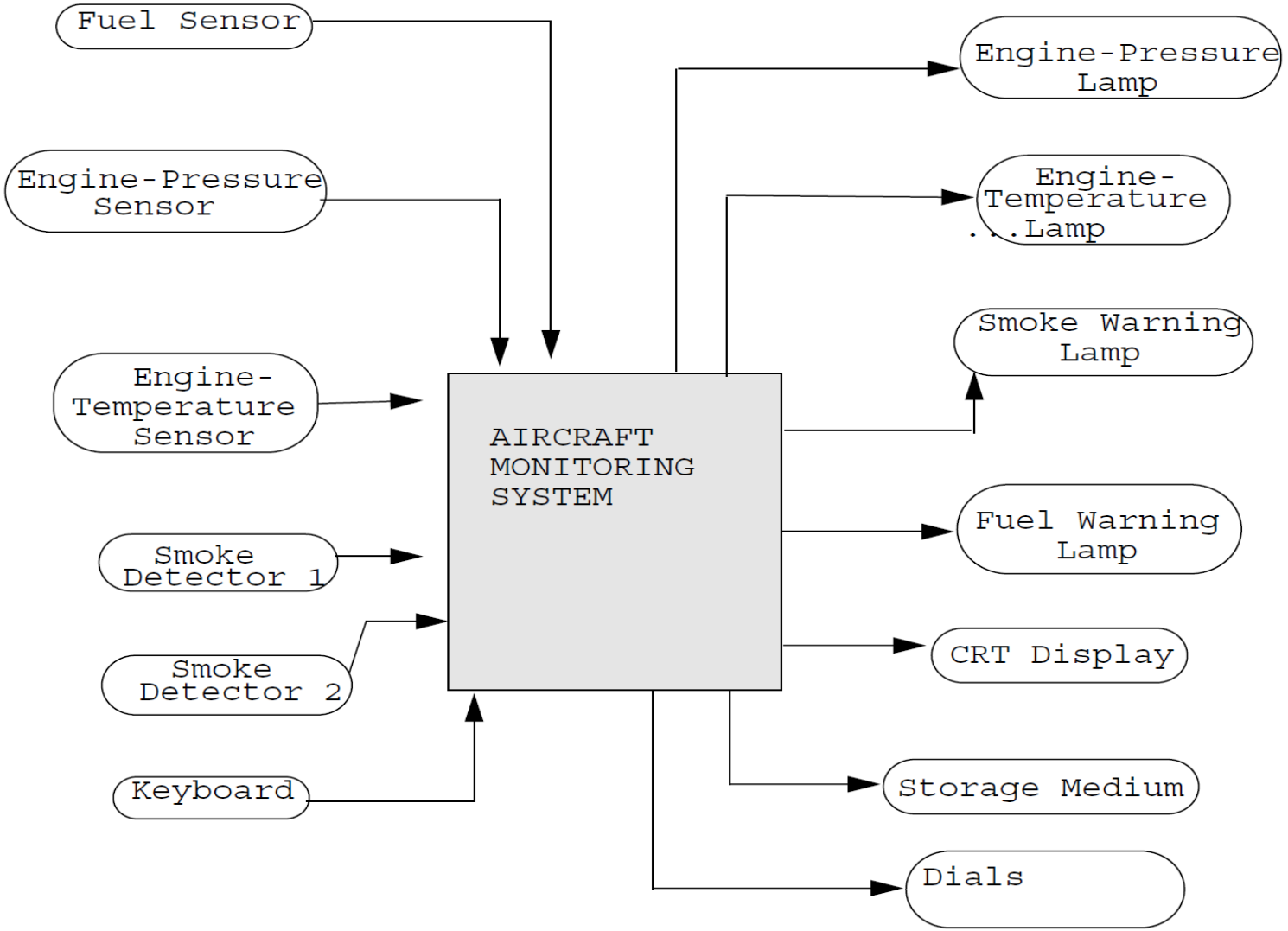


# Soft Real-Time Systems

- An Deadline overruns are tolerable, but not desired.
- There are no catastrophic consequences of missing one or more deadlines.
- There is a cost associated to overrunning, but this cost may be abstract.
- Often connected to Quality-of-Service (QoS)
- Eg: Mutlimedia, Interactive video games



# Aircraft Monitoring System (AMS), a Case Study



# Real Time Scheduling Algorithms

# Real-time System Properties

- Hard/Soft real-time tasks
- Periodic/Aperiodic/Sporadic tasks
- Preemptive/Non-preemptive tasks
- Multiprocessor/Single processor systems
- Fixed/Dynamic priority tasks
- Flexible/Static systems
- Independent/Dependent tasks

# Goals of Real-time Scheduling

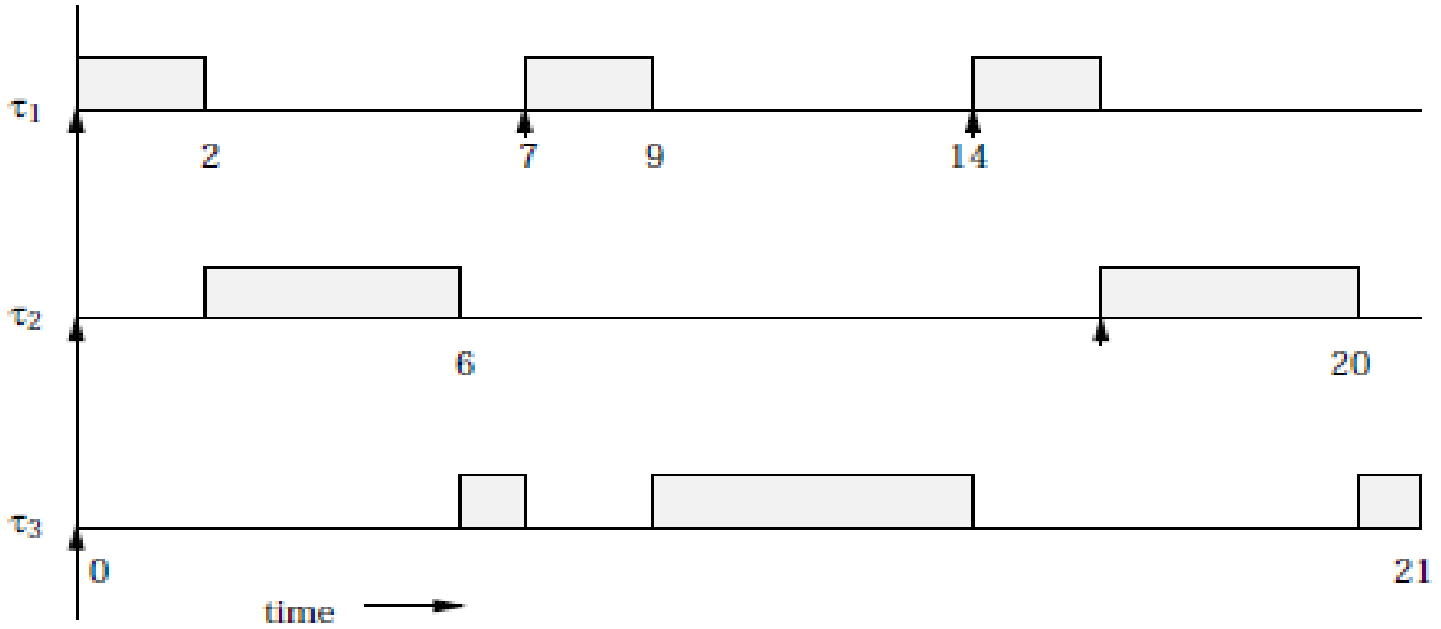
- Meeting the timing constraints of the system
- Preventing simultaneous access to shared resources and devices
- Attaining a high degree of utilization while satisfying the timing constraints of the system
- Reducing the cost of context switches caused by preemption

# Task Timing Properties

- **Each task(Ti) occurring in a real-time system has some timing properties, which should be considered when scheduling tasks.**
  - Release time (or ready time)
  - Deadline(Di)
  - Worst case execution time(Ci)
  - Period(Ti or Pi)

# Sample methods of analysis

- **Timing diagrams provide a good way to visualize and even to calculate the timing properties of simple programs.**



# Sample methods of analysis

- **Better method of analysis is to derive conditions to be satisfied by the timing properties of a program, to meet its deadlines**
- **Necessary Conditions:**
  - Worst cast execution time must be less than period (Ci < Ti)
  - CPU Utilization factor Ui for a periodic task Ti is (Ci/Pi )
  - Overall system utilization (U) = $\sum$ Ui $\leq$ 1

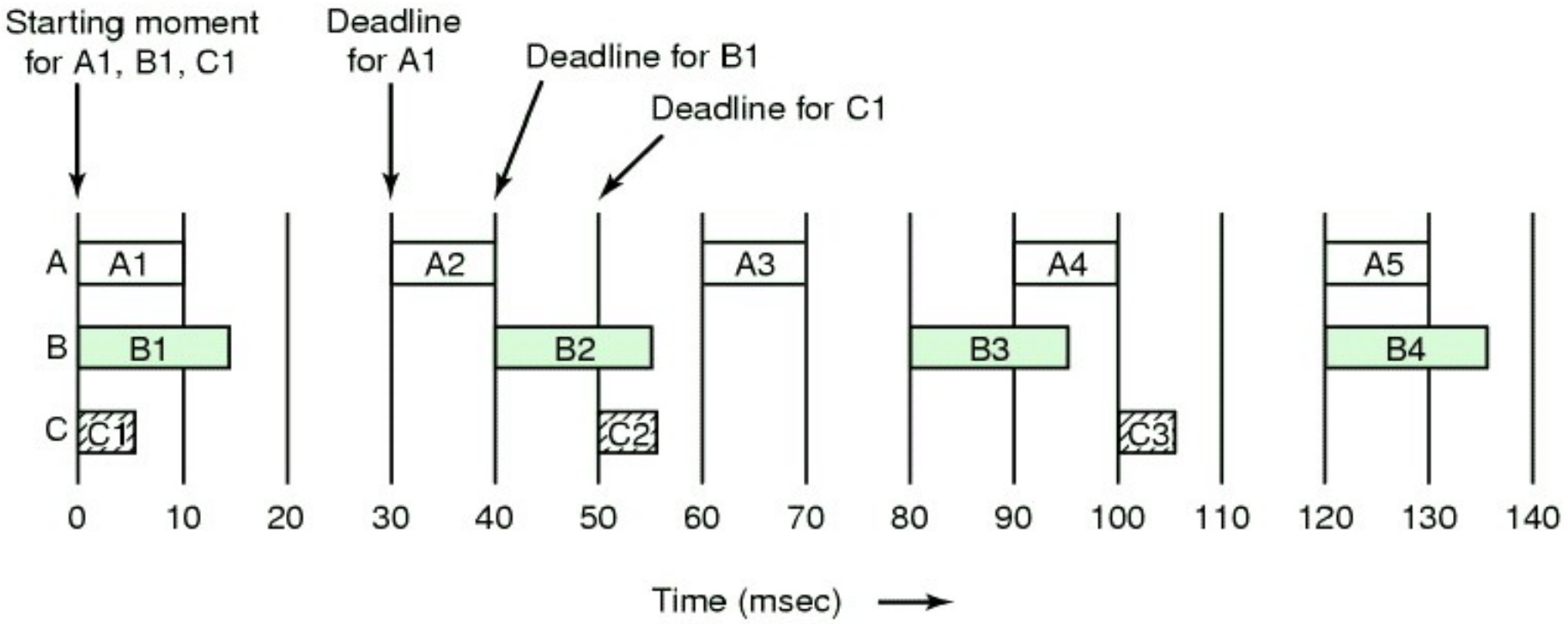
| Utilization (%) | Zone Type | Typical Application |
|---|---|---|
| 0-25 | significant excess processing power – CPU may be more powerful than necessary | various |
| 26-50 | very safe | various |
| 51-68 | safe | various |
| 69 | theoretical limit | embedded systems |
| 70-82 | questionable | embedded systems |
| 83-99 | dangerous | embedded systems |
| 100+ | overload | stressed systems |

# RM, EDF, LLF Scheduling

- **Rate Monotonic**
  - Static-priority preemptive scheme
  - Assumes that all tasks are periodic
  - The priorities are determined only by the period of the task.
- **Earliest Deadline First**
  - Dynamic-priority preemptive scheme
  - Higher priority is assigned to the task that has earlier deadline
  - Also called Deadline-Monotonic Scheduling
- **Least Laxity First**
  - Dynamic priority preemptive scheme
  - The laxity of a process is defined as the deadline minus remaining computation time.
  - Highest priority is given to the active job with the smallest laxity

# Scheduling Example

- **Consider 3 tasks with the following timing properties**



# Scheduling Example

- **Are the tasks schedulable ??**

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

$$\frac{10}{30} + \frac{15}{40} + \frac{5}{50} = 0.808$$

- YES

# Scheduling Example

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$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

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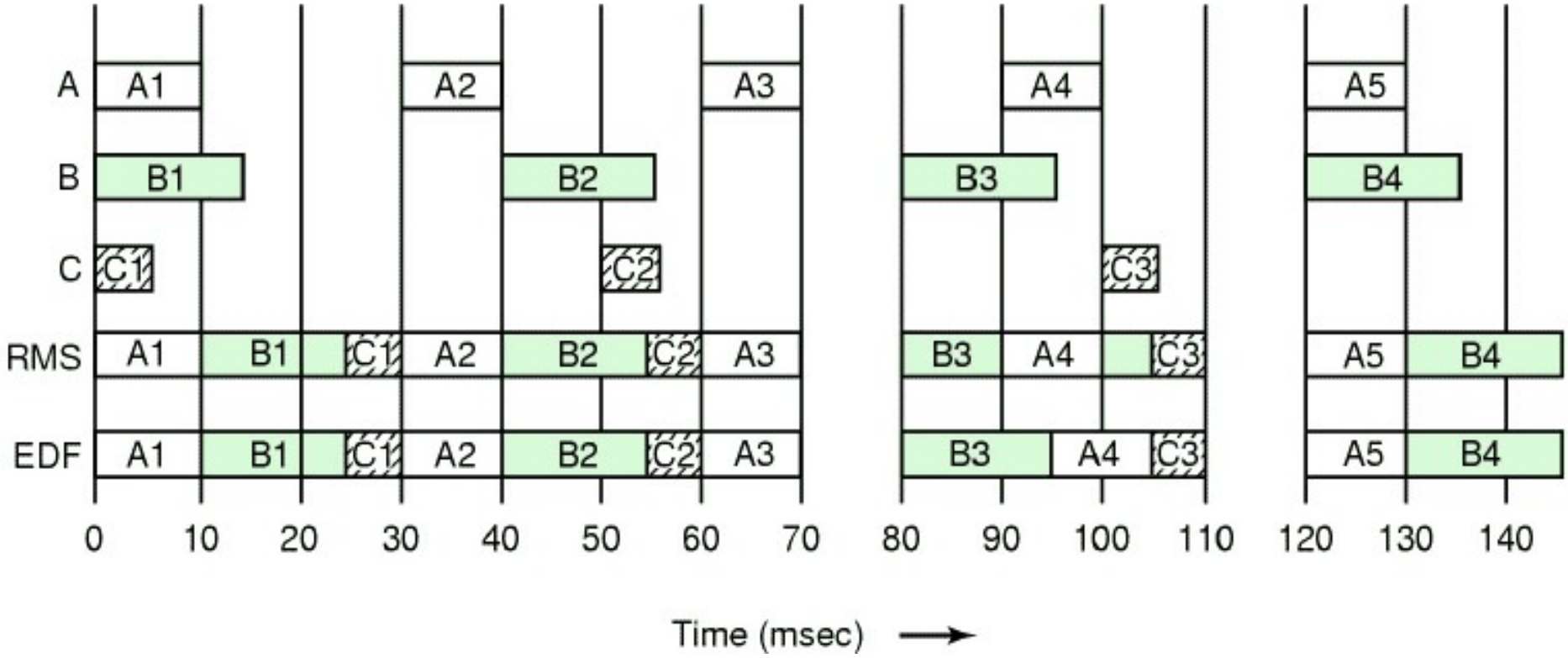
- YES

# Scheduling with RM and EDF

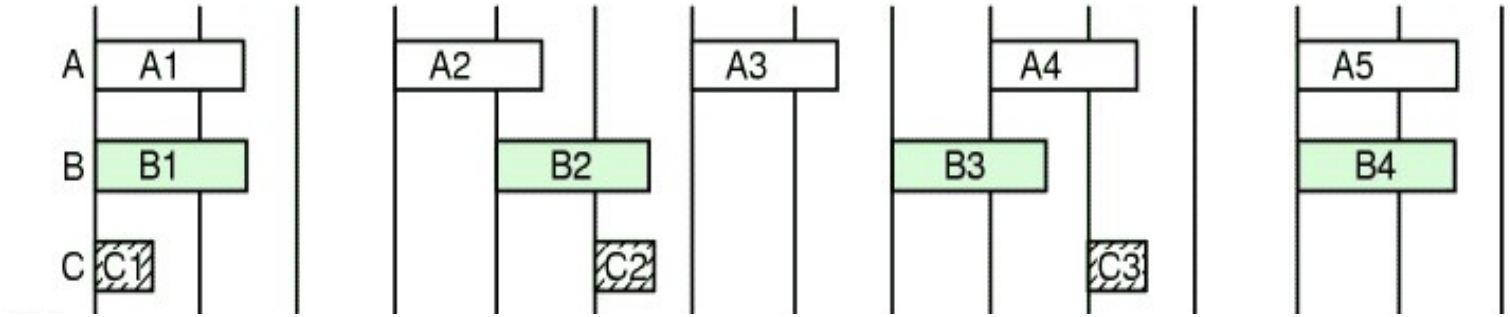
- **Analyze using  timing diagram**



# Modify Example

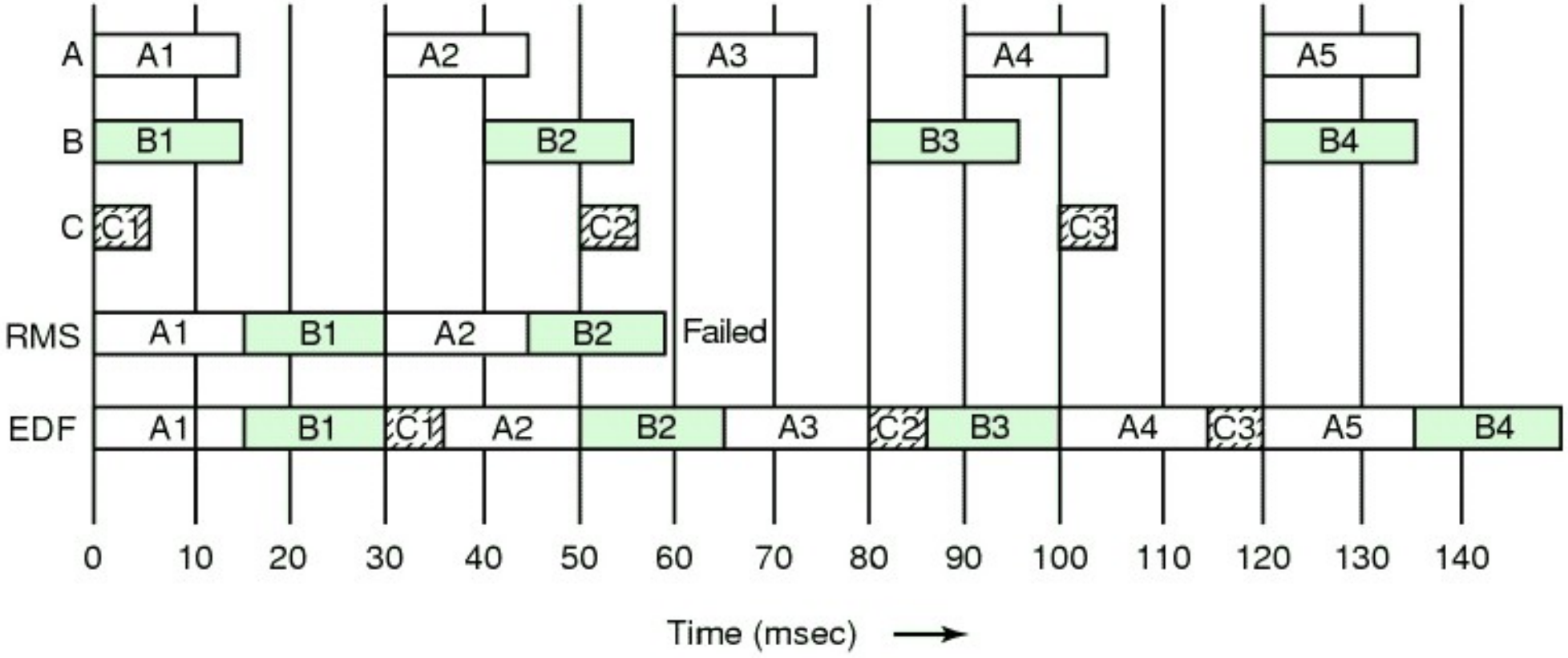
- **Increase A's CPU requirement to 15 milli sec**
- **The system is still schedulable**

$$\frac{15}{30}+\frac{15}{40}+\frac{5}{50}=0.975$$



# Scheduling using RM and EDF

- **Analyze using  timing diagram**



# RM Scheduling Condition

- **RM Scheduling is guaranteed to work if the CPU utilization is not too high**
- **Condition of Schedulability**

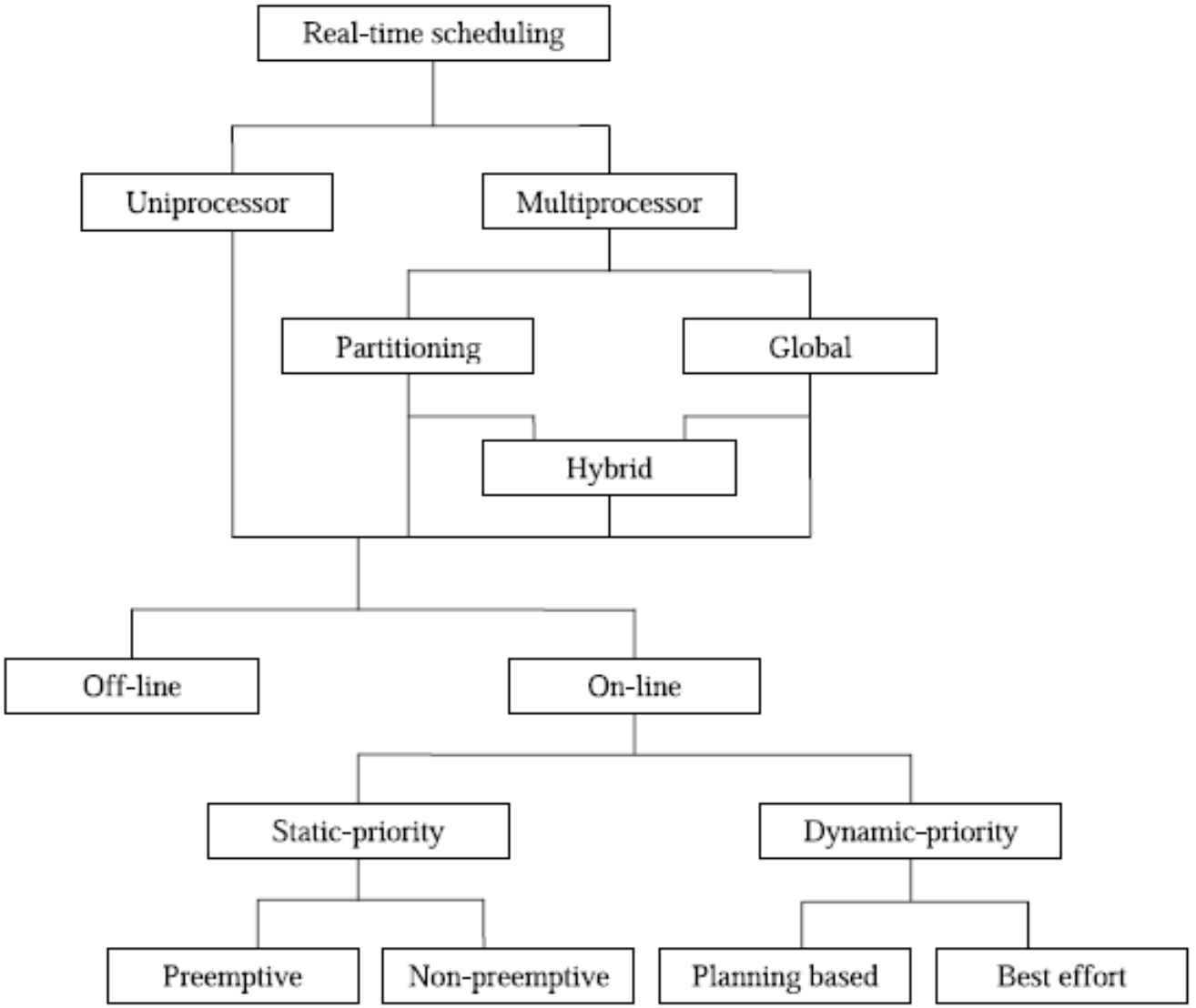
$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq m(2^{1/m} - 1)$$

  - Where m = number of tasks
  - For three tasks, CPU utilization must be less than 0.780

# Performance Comparison

- **RM Scheduling is simple and easy to implement, can be used for systems with low CPU utilization**
- **EDF Scheduling always works for any schedulable set of tasks. Upto 100% CPU utilization**
- **LLF Scheduling is similar in properties to EDF**
  - Takes into account that laxity time is more meaningful than deadline for tasks with mixed computing sizes

# Classification of Real-time Scheduling



# Off-line (Pre-run-time scheduling)

- **Generate scheduling information prior to system execution and utilize it during run-time.**
  - Uses precedence relations and prevents simultaneous access to shared resources
  - Reduces the cost of context switches by choosing algorithms that do not result in a large number of preemptions, such as the EDF algorithm
- **Suitable for applications where all characteristics are known prior and change very infrequently**
  - Ready times, execution times, deadlines are known and environment is completely predictable
- **Pros -** Significant reduction in run-time resources, including processing time for scheduling
- **Cons -** Any change requires re-computing the entire schedule

# Online Scheduling

- **Generate scheduling information while the system is running**
- **Pros**
  - No requirement to know tasks characteristics in advance
  - Flexible and easily adaptable to environment changes
- **Cons**
  - Require a large amount of run-time processing time.

# On-line Scheduling
# Static-priority based algorithms

- **Work well with fixed periodic tasks but do not handle aperiodic tasks particularly well**
- **Preemptive**
  - RM Scheduling
- **Non-preemptive**
  - Used when the execution order is known prior and each task completes before another task starts
  - Avoids the overhead associated with multiple context switches per task

# Online Scheduling
# Dynamic-priority based algorithms

- **Require a large amount of on-line resources, but are flexible**
- **Better response to aperiodic tasks or soft tasks while still meeting the timing constraints of the hard periodic tasks**
- **Two subsets:**
  - Planning based - feasibility check at run-time, schedule produced. Eg: EDF, LLF
  - Best effort - No feasibility check, attempts to meet deadlines but no guarantee.

# Multiprocessor Scheduling Algorithms
# Global Scheduling Algorithms

- **Store the tasks that have arrived in a queue, which is shared among all processors**
- **Each processor maintains**
  - Status table of tasks it has committed to run.
  - Table of the surplus computational capacity at every other processor. (Each processor regularly sends to others the fraction of the next window that is free)
- **A Overloaded processor selects a processor that is most likely to be able to successfully execute that task by its deadline and ships the tasks out**
- **Eg: Focused addressing and bidding algorithm**

# Multiprocessor Scheduling Algorithms
# Partitioning Scheduling Algorithms

- **Tasks are partitioned such that all tasks in a partition are assigned to the same processor**
  - Tasks of same class, are guaranteed to satisfy the RM schedulability on one processor
  - Tasks are not allowed to migrate
- **Partitioning scheduling has a low scheduling overhead compared to global scheduling, because tasks do not need to migrate across processors**
- **Eg: Next fit algorithm for RM scheduling**

# Scheduling of Sporadic Tasks

- **Methods**
  - Consider sporadic tasks as periodic tasks with a period equal to their minimum inter-arrival time
  - Define a fictitious periodic task of highest priority and when the task is scheduled, run any sporadic task awaiting service
  - The Deferred server
    - When sporadic tasks are scheduled and none is awaiting service, it schedules periodic tasks in order of priority
    - Wastes less bandwidth

# Scheduling of Aperiodic Tasks

- **Methods**
  - A Background Server executes at low priority, and makes use of CPU idle time to schedule aperiodic tasks. No guarantee of service
  - The Polling Server executes as a high-priority periodic task, and every cycle checks if an event needs to be processed
  - Priority Exchange and Deferred Servers
    - A periodic server(task) with highest priority is added. When there are no aperiodic tasks to service, exchange its priority with the next highest priority task, to allow it to execute

# Real Time Operating Systems

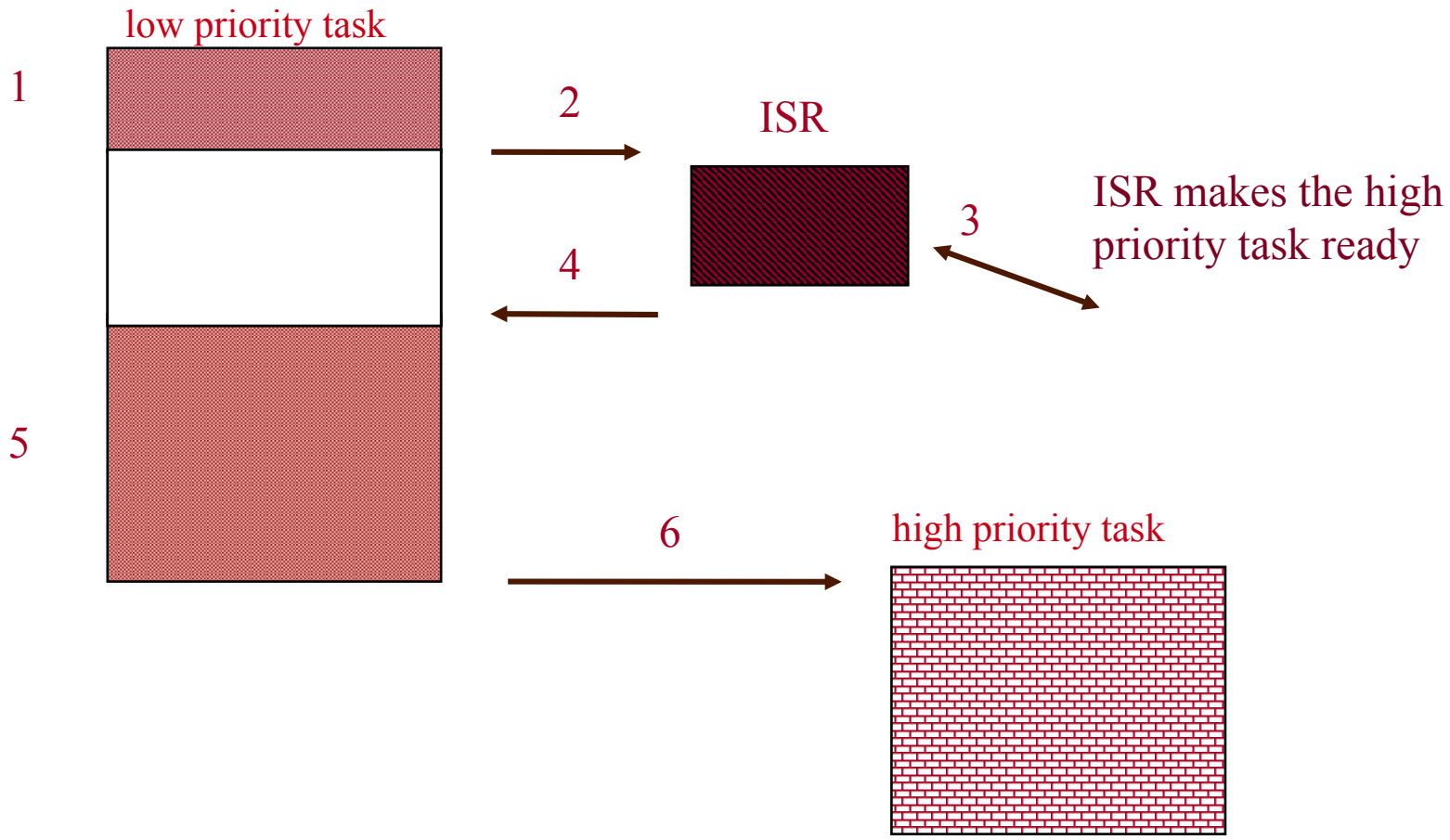
# Goals of an Operating System

- **General Purpose Operating System**
  - Maximum Throughput and CPU Utilization
  - User experience through enhanced graphics
- **Real Time Operating System**
  - Handling timing constraints imposed by the application
  - Respond to events quickly
  - Determinism

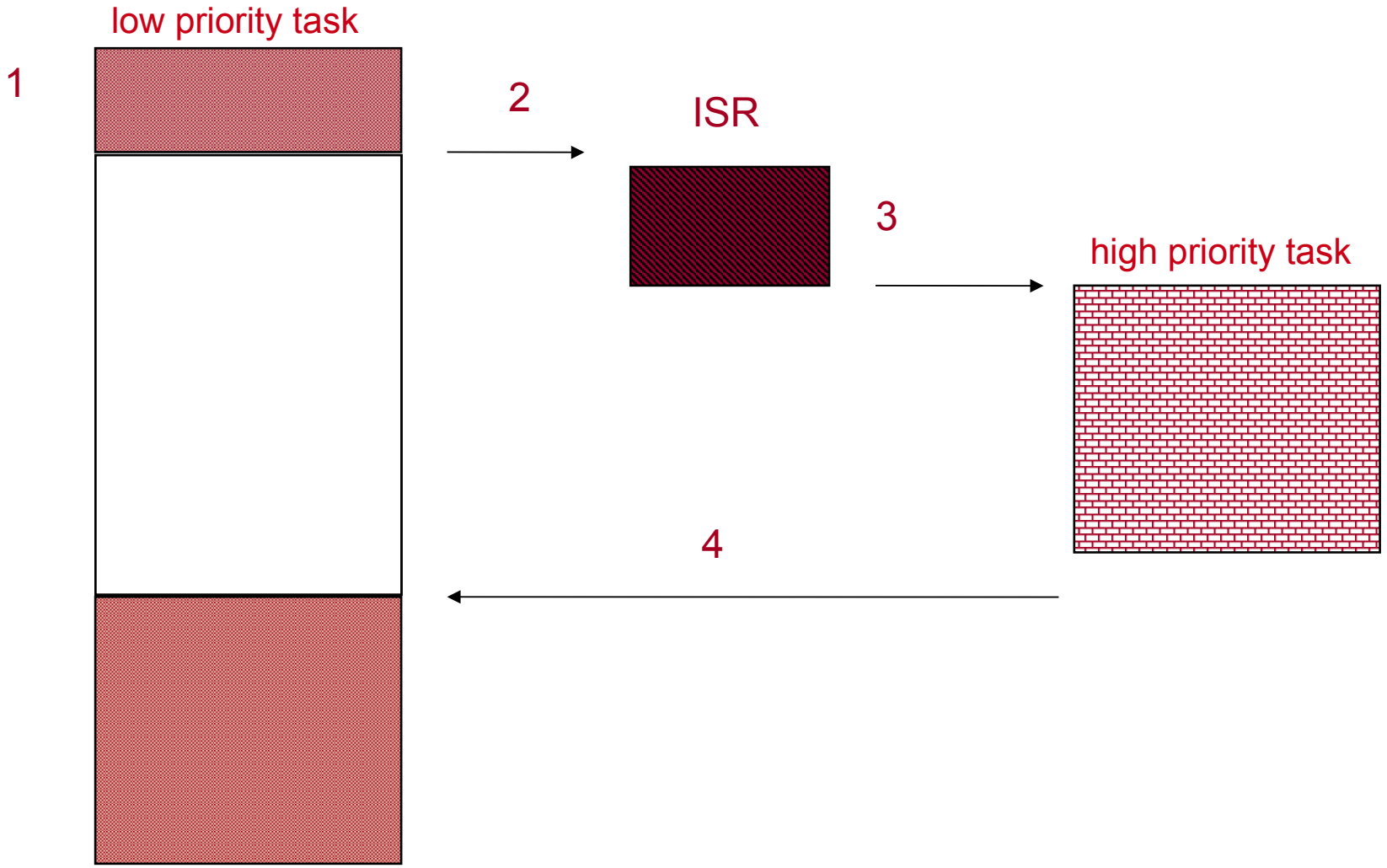
# RTOS Vs GPOS

| # | Evaluation Metrics | General Purpose OS | Real Time OS |
|---|---|---|---|
| 1 | Determinism | • Non Deterministic | • All RTOS functions should execute in a fixed/deterministic amount of time |
| 2 | Load Independent Timing | • Not Applicable<br>• Response becomes sluggish as number of tasks increase | • Remains Constant<br>• Irrespective of system load, performance of the RT system should remain predictable |
| 3 | Task Level Scheduling | • Generally Round Robin Scheduling<br>• Sometimes Priority based scheduling<br>• Efforts are made to ensure that all tasks get a chance to execute | • Generally Priority based Preemptive Scheduling .<br>• Time slicing only among tasks that hold the same priority<br>• Ensure that the Highest Priority task is always executed, even if it is the most frequent |
| 4 | Interrupt Management | • Nesting may be disabled.<br>• Interrupt latency, response and recovery are not performance metrics | • Nesting is always enabled.<br>• Interrupt latency, response and recovery are very important performance metrics |

# Kernel Types – Non Preemptive Kernel



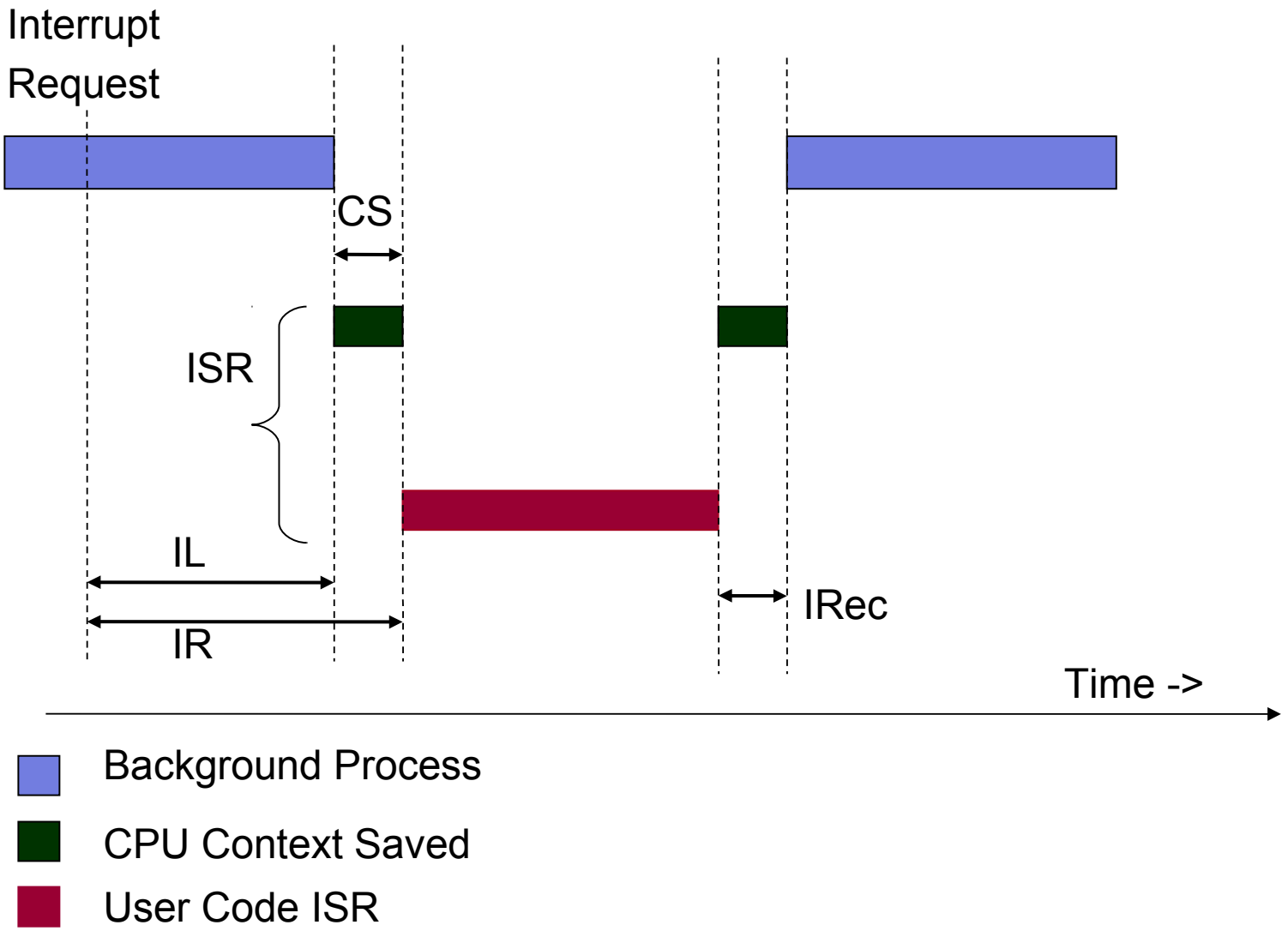
# Kernel Types – Preemptive Kernel



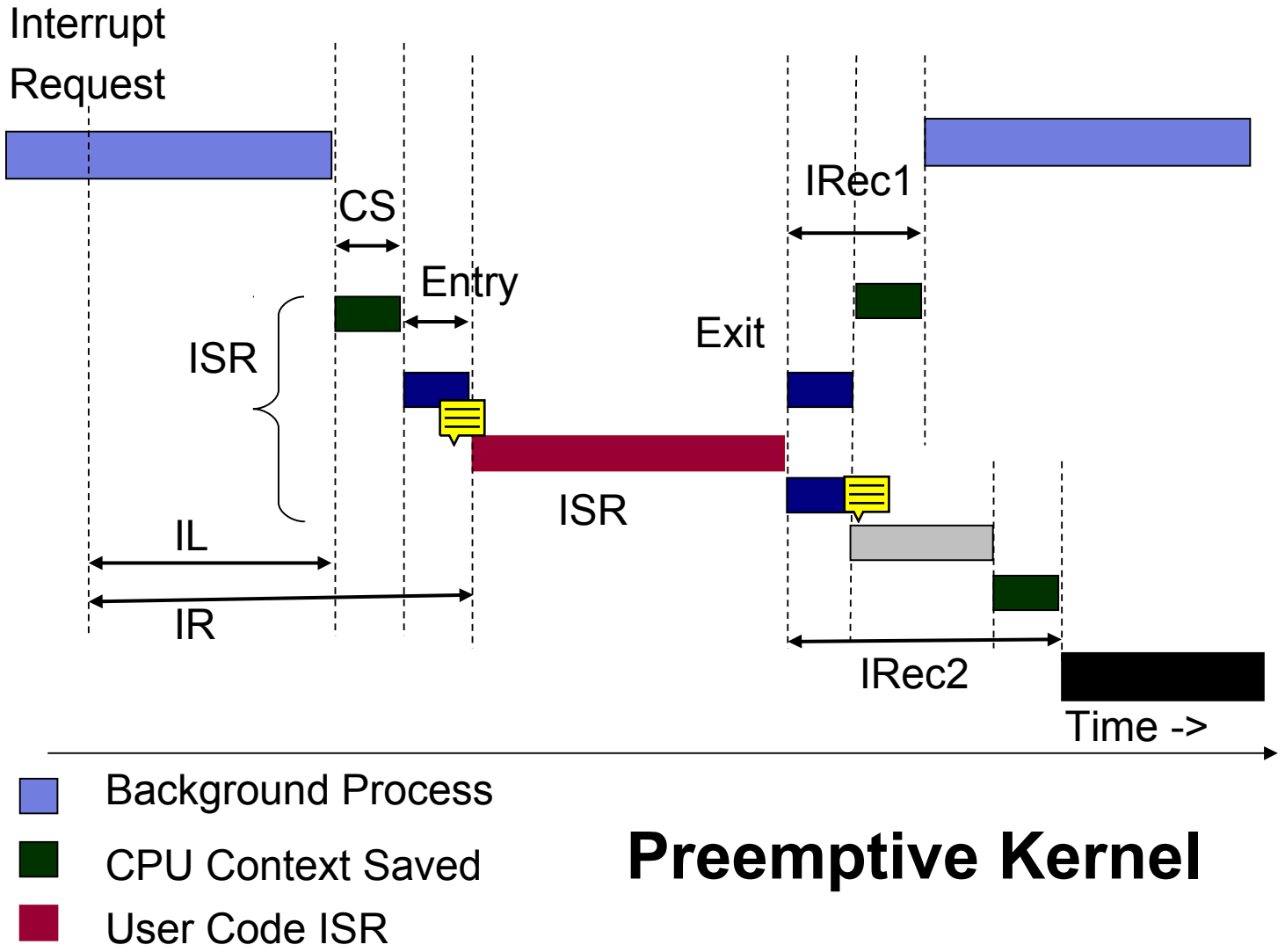
# Interrupts

- **When an interrupt occurs**
  - CPU saves its context on the stack, Jumps to the Interrupt Servicing Routine (ISR), Executes ISR and Returns
  - **Interrupt Latency**
    - max time interrupts are disabled + time to begin servicing the interrupt
  - **Interrupt Response Time**
    - Interrupt Latency + time to start execution of 1st instruction in ISR
  - **Interrupt Recovery Time**
    - time for CPU to return to interrupted code / highest priority task

# Interrupts in Non Preemptive Kernels

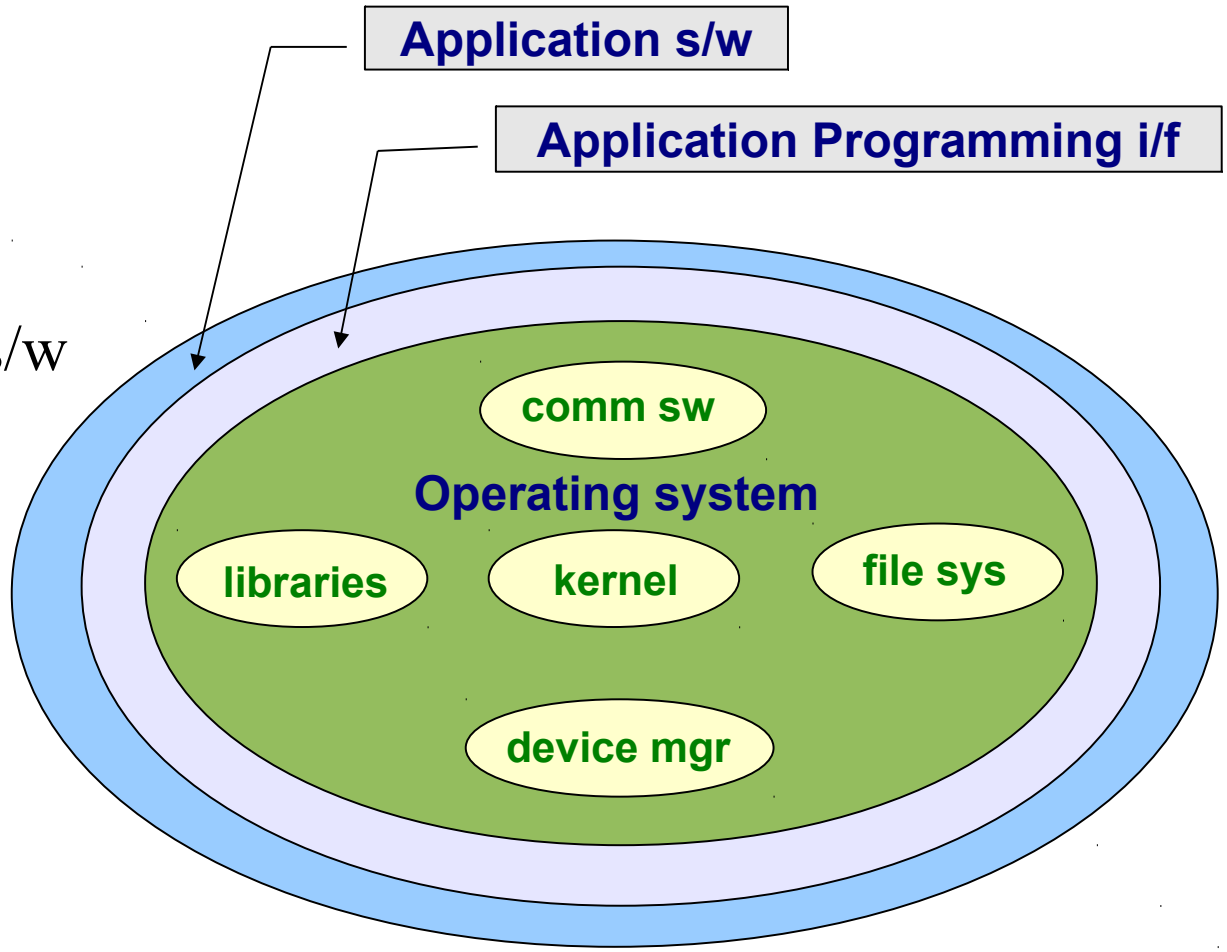


# Interrupts in a preemptive kernel



# RTOS Architecture

- An RTOS consists of
  - Kernel
  - Device Manager
  - Networking protocol s/w
  - Libraries
  - File system (optional)



# RTOS Services

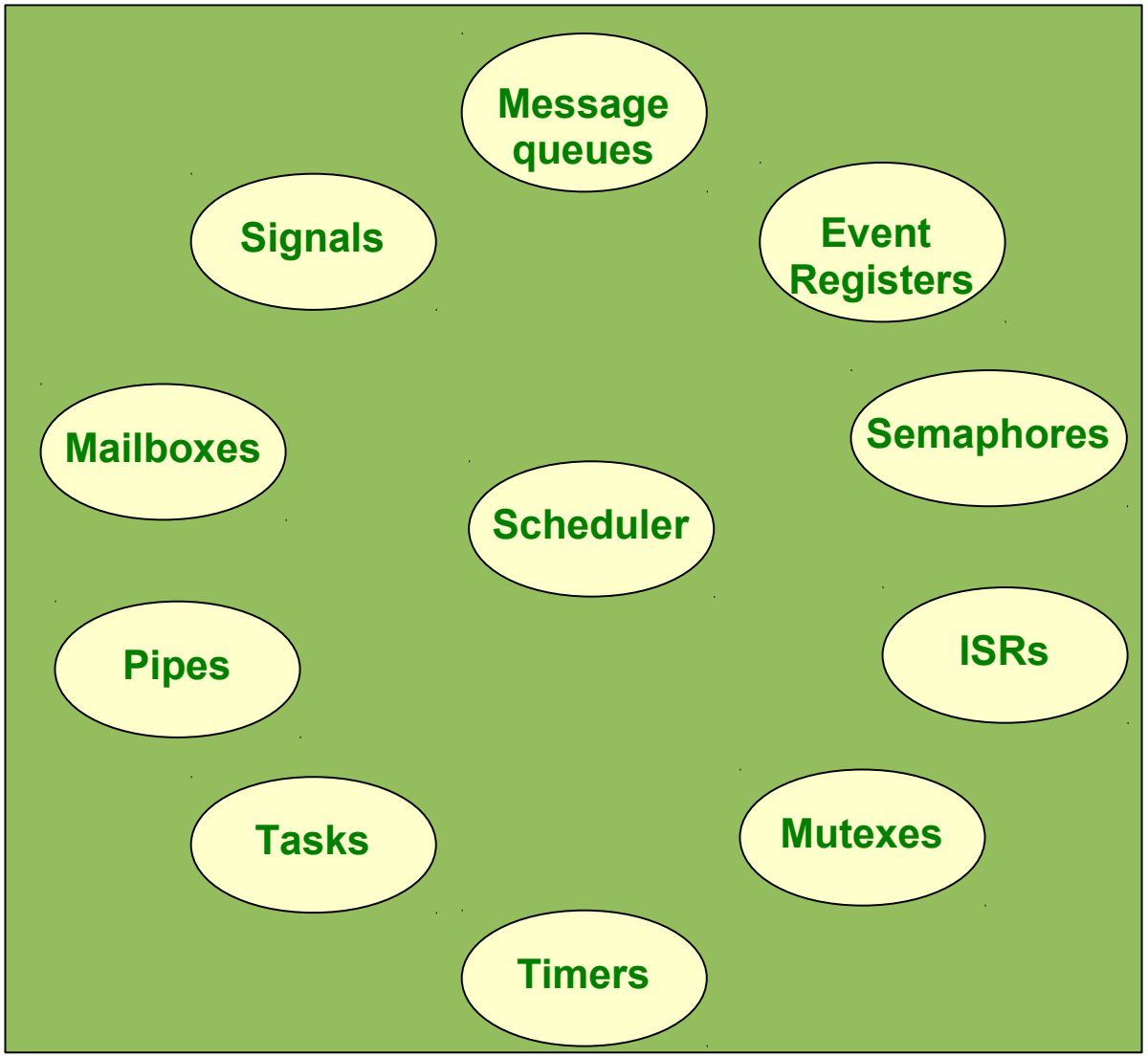
- **Multitasking, Task & Thread Management**
  - Creation and scheduling of tasks.
  - Priority based preemptive scheduling
- **Vectored Interrupt Service Routines**
- **Inter Task Synchronization and Inter Task Communications**
  - Mutual exclusions, signals, messages, shared memory, etc
- **Timer Services**
  - Periodic and aperiodic interrupts

# RTOS Services

- **Device drivers**
  - To service the needed special devices
- **Communication Protocol software**
  - Networking through Ethernet, wireless, etc
- **Application Programming Interface (APIs)**
  - To access kernel Services

# Kernel Objects

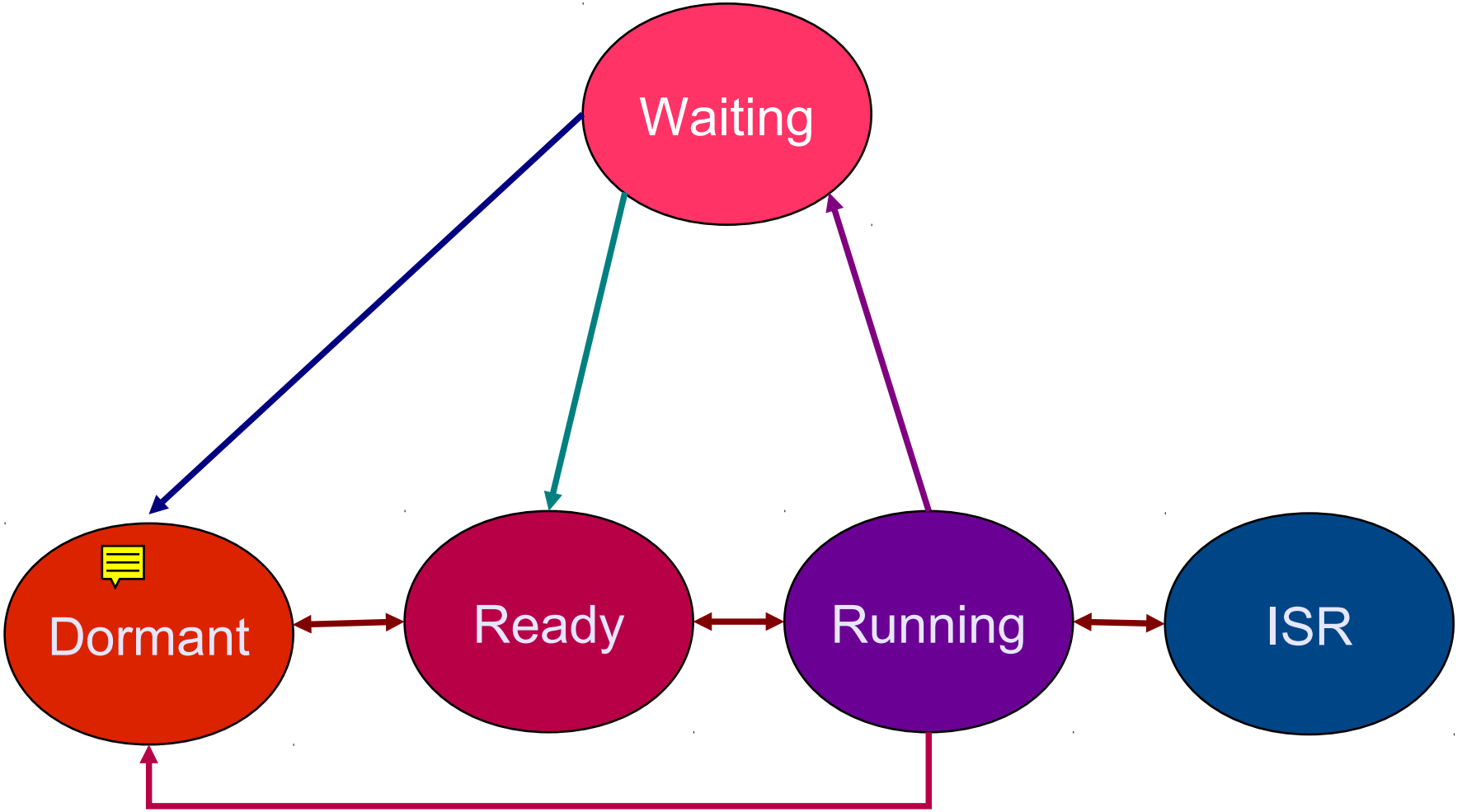
- Scheduler
- Tasks
- Interrupt Service Routines
- Semaphores
- Mutexes
- Mail boxes
- Message queues
- Pipes
- Event registers
- Signals
- Timers



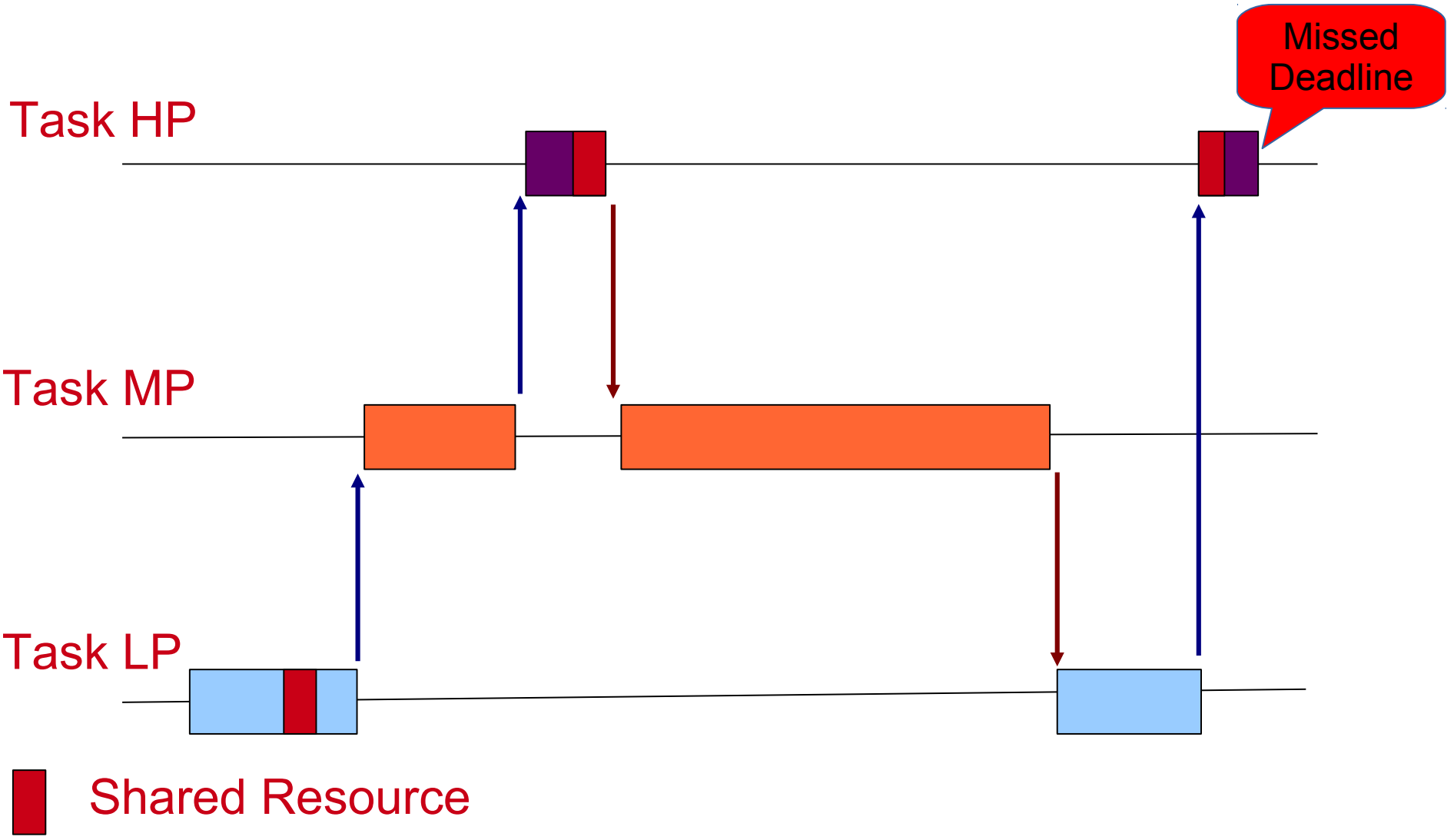
# Real Time Tasks

- **An RT application splits the work  to be done into Tasks.**
  - A real time  task, also called a thread, is a simple program that thinks it has the CPU all to itself.
  - It is generally implemented as an infinite loop (periodic tasks).
- **Each Task is assigned its own set of CPU Registers, Stack Area and a Priority.**
- **A Task may be visualized through 3 logical components**
  - **The Task Function** (Logic) – What the task is out to achieve
  - **The Task Control Block** – Holds configuration information of the task like Priority, State, Delay, Stack Pointer
  - **The Task Stack** – Maintains context information of the task during switches

# Task States

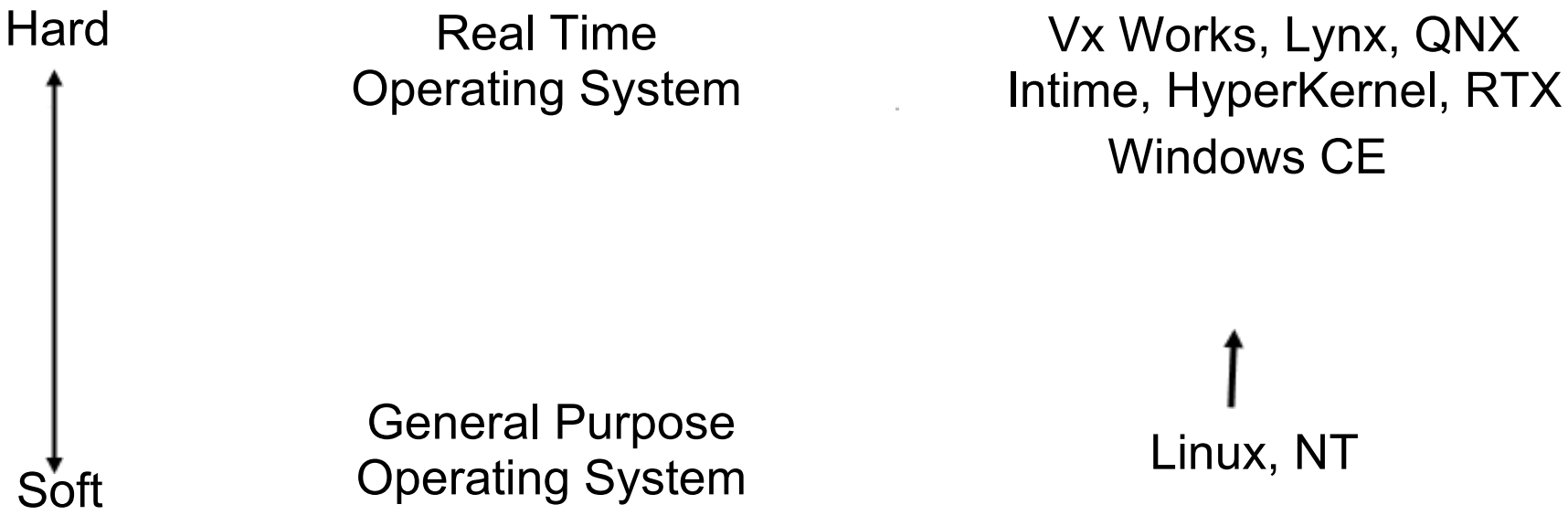


# Priority Inversion, Inheritance and Ceiling



# Overview of available RTOS's

- **Three categories of real-time operating systems:**
  - Small, proprietary kernels. e.g. VRTX32, pSOS, VxWorks, Windows CE, MicroC-OS/III*
  - Real-time Linux extensions: RT-Linux, Xenomai, RTAI
  - Research kernels: MARS, ARTS, Spring, Polis, MicroC-OS/II



# Small Fast Proprietary Kernels

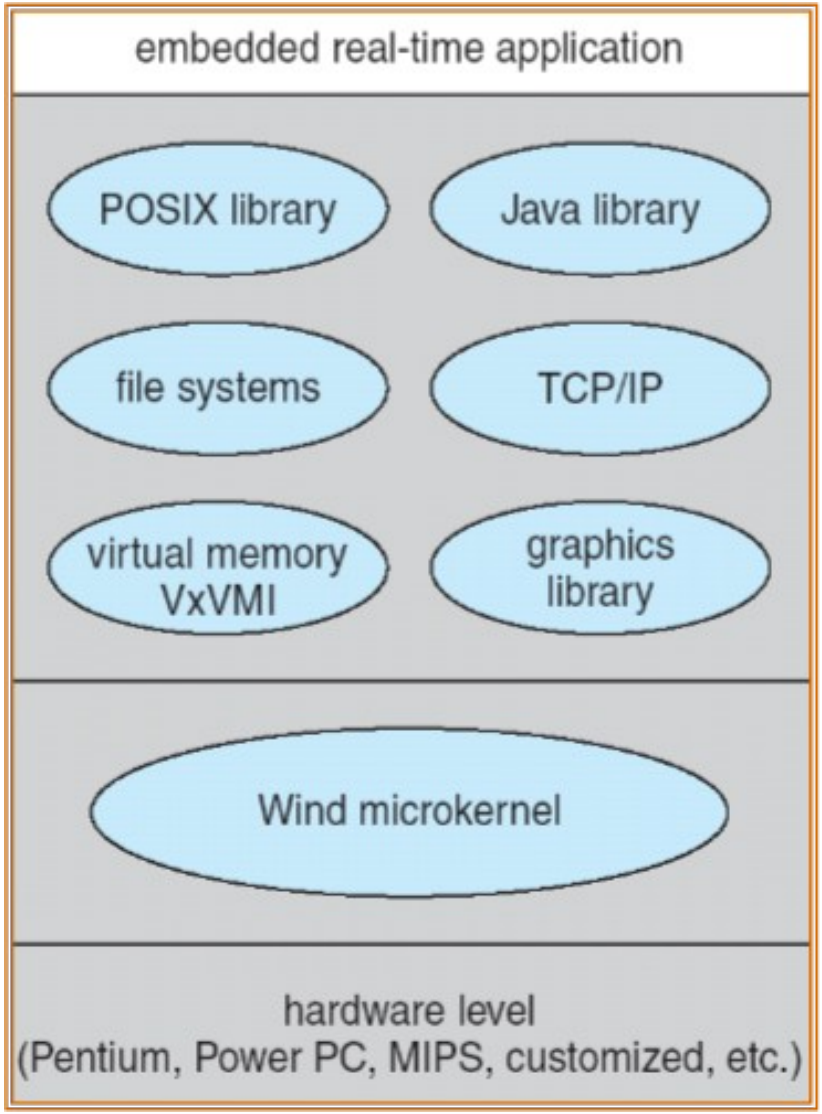
- **Stripped down and optimized versions of time-sharing operating systems.**
- **Intended to be fast**
  - a fast context switch
  - external interrupts recognized quickly (low interrupt latency)
  - special sequential files that can accumulate data at a fast rate
- **To deal with timing requirements**
  - a real-time clock with special alarms and timeouts
  - bounded execution time for most primitives (determinism)
  - real-time queuing disciplines such as earliest deadline first
  - primitives to delay/suspend/resume execution
  - priority-driven best-effort or a table-driven scheduling mechanism
- **Communication and synchronization -** mailboxes, events, signals, and semaphores

# QNX Neutrino

- Developed by Gordon Bell and the students at the University of Waterloo in 1980
- Supported on ARM, MIPS, Power PC, x86 and Pentium
- Micro-kernel based, and most of the OS is run in the form of a number of small tasks, known as servers
- Configurable to small size (64 K kernel ROM, 32 K kernel RAM)
- Supports Symmetric multiprocessing and strict priority-preemptive scheduling
- IEEE1003 real-time std compliant and POSIX threads
- Finds Applications in Embedded systems for over 20 years in mission and life critical systems, medical instrumentation, aviation and space systems, process control systems
- Avg Interrupt latency – 1.6us

# Vx Works

- Developed by Wind River Systems of California
- Pentium, Motorola, Power PC,  ARM
- Micro-kernel based
- Preemptive and non-preemptive scheduling
- Manages interrupts with bounded interrupt and dispatch latency times
- POSIX Compliant threads
- Shared memory and message passing for inter process communications
- Used in automobiles, routers, switches, Mars Pathfinder
- Avg interrupt latency – 1.7us



# Microsoft Windows CE

- Supported on x86, MIPS, ARM processors for embedded systems
- Supports threads, priority inheritance
- Non - POSIX compliant, 10% of Win32 APIs
- Applications can be developed on Visual Studio
- Windows Mobile, Pocket PC, Smart Phone are based on CE
- Avg interrupt latency – 2.4us

# LynxOS

- Lynx is a Unix like real time operating system
- Developed for Motorola 68010, ported to x86, ARM, Power PC
- Support hard real time applications, due to extremely fast interrupt routines known as Multiple Priority Light Weight kernel Task-based Interrupt Handling
- Mostly used in embedded systems in avionics, aerospace communications

# Variants of Real-Time Linux Extensions

- **Real Time Linux (RTLinux)**
  - Developed at the New Mexico Institute of Mining and Technology
  - RTOS Micro kernel running entire Linux in fully preemptive mode
  - Runs special real-time tasks and interrupt handlers
  - FiFo, Shared memory, Semaphores. POSIX mutexes and threads
  - Avg latency - 15us
  - Used to control robots, data acquisition systems, manufacturing plants, and other time-sensitive instruments and machines
- **Real Time Application Interface (RTAI)**
  - Developed by programmers at the Department of Aerospace Engineering, Milano
  - Adeos based patch over Linux kernel, with native real time tasks, interrupt handlers and services
  - Platforms - MIPS, x86-64, PowerPC, ARM
  - Semaphores, mailboxes, FIFOs, shared memory, and RPCs
  - POSIX 1003.1c & POSIX 1003.1b(pqueues)
  - Avg interrupt response - 20us
- **Xenomai Framework**
  - Implementing and migrating real time applications, based on standard APIs or emulators of proprietary RTOS interfaces, such as VxWorks and pSOS
  - Linux-hosted dual kernel, with pure Adeos. User space RT tasks
  - Platfroms - x86, ARM, POWER, IA-64, Blackfin, nios