RTOS

Characteristics
Time constraints
Scheduling

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Real-Time Systems

- Definition of real-time system
  - “A real-time system is one in which the correctness of the computation not only depends on the logical correctness of the computation, but also on the time at which the result is computed. If the timing constraints of the system are not met, system failure is said to have occurred”
- Tasks or processes attempt to control or react to external events occuring in “real time”
- RT processes must be able to keep up events
  - Hard Real Time: timing violation produces a disaster
  - Soft Real Time: timing violations are undesirable but not catastrophic

RTOS

- A Real-Time Operating System (RTOS)
  - Is just one element of a complete real-time system
  - Must provide sufficient functionality to enable the overall real-time system to meet its requirements
  - Should ensure that all time critical events are handled as quickly and efficiently as possible
- RTOS are characterized by these main features
  - Deterministic behaviour
  - Responsiveness
  - User control
  - Reliability and fail-soft operation

RTOS: Determinism

- Operations are performed at fixed, predetermined times or within predetermined time intervals
- Concerned with
  - How long the operating system delays **before** acknowledging an interrupt
  - Whether the system has sufficient capacity to handle all requests within required time
- RTOS should show minimum interrupt latency
  - Typical measure:
    - Max delay to start ISR with highest priority
    - RT: 1µs - 1ms
    - Non-RT: 10ms - 100 ms

RTOS: Responsiveness

- How long, after acknowledgment, the operating system takes to **service** the interrupt
- Includes the time to begin execution of the ISR
  - If a context switch is necessary, the delay is longer than an ISR executed within the context of the current process
- Includes the amount of time to perform the interrupt, depending also on the specific hardware
- Depends on the possible ISR nesting and if ISRs can be interrupted

RTOS: User control

- Much broader in RTOS than in ordinary O.S.
- User should be able to
  - Specify paging or process swapping
  - Decide which processes must reside in main memory
  - Establish the rights of processes
  - Fine-grained control over task priorities
  - Select algorithms for disks scheduling
  - ...

RTOS: Reliability

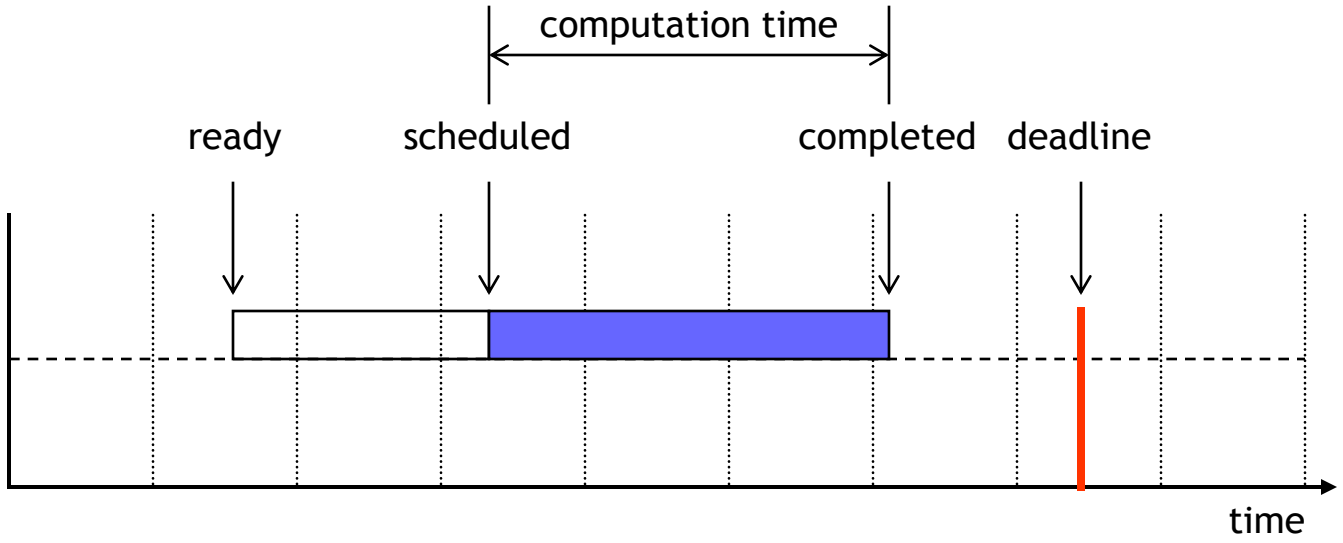
- In the application domain of RTOS, degradation of performances may have catastrophic consequences
  - Attempt either to fix the problem or minimize its effects while continuing to run
  - Graceful degradation can be not enough
- Fail-soft
  - Ability to fail in such a way to preserve as much data and capability as possible
    - E.g., multiple attempts to improve data consistency
- Stability
  - The system adopts policies such that the most critical high priority tasks execute first, even if some needs of less important tasks can be not always met

RTOS: Typical features

- Low cost, small size
- Management of at least 20 tasks
- Have minimum interrupt latency
- Deterministic execution time for all kernel services
- Provide at least the following services
  - Allow tasks to be dynamically created and deleted
  - Provide semaphore management services and IPC
  - Allow time delays and timeouts on kernel services
  - Management of special alarms
  - Use of special file to accumulate data at a fast rate
  - Preemptive priority-based scheduling with fast context switch

Time constraints

- Computational activities in a real-time system generally have timing constraints



Time constraints

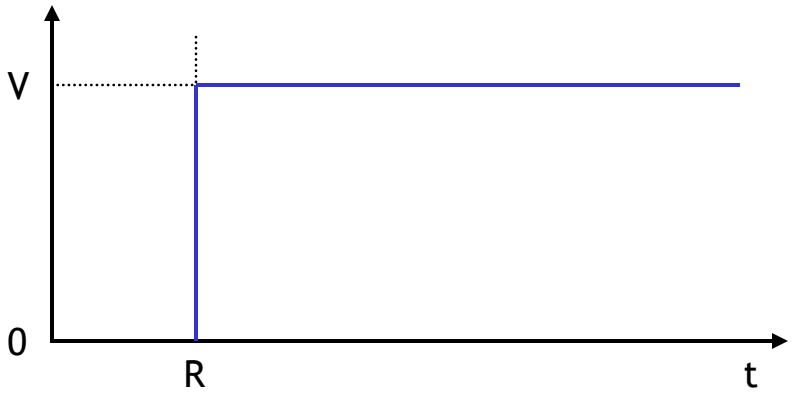
- The "ready" event may be
  - Periodic
    - Tasks: Overall activity
    - Jobs: Instantiations or individually scheduled computations of the task. A task is a stream of jobs
  - Aperiodic but predictable
  - Unpredictable
- The "computation time" may be
  - Fixed in duration
  - Variable
  - Unpredictable

Deadlines

- Deadlines
  - Hard
    - The computation must be completed by the deadline time or a fatal error will occur
  - Soft
    - The deadline may just be a recommendation or preference for completion of the computation
- A "Value Function"
  - Indicates the criticality of a deadline
  - Indicates the value that the completion of a task contributes to the overall value of the system

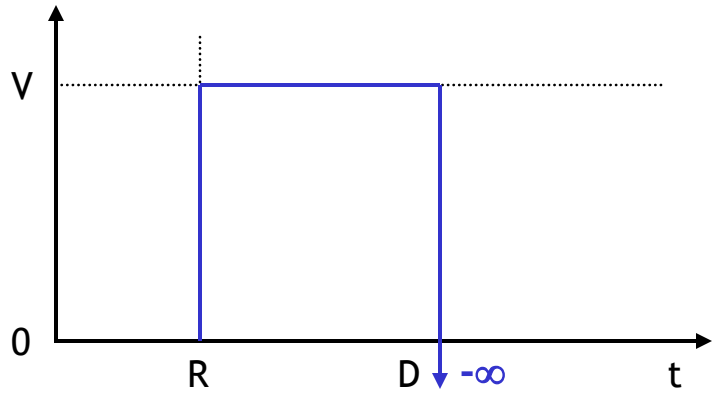
Deadlines

- In a non real-time system the time by which a task is completed does not influence the overall value – or quality – of the system
- The value function is the following

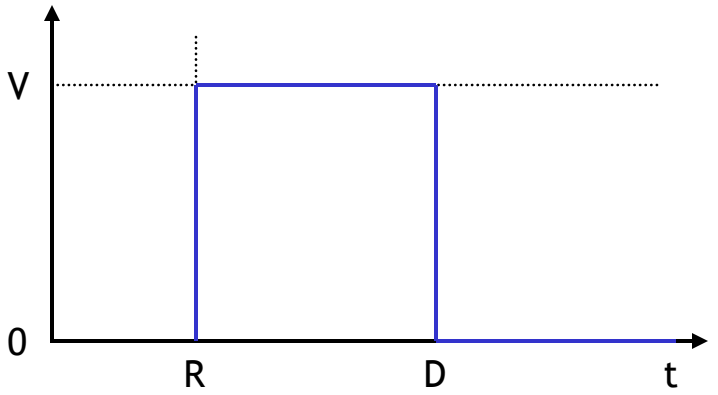


Deadlines

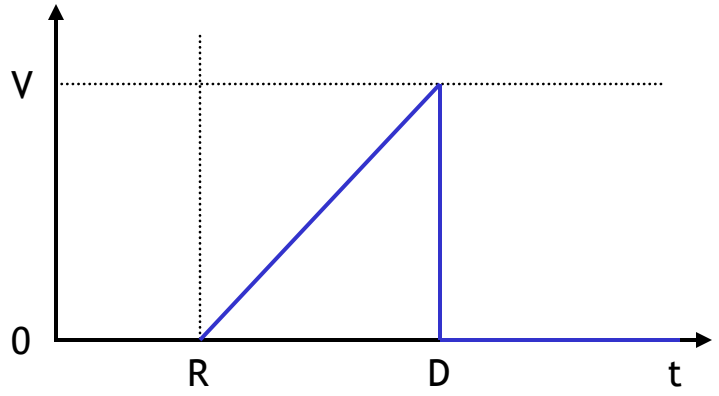
Catastrophic effect



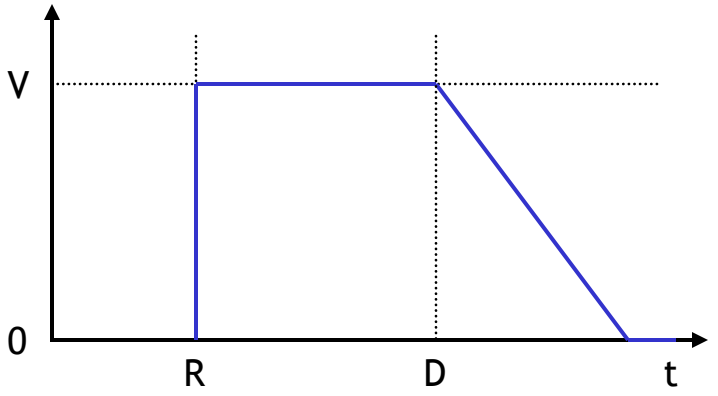
Hard Deadline



Ramped Hard Deadline



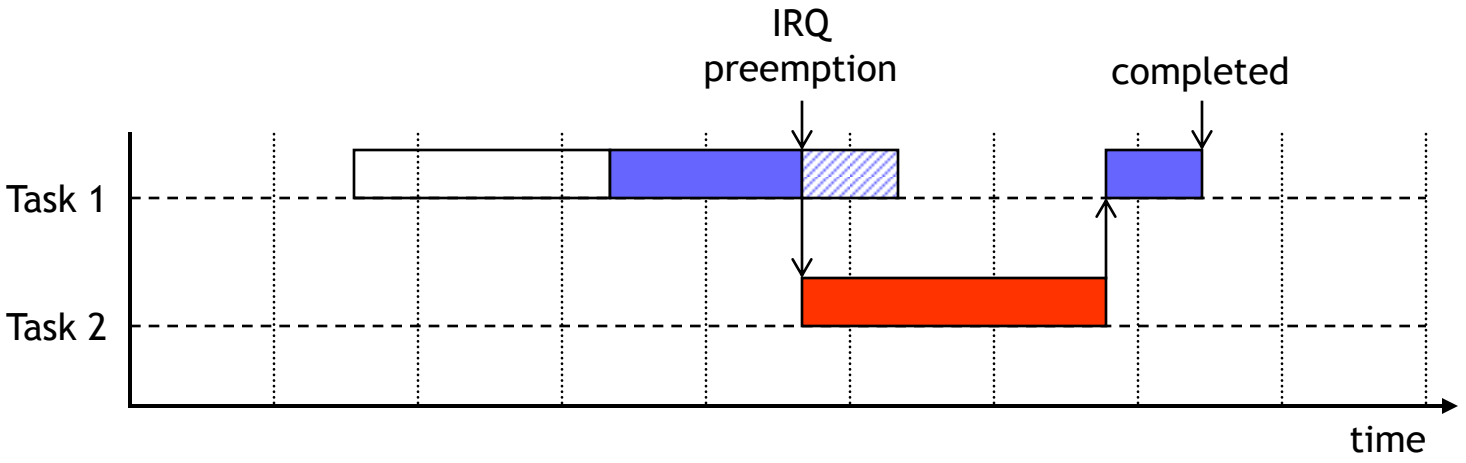
Soft Deadline

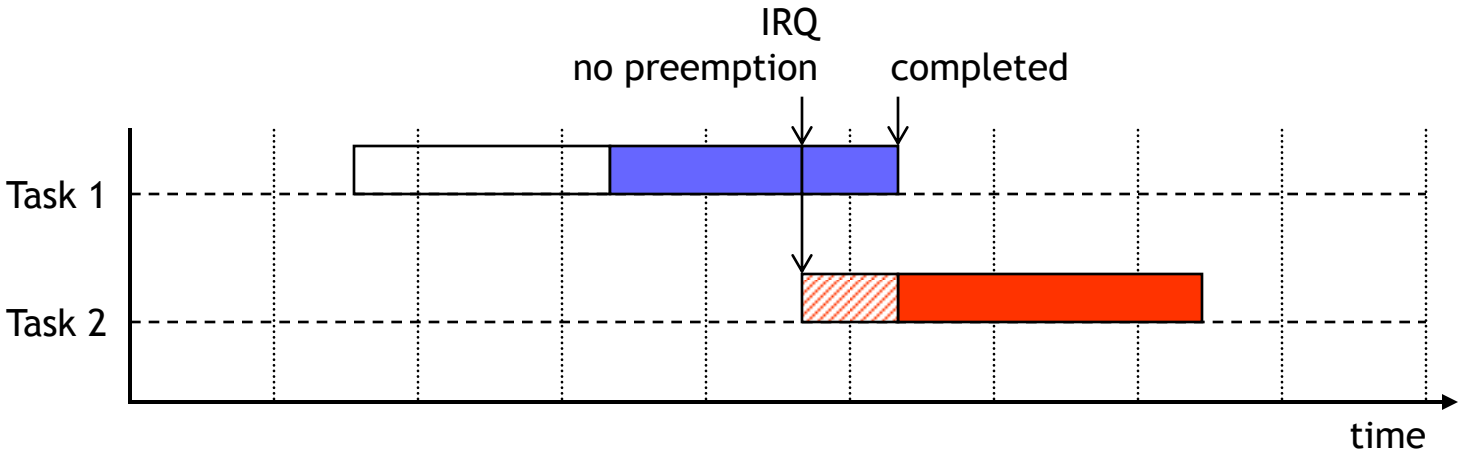


Preemption

- A computation or task is preemptable if it can be interrupted (suspended) when another more critical task needs to be executed
- A computation can be
  - Preemptable
  - Preemptable with one or more non-preemptible critical regions
  - Non-preemptable

Preemption


IRQ
preemption
completed
Task 1
Task 2
time

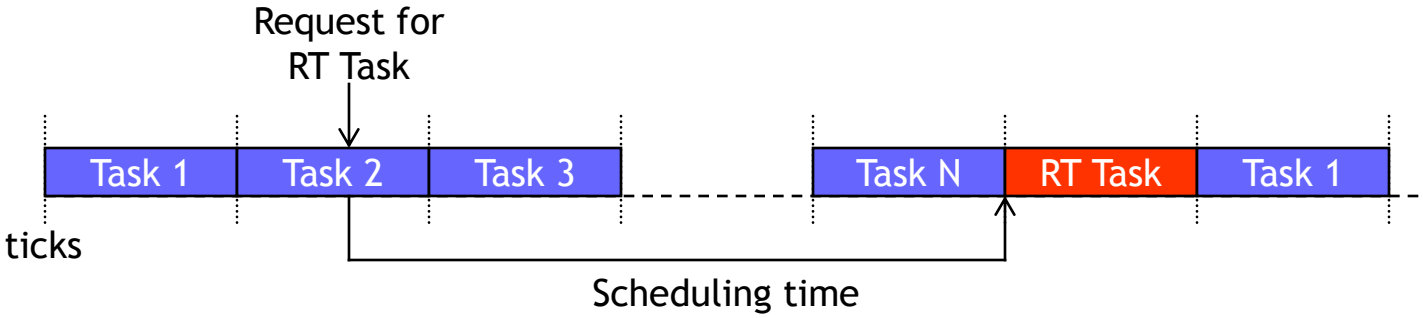

IRQ
no preemption
completed
Task 1
Task 2
time

Scheduling

- The heart of a RTOS is the short-term scheduler
  - Not crucial
    - Fairness, Minimum average response time, …
  - Crucial
    - All hard-RT tasks must complete by their deadline
    - As many soft-RT tasks as possible should also complete meeting their deadlines
- Most RTOSs are unable to deal with deadlines
  - Designed to be as responsive as possible to RT tasks
    - When deadline approaches, RT tasks can be quickly scheduled
  - This approach requires deterministic response time sometimes below milliseconds

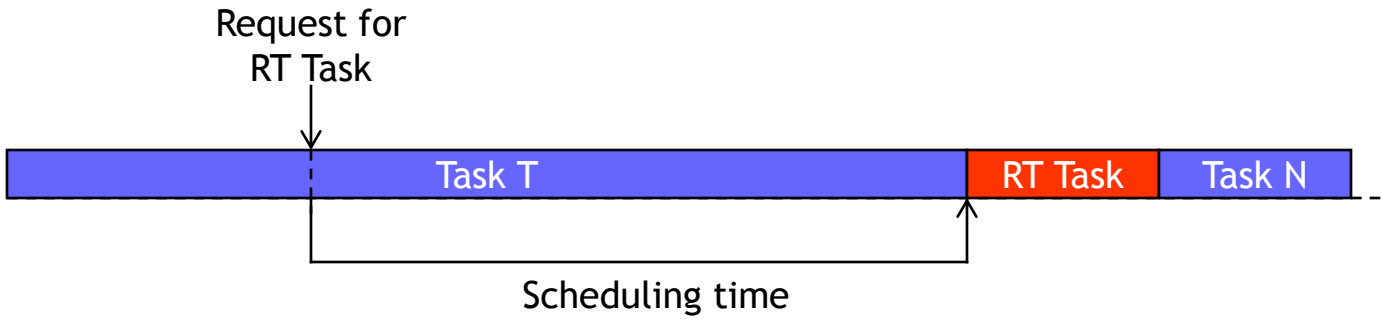
Scheduling

- In a Round Robin non-preemptive scheduler
  - The RT task is appended at the end of the ready queue
    - Wait for its next timeslice
  - The delay can be unacceptable for RT applications



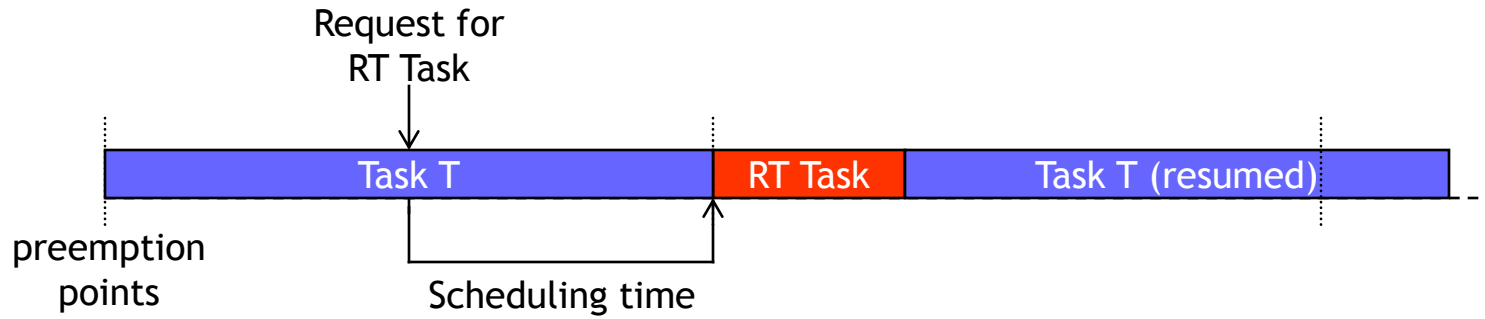
Scheduling

- Priority driven non-preemptive scheduler
  - RT tasks have higher priority
  - A RT task is scheduled when the current task T
    - Is blocked, or
    - Runs to completion (even if with low priority)
  - The RT is added at the head of the ready queue
  - Possible delay of seconds, unacceptable for real-time



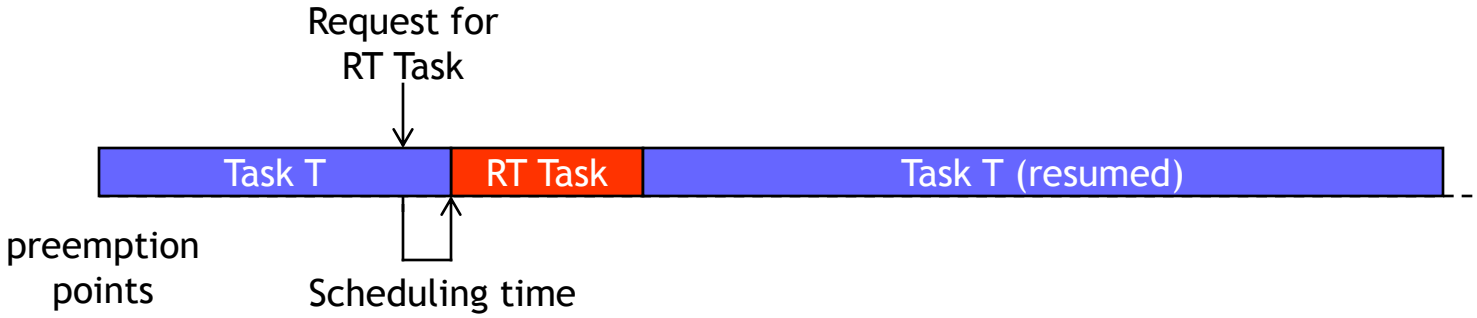
Scheduling

- Priority driven preemptive on preemption points
  - Preemption can only take place at the end of some regular intervals
  - In those points
    - The highest priority task is scheduled
    - Including kernel tasks
  - Delays in the order of some ms, adequate for some applications not for more demanding ones



Scheduling

- Immediate preemptive scheduling
  - The service to the interrupt is almost immediate
    - Apart from the case OS is executing a critical region
  - Scheduling delays fall down to 100 µs, or less
    - A minimum amount of time is nevertheless required to save the context and to switch to the new context
  - Good for critical systems



Factors influencing scheduling

- Schedulability analysis
  - Yes/No
  - Static/dynamic
- The result of the analysis can be
  - A clear scheduling
  - A "plan" to follow at run-time for task dispatching
- Classes of algorithms
  - Static table-driven
  - Static priority-driven preemptive
  - Dynamic planning-based
  - Dynamic best-effort

Static table-driven

- Through a static feasibility analysis of schedule, determines, at run-time, when a task must begin execution
  - Applicable to periodic tasks
- Analysis inputs
  - Periodic arrival time
  - Execution time
  - Periodic ending deadline
  - Relative priority of each task
- Predictable but inflexible approach
  - Any change in the requirements of tasks imply the computation of a new schedule
- Example: Earliest-deadline first

Static priority-driven preemptive

- Uses standard priority-driven preemptive scheduler
- Static analysis is performed
  - No schedule is drawn-up
  - Assigns priorities to tasks
  - In RT systems depends on time constraints associated to tasks
- Example: Rate Monotonic

Dynamic planning-based

- Feasibility is determined at run-time
  - Rather then offline
- A task is accepted for execution
  - If and only if it is feasible to meet its time constraints
- Before its execution
  - An attempt is made to create a schedule including previous tasks and the new one
  - The deadline of the extended task set must be met

Dynamic best-effort

- Used in many commercial RT systems
  - Easy to implement
  - No feasibility analysis is performed
    - Typically, the tasks are aperiodic and no static scheduling analysis is possible
- When a task arrives
  - The system assign a priority based on its characteristics
    - E.g., based on earliest deadlines
  - The system tries to meet deadlines and aborts any started process whose deadline is missed
  - Until the task is completed (or deadline arrives), it is unknown if time constraints will be met

Deadline scheduling

- Real-time applications are not concerned with speed but with completing tasks
- Priorities
  - Provide a crude tool
  - Do not capture the requirement of completion or initiation at the most valuable time
- Other deadline related information should be taken into account

Deadline scheduling: Other information

- Ready time
  - Time at which task is ready for execution
  - For periodic task it is a sequence of times
    - Known in advance
- Starting/completion deadline
  - Typical RT application have either deadlines, but not both
- Processing time
  - In some cases it is supplied
  - In others cases the operating system measures an exponential average
- Resource requirements
  - In addition to microprocessor

Deadline scheduling: Other information

- Priority
  - Measures relative importance of tasks
  - Hard-RT tasks have “absolute” priority
- Subtask structure
  - Task possibly decomposed in
    - Mandatory subtasks: the only with hard RT deadlines
    - Optional subtasks: all other subtasks
- …

Design issues

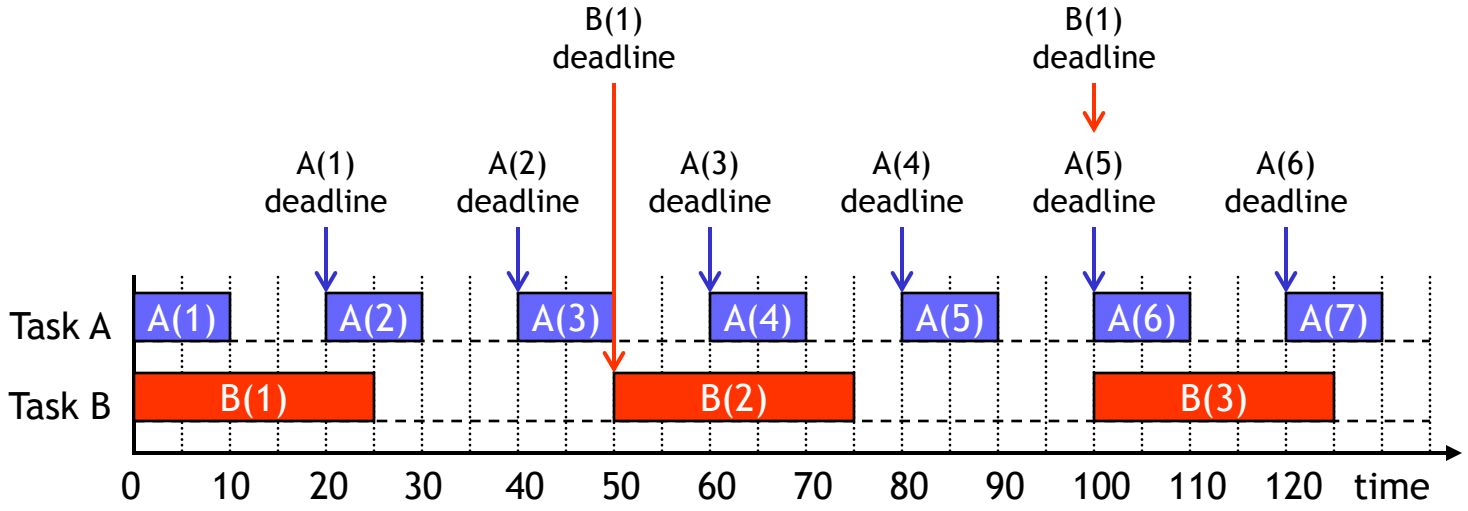
- Which task to schedule next?
  - For a given preemption strategy, scheduling tasks with the earliest deadline minimizes the fraction of tasks that miss their deadlines
    - True for single and multiprocessor configurations
- What sort of preemption is allowed?
  - When starting deadlines are given, non-preemptive scheduler makes sense
  - The RT task has the responsibility to block itself after
  - executing the critical portion, allowing starting other RT deadlines

Example: Periodic tasks

- A system collects and processes data from two sensors, A and B
- Deadlines:
  - A must be read every 20 ms
  - B must be read every 50 ms
- Processing time (including OS overhead):
  - Processing data from A requires 10 ms
  - Processing data from B requires 25 ms
- The system makes scheduling decision every 10 ms

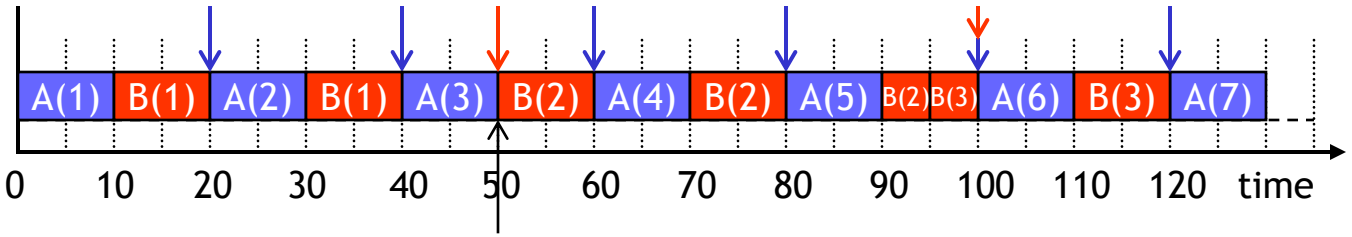
Example: Periodic tasks

Process	Arrival time	Execution time	Deadline
A(1)	0	10	20
A(2)	20	10	40
A(3)	40	10	60
A(4)	60	10	80
…	…	…	…
B(1)	0	25	50
B(2)	50	25	100
…	…	…	…



Example: Periodic tasks

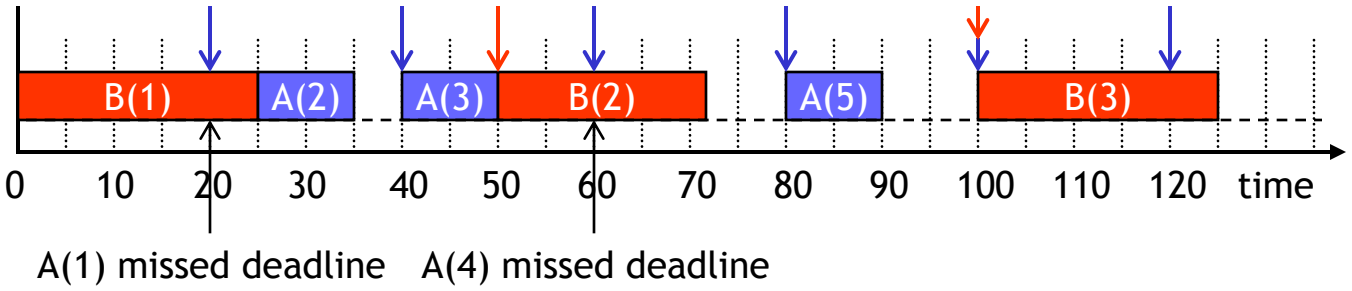
- Fixed priority scheduling
  - Task A has priority
  - Task B may miss some deadlines



B(1) is not rescheduled since its deadline has been reached and will thus be violated

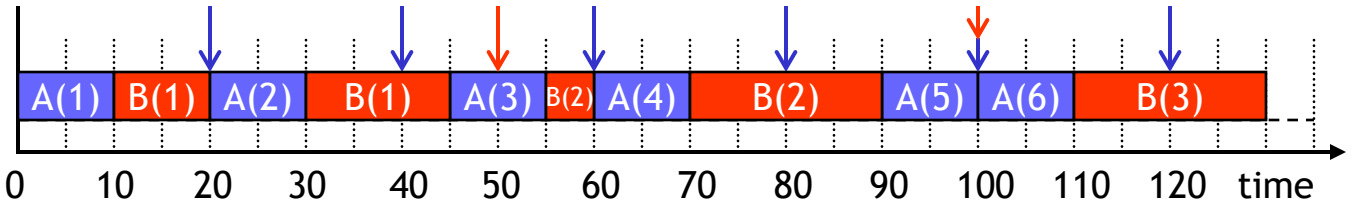
Example: Periodic tasks

- Fixed priority scheduling
  - Task B has priority
  - Task A may miss some deadlines



Example: Periodic tasks

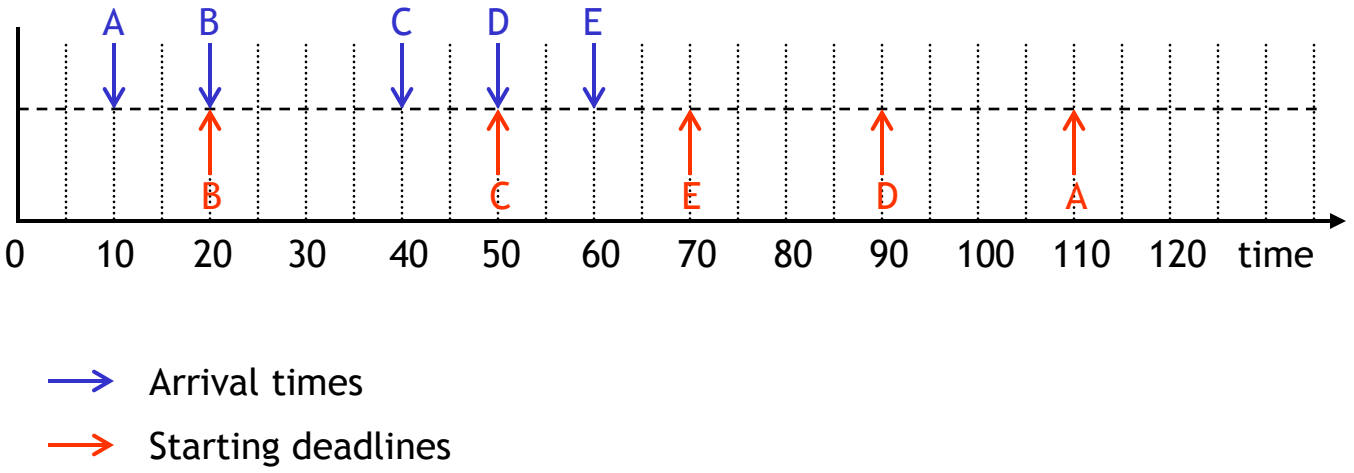
- Earliest deadline first with preemption
  - Completion deadlines are considered
  - At any preemption point the scheduler gives priority to the task with the earliest deadline
  - All task can meet their deadlines



All task can be scheduled within their completion deadlines

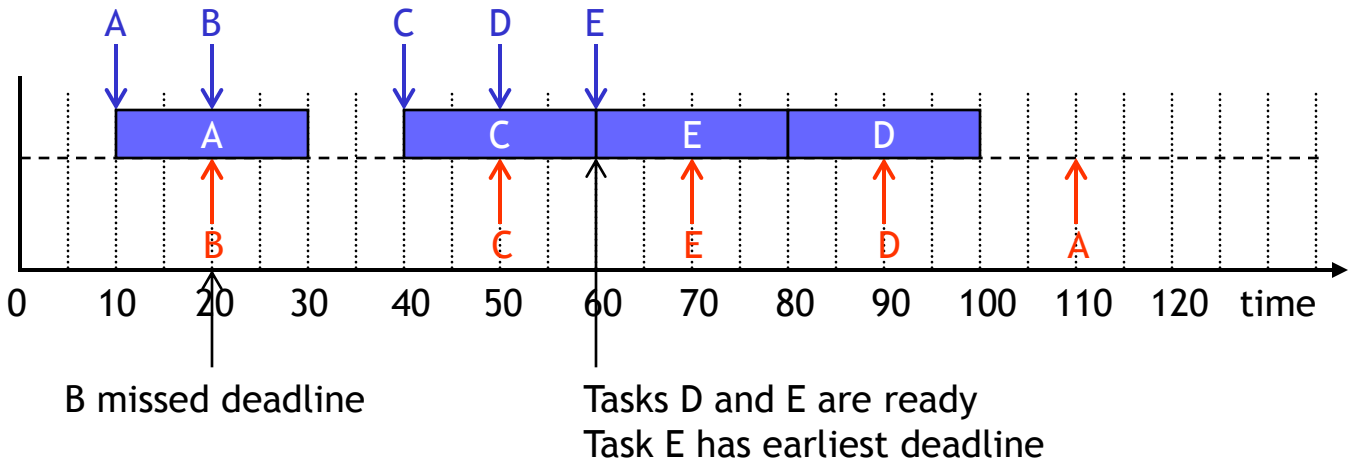
Example: Aperiodic tasks

- Five tasks
  - All tasks have an execution time of 20 ms
  - Arrival times are unknown
  - Starting deadlines are considered



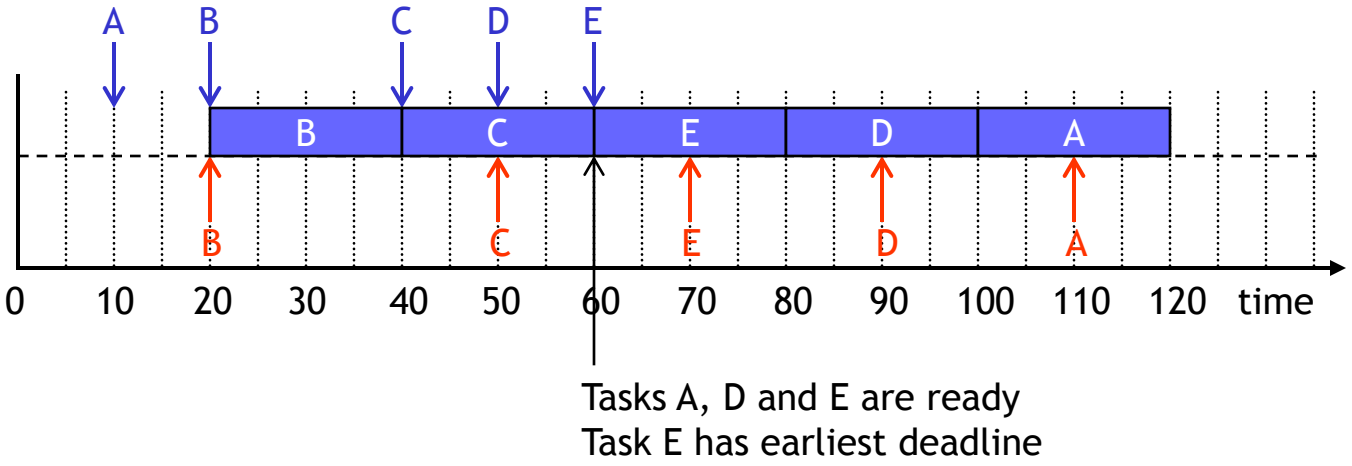
Example: Aperiodic tasks

- Earliest deadline first
  - Starting deadlines are unknown before the task becomes ready for scheduling
  - Schedule the ready task with the earliest deadline and let the task run to completion



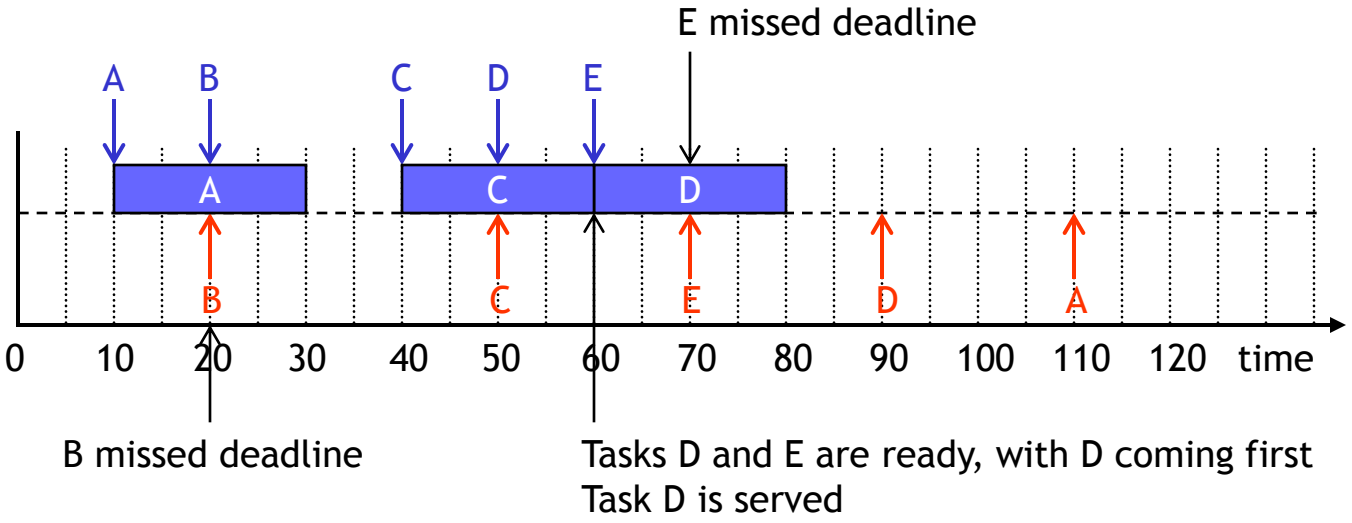
Example: Aperiodic tasks

- Earliest deadline with unforced idle times
  - Possible if deadlines are know before the task is ready
    - Schedule the eligible task with the earliest deadline
    - Let the task run to completion
  - Elegible tasks may not be ready
    - Processor remains idle even though ready tasks exist



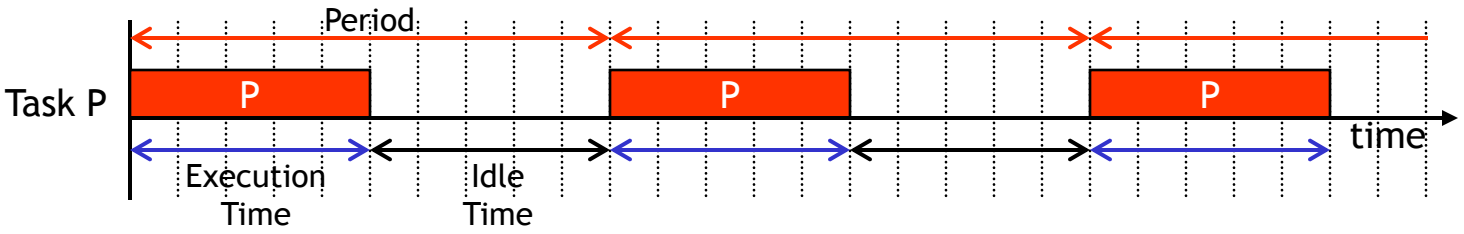
Example: Aperiodic tasks

- First-Come, First-Serve (FCFS)
  - Tasks are ordered based on their arrival times
  - Tasks are served if their starting deadline is met
  - Tasks B and E do not meet their deadlines



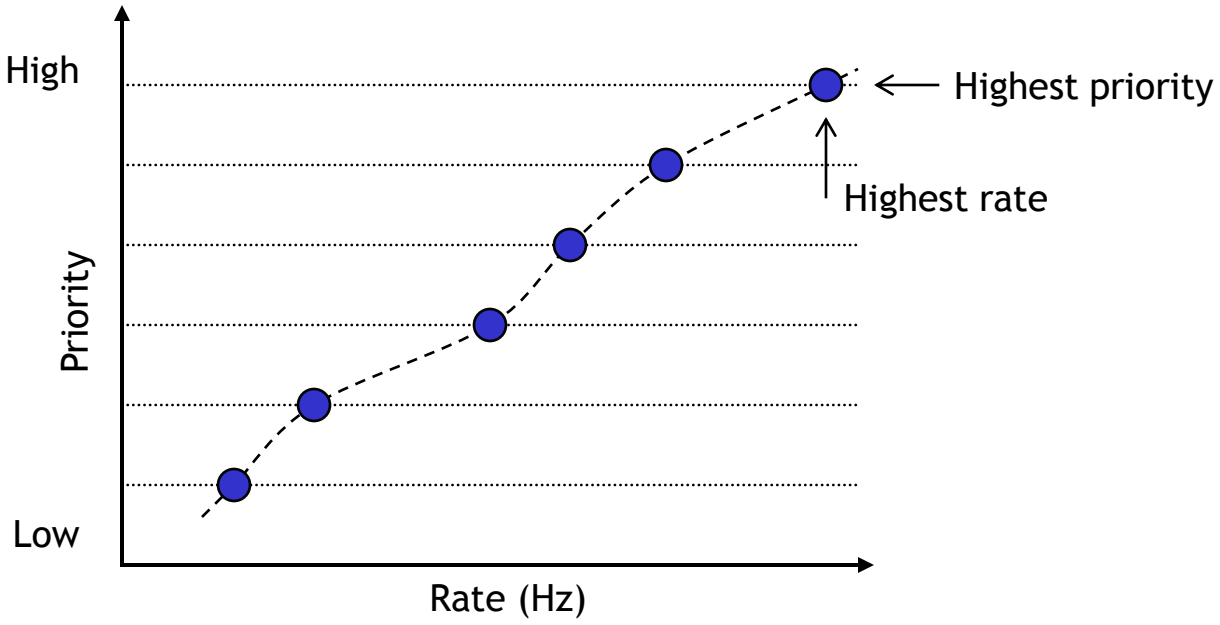
Rate Monotonic Scheduling

- Each task has
  - A period T
  - An execution time C for each occurrence
- In uniprocessor systems
  - C < T
  - Processor Utilization is U = C/T (<100%)



Rate Monotonic Scheduling

- Assigns priorities to tasks
  - On the basis of their periods
  - Shortest period task has highest priority



Rate Monotonic Scheduling

- A measure of a the effectiveness of a periodic scheduling algorithm is its capability to meet deadlines
- Consider N tasks with
  - A fixed period T_i
  - A fixed execution time C_i
- To meet all deadlines, the processor utilizations of individual tasks must not exceeds the available computational power and another condition

$$\sum_{i=1}^{N} \frac{C_i}{T_i} \leq 1 \qquad \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_n}{T_n} \leq n(2^{1/n} - 1)$$

RMS - schedulability analysis

- The total utilization of the tasks must be less than the upper bound
- Examples of upper bounds
  - n=2: 0.82
  - n=4: 0.75
  - n=6:0.73
  - ...
  - n->∞:0.693 (ln 2)
- The same constraint also holds for Earliest Deadline scheduling
- It is possible to achieve greater processor utilization with the EDF scheduling, nevertheless RMS is widely used for industrial applications…why?

RMS wins over EDF?

- Performance difference is small in practice
  - upper bound is conservative, usage of 90% frequent
- Most Hard RT systems also have soft RT components
  - e.g. built-in self test, displays, … can execute with low priority to absorb processor time left by RMS
- Stability is easier to achieve with RMS
  - in case system problems(e.g. due to transient errors), deadlines of essential tasks must be guaranteed
  - in static priority assignment one only need to ensure that essential tasks have relatively high priorities
  - in RMS is sufficient to organize essential tasks to have short periods or to modify RMS priority
  - in EDF a periodic task's priority can change from one period to another, difficult to meet deadlines

RT Scheduling - Addendum

Cyclic Scheduling

Deterministic Scheduling

Capacity-Based Scheduling

Dynamic Priority Scheduling

Scheduling Tasks with Imprecise Results

Scheduling

- Cyclic Scheduling
- Deterministic Scheduling
- Capacity-Based Scheduling
- Dynamic Priority Scheduling
- Scheduling Tasks with Imprecise Results

Cyclic Executive

- A cyclic executive is a supervisory control program
- It schedules tasks according to schedule constructed during the system design phase
- The schedule consists of a sequence of action to be taken
- Long-term external conditions are used to choose a schedule for execution

Cyclic Scheduling(1)

- The cyclic executive provides a practical means for executing a *cyclic schedule*
- The cyclic schedule is a timed sequence of computations which is to be repeated indefinitely, in a cyclic manner

Cyclic Scheduling(2)

- Event-based processing can be handled with the cyclic schedule in different ways
  - Higher priority to the processes that are reacting to events
  - Allocate slots in scheduling where aperiodic, event-based processes can be serviced
  - Service aperiodic events in the background

Cyclic Scheduling (3)

- Deterministic scheduling theory may be used to help find schedules
- Optimal deterministic scheduling algorithms require *a priori* knowledge
- Optimal non-preemptive scheduling of computations with timing constraints is NP-Hard

Cyclic Scheduling(4)

- Advantages
  - Simple to implement, efficient, predictable
- Critical issues
  - Design
  - Runtime: the system cannot adapt to a dynamically changing environment
  - Maintenance: the code may reflect job splitting and sequencing details of the schedule

Deterministic Scheduling(1)

- It provides methods for constructing schedules in which the assignment of tasks to processors is known exactly for each point in time
- Information needed a priori:
  - Vector processing time
  - Arrival time
  - Deadline
  - Priority
  - Task splitting (preemption vs non-preemption)

Deterministic Scheduling(2)

- A schedule is an assignment of processors to tasks

- Each task in a schedule has:
  - -Completion time
  - -Flow time
  - -Lateness
  - -Tardiness
  - -Unit penalty

- Schedules are evaluated using:
  - -Schedule length
  - -Mean flow time
  - -Mean weigthed flow time
  - -Maximum lateness
  - -Mean tardiness
  - -Mean weigthed tardiness
  - -Number of tardy tasks

Deterministic Scheduling(3)

- Properties of scheduling:
  - Not only measures for evaluating but also criteria for optimization
- Many of optimization problems are NP-hard
- Approximate solutions are found by relaxing some assumption

Deterministic Scheduling(4)

- Limits of deterministic schedule:
  - The computation times are not known in advance
  - Time to produce a schedule is larger than the time it takes to service the tasks
  - Tasks arrive dynamically, updated schedule is needed

Capacity-Based Scheduling(1)

- Requirements:
  - Information about the amount of computation
  - The amount of computation available
- For a restricted class of real-time activities it's possible to determine if a task is schedulable

Capacity-Based Scheduling(2)

- Assumptions:
  - Each task in the task set must be periodic
  - The deadline is the end of the period
  - The computation time must be constant
  - Neither communication nor synchronization between tasks
  - No critical regions in any of the computation

Capacity-Based Scheduling(3)

- Schedule by using fixed priority preemptive scheduling
  - Order the tasks according to their frequency
  - Assign integer priorities to the tasks
  - The higher priority assigned to highest frequency task
- This is called: Rate Monotonic Priority Assignment

Dynamic Priority Scheduling(1)

- Task priorities may change
- The approach:
  - Define a selection discipline
  - Make on-line scheduling decisions
  - Consider the instantaneous state of the system

Dynamic Priority Scheduling(2)

- Earliest-deadline-first:
  - All tasks are ready at time t=0
  - The computations are non-preemptive
  - If the algorithm can schedule without missing any deadlines it minimizes the maximum lateness in the task set.

Dynamic Priority Scheduling(3)

- Least-slack-time:
  - The slack-times the amount of time that the task can be delayed without missing its deadline
  - Order tasks according to nondecreasing slack-time
  - It maximizes minimum task lateness and minimum task tardiness

Scheduling Tasks with Imprecise Results(1)

- Considerations:
  - A certain amount of processor time will produce a reasonably accurate result.
  - Any additional processing time will increase the accuracy
- Each task is considered to be diveded into:
  - A mandatory subtask
  - An optional subtask

Scheduling Tasks with Imprecise Results(2)

- The schedule guarantees:
  - All mandatory subtasks will be completed by their deadlines.
  - The optinal subtasks are scheduled in the remaining processor time.
- Scheduling algorithms:
  - Mandatory subtasks: traditional deterministic scheduling theory
  - Optional subtasks: various scheduling criteria