Roadmap

- Overview of the RTSJ
- Memory Management
- Clocks and Time
- Scheduling and Schedulable Objects
- Asynchronous Events and Handlers
- Real-Time Threads
- Asynchronous Transfer of Control
- Resource Control
- **Schedulability Analysis**

Scheduling

- Lecture aims
  - To understand the role that scheduling and schedulability analysis plays in predicting that real-time applications meet their deadlines
    - Simple process model
    - The cyclic executive approach
    - Process-based scheduling. Utilization-based schedulability tests
    - Response time analysis for FPS and EDF
    - Worst-case execution time,
    - Sporadic and aperiodic processes
    - Process systems with D < T
    - Process interactions, blocking and priority ceiling protocols
    - Dynamic systems and on-line analysis

Scheduling

- In general, a scheduling scheme provides two features:
  - An algorithm for ordering the use of system resources (in particular the CPUs)
  - A means of predicting the worst-case behaviour of the system when the scheduling algorithm is applied
- The prediction can then be used to confirm the temporal requirements of the application

Simple Process Model

- The application is assumed to consist of a fixed set of processes
- All processes are periodic, with known periods
- The processes are completely independent of each other
- All system's overheads, context-switching times and so on are ignored (i.e, assumed to have zero cost)
- All processes have a deadline equal to their period (that is, each process must complete before it is next released)
- All processes have a fixed worst-case execution time

Standard Notation

`B`	Worst-case blocking time for the process (if applicable)
`C`	Worst-case computation time (WCET) of the process
`D`	Deadline of the process
`I`	The interference time of the process
`N`	Number of processes in the system
`P`	Priority assigned to the process (if applicable)
`R`	Worst-case response time of the process
`T`	Minimum time between process releases (process period)
`U`	The utilization of each process (equal to C/T)
`a-z`	The name of a process

Cyclic Executives

- One common way of implementing hard real-time systems is to use a cyclic executive
- Here the design is concurrent but the code is produced as a collection of procedures
- Procedures are mapped onto a set of minor cycles that constitute the complete schedule (or major cycle)
- Minor cycle dictates the minimum cycle time
- Major cycle dictates the maximum cycle time

Has the advantage of being fully deterministic

Properties

- No actual processes exist at run-time; each minor cycle is just a sequence of procedure calls
- The procedures share a common address space and can thus pass data between themselves. This data does not need to be protected (via a semaphore, for example) because concurrent access is not possible
- All "**process**" periods must be a multiple of the minor cycle time

Problems with Cycle Executives

- The difficulty of incorporating processes with long periods; the major cycle time is the maximum period that can be accommodated without secondary schedules
- Sporadic activities are difficult (impossible!) to incorporate
- The cyclic executive is difficult to construct and difficult to maintain — it is a NP-hard problem
- Any "process" with a sizable computation time will need to be split into a fixed number of fixed sized procedures (this may cut across the structure of the code, and may be error-prone)
- More flexible scheduling methods are difficult to support
- Determinism is not required, but predictability is

Process-Based Scheduling

- Scheduling approaches
  - Fixed-Priority Scheduling (FPS)
  - Earliest Deadline First (EDF)
  - Value-Based Scheduling (VBS)

Fixed-Priority Scheduling (FPS)

- This is the most widely used approach and is the main focus of this course
- Each process has a fixed, static, priority which is computer pre-run-time
- The runnable processes are executed in the order determined by their priority
- In real-time systems, the "priority" of a process is derived from its temporal requirements, not its importance to the correct functioning of the system or its integrity

FPS and Rate Monotonic Priority Assignment

- Each process is assigned a (unique) priority based on its period; the shorter the period, the higher the priority
- i.e, for two processes `i` and `j`,

$$T_i < T_j \Rightarrow P_i > P_j$$

- This assignment is optimal in the sense that if any process set can be scheduled (using pre-emptive priority-based scheduling) with a fixed-priority assignment scheme, then the given process set can also be scheduled with a rate monotonic assignment scheme
- Note, priority 1 is the lowest (least) priority

Example Priority Assignment

Process	Period, T	Priority, P
a	25	5
b	60	3
c	42	4
d	105	1
e	75	2

Utilisation-Based Analysis

- For D=T task sets only
- A simple sufficient but not necessary schedulability test exists

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq N(2^{1/N} - 1)$$

$$U \leq 0.69 \text{ as } N \text{ ® } \infty$$

Utilization Bounds

N	Utilization bound
1	100.0%
2	82.8%
3	78.0%
4	75.7%
5	74.3%
10	71.8%

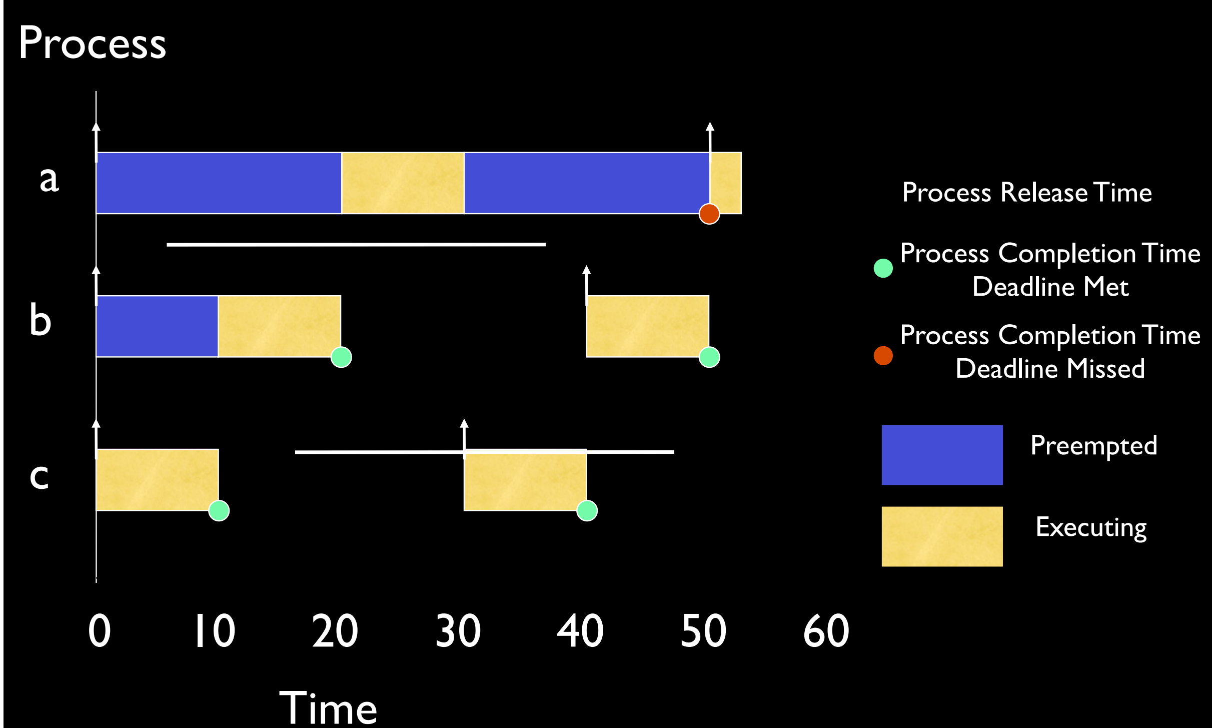
Approaches 69.3% asymptotically

Process Set A

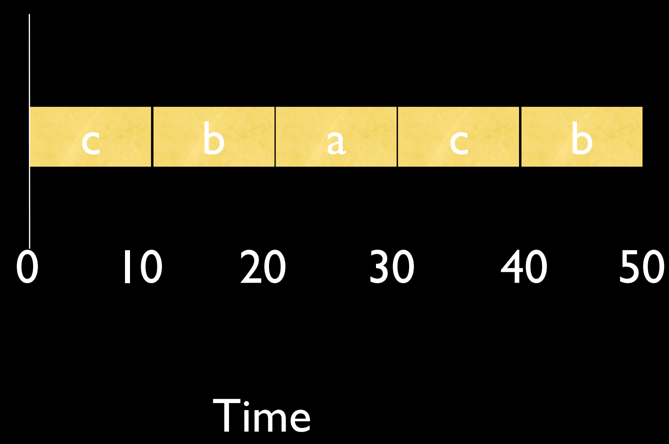
Process	Period T	ComputationTime C	Priority P	Utilization U
a	50	12	1	0.24
b	40	10	2	0.25
c	30	10	3	0.33

- The combined utilization is 0.82 (or 82%)
- This is above the threshold for three processes (0.78) and, hence, this process set fails the utilization test

Time-line for Process Set A



Gantt Chart for Process Set A



Process Set B

Process	Period T	ComputationTime C	Priority P	Utilization U
a	80	32	1	0.400
b	40	5	2	0.125
c	16	4	3	0.250

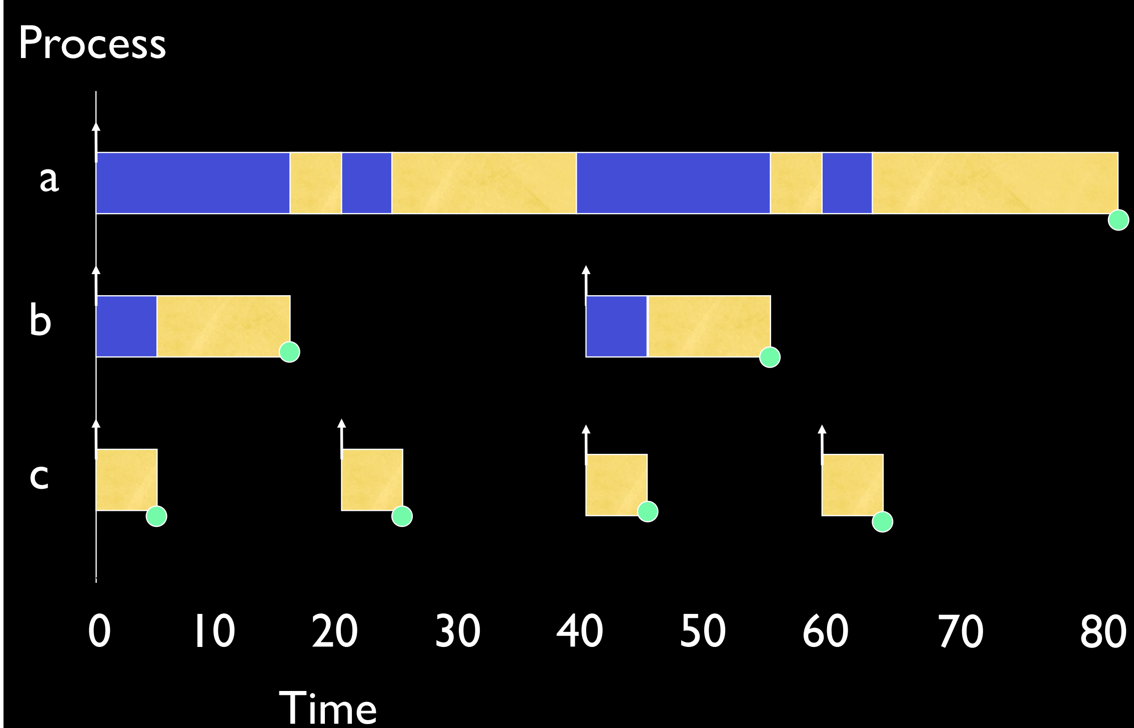
- The combined utilization is 0.775
- This is below the threshold for three processes (0.78) and, hence, this process set will meet all its deadlines

Process Set C

Process	Period T	ComputationTime C	Priority P	Utilization U
a	80	40	1	0.50
b	40	10	2	0.25
c	20	5	3	0.25

- The combined utilization is 1.0
- This is above the threshold for three processes (0.78) but the process set will meet all its deadlines

Time-line for Process Set C



Criticism of Utilisation-based Tests

- Not exact
- Not general
- BUT it is O(N)

The test is said to be **sufficient** but not **necessary**

Response-Time Analysis

- Here task i's worst-case response time, R, is calculated first and then checked (trivially) with its deadline

$$R_i \leq D_i$$

Where I is the interference from higher priority tasks

Calculating R

During R, each higher priority task j will execute a number of times:

$$\text{Number of Releases} = \left\lceil \frac{R_i}{T_j} \right\rceil$$

The ceiling function $\lceil \; \rceil$ gives the smallest integer greater than the fractional number on which it acts. So the ceiling of 1/3 is 1, of 6/5 is 2, and of 6/3 is 2.

Total interference is given by:

$$\left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

Response Time Equation

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

Where $hp(i)$ is the set of tasks with priority higher than task i

Solve by forming a recurrence relationship:

$$w_i^{n+1} = C_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

The set of values $w_i^0, w_i^1, w_i^2, \ldots, w_i^n, \ldots$ is monotonically non decreasing

When $w_i^n = w_i^{n+1}$ the solution to the equation has been found, w_i^0 must not be greater that R_i (e.g. 0 or C_i)

Process Set D

Process	Period	ComputationTime	Priority
	T	C	P
a	7	3	3
b	12	3	2
c	20	5	1

ECS 2009

Revisit: Process Set C

Process	Period T	ComputationTime C	Priority P	Response time R
a	80	40	1	80
b	40	10	2	15
c	20	5	3	5

- The combined utilization is 1.0
- This was above the ulilization threshold for three processes (0.78), therefore it failed the test
- The response time analysis shows that the process set will meet all its deadlines

Response Time Analysis

- Is sufficient and necessary
- If the process set passes the test they will meet all their deadlines; if they fail the test then, at run-time, a process will miss its deadline (unless the computation time estimations themselves turn out to be pessimistic)

Worst-Case Execution Time - WCET

- Obtained by either measurement or analysis
- The problem with measurement is that it is difficult to be sure when the worst case has been observed
- The drawback of analysis is that an effective model of the processor (including caches, pipelines, memory wait states and so on) must be available

WCET— Finding C

Most analysis techniques involve two distinct activities.

- The first takes the process and decomposes its code into a directed graph of basic blocks
- These basic blocks represent straight-line code
- The second component of the analysis takes the machine code corresponding to a basic block and uses the processor model to estimate its worst-case execution time
- Once the times for all the basic blocks are known, the directed graph can be collapsed

Need for Semantic Information

```
for I in 1.. 10 loop
  if Cond then
    -- basic block of cost 100
  else
    -- basic block of cost 10
  end if;
end loop;
```

- Simple cost 10*100 (+overhead), say 1005.
- But if `Cond` only true on 3 occasions then cost is 375

Sporadic Processes

- Sporadics processes have a minimum inter-arrival time
- They also require D<T
- The response time algorithm for fixed priority scheduling works perfectly for values of D less than T as long as the stopping criteria becomes
- It also works perfectly well with any priority ordering — hp(i) always gives the set of higher-priority processes

Hard and Soft Processes

- In many situations the worst-case figures for sporadic processes are considerably higher than the averages
- Interrupts often arrive in bursts and an abnormal sensor reading may lead to significant additional computation
- Measuring schedulability with worst-case figures may lead to very low processor utilizations being observed in the actual running system

General Guidelines

Rule 1 — all processes should be schedulable using average execution times and average arrival rates

Rule 2 — all hard real-time processes should be schedulable using worst-case execution times and worst-case arrival rates of all processes (including soft)

- A consequent of Rule 1 is that there may be situations in which it is not possible to meet all current deadlines
- This condition is known as a transient overload
- Rule 2 ensures that no hard real-time process will miss its deadline
- If Rule 2 gives rise to unacceptably low utilizations for "normal execution" then action must be taken to reduce the worst-case execution times (or arrival rates)

Aperiodic Processes

- These do not have minimum inter-arrival times
- Can run aperiodic processes at a priority below the priorities assigned to hard processes, therefore, they cannot steal, in a pre-emptive system, resources from the hard processes
- This does not provide adequate support to soft processes which will often miss their deadlines
- To improve the situation for soft processes, a server can be employed.
- Servers protect the processing resources needed by hard processes but otherwise allow soft processes to run as soon as possible.
- POSIX supports Sporadic Servers

Process Sets with D < T

$$D_i < D_j \Rightarrow P_i > P_j$$

- For D = T, Rate Monotonic priority ordering is optimal
- For D < T, Deadline Monotonic priority ordering is optimal

D < T Example Process Set

Process	Period T	Deadline D	ComputationTime C	Priority P	Response time R
a	20	5	3	4	3
b	15	7	3	3	6
c	10	10	4	2	10
d	20	20	3	1	20

Process Interactions and Blocking

- If a process is suspended waiting for a lower-priority process to complete some required computation then the priority model is, in some sense, being undermined
- It is said to suffer priority inversion
- If a process is waiting for a lower-priority process, it is said to be blocked

Response Time and Blocking

$$R_i = C_i + B_i + I_i$$

$$R_i = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

$$w_i^{n+1} = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

Dynamic Systems and Online Analysis

- There are dynamic soft real-time applications in which arrival patterns and computation times are not known **a priori**
- Although some level of off-line analysis may still be applicable, this can no longer be complete and hence some form of on-line analysis is required
- The main task of an on-line scheduling scheme is to manage any overload that is likely to occur due to the dynamics of the system's environment
- EDF is a dynamic scheduling scheme that is an optimal
- During transient overloads EDF performs very badly. It is possible to get a cascade effect in which each process misses its deadline but uses sufficient resources to result in the next process also missing its deadline

Admission Schemes

- To counter this detrimental domino effect, many on-line schemes have two mechanisms:
  - an admissions control module that limits the number of processes that are allowed to compete for the processors, and
  - an EDF dispatching routine for those processes that are admitted
- An ideal admissions algorithm prevents the processors getting overloaded so that the EDF routine works effectively

Values

- If some processes are to be admitted, whilst others rejected, the relative importance of each process must be known
- This is usually achieved by assigning value
- Values can be classified
  - Static: the process always has the same value whenever it is released.
  - Dynamic: the process's value can only be computed at the time the process is released (because it is dependent on either environmental factors or the current state of the system)
  - Adaptive: here the dynamic nature of the system is such that the value of the process will change during its execution
- To assign static values requires domain specialists to articulate their understanding of the desirable behavior of the system

Summary

- A scheduling scheme defines an algorithm for resource sharing and a means of predicting the worst-case behaviour of an application when that form of resource sharing is used.
- With a cyclic executive, the application code must be packed into a fixed number of minor cycles such that the cyclic execution of the sequence of minor cycles (the major cycle) will enable all system deadlines to be met
- The cyclic executive approach has major drawbacks many of which are solved by priority-based systems
- Simple utilization-based schedulability tests are not exact

Summary

- Response time analysis is flexible and caters for:
  - Periodic and sporadic processes
  - Blocking caused by IPC
  - Cooperative scheduling (not covered)
  - Arbitrary deadlines (not covered)
  - Release jitter (not covered)
  - Fault tolerance (not covered)
  - Offsets (not covered)
- RT Java supports preemptive priority-based scheduling
- RT Java addresses dynamic systems with the potential for on-line analysis