Implementing Task Schedulers (2)

Real-Time and Embedded Systems (M)

Lecture 11

UNIVERSITY *of* GLASGOW

Lecture Outline

- Real-time as *part of* a larger embedded system
- Open system architecture
  - Discussion of concepts
  - Advantages and disadvantages
  - Implementation using a two level scheduler
- Case study of an open system: RTLinux

Reading for this lecture: Chapters 7.9 and 12.5–12.7

Real-time Embedded Systems

- What is an embedded system?
  - "An embedded system is a special-purpose computer system built into a larger device."
  - "An embedded system is some combination of computer hardware and software, either fixed in capability or programmable, that is specifically designed for a particular kind of application device. Industrial machines, automobiles, medical equipment, cameras, household appliances, airplanes, vending machines, and toys (as well as the more obvious cellular phone and PDA) are among the myriad possible hosts of an embedded system."

⇒ Special purpose, limited resources, not generally upgradeable

Real-time Embedded Systems

- Embedded systems are *closed*:
  - Run a fixed suite of applications, known a-priori
  - Tasks are scheduled according to some well-known algorithm
  - Generally static and require predictability
  - Prove, or exhaustively demonstrate, correctness
  - Limited resources, tailored to the task at hand
  - Dedicated operating systems, scheduler support, etc.
- Embedded systems form part of the wider world:
  - Interact with the world through sensors and actuators
  - Often part of a wider system, comprising other embedded and general purpose systems
- Separation of concerns:
  - Embedded controllers engineered separately to other systems, including other embedded systems

Open Architecture for Real-Time Systems

- The advantage of a traditional embedded system is that resources are dedicated; predictability is guaranteed
- Disadvantage: resources are dedicated and typically underused
- Ensures predictability, but wasteful since many applications have both general-purpose and real-time components

- Desire a single system that can run general purpose and real-time applications simultaneously
  - An *open system architecture* that can support many different classes of application, removing the distinction between embedded and general purpose systems
  - Not always suitable, but can give large savings for some application types

Open System Architecture: Objectives

- Independent design choice
  - The developer of an application can use a scheduling discipline best suited to that application to control execution and resource access, independent of other applications on system
- Independent validation
  - If the system validates assuming it runs alone on a processor with normalised speed *S*, it will run on a virtual share of a real processor with equivalent performance
- Independent admission and timing guarantees
  - New applications subjected to an admission test before they are scheduled. If the admission test is passed, and the application accepted as a real-time task, the open system will guarantee its schedulability, regardless of other applications in the system

Independently developed and validated real-time applications can share a system with other real time and non-real time applications

Implementation

- Should be clear that the open system architecture can only be implemented on a strictly partitioned *virtual machine*
  - Partition processor time
  - Control access to global resources

- Each application to run submits its requirements (e.g. task characteristics, type of scheduler needed, etc.) to a virtual machine monitor that performs an acceptance test
  - The monitor partitions the physical resources into distinct virtual machines and runs schedulers for each application
  - The partitioning can be implemented using a *two-level scheduler*

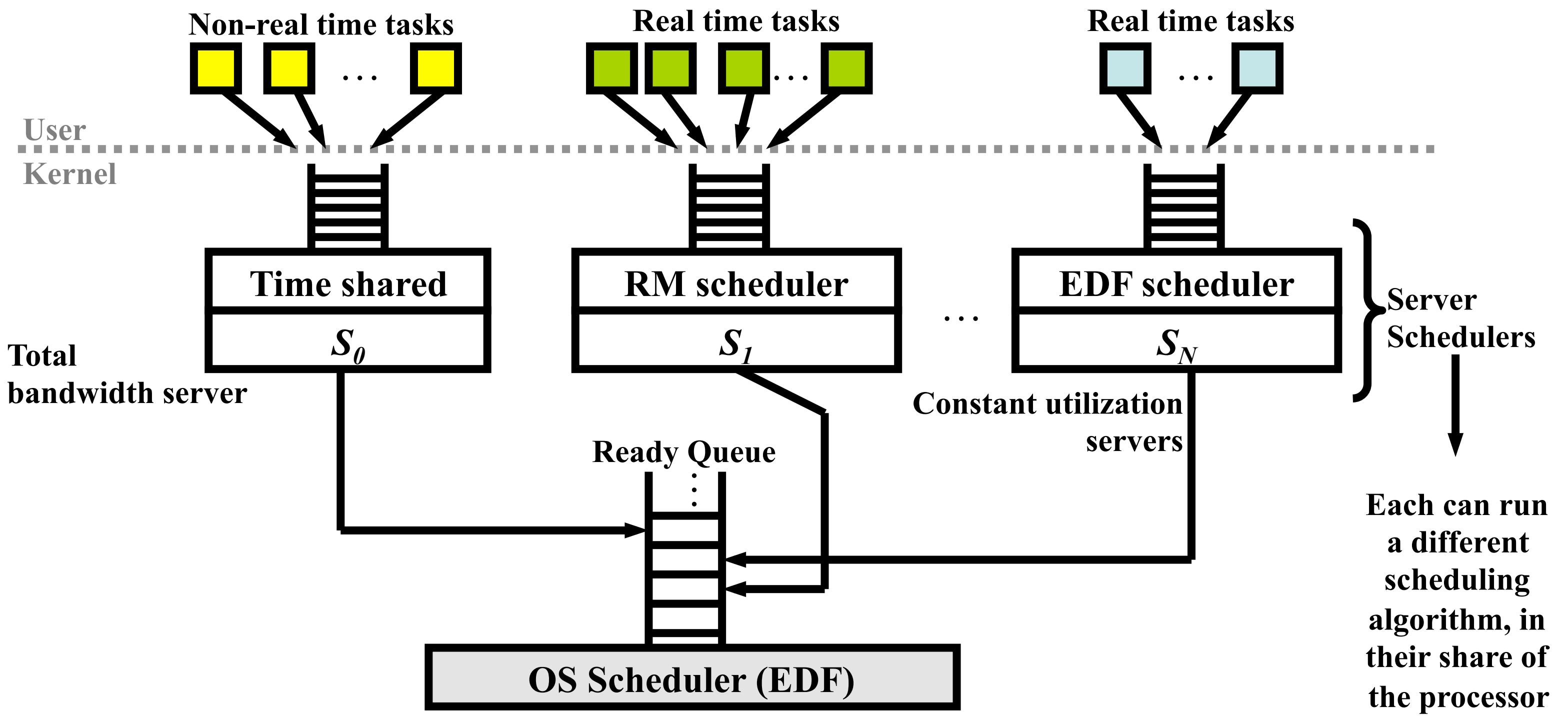
Two-Level Scheduler

- Recall:
  - A *constant utilization server* consumes a fraction $\tilde{u}_i$ of the processor
  - A *total bandwidth server* uses at least a fraction $\tilde{u}_i$ and claims idle time
  - Both run under an EDF scheduling algorithm and are defined by certain consumption and replenishment rules

- Consider a system comprising:
  - A set of constant utilization servers S_i for $i = 1, 2, \ldots, n$ each using fraction $\tilde{u}_i$ of the processor
  - A total bandwidth server, S_0, using a fraction $\geq \tilde{u}_0$
  - An EDF scheduler, running these servers
- If total size of the servers less than some threshold, they will fairly share a processor with S_0
  - The threshold – the maximum schedulable utilization – depends on the properties of the server tasks, and their workload

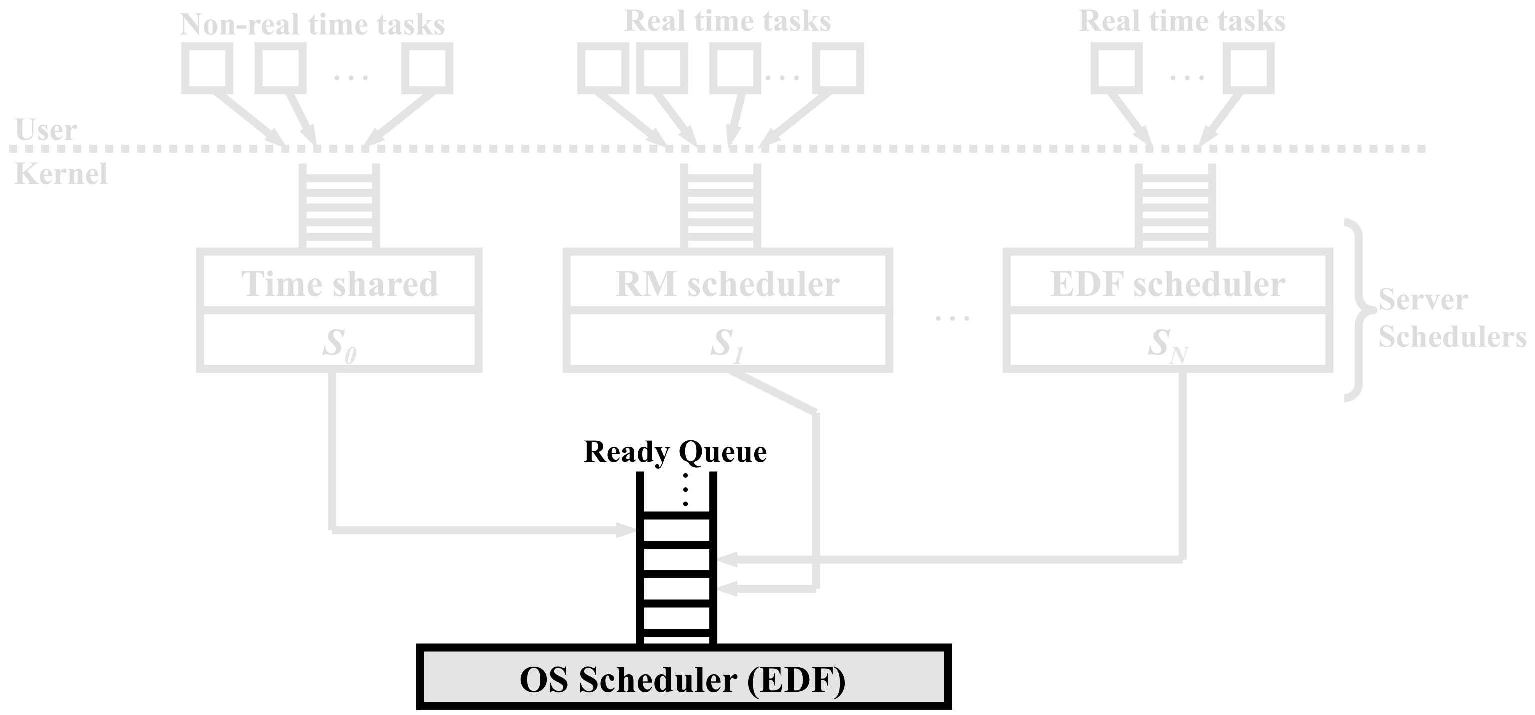
Operation of a Two-Level Scheduler

- The servers, S_i, are scheduled according to an EDF algorithm by the *OS scheduler*
- Each server runs an internal *server scheduler* to schedules jobs within the server, subdividing the time allocated to that server



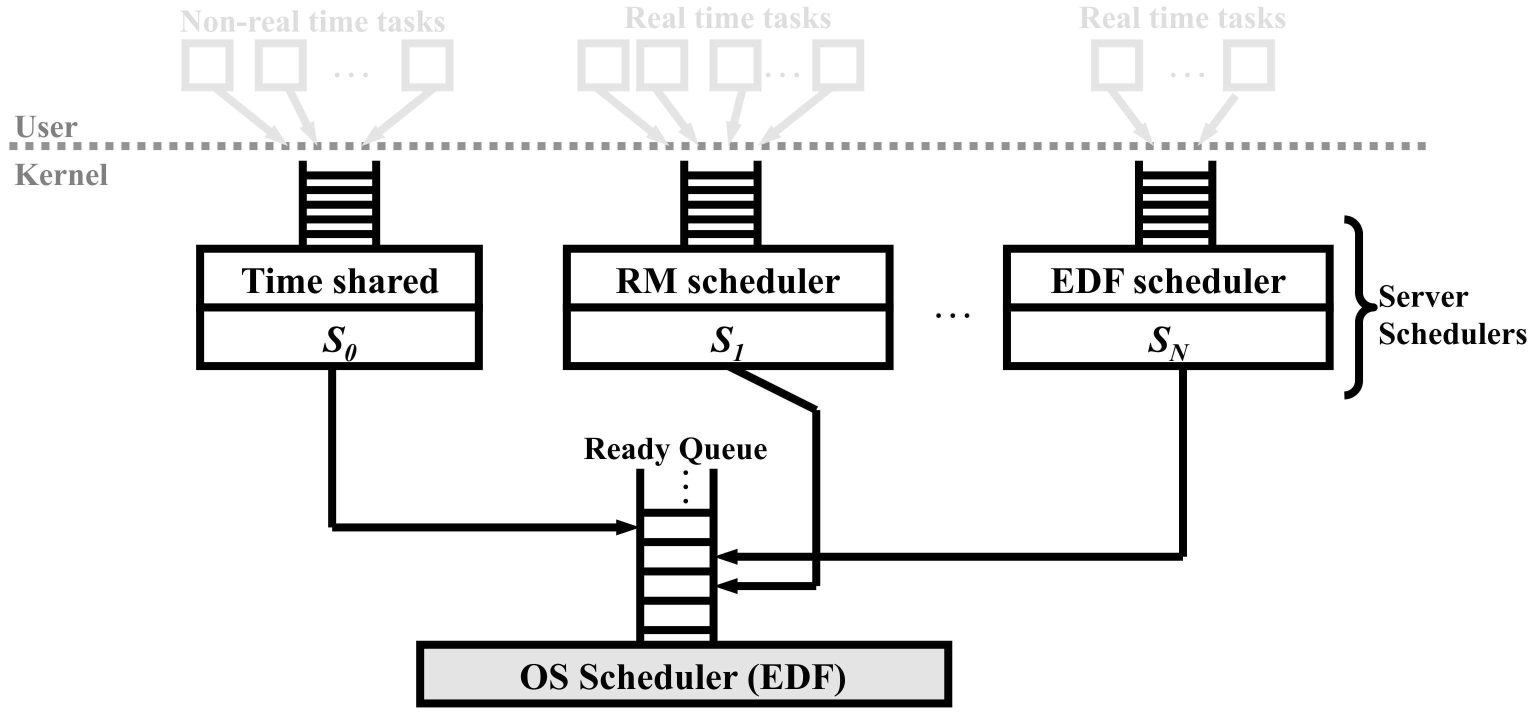
Operation of a Two-Level Scheduler

- The OS scheduler maintains an EDF ready queue, used to select which server to execute
  - Servers are eligible to run if they have work to do, and budget remaining
  - The server with the earliest deadline among the ready servers is scheduled



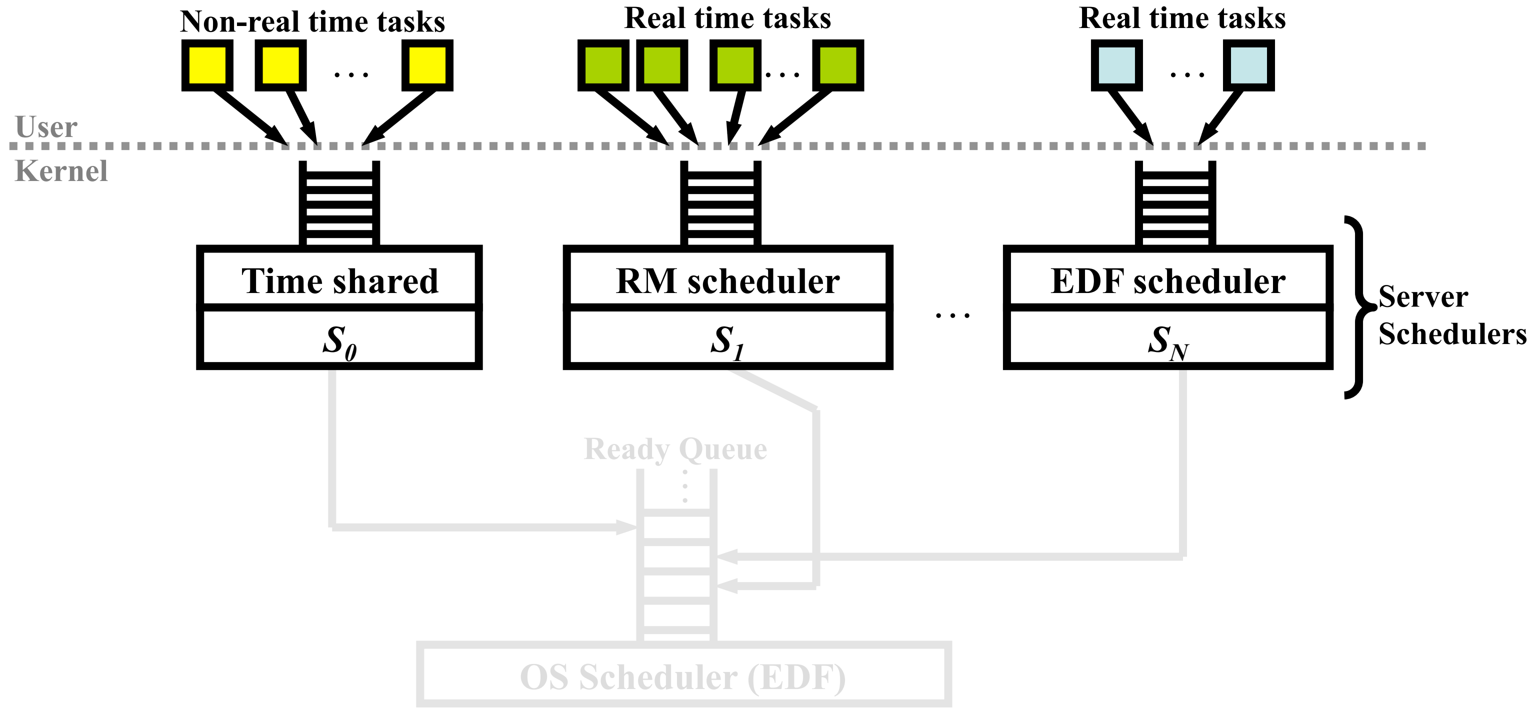
Operation of a Two-Level Scheduler

- Both levels of scheduler are implemented in the kernel, to avoid doubling the context switch overhead
  - Applications see a virtual machine: their server and its internal scheduler
  - The underlying OS scheduler is invisible to applications



Operation of a Two-Level Scheduler

- Servers maintain a list of the tasks comprising the applications running on that virtual machine
  - When executed by the OS scheduler, the server scheduler picks one of these threads to execute, according to its local policy
  - Each server scheduler can have different policy, and schedule its threads according to a different algorithm



Types of Application

- Each application running on the system is allocated a server
- The jobs comprising the application can be:
  - Non-real time
  - Real-time and predictable
  - Real-time and unpredictable

- For EDF scheduling, the OS scheduler needs to know when the next scheduling event – *deadline* – will occur on each server
  - Non-real time applications have no deadlines
  - Predictable real-time applications have known event times
  - Unpredictable applications must be estimate time of next event
- Server execution budgets are replenished and deadlines set based on event times of their applications

Non-Real Time Applications

- A total bandwidth server S_0 internally schedules the non-real time tasks according to a time sharing algorithm with time slice x
- Replenishment rules for the server:
  - When starting:
    - the server budget is set to x
    - the deadline is set to $x/\tilde{u}_0$ ($\tilde{u}_0 < 1$ so deadline scaled out)
  - When budget exhausted at time t, if there are ready jobs:
    - the server budget is reset to x
    - the deadline is set to either $t+x/\tilde{u}_0$ or current deadline plus $x/\tilde{u}_0$, whichever is greater
  - When a busy interval ends:
    - the server budget is reset to x
    - the deadline is set to the current time plus $x/\tilde{u}_0$
- Ensures non-real time applications scheduled as if on a slower processor with speed $\tilde{u}_0$

Real-Time Applications

- To schedule real-time applications, the underlying OS scheduler needs to know when each event that will trigger a context switch will occur

- Depends on the application:
  - An application scheduled according to a pre-emptive priority algorithm is *unpredictable* if it contains aperiodic or sporadic tasks, or periodic tasks with significant release time jitter
    - Occurrence of scheduling events only known at run-time
  - Other applications are *predictable*, since they contain only periodic tasks with fixed release times and known resource access patterns
    - The scheduler can compute event times for predictable applications before the application begins execution

Predictable Applications

- Predictable applications contain periodic tasks with fixed release times and known resource access patterns
- These include:
  - Clock driven schedulers
  - Priority scheduled but not preemptable
  - Priority scheduled and preemptable, with known event times

- Each can run on a constant utilization server, and meet deadlines, but each type of predictable task has slightly different constraints
  - The *required capacity* of the task
  - Replenishment rules for the server

Predictable Applications: Required Capacity

- A real-time application has to meet timing constraints
- To do this, it has been verified to need a certain amount of execution time, *e*

- The job is to run on a slower processor, speed $u < 1$
  - u denotes the fraction of the original processor speed
- Can multiply the execution time *e* of all jobs by $^1/_u$ to check if the system is still schedulable on the slow processor

- The minimum fraction of speed at which the application is schedulable is its *required capacity*, and is a critical parameter when scheduling jobs on the open system

Clock Driven Scheduling

- A clock driven scheduler is characterised by a cyclic frame of size f and the workload appears to the server as a single thread
- Scheduled on a constant utilization server of size $\tilde{u}_i$ equal to required capacity
  - Ready for execution at the start of each cyclic frame
  - Execution time of $f \cdot \tilde{u}_i$ each cycle
  - Budget replenished each cycle, deadline set to beginning of next cycle
- Loops using a fixed fraction of the processor time

- The server executes the application according to its pre-computed cycle

Priority Scheduled Non-preemptable Tasks

- Priority scheduled non-preemptable tasks can also be scheduled by a constant utilization server
  - The server scheduler orders jobs in the application within its allocation according to the scheduling algorithm requested by the application
  - Since jobs are non-preemptable, the server must not be pre-empted while a job is running
    - Otherwise a job could be pre-empted by another server running on the OS scheduler
- This limits maximum schedulable utilization of the complete system (not just this server):
  - Let B denote maximum execution time of all jobs
  - Let D_{min} denote the minimum relative deadline of all jobs
  - All servers are schedulable provided $\Sigma\tilde{u}_i < 1\text{-}B/D_{min}$
  - Implications on the acceptance test for the open system, since EDF non-optimal in this case

Priority Scheduled Preemptable Tasks

- Preemptable priority scheduled tasks executed on a server that is similar to a constant utilization server, but with slightly different replenishment rules

- Why different rules?
  - Consider two jobs J_1 and J_2 running on a slow processor with speed 0.25
    - Each job has execution time 0.25
    - Job J_1 is released at 0.5 and must complete by 1.5
    - Job J_2 is released at 0.0 and must complete by 2.0
  - Execution:
    - Job J_2 starts at time 0.0, by time 0.5 has executed for 0.125
    - Job J_1 starts at time 0.5, pre-empts J_2, and executes to completion by 1.5
    - Job J_2 resumes at 1.5, executes to completion at 2.0
    - All deadlines are met

Priority Scheduled Preemptable Tasks

- Consider the same jobs, on a constant utilization server of size ¼ on a normal speed processor
- A possible scenario is:
  - Job J_2 starts at time 0.0 with server budget 0.25 and deadline 1
  - Job J_2 uses the budget, and completes before time 0.5
  - Job J_1 is released at time 0.5, but the server budget is gone
  - At time 1.0 the server budget is replenished to 0.25 and its deadline set to 2.0; the server is eligible to run, and will execute job J_1 when it runs
  - Because the server deadline is 2.0, the server may not execute until after J_1 has missed it's deadline at 1.5

- Problem: J_2 consumed more execution time than it would on the slow processor, preventing J_1 from running
  - Used 0.25 compared to 0.125 on slow processor
  - Can be considered a form of priority inversion

Priority Scheduled Preemptable Tasks

- When running preemptable priority scheduled applications, the server uses slightly modified replenishment rules to avoid this problem
  - Let t be latest of the current deadline, or current time
  - Let t' be the release time of the next job in the task
  - Budget $= \min(e_i, (t' - t) \cdot \tilde{u}_i)$
  - Deadline $= \min(t + e_i / \tilde{u}_i, t')$

- These rules prevent jobs consuming more time than they would on a slower processor, if they would be limited by pre-emption, by explicitly taking into account pre-emption time

- With this slight modification, preemptable priority scheduled applications can be supported

Predictable Applications

- Have shown that we can support the following classes of predictable application using a constant utilization server, perhaps with slightly modified rules for budget replenishment
  - Clock driven schedulers
  - Priority scheduled but not preemptable
  - Priority scheduled and preemptable, with known event times
- The applications behave as if running on a slower processor, with the expected utilization

Unpredictable Applications

- If jobs unpredictable, cannot derive accurate replenishment rules
  - Run the server under the constant utilization rules, giving $q\tilde{u}_i$ units of budget every q time units
  - The scheduling quantum, q, is a key parameter
- The server can over-budget the application up to the size of the scheduling quantum
  - Can result in priority inversion, as before…

- If a bound, t', on time to the next event can be given, the server can be scheduled with
  - Budget $= (t' + q - t).s_i$
  - Deadline $= t' + q$
- Bounds the size of the scheduling quantum, and hence the duration of any priority inversion

Summary of Scheduling Behaviour

- Given certain constraints, can schedule non-real time and predictable real-time applications with correct behaviour
- Unpredictable real-time applications may see occasional priority inversion of their jobs

- Applications are isolated from each other, provided an acceptance test is enforced to ensure constraints are met

Scheduling Overhead

- Might think that the two-level scheduler is very inefficient
- Not so if all applications are predictable:
  - Same number of context switches
  - More work to determine what to run, but insignificant compared to context switch overhead
- In unpredictable applications running, overhead depends on the scheduling quantum
  - Small quantum gives better real-time performance, at the expense of more overheads
  - 30% overhead not unusual, but may still be better than using dedicated hardware

- If unpredictable jobs are rare, the two level scheduler works well and allows real-time and non-real-time jobs to share a processor

Admission Control

- All jobs start execution in non-real time mode, so they don't disrupt already running real-time jobs
- A job may switch to real-time scheduling on its own server, subject to an acceptance test
- Jobs must provide:
  - Required capacity $\tilde{u}_i$ and scheduling algorithm
  - Maximum execution time B_i of all non-preemptable sections
  - Existence of aperiodic/sporadic tasks, if any
  - Shortest relative deadline D_{min}

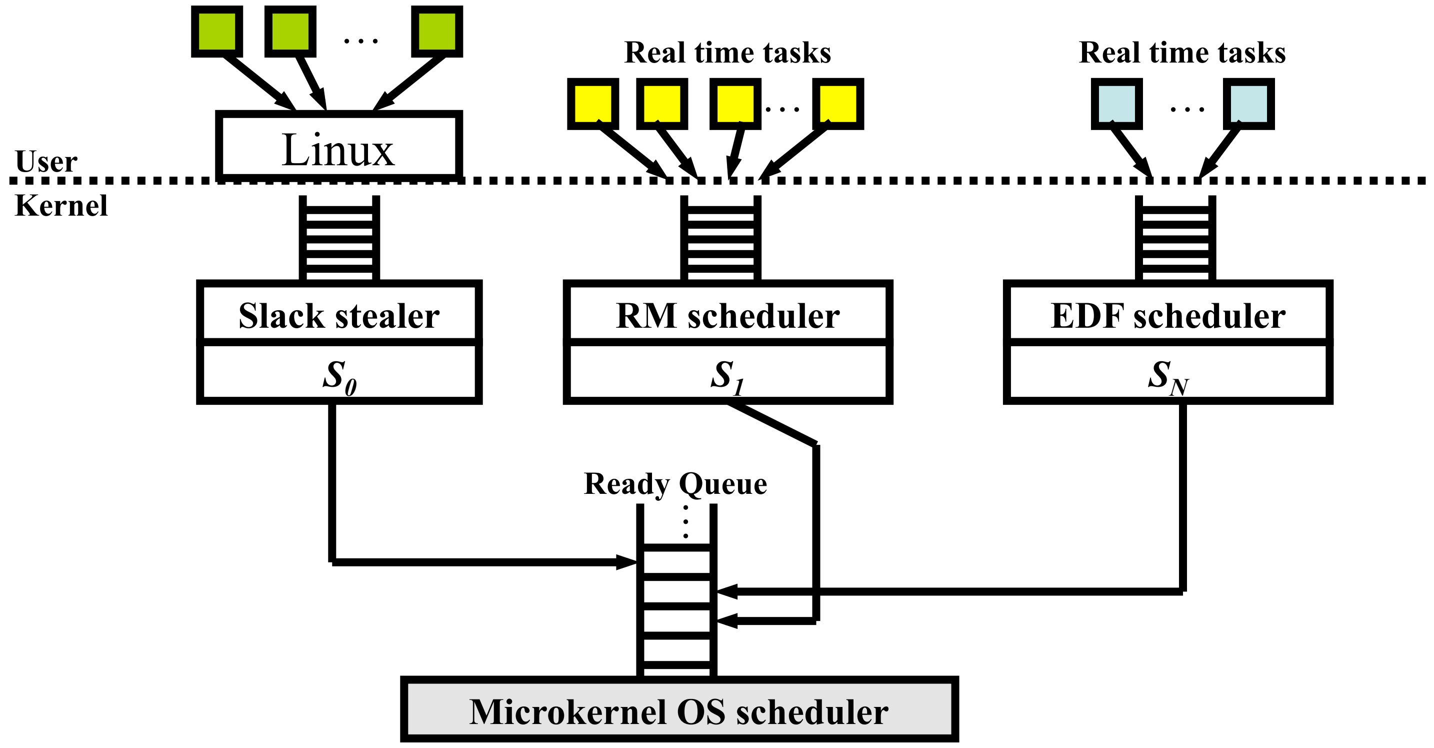
- Job is accepted if $\Sigma\tilde{u}_i < 1 - \max(B_i/D_{min})$

Summary

- The open system architecture provides a conceptually clean way to share resources between tasks with different requirements
- Disadvantage:
  - Several applications share a hardware resource, so failure of the hardware or OS scheduler can take down an entire set of applications
  - Trade-off cost saving for potential reduction in reliability
- Full concept not widely implemented:
  - Prototype demonstrated within Windows NT
  - Similar, but less powerful, systems are widely used commercially:
    - Symbian mobile phones running a real-time microkernel to handle the voice processing, with SymbianOS running as a background task to support the UI and user applications
    - RTLinux

Case Study: RTLinux

- A simple example of a two-level scheduler
  - The OS scheduler is a microkernel real-time operating system
  - Real-time tasks run directly on the microkernel
    - RM and EDF schedulers provided
  - Linux runs as the idle task



Case Study: RTLinux

- A modified Linux kernel runs above the microkernel
  - All hardware access is arbitrated by the microkernel
  - Interrupts emulated in software on the microkernel
  - Linux can *always* be pre-empted if a real-time task needs to run
- Communication between real-time and non-real-time tasks done by FIFO buffers, locked into memory
  - Appear as normal devices (**`/dev/rft1`**) under Linux
  - Non-blocking and atomic access from the real-time kernel

- Conceptually, RTLinux maps closely onto the open system architecture
  - Differs in the details

Summary

By now, you should know…

- Concepts of real-time on embedded systems
- The idea of an open system architecture, to support a range of application types on a single system
- Strategies for implementing the open system architecture, using a two-level scheduler
- Overview of RTLinux, as a simple system using a two-level scheduler

- See also the "Xen and the art of virtualisation" paper from the Advanced Topics in Computing Science module