Introduction to Real-Time Process Scheduling

郭大維 教授
ktw@csie.ntu.edu.tw
嵌入式系統暨無線網路實驗室
(Embedded Systems and Wireless Networking Laboratory)
國立臺灣大學資訊工程學系

Introduction to Real-Time Process Scheduling

- Q: Many theories and algorithms in real-time process scheduling seem to have simplified assumptions without direct solutions to engineers' problems. Why should we know them?
- A:
  - ◆ Provide insight in choosing a good system design and scheduling algorithm.
  - ◆ Avoid poor or erroneous choices.

Introduction to Real-Time Process Scheduling

- Checklist
  - ⊕ What do we really know about the rate monotonic (RM) and the earliest deadline first (EDF) scheduling?
  - ⊕ What is known about uniprocessor real-time scheduling problems?
  - ⊕ What is known about multiprocessor real-time scheduling problems?
  - ⊕ What is known about energy-efficient real-time scheduling problems?
  - ⊕ What task-set characteristics cause NP-hard?
  - ⊗ What is the impact of overloads on the scheduling results?
  - ⊗ What do we really know about theories for off-line schedulability such as the rate monotonic analysis?

Introduction to Real-Time Process Scheduling

Time

Job Shop Scheduling

Independent Process Scheduling
(Liu & Layland, 1973, etc.)

Multiprocessor Process Scheduling
(Dhall, 1972-, etc.)

Process Scheduling with Non-Preemptable Resources
(Mok, 1983, Sha, Rajkumar, 1986, Baker, 1991, etc.)

Sporadic Process Scheduling
(Sprunt, 1989, etc.)

Non-preemptable Scheduling
(Baruah, 1990-, etc.)

Process Scheduling with Probabilistic Guarantee
(Liu, Lehoczky, etc, since 1995.)

Process Scheduling with End-to-End Delays
(Stankovic, Gerber, Lin, etc, since ?.)

Process Scheduling with Realistic Task Characteristics
(Liu, Mok, etc, since 1996.)

Process Scheduling with Multiple Resources
(??)

Rate-Based Scheduling
(Buttazzo, Liu, Brauah, Kuo, etc, since 1995.)

Energy-Efficient Process Scheduling
(Mosse, Hakan Chen, Kuo, etc)

Multiprocessor Process Scheduling
(Barauh, Anderson, etc.)

Introduction to Real-Time Process Scheduling

Uniprocessor Process Scheduling

- *Rate Monotonic Scheduling*
- *Earliest Deadline First Scheduling*
- *Priority Ceiling Protocol*
- *Important Theories*

Reading: Stankovic, et al., "Implications of Classical Scheduling Results for Real-Time Systems," IEEE Computer, June 1995, pp. 16-25.
Krishna and Shin, "Real-TimeSystems," McGRAW-HILL, 1997.

Process Model

- Periodic process
  - each periodic process arrives at a regular frequency - a special case of demand.
    - **r**: ready time, **d**: relative deadline, **p**: period, **c**: maximum computation time.
  - For example, maintaining a display
- Sporadic process
  - An aperiodic process with bounded inter-arrival time p.
  - For example, turning on a light
- Other requirements and issues:
  - process synchronization including precedence and critical sections, process value, etc.

Performance Metrics

- Metrics for hard real-time processes:
  - Schedulability, etc.
- Metrics for soft real-time processes:
  - Miss ratio
  - Accumulated value
  - Response time, etc.
- Other metrics:
  - Optimality, overload handling, mode-change handling, stability, jitter, etc.
  - Combinations of metrics.

Basic definitions:

- Preemptive scheduling: allows process preemptions. (vs non-preemptive scheduling)
- Online scheduling: allocates resources for processes depending on the current workload. (vs offline scheduling)
- Static scheduling: operates on a fixed set of processes and produces a single schedule that is fixed at all time. (vs dynamic scheduling)
- Firm real-time process: will be killed after it misses its deadline. (vs hard and soft real-time)
- Fixed-priority scheduling: in which the priority of each process is fixed for any instantiation. (vs dynamic-priority scheduling)

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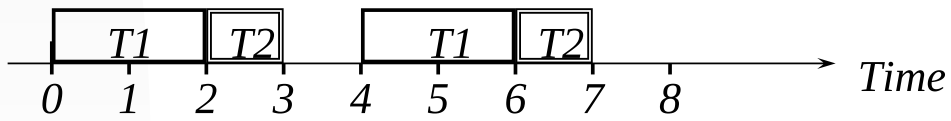
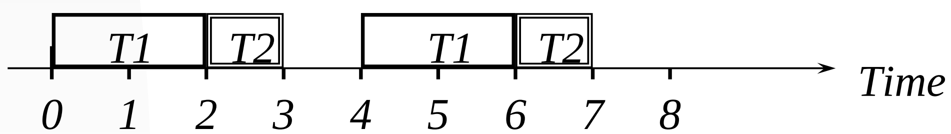
Rate Monotonic Scheduling Algorithm

- Assumptions:
  - all periodic fixed-priority processes
  - relative deadline = period
  - independent process - no non-preemptable resources
- Rate Monotonic (RM) Scheduling Algorithm
  - RM priority assignment: priority ~ 1/period.
  - preemptive priority-driven scheduling.
- Example: T1 (p1=4, c1=2) and T2 (p2=5, c2=1)



Rate Monotonic Scheduling Algorithm

- Critical Instant [1]
  - An instant at which a request of the process have the largest completion/response time.
  - An instance at which the process is requested simultaneously with requests of all higher priority processes
- Usages
  - Worst-case analysis
  - Fully utilization of the processor power
  - Example: T1 (p1=4, c1=2) and T2 (p2=5, c2=1→2)



[1] *Liu and Layland, "Scheduling Algorithms for multiprogramming in a hard real-time Environment," JACM, vol. 20, no. 1, January 1973, pp. 46-61.*

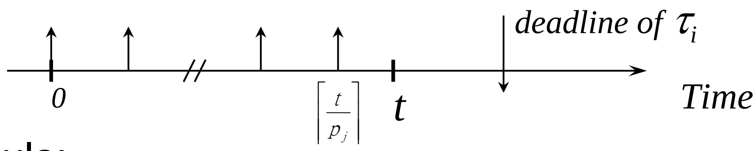
Rate Monotonic Scheduling Algorithm

- Schedulability Test:
  - A sufficient but not necessary condition
  - Achievable utilization factor α
    - of a scheduling policy P -> any process set with total utilization factor $\sum \frac{c_i}{p_i}$ no more than α is schedulable.
  - Given n processes, $\alpha = n\left(2^{1/n} - 1\right)$
- Stability:
  - Let processes be sorted in RM order. The ith process is schedulable if $\sum_{j=1}^{i} \frac{c_j}{p_j} \le i\left(2^{1/i} - 1\right)$
- An optimal fixed priority scheduling algorithm

Rate Monotonic Scheduling Algorithm

- Rate Monotonic Analysis (RMA) [2]
  - Basic Idea:

    Before time t after the critical instance of process τ_i, a high priority process τ_j may request $c_j \left\lceil \frac{t}{p_j} \right\rceil$ amount of computation time.



  - Formula:

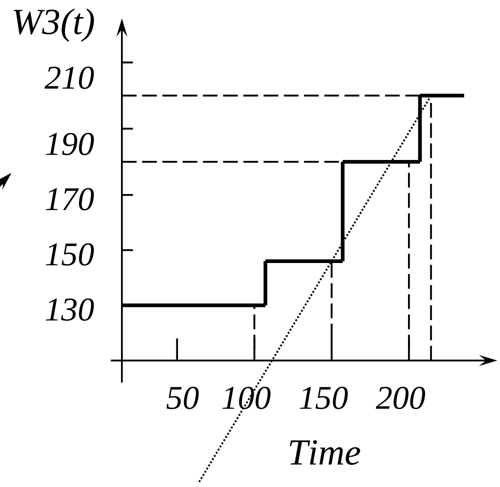
$$W_i(t) = \sum_{j=1}^{i} c_j \left\lceil \frac{t}{p_j} \right\rceil \le t \le d_i \qquad \text{for some } t \text{ in } \{ kp_j \mid j = 1, \ldots, i;\ k = 1, \ldots, \lceil p_i / p_j \rceil \}$$

  - A sufficient and necessary condition and many extensions...

[2] *Sha, "An Intorduction to Rate Monotonic Analysis," tutorial notes, SEI, CMU, 1992*

Rate Monotonic Scheduling Algorithm

- A RMA Example:
  - T1(20,100), T2(30,150), T3(80, 210), T4(100,400)
  - T1
    - c1 <= 100
  - T2
    - c1 + c2 <= 100 or
    - 2c1 + c2 <= 150
  - T3
    - c1 + c2 + c3 <= 100 or
    - 2c1 + c2 + c3 <= 150 or
    - 2c1 + 2c2 + c3 <= 200 or
    - 3c1 + 2c2 + c3 <= 210
  - T4
    - c1 + c2 + c3 + c4 <= 100 or
    - 2c1 + c2 + c3 + c4 <= 150 or
    - ....

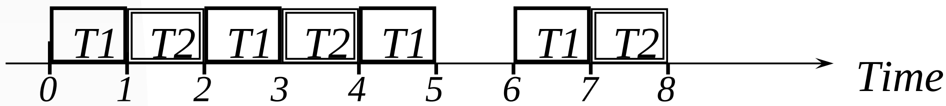


Rate Monotonic Scheduling Algorithm

- RM was chosen by
  - Space Station Freedom Project
  - FAA Advanced Automation System (AAS)
- RM influenced
  - the specs of IEEE Futurebus+
- RMA is widely used for off-line analysis of time-critical systems.

Earliest Deadline First Scheduling Algorithm

- Assumptions (similar to RM):
  - all periodic dynamic-priority processes
  - relative deadline = period
  - independent process - no non-preemptable resources
- Earliest Deadline First (EDF) Scheduling Algorithm:
  - EDF priority assignment: priority ~ absolute deadline. i.e.,arrival time **t** + relative deadline **d**.
  - preemptive priority-driven scheduling
- Example: T1(c1=1, p1=2), T2(c2=2, p2=7)



Earliest Deadline First Scheduling Algorithm

- Schedulability Test:
  - A sufficient and necessary condition
  - Any process set is schedulable by EDF iff

$$\sum_{j=1}^{i} \frac{c_j}{p_j} \le 1$$

- EDF is optimal for any independent process scheduling algorithms
- However, its implementation has considerable overheads on OS's with a fixed-priority scheduler and is bad for (transiently) overloaded systems.

Priority Ceiling Protocol

- Assumptions (as the same as RM for the first two):
  - all periodic fixed-priority processes
  - relative deadline = period
  - Non-preemptable resources guarded by semaphores
- Basic Ideas and Mechanisms:
  - Bound the priority inversions by early blocking of processes that could cause them, and
  - Minimize a priority inversion's length by allowing a temporary rise in the blocking process's priority.
- Contribution of the Priority Ceiling Protocol
  - Efficiently find a suboptimal solution with a clever allocation policy, guaranteeing at the same time a minimum level of performance.

Priority Ceiling Protocol

- Pre-requirements: nested critical sections!
- Priority Ceiling Protocol (PCP):
  - Define a semaphore's priority ceiling as the priority of the highest priority process that may lock the semaphore.
  - Lock request for a semaphore is granted only if the requesting process's priority is higher than the ceiling of all semaphores concurrently locked by other processes.
  - In case of blocking, the task holding the lock inherits the requesting process's priority until it unlocks the corresponding semaphore. (Def: priority inheritance)

[1] *Sha, Rajkumar, and Lehoczky, "Priority Inheritance Protocols: an Approach to Real-Time Synchronization," IEEE Transactions on computers, Vol. 39, No. 9, Sept. 1990, pp. 1,175-1,185.*

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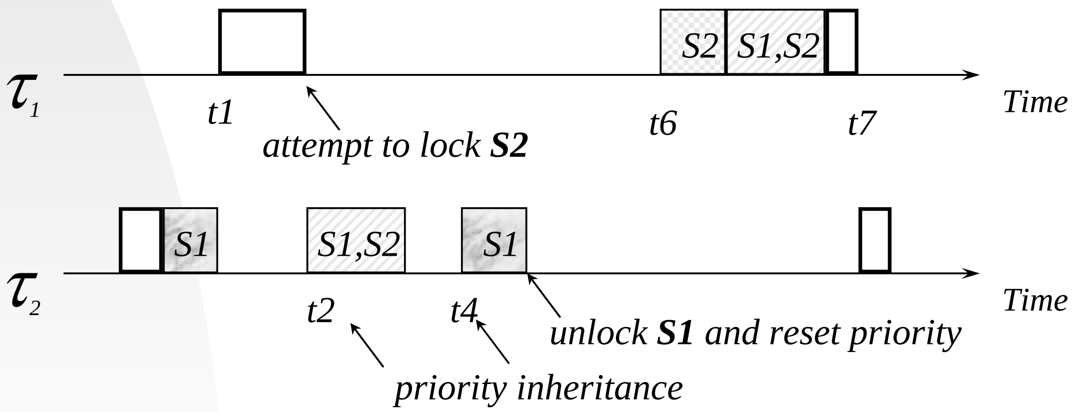
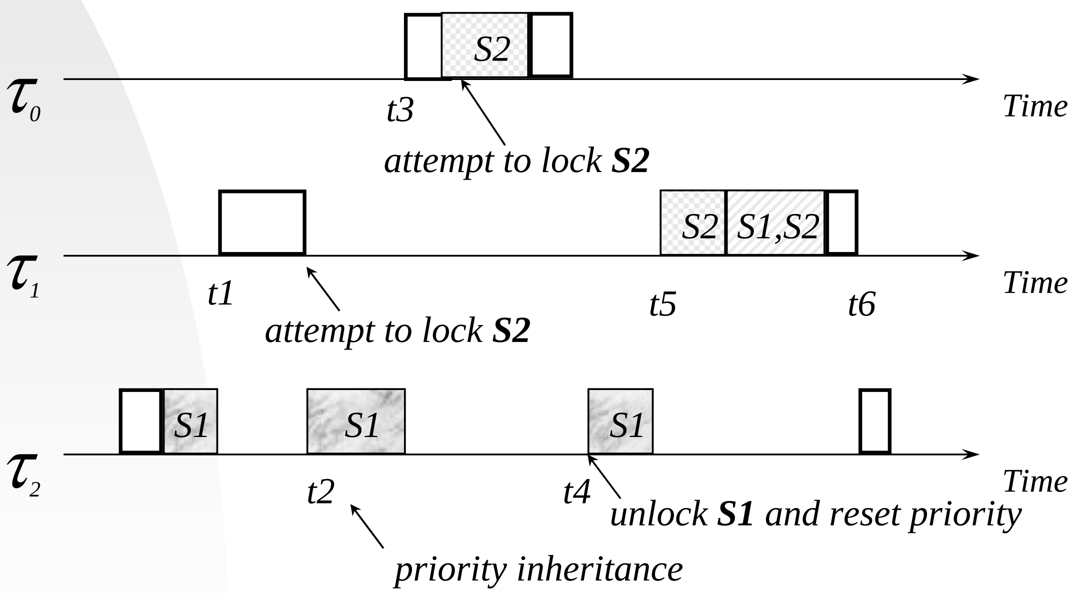
Priority Ceiling Protocol

- A PCP Example: deadlock avoidance



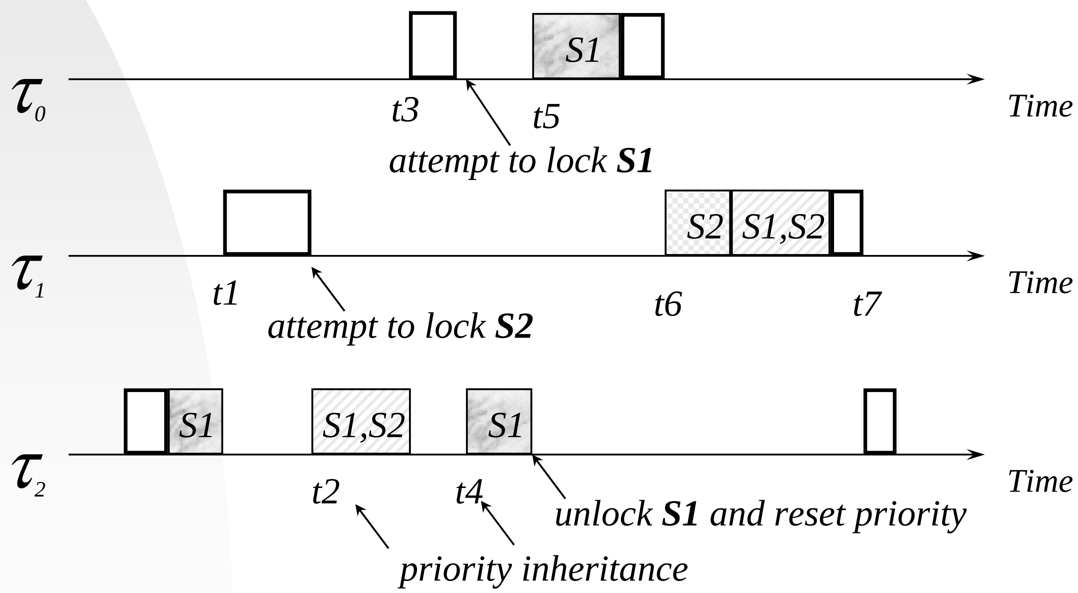
Priority Ceiling Protocol

- A PCP Example: avoid chain blocking



Priority Ceiling Protocol

- A PCP Example: one priority inversion



Priority Ceiling Protocol

- Important Properties:
  - A process is blocked at most once before it enters its critical section.
  - PCP prevents deadlocks.
- Schedulability Test of τ_i
  - worst case blocking time B_i - an approximation!
    - $S_j = \{ S \mid \text{semaphore } S \text{ is accessed by } \tau_j \}$
    - $BS_i = \{ \tau_j \mid j > i \ \&\ Max_{(s \text{ in } S_j)}(ceiling(s)) >= priority(\tau_i) \}$
    - $B_i = Max_{(\tau_j \text{ in } BS_i)} |critical\ section|$
  - Let processes be sorted in the RM priority order

$$\sum_{j=1}^{i-1} \left(\frac{c_j}{p_j}\right) + \frac{c_i + B_i}{p_i} \le i\left(2^{1/i} - 1\right)$$

Priority Ceiling Protocol

- Variations of PCP:
  - Stack Resource Policy - not permitted to start unless resources are all available.
    - ☞multi-units per resource
    - ☞dynamic and fixed priority assignments
  - Dynamic Priority Ceiling Protocol
    - ☞extend PCP into an EDF scheduler.

[2] *Baker, "Stack-Based Scheduling of Real-Time Processes," J. Real-Time Systems, Vol. 3, No. 1, March 1991, pp. 67-99.*
[3] *Chen and Lin, "Dynamic Priority Ceilings: A Concurrency Control Protocol for Real-time Systems," J. Real-Time Systems, Vol. 2, No. 4, Nov. 1990, pp. 325-340.*

Introduction to Real-Time Process Scheduling

Multiprocessor Process Scheduling

- *Important Theories*
- *Basic Approaches*

Reading: Stankovic, et al., "Implications of Classical Scheduling Results for Real-Time Systems," IEEE Computer, June 1995, pp. 16-25.
Krishna and Kang, "Real-TimeSystems," McGRAW-HILL, 1997.

Multiprocessor Process Scheduling

- Checklist
  - ⊕ Understand the boundary between polynomial and NP-hard problems to provide insights into developing useful heuristics.
  - ⊕ Understand the fundamental limitations of on-line algorithms to create robust system and avoid misconceptions and serious anomalies.
  - ⊕ Know the basic approaches in solving multiprocessing scheduling
- Remark: It is the area which we have very limited knowledge because of its complexity and our minimal experiences with multiprocessor systems.

Nonpreemptive Multiprocessor Scheduling

- Important Theorems[1]:
  - ◆ Conditions:
    - ☞Single deadline, identical processors, ready at time 0
  - ◆ Theorems: (“_”-marked items causes NP-completeness!)

Processors	*Resources*	*Ordering*	*Computation Time*	*Complexity*
2	*0*	*Arbitrary*	*Unit*	*Polynomial*[2]
2	*0*	*Independent*	*Arbitrary*	*NP-Complete*[3]
2	*0*	*Arbitrary*	*1 or 2 units*	*NP-Complete*[3]
2	*1*	*Forest*	*Unit*	*NP-Complete*[3]
3	*1*	*Independent*	*Unit*	*NP-Complete*[3]
N	*0*	*Forest*	*Unit*	*Polynomial*[4]
N	*0*	*Arbitrary*	*Unit*	*NP-Complete*[5]

1. Stankovic, et al., “Implications of Classical Scheduling Results for Real-Time Systems,” IEEE Computer, June 1995, pp. 16-25.
2. Coffman and Graham, “Optimal Scheduling for Two-Processor Systems,” ACTA Information, 1, 1972, pp.200-213.
3. Garey and Johnson, “Complexity Bounds for Multiprocessor Schedulingwith Resource Constraints,” SIAM J. Computing, Vol. 4, No.3, 1975, pp. 187-200.
4. Hu, “Parallel Scheduling and Assembly Line Problems,” Operating Research,, 9, Nov. 1961, pp. 841-848.
5. Ullman, “Polynomial Complete Scheduling Problem,” Proc. fourth Symp. Operating System Principles, ACM, 1973, pp. 96-101.

Preemptive Multiprocessor Scheduling

- Theorem of McNaughton in 1959.
  - Goal: Compare preemption and non-preemption.
  - Conditions:
    - ☞ identical processors.
  - Theorem 0: Given the metric to minimize the weighted sum of completion times, i.e., Sum($w_j c_j$), there exists a schedule with no preemption for which the performance is as good as for any schedule with a finite number of preemptions.
  - Note: It is NP-hard to find an optimal schedule! If the metric is to minimize the sum of completion times, the shortest-processing-time-first greedy approach is optimal.

McNaughton, "Scheduling with Deadlines and Loss Functions," Management Science, Vol. 6, No. 1, Oct. 1959, pp.1-12.

Preemptive Multiprocessor Scheduling

- Theorem of Lawler in 1983.
  - Goal: Show that heuristics are needed for real-time multiprocessor scheduling.
  - Conditions:
    - ☞ identical processors, different deadlines for processes.
  - Theorem 0: The multiprocessing problem of scheduling P processors with process preemption allowed and with minimization of the number of late processes is NP-hard.

Lawler, "Recent Results in the Theory of Machine Scheduling," Mathmatical Programming: The state of the Art, A. Bachen et al., eds., Springer-Verlag, New York, 1983, pp. 202-233.

Preemptive Multiprocessor Scheduling

- Theorems of Mok in 1983
  - Goal: Understand the limitations of EDF.
  - Conditions:
    - different ready times.
  - Theorem 0: Earliest-deadline-first scheduling is not optimal in the multiprocessor case.
  - Example, T1(c=1,d=1), T2(c=1,d=2), T3(c=3,d=3.5), two processors.
  - Theorem 1: For two or more processors, no deadline scheduling algorithm can be optimal without complete a priori knowledge of deadlines, computation times, and process start times.

A.K. Mok, "Fundamental Design Problems of Distributed Systems for the Hard Real-Time Environment," Ph.D. Thesis, Dept. of Electrical Engineering and Computer science, MIT, May 1983.

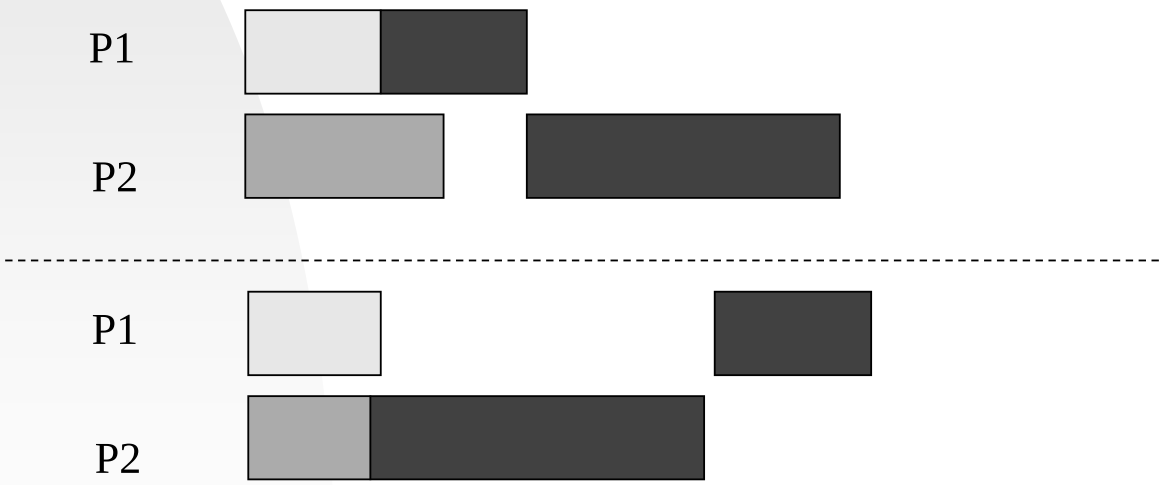
Multiprocessor Anomalies

- Theorem of Graham in 1976.
  - Goal: Notice anomaly and provide better design.
  - Conditions;
    - A set of processes is optimally scheduled on a multiprocessor with some priority order, fixed execution times, precedence constraints, and a fixed number of processors.
  - Theorem 0: For the stated problem, changing the priority list, increasing the number of processors, reducing execution times, or weakening the precedence constraints can increase the schedule length.

R. Graham, "Bounds on the Performance of Scheduling Algorithms," Computer and Job Shop Scheduling theory, E.G. Coffman, ed., John Wiley and Sons, 1976, pp. 165-227.

Multiprocessor Anomalies

- An Example



Multiprocessor Scheduling - Contemporary Approach

- Motivation:
  - The multiprocessor scheduling problem is NP-hard under any but the most simplifying assumptions.
  - The uniprocessor scheduling problem is usually tractable.
- Common Approach - 2 Steps
  - Assign processes to processors
  - Run a uniprocessor scheduling algorithm on each processor.
- Metrics:
  - Minimize the number of processors, fault tolerance, etc.

Multiprocessor Scheduling - Contemporary Approach

- However, the process assignment problem is again NP-hard in most cases.
- Heuristics:
  - Utilization balancing - balance workload of processors.[1]
  - Next-fit algorithm - used with RM. [2]
  - Bin-packing algorithm - set with a threshold and used with EDF [3], etc.
- Other considerations:
  - precedence constraints, dynamic overload handling, etc.

1. J.A. Bannister and K.S. Trivedi, "Task Allocation in Fault-Tolerance Distributed systems," Acta Informatica 20:261-281, 1983.
2. S. Davari and S.K. Dhall, "An On Line Algorithm for Real-Time Tasks Allocation," IEEE Real-Time Systems Symposium, 1986, pp.194-200, Dhall's Ph.D. thesis, UI.
3. D.S. Johnson, Near-Optimal Bin-Packing Algorithms," Ph.D. thesis, MIT, 1974.

Multiprocessor Scheduling

- Current Research
  - Classification: Migration(/Partition) & Static or Dynamic Priorities
  - Some Recent Results:
    - Utilization Bound = 42% by a bin-packing partitioning approach (JRTS, 1999)
    - Utilization Bound = 37.482% by RM-US – processes with a utlization > bound is given the highest priority; otherwise RM is adopted.
    - Utilization Bound = m – [(m-1)*Umax] if Umax <= 0.5, where Umax = max Ui. Or Utilization Bound = (m+1)/2+Umax if Umax > 0.5 – M-CBS (RTAS02)
    - Utilization Bound = 75% - EZDL (to appear)

Energy-Efficient Real-Time Task Scheduling

郭大維 教授
ktw@csie.ntu.edu.tw
嵌入式系統暨無線網路實驗室
(Embedded Systems and Wireless Networking Laboratory)
國立臺灣大學資訊工程學系

Introduction

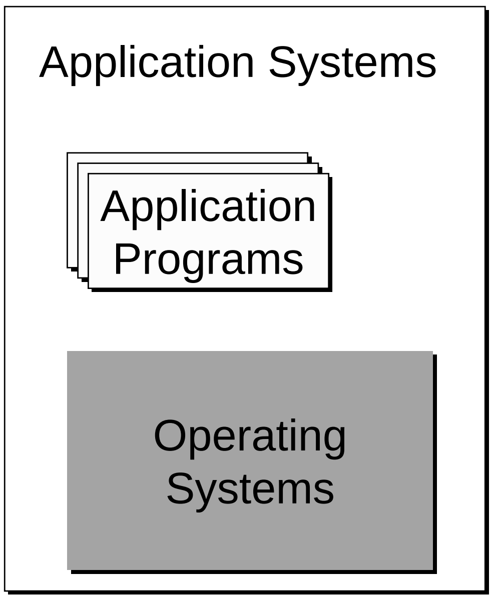
- Challenges in Embedded Systems Designs
  - Limited Resources
  - Limited Energy Supply
  - Variety in Product Designs
  - Strong Demands in Friendly User Interface
  - Strong Mutual Influence Between Hardware and Software Designs
  - Limited Lifetime in Many Products

Introduction

- Worlds are Getting More and More Complicated!
  - Processors with Voltage-Scaling Supports
  - I/O Devices with Different Voltage Supplies and Operating Modes
  - Communication Devices with Different Operating Modes
- Where To Save Energy Consumption?
  - Hardware Designs
  - Operating Systems/System Components Designs
  - Application Systems/Programs Designs

System Design Issues – Energy-Efficiency Designs

- Operating System Designs
- Application Program Designs
- Application System Designs



Operating System Designs

- Proper Voltage-Scaling Scheduling
  - HW Architectures, Task Characteristics, etc.
  - Task Scheduling, Multi-Resource Scheduling, etc.
- Intelligent Event Management
  - Idle Time, Synchronization, Multi-Event Waiting, etc.
- Intelligent Device Management
  - Device Status Scheduling, Request Scheduling, Polling-Style Programming, etc.

The Idle Task – *u*C/OS-II

- The idle task is always the lowest-priority task and can not be deleted or suspended by user tasks.
- To reduce power dissipation, you can issue a HALT-like instruction in the idle task.
  - Suspend services in OSTaskIdleHook()!!

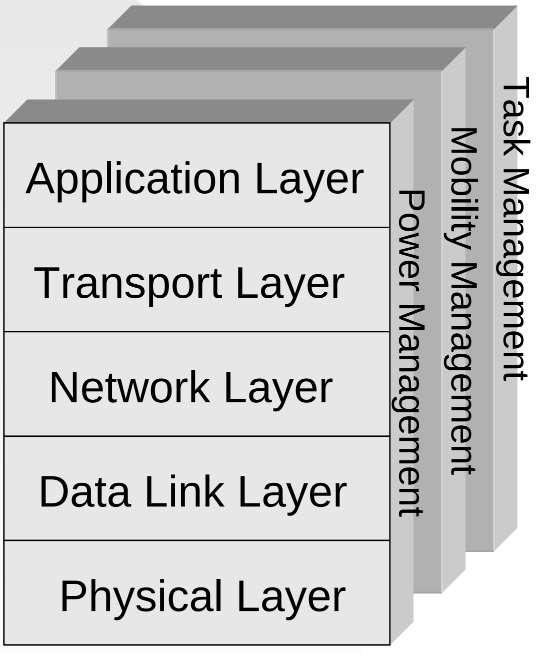
```
void  OS_TaskIdle (void *pdata)
{
#if OS_CRITICAL_METHOD == 3
   OS_CPU_SR  cpu_sr;
#endif


   pdata = pdata;
   for (;;) {
      OS_ENTER_CRITICAL();
      OSIdleCtr++;
      OS_EXIT_CRITICAL();
      OSTaskIdleHook();
   }
}
```

Application System Designs

- Application Characteristics
  - ◆ Assumptions, Optimization Goals, Architecture Choices, Topology Constraints, etc.
- Standard Constraints
  - ◆ Design Flexibility, Restrictions, Quality-of-Services, etc.
- Cross-Layer Optimization
  - ◆ Coupling Strength, Modularity, Upgradeability, etc.

Example Application System Designs – Adaptive Sensor Networks



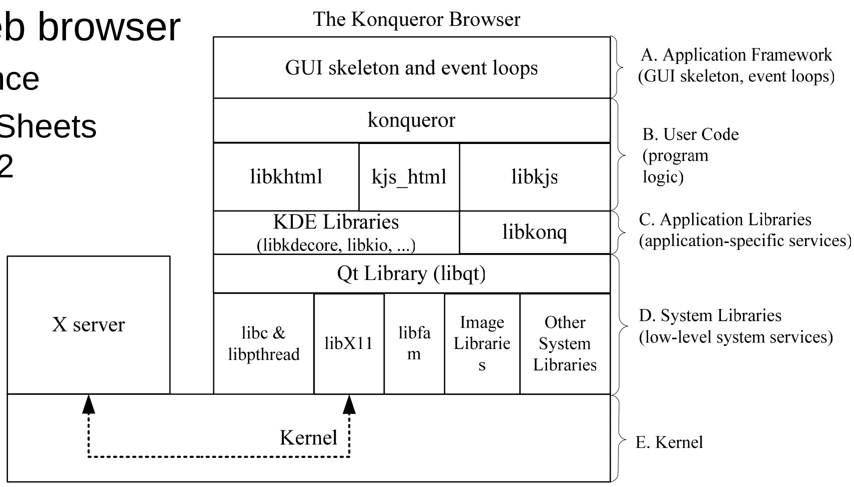
- Power Management
  - ◆ Consider power-efficiency for node and protocol designs.
- Mobility Management
  - ◆ Detect and manage nodes with dynamic movements.
- Task Management
  - ◆ Schedule and balance workloads performed by nodes.

Application Program Designs

- Application Characteristics
  - Design Logics, Hardware Supports, Resource Utilization & Patterns, etc.
- User/Process Behaviors
  - Bottleneck Identification, Program Structures, User Access Patterns, etc.

Case Study – Energy-Profiling of a Browser

- Konqueror
  - An open-source web browser running on Linux built upon a Qt application environment
  - A full-featured web browser
    - HTML 4 compliance
    - Cascading Style Sheets (CSS1) and CSS2
    - JavaScript
    - Java Applet
    - Flash
    - SSL, etc.



- Overheads
  - The profiling overheads were no more than 7% of the profiling system (Profiling Frequency = 20,000HZ).

Motivations on Energy-Efficient Process Scheduling

- Energy-Efficiency Considerations for Battery-Powered Embedded Systems
  - Operating Duration
  - Performance
- Dimensions in Problem Formulation
  - Architecture Considerations, e.g., Homogeneous/Heterogeneous Multiprocessors
  - Process Models, e.g., Frame-Based Process Sets
  - Processor Types, e.g., Available Processor Speeds

Definitions – Voltage Scaling and Power Consumption

- A Dynamic Voltage/Speed Scaling (*DVS*) system is a system that can execute tasks at different speeds.
  - A higher supply voltage results in a higher frequency (or higher execution speed).
    - $s = k * (V_{dd}-V_t)^2/(V_{dd})$, where
      - s is the corresponding speed of the supply voltage V_{dd} , and V_t is the threshold voltage
  - The dynamic power consumption function *P()* of the execution speeds is a convex function:
    - $P(s) = C_{ef}\, V_{dd}^2\, s$
    - $P(s) = C_{ef}\, s^3/k^2$, when $V_t = 0$

Example Voltage Scaling Processors:
Intel XScale, StrongARM, Transmeta, Intel Centrino

Dilemma – Performance versus Energy Consumption

- Definition: Energy-Efficient Process Scheduling
  - Given a process set with timing constraints and a set of processors with available processor speeds (and constraints), find a feasible schedule such that the energy consumption is minimized.

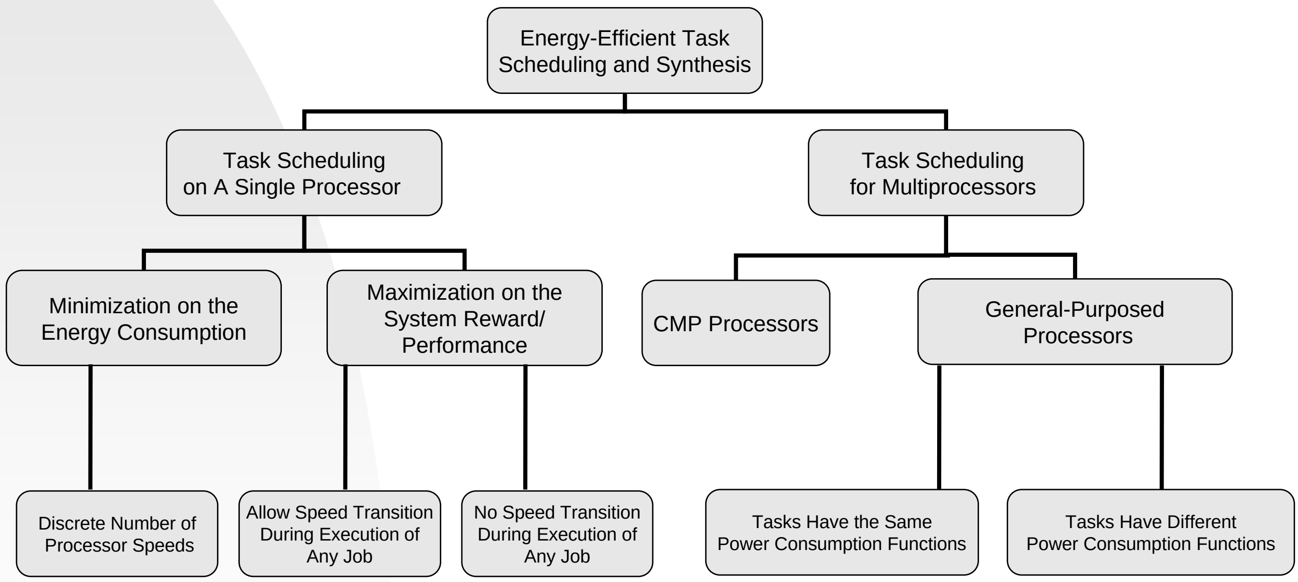
Task Models under Investigation

- Frame-Based Real-Time tasks
  - All the tasks are ready at time 0 and share a common deadline *D*.
  - Each task τ_i is associated with c_i amount of computation requirements.
- Periodic Real-Time Tasks
  - The job of each task τ_i arrives periodically in a period p_i after the first job of τ_i releases at time a_i.
  - Each task τ_i is associated with c_i amount of computation requirements.
  - The relative deadline of τ_i is equal to p_i.

Task Models under Investigation

- Aperiodic Real-Time Tasks
  - The job of each task τ_i might arrive with a minimum separation time p_i after the first job of τ_i releases at time a_i.
  - Each task τ_i is associated with c_i amount of computation requirements.
  - The relative deadline of τ_i is given as a constant d_i.
- Periodic Multi-Framed Real-Time Tasks
  - Periodic Real-Time Tasks
  - Each task τ_i is associated with a regular pattern of c_i amount of computation requirements in secutive periodis.

Our Roadmap on Energy-Efficient Process Scheduling



Potential Directions

- Realistic Task Models
- Leakage Current
- Process Synchronization
- Multi-Core System Architectures
- I/O Peripherial Considerations
- Complicated System Architectures

Papers to Study

- J. Stankovic, M. Spuri, M.D. Natale, G.C. Buttazo,"Implications of Classical Scheduling Results for Real-Time Systems," IEEE Computer, 1995
- C.L. Liu and J.W. Layland, "Scheduling Algorithms for Multiprogramming in a Hard Real-Time Environments," Journal of ACM, 1973.
- L. Sha, R. Rajkumar, J.P. Lehoczky, "Priority Inheritance Protocols: An Approach to Real-Time Synchronization," IEEE Transactions on Computers, 1990.

- http://140.112.28.119

Papers to Study

- A.K. Mok, “The Design of Real-Time Programming Systems Based on Process Models,” IEEE Real-Time Systems Symposium, Dec 1994.
- T.W. Kuo, Y.H. Liu, K.J. Lin, “Efficient On-Line Schedulability Tests for Priority Driven Real-Time Systems," the IEEE Real-Time Technology and Applications Symposium, June 2000.
- A.K. Mok, “A Graph-Based Computation Model for Real-Time Systems,” IEEE International Conference on Parallel Processing, Aug 1985.