Real-Time Operating Systems

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What's an Operating System?

- Provides environment for executing programs
- Process abstraction for multitasking/concurrency
  - Scheduling
- Hardware abstraction layer (device drivers)
- Filesystems
- Communication
- We will focus on concurrent, real-time issues

Do I Need One?

- Not always
- Simplest approach: cyclic executive

```
loop
  do part of task 1
  do part of task 2
  do part of task 3
end loop
```

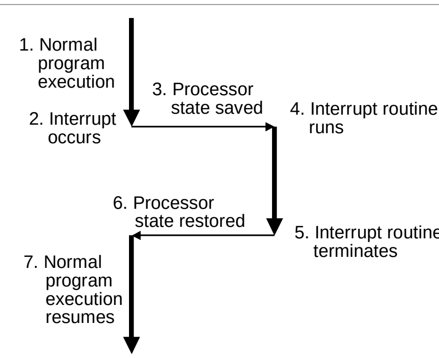

Cyclic Executive

- Advantages
  - Simple implementation
  - Low overhead
  - Very predictable
- Disadvantages
  - Can't handle sporadic events
  - Everything must operate in lockstep
  - Code must be scheduled manually

Interrupts

- Some events can't wait for next loop iteration
  - Communication channels
  - Transient events
- A solution: Cyclic executive plus interrupt routines
- Interrupt: environmental event that demands attention
  - Example: "byte arrived" interrupt on serial channel
- Interrupt routine: piece of code executed in response to an interrupt

Handling an Interrupt



Interrupt Service Routines

- Most interrupt routines:
- Copy peripheral data into a buffer
- Indicate to other code that data has arrived
- Acknowledge the interrupt (tell hardware)
- Longer reaction to interrupt performed outside interrupt routine
- E.g., causes a process to start or resume running

Cyclic Executive Plus Interrupts

- Works fine for many signal processing applications
- 56001 has direct hardware support for this style
- Insanely cheap, predictable interrupt handler:
  - When interrupt occurs, execute a single user-specified instruction
  - This typically copies peripheral data into a circular buffer
  - No context switch, no environment save, no delay

Drawbacks of CE + Interrupts

- Main loop still running in lockstep
- Programmer responsible for scheduling
- Scheduling static
- Sporadic events handled slowly

Cooperative Multitasking

- A cheap alternative
- Non-preemptive
- Processes responsible for relinquishing control
- Examples: Original Windows, Macintosh
- A process had to periodically call get_next_event() to let other processes proceed
- Drawbacks:
  - Programmer had to ensure this was called frequently
  - An errant program would lock up the whole system
- Alternative: preemptive multitasking

Concurrency Provided by OS

- Basic philosophy:

  Let the operating system handle scheduling, and let the programmer handle function

- Scheduling and function usually orthogonal
- Changing the algorithm would require a change in scheduling
- First, a little history

Batch Operating Systems

- Original computers ran in batch mode:
  - Submit job & its input
  - Job runs to completion
  - Collect output
  - Submit next job
- Processor cycles very expensive at the time
- Jobs involved reading, writing data to/from tapes
- Cycles were being spent waiting for the tape!

Timesharing Operating Systems

- Solution
  - Store multiple batch jobs in memory at once
  - When one is waiting for the tape, run the other one
- Basic idea of timesharing systems
- Fairness primary goal of timesharing schedulers
  - Let no one process consume all the resources
  - Make sure every process gets “equal” running time

Real-Time Is Not Fair

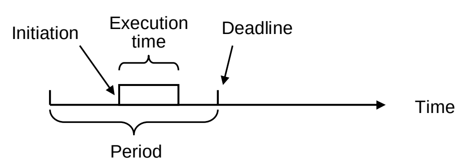
- Main goal of an RTOS scheduler: meeting deadlines
- If you have five homework assignments and only one is due in an hour, you work on that one
- Fairness does not help you meet deadlines

Priority-based Scheduling

- Typical RTOS based on fixed-priority preemptive scheduler
- Assign each process a priority
- At any time, scheduler runs highest priority process ready to run
- Process runs to completion unless preempted

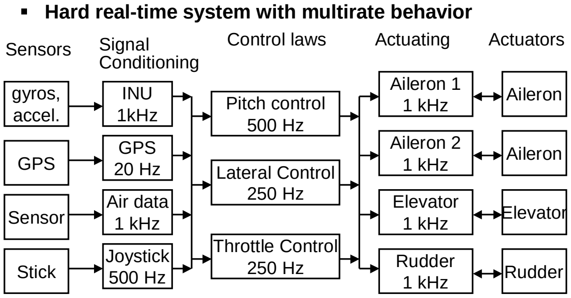
Typical RTOS Task Model

- Each task a triplet: (execution time, period, deadline)
- Usually, deadline = period
- Can be initiated any time during the period



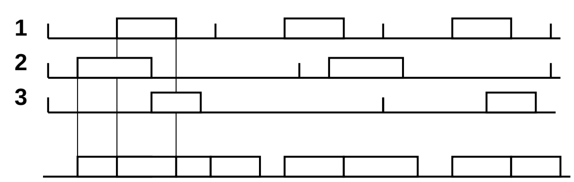
Example: Fly-by-wire Avionics

- Hard real-time system with multirate behavior



Priority-based Preemptive Scheduling

- Always run the highest-priority runnable process



Priority-Based Preempting Scheduling

- Multiple processes at the same priority level?
- A few solutions
  - Simply prohibit: Each process has unique priority
  - Time-slice processes at the same priority
    - Extra context-switch overhead
    - No starvation dangers at that level
  - Processes at the same priority never preempt the other
    - More efficient
    - Still meets deadlines if possible

Rate-Monotonic Scheduling

- Common way to assign priorities
- Result from Liu & Layland, 1973 (JACM)
- Simple to understand and implement:

Processes with shorter period given higher priority

- E.g.,

Period	Priority	
10	1	(highest)
12	2	
15	3	
20	4	(lowest)

Key RMS Result

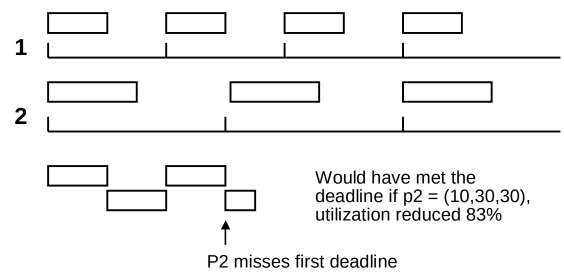
- Rate-monotonic scheduling is optimal:

If there is fixed-priority schedule that meets all deadlines, then RMS will produce a feasible schedule

- Task sets do not always have a schedule
- Simple example: P1 = (10, 20, 20) P2 = (5, 9, 9)
  - Requires more than 100% processor utilization

RMS Missing a Deadline

- p1 = (10,20,20) p2 = (15,30,30) utilization is 100%



When Is There an RMS Schedule?

- Key metric is processor utilization: sum of compute time divided by period for each process:

$U = \sum c_i / p_i$

- No schedule can possibly exist if U > 1
  - No processor can be running 110% of the time
- Fundamental result:
  - RMS schedule always exists if $U < n (2^{1/n} - 1)$
  - Proof based on case analysis (P1 finishes before P2)

When Is There an RMS Schedule?

n	Bound for U	
1	100%	Trivial: one process
2	83%	Two process case
3	78%	
4	76%	
∞	69%	Asymptotic bound

When Is There an RMS Schedule?

- **Asymptotic result:**

If the required processor utilization is under 69%, RMS will give a valid schedule

- **Converse is not true. Instead:**

If the required processor utilization is over 69%, RMS might still give a valid schedule, but there is no guarantee

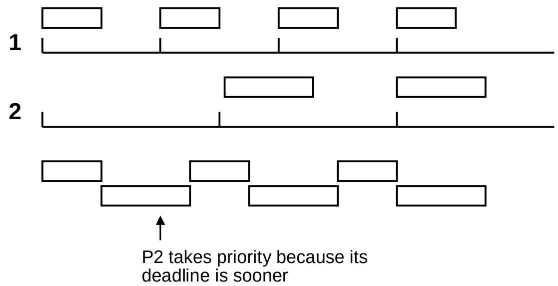
EDF Scheduling

- **RMS assumes fixed priorities**
- **Can you do better with dynamically-chosen priorities?**
- **Earliest deadline first:**

Processes with soonest deadline given highest priority

EDF Meeting a Deadline

- **p1 = (10,20,20) p2 = (15,30,30) utilization is 100%**



Key EDF Result

- **Earliest deadline first scheduling is optimal:**

If a dynamic priority schedule exists, EDF will produce a feasible schedule

- **Earliest deadline first scheduling is efficient:**

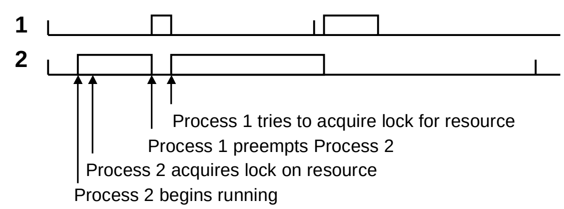
A dynamic priority schedule exists if and only if utilization is no greater than 100%

Static Scheduling More Prevalent

- **RMA only guarantees feasibility at 69% utilization, EDF guarantees it at 100%**
- **EDF is complicated enough to have unacceptable overhead**
- **More complicated than RMA: harder to analyze**
- **Less predictable: can't guarantee which process runs when**

Priority Inversion

- **RMS and EDF assume no process interaction**
- **Often a gross oversimplification**
- **Consider the following scenario:**

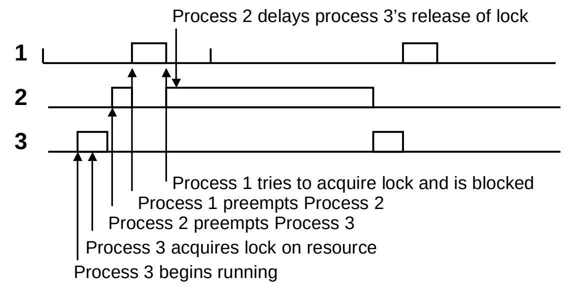


Priority Inversion

- Lower-priority process effectively blocks a higher-priority one
- Lower-priority process's ownership of lock prevents higher-priority process from running
- Nasty: makes high-priority process runtime unpredictable

Nastier Example

- Higher priority process blocked indefinitely



Priority Inheritance

- Solution to priority inversion
- Temporarily increase process's priority when it acquires a lock
- Level to increase: highest priority of any process that might want to acquire same lock
  - I.e., high enough to prevent it from being preempted
- Danger: Low-priority process acquires lock, gets high priority and hogs the processor
  - So much for RMS

Priority Inheritance

- Basic rule: low-priority processes should acquire high-priority locks only briefly
- An example of why concurrent systems are so hard to analyze
- RMS gives a strong result
- No equivalent result when locks and priority inheritance is used

Summary

- Cyclic executive
  - Way to avoid an RTOS
  - Adding interrupts helps somewhat
- Interrupt handlers
  - Gather data, acknowledge interrupt as quickly as possible
- Cooperative multitasking
  - But programs don't like to cooperate

Summary

- Preemptive Priority-Based Multitasking
  - Deadlines, not fairness, the goal of RTOSes
- Rate-monotonic analysis
  - Shorter periods get higher priorities
  - Guaranteed at 69% utilization, may work higher
- Earliest deadline first scheduling
  - Dynamic priority scheme
  - Optimal, guaranteed when utilization 100% or less

Summary

- **Priority Inversion**
  - **Low-priority process acquires lock, blocks higher-priority process**
  - **Priority inheritance temporarily raises process priority**
  - **Difficult to analyze**