Real-Time Operating Systems

COMS W4995-02

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Fall 2002
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What is 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 concurrency and real-time issues

Do I Need One?

Not always

Simplest approach: cyclic executive

```
for (;;) {
  do part of task 1
  do part of task 2
  do part of task 3
}
```

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

Interrupt: environmental event that demands attention

- Example: "byte arrived" interrupt on serial channel

Interrupt routine code executed in response to an interrupt

A solution: Cyclic executive plus interrupt routines

Handling an Interrupt

1. Program runs normally
2. Interrupt occurs
3. Processor state saved
    4. Interrupt routine runs
    5. "Return from Interrupt" instruction runs
6. Processor state restored
7. Normal program execution resumes

Interrupt Service Routines

Most interrupt routines do as little as possible

- Copy peripheral data into a buffer
- Indicate to other code that data has arrived
- Acknowledge the interrupt (tell hardware)

Additional processing usually deferred to outside

E.g., Interrupt causes a process to start or resume running

Objective: let the OS handle scheduling, not the interrupting peripherals

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 runs 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

Costly cycles were being spent waiting for the tape!

Timesharing Operating Systems

Way to spend time while waiting for I/O: Let another process run

- 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

Aside: Modern Computer Architectures

Memory latency now becoming an I/O-like time-waster.

CPU speeds now greatly outstrip memory systems.

All big processes use elaborate multi-level caches.

An Alternative:

Certain high-end chips (e.g., Intel's Xeon) now contain two or three contexts. Can switch among them "instantly."

Idea: while one process blocks on memory, run another.

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 has on fixed-priority preemptive scheduler

Assign each process a priority

At any time, scheduler runs highest priority process ready to run (processes can be blocked waiting for resources).

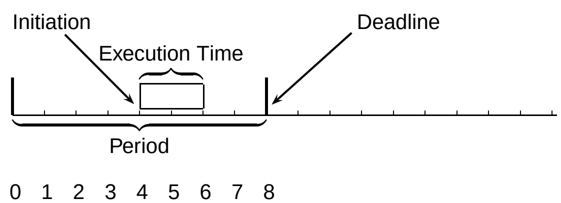
Process runs to completion unless preempted

Typical RTOS Task Model

Each task a triplet: (execution time, period, deadline)

Usually, deadline = period

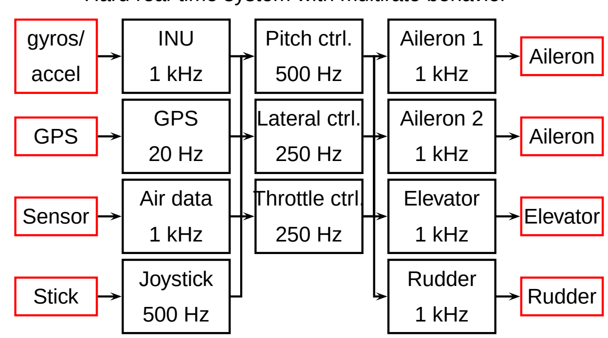
Can be initiated any time during the period



$p = (2, 8, 8)$

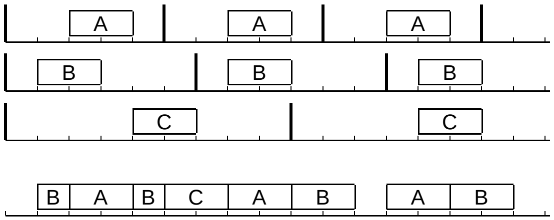
Example: Fly-by-wire Avionics

Hard real-time system with multirate behavior



Priority-based Preemptive Scheduling

Always run the highest-priority runnable process



Solutions to equal priorities

- 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
  - 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 (high)
12	2
15	3
20	4 (low)

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

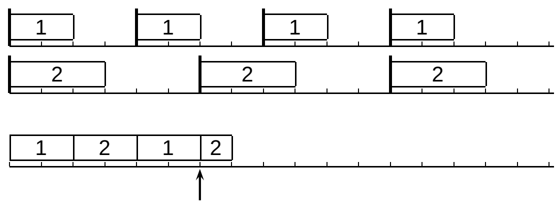
Task sets do not always have a schedule

Simple example: P1 = (10, 20, 20) P2 = (5, 9, 9)

Requires more than 100% processor utilization

RMS Missing a Deadline

$p_1 = (2,4,4)$, $p_2 = (3,6,6)$, 100% utilization



p_2 misses a deadline

Changing $p_2 = (2,6,6)$ would have met the deadline and reduced utilization to 83%.

When Is There an RMS Schedule?

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

$$U = \sum_i \frac{c_i}{p_i}$$

No schedule can possibly exist if $U > 1$ No processor can be running 110% of the time

Fundamental result: RMS schedule 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%	
$\vdots$		
∞	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.

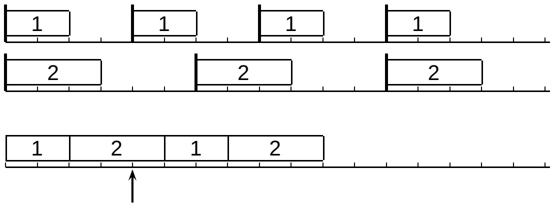
Can you do better with dynamically-chosen priorities?

Earliest deadline first:

Processes with soonest deadline given highest priority

EDF Meeting a Deadline

$p_1 = (2,4,4)$, $p_2 = (3,6,6)$, 100% utilization



p_2 takes priority with its earlier deadline

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%

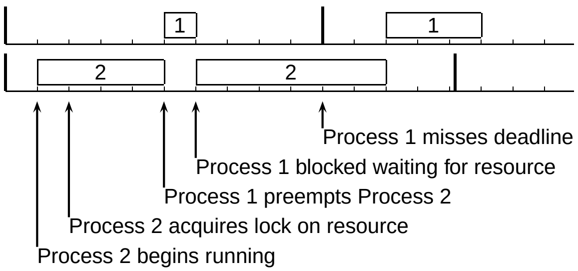
EDF is complicated enough to have unacceptable overhead

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



Priority Inversion

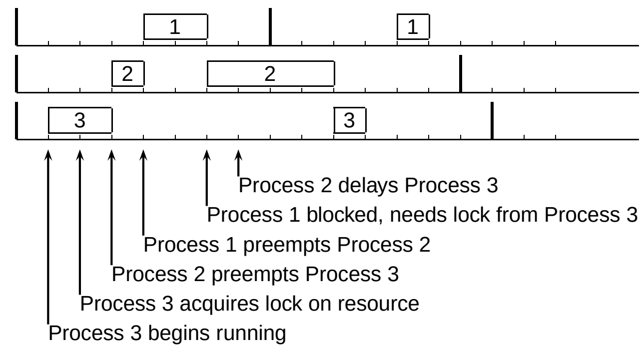
Lower-priority process effectively blocks a higher-priority one

Lower-priority process's ownership of lock prevents higher-priority process from running

Nasty: makes high-priority process runtime unpredictable

Nastier Example

Process 2 blocks Process 1 indefinitely



Priority Inheritance

Solution to priority inversion

Increase process's priority while it posseses 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—A 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