Performance Validation – Systems
CS 4271 Lecture 10

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Ack: Slides 4-19 are modified and augmented from Peter Marwedel's slides

So far in CS4271…

- Functionality analysis
  - Modeling, Model Checking
- Timing Analysis
  - Software level – WCET analysis
  - System level – Scheduling methods – Today!

Real-time Embedded Systems

- Embedded systems that monitor, respond to, or control external environment under timing constraints
- Examples:
  - Vehicles (car, aircraft, …)
  - Traffic control (highway, air, railway, …)
  - Process control (power plant, chemical plant, …)
  - Medical systems (radiation therapy, …)
  - Telephone, radio, satellite communication
  - Computer games

Characteristics

- Timing constraints / deadline
  - Functional and temporal correctness
- Hard deadline
  - Must always meet deadline
  - Air traffic controller
- Soft deadline
  - Must frequently meet deadline
  - MPEG decoder

Tasks

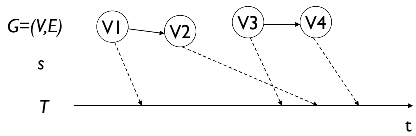
- A task is a block of code executed in a CPU in a sequential fashion.
- Several independent tasks may be executing on the same CPU
  - How to schedule them ?
  - Today's lecture
- There might also be dependences among tasks, captured by a task graph
  - Task mapping – which task on which CPU?
  - Task scheduling – in what order to run the tasks mapped to same CPU?

Why study scheduling?

- Increase CPU utilization or other metrics
- For real-time systems requiring hard guarantees
  - Study in advance whether all tasks can be scheduled without missing any deadlines.
  - Need computation time of each task
    - Typically given as a worst-case bound, called the Worst-case Execution Time (WCET)
    - How to derive these WCET bounds ?
      - Discussed in earlier 2 lectures.

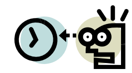
Informally, scheduling is

- Assume that we are given a task graph *G=(V,E)*.
- **Def.:** A **schedule** *s* of *G* is a mapping
  $V \rightarrow T$
  of a set of tasks *V* to start times from domain *T*.



Informally, scheduling is

- Typically, schedules have to respect a number of constraints, incl. resource constraints, dependency constraints, deadlines.
- **Scheduling** = finding such a mapping.
- Scheduling to be performed several times during ES design (early rough scheduling as well as late precise scheduling).



More precisely,

- Schedule
  - An assignment of tasks to the processor (assuming 1 processor!) over time.
- Feasible schedule
  - All tasks can be completed and all constraints (precedence, resource, deadline) can be respected.
- Scheduling Algorithm
  - A recipe for producing schedules
- Schedulability
  - If at least one scheduling algorithm producing a feasible schedule exists.

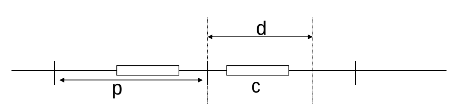
Periodic and Aperiodic

- **Def.:** Tasks which must be executed once every *p* units of time are called **periodic** tasks. *p* is called their period. Each execution of a periodic task is called a **job**.
- All other tasks are called **aperiodic**.
- **Def.:** Tasks requesting the processor at unpredictable times are called **sporadic**, if there is a minimum separation between the times at which they request the processor.

Periodic Task

- Activated on a regular basis between fixed interval
  - scan the airspace every 3 sec
- P = (s, c, p, d)
  - s = start time or arrival time
  - c = worst case execution time (WCET)
  - p = period or cycle time
  - d = deadline
  - c <= d <= p

Periodic Task (Contd.)



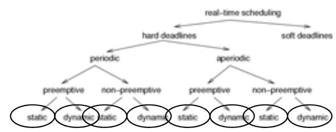
- Period: interval between task activations.
- Computation time: Typically the WCET.
- Initiation time: time at which task becomes ready.
- Deadline: time at which process must finish.
- In most cases, d = p

Preemptive and non-preemptive scheduling

- **Non-preemptive schedulers:**
  Tasks are executed until they are done.
  Response time for external events may be quite long.
- **Preemptive schedulers:** To be used if
  - some tasks have long execution times or
  - if the response time for external events to be short.

Dynamic/online scheduling

- **Dynamic/online scheduling:**
  Processor allocation decisions (scheduling) at run-time; based on the information about the tasks arrived so far.



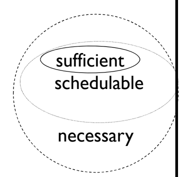
Static/offline scheduling

- **Static/offline scheduling:**
  Scheduling taking a priori knowledge about arrival times, execution times, and deadlines into account.
  Dispatcher allocates processor when interrupted by timer.
  Timer controlled by a table generated at design time.

Time	Action	WCET
10	start T1	12
17	send M5	
22	stop T1	
38	start T2	20
47	send M3	

Schedulability

- Set of tasks is **schedulable** under a set of constraints, if a schedule exists for that set of tasks & constraints.
- **Exact tests** cannot be efficiently computed in many situations.
- **Sufficient tests**: sufficient conditions for schedule checked. (Hopefully) small probability of indicating that no schedule exists even though one exists.
- **Necessary tests**: checking necessary conditions. Used to show no schedule exists. There may be cases in which no schedule exists & we cannot prove it.



To summarize

- Input to Scheduling Algorithm
  - One or more tasks
  - Activation time, execution time, deadline for each process
- Scheduling algorithm: a policy to allocate tasks to the processor(s)
- Feasible schedule if the scheduling algorithm can meet all the constraints
- Optimal algorithm: A scheduling algorithm that produces a feasible schedule if it exists

To summarize

- How do we evaluate a scheduling policy:
  - Ability to satisfy all deadlines.
  - CPU utilization: percentage of time devoted to useful work.
  - Scheduling overhead: time required to make scheduling decision.

Organization of Scheduling slides

- Real-time Systems
- Basics of Scheduling
- Periodic Scheduling Methods
  - RMS
  - EDF

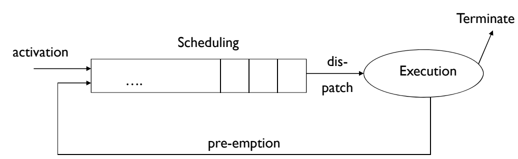
Recap: Why study scheduling?

- Increase CPU utilization or other metrics
- For real-time systems requiring hard guarantees
  - Study in advance whether all tasks can be scheduled without missing any deadlines.
  - Need computation time of each task
    - Typically given as a worst-case bound, called the Worst-case Execution Time (WCET)
    - How to derive these bounds ? –
      - We studied this just now (WCET analysis !)

Recap: Periodic tasks

- A task is a program!
- Activated on a regular basis between fixed interval
  - scan the airspace every 3 sec
- P = (s, c, p, d)
  - s = start time or arrival time
  - c = worst case execution time (WCET)
  - p = period or cycle time
  - d = deadline
  - c <= d <= p

Task Execution



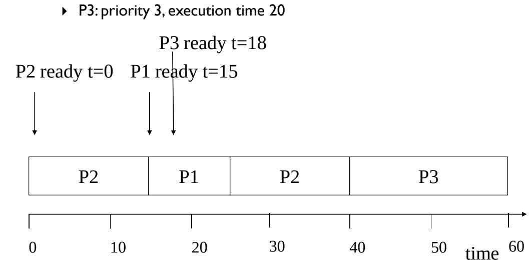
Dispatching from the ready queue will be based on the scheduling policy which takes into account task priority.

Priority driven scheduling

- Each task has a priority.
- CPU goes to highest-priority task that is ready.
- Priorities determine scheduling policy:
  - fixed priority;
  - time-varying priorities.
- Rules:
  - each task has a fixed priority (1 highest);
  - highest-priority ready task gets CPU
  - task continues until done (non pre-emptive) OR
  - Task can be pre-empted by a later arriving higher priority task.

Example (premptive)

- P1: priority 1, execution time 10
- P2: priority 2, execution time 30
- P3: priority 3, execution time 20



Rate-monotonic scheduling

- RMS (Liu and Layland 1973)
  - widely-used, analyzable scheduling policy.
- Analysis is known as Rate Monotonic Analysis
- RMS is an optimal fixed priority assignment method
  - If there exists a schedule that meets all the deadlines with fixed priority, then RMS will produce a feasible schedule.
- Fixed-priority, pre-emptive scheduling.

Assumptions in RMS

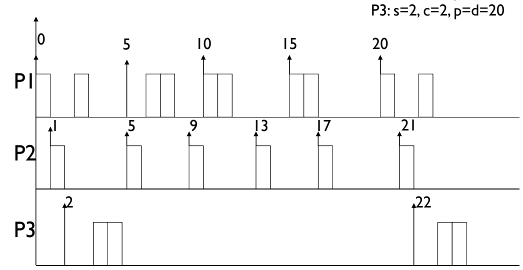
- All tasks run on single CPU.
- Zero context switch time.
  - If not, the context switch time needs to be added in response time computation.
- No data dependencies between tasks.
- Task execution time is constant.
  - If not, we take the WCET.
- Deadline is at end of period (p = d)
- Highest-priority ready task runs.

Priority assignment in RMS.

- Optimal (fixed) priority assignment:
  - shortest-period task gets highest priority;
  - priority inversely proportional to period;
  - break ties arbitrarily.
- Intuition: Tasks requiring frequent attention (smaller period) should receive higher priority

RMS Example

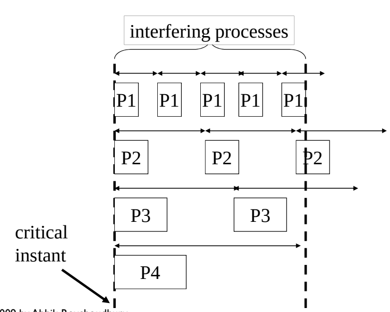
P1: s=0, c=2, p=d=5
P2: s=1, c=1, p=d=4
P3: s=2, c=2, p=d=20



Rate monotonic analysis

- Response time: time required to finish task.
- Critical instant: scheduling state that gives worst response time.
- Critical instant occurs when all higher-priority tasks are ready to execute.
- Worst case response time
  - Solved by iterative computation
  - $w_i = c_i + \sum_{j<i} c_j * \lceil w_i/p_j \rceil$

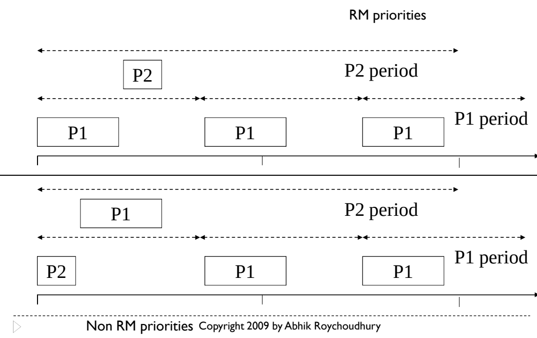
Critical Instant



Informal argument about optimality

- P1 = (c1, p1, d1) with p1 = d1
- P2 = (c2, p2, d2) with p2 = d2
- p1 < p2
- Suppose P1 and P2 can be scheduled with non-RM priority assignment, i.e., P2 has highest priority
- At critical instant, with non-RM priorities
  - **c1 + c2 <= p1;** [1]
- With RM priority
  - **$\lfloor$p2/p1$\rfloor$*c1 + c2 <= p2;** [2]
- If [1] is satisfied, then [2] is also satisfied

RMS optimality



RMS CPU utilization

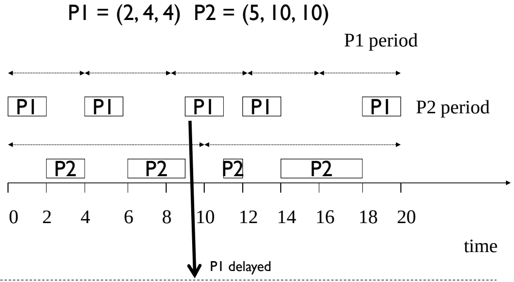
- Utilization for n processes is
  - $U = \sum_i c_i / p_i$
- U ≤1 is a necessary condition for feasibility regardless of scheduling policy
- Scheduling with fixed priorities is feasible if
  $U \le n\,(2^{1/n} - 1)$
- The bound is sufficient but not necessary.
- As number of tasks approaches infinity, maximum utilization approaches 69%.
  - RMS cannot use 100% of CPU, even with zero context switch overhead.
  - Must keep idle cycles available to handle worst-case scenario.

Earliest-Deadline-First

- EDF: dynamic priority scheduling scheme.
- Task closest to its deadline has highest priority.
- Requires recalculating tasks at every timer interrupt.
- EDF can use 100% of CPU.
- Implementation
  - On each timer interrupt:
    - compute time to deadline;
    - choose task closest to deadline.
  - Generally considered too expensive to use in practice.

EDF Example

P1 = (2, 4, 4) P2 = (5, 10, 10)



EDF Properties

- **EDF is optimal**
  - If a feasible schedule exists using dynamic priorities, then EDF will produce a feasible schedule
- EDF can always produce a feasible schedule if U ≤ 1
- **Scheduling with dynamic priority is feasible if and only if U ≤ 1**

Fixing scheduling problems …

- … in practice.
- What if your set of tasks is not schedulable?
  - Change deadlines in requirements.
  - Reduce execution times of processes.
  - Get a faster CPU.

Organization of Timing Analysis

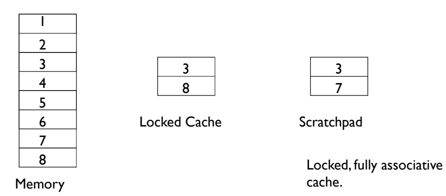
- Software timing analysis - **Completed!**
  - WCET analysis
- System level analysis – **Completed!**
  - Scheduling methods
- Design issues to improve timing predictability
  - Scratchpad memories

Scratchpad Memory

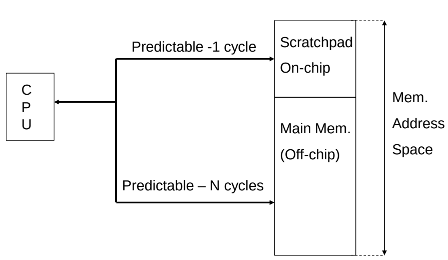
- Compiler controlled memory.
- Unlike cache, compiler has control over its contents.
- We can statically decide what to put in the scratchpad and lock it in.

- So, is it simply a statically locked cache?
  - No, it is a bit more!

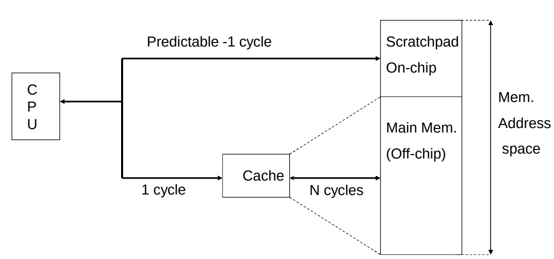
Cache locking and scratchpad



How scratchpad memory works?



Combination with cache is also possible.



Scratchpad allocation strategy

- Assume a scratchpad memory for data variables.
- We need to statically decide which variables to allocate in scratchpad memory.
  - Variables = $\{v_1, \ldots, v_n\}$
  - Say n_i = # of times v_i is executed in a given execution path.
    - n_i is constant.
  - Define $gain_i = n_i * (N - 1)$
    - $gain_i$ = gain from allocating v_i to scratchpad.
    - N = number of cycles needed to access main memory.
    - $gain_i$ is constant

Scratchpad allocation strategy

- Maximize
  - $\sum_{1 \le i \le n} choice_i * gain_i$
- Subject to
  - $\sum_{1 \le i \le n} choice_i * w_i \le Capacity$
- KNAPSACK Problem
  - w_i is the area occupied by variable v_i
- Capacity is the total area in scratchpad
  - $choice_i$ is 0 or 1
    - 0 if v_i is not allocated
    - 1 if v_i is allocated.

The gain is not constant

- Define $gain_i = n_i * (N - 1)$
  - $gain_i$ = gain from allocating v_i to scratchpad.
  - N = number of cycles needed to access main memory.
  - Say n_i = # of times v_i is executed in a given execution path.
  - n_i is constant.

  - Which execution path?
  - What if we want to allocate to scratchpad memory for reducing the program's WCET?

Knapsack problem

- Given n objects and a knapsack
  - Capacity of knapsack W
  - Object i has weight w_i and value $gain_i$
  - Fill up the knapsack so as to maximize value
- Perfect fit for our allocation problem if the gain by allocating a variable to scratchpad memory is a constant
  - Holds for ACET based allocation
  - Not true for WCET based allocation
- Knapsack problem can be easily solved by dynamic programming.

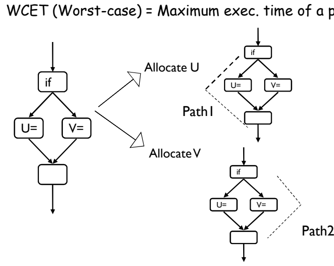
Knapsack

- Array V[0..n,0..W]
- V[i,j] = maximum value if we are restricted to objects 1..i, and the weight limit is j
- Define
  - $V[i,j] = \max(V[i-1,j], V[i-1,j-w_i] + v_i)$ for $i > 0$
  - $V[0,j] = 0$
- Final Answer V[n,W]

- This solution is useful only for ACET based allocation.

ACET vs WCET based

WCET (Worst-case) = Maximum exec. time of a pgm. for all possible inputs



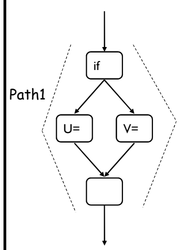
In this simple example assume

- *U and V have same size*
- *Only one of them can be allocated.*
- *ACET savings depends on the execution counts of Path1 and Path2* (whichever is the more frequent path forms our profile say)
- *WCET savings depend on which path is longer.*

Difficulty in WCET based allocation

Allocate V

	Path1	Path2
Before	90	100
After	90	80



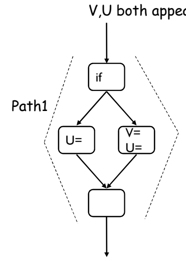
Contribution of V to WCET path = 20

Reduction in WCET by allocating V = 10

Path1 is now the WCET path which has different var. access frequencies from Path2

Sub-optimal allocation

V,U both appear in WCET path. Suppose #V > # U



WCET path based allocation = {V}

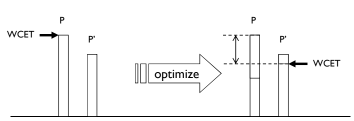
	Path1	Path2
Before	90	100
After	90	80

Optimal allocation = {U}

	Path1	Path2
Before	90	100
After	75	85

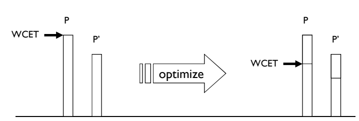
WCET based allocation

- gain in WCET reduction due to a variable v
  - *not a constant, depends on*
    - current WCET path
    - Diff in exec. Times of WCET path and other paths
    - # Occurrence of v in WCET path and other paths



WCET-based allocation

- gain in WCET reduction due to a variable allocation:
  - *not a constant*
  - *not cumulative*
    - $gain_{\{v,v'\}} \leq gain_v + gain_{v'}$



Summary: WCET-based allocation

- Optimal WCET based allocation
  - Must not be profile-guided (WCET path).
  - Cannot take WCET contribution of variables as constant.
    - Rules out Knapsack like solutions.
- ACET-based solution (where $gain_i$ is constant) is a well-known knapsack problem with known algorithmic solutions via dynamic programming.

Overall Summary of Timing Issues

- Correctness of many embedded systems depend on their timing behavior.
- Analysis / Validation Methods
  - Software level
    - WCET analysis – fine-grained
  - System level
    - Scheduling methods – use WCET estimates.
- Make the system more time predictable and easier to analyze
  - Scratchpad memories are one such solution.