Introduction to Real-Time Systems

ECE 397-1

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Homework index

Goals for lecture

- Resource representations
- Graph extensions for pre/post-computation and streaming/pipelining
- Scheduling problem categories
- Overview of scheduling algorithms
  - Will initially focus on static scheduling
- Sensor networks

Processing resource description

- Often table-based
- Price, area
- For each task
  - Execution time
  - Power consumption
  - Preemption cost
  - etc.
- etc.

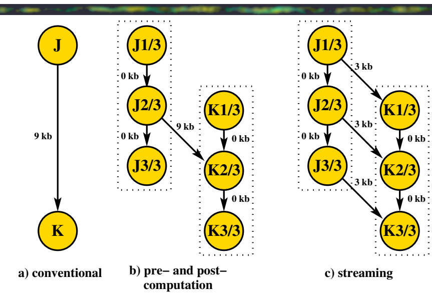
Similar characterization for communication resources

Wise to use process-based

Communication resource description

- Can use bus-bridge based models for distributed systems
  - Some protocols make static analysis difficult
- Wireless models
- System-level design, especially for a single chip, depends on wire delays!

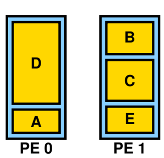
Graph extensions



Allows pipelining and pre/post-computation
In contrast with book, not difficult to use if conversion automated

Problem definition

minimize completion time



- Given a set of tasks,
- a cost function,
- and a set of resources,
- decide the exact time each task will execute on each resource

Types of scheduling problems

- Discrete time – Continuous time
- Hard deadline – Soft deadline
- Unconstrained resources – Constrained resources
- Uni-processor – Multi-processor
- Homogeneous processors – Heterogeneous processors
- Free communication – Expensive communication
- Independent tasks – Precedence constraints
- Homogeneous tasks – Heterogeneous tasks
- One-shot – Periodic
- Single rate – Multirate
- Non-preemptive – Preemptive
- Off-line – On-line

Discrete vs. continuous timing

System-level: Continuous

- Operations are not small integer multiples of the clock cycle

High-level: Discrete

- Operations are small integer multiples of the clock cycle

Implications:

- System-level scheduling is more complicated. . .
- . . . however, high-level also very difficult.
- Can we solve this by quantizing time? Why or why not?

Hard deadline – Soft deadline

Tasks may have hard or soft deadlines

- Hard deadline
  - Task must finish by given time or schedule invalid
- Soft deadline
  - If task finishes after given time, schedule cost increased

Real-time – Best effort

- Why make decisions about system implementation statically?
  - Allows easy timing analysis, hard real-time guarantees
- If a system doesn't have hard real-time deadlines, resources can be more efficiently used by making late, dynamic decisions
- Can combine real-time and best-effort portions within the same specification
  - Reserve time slots
  - Take advantage of slack when tasks complete sooner than their worst-case finish times

Unconstrained – Constrained resources

- Unconstrained resources
  - Additional resources may be used at will
- Constrained resources
  - Limited number of devices may be used to execute tasks

Uni-processor – Multi-processor

- Uni-processor
  - All tasks execute on the same resource
  - This can still be somewhat challenging
  - However, sometimes in $\mathbf{P}$
- Multi-processor
  - There are multiple resources to which tasks may be scheduled
- Usually $\mathbf{NP}$-$\mathbf{complete}$

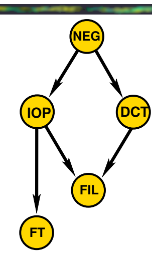
Homogeneous – Heterogeneous processors

- Homogeneous processors
  - All processors are the same type
- Heterogeneous processors
  - There are different types of processors
  - Usually $\mathbf{NP}$-$\mathbf{complete}$

Free – Expensive communication

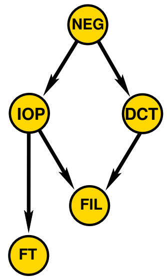
- Free communication
  - Data transmission between resources has no time cost
- Expensive communication
  - Data transmission takes time
  - Increases problem complexity
  - Generation of schedules for communication resources necessary
  - Usually $\mathbf{NP}$-$\mathbf{complete}$

Independent tasks – Precedence constraints



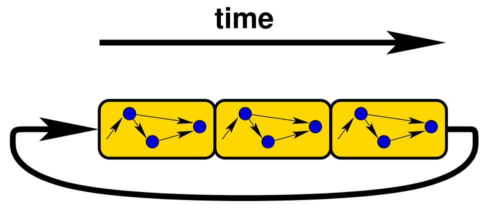
- Independent tasks: No previous execution sequence imposed
- Precedence constraints: Weak order on task execution order

Homogeneous – Heterogeneous tasks



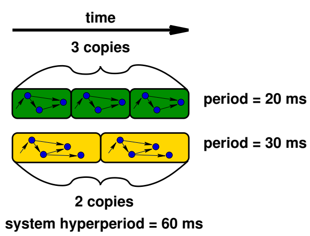
- Homogeneous tasks: All tasks are identical
- Heterogeneous tasks: Tasks differ

One-shot – Periodic



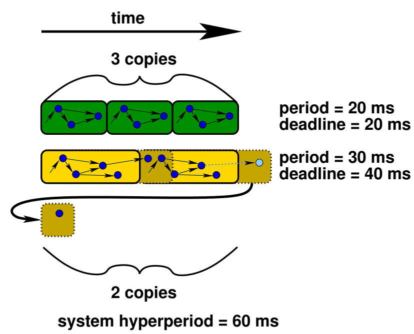
- One-shot: Assume that the task set executes once
- Periodic: Ensure that the task set can repeatedly execute at some period

Single rate – Multirate



- Single rate: All tasks have the same period
- Multirate: Different tasks have different periods
  - Complicates scheduling
  - Can copy out to the least common multiple of the periods (hyperperiod)

Periodic graphs



Aperiodic/sporadic graphs

- No precise periods imposed on task execution
- Useful for representing reactive systems
- Difficult to guarantee hard deadlines in such systems
  - Possible if minimum inter-arrival time known

Periodic vs. aperiodic

Periodic applications

- Power electronics
- Transportation applications
  - Engine controllers
  - Brake controllers
- Many multimedia applications
  - Video frame rate
  - Audio sample rate
- Many digital signal processing (DSP) applications

However, devices which react to unpredictable external stimuli have aperiodic behavior

Many applications contain periodic and aperiodic components

Aperiodic to periodic

Can design periodic specifications that meet requirements posed by aperiodic/sporadic specifications

- Some resources will be wasted

Example:

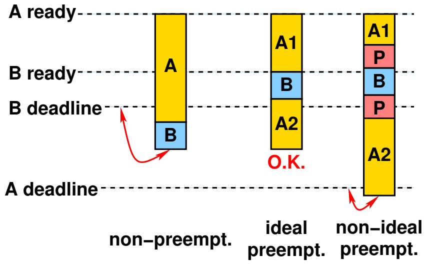
- At most one aperiodic task can arrive every 50 ms
- It must complete execution within 100 ms of its arrival time

Aperiodic to periodic

- Can easily build a periodic representation with a deadline and period of 50 ms
  - Problem, requires a 50 ms execution time when 100 ms should be sufficient
- Can use overlapping graphs to allow an increase in execution time
  - Parallelism required

The main problem with representing aperiodic problems with periodic representations is that the tradeoff between deadline and period must be made at design/synthesis time

Non-preemptive – Preemptive



- Non-preemptive: Tasks must run to completion
- Ideal preemptive: Tasks can be interrupted without cost
- Non-ideal preemptive: Tasks can be interrupted with cost

Off-line – On-line

Off-line

- Schedule generated before system execution
- Stored, e.g., in dispatch table. for later use
- Allows strong design/synthesis/compile-time guarantees to be made
- Not well-suited to strongly reactive systems

On-line

- Scheduling decisions made during the execution of the system
- More difficult to analyze than off-line
  - Making hard deadline guarantees requires high idle time
  - No known guarantee for some problem types
- Well-suited to reactive systems

Hardware-software co-synthesis scheduling

Automatic allocation, assignment, and scheduling of system-level specification to hardware and software

Scheduling problem is hard

- Hard and soft deadlines
- Constrained resources, but resources unknown (cost functions)
- Multi-processor
- Strongly heterogeneous processors and tasks
  - No linear relationship between the execution times of a tasks on processors

Hardware-software co-synthesis scheduling

- Expensive communication
  - Complicated set of communication resources
- Precedence constraints
- Periodic
- Multirate
- Strong interaction between $\mathbf{NP}$-complete allocation-assignment and $\mathbf{NP}$-complete scheduling problems
- Will revisit problem later in course if time permits

Behavioral synthesis scheduling

- Difficult real-world scheduling problem
  - Not multirate
  - Discrete notion of time
  - Generally less heterogeneity among resources and tasks
- What scheduling algorithms should be used for these problems?

Scheduling methods

- Clock
- Weighted round-robbin
- List scheduling
- Priority
  - EDF, LST
  - Slack
  - RMS
  - Multiple costs
- MILP
- Force-directed

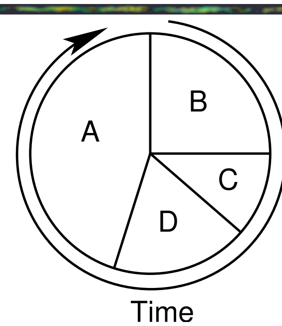
Clock-driven scheduling

Clock-driven: Pre-schedule, repeat schedule

Music box:

- Periodic
- Multi-rate
- Heterogeneous
- Off-line
- Clock-driven

Weighted round robbin



Weighted round-robin: Time-sliced with variable time slots

List scheduling

- Pseudo-code:
  - Keep a list of ready jobs
  - Order by priority metric
  - Schedule
  - Repeat
- Simple to implement
- Can be made very fast
- Difficult to beat quality

Priority-driven

- Impose linear order based on priority metric
- Possible metrics
  - Earliest start time (EST)
  - Latest start time
    - * Danger! LST also stands for least slack time.
  - Shortest execution time first (SETF)
  - Longest execution time first (LETF)
  - Slack (LFT - EFT)

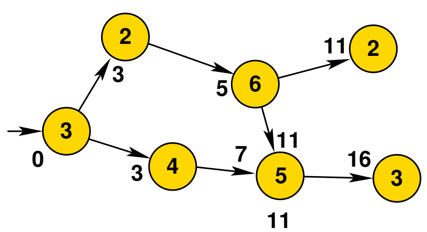
List scheduling

- Assigns priorities to nodes
- Sequentially schedules them in order of priority
- Usually very fast
- Can be high-quality
- Prioritization metric is important

Prioritization

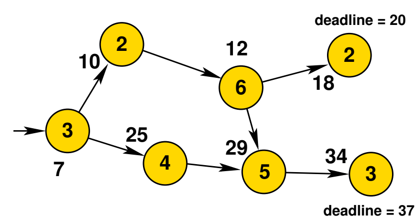
- As soon as possible (ASAP)
- As late as possible (ALAP)
- Slack-based
- Dynamic slack-based
- Multiple considerations

As soon as possible (ASAP)



- From root, topological sort on the precedence graph
- Propagate execution times, taking the max at reconverging paths
- Schedule in order of increasing earliest start time (EST)

As late as possible (ALAP)



- From deadlines, topological sort on the precedence graph
- Propagate execution times, taking the min at reconverging paths
- Consider precedence-constraint satisfied tasks
  - Schedule in order of increasing latest start time (LST)

Slack-based

- Compute EFT, LFT
- For all tasks, find the difference, LFT − EFT
- This is the *slack*
- Schedule precedence-constraint satisfied tasks in order of increasing slack
- Can recompute slack each step, expensive but higher-quality result
  - Dynamic critical path scheduling

Multiple considerations

- Nothing prevents multiple prioritization methods from being used
- Try one method, if it fails to produce an acceptable schedule, reschedule with another method

Effective release times

- Ignore the book on this
  - Considers simplified, uniprocessor, case
- Use EFT, LFT computation
- Example?

EDF, LST optimality

- EDF optimal if zero-cost preemption, uniprocessor assumed
  - Why?
  - What happens when preemption has cost?
- Same is true for slack-based list scheduling in absence of preemption cost

Breaking EDF, LST optimality

- Non-zero preemption cost
- Multiprocessor
- Why?

Rate mononotic scheduling (RMS)

- Single processor
- Independent tasks
- Differing arrival periods
- Schedule in order of increasing periods
- No fixed-priority schedule will do better than RMS
- Guaranteed valid for loading $\leq \ln 2 = 0.69$
- For loading $> \ln 2$ and < 1, correctness unknown
- Usually works up to a loading of 0.88
- More detail in later lectures

Reading assignment

- Skim and refer to K. Ramamritham and J. Stankovic, “Scheduling algorithms and operating systems support for real-time systems,” *Proc. IEEE*, vol. 82, pp. 55–67, Jan. 1994
- Skim and refer to Y.-K. Kwok and I. Ahmad, “Static scheduling algorithms for allocating directed task graphs to multiprocessors,” *ACM Computing Surveys*, vol. 31, no. 4, pp. 406–471, 1999
- J. W. S. Liu, *Real-Time Systems.* Prentice-Hall, Englewood Cliffs, NJ, 2000
- Finish Chapter 5, read Chapter 6 by Thursday