Today

- Intro to real-time scheduling
- Cyclic executives
  - Scheduling tables
  - Frames
  - Frame size constraints
  - Generating schedules
  - Non-independent tasks
  - Pros and cons

Real-Time Systems

- The correctness of a *real-time system* depends not just on the validity of results but on the times at which results are computed
  - Computations have *deadlines*
  - Usually, but not always, ok to finish computation early
- *Hard real-time system*: missed deadlines may be catastrophic
- *Soft real-time system*: missed deadlines reduce the value of the system
- Real-time deadlines are usually in the range of microseconds through seconds

Real-Time System Examples

- Hard real-time
  - Most feedback control systems
    - E.g. engine control, avionics, …
    - Missing deadlines affects stability of control
  - Air traffic control
    - Missing deadlines affects ability of airplanes to fly
- Soft real-time
  - Windows Media Player
  - Software DVD player
  - Network router
  - Games
  - Web server
  - Missing deadlines reduces quality of user experience

Real-Time Abstractions

- System contains n periodic tasks $T_1, \ldots, T_n$
- T_i is specified by (P_i, C_i, D_i)
  - P is period
  - C is worst-case execution cost
  - D is relative deadline
- Task T_i is "released" at start of period, executes for C_i time units, must finish before D_i time units have passed
  - Often P_i==D_i, and in this case we omit D_i
- Intuition behind this model:
  - Real-time systems perform repeated computations that have characteristic rates and response-time requirements
- What about non-periodic tasks?

Real Time Scheduling

- Given a collection of runnable tasks, the scheduler decides which to run
  - If the scheduler picks the wrong task, deadlines may be missed
- Interesting schedulers:
  - Fixed priorities
  - Round robin
  - Earliest deadline first (EDF)
  - Many, many more exist
- A scheduler is optimal when, for a class of real-time systems, it can schedule any task set that can be scheduled by any algorithm

Real-Time Analysis

- Given:
  - A set of real-time tasks
  - A scheduling algorithm
- Is the task set schedulable?
  - Yes → all deadlines met, always
  - No → at some point a deadline might be missed
- Important: Answer this question at design time
- Other questions to ask:
  - Where does worst-case execution cost come from?
  - How close to schedulable is a non-schedulable task set?
  - How close to non-schedulable is a schedulable task set?
  - What happens if we change scheduling algorithms?
  - What happens if we change some task's period or execution cost?

Cyclic Schedule

- This is an important way to sequence tasks in a real-time system
  - We'll look at other ways later
- Cyclic scheduling is static – computed offline and stored in a table
  - For now we assume table is given
  - Later look at constructing scheduling tables
- Task scheduling is non-preemptive
  - No RTOS is required
- Non-periodic work can be run during time slots not used by periodic tasks
  - Implicit low priority for non-periodic work
  - Usually non-periodic work must be scheduled preemptively

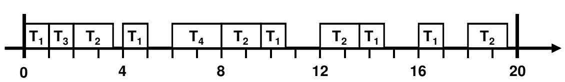
Cyclic Schedule Table

$$T(t_k) = \begin{cases} T_i & \text{if } T_i \text{ is to be scheduled at time } t_k \\ I & \text{if no periodic task is scheduled at time } t_k \end{cases}$$

- Table executes completely in one *hyperperiod* H
  - Then repeats
  - H is least common multiple of all task periods
  - N quanta per hyperperiod
- Multiple tables can support multiple system *modes*
  - E.g., an aircraft might support takeoff, cruising, landing, and taxiing modes
  - Mode switches permitted only at hyperperiod boundaries
    - Otherwise, hard to meet deadlines

Example

- Consider a system with four tasks
  - $T_1 = (4,1)$
  - $T_2 = (5, 1.8)$
  - $T_3 = (20, 1)$
  - $T_4 = (20, 2)$
- Possible schedule:



- Table starts out with:
  - $(0, T_1)$, $(1, T_3)$, $(2, T_2)$, (3.8, I), $(4, T_1)$, …

Refinement: Frames

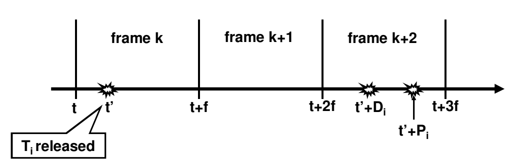
- We divide hyperperiods into *frames*
  - Timing is enforced only at frame boundaries
  - Each task is executed as a function call and must fit within a single frame
  - Multiple tasks may be executed in a frame
  - Frame size is f
  - Number of frames per hyperperiod is F = H/f

Frame Size Constraints

1. Tasks must fit into frames
   - So, $f \geq C_i$ for all tasks
   - Justification: Non-preemptive tasks should finish executing within a single frame
2. f must evenly divide H
   - Equivalently, f must evenly divide P_i for some task i
   - Justification: Keep table size small

More Frame Size Constraints

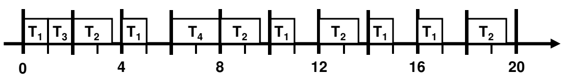
3. There should be a complete frame between the release and deadline of every task
   - Justification: Want to detect missed deadlines by the time the deadline arrives



   - Therefore: $2f - \gcd(P_i, f) \leq D_i$ for each task i

Example Revisited

- Consider a system with four tasks
  - $T_1 = (4,1)$, $T_2 = (5, 1.8)$, $T_3 = (20, 1)$, $T_4 = (20, 2)$
  - H = lcm (4,5,20) = 20
- By Constraint 1: $f \geq 2$
- By Constraint 2: f might be 1, 2, 4, 5, 10, or 20
- By Constraint 3: only 2 works



Task Slices

- What if frame size constraints cannot be met?
  - Example: T = { (4, 1), (5, 2, 7), (20, 5) }
    - By Constraint 1: $f \geq 5$
    - By Constraint 3: $f \leq 4$
- Solution: "slice" a task into smaller sub-tasks
  - So (20, 5) becomes (20, 1), (20, 3), and (20, 1)
  - Now f = 4 works
- What is involved in slicing?

Design Decision Summary

- Three decisions:
  - Choose frame size
  - Partition tasks into slices
  - Place slices into frames
- In general these decisions are not independent

Cyclic Executive Pseudocode

```
// L is the stored schedule
current time t = 0;
current frame k = 0;
do forever
   accept clock interrupt;
   currentBlock = L(k);
   t++;
   k = t mod F;
   if last task not completed, take appropriate action;
   execute slices in currentBlock;
   sleep until next clock interrupt;
```

Practical Considerations

- Handling frame overrun
  - Main issue: Should offending task be completed or aborted?
  - How can we eliminate the possibility of overrun?
- Mode changes
  - At hyperperiod boundaries
  - How to schedule the code that figures out when it's time to change modes?
- Multiprocessor systems
  - Similar to uniprocessor but table construction is more difficult
- Splitting tasks
  - Painful and error prone

Computing a Static Schedule

- Problem: Derive a frame size and schedule meeting all constraints
- Solution: Reduce to a network flow problem
  - Use constraints to compute all possible frame sizes
  - For each possible size, try to find a schedule using network flow algorithm
    - If flow has a certain value:
      - A schedule is found and we're done
    - Otherwise:
      - Schedule is not found, look at the next frame size
  - If no frame size works, system is not schedulable using cyclic executive

Network Flow Problem

- Given a graph of links, each with a fixed capacity, determine the maximum flow through the network
- Efficient algorithms exist

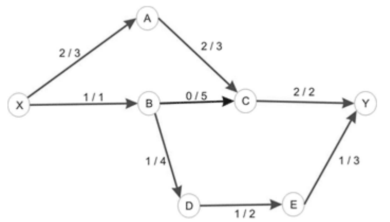
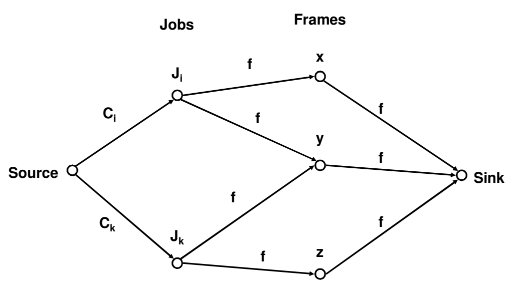


Figure 1a - Maximum Flow in a network

Flow Graph Definitions

- Denote all jobs in hyperperiod of F frames as $J_1 \ldots J_n$
- Vertices:
  - N job vertices $J_1, J_2, \ldots, J_N$
  - F frame vertices 1, 2, …, F
- Edges:
  - (source, J_i) with capacity C_i
    - Encodes jobs' compute requirements
  - (J_i, x) with capacity f iff J_i can be scheduled in frame x
    - Encodes periods and deadlines
  - (f, sink) with capacity f
    - Encodes limited computational capacity in each frame

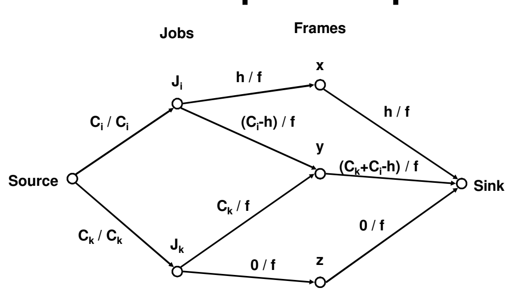
Flow Graph Illustration



Finding a Schedule

- Maximum attainable flow is $\Sigma_{i=1..N}\ C_i$
  - Total amount of computation in the hyperperiod
  - If a max flow is found with this amount then we have a schedule
- If a task is scheduled across multiple frames, we must slice it into subtasks
  - Potentially difficult
  - However, if we don't allow the algorithm to split tasks, the problem becomes NP-complete
    - Common pattern in this sort of problem
      - E.g. optimal bin packing becomes easy if we can split objects

Flow Graph Example



- This flow is telling us to split J_i into two jobs, one in x and one in y, while J_k executes entirely in y

Non-Independent Tasks

- *Precedence constraints*: "T_i must execute before T_j"
  - Enforce these by adjusting tasks' release times and deadlines
- *Critical sections*: "T_i must not be sliced in such a way that T_j runs in the middle"
  - These make the problem of finding a schedule NP-hard

CE Advantages

- Main advantage: Cyclic executives are very simple – you just need a table
  - Table makes the system very predictable
    - Can validate and test with very high confidence
  - No race conditions, no deadlock
  - No processes, no threads, no locks, …
  - Task dispatch is very efficient: just a function call
  - Lack of scheduling anomalies

CE Disadvantages

- Cyclic executives are brittle – any change requires a new table to be computed
- Release times of tasks must be fixed
- F could be huge
  - Implies mode changes may have long latency
- All combinations of tasks that could execute together must be analyzed
- Slicing tasks into smaller units is difficult and error-prone

Summary

- Cyclic executive is one of the major software architectures for embedded systems
  - Historically, cyclic executives dominate safety-critical systems
  - Simplicity and predictability win
  - However, there are significant drawbacks
  - Finding a schedule might require significant offline computation