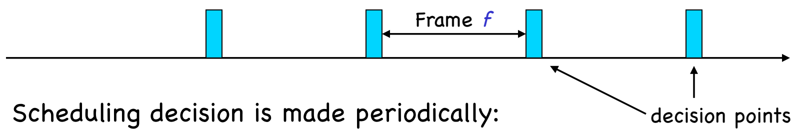
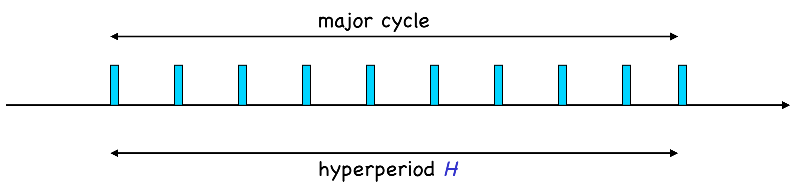
Cyclic Schedules: General Structure

- Scheduling decision is made periodically:



- Scheduling decision is made periodically:
  - choose which job to execute
  - perform monitoring and enforcement operations
- **Major Cycle**: Frames in a hyperperiod.



Frame Size Constraints

- Frames must be sufficiently long so that every job can start and complete within a single frame:

$$(1) \qquad f \geq \max(e_i)$$

- The hyperperiod must have an integer number of frames:

$$(2) \qquad f | H \qquad (f \text{ "divides" } H)$$

- For monitoring purposes, frames must be sufficiently small that between release time and deadline of every job there is at least one frame:

$$2f - (t'-t) \leq D_i$$

$$t'-t \geq \gcd(p_i, f)$$

$$(3) \qquad 2f - \gcd(p_i, f) \leq D_i$$

Frame Sizes: Example

- Task set:

	p_i	e_i	D_i
T_1 =	(15,	1,	14)
T_2 =	(20,	2,	26)
T_3 =	(22,	3,	22)

$H = 660$

(1) $\forall i : f \geq e_i \quad \Rightarrow f \geq 3$

(2) $f \mid H \quad \Rightarrow f = 2,3,4,5,6,10,..$

(3) $\forall i : 2f - \gcd(pi, f) \leq Di \quad \Rightarrow f = 2,3,4,5,6$

$\Rightarrow$ possible values for f : 3,4,5,6

Slicing and Scheduling Blocks

- Slicing

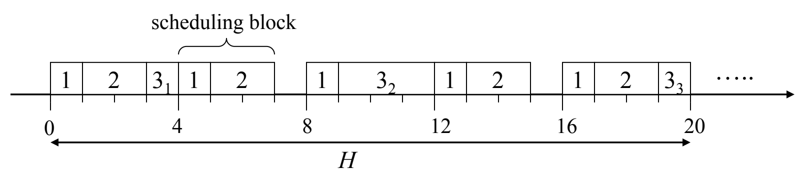
	p_i	e_i	D_i
T_1 =	(4,	1,	4)
T_2 =	(5,	2,	5)
T_3 =	(20,	5,	20)

(1) $\Rightarrow f \geq 5$
(3) $\Rightarrow f \leq 4$ } ?!

slice T_3

T_1 =	(4,	1,	4)
T_2 =	(5,	2,	5)
T_{31} =	(20,	1,	20)
T_{32} =	(20,	3,	20)
T_{33} =	(20,	1,	20)

(1) $\Rightarrow f \geq 3$
(3) $\Rightarrow f \leq 4$ } $f = 4$



Cyclic Executive

Input: Stored schedule: L(k) for k = 0,1,…,F-1;
Aperiodic job queue.

```
TASK CYCLIC_EXECUTIVE:
  t = 0; /* current time */        k = 0; /* current frame */
  CurrentBlock := empty;
  BEGIN LOOP
    IF <any slice in CurrentBlock is not completed> take action;
    CurrentBlock := L(k);
    k := k+1 mod F; t := t+1;
    set timer to expire at time tF;
    IF <any slice in CurrentBlock is not released> take action;
    wake up periodic task server to handle slices in CurrentBlock;
    sleep until periodic task server completes or timer expires;
    IF <timer expired> CONTINUE;
    WHILE <the aperiodic job queue is not empty>
      wake up the first job in the queue;
      sleep until the aperiodic job completes;
      remove the just completed job from the queue;
    END WHILE;
    sleep until next clock interrupt;
  END LOOP;
END CYCLIC_EXECUTIVE;
```


What About Aperiodic Jobs?

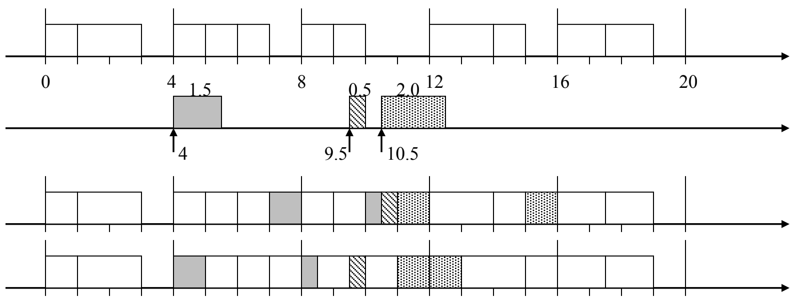
- Typically:
  - Scheduled in the background.
  - Their execution may be delayed.
- But:
  - Aperiodic jobs are typically results of external events.
- Therefore:
  - The sooner the completion time, the more responsive the system
  - Minimizing response time of aperiodic jobs becomes a design issue.
- Approach:
  - Execute aperiodic jobs ahead of periodic jobs whenever possible.
  - This is called Slack Stealing.

Slack Stealing (Lehoczky *et al.*, RTSS'87)

x_k Amount of time allocated to slices executed during frame F_k.

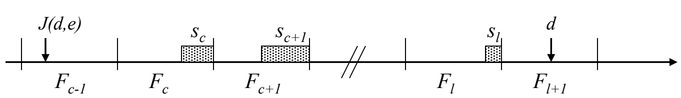
s_k Slack during frame F_k: $s_k := f - x_k$.

- The cyclic executive can execute aperiodic jobs for s_k amount of time without causing jobs to miss deadlines.
- Example:



Sporadic Jobs

- Reminder: Sporadic jobs have hard deadlines; the release time and the execution time are not known *a priori*.
  Worst-case execution time known when job is released.
- Need acceptance test:



$$S(c,l) = \sum_{i=c}^{l} s_i$$: Total amount of slack in Frames F_c, ..., F_l.

- Acceptance Test:

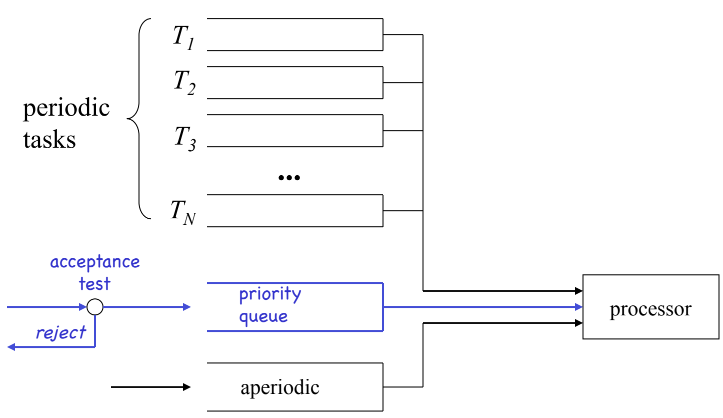
```
IF S(c,l) < e THEN
  reject job;
ELSE
  accept job;
  schedule execution;
END;
```

how?!

Scheduling of Accepted Jobs

- **Static scheduling**:
  - Schedule as large a slice of the accepted job as possible in the current frame.
  - Schedule remaining portions as late as possible.
- Mechanism:
  - Append slices of accepted job to list of periodic-task slices in frames where they are scheduled.
- Problem: **Early commit**.
- Alternatives:
  - Rescheduling upon arrival.
  - Priority-driven scheduling of sporadic jobs.

EDF-Scheduling of Accepted Jobs



Acceptance Test for EDF-Scheduled Sporadic Jobs

- Sporadic Job J with deadline d arrives:
- Test 1: Test whether current amount of slack before d is enough to accommodate J. (*)
  If not, reject!
- Test 2: Test whether sporadic jobs still in system with deadlines after d will miss deadline if J is accepted. (**)
  If yes, reject!
- Accept!

- (*) Define $S(J_i)$: Amount of slack up to time d_i after J_i has been scheduled.
- (**) Update all $S(J_i)$ with $d_i > d$, that is,

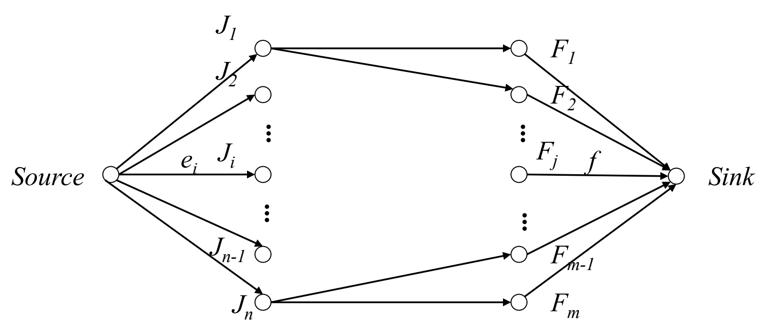
$$\forall i \quad \text{such that} \quad d_i > d : \quad S(J_i) = S(J_i) - e$$

Accept. Test for EDF Spor. Jobs (Implementation)

- Define
  $S_{i,k}$: slack in Frames F_i, ..., F_k
- Precompute all $S_{i,k}$ in first major cycle
- Initial amounts of slack in later cycles can be computed as
  $S_{i+jF,k+j'F} = S_{i,F} + S_{1,k} + (j'-j)S_{1,F}$
- Compute current slack of job with release time in F_{c-1} and deadline in F_{l+1}:
  $S^{new}_{c,l} = S_{c,l} - \Sigma_{(dk<d)} e_k(c)$
- Implementation:
  - Initially compute $S_{c,l}$ for newly arriving job. If negative, reject.
  - Whenever job with earlier deadline arrives, decrease this value. If negative, reject new job.

Static Scheduling of Jobs in Frames

- Layout of task schedule for cyclic executive can be formulated as a schedule for jobs in a hyperperiod.
- This can be formulated as a **network flow problem**.



Pros and Cons of Clock-Driven Scheduling

- Pros:
  - Conceptual simplicity
  - Timing constraints can be checked and enforced at frame boundaries.
  - Preemption cost can be kept small by having appropriate frame sizes.
  - Easy to validate: Execution times of slices known *a priori*.
- Cons:
  - Difficult to maintain.
  - Does not allow to integrate hard and soft deadlines.

Putting the Cyclic Executive into Practice

T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"

- Implementation approaches for a Cyclic Executive: Solutions and Difficulties
  - Naive solution using the DELAY statement
  - Using an interrupt from a hardware clock
  - Dealing with lost or buffered interrupts
  - Handling frame overruns

Naive Solution Using the DELAY Statement

```
task CYCLIC_EXECUTIVE_1;

task body CYCLIC_EXECUTIVE_1 is
     use CALENDAR;
     INTERVAL: constant:= 0.01;
     NEXT_TIME: TIME:= CLOCK + INTERVAL;
     FRAME_NUMBER: INTEGER:= 1;
begin loop delay NEXT_TIME - CLOCK;
           FRAME_NUMBER:=(FRAME_NUMBER+1) mod 2;
           case FRAME_NUMBER is
           when 0=> A; B; C; D1;
           when 1=> A; B; D2;
           end case;
           NEXT_TIME:= NEXT_TIME + INTERVAL;
           if CLOCK>NEXT_TIME
           then HANDLE_FRAME_OVERRUN; end if;
      end loop;
end CYCLIC_EXECUTIVE_1;
```

Source: T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"

Using an Interrupt from a Hardware Clock

```
task CYCLIC_EXECUTIVE_2 is
   entry TIMER_INTERRUPT;
   for TIMER_INTERRUPT'address use at TIMER'address;
end CYCLIC-EXECUTIVE_2;

task body CYCLIC_EXECUTIVE_2 is
   FRAME_NUMBER: INTEGER:= 1;
begin loop accept TIMER_INTERRUPT;
            FRAME_NUMBER:=(FRAME_NUMBER+1) mod 2;
            case FRAME_NUMBER is
            when 0=> A; B; C; D1;
            when 1=> A; B; D2;
            end case;
       end loop;
end CYCLIC_EXECUTIVE_2;
```

Source: T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"

Dealing with Lost or Buffered Interrupts

```
task CYCLIC_EXECUTIVE_3 is -- the task that
                           -- controls timing
   entry TIMER_INTERRUPT;
   for TIMER_INTERRUPT'address use at TIMER'address;
   pragma PRIORITY(SYSTEM. PRIORITY'last);
end CYCLIC_EXECUTIVE_3;

task ACTION is -- the task that does the work
   entry NEXT_FRAME;
end ACTION;

task body CYCLIC_EXECUTIVE_3 is
begin loop accept TIMER_INTERRUPT;
           select ACTION.NEXT_FRAME;
             else HANDLE_FRAME_OVERRUN;
           end select;
      end loop;
end CYCLIC_EXECUTIVE_3;

task body ACTION is
   FRAME_NUMBER: INTEGER:=1;
begin loop accept NEXT_FRAME;
           FRAME_NUMBER:=(FRAME_NUMBER+1) mod 2;
           case FRAME_NUMBER is
           when 0=> A; B; C; D1;
           when 1=> A; B; D2;
           end case;
       end loop;
end ACTION;
```

Source: T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"

Handling Frame Overruns (I)

ABORTION:

```
task type ACTION is -- the task that does the work
  entry NEXT_FRAME;
end ACTION;

type ACCESS_ACTION is access ACTION;

CURRENT_ACTION: ACCESS_ACTION:= new ACTION;

task body CYCLIC_EXECUTIVE_5 is
begin loop accept TIMER_INTERRUPT;
           select CURRENT_ACTION.NEXT_FRAME;
             else abort CURRENT_ACTION;
                  CURRENT_ACTION:= new ACTION;
           end select;
       end loop;
end CYCLIC_EXECUTIVE_5;
```

Source: T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"

Handling Frame Overruns (II)

EXCEPTIONS:

```
task body CYCLIC_EXECUTIVE_6 is
begin loop accept TIMER_INTERRUPT;
           select ACTION.NEXT_FRAME;
             else raise ACTION'failure;
           end select;
      end loop;
end CYCLIC_EXECUTIVE_6;

task body ACTION is
   FRAME_NUMBER: INTEGER:= 1;
begin loop accept NEXT_FRAME;
         begin FRAME_NUMBER:=(FRAME_NUMBER+1) mod 2;
               case FRAME_NUMBER is
               when 0=> A; B; C; D1;
               when 1=> A; B; D2;
               end case;
         exception when others=> RECOVER_FROM_OVERRUN;
         end;
      end loop;
end ACTION;
```

Source: T. P. Baker, Alan Shaw, "The Cyclic Executive Model and Ada"