Embedded Systems Programming - PA8001

http://goo.gl/YdEcZU

Lecture 5

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Real Time?

In what ways can a program be related to time in the environment (the *real time*)?

Salvador Dali, The Persistence of Memory.

Real Time

An external process to . . .

- Sample: reading a clock,
- React: a handler for an interrupt clock, and
- Constraint: a deadline to respect.

Sampling the time

Requires a hardware clock (read as an external device)

Multitude of alternatives

- Units? Seconds? Milliseconds? CPU cycles?
- Since when? Program start? System boot? Jan 1, 1970?
- Real time? Time stops when: other threads are running? when CPU sleeps? Time that cannot be set and always increases?

Timestamps

Relative timing: prevalent in reactive systems, reactions are relative to events

Example

Teacher left 15 min. after the start of the lecture.

In embedded programming, time-stamping an event: reading performed around the event detection.

Time spans

The difference between two time-stamps: a time span independent of the nominal clock values (modulo clock resolution).

The meaning of time-stamp

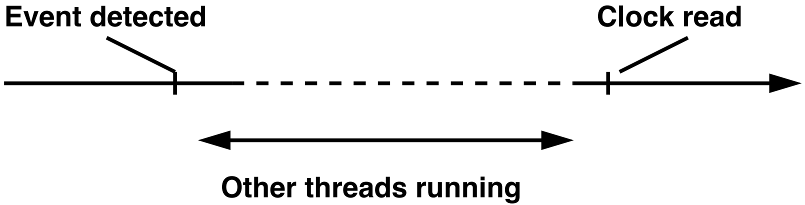
- The time of some arbitrary program instruction?
- The beginning or end of a function call?
- The time of sending or receiving an asynchronous message?

Too much program dependent!

In a scheduled system

What looks like . . .

might very well be . . .



Close proximity is not the same as subsequent statements!

Time-stamping events

Solution: to time-stamp events that *drive* a system

Idea!

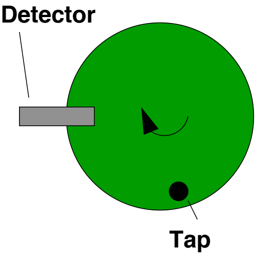
Read the clock in the interrupt handler detecting the event

- Disable other interrupts, hence no threads might interfere
- Tight predictable upper bound on the time-stamp error

Example

Calculate the speed

For a rotating wheel, measuring the time between two subsequent detections of a passing tap.




```
typedef struct{
 Object super;
 int previous;
 Other *client;
} Speedo;
...
Speedo speedo;
int main(){
   INSTALL(&speedo, detect, SIG_XX);
   return TINYTIMBER(...)
}
```

Example

Calculate the speed

For a rotating wheel, measuring the time between two subsequent detections of a passing tap.

```
int detect(Speedo *self, int sig){
   int timestamp = TCNT1;
   ASYNC(self -> client,
        newSpeed,
        PERIMETER/DIFF(timestamp,self->previous));
   self->previous=timestamp;
}
```

`DIFF` will have ot take care of timer overflows!

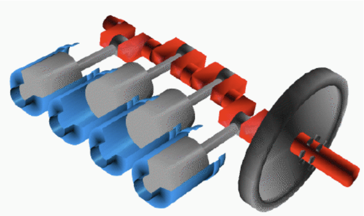
Real-time events to react to

So far: how to sample the real-time clock to know about time

Now: how to take action after a certain amount of time

Example

The wheel is an engine crankshaft and we have to emit ignition signals to each cylinder



How to postpone program execution until certain time

Reacting to real time events

Very poor man's solution

Consume a fixed amount of CPU cycles in a (silly) loop

```
int i;
for(i=0;i<N;i++);  // wait
do_future_action();
```

Problems

1. Determine `N` by testing!
2. `N` will be highly platform dependent!
3. A lot of CPU cycles will simply be wasted!

Reacting to real time events

The nearly as poor man's solution

Configure a timer/counter with a known clock speed, and busy-wait for a suitable time increment

```
unsigned int i = TCNT1+N;
while(TCNT1<i); // wait
do_future_action();
```

Problems

1. Determine `N` by calculation
2. Still a lot of wasted CPU!

Reacting to real time events

The standard solution

Use the OS to *fake* busy-waiting

```
delay(N);   // wait (blocking OS call)
do_future_action();
```

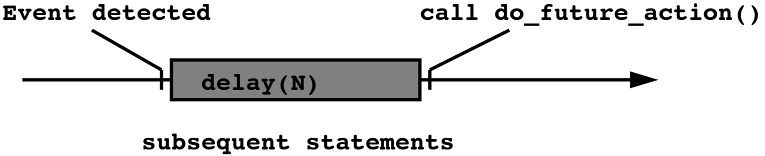
- No platform dependency!
- No wasted CPU cycles (at the expense of a complex OS)

Still a problem ...

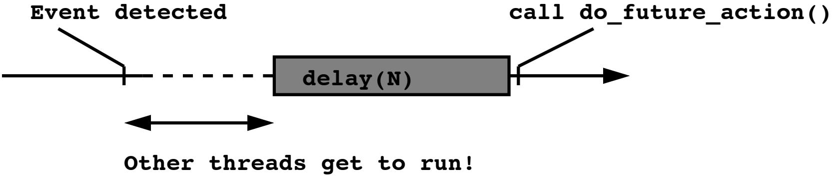
... common to all solutions ...

In a scheduled system

What looks like . . .



might very well be . . .



Had we known the scheduler's choice, a smaller `N` had been used!

Relative delays

The problem: relative time without fixed references:

- The constructed real-time event will occur at after `N` units from *now*.
- What is *now*?!

Other common OS services share this problem: `sleep`, `usleep` and `nanosleep`.

We are not going to use OS services in the course.

Yet another problem

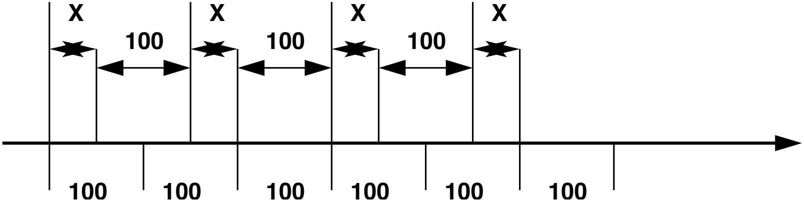
Threads and interleaving make it worse

Example

Consider a task running a CPU-heavy function `do_work()` every 100 millisecods. The naive implementation sing `delay()`:

```
while(1){
  do_work();
  delay(100);
}
```

Accumulating drift

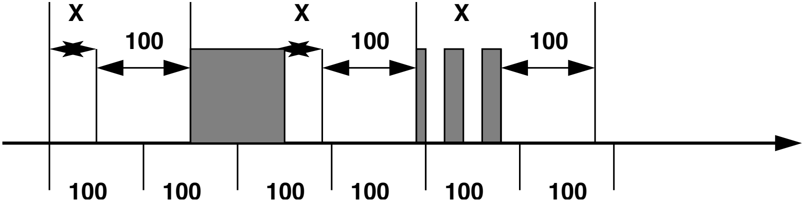


X is the time take to do_work

Each turn takes at least 100+X milliseconds.

A drift of X milliseconds will accumulate every turn!

Accumulating drift



With threads and interleaving, the bad scenario gets worse!

Even with a known `X`, delay time is not predictable.

A stable reference

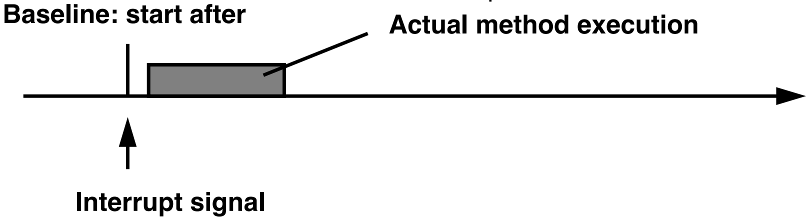
What we need is a stable time reference to use as a basis whenever we specify a relative time (instead of now).

Baselines

We introduce the baseline of a message to mean the earliest time a message is allowed to start.

Time stamps of interrupts!

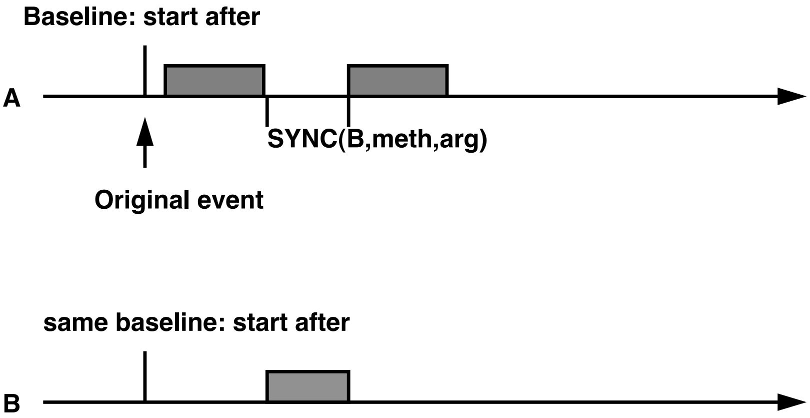
The baseline of an event is its time-stamp:



A stable reference

SYNC

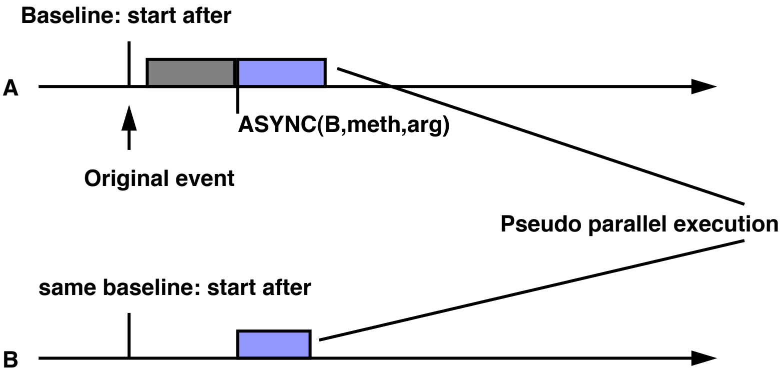
Calling methods with `SYNC` doesn't change the baseline (the call inherits the baseline)



A stable reference

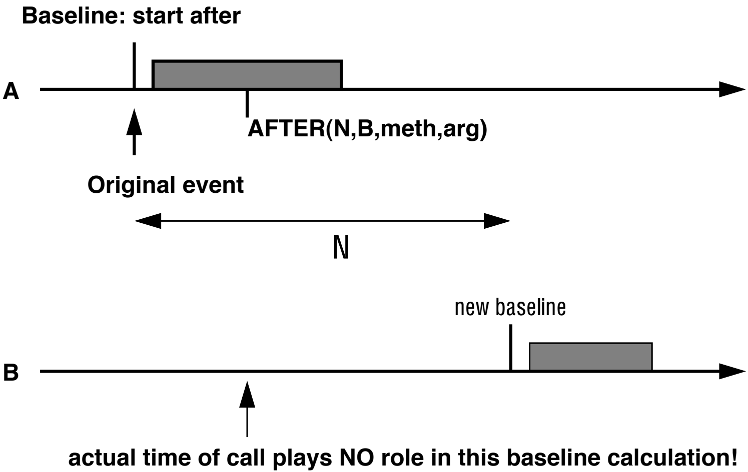
ASYNC

By default `ASYNC` method calls will inherit the baseline



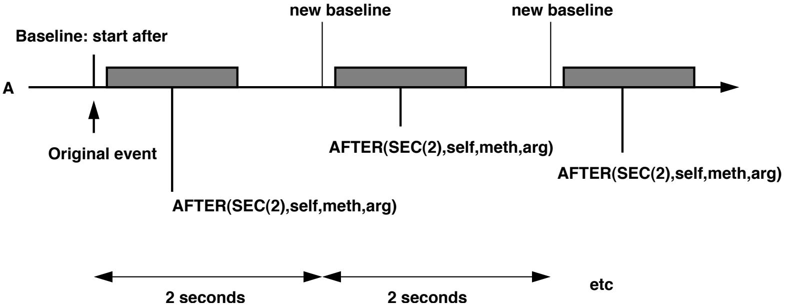
A stable reference

For `ASYNC` we may also consider adding a baseline offset `N`!



Periodic tasks

To create a cyclic reaction, simply call **self** with the same method and a new baseline:



`SEC` is a convenient macro that makes the call independent of current timer resolution.

Implementing `AFTER`

1. Let the baseline be stored in every message (as part of the `Msg` structure)
2. `AFTER` is the same as `ASYNC`, but
   - New baseline is
     `MAX(now, offset+current->baseline)`
   - If `baseline > now` , put message in a timerQ instead of readyQ
   - Set up a timer to generate an interrupt after earliest baseline
   - At each timer interrupt, move first timerQ message to readyQ and configure a new timer interrupt

In fact `ASYNC` can now be defined as

```
#define ASYNC(to,meth,arg) AFTER(0,to,meth,arg)
```

Priority assignment

Question

How do we set thread/message priority for the purpose of meeting deadlines?

Static priorities

Assign a fixed priority to each thread and keep it constant until termination.

Dynamic priorities

Determine the priority at run-time from factors such as the time remaining until deadline.

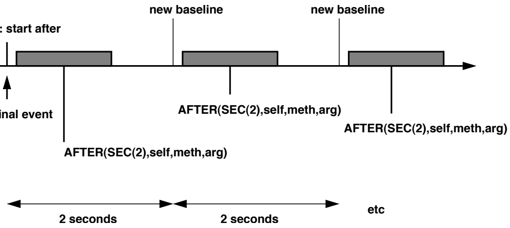
:-(

In neither case a method exists that is both predictable and generally applicable to all programs!

:-)

It is possible to get by if we concentrate on programs of a restricted form.

Initial restricted model



- Only periodic reactions
- Fixed periods
- No internal communication
- Known, fixed WCETs
- Deadlines = periods

If time allows, we will discuss how to remove these restrictions.

Static priorities – method

Rate monotonic (RM)

Under the given assumptions, there exists a static priority assignment rule that is really simple

The shorter the period, the higher the priority

d For RM, the actual priority values do not matter, only their relative order.

Because of our inverse priority scale, we can simply implement RM by letting $P_i = D_i \ (=T_i)$

RM example

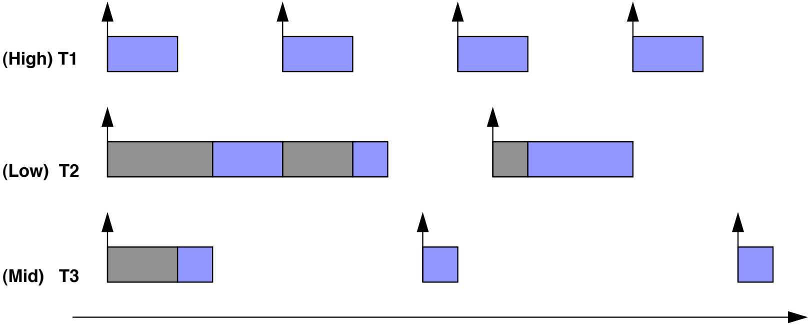
Given a set of periodic tasks with periods

T1	=	25ms
T2	=	60ms
T3	=	45ms

Valid priority assignments

P1	=	10	P1	=	1	P1	=	25
P2	=	19	P2	=	3	P2	=	60
P3	=	12	P3	=	2	P2	=	45

RM example



Period = Deadline. Arrows mark start of period.
Blue: running. Gray: waiting.

Dynamic priorities – method

Earliest Deadline First – EDF

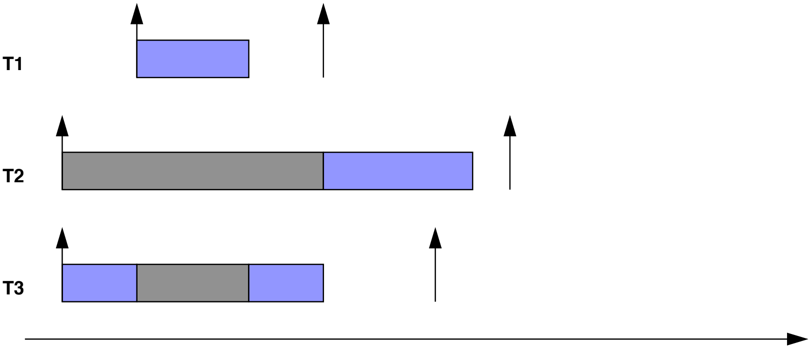
Dynamic priority assignment rule:

> The shorter the time remaining until deadline, the higher the priority

To use absolute deadlines: priorities = remaining clock cycles (before missing the deadline)

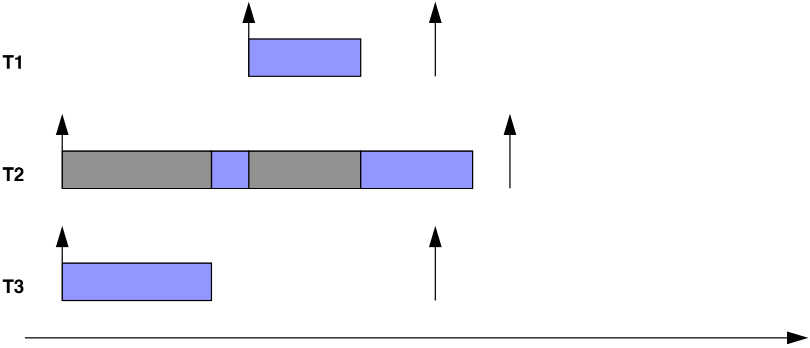
Under EDF, each activation n of periodic task i will receive a new priority: $P_{i(n)} = baseline_{i(n)} + D_i$

EDF example



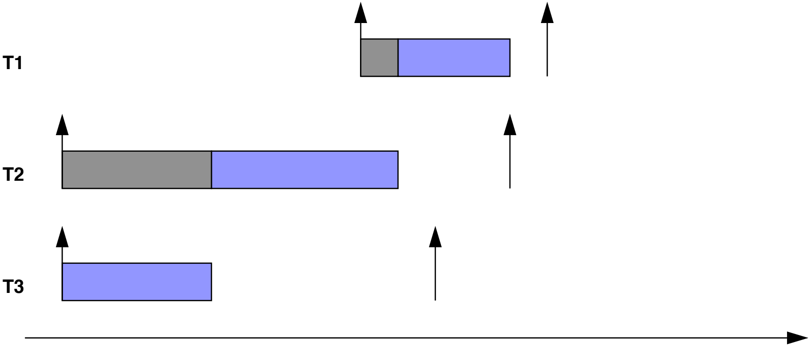
T1 arrives later, but its deadline is earlier than both T2's and T3's absolute deadlines!

EDF example



Deadline of T1 $<$ Deadline of T2

EDF example



(absolute) Deadline of T1 > (absolute) Deadline of T2

Optimality

Multiple ways assigning priorities to meet deadlines

Optimal: a method which fails only if every other method fails

- RM is optimal among static assignment methods
- EDF is optimal among dynamic methods

Schedulability

An optimal method may also fail
A set of task may not be schedulable at all

Example

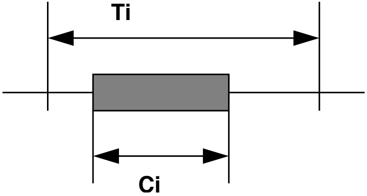
The shortest path from A to B is 200km (the optimal scheduling).
We have only one hour to reach the destination and the maximum speed is 120 km/h (deadline and platform constraints).
Can we be there on time (schedulability analysis)

Schedulability

To determine whether task set is at all schedulable (with optimal methods)

Schedulability must take the WCETs of tasks into account.

Utilization-based analysis



For a periodic task set, an important measure is how big a fraction of each turn a task is actually using the CPU.

That is, the CPU utilization of a periodic task i is the ratio $\frac{C_i}{T_i}$, where C_i is the WCET and T_i is the period.

Note

Any task for which $C_i = T_i$ will effectively need exclusive access to the CPU!

Utilization-based analysis (RM)

Given a set of simple periodic tasks, scheduling with priorities according to RM will succeed if

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq N(2^{1/N} - 1)$$

where N is the number of threads.

That is, the sum of all CPU utilizations must be less than a certain bound that depends on N.

Utilization bounds

N	Utilization bound
1	100.0 %
2	82.8 %
3	78.0 %
4	75.7 %
5	74.3 %
10	71.8 %

Approaches 69.3% asymptotically

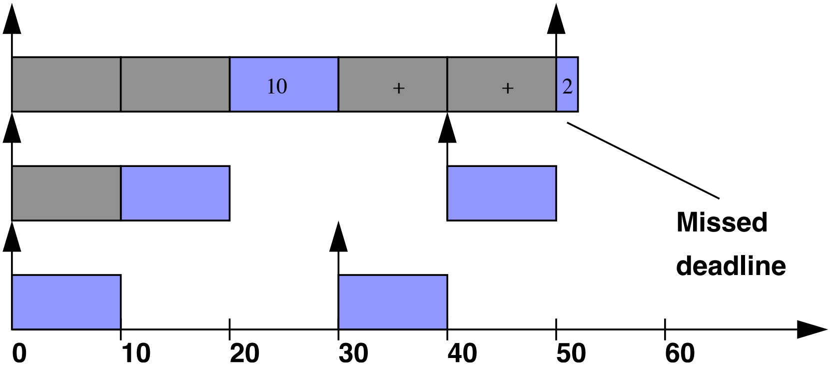
Example A

Task	Period	WCET	Utilization
i	T_i	C_i	U_i
1	50	12	24%
2	40	10	25%
3	30	10	33%

The combined utilization U is 82%, which is above the bound for 3 threads (78%).

The task set fails the utilization test.

Time-line for example A



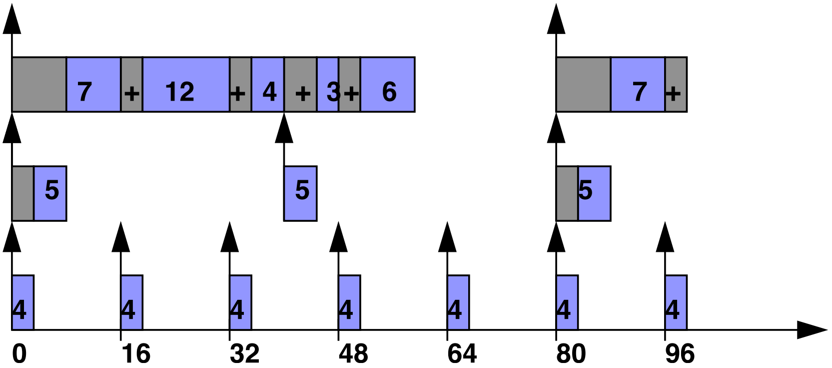
Example B

Task	Period	WCET	Utilization
i	T_i	C_i	U_i
1	80	32	40%
2	40	5	12.5%
3	16	4	25%

The combined utilization U is 77.5%, which is below the bound for 3 threads (78%).

The task set will meet all its deadlines!

Time-line for example B



Example C

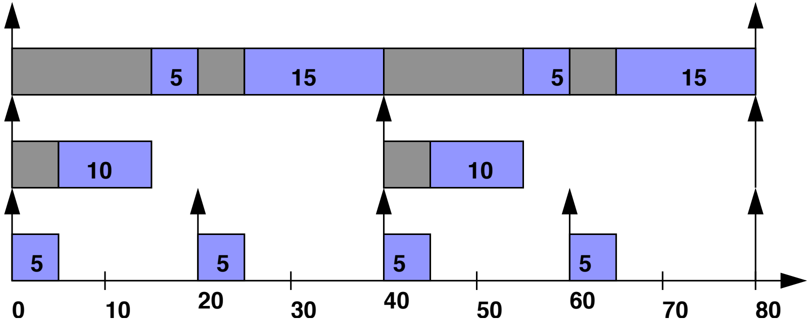
Task	Period	WCET	Utilization
i	T_i	C_i	U_i
1	80	40	50%
2	40	10	25%
3	20	5	25%

The combined utilization U is 100%, which is well above the bound for 3 threads (78%).

However, this task set still meets all its deadlines!

How can this be??

Time-line for example C



Characteristics

The utilization-based test

- Is sufficient (pass the test and you are OK)
- Is not necessary (fail, and you might still have a chance)

Why bother with such a test?

- Because it is so simple!
- Because only very specific sets of tasks fail the test and still meet their deadlines!

Utilization-based analysis (EDF)

Given a set of simple periodic tasks, scheduling with priorities according to EDF will succeed if

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq 1$$

That is, the sum of all CPU utilizations must be less than or equal 100%, independent of the number of tasks.

Unlike the case for RM, the utilization-based test for EDF is both sufficient and necessary (demand more than 100% of the CPU and you are bound to fail!)

EDF vs RM

Similarities

- Both algorithms are optimal within their class
- Both are easy to implement in terms of priority queues
- Both have simple utilization-based schedulability tests
- Both can be extended in similar ways

Advantages of EDF

- Close relation to terminology of real-time specifications
- Directly applicable to sporadic, interrupt-driven tasks
- superior CPU utilization

EDF vs RM

Drawbacks of EDF

- It exhibits random behaviour under transient overload (but so does RM, in fact, in a different way)
- RM predictably skips low priority tasks under constant overload (but EDF rescales task priorities instead)
- Utilization-based test becomes more elaborate for EDF when $D_i \leq T_i$ (but is still feasible)
- Operating systems generally don't support it (priority scales lack granularity, no automatic time-stamping)
- Few languages allow for natural deadline constraints

However, for reactive objects, EDF fits nice as an alternative to RM

Implementation (RM)

In `TinyTimber.c`

```
struct msg_block{
  ...
  Time baseline;
  Time priority;
  ...
};

void async(Time offset, Time prio,
           OBJECT *to, METHOD meth, int arg){
   ...
   m->baseline=MAX(TIMERGET(),
                   current->baseline+offset);
   m->priority = prio;
   ...
}
```

Implementation (EDF)

In `TinyTimber.c`

```
struct msg_block{
  ...
  Time baseline;
  Time deadline;
  ...
};

void async(Time BL, Time DL,
           OBJECT *to, METHOD meth, int arg){
   ...
   m->baseline=MAX(TIMERGET(),
                   current->baseline+BL);
   m->deadline = m->baseline+DL;
   ...
}
```

Loosening the assumptions

Sporadic Tasks

Sporadic tasks: no fixed period (interrupt handlers), urgent deadlines

Characteristics needed for schedulability analysis

Characteristics

Minimum inter-arrival time: minimum time between two events causing sporadic tasks (e.g., key strokes, signal updates)

Period T interpreted as inter-arrival time

For sporadic tasks: $D < T$

Scheduling Sporadic Tasks

Deferrable Servers

A task with period T and the highest priority

Fixed capacity C

Scheduling

Sporadic events scheduled in the server when there is capacity left

Capacity is replenished every T units

Bonus question

Name an alternative to deferrable servers. Compare it with deferrable servers.
Send in your answers before 08:30 tomorrow.

More on real-time

Other analysis

Response-time analysis: more powerful technique than utilization based

More on this in specialized courses on real-time (such as distributed real time systems)