Real-Time Embedded Systems

DT8025, Fall 2016

http://goo.gl/AZfc9l

Lecture 6

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Scheduler

When there are fewer processors than tasks or when tasks must be performed at a particular time, a scheduler must intervene.

The core of an implementation of threads is a scheduler.

Scheduler makes the decision about what to do next at certain points in time.

Multiprocessor scheduler decides not only which task to execute next, but also on which processor to execute it.

Basics of Scheduling

Scheduling Decision

- assignment: which processor should execute the task.
- ordering: in what order each processor should execute its tasks.
- timing: the time at which each task executes.

Each of these three decisions may be made at

- design time, before the program begins executing, or at
- run time, during the execution of the program.

Basics of Scheduling

Different types of schedulers based on decision time

- Fully-static Scheduler
  - Makes all three decisions at design time.
- Static Order Scheduler
  - performs the task assignment and ordering at design time, and defers timing until run time.
- Static Assignment Scheduler
  - performs the assignment at design time, and ordering and timing at run time.
- Fully-dynamic Scheduler
  - performs all decisions at run time.
- ... and more combinations!

Basics of Scheduling

Preemptive vs. non-preemptive

Preemptive Scheduler

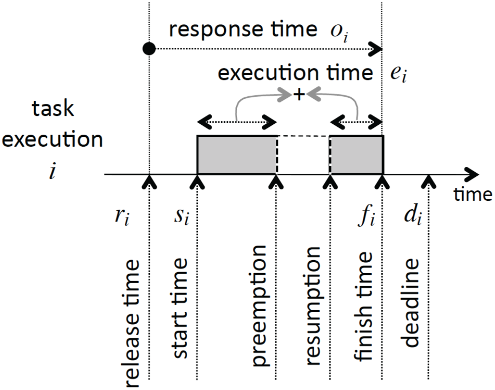
Makes scheduling decision during the execution of a task. It may decide to stop the execution of a task and begin execution of another one.
The interruption of the first task is called preemption.

Non-preemptive Scheduler

Always lets tasks run to completion before assigning another task to execute on the same processor.

Basics of Scheduling

Basic definitions



Scheduling Strategies

The choice of scheduling strategy is governed by considerations that depend on the goals of the application.

- e.g. all task executions meet their deadlines: $f_i \leq d_i$.

Feasible Schedule

A schedule that accomplishes the goal that all task executions meet their deadlines.

Priority assignment

Question

How do we set thread/task 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.

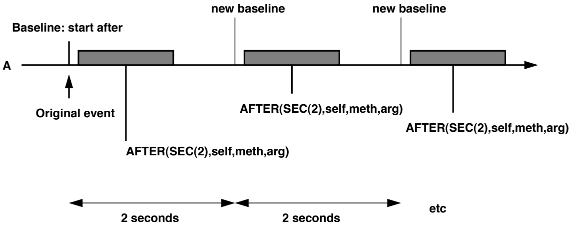
:-(

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

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

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

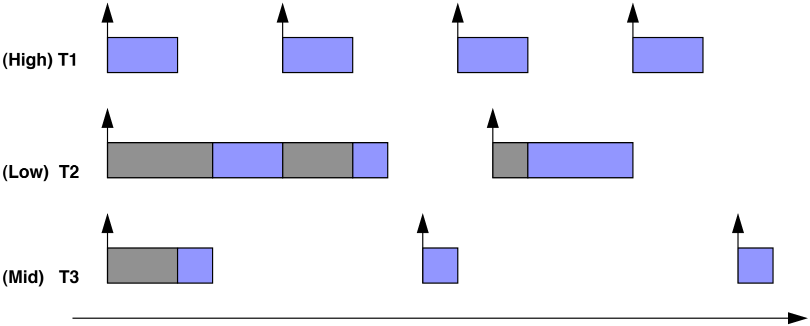
Given a set of periodic tasks with periods

$$\begin{aligned} T1 &= 25ms \\ T2 &= 60ms \\ T3 &= 45ms \end{aligned}$$

Valid priority assignments

$$\begin{aligned} P1 &= 10 \\ P2 &= 19 \\ P3 &= 12 \end{aligned} \qquad \begin{aligned} P1 &= 1 \\ P2 &= 3 \\ P3 &= 2 \end{aligned} \qquad \begin{aligned} P1 &= 25 \\ P2 &= 60 \\ P2 &= 45 \end{aligned}$$

RM example



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

Dynamic priorities – method

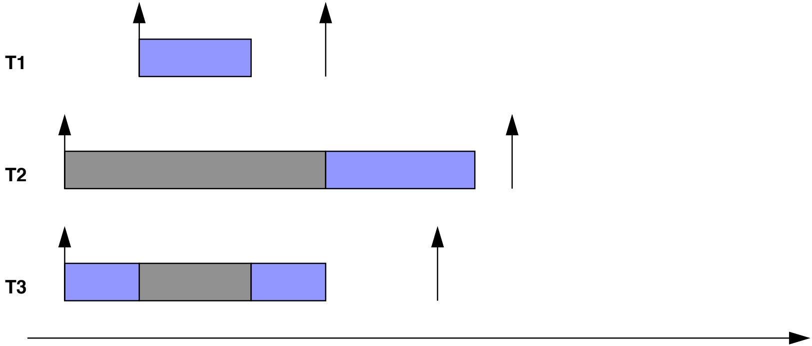
Earliest Deadline First – EDF

Dynamic priority assignment rule:

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

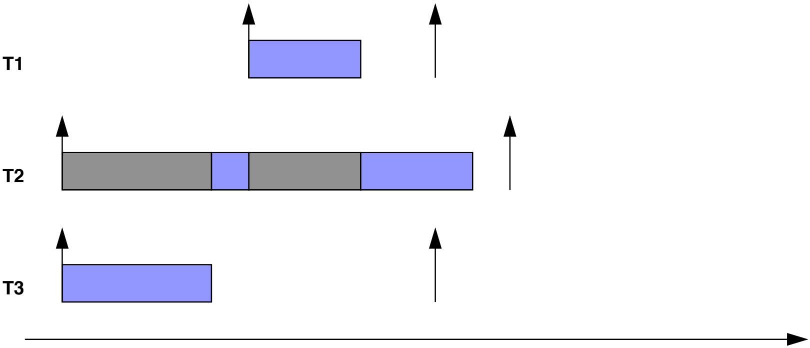
To use absolute deadlines: priorities = remaining clock cycles (before missing the deadline)

EDF example



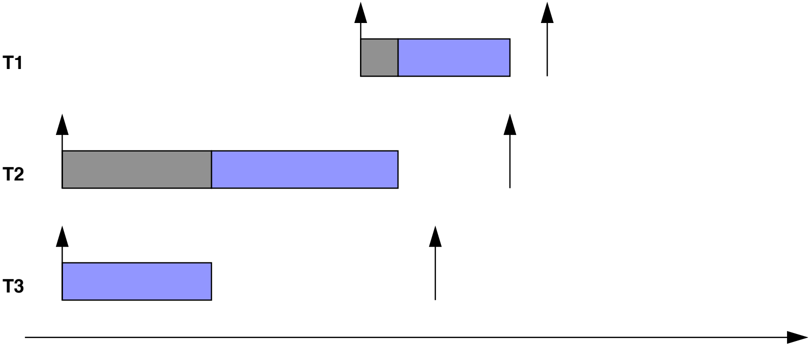
T1 arrives later, but its deadline is earlier than both T2's and T3's absolute deadlines!

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

Next lecture: Liu and Layland's Theorem (RM is optimal with respect to feasibility).

Schedulability

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

Example

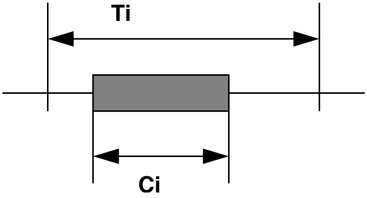
The shortest path from A to B is 200km (the optimal scheduling). We have only one hour to reach the destination and the maximum speed is 120 km/h (deadline and platform constraints).
Can we be there on time (schedulability analysis)

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

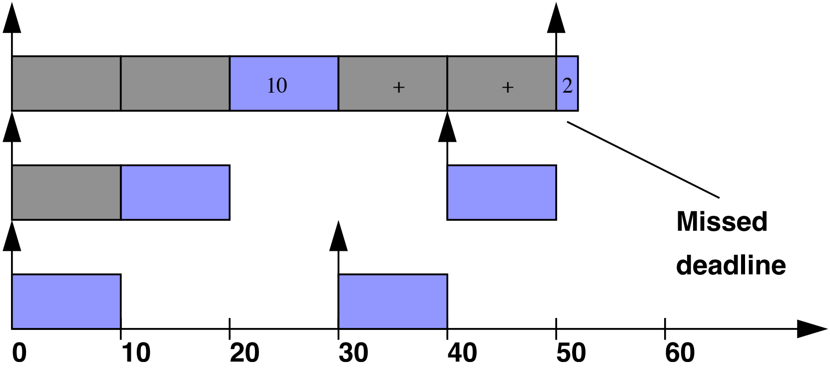
Example A

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



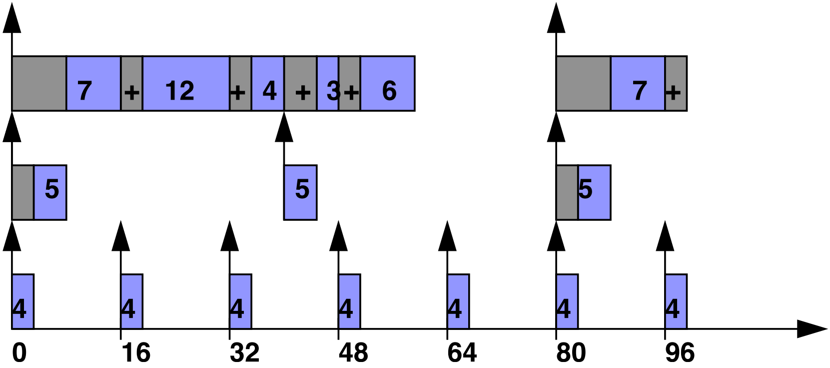
Example B

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

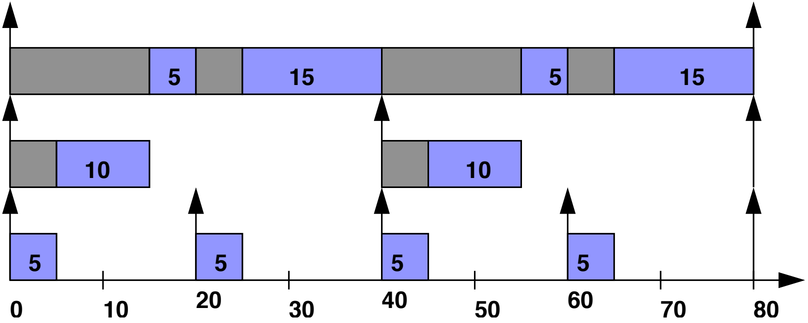
Task	Period	WCET	Utilization
i	T_i	C_i	U_i
1	80	40	50%
2	40	10	25%
3	20	5	25%

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!)

Bonus Question

Bonus Question

1. EDF is not optimal for a task set with precedences. Give a counter example and introduce an extension to it which is optimal with precedences.
2. Explain briefly the priority inversion and how it is managed.

Deadline

Thursday 06/10/2016, noon (12:00).

Format

A simple document (e.g. PDF). Don't forget your name!

Email your answers to m.taromirad@hh.se. Beware of plagiarism!

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

Real-time Systems

When in addition to any ordering constraints between the tasks, there are also timing constraints which relate the execution of a task to real-time.

Real-time

The physical time in the environment of the computer executing the task.

Real-time programs can have all manner of timing constraints

- deadline
- executed no earlier than a particular time
- executed periodically with some specified period
- ...

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).

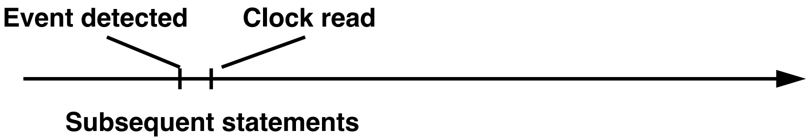
The meaning of time-stamp

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

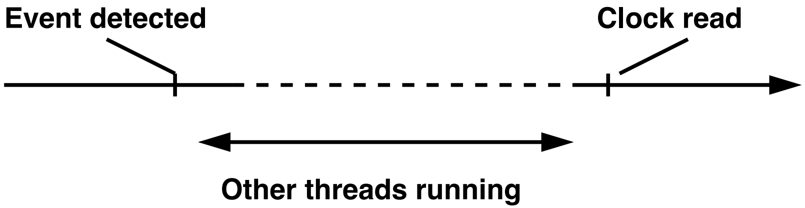
Too much program dependent!

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

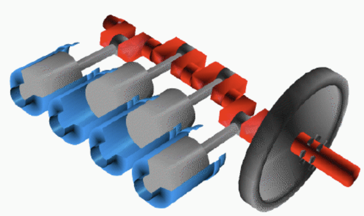
Real-time events to react to

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();
```

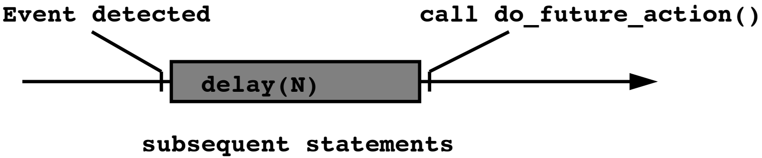
- No platform dependency!
- No wasted CPU cycles (at the expense of a complex OS)

Still a problem . . .

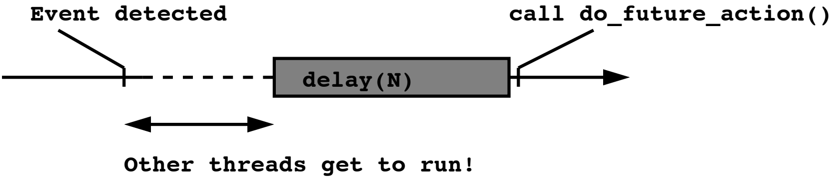
. . . common to all solutions . . .

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`.

Yet another problem

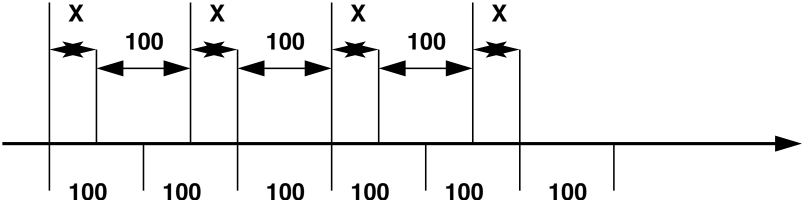
Threads and interleaving make it worse

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

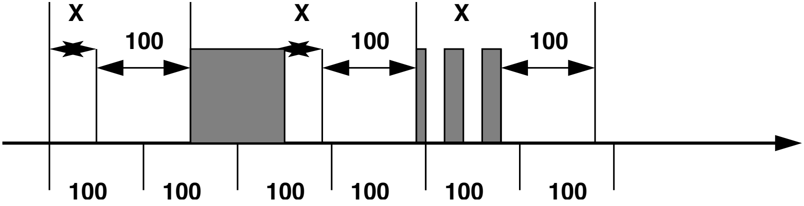


X is the time take to `do_work`

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

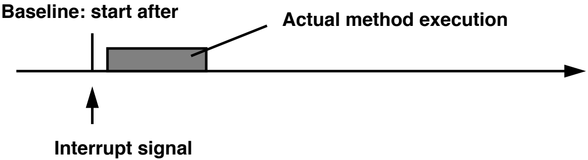
What we need is a stable time reference to use as a basis whenever we specify a relative time (instead of now).

Baselines

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

Time stamps of interrupts!

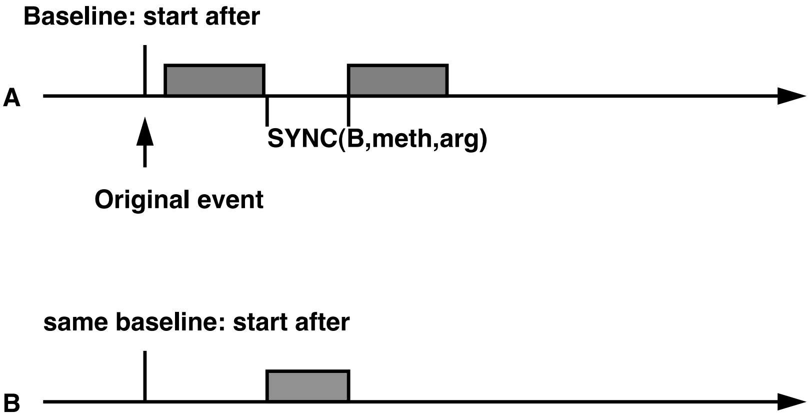
The baseline of an event is its time-stamp:



A stable reference

SYNC

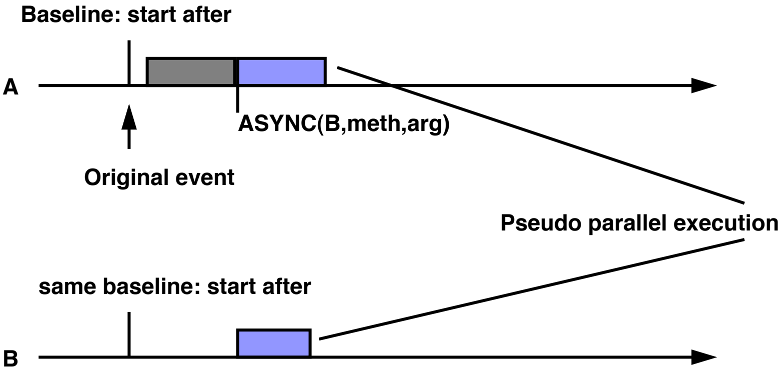
Calling methods with `SYNC` doesn't change the baseline (the call inherits the baseline)



A stable reference

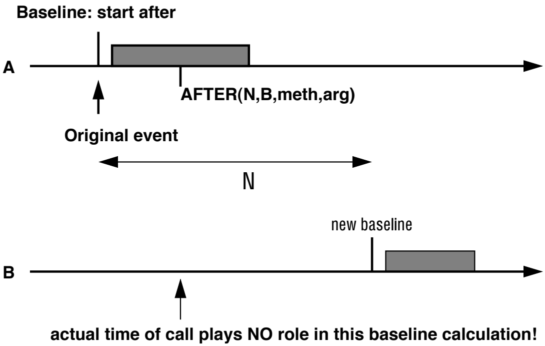
ASYNC

By default `ASYNC` method calls will inherit the baseline



A stable reference

ASYNC with a baseline offset N!



Periodic tasks

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