Logical time and real-time in the Synchronous approach

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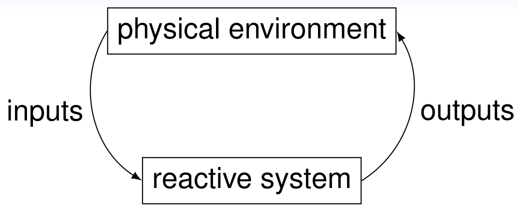
Overview

At the end of this session you should understand:

- Why introducing explicit real-time constraints in a synchronous language is useful;
- How we can deal with **both** logical-time and real-time;
- The implications of the introduction of real-time in the language structure and compilation.

Outline

Reactive system (reminder)



- React to inputs:
  1. Acquire inputs on sensors;
  2. Compute;
  3. Produce values on actuators.
- Actions impact the environment, thus subsequent inputs;
- Response time must be **bounded**, due to environment evolving autonomously.

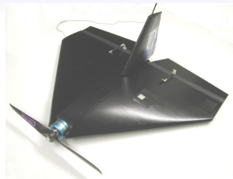
Real-time system

Definition

Real-time systems must guarantee response within strict time constraints, often referred to as “deadlines”. (Wikipedia)

- Similar to reactive systems;
- **Several, predefined time bounds**.

Example: UAV control

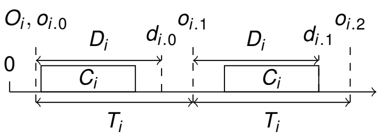


Real-time constraints:

- GPS (input): 1 frame every 250 ms.
  - Deadline miss $\Rightarrow$ frame lost (current position), wrong trajectory.
- Attitude regulation (output): consolidate actuator orders every 60ms
  - Deadline miss $\Rightarrow$ loss of control.
- Failure detection (internal): check inconsistencies every 200ms
  - Deadline miss $\Rightarrow$ crash with motors on.
- ...

Classic model

Program=a set of tasks (threads) τ_i:



- T_i: period;
- D_i: relative deadline ($D_i <= T_i$);
- C_i: worst-case execution time (WCET);
- O_i: initial release date;
- $\tau_{i.p}$: p^{th} job of τ_i.

Deadlines and periods

- **Deadline**: respond before some specified time;
- **Period**: processes are recurring at regular time intervals;
- The period is often an implicit deadline (non-reentrant tasks);
- Choice of the periods/deadlines:
  - Lower-bound: physical constraints of the sensors/actuators;
  - Lower-bound: computation time;
  - Upper-bound: too slow can lead to an unsteady system.

Execution times

- Evaluating the execution time of some process is HARD
  - Depends on the content of the memory;
  - Depends on the content of the pipeline;
  - Depends on the values processed;
  - Other processes may interfere;
  - OS may interfere...
- Validating temporal behaviour with variable execution times is complex;

⇒ Execution times are (largely) over-evaluated by a **Worst-Case Execution Time** (WCET).

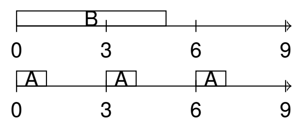
Real-time multi-tasking

Some classic problems:

- **Scheduling policy**: define an algorithm that finds an execution order (a schedule), that respects all deadlines;
- **Schedulability analysis**: ensure before execution that deadlines can and will be met (for a given policy);
- Data-dependencies $\Rightarrow$ scheduling policy for dependent tasks + synchronization primitives (e.g. semaphores, buffers, ...);
- Shared resources $\Rightarrow$ problems similar to communication synchronizations.

Scheduling: multi-processor example

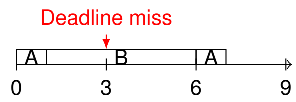
$\tau_B(T_B = 9, C_B = 5)$ and $\tau_A(T_A = 3, C_A = 1)$:



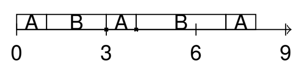
Scheduling: mono-processor example

$\tau_B(T_B = 9, C_B = 5)$ and $\tau_A(T_A = 3, C_A = 1)$:

- Without preemption:



- With preemption:



Scheduling policy example: Rate-Monotonic

- Fixed-task priorities: a fixed priority is assigned to each task;
- Task with smaller relative deadline (=period) gets a higher priority;
- Works only when $D_i = T_i$;
- This policy is **optimal** among the fixed-task priority policies.
  $\Rightarrow$ What does **optimal** mean ?

Rate-Monotonic analysis

Sufficient schedulability test:

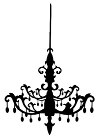
$$\sum_{i=0}^{m} \frac{C_i}{T_i} \leq m(2^{1/m} - 1)$$

$\simeq$ 0.8 for $m = 2$ and tends towards 0.7 for big m.
$\Rightarrow$ What does **sufficient** mean ?

NB: More general cases ($D_i \leq T_i$, multi-core, ...) are in many cases NP.

Okay...

But, we were told to ignore real-time !

(cf )

Yet, knowing real-time constraints is useful

Based on real-time constraints we can:

- Schedule better:
  - Optimize processor utilization (do not execute tasks more frequently than required);
  - Ensure temporal correction by assigning priorities based on deadlines.
- Statically analyze the real-time behaviour: check before execution that the system will not become overloaded/late;
- As a side effect, this also enables a better dimensioning of the hardware platform.

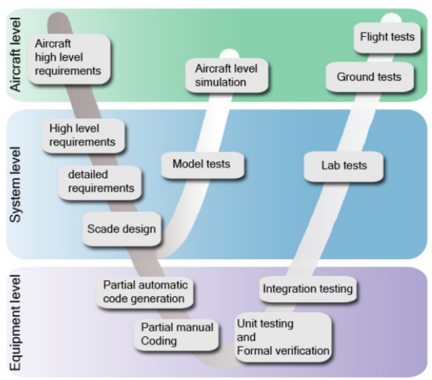
So...

Did we break it ?

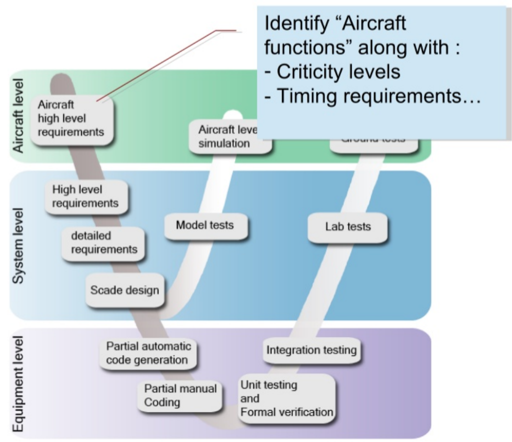
No, but we need more to cover the development cycle.

Outline

Programming in the large: Aeronautics system design



Aeronautics system design

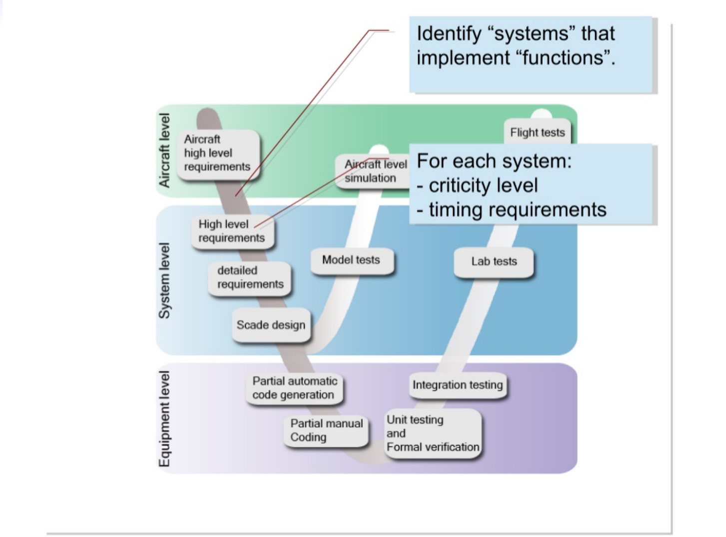


Aircraft functions

Example:

- Thruster control;
- Flight plan control;
- Aircraft control on ground;
  - Transition air/ground;
  - **Deceleration**;
  - Direction control on ground;
  - ...
- ...

Aeronautics system design

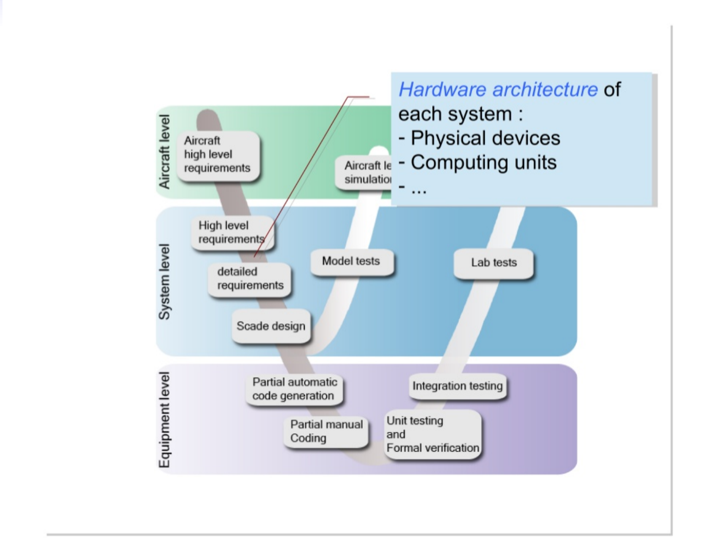


Aircraft systems

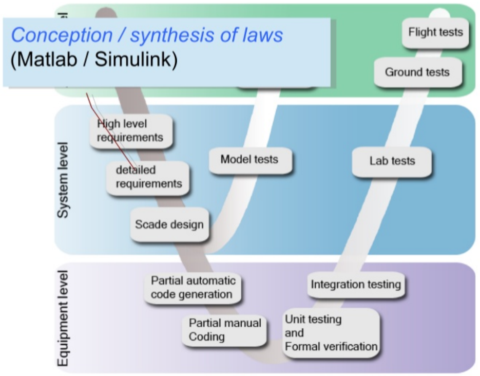
Example: **Ground deceleration** is made up of:

- The “thrust reversal” function of the **motor control** system;
- The “spoiler control” function of the **flight command** system;
- The **wheel brake** system.

Aeronautics system design



Aeronautics system design



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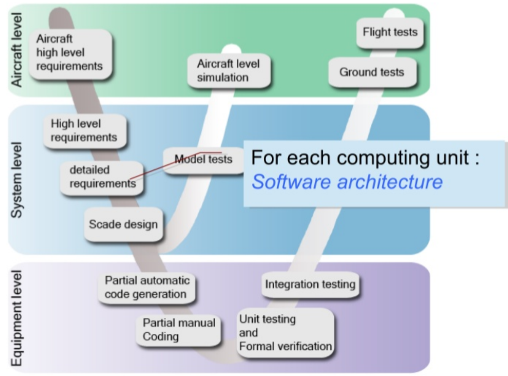
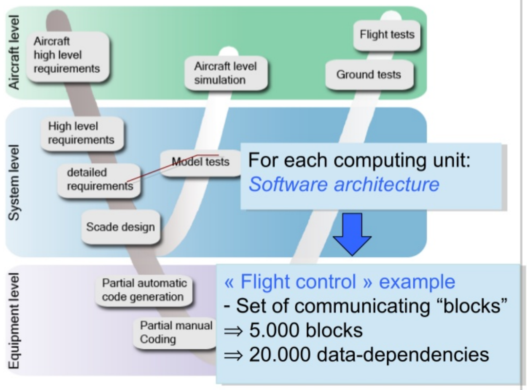
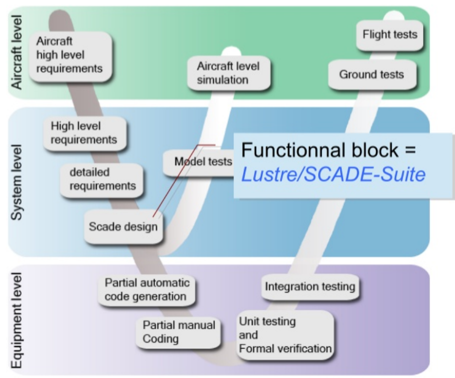


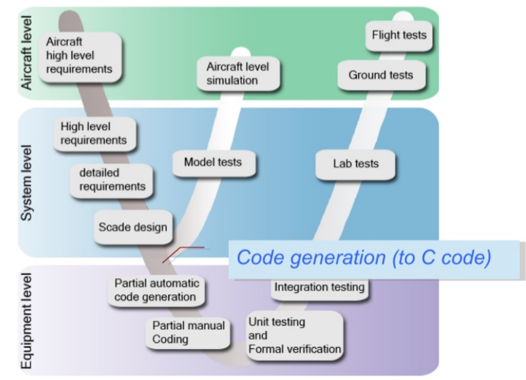
Aeronautics system design



Aeronautics system design



Aeronautics system design



Synchronous languages in the design

- On the “system” level:
  - Functional level (SCADE, LUSTRE);
  - Software architecture level ?
- Timing requirements:
  - Attached to blocks (software architecture);
  - **Abstracted** on functional level: blocks are mono-periodic.

⇒ Can we introduce the synchronous paradigm at the software architecture level and deal with timing requirements there ?

Outline

Synchronous approach (reminder)

Real-time is replaced by a simplified, abstract, logical time.

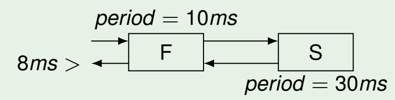
- Instant: one reaction of the system;
- **Logical time**: sequence of instants;
- The program describes what happens at each instant;
- Synchronous hypothesis: **computations complete before the next instant**. If so:
  - ⇒ We can ignore time inside an instant, only the order matters;
  - ⇒ We are only interested in how instants are chained together.

A question of semantics

- Zero-time ?
  - In the semantics, the execution of one instant takes no time, everything happens simultaneously;
  - When implemented, the execution of one instant **does take time**;
  - The point is, when writing a synchronous program, we do not care about real-time.
- Synchronous hypothesis validation:
  - In aeronautics design (and in many other cases), the periodicity of a block (LUSTRE program) sets the bound for the duration of an instant;
  - At the end of the implementation process, the synchronous hypothesis must be validated, i.e. “do we have $C_i \leq T_i$?” (WCET analysis)

Multi-rate in LUSTRE/SCADE

Example



Program (base period=10ms)

```
node multi_rate(i: int) returns (o: int)
var vf: int; clock3: bool; vs: int when clock3;
let
  (o, vf)=F(i, current(0 fby vs));
  clock3=everyN(3);
  vs=S(vf when clock3);
tel
```


Multi-rate in LUSTRE/SCADE

Behaviour:

`vf`	vf_0	vf_1	vf_2	vf_3	vf_4	vf_5	vf_6	...
`vf when clock3`	vf_0			vf_3			vf_6	...
`vs`	vs_0			vs_1			vs_2	...
`0 fby vs`	0			vs_0			vs_1	...
`current (0 fby vs)`	0	0	0	vs_0	vs_0	vs_0	vs_1	...

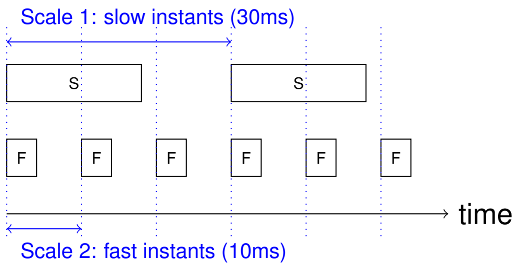
Program (base period=10ms)

```
node multi_rate(i: int) returns (o: int)
var vf: int; clock3: bool; vs: int when clock3;
let
  (o, vf)=F(i, current(0 fby vs));
  clock3=everyN(3);
  vs=S(vf when clock3);
tel
```


What’s missing ?

- **For the programmer**: not immediate to see that `vf when clock3` is 3 times slower than `vf`;
- **For the static analyses**: clocks = Boolean expressions ⇒ compiler does not see that ”some clock is 3 times slower than another”;
- **For the code generation**: computations must all complete during one base period (10ms).

Objective: multi-Rate Synchronous



Requirements:

- Define several logical time scales;
- Compare different logical time scales;
- Transition from one scale to another.

Bridging the gap

Main ideas:

- **Arithmetic clocks**: clocks defined, compared and transformed, using numbers and/or operations on numbers;
- **Multi-threaded execution**: not all operations must be executed within the same base period.

Outline

N-Synchronous

- **Motivation**: implementing real-time streaming applications (e.g. video systems);
  - Multi-rate systems;
  - Combine flows that are “nearly synchronous”, i.e. the same production rate on a period of time, but not at the same instants.
- Compiled into classic synchronous code + buffering mechanisms.

N-Synchronous (2)

Example

```
let node resync x = o where
  rec x1 = x when (10)
  and x2 = x when (01)
  and o = (buffer x1) + x2
```

Operators

- `x when (01)`: drop value, keep value, drop value, keep value, ...;
- `buffer(x1)`: buffer values to enable clock “resynchronization”.

N-Synchronous (2)

Example

```
let node resync x = o where
  rec x1 = x when (10)
  and x2 = x when (01)
  and o = (buffer x1) + x2
```

flow								clock
`x`	5	7	3	6	2	8	...	(1)
`x1`	5		3		2		...	(10)
`buffer(x1)`		5		3		2	...	(01)
`x2`		7		6		8	...	(01)
`o`		12		9		10	...	(01)

N-Synchronous (3)

- Rate relations are more explicit;
- Better static analyses;
- More general (too general ?) than purely multi-periodic systems (e.g. clock (10110));
- Semantics still requires computations to fit within an instant.

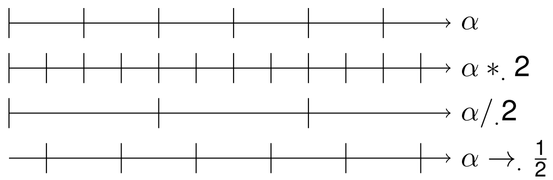
CCSL

(Presented previously by AG).

- Very expressive: periodic, sampled, alternation, etc;
- Targeted mainly for simulation/verification;
- Too general for efficient compilation (?)

Strictly Periodic Clocks

- Definition: Clock (n, p) is a clock of period n and phase p;
- Example: $(120, 1/2)$ activates at **dates** 60, 180, 300, 420, ...
- Rate transformations:
  - $\alpha/.k$: divide frequency;
  - $\alpha *. k$: multiply frequency;
  - $\alpha \rightarrow. q$: offset activations.



Strictly Periodic Clocks(2)

- Strictly periodic clocks are dedicated to multi-periodic real-time systems;
- Strictly periodic clocks are a sub-class of Boolean clocks and of N-Synchronous clocks;
- This restriction enables to compile real-time aspects more efficiently.

Outline

Relaxed Synchronous hypothesis

Classic Synchronous hypothesis

All computations complete before the end of the instant.

Relaxed Synchronous hypothesis

Computations complete before their next activation.

- Relaxed: mere reformulation of classic;
- Classic: particular case of relaxed;
- Relaxed: supports several logical time scales;
- Relaxed: **fits with periodicity constraints** “a task instance must complete before the next task release”.

Automated code distribution into threads

(Presented previously by AG-not the same).

Approach 1: Automatically split the code into several threads:

- In Signal: split code based on clocks;
- In Lustre: split code based on inputs/outputs;
- Add buffers to communicate between threads.

Automated code distribution into threads (2)

More general than periodic systems, thus:

- Buffer dimensioning is harder;
- Temporal analyses is harder;
- The user must specify the distribution criteria.

Lustre with Futures

Approach 2: Explicit thread encapsulation.

Example

```
node slow_fast() = (y:float)
var big :bool; yf, v : float; ys :future float;
let
  big = everyN(3);
  ys = (async 0.0) fby (async slow(y when big));
  yf = fast (v whenot big);
  y = merge big (!ys) (yf);
  v = 0.0 fby y;
tel
```

- `async` encapsulates a node inside a thread;
- The value of an asynchronous flow is fetched using operator `!`.

NB The values and clocks of `!x` and `x` are exactly the same.

Lustre with Futures

Approach 2: Explicit thread encapsulation.

Example

```
node slow_fast() = (y:float)
var big :bool; yf, v : float; ys :future float;
let
  big = everyN(3);
  ys = (async 0.0) fby (async slow(y when big));
  yf = fast (v whenot big);
  y = merge big (!ys) (yf);
  v = 0.0 fby y;
tel
```


big	true	false	false	true	false	...
!ys	0.0			3.14		...
yf		1.0	2.0		4.14	...
y	0.0	1.0	2.0	3.14	4.14	...
v	0.0	0.0	1.0	2.0	3.14	...

Lustre with Futures (2)

- Good multi-thread support;
- No real-time constraints attached to threads.

Prelude

Approach 3: Thread assembly language.

- Each node invocation is encapsulated inside a thread;
- Targeted for the software architecture level;
- Real-time characteristics are associated to each node/thread.

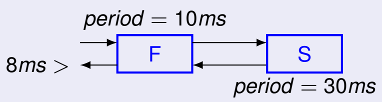
Outline

Prelude: a real-time synchronous language

- **Initial question**: how to program systems with multiple real-time constraints in a synchronous style ?
- **Context**:
  - Defined and developed at ONERA (first during speaker thesis);
  - Motivated by collaborations with Airbus and Astrium (satellites).
- **Main principles**:
  - Strictly periodic clocks;
  - Relaxed synchronous hypothesis;
  - Fully multi-threaded;
  - At the software architecture level.

Operations

Multi-rate system



Operations: imported nodes

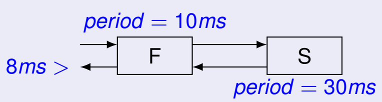
- Operations of the system are imported nodes;
- External functions (e.g. C, or LUSTRE);
- Declare the worst case execution time (wcet) of the node.

Example

```
imported node F(i, j: int) returns (o, p: int) wcet 2;
imported node S(i: int) returns (o: int) wcet 10;
```


Real-time constraints

Multi-rate system



Real-time constraints: clocks and deadlines

- Real-time constraints are specified in the signature of a node;
- Periodicity constraints on inputs/outputs;
- Deadline constraints on inputs/outputs.

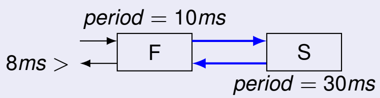
Example

```
node sampling(i: rate (10,0)) returns (o: rate (10,0) due 8)
let
  ...
tel
```

Input/output rate can be unspecified, the compiler will infer it.

Multi-rate communications

Multi-rate system



Multi-rate communications: rate transition operators

Example

```
node sampling(i: rate (10, 0)) returns (o)
  var vf, vs;
let
  (o, vf)=F(i, (0 fby vs)*^3);
  vs=S(vf/^3);
tel
```

Rate transition operators:

- Sub-sampling: $x/\hat{}3$ ($ck(x)/_{.}3$);
- Over-sampling: $x*\hat{}3$ ($ck(x)*_{.}3$).

Multi-rate communications: rate transition operators

Example

```
node sampling(i: rate (10, 0)) returns (o)
  var vf, vs;
let
  (o, vf)=F(i, (0 fby vs)*^3);
  vs=S(vf/^3);
tel
```

date	0	10	20	30	40	50	60	70	80	...
`vf`	vf_0	vf_1	vf_2	vf_3	vf_4	vf_5	vf_6	vf_7	vf_8	...
`vf/^3`	vf_0			vf_3			vf_6			...
`vs`	vs_0			vs_1			vs_2			...
`0 fby vs`	0			vs_0			vs_1			...
`(0 fby vs)*^3`	0	0	0	vs_0	vs_0	vs_0	vs_1	vs_1	vs_1	...

And...

That's all folks !

Formal semantics: Strictly Periodic Clocks

- Flow values are tagged by a date: $f = (v_i, t_i)_{i\in\mathbb{N}}$;
- Clock = sequence of tags of the flow;
- Value v_i must be produced during time interval $[t_i, t_{i+1}[$;
- A clock is **strictly periodic** iff:

$$\exists n \in \mathbb{N}^*,\ \forall i \in \mathbb{N},\ t_{i+1} - t_i = n$$

- n is the period of h, t_0 is the phase of h.
- Eg: $(120, 1/2)$ is the clock of period 120 and phase 60.

Formal semantics: operators

Example

$+^{\#}((v,t).s, (v',t).s') = (v+v',t).+^{\#}(s,s')$

- $(v,t).s$: denotes value v produced at time t and followed by sequence s;
- $op^{\#}(f,f') = (v_1,t_1).(v_2,t_2)\ldots$ denotes the flow produced when applying op to flows f and f'.

Warning:

- The semantics is **ill-defined for asynchronous flows**;

⇒ Static analyses required to check that program semantics is well-defined before further compilation.

Formal semantics: classic operators

$$\texttt{fby}^{\#}(v, (v',t).s) = (v,t).\ \texttt{fby}^{\#}(v', s)$$

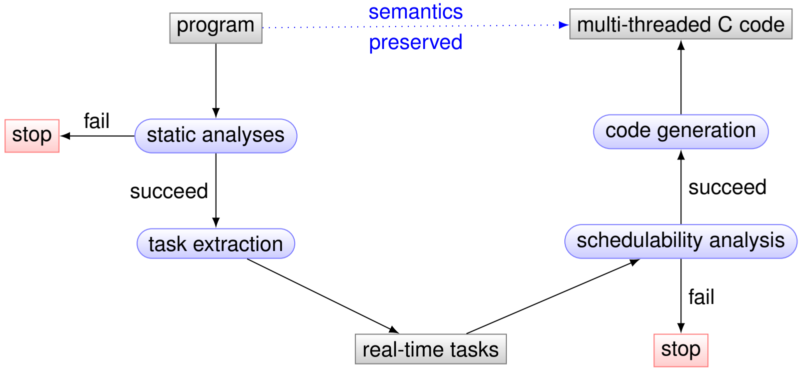
$$\texttt{when}^{\#}((v,t).s, (true,t).cs) = (v,t).\ \texttt{when}^{\#}(s, cs)$$
$$\texttt{when}^{\#}((v,t).s, (false,t).cs) = \texttt{when}^{\#}(s, cs)$$

Formal semantics: rate transitions

$$*\hat{}^{\#}((v,t).s,k) = \prod_{i=0}^{k-1}(v,t'_i).*\hat{}^{\#}(s,k)$$
$$(\text{with } t'_0 = t \text{ and } t'_{i+1} - t'_i = \pi(s)/k)$$

$$/\hat{}^{\#}((v,t).s,k) = \begin{cases}(v,t)./\hat{}^{\#}(s,k) & \text{if } k*\pi(s)|t\\ /\hat{}^{\#}(s,k) & \text{otherwise}\end{cases}$$

Compilation overview



Static analyses

- Typing: no run-time type error;
- Causality analysis: no cyclic data-dependencies;
- Clock calculus: values are only accessed when they should be.

Clock calculus: example

Example

```
node under_sample(i) returns (o)
let o=i/^2; tel

node poly(i: int rate (10, 0); j: int rate (5, 0))
returns (o, p:  int)
let
  o=under_sample(i);
  p=under_sample(j);
tel
```

Result inferred by the clock calculus

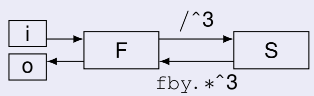
```
under_sample: 'a->'a/.2
poly: ((10,0) * (5,0))->((20,0) * (10,0))
```


Task graph extraction

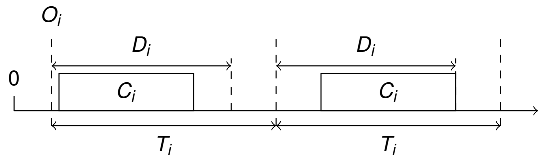
Program

```
node sampling(i: rate (10, 0)) returns (o)
  var vf, vs;
let
  (o, vf)=F(i, (0 fby vs)*^3);
  vs=S(vf/^3);
tel
```

Task graph



Real-time characteristics



For each task:

- Repetition period: $T_i = \pi(ck_i)$;
- Relative deadline: $D_i = T_i$ by default or explicit constraint (eg `o: due 8`);
- Worst case execution time: C_i, declared for each imported node;
- Initial release date: $O_i = \varphi(ck_i)$.

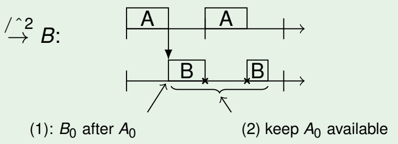
Multi-rate data-dependencies

For each task dependency:

1. **Data can only be consumed after being produced** $\Rightarrow$ precedence constraints for the scheduler;
2. **Data must not be overwritten before being consumed** $\Rightarrow$ communication protocol.

Example

$A \overset{/\hat{}2}{\rightarrow} B$:



Communication protocol

- Tailor-made buffering mechanism;
- For each dependency, computes:
  - Size of the buffer;
  - Where each job writes/reads;
- **Independent of the scheduling policy**;
- Requires a single central memory.

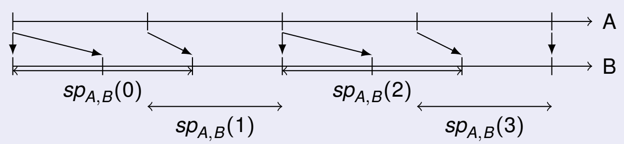
Communication protocol

Ex: `B(A(x)*^3/^2)`, ie $A \overset{*\hat{}3./\hat{}2}{\rightarrow} B$:

Semantics

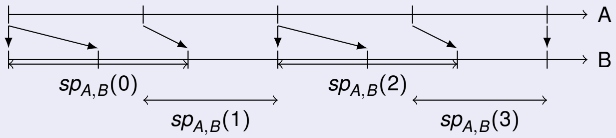
date	0	10	20	30	40	50	60	70	80	...
`A(x)`	a_0			a_1			a_2			...
`A(x)*^3`	a_0	a_0	a_0	a_1	a_1	a_1	a_2	a_2	a_3	...
`A(x)*^3/^2`	a_0		a_0		a_1		a_2		a_3	...

Lifespans



Communication protocol (2)

Lifespans



- Buffer of size 2;
- Write in the buffer cyclically;
- Read from the buffer cyclically;
- Do not advance at the same pace for reading and writing.

Scheduling: problem parameters

- A set of recurring tasks with:
  - Periods, deadlines, wcets, release dates;
  - Multi-rate precedence constraints.
- Hardware architecture:
  - Mono-core;
  - Multi-core (with a single central shared memory).
- Scheduler class:
  - **On-line**/off-line;
  - Static/dynamic priorities;

Outline

Summary

What you should remember:

- When we deal with multi-periodic systems, we need explicit real-time constraints;
- Explicit RT constraints enable:
  - Static real-time analyses;
  - Optimized processor utilization and platform dimensioning.
- Real-time constraints can be introduced without breaking the synchronous paradigm;
- Mixing real time and logical time can be done by using real-time as a “dimension” for logical time.

My sources

Some inspirations for this course:

- **Frédéric Boniol (ONERA Toulouse)**, Modélisation et programmation des systèmes embarqués critiques : la voie synchrone, *course at Ecole Polytechnique de Montreal, 2013*
- **Emmanuel GROLLEAU (LIAS/ISAE-ENSMA)**, Ordonnancement et ordonnançabilité monoprocesseur, *Ecole d'Eté Temps Réel (ETR'2011), Brest, 2011*

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In *25th ACM Symposium On Applied Computing (SAC'10)*, Sierre, Switzerland, March 2010.

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Multi-task implementation of multi-periodic synchronous programs.
Discrete Event Dynamic Systems, 21(3):307–338, 2011.