System and Language Support for Timing Constraints

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Goals

- Understand different concepts about temporal constraints.
- Understand how temporal constraints can be incorporated into a programming language.
- Discuss how you would design your language.

Overview of Temporal Constraints

Why Temporal Constraints?

- A number of control applications puts temporal constraints on the control software.
  - Engine simulation: 1kHz recording frequency over a distributed system
  - Clock synchronization: down to 1 nanosecond
  - Industrial process control
  - Drive-by-wire
  - Anti-lock brakes
  - Pacemakers
  - Helicopter control
    - 200 Hz pilot stick, 400 Hz sensors, 200 Hz flight control, 1kHz actuator electronics
  - Heating control: 10 seconds

Temporal Constraints

- Real-time is about producing the correct result at the right time.

Value	Timing	Result
Wrong	Too late	Failure
Wrong	On time	Failure
Correct	Too late	Failure
Correct	**On time**	**Ok**

- Temporal constraints are a way to specify, when the value is on time.

Types of Temporal Constraints

- Absolute temporal constraints
  - Measured with respect to a global clock
  - Xmas tree should light up between 5pm and 7am from November 27th 2006 until December 27th 2006
- Relative temporal constraints
  - Measured with respect to a local clock
  - The ventilation task should restart in five seconds
- Timing violation
  - Occurs when a temporal constraint is violated

Types of Temporal Constraints

- Hard temporal constraints
- Soft temporal constraints
- Firm temporal constraints

- Deterministic temporal constraints

Soft Temporal Constraints

- A **soft real-time system** is one where the response time is normally specified as an average value. This time is normally dictated by the business or market.

- A single computation arriving late is not significant to the operation of the system, though many late arrivals might be.

- Ex: Airline reservation system - If a single computation is late, the system's response time may lag. However, the only consequence would be a frustrated potential passenger.

Hard Temporal Constraints

- A **hard real-time system** is one where the response time is specified as an absolute value. This time is normally dictated by the environment.
- A system is called a hard real-time if tasks always must finish execution before their deadlines or if message always are delivered within a specified time interval.
- Hard real-time is often associated with safety critical applications. A failure (e.g. missing a deadline) in a safety-critical application can lead to loss of human life or severe economical damage.

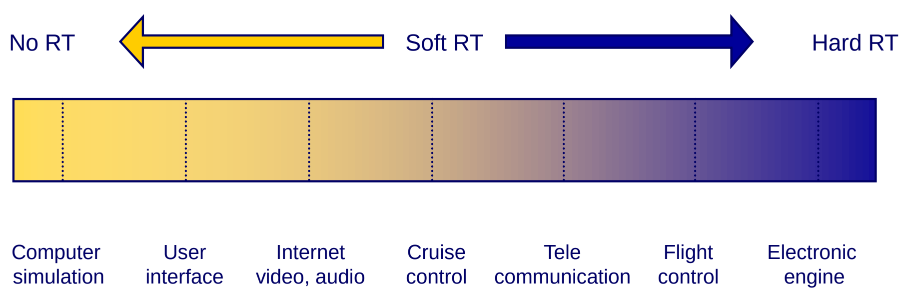
Firm Temporal Constraints

- In a **firm real-time system** timing requirements are a combination of both hard and soft ones. Typically the computation will have a shorter soft requirement and a longer hard requirement.
- Ex: Ventilator – The system must ventilate a patient so many times within a given time period. But a few second delay in the initiation of the patient's breath is allowed, but not more.

Deterministic Temporal Constraints

- In a **temporal deterministic real-time system** timing requirements are a deterministic. An external observer can tell the temporal state at any time.
- A system with deterministic temporal constraints finishes execution exactly at the deadline (not before [hard] and not about [soft]).
- Ex. Similar to hard real-time systems, however, temporal determinism simplifies guaranteeing compositionality.

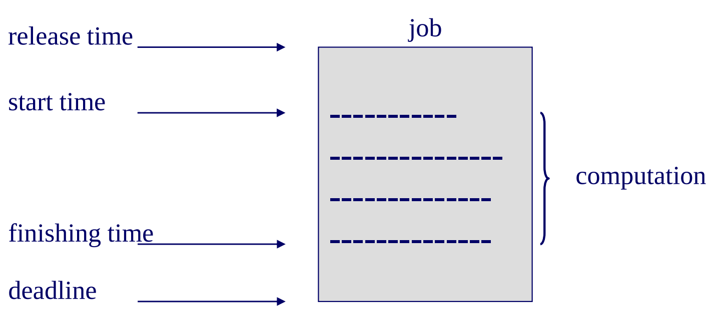
Real-Time Spectrum



Terminology of Temporal Constraints

Tasks, Job

- A **task** is a piece of code that can be executed many times with different input data. (thread or process)
- A **job** is an instance of a task.

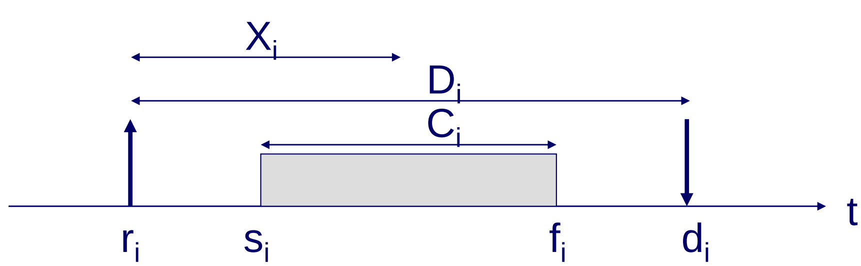


Parameters

- Release or Arrival Time (ri)
  - is the time at which the task becomes ready for execution.
- Computation time (Ci)
  - is the time necessary to the processor for executing the task without interruption.
- Deadline (di)
  - is the time before which a task should be complete to avoid damage to the system.
  - Relative Deadline (Di): Di = di - ri
- Start time (si)
  - is the time at which the task starts its execution.

Parameters

- Finishing time (fi)
  - is the time at which the task finishes its execution.
- Laxity (Slack time) (X_i)
  - $X_i = d_i - r_i - C_i$ is the maximum time a task can be delayed on its activation to complete within its deadline.



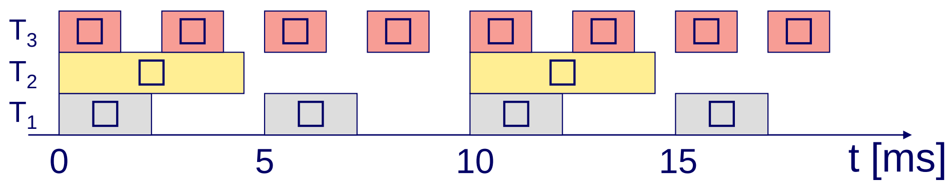
Temporal Constraint Specifications

Task Types

- A periodic task has invocations within regular time intervals.
  - E.g., reading a heat sensor.
- A sporadic task has unknown arrival times, but have bounds such as maximum frequency.
  - E.g., routinely memory status check.
- An aperiodic task has an unknown arrival time.
  - E.g., an emergency shutoff.

Frequency, Period

- Period, frequency:
  - T_1: Period=10ms, Frequency=2
- Period:
  - T_2: Period=10ms
- Frequency
  - T_3: Frequency=400Hz



Additional Terms

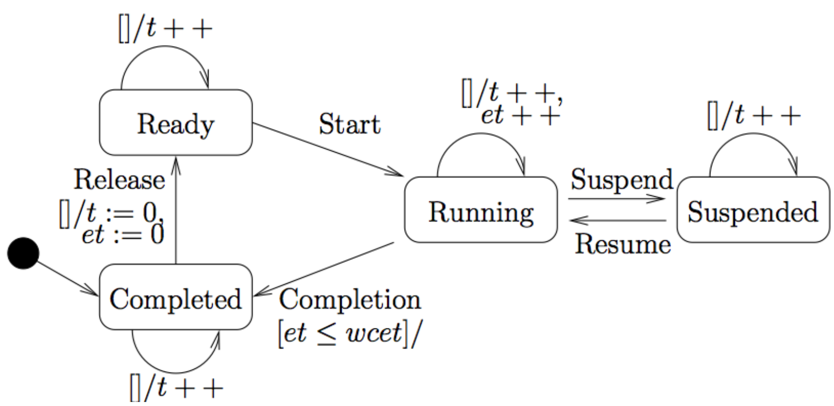
- Execution time: total time of execution of a specific task
- Elapse time: the task's execution time + all delays
- Maximum time constraint: no more than t time units will elapse
- Minimum time constraint: no less than t time units will elapse

Hyper-Period

- Hyper-Period is the time span after which the system repeats its behavior.
  - T_1: Period=10ms, Frequency=2
  - T_2: Period=10ms
  - T_3: Frequency=400Hz

  - Hyper period = 10ms

Basic Model

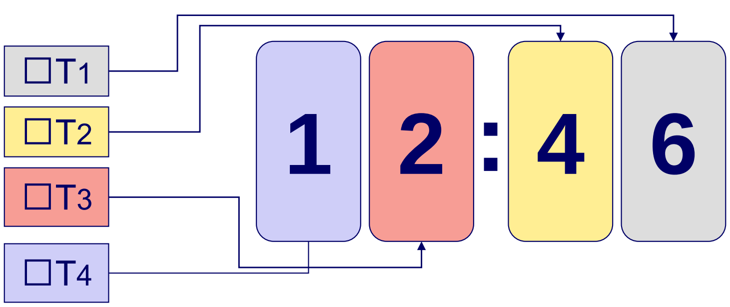


Example

Independent-Digit Clock

- Consider a clock with each digit as an independent task.

T_1: P=1s
T_2: P=10s
T_3: P=60s
T_4: P=600s



Properties

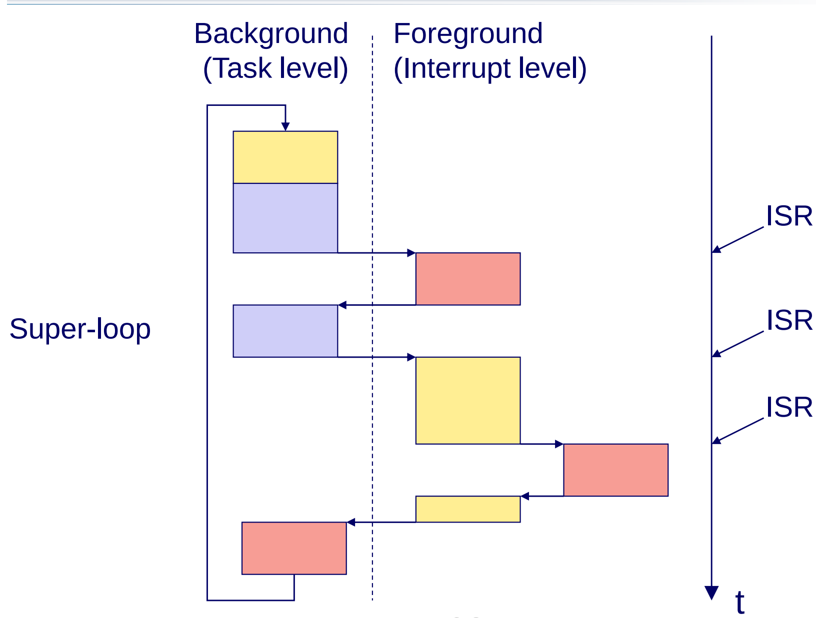
- Timliness is key
  - Invalid time value displayed
- Jitter accumulates and causes incorrect display.
- Value outputs need to be synchronized.
- Nearly no computation required.

Implicit Temporal Control

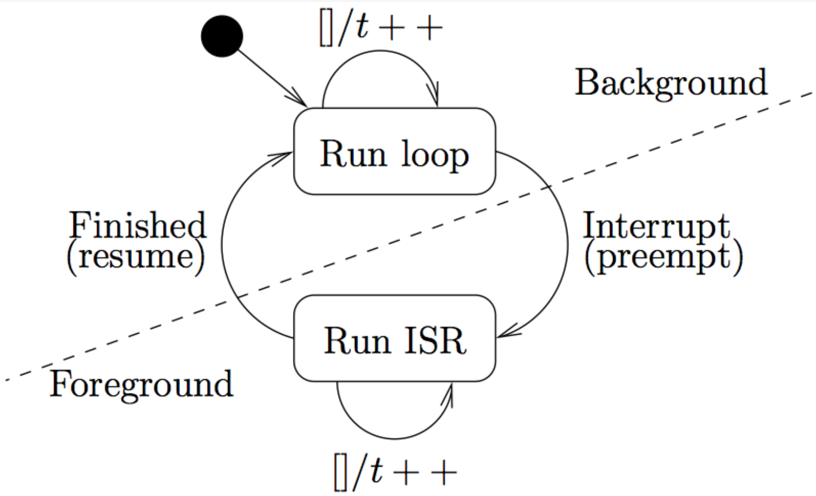
Foreground/Background System

- Using **super-loops** as the main routine with two levels: the task level and the interrupt level.
  - Task level (aka background): executes modules
  - Interrupt level (aka foreground): handles asynchronous evens via ISRs.
- Foreground can preempt the background, thus:
  - Critical tasks must be in the foreground part.
  - Task level response = an ISR prepares data for the super-loop.
- Used for small devices (e.g., microcontrollers in microwaves, washers, dryers, radio)

Foreground/Background System



Foreground/Background Model



Code for the Example

```
void main(void) {
  unsigned short val;  unsigned int i;

  while ( 1 ) {
    val = get_curr_sec();
    val++;
    update_display_seconds(val);

    if (val%60 == 0 ) {
      // update tens
    }
    ...
    // may have nested loops, if too short
    i=WHILE_INSTRUCTIONS_PER_SECOND
    while( --i );
  }
}
```

Foreground/Background Properties

- Simple system/low overhead
  - No maintenance, basically no “system” at all
- Difficult to specify temporal behavior
  - F/B systems require hand tuning to meet a timing criteria; if the system is not responsive enough, then the developer will optimize the super-loop.
- Sensitive to changes
  - Changing a module constantly changes the timing of the super-loop.
  - Changing code in an ISR changes may change the overall timing behavior.

Programming-Language Timing Control

Type of Specification

- Program-based temporal constraints
  - Programmed in the target language.
  - Often mix program logic and temporal behavior
- Specification-based temporal constraints
  - Temporal constraints are specified in a separate language (=> Coordination language)
  - Can be high-level, e.g., *task A frq 0.2*

Temporal Scopes

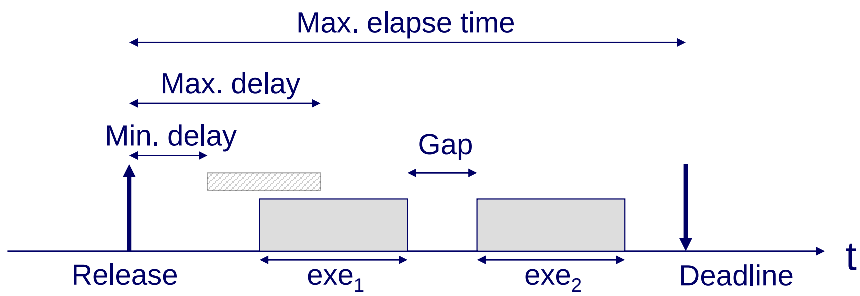
Temporal Scopes

- Source: [Lee1985], the Distributed Programming System (DPS).
- Temporal scopes and DPS describes a system to specify generic temporal constraints at the statement level.
- The main goals for temporal scopes are:
  - Provide language constructs for specifying timing constraints,
  - Apt for distributed systems,
  - Extend an existing language, and
  - Run-time monitoring and exception handling.
- Its properties are:
  - The program is configured offline.
  - All processes are created before start-up.
    - No dynamic create of RT processes.
  - The system has two modes: initialization and operation.
- Timing support is specification-based.

Timing Specification

- **Deadline**. The latest time in which the execution of a temporal scope can be completed.
- **Minimum delay.** The minimum amount of time that should pass before starting the execution of a temporal scope.
- **Maximum delay.** the maximum amount of time that should pass before starting the execution of a temporal scope.
- **Maximum execution time.** The maximum computation time necessary for the execution of a temporal scope. **Maximum elapse time.** The maximum execution time plus all user-defined delay during the execution of a temporal scope.

Timing Specification



Max. execution time = WCET

The Temporal Scope

- start <delay-part> [<exe-part>] [<dl-part>]
  do
      <start-body>
      [<exceptions>]
  end

- <delay-part>:==now|at <abs-time>|after <rel-time>
- <exe-part>:==execute <rel-time>|elapse <rel-time>
- <dl-part>:==by <abs-time>|within <rel-time>

- **Examples:**
- **Start after** 10 sec **do** … **end**
- **Start at** (9h:00m) **within** 10 sec **do** … end

Repetitive Temporal Scope

- from <start_time> to <end time> every <period>
  execute <exec_time> within <deadline> do
  <stmts>
  [<exceptions>]
  end

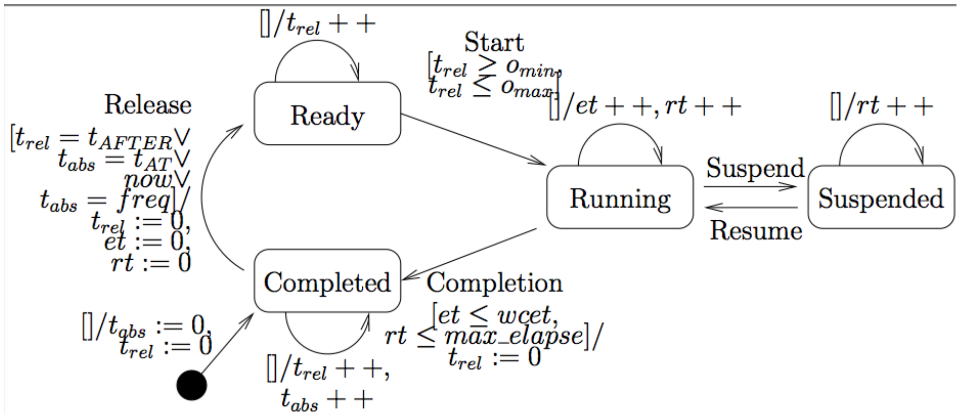
- **Example:**
- **from** (8h:00m) **to** (18h:00m) **every** (0h:30m)
  within 10 sec **do**
      relax_eyes()
  end

Consecutive Temporal Scope

- cstart <delay$_1$> [<execute$_1$>] [<deadline$_1$>] do
  <stmts$_1$>
  [<exceptions$_1$>]
- cstart <delay$_2$> [<execute$_2$>] [<deadline$_2$>] do
  <stmts$_2$>
  [<exceptions$_2$>]
- cstart <delay$_n$> [<execute$_n$>] [<deadline$_n$>] do
  <stmts$_n$>
  [<exceptions$_n$>]
- end

- **Example:**
- **cstart within** 2 sec **do** fill_glass_with_water()
  cstart after 2 sec **do** empty_glass() **end**

Temporal Scopes Task Life Cycle



Temporal Scopes Example

```
from 00:00 to 59:59 every 10s execute 20ms within 1s
do
  var ctr;
  ctr=get_cur_tsecs();
  ctr=(ctr+1)%6;
  set_cur_tsecs(ctr);

  exception
    display_warning_light();
end
```

PEARL

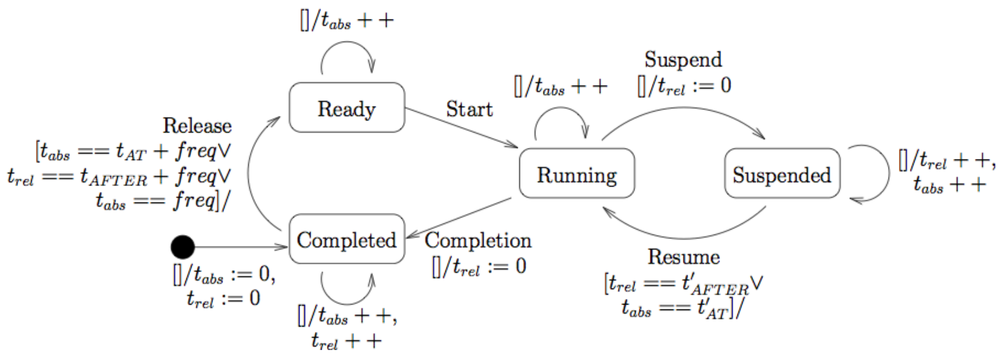
PEARL Overview

- Acronym for *Process Automation Real-time Language*
- Aimed to be a high-level programming language with elaborate constructs for programming temporal constraints.

- Developed at the same time as PASCAL, so both share similar syntax.
- PEARL forbids recursive procedures to eliminate out-of-memory errors.
- Strong emphasis on the I/O part, because of its target domain.

- Standardized as DIN 66253
- PEARL-90 is the revised version

PEARL Task Life Cycle



Timing Specification

StartCondition ::=

- **AT** Expression§Time [Frequency]
- | **AFTER** Expression§Duration [Frequency]
- | **WHEN** Name§Interrupt [**AFTER** Expression§Duration] [Frequency]
- | Frequency

Frequency ::=

- **ALL** Expression§Duration [{ **UNTIL** Expression§Time }
- | { **DURING** Expression§Duration }]

Examples:

- `ALL 0.00005 SEC ACTIVATE Highspeedcontroller;`
- `AT 12:00 ALL 4 SEC UNTIL 12:30 ACTIVATE lunchhour;`
- `WHEN fire ACTIVATE extinguish;`

PEARL Example

```
WHEN start ALL 1 sec UNTIL stop ACTIVATE clock_sec;
WHEN start ALL 10 sec UNTIL stop ACTIVATE clock_tsec;
WHEN start ALL 60 sec UNTIL stop ACTIVATE clock_min;
WHEN start ALL 600 sec UNTIL stop ACTIVATE clock_tmin;

clock_tsec:TASK PRIO 2;
  DCL ctr INTEGER;
BEGIN
  GET ctr FROM DISPLAY_T_ONES;
  ctr := (ctr+1)%6;
  PUT ctr TO DISPLAY_T_ONES;
END
```

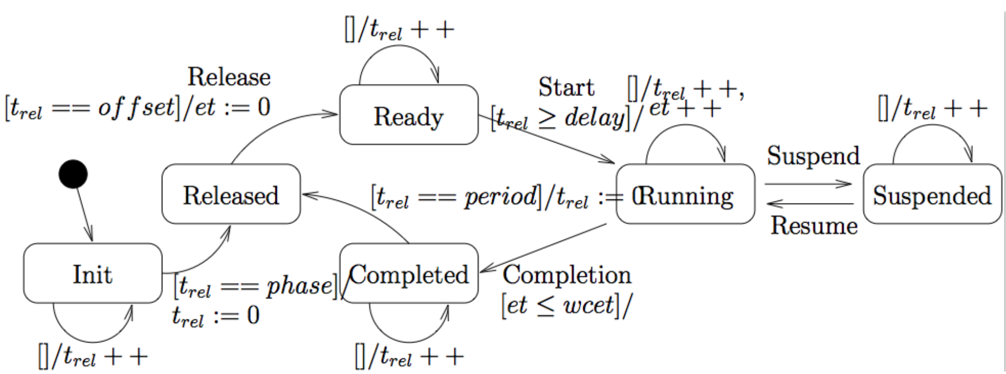

The ARTS Kernel & The Time Fence Protocol

Time Fence in the ARTS Kernel

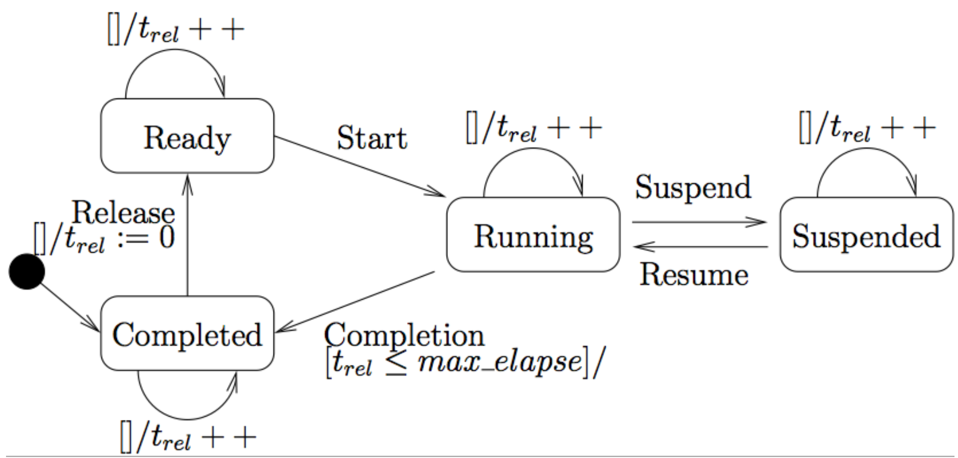
- Source: [Tokuda, Mercer,1998].
- The time-fence protocol allows for temporal constraints in a distributed real-time system. The time-fence protocol is built into the ARTS kernel.
- The ARTS kernel aims at distributed real-time systems.

- The *artsobject* is the abstraction for computation:
  - The *artsobject* has a WCET.
  - The *artsobject* minimizes inter-module dependence.
  - It provides time-encapsulation (however, the designer must guarantee this).
- Timing support is specification-based.

Thread Life Cycle



Function Life Cycle



Specification

```
// An example of a real-time thread
Thread Sample._Artobject::RT_Thread( )
//# priority, stack_size, wcet, period, phase, delay
{ //thread body …
  ThreadExit( );
}
```

The implementation also allows for object methods:

```
type opt1 (type arg .... );//# within time except opr()
```

Stopwatch Example

```
Thread Minutes::RT_Thread( ) //# 2, _, 10ms, 10s, 0, 0s
{
  //thread body
  int tens_seconds = get_cur_tens_seconds();
  tens_seconds= (tens_seconds + 1) % 6;
  set_cur_seconds(tens_seconds);

  ThreadExit( ); //reincarnate this thread
}
```


The Time Fence Protocol

- The system scheduler checks for transient overloads (not enough CPU cycles) and rejects tasks in case of such an overload.

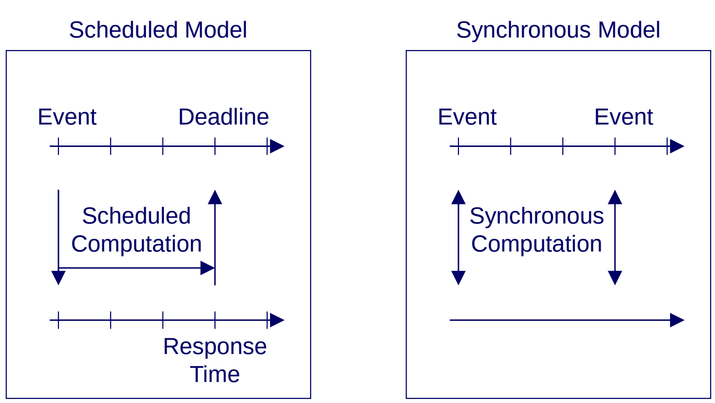
- Each RT computation has a WCET.
- The time fence uses the deadline to set a timer.
- The scheduler checks schedulability using the time fence and the WCET.

$$Callee_{wrtv} < Caller_{ctv} - 2*comm+clockdrift$$

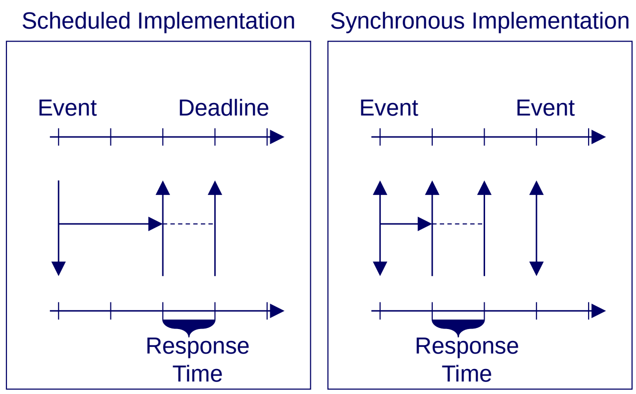
- *Comm* can include communication overhead for the distributed system.

Esterel

Synchronous Model

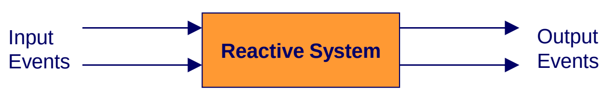


Synchronous Model

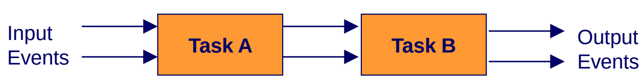


Basic Concepts

- **Specification language** has been specialized for reactive systems.
- **Reactive system:**
  - In continuous interaction with its environment.
  - A reaction begins when the system receives an input event and ends when it generates the corresponding output event.
- **Black-box approach**
  - Inputs produce outputs, continuously.

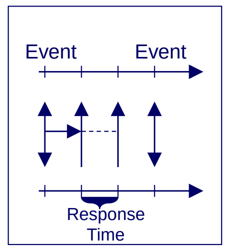


  - Only define relationships between input and output events.
  - A task may be complex; but, you don't care.



Basic Concepts

- Based on **synchronous model of time** (synchrony hypothesis)
  - The underlying machine is infinitely fast, and hence, the reaction of the system to an input event is instantaneous; in between reactions, the system is idle.
  - No reaction intervals → only reaction instants → reactions do not overlap.
  - The synchrony hypothesis simplifies the behavioral specification of reactive systems (see the example later on).
  - Looks flawed (or sounds unreal), *but* the machine must react to an input event before the next input event arrives.



Basic Concepts

- Determinism
  - A non-deterministic system does not have a unique response to a given input event → the external observer cannot predict the response.
  - Example:
    - Waiting for 60 seconds and *then(??)* signal "minute".
    - Broadcasting the signal, timing delays.

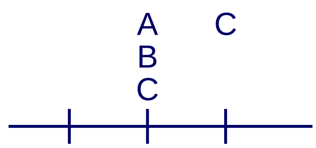
```
loop
  delay 60; B.MINUTE;    (C.MINUTE)
end
```

  - Esterel guarantees determinism
    - All statements and constructs are well defined (syntax and semantics).
    - A compiler checks the program and ensures determinism.

Signal Handling: Example

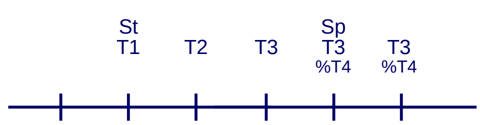
- Example program:

```
pause;
emit A;
emit B;
present B then emit C; end
pause;
emit C;
```



Example StopWatch

```
module SW1:
input START, STOP, MS;
output TIME(integer);
relation START # STOP;

var count := 0 : integer

in

  await immediate START;
% weak abort
  abort
    every immediate MS do
       count := count + 1;
       emit TIME(count);
    end
   when STOP
% pause;
  sustain TIME(count);

end var

end module
```



Real-Time Specification for Java (RTSJ)

Introduction

- The correct name is: Real-Time Specification for Java (RTSJ).
- Started in 1999 as Sun Microsystems' Java Community Process under Real-Time for Java Expert Group (RTJEG).
- Guiding Principles:
  - **Applicability to Java Environments:** The RTSJ shall not include specifications that restrict its use to particular Java environments.
  - **Backward Compatibility:** The RTSJ shall not prevent existing, properly written, non-real-time Java programs from executing on implementations of the RTSJ.
  - **Write Once, Run Anywhere.**
  - **Current Practice vs. Advanced Features:** The RTSJ should address current real-time system practice as well as allow future implementations to include advanced features.
  - **Predictable Execution:** The RTSJ shall hold predictable execution as first priority in all trade-offs.
  - **No Syntactic Extension.**
  - **Allow Variation in Implementation Decisions.**

Overview

- RT Java consists of an RTJVM and the RTSJ class library.
- RTSJ-compliant JVMs can be considered Real-Time Java Virtual Machines (RTJVMs).
- Resides in the package javax.realtime with modifications to the non RT Java such as
  - A RT Thread class extending java.lang.Thread
  - Sophisticated scheduling support
  - No mandatory RT garbage collection, instead memory partitioning
  - Raw memory access for device drivers

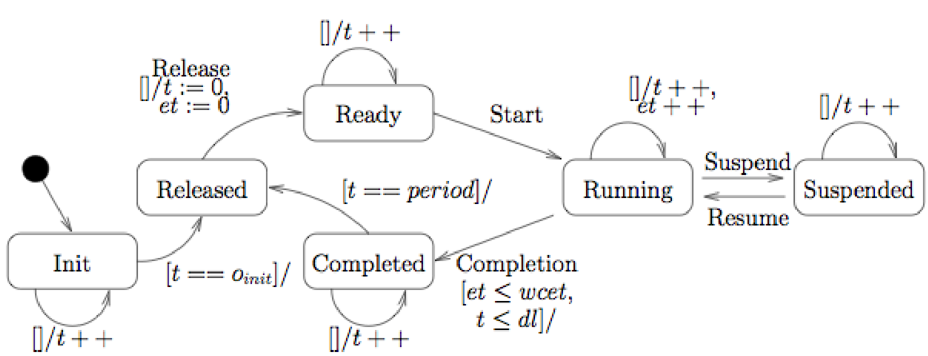
Handling of Time

- Clock:
  - A clock marks the passing of time.
  - `System.getRealtimeClock()` for singletons.
  - Can have an arbitrary resolution (see RelativeTime).
- Based on the clock, a number of classes dealing with time exist:
  - **HighResolutionTime:** is an abstract class and the base class for all time-related classes. Used to express time with nanosecond accuracy.
  - **AbsoluteTime:** represents a specific point in time given by milliseconds plus nanoseconds past some point in time fixed by the clock.
  - **RationalTime:** represents a time interval that is divided into subintervals by some frequency. Used to periodic events, threads, and feasibility analysis.
  - **RelativeTime:** is generally used to represent a time relative to now
- All time objects must maintain nanosecond precision.

Real-Time Threads

- Two types of threads:
  - NoHeapRealtimeThread
  - RealtimeThread
- Release parameters specify the thread's behavior in the time domain:
  - **PeriodicParameters:** indicates that the schedulable object is released on a regular basis.
  - **SporadicParameters:** notes that the associated schedulable object's run method will be released aperiodically but with a minimum time between releases.
  - **AperiodicParameters:** characterizes a schedulable object that may be released at any time.

Task Life Cycle



Stopwatch Example

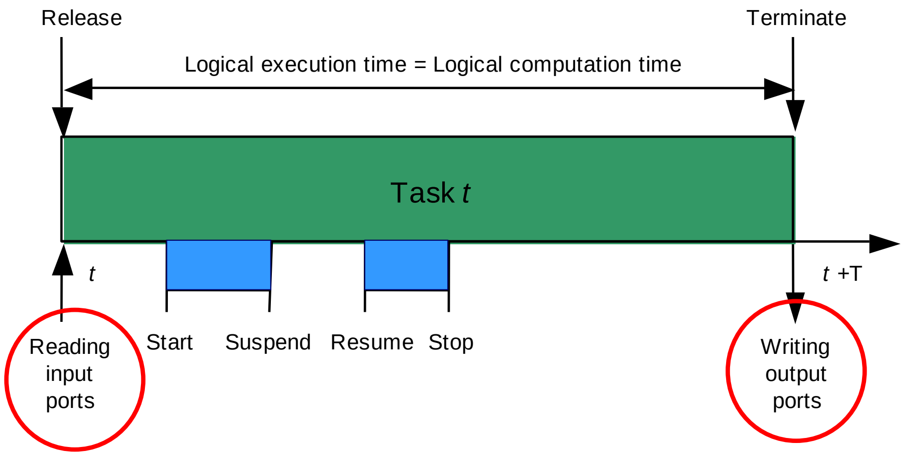
```
public class TSec extends RealTimeThread {
   public void run() {
     while (true) {
       int val = getCurrentTSecValue();
       val=(val+1)%6;
       setCurrentTSecValue(val);
       waitForNextPeriod();
     }  }

  TMin createInstance() {
     ...
     PeriodicParameters pp = new PeriodicParameters(offset,
       new RelativeTime(10.0*SECONDS),    // the period
       new RelativeTime(5.0),             // the cost
       new RelativeTime(10.0*SECONDS),    // the deadline
       null, null);

     return new TSec(priority, pp);
     }}
```


Giotto

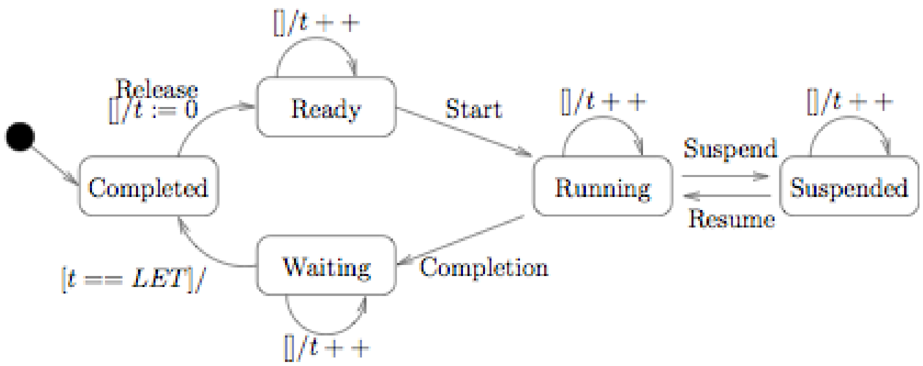
Overview

- Source: [T. Henzinger et al, 2002]
- One of the main issues was to create verifiable RT programs.
- Rigid control of the system's behavior.
  - Input/output values are buffered in ports (similar to the process image with PLCs)
  - Value determinism
  - Time determinism
- An embedded machine controls the task's execution.

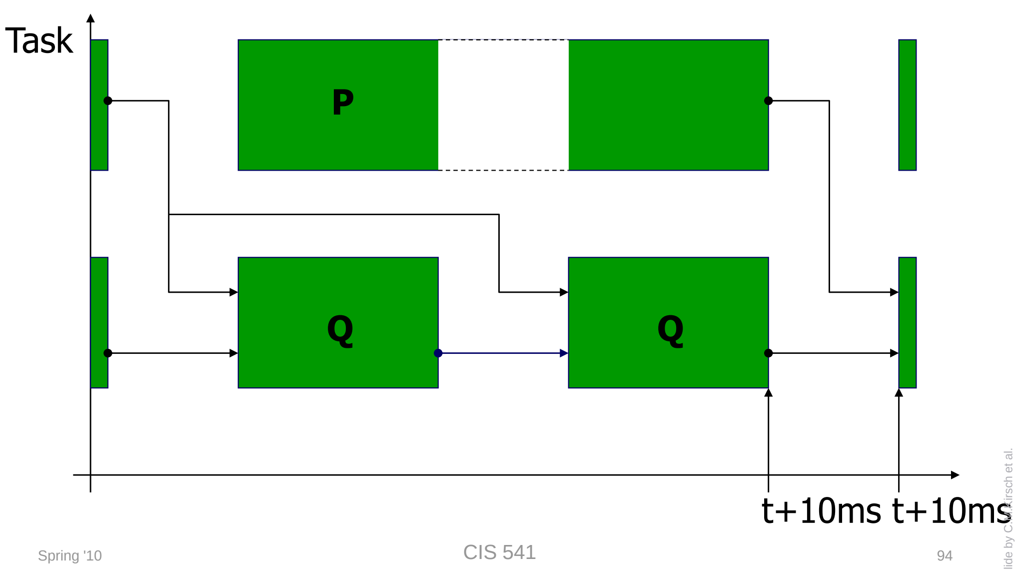
Logical Execution Time



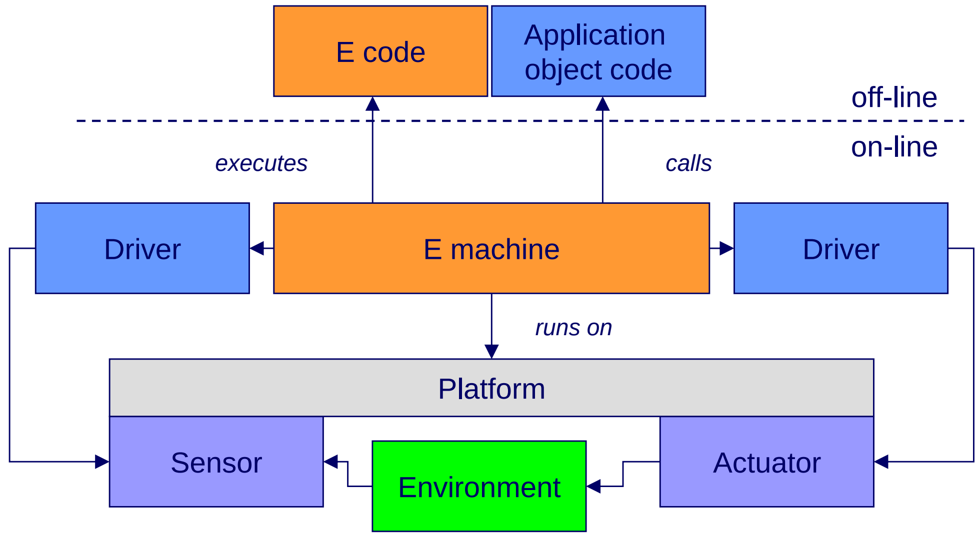
Task Life Cycle



Example



Runtime Environment



E-Code

- E-Code controls the execution behavior

- **Call**: executes drivers
- **Schedule**: enqueues tasks
- **Future**: schedules a resume
- **Return**: exists the interpreter

```
lbl1: → call d [ t1 ]
      → call d [ t2 ]
      → schedule t1
      → schedule t2
      → future, 200, lbl2
      → return
lbl2: → call d[ t2 ]
      → schedule t2
      → future, 200, lbl1
      → return
```

Timing Specification

- Only allows periodic tasks.
- Defined by period and frequency.
- Each mode has a period.
- Each task has a frequency within the mode.

```
mode Flight ( ) period 10ms
    {
          actfreq 1 do Actuator ( actuating ) ;
          taskfreq 1 do Control ( input ) ;
          taskfreq 2 do Navigation ( sensing ) ;
    }
```


Stopwatch Example

```
start Started {

 mode Started() period 3600 {
   actfreq 3600 do act_sec(a_sec_driver);
   taskfreq 3600 do comp_sec(sec_driver);

   actfreq 60 do act_tsec(a_tsec_driver);
   taskfreq 60 do comp_tsec(tsec_driver);

   actfreq 10 do act_min(a_min_driver);
   taskfreq 10 do comp_min(min_driver);

   actfreq 1 do act_tmin(a_tmin_driver);
   taskfreq 1 do comp_tmin(tmin_driver);
  }
}
```

Summary

Name	Granularity	Task model	Type	Constr.	Err. handling
PEARL-90	Task	per,sus	Spec.	Abs.&rel.	No
Temp. scopes	Statement	off, per, dl[a]	Spec.[b]	Abs.&rel.	Exceptions
ARTS kernel	Task, fun.[c]	ph, off, per[d]	Spec.[b]	Rel.	No
RTSJ	Task	off, per, dl	Prgm.	Abs.&rel.	Exceptions
Esterel	Statement	Reactive	Prgm.	-	No
Giotto	Task	per	Spec.	Rel.	No

[a] Also timing control for one-time execution (e.g., statement blocks) with offset.
[b] Although it is specification-based, it intertwines code and timing specification.
[c] Arts provides different temporal control elements for tasks and functions.
[d] Also offers deadlines for function calls.

Take Away Messages

- Timing constraints in programming languages are a topic since at least 1968.
  - What are the right abstractions?
    (Modules, tasks, statements)
  - What is the right notion of time?
    (Zero, continuous, discrete time)
  - Who checks timing constraints?
    (Offline, online)
  - How do you specify timing?
    (Specification-based vs. programming)
  - How to ensure timing constraints?
    (Verification, runtime checking, offline, online)

Summary

Name	Abstraction level	Type	Guarantee	Enforcement	Note
F/B Sys	Superloop	Prog.	None	None	Simple
Temporal Scopes	Statement level	Spec.	Impl.	Runtime	Exceptions
Time Fences	Thread/Op level	Spec.	Impl.	Runtime	Simpler temporal scopes
Esterel	Stmt.	Prog.	Exact	Compiler	Toolchain
PLC	Block	Spec	Best eff.	Runtime	Commercial
TMO	Method	Spec.	Best eff.	Runtime	
RTSJ	Thread	Prog.	Best eff.	Runtime	By popular demand
Giotto	Thread	Spec.	Exact (??)	By constr.	E-Code
TAC	Transaction	Spec	Impl.	Runtime	Bases on temporal sc.

Personal Note & Observations

- PLCs & Sequential Function Charts are a rock solid method, sold billion times, defeats many theoretic and academic models.
- Synchronous languages are about to become a huge industry-strength concept: Airbus uses SCADE.
- Temporal scopes present a general abstraction, but did not catch on.
- Simple, but effective solutions - or - a complete tool chain.
- Retrofitting does not work - it did not for security, it will not for RT systems.

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