The egg and the hen
Or,
Which comes first:
the problem or the solution?

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2001-2002

Outline of the talk

- **Challenges of embedded real-time systems**
  - ✓ **Design for verifiability**
  - ✓ **Problem modelling, expressive power of the solution**
  - ✓ **Determinism versus inflexibility**
- **Desirable characters of the solution**
  - ✓ **Expressiveness, scalability, verifiability,**
- **The Ravenscar profile**
  - ✓ **Motivation, features, coverage**

Challenges (1/6)

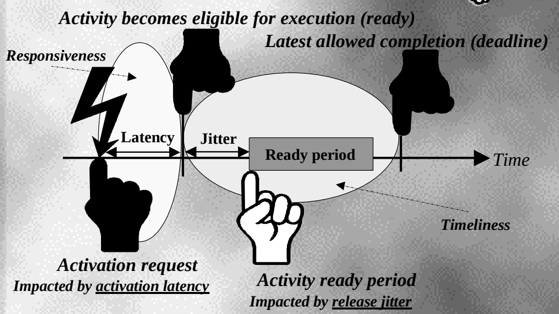
- **Embedded real-time systems control and interact with a surrounding physical environment**
  - **Their interactive nature demands accurate modelling of the physical reality**
  - **Their real-time nature demands timeliness and responsiveness of control activities**

Challenges (2/6)

- **Timeliness**
  - **Control (by avoidance or minimisation) of *release jitter***
  - **Assurance of completion within specified time bounds (*deadline*)**
- **Responsiveness**
  - **Minimisation of *activation latency***

Recall of basics

1



Recall of basics

2

- **Requests for activation can be periodic (regularly repeated *time event*) or aperiodic (irregular event)**
  - **Periodic activities need a reliable and accurate time reference**
  - **Aperiodic activities need characterisation of maximum frequency of arrival**
    upon which they become *sporadic*
  - **Both need low activation latency and controlled release jitter**

Recall of basics

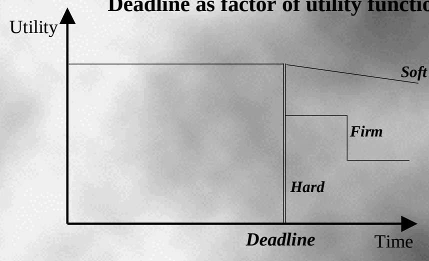
3

- **The latency of activation is a function of the *performance* of the runtime scheduling mechanisms**
  - **The more elaborate, the greater the latency**
    - ✓ **Hence we prefer *simple but not simplistic* schedulers**
- **The release jitter is a function of the *interference* caused by other activities**
  - **Execution priority is the key to jitter control**

Recall of basics

4

Deadline as factor of utility function



Challenges (3/6)

- **Embedded real-time systems model real-world entities, which are *inherently concurrent***
  - **Multiple activation requests**
    - ✓ **Some fully independent of one another**
  - **Multiple sources**
    - ✓ **Time, external interrupts, software events**
  - **Diverse processing needs**
    - ✓ **Some require collaboration**
      - **Typically in a *producer-consumer* fashion**

Challenges (4/6)

- **To build embedded real-time systems we need:**
  - ***Expressive means* to accurately model the physical reality**
  - ***Runtime mechanisms* to ensure efficient and predictable implementation of concurrency**
  - ***Analytical devices* to assess the satisfaction of real-time requirements**

Challenges (5/6)

- **Accurate modelling of physical reality**
  - **We want a solution that fits the problem**
    - ✓ **Not a (degenerated) problem representation that fits a prefabricated solution**
- **Efficient and predictable runtime**
  - **Not all problems allow all scheduling decisions to be made off line without losing value**
    - ✓ **The solution must warrant determinism (i.e., predictable behaviour)**
    - ✓ **The solution should not inflict inflexibility**

Challenges (6/6)

- **Static verification**
  - **To accept an implementation (design + code) we must be able to assess whether it meets the real-time requirements of the problem**
    - ✓ **We seek correctness by construction**
  - **We cannot afford to defer the assessment to the operation phase**
    - ✓ **Dynamic testing is best suited for functional requirements**
    - ✓ **Static analysis is far more practical and superior for real-time requirements**

Desirable characters (1/6)

- **Expressive power** (1/2)
  - **We should be able to:**
    - ✓ **Model concurrency with *periodic* and *sporadic* activities**
    - ✓ **Capture *external* (i.e.: interrupt) and *internal* (i.e.: software) events in addition to the passage of time**
    - ✓ **Support *collaborative* processing**
      - **Precedence of activation**
      - **(Data-oriented) synchronisation**
      - **Resource sharing**
    - ✓ **Assign *cohesive* functions to activities**

Desirable characters (2/6)

- **Expressive power** (2/2)
  - **We must ensure that:**
    - ✓ **The design determines the implementation**
    - ✓ **The implementation corresponds to the design, so that they can be *consistently analysed***
      - **A powerful form of *fault avoidance***
  - **We must enable:**
    - ✓ **Feedback from design to specification**
    - ✓ **Feedback from implementation to design and specification**
      - **Understanding and requirements *evolve* during development**

Design vs. Implementation

- The concurrency of system components must be an *explicit* dimension of design
- The design method must offer a *coherent* set of abstractions and relations to represent concurrency

Design phase

Determines

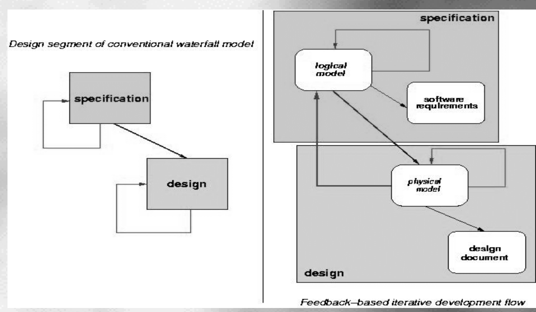
Corresponds

Implementation phase

- The implementation language must offer a range of concurrency constructs that correspond, *semantically*, to those used for design

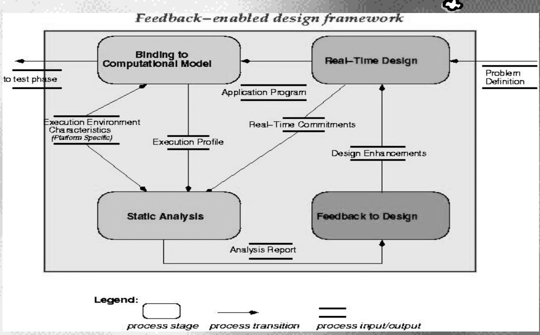
Design feedback

1



Design feedback

2



Computational model

- ***The* design and implementation dictionary, which captures**
  - **The *real-time attributes* and the *activation characteristics* of the system components**
    - **E.g.: periodic, interrupt / software sporadic**
  - **The *runtime execution* model that underpins the system design**
    - **E.g.: with / without pre-emption, priority**
  - **The means of *communication* and *synchronisation* availed to system components**
    - **E.g.: protected regions, signals, guards, wait queues**

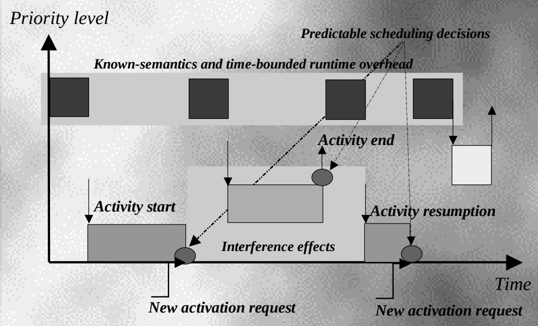
Desirable characters (3/6)

- **Flexibility**
  - **To tolerate development *feedback***
    - **We must contemplate *late* design changes**
    - **Design can hardly be fixed at specification time**
  - **To favour *modularity* and *scalability* of design**
    - **We want to enable *loosely-coupled* development of components**
  - **To achieve *scalability* of system**
    - **We need a system concept that scales to needs *efficiently***
    - **Efficiency is inversely proportional to the # of wasted cycles**

Desirable characters (4/6)

- **Runtime efficiency**
  - **Deterministic behaviour**
    - ✓ **Predictability**
    - ✓ **Time-bounded services**
  - **Performance**
    - ✓ **Simple on-line scheduling decisions**
  - **Flexible scheduling criteria**
    - ✓ **Fixed priority, permanent attribute to reflect urgency of service**
    - ✓ **Pre-emption, to reflect priority**

Desirable characters (5/6)



Desirable characters (6/6)

- **Statically verifiable**
  - **The scheduling algorithm and its effects must be mathematically representable**
    - **Period of activation(, minimum inter-arrival time), *T***
    - **Worst-case computation time, *C***
    - **Worst-case blocking time, *B***
    - **Deadline, *D***
    - **Priority, *P***
    - **Response time, *R*** $(R \le D)$
    - ✓ ***T,C,D* are *real-time attributes* of the application**
    - ✓ ***R* is a *runtime function* of *P,C,B***

Response Time Analysis

- **Response time for thread i**
  $R_i^n = B_i + C_i + I_i^{R_i^{n-1}} + K_i^{R_i^{n-1}}$
- **Interference from higher-priority threads**
  $I_i^t = \Sigma_{j\in HP(i)} \lceil t/T_j \rceil C_j$
- **Interference from interval timer**
  $K_i^t = \Sigma_{j\in HP\_Cyclic(i)} \lceil t/T_j \rceil (Clock\_Int + Ready + Select)$
- **Worst-case blocking maximum =** B_i **= interference from lower-priority threads**

The Ravenscar profile (1/10)

- **A concurrent language runtime subset with**
  - ✓ **Adequate expressive power**
    - **Designed to meet the requirements of high-integrity embedded real-time systems**
  - ✓ **Minimal footprint**
    - **Strips away all disallowed services**
  - ✓ **High efficiency**
    - **Simple and predictable scheduling decisions**
  - ✓ **Statically verifiable behaviour**
    - **Based on sound scheduling theory**
  - ✓ **Certifiable runtime code**

The Ravenscar profile (2/10)

- **Requires:**
  - ***Single* activation event per thread of control**
    - ✓ **Time, external interrupt, software synchronisation**
      - Rationale: **to comply with the power of the associated scheduling theory (e.g. Response Time Analysis)**
  - ***Non-suspending* execution within activation**
    - ✓ **Only *suspension* for next activation event**
      - Rationale: **ditto**
  - **No termination, no dynamic creation**

The Ravenscar profile (3/8)

- **Requires** (cont'd):
  - **Data-oriented synchronisation via *protected objects* with *priority ceiling emulation***
    - ✓ **To enable concurrent collaborative processing**
      - **Rationale: to bound priority inversion while controlling blocking effects**
  - **Simple synchronisation via *suspension objects***
    - ✓ ***To enable very-l ow-overhead* activation**
      - ***Rationale: to give users access to low-level high-efficiency private-semaphore P and V***

The Ravenscar profile (4/10)

- **Requires** (cont'd):
  - **Single-position entry queues**
    - ✓ **Fully deterministic synchronisation service**
      - **Rationale: to avoid non-deterministic waiting time upon task queues forming on entry and to permit simpler and leaner runtime**
  - **At most one entry per protected object**
    - ✓ **No two barriers simultaneously open**
      - **Rationale: to avoid non-determinism select policy and permit simpler and leaner runtime**

The Ravenscar profile (4/10)

- **Requires** (cont'd):
  - **Absolute time delay**
    - ✓ **Exclusive use of high-precision time type package**
      - **Rationale: to attain monotonic, accurate, fined-grained time base**
- **Prohibits:**
    - ✓ **All other concurrency features** (a whole load of them!)
      - **Sophistication that *raises* expressive power but *detracts* from predictability and static verification**
    - ✓ **Potentially blocking protected operations**

The Ravenscar profile (6/10)

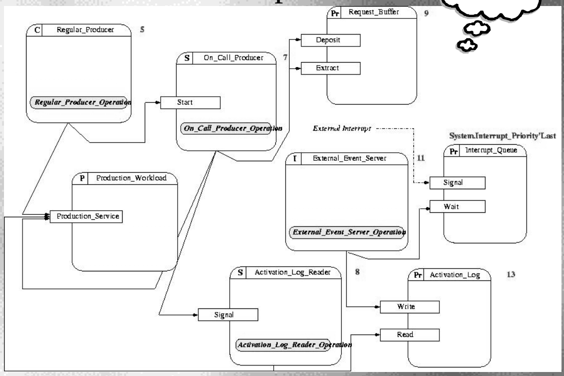
- **Best placed in a concurrent language with compile-time and run-time conformance checks**
  - **So much preferable to manual checks!**
    - ✓ **Facilitates *enforcement* of design and coding rules**
  - **You *code* activities and *not* the scheduler**
  - **You *tell* the scheduler what you want by:**
    - ✓ **Defining the activation event of tasks**
    - ✓ **Setting the priority level of tasks**

The Ravenscar profile (7/10)

- **Inherently avoids deadlock**
  - **On single CPU, priority ceiling emulation prevents circularities in ownership of and contention for locks**
- **Is in perfect match with HRT-HOOD**
  - **Which provides *specification-to-implementation* support for the RP computational model**

Ravenscar example

1



Ravenscar example

2

```
task Regular_Producer is
   pragma Priority(5);
end Regular_Producer;

task body Regular_Producer is
   Period : constant Ada.Real_Time.Time_Span := ...;
   Next_Time : Ada.Real_Time.Time := Start_Time;
begin
   delay until Next_Time;
   loop
      Next_Time := Next_Time + Period;
      Regular_Producer_Operation(...);
      delay until Next_Time;
   end loop;
end Regular_Producer;

procedure Regular_Producer_Operation(...) is
begin
   Producer_Workload.Production_Service(...);
end Regular_Producer_Operation;
```

Ravenscar example

3

```
task On_Call_Producer is
   pragma Priority(7);
end On_Call_Producer;

task body On_Call_Producer is
   Required_Workload : ...;
   Next_Time : Ada.Real_Time.Time := Start_Time;
begin
   delay until Next_Time;
   loop
      Request_Buffer.Extract(...,Required_Workload);
      On_Call_Producer_Operation(...);
   end loop;
end On_Call_Producer;

procedure On_Call_Producer_Operation(...) is
begin
   Producer_Workload.Production_Service(...);
   if Condition then Activation_Log_Reader.Signal; end if;
end On_Call_Producer_Operation;
```

Ravenscar example

4

```
protected Request_Buffer is
   pragma Priority(9);
   procedure Deposit(...);
   entry Extract(...);
private
   Barrier : Boolean := False;
end Request_Buffer;

protected body Request_Buffer is
   procedure Deposit(...) is
   begin
      ...; Barrier := True;
   end Deposit;
   entry Extract(...) when Barrier is
   begin
      ...; Barrier := False;
   end Extract;
end Request_Buffer;
```

Ravenscar example

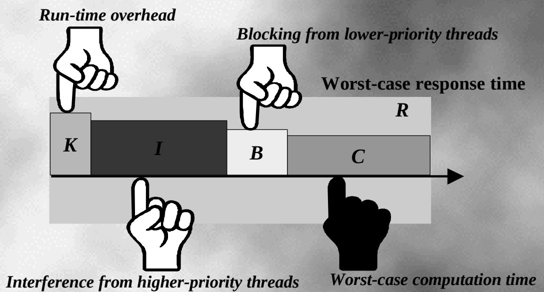
5

```
task External_Event_Server is
   pragma Priority(11);
end External_Event_Server;

task body External_Event_Server is
   Next_Time : Ada.Real_Time.Time := ...;
begin
   delay until Next_Time;
   loop
      Interrupt_Queue.Wait;
      Activation_Log.Write(...);
   end loop;
end External_Event_Server;

protected Interrupt_Queue is
   pragma Interrupt_Priority(Interrupt_Priority'Last));
   procedure Signal;
   entry Wait;
   pragma Attach_Handler(Signal, The_External_Event);
private
   Barrier : Boolean := False;
end Interrupt_Queue;
```

The Ravenscar profile (8/10)



The Ravenscar profile (9/10)

- **With the Ravenscar profile we have:**
  - **The *expressive power* to represent the entities of the problem domain accurately**
  - **A highly *efficient and predictable* runtime**
  - **A computational model directly amenable to *static analysis***
  - **High-level means to *control jitter* and minimise *latency***
  - ***Effective means for modular* and *scalable* design**

The Ravenscar profile (10/10)

Runtime Primitive	Executed by runtime for
Enter_Protected_Object	All threads
Leave_Protected_Object	All threads
Enter_Interrupt_Wait	Protected interrupt handlers
Leave_Interrupt_Wait	Protected interrupt handlers
Enter_Semaphore_Wait	Sporadic threads
Leave_Semaphore_Wait	Sporadic threads (enter Ready queue)
Handle_Semaphore_Queue	Sporadic threads
Select_from_Ready_Queue	All threads
Switch_Running_Context	All threads
Insert_in_Delay_Queue	Periodic threads
Handle_Interval_Timer_Interrupt	Periodic threads
Insert_In_Ready_Queue	Periodic threads
Handle_External_Interrupt	Protected interrupt handlers
Defer_Preemption	Runtime structures

Conclusion (1/4)

- **The Ravenscar profile happens to be a *natural restriction* of *standard* Ada tasking**
- **It could equally well find a home in *real-time Java***
- **The profile allows us to *design solutions for* embedded real-time system *problems***
- **It delivers us from *finding problem* representations that fit invariant solutions**

Conclusion (2/4)

- **Standardisation status**
  - **Profile *outline* in**
    - ✓ **"Guide for the use of the Ada Language in High Integrity Systems"**
    - ✓ **ISO/IEC TR 15942:2000**
  - **Profile *rationale* in**
    - ✓ **"Guide for the use of the Ada Ravenscar Profile in High Integrity Systems"**
    - ✓ **ISO/IEC TR being finalised**

Conclusion (3/4)

- **Standardisation status (cont'd)**
  - **Profile *definition* in**
    - ✓ **Ada Issue 249**
    - ✓ **Will become an official amendment in the forthcoming language revision**
  - **2 official implementations, more to come**
    - ✓ **Aonix/ObjectAda RAVEN**
      - **Proprietary, for PowerPC, Intel, ERC32 targets**
    - ✓ **GNAT/ORK**
      - **Open source, for ERC32, Intel targets**

Conclusion (4/4)

- **Relation to Real-Time Java Specification**
  - **NIST requirements spec [www.nist.gov/rt-java]**
    - ✓ **Too open-ended, not tight enough, soft RT**
  - **J Consortium [www.j-consortium.org]**
    - ✓ **Aims at an ISO PAS (no standard!) –** *declining interest* ☹
    - ✓ **Captures the RP as a Real-Time Core Profile**
      - **Real time with Java flavour**
  - **Sun's Real-Time Expert Group [www.rtj.org]**
    - ✓ **Values JVM compatibility more than meeting HRT**
      - **Java with real-time flavour**