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Real-Time Systems

Lecture #2

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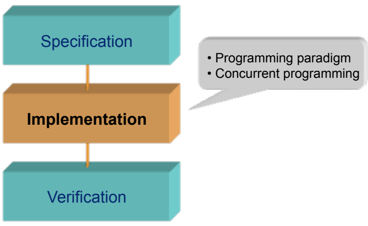
Real-time systems



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Real-time programming

Recommended programming paradigm:

- Concurrent programming
  - Reduces unnecessary dependencies between tasks
  - Enables a composable schedulability analysis
- Reactive programming
  - Certifies that tasks are activated only when work should be done; tasks are kept idle otherwise
  - Maps directly to the task model used in schedulability analysis
- Timing-aware programming
  - Certifies that timing constraints are visible at the task level
  - Enables priority-based scheduling of tasks, which in turn facilitates schedulability analysis

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Real-time programming

Desired properties of a real-time programming language:

- Support for partitioning software into units of concurrency
  - tasks or threads (Ada95, Java or POSIX C)
  - object methods (C/C++ using the TinyTimber kernel)
- Support for communication with the environment
  - access to I/O hardware (e.g. view I/O registers as variables)
  - machine-level data types (e.g. bit-field type, address pointers)
- Support for the schedulability analysis
  - notion of (high-resolution) time (⇒ timing-aware programming)
  - task priorities (reflects constraints ⇒ timing-aware programming)
  - task delays (idle while not doing useful work ⇒ reactive model)
  - hardware interrupt handlers (event generators ⇒ reactive model)

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Real-time programming

What programming languages are suitable?

- C, C++
  - Support for machine-level programming
  - Concurrent programming via run-time system (POSIX, TinyTimber)
  - Priorities and notion of time via run-time system (POSIX, TinyTimber)
- Java
  - Support for machine-level programming
  - Support for concurrent programming (threads)
  - Support for priorities and notion of time (Real-Time Java)
- Ada 95
  - Support for machine-level programming
  - Support for concurrent programming (tasks)
  - Support for priorities and notion of time

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Why concurrent programming?

Most real-time applications are inherently parallel

- Events in the target system's environment often occur in parallel
- By viewing the application as consisting of multiple tasks, this parallel reality can be reflected
- While a task is waiting for an event (e.g., I/O or access to a shared resource) other tasks may execute

Enables a composable schedulability analysis

- First, the local timing properties of each task are derived
- Then, the interference between tasks are analyzed

System can obtain reliability properties

- Redundant copies of the same task makes system fault-tolerant

Issues with concurrent programming

Access to shared resources
- Many hardware and software resources can only be used by one task at a time (e.g., processor, data structures)
- Only pseudo-parallel access is possible in many cases

Synchronization and information exchange
- System modeling using concurrent tasks also introduces a need for synchronization and information exchange.

Concurrent programming must hence be supported by an advanced run-time system that handles the scheduling of shared resources and communication between tasks.

Support for concurrent programming

Support in the programming language:
- Program is easier to read and comprehend, which means simpler program maintenance
- Program code can be easily moved to another operating system
- For some embedded systems, a full-fledged operating system is unnecessarily expensive and complicated
- Examples: Ada 95, Java, Modula, Occam, ...

Example:

Ada 95 offers support via task, rendezvous & protected objects

Java offers support via threads & synchronized methods

Support for concurrent programming

Support in the run-time system:
- Simpler to combine programs written in different languages whose concurrent programming models are incompatible
- There may not exist a simple one-to-one mapping between the language's model and the run-time system's model
- Operating systems become more and more standardized, which makes program code more portable between OS's (e.g., POSIX for UNIX, Linux, Mac OS X, and Windows)

Example:

UNIX, Linux, etc offer support via fork, semctl & msgctl

POSIX offers support via threads & mutex methods

TinyTimber offers support via reactive objects & mutex methods

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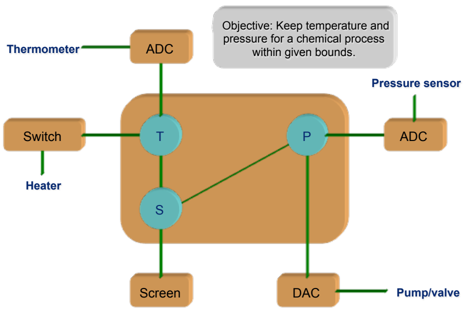
Example: a simple control system



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Sequential solution (Ada95)

```
procedure Controller is
  TR : Temp_Reading;
  PR : Pressure_Reading;
  HS : Heater_Setting;
  PS : Pressure_Setting;
begin
  loop
    T_Read(TR);                    -- read temperature
    Temp_Convert(TR,HS);           -- convert to temperature setting
    T_Write(HS);                   -- to temperature switch
    PrintLine("Temperature: ", TR); -- to screen

    P_Read(PR);                    -- read pressure
    Pressure_Convert(PR,PS);       -- convert to pressure setting
    P_Write(PS);                   -- to pressure control
    PrintLine("Pressure: ", PR);   -- to screen
  end loop;
end Controller;
```

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Sequential solution (C)

```
void Controller() {
  Temp_Reading TR;
  Pressure_Reading PR;
  Heater_Setting HS;
  Pressure_Setting PS;

  while (1) {
    T_Read(&TR);                   -- read temperature
    Temp_Convert(TR,&HS);          -- convert to heater setting
    T_Write(HS);                   -- set temperature switch
    PrintLine("Temperature: ", TR); -- write to screen

    P_Read(&PR);                   -- read pressure
    Pressure_Convert(PR,&PS);      -- convert to pressure setting
    P_Write(PS);                   -- set pressure control
    PrintLine("Pressure: ", PR);   -- write to screen
  }
}
```

Sequential solution

Drawback:

- the inherent parallelism of the application is not exploited
  - Procedures `T_Read` and `P_Read` block the execution until a new temperature or pressure sample is available from the sensor
  - while waiting to read the temperature, no attention can be given to the pressure (and vice versa)
  - if the call for reading the temperature does not return because of a fault, it is no longer possible to read the pressure
- the independence of the control functions are not considered
  - temperature and pressure must be read with the same interval
  - the iteration frequency of the loop is mainly determined by the blocking time of the calls to `T_Read` and `P_Read`.

Improved sequential solution (C)

The Boolean function **Ready_Temp** indicates whether a sample from the sensor is available

```
void Controller() {
  ...;

  while (1) {
    if (Ready_Temp()) {
      T_Read(&TR);                    -- read temperature
      Temp_Convert(TR,&HS);           -- convert to heater setting
      T_Write(HS);                    -- set temperature switch
      PrintLine("Temperature: ", TR);
    }

    if (Ready_Pres()) {
      P_Read(&PR);                    -- read pressure
      Pressure_Convert(PR,&PS);       -- convert to pressure setting
      P_Write(PS);                    -- set pressure control
      PrintLine("Pressure: ", PR);
    }
  }
}
```


Improved sequential solution

Advantages:

- the inherent parallelism of the application is exploited
  - pressure and temperature control do not block each other

Drawbacks:

- the program spends a large amount of time in "busy wait" loops
  - processor capacity is unnecessarily wasted
  - schedulability analysis is made complicated/impossible
- the independence of the control functions is not considered
  - if the call for reading the temperature does not return because of a fault, it is no longer possible to read the pressure

Concurrent solution

Step 1: Make concurrent:

- Partition the software into units of concurrency

  Ada95:
  Create two units of type **task**, `T_Controller` and `P_Controller`, each containing the code for handling the data from respective sensor.

  TinyTimber: First create two objects, `T_Obj` and `P_Obj`, each with one method (`T_Controller` and `P_Controller`) containing the code for handling the data from respective sensor. Then create two interrupt handlers, one for each sensor, that calls the respective object method when data becomes available.

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Concurrent solution

Step 2: Make reactive:

- Tasks should be idle if there is no work to be done

  Ada95: Call the blocking procedures `T_Read` and `P_Read` to idle.

  TinyTimber: Since methods `T_Controller` and `P_Controller` must be called to be activated they are by default idle.

- Activate task as a reaction to an incoming event

  Ada95: A call to procedure `T_Read` or `P_Read` unblocks when data becomes available at a sensor, thus activating the calling task.

  TinyTimber: An interrupt handler calls (activates) its corresponding method when data becomes available at a sensor.

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Concurrent solution (Ada95)

```
procedure Controller is

task T_Controller;
task P_Controller;

task body T_Controller is
begin
  loop
     T_Read(TR);
     Temp_Convert(TR,HS);
     T_Write(HS);
     PrintLine("Temperature: ", TR);
  end loop;
end T_Controller;

task body P_Controller is
begin
  loop
     P_Read(PR);
     Pressure_Convert(PR,PS);
     P_Write(PS);
     PrintLine("Pressure: ", PR);
  end loop;
end P_Controller;

begin
  null;        -- begin parallel execution
end Controller;
```

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Concurrent solution (TinyTimber)

```
// Define two new objects of TinyTimber basic class Object

Object T_Obj = InitObject();
Object P_Obj = InitObject();

// Declare the methods for each new object

void T_Controller(Object*, int);
void P_Controller(Object*, int);

// Define two new objects of class Sensor (definition not shown here),
// representing the sensors

Sensor sensor_t = initSensor(SENSOR_PORT0, &T_Obj, T_Controller);
Sensor sensor_p = initSensor(SENSOR_PORT1, &P_Obj, P_Controller);

...
```

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Concurrent solution (TinyTimber)

```
// Define the methods for handling the input data. Each method is
// called with the data from the sensor as parameter.

void T_Controller(Object *self, int data) {
  Heater_Setting HS;

  Temp_Convert(data, &HS);          -- convert to heater setting
  T_Write(HS);                      -- set temperature switch
  PrintLine("Temperature: ", data);
}

void P_Controller(Object *self, int data) {
  Pressure_Setting PS;

  Temp_Convert(data, &PS);          -- convert to pressure setting
  P_Write(PS);                      -- set pressure control
  PrintLine("Pressure: ", data);
}

...
```

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Concurrent solution (TinyTimber)

```
...

// Initialize the two sensor objects

void kickoff(Object *self, int unused) {
  SENSOR_INIT(&sensor_t);
  SENSOR_INIT(&sensor_p);
}

// Install interrupt handlers for the sensors, and then kick off
// the TinyTimber run-time system

int main() {
    INSTALL(&sensor_t, sensor_interrupt, SENSOR_INT0);
    INSTALL(&sensor_p, sensor_interrupt, SENSOR_INT1);
    TINYTIMBER(&P_Obj, kickoff, 0);
    return 0;
}
```

Concurrent solution

Advantages:

- the inherent parallelism of the application is fully exploited
  - pressure and temperature control do not block each other
  - the control functions can work at different frequencies
  - no processor capacity are unnecessarily consumed
  - the application becomes more reliable

Drawbacks:

- the parallel tasks share a common resource
  - the screen can only be used by one task at a time
  - a resource handler must be implemented, for controlling the access to the screen (to avoid garbled text)
  - the resource handler must guarantee *mutual exclusion* (*mutex*)

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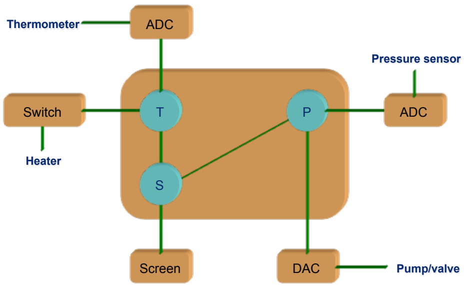
Example: control system



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Solid concurrent solution (Ada95)

```
-- Protected objects in Ada95 guarantee mutual exclusion for their
   declared procedures: a calling task will be blocked if any of the
   procedures in the object are already being used.

protected type Screen_Controller is
  procedure T_Printline(data: in Temp_Reading);
  procedure P_Printline(data: in Pressure_Reading);
end Screen_Controller;

protected body Screen_Controller is
begin
  procedure T_Printline(data : in Temp_Reading) is
  begin
    Printline("Temperature: ", data);
  end T_Printline;

  procedure P_Printline(data : in Pressure_Reading) is
  begin
    Printline("Pressure: ", data);
  end P_Printline;
end Screen_Controller;
```

Solid concurrent solution (Ada95)

```
procedure Controller is
task T_Controller;
task P_Controller;
task body T_Controller is
begin
  loop
    T_Read(TR);
    Temp_Convert(TR,HS);
    T_Write(HS);
    Screen_Controller.T_PrintLine(TR);
  end loop;
end T_Controller;
task body P_Controller is
begin
  loop
    P_Read(PR);
    Pressure_Convert(PR,PS);
    P_Write(PS);
    Screen_Controller.P_PrintLine(PR);
  end loop;
end P_Controller;
begin
  null;        -- begin parallel execution
end Controller;
```


Solid concurrent solution (TinyTimber)

```
/*
 * TinyTimber objects guarantee mutual exclusion for their declared
 * methods: a call to the method will be blocked if any of the methods
 * in the object are already being used.
 */

// Define a new object of TinyTimber basic class Object

Object Screen_Controller = InitObject();

// Define mutex methods for the new object

void T_Printline(Object *self, int data) {
    PrintLine("Temperature: ", data);
}

void P_Printline(Object *self, int data) {
    PrintLine("Pressure: ", data);
}
```


Solid concurrent solution (TinyTimber)

```
/*
 * TinyTimber supports synchronous calls: the caller will be blocked
 * if any of the methods in the object are already being used.
 */

void T_Controller(Object *self, int data) {
  Heater_Setting HS;

  Temp_Convert(data, &HS);          -- convert to heater setting
  T_Write(HS);                      -- set temperature switch
  SYNC(&Screen_Controller, T_PrintLine, data);
}

void P_Controller(Object *self, int data) {
  Pressure_Setting PS;

  Temp_Convert(data, &PS);          -- convert to pressure setting
  P_Write(PS);                      -- set pressure control
  SYNC(&Screen_Controller, P_PrintLine, data);
}
```

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Solid concurrent solution (TinyTimber)

```
/*
 * TinyTimber also supports asynchronous calls: the caller can continue
 * immediately after posting the method call, regardless of whether any
 * of the methods in the object are already being used or not.
 */

void T_Controller(Object *self, int data) {
  Heater_Setting HS;

  Temp_Convert(data, &HS);          -- convert to heater setting
  T_Write(HS);                      -- set temperature switch
  ASYNC(&Screen_Controller, T_PrintLine, data);
}

void P_Controller(Object *self, int data) {
  Pressure_Setting PS;

  Temp_Convert(data, &PS);          -- convert to pressure setting
  P_Write(PS);                      -- set pressure control
  ASYNC(&Screen_Controller, P_PrintLine, data);
}
```