Operating System & Networks 2003

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Operating Systems & Networks

what is offered here?

Overviews, Paths, Definitions, Terminology,
Foundations, Methods, Algorithms
Realities,
Current research trends, Projects,
Perspectives,
… and some theory

into/for/about Operating Systems & Networks

Operating Systems & Networks

who could be interested in this?

anybody who …

… would like to see
how rich, diverse and deep the real world of operating systems goes

… would like to learn how to create predictability
and fault-tolerant operating systems

… would like to know more about the usage of
95% of all μprocessors (and thus operating systems)

Operating Systems & Networks

who are these people? – introduction

This course will be given by

Holger Kenn *for the networks sections*

and

Uwe R. Zimmer *for the operating systems sections*

how will this all be done?

- Lectures (320-202):
  - 2 per week … all the nice stuff and theory
    Tuesday, 8:00-9:15; Friday, 11-12:15 – all in Conrad Naber lecture hall
- Labs (Advanced CS lab), independent course, but related (320-222):
  - 2 sessions per week … all the rough stuff and practice
    Monday 15:30-19:30; Tuesday 15:30-19:30
- Resources:
  - introduced in the lectures and collected on the course page:
    `http://www.faculty.iu-bremen.de/course/FundCS2/`
    … as well as schedules, slides, code, etc. pp. … keep an eye on these pages!
- Assessment:
  - Two exams, 50% each, one oral exam, one written exam – assignments for self-checking

Topics in operating systems

Table of contents

2. Hardware Fundamentals

- **General computer architecture**
- **CPU**
  - Registers
  - Traps/Interrupts & protected modes
- **Memory**
  - General memory layout
  - Caching
- **I/O systems**
  - I/O controllers, I/O buses, device programming
- **Some examples of μprocessors**
  - Small scale μcontroller (68HC05)
  - Full scale integrated processor (MCP565)

Table of contents

3. Processes

- **Processes and threads**
  - Architectures, definitions, process states
- **Synchronization**
  - Shared memory based synchronization
  - Message based synchronization
- **Deadlocks**
  - Detection, avoidance, and prevention (& recovery)
- **Scheduling**
  - Basic performance based scheduling
  - Basic predictable scheduling
  - Aperiodic, sporadic, and synchronized tasks

3.1 Synchronization methods

- **Shared memory based synchronization**
  - Semaphores ☞ 'C', POSIX — Dijkstra
  - Conditional critical regions ☞ Edison (experimental)
  - Monitors ☞ Modula-1, Mesa — Dijkstra, Hoare, …
  - Mutexes & conditional variables ☞ POSIX
  - Synchronized methods ☞ Real-time Java
  - Protected objects ☞ Ada95
- **Message based synchronization**
  - Asynchronous messages ☞ e.g. POSIX, …
  - Synchronous messages ☞ e.g. Ada95, CHILL, Occam2
  - Remote invocation, remote procedure call ☞ e.g. Ada95, …
  - Synchronization in distributed systems ☞ e.g. CORBA, …

3.2 Deadlocks

- **Ignorance & recovery**
  - ☞ 'kill some seemingly persistently blocked processes from time to time' (exasperation)
- **Deadlock detection & recovery**
  - ☞ multiple methods for detection, e.g. resource allocation graphs, Banker's algorithm
  - ☞ recovery is mostly 'ugly'
- **Deadlock avoidance**
  - ☞ check system safety before allocating resources, e.g. Banker's algorithm
- **Deadlock prevention**
  - ☞ eliminate one of the pre-conditions for deadlocks

3.3 Scheduling

- **Basic performance based scheduling**
  - C_i *is not known*: first-come-first-served (FCFS), round robin (RR), and feedback-scheduling
  - C_i *is known*: shortest job first (SJF), highest response ration first (HRRF), shortest remaining time first (SRTF)-scheduling
- **Basic predictable scheduling**
  - Fixed Priority Scheduling (FPS) with Rate Monotonic (RMPO)
  - Earliest Deadline First (EDF)
- **Real-world extensions**
  - Aperiodic, sporadic, soft real-time tasks
  - Synchronized talks (priority inheritance, priority ceiling protocols)

4. Memory

- **Requirements & hardware structures**
  - MMU features & requirements
- **Partitioning, segmentation, paging & virtual memory**
  - Simple segmentation
  - Simple paging, multi-level paging, combined segmentation & paging
  - Translation look aside buffers
  - Hashed tables, Inverted page tables
- **Virtual memory management algorithms**
  - Fetching & placement
  - Replacement
  - Resident set management
  - Cleaning
  - Load control

1

Introduction

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References for this chapter

[Silberschatz01]
Abraham Silberschatz, Peter Bear Galvin, Greg Gagne
Operating System Concepts
John Wiley & Sons, Inc., 2001

[Stallings2001]
William Stallings
Operating Systems
Prentice Hall, 2001

[Tanenbaum97]
Andrew S. Tanenbaum, Albert S. Woodhull
Operating Systems: Design and Implementation
Prentice Hall, 1997

[Tanenbaum95]
Andrew S. Tanenbaum
Distributed Operating Systems
Prentice Hall, 1995

all references and some links are available on the course page

What are operating system based on?

Hardware environments / configurations:

- stand-alone, universal, single-processor machines
- symmetrical multiprocessor-machines
- local distributed systems
- open, web-based systems
- dedicated/embedded computing

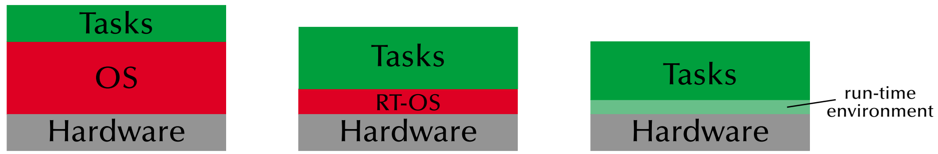
What is the common ground for operating systems?

What is an operating system?

What is an operating system?

1. A virtual machine!

… offering a more comfortable, robust, reliable, flexible … machine



Typ. general OS   Typ. real-time system   Typ. embedded system

What is an operating system?

2. A resource manager!

… dealing with all sorts of devices and coordinating access

Operating systems deal with

- processors,
- memory
- mass storage
- communication channels
- devices
  (timers, special purpose processors, interfaces, …)

☞ and many tasks/processes/programs, which are applying for access to these resources

What is an operating system?

Is there a standard set of features for an operating system?

☞ **no**,
the term 'operating systems' covers 4KB kernels,
as well as 1GB installations of general purpose OSs.

Is there a minimal set of features?

☞ **almost**,
memory management, *process management* and *inter-process communication/synchronization* will be considered essential in most systems.

Is there always an explicit operating system?

☞ **no**,
some languages and development systems operate with stand-alone run-time-environments.

The evolution of operating systems

- in the beginning: single user, single program, single task, serial processing ☞ *no OS*
- 50s: System monitors / batch processing
  ☞ the monitor ordered the sequence of jobs and triggered their sequential execution
- 50s-60s: Advanced system monitors / batch processing:
  ☞ the monitor is handling interrupts and timers
  ☞ first support for memory protection
  ☞ first implementations of privileged instructions (accessible by the monitor only).
- early 60s: Multiprogramming systems:
  ☞ employ the long device I/O delays for switches to other, runable programs
- early 60s: Multiprogramming, time-sharing systems:
  ☞ assign time-slices to each program and switch regularly
- early 70s: Multitasking systems – multiple developments resulting in UNIX (besides others)
- early 80s: single user, single tasking systems, with emphasis on user interface (MacOS) or APIs.
  MS-DOS, CP/M, MacOS and others first employed 'small scale' CPUs (personal computers).
- mid-80s: Distributed/multiprocessor operating systems - modern UNIX systems (SYSV, BSD)

The evolution of communication systems

- 1901: first wireless data transmission (Morse-code from ships to shore)
- '56: first transmission of data through phone-lines
- '62: first transmission of data via satellites (Telstar)
- '69: ARPA-net (predecessor of the current internet)
- 80s: introduction of fast local networks (LANs): ethernet, token-ring
- 90s: mass introduction of wireless networks (LAN and WAN)

Currently: standard consumer computers come with

- High speed network connectors (e.g. GB-ethernet)
- Wireless LAN (e.g. IEEE802.11)
- Local device bus-system (e.g. firewire)
- Wireless local device network (e.g. bluetooth)
- Infrared communication (e.g. IrDA)
- Modem

Personal computing systems and workstations:

- late 70s: Workstations starting by porting UNIX or VMS to ‘smaller’ computers.
- 80s: PCs starting with almost none of the classical OS-features and services,
  but with an user-interface (MacOS) and simple device drivers (MS-DOS)

☞ last 20 years: evolving and expanding into current general purpose OSs:

  - Solaris (based on SVR4, BSD, and SunOS)
  - LINUX (open source UNIX re-implementation for x86 processors and others)
  - current Windows (proprietary, partly based on Windows NT, which is ‘related’ to VMS)
  - MacOS X (Mach kernel with BSD Unix and an proprietary user-interface)

- Multiprocessing is supported by all these OSs to some extend.
- None of these OSs is very suitable for embedded systems, also trials have been performed.
- All of these OSs are not suitable at all for distributed or real-time systems.

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Types of current operating systems

Parallel operating systems

- support for a large number of processors, either:
  - symmetrical:
    each CPU has a full copy of the operating system

  or

  - asymmetrical:
    only one CPU carries the full operating system,
    the others are operated by small operating system stubs to transfer code or tasks.

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Types of current operating systems

Distributed operating systems

- all CPUs carry a small kernel operating system for communication services.
- all other OS-services are distributed over available CPUs
- services may migrate
- services can be multiplied in order to
  - guarantee availability (hot stand-by)
  - or to increase throughput (heavy duty servers)

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Types of current operating systems

Real-time operating systems

- ~~Fast context switches?~~ ☞ should be fast anyway
- ~~Small size?~~ ☞ should be small anyway
- ~~Quick responds to external interrupts?~~ ☞ not ‘quick’, but predictable
- ~~Multitasking?~~ ☞ real time systems are often multitasking systems
- ~~‘low level’ programming interfaces?~~ ☞ needed in many operating systems
- ~~Interprocess communication tools?~~ ☞ needed in almost all operating systems
- ~~High processor utilization?~~ ☞ fault tolerance builds on redundancy!

Types of current operating systems

Real-time operating systems requesting …

☞ the logical correctness of the results as well as

☞ the correctness of the time, when the results are delivered

☞ *Predictability!*

(not performance!)

☞ All results are to be delivered **just-in-time** – not too early, not too late.

Timing constraints are specified in many different ways …
… often as a response to 'external' events ☞ reactive systems

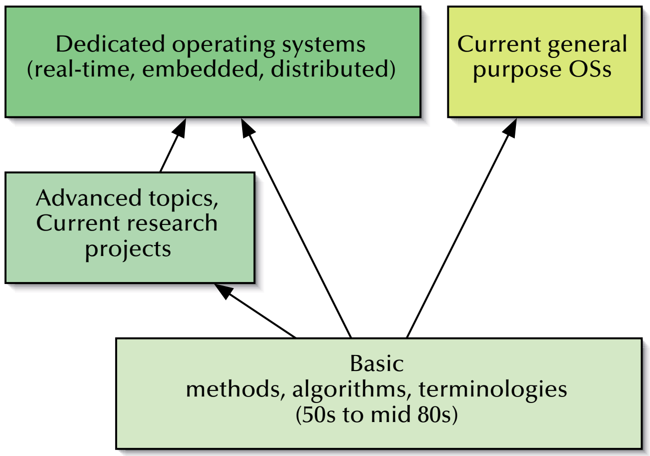
Types of current operating systems

Embedded operating systems

- usually real-time systems, often hard real-time systems
- very small footprint (often a few KBs)
- none or limited user-interaction

☞ 90-95% of all processors are working here!

Roots of current commercial operating systems

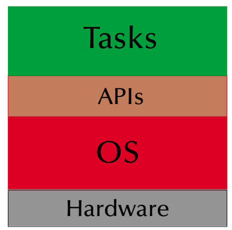


Typical structures of operating systems

'Monolithic' or 'the big mess'

- non-portable
- hard to maintain
- lacks reliability
- all services are in the kernel (on the same privilege level)

☞ may reach very high efficiency



Monolithic

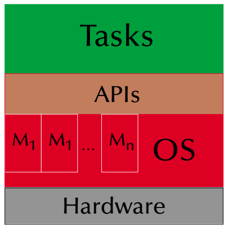
e.g. most early UNIX implementations (70s),
MS-DOS (80s), Windows (basically all versions besides NT and NT-based editions),
MacOS (until version 9),

Typical structures of operating systems

‘Monolithic & modular’

- Modules can be platform independent
- Easier to maintain and to develop
- Reliability is increased
- all services are still in the kernel (on the same privilege level)

☞ may reach very high efficiency



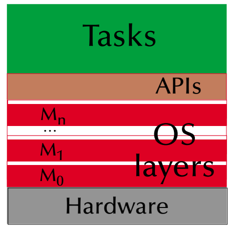
Modular

e.g. current LINUX versions

Typical structures of operating systems

‘Monolithic & layered’

- easily portable
- significantly easier to maintain
- crashing layers do not necessarily stop the whole OS
- possibly reduced efficiency through many interfaces
- rigorous implementation of the stacked virtual machine perspective on OSs



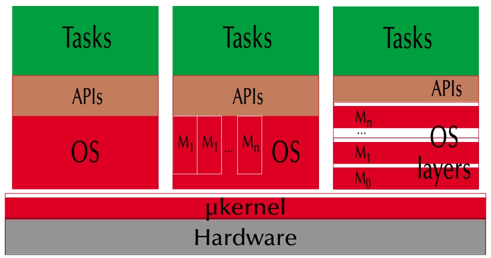
Layered

e.g. some current UNIX implementations (e.g. Solaris) to a certain degree, many research OSs (e.g. ‘THE system’, Dijkstra ‘68)

Typical structures of operating systems

‘μkernels and virtual machines’

- μkernel implements essential process, memory, and message handling
- all ‘higher’ services are dealt with outside the kernel ☞ no threat for the kernel stability
- significantly easier to maintain
- multiple OSs can be executed at the same time
- μkernel is highly hardware dependent ☞ only the μkernel need to be ported.
- possibly reduced efficiency through increased communications



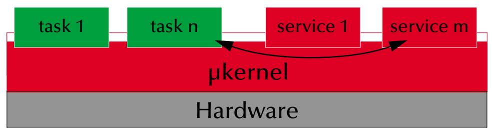
μkernel, virtual machine

e.g. wide spread concept: as early as the CP/M, VM/370 (‘79) or as recent as MacOS X (mach kernel + BSD unix)

Typical structures of operating systems

‘μkernels and client-server models’

- μkernel implements essential process, memory, and message handling
- all ‘higher’ services are user-level servers
- kernel ensures the reliable message passing between clients and servers
- highly modular and flexible
- servers can be redundant and easily replaced
- possibly reduced efficiency through increased communications



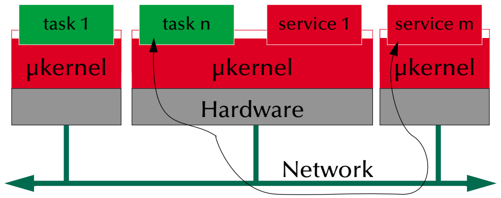
μkernel, client server structure

e.g. current μkernel research projects

Typical structures of operating systems

'µkernels and distributed systems'

- µkernel implements essential process, memory, and message handling
- all 'higher' services are user-level servers
- kernel ensures the reliable message passing between clients and servers: locally and via a communication system
- highly modular and flexible
- servers can be redundant and easily replaced
- possibly reduced efficiency through increased communications



µkernel, distributed systems

e.g. Java machines, distributed real-time operating systems + current distributed OSs research projects

Basic programming styles

- Imperative (sequential) ☞ Ada, JAVA, Eiffel, C…
- Functional (recursive) ☞ Lisp, OCaml, …
- Declarative (logic) ☞ Prolog, …
- Data-flow machines ☞ Lustre, Signal, …
- (hierarchical) Finite state machines ☞ synchronous languages: Esterel, syncEifel, synERJY, …

Programming styles alternatives

Imperative ↔ Functional ↔ Declarative ↔ Data-flow ↔ Finite state machines
Static ↔ Dynamic
Modular ↔ Concurrent ↔ Distributed
Synchronous ↔ Continuous time
Control oriented ↔ Data oriented

Programming styles

What makes a language suitable for operating systems?

- Precise expressions on machine level ☞ address physical memory + I/O
- Concurrency ☞ support for tasking/threading
- Distribution ☞ support for message passing or rpc
- Reliability ☞ detect errors at compile-time or in the run-time environment
- Large systems ☞ scalable, modular, or object-oriented + separate compilation
- Predictability
  ☞ no operations which will lead to unforeseeable timing behaviours (e.g. garbage collection)

Programming styles

Languages considered in this course

- C/C++ (for the lab-assignments)
- Ada95 (for your understanding)
- JAVA (for some distribution and object orientated features)
- POSIX (as the IEEE standard for (UNIX-) OS interfaces)

… others in places

Ada95

Ada95 is a **standardized** (ISO/IEC 8652:1995(E)) 'general purpose' language with **core** language primitives for

- strong typing, separate compilation (specification and implementation), object-orientation,
- concurrency, monitors, rpcs, timeouts, scheduling, priority ceiling locks
- strong run-time environments

… and **standardized** language-**annexes** for

- additional real-time features, distributed programming, system-level programming, numeric, informations systems, safety and security issues.

Ada95

A crash course

… refreshing:

- specification and implementation (body) parts, basic types
- exceptions
- information hiding in specifications ('private')
- generic programming
- class-wide programming ('tagged types')
- monitors and synchronisation ('protected', 'entries', 'selects', 'accepts')
- abstract types and dispatching

Ada95

Basics

… introducing:

- specification and implementation (body) parts
- constants
- some basic types (integer specifics)
- some type attributes
- parameter specification

*A simple queue **specification***

```
package Queue_Pack_Simple is
   QueueSize : constant Positive := 10;
   type Element is new Positive range 1_000..40_000;
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_Type is record
      Top, Free : Marker := Marker'First;
      Elements  : List;
   end record;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

end Queue_Pack_Simple;
```

A simple queue implementation

```
package body Queue_Pack_Simple is

   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free := Queue.Free - 1;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item       := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
    end Dequeue;

end Queue_Pack_Simple;
```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A simple queue test program

```
with Queue_Pack_Simple; use Queue_Pack_Simple;

procedure Queue_Test_Simple is

   Queue : Queue_Type;
   Item  : Element;

begin
   Enqueue (2000, Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce an unpredictable result!
end Queue_Test_Simple;
```


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Ada95

Exceptions

… introducing:

- exception handling
- enumeration types
- functional type attributes

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A queue specification with proper exceptions

```
package Queue_Pack_Exceptions is

   QueueSize : constant Integer := 10;
   type Element is (Up, Down, Spin, Turn);
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

   Queueoverflow, Queueunderflow : exception;

end Queue_Pack_Exceptions;
```

A queue implementations with proper exceptions

```
package body Queue_Pack_Exceptions is
   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Marker'Pred (Queue.Free);
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Marker'Pred (Queue.Top);
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;

end Queue_Pack_Exceptions;
```


A queue test program with proper exceptions

```
with Queue_Pack_Exceptions; use Queue_Pack_Exceptions;
with Ada.Text_IO;           use Ada.Text_IO;

procedure Queue_Test_Exceptions is

   Queue : Queue_Type;
   Item  : Element;

begin
   Enqueue (Turn, Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce a 'Queue underflow'

exception
   when Queueunderflow   => Put ("Queue underflow");
   when Queueoverflow    => Put ("Queue overflow");

end Queue_Test_Exceptions;
```


Ada95

Information hiding (private parts)

... introducing:

- private ☞ assignments and comparisons are allowed
- limited private ☞ entity cannot be assigned or compared

A queue specification with proper information hiding

```
package Queue_Pack_Private is
   QueueSize : constant Integer := 10;
   type Element is new Positive range 1..1000;
   type Queue_Type is limited private;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

   Queueoverflow, Queueunderflow : exception;

private
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

*A queue **implementation** with proper information hiding*

identical

```
package body Queue_Pack_Private is
   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Queue.Free - 1;
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;
end Queue_Pack_Private;
```


A queue test program with proper information hiding

```
with Queue_Pack_Private; use Queue_Pack_Private;
with Ada.Text_IO;        use Ada.Text_IO;

procedure Queue_Test_Private is

   Queue, Queue_Copy : Queue_Type;
   Item              : Element;

begin
   Queue_Copy := Queue;
      -- compiler-error: left hand of assignment must not be limited type
   Enqueue (Item => 1, Queue => Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce a 'Queue underflow'

exception
   when Queueunderflow   => Put ("Queue underflow");
   when Queueoverflow    => Put ("Queue overflow");
end Queue_Test_Private;
```


Ada95

Generic packages

… introducing:

- specification of generic packages
- instantiation of generic packages

*A generic queue **specification***

```
generic
   type Element is private;

package Queue_Pack_Generic is

   QueueSize: constant Integer := 10;
   type Queue_Type is limited private;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

   Queueoverflow, Queueunderflow : exception;

private
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

A generic queue implementation


```
package body Queue_Pack_Generic is

   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Queue.Free - 1;
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;

end Queue_Pack_Generic;
```


A generic queue test program

```
with Queue_Pack_Generic;
with Ada.Text_IO;         use Ada.Text_IO;

procedure Queue_Test_Generic is

   package Queue_Pack_Positive is
      new Queue_Pack_Generic (Element => Positive);
   use Queue_Pack_Positive;

   Queue : Queue_Type;
   Item  : Positive;

begin
   Enqueue (Item => 1, Queue => Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce a 'Queue underflow'

exception
   when Queueunderflow   => Put ("Queue underflow");
   when Queueoverflow    => Put ("Queue overflow");
end Queue_Test_Generic;
```


Ada95

Object oriented programming I

… introducing:

- tagged types ☞ the Ada-way to say that this type can be extended
- derivation of tagged types
- method overwriting
- usage of parent entities

An open queue base class specification

```
package Queue_Pack_Object_Base is

   QueueSize : constant Integer := 10;
   type Element is new Positive range 1..1000;
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is tagged record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

   Queueoverflow, Queueunderflow : exception;

end Queue_Pack_Object_Base;
```

*An open queue base class **implementation***

identical

```
package body Queue_Pack_Object_Base is
   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Queue.Free - 1;
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;

end Queue_Pack_Object_Base;
```


*A derived open queue class **specification***

```
with Queue_Pack_Object_Base; use Queue_Pack_Object_Base;

package Queue_Pack_Object is

   type Ext_Queue_Type is new Queue_Type with record
      Reader       : Marker      := Marker'First;
      Reader_State : Queue_State := Empty;
   end record;

   procedure Enqueue    (Item: in  Element; Queue: in out Ext_Queue_Type);
   procedure Read_Queue (Item: out Element; Queue: in out Ext_Queue_Type);

end Queue_Pack_Object;
```


*A derived open queue class **implementation***

```
package body Queue_Pack_Object is

   procedure Enqueue (Item: in  Element; Queue: in out Ext_Queue_Type) is
   begin
      Enqueue (Item, Queue_Type (Queue));
      Queue.Reader_State := Filled;
   end Enqueue;

   procedure Read_Queue (Item: out Element; Queue: in out Ext_Queue_Type) is
   begin
      if Queue.Reader_State = Empty then
         raise Queueunderflow;
      end if;
      Item         := Queue.Elements (Queue.Reader);
      Queue.Reader := Queue.Reader - 1;
      if Queue.Reader = Queue.Free then Queue.Reader_State := Empty; end if;
   end Read_Queue;

end Queue_Pack_Object;
```


An open class test program

```
with Queue_Pack_Object_Base; use Queue_Pack_Object_Base;
with Queue_Pack_Object;      use Queue_Pack_Object;
with Ada.Text_IO;            use Ada.Text_IO;

procedure Queue_Test_Object is

   Queue : Ext_Queue_Type;
   Item  : Element;

begin
   Enqueue (Item => 1, Queue => Queue);
   Read_Queue (Item, Queue);
   Enqueue (Item => 5, Queue => Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce a 'Queue underflow'

exception
   when Queueunderflow   => Put ("Queue underflow");
   when Queueoverflow    => Put ("Queue overflow");
end Queue_Test_Object;
```

Ada95

Object oriented programming II

… introducing:

- private tagged types
- objects which are protected against their children also

An encapsulated queue base class specification

```
package Queue_Pack_Object_Base_Private is

   QueueSize : constant Integer := 10;
   type Element is new Positive range 1..1000;
   type Queue_Type is tagged limited private;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);

   Queueoverflow, Queueunderflow : exception;

private
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is tagged limited record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;

end Queue_Pack_Object_Base_Private;
```


An encapsulated queue base class implementation

```
package body Queue_Pack_Object_Base_Private is
   procedure Enqueue (Item: in Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Queue.Free - 1;
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;

end Queue_Pack_Object_Base_Private;
```

identical

A derived encapsulated queue class specification

```
with Queue_Pack_Object_Base_Private; use Queue_Pack_Object_Base_Private;

package Queue_Pack_Object_Private is

   type Ext_Queue_Type is new Queue_Type with private;
   subtype Depth_Type is Positive range 1..QueueSize;

   procedure Look_Ahead (Item: out Element;
                         Depth: in Depth_Type; Queue: in out Ext_Queue_Type);

private
   type Ext_Queue_Type is new Queue_Type with null record;

end Queue_Pack_Object_Private;
```

A derived encapsulated queue class *implementation*

```
package body Queue_Pack_Object_Private is

   procedure Look_Ahead (Item: out Element;
                         Depth: in Depth_Type; Queue: in out Ext_Queue_Type) is

      Storage     : Queue_Type;
      ShuffleItem : Element;

   begin
      for I in 1..Depth - 1 loop
         Dequeue (ShuffleItem, Queue);
         Enqueue (ShuffleItem, Storage);
      end loop;
      Dequeue (Item, Queue);
      Enqueue (Item, Storage);
(…)
```



```
(…)
  Read_The_Rest:
      begin
         for I in 1..QueueSize - Depth loop
            Dequeue (ShuffleItem, Queue);
            Enqueue (ShuffleItem, Storage);
         end loop;
      exception
         when Queueunderflow => null; -- read the rest is done
      end Read_The_Rest;
  Restore_The_Queue:
      begin
         for I in 1..QueueSize loop
            Dequeue (ShuffleItem, Storage);
            Enqueue (ShuffleItem, Queue);
         end loop;
      exception
         when Queueunderflow => null; -- restore is done
      end Restore_The_Queue;

   end Look_Ahead;

end Queue_Pack_Object_Private;
```

bad

An encapsulated class test program

```
with Queue_Pack_Object_Base_Private; use Queue_Pack_Object_Base_Private;
with Queue_Pack_Object_Private;      use Queue_Pack_Object_Private;
with Ada.Text_IO;                    use Ada.Text_IO;

procedure Queue_Test_Object_Private is

   Queue : Ext_Queue_Type;
   Item  : Element;

begin
   Enqueue (Item => 1, Queue => Queue);
   Enqueue (Item => 1, Queue => Queue);
   Look_Ahead (Item => Item, Depth => 2, Queue => Queue);
   Enqueue (Item => 5, Queue => Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue);
   Dequeue (Item, Queue); -- will produce a 'Queue underflow'

exception
   when Queueunderflow   => Put ("Queue underflow");
   when Queueoverflow    => Put ("Queue overflow");
end Queue_Test_Object_Private;
```


Ada95

Tasks & Monitors

… introducing:

- protected types
- tasks (definition, instantiation and termination)
- task synchronisation
- entry guards
- entry calls
- accept and selected accept statements

A protected queue specification

```
Package Queue_Pack_Protected is

   QueueSize : constant Integer := 10;
   subtype Element is Character;
   type Queue_Type is limited private;

   Protected type Protected_Queue is

      entry Enqueue (Item: in  Element);
      entry Dequeue (Item: out Element);

   private
      Queue : Queue_Type;

   end Protected_Queue;

private
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Queue_Type is record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;
end Queue_Pack_Protected;
```


A protected queue implementation

```
package body Queue_Pack_Protected is

   protected body Protected_Queue is

      entry Enqueue (Item: in Element) when
        Queue.State = Empty or Queue.Top /= Queue.Free is
      begin
         Queue.Elements (Queue.Free) := Item;
         Queue.Free  := Queue.Free - 1;
         Queue.State := Filled;
      end Enqueue;

      entry Dequeue (Item: out Element) when
        Queue.State = Filled is
      begin
         Item      := Queue.Elements (Queue.Top);
         Queue.Top := Queue.Top - 1;
         if Queue.Top = Queue.Free then Queue.State := Empty; end if;
      end Dequeue;

   end Protected_Queue;
end Queue_Pack_Protected;
```


A multitasking protected queue test program

```
with Queue_Pack_Protected; use Queue_Pack_Protected;
with Ada.Text_IO;          use Ada.Text_IO;

procedure Queue_Test_Protected is

   Queue : Protected_Queue;

   task Producer is entry shutdown; end Producer;
   task Consumer is                 end Consumer;

   task body Producer is
      Item   : Element;
      Got_It : Boolean;
   begin
      loop
         select
            accept shutdown; exit; -- main task loop
         else
            Get_Immediate (Item, Got_It);
            if Got_It then
               Queue.Enqueue (Item); -- task might be blocked here!
            else
               delay 0.1; --sec.
            end if;
         end select;
      end loop;
   end Producer;
(…)
```


A multitasking protected queue test program (cont.)

```
(…)
   task body Consumer is
      Item  : Element;
   begin
      loop
         Queue.Dequeue (Item); -- task might be blocked here!
         Put ("Received: "); Put (Item); Put_Line ("!");
         if Item = 'q' then
            Put_Line ("Shutting down producer"); Producer.Shutdown;
            Put_Line ("Shutting down consumer"); exit; -- main task loop
         end if;
      end loop;
   end Consumer;

begin
   null;
end Queue_Test_Protected;
```

Ada95

Abstract types & dispatching

… introducing:

- abstract tagged types
- abstract subroutines
- concrete implementation of abstract types
- dispatching to different packages, tasks, and partitions according to concrete types

An abstract queue specification

```
package Queue_Pack_Abstract is
   subtype Element is Character;
   type Queue_Type is abstract tagged limited private;

   procedure Enqueue (Item: in  Element; Queue: in out Queue_Type) is
      abstract;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
      abstract;

private
   type Queue_Type is abstract tagged limited null record;
end Queue_Pack_Abstract;
```


A concrete queue specification

```
with Queue_Pack_Abstract; use Queue_Pack_Abstract;
package Queue_Pack_Concrete is

   QueueSize : constant Integer := 10;
   type Real_Queue is new Queue_Type with private;

   procedure Enqueue (Item: in  Element; Queue: in out Real_Queue);
   procedure Dequeue (Item: out Element; Queue: in out Real_Queue);

   Queueoverflow, Queueunderflow : exception;

private
   type Marker is mod QueueSize;
   type List is array (Marker'Range) of Element;
   type Queue_State is (Empty, Filled);
   type Real_Queue is new Queue_Type with record
      Top, Free : Marker      := Marker'First;
      State     : Queue_State := Empty;
      Elements  : List;
   end record;
end Queue_Pack_Concrete;
```


A concrete queue implementation

```
package body Queue_Pack_Concrete is
   procedure Enqueue (Item: in Element; Queue: in out Real_Queue) is
   begin
      if Queue.State = Filled and Queue.Top = Queue.Free then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free  := Queue.Free - 1;
      Queue.State := Filled;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Real_Queue) is
   begin
      if Queue.State = Empty then
         raise Queueunderflow;
      end if;
      Item      := Queue.Elements (Queue.Top);
      Queue.Top := Queue.Top - 1;
      if Queue.Top = Queue.Free then Queue.State := Empty; end if;
   end Dequeue;

end Queue_Pack_Concrete;
```

A multitasking dispatching test program

```
with Queue_Pack_Abstract; use Queue_Pack_Abstract;
with Queue_Pack_Concrete; use Queue_Pack_Concrete;

procedure Queue_Test_Dispatching is

   type Queue_Class is access all Queue_Type'class;

   task Queue_Holder is -- could be on an individual partition
      entry Queue_Filled;
   end Queue_Holder;

   task Queue_User is   -- could be on an individual partition
      entry Send_Queue (Remote_Queue: in Queue_Class);
   end Queue_User;
(…)
```



```
   task body Queue_Holder is
      Local_Queue : Queue_Class;
      Item        : Element;
   begin
     Local_Queue := new Real_Queue; -- could be a different implementation!
      Queue_User.Send_Queue (Local_Queue);
      accept Queue_Filled do
         Dequeue (Item, Local_Queue.all); -- Item will be 'r'
      end Queue_Filled;
   end Queue_Holder;

   task body Queue_User is
      Local_Queue : Queue_Class;
      Item        : Element;
   begin
     Local_Queue := new Real_Queue; -- could be a different implementation!
      accept Send_Queue (Remote_Queue: in Queue_Class) do
         Enqueue ('r', Remote_Queue.all); -- potentially a rpc!
         Enqueue ('l', Local_Queue.all);
      end Send_Queue;
      Queue_Holder.Queue_Filled;
      Dequeue (Item, Local_Queue.all); -- Item will be 'l'
   end Queue_User;

begin null; end Queue_Test_Dispatching;
```


Ada95

Ada95 language status

- Established language standard with free and commercial compilers available for all major OSs.
- Stand-alone runtime environments for embedded systems (some are only available commercially).
- Special (yet non-standard) extensions (i.e. language reductions and proof systems) for extreme small footprint embedded systems or high integrity real-time environments available ☞ Ravenscar profile systems.

☞ has been used and is in use in numberless large scale projects
(e.g. in the international space station, and in some spectacular crashes: e.g. Ariane 5)

POSIX

Portable Operating System Interface for Computing Environments

- IEEE/ANSI Std 1003.1 and following
- Program Interface (API) [C Language]
- more than 30 different POSIX standards
  (a system is 'POSIX compliant', if it implements parts of just one of them!)

POSIX – some of the real-time relevant standards

1003.1 12/01	OS Definition	single process, multi process, job control, signals, user groups, file system, file attributes, file device management, file locking, device I/O, device-specific control, system database, pipes, FIFO, …
1003.1b 10/93	Real-time Extensions	real-time signals, priority scheduling, timers, asynchronous I/O, prioritized I/O, synchronized I/O, file sync, mapped files, memory locking, memory protection, message passing, semaphore, …
1003.1c 6/95	Threads	multiple threads within a process; includes support for: thread control, thread attributes, priority scheduling, mutexes, mutex priority inheritance, mutex priority ceiling, and condition variables
1003.1d 10/99	Additional Real-time Extensions	new process create semantics (spawn), sporadic server scheduling, execution time monitoring of processes and threads, I/O advisory information, timeouts on blocking functions, device control, and interrupt control
1003.1j 1/00	Advanced Real-time Extensions	typed memory, nanosleep improvements, barrier synchronization, reader/writer locks, spin locks, and persistent notification for message queues
1003.21 -/-	Distributed Real-time	buffer management, send control blocks, asynchronous and synchronous operations, bounded blocking, message priorities, message labels, and implementation protocols

POSIX – 1003.1b

Frequently employed POSIX features include:

- **Timers:** delivery is accomplished using POSIX signals
- **Priority scheduling:** fixed priority, 32 priority levels
- **Real-time signals:** signals with multiple levels of priority
- **Semaphore:** named semaphore
- **Memory queues:** message passing using named queues
- **Shared memory:** memory regions shared between multiple processes
- **Memory locking:** no virtual memory swapping of physical memory pages

POSIX – support in some OSs

	POSIX 1003.1 (Base POSIX)	POSIX 1003.1b (Real-time extensions)	POSIX 1003.1c (Threads)
Solaris	Full support	Full support	Full support
IRIX	Conformant	Full support	Full support
LynxOS	Conformant	Full support	Conformant (Version 3.1)
QNX Neutrino	Full support	Partial support (no memory locking)	Full support
Linux	Full support	Partial support (no timers, no message queues)	Full support
VxWorks	Partial support (different process model)	Partial support (different process model)	Supported through third party product

POSIX – other languages

POSIX is a 'C' standard …

… but **bindings to other languages** are also (suggested) POSIX standards:

- Ada: 1003.5*, 1003.24 (some PAR approved only, some withdrawn)
- Fortran: 1003.9 (6/92)
- Fortran90: 1003.19 (withdrawn)

… and there are POSIX standards for **task-specific POSIX profiles**, e.g.:

- Super computing: 1003.10 (6/95)
- Realtime: 1003.13, 1003.13b (3/98)
  - profiles 51-54: combinations of the above RT-relevant POSIX standards ☞ RT-Linux
- Embedded Systems: 1003.13a (PAR approved only)

POSIX – example: setting a timer

```
void timer_create(int num_secs, int num_nsecs)
{
    struct sigaction sa;
    struct sigevent sig_spec;
    sigset_t allsigs;
    struct itimerspec tmr_setting;
    timer_t timer_h;

    /* setup signal to respond to timer */
    sigemptyset(&sa.sa_mask);
    sa.sa_flags = SA_SIGINFO;
    sa.sa_sigaction = timer_intr;

    if (sigaction(SIGRTMIN, &sa, NULL) < 0)
        perror('sigaction');

    sig_spec.sigev_notify = SIGEV_SIGNAL;
    sig_spec.sigev_signo = SIGRTMIN;
```


POSIX – example: setting a timer (cont.)

```
    /* create timer, which uses the REALTIME clock */
    if (timer_create(CLOCK_REALTIME, &sig_spec, &timer_h) < 0)
        perror('timer create');

    /* set the initial expiration and frequency of timer */
    tmr_setting.it_value.tv_sec = 1;
    tmr_setting.it_value.tv_nsec = 0;
    tmr_setting.it_interval.tv_sec = num_secs;
    tmr_setting.it_interval.tv_sec = num_nsecs;
    if ( timer_settime(timer_h, 0, &tmr_setting,NULL) < 0)
        perror('settimer');

    /* wait for signals */
    sigemptyset(&allsigs);
    while (1) {
        sigsuspend(&allsigs);
    }
}

/* routine that is called when timer expires */
void timer_intr(int sig, siginfo_t *extra, void *cruft)
{
    /* perform periodic processing and then exit */
}
```


POSIX – example: setting a timer (cont.)

```
    /* create timer, which uses the REALTIME clock */
    if (timer_create(CLOCK_REALTIME, &sig_spec, &timer_h) < 0)
        perror('timer create');

    /* set the initial expiration and frequency of timer */
    tmr_setting.it_value.tv_sec = 1;
    tmr_setting.it_value.tv_nsec = 0;
    tmr_setting.it_interval.tv_sec = num_secs;
    tmr_setting.it_interval.tv_sec = num_nsecs;
    if ( timer_settime(timer_h, 0, &tmr_setting,NULL
        perror('settimer');

    /* wait for signals */
    sigemptyset(&allsigs);
    while (1) {
        sigsuspend(&alls
    }
}

/* routine that is called when timer expires */
void timer_intr(int sig, siginfo_t *extra, void *cruft)
{
    /* perform periodic processing and then exit */
}
```

remember the Pearl timers?
AFTER 30 MIN ALL 5 MIN DURING 1 HRS ACTIVATE Help;

Languages

Languages used in this course

	Ada	RT-Java	C/C++	Posix
Predictability	*** (specific run-time env.)	--- (OOP)	implementation dependent	implementation dependent
low-level interfaces	***	-	**	**
Concurrency	***	**	---	**
Distribution	**	***	---	*
Error detection (compiler, tools)	** (strong typing)	**	---	---
Large systems	***	***	OOP C++ style (no support in C)	/

Summary

Introduction to operating systems

- **Features (and non-features) of operating system**
- **Common grounds for operating systems**
- **Historical perspectives**
- **Types of current operating systems**
- **Design principles for system software (monoliths & μkernels)**
- **Examples of languages considered for system level programming:**
  - Java
  - Ada95
  - POSIX interfaces
  - C/C++

2

Hardware Fundamentals

Uwe R. Zimmer – International University Bremen

References for this chapter

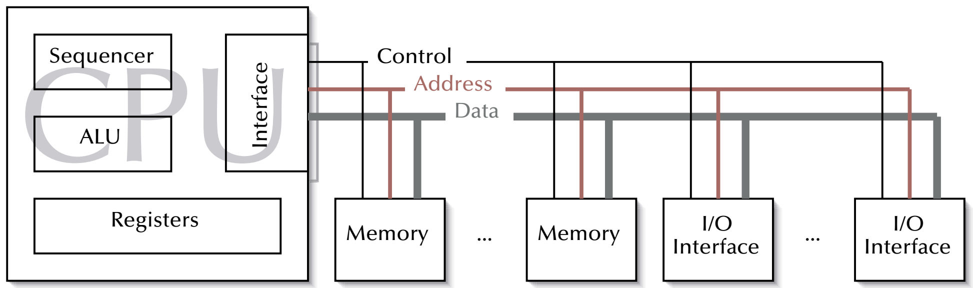
[Silberschatz01] – Chapter 2
Abraham Silberschatz, Peter Bear Galvin, Greg Gagne
Operating System Concepts
John Wiley & Sons, Inc., 2001

[Stallings2001] – Chapter 1
William Stallings
Operating Systems
Prentice Hall, 2001

all references and some links are available on the course page

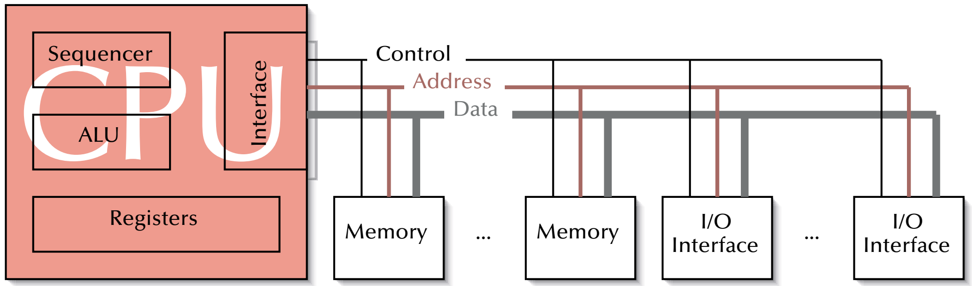
Hardware Fundamentals

A common computer architecture:



- Bus-systems carry device, address information and data (8-64 bit wide) as well as control lines in groups such as:
  - arbitration, synchronization, requests, interrupts, priorities

The CPU

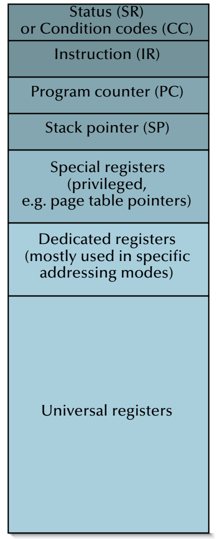


- CPU components relevant for this course:
  - register-set, sequencer ('normal operation'), interrupt controller, protected modes

Register set

- SR: Status / Condition codes (CC), e.g.:
  privilege level, interrupt level, result of last operation
- IR: current instruction
- PC: Address of current (next) instruction
- SP: Top of stack address
- Special privileged registers, e.g.:
  page table entries, memory protection maps
- Dedicated registers, e.g.:
  registers which can by employed in some contexts only
- Universal registers:
  registers, which can be employed for any purpose
  (addressing, storage, index, parameters, …)

Register structure



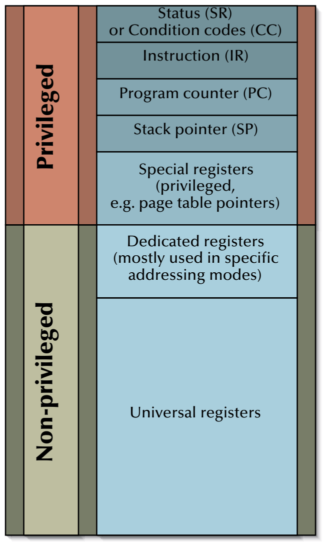
Register set

- Often divided into a
  privileged and non-privileged section
- Switch from non-privileged to privileged mode
  only via traps or interrupts (later in this chapter)

☞ SR, IR, PC, SP
  + some general registers (or at least one 'accumulator')
  are found in all current processor designs

- Special and dedicated registers are
  not used in all architectures

Register structure

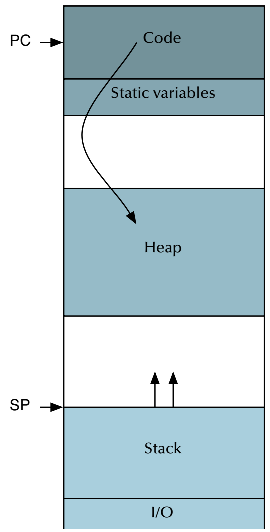


Memory layout

- Classical usage of the
  RAM areas in most processors
- Main storage of data in
  - heap
  - stack
  - or local static

  depends on the usage of the
  programming language

Main memory layout

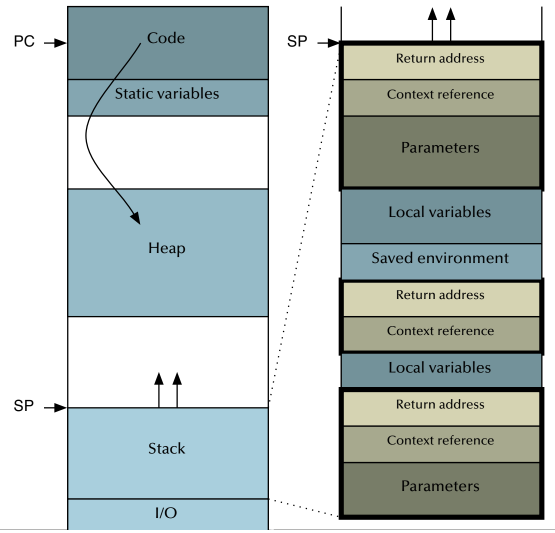


Hardware Fundamentals

Main memory layout

Stack frames

- Every sub-program call leaves an entry on the stack with all relevant information:
  - parameters
  - context (not in 'C')
  - return address
- Parameters may be removed by:
  - the calling routine ('C')
  - or the called routine
- Special architectures support faster parameter passing (e.g. register-bands)



Hardware Fundamentals

Privileged instructions

Purpose:

- prevent user level tasks from by-passing the operating system
- restrict access form user-level tasks to resources, which are managed by the operating system:
  - Memory
  - I/O
  - Structures which are used to administer memory or I/O access (e.g. special registers, MMUs, etc.)

Implementation:

- declare some instructions privileged
- implement two (or more) protection levels in the CPU
- allow changes to a higher privilege level by means of traps/exceptions/interrupts only.

Asynchronism

Interrupts

Required mechanisms for interrupt driven programming:

- **Interrupt control**: grouping, encoding, prioritising, and en-/disabling interrupt sources
- **Context switching**: mechanisms for cpu-state saving and restoring + task-switching
- **Interrupt identification**: Interrupt vectors, interrupt states

☞ hardware-supported

Asynchronism

Interrupts

Interrupt control:

… at the individual device level

… at the system interrupt controller level

… at the operating system level
- beyond task-level (interrupt service routines)
- communicating interrupts to task
- transforming interrupts to signals

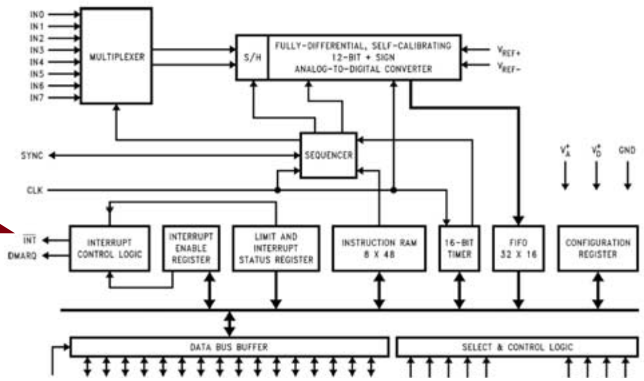
… at the language level

Interrupts

LM12L458

(National Semiconductor)

Interrupt signal



☞ only one interrupt signal line available!

☞ in order to identify the interrupt reason, an additional read cycle is required!

A/D, D/A & Interfaces

LM12L458

12-Bit + sign, 8 channel, A/D converter, controller and interface

Controller features:

- Programmable acquisition times and conversion rates
- 32-word conversion FIFO
- Self-calibration and diagnostic mode
- 8- or 16-bit wide data bus microprocessor or DSP

Typ. applications:

- Data Logging
- Process Control

LM12L458 – *accessible registers*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 01)	R/W	Don't Care						$>/\overline{<}$	Sign	Limit #1							
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 10)	R/W	Don't Care						$>/\overline{<}$	Sign	Limit #2							
1	0	0	0	Configuration Register	R/W	Don't Care				DIAG	Test = 0	RAM Pointer		I/O Sel	Auto $Zero_{ec}$	Chan Mask	Stand-by	Full CAL	Auto-Zero	Reset	Start
1	0	0	1	Interrupt Enable Register	R/W	Number of Conversions in Conversion FIFO to Generate INT2					Sequencer Address to Generate INT1			INT7	Don't Care	INT5	INT4	INT3	INT2	INT1	INT0
1	0	1	0	Interrupt Status Register	R	Actual Number of Conversion Results in Conversion FIFO					Address of Sequencer Instruction being Executed			INST7	"0"	INST5	INST4	INST3	INST2	INST1	INST0
1	0	1	1	Timer Register	R/W	Timer Preset High Byte								Timer Preset Low Byte							
1	1	0	0	Conversion FIFO	R	Address or Sign			Sign	Conversion Data: MSBs				Conversion Data: LSBs							
1	1	0	1	Limit Status Register	R	Limit #2: Status								Limit #1: Status							

LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 01)	R/W	Don't Care						$>/\overline{<}$	Sign	Limit #1							
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 10)	R/W	Don't Care						$>/\overline{<}$	Sign	Limit #2							

every entry in the **instruction RAM** consists of:

- **Loop** (1 bit): indicates the last instruction and branches to the first one.
- **Pause** (1 bit): halts the sequencer before this instruction.
- V_{IN+}, V_{IN-} (2*3 bit): select the input channels (000 selects ground in V_{IN-})
- **Sync** (1 bit): wait for an external sync. signal before this instruction.
- **Timer** (1 bit): wait for a preset 16-bit counter delay before this instruction.

LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 01)	R/W	Don't Care						$>/\overline{\leq}$	Sign	Limit #1							
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 10)	R/W	Don't Care						$>/\overline{\leq}$	Sign	Limit #2							

every entry in the **instruction RAM** consists of (cont.):

- **$8/\overline{12}$** (1 bit): selects the resolution (8 bit + sign or 12 bit + sign).
- **Watchdog** (1 bit): activates comparisons with two programmed limits.
- **Acquisition time** (D) (4 bit): the converter takes $9 + 2D$ cycles (12 bit mode) or $2 + 2D$ cycles (8 bit mode) to sample to input. Depends on the input resistance: $D \approx 0.45 \cdot R_S[k\Omega] \cdot f_{CLK}[MHz]$ for 12 bit conversions.
- **Limits** (including sign and comparator): used for Watchdog operation.

LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop


```
type ChannelPlus  is (Ch0, Ch1, Ch2, Ch3, Ch4, Ch5, Ch6, Ch7);
type ChannelMinus is (Gnd, Ch1, Ch2, Ch3, Ch4, Ch5, Ch6, Ch7);
type Resolutions  is (TwelveBit, EightBit);
type Aquisition_D is new Integer range 0..15; -- 9+2D (12bit), 2+2D (8bit)

for ChannelPlus  use (Ch0 => 0, Ch1 => 1, Ch2 => 2, Ch3 => 3,
                      Ch4 => 4, Ch5 => 5, Ch6 => 6, Ch7 => 7);
for ChannelMinus use (Gnd => 0, Ch1 => 1, Ch2 => 2, Ch3 => 3,
                      Ch4 => 4, Ch5 => 5, Ch6 => 6, Ch7 => 7);
for Resolutions  use (TwelveBit => 0, EightBit => 1);

type Instruction is record
        EndOfLoop, Pause, Sync, Timer, Watchdog : Boolean;
        Vplus                                   : ChannelPlus;
        Vminus                                  : ChannelMinus;
        Resolution                              : Resolutions;
        AquisitionTime                          : Aquisition_D;
     end record;
```


LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop


```
Units_Per_Word : constant Integer := Word_Size / Storage_Unit;

for Instruction use record
       EndOfLoop      at 0*Units_Per_Word range  0.. 0;
       Pause          at 0*Units_Per_Word range  1.. 1;
       Vplus          at 0*Units_Per_Word range  2.. 4;
       Vminus         at 0*Units_Per_Word range  5.. 7;
       Sync           at 0*Units_Per_Word range  8.. 8;
       Timer          at 0*Units_Per_Word range  9.. 9;
       Resolution     at 0*Units_Per_Word range 10..10;
       Watchdog       at 0*Units_Per_Word range 11..11;
       AquisitionTime at 0*Units_Per_Word range 12..15;
    end record;
```


LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 1	0 to 1	0 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop


```
for Instruction'Size      use 16;  -- Bits
for Instruction'Alignment use 2;   -- Storage_Units (Bytes)
for Instruction'Bit_Order use High_Order_First;

type Instructions is array (0..7) of Instruction;
   pragma Pack (Instructions);

ADC_Instructions : Instructions;
for ADC_Instructions'Address use To_Address (16#0000132D#);
```

LM12L458 – instruction RAM

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 to 1	0 to 1	0 to 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	8/$\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop

```
ADC_Instructions (0) := (EndOfLoop      => False,
                         Pause          => False,
                         Vplus          => Ch0,
                         Vminus         => Gnd,
                         Sync           => True,
                         Timer          => False,
                         Resolution     => EightBit,
                         Watchdog       => False,
                         AquisitionTime => 10);
ADC_Instructions (1) := (EndOfLoop      => True,  -- last instruction
                         Pause          => False,
                         Vplus          => Ch1,
                         Vminus         => Ch2,
                         Sync           => False,
                         Timer          => False,
                         Resolution     => TwelveBit,
                         Watchdog       => False,
                         AquisitionTime => 0);
```


LM12L458 – instruction RAM

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 to 1	0 to 1	0 to 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	8/$\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop

Data structures in 'C':

```
enum ChannelPlus  {Ch0=0, Ch1, Ch2, Ch3, Ch4, Ch5, Ch6, Ch7};
enum ChannelMinus {Gnd=0, Ch1, Ch2, Ch3, Ch4, Ch5, Ch6, Ch7};
enum Resolutions  {TwelveBit=0, EightBit};

struct {
   unsigned int EndOfLoop      : 1;
   unsigned int Pause          : 1;
   ChannelPlus  Vplus          : 3;
   ChannelMinus Vminus         : 3;
   unsigned int Sync           : 1;
   unsigned int Timer          : 1;
   Resolutions  Resolution     : 1;
   unsigned int Watchdog       : 1;
   unsigned int AquisitionTime : 4;
 } Instruction;
```


LM12L458 – instruction RAM

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 to 1	0 to 1	0 to 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	8/$\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop

Data structures in 'C':

```
struct {
   unsigned int EndOfLoop      : 1;
   unsigned int Pause          : 1;
   ChannelPlus  Vplus          : 3;
   ChannelMinus Vminus         : 3;
   unsigned int Sync           : 1;
   unsigned int Timer          : 1;
   Resolutions  Resolution     : 1;
   unsigned int Watchdog       : 1;
   unsigned int AquisitionTime : 4;
} Instruction;

Instruction    InstructionsA[8];
InstructionsA *Instructions;
Instructions = 0x0000132D;
```


LM12L458 – instruction RAM

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 to 1	0 to 1	0 to 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	8/$\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop

Data structures in 'C':

```
*Instructions (0).EndOfLoop      = 0;
*Instructions (0).Pause          = 0;
*Instructions (0).Vplus          = Ch0;
*Instructions (0).Vminus         = Gnd;
*Instructions (0).Sync           = 1;
*Instructions (0).Timer          = 0;
*Instructions (0).Resolution     = EightBit;
*Instructions (0).Watchdog       = 0;
*Instructions (0).AquisitionTime = 10;
```

don't!

If this works, you were lucky two times:

- The compiler implemented the struct-fields in the intended places and order.
- The bit ordering in your device is the way the compiler assumed it.

LM12L458 – *instruction RAM*

A4	A3	A2	A1	Purpose	Type	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
0	0 to 1	0 to 1	0 to 1	Instruction RAM (RAM Pointer = 00)	R/W	Acquisition Time				Watch-dog	$8/\overline{12}$	Timer	Sync	V_{IN-}			V_{IN+}			Pause	Loop

☞ *Macro-Assembler style programming:*

In order to produce portable code in 'C', it is necessary to set bits manually:

```
unsigned int setbits (unsigned int *r,
                      unsigned int n,          /* set n bits     */
                      unsigned int p,          /* at position p  */
                      unsigned int x)          /* to bitstring x */
{
   unsigned int mask;

   mask  = ~(~0 << n);
   *r   &= ~(mask << p);
   *r   |= (x & mask) << p;
   return (*r);
}
```


Interrupts

Interrupt control:

… at the individual device level

… at the system interrupt controller level

… at the operating system level

- beyond task-level (interrupt service routines)
- communicating interrupts to task
- transforming interrupts to signals

… at the language level

Interrupt service routines

(available only in some OSs, e.g. VxWorks)

Purpose:

- Allow full access to the interrupt controller (interrupt vectors, priorities).
- Change to an interrupt service routine in a predictable amount of time.

☞ *Cannot* operate on the level of threads or tasks!

☞ Limitations regarding the accessibility of some OS-facilities (task level system calls).

Interrupt service routines

(available only in some OSs, e.g. VxWorks)

Some VxWorks OS entries:

intConnect	Connect a routine to an interrupt vector
intLevelSet	Set the interrupt mask level
intLock	Disable interrupts (besides NMI)
intUnlock	Enable interrupts
intVecBaseSet	Set the interrupt vector base address
intVecBaseGet	Get the interrupt vector base address
intVecSet	Set an interrupt vector
intVecGet	Get an interrupt vector

these calls are employed by the language run-time environment or used directly from 'C'-code

Interrupt service routines

(available only in some OSs, e.g. VxWorks)

Minimal hardware support (supplied by the cpu):

```
save essential CPU registers (IP, condition flags)
jump to the vectorized interrupt service routine
```

Minimal wrapper (supplied by the operating system):

```
save remaining CPU registers (or switch to another register set)
save stack-frame
--> execute user level interrupts service code
restore stack-frame
restore CPU registers (or switch back to the former register set)
restore IP
```


Interrupt service routines

(available only in some OSs, e.g. VxWorks)

Interrupt service routine to task communication methods:

- **Shared memory and ring buffers**:
  most low level communication scheme (should be avoided)
- **Semaphore**: trigger a semaphore, where a task has been blocked before.
- **Monitors**:
  free a task, which is blocked at a monitor entry (standard Ada-method: protected object).
- **Message queues**: Send messages to a task (if queue is not full).
- **Pipes**: Write to a pipe (if pipe is not full).
- **Signals**: indicate an asynchronous task switch to the scheduler

Interrupt service routines

(available only in some OSs, e.g. VxWorks)

Interrupt service routine to task communication methods:

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  most low level communication scheme (should be avoided)
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- **Monitors**:
  free a task, which is blocked at a monitor entry (standard Ada-method: protected object).
- **Message queues**: Send messages to a task (if queue is not full).
- **Pipes**: Write to a pipe (if pipe is not full).
- **Signals**: indicate an asynchronous task switch to the scheduler

☞ in all of the above: the interrupt service routines *cannot* block!

Interrupts ➪ 'Signals'

Interrupt control:

… at the individual device level

… at the system interrupt controller level

… at the operating system level
- beyond task-level (interrupt service routines)
- communicating interrupts to task
- transforming interrupts to signals

… at the language level

Interrupts ➪ ‘Signals’

Some characteristics of signals:

- Involve a full task-switch operation
- ☞ Hard to predict timing behaviour
- Limited information about the interrupt-source
- Traditionally used to ‘kill’ processes
- Concept stems from a time before thread models, therefore the signal-to-thread propagation is implementation dependent and sometimes tricky.

Interrupts ➪ ‘Signals’

Some common UNIX OS entries:

POSIX 1003.1b	BSD-UNIX	
signal (…)	signal (…)	Specify the handler associated with a signal
sigaction (…)	sigvec (…)	Examine or set the signal handler for a signal
kill (…)	kill (…)	Send a signal (overwrite all other pending signals)
sigqueue (…)	N/A	Send a queued signal
sigsuspend (…)	pause (…)	Wait for a signal
sigwaitinfo (…) sigtimedwait (…)		Wait for a signal, but do not involve the handler
sigemptyset (…)	sigsetmask (…)	Manipulate and set the mask of blocked signals
sigprocmask (…)	sigblock (…)	Add to a set of blocked signals

Interrupts ➪ ‘Signals’

- Signals are originally process-level synchronization methods (‘kill’) and have been expanded to be used for everything from hardware-interrupts and timers to asynchronous task messaging.

- ☞ Signals are passed through a global task-scheduler.
- ☞ in many OSs: unpredictable ‘work-arounds’ for missing direct hardware interrupt propagation.

☞ make sure that you understand the attached strings in your OS, before employing any signals.

Interrupts

Interrupt control:

… at the individual device level

… at the system interrupt controller level

… at the operating system level

- beyond task-level (interrupt service routines)
- communicating interrupts to task
- transforming interrupts to signals

… at the language level

Exception/Trap/Interrupt indication

Four cases of modern exception indication:

raised: \ from:	run-time environment	task
synchronously	run-time exceptions	exceptions or traps
asynchronously	interrupts / signals	asynchronous transfer of control

Exception/Trap/Interrupt indication

Ada95:

raised: \ from:	run-time environment	task
synchronously	exceptions	
asynchronously	interrupt/signal handler	asynchronous transfer of control

Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID           is implementation-defined;
   type Parameterless_Handler is access protected procedure;

   function Is_Reserved (Interrupt : Interrupt_ID) return Boolean;
   function Is_Attached (Interrupt : Interrupt_ID) return Boolean;

   function  Current_Handler  (Interrupt : Interrupt_ID)
                                     return Parameterless_Handler;
   procedure Attach_Handler   (New_Handler : in  Parameterless_Handler;
                               Interrupt   : in  Interrupt_ID);
   procedure Exchange_Handler (Old_Handler : out Parameterless_Handler;
                               New_Handler : in  Parameterless_Handler;
                               Interrupt   : in  Interrupt_ID);
   procedure Detach_Handler   (Interrupt   : in  Interrupt_ID);

   function Reference (Interrupt : Interrupt_ID) return System.Address;

end Ada.Interrupts;
```


Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID           is implementation-defined;
   type Parameterless_Handler is access protected procedure;

   function Is_Reserved (Interrupt : Interrupt_ID) return Boolean;
   function Is_Attached (Interrupt :

   function  Current_Handler  (Interr

   procedure Attach_Handler   (New_H
                               Inter
   procedure Exchange_Handler (Old_H
                               New_H
                               Inter
   procedure Detach_Handler   (Inter

   function Reference (Interrupt : I

end Ada.Interrupts;
```

Protected procedures need to qualify as an interrupt handler:

1. use `pragma Interrupt_Handler`
2. let the compiler evaluate the suitability of the routine as an interrupt handler.

Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID            is implementation-defined;
   type Parameterless_Handler is access protected procedure;
   function Is_Reserved (Interrupt : Interrupt_ID) return Boolean;
   function Is_Attached (Interrupt : Interrupt_ID) return Boolean;
   function  Current_Handler  (Inter
   procedure Attach_Handler   (New_H
                               Inter
   procedure Exchange_Handler (Old_H
                               New_H
                               Inter
   procedure Detach_Handler   (Inter
   function Reference (Interrupt : I
end Ada.Interrupts;
```

Protected procedures can also be attached statically to an interrupt:

use pragma `Interrupt_Handler_Attach`

Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID            is implementation-defined;
   type Parameterless_Handler is access protected procedure;
   function Is_Reserved (Interrupt : Interrupt_ID) return Boolean;
   function Is
   function  C
   procedure A
   procedure E
   procedure D
   function Re
end Ada.Interr
```

The mechanism to invoke an interrupt handler may be different from calling a protected procedure from a task.

Implementation advice: Whenever possible, the implementation should allow interrupt handlers to be called directly by the hardware.

Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID            is implementation-defined;
   type Parameterless_Handler is access protected procedure;
   function Is_Reserved (Interrupt : Interrupt_ID) return Boolean;
   function Is_Attached (Interrupt : Interrupt_ID) return Boolean;
   function  C
   procedure A
   procedure E
   procedure Detach_Handler   (Interrupt   : in  Interrupt_ID);
   function Reference (Interrupt : Interrupt_ID) return System.Address;
end Ada.Interrupts;
```

Metrics: *The implementation shall document the worst case overhead for an interrupt handler invocation (in clock cycles).*

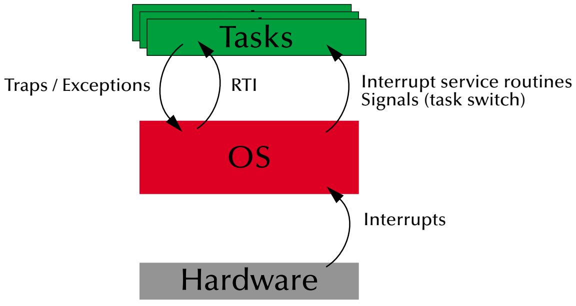
Ada95: Interrupt handlers

```
package Ada.Interrupts is
   type Interrupt_ID            is implementation-defined;
   type Parameterless_Handler is access protected procedure;
   function Is
   function Is
   function  C
   procedure A
   procedure E
                               New_Handler : in  Parameterless_Handler;
                               Interrupt   : in  Interrupt_ID);
   procedure Detach_Handler   (Interrupt   : in  Interrupt_ID);
   function Reference (Interrupt : Interrupt_ID) return System.Address;
end Ada.Interrupts;
```

Direct access to the invocation address:
May be used to connect task-entries to interrupts
☞ *risky! — use with special care.*

What is an operating system?

3. A virtual machine, which is handling exceptions!

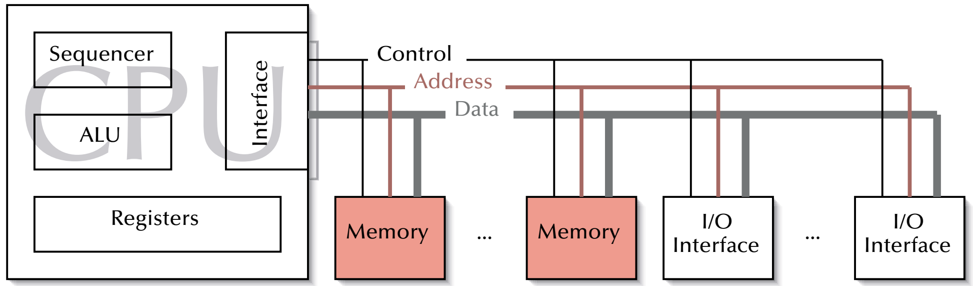


Typ. general OS

Operating Systems & Networks

Hardware Fundamentals

A common computer architecture:



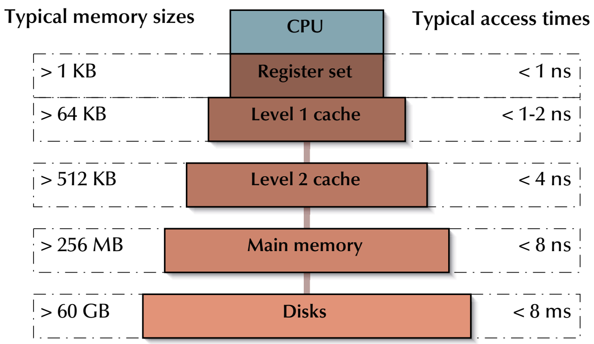
- Memory:
  - Hierarchy, Caching, Mapping

Operating Systems & Networks

Hardware Fundamentals

Memory sizes and access times: *(typical workstation)*

Basic memory hierarchy

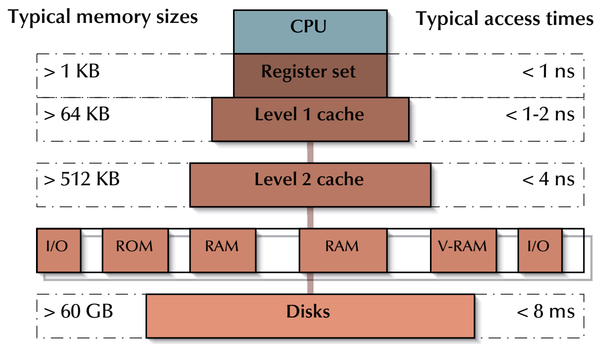


Operating Systems & Networks

Hardware Fundamentals

Main memory layout:

Basic memory hierarchy



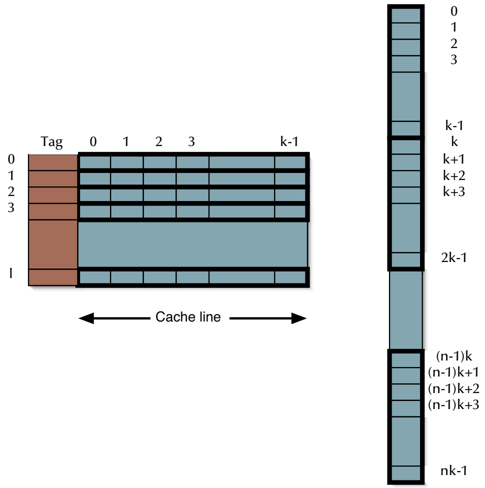
Hardware Fundamentals

Caching

- Introduce a intermediate memory (cache), which is:
    - faster than the original memory
    - organized in 'cache lines'
    - addressed via tags and a fast matching hardware (e.g. associative memory)

Caché is actually French, meaning 'hidden', hence the cache memory is supposed to be 'invisible' to the user (the 'shadow memory').

Cache



Operating Systems & Networks

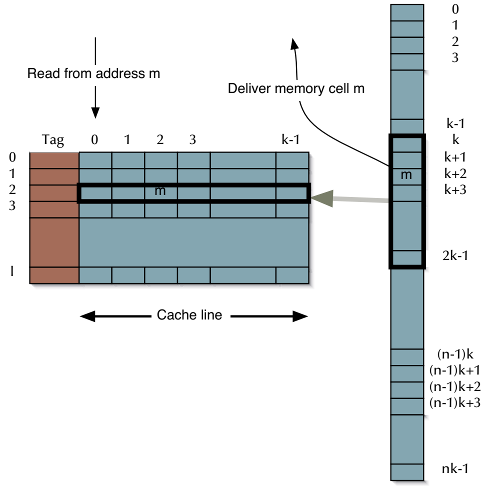
Hardware Fundamentals

Cache misses

Memory read requests to cells, which are not currently stored in the cache, result in:

1. transfer of the full cache line into an empty of replaceable cache entry.
2. transfer of the data directly from the main memory to the requester.

Cache miss



Operating Systems & Networks

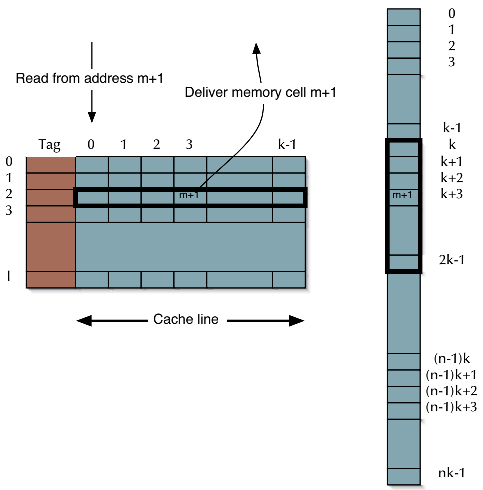
Hardware Fundamentals

Cache hits

Memory read requests to cells, which are currently stored in the cache, result in:

- transfer of the requested data from the cache memory to the requester.
- *no access* to the main memory

Cache hit



Operating Systems & Networks

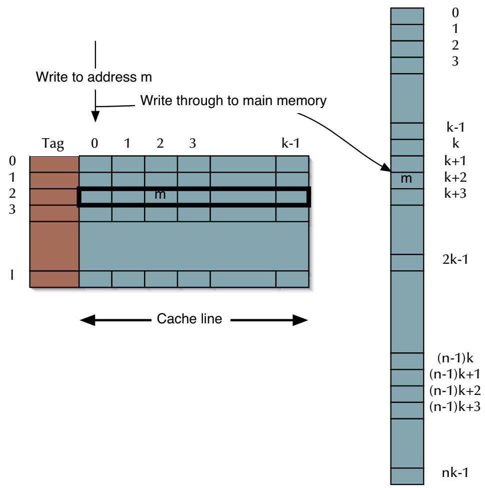
Hardware Fundamentals

Cache write through

Write requests to cells, which are currently stored in the cache, result in:

1. update of the cache entry
2. update of the main memory cell

Cache write through

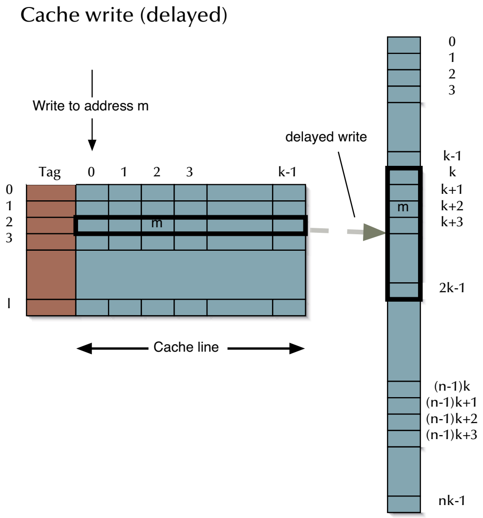


Cache, delayed writes

Write requests to cells, which are currently stored in the cache, result in:

1. update of the cache entry
2. transfer of the full cache line (or the 'touched' entries) at a later point in time.

☞ **Critical in multi-processor / shared memory environments!**



Caching considerations

- Caches (two-level memories) are meant to maximize the **throughput** – not the predictability of a system.
- Cache performance is relying on:
  - **Spatial locality**: nearby memory cells are likely to be accessed soon
  - **Temporal locality**: recently addressed memory cells are likely to be accessed again soon

☞ The length of the cache lines are given by the relation between spatial and temporal locality

- According to some practical evaluations, the locality radius seems to be *independent* of the size of the main memory

  ☞ thus there is an absolute maximum cache-size, beyond which the performance is no longer improving (memory caches of up to about 128KB are considered adequate in most cases).

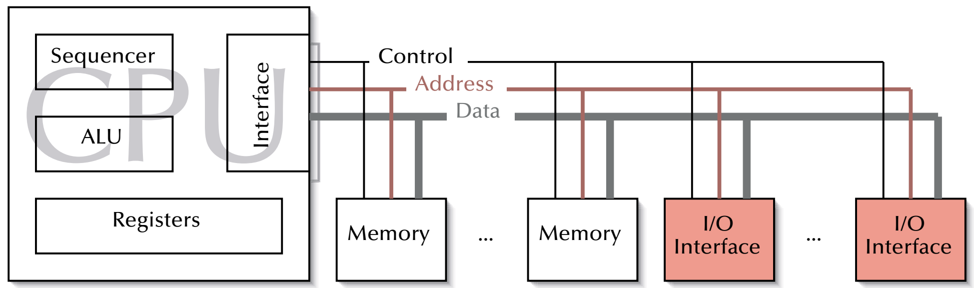
More on memory locality

- *Imperative programming* will generate linear sequences of instructions mostly (☞ **spatial locality**).
- *Functional and declarative programming* turns out to generate more 'jumpy' code, but due to extensive usage of recursions it will show strong **temporal locality**.
- *Under all programming paradigms* CPU-time is often spent in relatively small loops/iterations (☞ **spatial & temporal locality**)
- Languages, which are using *explicit data structures* (like arrays and records) will store this data in a compact format (☞ **spatial locality**).

☞ The locality assumptions will thus be justified in the vast majority of all cases

… still it's an heuristic.

A common computer architecture:



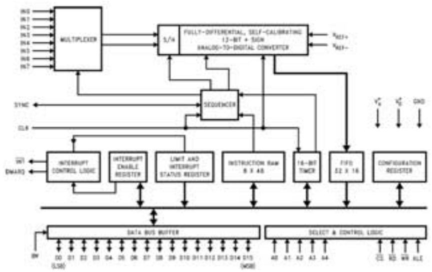
- I/O interfaces:
  - devices, controllers, communication with CPU, basic device programming

I/O devices

☞ the essential parts of a computer system, which (may) make the computations meaningful.

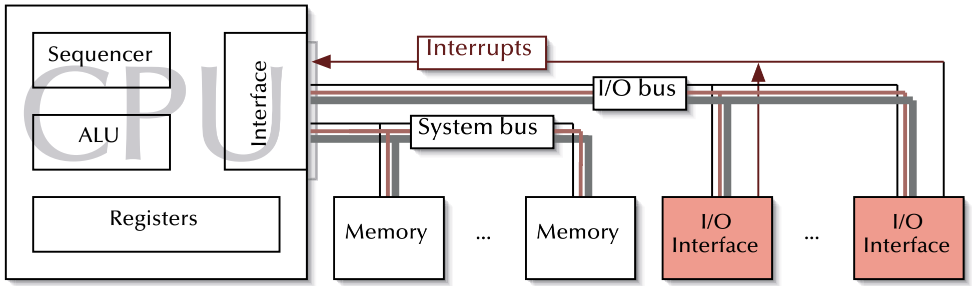
- Some typical classes of I/O devices:
  - clocks, timers
  - user-interface devices
  - document I/O devices (scanners, printers, …)
  - audio & video equipment
  - network interfaces
  - mass storage devices
  - all kinds of sensors and actuators in control applications

I/O controllers



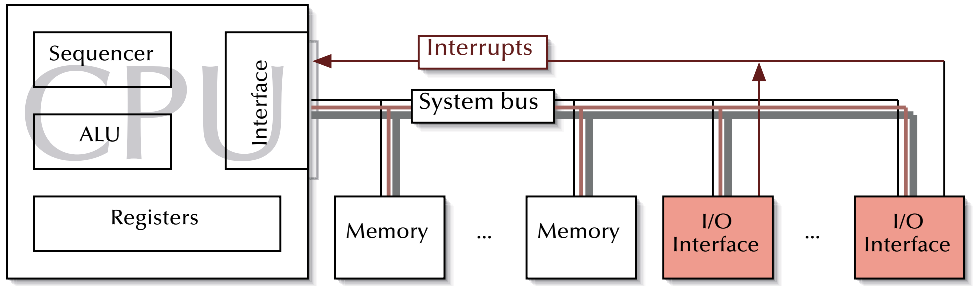
- Interfacing between a local bus-system (system bus, peripheral bus) and an concrete hardware device
- Accessible from the CPU via control, status and data registers
- Major tasks:
  - convert electrical signals
  - buffer data in case of different signal speeds
  - multiplexing different channels
  - communicate with the external device independently of the CPU as far as possible
    ☞ often up to the level of a complete embedded µcontroller

I/O interfaces via dedicated ***I/O-buses***



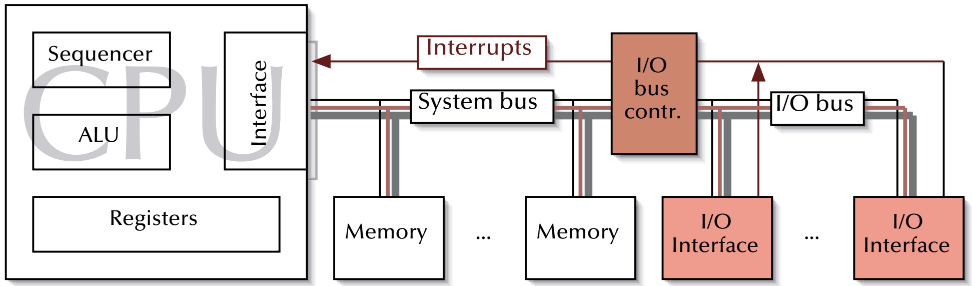
- **I/O protection** is given by protected CPU instructions ☞ need to be done in protected mode.
- Potentially less efficient, since *all* I/O operations need to be done in the OS-kernel
  no obvious DMA - everything needs to be transferred via the CPU, I/O bus is processor specific

I/O interfaces via ***system-bus***



- **I/O protection** requires / is identical with **memory protection,** DMA possibilities, expandible
- System bus can be a bottle-neck, I/O interfaces are processor dependent

I/O interfaces via **system-bus and I/O bus controller**

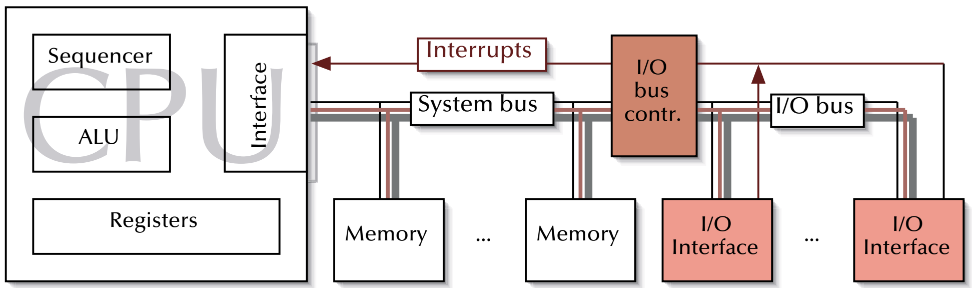


- **I/O protection** requires / is identical with **memory protection,** DMA possibilities, expandible
- System bus load can be reduced, I/O bus is platform independent, e.g. PCI, SCSI, …

Basic I/O device programming

- **Status driven:** the computer polls for information
  (used in dedicated µcontrollers and pre-scheduled hard real-time environments)
- **Interrupt driven:** The data generating device may issue an interrupt
  when new data had been detected / converted or when internal buffers are full
  - **Program controlled:** The interrupts are handled by the CPU directly
    (by changing tasks, calling a procedure, raising an exception,
    free tasks on a semaphore, sending a message to a task, …)
  - **Program initiated:** The interrupts are handled by a DMA-controller.
    No processing is performed. Depending on the DMA setup,
    cycle stealing can occur and needs to be considered for the worst case computing times.
  - **Channel program controlled:** The interrupts are handled by a dedicated channel device. The data is transferred and processed. Optional memory-based communication with the CPU. ☞ the channel controller is usually itself a dedicated µengine / µcontroller.

Concurrency is an intrinsic feature of real architectures!

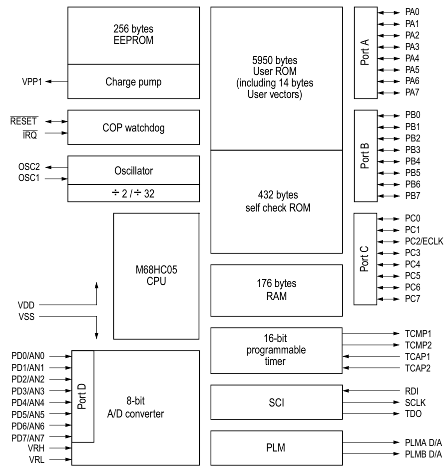


☞ Operating systems need to take care of all asynchronous and concurrent resources.

☞ ***Concurrency and synchronization are fundamentals of operating systems design!***

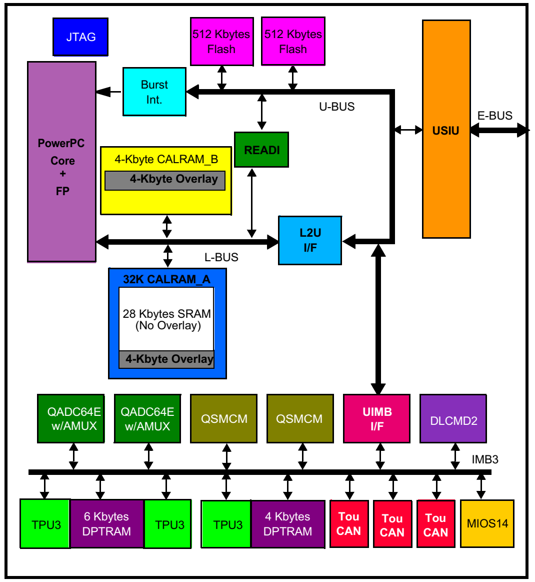
MC68HC05

- **Clock**: max. 2.1MHz internal (4.2MHz external)
- **Registers**: PC, SP (16 bit); Accu, Index, CC (8 bit)
- **RAM**: 176bytes
- **ROM**: 5936bytes
- **EEPROM**: 256bytes
- **Power saving modes** (stop, wait, slow)
- **Serial**: 46-76800 baud (at 2.4576MHz)
- **Parallel** I/O: 3*8bit; Parallel in: 1*8bit
- **Timers**: 1*16bit
- **A/D**: 8 channels, 8bit
- **PWM**: 2 generators

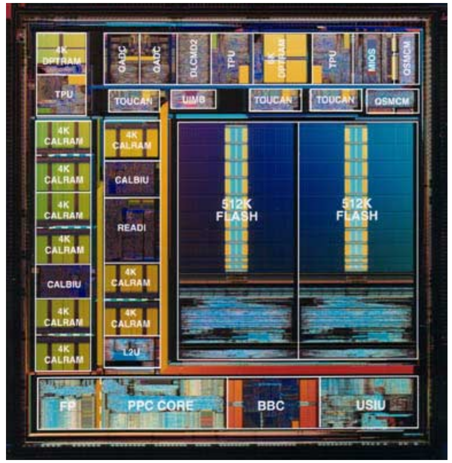


```
MAIN   BRCLR  6,TSR,MAIN      ;Loop here till Output Compare flag set
       LDA    OCMP+1          ;Low byte of Output Compare register
       ADD    #$D4            ;Add Δt1 = (50ms/4µs)mod2^8 = $D4
       STA    TEMPA           ;Save till high half calculated
       LDA    OCMP            ;High byte of Output Compare register
       ADC    #$30            ;Add Δth = (50ms/4µs)div2^8 = $30 (+carry)
       STA    OCMP            ;Update high byte of Output Compare register
       LDA    TEMPA           ;Get low half of updated value
       STA    OCMP+1          ;Update low half and reset Output Compare flag
       LDA    TIC             ;Get current TIC value
       INCA                   ;TIC := TIC + 1
       STA    TIC             ;Update TIC
       CMP    #20             ;20th TIC?, 1 second passed?
       BLO    NOSEC           ;If not, skip next clear
       CLR    TIC             ;Clear TIC on 20th
NOSEC  EQU    *
       JSR    TIME            ;Update time-of-day & day-of-week
       JSR    KYPAD           ;Check/service keypad
       JSR    A2D             ;Check Temp Sensors
       JSR    HVAC            ;Update Heat/Air Cond Outputs
       JSR    LCD             ;Update LCD display
       BRA    MAIN            ;End of main loop
```


µControllers



MPC565



µControllers MPC565

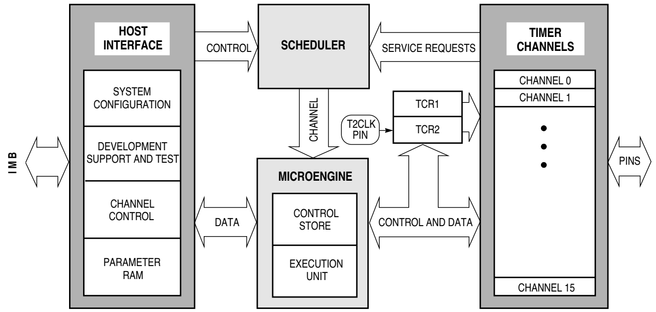
- -40° - +125°C, power dissipation: 0.8 - 1.12W
- **CPU**: PowerPC core (incl. FPU & BBC), 40/56MHz
- **Memory**: flash: 1M, static: 36K, 32 32-bit registers
- **Time processing units**: 3 (via dual-ported RAM)
- **Timers**: 22 channels (PWM & RTC supported)
- **A/D convertors**: 40 channels, 10bit, 250kHz
- **Can-bus**: 3 TOUCAN modules
- **Serial**: 2 interfaces
- **Interrupt controller**: 48 sources on 32 levels
- **Data link controller**: SAE J1850 class B communications module
- **Real-time embedded application development interface**: NEXUS debug port (IEEE-ISTO 5001-1999)
- **Packing**: 352/388 ball PBGA

µControllers MPC565

Time processing unit

a special-purpose µcontroller:

- Independent µengine.
- 16 digital I/O channels with independent *match* and *capture* capabilities.
- Meant to operate these I/O channels for timing control purposes.
- Predefined µengine command set (ROM functions in control store).
- 2 16-bit time bases



Summary

Hardware Fundamentals

- **General computer architecture**
- **CPU**
  - Registers
  - Traps/Interrupts & protected modes
- **Memory**
  - General memory layout
  - Caching
- **I/O systems**
  - I/O controllers, I/O buses, device programming
- **Some examples of µprocessors**
  - Small scale µcontroller (68HC05)
  - Full scale integrated processor (MCP565)

3

Processes

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John Wiley & Sons, Inc., 2001

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all references and some links are available on the course page

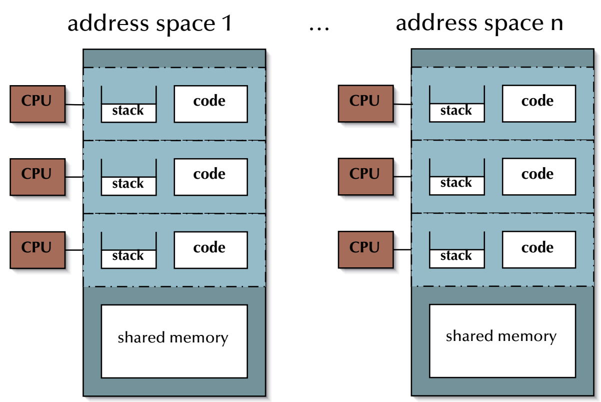
Introduction to processes and threads

1 CPU per control-flow

for specific configurations only:

- distributed µcontrollers
- physical process control systems:
  1 cpu per task,
  connected via a typ. fast bus-system (VME, PCI)

☞ no need for process management

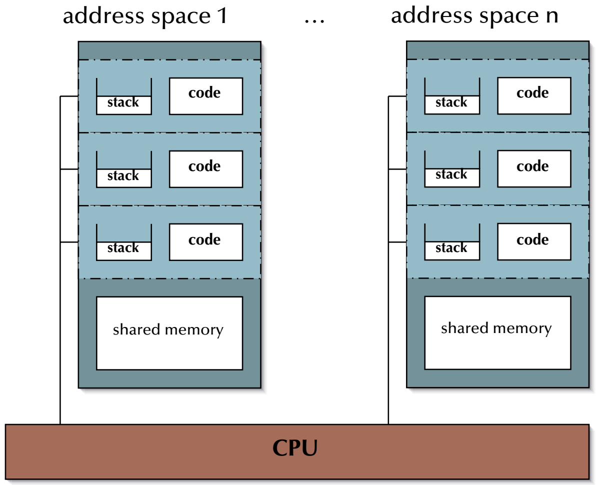


1 CPU for all control-flows

- OS: emulate one CPU for every control-flow

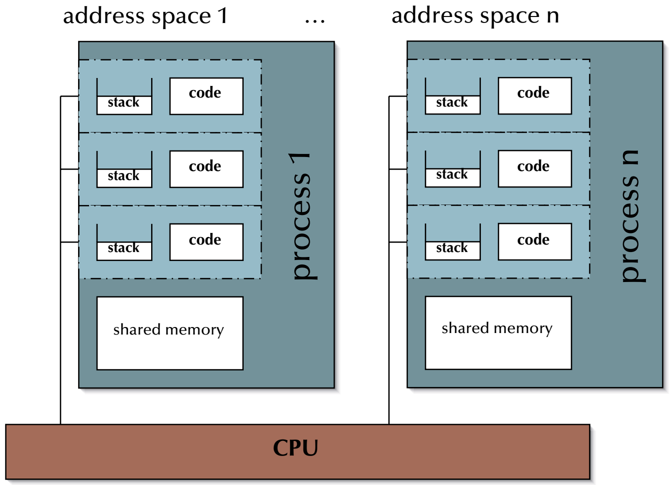
☞ **multi-tasking** operating system

- support for memory protection becomes essential



Processes

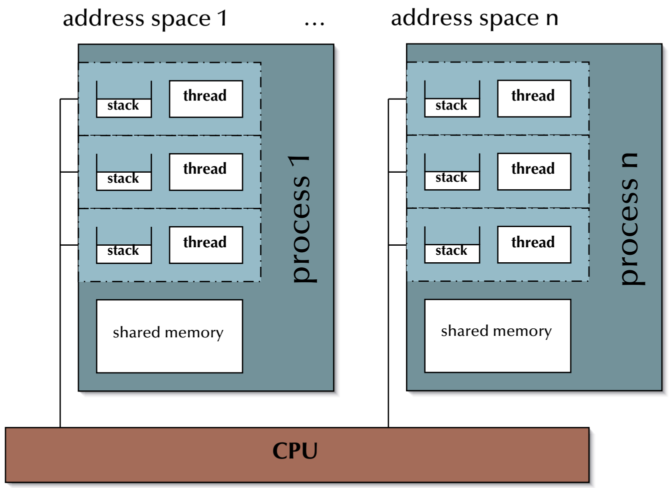
- **Process** ::= address space + control flow(s)
- Kernel has full knowledge about all *processes* as well as their *requirements* and current *resources* (see below)



Threads

Threads (individual control-flows) can be handled:

- *inside the kernel*:
  - kernel scheduling
  - I/O block-releases according to external signal
- *outside the kernel*:
  - user-level scheduling
  - no signals to threads

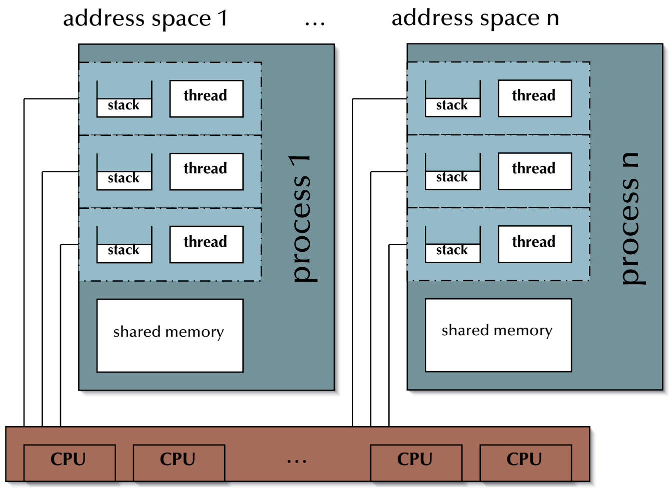


Multi-processor-systems

- The kernel may execute multiple processes at a time.

☞ Address space and resource restrictions of individual CPUs and processes/threads need to be considered.

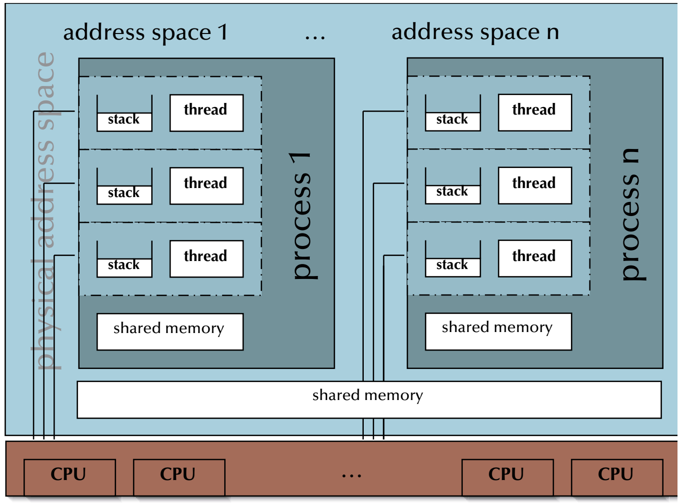
☞ Caching, synchronization, and memory protection need to be adapted.



Symmetric Multi-processing (SMP)

- all CPUs share the same physical address space (and access to resources)

☞ processes/threads can be executed on any available CPU



Processes ↔ Threads

Also processes can share memory
and the exact interpretation of threads is different in different operating systems:

☞ Threads can be regarded as a group of processes, which share some resources (☞ process-hierarchy)

☞ Due to the overlap in resources, the attributes attached to threads are less than for 'first-class-citizen-processes'

☞ Thread switching and inter-thread communications can be more efficient than on full-process-level

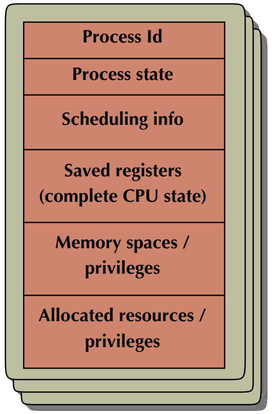
☞ Scheduling of threads depends on the actual thread implementations:

- e.g. user-level control-flows, which the kernel has no knowledge about at all
- e.g. kernel-level control-flows, which are handled as processes with some restrictions

Process Control Blocks

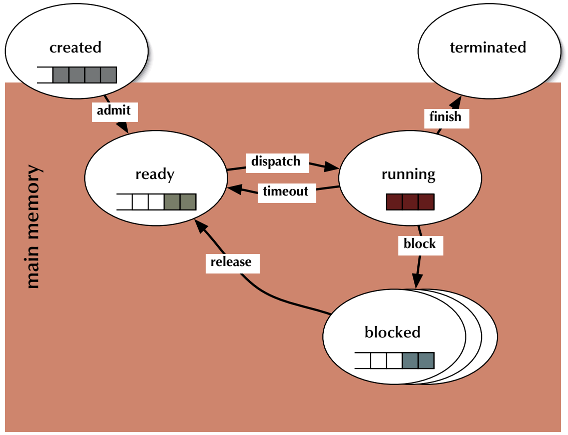
- **Process Id**
- **Process state:**
  {created, ready, executing, blocked, suspended, …}
- **Scheduling info:**
  priorities, deadlines, consumed CPU-time, …
- **CPU state:**
  saved/restored information while context switches (incl. the program counter, stack pointer, …)
- **Memory spaces / privileges:**
  memory base, limits, shared areas, …
- **Allocated resources / privileges:**
  open and requested devices and files

Process Control Blocks (PCBs)



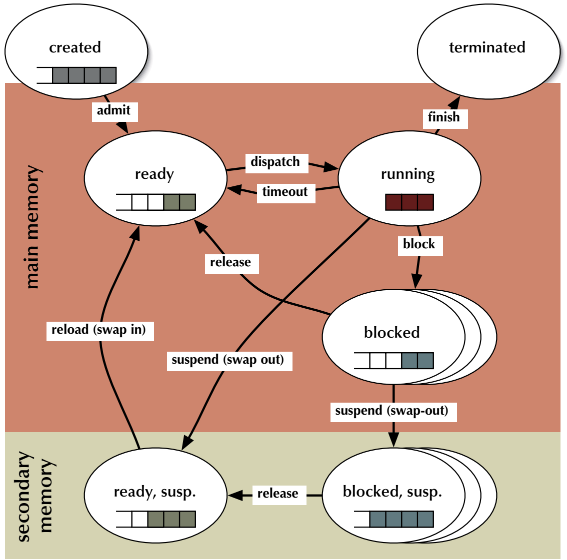
… PCBs are usually enqueued at a certain state or condition

Process states



- **created**: the task is ready to run, but not yet considered by any dispatcher – waiting for admission
- **ready**: ready to run – waiting for a free CPU
- **running**: holds a CPU and executes
- **blocked**: not ready to run – waiting for a a resource to become available

Process states



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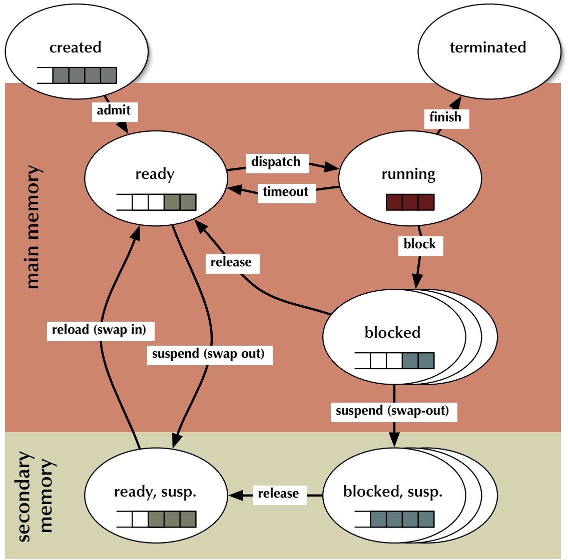
Process states



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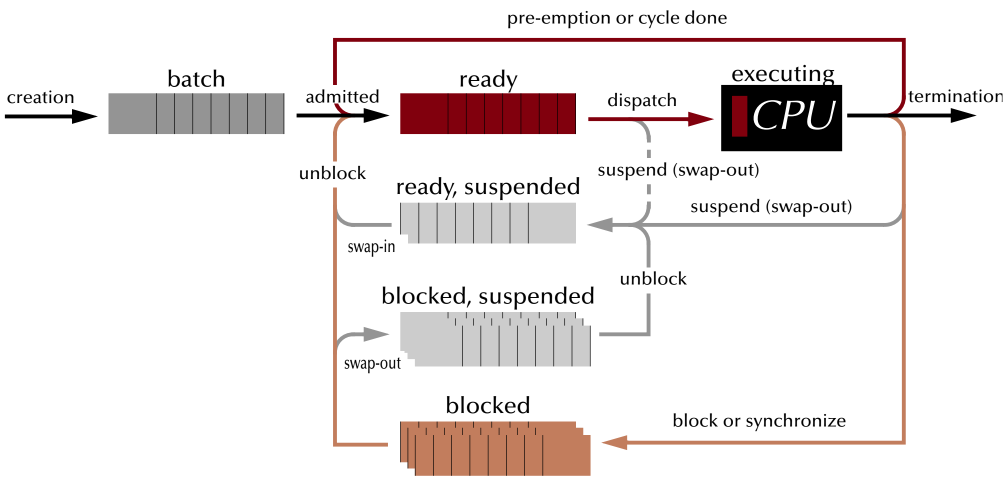
☞ dispatching and suspending can be independent modules here

Process states



Synchronization

Synchronization methods

- **Shared memory based synchronization**
  - Semaphores ☞ 'C', POSIX — Dijkstra
  - Conditional critical regions ☞ Edison (experimental)
  - Monitors ☞ Modula-1, Mesa — Dijkstra, Hoare, …
  - Mutexes & conditional variables ☞ POSIX
  - Synchronized methods ☞ Real-time Java
  - Protected objects ☞ Ada95
- **Message based synchronization**
  - Asynchronous messages ☞ e.g. POSIX, …
  - Synchronous messages ☞ e.g. Ada95, CHILL, Occam2
  - Remote invocation, remote procedure call ☞ e.g. Ada95, …
  - Synchronization in distributed systems ☞ e.g. CORBA, …

Synchronization in operating systems

☞ There are many concurrent entities in operating systems:

- Interrupt handlers
- Processes
- Dispatchers
- Timers
- …

… and … operating systems need to be expandible or very robust …

Thus *all* data is declared …

☞ … ***either*** local (and protected by language-, or hardware-mechanisms)

☞ … ***or*** it is 'out in the open' and all access need to be synchronized!

The need for synchronization

Synchronization: the run-time overhead?

☞ Is the potential overhead justified for simple data-structures:

```
int i;
......
i++;  {in one thread}     |     i=0; {in another thread}
```

- Are those operations atomic?
- Do we really need to introduce full featured synchronization methods here?

The need for synchronization

```
int i;
......
i++;  {in one thread}     |     i=0; {in another thread}
```

- Depending on the hardware and the compiler, it might be atomic, it might be not:

☞ Handling a 64-bit integer on a 8- or 16-bit controller *will not be atomic*
… but perhaps it is an 8-bit integer.

☞ Any manipulations on the main memory *will not be atomic*
… but perhaps it is a register.

☞ Broken down to a load-operate-store cycle, the operations *will not be atomic*
… but perhaps the processor supplies atomic operations for the actual case.

☞ Assuming that all 'perhapses' are applying: how to expand this code?

The need for synchronization

```
int i;
......
i++;  {in one thread}     |     i=0; {in another thread}
```

☞ Unfortunately: the chances that such programming errors turn out are usually small and some implicit by chance synchronization in the rest of the system might prevent them at all.

- Many effects stemming from asynchronous memory accesses are interpreted as (hardware) 'glitches', since they are rare and effect usually only some parts of the data.
- On assembler level: synchronization by employing knowledge about the atomicity of CPU-operations and interrupt structures is nevertheless possible and done frequently.

In anything higher than assembler level on small, predictable µcontrollers:

☞ Measures for synchronization are required!

Some synchronization terms:

- ***Condition synchronization:***
  synchronize a task with an event given by another task.
- ***Critical sections:***
  code fragments which contain access to shared resources and need to be executed without interference with other critical sections, sharing the same resources.
- ***Mutual exclusion:***
  protection against asynchronous access to critical sections.
- ***Atomic operations:***
  the set of operations, which atomicity is guaranteed by the underlying system (e.g. hardware).

☞ there must be a set of atomic operations to start with!

Synchronization by flags

Word-access atomicity:

Assuming that any access to a word in the system is an atomic operation:

e.g. assigning two values (not wider than the size of word) to a memory cell simultaneously:

Task 1: `x := 0;` | Task 2: `x := 5;`

will result in **either** `x = 0` **xor** `x = 5` — and no other value is ever observable.

Synchronization by flags

Assuming further that there is a shared memory area between two processes:

- A set of processes agree on a (word-size) atomic variable operating as a flag to indicate synchronization conditions.

Condition synchronization by flags

```
var Flag : boolean := false;
```

`process P1;`	`process P2;`
`statement X;`	`statement A;`
`repeat until Flag;`	`Flag := true;`
`statement Y;`	`statement B;`
`end P1;`	`end P2;`

Sequence of operations: [A | X] ➠ [B | Y]

Synchronization by flags

Assuming further that there is a shared memory between two processes:

- A set of processes agree on a (word-size) atomic variable operating as a flag to indicate synchronization conditions:

Memory flag method is ok for simple condition synchronization, but …

☞ … is not sufficient for general mutual exclusion in critical sections!

☞ … busy-waiting is required to poll the synchronization condition!

☞ More powerful synchronization operations are required for critical sections

Synchronization by semaphores

(Dijkstra 1968)

Assuming further that there is a shared memory between two processes:

- a set of processes agree on a variable `S` operating as a flag to indicate synchronization conditions … *and* …
- an atomic operation `P` on `S` — `P` stands for 'passeren' (Dutch for 'pass'):
  - `P: [if S > 0 then S := S - 1]` also: '`Wait`', '`Suspend_Until_True`'
- an atomic operation `V` on `S` — `V` stands for 'vrygeven' (Dutch for 'to release'):
  - `V: [S := S + 1]` also: '`Signal`', '`Set_True`'

☞ the variable `S` is then called a **semaphore**.

OS-level: `P` is usually also suspending the current task until `S > 0`.
CPU-level: `P` indicates whether it was successful, but the operation is not blocking.

Condition synchronization by semaphores

```
var sync : semaphore := 0;
```

```
process P1;
   statement X;

   wait (sync);

   statement Y;
end P1;
```

```
process P2;
   statement A;

   signal (sync);

   statement B;
end P2;
```

Sequence of operations: [A | X] ➟ [B | Y]

Mutual exclusion by semaphores

```
var mutex : semaphore := 1;
```

```
process P1;
   statement X;

   wait (mutex);
      statement Y;
   signal (mutex);

   statement Z;
end P1;
```

```
process P2;
   statement A;

   wait (mutex);
      statement B;
   signal (mutex);

   statement C;
end P2;
```

Sequence of operations: [A | X] ➟ [B ➟ Y **xor** Y ➟ B] ➟ [C | Z]

Semaphores

Types of semaphores:

- **General semaphores (counting semaphores)**: non-negative number; (range limited by the system) `P` and `V` increment and decrement the semaphore by one.
- **Binary semaphore**s: restricted to [0, 1]; Multiple `V` (`Signal`) calls have the same effect than 1 call.
  - binary semaphores are sufficient to create all other semaphore forms.
  - atomic 'test-and-set' operations at hardware level are usually binary semaphores.
- **Quantity semaphores**: The increment (and decrement) value for the semaphore is specified as a parameter with `P` and `V`.

Semaphores in Ada95

```
package Ada.Synchronous_Task_Control is
   type Suspension_Object is limited private;
   procedure Set_True  (S : in out Suspension_Object);
   procedure Set_False (S : in out Suspension_Object);
   function Current_State (S : Suspension_Object) return Boolean;
   procedure Suspend_Until_True (S : in out Suspension_Object);
private
   … -- not specified by the language
end Ada.Synchronous_Task_Control;
```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- only one task can be blocked at `Suspend_Until_True`! ('strict version of a binary semaphore') (`Program_Error` will be raised with the second task trying to suspend itself)

☞ no queues! ☞ minimal run-time overhead

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- only one task can be blocked at `Suspend_Until_True`! (strict version of a binary semaphore) (`Program_Error` will be raised with the second task trying to suspend itself)

☞ no queues ☞ minimal run-time overhead

for very special cases only, in general:

medieval

Semaphores in POSIX

```
int sem_init      (sem_t *sem_location, int pshared, unsigned int value);
int sem_destroy   (sem_t *sem_location);

int sem_wait      (sem_t *sem_location);
int sem_trywait   (sem_t *sem_location);
int sem_timedwait (sem_t *sem_location, const struct timespec *abstime);

int sem_post      (sem_t *sem_location);

int sem_getvalue  (sem_t *sem_location, int *value);
```


Semaphores in POSIX

```
int sem_init      (sem_t *sem_location, int pshared, unsigned int value);
int sem_destroy   (sem_t *sem_location);

int sem_wait      (sem_t *sem_location);
int sem_trywait   (sem_t *sem_location);
int sem_timedwait (sem_t *sem_location, const struct timespec *abstime);

int sem_post      (sem_t *sem_location);

int sem_getvalue  (sem_t *sem_location, int *value);
```

generate semaphore for usage between processes
(otherwise for threads of the same process only)

Semaphores in POSIX

```
int sem_init      (sem_t *sem_location, int pshared, unsigned int value);
int sem_destroy   (sem_t *sem_location);

int sem_wait      (sem_t *sem_location);
int sem_trywait   (sem_t *sem_location);
int sem_timedwait (sem_t *sem_location, const struct timespec *abstime);

int sem_post      (sem_t *sem_location);

int sem_getvalue  (sem_t *sem_location, int *value);
```

delivers the number of waiting processes as a negative integer,
if there are processes waiting on this semaphore

Semaphores in POSIX

```
void allocate (priority_t P)
{
   sem_wait (&mutex);
   if (busy) {
      sem_post (&mutex);
      sem_wait (&cond[P]);
   }
   busy = 1;
   sem_post (&mutex);
}
```

```
sem_t mutex, cond[2];
typedef emun {low, high} priority_t;
int waiting
int busy
```

```
void deallocate (priority_t P)
{
   sem_wait (&mutex);
   busy = 0;
   sem_getvalue (&cond[high],
                 &waiting);
   if (waiting < 0) {
      sem_post (&cond[high]);
   }
   else {
      sem_getvalue (&cond[low],
                    &waiting);
      if (waiting < 0) {
         sem_post (&cond[low]);
      }
      else {
         sem_post (&mutex);
} } }
```

Deadlock by semaphores

```
with Ada.Synchronous_Task_Control; use Ada.Synchronous_Task_Control;
X, Y : Suspension_Object;
```

```
task B;
task body B is
begin
   …
   Suspend_Until_True (Y);
   Suspend_Until_True (X);
   …
end B;
```

```
task A;
task body A is
begin
   …
   Suspend_Until_True (X);
   Suspend_Until_True (Y);
   …
end A;
```

☞ could raise a `Program_Error` in Ada95.

☞ produces a potential **deadlock** when implemented with general semaphores.

☞ Deadlocks can be generated by all kinds of synchronization methods.

Criticism of semaphores

- Semaphores are not bound to any resource or method or region
  - ☞ Adding or deleting a single semaphore operation some place might stall the whole system
- Semaphores are scattered all over the code
  - ☞ hard to read, error-prone

☞ Semaphores are considered not adequate for complex systems.

(all concurrent and real-time languages offer more abstract and safer synchronization methods).

Conditional critical regions

Basic idea:

- Critical regions are *a set of code sections in different processes*, which are guaranteed to be ***executed in mutual exclusion***:
  - Shared data structures are grouped in named regions and are tagged as being private resources.
  - Processes are prohibited from entering a critical region, when another process is active in any associated critical region.
- ***Condition synchronisation*** is provided by *guards*:
  - When a process wishes to enter a critical region it evaluates the guard (under mutual exclusion). If the guard evaluates false, the process is suspended / delayed.
- As with semaphores, no access order can be assumed.

Conditional critical regions

```
buffer : buffer_t;
resource critical_buffer_region : buffer;
```

```
process producer;
   loop
      region critical_buffer_region
         when buffer.size < N do
            -- place in buffer etc.
      end region
   end loop;
end producer
```

```
process consumer;
   loop
      region critical_buffer_region
         when buffer.size > 0 do
            -- take from buffer etc.
      end region
   end loop;
end consumer
```

Criticism of conditional critical regions

- All guards need to be re-evaluated, when any conditional critical region is left:
  - ☞ all involved processes are activated to test their guards
  - ☞ there is no order in the re-evaluation phase ☞ potential livelocks
- As with semaphores the conditional critical regions are scattered all over the code.
  - ☞ on a larger scale: same problems as with semaphores.

The language Edison uses conditional critical regions
for synchronization in a multiprocessor environment
(each process is associated with exactly one processor).

Monitors

(Modula-1, Mesa — Dijkstra, Hoare)

Basic idea:

- Collect all operations and data-structures shared in critical regions in one place, the monitor.
- Formulate all operations as procedures or functions.
- Prohibit access to data-structures, other than by the monitor-procedures.
- Assure mutual exclusion of the monitor-procedures.

Monitors

```
monitor buffer;
   export append, take;
   var (* declare protected vars *)
   procedure append (I : integer);
      …
   procedure take (var I : integer);
      …
begin
   (* initialisation *)
end;
```

How to realize conditional synchronization?

Monitors with condition synchronization

(Hoare)

Hoare-monitors:

- Condition variables are implemented by semaphores (`Wait` and `Signal`).
- Queues for tasks suspended on condition variables are realized.
- A suspended task releases its lock on the monitor, enabling another task to enter.

☞ More efficient evaluation of the guards:
the task leaving the monitor can evaluate all guards and the right tasks can be activated.

☞ Blocked tasks may be ordered and livelocks prevented.

Monitors with condition synchronization

```
monitor buffer;
   export append, take;
   var BUF                       : array [ … ] of integer;
   top, base                     : 0..size-1;
   NumberInBuffer                : integer;
   spaceavailable, itemavailable : condition;

   procedure append (I : integer);
      begin
         if NumberInBuffer = size then

            wait (spaceavailable);

         end if;
         BUF[top] := I; NumberInBuffer := NumberInBuffer+1;
         top := (top+1) mod size;

         signal (itemavailable)

      end append;    …
```


Monitors with condition synchronization

```
…
   procedure take (var I : integer);
      begin
         if NumberInBuffer = 0 then

            wait (itemavailable);

         end if;
         I := BUF[base];
         base := (base+1) mod size;
         NumberInBuffer := NumberInBuffer-1;

         signal (spaceavailable);

      end take;
begin (* initialisation *)
   NumberInBuffer := 0;
   top := 0; base := 0
end;
```

The signalling and the waiting process are both active in the monitor!

Monitors with condition synchronization

Suggestions to overcome the multiple-tasks-in-monitor-problem:

- A `signal` is allowed **only as the last action** of a process before it leaves the monitor.
- A `signal` operation has the side-effect of **executing a `return`** statement.
- Hoare, Modula-1, POSIX: a `signal` operation which unblocks another process has the side-effect of **blocking the current process**; this process will only execute again once the monitor is unlocked again.
- A `signal` operation which unblocks a process does not block the caller, but the unblocked process must **gain access to the monitor again**.

Monitors in Modula-1

- `wait (s, r)`:
  delays the caller until condition variable `s` is true (`r` is the rank (or 'priority') of the caller).
- `send (s)`:
  If a process is waiting for the condition variable `s`,
  then the process at the top of the queue of the highest filled rank is activated
  (and the caller suspended).
- `awaited (s)`:
  check for waiting processes on `s`.

Monitors in Modula-1

```
INTERFACE MODULE resource_control;

   DEFINE allocate, deallocate;
   VAR busy : BOOLEAN; free : SIGNAL;

   PROCEDURE allocate;
   BEGIN
      IF busy THEN WAIT (free) END;
      busy := TRUE;
   END;

   PROCEDURE deallocate;
   BEGIN
      busy := FALSE;
      SEND (free); -- or: IF AWAITED (free) THEN SEND (free);
   END;

BEGIN
   busy := false;
END.
```


Monitors in 'C' / POSIX

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init     (       pthread_mutex_t     *mutex,
                             const pthread_mutexattr_t *attr);
int pthread_mutex_destroy  (       pthread_mutex_t     *mutex);

int pthread_cond_init      (       pthread_cond_t      *cond,
                             const pthread_condattr_t  *attr);
int pthread_cond_destroy   (       pthread_cond_t      *cond);
…
```


Monitors in 'C' / POSIX

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init     (
                             const
int pthread_mutex_destroy  (

int pthread_cond_init      (
                             const
int pthread_cond_destroy   (
…
```

Attributes include:

- semantics for trying to lock a mutex which is locked already by the same thread
- sharing of mutexes and condition variables between processes
- priority ceiling
- clock used for timeouts
- … … …

Monitors in 'C' / POSIX

(types and creation)

Synchronization between POSIX-threads:

```
typedef … pthread_mutex_t;
typedef … pthread_mutexattr_t;
typedef … pthread_cond_t;
typedef … pthread_condattr_t;

int pthread_mutex_init     (       pthread_mutex_t     *mutex,
int pthread_mutex_destroy  (
int pthread_cond_init      (
int pthread_cond_destroy   (
…
```

Undefined, if locked

Undefined, if threads are waiting

Monitors in 'C' / POSIX

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t     *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t     *mutex);
int pthread_mutex_timedlock (       pthread_mutex_t     *mutex,
                             const struct timespec      *abstime);
int pthread_mutex_unlock    (       pthread_mutex_t     *mutex);
int pthread_cond_wait       (       pthread_cond_t      *cond,
                                    pthread_mutex_t     *mutex);
int pthread_cond_timedwait  (       pthread_cond_t      *cond,
                                    pthread_mutex_t     *mutex,
                             const struct timespec      *abstime);
int pthread_cond_signal     (       pthread_cond_t      *cond);
int pthread_cond_broadcast  (       pthread_cond_t      *cond);
```


Monitors in 'C' / POSIX

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t     *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t     *mutex);
int pthread_mutex_timedlock (       pthread_mutex_t     *mutex,
                             const struct timespec      *abstime);
int pthread_mutex_unlock    (       pthread_mutex_t     *mutex);
int pthread_cond_wait       (       p
                                    p
int pthread_cond_timedwait  (       p
                                    p
                             const s
int pthread_cond_signal     (       pthread_cond_t      *cond);
int pthread_cond_broadcast  (       pthread_cond_t      *cond);
```

unblocking 'at least one' thread

unblocking all threads

Monitors in 'C' / POSIX

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t     *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t     *mutex);
int pthread_mutex_timedlock (       pthr
                             const stru
int pthread_mutex_unlock    (       pthr
int pthread_cond_wait       (       pthr
                                    pthr
int pthread_cond_timedwait  (       pthr
                                    pthread_mutex_t     *mutex,
                             const struct timespec      *abstime);
int pthread_cond_signal     (       pthread_cond_t      *cond);
int pthread_cond_broadcast  (       pthread_cond_t      *cond);
```

undefined,

if called out of order!

Monitors in 'C' / POSIX

(operators)

```
…
int pthread_mutex_lock      (       pthread_mutex_t     *mutex);
int pthread_mutex_trylock   (       pthread_mutex_t     *mutex);
int pthread_mutex_timedlock (
                             const
int pthread_mutex_unlock    (
int pthread_cond_wait       (       pthread_cond_t      *cond,
                                    pthread_mutex_t     *mutex);
int pthread_cond_timedwait  (       pthread_cond_t      *cond,
                                    pthread_mutex_t     *mutex,
                             const struct timespec      *abstime);
int pthread_cond_signal     (       pthread_cond_t      *cond);
int pthread_cond_broadcast  (       pthread_cond_t      *cond);
```

can be called any time, anywhere
(multiple lock reaction can be specified)

Monitors in 'C' / POSIX

(example, definitions)

```
#define BUFF_SIZE 10

typedef struct {
   pthread_mutex_t mutex;
   pthread_cond_t  buffer_not_full;
   pthread_cond_t  buffer_not_empty;
   int             count, first, last;
   int             buf[BUFF_SIZE];
} buffer;
```


Monitors in 'C' / POSIX

(example, operations)

```
int append (int item, buffer *B) {
   PTHREAD_MUTEX_LOCK (&B->mutex);
   while (B->count == BUFF_SIZE) {
      PTHREAD_COND_WAIT (
         &B->buffer_not_full,
         &B->mutex);
   }
   PTHREAD_MUTEX_UNLOCK (&B->mutex);
   PTHREAD_COND_SIGNAL (
      &B->buffer_not_empty);
   return 0;
}
```

```
int take (int *item, buffer *B) {
   PTHREAD_MUTEX_LOCK (&B->mutex);
   while (B->count == 0) {
      PTHREAD_COND_WAIT (
         &B->buffer_not_empty,
         &B->mutex);
   }
   PTHREAD_MUTEX_UNLOCK (&B->mutex);
   PTHREAD_COND_SIGNAL (
      &B->buffer_not_full);
   return 0;
}
```


Monitors in Java

Java provides two mechanisms to construct monitors:

- Synchronized methods and code blocks
  all methods and code blocks which are using the `synchronized` tag are mutually exclusive with respect to the addressed class.
- Notification methods: `wait`, `notify`, and `notifyAll`
  can be used only in synchronized regions and are waking any or all threads, which are waiting in the same synchronized object.

Monitors in Java

Considerations:

1. Synchronized methods and code blocks:

- In order to implement a monitor *all* methods in an object need to be synchronized.
  ☞ any other standard method can break the monitor and enter at any time.
- Methods outside the monitor-object can synchronize at this object.
  ☞ it is impossible to analyse a monitor locally, since lock accesses can exist all over the system.
- Static data is shared between all objects of a class.
  ☞ access to static data need to be synchronized over the whole class.

  Either in static synchronized blocks: `synchronized (this.getClass()) {…}`
  or in static methods: `public synchronized static` *<method>* `{…}`

Monitors in Java

Considerations:

2. Notification methods: `wait`, `notify`, and `notifyAll`

- `wait` suspends the thread and releases the local lock only
  ☞ nested `wait`-calls will keep all enclosing locks.
- `notify` and `notifyAll` does not release the lock.
  ☞ methods, which are activated via notification need to wait for lock-access.
- `wait`-suspended threads are hold in a queue (Real-time Java only!), thus `notify{All}` is waking the threads in order ☞ livelocks are prevented at this level .
- There are no explicit conditional variables.
  ☞ every notified thread needs to wait for the lock to be released **and** to re-evaluate its entry condition

Monitors in Java

(multiple-readers-one-writer-example)

each of the **readers** uses these monitor.calls:

```
startRead ();
   // read the shared data only
stopRead ();
```

each of the **writers** uses these monitor.calls:

```
startWrite ();
   // manipulate the shared data
stopWrite ();
```

☞ construct a monitor, which allows
multiple readers
or
one writer
at a time inside the critical regions

Monitors in Java

(multiple-readers-one-writer-example: wait-notifyAll method)

```
public class ReadersWriters
{
   private int     readers        = 0;
   private int     waitingWriters = 0;
   private boolean writing        = false;

…
```


Monitors in Java

(multiple-readers-one-writer-example: wait-notifyAll method)

```
…  public synchronized void StartWrite () throws InterruptedException
   {
      while (readers > 0 || writing)
      {
         waitingWriters++;
         wait();
         waitingWriters--;
      }
      writing = true;
   }

   public synchronized void StopWrite()
   {
      writing = false;
      notifyAll ();
   } …
```

Monitors in Java

(multiple-readers-one-writer-example: wait-notifyAll method)

```
…  public synchronized void StartRead () throws InterruptedException
   {
      while (writing || waitingWriters > 0)
      {
         wait();
      }
      readers++;
   }
   public synchronized void StopRead()
   {
      readers--;
      if (readers == 0) notifyAll();
   }
}
```

whenever a synchronized region is left:

- **all** thread are notified
- **all** threads are re-evaluating their guards

Monitors in Java

Standard monitor solution:

- declare the monitored data-structures private to the monitor object (non-static).
- introduce a class `ConditionVariable`:

```
public class ConditionVariable {
   public boolean wantToSleep = false;
}
```

- introduce synchronization-scopes in monitor-methods:
  ☞ synchronize on the *adequate conditional variables* ***first*** and
  ☞ synchronize on the *monitor-object* ***second.***
- make sure that ***all*** methods in the monitor are implementing the correct synchronizations.
- make sure that ***no other method*** in the whole system is synchronizing on this monitor-object.

Monitors in Java

(multiple-readers-one-writer-example: usage of external conditional variables)

```
public class ReadersWriters
{
   private int     readers        = 0;
   private int     waitingReaders = 0;
   private int     waitingWriters = 0;
   private boolean writing        = false;

   ConditionVariable OkToRead  = new ConditionVariable ();
   ConditionVariable OkToWrite = new ConditionVariable ();

…
```


Monitors in Java

```
…  public void StartWrite () throws InterruptedException
   {
      synchronized (OkToWrite)
      {
         synchronized (this)
         {
            if (writing | readers > 0) {
               waitingWriters++;
               OkToWrite.wantToSleep = true;
            } else {
               writing = true;
               OkToWrite.wantToSleep = false;
            }
         }
         if (OkToWrite.wantToSleep) OkToWrite.wait ();
   }  } …
```

Monitors in Java

```
…  public void StopWrite ()
   {
      synchronized (OkToRead)
      {
         synchronized (OkToWrite)
         {
            synchronized (this)
            {
               if (waitingWriters > 0) {
                  waitingWriters--;
                  OkToWrite.notify (); // wakeup one writer
               } else {
                  writing = false;
                  OkToRead.notifyAll (); // wakeup all readers
                  readers = waitingReaders;
                  waitingReaders = 0;
               }
   }  }  }  } …
```


Monitors in Java

```
…  public void StartRead () throws InterruptedException
   {
      synchronized (OkToRead)
      {
         synchronized (this)
         {
            if (writing | waitingWriters > 0) {
               waitingReaders++;
               OkToRead.wantToSleep = true;
            } else {
               readers++;
               OkToRead.wantToSleep = false;
            }
         }
         if (OkToRead.wantToSleep) OkToRead.wait ();
   }  } …
```


Monitors in Java

```
…  public void StopRead ()
   {
      synchronized (OkToWrite)
      {
         synchronized (this)
         {
            readers--;
            if (readers == 0 & waitingWriters > 0) {
               waitingWriters--;
               OkToWrite.notify ();
            }
         }
      }
   }
}
```


Object-orientation and synchronization

Since mutual exclusion, notification, and condition synchronization schemes need to be designed and analysed considering the implementation of all involved methods and guards:

☞ new methods cannot be added without re-evaluating the whole class!

In opposition to the general re-usage idea of object-oriented programming,
the re-usage of synchronized classes (e.g. monitors) need to be considered carefully.

☞ The parent class might need to be adapted in order to suit the global synchronization scheme.

☞ Inheritance anomaly (Matsuoka & Yonezawa '93)

Methods to design and analyse expandible synchronized systems exist,
but are fairly complex and are not provided in any current object-oriented language.

Monitors in POSIX & Java

☞ flexible and universal,
but relies on conventions rather than compilers

POSIX offers conditional variables

Java is more supportive than POSIX
in terms of data-encapsulation

Extreme care must be taken when employing
object-oriented programming and monitors

Nested monitor calls

Assuming a thread in a monitor is calling an operation in another monitor
and is suspended at a conditional variable there:

☞ the called monitor is aware of the suspension and allows other threads to enter.

☞ the calling monitor is possibly *not aware* of the suspension and **keeps its lock!**

☞ the unjustified locked calling monitor
reduces the system performance and leads to potential deadlocks.

Suggestions to solve this situation:

- Maintain the lock anyway: e.g. POSIX, Real-time Java
- Prohibit nested procedure calls: e.g. Modula-1
- Provide constructs which specify the release of a monitor lock for remote calls, e.g. Ada95

Criticism of monitors

- Mutual exclusion is solved elegantly and safely.
- Conditional synchronization is on the level of semaphores still
  ☞ all criticism on semaphores apply

☞ mixture of low-level and high-level synchronization constructs.

Synchronization by protected objects

Combine

- the **encapsulation** feature of monitors

with

- the **coordinated entries** of conditional critical regions

to

☞ Protected objects

- *all* controlled data and operations are encapsulated
- *all* operations are mutual exclusive
- entry guards are *attached* to operations
- the protected interface allows for operations on data
- no protected data is accessible (other than by defined operations)
- tasks are queued (according to their priorities)

Synchronization by protected objects in Ada95

(simultaneous read-access)

Some read-only operations *do not need to be mutual exclusive*:

```
protected type Shared_Data (Initial : Data_Item) is
   function  Read return Data_Item;
   procedure Write (New_Value : in Data_Item);
private
   The_Data : Data_Item := Initial;
end Shared_Data_Item;
```

- protected *functions* can have 'in' parameters only and are not allowed to alter the private data (enforced by the compiler).

☞ protected functions allow **simultaneous access** (but mutual exclusive with other operations).

- there is no defined priority between functions and other protected operations in Ada95.

Synchronization by protected objects in Ada95

Condition synchronization is realized in the form of protected procedures combined with boolean conditional variables (**barriers**): ☞ **entries** in Ada95:

```
Buffer_Size : constant Integer := 10;
type     Index    is mod Buffer_Size;
subtype  Count    is Natural range 0 .. Buffer_Size;
type     Buffer_T is array (Index) of Data_Item;
protected type Bounded_Buffer is
   entry Get (Item : out Data_Item);
   entry Put (Item : in Data_Item);
private
   First  : Index := Index'First;
   Last   : Index := Index'Last;
   Num    : Count := 0;
   Buffer : Buffer_T;
end Bounded_Buffer;
```


Synchronization by protected objects in Ada95

(barriers)

```
protected body Bounded_Buffer is
   entry Get (Item : out Data_Item) when Num > 0 is
      begin
         Item  := Buffer (First);
         First := First + 1;
         Num   := Num - 1;
      end Get;
   entry Put (Item : in Data_Item) when Num < Buffer_Size is
      begin
         Last           := Last + 1;
         Buffer (Last) := Item;
         Num            := Num + 1;
      end Put;
end Bounded_Buffer;
```


Synchronization by protected objects in Ada95

Protected entries are used like task entries:

```
Buffer : Bounded_Buffer;
```

```
select
   Buffer.Put (Some_Data);
or
   delay 10.0;
      -- do something after 10 s.
end select;
```

```
select
   delay 10.0;
then abort
   Buffer.Put (Some_Data);
      -- try to enter for 10 s.
end select;
```

```
select
   Buffer.Get (Some_Data);
else
   -- do something else
end select;
```

```
select
   Buffer.Get (Some_Data);
then abort
   -- meanwhile try something else
end select;
```

Synchronization by protected objects in Ada95

(barrier evaluation)

Barrier evaluations and task activations:

- on ***calling a protected entry***, the associated barrier is evaluated (only those parts of the barrier which might have changed since the last evaluation).
- on ***leaving a protected procedure or entry***, related barriers with tasks queued are evaluated (only those parts of the barriers which might have been altered by this procedure / entry or which might have changed since the last evaluation).

Barriers are not evaluated *while inside* a protected object or *on leaving a protected function*.

Synchronization by protected objects in Ada95

(operations on entry queues)

The `count` attribute indicate the number of tasks waiting at a specific queue:

```
protected Blocker is
   entry Proceed;
private
   Release : Boolean := False;
end Blocker;
```

```
protected body Blocker is
   entry Proceed
      when Proceed'count = 5
        or Release is
   begin
      Release := Proceed'count > 0;
   end Proceed;
end Blocker;
```


Synchronization by protected objects in Ada95

(operations on entry queues)

The `count` attribute indicate the number of tasks waiting at a specific queue:

```
protected type Broadcast is
   entry Receive  (M: out Message);
   procedure Send (M: in  Message);
private
   New_Message : Message;
   Arrived     : Boolean := False;
end Blocker;
```

```
protected body Broadcast is
   entry Receive (M: out Message)
      when Arrived is
   begin
      M := New_Message
      Arrived := Receive'count > 0;
   end Proceed;
   procedure Send (M: in  Message) is
   begin
      New_Message := M;
      Arrived := Receive'count > 0;
   end Send;
end Blocker;
```


Synchronization by protected objects in Ada95

(entry families, requeue & private entries)

Further refinements on task control by:

- ***Entry families***:
  a protected entry declaration can contain a discrete subtype selector, which can be evaluated by the barrier (other parameters cannot be evaluated by barriers) and implements an array of protected entries.
- ***Requeue facility***:
  protected operations can use '`requeue`' to redirect tasks to other internal, external, or private entries. The current protected operation is finished and the lock on the object is released.

  '***Internal progress first*'*-rule***: internally requeued tasks are placed at the **head** of the waiting queue!
- ***Private entries***:
  protected entries which are not accessible from outside the protected object, but can be employed as destinations for requeue operations.

Synchronization by protected objects in Ada95

(requeue & private entries)

How to implement a queue, at which every task can be released only once per triggering event?

```
package Single_Release is
   entry     Wait;
   procedure Trigger;
end Single_Release;
```


Synchronization by protected objects in Ada95

(requeue & private entries)

How to implement a queue, at which every task can be released only once per triggering event?

☞ e.g. by employing a second (private) entry:

```
package Single_Release is
   entry     Wait;
   procedure Trigger;
private
   Front_Door,
   Main_Door  : Boolean := False;
   entry Queue;
end Single_Release;
```


Synchronization by protected objects in Ada95

(requeue & private entries)

```
package body Single_Release is
   entry Wait
      when Front_Door is
      begin
         if Wait'Count = 0 then
            Front_Door := False;
            Main_Door  := True;
         end if;
         requeue Queue;
      end Wait;

   entry Queue
      when Main_Door is
      begin
         if Queue'count = 0 then
            Main_Door := False;
         end if;;
      end Queue;
   procedure Trigger is
      begin
         Front_Door := True;
      end Trigger;
end Single_Release;
```

opening the main door before requeuing?

Synchronization by protected objects in Ada95

(restrictions applying to protected operations)

Code inside a protected procedure, function or entry is bound to non-blocking operations (which would keep the whole protected object locked).

Thus the following operations are prohibited:

- entry call statements
- delay statements
- task creations or activations
- calls to sub-programs which contains a potentially blocking operation
- select statements
- accept statements

☞ The `requeue` facility allows for a potentially blocking operation, but releases the current lock!

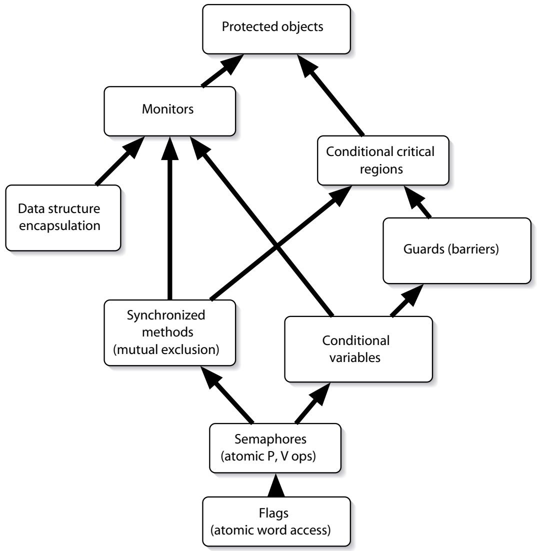
Summary

Shared memory based synchronization

General

Criteria:

- level of abstraction
- centralized vs. distributed concepts
- support for consistency and correctness validations
- error sensitivity
- predictability
- efficiency

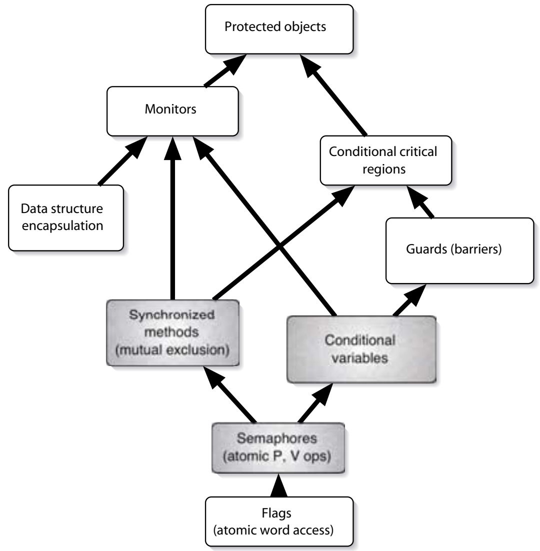


Summary

Shared memory based synchronization

POSIX

- all low level constructs available.
- no connection with the actual data-structures.
- error-prone.
- non-determinism introduced by 'release some' semantics of conditional variables (cond_signal).

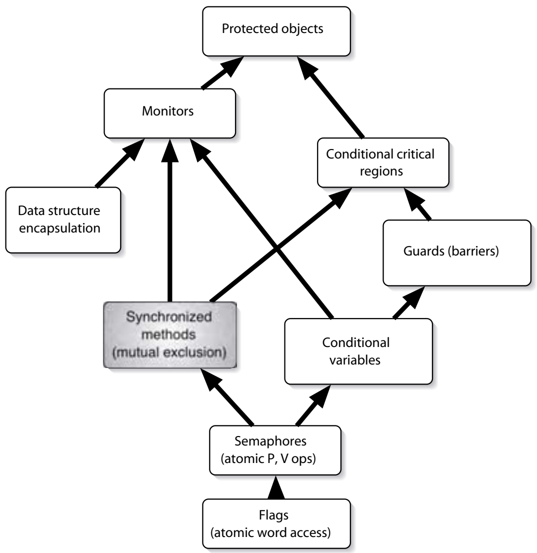


Summary

Shared memory based synchronization

Java

- mutual exclusion (synchronized methods) as the only support.
- general notification feature (no conditional variables)
- non-restricted object oriented extension introduces hard to predict timing behaviours.



Summary

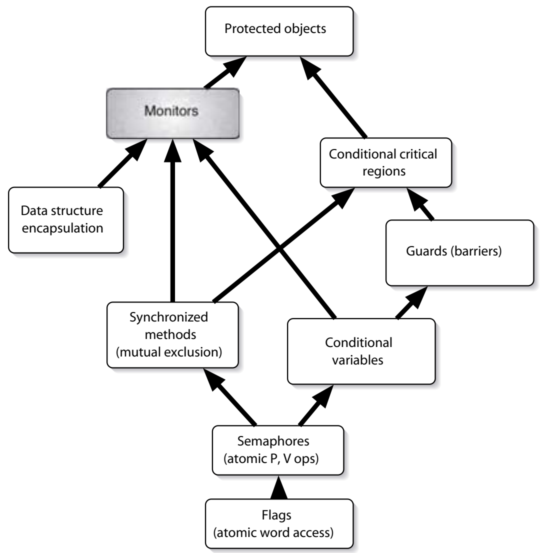
Shared memory based synchronization

Modula-1, CHILL

- full monitor implementation (Dijkstra-Hoare monitor concept).

… no more, no less, …

☞ all features of and criticism about monitors apply.



Summary

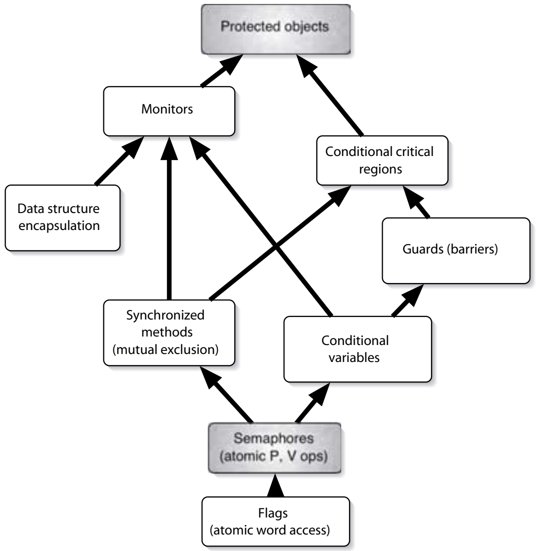
Shared memory based synchronization

Ada95

- complete synchronization support
- low-level semaphores for very special cases.
- predictable timing (☞ scheduler).

☞ most memory oriented synchronization conditions are realized by the compiler or the run-time environment directly rather then the programmer.

(Ada95 is currently without any mainstream competitor in this field)



Synchronization

Message-based synchronization

- Synchronization model
  - Asynchronous
  - Synchronous
  - Remote invocation
- Addressing (name space)
  - direct communication
  - mail-box communication
- Message structure
  - arbitrary
  - restricted to 'basic' types
  - restricted to un-typed communications

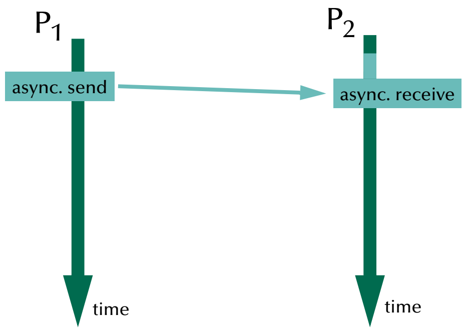
Synchronization

Message-based synchronization

Asynchronous messages

If there is a listener:

☞ send the message directly



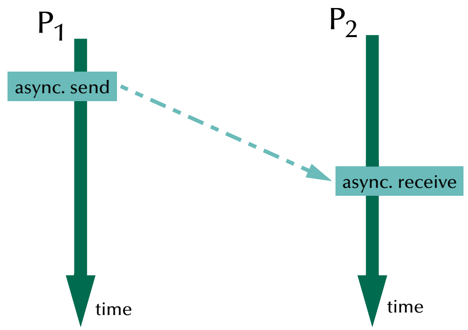
Synchronization

Message-based synchronization

Asynchronous messages

If the receiver becomes available at a later stage:

☞ the message need to be buffered

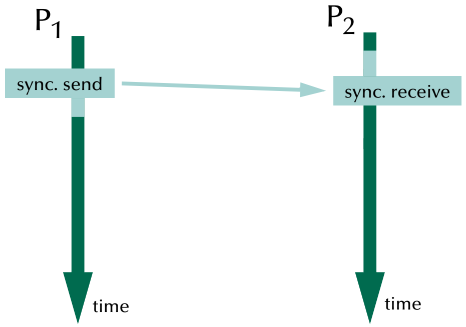


Message-based synchronization

Synchronous messages

Delay the sender:

- until the receiver got the message

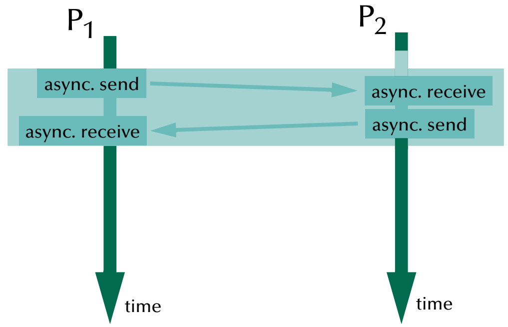


Message-based synchronization

Synchronous messages

Delay the sender:

- until the receiver got the message
- ☞ two asynchronous messages required

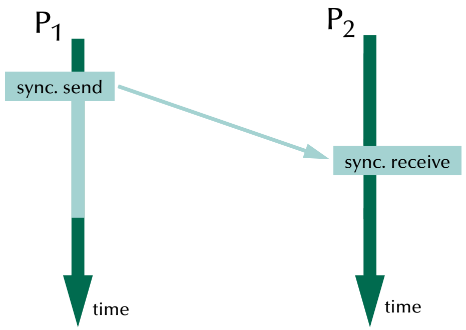


Message-based synchronization

Synchronous messages

Delay the sender until:

- a receiver is available
- a receiver got the message

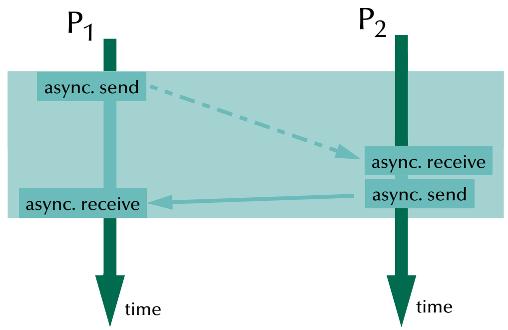


Message-based synchronization

Synchronous messages

If the receiver becomes available at a later stage:

- ☞ messages need to be buffered

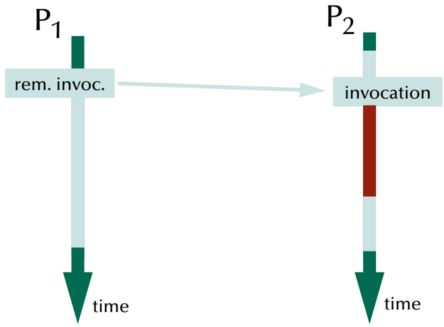


Message-based synchronization

Remote invocation

Delay the sender, until:

- a receiver got the message
- a receiver executed an addressed routine

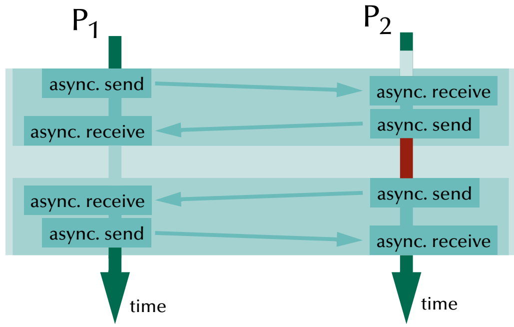


Message-based synchronization

Remote invocation

Delay the sender, until:

- a receiver got the message
- a receiver executed an addressed routine

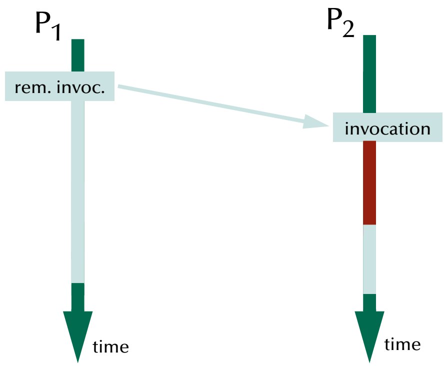


Message-based synchronization

Remote invocation

Delay the sender, until:

- a receiver becomes available
- a receiver got the message
- a receiver executed an addressed routine

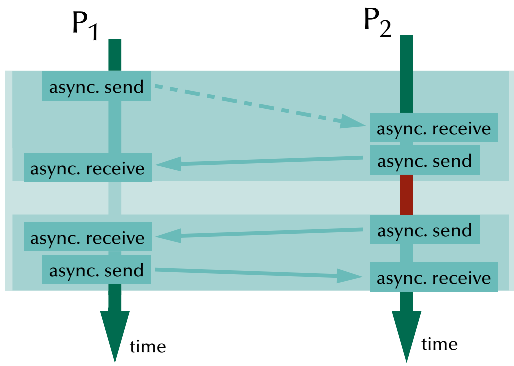


Message-based synchronization

Remote invocation

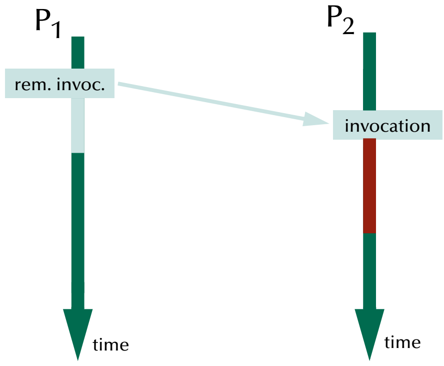
Delay the sender, until:

- a receiver becomes available
- a receiver got the message
- a receiver executed an addressed routine



Message-based synchronization

Asynchronous remote invocation

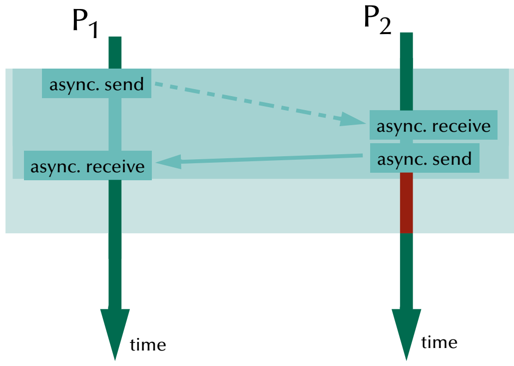


Delay the sender, until:

- a receiver becomes available
- a receiver got the message

Message-based synchronization

Asynchronous remote invocation



Delay the sender, until:

- a receiver becomes available
- a receiver got the message

Synchronous vs. asynchronous communications

Purpose '**synchronization**': ☞ synchronous messages / remote invocations
Purpose '**in-time delivery**': ☞ asynchronous messages / asynchronous remote invocations

☞ 'Real' synchronous message passing in distributed systems requires hardware support.

☞ Asynchronous message passing requires the usage of (infinite?) buffers.

- Synchronous communications are emulated by a combination of asynchronous messages in some systems.
- Asynchronous communications can be emulated in synchronized message passing systems by introducing 'buffer-tasks' (de-coupling sender and receiver as well as allowing for broadcasts).

Addressing (name space)

Direct vs. indirect:

```
send     <message> to   <process-name>
wait for <message> from <process-name>
send     <message> to   <mailbox>
wait for <message> from <mailbox>
```

Asymmetrical addressing:

```
send     <message> to …
wait for <message>
```

☞ Client-server paradigm

Addressing (name space)

Communication medium:

Connections	*Functionality*
one-to-one	buffer, queue, synchronization
one-to-many	multicast
one-to-all	broadcast
many-to-one	local server, synchronization
all-to-one	general server, synchronization
many-to-many	general network- or bus-system

Message structure

- Machine dependent representations need to be taken care of in a distributed environment.
- Communication system is often outside the typed language environment.

  Most communication systems are handling streams (packets) of a basic element type only.

☞ Conversion routines for data-structures other then the basic element type are supplied …

… manually (POSIX)
… semi-automatic (Real-time CORBA)
… automatic and are typed-persistent (Ada95)

Message structure (Ada95)

```
package Ada.Streams is
   pragma Pure (Streams);

   type Root_Stream_Type is abstract tagged limited private;

   type Stream_Element is mod implementation-defined;

   type Stream_Element_Offset is range implementation-defined;

   subtype Stream_Element_Count is
      Stream_Element_Offset range 0..Stream_Element_Offset'Last;

   type Stream_Element_Array is
      array (Stream_Element_Offset range <>) of Stream_Element;

   procedure Read  (…) is abstract;
   procedure Write (…) is abstract;

private
   … -- not specified by the language
end Ada.Streams;
```


Message structure (Ada95)

Reading and writing values of any type to a stream:

```
procedure S'Write(
   Stream : access Ada.Streams.Root_Stream_Type'Class; Item : in  T);
procedure S'Class'Write(
   Stream : access Ada.Streams.Root_Stream_Type'Class; Item : in  T'Class);

procedure S'Read(
   Stream : access Ada.Streams.Root_Stream_Type'Class; Item : out T);
procedure S'Class'Read(
   Stream : access Ada.Streams.Root_Stream_Type'Class; Item : out T'Class)
```

Reading and writing values, bounds and discriminants of any type to a stream:

```
procedure S'Output(
   Stream : access Ada.Streams.Root_Stream_Type'Class; Item : in  T);

function  S'Input(
   Stream : access Ada.Streams.Root_Stream_Type'Class) return T;
```


Message-based synchronization

Practical message-passing systems:

POSIX:	“message queues”: ☞ **ordered indirect [asymmetrical | symmetrical] asynchronous byte-level many-to-many message passing**
CHILL:	“buffers”, ”signals”: ☞ **ordered indirect [asymmetrical | symmetrical] [synchronous | asynchronous] typed [many-to-many | many-to-one] message passing**
Occam2:	“channels”: ☞ **indirect symmetrical synchronous fully-typed one-to-one message passing**
Ada95:	“(extended) rendezvous”: ☞ **ordered direct asymmetrical [synchronous | asynchronous] fully-typed many-to-one remote invocation**
Java:	no communication via messages available

Message-based synchronization

Practical message-passing systems:

	ordered	symmetrical	asymmetrical	synchronous	asynchronous	direct	indirect	contents	one-to-one	many-to-one	many-to-many	method
POSIX:	*	*	*		*		*	**bytes**			*	**message passing**
CHILL:	*	*	*	*	*		*	**typed**		*	*	**message passing**
Occam2:		*		*			*	**fully typed**	*			**message passing**
Ada95:	*		*	*	*	*		**fully typed**		*		**remote invocation**
Java:	no communication via messages available											

Message-based synchronization in Occam2

Communication is ensured by means of a ‘channel’, which:

- can be used by one writer and one reader process only
- and is synchronous:

```
CHAN OF INT SensorChannel:
PAR
   INT reading:
   SEQ i = 0 FOR 1000
      SEQ
         -- generate reading
         SensorChannel ! reading
   INT data:
   SEQ i = 0 FOR 1000
      SEQ
         SensorChannel ? data
         -- employ data
```

tasks are synchronized at these points

Message-based synchronization in CHILL

CHILL is the ‘CCITT High Level Language’,
where **CCITT** is the Comité Consultatif International Télégraphique et Téléphonique.
The CHILL language development was started in 1973 and standardized in 1979.

☞ strong support for concurrency, synchronization, and communication (monitors, buffered message passing, synchronous channels)

```
dcl SensorBuffer buffer (32) int;
…
send SensorBuffer (reading);       |       receive case
                                   |          (SensorBuffer in data) : …
                                   |       esac;
signal SensorChannel = (int) to consumertype;
…
send SensorChannel (reading)       |       receive case
   to consumer                     |          (SensorChannel in data): …
                                   |       esac;
```

Message-based synchronization in CHILL

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The CHILL language development was started in 1973 and standardized in 1979.

☞ strong support for concurrency, synchronization, and communication (monitors, buffered message passing, synchronous channels)

```
dcl SensorBuffer buffer (32) int;
…
send SensorBuffer (reading);   --- [asynchronous] --->   receive case
                                                          (SensorBuffer in data) : …
                                                          esac;

signal SensorChannel = (int) to consumertype;
…
send SensorChannel (reading)   <--- [synchronous] --->   receive case
    to consumer                                           (SensorChannel in data): …
                                                          esac;
```


Message-based synchronization in Ada95

Ada95 supports remote invocations ((extended) rendezvous) in form of:

- **entry points** in tasks
- **full set of parameter profiles** supported

If the local and the remote task are on different architectures,
or if an intermediate communication system is employed:

☞ parameters incl. bounds and discriminants are 'tunnelled' through byte-stream-formats.

Synchronization:

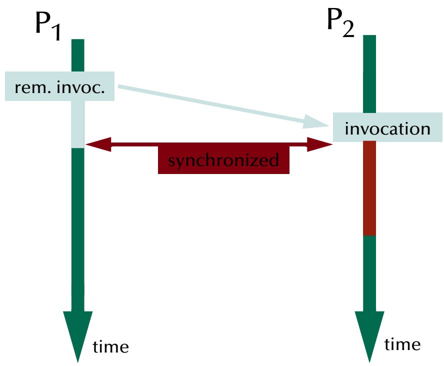
- both tasks are synchronized at the beginning of the remote invocation (☞ '**rendezvous**')
- the calling task if blocked until the remote routine is completed (☞ '**extended rendezvous**')

Message-based synchronization in Ada95

Remote invocation
(Rendezvous)

Delay the sender, until:

- a receiver becomes available
- a receiver got the message
- a receiver started an addressed routine

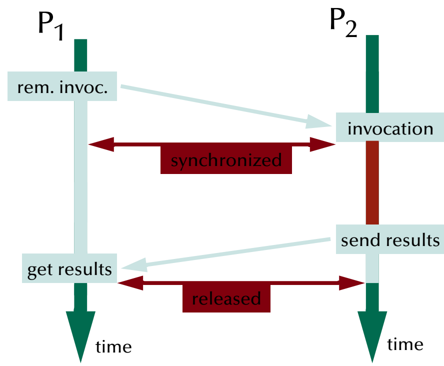


Message-based synchronization in Ada95

Remote invocation
(Extended rendezvous)

Delay the sender, until:

- a receiver becomes available
- a receiver got the message
- a receiver executed an addressed routine
- a receiver passed the results



Message-based synchronization in Ada95

(Rendezvous)

```
…                                            …
<entry_name> [(index)] <parameters>          …
… -- waiting for synchronization             …
… --                                         …
… --                                         …
… -- <----- synchronized ------------------> accept <entry_name> [(index)]
…                                                       <parameter_profile>;
…                                            …
…                                            …
…                                            …
…                                            …
                                             …
```


Message-based synchronization in Ada95

(Rendezvous)

```
…                                            …
…                                            accept <entry_name> [(index)]
…                                                       <parameter_profile>;
…                                            … -- waiting for synchronization
…                                            … --
<entry_name> [(index)] <parameters> <------- … --- synchronized --------->
…                                            …
…                                            …
…                                            …
…                                            …
```


Message-based synchronization in Ada95

(Extended rendezvous)

```
…                                            …
<entry_name> [(index)] <parameters>          …
… -- waiting for synchronization             …
… --                                         …
… --                                         …
… -- <----- synchronized ------------------> accept <entry_name> [(index)]
      … --                                              <parameter_profile> do
      … -- blocked                              … --
      … --                                      … -- remote invocation
      … --                                      … --
… <------- return results ------------------ end <entry_name>;
                                             …
```


Message-based synchronization in Ada95

(Extended rendezvous)

```
…                                            …
…                                            accept <entry_name> [(index)]
…                                                       <parameter_profile> do
…                                            … -- waiting for synchronization
…                                            … --
<entry_name> [(index)] <parameters> <------- … --- synchronized --------->
      … --                                      … --
      … -- blocked                              … --
      … --                                      … -- remote invocation
      … --                                      … --
… <------- return results ------------------ end <entry_name>;
                                             …
```

Message-based synchronization in Ada95

Some things to consider for task-entries:

- In contrast to protected-object-entries, task-entries *can* call other blocking operations.
- Accept statements can be nested (but need to be different).

  ☞ helpful e.g. to synchronize more than two tasks.
- Accept statements can have a dedicated exception handler (like any other code-block).

  Exceptions, which are not handled during the rendezvous phase are propagated to *all* involved tasks.
- Parameters cannot be direct '`access`' parameters, but can be access-types.

Message-based synchronization in Ada95

Some things to consider for task-entries:

- In contrast to protected-object-entries, task-entries *can* call other blocking operations.
- Accept statements can be nested (but need to be different).

  ☞ helpful e.g. to synchronize more than two tasks.
- Accept statements can have a dedicated exception handler (like any other code-block).

  Exceptions, which are not handled during the rendezvous phase are propagated to *all* involved tasks.
- Parameters cannot be direct '`access`' parameters, but can be access-types.
- `'count` on task-entries is defined, but is only accessible from inside the tasks owning the entry.
- **Entry families** (arrays of entries) are supported.
- **Private entries** (accessible for internal tasks) are supported.

Selective waiting

Dijkstra's guarded commands:

```
if x <= y -> m := x
❑ x >= y -> m := y
fi
```

selection is non-deterministic!

☞ the programmer needs to design the alternatives as 'parallel' options: all cases need to be covered and overlapping conditions need to lead to the same result

Extremely different philosophy: 'C'-switch:

```
switch (x) {
   case 1: r := 3;
   case 2: r := 2; break;
   case 3: r := 1;
}
```

☞ the sequence of alternatives has a crucial role.

Message-based selective synchronization in Ada95

Forms of selective waiting:

```
select_statement ::= selective_accept          |
                     conditional_entry_call    |
                     timed_entry_call          |
                     asynchronous_select
```

... underlying concept: Dijkstra's guarded commands

`selective_accept` implements ...

- ... wait for more than a single rendezvous at any one time
- ... time-out if no rendezvous is forthcoming within a specified time
- ... withdraw its offer to communicate if no rendezvous is available immediately
- ... terminate if no clients can possibly call its entries

Message-based selective synchronization in Ada95

`selective_accept` in its full syntactical form in Ada95:

```
selective_accept ::= select
                         [guard] selective_accept_alternative
                     { or    [guard] selective_accept_alternative
                     [ else sequence_of_statements ]
                     end select;

guard ::= when <condition> =>

selective_accept_alternative ::= accept_alternative     |
                                 delay_alternative      |
                                 terminate_alternative

accept_alternative    ::= accept_statement [ sequence_of_statements ]
delay_alternative     ::= delay_statement [ sequence_of_statements ]
terminate_alternative ::= terminate;
```


Basic forms of selective synchronization

(select-or)

```
select
   accept … do …
   end …
or
   accept … do …
   end …
or
   accept … do …
   end …
or
   accept … do …
   end …
…
end select;
```

- If none of the named entries have been called, the task is suspended until one of the entries is addressed by another task.
- The selection of an accept is non-deterministic, in case that multiple entries are called.
- ☞ The selection can be controlled by means of the real-time systems annex.
- The select statement is completed, when at least one of the entries has been called and those accept-block has been executed.

Basic forms of selective synchronization

(guarded select-or)

```
select
   when <condition> =>
      accept … do …
      end …
or
   when <condition> =>
      accept … do …
      end …
or
   when <condition> =>
      accept … do …
      end …
…
end select;
```

- Analogue to Dijkstra's guarded commands
- all accepts closed will raise a Program_Error
- ☞ set of conditions need to be complete

Basic forms of selective synchronization

(guarded select-or-else)

```
select
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      accept … do …
      end …
else
   <statements>
…
end select;
```

- If none of the open entries can be accepted immediately, the else alternative is selected.
- There can be only one else alternative and it cannot be guarded.

Synchronization

Basic forms of selective synchronization

(guarded select-or-delay)

```
select
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      delay …
      <statements>
or
   [ when <condition> => ]
      delay …
      <statements>
…
end select;
```

- If none of the open entries has been called before the amount of time specified in the earliest open delay alternative, this delay alternative is selected.
- There can be multiple delay alternatives if more than one delay alternative expires simultaneously, either one may be chosen.
- `delay` and `delay until` can be employed.

Synchronization

Basic forms of selective synchronization

(guarded select-or-terminate)

```
select
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      terminate;
…
end select;
```

The terminate alternative is chosen if none of the entries can ever be called again, i.e.:

- all tasks which can possibly call any of the named entries are terminated.

or

- all remaining active tasks which can possibly call any of the named entries are waiting on selective terminate statements and none of their open entries can be called any longer.

☞ This task and all its dependent waiting-for-termination tasks are terminated together.

Synchronization

Basic forms of selective synchronization

(guarded select-or-else select-or-delay select-or-terminate)

```
select

or

else
   <statements>
…
end select;
```

`else` - `delay` - `terminate` alternatives cannot be mixed!

```
select
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      delay …
      <statements>
…
end select;

select
   [ when <condition> => ]
      accept … do …
      end …
or
   [ when <condition> => ]
      terminate;
…
end select;
```


Synchronization

Non-determinism in selective synchronizations

☞ If equal alternatives are given, then the program correctness (incl. the timing specifications) must not be affected by the actual selection.

- If alternatives have different priorities, this can be expressed e.g. by means of the Ada real-time annex.

- Non-determinism in concurrent systems is or can be also introduced by:
  - non-ordered monitor or other queues
  - buffering / routing message passing systems
  - non-deterministic schedulers
  - timer quantization
  - … any form of asynchronism

Conditional & timed entry-calls

```
conditional_entry_call ::=
   select
      entry_call_statement
      [sequence_of_statements]
   else
      sequence_of_statements
   end select;
```

```
timed_entry_call ::=
   select
      entry_call_statement
      [sequence_of_statements]
   or
      delay_alternative
   end select;
```

```
select
   Light_Monitor.Wait_for_Light;
   Lux := True;
else
   Lux := False;
end;
```

```
select
   Controller.Request (Medium)
      (Some_Item);
   -- process data
or
   delay 45.0;
   -- try something else
end select;
```


Conditional & timed entry-calls

```
conditional_entry_call ::=
   select
      entry_call_statement
      [sequence_of_statements]
   else
      sequence_of_statements
   end select;
```

```
timed_entry_call ::=
   select
      entry_call_statement
      [sequence_of_statements]
   or
      delay_alternative
   end select;
```

```
select
   Light_Monitor.Wait_for_
   Lux := True;
else
   Lux := False;
end;
```

There is only
one entry call
and either
one '`else`'
or
one '`or delay`'

```
ler.Request (Medium)
e_Item);
ess data
5.0;
something else
end select;
```


Conditional & timed entry-calls

```
conditional_entry_call ::=
   select
      entry_call_statement
      [sequ
   else
      seque
   end sele
```

```
timed_entry_call ::=
   select
      entry_call_statement
      [sequence_of_statements]
```

The idea in both cases is to ***withdraw a synchronization request*** and *not* to implement polling or busy-waiting.

```
select
   Light_Monitor.Wait_for_Light;
   Lux := True;
else
   Lux := False;
end;
```

```
select
   Controller.Request (Medium)
      (Some_Item);
   -- process data
or
   delay 45.0;
   -- try something else
end select;
```


Synchronization

- **Shared memory based synchronization**
  - Flags, condition variables, semaphores, …
    … conditional critical regions, monitors, protected objects.
  - Guard evaluation times, nested monitor calls, deadlocks, …
    … simultaneous reading, queue management.
  - Synchronization and object orientation, blocking operations and re-queuing.
- **Message based synchronization**
  - Synchronization models, addressing modes, message structures
  - Selective accepts, selective calls
  - Indeterminism in message based synchronization

Deadlocks

Synchronization may lead to

☞ *DEADLOCKS*

… a closer look on deadlocks
and what can be done about them …

Deadlocks

Reserving resources in reverse order

```
var reserve_1, reserve_2: semaphore := 1;

process P1;
   statement X;

   wait (reserve_1);
   wait (reserve_2);
      statement Y; - employ resources
   signal (reserve_2);
   signal (reserve_1);

   statement Z;
end P1;

process P2;
   statement A;

   wait (reserve_2);
   wait (reserve_1);
      statement B; - employ resources
   signal (reserve_1);
   signal (reserve_2);

   statement C;
end P2;
```

Sequence of operations : [A | X] ➟ {[B ➟ Y] xor [Y ➟ B]} ➟ [C | Z]
or : [A | X] ➟ deadlocked!

Deadlocks

Circular dependencies

```
var reserve_1, reserve_2, reserve_3: semaphore := 1;

process P1;
   statement X;

   wait (reserve_1);
   wait (reserve_2);
      statement Y;
   signal (reserve_2);
   signal (reserve_1);

   statement Z;
end P1;

process P2;
   statement A;

   wait (reserve_2);
   wait (reserve_3);
      statement B;
   signal (reserve_3);
   signal (reserve_2);

   statement C;
end P2;

process P3;
   statement K;

   wait (reserve_3);
   wait (reserve_1);
      statement L;
   signal (reserve_1);
   signal (reserve_3);

   statement M;
end P3;
```

Sequence of operations : [A | X | K] ➟ {[B ➟ Y ➟ L] xor …} ➟ [C | Z | M]
or : [A | X | K] ➟ deadlocked!

Deadlocks

Necessary deadlock conditions:

1. **Mutual exclusion**:
   resources cannot be used simultaneously
2. **Hold and wait**:
   a process applies for a resource, while it is holding another resource (sequential requests)
3. **No pre-emption**:
   resources cannot be pre-empted; only the process itself can release resources
4. **Circular wait**:
   a ring list of processes exists, where every process waits for release of a resource by the next one

☞ system may be deadlocked, when ***all*** these conditions apply!

Deadlock strategies:

1. Ignorance
   ☞ Kill unresponsive processes
2. Deadlock detection & recovery
   ☞ find deadlocked processes and recover the system in a coordinated way
3. Deadlock avoidance
   ☞ the resulting system state is checked before any resources are actually assigned
4. Deadlock prevention
   ☞ the system prevents deadlocks by its structure

Deadlock prevention

(remove one of the four deadlock conditions)

1. **Mutual exclusion**:
   Applicable to specific cases only; usually this can only be removed by replication of resources.
2. **Hold and wait**:
   Processes are forced to allocate all their required resources at once,
   often at the time of admittance to the main dispatcher – done in many static realtime-systems.
3. **No pre-emption**:
   If the current state of a resource can be stored and restored easily, then they can be pre-empted.
   Usually resources are pre-empted from processes, which are currently not ready to run.
4. **Circular wait**:
   A circular wait can be avoided by a global ordering of all resources, e.g. resources can only be requested in a specific order – hard to maintain in a dynamic system configuration.

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

$RAG = \{V, E\}$; vertices and edges

$V = P \cup R$; vertices are processes or resource types:

$P = \{P_1, P_2, \ldots, P_n\}$; processes

$R = \{R_1, R_2, \ldots R_k\}$; resource types

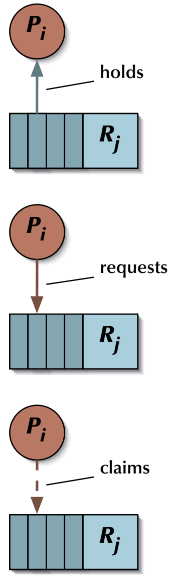
$E = E_r \cup E_a \cup E_c$; claims, requests and assignments

$E_c = \{P_i \to R_j, \ldots\}$; claims

$E_r = \{P_i \to R_j, \ldots\}$; requests

$E_a = \{R_i \to P_j, \ldots\}$; assignments

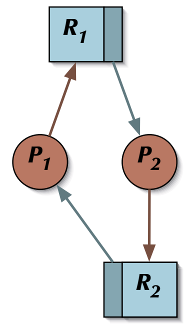
Note: a resourcefully may have more than one instance



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

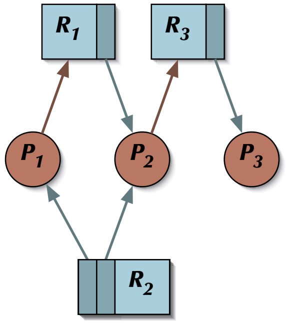
the two process, reverse allocation deadlock:



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

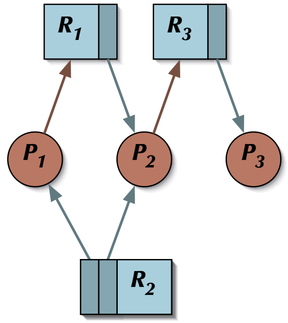
Is this a deadlock situation? ☞



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

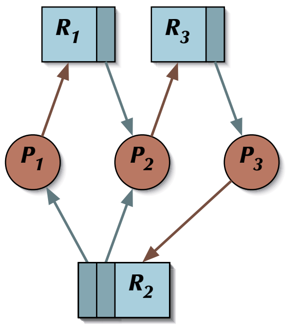
no, there is no circular dependency



Resource Allocation Graphs

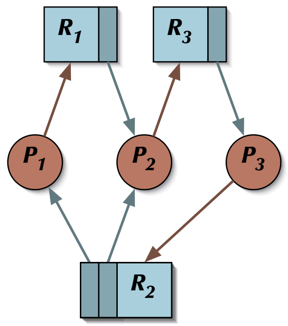
(Silberschatz, Galvin & Gagne)

Is this a deadlock situation? ☞



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



yes, there are circular dependencies:

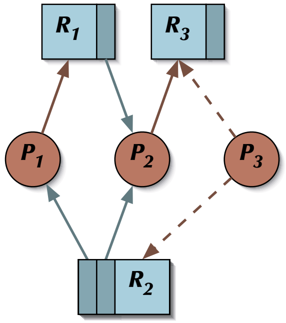
$P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

as well as: $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

☞ ***IF some processes are deadlocked, THEN there are cycles in the resource allocation graph***

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

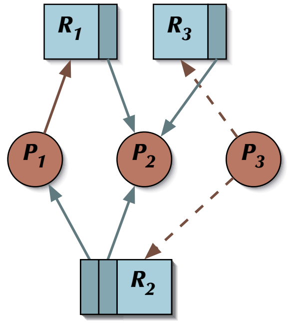


Assuming all claims of P_3 are known in advance,

☞ Could the deadlock situation be avoided?

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

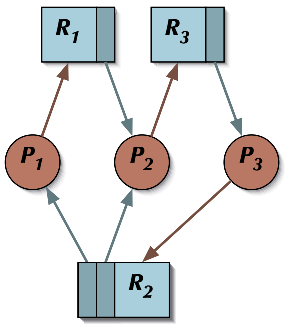


yes, when resources are assigned so that there are no resulting circular dependencies:

☞ in this case: assign R_3 to P_2 (instead of P_3)

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



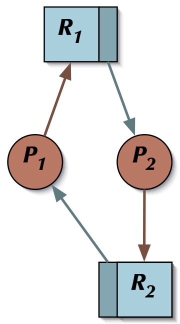
$P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

as well as: $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

☞ ***ARE some processes deadlocked, IF there are cycles in the resource allocation graph?***

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

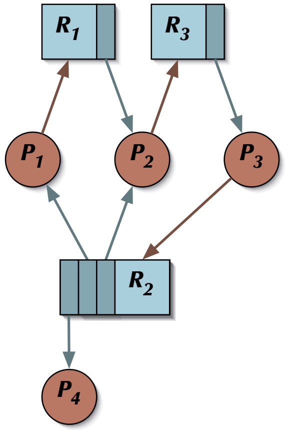


yes,
if there is only one instance per resource type:

☞ ***IF there are cycles in the resource allocation graph AND there is only one instance per resource type, THEN some processes are deadlocked!***

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

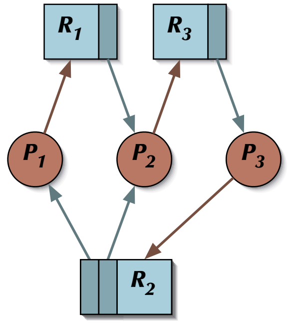


no,
if there is more than one instance
per resource type:

☞ ***IF there are cycles in the resource allocation graph AND there is more than one instance per resource type, THEN some processes may be deadlocked!***

How to detect deadlocks in the general case?

(of multiple instances per resource)



Banker's algorithm

There are n processes and m resource types in the system. Let $i \in 1 \ldots n$ and $j \in 1 \ldots m$:

- *Allocated*$[i, j]$
  ☞ the number of resources of type j allocated by process i.
- *Free*$[j]$
  ☞ the number of available resources of type j.
- *Claimed*$[i, j]$
  ☞ the number of resources of type j required by process i to complete *eventually*.
- *Request*$[i, j]$
  ☞ the number of *currently* requested resources of type j by process i.

Temporary variables:

- *Completed*$[i]$: boolean vector indicating processes, which may complete right now.
- *Simulated_Free*$[j]$: available resources, if some processes complete and de-allocate.

Banker's algorithm

Checking for a deadlock situation

1. $Simulated\_Free \Leftarrow Free;\ \forall i: Completed[i] \Leftarrow False$

2. **While** $\exists i: \neg Completed[i]$
   and $\forall j: Requested[i, j] < Simulated\_Free[j]$ **do**: {request i can be granted}

   $\forall j: Simulated\_Free[j] \Leftarrow Simulated\_Free[j] + Allocated[i, j]$
   $Completed[i] \Leftarrow True$

3. **If** $\forall i: Completed[i]$ **then** the system is **deadlock-free**!
   (otherwise all processes i with $Completed[i] = False$ are deadlocked)

Banker's algorithm

Checking the current system state

1. *Simulated_Free* $\Leftarrow$ *Free*; $\forall i$: *Completed*$[i] \Leftarrow$ *False*

2. **While** $\exists i$: $\neg$*Completed*$[i]$
   and $\forall j$: *Claimed*$[i, j]$ < *Simulated_Free*$[j]$ **do:** {meaning process *i* can complete}

   $\forall j$: *Simulated_Free*$[j] \Leftarrow$ *Simulated_Free*$[j]$ + *Allocated*$[i, j]$
   Completed$[i] \Leftarrow$ *True*

3. **If** $\forall i$: *Completed*$[i]$ **then** the system is **safe**!
   (e.g. no process is currently deadlocked and no process can be deadlocked in any future state)

Banker's algorithm

Checking the validity of a resource request

```
If (Request < Claimed) and (Request < Free) then
   Free      := Free      - Request;
   Claimed   := Claimed   - Request;
   Allocated := Allocated + Request;
```

☞ ***Apply system state check (as above)***

```
   If System_is_safe then
```

☞ ***Actually grant request***

```
   else
      -- restore former system state (Free, Claimed, Allocated)
   end if;
end if;
```


Deadlock recovery

☞ Stop or restart one or multiple of the deadlocked processes and reclaim its resources

☞ Pre-empt one of the involved resources (and restore an earlier state of the victim process)

Deadlock recovery does not deal with the source of the problem!
(the system may deadlock again right away)

☞ use deadlock prevention or deadlock avoidance instead

Deadlocks

- **Ignorance & recovery**
  - ☞ 'kill some seemingly persistently blocked processes from time to time' (exasperation)
- **Deadlock detection & recovery**
  - ☞ multiple methods for detection, e.g. resource allocation graphs, Banker's algorithm
  - ☞ recovery is mostly 'ugly'
- **Deadlock avoidance**
  - ☞ check system safety before allocating resources, e.g. Banker's algorithm
- **Deadlock prevention**
  - ☞ eliminate one of the pre-conditions for deadlocks

Purpose of scheduling

A scheduling scheme provides two features:

- Ordering the use of resources (e.g. CPUs, networks)
- Predicting the worst-case behaviour of the system when the scheduling algorithm is applied
  … in case that some or all information about the expected resource requests are known

A prediction can then be used

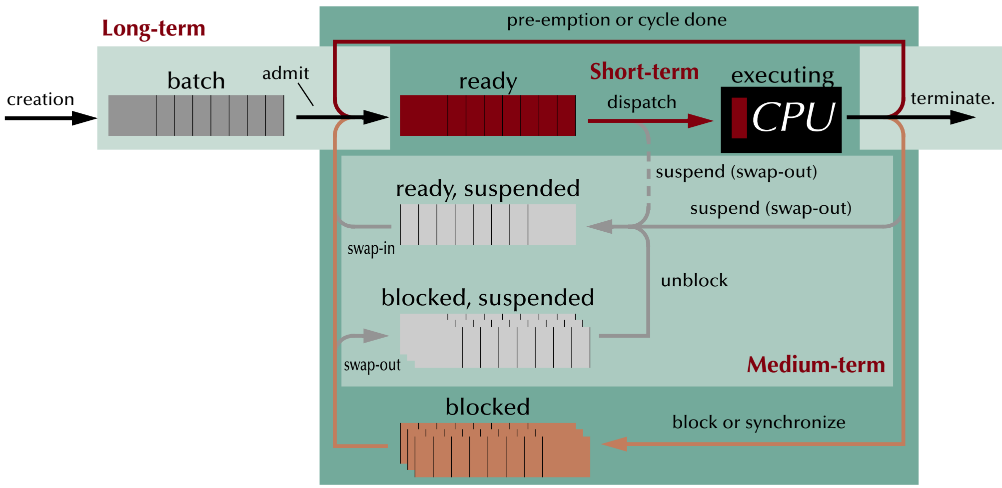
☞ at compile-run: to confirm the overall resource requirements of the application, or

☞ at run-time: to permit acceptance of additional usage/reservation requests.

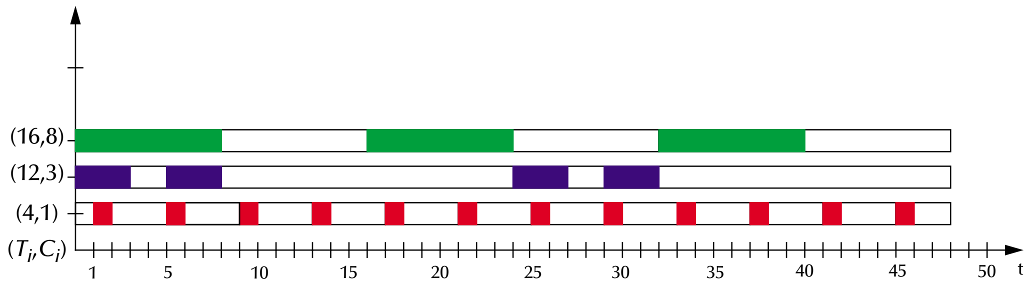
Criteria for scheduling methods

	Performance criteria: minimize the …	**Predictability criteria:** minimize the diversion from given
Process / user perspective:		
Waiting time	maximum / average / variance	minimal and maximal waiting times
Response time	maximum / average / variance	minimal and maximal response times
Turnaround time	maximum / average / variance	deadlines
System perspective:		
Throughput	maximum / average / variance of CPU time per process	–
Utilization	CPU idle time	–

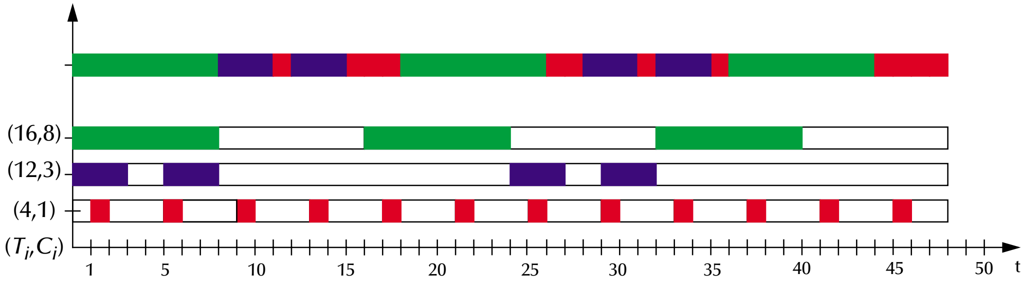
Time scales of scheduling



Example: Requested times

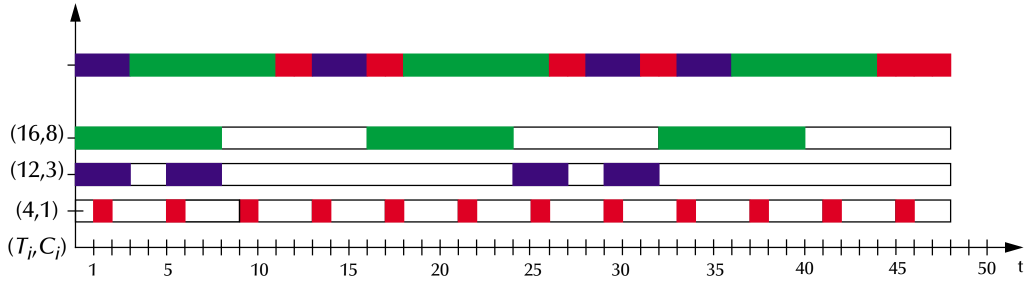


First come, first served (FCFS) – *bad case: (arrival order: green, purple, red)*



Waiting time: 0…11; average: **5.95** – **Turnaround time: 3…12**; average: **8.47**

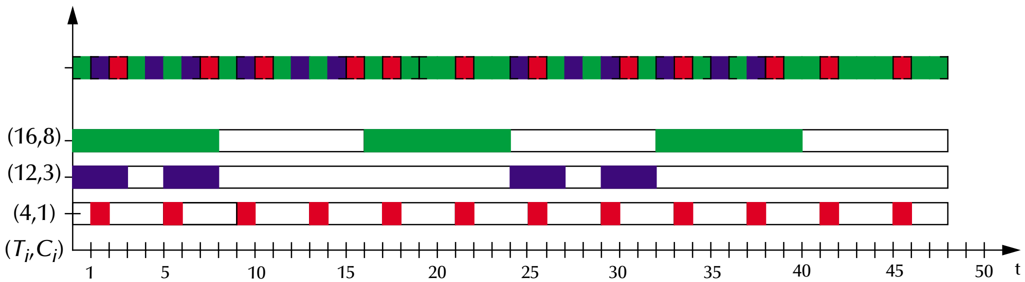
First come, first served (FCFS) – *nice case: (arrival order: red, purple, green)*



Waiting time: 0…11; average: **5.47** – **Turnaround time: 3…12**; average: **8.00**

☞ The actual average waiting time for FCFS may vary here between: **5.47** and **5.95**

Round robin (RR) – *pre-emption*



Waiting time: 0…4; average: **1.21** – **Turnaround time: 1…19**; average: **5.63**

☞ *Waiting* and *average turnaround time* is going down, but *maximal turnaround* time is going up

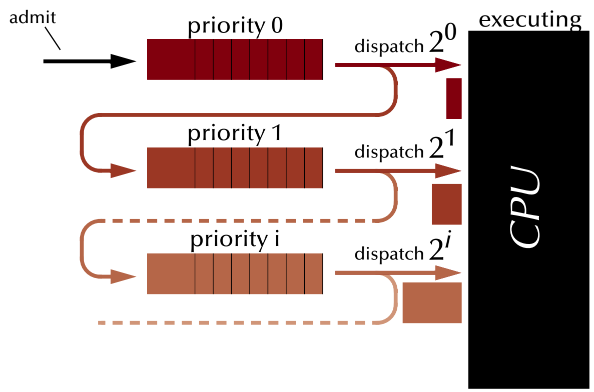
… assuming that task-switching is free and always possible

Feedback with 2^i pre-emption intervals – *pre-emption*

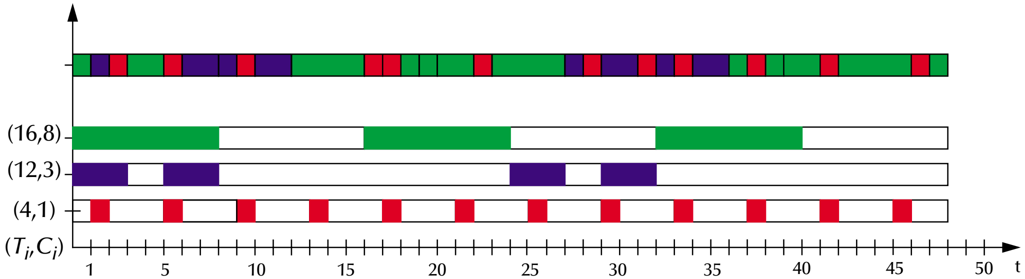
- implement multiple hierarchical ready-queues
- fetch processes from the highest filled ready queue
- dispatch more CPU time for lower priorities (2^i units)

☞ processes on lower ranks may suffer starvation

☞ new and short tasks will be preferred



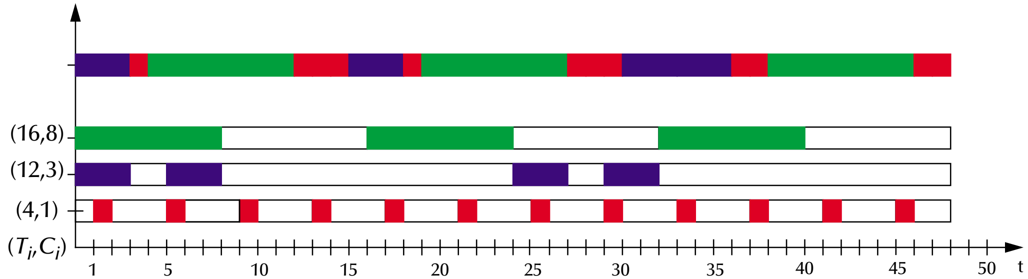
Feedback with 2^i pre-emption intervals – *pre-emption*



Waiting time: 0…6; average: **1.79** – **Turnaround time**: 1…21; average **5.63**

☞ *less task switches* than RR,
but long processes can suffer starvation!

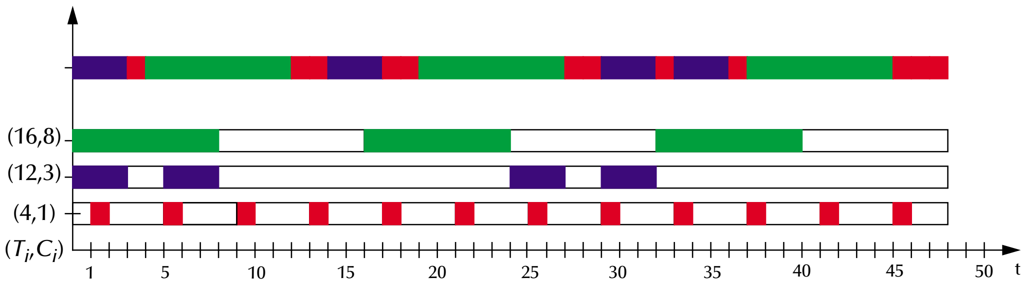
Shortest job first (SJF) – *C_i is known*



Waiting time: 0…10; average: **3.47** – **Turnaround time: 1…14**; average: **6.00**

☞ *on average* this is doing better than FCFS

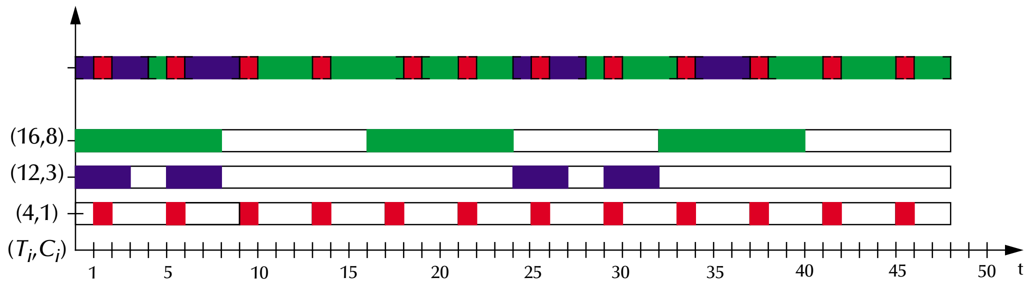
Highest response ratio first (HRRF) – *C_i is known*



Response ratio: $(W_i + C_i)/C_i$ – **Waiting time**: 0…9; average: **4.11** – **Turnaround time**: 1…13; average **6.63**

☞ *on average* this is doing worse than SJF,
but the *maximal* waiting and turnaround times and variance might be reduced!

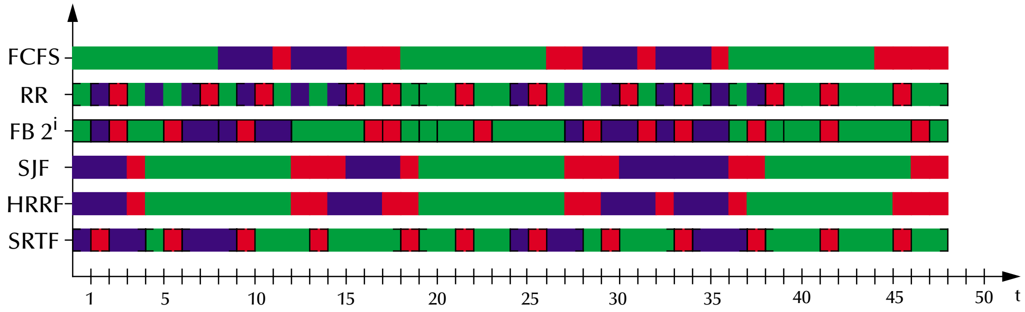
Shortest remaining time first (SRTF) – *C_i is known + pre-emption*



Waiting time: 0…6; average: **1.05** – **Turnaround time**: 1…18; average **4.42**

☞ *on average* this is doing better than FCFS, SJF or HRRF,
but the *maximal turnaround* time is going up and there are many task-switches!

Non-realtime scheduling methods



- CPU utilization: 100% in all cases.
- Pre-emptive methods perform better, assuming that the overhead is negligible.
- Knowledge of C_i (computation times) has a significant impact on scheduler performance.

	Selection	Pre-emption	Waiting (in high load situations)	Turnaround (in high load situations)	Preferred processes	Starvation possible?
FCFS	$max(W_i)$	no	possibly long	possibly long	long	no
RR	equal share	yes	bound	possibly long	none	no
Feedback	priority queues	yes	short on average	very short on average, large maximum	short	yes
SJF	$min(C_i)$	no	short on average	short on average	short	yes
HRRF	$max\left(\frac{W_i + C_i}{C_i}\right)$	no	short on average, lower variance	short on average, lower variance	balanced, towards short	no
SRTF	$min(C_i - E_i)$	yes	very short on average	very short on average, large maximum	short	yes

Towards predictable scheduling …

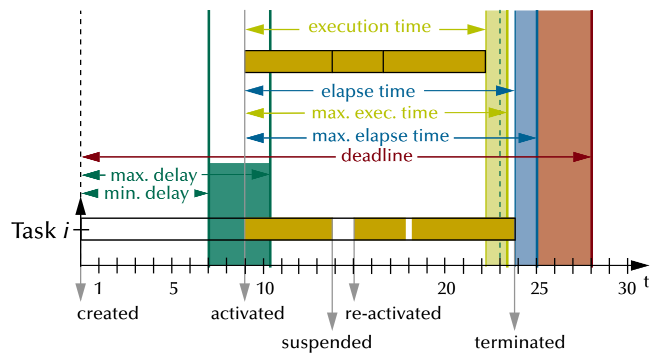
- Task behaviours are more specified (restricted).
- Task requirements from the operating systems are more specific.
- Task sets are often fully or mostly static.
- Sporadic and urgent requests (e.g. user interaction, alarms) need to be addressed.

¬ CPU-utilization and throughput (system oriented performance measures) are not important!

Temporal scopes

Common attributes:

- Minimal & maximal delay after creation
- Maximal elapsed time
- Maximal execution time
- Absolute deadline



Some common scope attributes

Temporal Scopes can be:

Periodic	– e.g. controllers, samplers, monitors
Aperiodic	– e.g. ‘periodic on average’ tasks, burst requests
Sporadic / Transient	– e.g. mode changes, occasional services

Deadlines (absolute, elapse, or execution time) can be:

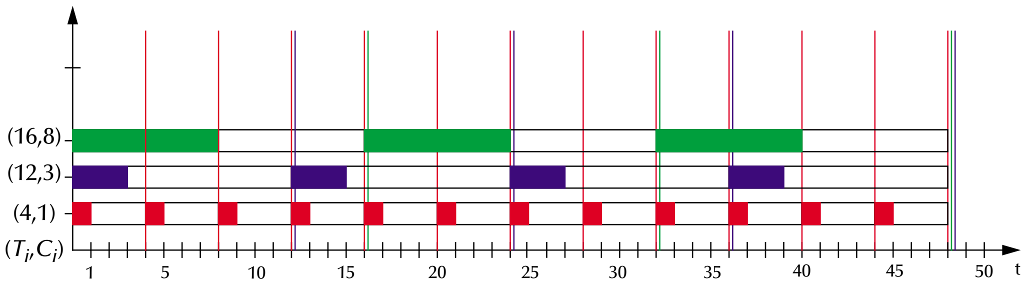
Hard	– single failure leads to severe malfunction
Firm	– results are meaningless after the deadline
	– only multiple or permanent failures threaten the whole system
Soft	– results may still by useful after the deadline

A simple process model

- The number of processes in the system is fixed.
- All processes are periodic and all periods are known.
- All deadlines are identical with the process cycle times (periods).
- The worst case execution time is known for all processes.
- All processes are independent.
- All processes are released at once.
- The task-switching overhead is negligible.

☞ this model can only be applied to a specific group of hard real-time systems.
(extensions to this model will be discussed later in this chapter).

Introducing deadlines



Earliest deadline first (EDF)

1. Determine (one of) the processe(s) with the closest deadline.
2. Execute this process

   2-a until it finishes

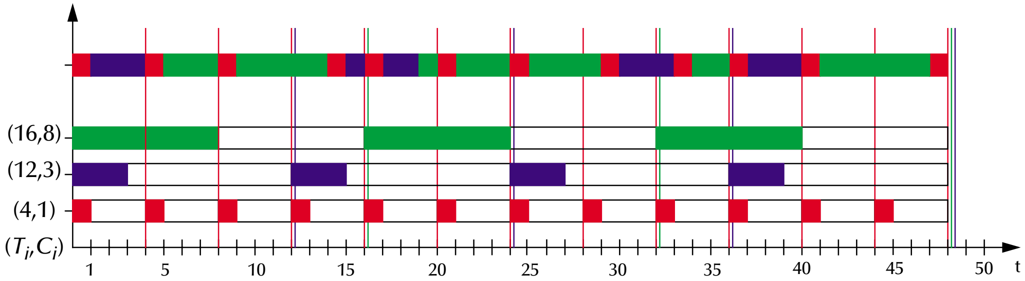
   2-b or until another process’ deadline is found closer then the current one.

☞ Pre-emptive scheme

☞ Dynamic scheme,
since the dispatched process is selected at run-time, due to the current deadlines.

Dynamic scheduling: Earliest Deadline First (EDF)

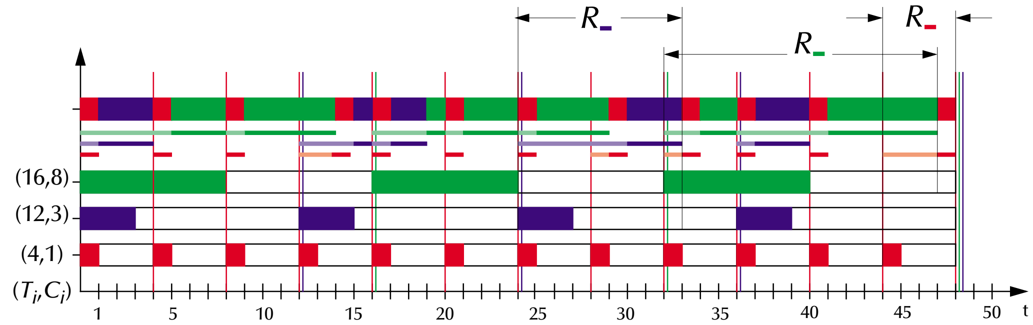
Earliest deadline first



1. Schedule the earliest deadline first
2. Avoid task switches (in case of equal deadlines)

Dynamic scheduling: Earliest Deadline First (EDF)

Earliest deadline first: Response times



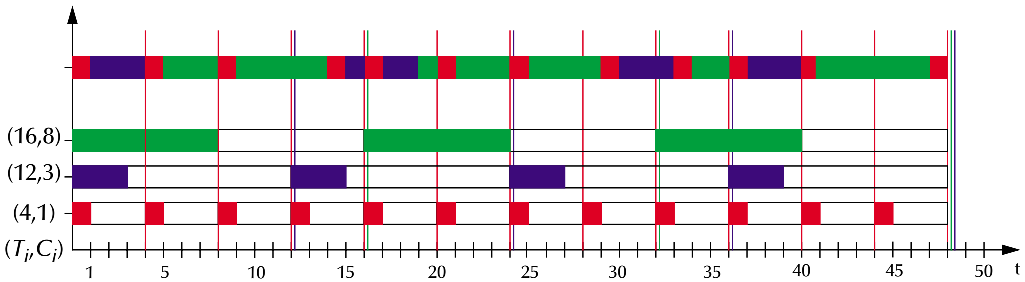
worst case response times R_i (maximal time in which the request from task T_i is served):

☞ can be close or identical to deadlines.

☞ small or none spare capacity, if any task misses its expected computation time.

Dynamic scheduling: Earliest Deadline First (EDF)

Earliest deadline first: Maximal utilization



☞ maximal possible utilization: $\sum_{i=1}^{n} \frac{C_i}{T_i} \le 1$ ☞ sufficient & necessary test!

with C_i, T_i the computation and cycle times of task *i*

(the deadlines D_i are assumed to be identical with the cycles times T_i here)

Static scheduling

Fixed Priority Scheduling (FPS), rate monotonic

1. Each process is assigned a fixed priority according to its cycle time T_i:

$$T_i < T_j \Rightarrow P_i > P_j$$

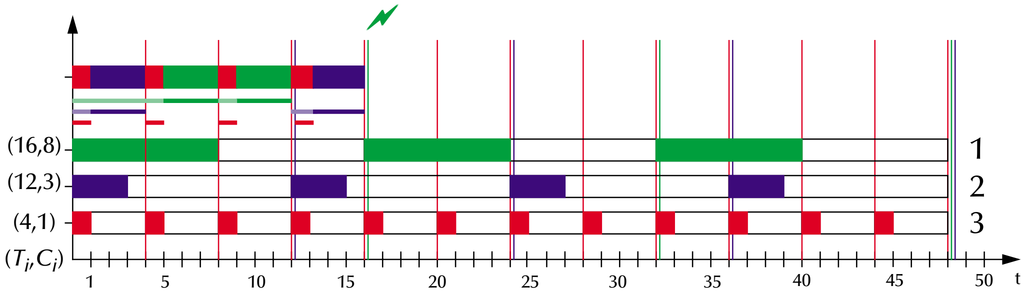
2. At any point in time: dispatch the process with the highest priority

☞ Pre-emptive scheme

☞ Static scheme,
since the dispatch order of processes is fixed and calculated off-line.

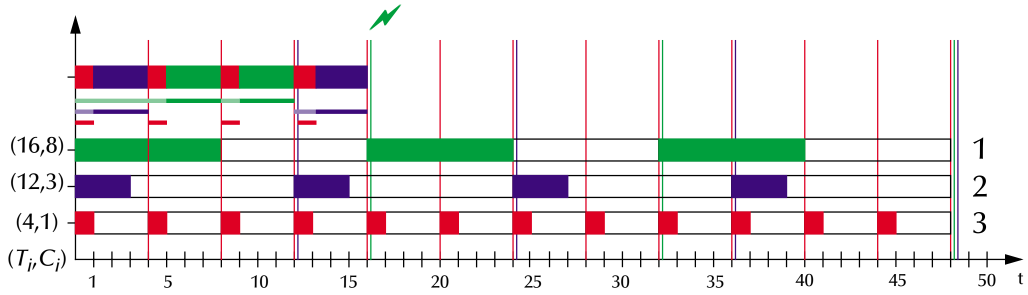
- Rate monotonic ordering is **optimal** (in the framework of fixed priority schedulers), i.e. ***if*** a process set is schedulable under a FPS-scheme, ***then*** it is also schedulable by applying rate monotonic priorities.

Rate monotonic priorities



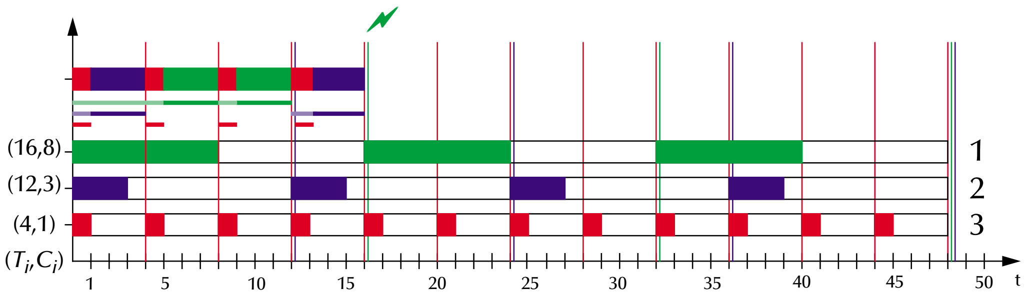
☞ assign task priorities according to the cycle times T_i (identical to deadline D_i).

Rate monotonic priorities



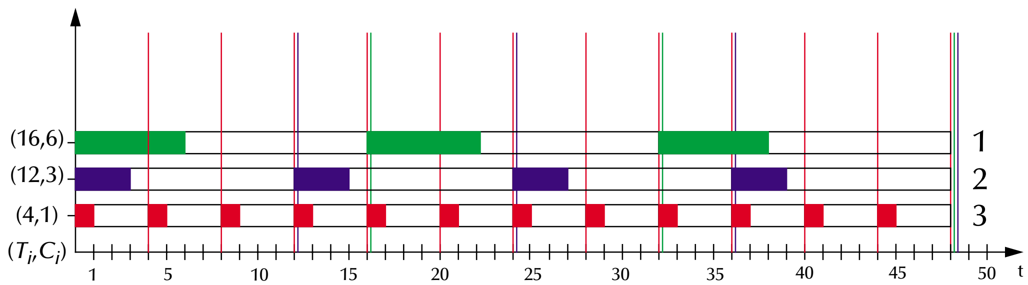
max. utilization test: $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$ ☞ sufficient, but not necessary test!

Rate monotonic priorities



utilization test: $\sum_{i=1}^{n} \frac{C_i}{T_i} = 1 > 0.779 \approx N\left(2^{\frac{1}{N}} - 1\right)$ ☞ not guaranteed!

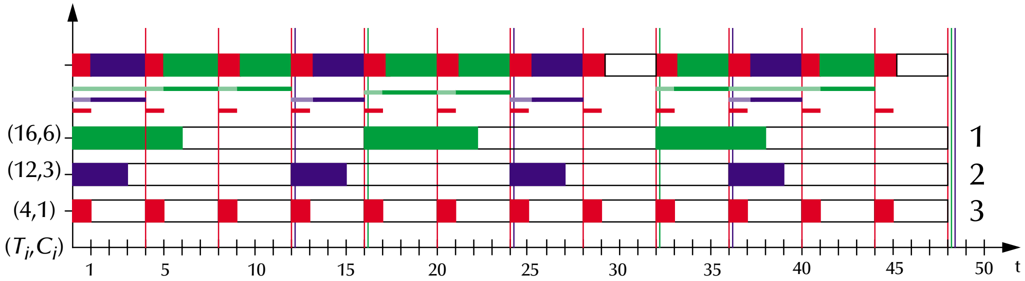
Rate monotonic priorities *(reduced requests)*



max. utilization test: $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

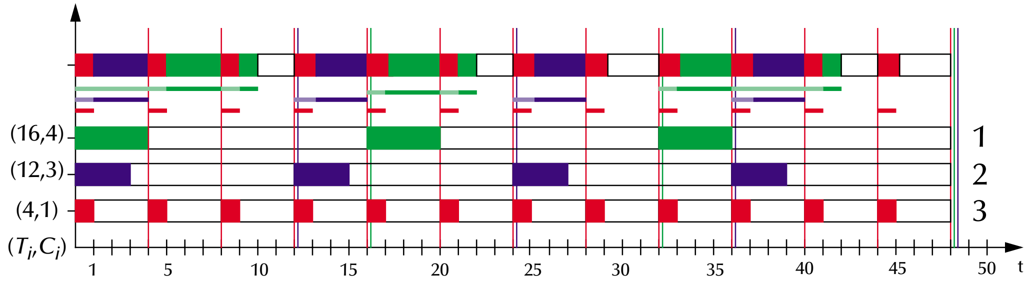
Rate monotonic priorities (reduced requests)



☞ utilization: $\frac{6}{16} + \frac{3}{12} + \frac{1}{4} = 0.875 > 0.779 \approx 3\left(2^{\frac{1}{3}} - 1\right)$; $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$ ☞ not guaranteed!

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

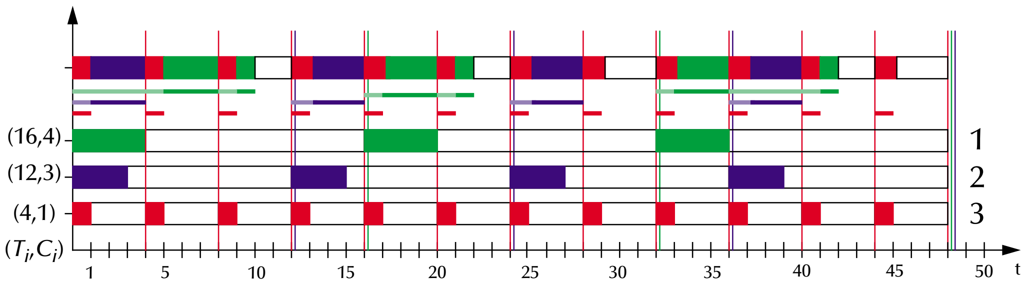
Rate monotonic priorities (further reduced requests)



☞ utilization: $\frac{4}{16} + \frac{3}{12} + \frac{1}{4} = 0.75 \le 0.779 \approx 3\left(2^{\frac{1}{3}} - 1\right)$; $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$ ☞ guaranteed!

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

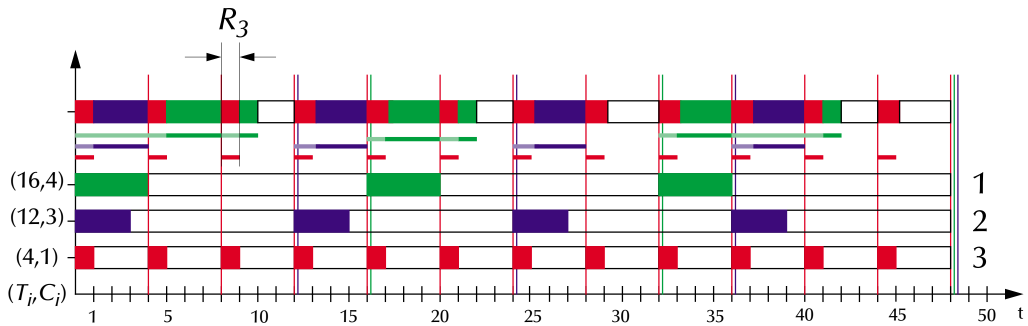
Response time analysis (further reduced requests)



☞ calculate the worst case response times for each task individually.

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

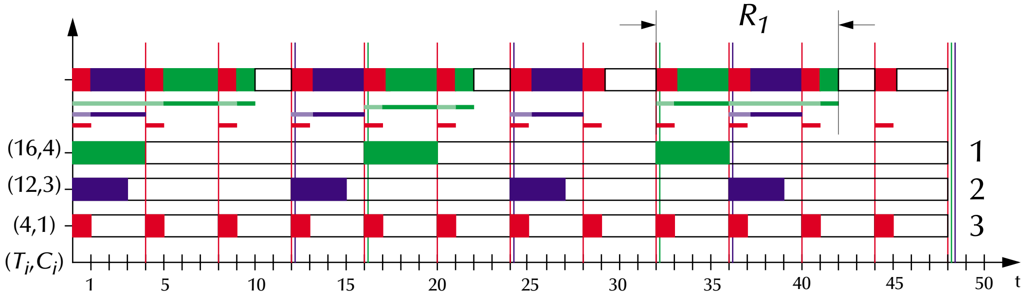
Response time analysis (further reduced requests)



☞ for the highest priority task: $R_3 = C_3$

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

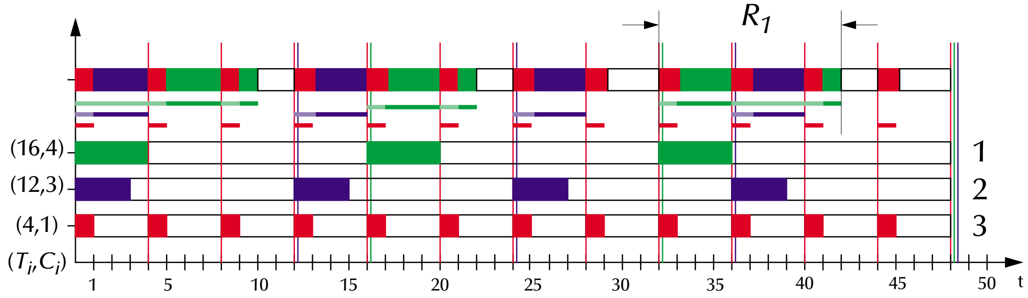
Response time analysis (further reduced requests)



☞ for other tasks: $R_i = C_i + I_i$ = computation C_i + interference I_i

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



for other tasks: $R_i = C_i + \sum_{j > i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis

$$R_i = C_i + \sum_{j > i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

☞ fixed-point equation!

☞ form recurrent equation: $R_i^{k+1} = C_i + \sum_{j > i} \left\lceil \frac{R_i^k}{T_j} \right\rceil C_j$ (1)

☞ starting with $R_i^0 = C_i$

☞ Iterate (1) until $R_i^{k+1} = R_i^k$ or $R_i^{k+1} > T_i$

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis

The worst case for EDF is *not* necessarily when all tasks are released at once!

☞ all possible combinations in a full hyper -cycle need to be considered!

- The response times are bounded by the cycle times as long as the maximal utilization is ≤ 1.
- Other tasks need to be considered only, if their deadline is closer or equal to the current task.

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis

$$R_i(a) = \left\lfloor \frac{a}{T_i} + 1 \right\rfloor C_i + \sum_{j \neq i} \min \left\{ \left\lceil \frac{R_i(a)}{T_j} \right\rceil, \max \left\{ 0, \left\lfloor \frac{a + T_i - T_j}{T_j} \right\rfloor + 1 \right\} \right\} C_j$$

☞ $R_i^{k+1}(a) = \left\lfloor \frac{a}{T_i} + 1 \right\rfloor C_i + \sum_{j \neq i} \min \left\{ \left\lceil \frac{R_i^k(a)}{T_j} \right\rceil, \max \left\{ 0, \left\lfloor \frac{a + T_i - T_j}{T_j} \right\rfloor + 1 \right\} \right\} C_j$ (2)

☞ starting with $R_i^0(a) = a + C_i$

☞ Iterate (2) until $R_i^{k+1}(a) = R_i^k(a)$

☞ $R_i = \max\{R_i(a) - a\}_{a \in A}$; where $A = scm\{T_i\}$

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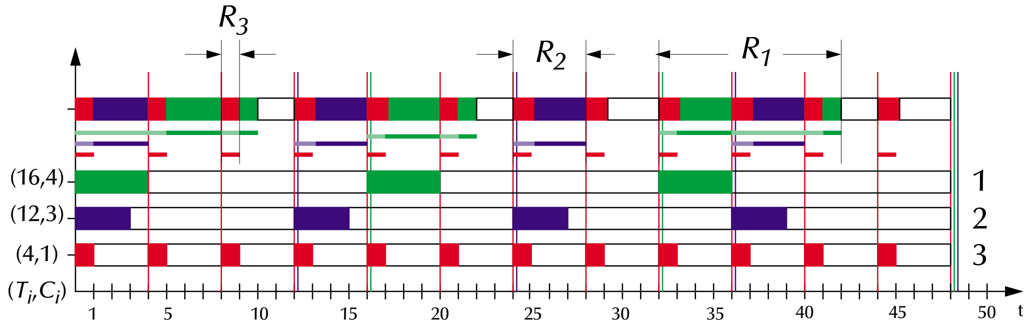
Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)

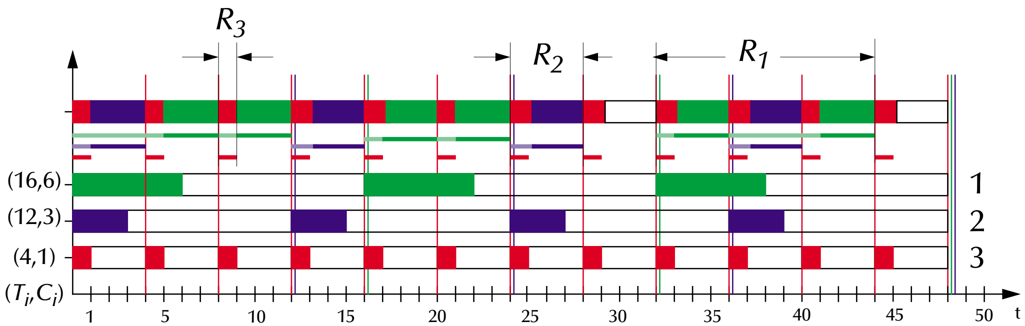


☞ $R_i = C_i + \sum_{j>i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$; $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 10$✔ and $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$✔

Operating Systems & Networks

Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (reduced requests)



☞ $R_i = C_i + \sum_{j>i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$; $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 12$✔ but $\sum_{i=1}^{n} \frac{C_i}{T_i} > N\left(2^{\frac{1}{N}} - 1\right)$✘

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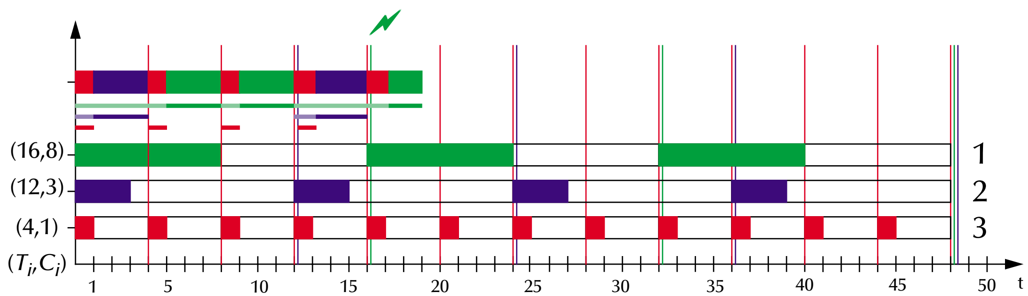
Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

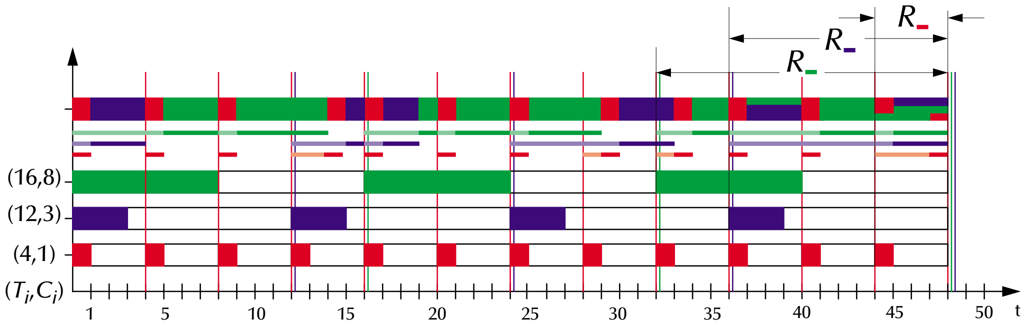
Response time analysis (full requests)



☞ $R_i = C_i + \sum_{j>i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$; $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 19$✘ and $\sum_{i=1}^{n} \frac{C_i}{T_i} > N\left(2^{\frac{1}{N}} - 1\right)$✘

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis (full requests)



☞ testing all combinations in a hyper-period: LCM of $\{T_i\}$ — here: 48

$R_{-} : 16 \le 16 ✔ = T_{-}$; $R_{-} : 12 \le 12 ✔ = T_{-}$; $R_{-} : 4 \le 4 ✔ = T_{-}$

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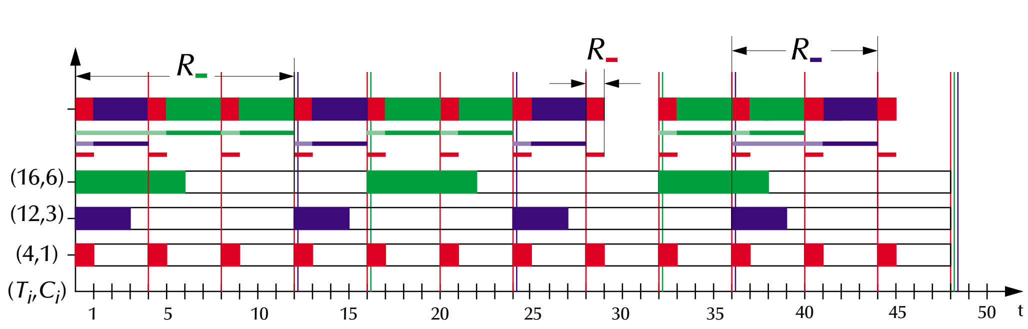
Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis (reduced requests)



☞ relaxed task-set changes:

$R_{-} : 16 \rightarrow 12 \le 16 ✔ = T_{-}$; $R_{-} : 12 \rightarrow 8 \le 12 ✔ = T_{-}$; $R_{-} : 4 \rightarrow 1 \le 4 ✔ = T_{-}$

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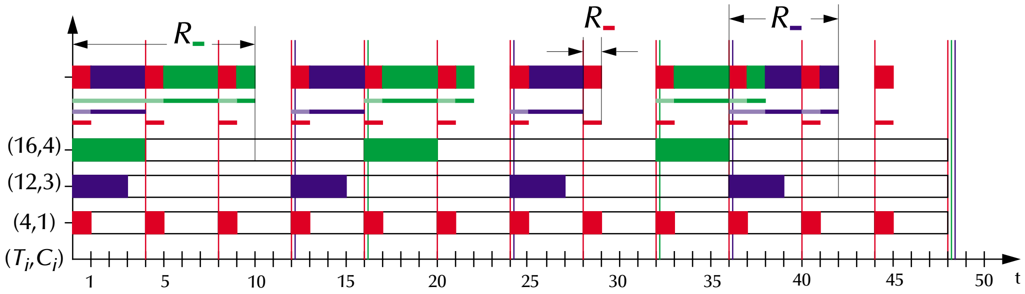
Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis (further reduced requests)



☞ further relaxed task-set changes:

$R_{-} : 12 \rightarrow 10 \le 16 ✔ = T_{-}$; $R_{-} : 8 \rightarrow 6 \le 12 ✔ = T_{-}$; $R_{-} : 1 \rightarrow 1 \le 4 ✔ = T_{-}$

Operating Systems & Networks

Real-time scheduling

Response time analysis (comparison)

	Fixed Priority Scheduling		Earliest Deadline First	
	utilization test	response times $\{R_i\}$	utilization test	response times $\{R_i\}$
$\{(T_i, C_i)\} = \{(16, 8);(12, 3);(4, 1)\}$	✘ (1.000)	{✘, 4, 1}	✔ (1.000)	{16, 12, 4}
$\{(T_i, C_i)\} = \{(16, 6);(12, 3);(4, 1)\}$	✘ (0.875)	{12, 4, 1}	✔ (0.875)	{12, 8, 1}
$\{(T_i, C_i)\} = \{(16, 4);(12, 3);(4, 1)\}$	✔ (0.750)	{10, 4, 1}	✔ (0.750)	{10, 6, 1}
	$\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$	$C_i + \sum_{j>i} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$	$\sum_{i=1}^{n} \frac{C_i}{T_i} \le 1$	check full hyper-cycle

Real-time scheduling

Fixed Priority Scheduling ↔ Earliest Deadline First

- EDF can handle higher (full) utilization than FPS.
- FPS is easier to implement and implies less run-time overhead

- Graceful degradation features (resource is over-booked):
  - FPS: processes with lower priorities will always miss their deadlines first.
  - EDF: any process can miss its deadline ☞ and can trigger a cascade of failed deadlines.

- Response time analysis and utilization tests:
  - FPS: O(n) utilization test — response time analysis: fixed point equation
  - EDS: O(n) utilization test — response time analysis: fixed point equation in hyper-cycle

Scheduling

Extensions which we will introduce:

- tasks are periodic
  ☞ we will introduce sporadic and aperiodic processes
- tasks are independent
  ☞ we will introduce schedules for interacting tasks
- deadlines are identical with task's period time ($D = T$)
  ☞ Real-time course
- pre-emptive scheduling
  ☞ Real-time course
- worst case execution times are known
  ☞ Real-time course

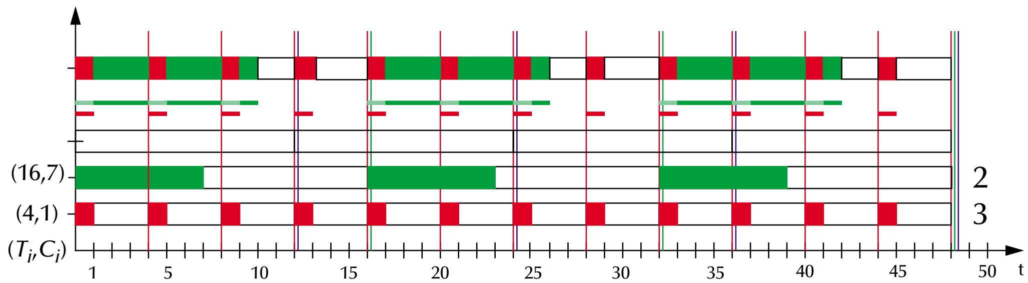
Scheduling — real-world considerations

... including

aperiodic, sporadic & 'soft' real-time tasks

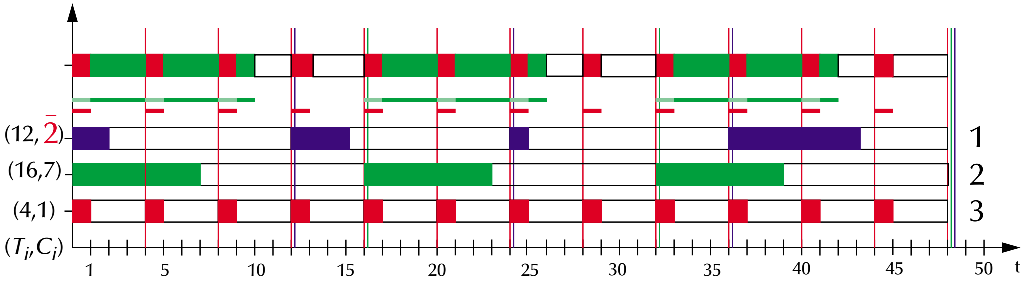
Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Hard real-time tasks



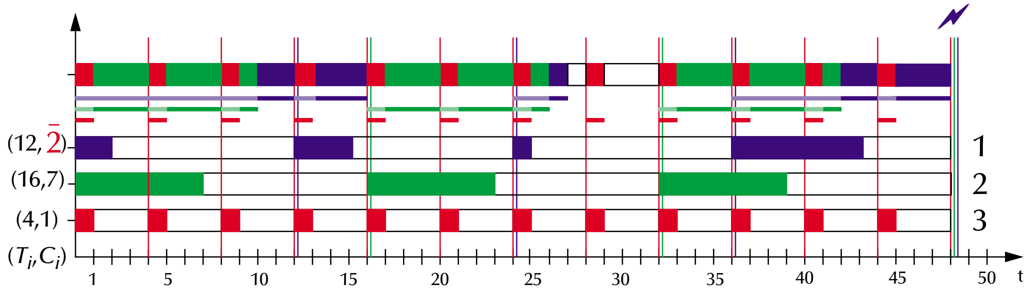
Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Introducing soft real-time tasks



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

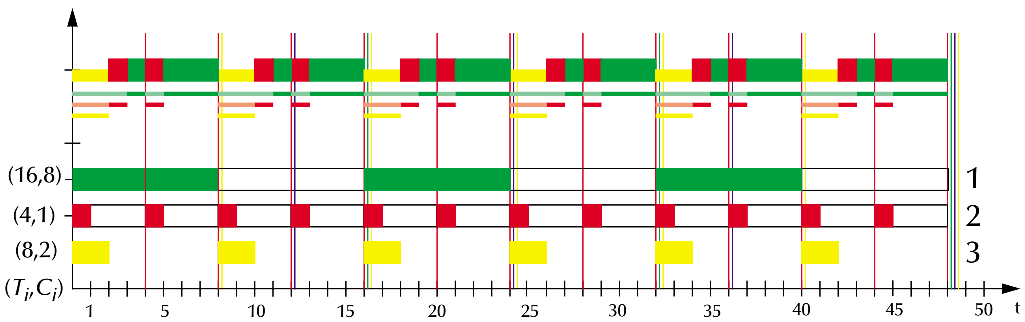
Introducing soft real-time tasks



- ☞ set can be scheduled using average computation and period times
- ☞ hard real-time tasks can be scheduled under worst case conditions (including worst case behaviours of soft real-time tasks)

Static scheduling: FPS, rate monotonic + server

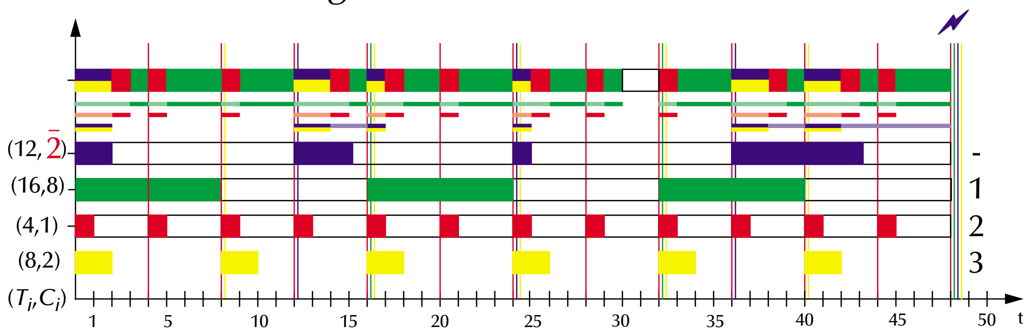
Introducing a server task



Server is established at a high priority

Static scheduling: FPS, rate monotonic + server

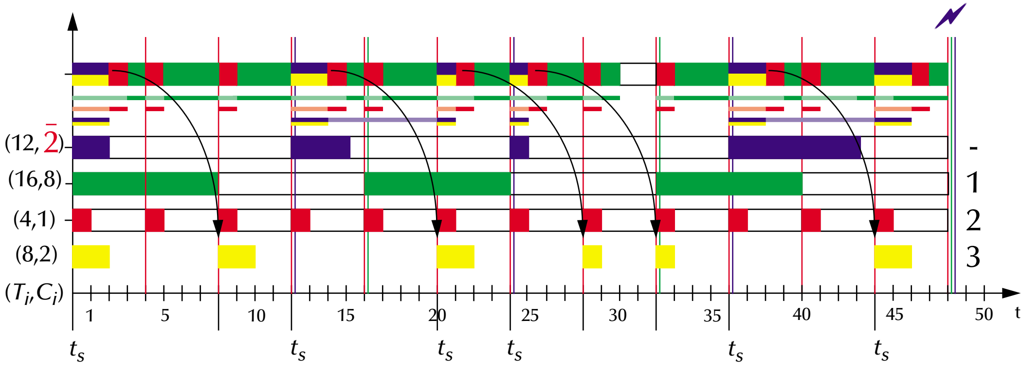
Introducing a server task: Deferrable Server



- ☞ Deferrable Server (DS): Capacity replenished every T_s (here: 8)

Static scheduling: FPS, rate monotonic + server

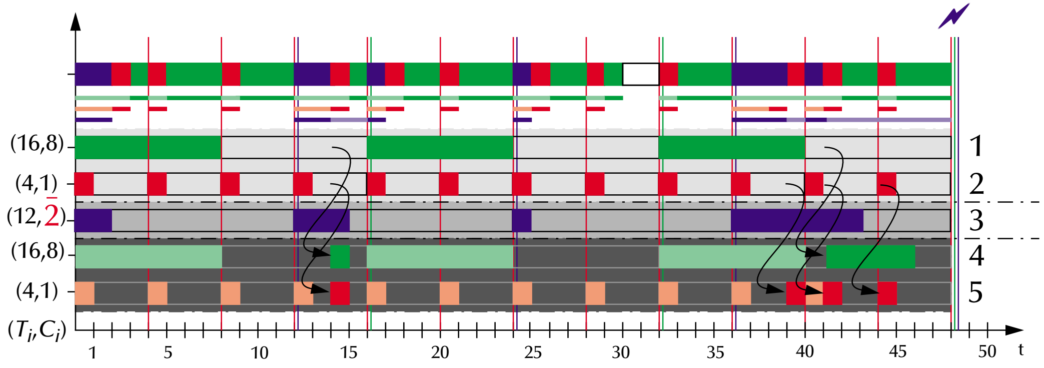
Introducing a server task: Sporadic Server



☞ Sporadic Server (SS): Capacity replenished T_s units after t_s ☞ POSIX

Static scheduling: Fixed Priority Scheduling (FPS), dual-priorities

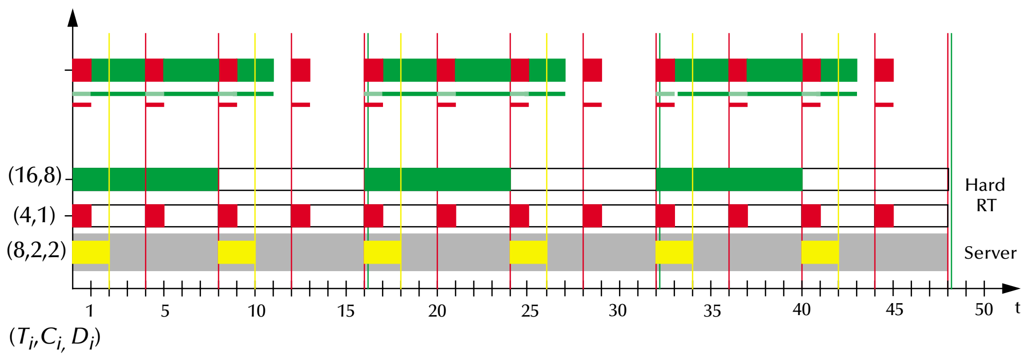
Introducing dual priorities



☞ start hard rt-tasks in low priorities; promote them in time to higher ones

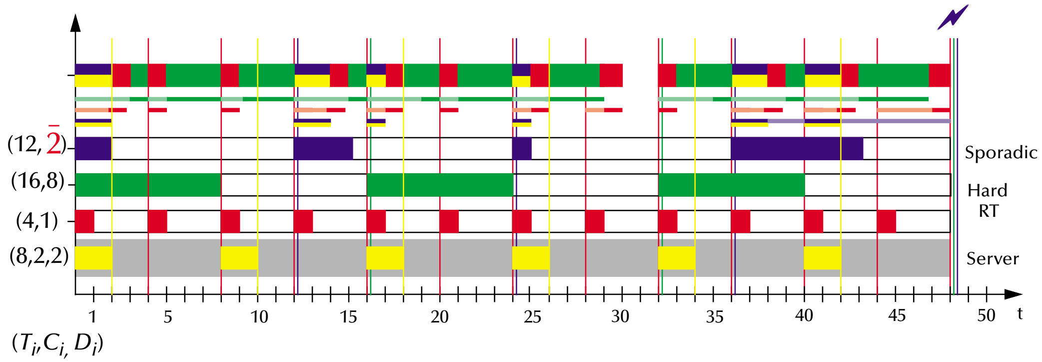
Dynamic scheduling: Earliest Deadline First+ aperiodic server

Introducing a server task to EDF



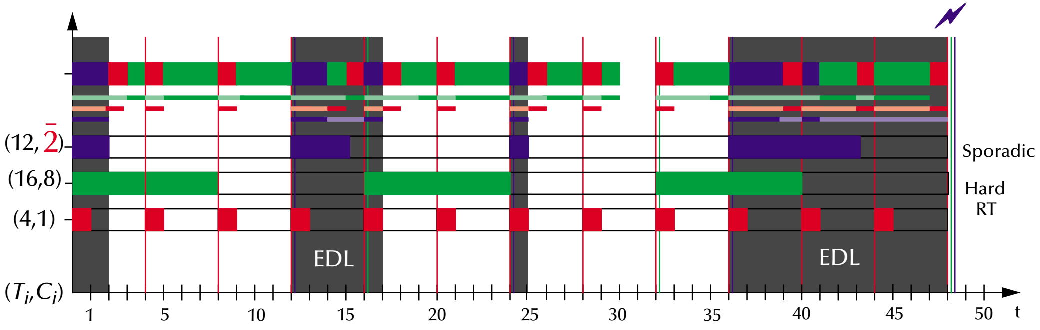
Dynamic scheduling: Earliest Deadline First + aperiodic server

Introducing a server task to EDF



Dynamic scheduling: Earliest Deadline First + aperiodic tasks

Switching between EDF & Earliest Deadline Last (EDL)



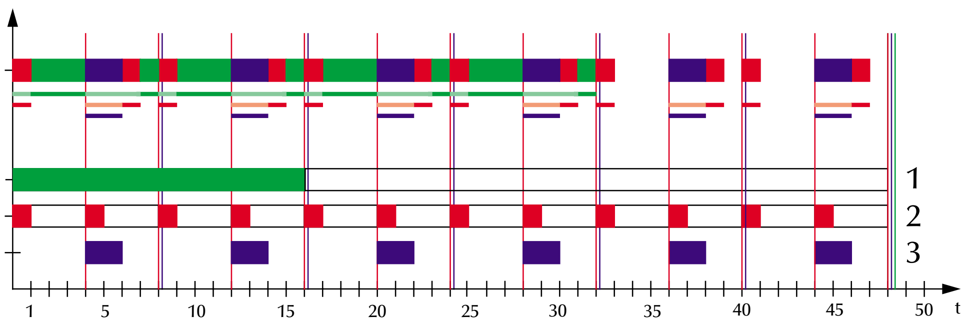
Scheduling — real-world considerations

... including

task interdependencies

Scheduling: Interdependencies

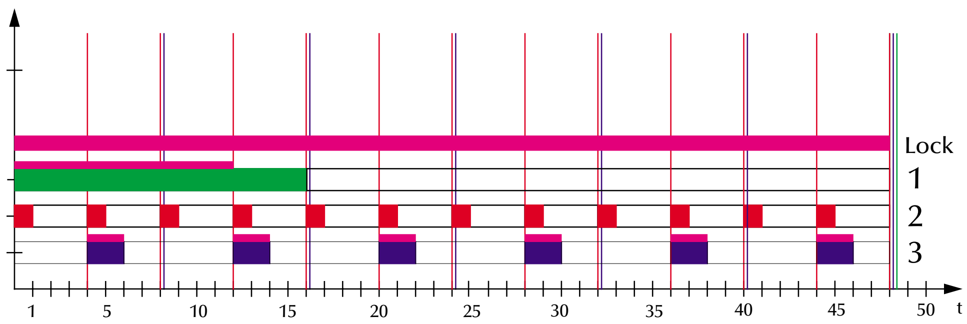
Schedule for independent tasks



(independent task set)

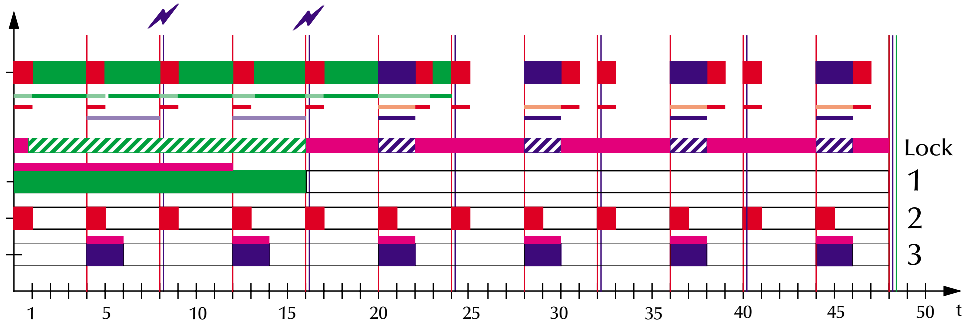
Scheduling: Interdependencies

Synchronized via lock



(interdependent task set ☞ lock ■ shared between ■ and ■)

Synchronized via lock



☞ *Priority inversion*

(interdependent task set ☞ lock ■ shared between ■ and ■)

Priority inheritance

Task t_i inherits the priority of t_j, if:

1. $P_i < P_j$
2. task t_i has locked a resource Q
3. task t_j is blocked waiting for resource Q to be released

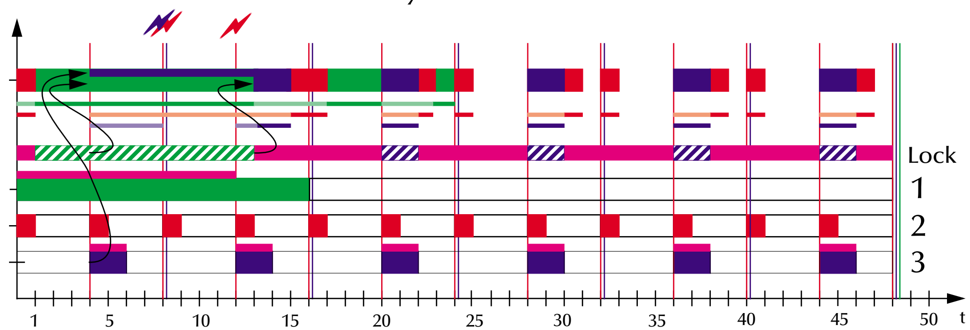
Priority inheritance

Maximal blocking time for task t_i: $B_i = \sum_{r=1}^{R} usage(r, i) C(r)$

- with R the number of critical sections
- $usage(r, i)$ a boolean (0/1) function indicating that r is used by at least one t_j with $P_j < P_i$ and at least one t_k with $P_k \geq P_i$
- $C(r)$ is the worst case computation time in critical section r

a task can only be blocked once for each employed resource!

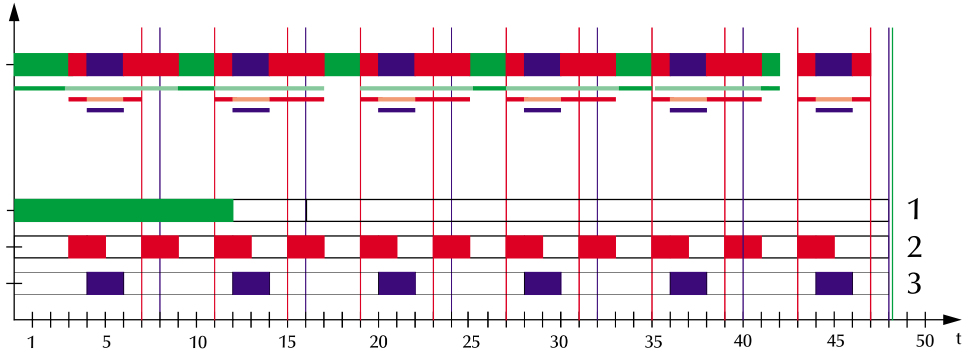
Priority inheritance



(■ inherits priority of ■, when ■ is in lock and ■ is dispatched)

Scheduling: Interdependencies

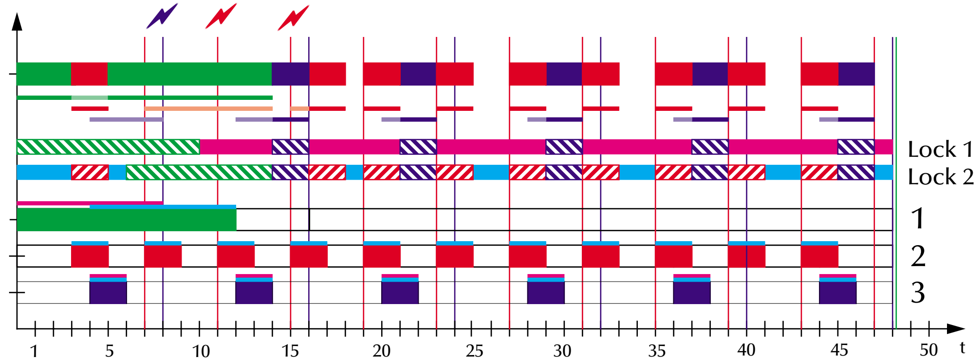
A more complex example



(independent task set)

Scheduling: Interdependencies

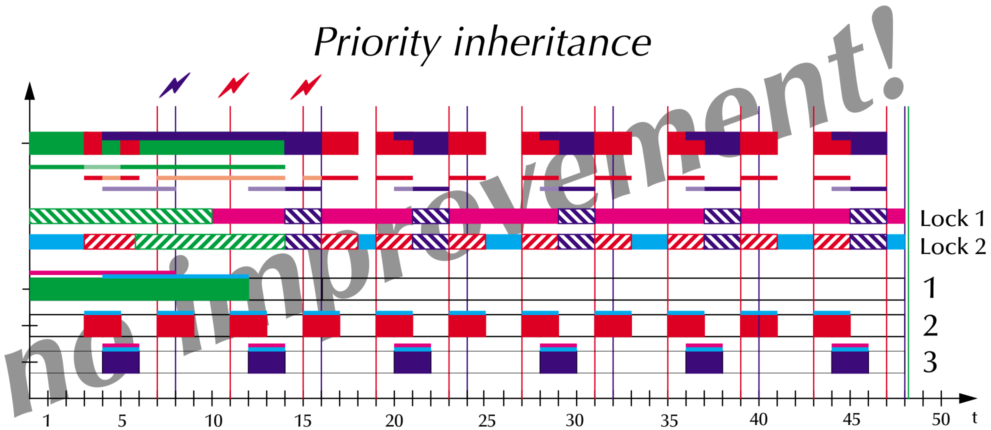
Interdependencies



☞ Priority inversion

Scheduling: Interdependencies

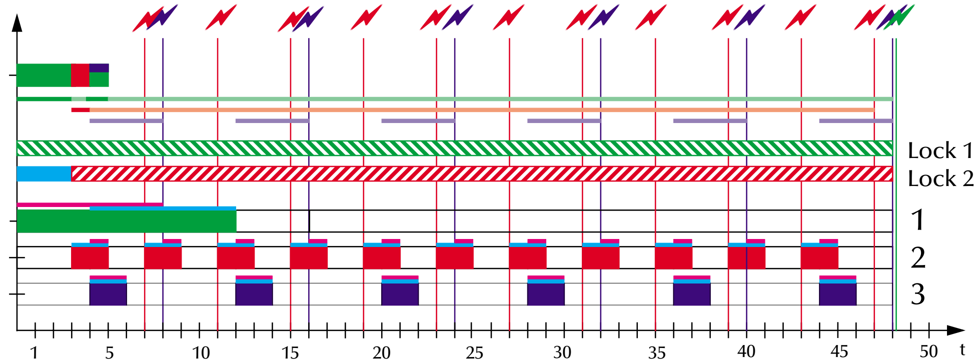
Priority inheritance



(■ and ■ inherit priority of ■, when in lock and ■ is dispatched)

Scheduling: Interdependencies

One additional lock request



☞ Deadlock

Immediate ceiling priority protocol (POSIX, Ada, RT-Java)

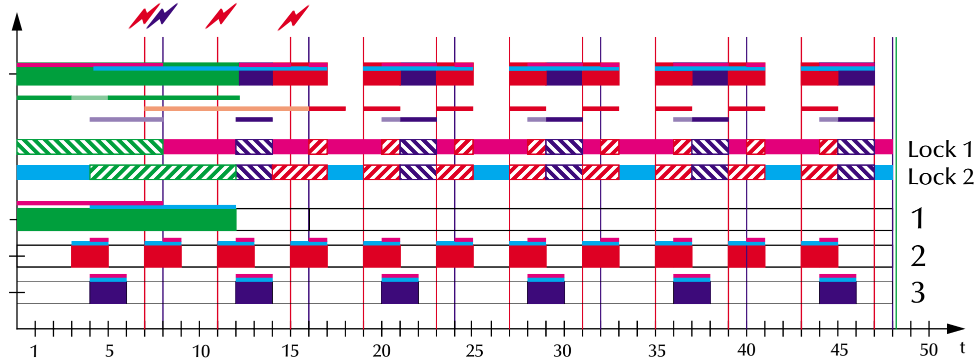
- Each task t_i has static default priority P_i.
- Each resource (lock, monitor) R_k has a static ceiling priority C_k, which is the maximum of priorities of the tasks t_i which employ this resource.

$$C_k = max_i\{employ(i,k) \cdot P_i\}$$

- Each task t_i has a dynamic priority P_i^D, which is the maximum of its own static priority and the ceiling priorities of any resource it has locked.

$$P_i^D = max\{P_i, max_k\{locked(i,k) \cdot C_k\}\}$$

Immediate ceiling priority protocol (POSIX, Ada, RT-Java)



(■, ■ and ■ inherit the ceiling priority of ■ or ■ when entering the lock)

Immediate ceiling priority protocol (POSIX, Ada, RT-Java)

- ☞ Tasks are dispatched only if all employed resources are available.
- ☞ Deadlocks are prevented
- ☞ Number of context switches is reduced

Immediate ceiling priority protocol (POSIX, Ada, RT-Java)

Maximal blocking time: $B_i = max_{r=1}^{R}\{usage(r,i) \cdot C(r)\}$

- with R the number of critical sections
- $usage(r,i)$ a boolean (0/1) function indicating that r is used by at least one t_j with $P_j < P_i$ and at least one t_k with $P_k \geq P_i$
- $C(r)$ is the worst case computation time in critical section r

a task can only be blocked once by any lower priority task!

Summary

Scheduling

- **Basic performance based scheduling**
  - C_i *is not known*: first-come-first-served (FCFS), round robin (RR), and feedback-scheduling
  - C_i *is known*: shortest job first (SJF), highest response ration first (HRRF), shortest remaining time first (SRTF)-scheduling
- **Basic predictable scheduling**
  - Fixed Priority Scheduling (FPS) with Rate Monotonic (RMPO)
  - Earliest Deadline First (EDF)
- **Real-world extensions**
  - Aperiodic, sporadic, soft real-time tasks
  - Synchronized talks (priority inheritance, priority ceiling protocols)

Summary

Processes

- **Processes and threads**
  - Architectures, definitions, process states
- **Synchronization**
  - Shared memory based synchronization
  - Message based synchronization
- **Deadlocks**
  - Detection, avoidance, and prevention (& recovery)
- **Scheduling**
  - Basic performance based scheduling
  - Basic predictable scheduling
  - Aperiodic, sporadic, and synchronized tasks

4

Memory

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References for this chapter

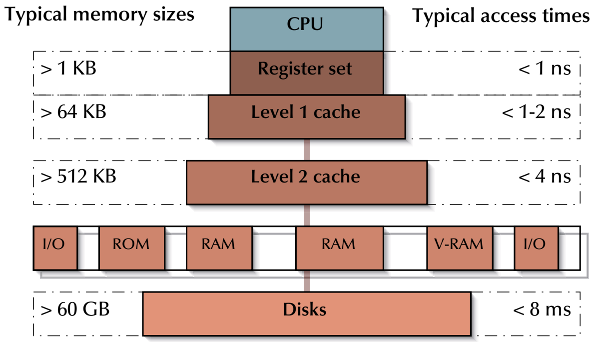
[Silberschatz01] – Chapter 9,10
Abraham Silberschatz, Peter Bear Galvin, Greg Gagne
Operating System Concepts
John Wiley & Sons, Inc., 2001

[Stallings2001] – Chapter 7,8
William Stallings
Operating Systems
Prentice Hall, 2001

all references and some links are available on the course page

Memory levels and fragments

Basic memory hierarchy



What is the challenge?

- Main memory is too small (regardless how large it is)

☞ The operating system needs to place (parts of) processes in and out of main memory during the life-time of the system.

- Swapping memory blocks between primary and secondary memory is an extremely slow operation.

☞ The operating system needs to supply highly efficient strategies to avoid system stalls or unacceptable delays.

Goals / optimization criteria

- Supply address spaces, which are independent from the physically available address space.
- Supply multiple memory modes, e.g. allow processes to reside permanently in main memory
- Support for multiple address spaces

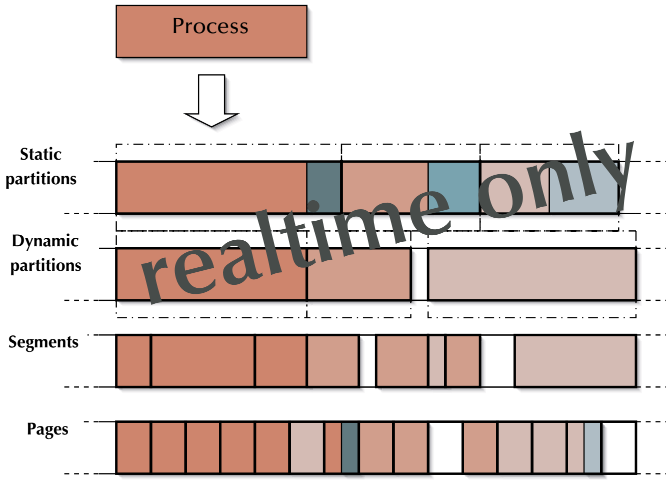
- Protection between address spaces
- Supply methods to share address spaces

- Support memory based I/O methods
- Allow for predictable behaviours of memory accesses
- Minimize any overhead for memory accesses and program executions

Required support

- **Relocation**
  Assembler level addressing modes as well as compilers and linkers need to support relocatable programs and data structures.
- **Protection**
  Memory protection needs hardware support, since the operating system itself has no knowledge which memory cells will be addressed by a specific process next.
- **Sharing**
  The protection scheme needs to be flexible enough to allow for shared memory areas.
- **Control of secondary memory**
  Since swapping speeds between primary and secondary memory is a critical factor, the operating system needs to have close access to the secondary memory interface.
- **Project logical structures to memory modules** (optional)
  It might be useful to supply addressing modes, which allow the use of logical structures in the programs itself as the basis for memory structuring.

Process Mapping



Pros	Cons
simple	internal & strong external fragmentation
no internal fragmentation	strong external fragmentation
no internal fragmentation	external fragmentation
no external fragmentation	a small amount of internal fragmentation

Virtual addressing

The step from pagination/segmentation to

Virtual addressing

Segmentation / Paging:

- all memory references are logical addresses
- there is support to translate logical to physical addresses at run-time
- processes may be moved in memory and suspended to or loaded from secondary storage
- processes are divided in pages or segments (or both)
- pages or segments can be loaded in any order into primary memory (i.e. they need not to be dense or in sequence)

☞ Virtual addressing:

- not all pages or segments need to be loaded in order to run a process

MMU

Translating virtual to physical addresses

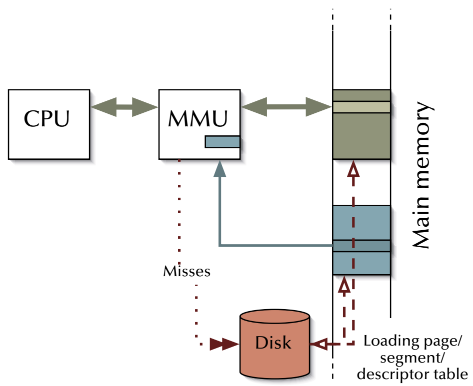
MMU

1. **Translate virtual to physical addresses**

   without any delay in most cases.

2. **Provide memory protection**

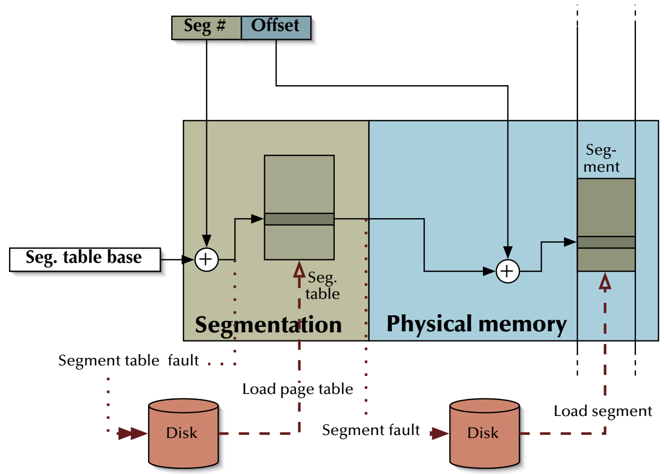
   according to the attributes, which are attached to individual memory areas in form of page or segment descriptors.



Memory – Segmentation

- Segment lengths is stored in segment table ☞ needs to be evaluated by the memory protection unit.
- Segment base address and offset need to be added.
- Parts of segment tables as well as segments themselves can be suspended to secondary memory.

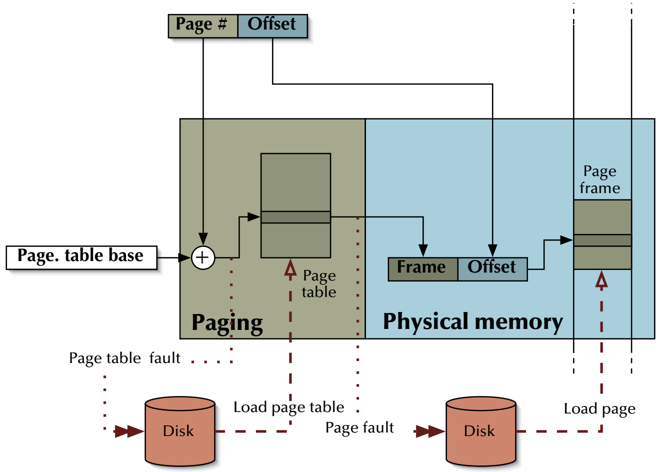
e.g. Intel x86



Memory – Paging

- Page frame address and address offset can be concatenated.
- Parts of page tables as well as pages themselves can be suspended to secondary memory (into 'frames').
- Page tables would be very large for modern processors (32-64 bit addressing)

not implemented in this pure form.

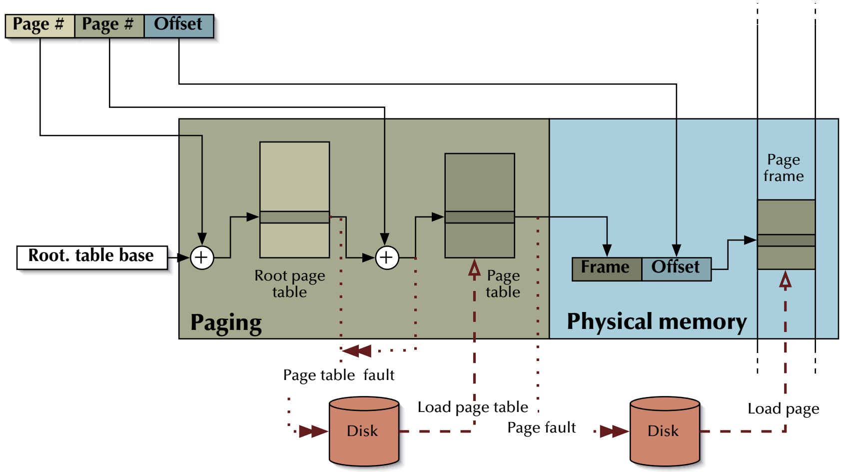


Operating Systems & Networks

Memory – Multi stage page tables

- Reducing page table sizes
- Up to four page levels (Sparc)
- More memory accesses required.

Sparc, PowerPC, Alpha, HP

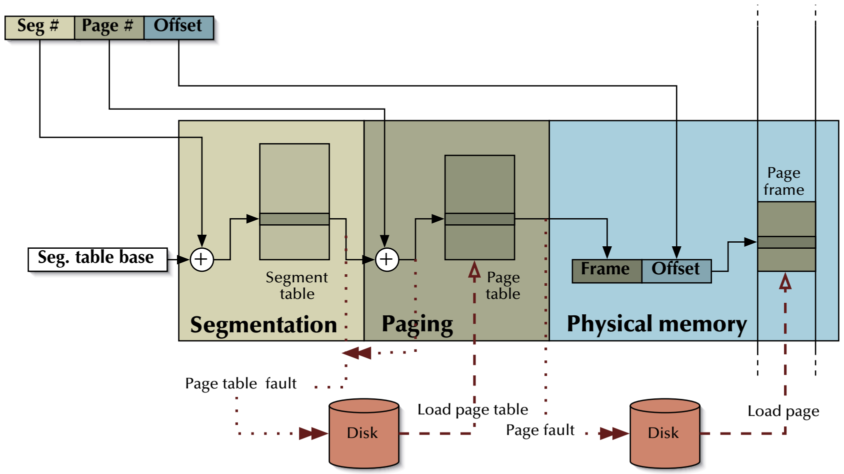


Operating Systems & Networks

Memory – Segmentation & Paging

- Allow segmentation for logical structure
- Allow paging for effective virtual memory management

x86, (PowerPC)

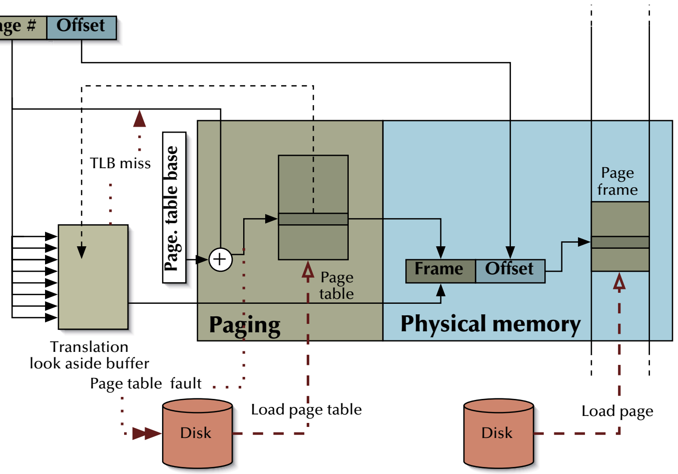


Operating Systems & Networks

Memory – Translation look aside buffers

- Accessing page tables for each access is ineffective.
- ☞ Introducing address translation caches: **Translation look aside buffers (tlb).**
- Access cache (tlb) - memory - disk (in this order) for address translation

all modern MMUs



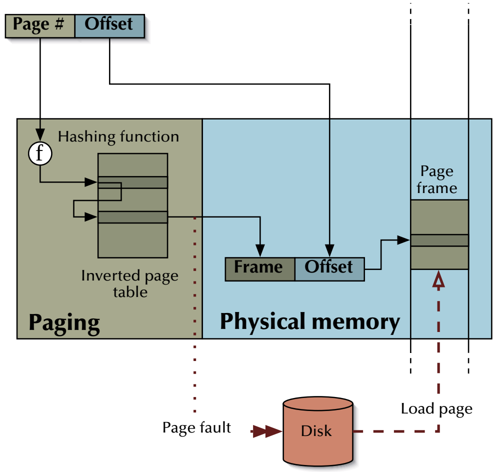
Memory – Inverted page tables

- Forward page tables grow with the size of the virtual address space.
- The number of loaded pages is bound by the physical memory.

☞ Keep only the loaded pages in the page table and resolve the virtual addresses via a hash table: ☞ **Inverted page tables (ipt)**

- IPTs are not suspended to secondary memory, but more than one access is required to translate the page number.

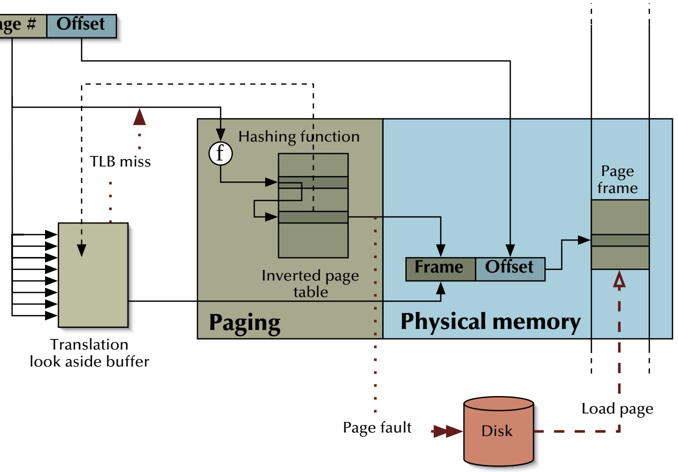
not implemented in this pure form.



Memory – Translation look aside & Inverted page tables

- Combining translation look aside buffers and inverted page tables.
- Mostly no delay (look aside buffer).
- Short delay if tlb misses (inverted page table).
- No page table loading.

PowerPC, UltraSparc



Addressing

Some current MMU implementations

	Physical addresses	Virtual addresses	TLB size	Segments	Pages	Inverted/hashed tables
Pentium 4	36 bit	32 bit (per segment)	64	different types	4 k, 4 M (optional)	-
Itanium 2	50 bit	64 bit	4*32	-	4k … 4G	-
Power PC 604	32 bit	52 bit	256	< 256 MB, (optional)	4 k	yes
Power PC 970	42 bit	64 bit	1024	< 256 MB, (optional)	4 k	yes
UltraSparc	36 bit	64 bit	64	-	8 k … 4 M	yes
Alpha	41 bit	64 bit	256	-	8 k … 4 M	-

Designing an OS memory module

Design alternatives

- Employ virtual memory in the first place?
- Employ segmentation, pagination, or a combination of those?
- Which algorithms should be applied to answer:
    - *when* to *load* a page/segment? ☞ **fetching**
    - *where* to *place* a page/segment? ☞ **placement**
    - *which* page/segment to *suspend*? ☞ **replacement**
    - *how many* pages/segments to *load* for a specific process? ☞ **resident set management**
    - *when* to *suspend* a page/segment? ☞ **cleaning**
    - *which* processes to run/suspend? ☞ **load control**

Fetching

- **Demand paging**:

  Fetch pages only if and exactly when requested by a reference to an address inside this page.

☞ may lead to a burst of page faults in some situations (e.g. starting a process).

☞ reduces the transfer between primary and secondary storage to a minimum.

- **Prepaging**:

  Predict which pages will also be required in the near future and pre-load them (together with the currently requested page).

☞ pages may be loaded, which will be never referenced

☞ multiple page loads can be more efficient if organized as a few transfers of a larger blocks

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Most systems will combine both pure forms

Placement

☞ Required for partition or pure segmentation systems

apply standard 'best-fit', 'first-fit', etc. strategies to minimize fragmentation
– there is a trade-off between minimal fragmentation and minimal placement overhead

☞ Irrelevant for all paging or mixed segmentation/paging systems

external fragmentation is not an issue here

Replacement

In order to load a new page, another page need to be suspended ☞ which one?

- **Optimal**:
  the page which will not be referenced for the longest period of *future* time

- **Least Recently Used** (**LRU**):
  the page which has not be referenced for the longest period of *past* time

- **First-In-First-Out** (**FIFO**):
  the page which resides in primary memory for the longest period of *past* time

Replacement

The practical implementation aspect of replacement algorithms:

- **Optimal**:
  ☞ can only be implemented, if all *future* memory references are known ☞ ✘

- **Least Recently Used** (**LRU**):
  ☞ can only be implemented, if all past access times/order are known ☞ check hardware support

- **First-In-First-Out** (**FIFO**):
  ☞ can be implemented without any hardware support ☞ ✔

Replacement

Full LRU implementations:

- ***Counter*** or ***time-of-access*** field in the page table:
  Update this entry with each reference to this page

  ☞ need to be supplied by hardware (not implemented in any practical system)

- ***Page stack***:
  bring a reference to the page on top of a stack with each access to this page
  (and replace the pages at the bottom of the stack)

  ☞ need to be supplied by hardware (not implemented in any practical system)

Replacement

LRU-approximations:

- **Reference-bit-shift-history algorithm***:*

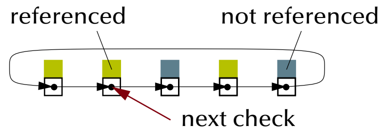
  Shift the reference bit of each page into a bit-field (□→□□□□□□□□) in each page table entry at regular intervals (employing a timer-interrupt).
  Interpret the resulting bit-field as an integer and replace the page with the smallest value

  ☞ requires a reference-bit, which is updates by hardware, as well as a hardware timer (usually provided).

Replacement

LRU-approximations:

- **Second-chance (clock) algorithm***:*



  Implement a circular list of all pages. Search the list for a not referenced page:

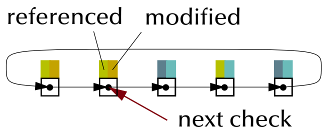
  WHILE page was referenced DO
      reset reference bit and proceed to next page
  END WHILE

  ☞ requires a reference-bit, which is updates by hardware (usually provided).

Replacement

LRU-approximations:

- **Enhanced second-chance (clock) algorithm**:



Replace pages applying the priorities:

- not referenced (first scan)
- referenced-but-not-modified (second scan)
- referenced-and-modified

☞ requires a reference and a modified-bit, which is updates by hardware (usually provided).

Replacement

Performances:

- **Optimal**:
obviously the best algorithm — impossible to implement
- **Least Recently Used** (**LRU**):
good approximation of the optimal algorithm — cannot be implemented in any current system
- **Approximated Least Recently Used** (**LRU**):
approximates the performance of LRU — can be implemented in most systems
- **First-In-First-Out** (**FIFO**):
performs worst — can be implemented in any system

Resident set management

How many pages are assigned to a specific process:

- too many:
  - the number of resident processes is reduced
  - due to localities, there is no noticeable speed-up for the specific process
- too few:
  - significant increase in the page-fault rate

☞ Challenge: find the essential working set of pages for each process at any given time

Resident set management

Strategies:

- Number of allocated pages per process can be
  - *fixed*
  - or *variable*
- Replacement can be either
  - *local* (inside each process' page set) – only possibility for fixed allocation scenes
  - *prioritized* (allow higher priority processes to expand their page sets)
  - or *global* (replace pages regardless of the processes which are using them)

Resident set management

☞ Challenge:
find the essential working page set for each process at any given time

- Calculating the optimal working set, required full knowledge of the future process behaviour
- Many approximations are suggested (and implemented), mostly employing:

Page Fault Frequencies (PFF)
or related statistical information on the past process behaviour

Problems:
- "the past does not always predict the future"
i.e. multiple locality assumptions must hold

Cleaning

- **Demand cleaning**:

Clean pages only if and exactly when a free pages is required.

☞ slows down process reaction times, since each page fault will result in a page cleaning.

☞ reduces the total transfer between primary and secondary storage to a minimum.

- **Precleaning**:

Clean multiple pages according to replacement criteria introduced above
before a page fault occurs.

☞ too many pages might be cleaned, resulting in an increase of page faults

☞ multiple page cleanings can be more efficient if organized as a few transfers of a larger blocks

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Load Control

How many processes will be resident in primary memory?

- More processes in primary memory implies less pages per process
- Beyond a critical threshold of pages per process, the page fault rate rises significantly

☞ **Thrashing** occurs

- The overall performance of the system is approaching nil,
since most of the time is spent for page loads

☞ Reduce the number of resident processes immediately

Load Control

Which process is to be suspended?

- Lowest priority process
- Process with the highest page fault frequency
- Process with the smallest current resident page set
- Process with the largest current resident page set
- Last activated process
- Process with the largest remaining execution time (see scheduling)

Design alternatives

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Real-time / predictable systems:
no virtual memory!

Memory

- **Requirements & hardware structures**
  - MMU features & requirements
- **Partitioning, segmentation, paging & virtual memory**
  - Simple segmentation
  - Simple paging, multi-level paging, combined segmentation & paging
  - Translation look aside buffers
  - Hashed tables, Inverted page tables
- **Virtual memory management algorithms**
  - Fetching & placement
  - Replacement
  - Resident set management
  - Cleaning
  - Load control