Concurrent & Distributed Systems 2006

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what is offered here?

Fundamentals & Overview

as well as perspectives, paths, methods, implementations

of/into/for/about

Concurrent & Distributed Systems

who could be interested in this?

anybody who …

… works with real-world scale computer systems

… would like to learn how to analyse and design operational and robust systems

… would like to understand more about the existing trade-off between theory, the real-world, traditions, and pragmatism in computer science

… would like to know what you do not know about concurrent systems

who are these people? – introduction

This course will be given by

Uwe R. Zimmer

how will this all be done?

☞ Lectures:

- 3 per week … all the nice stuff and theory
  Tuesday, 14:00 (PHYS-T1); Wednesday 12:00 (CHEM-T); Thursday 14:00 (CHEM-T)

☞ Laboratories:

- 2 hours per week … all the rough stuff and practice
  dates tba – all in CSIT Nxxx
  laboratory-enrolment: `https://cs.anu.edu.au/streams/`

☞ Resources:

- introduced in the lectures and collected on the course page:
  `http://cs.anu.edu.au/student/comp2310/`
  … as well as schedules, slides, sources, etc. pp. … keep an eye on this page!

☞ Assessment:

- exam at the end of the course (70%) plus two assignments (15% each), and mid-term check (0%)

Useful Literature

[Ben-Ari06]
M. Ben-Ari
Principles of Concurrent and Distributed Programming
2006, second edition
Prentice-Hall,
ISBN 0-13-711821-X

- Many algorithms and basic concepts will be found here

Main technical textbook for this course.

☞ references for specific aspects of the course will be given at appropriate places

Concurrent & Distributed Systems

Lectures 2006

[number of lectures] - total: ≈28

1. Concurrency [3]

1.1. Forms of concurrency [1]
- Coupled dynamical systems

1.2. Models and terminology [1]
- Abstractions
- Interleaving
- Atomicity
- Proofs in concurrent and distributed systems

1.3. Processes & threads[1] [1]
- Basic definitions
- Process states
- Implementations

2. Mutual exclusion [3]

2.1. by shared variables [2]
- Failure possibilities
- Dekker's algorithm

2.2. by test-and-set hardware support [0.5]
- Minimal hardware support

2.3. by semaphores[1] [0.5]
- Dijkstra definition
- OS semaphores

3. Condition synchronization [4]

3.1. Shared memory synchronization [2]
- Semaphores[1]
- Cond. variables
- Conditional critical regions
- Monitors
- Protected objects

3.2. Message passing [2]
- Asynchronous / synchronous[1]
- Remote invocation / rendezvous
- Message structure
- Addressing

4. Non-determinism [2] in concurrent systems

4.1. Correctness under non-determinism [1]
- Forms of non-determinism
- Non-determinism in concurrent/distributed systems
- Is consistency/correctness plus non-determinism a contradiction?

4.2. Select statements[1] [1]
- Forms of non-deterministic message reception

5. Scheduling [2]

5.1. Problem definition and design space [1]
- Which problems are addressed / solved by scheduling?

5.2. Basic scheduling methods [1]
- Assumptions for basic scheduling
- Basic methods

6. Safety and liveness [3]

6.1. Safety properties
- Examples for essential time-independent safety properties

6.2. Livelocks, fairness
- Forms of livelocks
- Classification of fairness

6.3. Deadlocks
- Detection
- Avoidance
- Prevention (& recovery)

6.4. Failure modes

6.5. Idempotent & atomic operations
- Definitions
- Examples

7. Architectures for CDS [3]

7.1. Academic
- CSP
- occam

7.2. Production
- Ada95
- JAVA

7.3. Historical roots: UNIX[1]
- UNIX processes
- UNIX communication schemes

1. additional UNIX / C / POSIX references and examples

7.4. Dedicated hardware
- Communication controllers

7.5. Embedded systems

8. Distributed systems [8]

8.1. Networks [1]
- OSI model
- Network implementations

8.2. Global times [1]
- synchronized clocks
- logical clocks

8.3. Distributed states [1]
- Consistency
- Snapshots
- Termination

8.4. Distributed communication [1]
- Name spaces
- Multi-casts
- Elections
- Network identification
- Dynamical groups

8.5. Distributed safety and liveness [1]
- Distributed deadlock detection

8.6. Forms of distribution/redundancy [1]
- computation
- memory
- operations

8.7. Transactions [2]

Laboratories & Assignments 2006

[number of labs] - total: 9

Laboratories

1. Concurrency language support basics (in Ada95) [3]

1.1. Structured, strongly typed programming
- Program structures
- Data structures

1.2. Generic, re-usable programming
- Generics
- Abstract types

1.3. Concurrent processes:
- Creation
- Termination
- Rendezvous

2. Concurrent programming [3]

2.1. Synchronization
- Protected objects

2.2. Remote invocation
- Extended rendezvous

2.3. Client-Server architectures
- Entry families
- Requeue facility

3. Concurrency in UNIX [3]

3.1. UNIX process creation, termination

3.2. UNIX process communication
- Pipes
- Sockets

Assignments

1. Concurrent programming [15%]

Ada95 programming task involving:
- Mutual exclusion
- Synchronization
- Message passing

2. Concurrent programming in UNIX [15%]

UNIX programming task involving:
- Semaphores
- Process communication

Examination & Checkpoints

1. Mid-term check

- Test question set with supplied answers [not marked]

2. Final exam – [70%]

- Examining the complete lecture

Marking

The final mark is based on the assignments [30%] plus the final examination [70%]

Ada refresher course

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References for this chapter

[Cohen96]

Norman H. Cohen
Ada as a second language
McGraw-Hill series in computer science, 2nd edition

[Ada 95 Reference manual]

(see lab pages or web)

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.

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

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;
```

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;
```

Exceptions

… introducing:

- exception handling
- enumeration types
- functional type attributes

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;
```


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 implementations with proper information hiding

```
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  := 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_Private;
```

identical

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;
```

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;
```

identical

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;
```

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;
```

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;
```

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;
```

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;
```

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 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)

☞ ***Ada2005 compilers are available now!***

Summary

Ada refresher course

- 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

2

Concurrency – The Basic Concepts

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References for this chapter

[Ben-Ari90]

M. Ben-Ari
Principles of Concurrent and Distributed Programming
1990
Prentice-Hall,
ISBN 0-13-711821-X

What is concurrency?

Working definitions:

- literally 'concurrent' means:

  Adj.: Running together in space, as parallel lines; going on side by side, as proceedings; occurring together, as events or circumstances; existing or arising together; conjoint, associated [Oxfords English Dictionary]

- technically 'concurrent' is usually defined negatively as:

  If there is no observer who can identify two events as being in strict temporal sequence (i.e. one event has fully terminated before the other one started) then these two events are considered concurrent.

Why do we need/have concurrency?

- Physics, engineering, electronics, biology, …

☞ basically *every* real world system is **concurrent**!

- Sequential processing is suggested by most kernel computer architectures

… *but* almost all current processor architectures have **concurrent elements**
… and *most* computer systems are part of a **concurrent network**

- Strict sequential processing is suggested by the most widely used programming languages

… which is a reason why you might believe that concurrent computing is rare/exotic/hard

☞ sequential programming delivers some *fundamental parts* for concurrent programming

☞ ***but we need to add a number of further crucial concepts***

Why would a computer scientist consider concurrency?

- ☞ … to *be able* to connect computer systems with the real world
- ☞ … to *be able* to employ / design concurrent parts of computer architectures
- ☞ … to *construct* complex software packages (operating systems, compilers, databases, …)
- ☞ … to *understand* where sequential **and/or** concurrent programming is **required**

  … or: to *understand* where sequential or concurrent programming can be chosen freely
- ☞ … to *enhance* the reactivity of a system
- ☞ …

Forms of concurrency

A computer scientist's view on concurrency

- Overlapped I/O and computation

  ☞ employ interrupt programming
  to handle I/O

- Multi-programming

  ☞ allow multiple independent programs
  to be executed on one cpu

- Multi-tasking

  ☞ allow multiple interacting processes
  to be executed on one cpu

- Multi-processor systems

  ☞ add physical/real concurrency

- Parallel Machines &
  distributed operating systems

  ☞ add (non-deterministic)
  communication channels

- General network architectures

  ☞ allow for any form of
  communicating, distributed entities

A computer scientist's view on concurrency

Terminology for real parallel machines architectures:

- **SISD** [singe instruction, single data]
  - ☞ standard sequential processors
- **SIMD** [singe instruction, multiple data]
  - ☞ vector processors
- **MISD** [multiple instruction, single data]
  - ☞ pipelines
- **MIMD** [multiple instruction, multiple data]
  - ☞ multiprocessors or computer networks

An engineer's view on concurrency

☞ Multiple **physical, coupled, dynamical systems** form the actual environment and/or task at hand

- ☞ In order to model and control such a system, its **inherent concurrency** needs to be considered
- ☞ **Multiple less powerful processors** are often preferred over a single high-performance cpu
- ☞ The system design of usually strictly **based on the structure of the given physical system**.

Does concurrency lead to chaos?

Concurrency often leads to the following features / issues / problems:

- non-deterministic phenomena
- non-observable system states
- results may depend on more than just the input parameters and states at start time (timing, throughput, load, available resources, signals … throughout the execution)
- non-reproducibility ☞ debugging?

Meaningful employment of concurrent systems features:

- non-determinism employed where the underlying system is non-deterministic
- non-determinism employed where the actual execution sequence is meaningless
- synchronization employed where adequate … but only there

☞ Control & monitor where required (and do it right), but not more …

Concurrency on different abstraction levels / perspectives

☞ **Networks**

- Multi-CPU network nodes and other specialized sub-networks
- Single-CPU network nodes – still including buses & I/O sub-systems
- Single-CPUs
- Operating systems (& distributed operating systems)

☞ **Processes & threads**

☞ **High-level concurrent programming**

☞ **Assembler level concurrent programming**

- Individual concurrent units inside one CPU
- Individual electronic circuits
- …

The concurrent programming abstraction

1. What appears *sequential* on a higher abstraction level,
   is usually *concurrent* at a lower abstraction level:

   ☞ e.g. low-level concurrent I/O drivers, which might not be visible at a high programming level

2. What appears *concurrent* on a higher abstraction level,
   might be *sequential* at a lower abstraction level:

   ☞ e.g. Multi-processing systems, which are executed on a single, sequential CPU

The concurrent programming abstraction

- technically 'concurrent' is usually defined negatively as:

  If there is no observer who can identify two events as being in strict temporal sequence (i.e. one event has fully terminated before the other one starts up), then these two events are considered concurrent.

- 'concurrent' in the context of programming:

  "Concurrent programming abstraction is the study of interleaved execution sequences of the atomic instructions of sequential processes."

  (Ben-Ari)

The concurrent programming abstraction

Concurrent program ::=
Multiple sequential programs (processes)
which are executed *simultaneously*

P.S. it is generally assumed that simultaneous execution means
that there is one execution unit (processor) per sequential program

– even though this is usually not correct,
it is an often valid assumption in the context of concurrent programming.

The concurrent programming abstraction

☞ No interaction between concurrent system parts means that we can analyse them individually as pure sequential programs.

☞ Interaction points:

- *Contention*:
  multiple concurrent execution units compete for one shared resource
- *Communication*:
  Explicit passing of information **and/or** synchronization

The concurrent programming abstraction

Time-line or Sequence?

Consider time (durations) explicitly:

☞ Real-time systems ☞ *join the appropriate courses*

Consider the sequence of interaction points only:

☞ Non-real-time systems ☞ *this course*

The concurrent programming abstraction

Correctness of concurrent non-real-time systems [logical correctness]:

- does *not depend* on speeds / execution times / delays
- does *not depend* on actual interleaving of concurrent processes [scheduler]

☞ **does *depend* on all possible sequences of interaction points**

The concurrent programming abstraction

Correctness vs. testing in concurrent systems:

Slight changes in external triggers may (and usually will) result in complete different schedules (interleaving):

- ☞ Concurrent programs which depend in any way on external influences **cannot be tested easily**
- ☞ Designs which are *provably correct* with respect to the specification and are *independent of the actual timing behaviour* are essential.

P.S. some timing restrictions for the scheduling still persist in non-real-time systems, e.g. ‘fairness’

The concurrent programming abstraction

Atomic operations:

Correctness proofs / designs in concurrent systems rely on the assumptions of

'atomic operations' [detailed discussion later]:

- complex and powerful atomic operations ease the correctness proofs, but may limit flexibility in the design
- simple atomic operations are theoretically sufficient, but may lead to complex systems which correctness cannot be proven in practice.

The concurrent programming abstraction

Standard concepts of correctness:

- Partial correctness:

$$(P(I) \wedge terminates(Program(I, O))) \Rightarrow Q(I, O)$$

- Total correctness:

$$P(I) \Rightarrow (terminates(Program(I, O)) \wedge Q(I, O))$$

where I, O are input and output sets,
P is a property on the input set,
and Q is a relation between input and output sets

☞ do these concepts apply to and are sufficient for concurrent systems?

The concurrent programming abstraction

Extended concepts of correctness in concurrent systems:

¬ Termination is often not intended or even considered a failure

- Safety properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Box Q(I, S)$$

where $\Box Q$ means that Q does *always* hold

- Liveness properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond Q(I, S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)
and S is the current state of the concurrent system

The concurrent programming abstraction

- Safety properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Box Q(I, S)$$

where $\Box Q$ means that Q does *always* hold

Examples:

- Mutual exclusion (no resource collisions)
- Absence of deadlocks
  (and other forms of 'silent death' and 'freeze' conditions)
- Specified responsiveness or free capabilities
  (typical in real-time / embedded systems or server applications)

The concurrent programming abstraction

- Liveness properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond Q(I, S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)

Examples:

- Requests need eventually to be completed
- The state of the system needs eventually be displayed to the outside
- No part of the system is to be delayed forever (fairness)

☞ Interesting liveness properties can be extremely hard to be proven

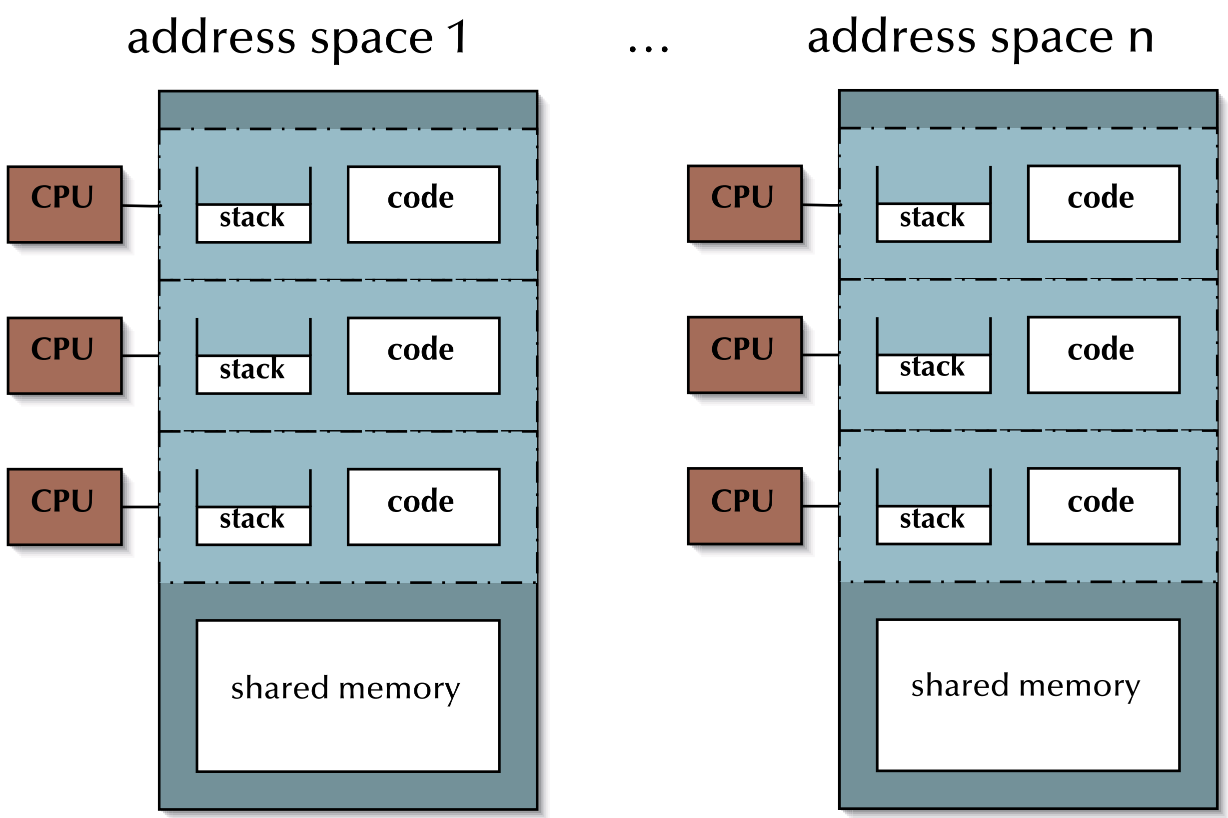
Introduction to processes and threads

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



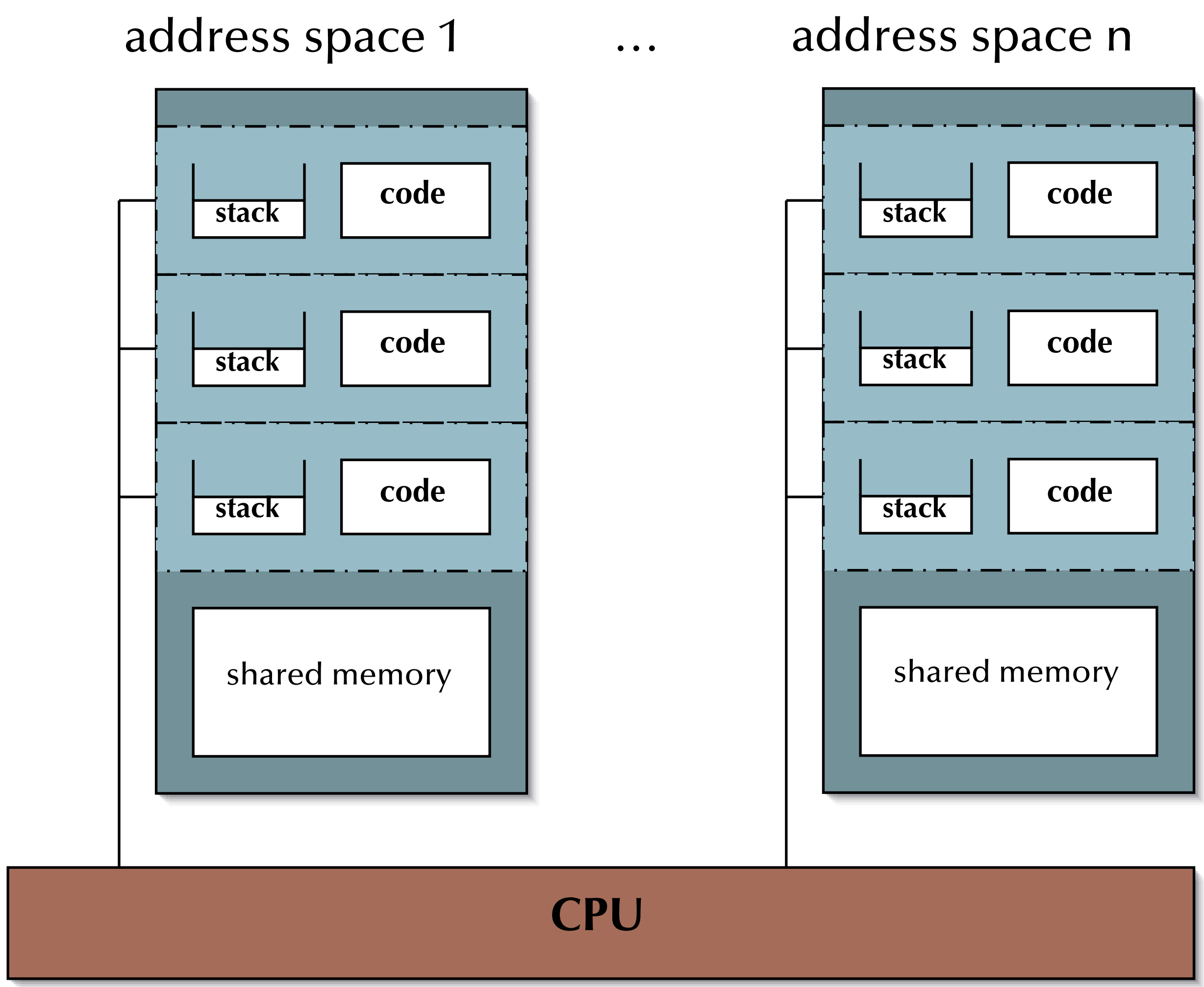
Introduction to processes and threads

1 CPU for all control-flows

- OS: emulate one CPU for every control-flow

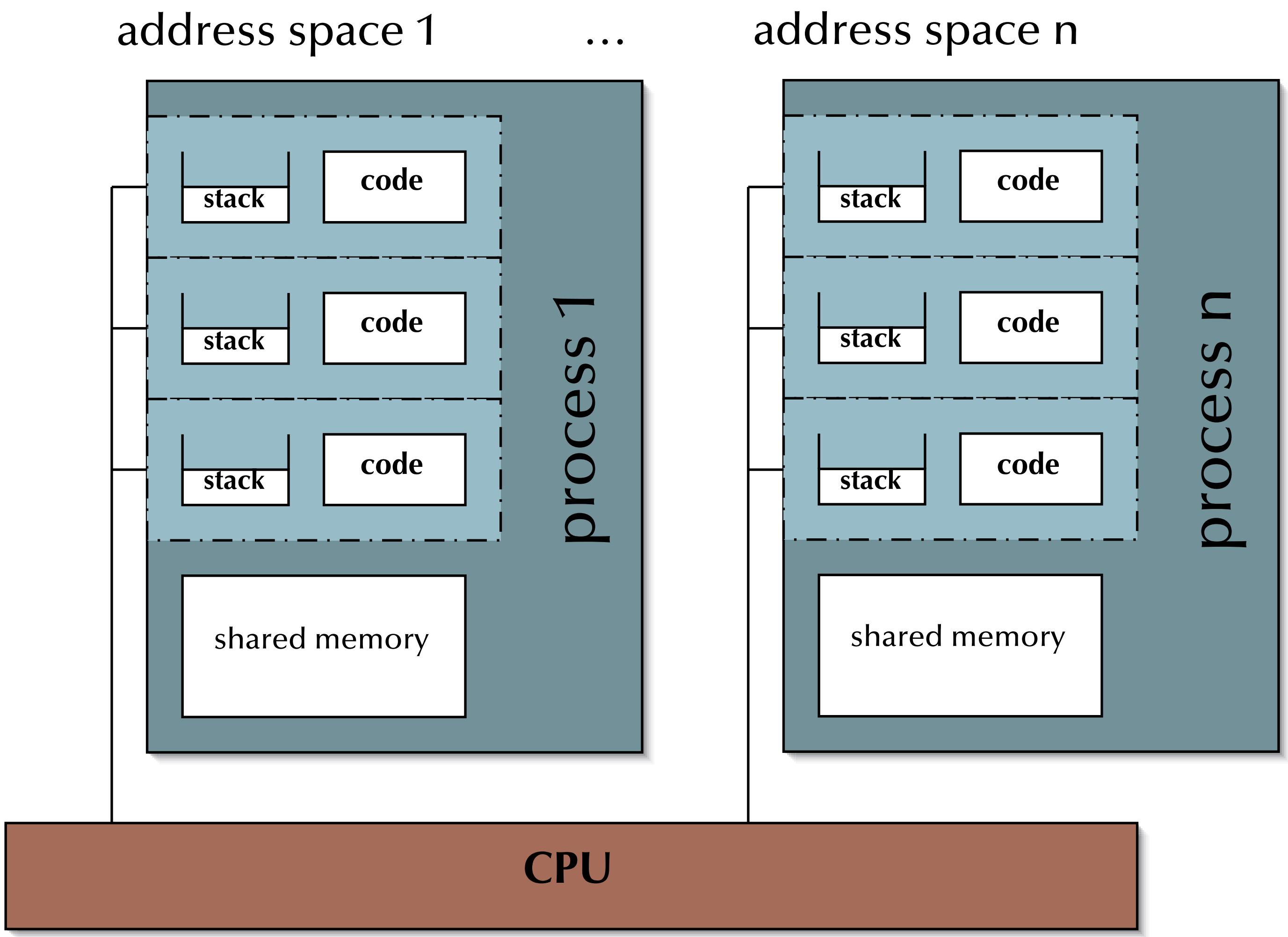
☞ **multi-tasking** operating system

- support for memory protection becomes essential



Processes

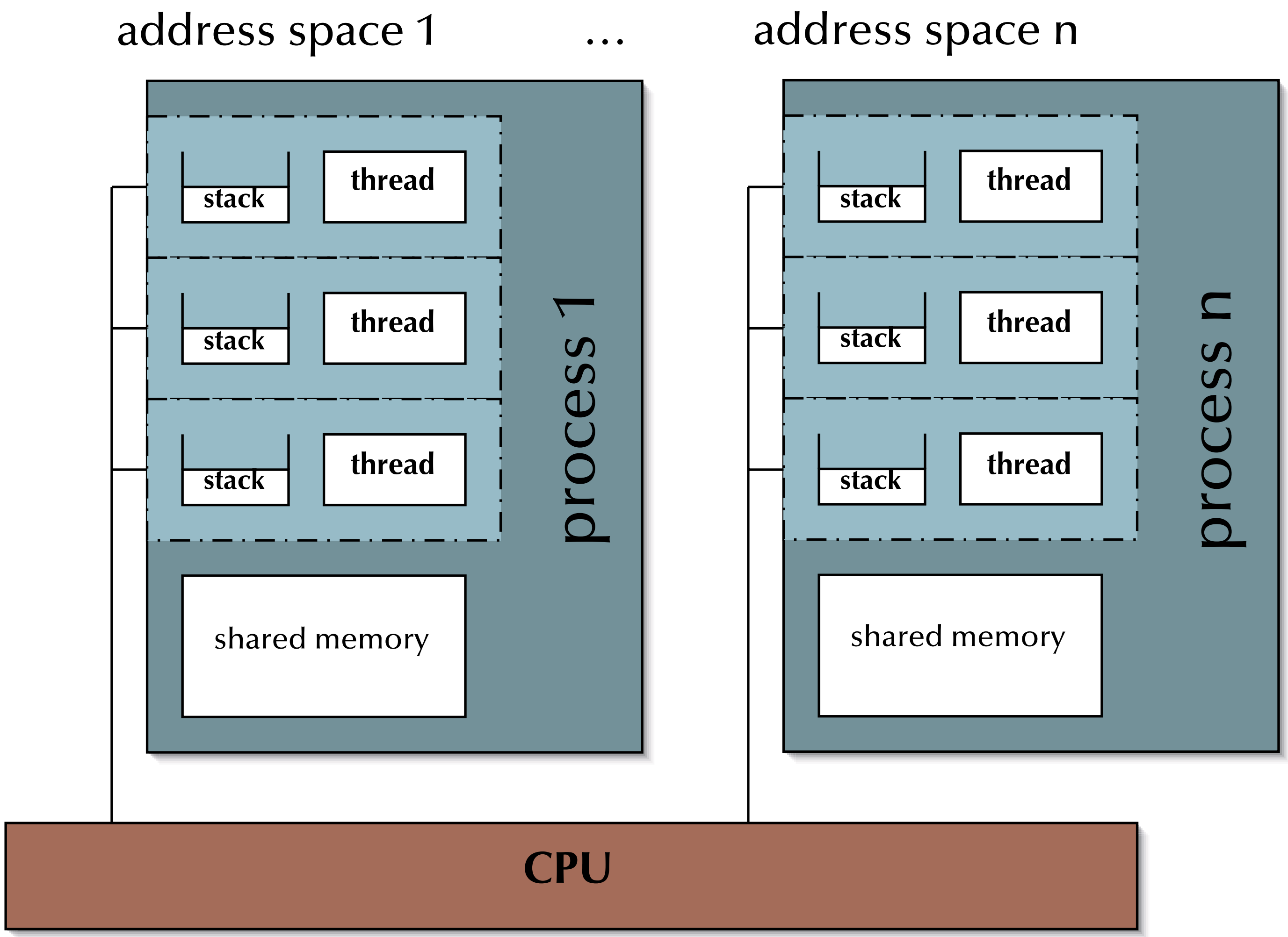
- **Process** ::=
  address space
  + control flow(s)
- Kernel has full knowledge about all *processes* as well as their *requirements* and current *resources* (see below)



Threads

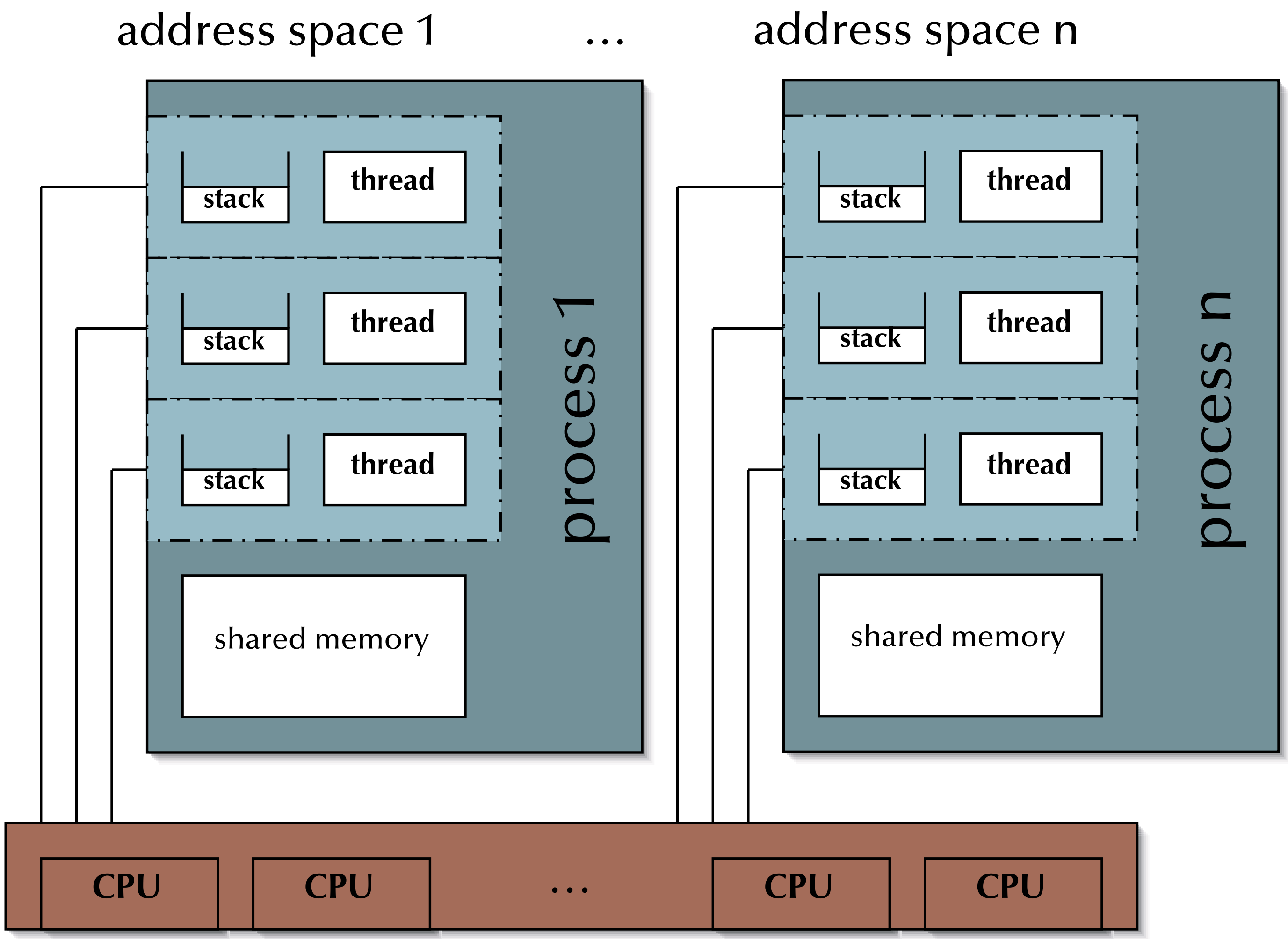
Threads (individual control-flows) can be handled:

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



Introduction to processes and threads

Multi-processor-systems



- The kernel may execute multiple processes at a time.

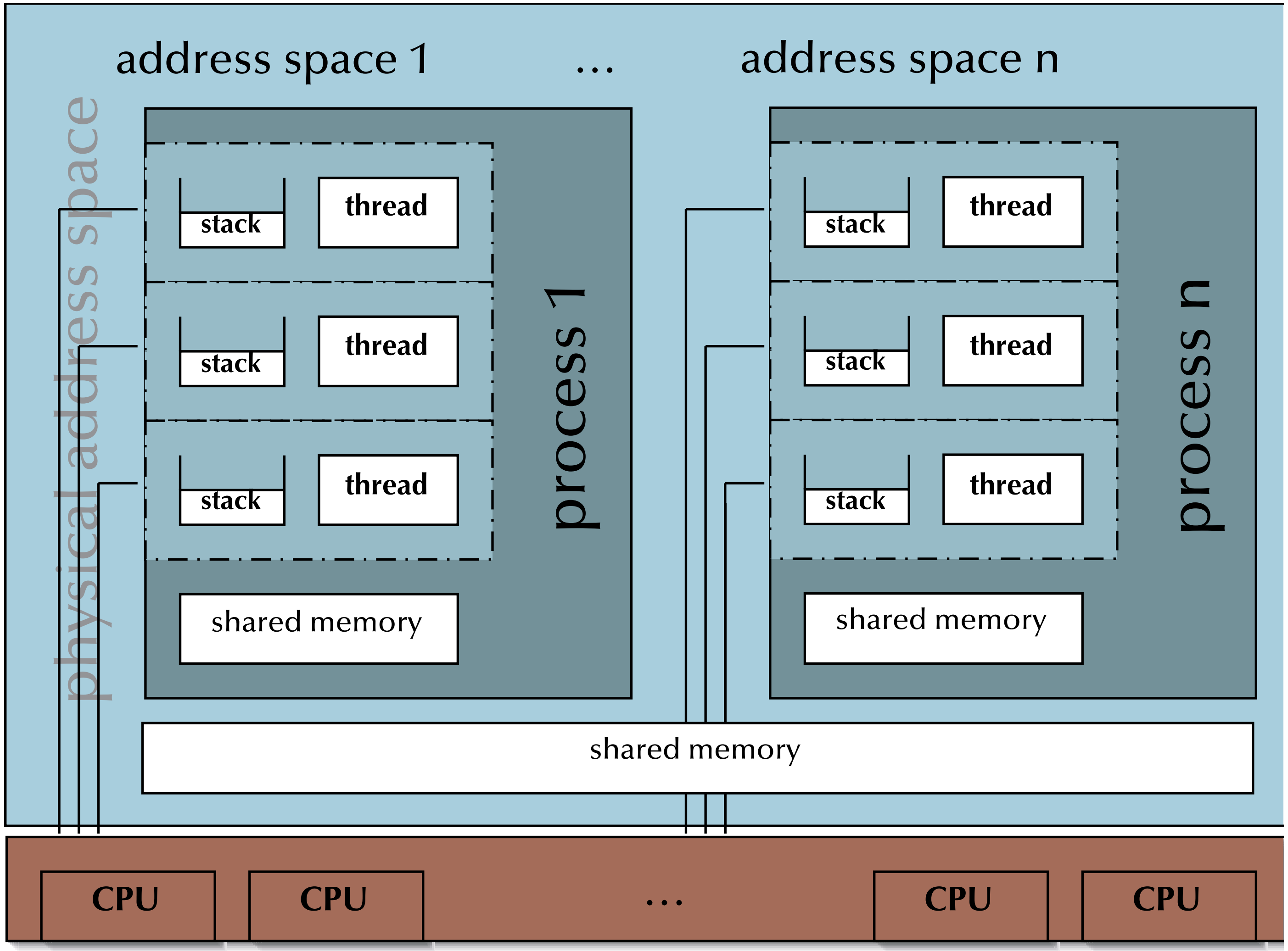
☞ Address space and resource restrictions of individual CPUs and processes/threads need to be considered.

☞ 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:

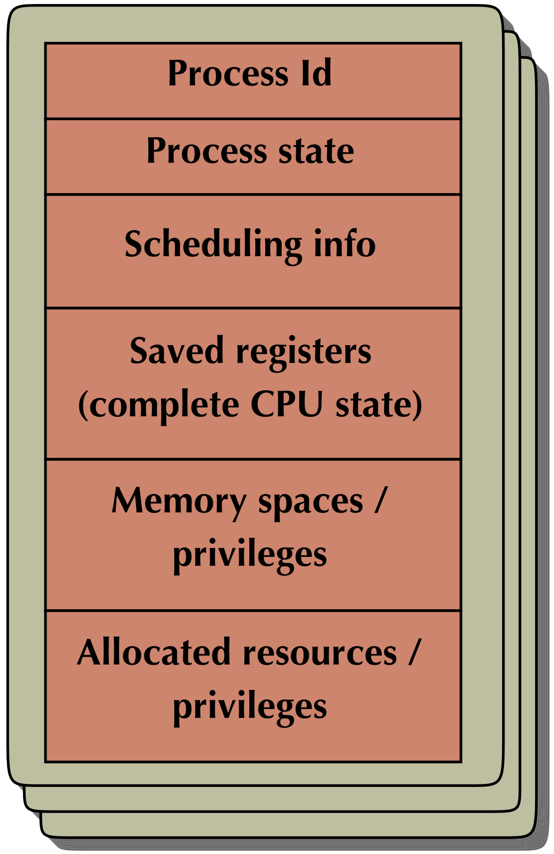
- e.g. user-level control-flows, which the kernel has no knowledge about at all
- e.g. kernel-level control-flows, which are handled as processes with some restrictions

Process Control Blocks

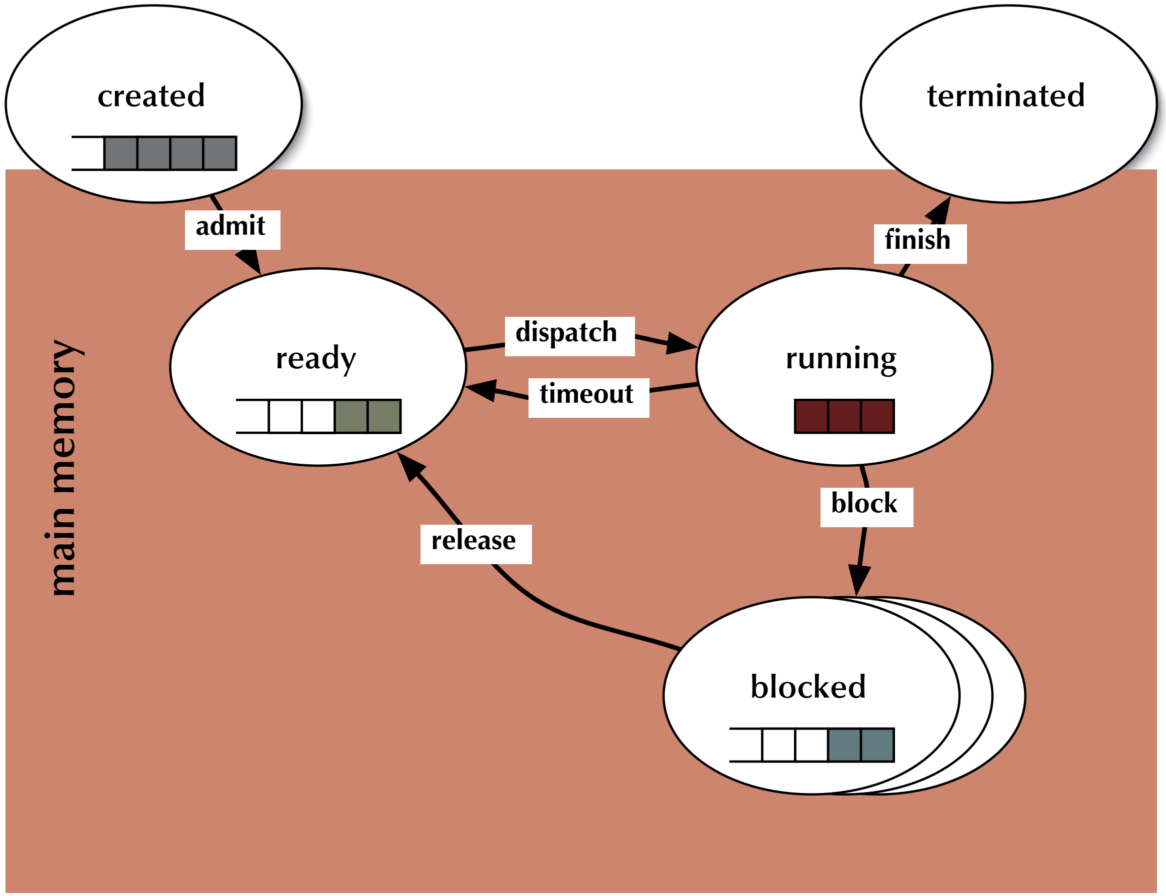
- **Process Id**
- **Process state**:
  {created, ready, executing, blocked, suspended, …}
- **Scheduling info**:
  priorities, deadlines, consumed CPU-time, …
- **CPU state**:
  saved/restored information while context switches
  (incl. the program counter, stack pointer, …)
- **Memory spaces / privileges**: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

… PCBs are usually enqueued at a certain state or condition

Process Control Blocks (PCBs)

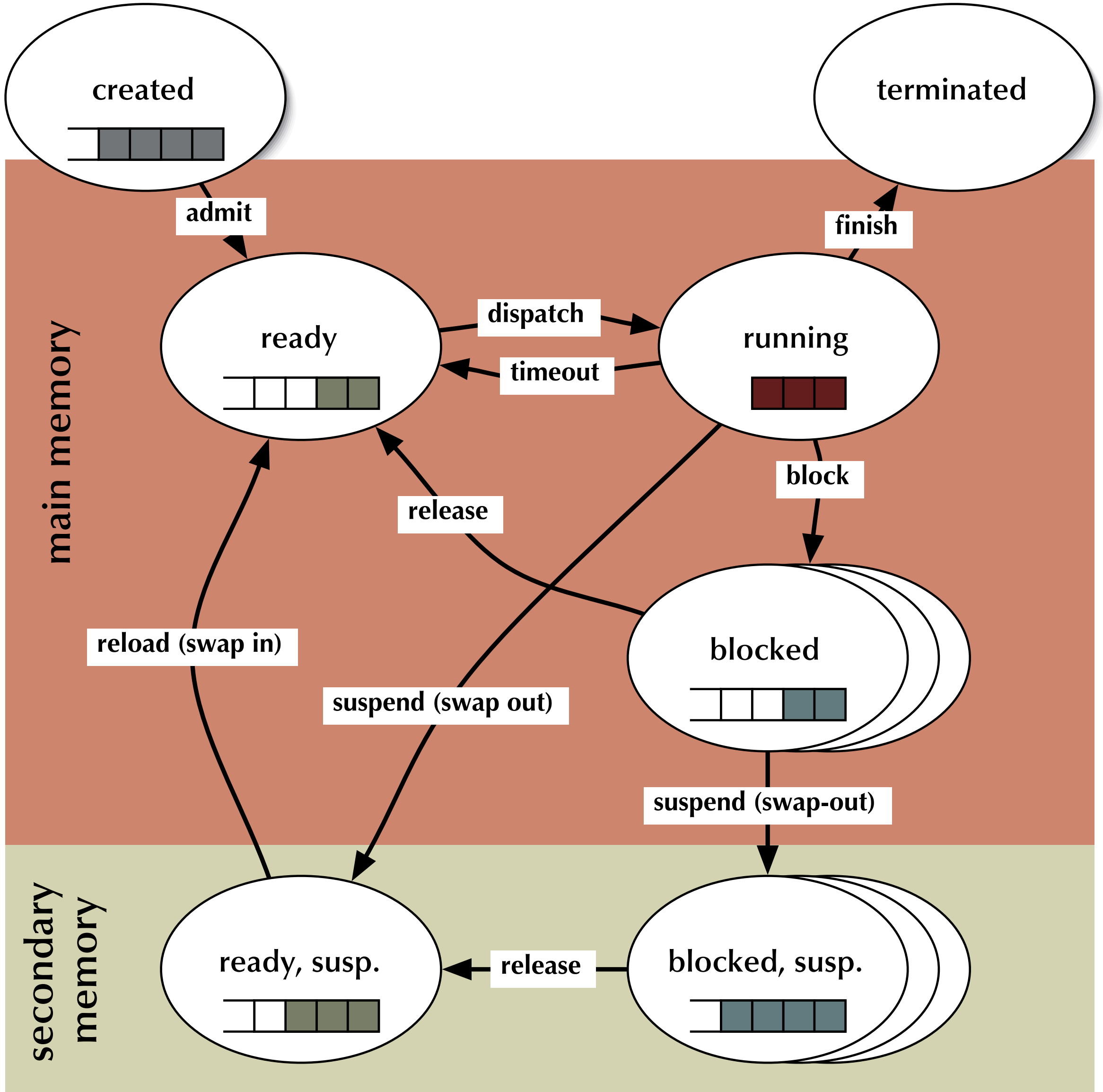


Process states



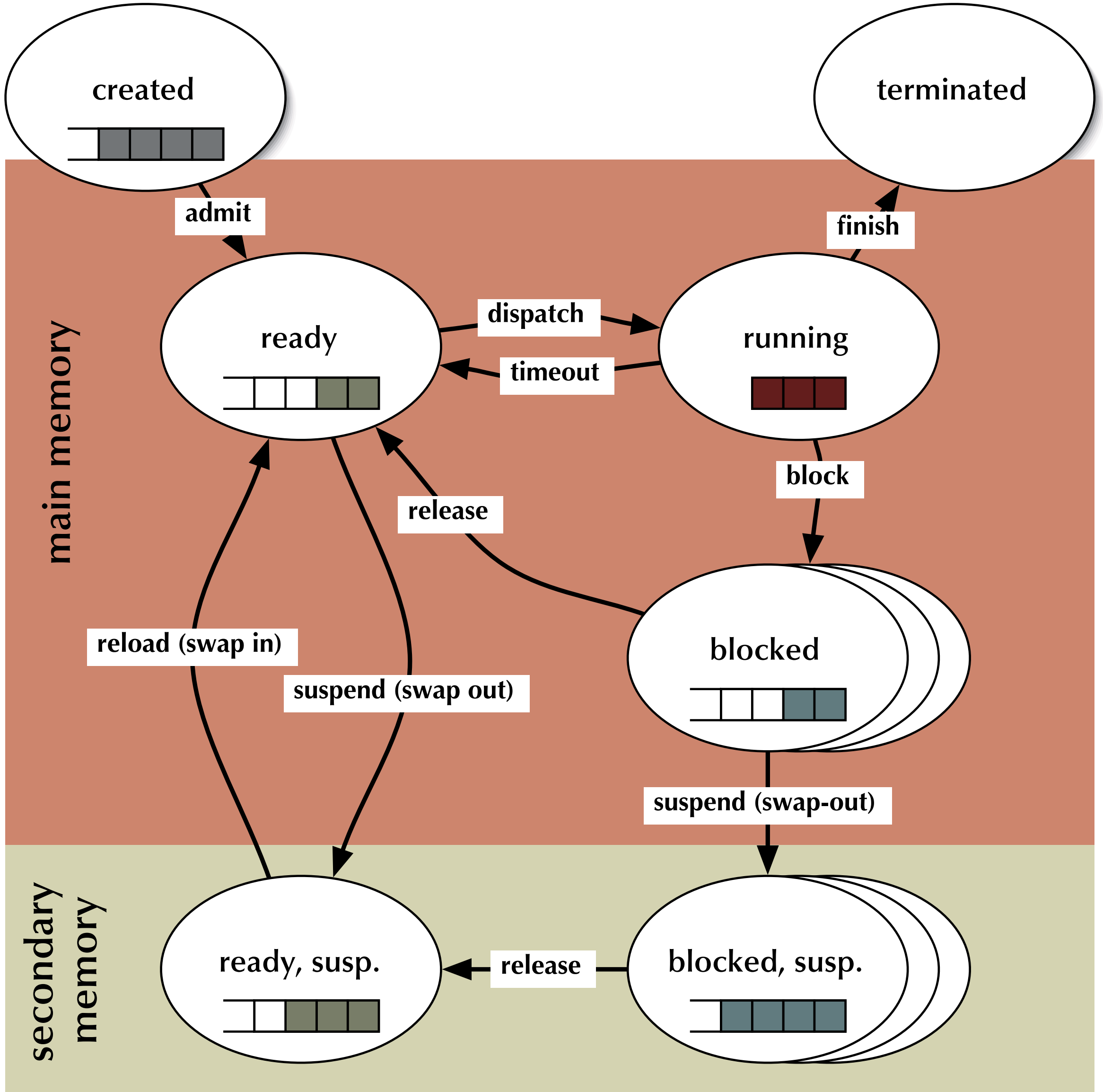
- **created**: the task is ready to run, but not yet considered by any dispatcher – waiting for admission
- **ready**: ready to run – waiting for a free CPU
- **running**: holds a CPU and executes
- **blocked**: not ready to run – waiting for a a resource to become available

Process states



- **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 resource
- **suspended states**: swapped out of main memory (not time critical processes)
  – waiting for main memory space (and other resources)

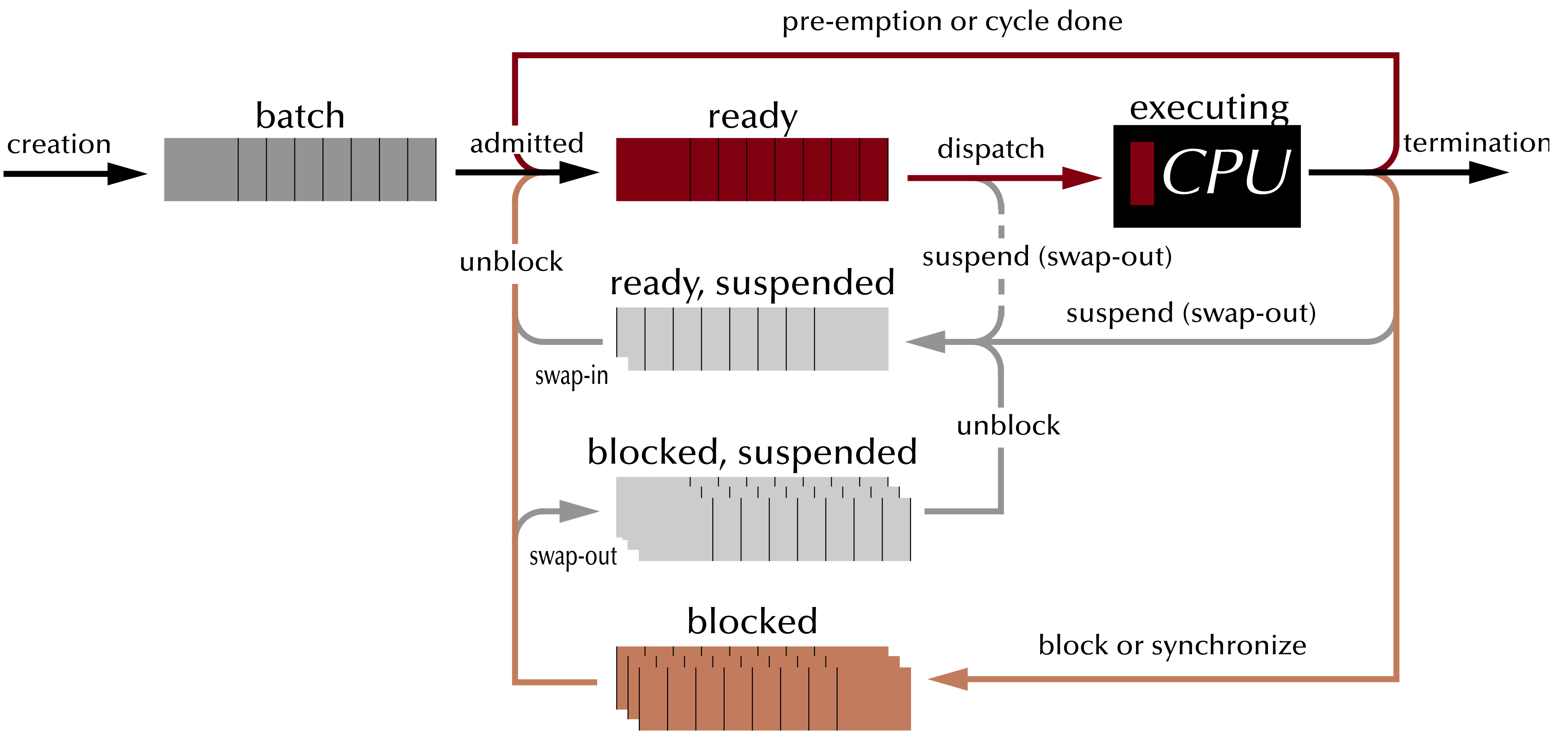
Process states



- **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 resource
- **suspended states**: swapped out of main memory (not time critical processes)
  – waiting for main memory space (and other resources)

☞ dispatching and suspending can be independent modules here

Process states



UNIX processes

In UNIX systems tasks are created by 'cloning'

```
pid = fork ();
```

resulting in a *duplication* of the *current* process

- returning **0** to the newly created process (the 'child' process)
- returning the **process id** of the child process to the creating process (the 'parent' process) or **-1** for a failure

Frequent usage:

```
if (fork () == 0) {
  … the child's task …
  … often implemented as: exec ("absolute path to executable file", "args");
  exit (0);                      /* terminate child process */
} else {
  … the parent's task …
  pid = wait ();                 /* wait for the termination of one child process */
}
```


Communication between UNIX tasks ('pipes')

```
int data_pipe [2], c, rc;

if (pipe (data_pipe) == -1) {
 perror ("no pipe"); exit (1);
}

if (fork () == 0) {
 close (data_pipe [1]);
 while ((rc = read
   (data_pipe [0], &c, 1)) > 0) {
    putchar (c);
 }
 if (rc == -1) {
  perror ("pipe broken");
  close (data_pipe [0]);
  exit (1);
 }
 close (data_pipe [0]); exit (0);
} else {

 close (data_pipe [0]);
 while ((c = getchar ()) > 0) {
  if (write
   (data_pipe[1], &c, 1) == -1) {
    perror ("pipe broken");
    close (data_pipe [1]);
    exit (1);
  };
 }
 close (data_pipe [1]);
 pid = wait ();
}
```

Concurrent programming languages

Requirement

- Concept of **tasks**, **threads** or other **potentially concurrent entities**

Frequently requested essential elements

- Support for **management** or concurrent entities (create, terminate, …)
- Support for **contention management** (mutual exclusion, …)
- Support for **synchronization** (semaphores, monitors, …)
- Support for **communication** (message passing, shared memory, rpc, …)
- Support for **protection** (tasks, memory, devices, …)

Concurrent programming languages

Language candidates

- Ada95, Chill, Erlang
- Occam, CSP
- Java, C#
- Modula-2
- Lisp, Haskell, Caml, Miranda
- Smalltalk, Squeak
- Prolog
- Esterel, Signal

Without any support for concurrency: Eiffel, C, C++, Pascal, Fortran, Cobol, Basic…

C-libraries & interfaces

- POSIX
- MPI (message passing interface)

Languages explicitly supporting concurrency: e.g. 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.

A protected queue specification

```
generic
   type Element is private;

package Queue_Pack_Protected_Generic is

   QueueSize : constant Integer := 10;
   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_Generic;
```

A protected queue *implementation*

```
package body Queue_Pack_Protected_Generic 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_Generic;
```

A protected queue test task set

```
with Queue_Pack_Protected_Generic;
with Ada.Text_IO; use Ada.Text_IO;

procedure Queue_Test_Protected_Generic is


   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character);
   use Queue_Pack_Protected_Character;


   Queue : Protected_Queue;


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


(…)
```

… what's left to do: implement the tasks '`Producer`' and '`Consumer`'

A protected queue test task set (producer)

```
(…)

   task body Producer is

      Item   : Character;
      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 protected queue test task set (consumer)

```
(…)

   task body Consumer is

      Item   : Character;

   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_Generic;
```

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)

Languages suggesting concurrency: e.g. functional programming

Implicit concurrency in some programming schemes

```
qsort []     = []
qsort (x:xs) = qsort [y | y <- xs, y < x] ++ [x] ++ qsort [y | y <- xs, y >= x]
```

Strict functional programming is **side-effect free**

☞ Parameters can be evaluated independently ☞ concurrently

Some functional languages allow for '**lazy evaluation**',
i.e. sub-expressions are not necessarily evaluated completely:

```
borderline = (n /= 0) && (g (n) > h (n))
```

- ☞ if `n` equals zero the evaluation of `g(n)` and `h(n)` can be stopped (or not even be started)
- ☞ concurrent program parts need to be interruptible in this case

(Lazy) sub-expression evaluations in imperative languages assume sequential execution:

```
if Pointer /= nil and then Pointer.next = nil then …
```

Concurrency – The Basic Concepts

- **Forms of concurrency**
- **Models and terminology**
  - Abstractions and perspectives: computer science, physics & engineering
  - Observations: non-determinism, atomicity, interaction, interleaving
  - Correctness in concurrent systems
- **Processes and threads**
  - Basic concepts and notions
  - Process states
- **First examples of concurrent programming languages:**
  - Explicit concurrency: Ada95
  - Implicit concurrency: functional programming – Lisp, Haskell, Caml, Miranda

3

Mutual Exclusion

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References for this chapter

[Ben-Ari90]

M. Ben-Ari
Principles of Concurrent
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The general mutual exclusion scenario

- *N* processes execute (infinite) instruction sequences concurrently.
  Each instruction belongs to either a *critical* or *non-critical section*.

☞ Safety property 'Mutual exclusion':

Instructions from critical sections of two or more processes must never be interleaved!

- More required properties:
  - **No deadlocks**: If one or multiple processes try to enter their critical sections then *exactly one* of them must succeed.
  - **No starvation**: Every process which tries to enter one of his critical sections must *succeed eventually*.
  - **Efficiency**: The decision which process may enter the critical section must be made *efficiently* in all cases, i.e. also when there is no contention.

The general mutual exclusion scenario

- *N* processes execute (infinite) instruction sequences concurrently.
  Each instruction belongs to either a *critical* or *non-critical section*.

☞ Safety property 'Mutual exclusion':

Instructions from critical sections of two or more processes must never be interleaved!

- Further assumptions:
  - **Pre- and post-protocols** can be executed before and after each critical section.
  - Processes may *delay infinitely in non-critical sections*.
  - Processes do *not delay infinitely in critical sections*.

Mutual exclusion: Atomic load & store operations

Atomic load & store operations

☞ Assumption 1: every individual base memory cell (word) **load** and **store** access is atomic

☞ Assumption 2: there is *no* atomic combined **load-store** access

```
G : Natural := 0; -- assumed to be mapped on a 1-word cell in memory
```

```
task body P1 is
begin
 G := 1
 G := G + G;
end P1;
```

```
task body P2 is
begin
 G := 2
 G := G + G;
end P2;
```

```
task body P3 is
begin
 G := 3
 G := G + G;
end P3;
```

☞ After the first global initialisation, `G` can have *many* values between `0` and `24`

☞ After the first global initialisation, `G` will have *exactly one* value between `0` and `24`

Mutual exclusion: first attempt

```
Turn: Positive range 1..2 := 1;

task body P1 is
begin
  loop
    -- non_critical_section_1;
    loop exit when Turn = 1; end loop;
      -- critical_section_1;
    Turn := 2;
  end loop;
end P1;
```

```
task body P2 is
begin
  loop
    -- non_critical_section_2;
    loop exit when Turn = 2; end loop;
      -- critical_section_2;
    Turn := 1;
  end loop;
end P2;
```

- ☞ Mutual exclusion!
- ☞ No deadlock!
- ☞ No starvation!
- ☞ Locks up, if there is no contention!

Mutual exclusion: second attempt

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;
```

```
task body P1 is
begin
 loop
   -- non_critical_section_1;
   loop
    exit when C2 = Out_CS;
   end loop;
   C1 := In_CS;
     -- critical_section_1;
   C1 := Out_CS;
 end loop;
end P1;
```

```
task body P2 is
begin
 loop
   -- non_critical_section_2;
   loop
    exit when C1 = Out_CS;
   end loop;
   C2 := In_CS;
     -- critical_section_2;
   C2 := Out_CS;
 end loop;
end P2;
```

☞ No mutual exclusion!

Mutual exclusion: third attempt

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;
```

```
task body P1 is
begin
  loop
    -- non_critical_section_1;
    C1 := In_CS;
    loop
      exit when C2 = Out_CS;
    end loop;
      -- critical_section_1;
    C1 := Out_CS;
  end loop;
end P1;
```

```
task body P2 is
begin
  loop
    -- non_critical_section_2;
    C2 := In_CS;
    loop
      exit when C1 = Out_CS;
    end loop;
      -- critical_section_2;
    C2 := Out_CS;
  end loop;
end P2;
```

☞ Mutual exclusion!

Mutual exclusion: third attempt

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;
```

```
task body P1 is
begin
  loop
    -- non_critical_section_1;
    C1 := In_CS;
    loop
      exit when C2 = Out_CS;
    end loop;
        -- critical_section_1;
    C1 := Out_CS;
  end loop;
end P1;
```

```
task body P2 is
begin
  loop
    -- non_critical_section_2;
    C2 := In_CS;
    loop
      exit when C1 = Out_CS;
    end loop;
        -- critical_section_2;
    C2 := Out_CS;
  end loop;
end P2;
```

- ☞ Mutual exclusion!
- ☞ Deadlock possible!

Mutual exclusion: fourth attempt

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;
```

```
task body P1 is
begin
  loop
    -- non_critical_section_1;
    C1 := In_CS;
    loop
      exit when C2 = Out_CS;
      C1 := Out_CS;
      C1 := In_CS;
    end loop;
      -- critical_section_1;
    C1 := Out_CS;
  end loop;
end P1;
```

```
task body P2 is
begin
  loop
    -- non_critical_section_2;
    C2 := In_CS;
    loop
      exit when C1 = Out_CS;
      C2 := Out_CS;
      C2 := In_CS;
    end loop;
      -- critical_section_2;
    C2 := Out_CS;
  end loop;
end P2;
```

☞ Mutual exclusion!, No deadlock!

Mutual exclusion: fourth attempt

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;
```

```
task body P1 is
begin
  loop
    -- non_critical_section_1;
    C1 := In_CS;
    loop
      exit when C2 = Out_CS;
      C1 := Out_CS;
      C1 := In_CS;
    end loop;
      -- critical_section_1;
    C1 := Out_CS;
  end loop;
end P1;
```

```
task body P2 is
begin
  loop
    -- non_critical_section_2;
    C2 := In_CS;
    loop
      exit when C1 = Out_CS;
      C2 := Out_CS;
      C2 := In_CS;
    end loop;
      -- critical_section_2;
    C2 := Out_CS;
  end loop;
end P2;
```

☞ Mutual exclusion!, No deadlock!

☞ Individual starvation & global livelock possible!

Mutual exclusion: Decker's Algorithm

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2: Critical_Section_State := Out_CS;  Turn : Positive range 1..2 := 1;

task body P1 is
begin
  loop
    -- non_critical_section_1;
    C1 := In_CS;
    loop
      exit when C2 = Out_CS;
      if Turn = 2 then
        C1 := Out_CS;
        loop exit when Turn = 1;
        end loop;
        C1 := In_CS;
      end if;
    end loop;
      -- critical_section_1;
    C1 := Out_CS; Turn := 2;
  end loop;
end P1;
```

- ☞ Mutual exclusion!
- ☞ No deadlock!
- ☞ No starvation!
- ☞ No livelock!

```
                                ion_2;
                                _CS;
                                rn = 2;
        end loop;
        C2 := In_CS;
      end if;
    end loop;
      -- critical_section_2;
    C2 := Out_CS; Turn := 1;
  end loop;
end P2;
```

Mutual exclusion: Peterson's Algorithm

```
type Critical_Section_State is (In_CS, Out_CS);
C1, C2 : Critical_Section_State := Out_CS;
Last   : Positive range 1..2    := 1;

task body P1 is
begin
 loop
   -- non_critical_section_1;
   C1   := In_CS;
   Last := 1;
   loop
    exit when C2 = Out_CS
          or else Last /= 1;
   end loop;
      -- critical_section_1;
   C1 := Out_CS;
 end loop;
end P1;
```

- ☞ Mutual exclusion!
- ☞ No deadlock!
- ☞ No starvation!
- ☞ No livelock!

… and it's simpler

```
on_2;
S
= 2;
n_2;
 end loop;
end P2;
```

The general mutual exclusion scenario

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  Each instruction belongs to either a *critical* or *non-critical section*.

☞ Safety property 'Mutual exclusion':

Instructions from critical sections of two or more processes must never be interleaved!

- More required properties:
  - **No deadlocks**: If one or multiple processes try to enter their critical sections then *exactly one* of them must succeed.
  - **No starvation**: Every process which tries to enter one of his critical sections must *succeed eventually.*
  - **Efficiency**: The decision which process may enter the critical section must be made *efficiently* in all cases, i.e. also when there is no contention.

The idea of the Bakery Algorithm

A set of N Processes $P_1 \ldots P_N$ competing for mutually exclusive execution of their critical regions.

Every process P_i out of $P_1 \ldots P_N$ supplies: a globally readable number t_i ('ticket') (initialized to '0').

- Before a process P_i enters a critical section:
  - P_i draws a new number $t_i > t_j; \forall j \neq i$
  - P_i is allowed to enter the critical section iff: $\forall j \neq i$: $t_i < t_j$ or $t_j = 0$
- After a process P_i left a critical section:
  - P_i resets its $t_i = 0$

Issues:

☞ Can you ensure that processes won't read each others ticket numbers while still calculating?

☞ Can you ensure that no two processes draw the same number?

Mutual exclusion: Bakery Algorithm

```
type Choosing_State is (Yes, No);
Choosing: array (1..N) of Choosing_State := (others => No);
Number  : array (1..N) of Natural        := (others => 0);

task type P (I: Natural) is end P;

task body P is
begin
 loop
  -- non_critical_section_1;
  Choosing (I) := Yes;
  Number   (I) := Max (Number) + 1;
  Choosing (I) := No;
  for J in 1..N loop
   if J /= I then
    loop
     exit when Choosing (J) = No;
    end loop;
    loop
     exit when
      Number (J) = 0 or
      Number (I) < Number (J) or
      (Number (I) = Number (J)
       and I < J);
    end loop;
   end if;
  end loop;
  -- critical_section_1;
  Number (I) := 0;
 end loop;
end P;
```

☞ Intensive communication with all processes, even if just one process tries to enter!

Realistic hardware support

Atomic **test-and-set** operations [Motorola 68xxx; Intel 80x86]:

- [*L* := *C*; *C* := 1]

Atomic **exchange** operations [Motorola 68xxx; Intel 80x86]:

- [*Temp* := *L*; *L* := *C*; *C* := *Temp*]

Memory cell **reservations** [Motorola PowerPC]:

- *L* := *C*; – by using a special instruction, which puts a '**reservation**' on *C*
- … calculate a <new value> for *C* …
- *C* := <new value>;
  – succeeds iff *C* was not manipulated by other processors or devices since the reservation

Mutual exclusion: atomic test-and-set operation

```
type Flag is Natural range 0..1;  C : Flag := 0;
```

```
task body Pi is
L : Flag;
begin
  loop
    -- non_critical_section_i;
    loop
      [L := C; C := 1]
      exit when L = 0;
    end loop;
      -- critical_section_i;
    C := 0;
  end loop;
end Pi;
```

```
task body Pj is
L : Flag;
begin
  loop
    -- non_critical_section_j;
    loop
      [L := C; C := 1]
      exit when L = 0;
    end loop;
      -- critical_section_j;
    C := 0;
  end loop;
end Pj;
```

☞ Mutual exclusion!, No deadlock!, No global live-lock! – for *N* processes

☞ Individual starvation possible!

Mutual exclusion: atomic exchange operation

```
type Flag is Natural range 0..1;  C : Flag := 0;
```

```
task body Pi is
L : Flag := 1;
begin
  loop
   -- non_critical_section_i;
   loop
    [Temp := L; L := C; C := Temp];
    exit when L = 0;
   end loop;
     -- critical_section_i;
   [Temp := L; L := C; C := Temp];
  end loop;
end Pi;
```

```
task body Pj is
L : Flag := 1;
begin
  loop
   -- non_critical_section_j;
   loop
    [Temp := L; L := C; C := Temp];
    exit when L = 0;
   end loop;
     -- critical_section_j;
   [Temp := L; L := C; C := Temp];
  end loop;
end Pj;
```

☞ Mutual exclusion!, No deadlock!, No global live-lock! – for *N* processes

☞ Individual starvation possible!

Mutual exclusion: memory cell reservation

```
type Flag is Natural range 0..1;  C : Flag := 0;
```

```
task body Pi is
L : Flag;
begin
  loop
    -- non_critical_section_i;
    loop
      L := C; -- reservation on C
      C := 1; -- works if untouched
      exit when Untouched and L = 0;
    end loop;
      -- critical_section_i;
    C := 0;
  end loop;
end Pi;
```

```
task body Pj is
L : Flag;
begin
  loop
    -- non_critical_section_j;
    loop
      L := C; -- reservation on C
      C := 1; -- works if untouched
      exit when Untouched and L = 0;
    end loop;
      -- critical_section_j;
    C := 0;
  end loop;
end Pj;
```

☞ Mutual exclusion!, No deadlock!, No global live-lock! – for *N* processes

☞ Individual starvation possible!

Semaphores

Basic definition (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(S): [if S > 0 then S := S - 1]`
- an **atomic** operation `V` on `S` — `V` stands for ‘vrygeven’ (Dutch for ‘to release’):
  - `V(S): [S := S + 1]`

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

Semaphores

… as supplied by operating systems

- a set of processes `P(1)` … `P(N)` agree on a variable `S` operating as a flag to indicate synchronization conditions … *and* …
- an **atomic** operation `Wait` on `S`: — also: , '`Suspend_Until_True`', '`sem_wait`'
  - `Process P(i): Wait (S):`
```
[if S > 0
     then S := S - 1
     else “suspend P(i) on S”]
```
- an **atomic** operation `Signal` on `S`: — also: '`Set_True`', '`sem_post`'
  - `Process P(i): Signal (S):`
```
[if ∃j: “P(j) is suspended on S”
     then “release P(j)”
     else S := S + 1]
```

a release order is *not* specified!

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 semaphores**: 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 support binary semaphores at hardware level.
- **Quantity semaphores**: The increment (and decrement) value for the semaphore is specified as a parameter with `P` and `V`.

☞ all types of semaphores must be initialized with a non-negative number: often the number of processes which are allowed inside a critical section, i.e. "1".

Mutual exclusion: Semaphores

```
S : Semaphore := 1;
```

```
task body Pi is

begin
  loop
    -- non_critical_section_i;
    wait (S);
      -- critical_section_i;
    signal (S);
  end loop;
end Pi;
```

```
task body Pj is

begin
  loop
    -- non_critical_section_j;
    wait (S);
      -- critical_section_j;
    signal (S);
  end loop;
end Pj;
```

☞ Mutual exclusion!, No deadlock!, No global live-lock! – for *N* processes

☞ Individual starvation possible!

Mutual exclusion: Semaphores

```
S1, S2: Semaphore := 1;
```

```
task body Pi is

begin
  loop
    -- non_critical_section_i;
    wait (S1);
    wait (S2);
       -- critical_section_i;
    signal (S2);
    signal (S1);
  end loop;
end Pi;
```

```
task body Pj is

begin
  loop
    -- non_critical_section_j;
    wait (S2);
    wait (S1);
       -- critical_section_j;
    signal (S1);
    signal (S2);
  end loop;
end Pj;
```

- ☞ Mutual exclusion!, No global live-lock!
- ☞ Individual starvation possible!
- ☞ Possible deadlock!

Concurrency – The Basic Concepts

- **Definition of mutual exclusion**
- **Atomic load and atomic store operations**
  - … some classical errors
  - Decker's algorithm, Peterson's algorithm
  - Bakery algorithm
- **Realistic hardware support**
  - Atomic test-and-set, Atomic exchanges, Memory cell reservations
- **Semaphores**
  - Basic semaphore definition
  - Operating systems style semaphores

4

Synchronization

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all references and links are available on the course page

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 ☞ 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 concurrent systems

All data is declared …

- ☞ … ***either*** local (and protected by language-, os-, or hardware-mechanisms)
- ☞ … ***or*** it is 'out in the open' and all access need to be synchronized!

Synchronization in concurrent systems

Synchronization: the run-time overhead?

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

```
int i;
......
i++;              |       if i>n {i=0;}

{in one thread}           {in another thread}
```

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

Synchronization in concurrent systems

```
                int i;
                 ......
i++;              |        if i>n {i=0;}
```

- 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 usually not be atomic*
… but perhaps it is a register.

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

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

Synchronization in concurrent systems

```
int i;
......
i++;          |          if i>n {i=0;}
```

☞ 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 usually rare but then often disastrous.
- 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!**

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.

Condition synchronization by flags

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

```
process P1;
   statement X;

   repeat until Flag;

   statement Y;
end P1;
```

```
process P2;
   statement A;

   Flag := true;

   statement B;
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 suitable 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 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;
```

- 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

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);
}
```

```
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);
} } }
```

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

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 inadequate for non-trivial systems.

(all concurrent languages and environments offer efficient higher-level 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 critial_buffer_region : buffer;
```

```
process producer;

   loop

      region critial_buffer_region
         when buffer.size < N do

            -- place in buffer etc.

      end region

   end loop;
end producer
```

```
process consumer;

   loop

      region critial_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 and functions.
- Assure mutual exclusion of all monitor-procedures and functions.

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;
```


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                     cond,
                                    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   (       p
                               const  
int pthread_mutex_unlock      (       p
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 with *all* objects of a 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` do not release the lock.
  - ☞ methods, which are activated via notification need to wait for lock-access.
- Java does *not* require any specific release order (like a queue) for `wait`-suspended threads
  - ☞ livelocks are *not* prevented at this level (in opposition to RT-Java).
- There are no explicit conditional variables.
  - ☞ notified threads need 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** threads 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 & Real-time Java

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

POSIX offers conditional variables

Real-time 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, 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
   Buffer.Get (Some_Data);
else
   -- do something else
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);
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 indicates 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 indicates 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 Broadcast;
```

```
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 Broadcast;
```


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

(entry families)

```
package Modes is

   type Mode_T is
      (Takeoff, Ascent, Cruising,
       Descent, Landing);

   protected Mode_Gate is

      procedure Set_Mode
                   (Mode: in Mode_T);
      entry Wait_For_Mode
                   (Mode_T);

   private
      Current_Mode : Mode_Type
                         := Takeoff;

   end Mode_Gate;
end Modes;
```

```
package body Modes is
   protected body Mode_Gate is

      procedure Set_Mode
                   (Mode: in Mode_T) is

         begin
            Current_Mode := Mode;
         end Set_Mode;

      entry Wait_For_Mode
         (for Mode in Mode_T)
         when Current_Mode = Mode is

         begin null;
         end Wait_For_Mode;

   end Mode_Gate;
end Modes;
```

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 two entries:

```
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!

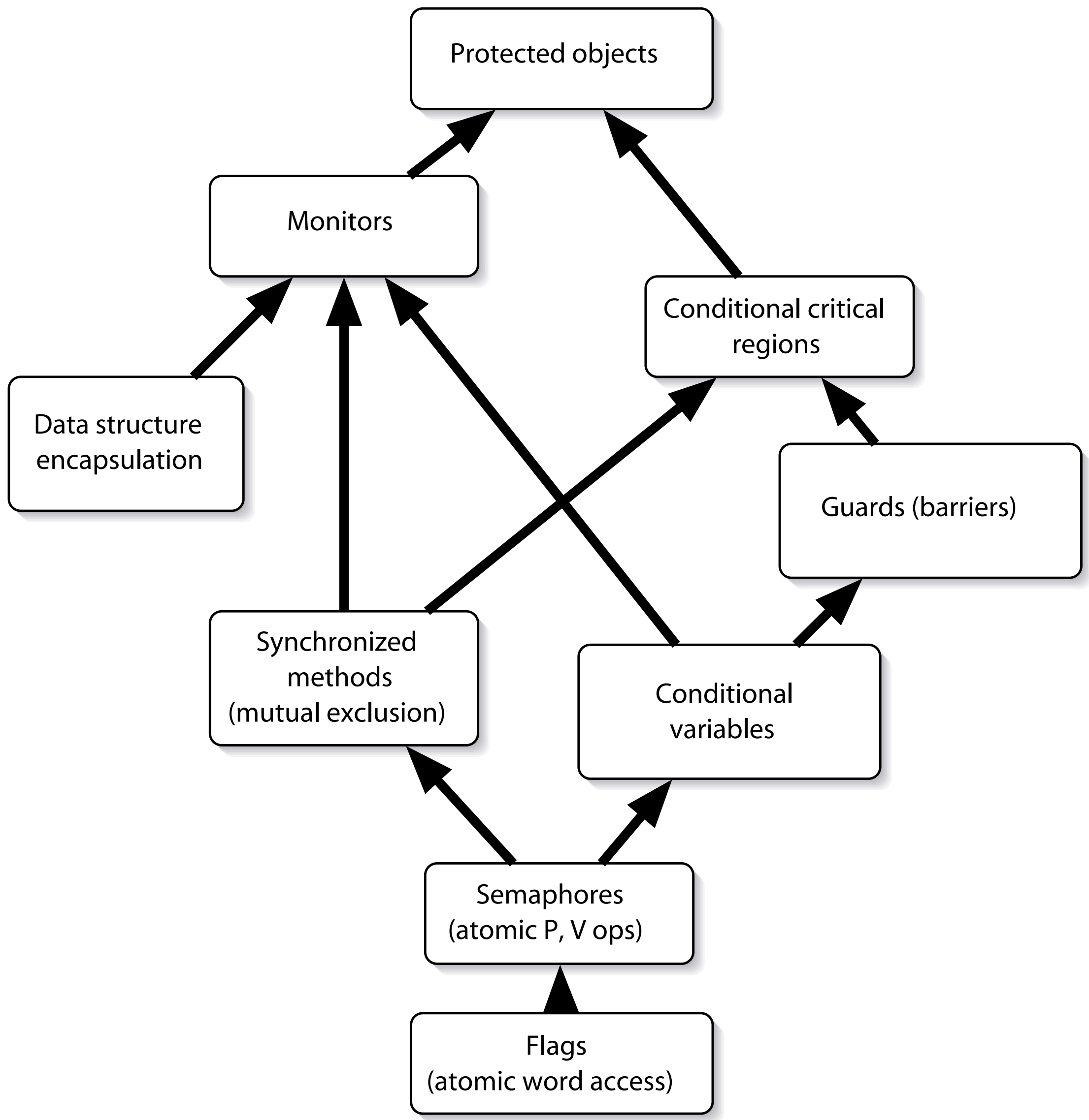
Summary

Shared memory based synchronization

General

Criteria:

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

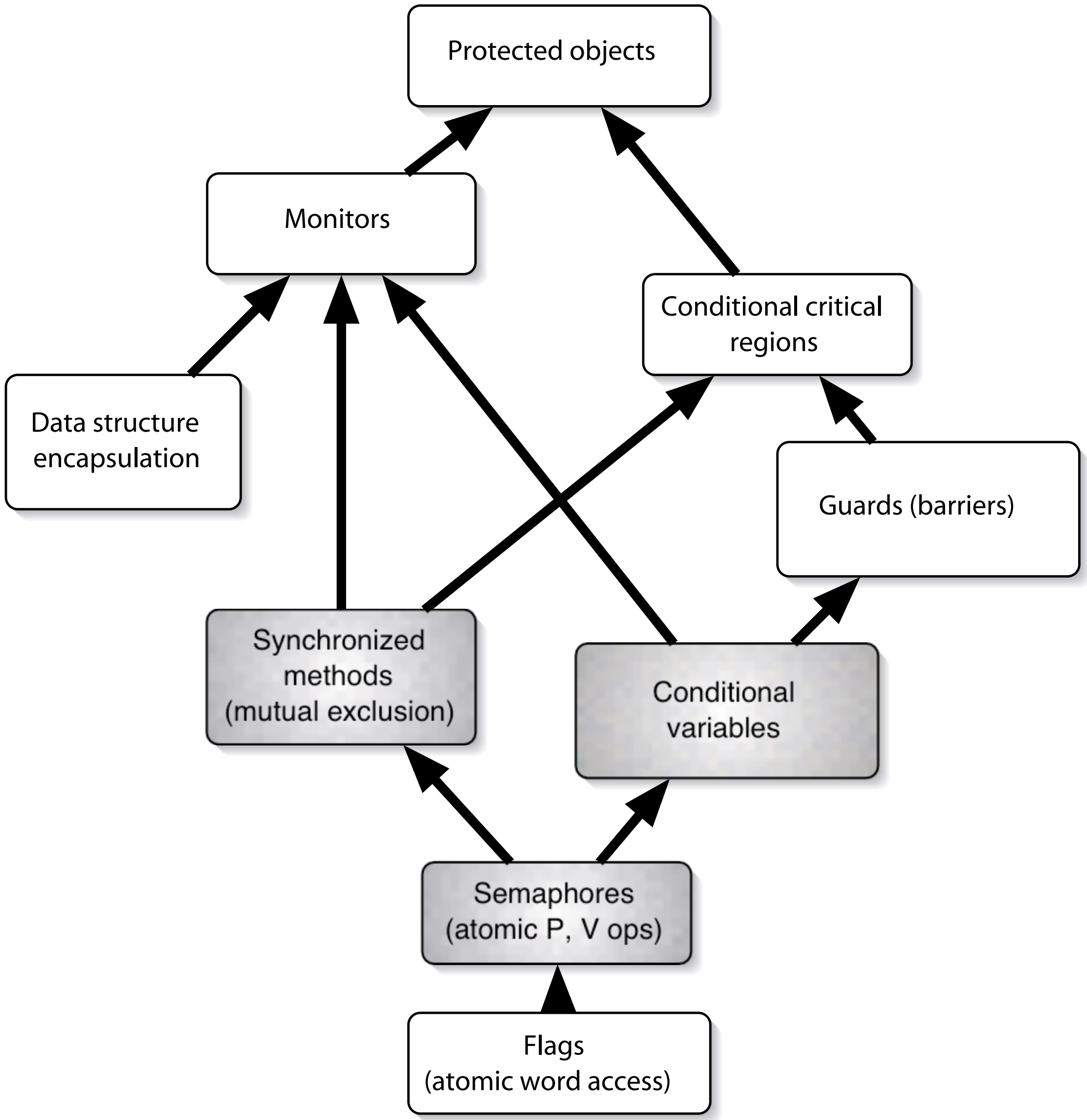


Summary

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).

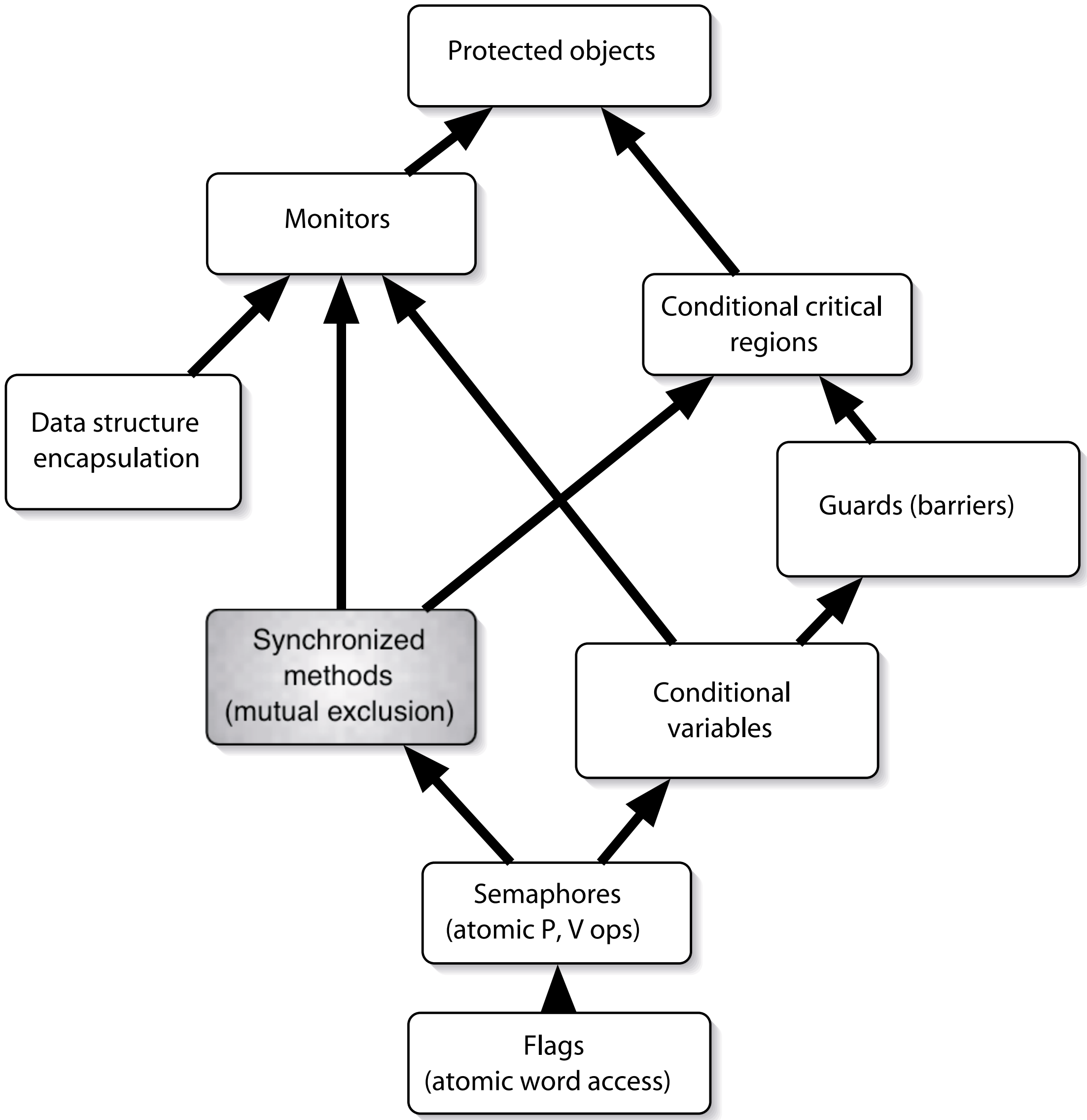


Summary

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

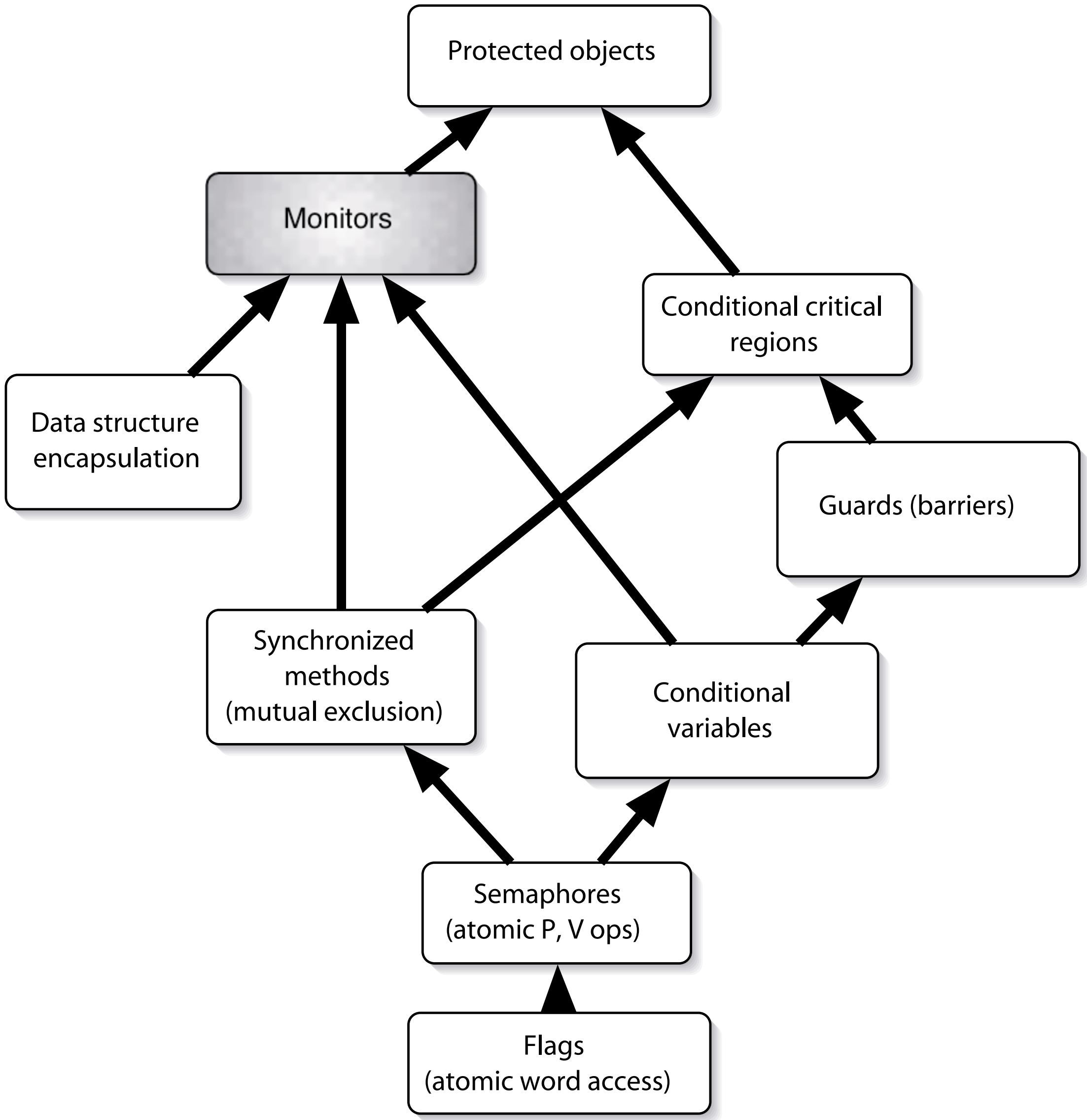
Shared memory based synchronization

Modula-1, CHILL

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

… no more, no less, …

☞ all features of and criticism about monitors apply.



Summary

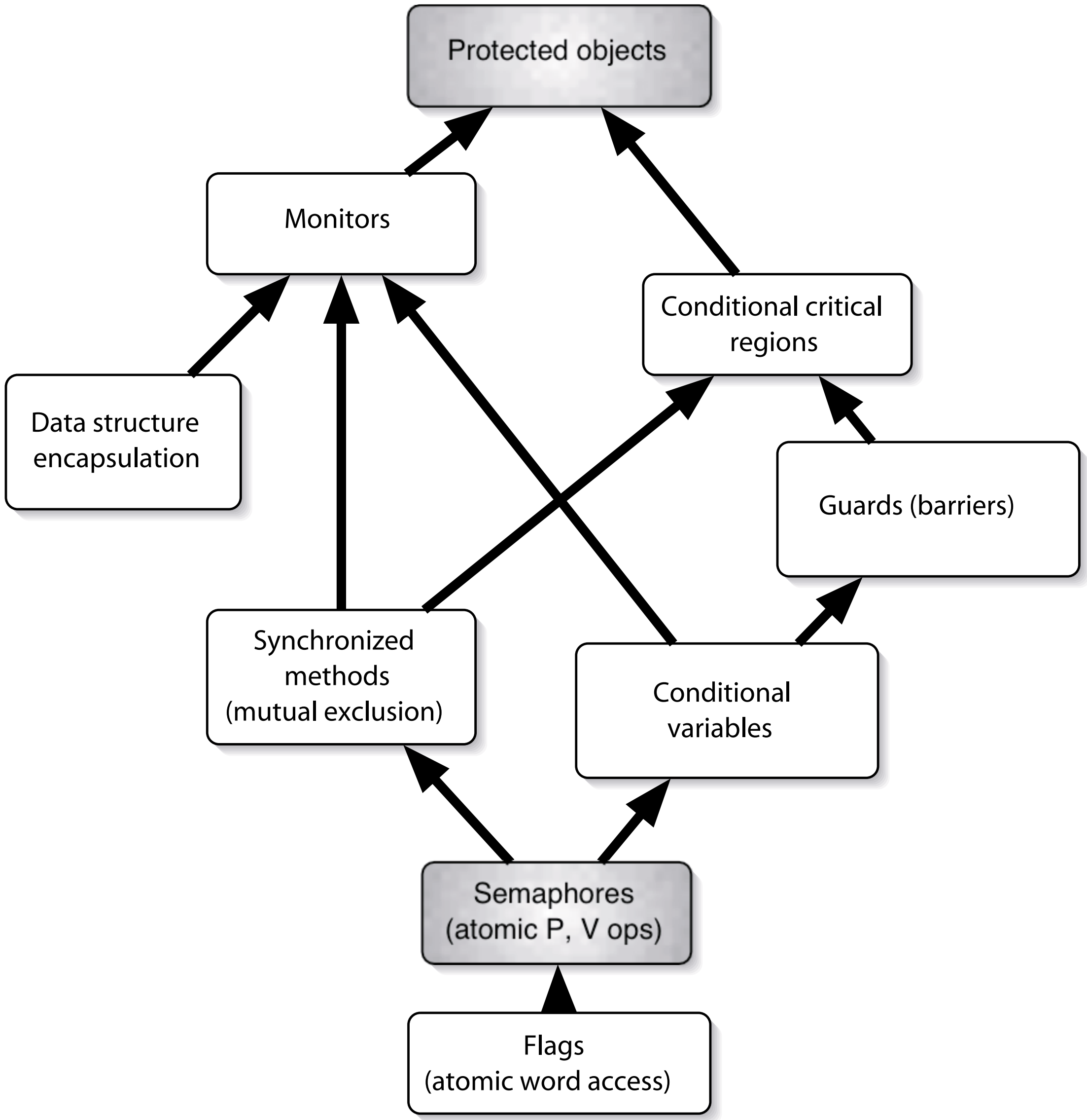
Shared memory based synchronization

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)



Message-based synchronization

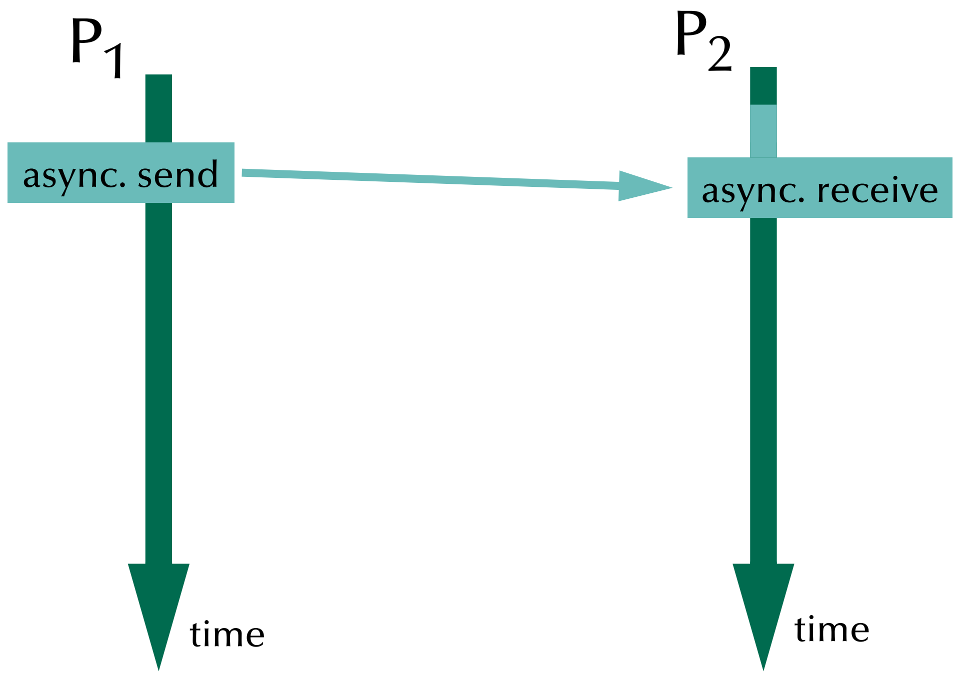
- Synchronization model
  - Asynchronous
  - Synchronous
  - Remote invocation
- Addressing (name space)
  - direct communication
  - mail-box communication
- Message structure
  - arbitrary
  - restricted to ‘basic’ types
  - restricted to un-typed communications

Message-based synchronization

Asynchronous messages

If there is a listener:

☞ send the message directly

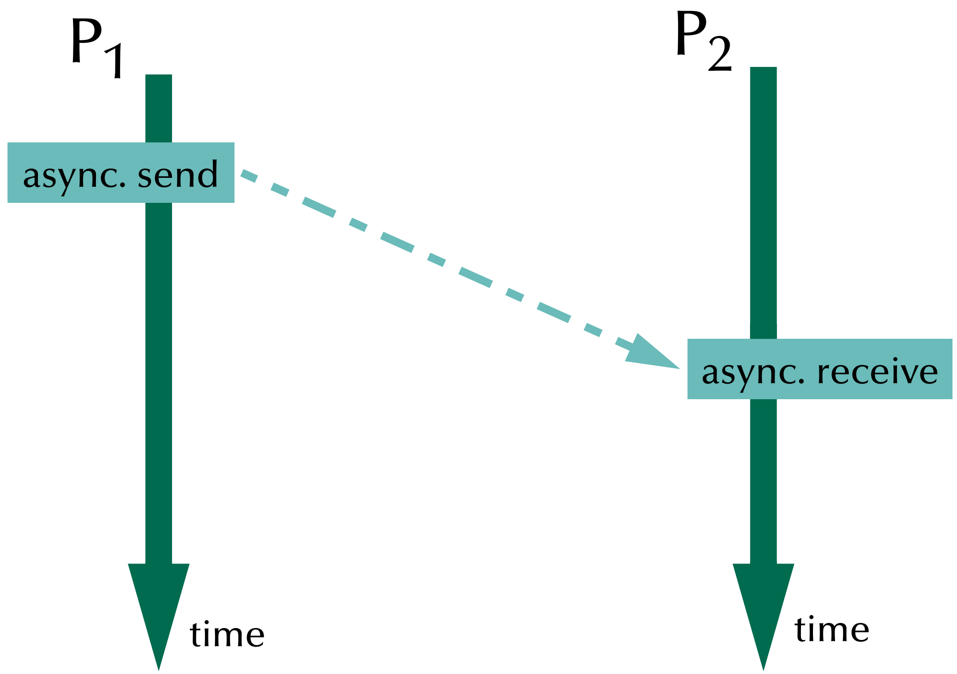


Message-based synchronization

Asynchronous messages

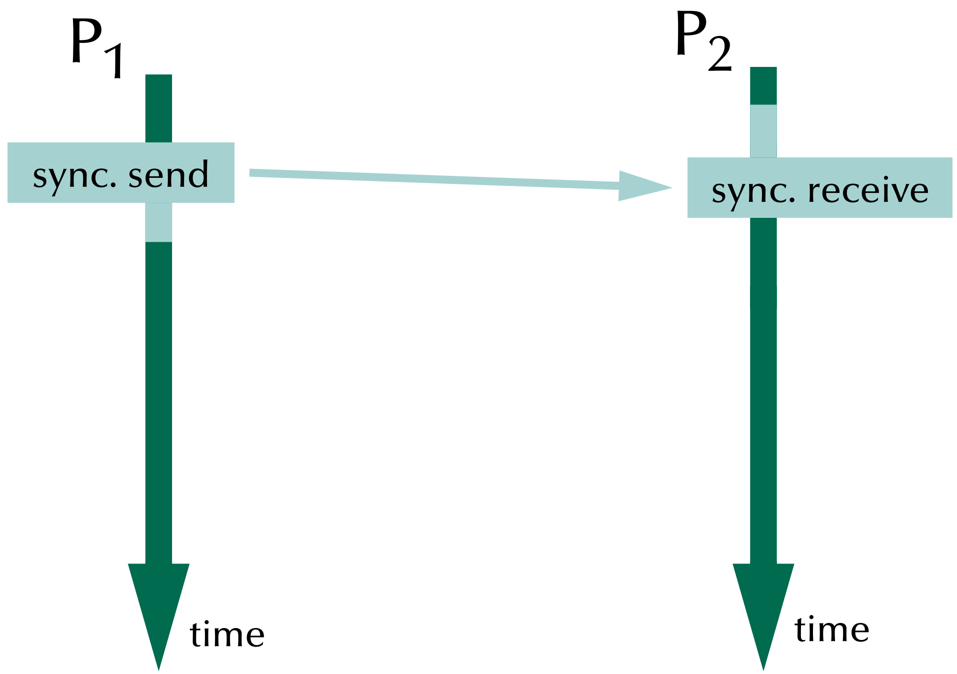
If the receiver becomes available at a later stage:

☞ the message needs to be buffered



Message-based synchronization

Synchronous messages



Delay the receiver:

- until the message becomes available

Message-based synchronization

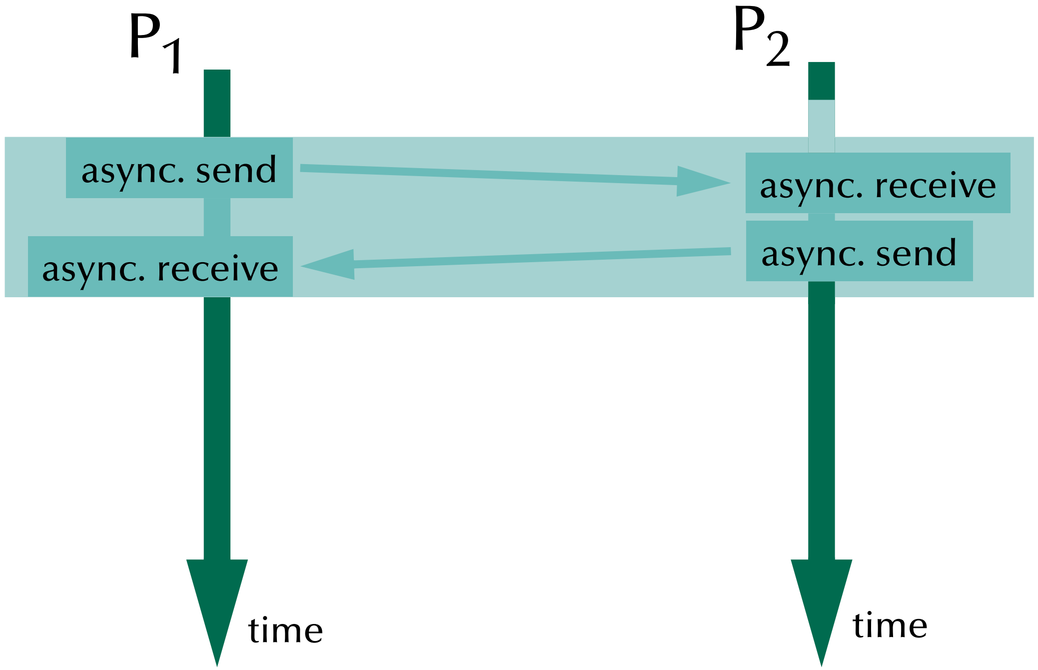
Synchronous messages

Delay the receiver:

- until the message becomes available

Simulated by asynchronous messages:

☞ two asynchronous messages required

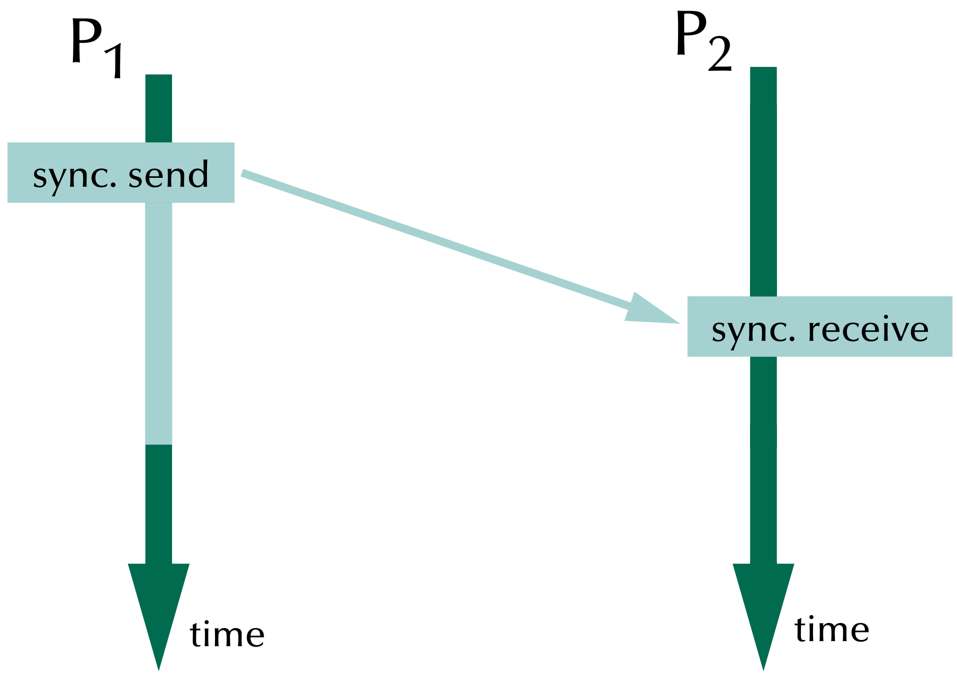


Message-based synchronization

Synchronous messages

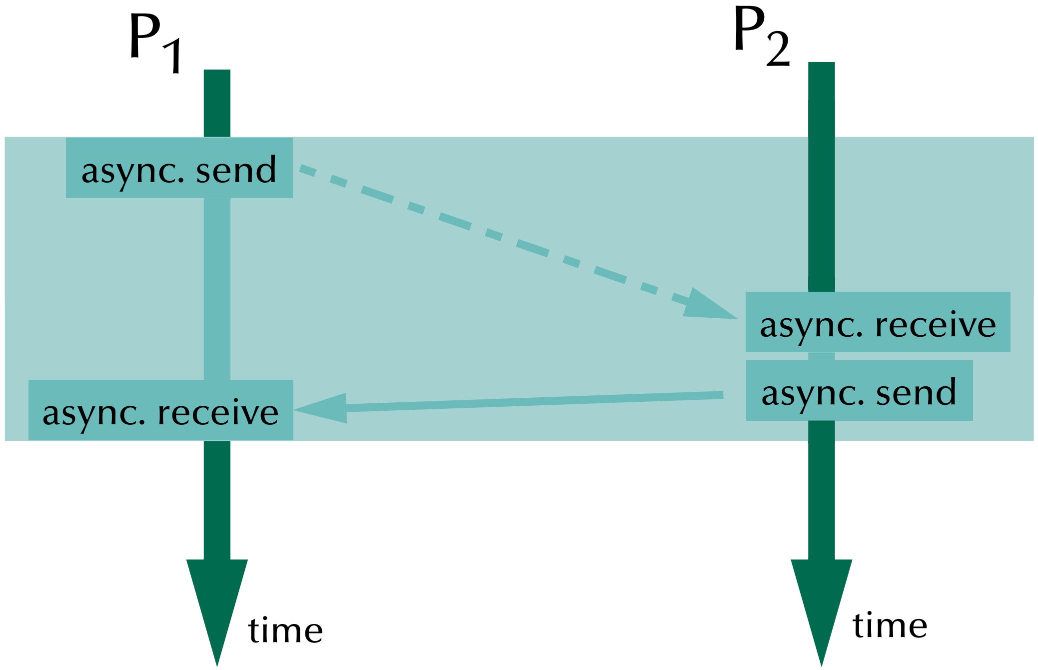
Delay the sender until:

- a receiver is available
- a receiver got the message



Message-based synchronization

Synchronous messages



Delay the sender until:

- a receiver is available
- a receiver got the message

Simulated by asynchronous messages:
If the receiver becomes available at a later stage:

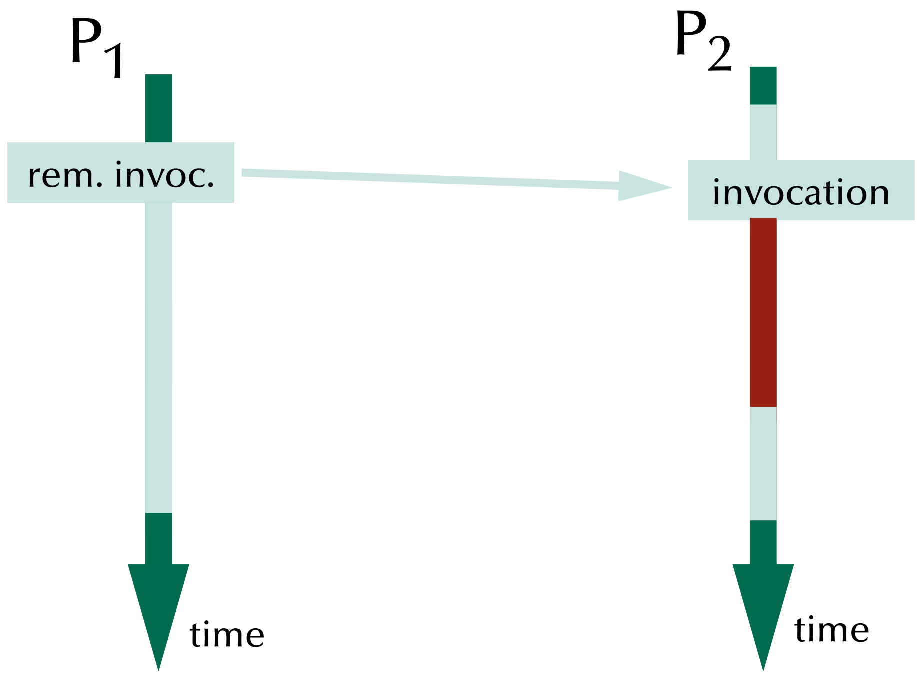
☞ message needs to be buffered

Message-based synchronization

Remote invocation

Delay the receiver, until:

- an invocation is available
- a receiver executed an addressed routine



Message-based synchronization

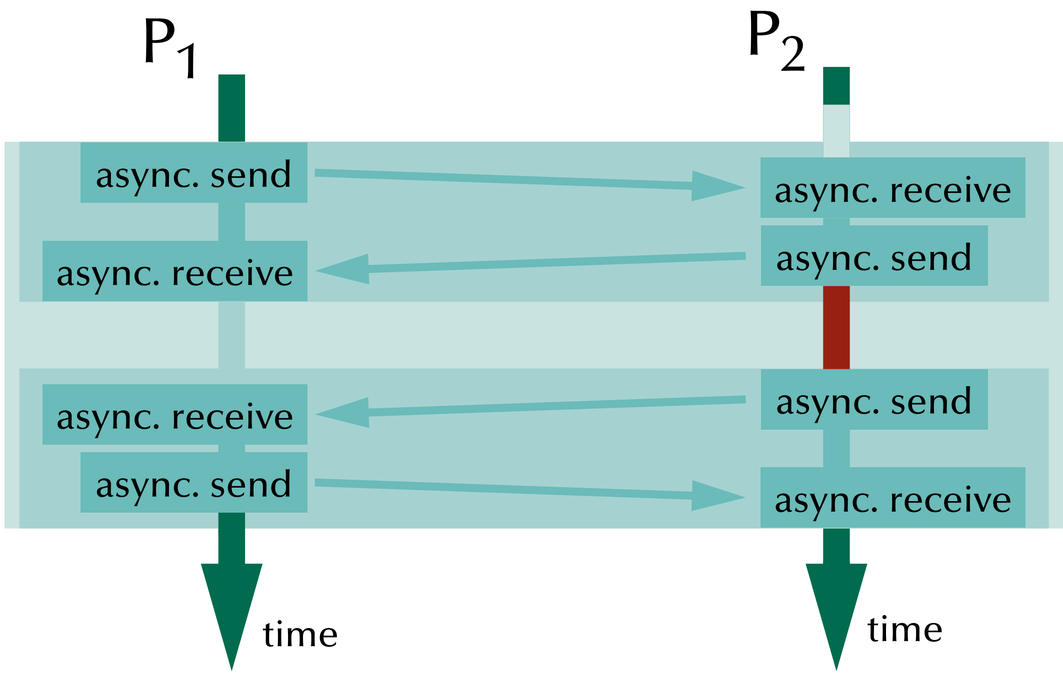
Remote invocation

Delay the receiver, until:

- an invocation is available
- a receiver executed an addressed routine

Simulated by asynchronous messages:

☞ four messages are required

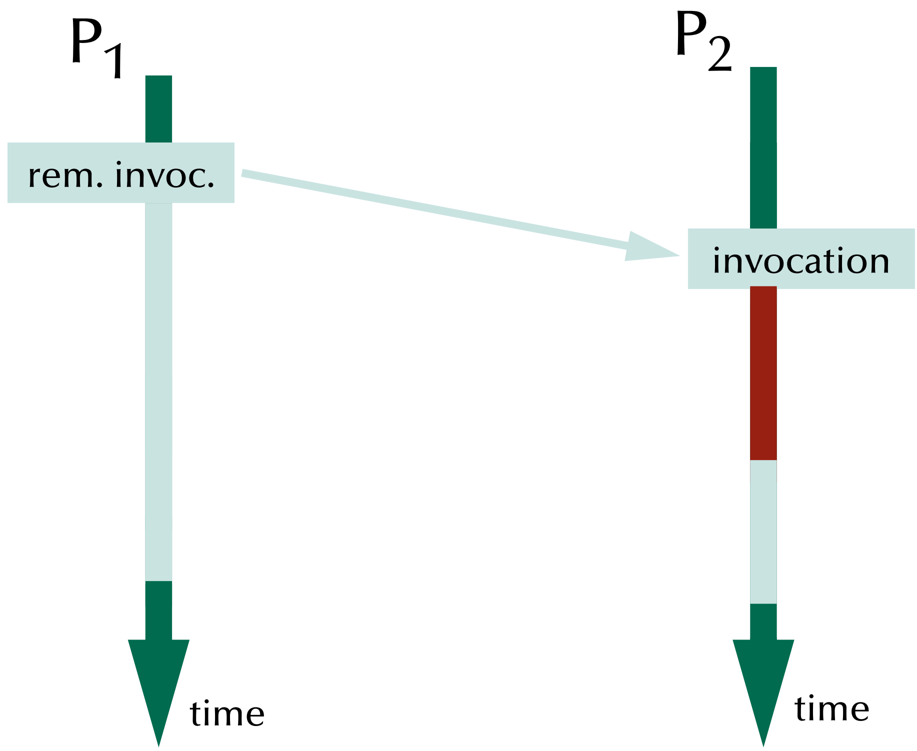


Message-based synchronization

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

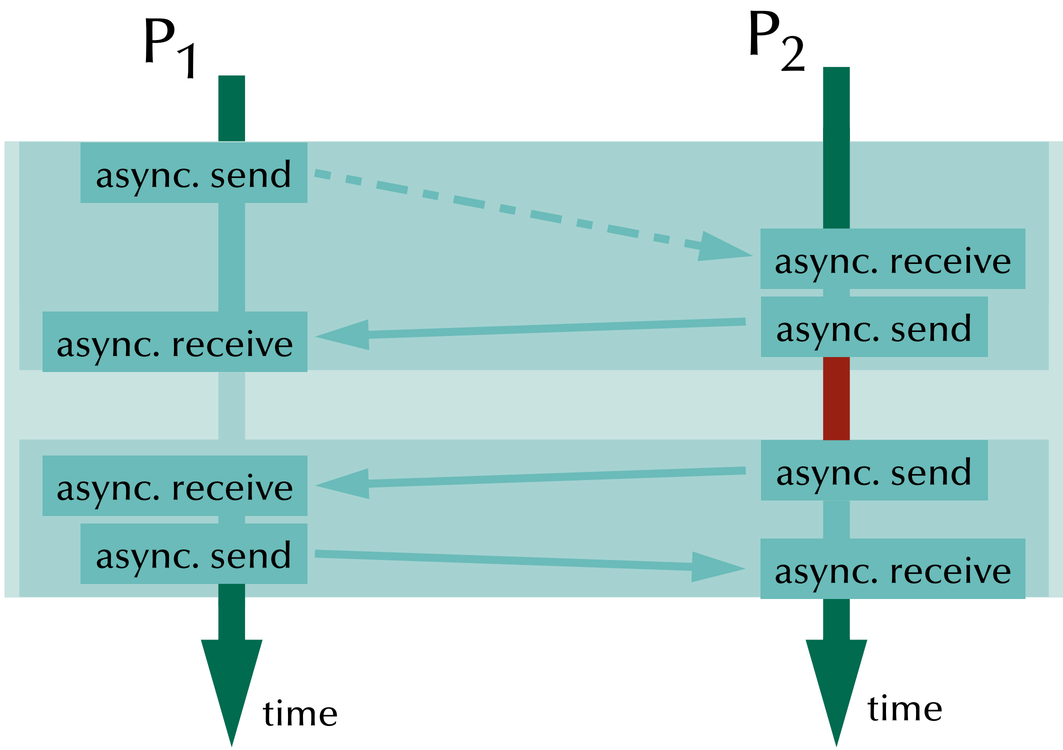
Delay the sender, until:

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

Simulated by asynchronous messages:

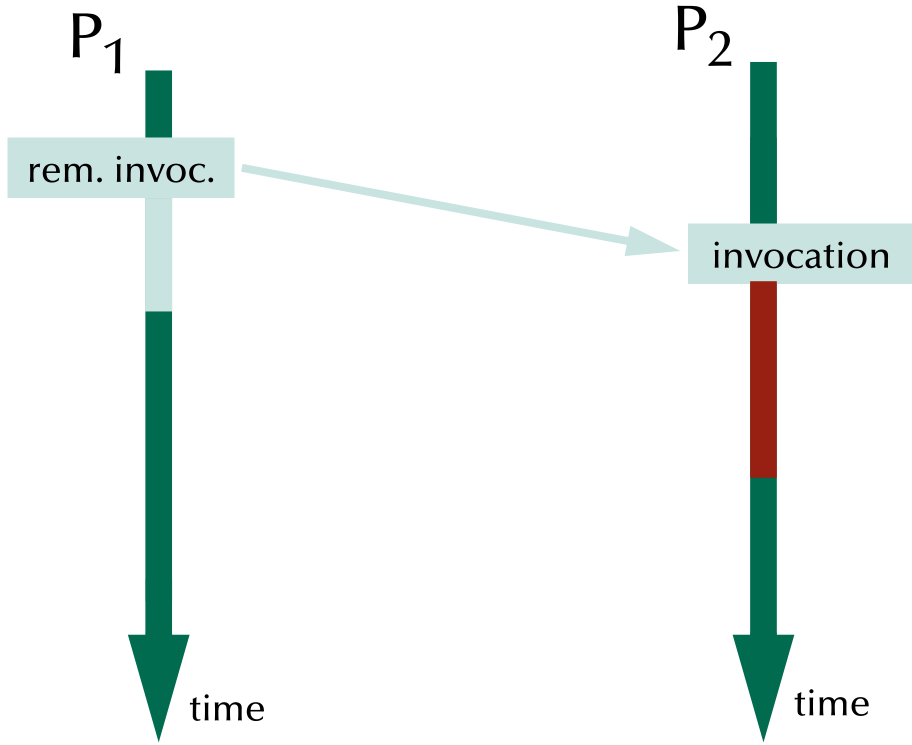
☞ four messages are required

☞ message buffering required



Message-based synchronization

Asynchronous remote invocation



Delay the sender, until:

- a receiver becomes available
- a receiver got the message

Message-based synchronization

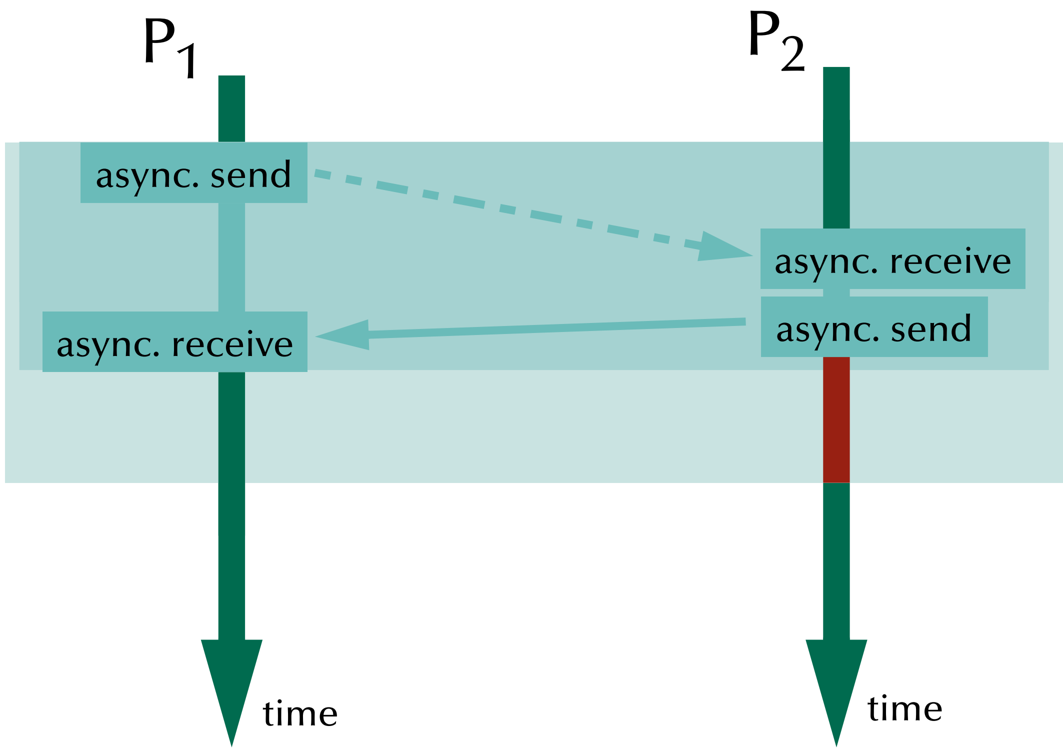
Asynchronous remote invocation

Delay the sender, until:

- a receiver becomes available
- a receiver got the message

Simulated by asynchronous messages:

☞ two messages are required



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.

Can both communication modes emulate each other?

- 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, 'C/C++', Java)
… semi-automatic (CORBA)
… automatic and are typed-persistent (Ada95, CHILL, Occam2)

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

Practical message-passing systems for strict synchronisation purposes:

	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
      --- [asynchronous] --->            (SensorBuffer in data) : ...
                                       esac;

signal SensorChannel = (int) to consumertype;
...
send SensorChannel (reading)           receive case
    to consumer  <--- [synchronous] --->  (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:

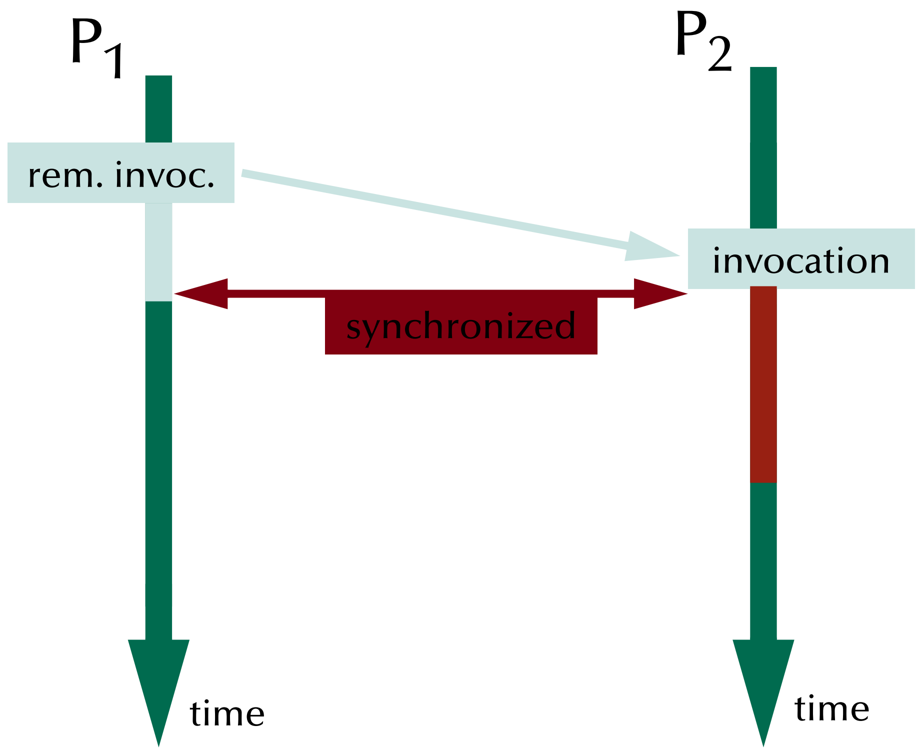
☞ parameters incl. bounds and discriminants are ‘tunnelled’ through byte-stream-formats.

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:

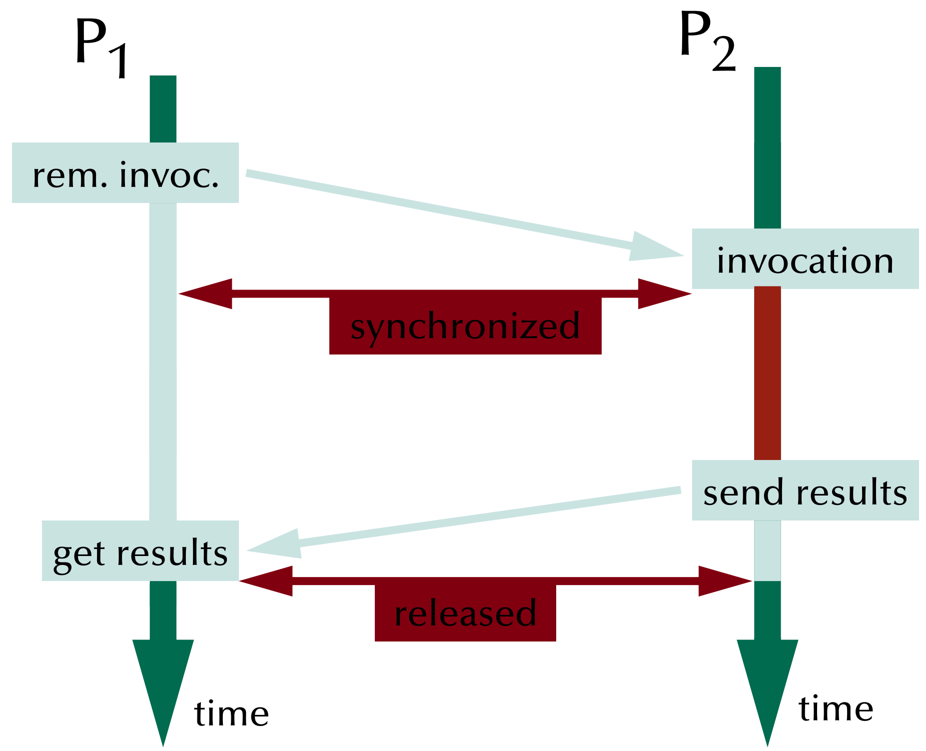
- a receiver becomes available
- a receiver got the message
- a receiver started an addressed routine

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



Synchronization

Message-based synchronization in Ada95

(Rendezvous)

```
...
<entry_name> [(index)] <parameters>
... -- waiting for synchronization
... --
... --
... --
...
...
...
...
...
```

synchronized

```
...
...
...
...
...
accept <entry_name> [(index)]
          <parameter_profile>;
...
...
...
...
...
```

Synchronization

Message-based synchronization in Ada95

(Rendezvous)

```
...
...
...
...
...
<entry_name> [(index)] <parameters>
...
...
...
...
```

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

synchronized

Message-based synchronization in Ada95

(Extended rendezvous)

```
…
<entry_name> [(index)] <parameters>
… -- waiting for synchronization
… --
… --
… --
      … --
      … -- blocked
      … --
      … --
…
```

synchronized

return results

```
…
…
…
…
…
accept <entry_name> [(index)]
              <parameter_profile> do
  … --
  … -- remote invocation
  … --
end <entry_name>;
…
```


Synchronization

Message-based synchronization in Ada95

(Extended rendezvous)

```
...
...
...
...
...
<entry_name> [(index)] <parameters>
        ... --
        ... -- blocked
        ... --
        ... --
...
```

```
...
accept <entry_name> [(index)]
           <parameter_profile> do
... -- waiting for synchronization
... --
...
    ... --
    ... --
    ... -- remote invocation
    ... --
end <entry_name>;
...
```

synchronized

return results

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.

Summary

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
  - Examples

5

Non-Determinism

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all references and links are available on the course page

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.

Selective waiting in Occam2

```
ALT
   Guard1
      Process1
   Guard2
      Process2
...
```

- Guards are referring to boolean expressions and/or channel input operations.
- The boolean expressions are local expressions, i.e. if none of them evaluates to true at the time of the evaluation of the `ALT`-statement, then the process is stopped.
- If all triggered channel input operations evaluate to false, the process is suspended until further activity on one of the named channels.
- Any Occam2 process can be employed in the `ALT`-statement
- The `ALT`-statement is non-deterministic (there is also a deterministic version: `PRI ALT`).

Selective waiting in Occam2

```
ALT
  NumberInBuffer < Size & Append ? Buffer [Top]
    SEQ
      NumberInBuffer := NumberInBuffer + 1
      Top            := (Top + 1) REM Size
  NumberInBuffer > 0 & Request ? ANY
    SEQ
      Take ! Buffer [Base]
      NumberInBuffer := NumberInBuffer - 1
      Base           := (Base + 1) REM Size
```

- synchronization on input-channels only:
  - ☞ to initiate the sending of data (`Take ! Buffer [Base]`), a request need to be made first (`Request ? ANY`)

CSP (Hoare) also supports non-deterministic selective waiting

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

Selective Synchronization

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.

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.

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.

Selective Synchronization

Basic forms of selective synchronization

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

```
select

or

else
   <statements>
…
end select;

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;
```

else - delay - terminate alternatives cannot be mixed!

Conditional & timed entry-calls

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

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

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

```
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;
```

```
      ler.Request (Medium)
      e_Item);
      ess data

      5.0;
       something else
end select;
```

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

Selective Synchronization

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;
```

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
    - clock drifts
    - network congestions
    - … any other form of asynchronism

remember our introduction: Models and Terminology

The concurrent programming abstraction

Correctness of concurrent non-real-time systems [logical correctness]:

- does *not depend* on speeds / execution times / delays
- does *not depend* on actual interleaving of concurrent processes

☞ **does *depend* on all possible sequences of interaction points**

The concurrent programming abstraction

Extended concepts of correctness in concurrent systems:

¬ Termination is often not intended or even considered a failure

- Safety properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Box Q(I, S)$$

where $\Box Q$ means that Q does *always* hold

- Liveness properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond Q(I, S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)
and S is the current state of the concurrent system

The concurrent programming abstraction

Correctness of concurrent non-real-time systems [logical correctness]:

☞ **does *depend* on all possible sequences of interaction points**

☞ Isn't there an actual unique sequence of interaction points,
… ☞ which is determined by the system and can be calculated?

in general: NO

- due to common intrinsically non-deterministic effects

Non-Determinism

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

☞ *Systems based on non-deterministic alternatives extent canonically to concurrent systems*

Basic forms of selective synchronization in Ada95

(guarded select-or)

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

Considering all alternatives
leads to many different interleavings!

How to keep it understandable / verifiable?

- ☞ avoid combinatorial explosions!
- ☞ reunite different paths as soon as possible
- ☞ specify unique system-wide synchronization-(check)-points

Non-Determinism

- **Selective synchronization**
    - Selective accepts
    - Selective calls
    - Indeterminism in message based synchronization
- **General Non-Determinism in Concurrent Systems**

6

Scheduling

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The Australian National University

References for this chapter

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all references and some links are available on the course page

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

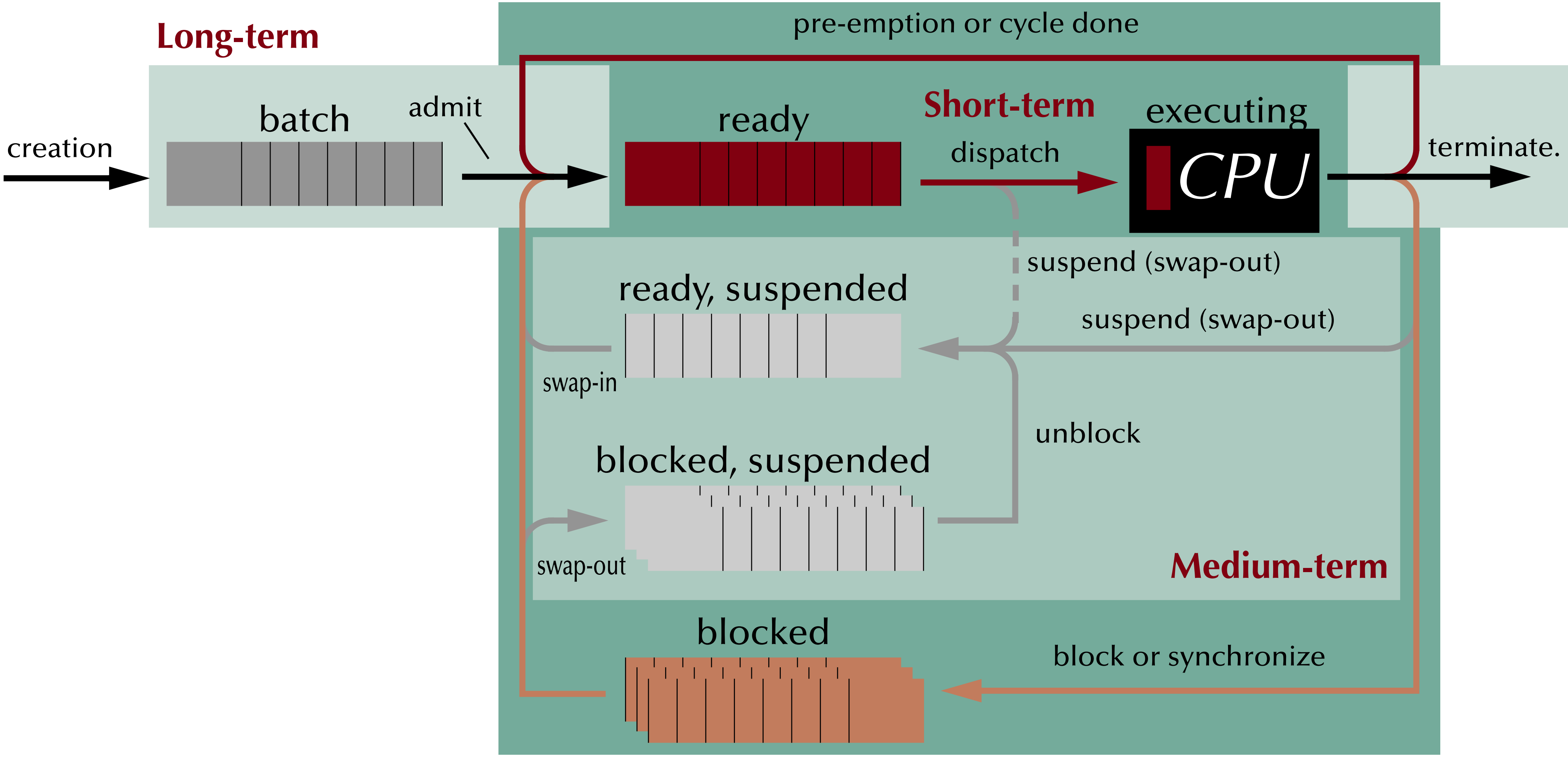
☞ at run-time: to permit acceptance of additional usage/reservation requests.

Criteria for scheduling methods

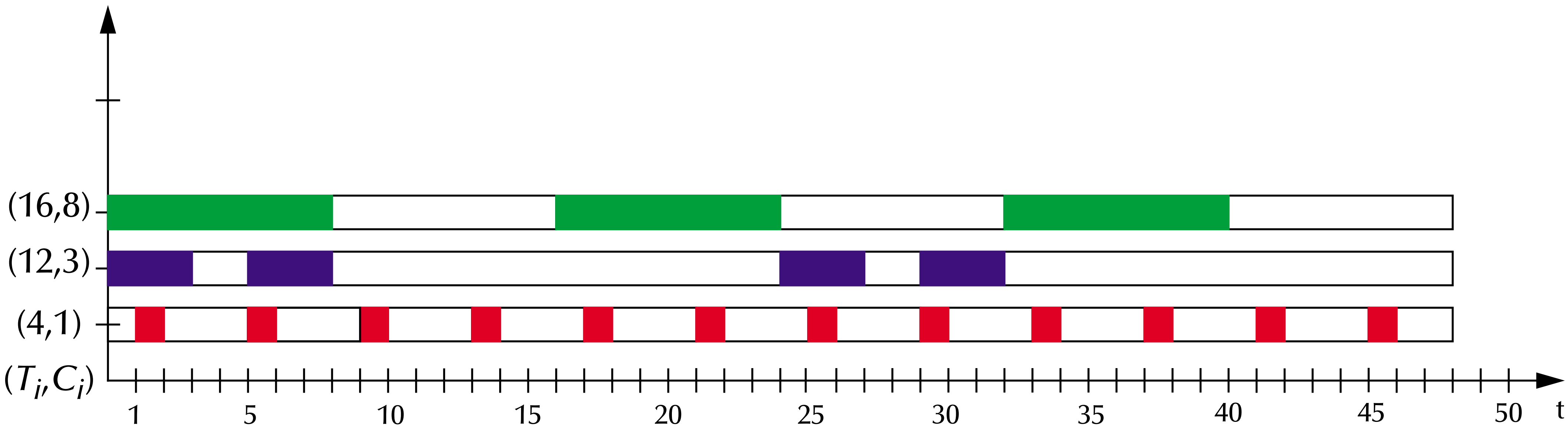
	Performance criteria: minimize the …	**Predictability criteria:** minimize the diversion from given
Process / user perspective:		
Waiting time	maximum / average / variance	minimal and maximal waiting times
Response time	maximum / average / variance	minimal and maximal response times
Turnaround time	maximum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

Scheduling

Time scales of scheduling

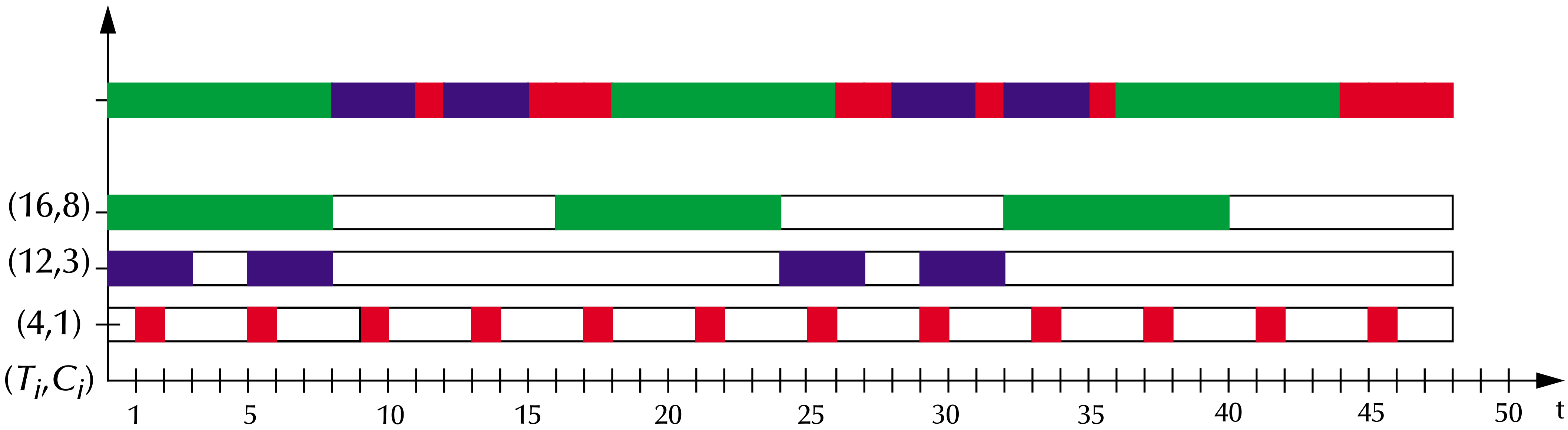


Example: Requested times



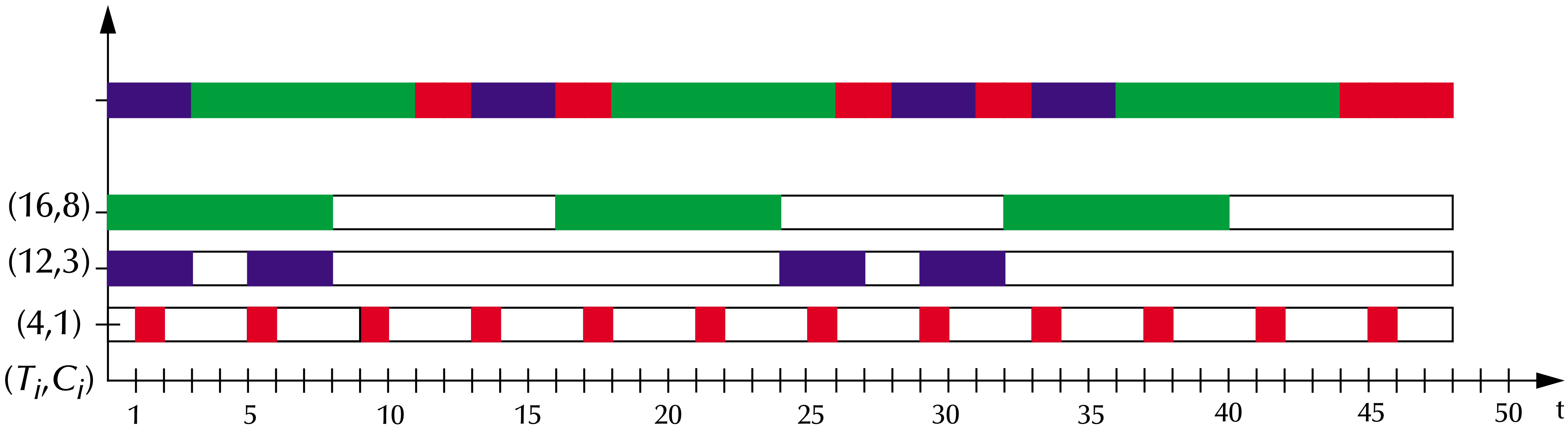
Scheduling

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**

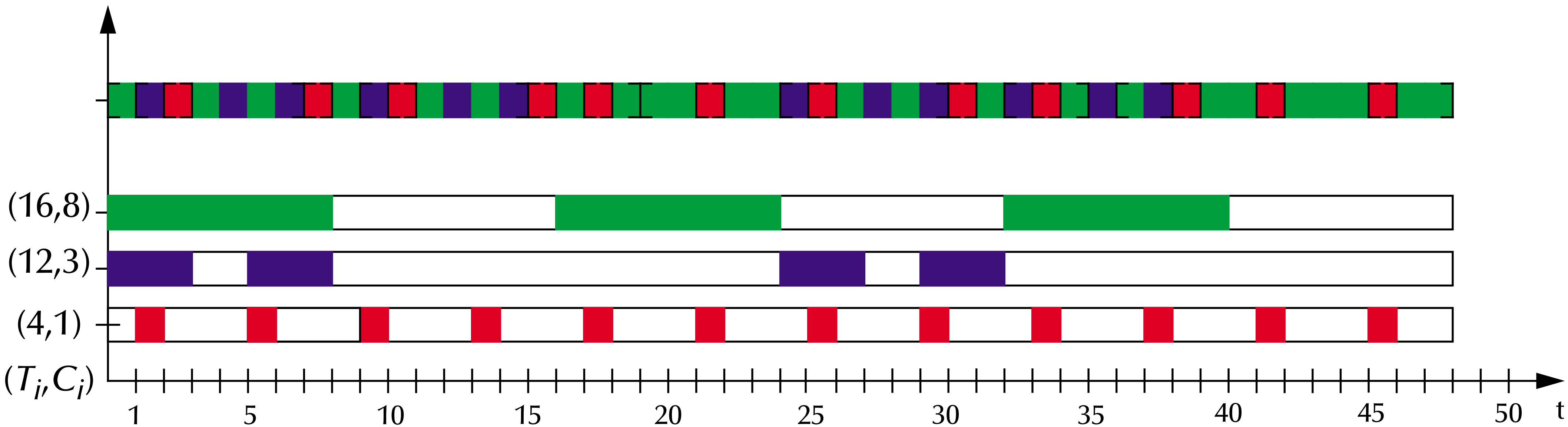
First come, first served (FCFS) *– nice case: (arrival order: red, purple, green)*



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

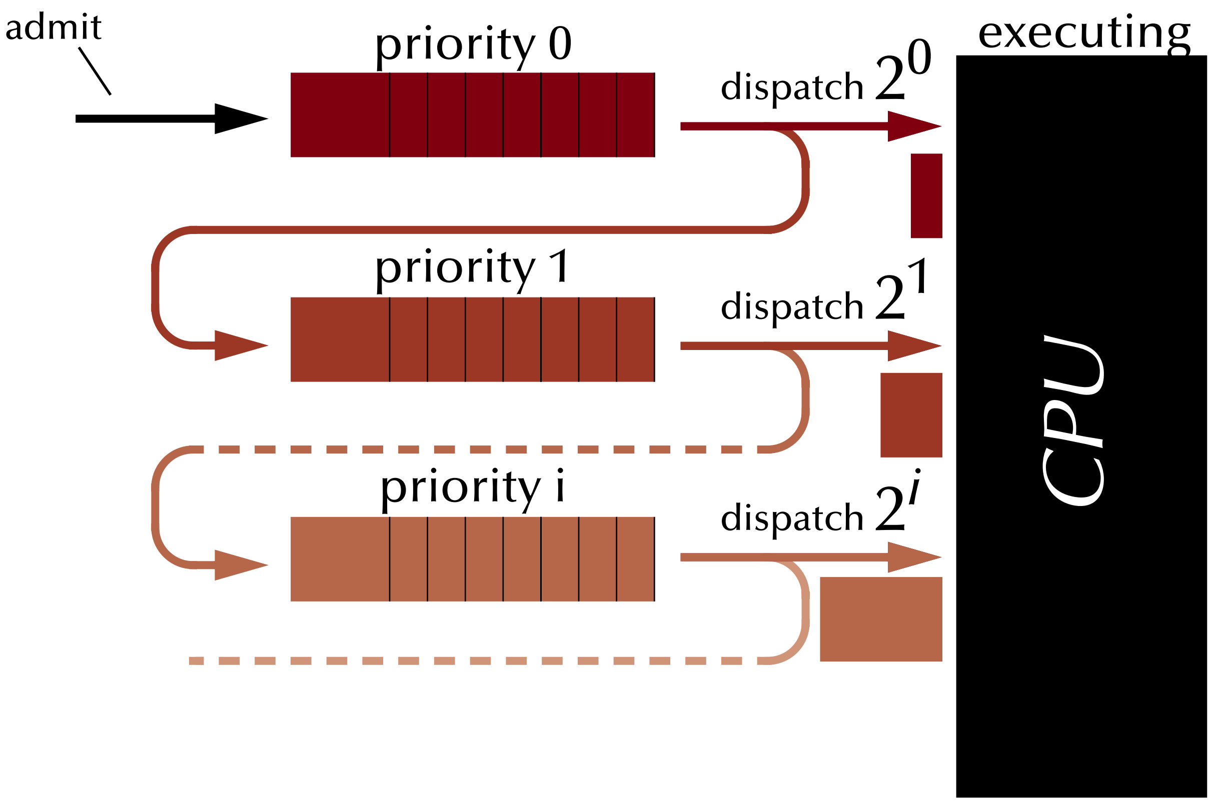
… assuming that task-switching is free and always possible

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

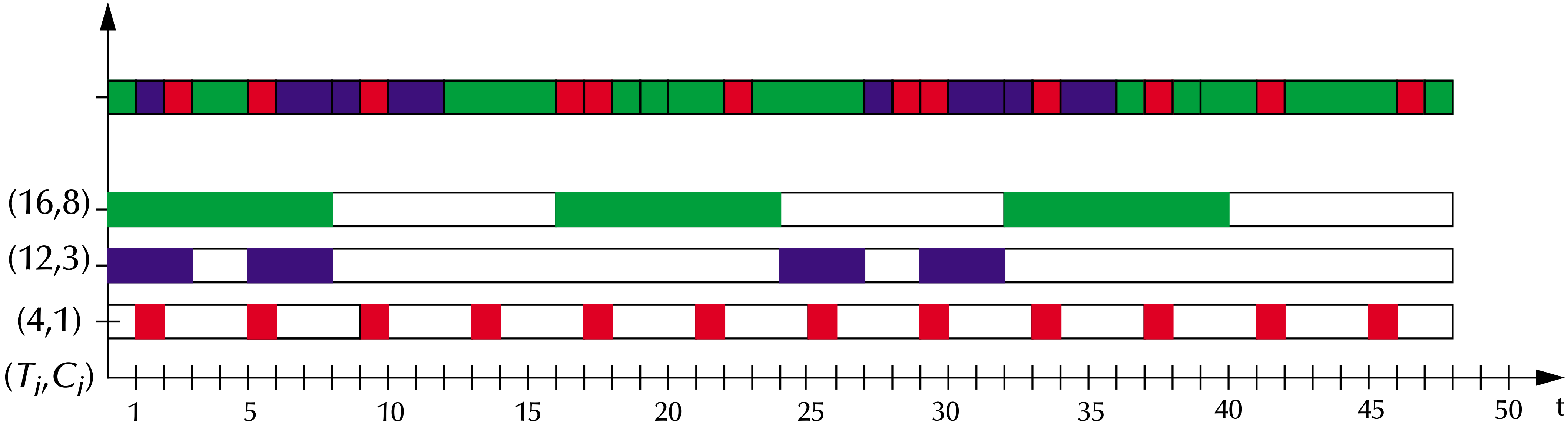
- implement multiple hierarchical ready-queues
- fetch processes from the highest filled ready queue
- dispatch more CPU time for lower priorities (2^i units)

☞ processes on lower ranks may suffer starvation

☞ new and short tasks will be preferred



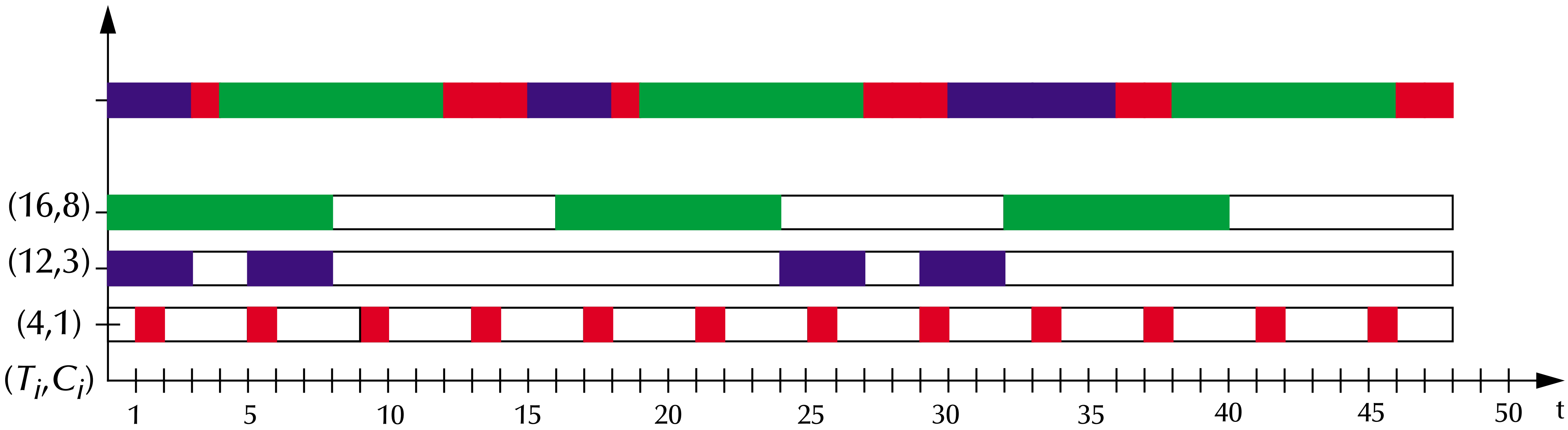
Feedback with 2^i pre-emption intervals *– pre-emption*



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!

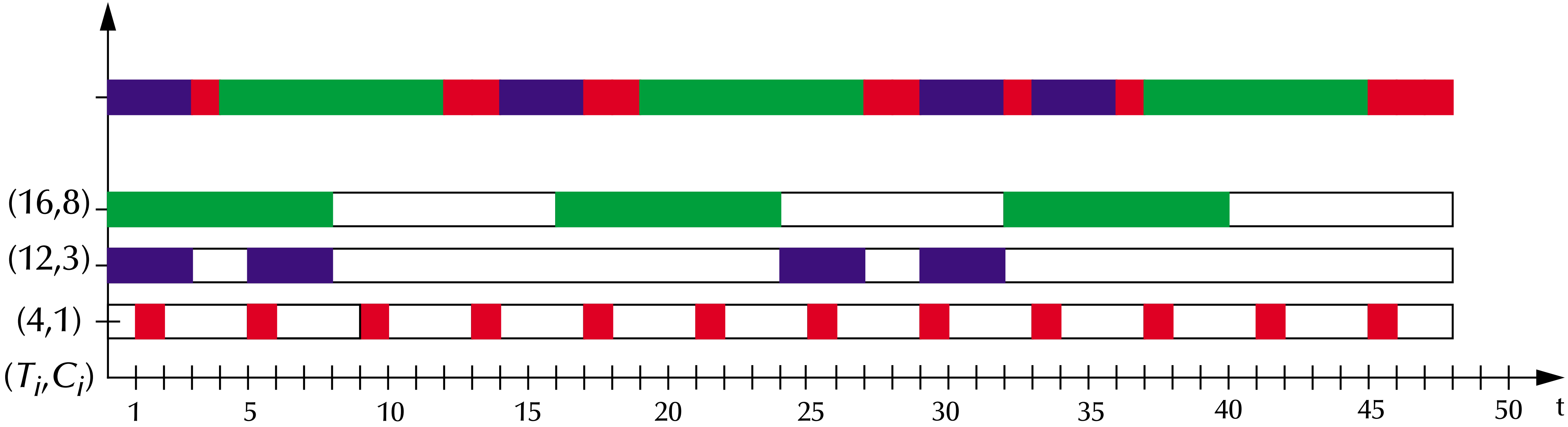
Shortest job first (SJF) – C_i is known



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

☞ *on average* this is doing better than FCFS

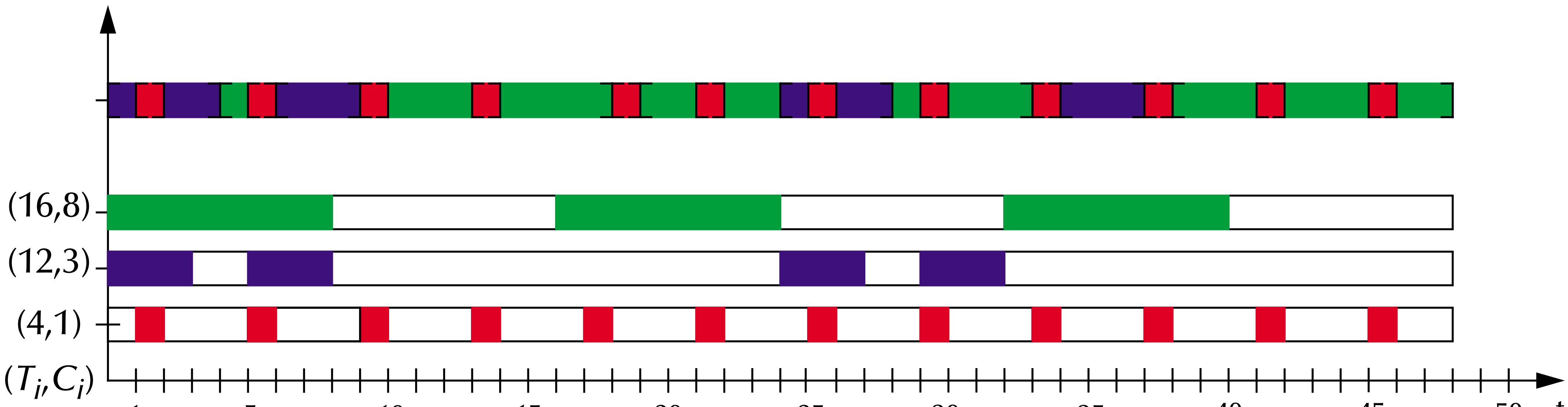
Highest response ratio first (HRRF) – C_i is known



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!

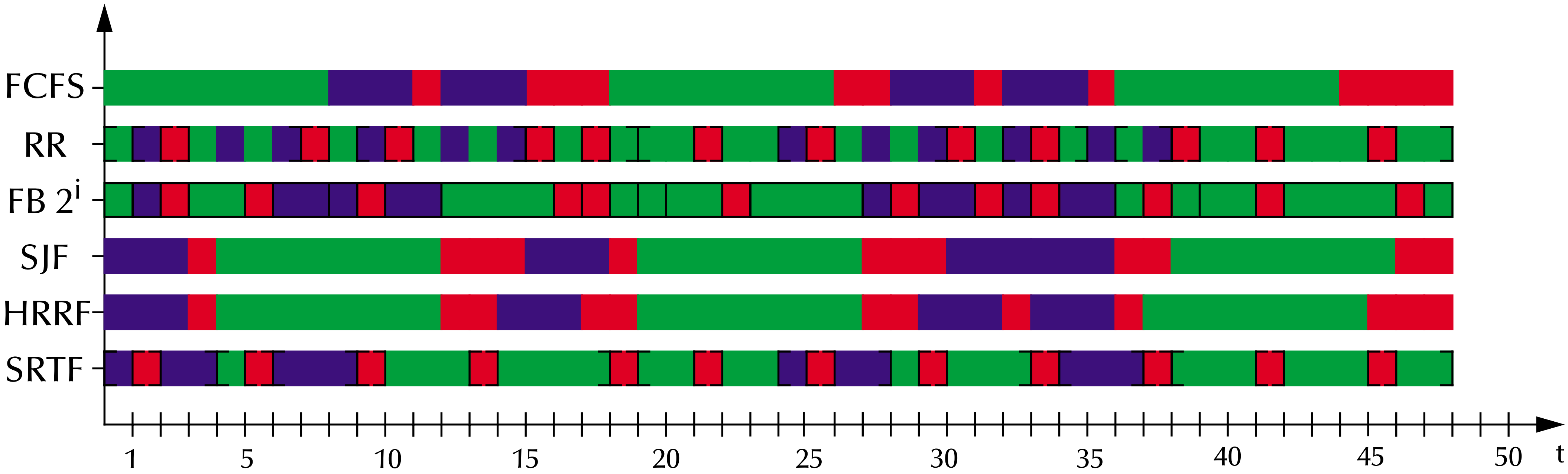
Shortest remaining time first (SRTF) – C_i is known + pre-emption



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.

Non-realtime scheduling methods

	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 are more specific (time scopes).

☞ Task sets are often fully or mostly static.

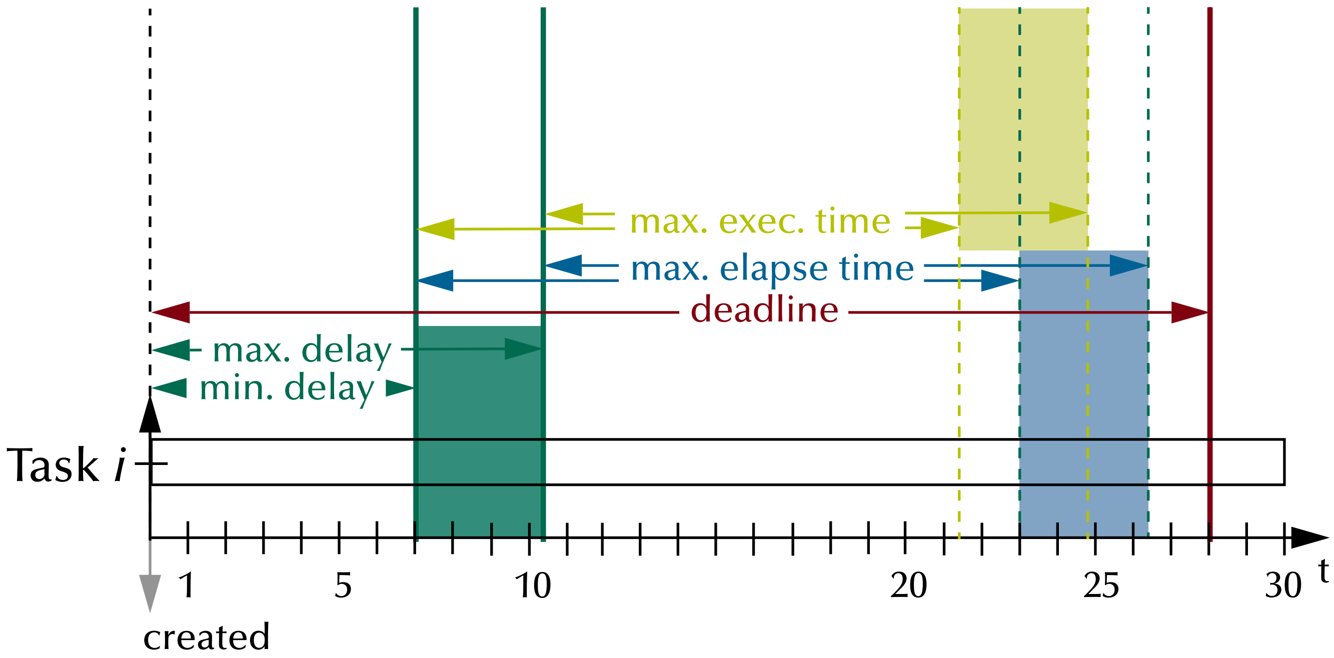
☞ Sporadic and urgent requests (e.g. user interaction, alarms) need to be addressed.

¬ 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

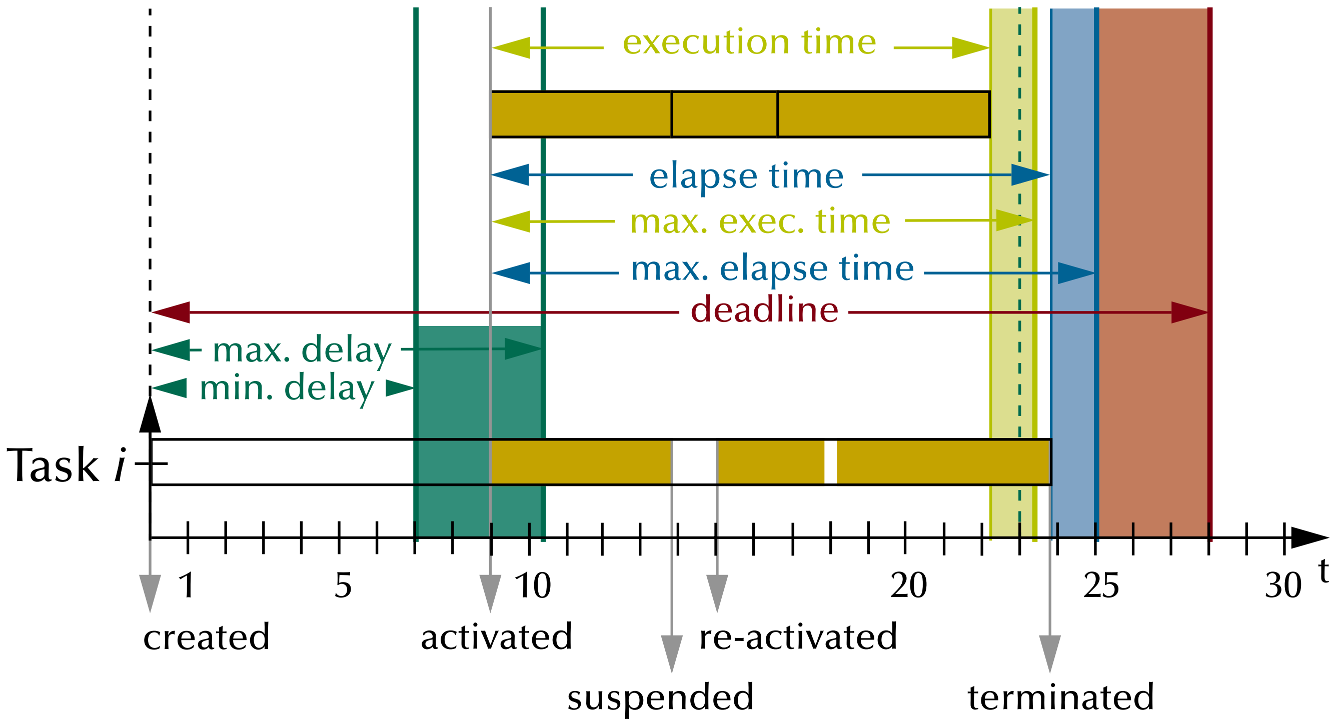


Specifying timing requirements

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

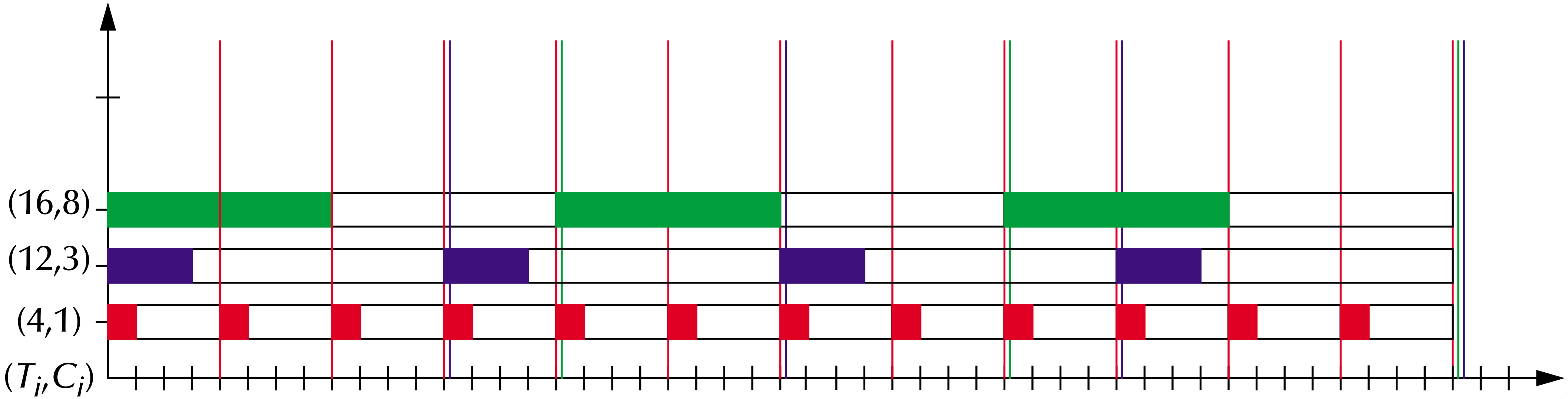
A simple process model

- 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 very specific group of systems.
(more real-world extensions to this model will be discussed in other courses).

Predictable scheduling

Introducing deadlines



Earliest deadline first (EDF)

1. Determine (one of) the processe(s) with the closest deadline.

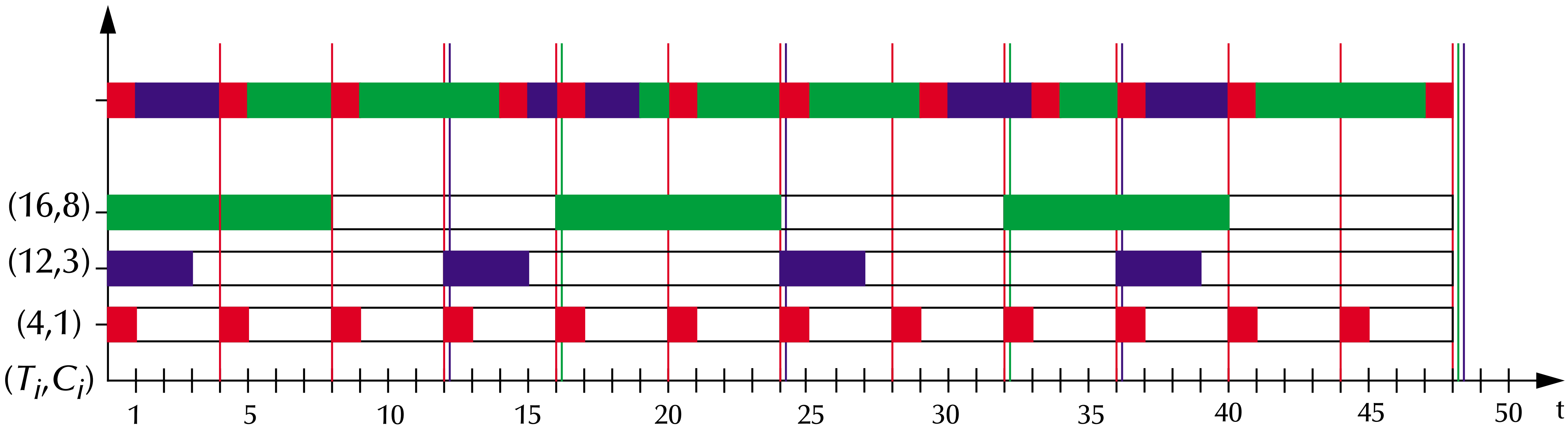
2. Execute this process

   2-a until it finishes

   2-b or until another process' deadline is found closer than the current one.

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

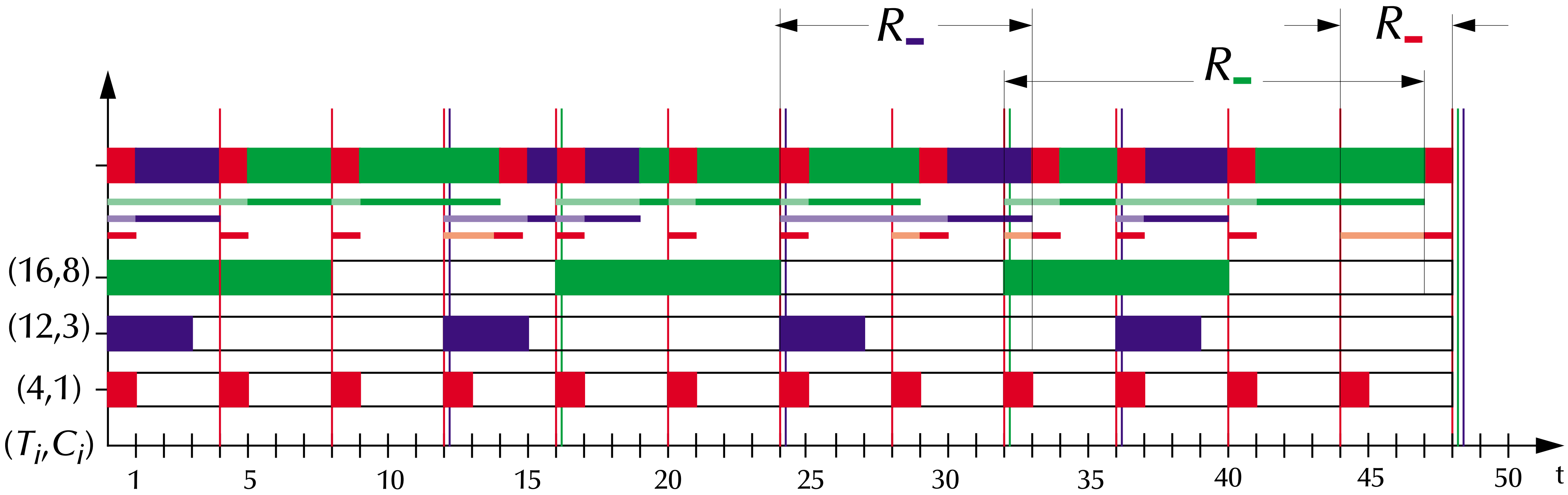
Earliest deadline first



1. Schedule the earliest deadline first

2. Avoid task switches (in case of equal deadlines)

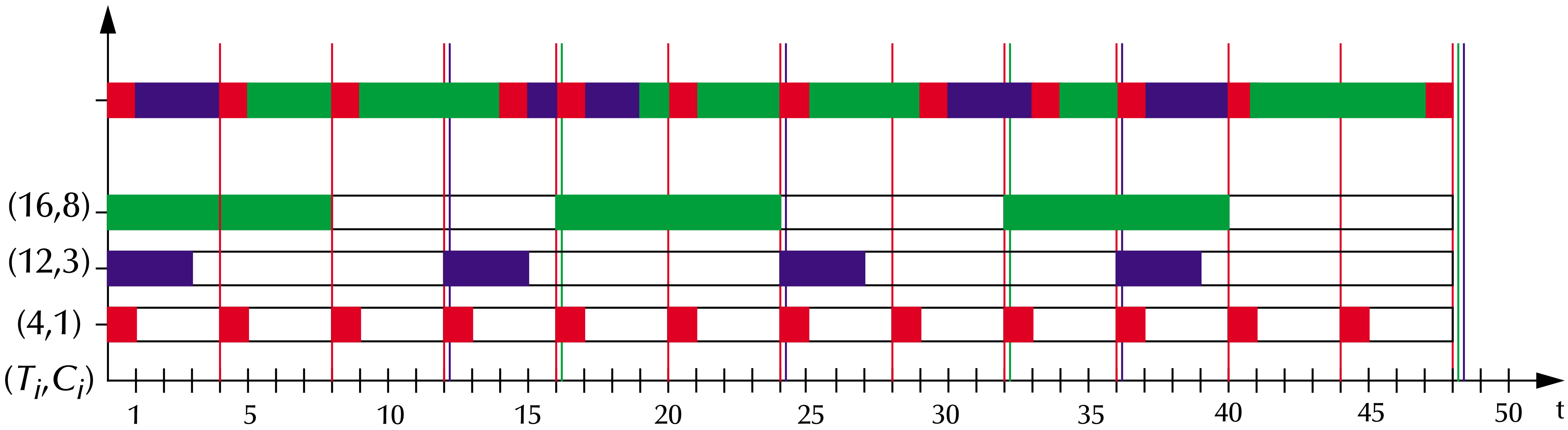
Earliest deadline first: Response times



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.

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)

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.

Static scheduling

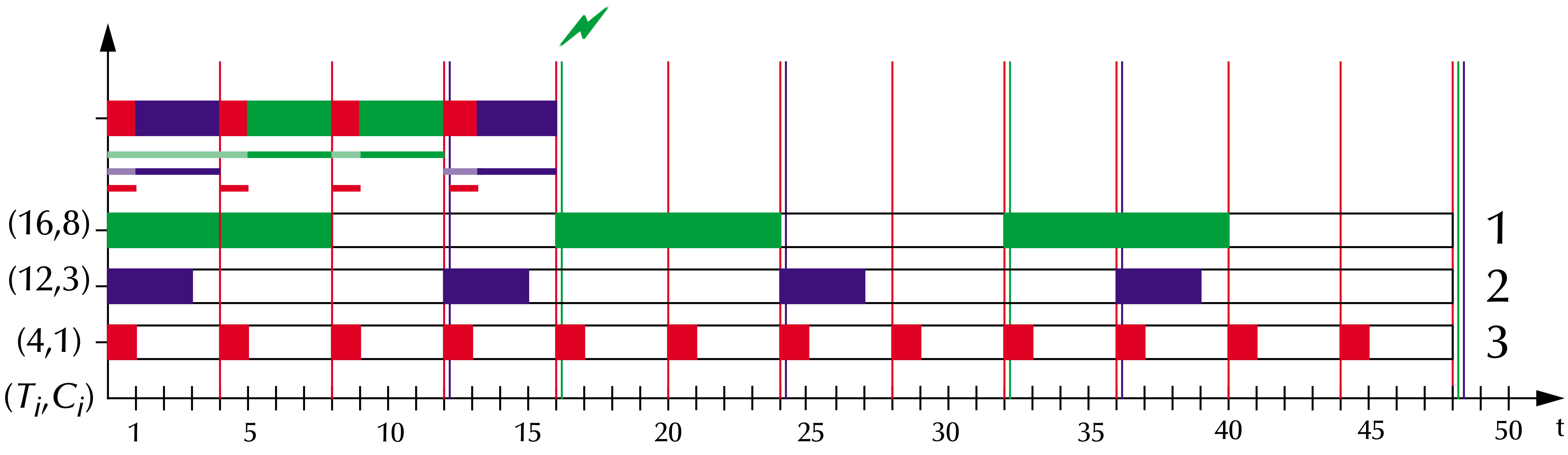
Fixed Priority Scheduling (FPS), rate monotonic

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.

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

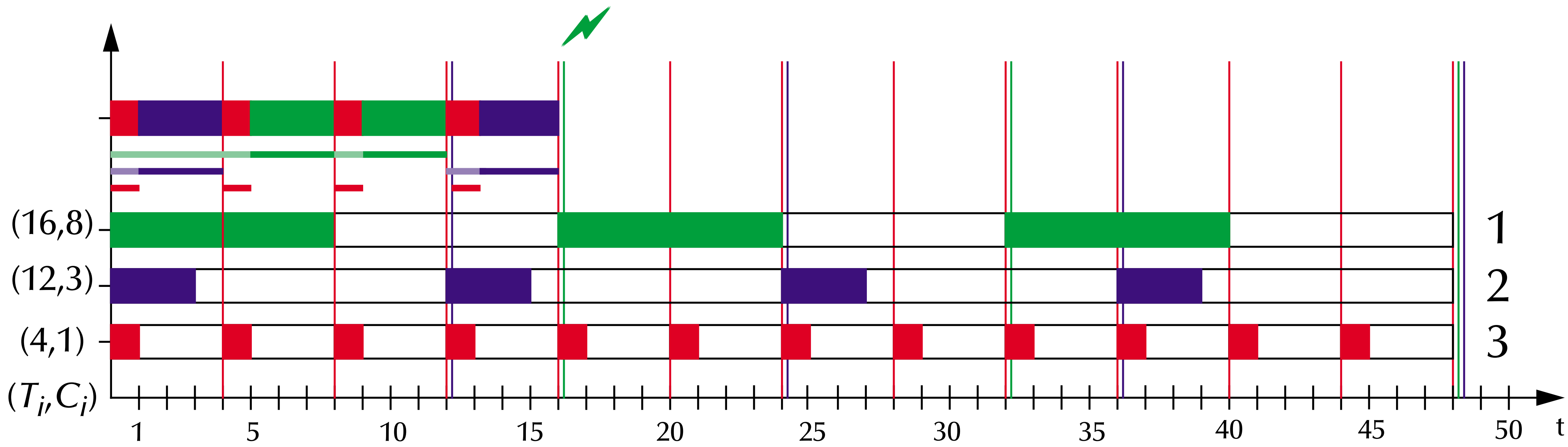
Rate monotonic priorities



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!

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

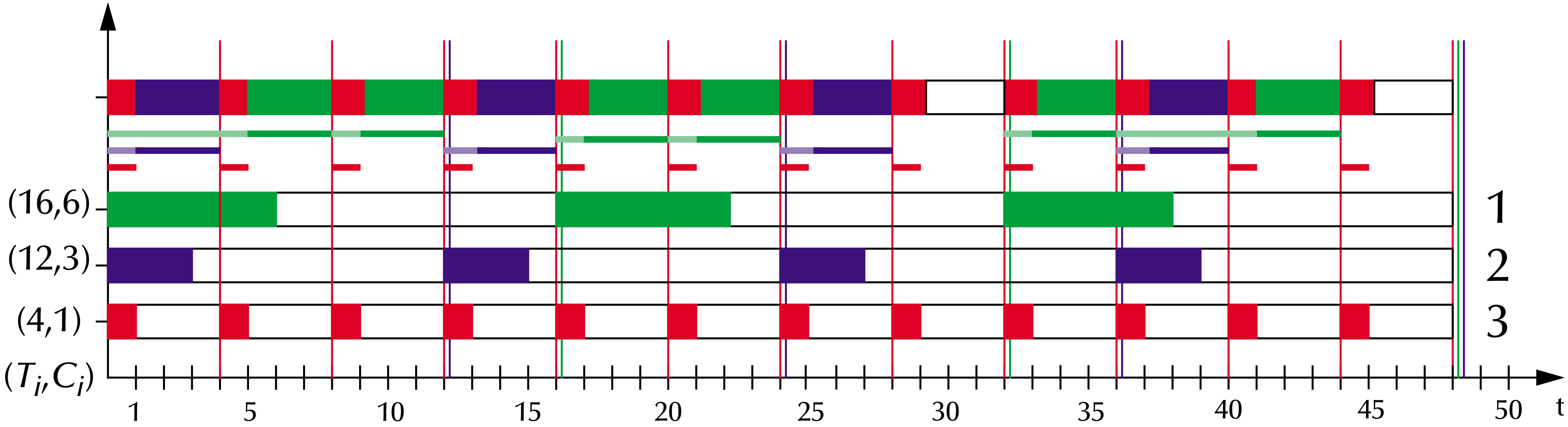
Rate monotonic priorities



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!

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

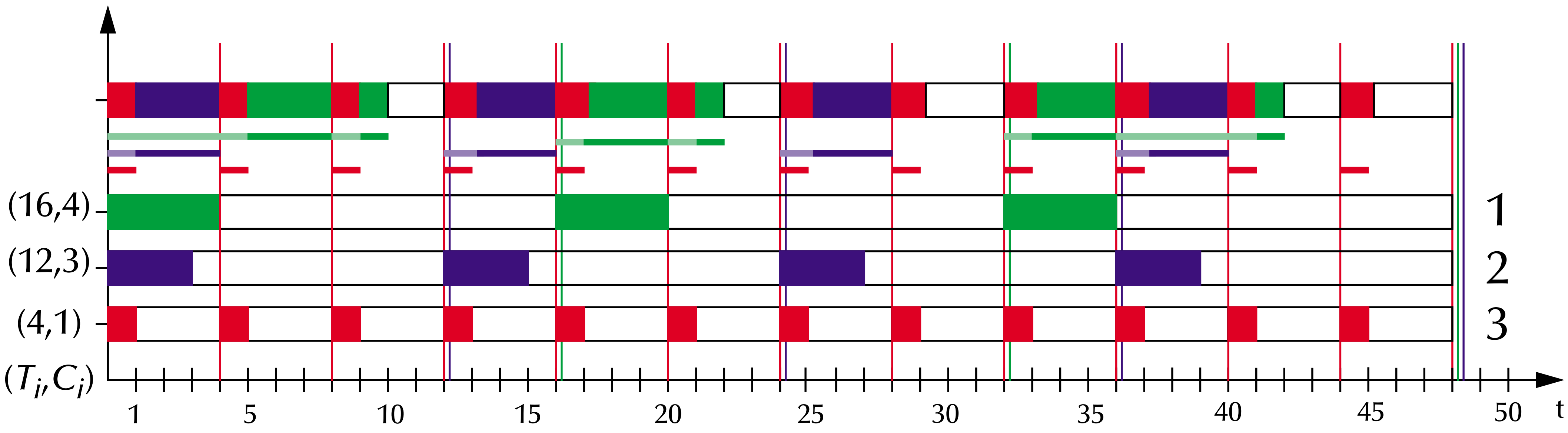
Rate monotonic priorities *(reduced requests)*



☞ 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

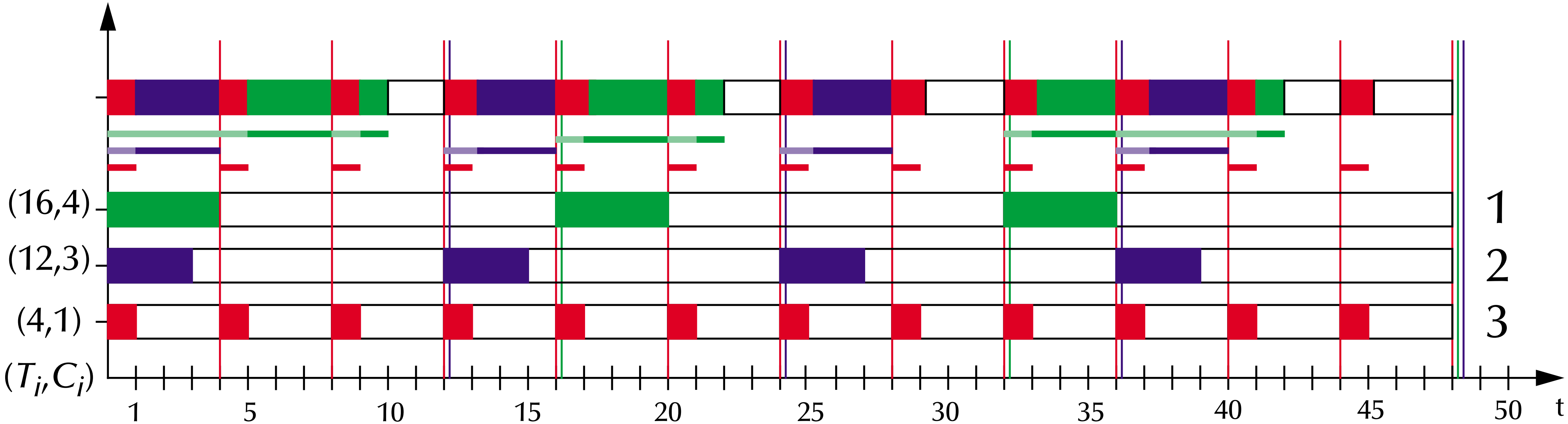
Rate monotonic priorities *(further reduced requests)*



☞ 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

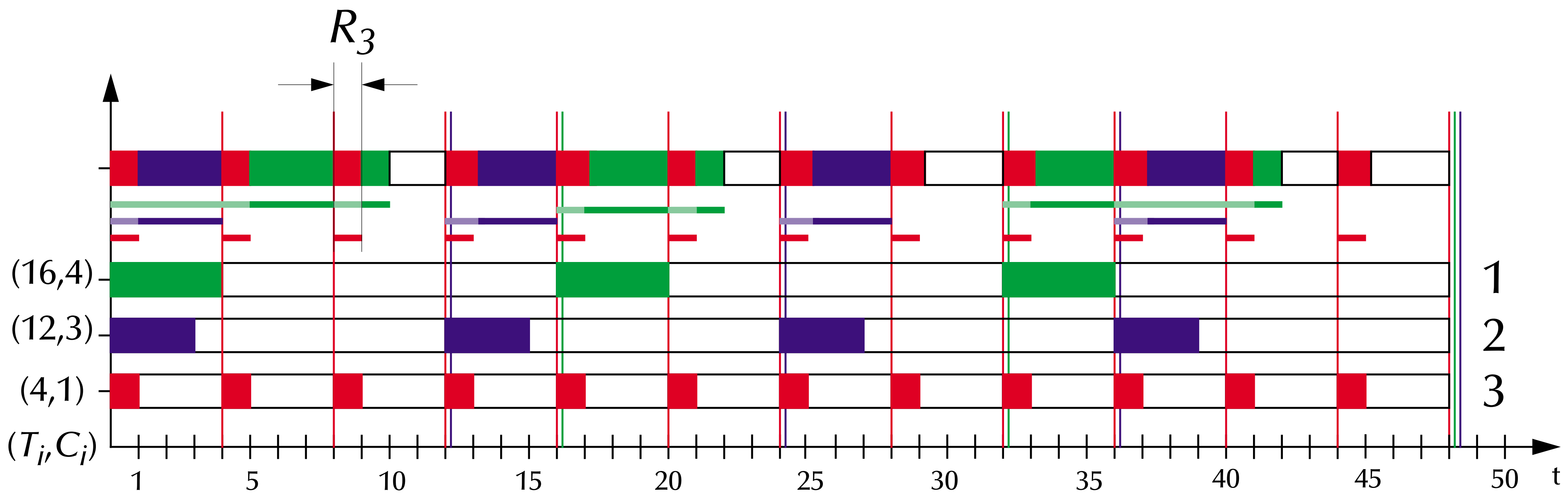
Response time analysis *(further reduced requests)*



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

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

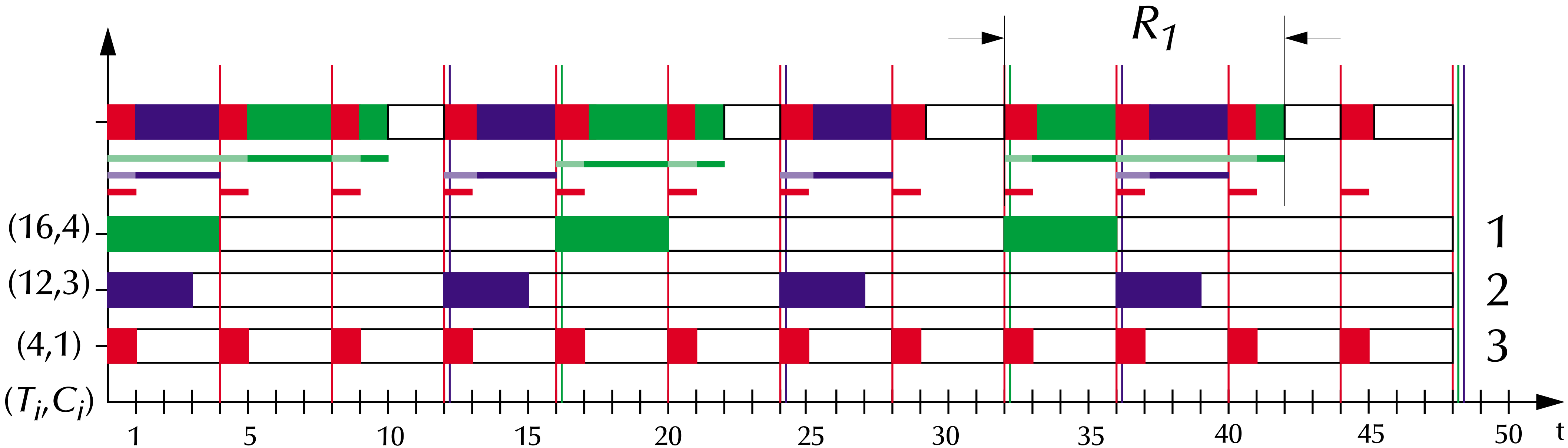
Response time analysis *(further reduced requests)*



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

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

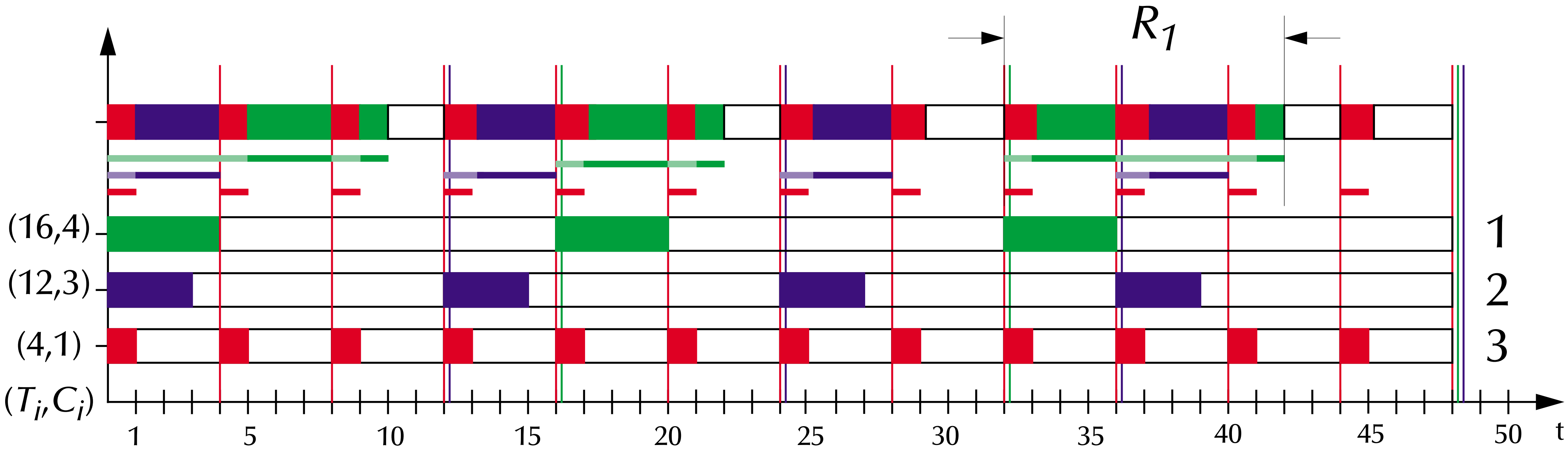
Response time analysis *(further reduced requests)*



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

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

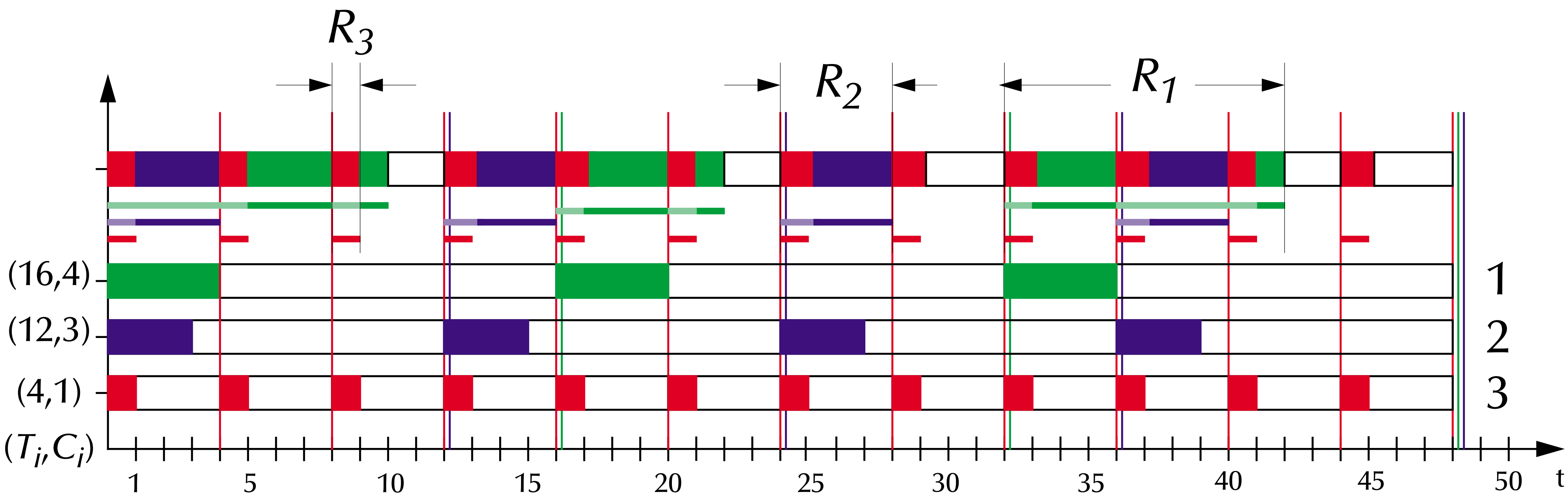
Response time analysis *(further reduced requests)*



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

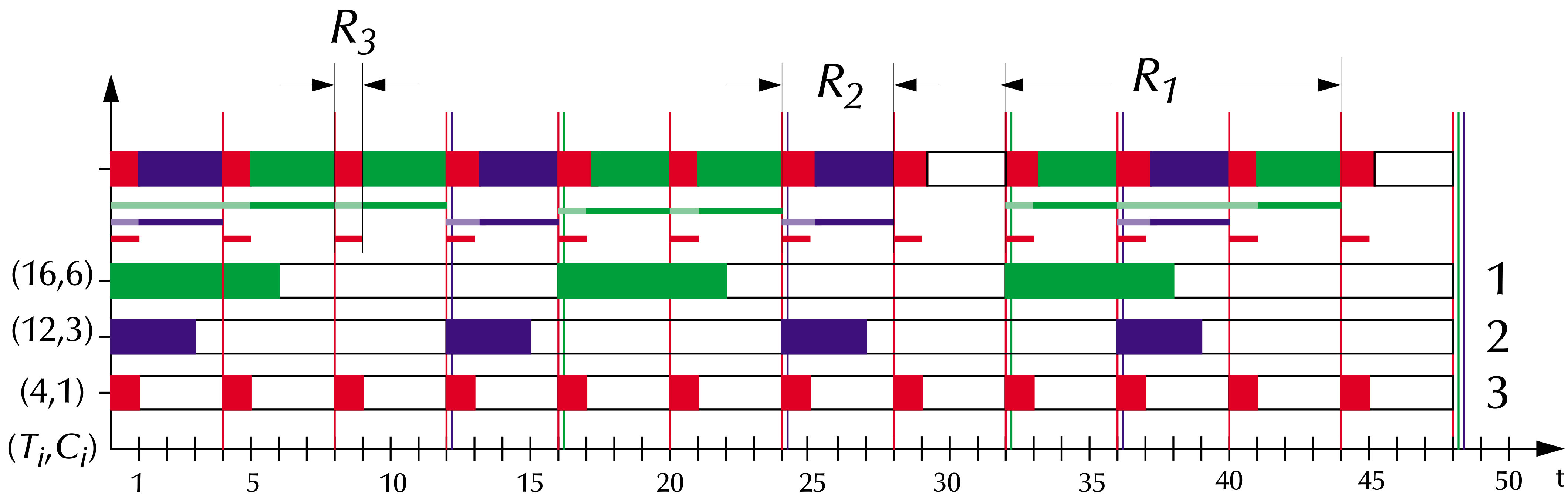
Response time analysis (further reduced requests)



☞ $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 10$✔ and $\sum_{i=1}^{n} \frac{C_i}{T_i} \le N\left(2^{\frac{1}{N}} - 1\right)$✔

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

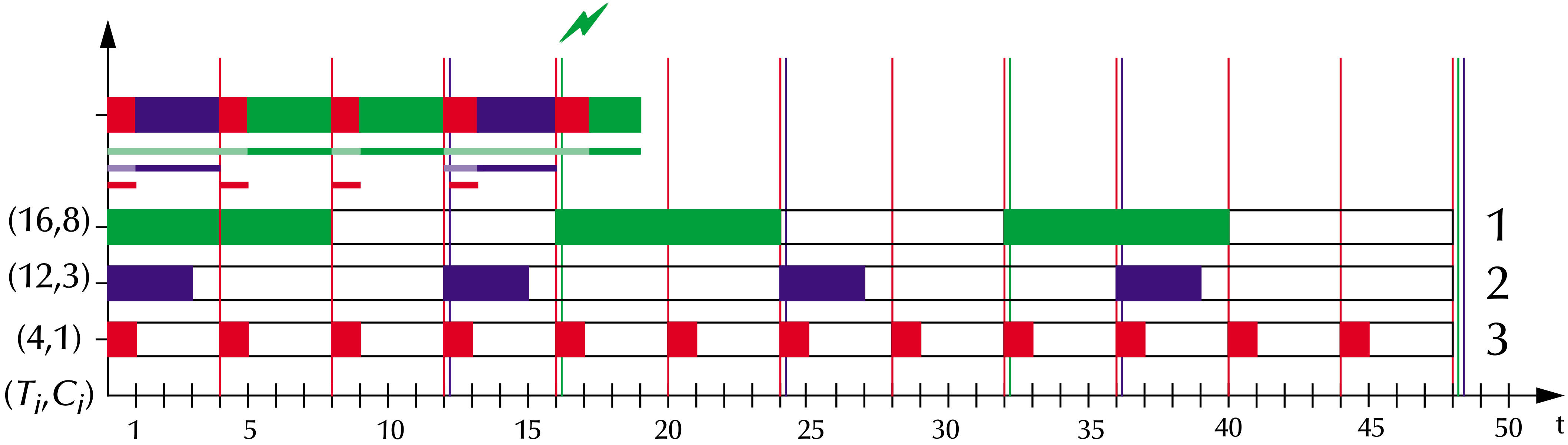
Response time analysis (reduced requests)



☞ $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 12$✔ but $\sum_{i=1}^{n} \frac{C_i}{T_i} > N\left(2^{\frac{1}{N}} - 1\right)$ ✖

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

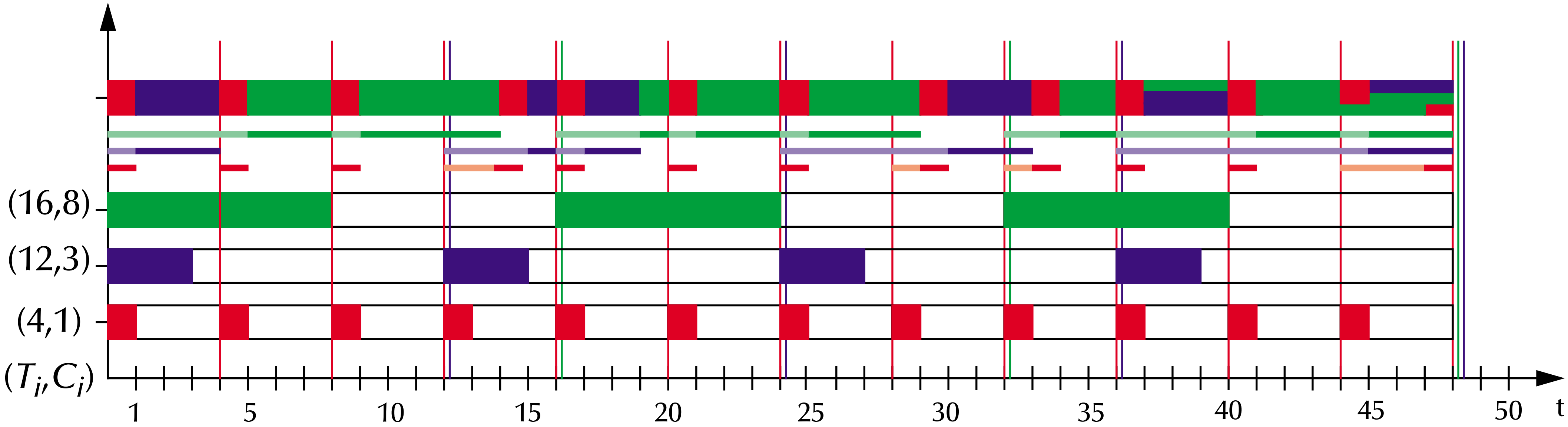
Response time analysis *(full requests)*



☞ $R_3 = 1$✔; $R_2 = 4$✔; $R_1 = 19$✖ and $\sum_{i=1}^{n} \frac{C_i}{T_i} > N\left(2^{\frac{1}{N}} - 1\right)$✖

Dynamic scheduling: Earliest Deadline First (EDF)

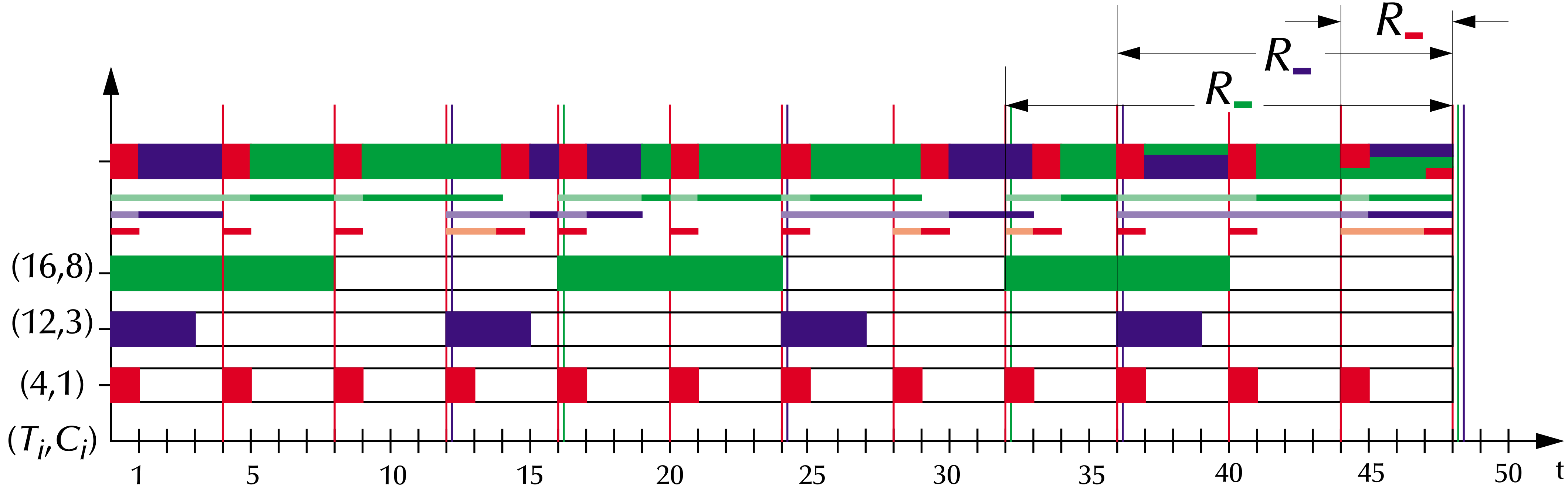
Response time analysis *(full requests)*



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

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis *(full requests)*

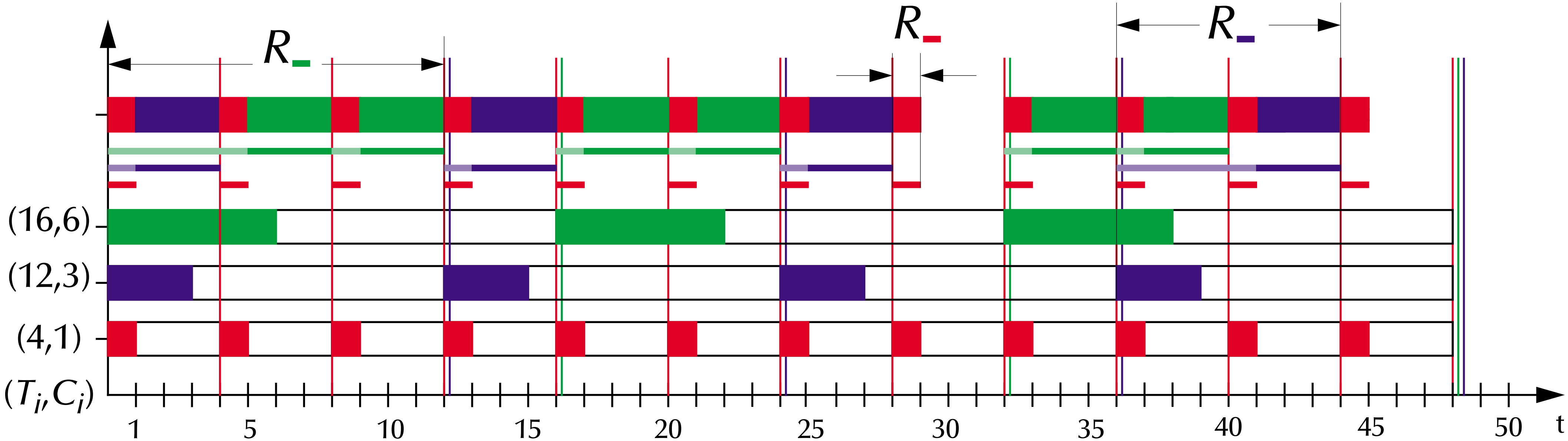


☞ testing all combinations in a hyper-period: LCM of $\{T_i\}$ — here: 48

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

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis *(reduced requests)*

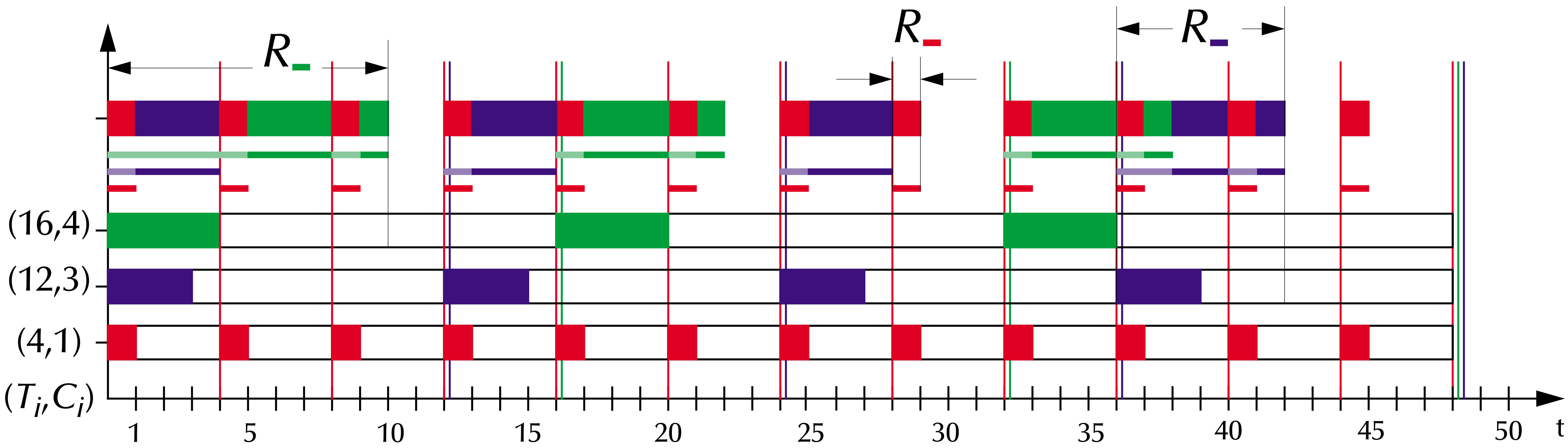


☞ relaxed task-set changes:

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

Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis *(further reduced requests)*



☞ further relaxed task-set changes:

R : 12 → 10 ≤ 16✔ = T ; R : 8 → 6 ≤ 12✔ = T ; R : 1 → 1 ≤ 4✔ = T

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

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

	Selection	Pre-emption	Waiting	Turnaround	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	$max((W_i + C_i)/C_i)$	no	short on average, lower variance	short on average, lower variance	balanced	no
SRTF	$min(C_i - E_i)$	yes	very short on average	very short on average, large maximum	short	yes
FPS	$max(P_i)$	yes	priority based	priority based	higher priority	yes
EDF	$min(D_i)$	yes	deadline based	often close to deadlines	most urgent	no

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)

7

Safety & Liveness

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References for this chapter

[Ben-Ari90]

M. Ben-Ari
Principles of Concurrent and Distributed Programming
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[Bacon98]

J. Bacon
Concurrent Systems
1998 (2nd Edition)
Addison Wesley Longman Ltd,
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Correctness in concurrent systems

Extended concepts of correctness in concurrent systems:

¬ Termination is often not intended or even considered a failure

- Safety properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Box\, Q(I, S)$$

where $\Box\, Q$ means that Q does *always* hold

- Liveness properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond\, Q(I, S)$$

where $\Diamond\, Q$ means that Q does *eventually* hold (and will then stay true)
and S is the current state of the concurrent system

Correctness in concurrent systems

- Liveness properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond Q(I, S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)

Examples:

- Requests need eventually to be completed
- The state of the system needs eventually be displayed to the outside
- No part of the system is to be delayed forever (fairness)

☞ Interesting liveness properties can be extremely hard to be proven

one central liveness property: Fairness

- **Liveness properties**:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Diamond Q(I, S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)

Fairness (as a means to avoid starvation):

- **Weak fairness**: $\Diamond \Box R \Rightarrow \Diamond G$
  resource will eventually be granted, if a process requests continually
- **Strong fairness**: $\Box \Diamond R_i \Rightarrow \Diamond G$
  resource will eventually be granted, if a process requests infinitely often
- **Linear waiting**: resource will be granted
  before any other process had the same resource granted more than once.
- **First-in, first-out**: resource will be granted
  before any other process which applied for the same resource at a later point in time.

Correctness in concurrent systems

- Safety properties:

$$(P(I) \wedge Processes(I, S)) \Rightarrow \Box Q(I, S)$$

where $\Box Q$ means that Q does *always* hold

Examples:

- Mutual exclusion (no resource collisions)
- Absence of deadlocks
  (and other forms of 'silent death' and 'freeze' conditions)
- Specified responsiveness or free capabilities
  (typical in real-time / embedded systems or server applications)

Deadlocks

Synchronization may lead to

☞ *DEADLOCKS*

(avoidance / prevention of those is one central safety property)

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

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 : $[A \mid X] \rightarrow \{[B \rightarrow Y] \text{ xor } [Y \rightarrow B]\} \rightarrow [C \mid Z]$

or : $[A \mid X] \rightarrow$ `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!

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, if ***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

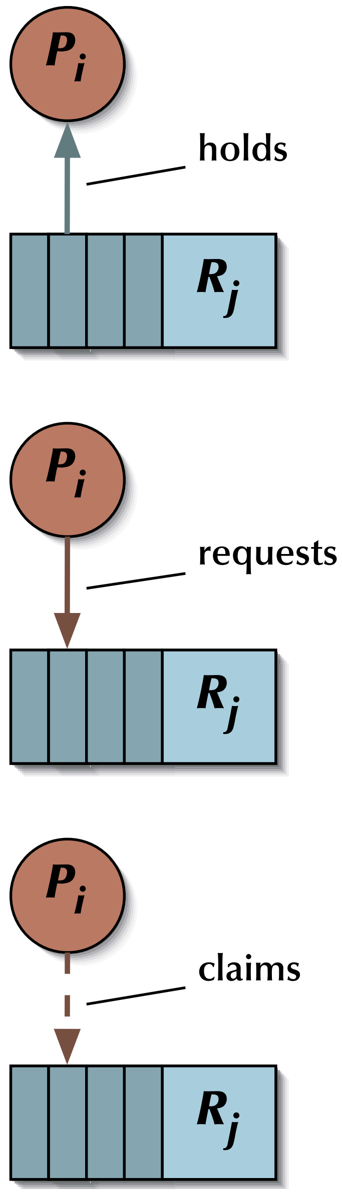
$E = E_r \cup E_a \cup E_c$; claims, requests and assignments

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

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

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

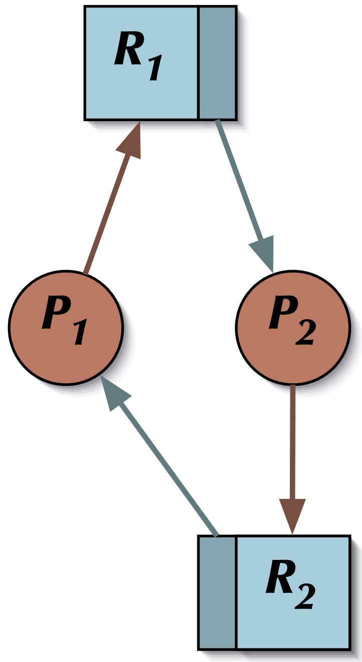
Note: a resource may have more than one instance



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

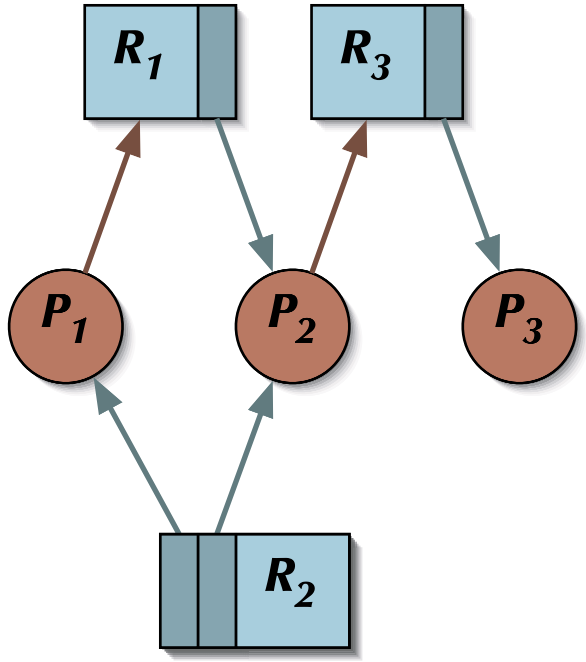
the two process, reverse allocation deadlock:



Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

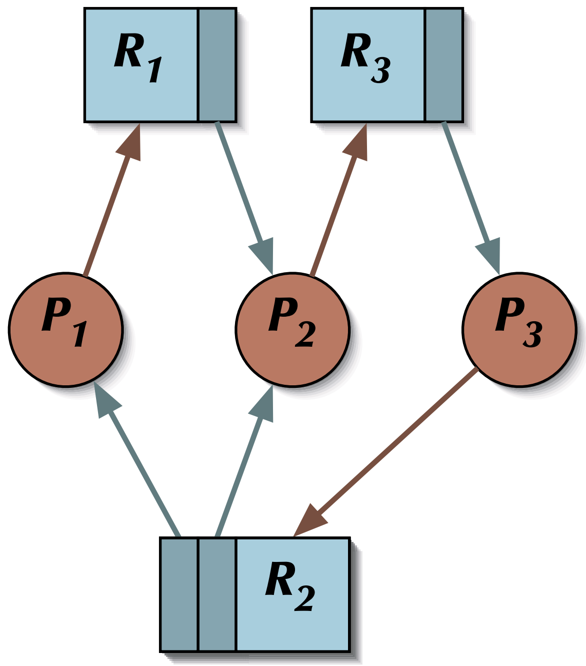


no, there is no circular dependency

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



yes, there are circular dependencies:

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

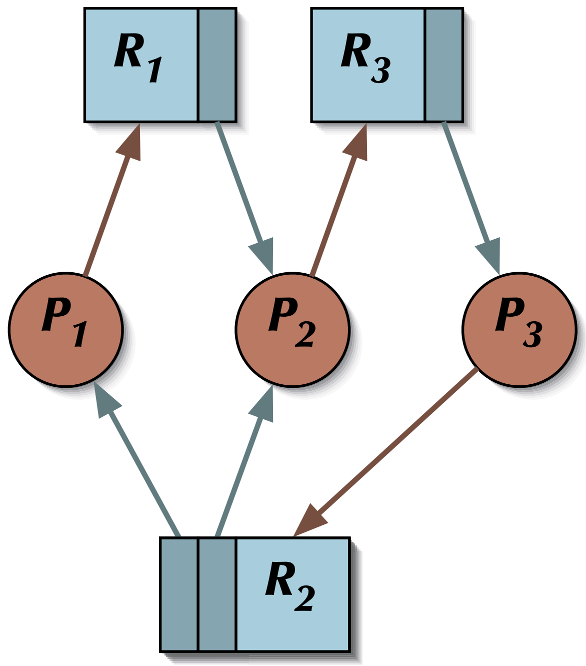
as well as: $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

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

Deadlocks

Edge Chasing

(Chandy, Misra & Haas ☞ distributed version)



∀ blocking process:

- send probe containing three process id's:

  [the blocked, the sending, the receiving process]

∀ blocked process receiving a probe:

- propagate the probe to the process holding the resource, which this process requests
  (while updating the second and third proc.-id's.)

∀ blocking process receiving its own probe:

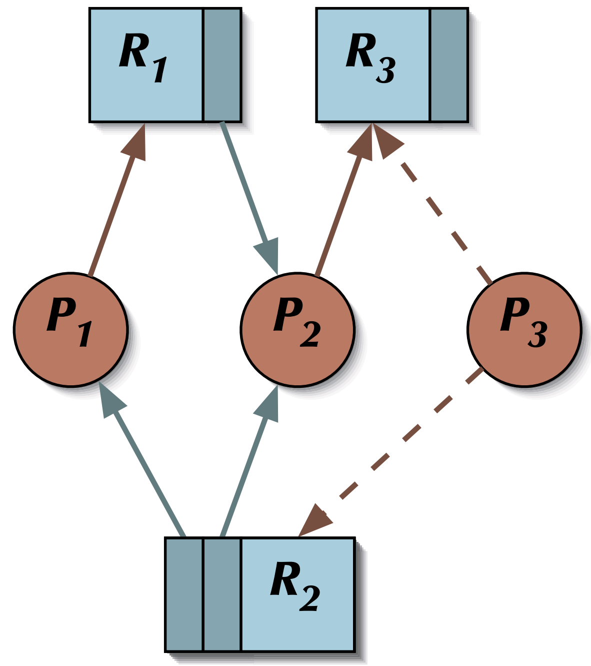
☞ possible deadlock detected!

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

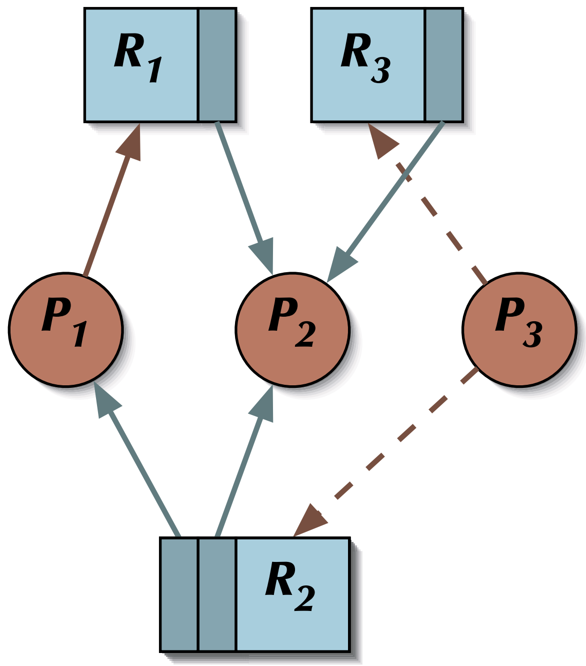
Assuming all claims of P_3 are known in advance,

☞ Could the deadlock situation be avoided?



Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

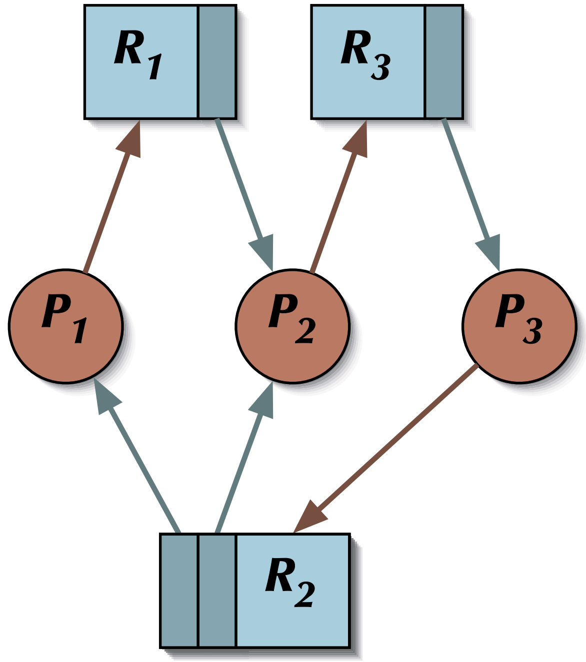


yes, when resources are assigned so that there are no resulting circular dependencies:

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

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



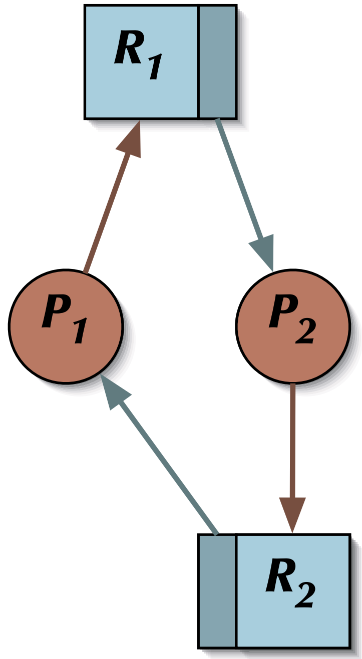
$P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

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)

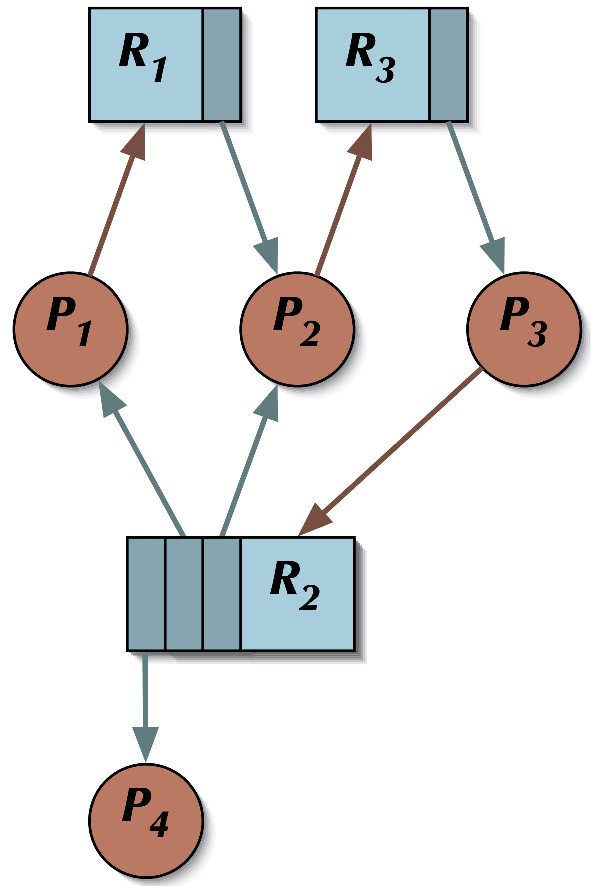


yes,
if there is only one instance per resource type:

☞ ***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)



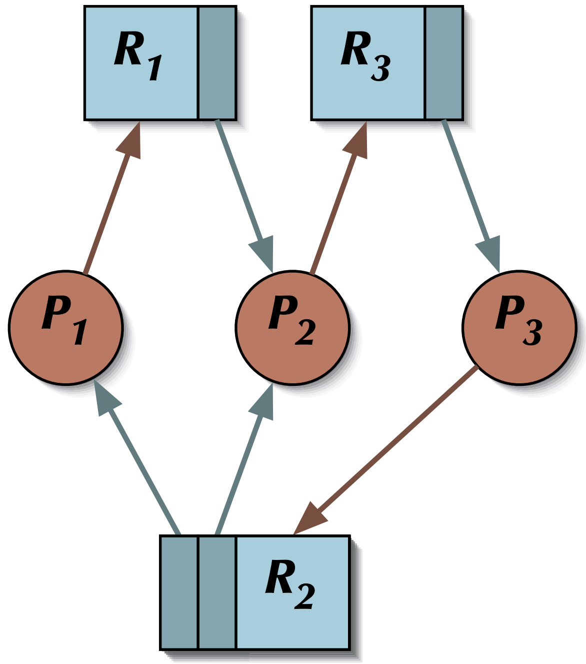
no,
if there is more than one instance
per resource type:

☞ ***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!***

Deadlocks

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. $\mathit{Simulated\_Free} \Leftarrow \mathit{Free}; \forall i: \mathit{Completed}[i] \Leftarrow \mathit{False}$

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

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

3. **If** $\forall i: \mathit{Completed}[i]$ **then** the system is **deadlock-free**!
   (otherwise all processes *i* with $\mathit{Completed}[i] = \mathit{False}$ 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 detection / prevention

☞ Distributed version?

- Most resources are assigned to a local group of processes.

☞ Split the system into nodes

☞ Organize them as hierarchical trees or other topologies

☞ Check for deadlocks locally
  ☞ **find local deadlocks immediately**

☞ Exchange information about blocked tasks occasionally
  ☞ **detect global deadlocks eventually**

Menasce & Muntz – Ho & Ramamoorthy

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

Summary

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

Terminology

Reliability ::=

measure of success with which a system conforms to its specification

or

low failure rate.

Failure ::= deviation of a system from its specification

Error ::= system state which lead to failures

Fault ::= the reason for an error

Faults on different levels

- Inconsistent or inadequate specification

  ☞ frequent source for disastrous faults

- Software design errors

  ☞ frequent source for disastrous faults

- Component & communication system failures

  ☞ rare and mostly predictable

Faults in the logic domain

- Non-termination / -completion

  ☞ systems frozen in a deadlock state, blocked for missing input, or in infinite loop

- Value overruns, other inconsistent states

  ☞ sometimes caught by the run-time environment

- Wrong results

  ☞ wrong implementation with respect to the specification

Faults in the time domain

- Transient faults

  ☞ many communication system failures, electric interference, etc.

- Intermittent faults

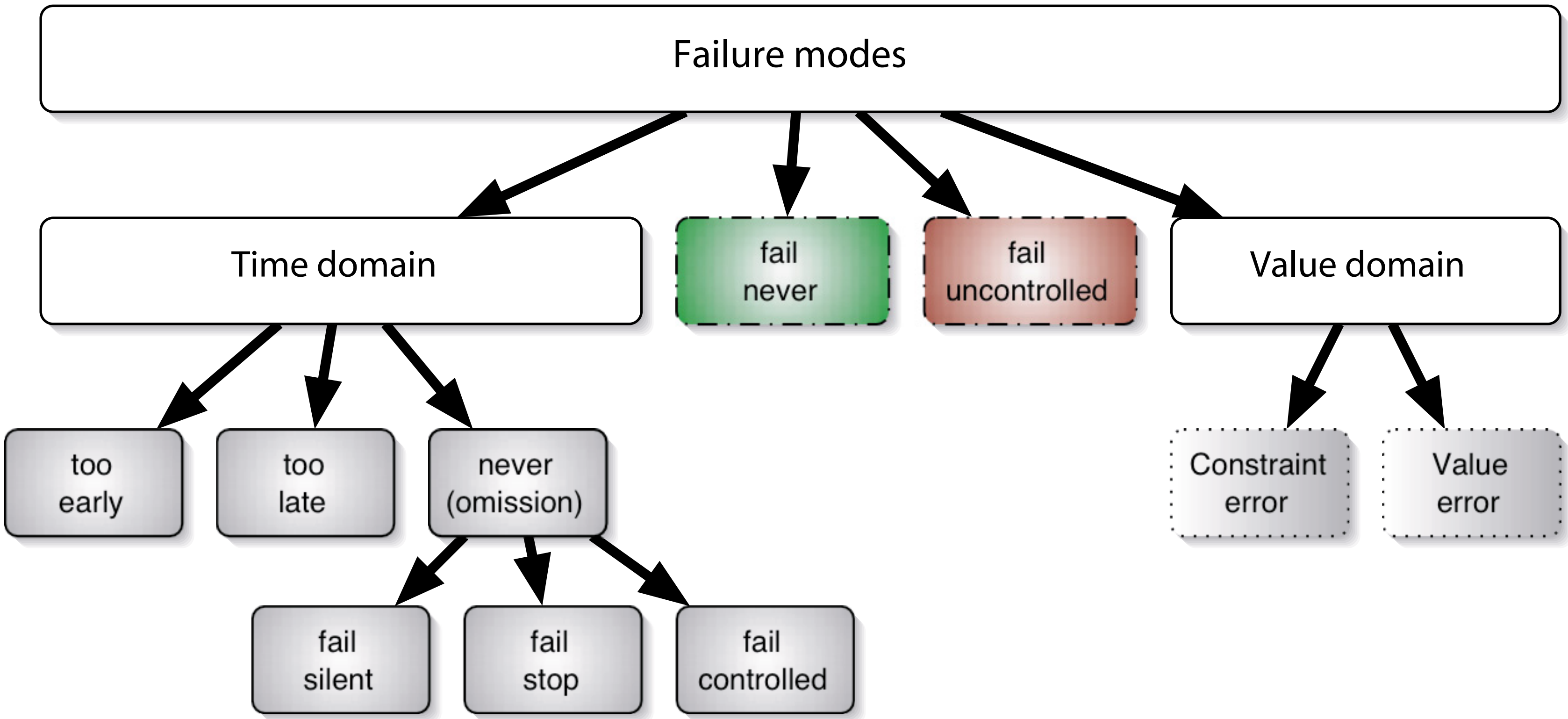
  ☞ transient errors which occur more than once (e.g. overheating effects)

- Permanent faults

  ☞ stay in the system until they are repaired by some means

Failure modes

Observable failures states



Reliability

Fault prevention, avoidance, removal, …

and / or

☞ *Fault tolerance*

Fault tolerance

- Full fault tolerance

  the system continues to operate in the presence of 'foreseeable' error conditions without any significant failures — also this might induct a reduced operation period.

- Graceful degradation (fail soft)

  the system continues to operate in the presence of 'foreseeable' error conditions, accepting a partial loss of functionality or performance.

- Fail safe

  the system halts and maintains its integrity

☞ Full fault tolerance is not maintainable for an infinite operation time!

☞ Graceful degradation might have multiple levels of reduced functionality.

Atomic operations

Definitions given in different scenarios:

An operation is atomic if the processes performing it …

- … *are not aware of the existence of any other active process,*
  and *no other active process is aware of the activity of the processes*
  during the time the processes are performing the action.
- … *do not communicate* with other processes while the action is being performed.
- … *cannot detect any outside state change* and
  do not reveal their own state changes until the action is complete.

☞ … can be considered to be *indivisible and instantaneous*.

Atomic operations

Important implications:

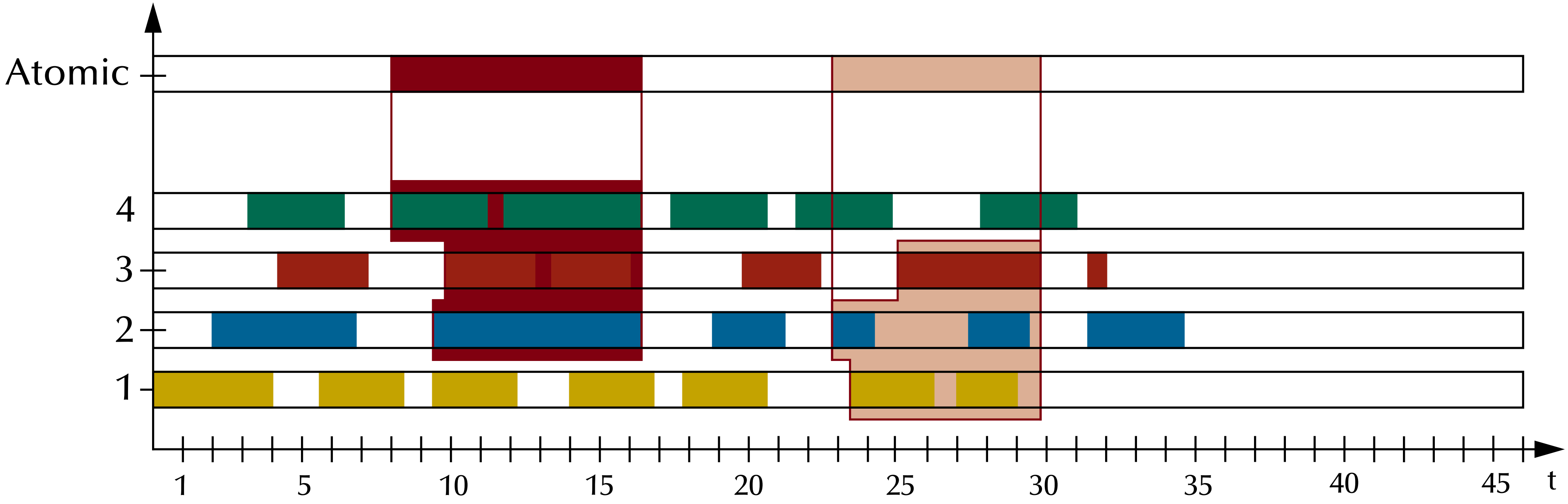
☞ An atomic operation …

- … is either performed fully, or not at all.
- … is declared as failed, if any part of the operation fails (and everything is reset to the original state).

Atomic & idempotent operations

Atomic operations

Time-lines:



Idempotent operations

Definition:

An operation is idempotent if …

- … the observable effects of the operation are *identical* after executing it *once* and after executing it *multiple times*.

Observations:

- Idempotent operations are often atomic, but do not need to be.
- Atomic operations do not need to be idempotent.

Safety & Liveness

- **Liveness**
  - Fairness
- **Safety**
  - Deadlock detection
  - Deadlock avoidance
  - Deadlock prevention
- **Failure modes**
  - Definitions, fault sources and basic fault tolerance
- **Atomic & Idempotent operations**
  - Definitions & implications

8

Architectures

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References for this chapter

[Bacon98]

J. Bacon
Concurrent Systems
1998 (2nd Edition)
Addison Wesley Longman Ltd,
ISBN 0-201-17767-6

Language architectures

(Some workfloor languages are already introduced at this point, so we turn to another style of clean concurrent architectures here)

occam 2.1

William of Ockham (born at Ockham in Surrey (England) in 1280 and died in Munich in 1349):

- Philosopher and Franciscan monk
- Reasoning in the frame of the school of Nominalism:
    - … science has nothing to do directly with things, but only with concepts of them
    - … leading to the absolute subjectivity of all concepts and universals
- Pioneer of modern Epistemology
  (will also help to develop the concept of Phenomenology 500 years later)

- 'Occam's razor':

“Pluralitas non est ponenda sine neccesitate”
or “plurality should not be posited without necessity”

(a common place in medieval philosophy)

occam 2.1

Origins:

- EPL (Experimental Programming Language) by David May
- CSP (Communicating Sequential Processes) by Tony Hoare
- “Dijkstra-Style” programming

Goals:

- Minimalist approach (☞ Occam’s razor) supplying all means for:

☞ Concurrency & communication,
☞ Distributed systems
☞ Realtime / Predictable systems

occam 2.1

Implementations:

- Transputer networks as an hardware implementation of the occam architecture (inmos, now SGS-Thomson)
- spoc (Southampton Portable occam Compiler)
- KRoC (Kent Retargetable Occam Compiler)

Historical:

- 1982: First conception
- 1992: occam 3 (draft)
- 1994: latest complete version: 2.1

Current state: academic (education)

occam 2.1

Characteristics (... everything is a process):

- Primitive processes are
  - *assignments*
  - *input*, or *output* statements (channel operations)
  - ***SKIP***, or ***STOP*** *(elementary processes)*

- Constructors are:
  - **SEQ** (sequence) + replication
  - **PAR** (parallel) + replication
  - **ALT** (alternation) + replication + priorities

  - **IF** (conditional) + replication
  - **CASE** (selection)
  - **WHILE** (conditional loop)

occam 2.1

Characteristics (… everything is a process and static):

☞ no dynamic process creation

☞ no unlimited recursion

Syntax structure:

- Indention is used block indication
  (instead of ‘begin-end brackets’)

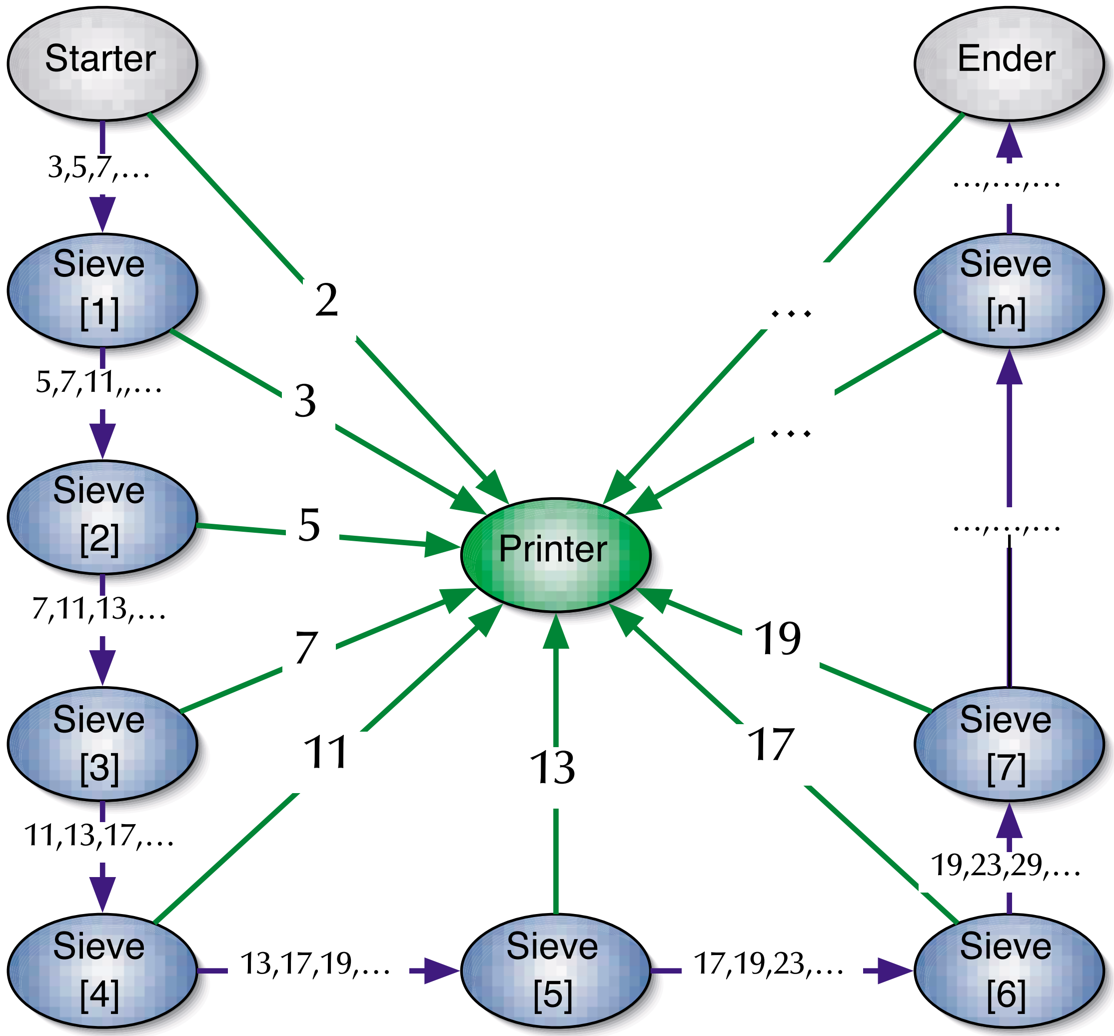
Scope of names:

- strictly local, indicated by indention
- no ‘forward declarations’, ‘exports’, ‘global variables’, or ‘shared memories’

occam 2.1

An example

- use processes and channels
  to implement a simple prime sieve



occam 2.1

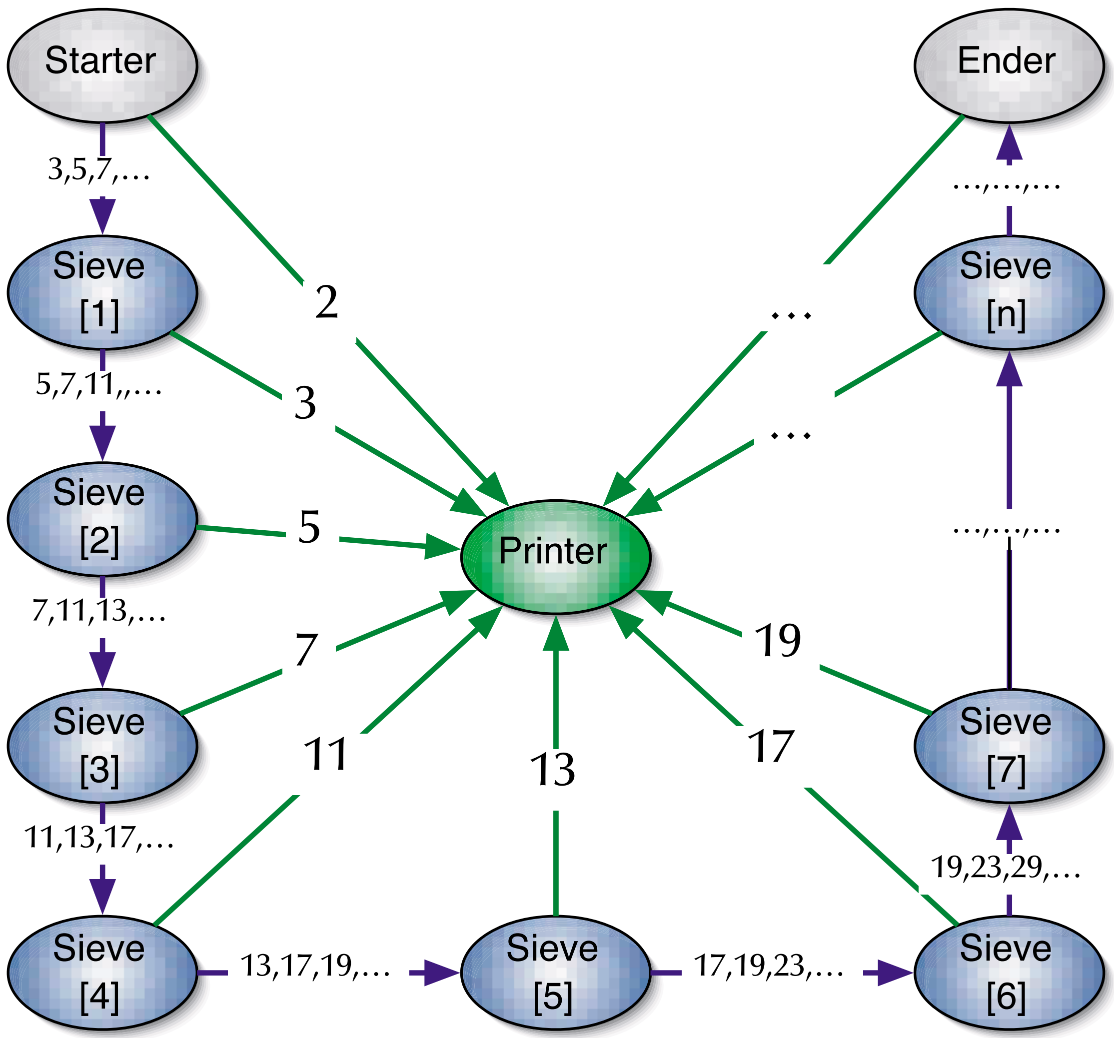
```
VAL INT n IS 50:
    -- # of primes to be generated

VAL INT limit is 1000:
    -- range to check

[n-2] CHAN of INT link:
    -- links between filters

[n-1] CHAN of INT prime:
    -- channels to Print process

CHAN OF INT display:
PLACE display AT 1:
    -- output display to device 1
```



occam 2.1

```
PROC Starter
  (CHAN OF INT out, print)
    -- feed number into the chain

INT i:
  SEQ
    print ! 2  -- 2 is prime
    i := 3
    WHILE i < limit
      SEQ
        out ! i
        i := i + 2:
            -- generate odd numbers
```

```
PROC Sieve
  (CHAN OF INT in, out, print)
    -- filter out one prime

INT p, next:
  SEQ
    in ? p
    print ! p  -- p is prime
    WHILE TRUE
      SEQ
        in ? next
        IF
          (next\p) <> 0 -- remainder?
            out ! next
          TRUE
            SKIP
```

occam 2.1

```
PROC Ender
  (CHAN OF INT in, print)
    -- consume rest of numbers

INT p:
  SEQ
    in ? p
    print ! p   -- p is prime
    WHILE TRUE
      in ? p:
```

```
PROC Printer ([] CHAN OF INT value)
    -- print each prime, in order

INT p:
  SEQ i = 0 FOR SIZE value
    SEQ
      value [i] ? p
      display ! p:


PAR -- main program

  Starter (link [0], prime [0])
  PAR i = 1 FOR n-2
    Sieve (link [i-1],
           link [i],
           prime [i])
  Ender (link [n-1], prime [n-1])
  Printer (prime)
```

occam 2.1 versus Ada95

	occam 2.1	Ada95
Addressing:	one-to-one	many-to-one
message formats defined by:	the channels' profiles	the 'accepting' tasks' parameter profiles
synchronization form:	rendezvous	
data-flow:	one way	one way or two ways (extended rendezvous)
selection of open alternatives:	non-deterministic	
Processes:	static	dynamic
shared memory ('monitors'):	-	yes

Operating systems architectures

Operating System based architectures

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

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. IEEE802.11g)
- Local device bus-system (e.g. firewire)
- Wireless local device network (e.g. bluetooth)
- Infrared communication (e.g. IrDA)
- Modem/ADSL

Types of current operating systems

Personal computing systems, workstations, and workgroup servers:

- 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 are suitable for embedded systems, also trials have been performed.
- None of these OSs are suitable for distributed or real-time systems.

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.

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)

Types of current operating systems

Real-time operating systems

- Fast context switches?
- Small size?
- Quick responds to external interrupts?
- Multitasking?
- 'low level' programming interfaces?
- Interprocess communication tools?
- High processor utilization?

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

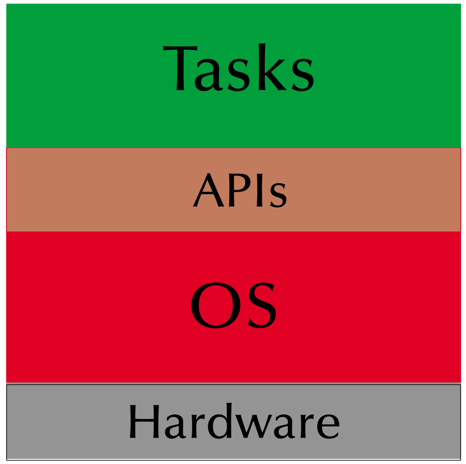
☞ 90-95% of all processors are working here!

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

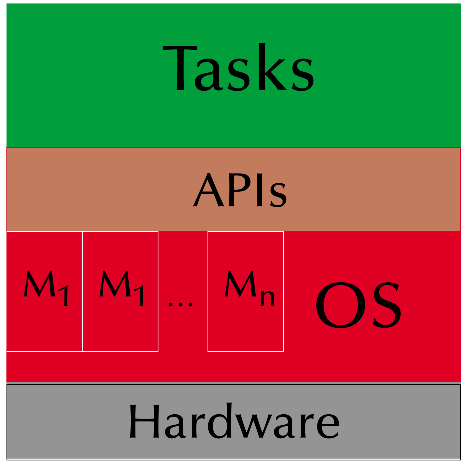
e.g. most early UNIX implementations (70s),
MS-DOS (80s), Windows (basically all versions besides NT and NT-based editions),
MacOS (until version 9), … and many others …

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



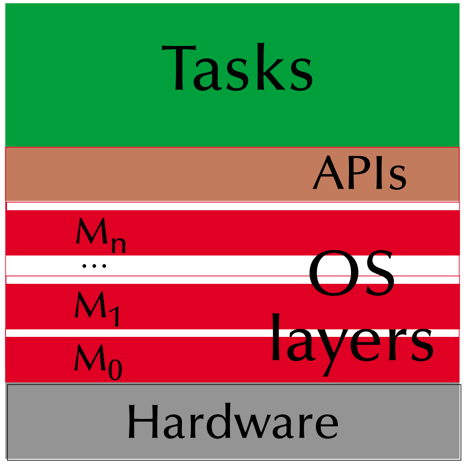
Modular

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



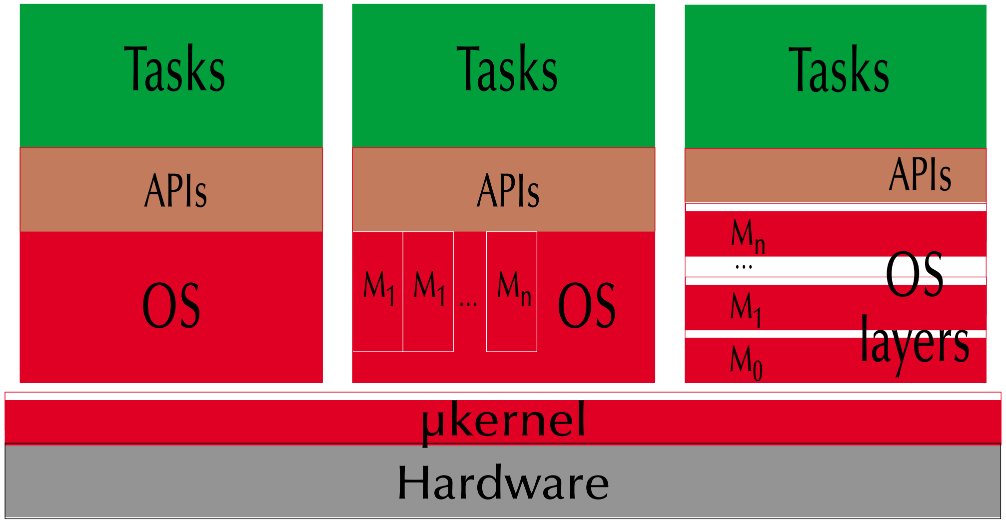
Layered

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



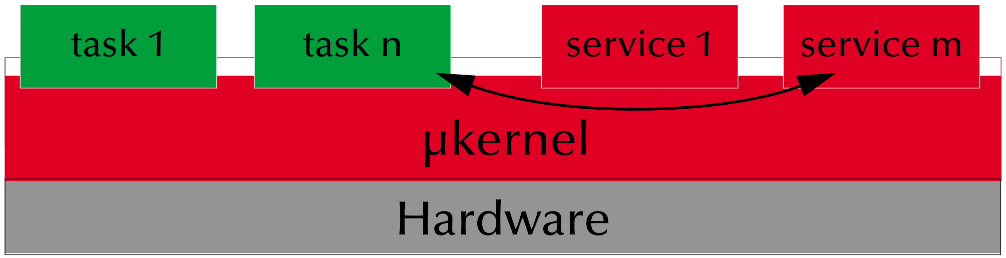
µkernel, virtual machine

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



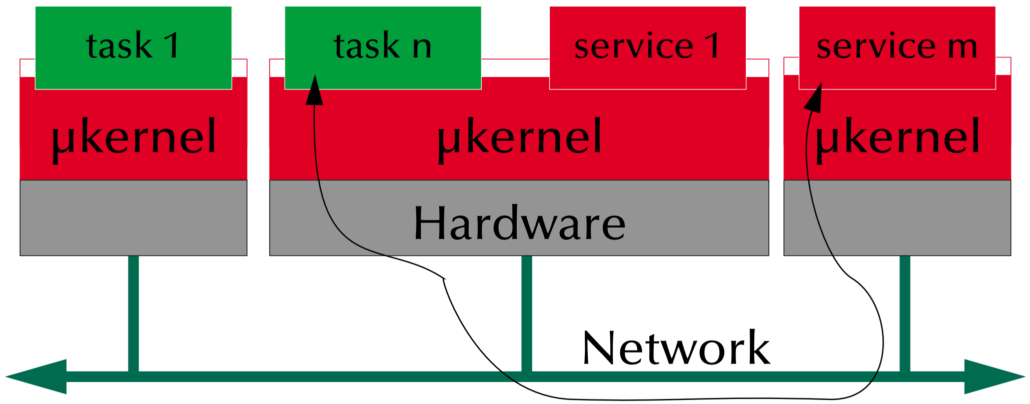
μkernel, client server structure

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 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 engines,
distributed real-time operating systems, current distributed OSs research projects

UNIX features

- **Hierarchical file-system** (maintained via ‘mount’ and ‘demount’)
- **Universal file-interface** applied to files, devices (I/O), as well as IPC
- Dynamic process creation via duplication
- Choice of shells
- Internal structure as well as all APIs are based on ‘C’
- Relatively high degree of portability

☞ UNICS, UNIX, **BSD**, XENIX, **System V**, **QNX**, IRIX, SunOS, Ultrix, Sinix, **Mach**, Plan 9, NeXTSTEP, **AIX**, HP-UX, **Solaris**, **NetBSD**, **FreeBSD**, **Linux**, OPENSTEP, **OpenBSD**, **Darwin**, **QNX/Neutrino**, **OS X**, **QNX RTOS**, … … …

Dynamic process creation

```
pid = fork ();
```

resulting in a *duplication* of the *current* process

- returning **0** to the newly created process (the 'child' process)
- returning the **process id** of the child process to the creating process (the 'parent' process) or **-1** for a failure

Frequent usage:

```
if (fork () == 0) {
  … the child's task …
  … often implemented as: exec ("absolute path to executable file", "args");
  exit (0);                    /* terminate child process */
} else {
  … the parent's task …
  pid = wait ();               /* wait for the termination of one child process */
}
```

Synchronization in UNIX ☞ Signals

```
#include <unistd.h>
#include <sys/types.h>
#include <signal.h>

pid_t id;

void catch_stop (int sig_num)
{
   /* do something with the signal */
}
```

```
id = fork ();

if (id == 0) {

 signal (SIGSTOP, catch_stop);
 pause ();
 exit (0);

 }

} else {

 kill (id, SIGSTOP);
 pid = wait ();

}
```

Message passing in UNIX ☞ Pipes

```
int data_pipe [2], c, rc;

if (pipe (data_pipe) == -1) {
 perror (“no pipe“); exit (1);
}

if (fork () == 0) {
 close (data_pipe [1]);
 while ((rc = read
   (data_pipe [0], &c, 1)) > 0) {
    putchar (c);
 }
 if (rc == -1) {
  perror (“pipe broken“);
  close (data_pipe [0]);
  exit (1);
 }
 close (data_pipe [0]); exit (0);
} else {

  close (data_pipe [0]);
  while ((c = getchar ()) > 0) {
    if (write
     (data_pipe[1], &c, 1) == -1) {
      perror (“pipe broken“);
      close (data_pipe [1]);
      exit (1);
    };
  }
  close (data_pipe [1]);
  pid = wait ();
}
```

Processes & IPC in UNIX

Processes:

- Process creation results in a duplication of address space ('copy-on-write' becomes necessary)

☞ inefficient, but can generate new tasks out of any user process – no shared memory!

Signals:

- limited information content, no buffering, no timing assurances (signals are *not* interrupts!)

☞ very basic, yet not very powerful form of synchronization

Pipes:

- unstructured byte-stream communication, access is identical to file operations

☞ not sufficient to design client-server architectures or network communications

Sockets in BSD UNIX (also in System V.R4)

Sockets try to keep the paradigm of a universal file interface for everything and introduce:

Connectionsless interfaces (e.g. UDP/IP):

- Server side: `socket` ➠ `bind` ➠ `recvfrom` ➠ `close`
- Client side: `socket` ➠ `sendto` ➠ `close`

Connection oriented interfaces (e.g. TCP/IP):

- Server side: `socket` ➠ `bind` ➠ {`select`} [`connect` | `listen` ➠ `accept`
  ➠ `read` | `write` ➠ [`close` | `shutdown`]
- Client side: `socket` ➠ `bind` ➠ `connect` ➠ `write` | `read` ➠ [`close` | `shutdown`]

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:

- **Threads**: a common interface to threading - differences to 'classical UNIX processes'
- **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 – 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)

Architectures

- **Academic**
    - occam 2.1, CSP, …
- **Workfloor**
    - Ada95, Java, …
- **Environments / Operating Systems**
    - Operating systems architectures
    - UNIX as a concept and basic UNIX features
    - POSIX

9

Distributed Systems

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OSI network reference model

- Standardized as the

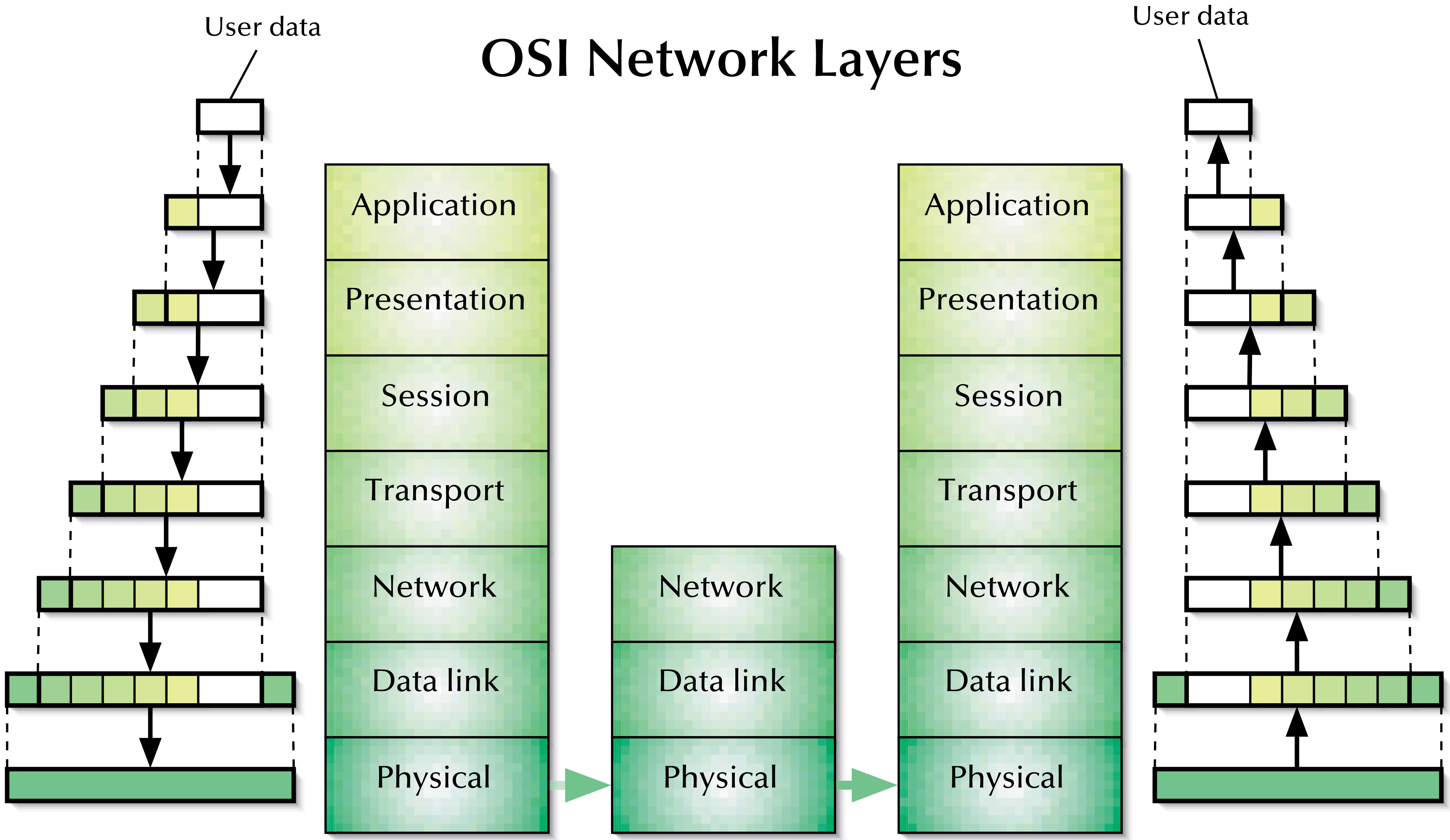
Open Systems Interconnection (OSI) reference model
by the International Standardization Organization (ISO) in 1977

- 7 layer architecture
- Connection oriented

Hardy implemented anywhere as such …

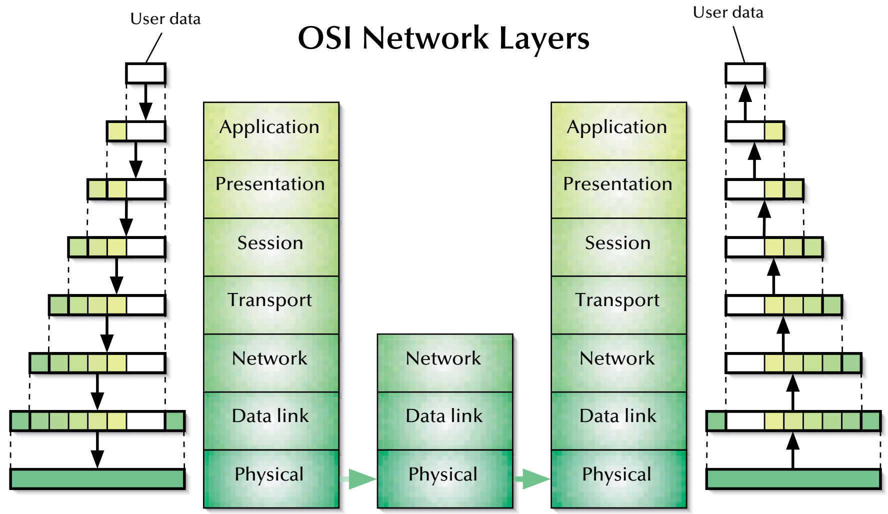
…but its concepts and terminology are widely used,
when designing new protocols …

Network protocols & standards



Network protocols & standards

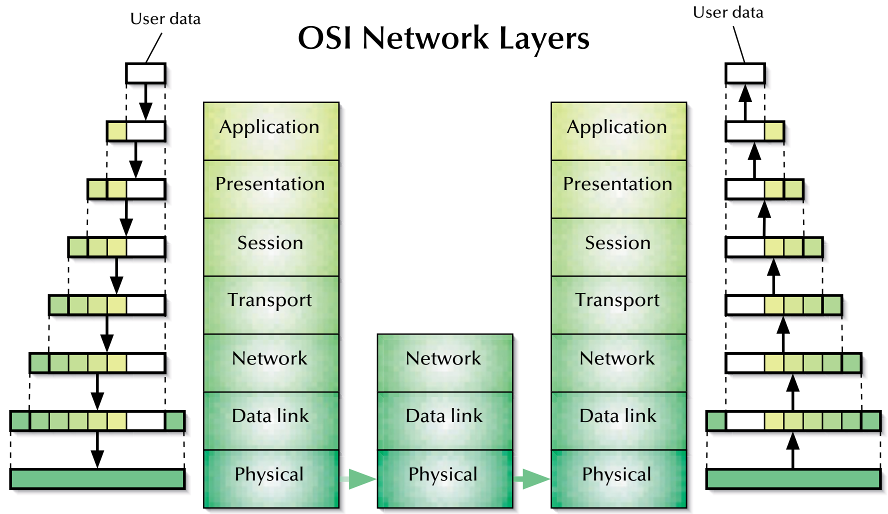
1: Physical Layer



- *Service*: Transmission of a raw bit stream over a communication channel
- *Functions*: Conversion of bits into electrical or optical signals
- *Examples*: X.21, Ethernet (cable, detectors & amplifiers)

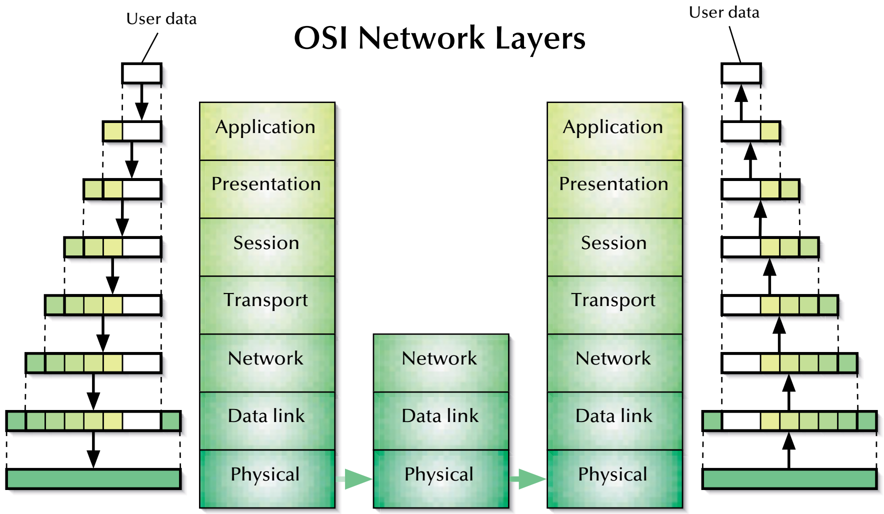
Network protocols & standards

2: Data Link Layer



- *Service*: Reliable transfer of frames over a link
- *Functions*: Synchronization, error correction, flow control
- *Examples*: HDLC (high level data link control protocol), LAP-B (link access procedure, balanced), LAP-D (link access procedure, D-channel), LLC (link level control), …

Network protocols & standards

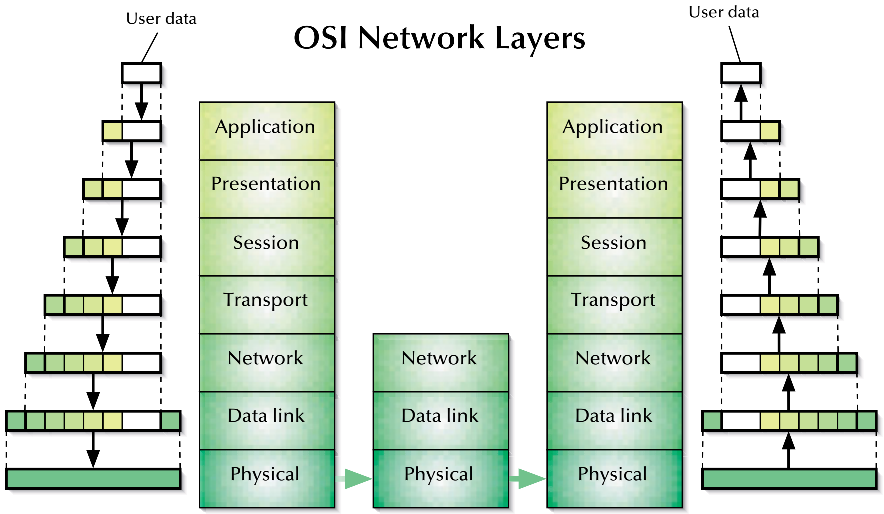


3: Network Layer

- *Service*: Transfer of packets inside the network
- *Functions*: Routing, addressing, switching, congestion control
- *Examples*: IP, X.25

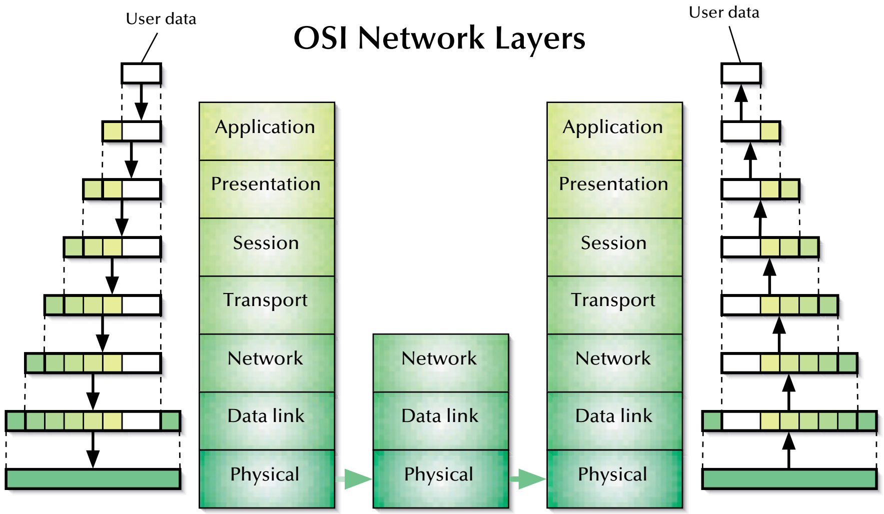
Network protocols & standards

4: Transport Layer



- *Service*: Transfer of data between hosts
- *Functions*: Connection establishment, management, termination, flow control, multiplexing, error detection
- *Examples*: TCP, UDP, ISO TP0-TP4

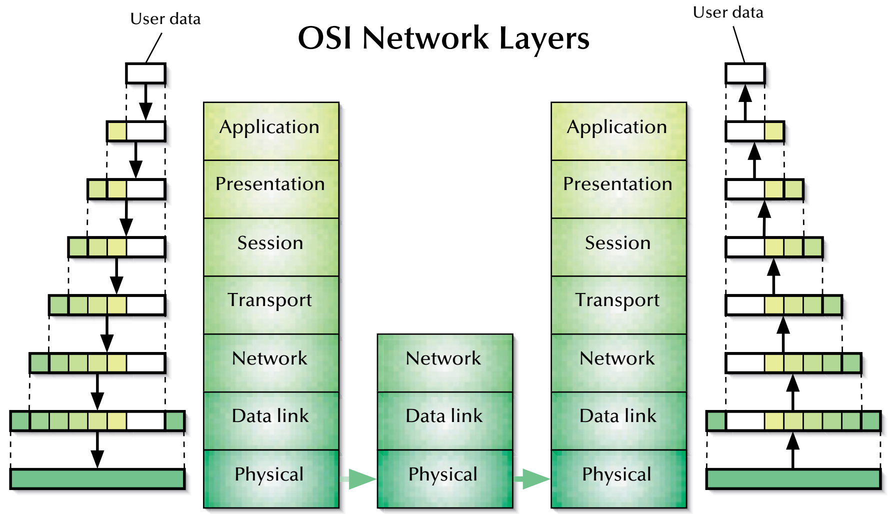
5: Session Layer



- *Service*: Coordination of the dialogue between application programs
- *Functions*: Session establishment, management, termination
- *Examples*: RPC

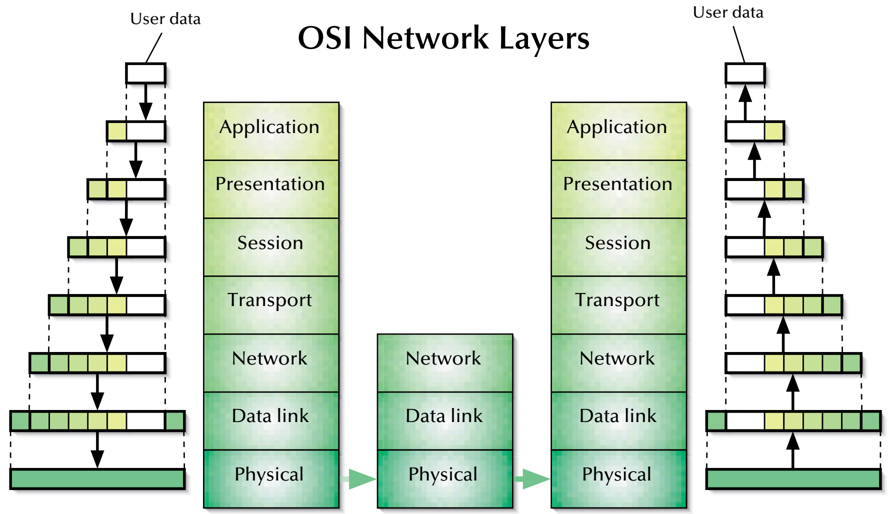
Network protocols & standards

6: Presentation Layer



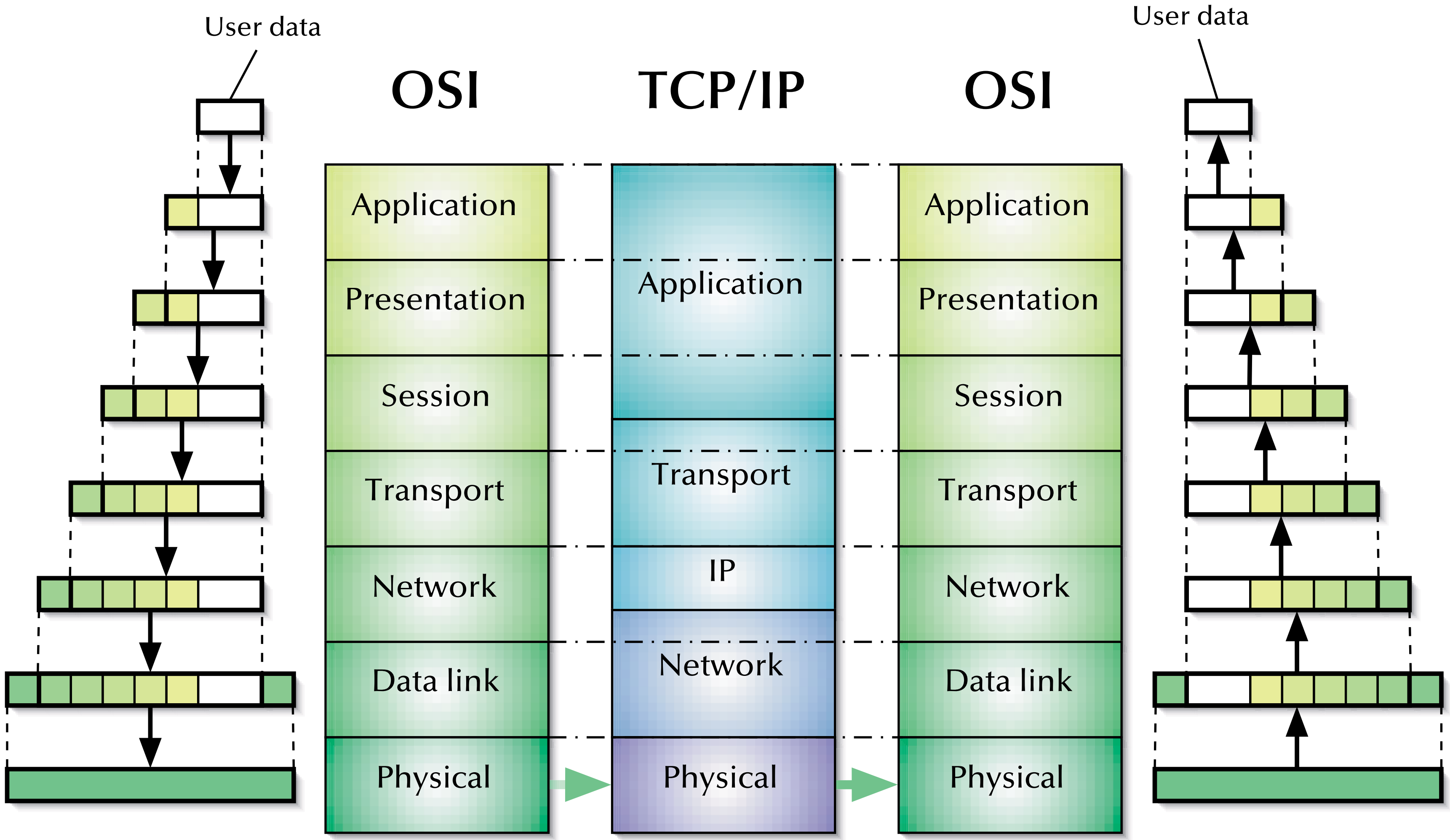
- *Service*: Provision of platform independent coding and encryption
- *Functions*: Code conversion, encryption, virtual devices
- *Examples*: ISO code

7: Application Layer

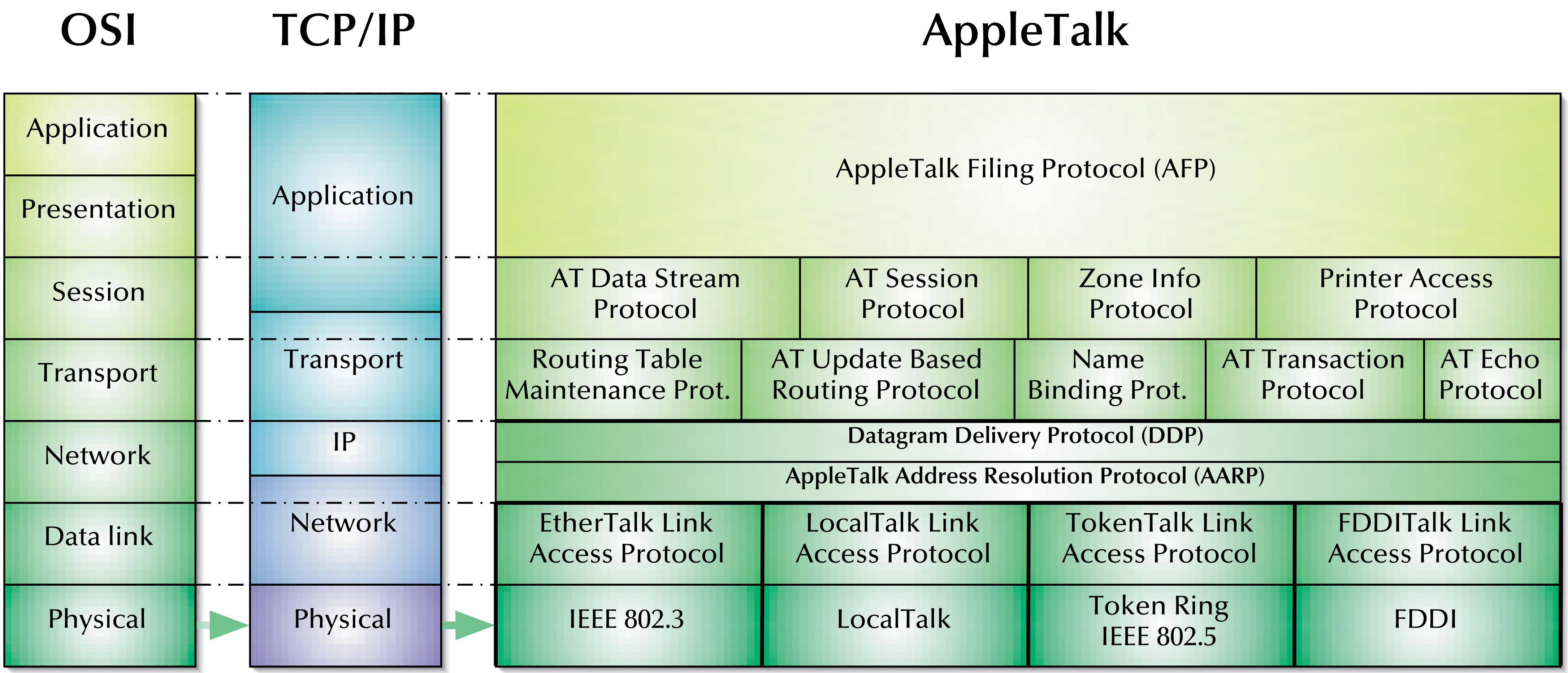


- *Service*: Network access to application programs
- *Functions*: application specific
- *Examples*: APIs for mail, ftp, ssh, scp, …

Network protocols & standards

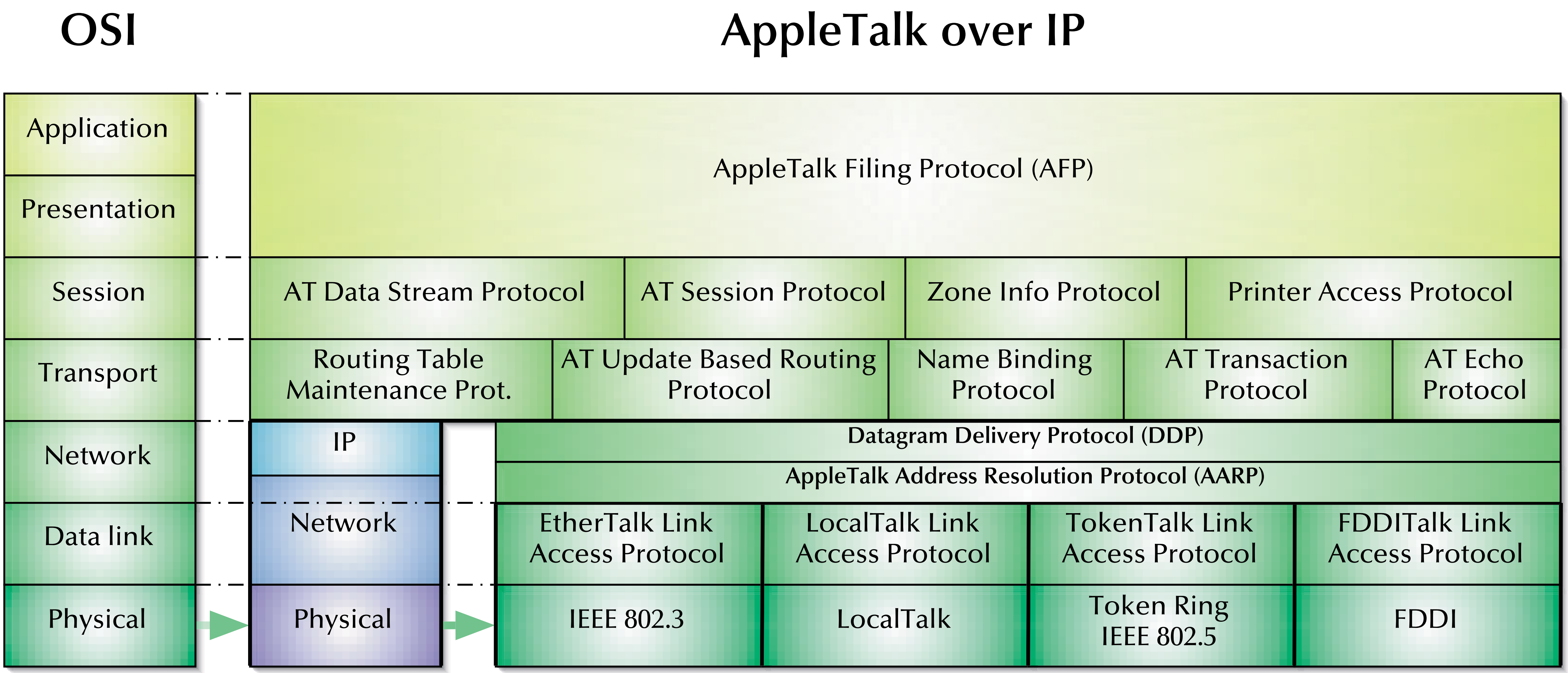


Network protocols & standards



Network protocols & standards

OSI — AppleTalk over IP

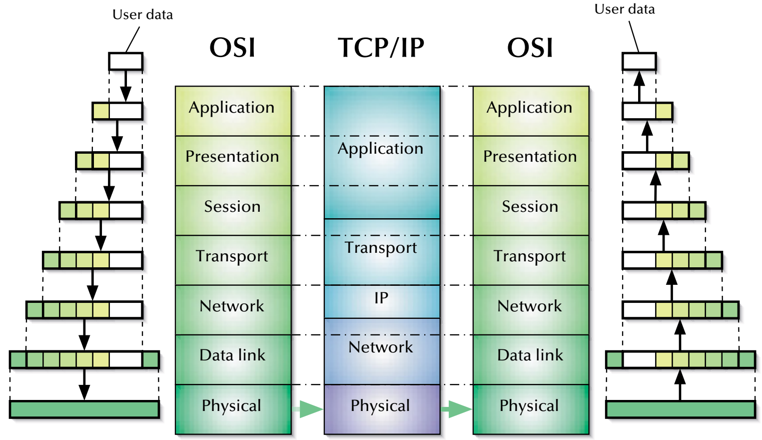


Network protocols & standards

Ethernet / IEEE 802.3

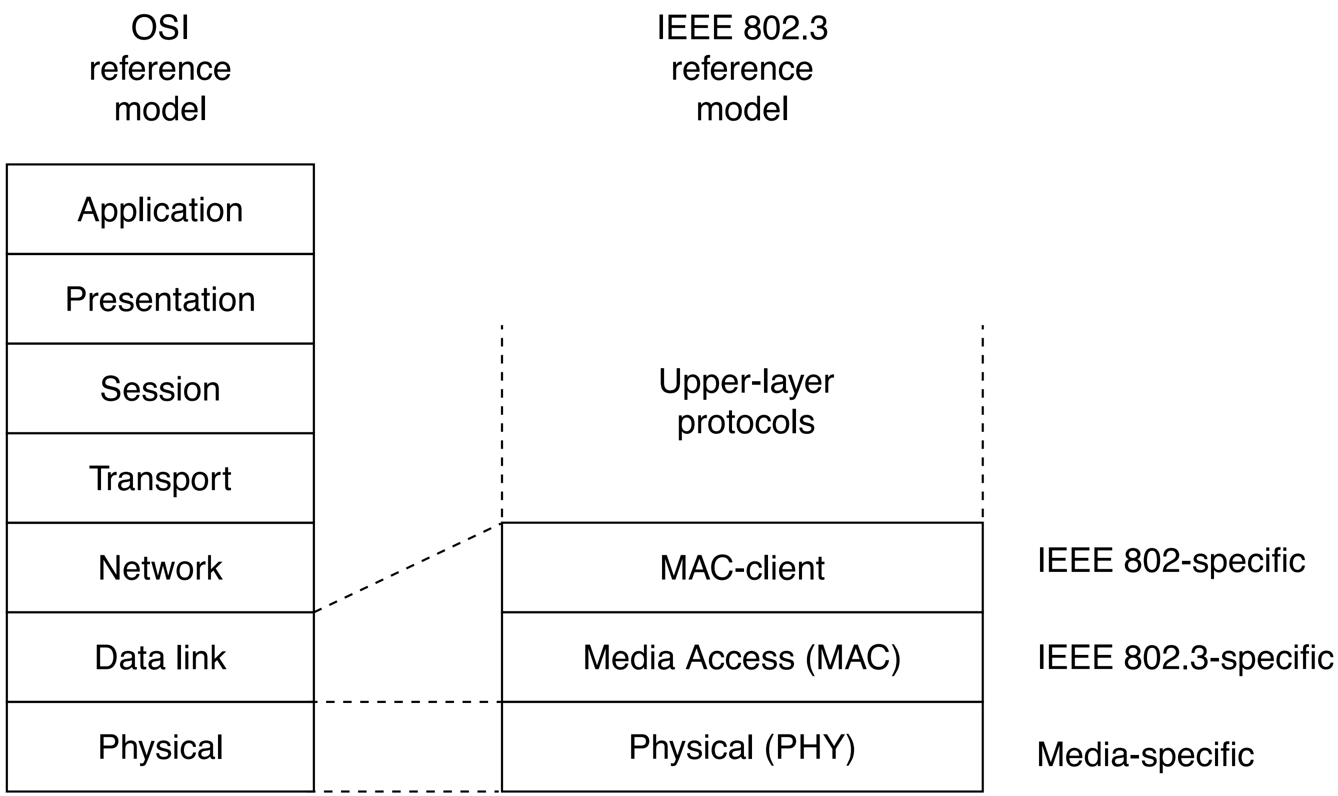
- local area network (LAN) developed by Xerox in the 70's
- 10 Mbps specification 1.0 by DEC, Intel, & Xerox in 1980
- specified by the IEEE 802.3 standard in 1983
- 10 Mbps - 1 Gbps (10 Gbps in preparation)
- approx. 85 % of current LAN lines worldwide

☞ Carrier Sense Multiple Access with Collision Detection (CSMA/CD)



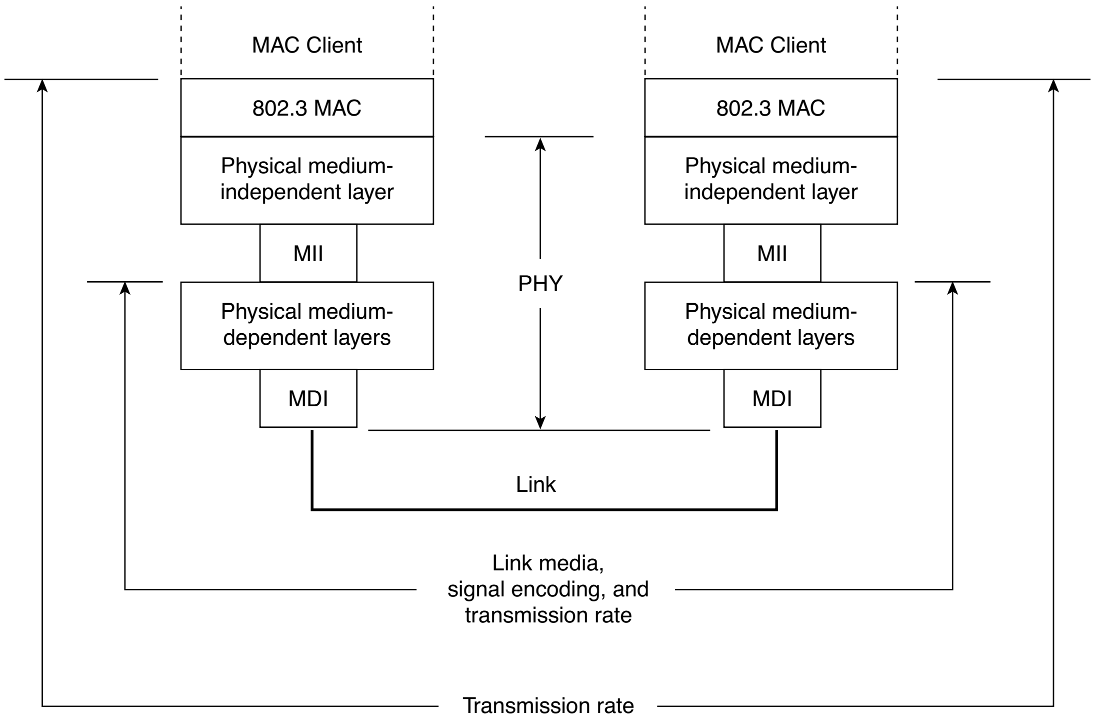
Ethernet

OSI reference model classification

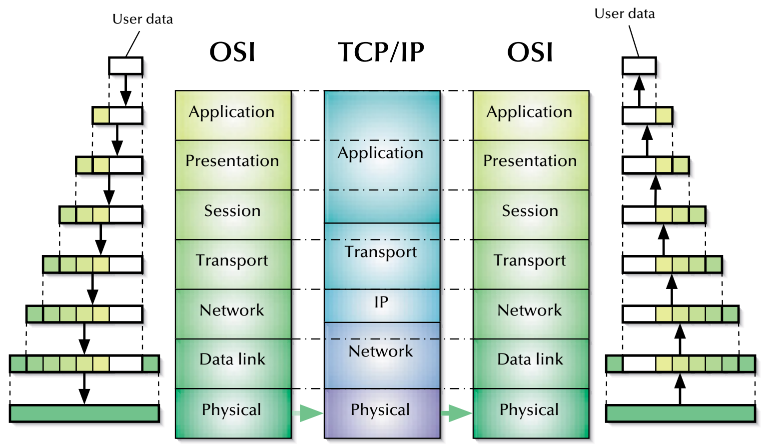


Ethernet

MAC & PHY layer



MII = Medium-independent interface
MDI = Medium-dependent interface - the link connector



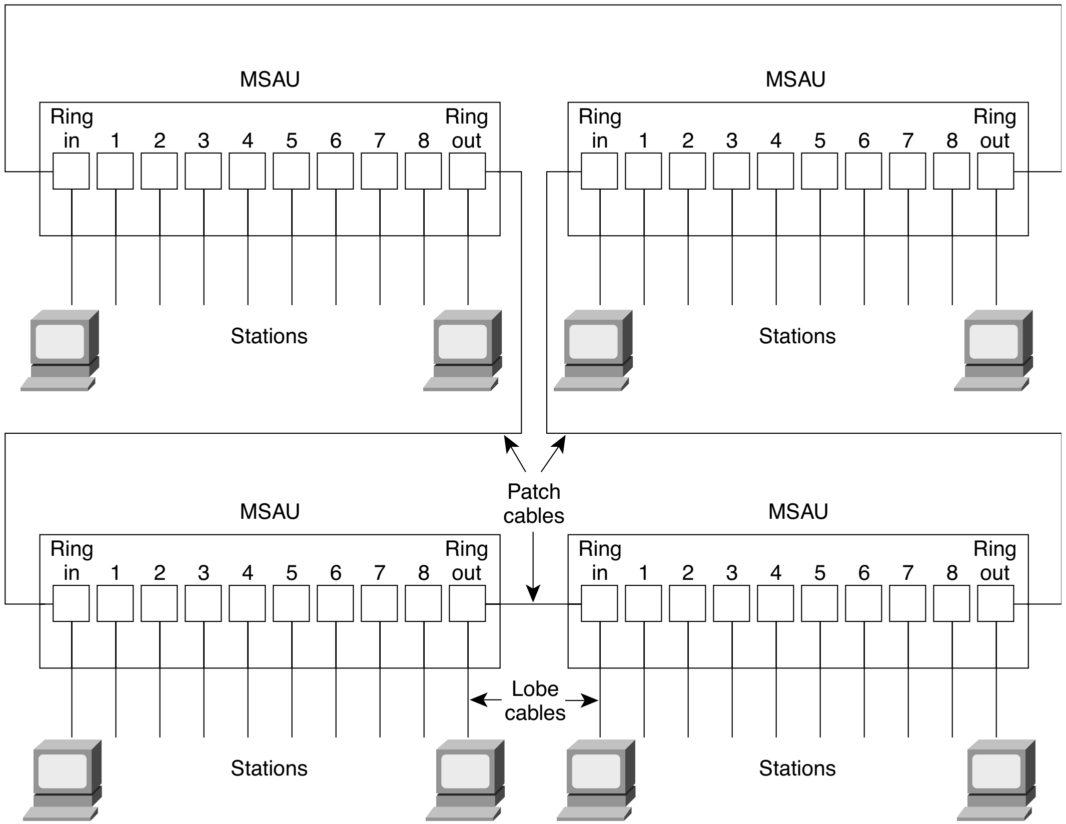
Token Ring / IEEE 802.5

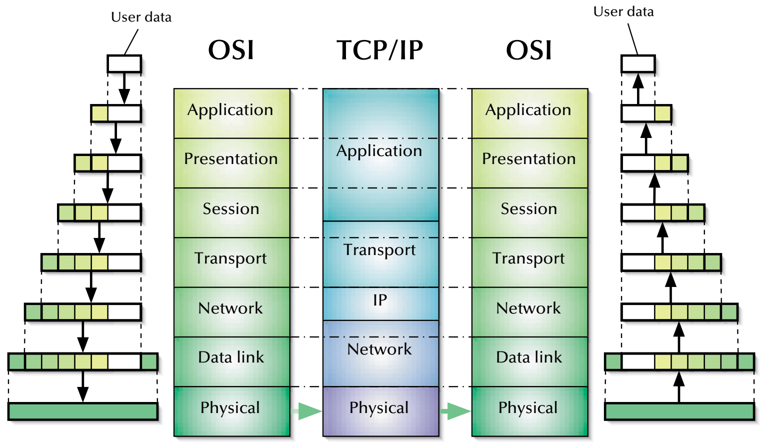
- Developed by IBM in the 70's
- IEEE 802.5 standard is modelled after the IBM Token Ring architecture
  (specifications are slightly different, but basically compatible)
- IBM Token Ring requests are star topology as well as twisted pair cables, while IEEE 802.5 is unspecified in topology and medium

☞ Unlike CSMA/CD, the token ring is **deterministic**
(with respect to its timing behaviour)

Token Ring / IEEE 802.5

Topology (IBM)





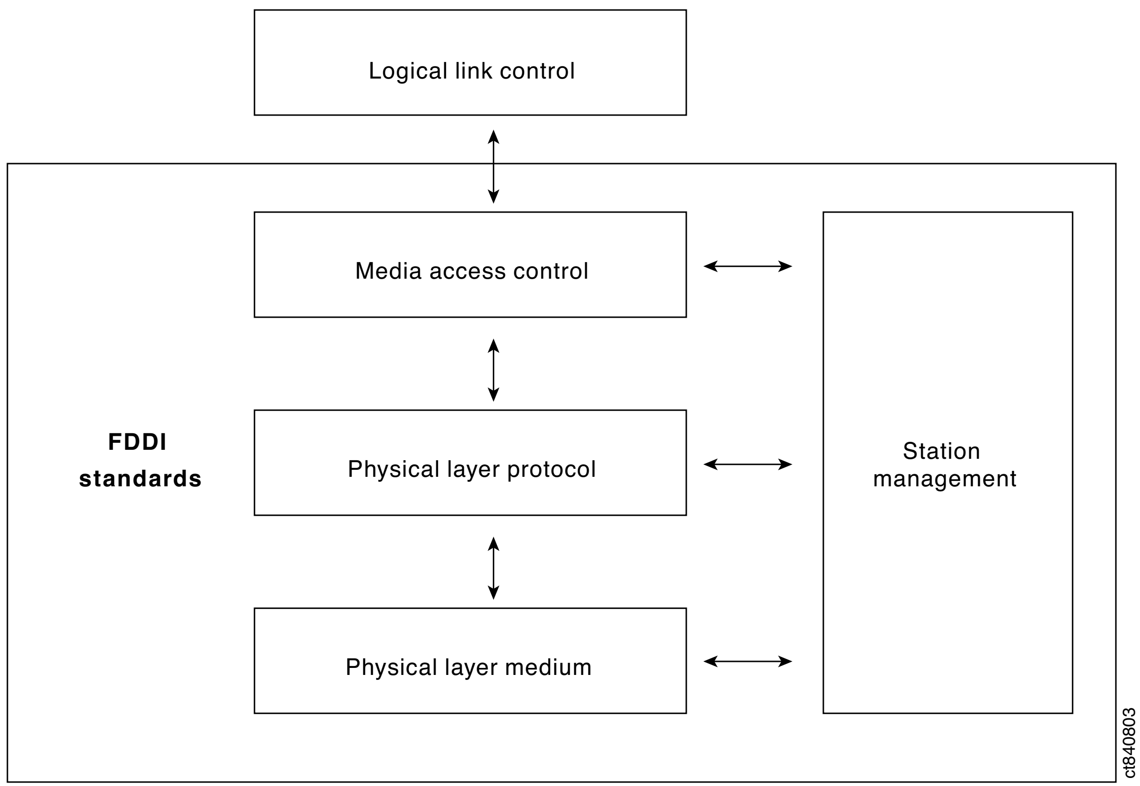
Fiber Distributed Data Interface (FDDI)

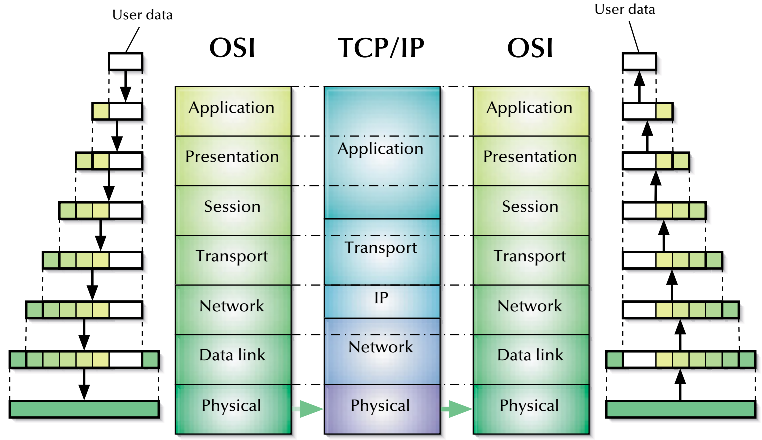
- Designed in the 80's as a standard for 'backbone networks'
- American National Standards Institute (ANSI) X3T9.5 standard
- 100 Mbps token passing, dual ring local area network
  using fiber optical cable (or copper in case of CDDI)
- Second ring is idle in normal operations

☞ **Deterministic** and **Failure resistant**

FDDI / ANSI X3T9.5

OSI reference model classification

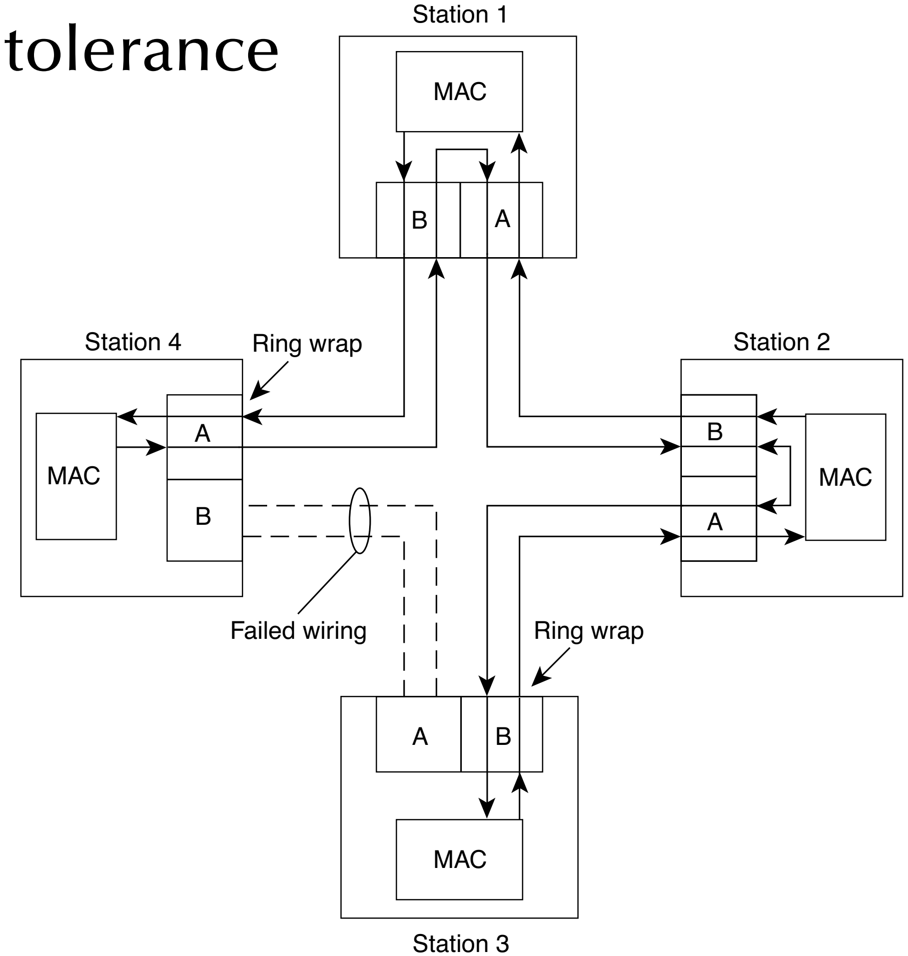


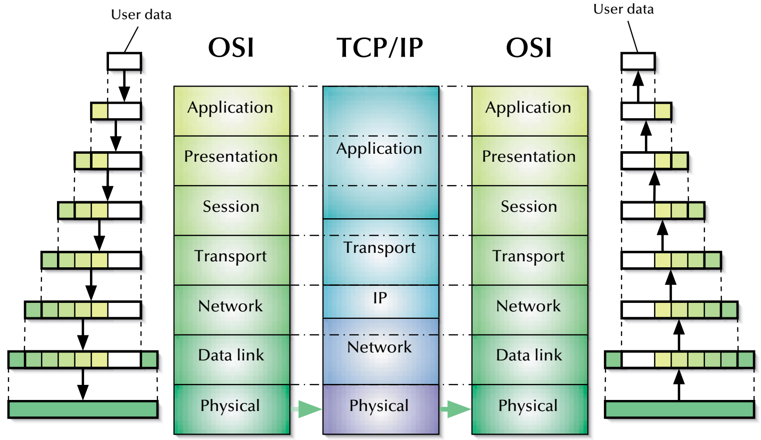


Network protocols & standards

FDDI / ANSI X3T9.5

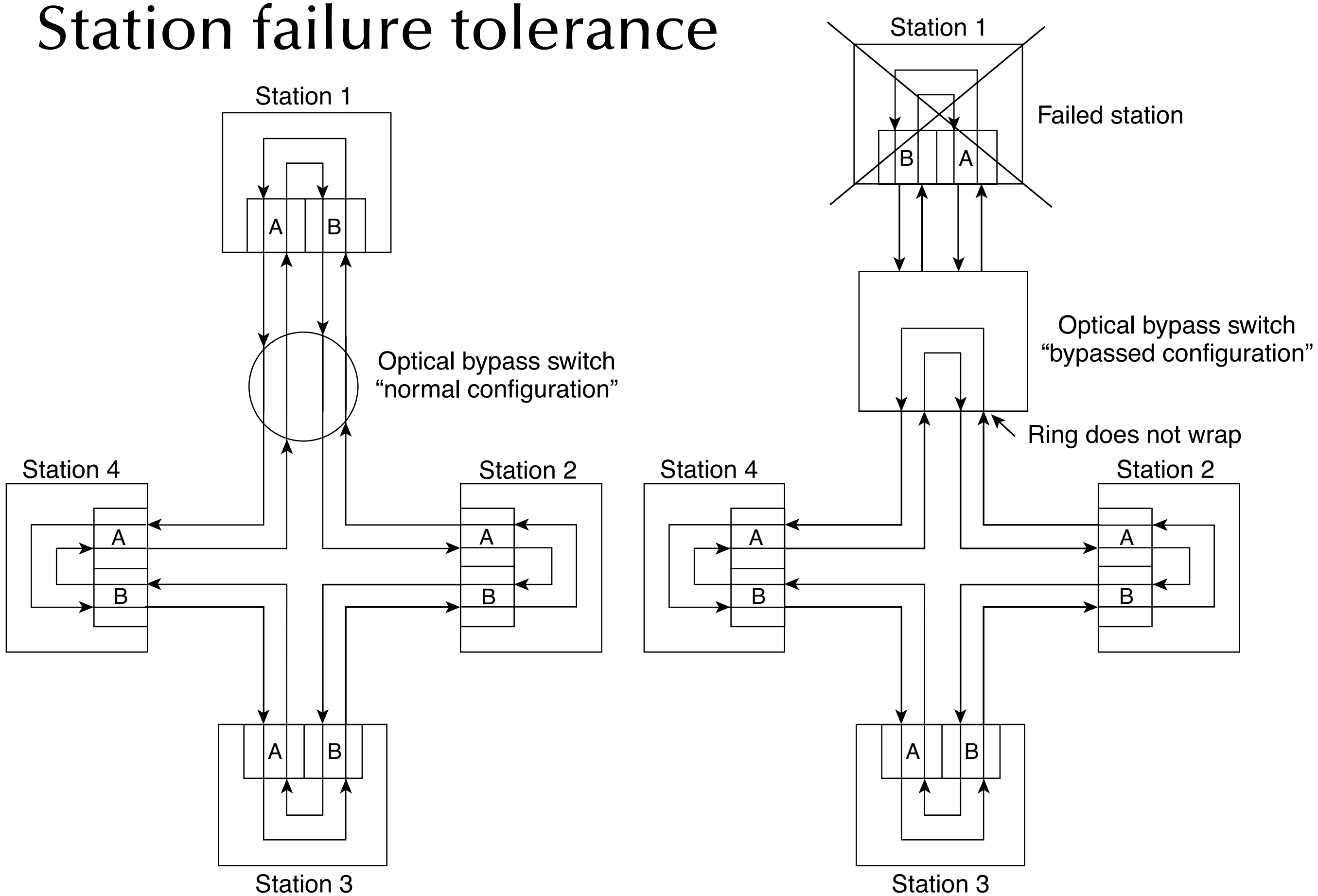
Cable failure tolerance

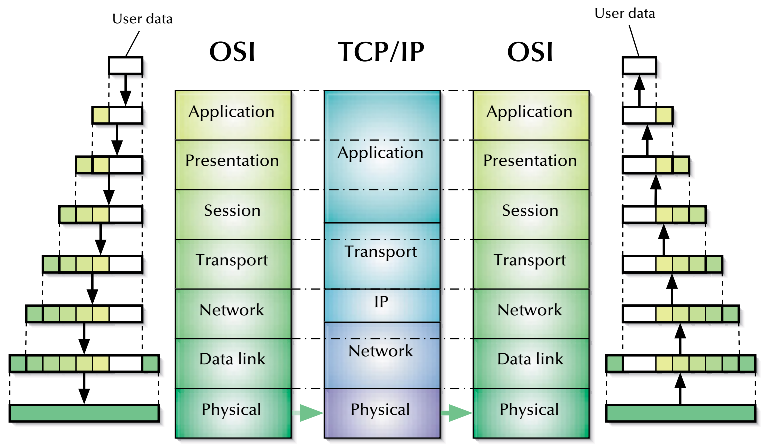




FDDI / ANSI X3T9.5

Station failure tolerance





Distributed Systems

☞ *finally: distribution!*

What are potential benefits?

- Fits an **existing physical distribution** (e-mail system, devices in a large aeroplane, …).
- Possible **high performance** due to potentially high degree of parallel computing.
- Possible **high reliability** due to redundancy of hardware and software.
- Possible **scalability**.
- Integration of a large number of **heterogeneous nodes/devices** tailored to specific needs.

Distributed Systems

What can be distributed?

- State ☞ common methods on distributed databases, e-mail
- Function ☞ distributed methods on central data
- State & Function ☞ client/server clusters
- none of those ☞ pure replication, redundancy

Common design criteria

- ☞ Achieve decoupling / high degree of local autonomy
- ☞ Cooperation rather than central control
- ☞ Consider reliability
- ☞ Consider scalability
- ☞ Consider performance

Common phenomena in distributed systems

1. Unpredictable delays (communication)
   - Are we done yet?
2. Missing or imprecise time-base
   - Was there a causal relation?
   - Was there a temporal relation?
3. Partial failures
   - Likelihood of individual failures increases
   - Likelihood of complete failure decreases (in case of a good design)

Time in distributed systems

Two principle alternative strategies:

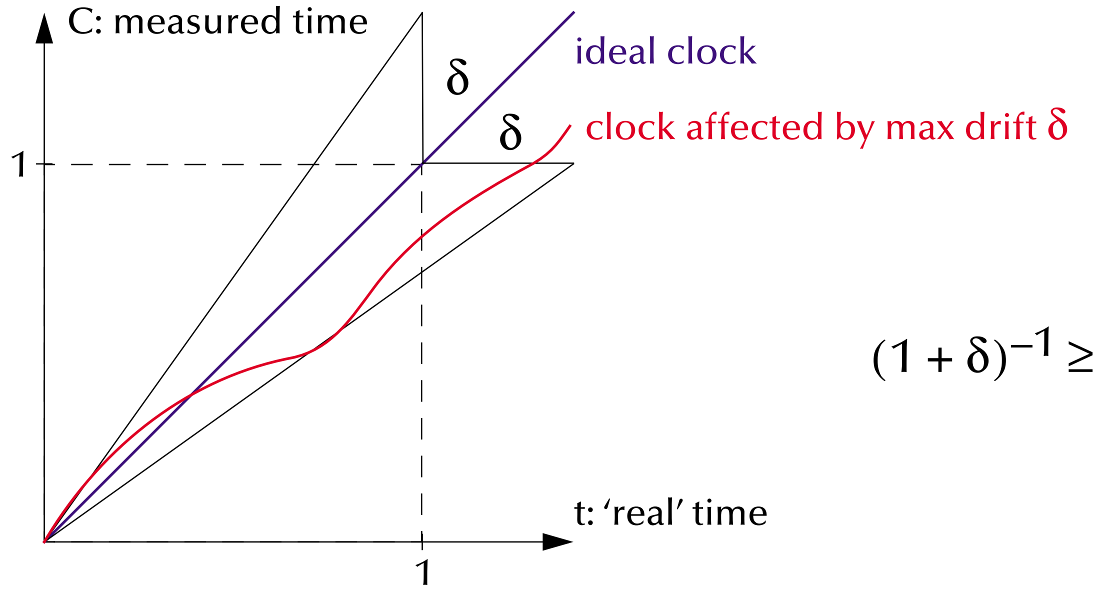
☞ *Synchronize clocks*

☞ *Create a virtual time*

'Real-time' clocks in computer systems

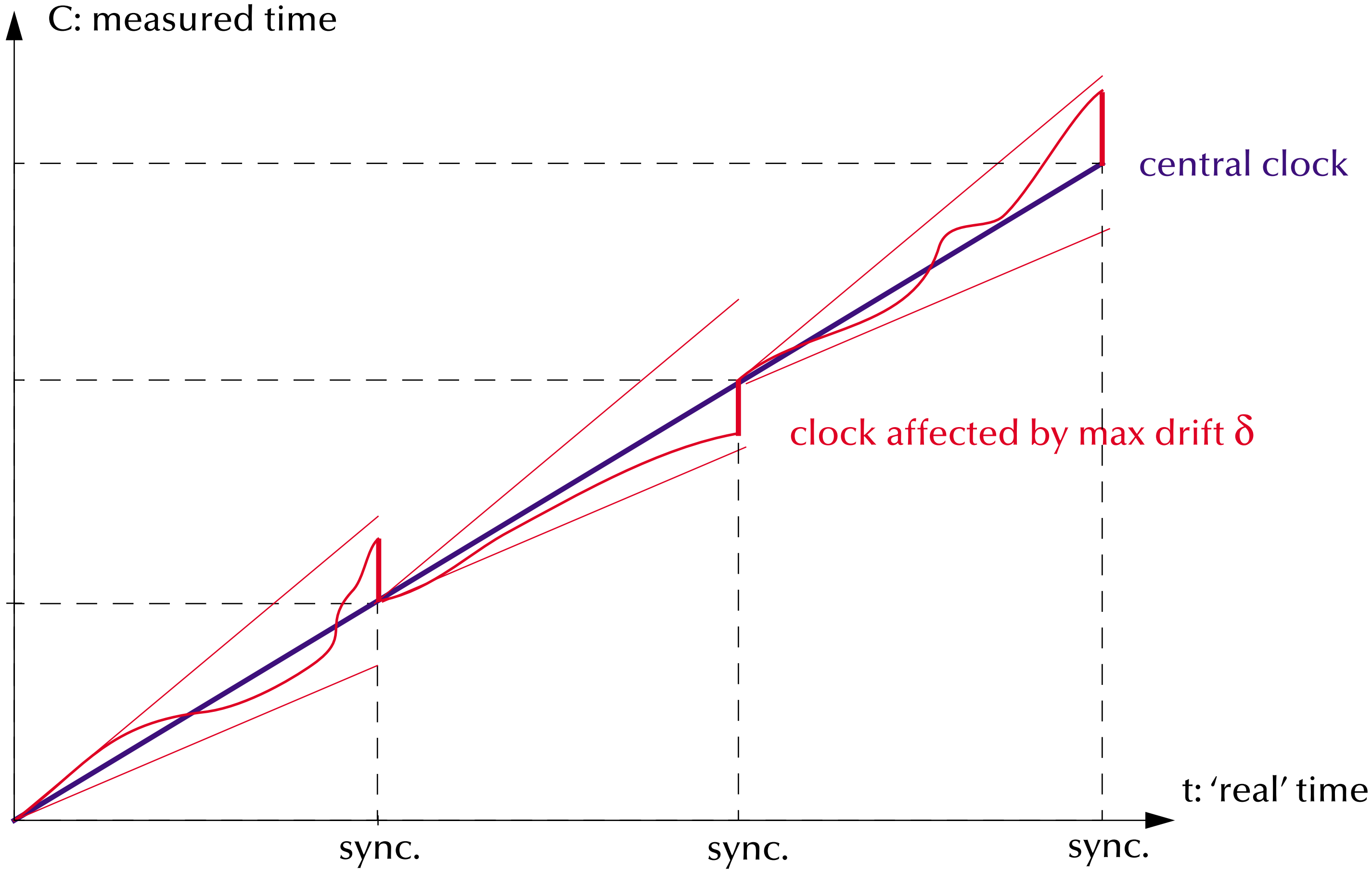
are:

- discrete, i.e. time is not 'dense', there is a minimal granularity
- drift affected

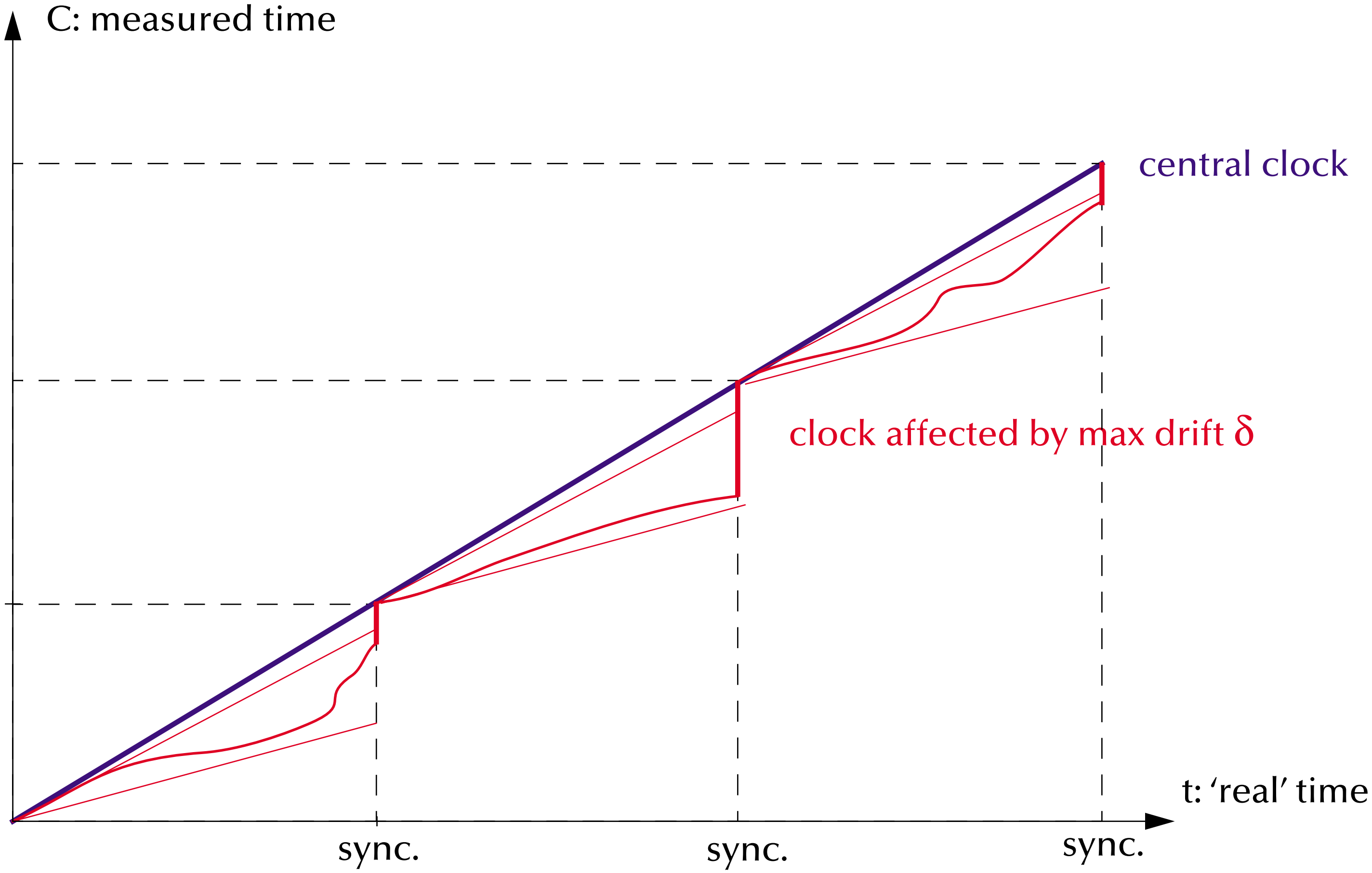


$$(1+\delta)^{-1} \geq \frac{C(t_2) - C(t_1)}{t_2 - t_1} \geq (1+\delta)$$

Synchronize local, drift affected clocks (both ways)



Synchronize local, drift affected clocks (forward only)



Distributed critical regions with synchronized clocks

1. **Create** *OwnRequest* and **attach** current time-stamp

2. **Add** *OwnRequest* to local *RequestQueue* (ordered by time)
   S**end** *OwnRequest* to *all* processes

3. **Delay** $2L$ (L being the time it takes for a message to reach all network nodes)

4. **Add** all received *Request*s in local *RequestQueue* (ordered by time)

5. **While** $Top(RequestQueue) \neq OwnRequest$ **do**

   5-a for all received release messages **delete** corresponding *Request* in local *RequestQueue*

6. **Enter** and **leave** critical region

7. **Send** *Release*-message to *all* processes

Distributed critical regions with synchronized clocks

Analysis

- No deadlock, no individual starvation, no livelock
- Minimal request delay: $2L$
- Minimal release delay: L
- Communications requirements per requesting process: $2(N-1)$ messages (can be significantly improved by employing broadcast mechanisms)

Assumptions:

- L is known and constant
- no messages are lost

Virtual (logical) time [Lamport 1978]

- $a \to b \Rightarrow C(a) < C(b)$

  with $a \to b$ being a causal relation between a and b
  and $C(a)$, $C(b)$ the (virtual) times associated with a and b

- $a \to b$ holds when

  - a happens earlier than b in the same sequential process
  - a denotes the event of sending of message m, while b denotes the receiving event of m (in different processes)
  - there is a transitive causal relation: $a \to e_1 \to \ldots \to e_n \to b$

- $a \parallel b \Rightarrow \neg(a \to b) \land \neg(b \to a)$

Virtual (logical) time

Implications:

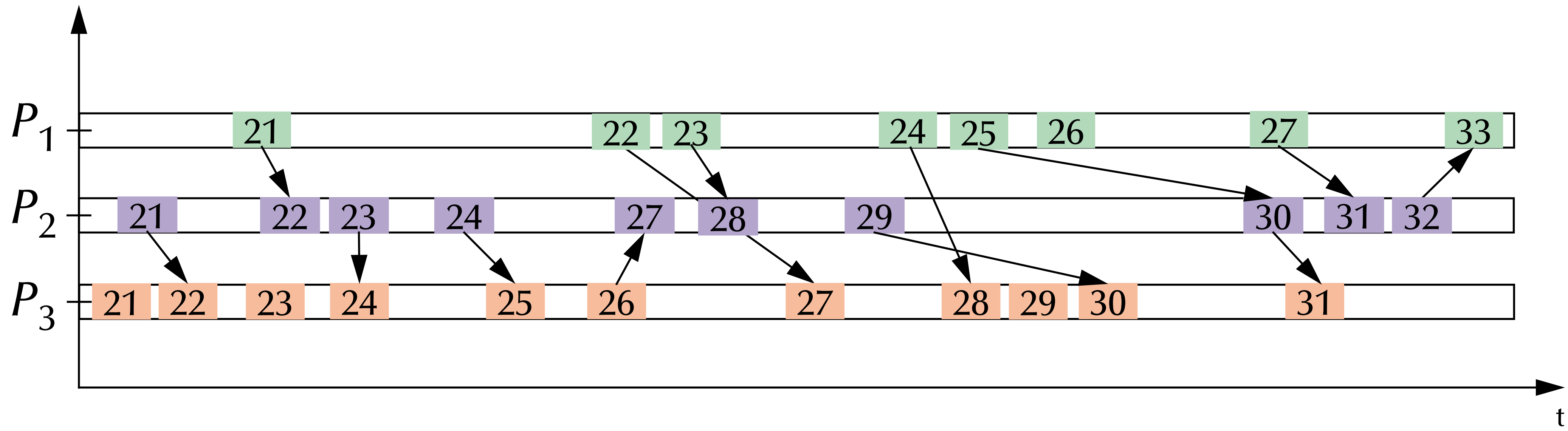
$$a \rightarrow b \Rightarrow C(a) < C(b)$$

$$C(a) < C(b) \Rightarrow (a \rightarrow b) \vee (a \parallel b)$$

$$C(a) = C(b) \Rightarrow a \parallel b$$

Virtual (logical) time

- time is no longer global and is attached to observable causal relations



- all events in between communications are considered concurrent in different processes

Implementing a virtual (logical) time

1. $\forall P_i$: $C_i = 0$

2. $\forall P_i$:

   2-a $\forall$ local events: $C_i = C_i + 1$

   2-b $\forall$ send m operations: $C_i = C_i + 1$; Send (m, C_i)

   2-c $\forall$ receive m operations: Receive (m, C_m); $C_i = max(C_i, C_m) + 1$

Distributed critical regions with logical clocks

Concurrently:

- *Request*-message received:
  ☞ **Add** *Request* in local *RequestQueue* (ordered by time)
  ☞ if *OwnRequest* pending **reply** with *OwnRequest* else **reply** with *Ack*
- *Release*-message received ☞ if **delete** corresponding *Request* in local *RequestQueue*
- if access to critical region required:

1. **Create** *OwnRequest* and **attach** current time-stamp
2. **Add** *OwnRequest* to local *RequestQueue* (ordered by time)
   Send *OwnRequest* to *all* processes
3. **Wait for** *Top*(*RequestQueue*) = *OwnRequest* & no outstanding replies
4. **Enter** and **leave** critical region
5. **Send** *Release*-message to *all* processes

Distributed critical regions with logical clocks

Analysis

- No deadlock, no individual starvation, no livelock
- Minimal request delay: $N-1$ request messages, $N-1$ reply messages
- Minimal release delay: $N-1$ release messages
- Total communications requirements per requesting process: $3(N-1)$ messages (can be significantly improved by employing broadcast mechanisms)

Assumption:

- no messages are lost

No assumptions about:

- runtime of messages over the communication system

Distributed critical regions with a token ring structure

1. Organize all processes in a ring (physically or logically)
2. Pass a 'token'-message along the ring
3. On receiving the token:

   3-a If the local process wants to enter a critical section it does so now (while storing the token)

   3-b The token is passed along

☞ What happens if the token is lost?

(there are simple recovery algorithms similar to the 'election' scheme following)

Distributed critical regions with a central coordinator

- a global, static, central coordinator invalidates the concept of a distributed system, but enables very simple mutual exclusion algorithms, so …

  … we pronounce one processes as the central coordinator, but
  … if this one fails, the rest of the processes are able to come up with a new coordinator.

☞ This is done by a distributed 'election' algorithm, i.e. the Bully-algorithm [Garcia-Molina 1982]

Electing a central coordinator (the Bully algorithm)

Any process *P* which notices that the central coordinator is done, performs:

1. Sending an `Election`-message to all processes with higher process numbers

2. *P* wait for response messages

   2-a If no one responds after a pre-defined amount of time:
   P declares itself the new coordinator and sends out a `Coordinator`-message to all.

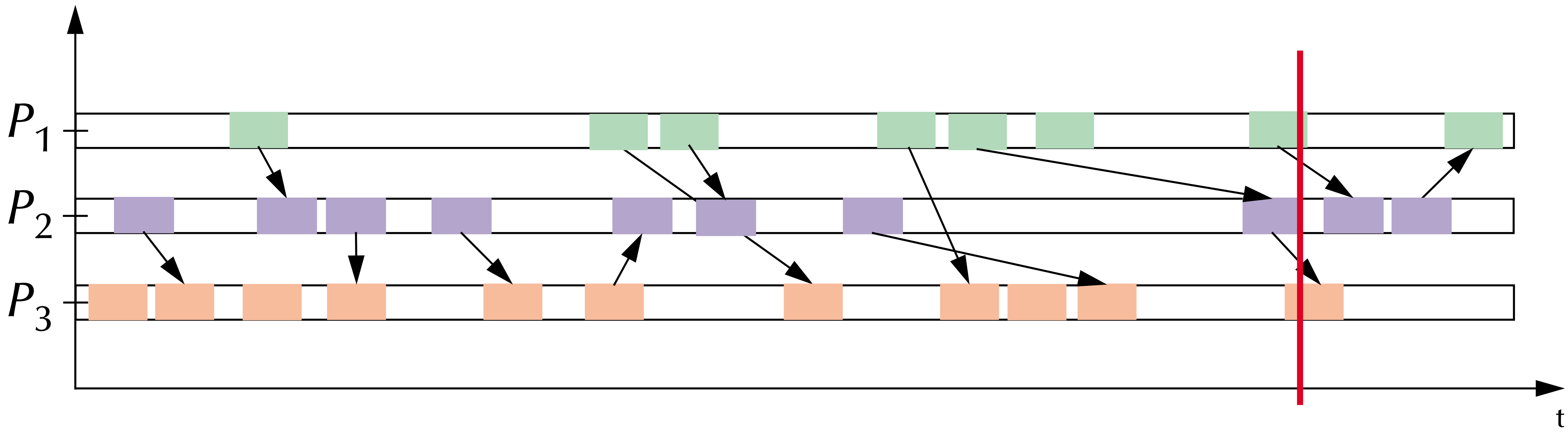
   2-b If any process responds, the election activity for *P* is over
   and *P* waits for a `Coordinator`-message

All processes P_i:

If P_i receives a `Election`-message from a process with a lower process number,
it responds to the originating process and starts an election process itself (if not running already).

Distributed states

- collect all local states at a given time:



Distributed states

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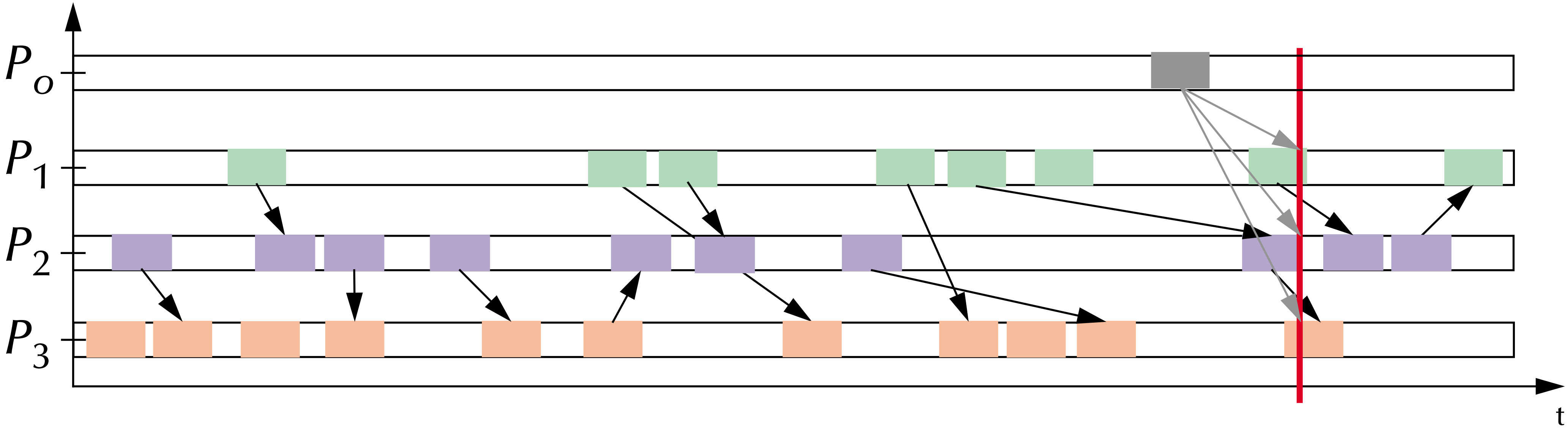

Distributed states

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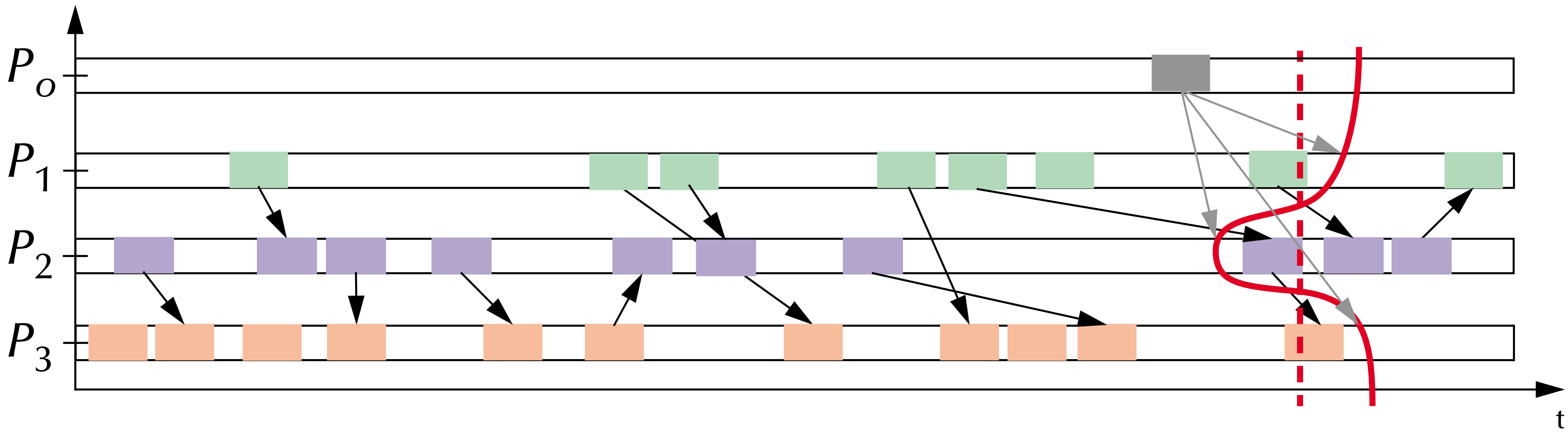
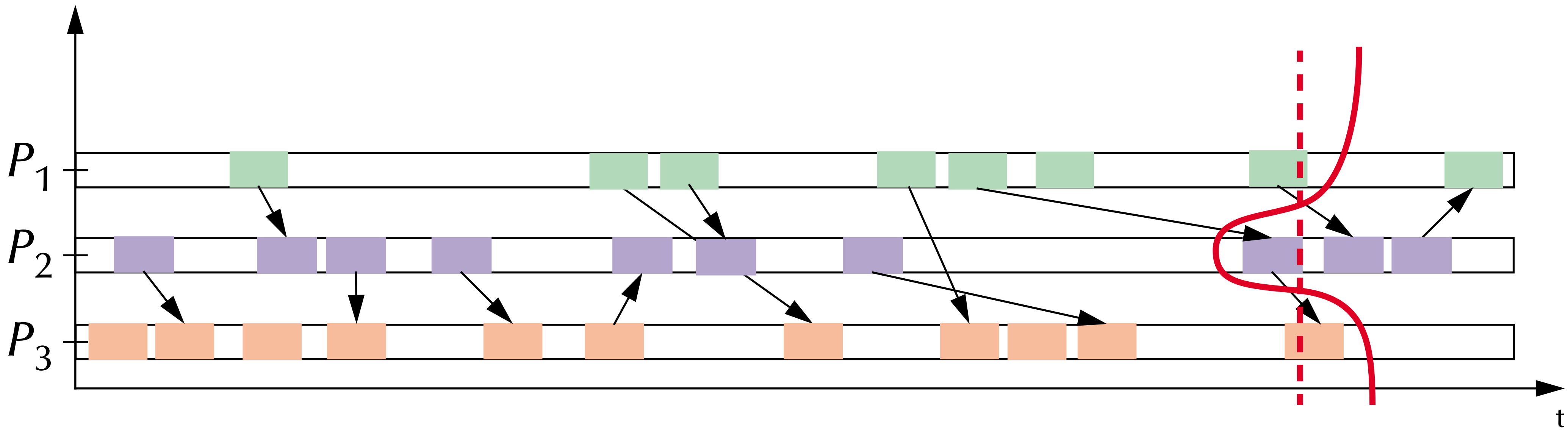


Distributed states

- collect all local states at a given time (snapshot):



☞ collecting all local states at an absolute, global point in time is impossible

☞ make sure that the observed distributed state (snapshot) is at least consistent

Distributed states

Consistent global state (snapshot):

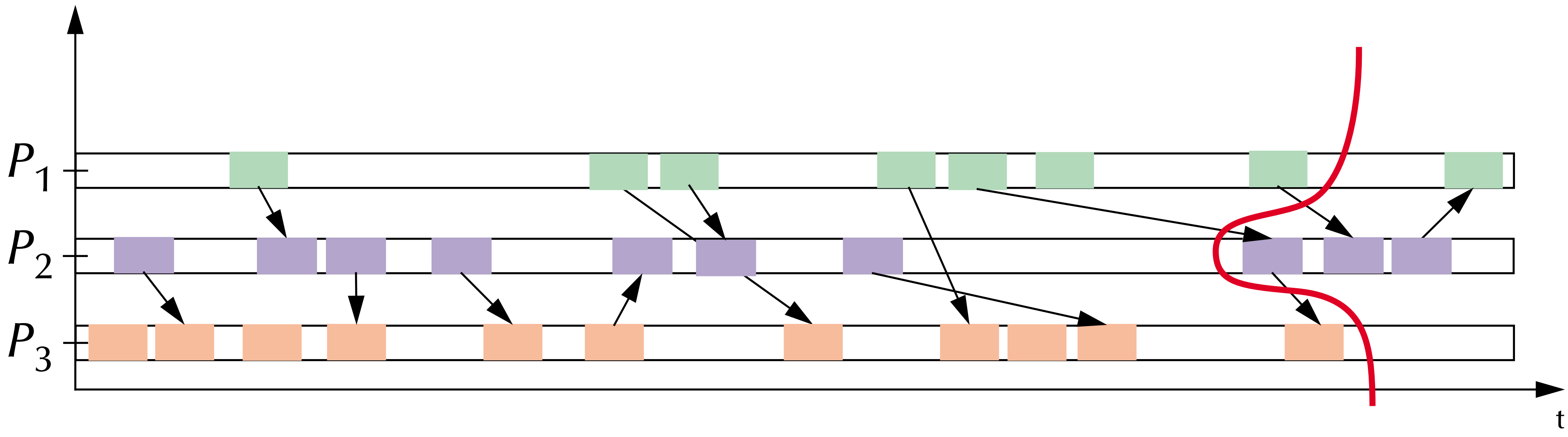
Make sure that all events can be uniquely divided in:

- *before* the snapshot (belonging to the past P):
  $(e_2 \in P) \wedge (e_1 \rightarrow e_2) \Rightarrow e_1 \in P$

- *after* the snapshot (belonging to the future F):
  $(e_1 \in F) \wedge (e_1 \rightarrow e_2) \Rightarrow e_2 \in F$

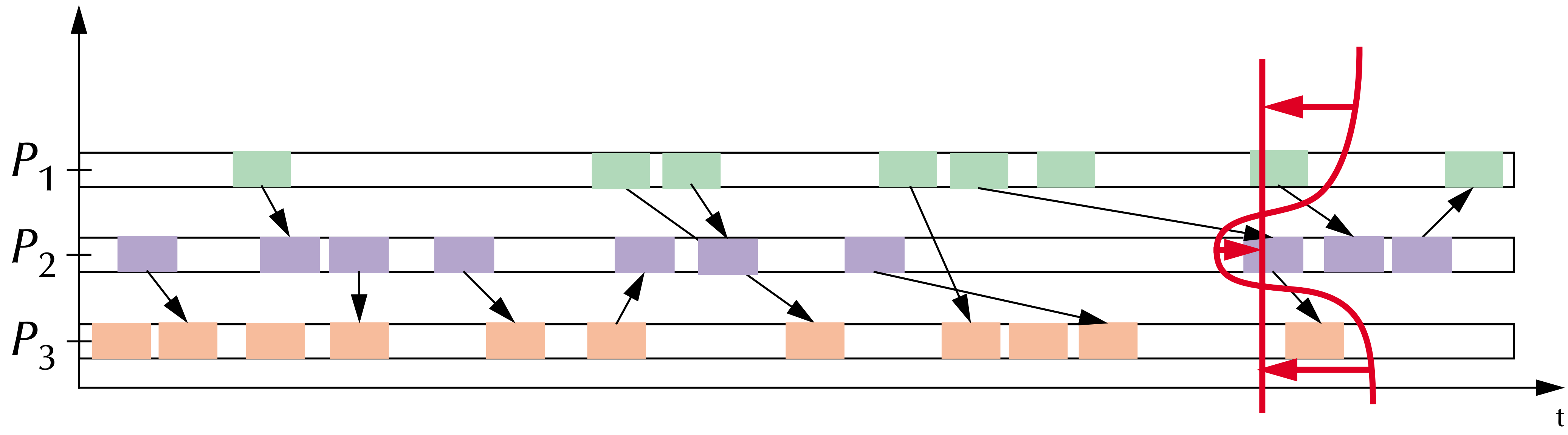
Distributed states

- check for consistency: straighten out the snapshot cut



Distributed states

- check for consistency: straighten out the snapshot cut



Distributed states

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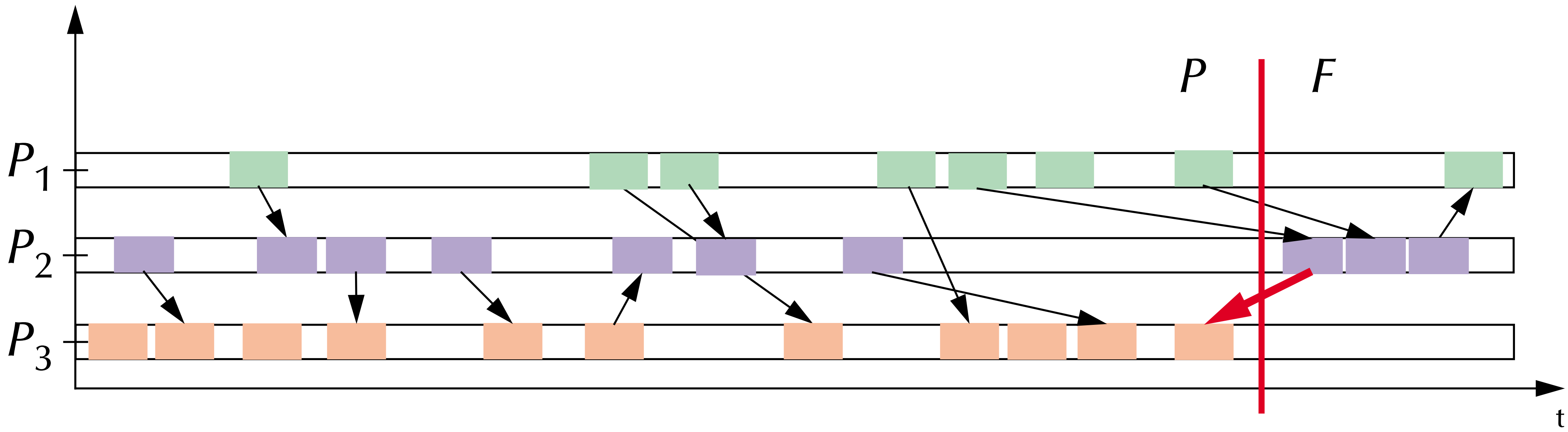


- $(e_1 \in F) \wedge (e_1 \rightarrow e_2) \Rightarrow e_2 \in P$ … or: the future influences the past

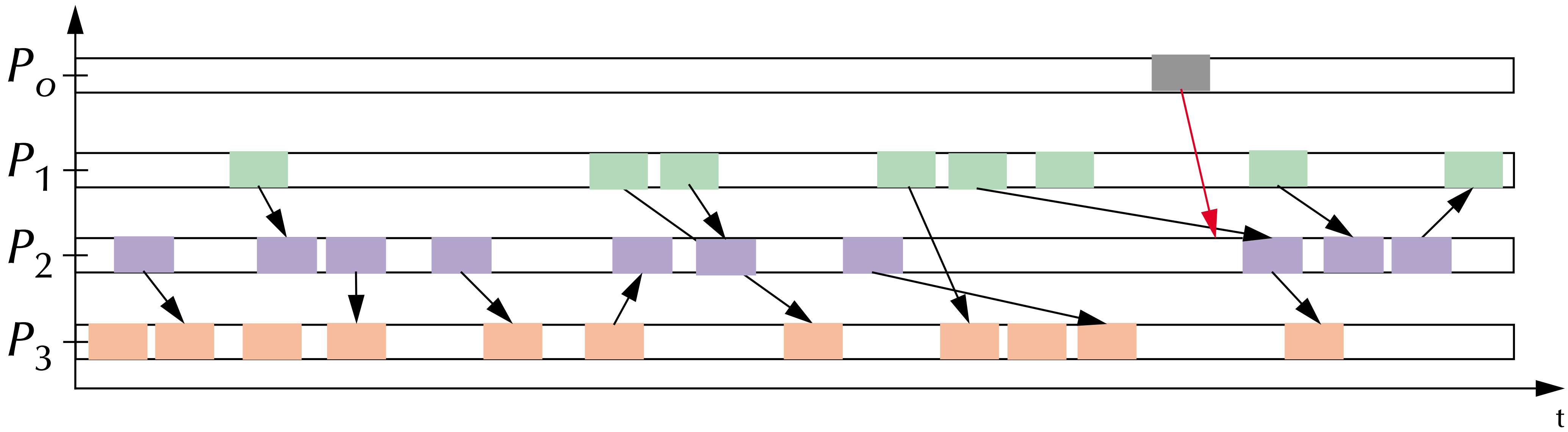
☞ inconsistent snapshot

Snapshot algorithm

- Observer-process P_o (any process) creates a snapshot token t_s and saves its local state s_o
- P_o sends t_s to all other processes.
- $\forall P_i$ which receive the t_s (as a token-message, or as part of another message):
    - save local state s_i and send s_i to P_o
    - attach t_s to all further messages, which are to be sent to other processes
    - save t_s and ignore all further incoming t_s's
- $\forall P_i$ which previously received t_s and receive a message m without t_s:
    - forward m to P_o (this message belongs to the snapshot)

Distributed states

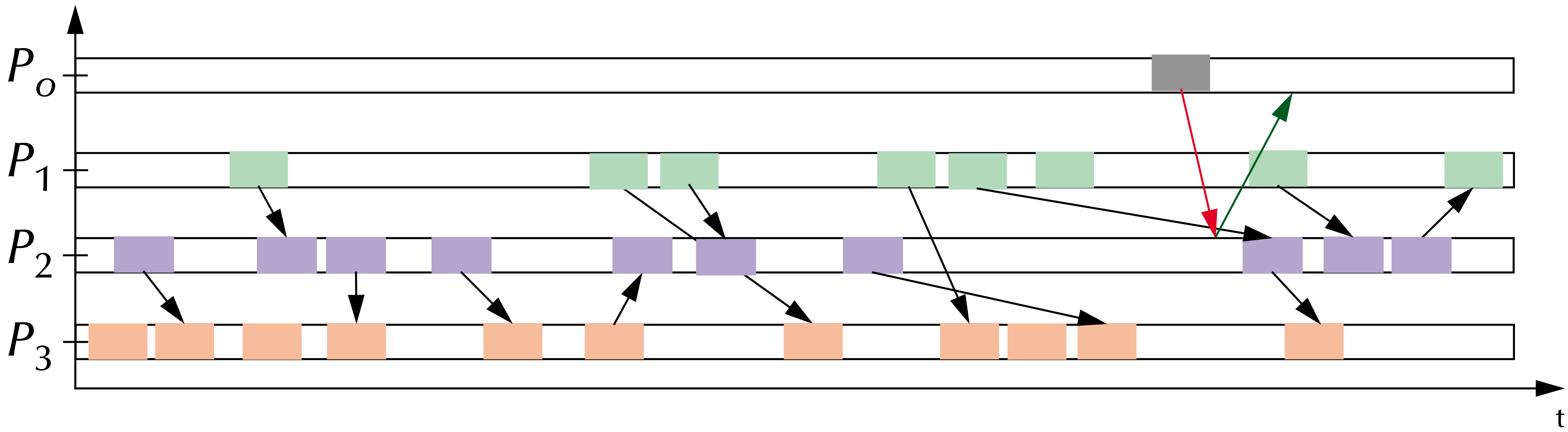
- apply snapshot algorithm:



- P_o send out snapshot token to all

Distributed states

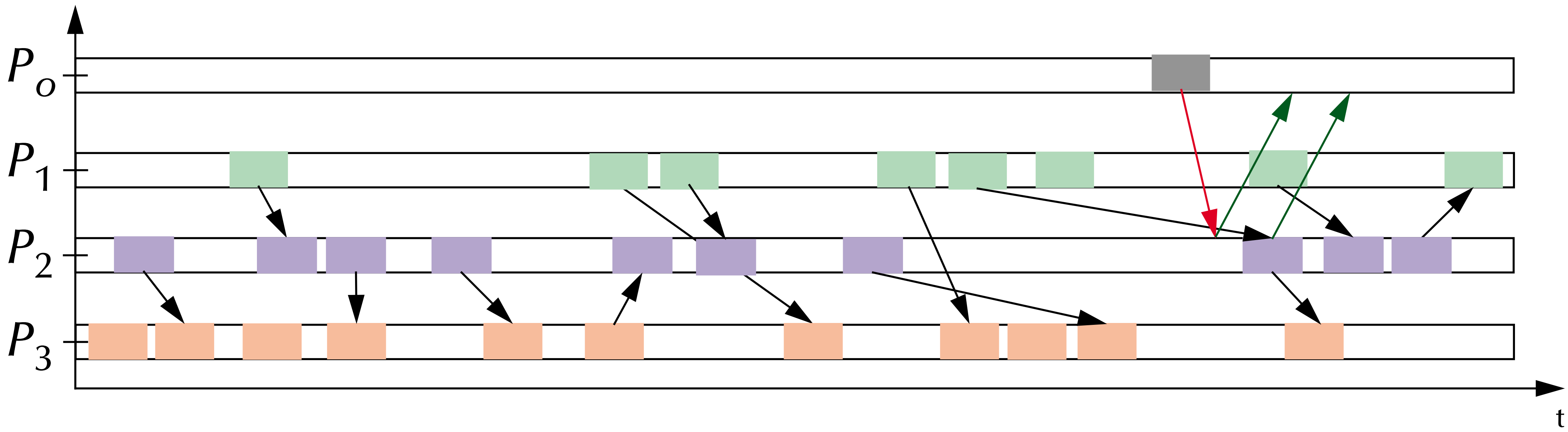
- apply snapshot algorithm:



- P_2 responds with its local state

Distributed states

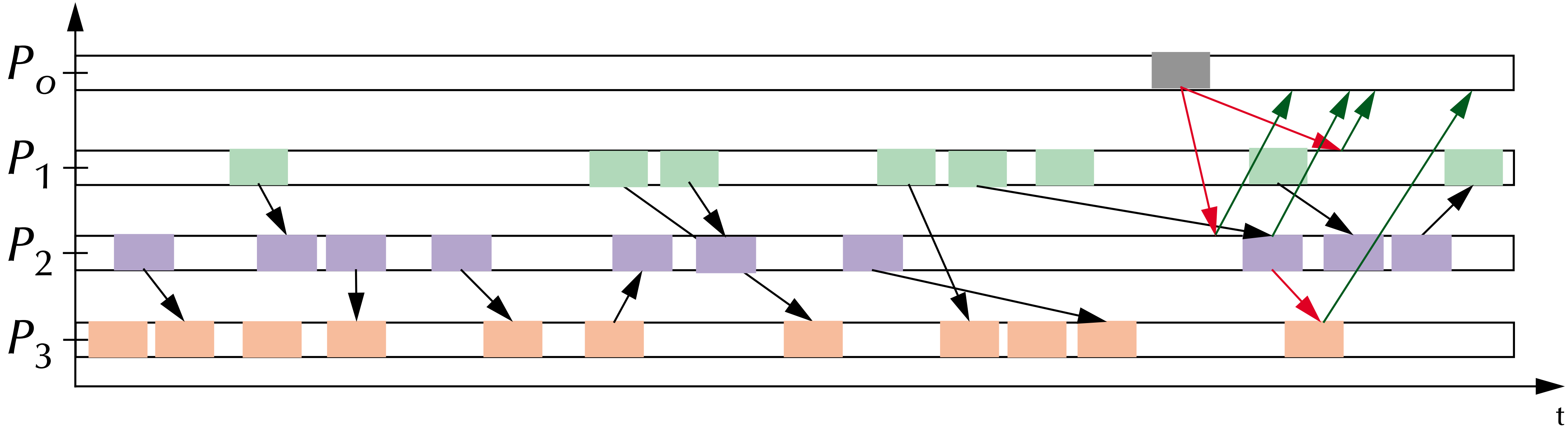
- apply snapshot algorithm:



- P_2 forwards an untagged message

Distributed states

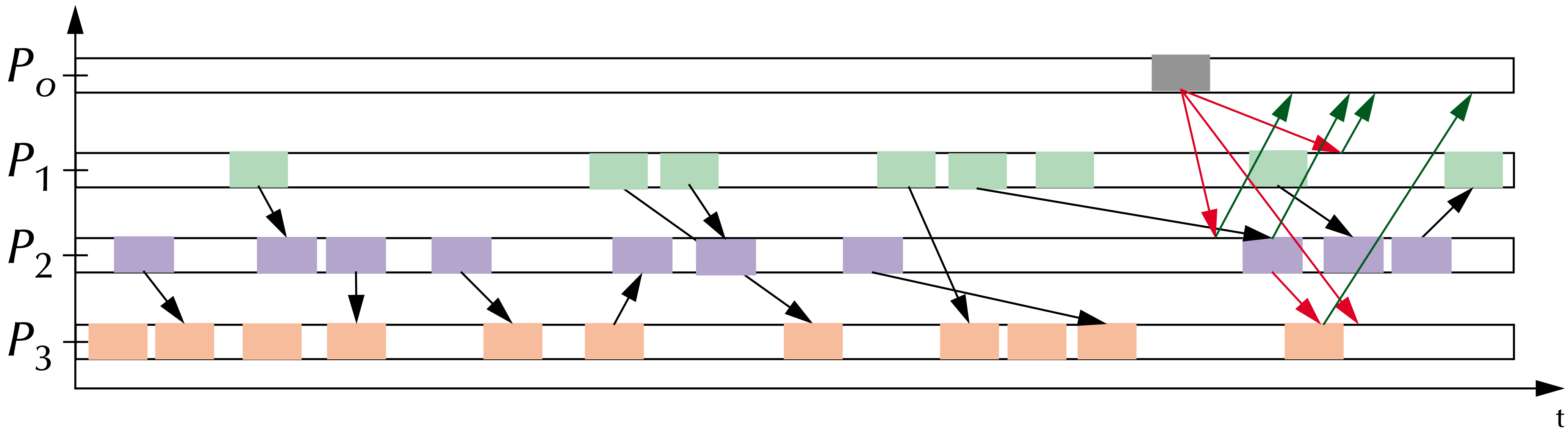
- apply snapshot algorithm:



- P_1 responds with its local state
- P_3 responds with its local state (due to a tagged message)

Distributed states

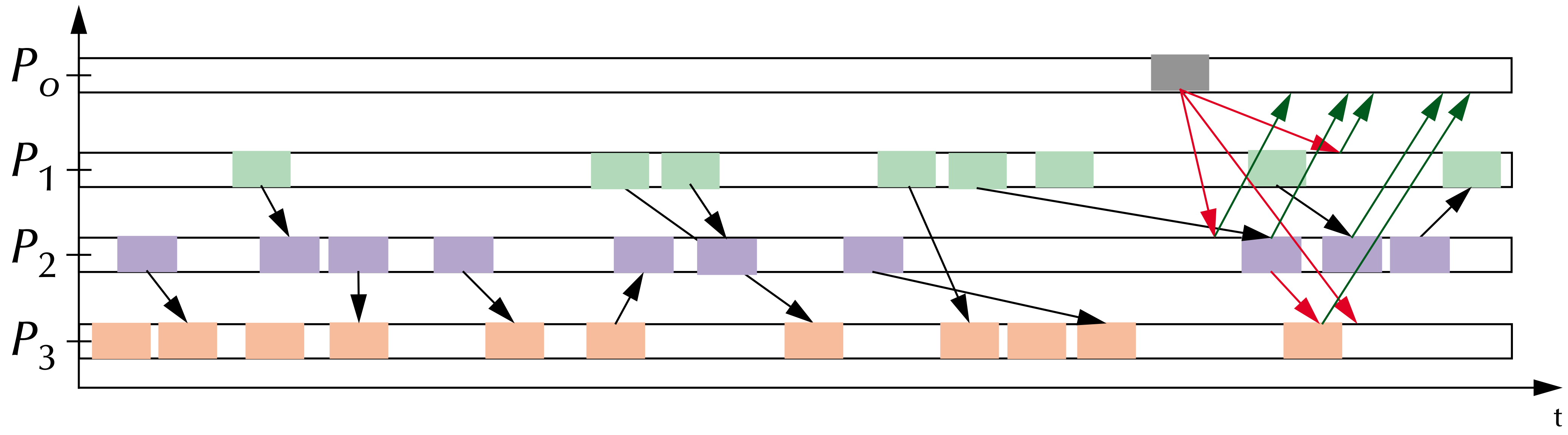
- apply snapshot algorithm:



- P_3 ignores the snapshot token
  (token was previously received as part of a message, local state is already reported)

Distributed states

- apply snapshot algorithm:



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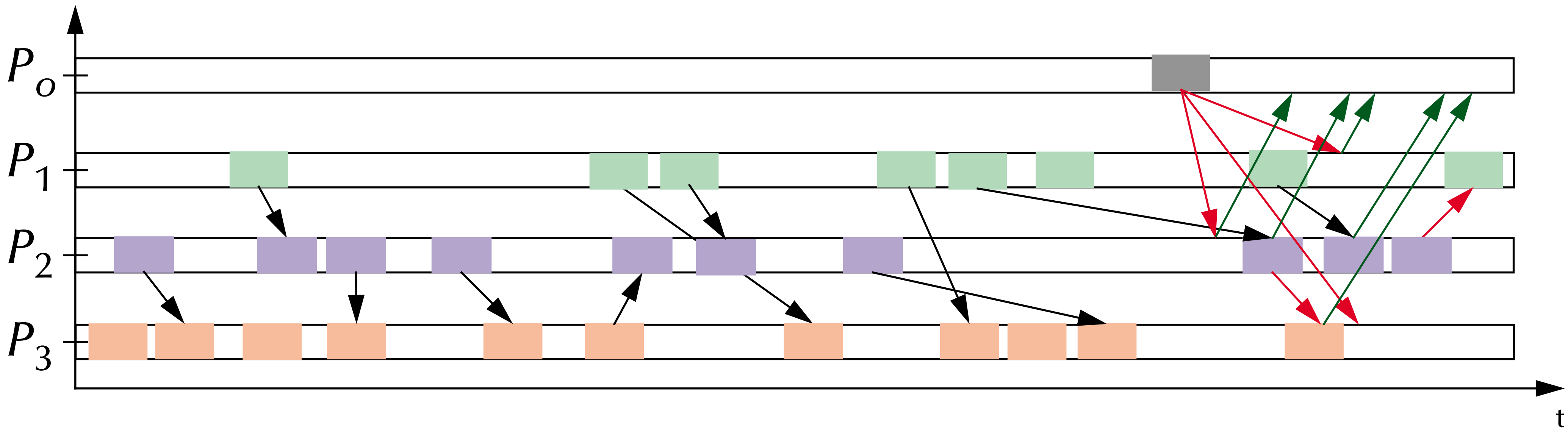
Distributed states

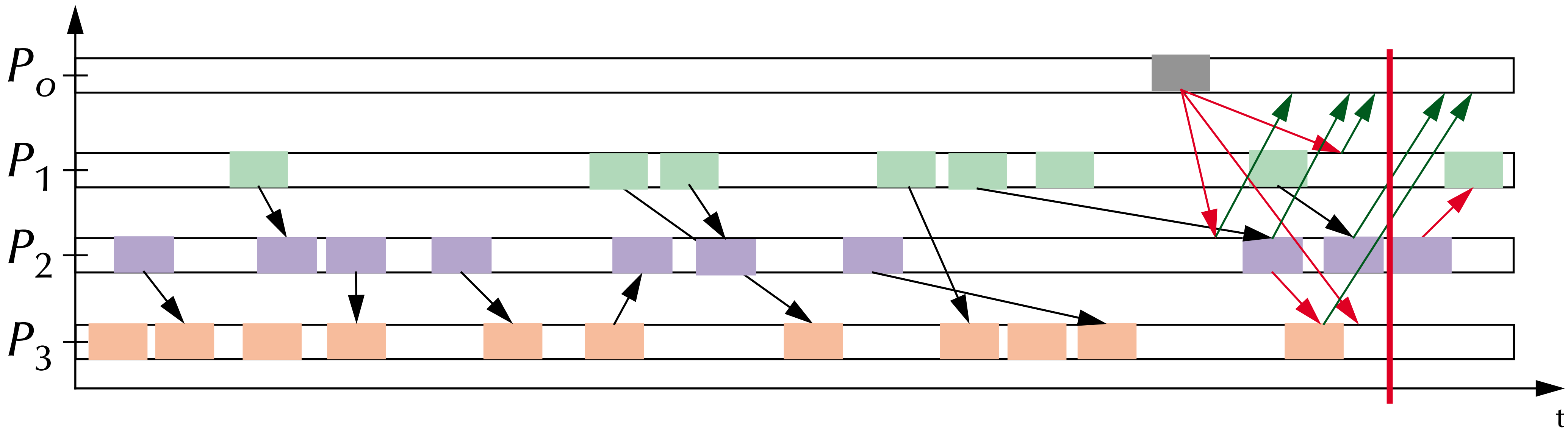
- apply snapshot algorithm:



- P_1 ignores a tagged message (token was previously received, local state is already reported)

Distributed states

- apply snapshot algorithm:



☞ the effective snapshot of the system
… which is known to the observer P_o after it received all reports

Snapshot algorithm

Termination?

either

- make assumptions about the delays in the system

or

- count the sent and received messages for each process (include this in the local state) and keep track of outstanding messages in the observer process

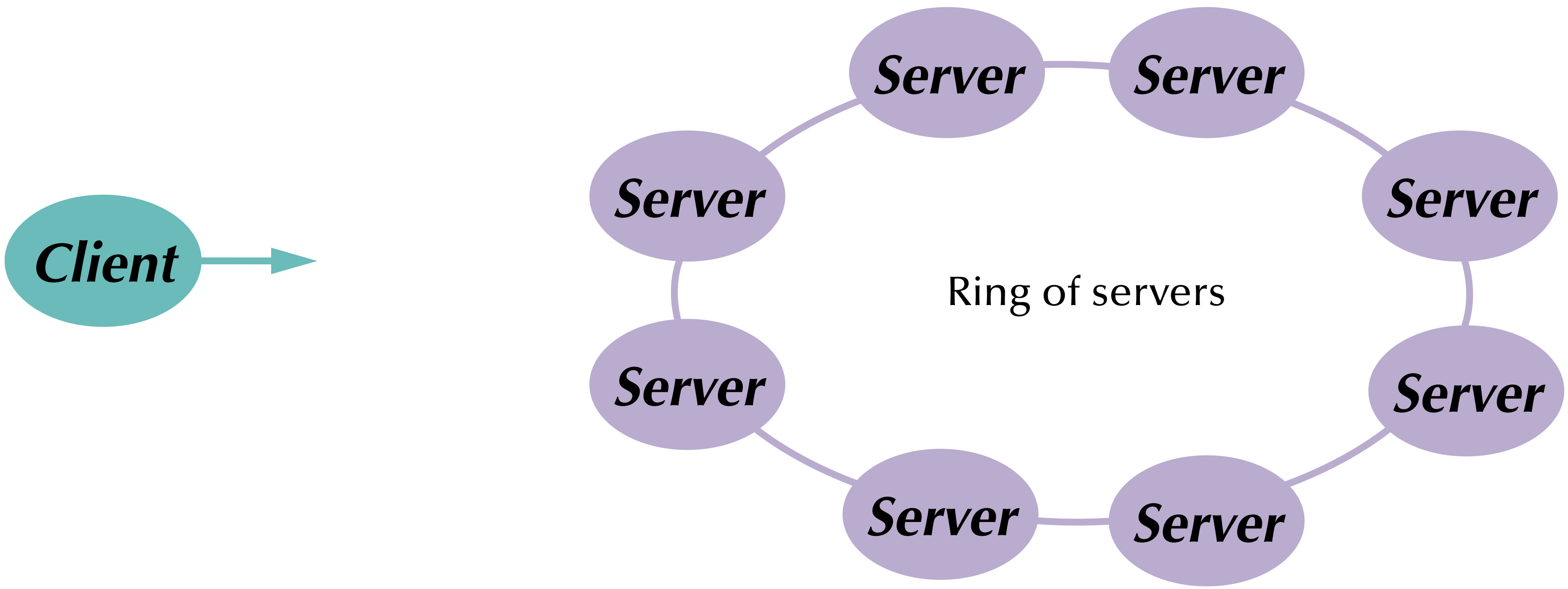
or …

Consistent distributed states

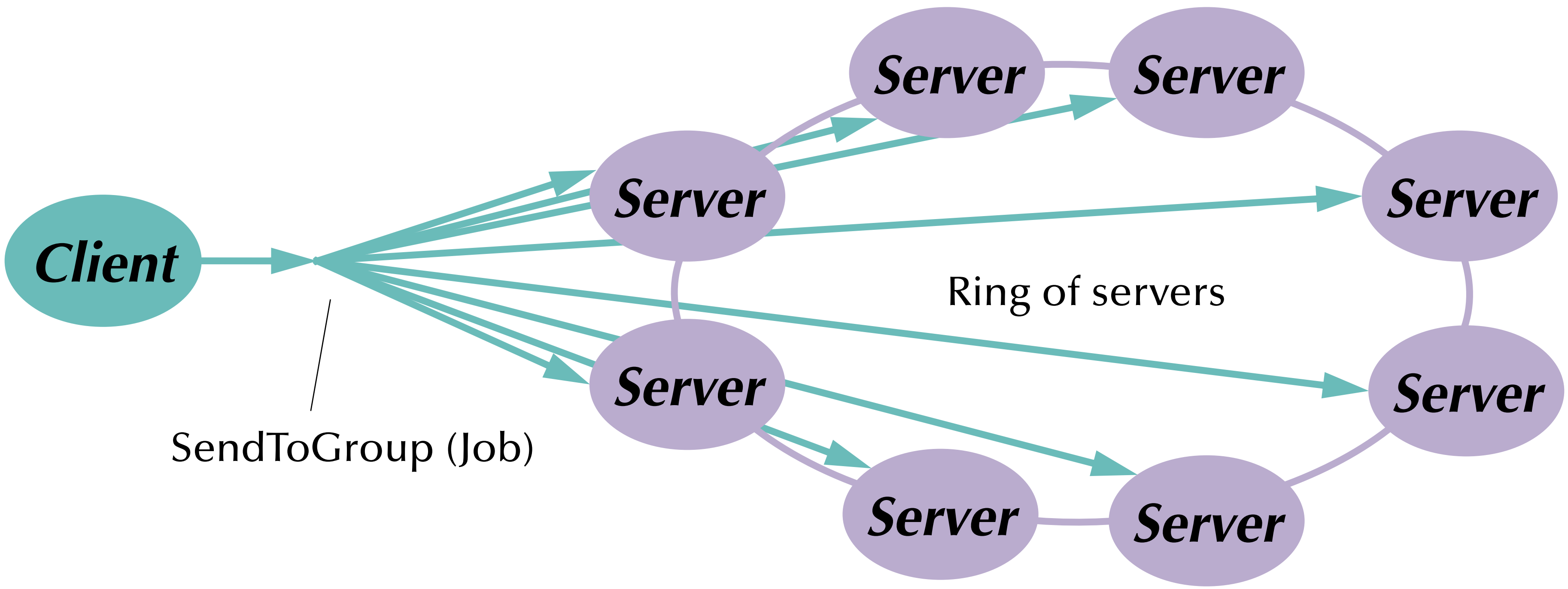
Why do we need that?

- find deadlocks
- find termination / completion conditions
- any other safety of liveness property
- collect a consistent system state for further processing (distributed databases)

A distributed server

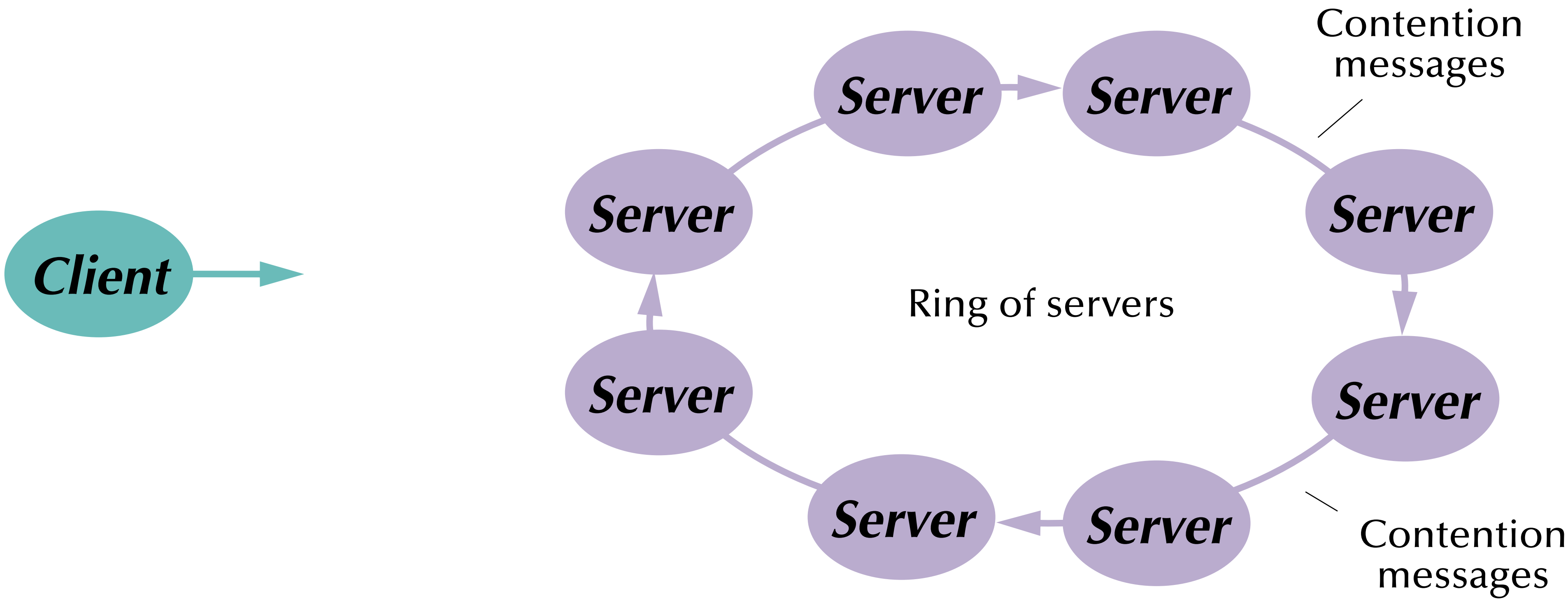


A distributed server

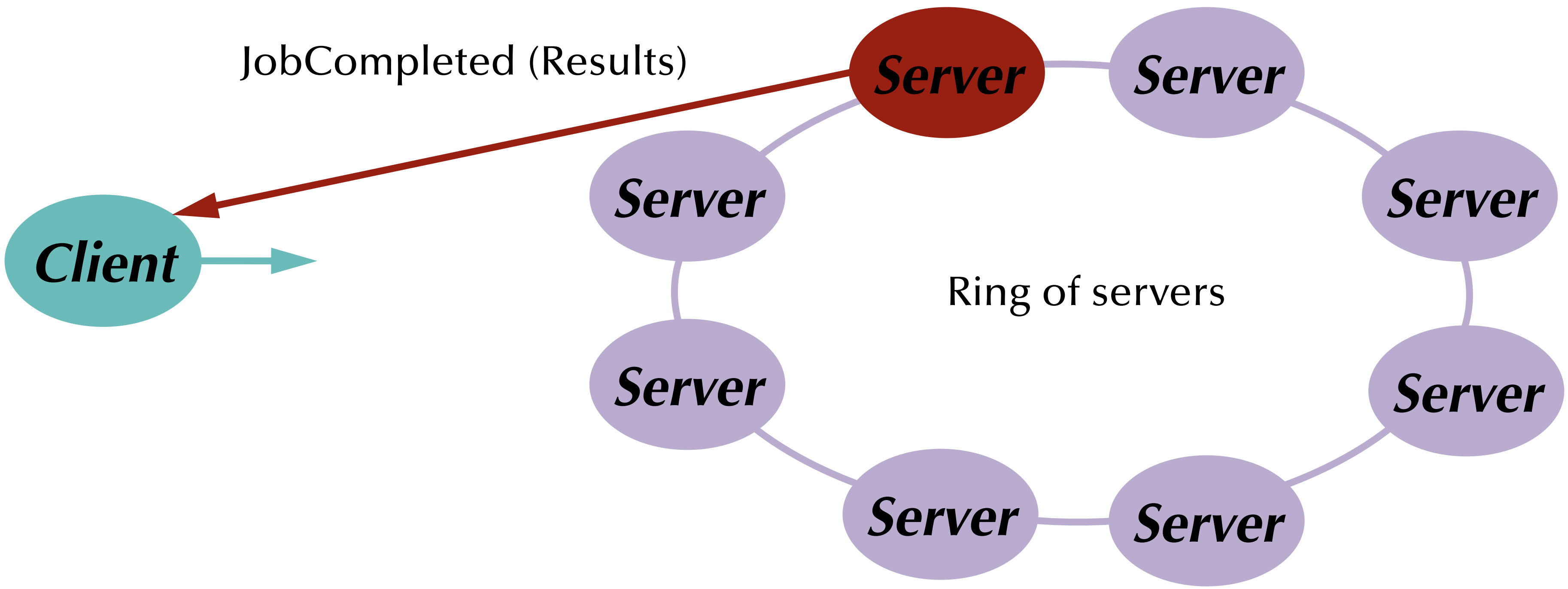


Distributed Systems

A distributed server



A distributed server



A distributed server

```
with GroupCommunication; use GroupCommunication;

task type Client is
end Client;

task body Client is
 begin
  SendToGroup (PrintServerGroup, ClientId, PrintJob);
 end Client;
```

A distributed server

```
with Ada.Task_Identification; use Ada.Task_Identification;

task type PrintServer is
  entry SendToServer ( PrintJob : in  Job_Type;
                       JobDone  : out Boolean);

  entry Contention (   ServerId : in Task_Id;
                       PrintJob : in Job_Type);

end PrintServer;
```

A distributed server

```
task body PrintServer is
begin
  loop
    select

      accept SendToServer (PrintJob : in Job_Type;
                           JobDone  : out Boolean) do

        if not PrintJob in TurnedDownJobs then

          if not_too_busy then
            AppliedForJobs := AppliedForJobs + PrintJob;
            NextServerOnRing.Contention (Current_Task, PrintJob);
            Requeue InternalPrintServer.PrintJobQueue;

          else
            TurnedDownJobs := TurnedDownJobs + PrintJob;
          end if;
        end if;
      end SendToServer;
```

```
…
    or
      accept Contention ( ServerId : in Task_Id;
                          PrintJob : in Job_Type) do
        if PrintJob in AppliedForJobs then
          if ServerId = Current_Task then
            InternalPrintServer.StartPrint (PrintJob);
          elsif ServerID > Current_Task then
            InternalPrintServer.CancelPrint (PrintJob);
            NextServerOnRing.Contention (ServerId, PrintJob);
          else
            null; -- removing the contention message from ring
          end if;
        else
          TurnedDownJobs := TurnedDownJobs + PrintJob;
          NextServerOnRing.Contention (ServerId, PrintJob);
        end if;
      end Contention;
    or
      terminate;
    end select;
  end loop;
end PrintServer;
```

Distributed Systems

How to construct predictable client-server systems
beyond a single remote procedure call / rendezvous?

☞ Transactions:

- **Atomicity**: All or none of the sub-operations are performed. Atomicity helps achieve crash resilience. If a crash occurs, then it's possible to roll back the system to the state before the transaction was invoked.
- **Consistency**: Transforms the system from one consistent state to another.
- **Isolation**: Results (including partial results) are not revealed unless and until the transaction commits. If the operation accesses a shared data object, invocation does not interfere with other operations on the same object.
- **Durability**: After a commit, results are guaranteed to persist, even after a subsequent system failure.

☞ known as the 'ACID'-properties

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- if the transactions are not completely side-effect free,
  they cannot operate on the same server data-structures concurrently? …

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☞ how to achieve *consistency* and *isolation* in a concurrent / distributed system?

- if the transactions are not completely side-effect free,
  they cannot operate on the same server data-structures concurrently? …

… maybe we can implement the *appearance* of isolation and the full effect of consistency?

A closer look at transactions

- Transactions consist of a sequence of individual ***operations***.
- If two operations out of two transactions can be performed in any order with the same final effect, they are ***commutative*** and not critical for our purposes.
- Some of the operations out of transactions have side-effects ☞ those are the ***critical*** operations.
- Any sequential execution of multiple transactions *fulfils* the ACID-properties, by definition of a single transaction.
- Some concurrent executions (interleavings) of multiple transactions *might fulfil* the ACID-properties.

☞ If a specific interleaving can be shown to be equivalent to a specific sequential execution of the involved transactions then this specific interleaving is called '**serializable**'.

☞ Construct an interleaving which ensures that no transaction ever encounters an inconsistent state (ensure the *appearance* of isolation).

Achieving serializability

- If two side-effecting operations out of two different transactions (affecting the same object) cannot be executed in any order with the same final effect then those are *conflicting pairs of operations*.

☞ For **serializability** of two transactions it is **necessary** and **sufficient** for the order of their invocations of all conflicting pairs of operations to be the same for all the objects which are invoked by both transactions.

Order of operations needs to be determined:

☞ distributed time-stamps are required, e.g. Lamport clocks

Serialization graphs

☞ For **serializability** of two transactions it is **necessary** and **sufficient** for the order of their invocations of all conflicting pairs of operations to be the same for all the objects which are invoked by both transactions.

☞ Above order gives also an order dependency between the transactions as a whole.

- **Serialization graph**: directed graph; vertices i represent *transactions* T_i; edges $T_i \rightarrow T_j$ represent that an observer witnessed that *order dependency*.

A multiple transactions interleaving is serializable
$\Leftrightarrow$ its serialization graph is acyclic

Transaction schedulers

Three major designs:

- **Locking methods**:
  Impose strict mutual exclusion on all critical sections.
- **Time-stamp ordering**:
  Note relative starting times and keep order dependencies consistent.
- **"Optimistic" methods**:
  Go ahead until a conflict is observed - then roll back.

Transaction schedulers – Locking methods

Locking methods include the possibility of deadlocks ☞ careful from here on out …

- **Complete resource allocation** before the start and release at the end of every transaction:
  ☞ this will impose a strict sequential execution of all critical transactions.
- **(Strict) two-phase locking**:
  Each transaction follows the following two phase pattern during its operation:
  - Growing phase: locks can be acquired, but not released
  - Shrinking phase: locks can be released, but not acquired (two phase locking) or locks are released on commit (strict two phase locking).

  ☞ possible deadlocks
  ☞ serializable interleavings
  ☞ strict isolation (in case of strict two-phase locking)
- **Semantic locking**: Allow for separate read-only and write-locks
  ☞ higher level of concurrency (see also: use of *functions* in *protected objects*)

Transaction schedulers – Time stamp ordering

- Put a unique time-stamp (any global order criterion) on every transaction upon start.
  Each involved object can inspect the time-stamps of all requesting transactions.

  - Case 1:
    A transaction with a time-stamp *later* than all currently active transactions applies:
    ☞ the request is accepted and the transaction can go ahead
  - Case 2:
    A transaction with a time-stamp *earlier* than all currently active transactions applies:
    ☞ the request is not accepted and the applying transaction is to be aborted.

☞ no isolation ☞ cascading aborts possible.

  - Alternative case 1 (strict time-stamp ordering):
    ☞ the request is delayed until the currently active earlier transaction has committed

☞ simple implementation, high degree of concurrency
– also in a distributed environment, as long as a global event order (time) can be supplied.

Transaction schedulers – Optimistic concurrency control

Premise:

If conflict is unlikely the overhead to ensure a serializable interleaving might not be justified

Idea:

- get a local copy (shadow copy) of the involved objects
- perform a subset of the required transactions locally
- check for the current state of the object again and see whether the results of the local operations can be embedded without violating consistency
- depending on the previous check:
  either delete all local results or write them back to the actual object

Transaction schedulers – Optimistic concurrency control

Three phases

1. **Read & execute**:
   generate a shadow copy of all involved objects and perform all required operations there.

2. **Validate**:
   after local commit, check all occurred interleavings for serializability

3. **Update or abort**:
   IF serializability could be ensured in step 2 then all results of involved transactions (one transaction at a time) are written to all involved objects (in dependency order of the transactions).
   Otherwise destroy shadow copies and possibly start over with the failed transactions.

☞ Open issue: how to gain a consistent set of shadow copies in phase one and how to update all involved objects consistently (atomically) in phase three?

Transaction schedulers – Optimistic concurrency control

Premise:

If conflict is unlikely the overhead to ensure a serializable interleaving might not be justified

Results:

- ☞ possibly many additional copies
- ☞ deadlock free
- ☞ maximum concurrency
- ☞ with more overlapping transactions this scheduler breaks down rapidly
  - ☞ starvation & live-locks

Distributed transaction schedulers

The three major designs again:

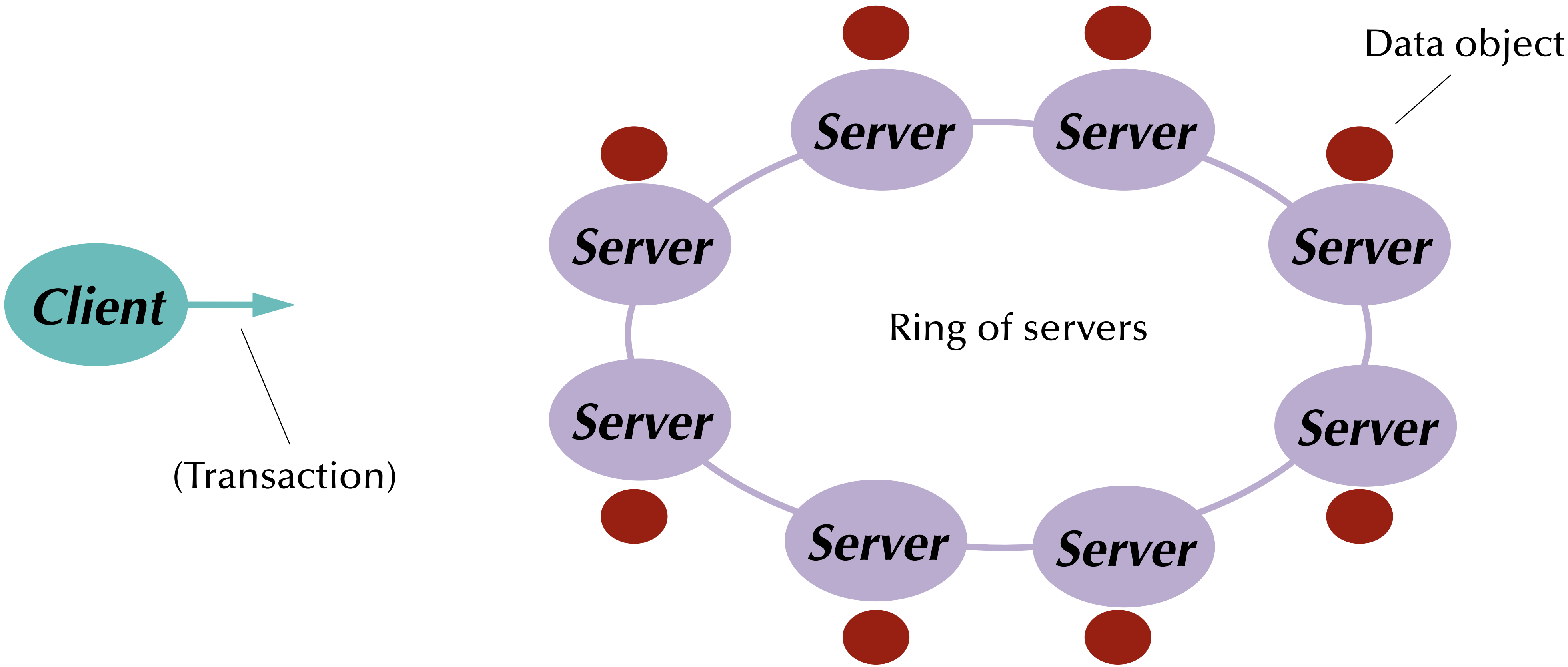
- **Locking methods**:
  Impose strict mutual exclusion on all critical sections.
- **Time-stamp ordering**:
  Note relative starting times and keep order dependencies consistent.
- **“Optimistic” methods**:
  Go ahead until a conflict is observed - then roll back.

☞ *Commit* or *abort* operations are required in many places above

How to implement those in a distributed environment?

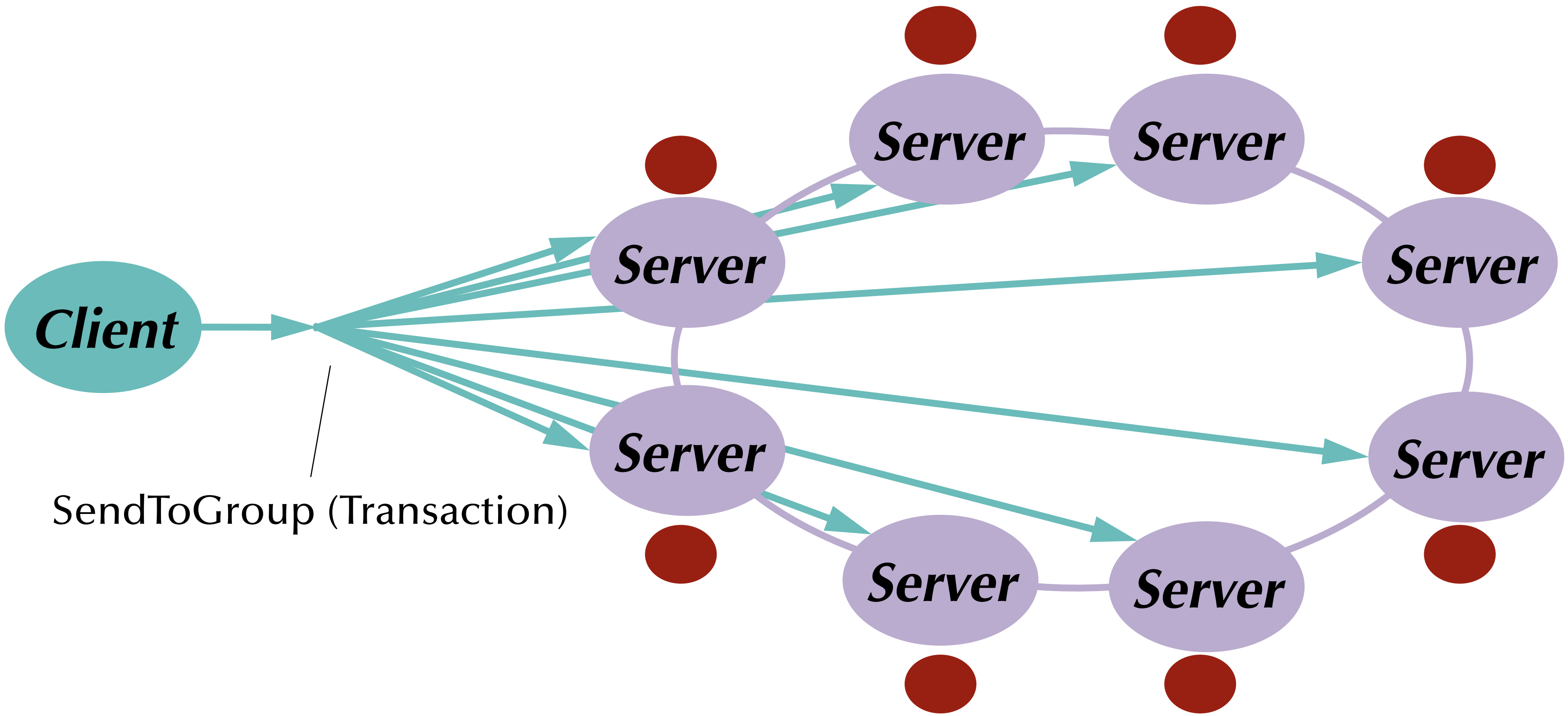
Two phase commit protocol

Start-up (initialization) phase



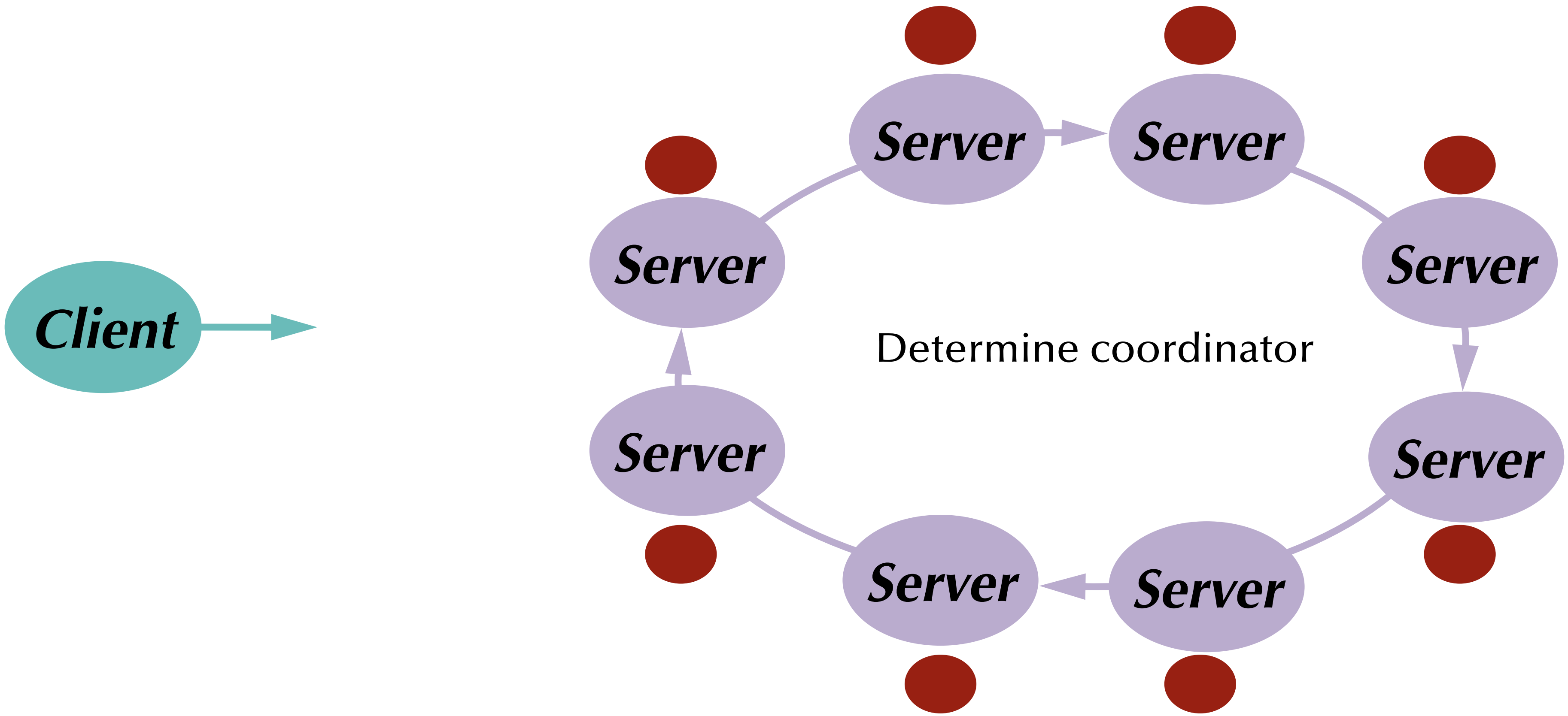
Two phase commit protocol

Start-up (initialization) phase



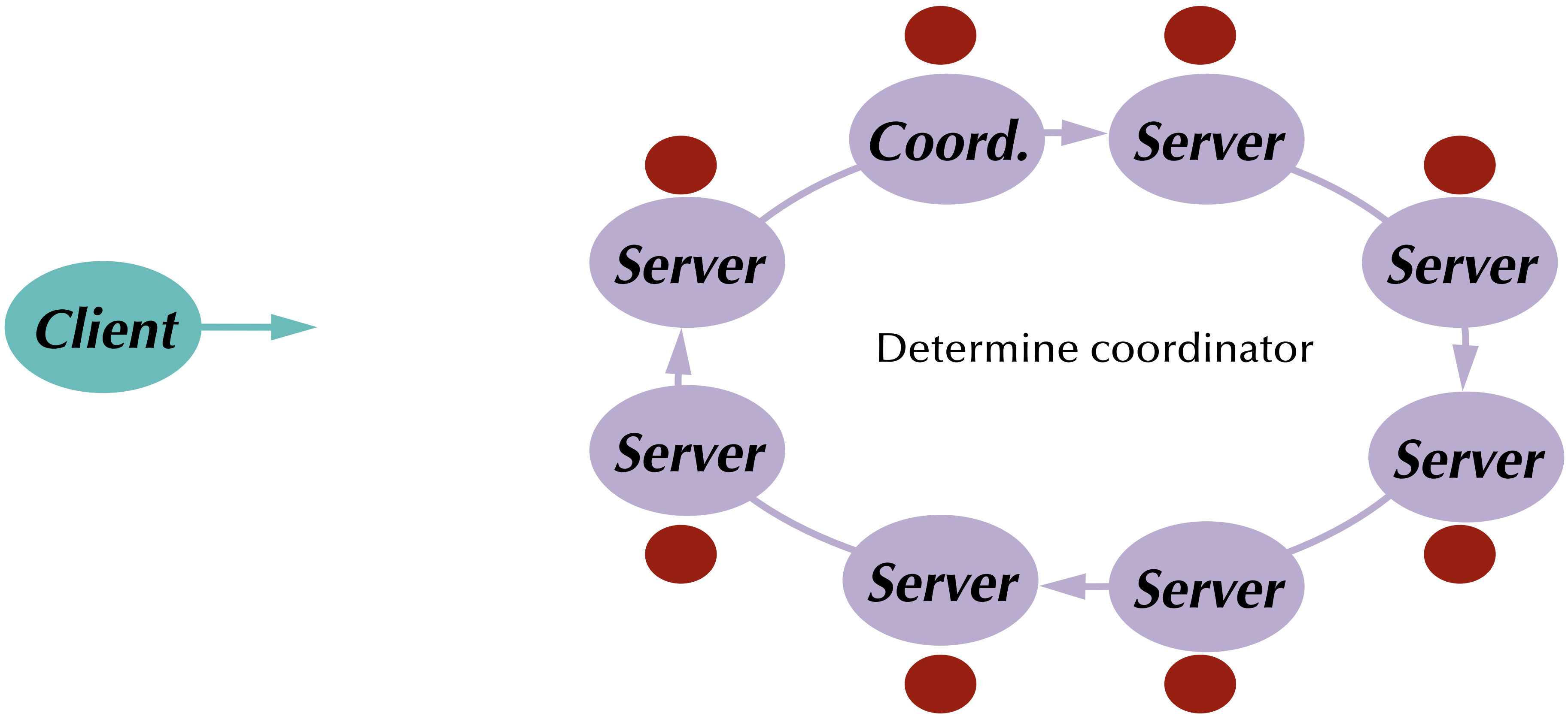
Two phase commit protocol

Start-up (initialization) phase



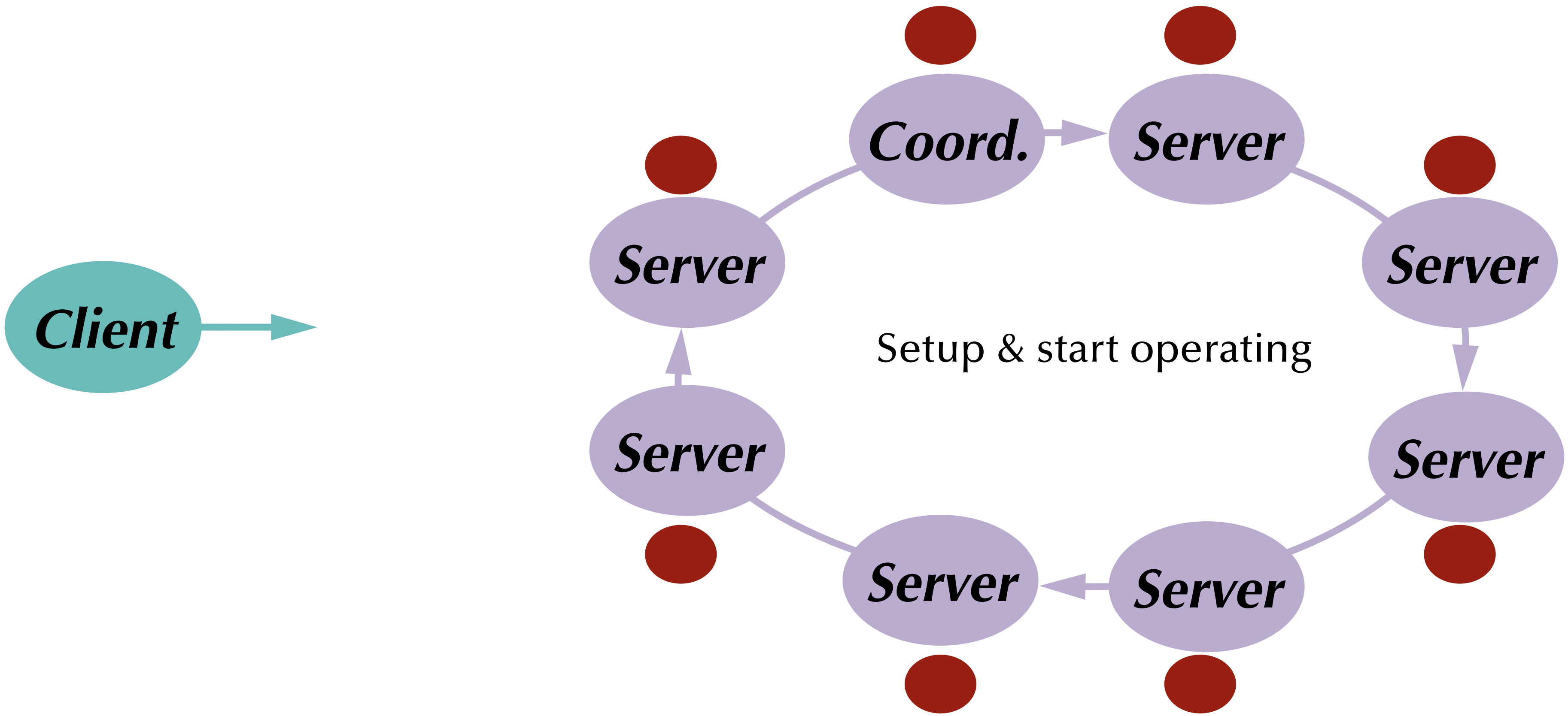
Two phase commit protocol

Start-up (initialization) phase



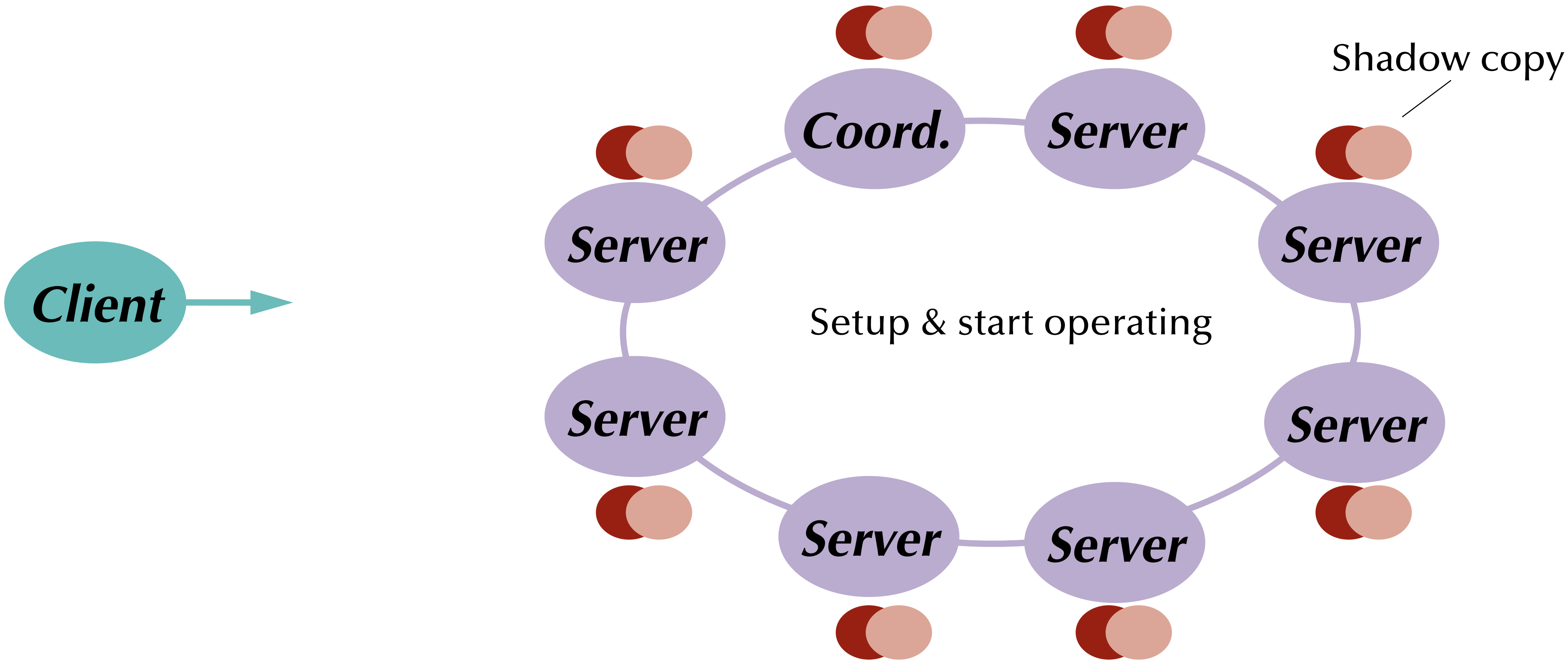
Two phase commit protocol

Start-up (initialization) phase



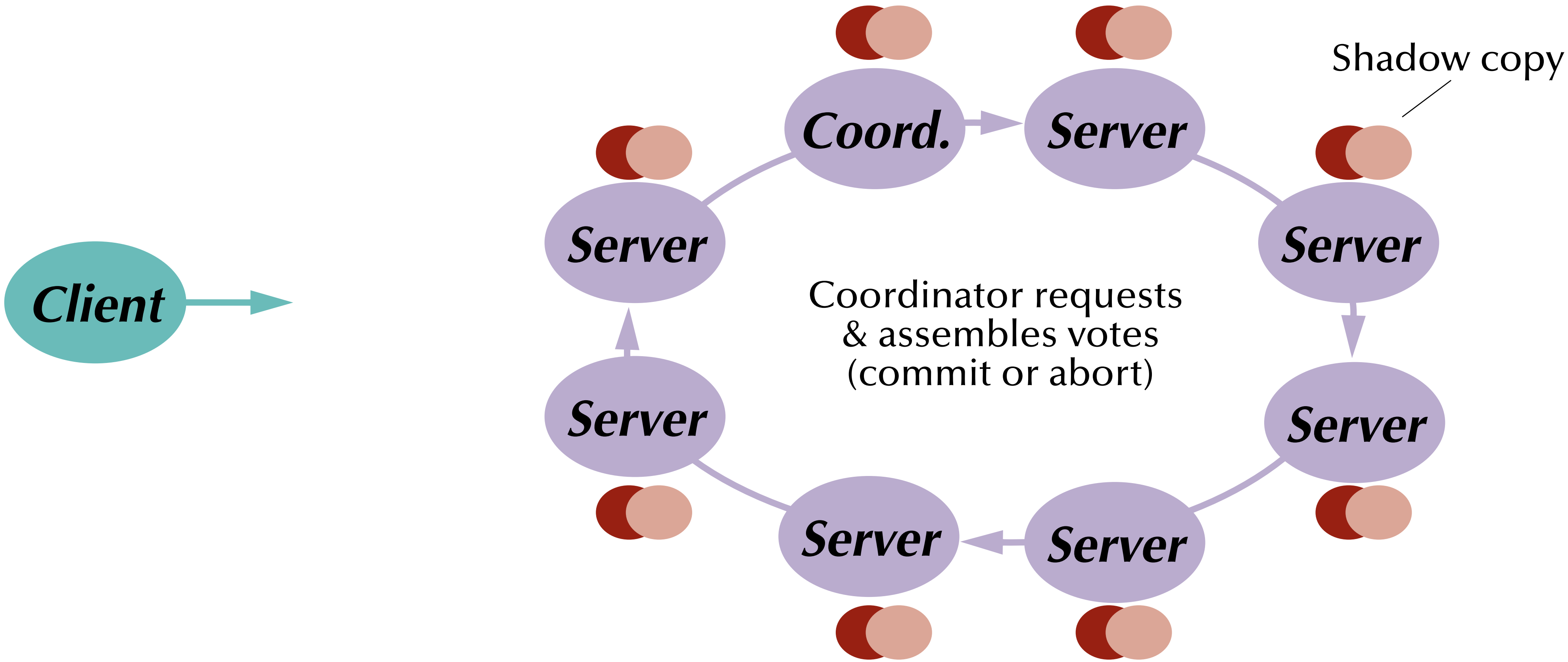
Two phase commit protocol

Start-up (initialization) phase



Two phase commit protocol

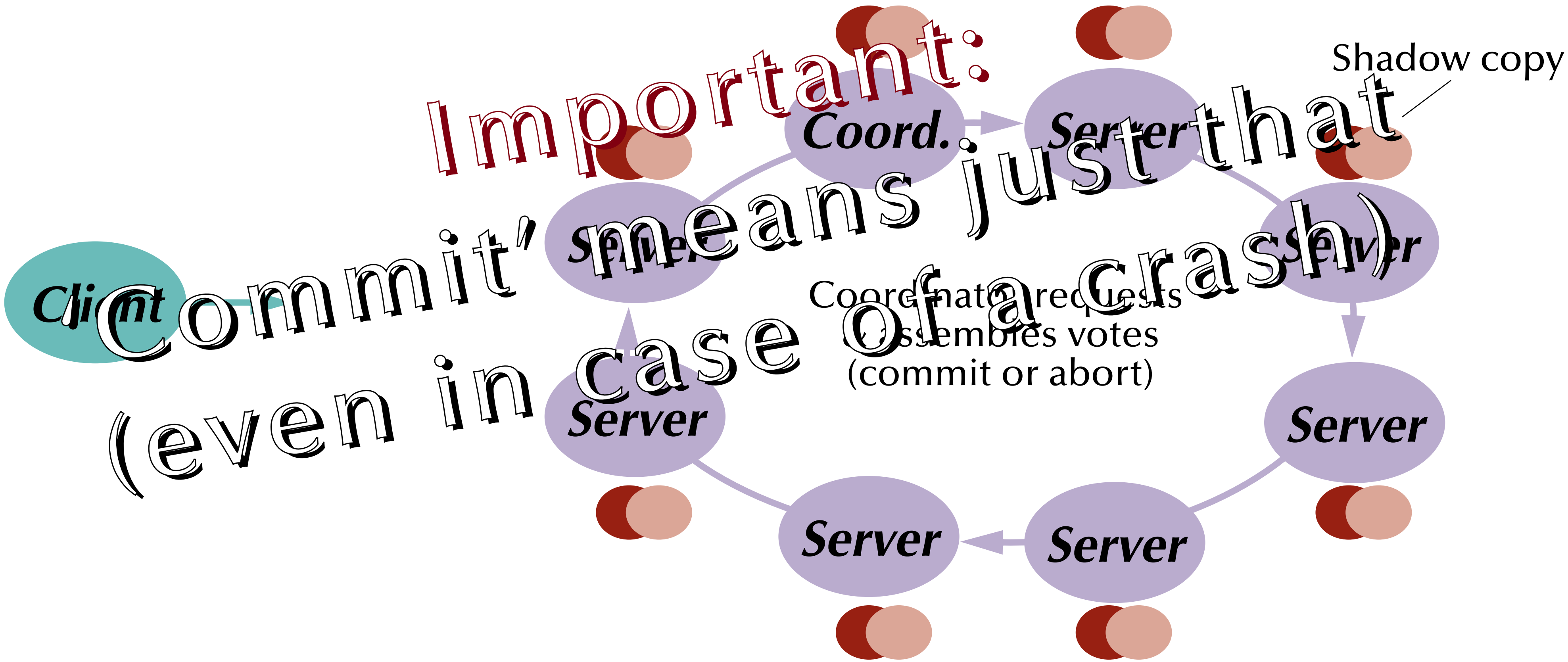
Phase 1: Determine result state



Two phase commit protocol

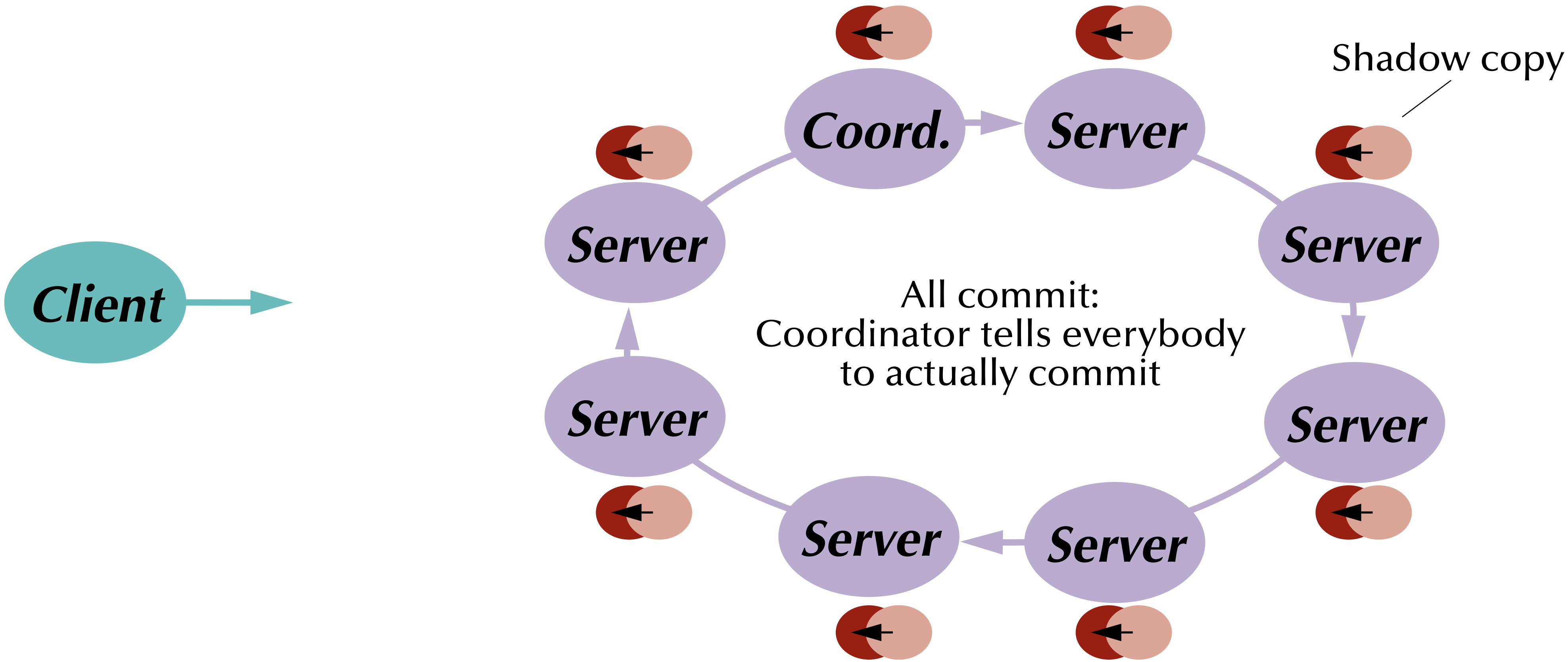
Phase 1: Determine result state

Important:
Commit’ means just that
(even in case of a crash)



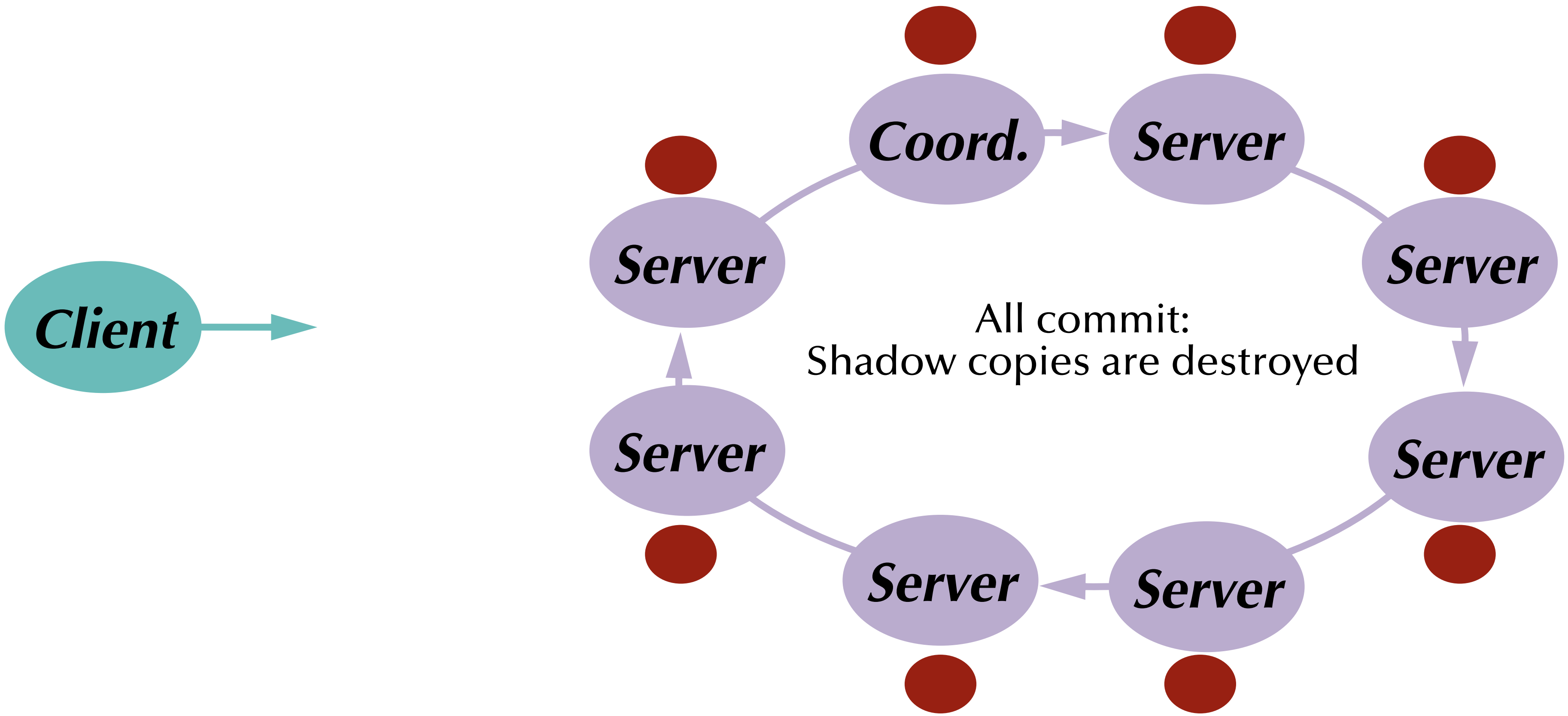
Two phase commit protocol

Phase 2: Implement results



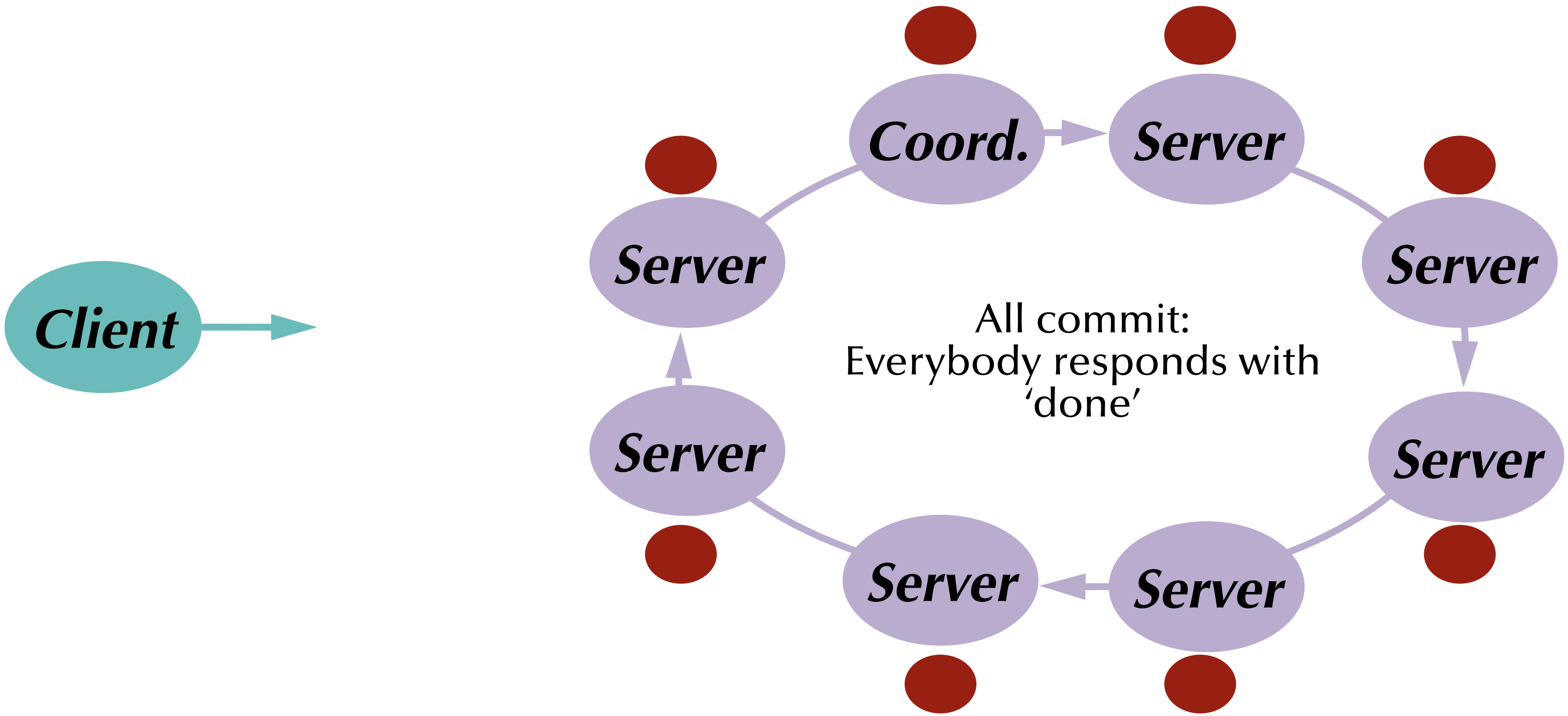
Two phase commit protocol

Phase 2: Implement results



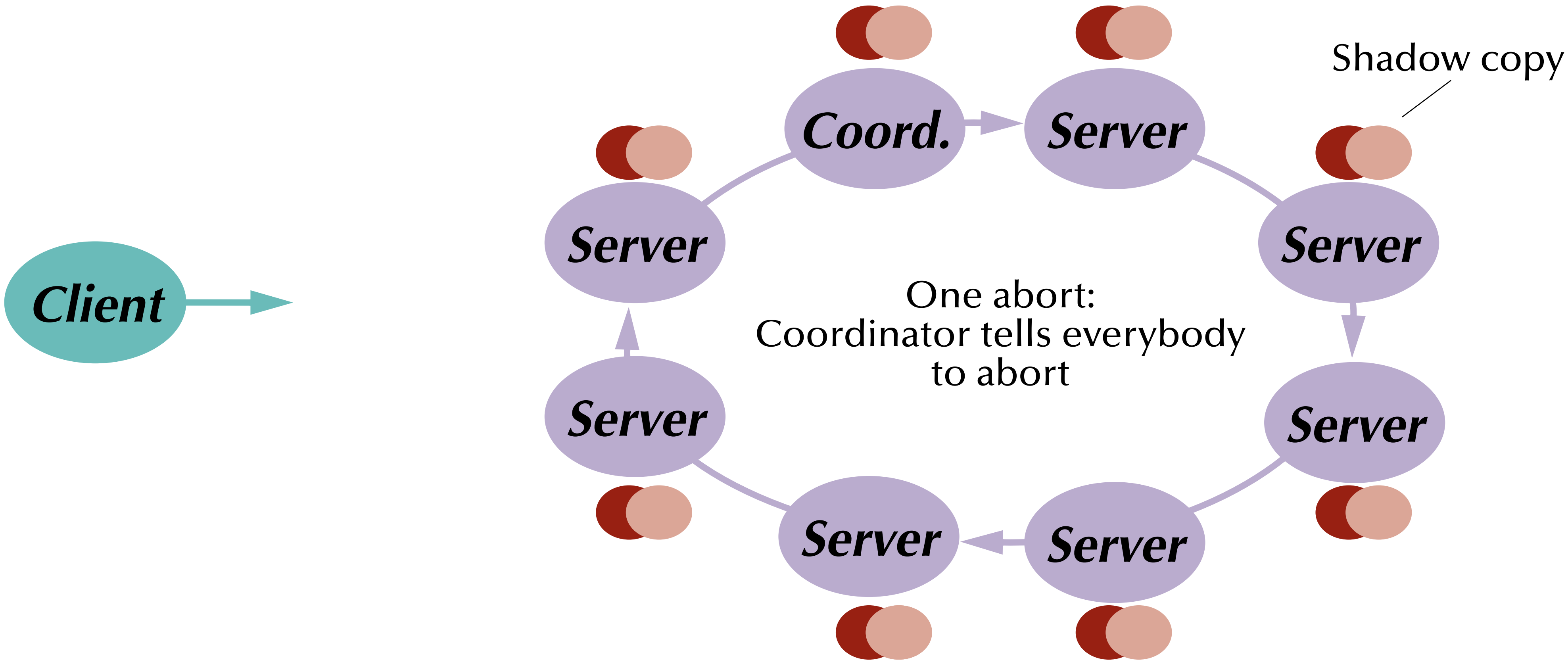
Two phase commit protocol

Phase 2: Implement results



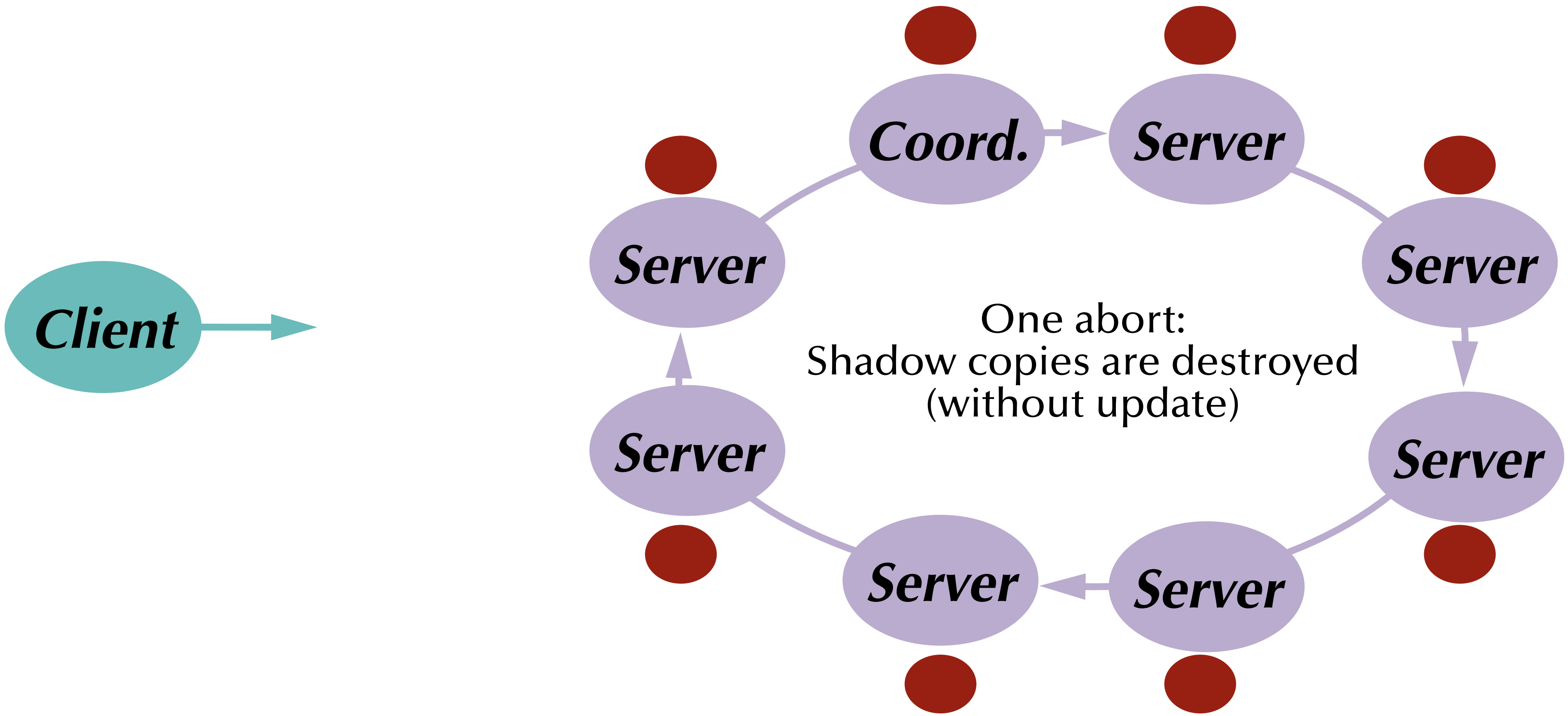
Two phase commit protocol

or phase 2: global roll back



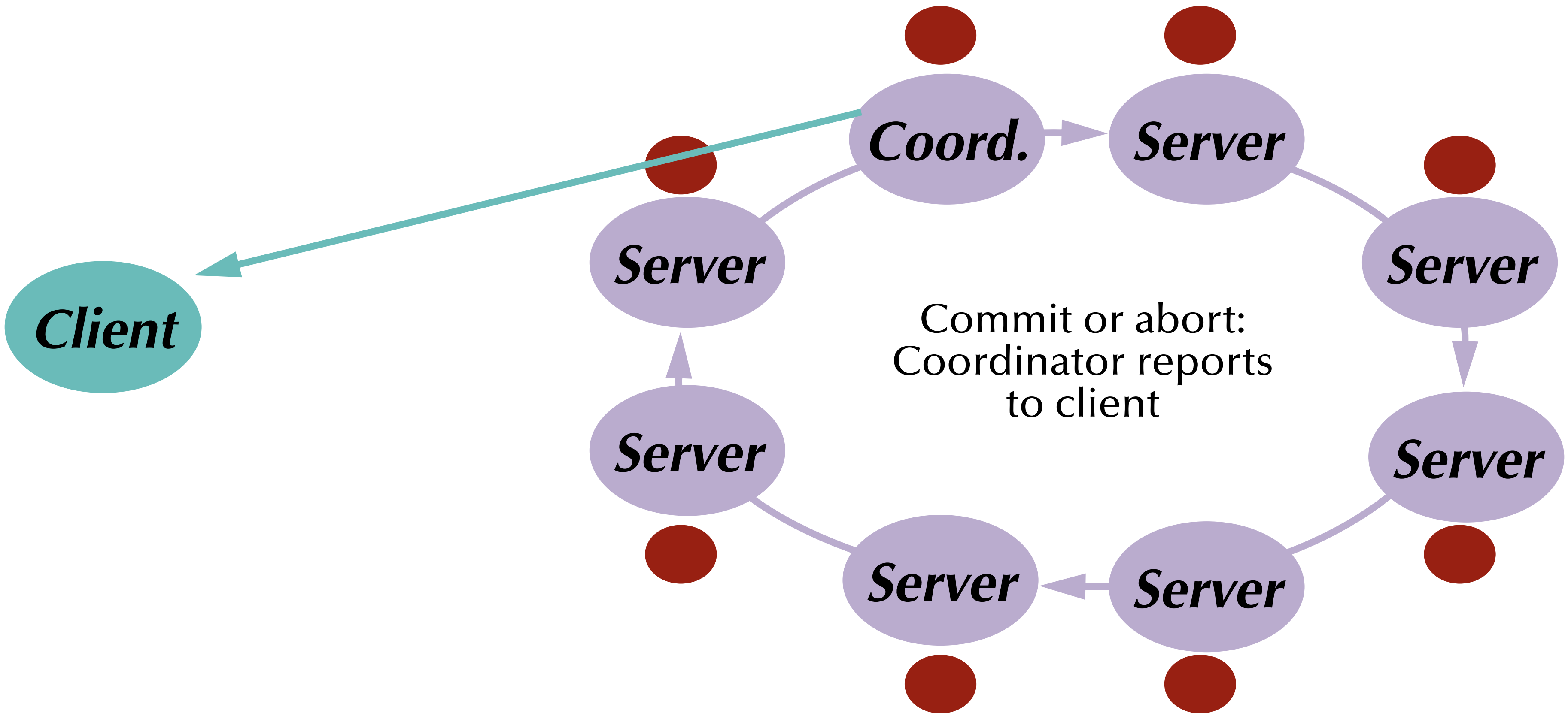
Two phase commit protocol

or phase 2: global roll back



Two phase commit protocol

Phase 2: Report result of distributed transaction



Distributed transactions

Evaluating the three major design methods in a distributed environment:

- **Locking methods**:
  Large overheads; distributed deadlock detection required.
- **Time-stamp ordering**:
  If time-stamps can be provided: Recommends itself for distributed applications, since decisions are taken locally and communication overhead is relatively small.
- **"Optimistic" methods**:
  Maximises concurrency, but also data replication; chances of aborts and roll-backs are higher.

☞ side-aspect *data replication*: large body of literature on this topic (see: distributed data-bases / operating systems / shared memory, cache management, …)

Redundancy (replicated servers)

Premise:

A crashing server computer should not compromise the functionality of the system (full fault tolerance)

- *k* computers inside the server cluster might crash without losing functionality.

☞ Replication: at least *k*+1 servers.

- the server cluster can reorganize any time (and specifically after the loss of a computer).

☞ Hot stand-by components, dynamical server group management.

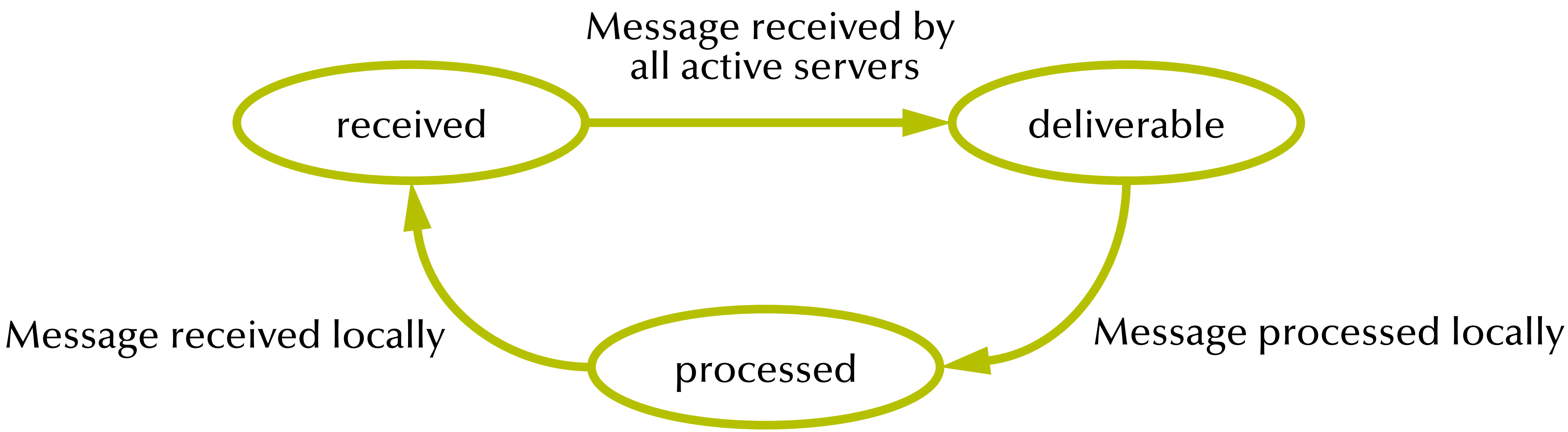
- the server is described fully by the current state and the sequence of messages received.

☞ State machines: we have to implement consistent state adjustments (re-organization) and consistent message passing (order needs to be preserved).

[Schneider90]

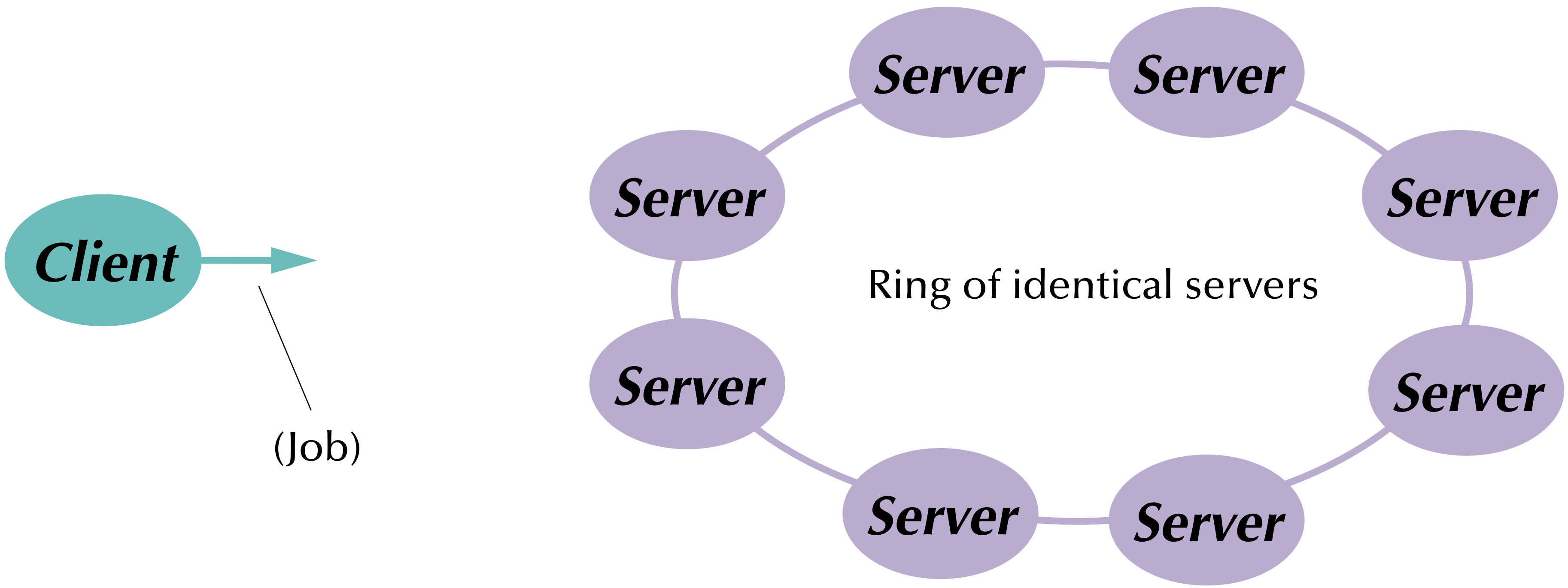
Redundancy (replicated servers)

Message processing stages in each server:



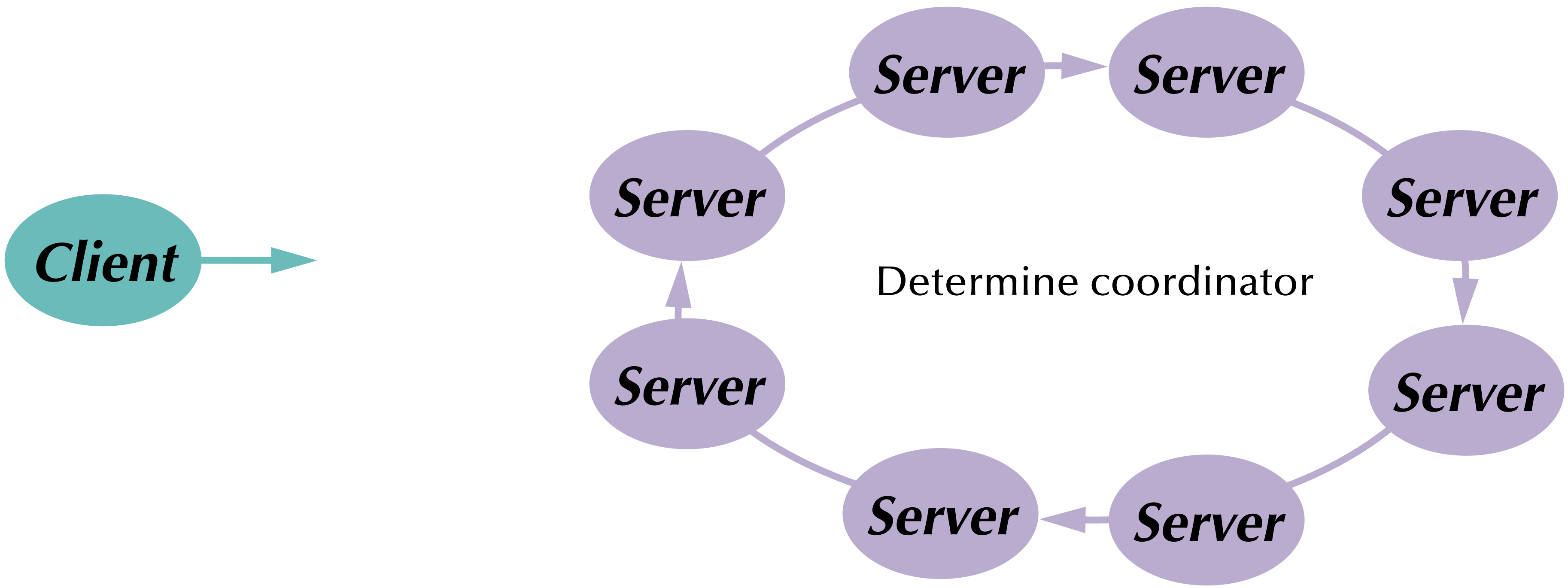
Fault tolerance (replicated servers)

Start-up (initialization) phase



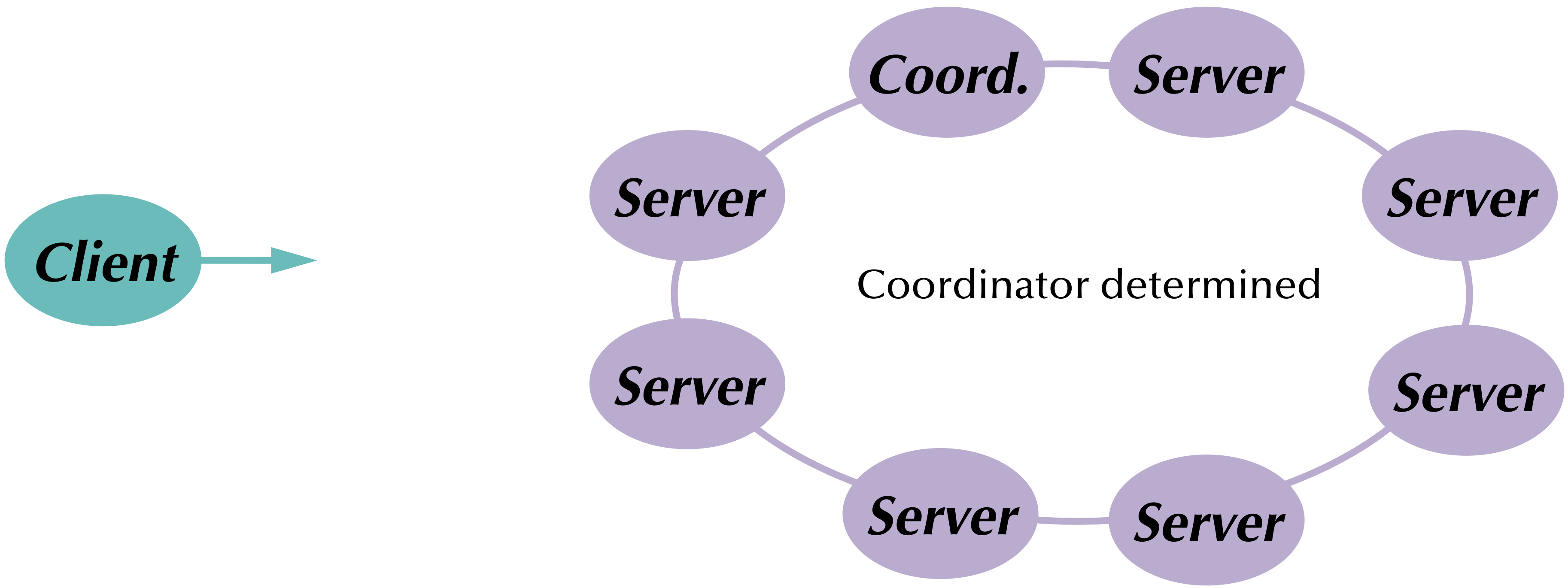
Fault tolerance (replicated servers)

Start-up (initialization) phase



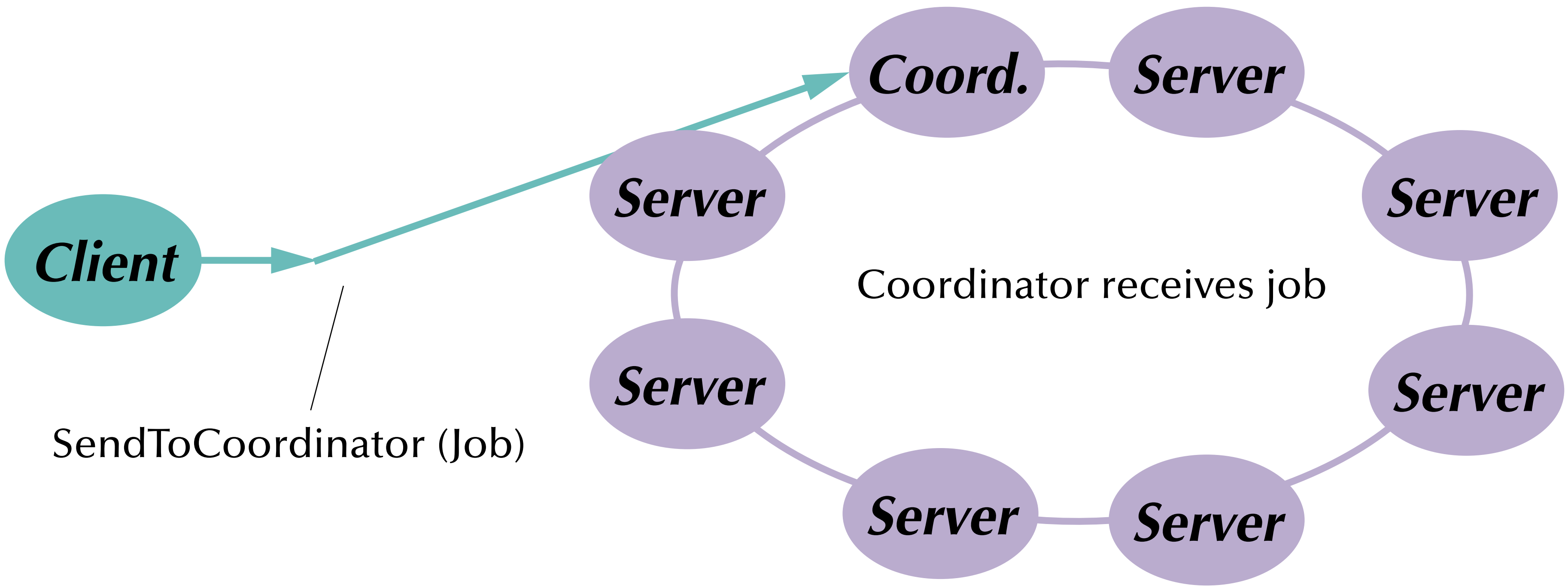
Fault tolerance (replicated servers)

Start-up (initialization) phase



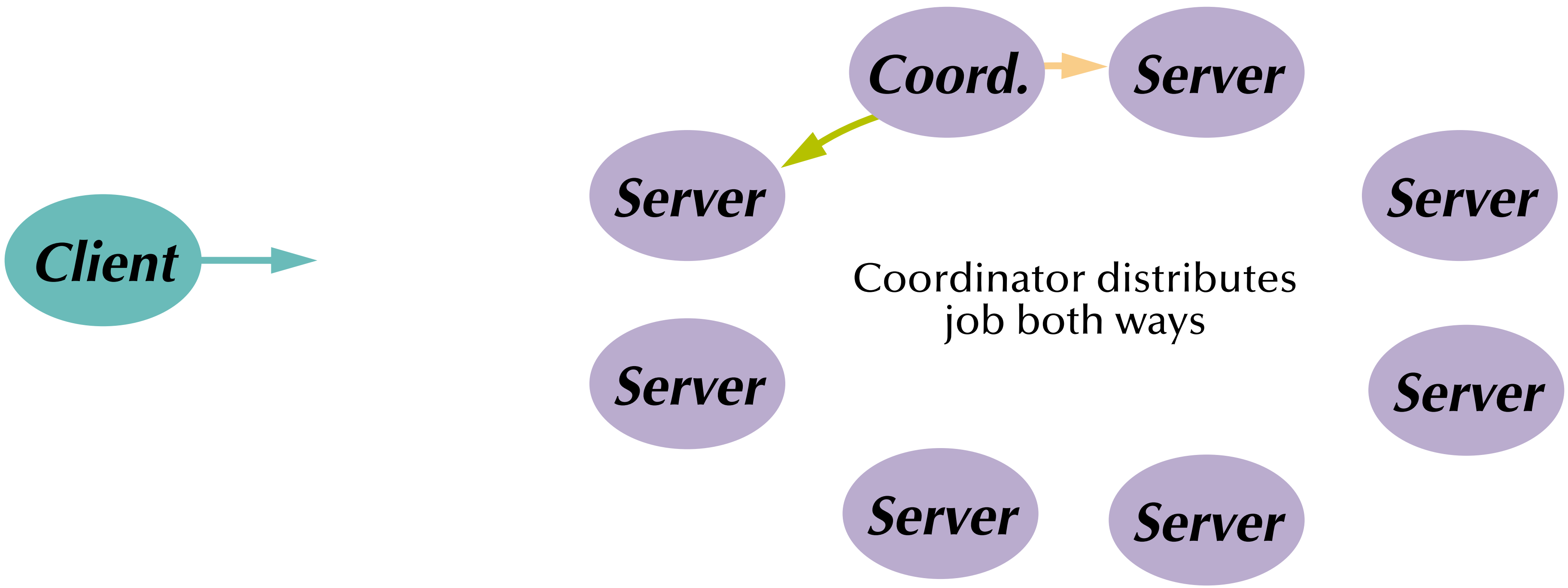
Fault tolerance (replicated servers)

Receive job-message at coordinator



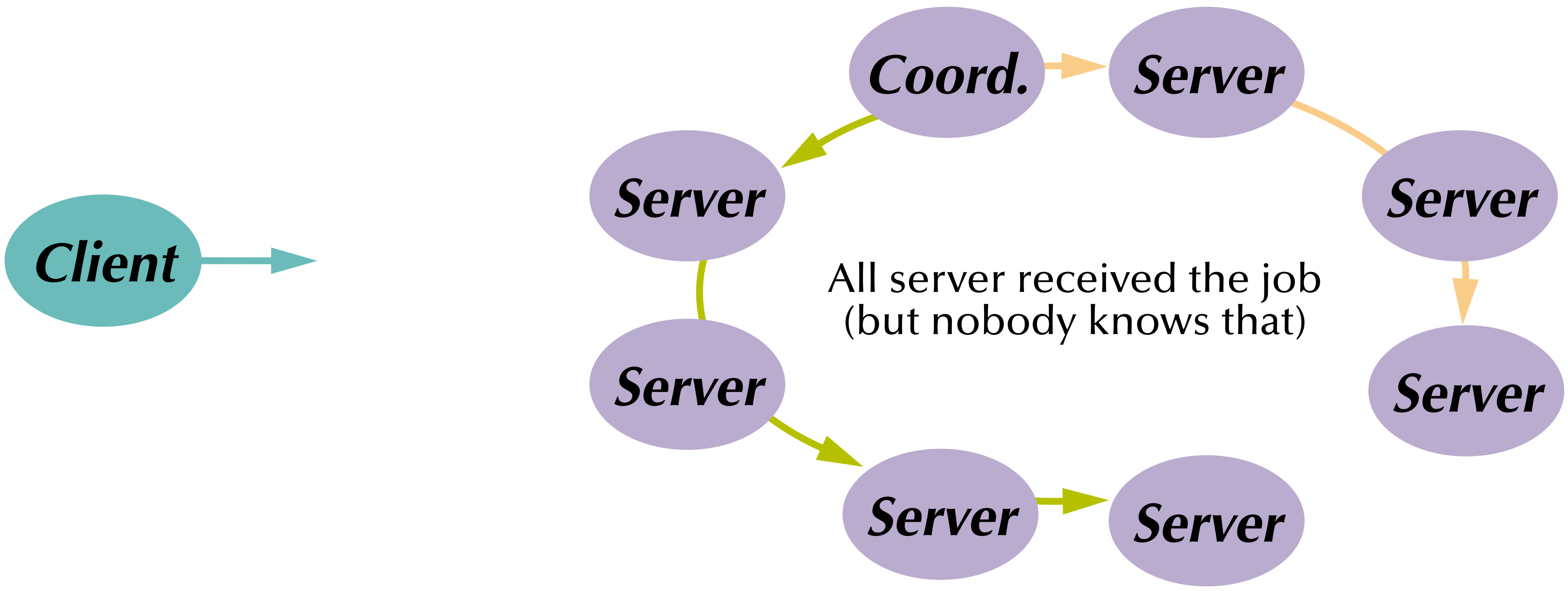
Fault tolerance (replicated servers)

Distribute job-message



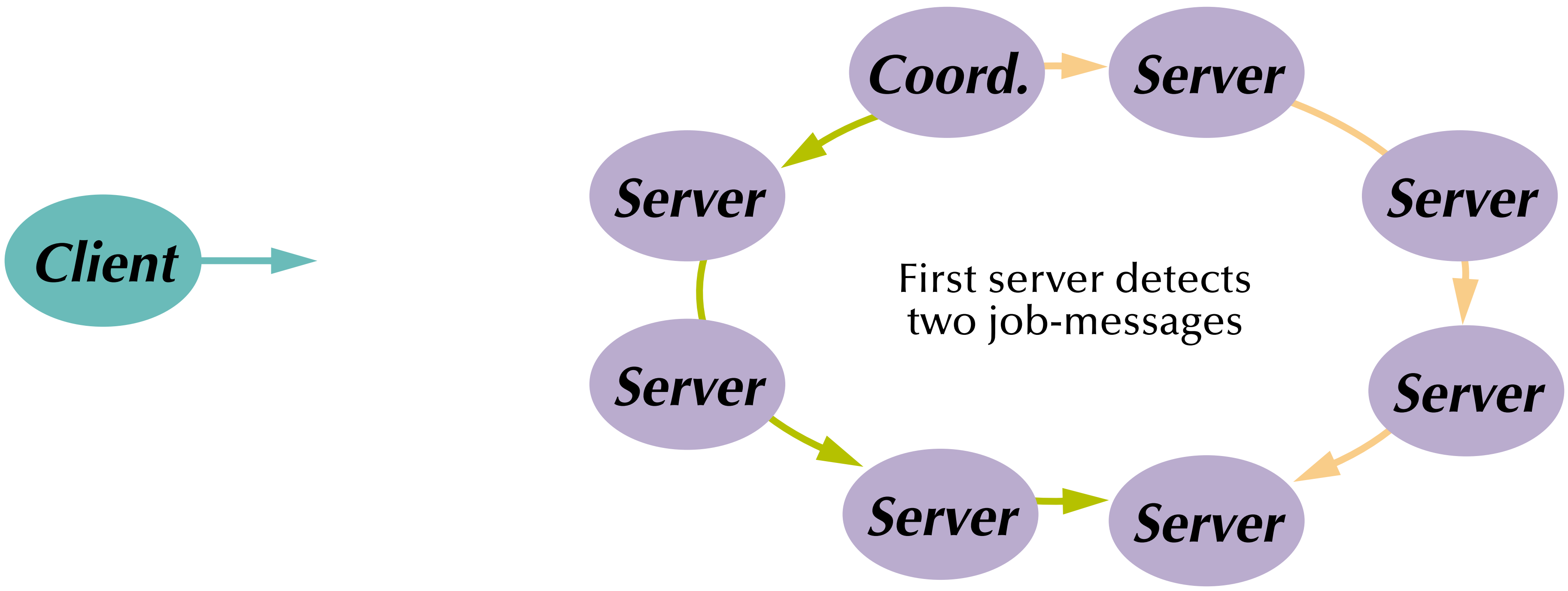
Fault tolerance (replicated servers)

Distribute job-message



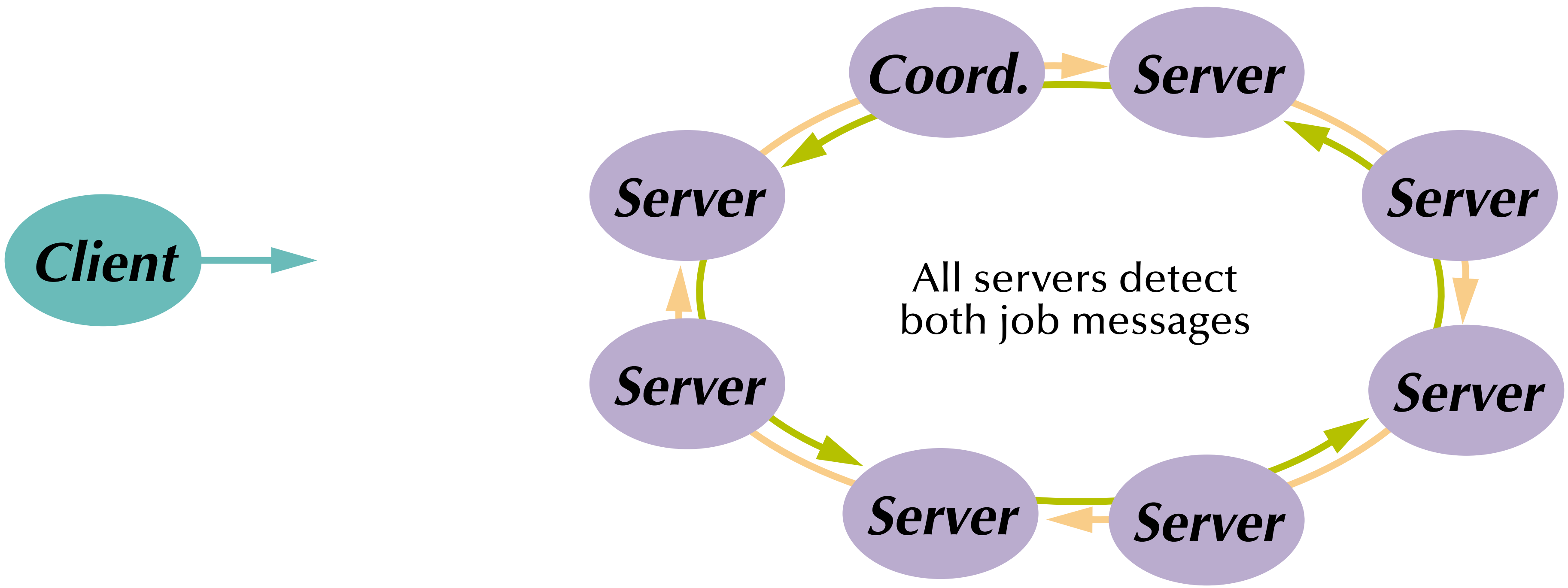
Fault tolerance (replicated servers)

Distribute job-message



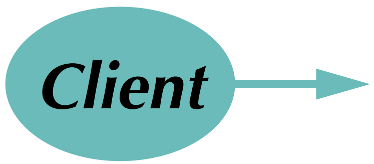
Fault tolerance (replicated servers)

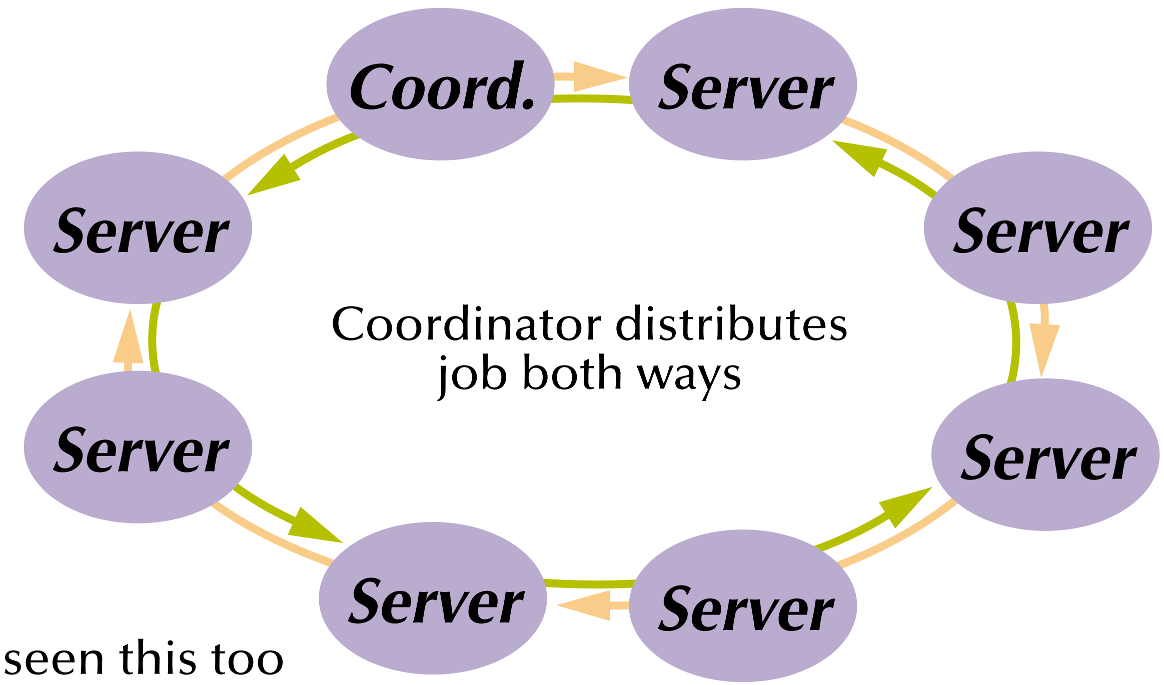
Distribute job-message



Fault tolerance (replicated servers)

servers decide whether this message is known to everybody else ☞ process job





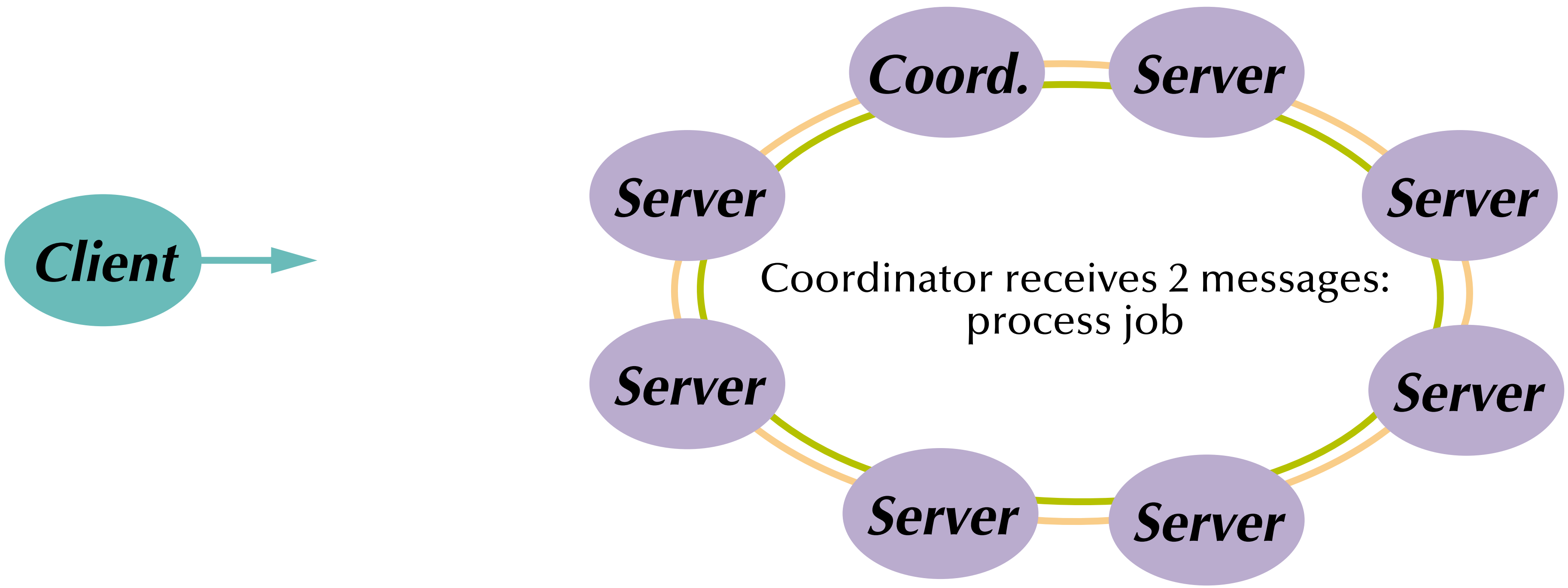
each server
received 0, 1, or 2 messages:

2 received messages means:

"everybody else must have seen this too
☞ process job"

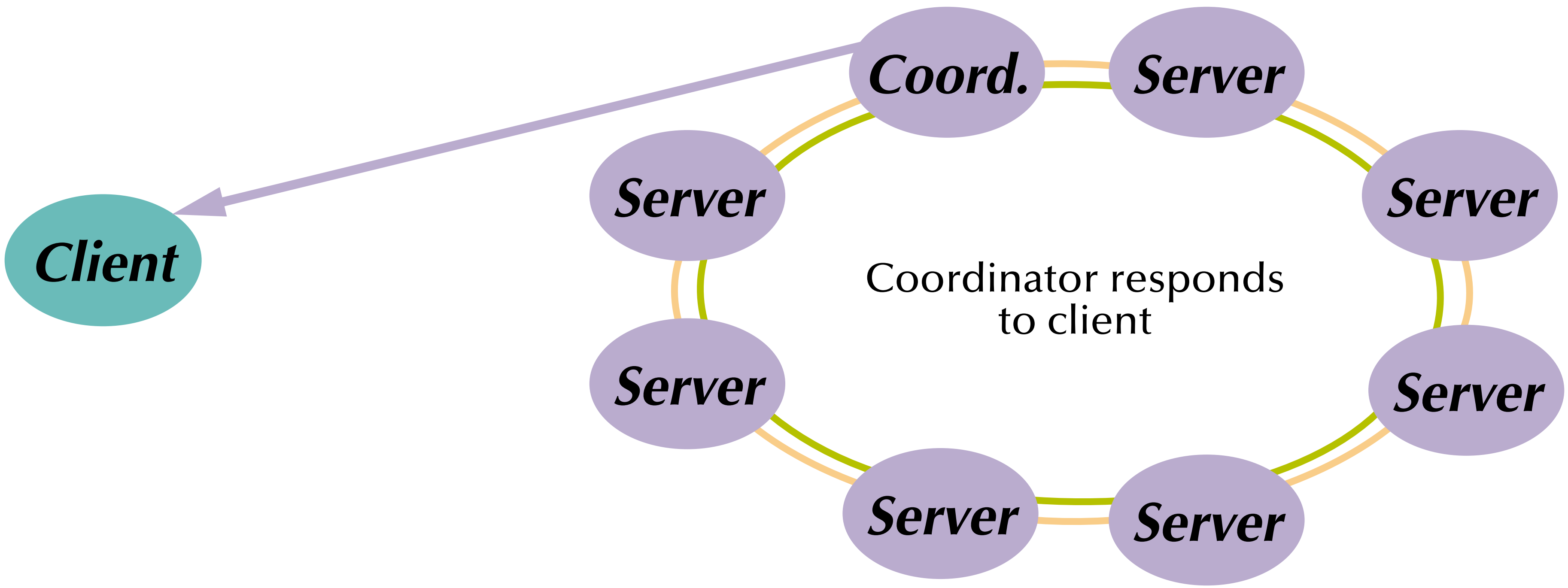
Fault tolerance (replicated servers)

Coordinator processes job-message



Fault tolerance (replicated servers)

All servers are in the same state again - Coordinator delivers response



Fault tolerance (replicated servers)

servers crash!, new servers joining, old servers leaving …

☞ somebody (either a server detecting a time-out, or an explicitly joining or leaving server) sends a '`FormNewGroup`' signal to all current servers (this message passing mechanism is assumed to be part of the distributed operating system)

1. Wait for local job processing to complete or time-out
2. Store local consistent state S_i
3. Re-organize server ring, send local state around the ring
4. If a state S_j with $j > i$ is received ☞ $S_i := S_j$
5. Elect coordinator
6. Enter 'Coordinator-' or 'Replicate-mode'

Summary

Distributes Systems

- **Networks**
  - OSI, topologies, standards
- **Time**
  - Synchronized clocks, virtual (logical) times
  - Distributed critical regions (synchronized, logical, token ring)
- **Distributed systems**
  - Elections
  - Distributed states, consistent snapshots
  - Distributed servers (replicates, distributed processing, distributed commits)
  - Transactions (ACID properties, serializable interleavings, transaction schedulers)

Summary

Uwe R. Zimmer
The Australian National University

Topics in this course

1. Concurrency [3]
2. Mutual exclusion [3]
3. Condition synchronization [4]
4. Non-determinism in concurrent systems [2]
5. Scheduling [2]
6. Safety and liveness [3]
7. Architectures for CDS [3]
8. Distributed systems [8]

Concurrency – The Basic Concepts

- **Forms of concurrency**
- **Models and terminology**
    - Abstractions and perspectives: computer science, physics & engineering
    - Observations: non-determinism, atomicity, interaction, interleaving
    - Correctness in concurrent systems
- **Processes and threads**
    - Basic concepts and notions
    - Process states
- **First examples of concurrent programming languages:**
    - Explicit concurrency: Ada95
    - Implicit concurrency: functional programming – Lisp, Haskell, Caml, Miranda

Mutual Exclusion

- **Definition of mutual exclusion**
- **Atomic load and atomic store operations**
  - … some classical errors
  - Decker's algorithm, Peterson's algorithm
  - Bakery algorithm
- **Realistic hardware support**
  - Atomic test-and-set, Atomic exchanges, Memory cell reservations
- **Semaphores**
  - Basic semaphore definition
  - Operating systems style semaphores

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
  - Examples

Summary

Non-Determinism

- **Selective synchronization**
  - Selective accepts
  - Selective calls
  - Indeterminism in message based synchronization
- **General Non-Determinism in Concurrent Systems**

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)

Safety & Liveness

- **Liveness**
  - Fairness
- **Safety**
  - Deadlock detection
  - Deadlock avoidance
  - Deadlock prevention
- **Failure modes**
  - Definitions, fault sources and basic fault tolerance
- **Atomic & Idempotent operations**
  - Definitions & implications

Architectures

- **Academic**
  - occam 2.1, CSP, …
- **Workfloor**
  - Ada95, Java, …
- **Environments / Operating Systems**
  - Operating systems architectures
  - UNIX as a concept and basic UNIX features
  - POSIX

Distributes Systems

- **Networks**
  - OSI, topologies, standards
- **Time**
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  - Distributed critical regions (synchronized, logical, token ring)
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  - Elections
  - Distributed states, consistent snapshots
  - Distributed servers (replicates, distributed processing, distributed commits)
  - Transactions (ACID properties, serializable interleavings, transaction schedulers)