1

Systems, Networks & Concurrency 2020

Uwe R. Zimmer - The Australian National University

2

Systems, Networks & Concurrency 2020

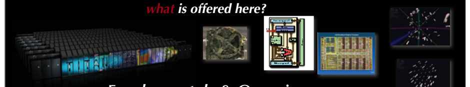
Organization & Contents

Uwe R. Zimmer - The Australian National University

3

Organization & Contents

what is offered here?



Fundamentals & Overview

as well as perspectives, paths, methods, implementations, and open questions

of/into/for/about

Concurrent & Distributed Systems

4

Organization & Contents

who could be interested in this?

anybody who …

… wants to work 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 understand why *concurrent systems* are an **essential basis** for most contemporary devices and systems

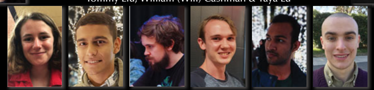
5

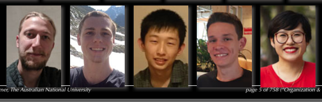
Organization & Contents

who are these people? – introductions

Uwe R. Zimmer & Charles Martin

Abigail (Abi) Thomas, Aditya Chilukuri, Brent Schuetze, Calum Snowdon, Chinmay Garg, Felix Friedlander Johannes (Johnny) Schmalz, Nicholas Philip Miehlbradt, Tommy Liu, William (Will) Cashman & Yaya Lu





6

Organization & Contents

how will this all be done?

☞ Lectures:

- 2x 1.5 hours lectures per week … all the nice stuff
  Tuesday 12:00 & Friday 11:00 (all live on-line)

☞ Laboratories:

- 3 hours per week … all the rough and action stuff
  time slots: on our web-site
  -enrolment: https://cs.anu.edu.au/streams/ (open since last Monday, more slots today)

☞ Resources:

- Introduced in the lectures and collected on the course page:
  https://cs.anu.edu.au/courses/comp2310/ … as well as schedules, slides, sources, links to forums, etc. pp. … keep an eye on this page!

☞ Assessment (for discussion):

- Exam at the end of the course (50%)
  plus one hurdle lab in week 4 (5%)
  plus two assignments (15% + 15%)
  plus one mid-semester exam (15%)

7

Organization & Contents

Text book for the course

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

☞ Many algorithms and concepts for the course are in there
– *but not all!*

☞ *References for specific aspects of the course are provided during the course and are found on our web-site.*

8

Organization & Contents

Topics

Language refresher [3]
1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Communication & Synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

9

Organization & Contents

Topics

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]**
     - Basic definitions
     - Process states
     - Implementations
2. *Mutual exclusion [2]*
3. *Communication & Synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

10

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
   - **2.1. by shared variables [1]**
     - Failure possibilities
     - Dekker's algorithm
   - **2.2. by test-and-set hardware support [0.5]**
     - Minimal hardware support
   - **2.3. by semaphores [0.5]**
     - Dijkstra definition
     - OS semaphores
3. *Communication & Synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

11

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Communication & Synchronization [4]*
   - **3.1. Shared memory synchronization [2]**
     - Semaphores
     - Cond. variables
     - Conditional critical regions
     - Monitors
     - Protected objects
   - **3.2. Message passing [2]**
     - Asynchronous / synchronous
     - Remote invocation / rendezvous
     - Message structure
     - Addressing
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

12

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
   - **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]**
     - Forms of non-deterministic message reception
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

13

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
   - **5.1. Data-Parallelism**
     - Vectorization
     - Reduction
     - General data-parallelism
   - **5.2. Examples**
     - Image processing
     - Cellular automata
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

14

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
   - **6.1. Problem definition and design space [1]**
     - Which problems are addressed / solved by scheduling?
   - **6.2. Basic scheduling methods [1]**
     - Assumptions for basic scheduling
     - Basic methods
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

15

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
   - **7.1. Safety properties**
     - Essential time-independent safety properties
   - **7.2. Livelocks, fairness**
     - Forms of livelocks
     - Classification of fairness
   - **7.3. Deadlocks**
     - Detection
     - Avoidance
     - Prevention (& recovery)
   - **7.4. Failure modes**
   - **7.5. Idempotent & atomic operations**
     - Definitions
8. *Distributed systems [4]*
9. *Architectures [1]*

16

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [3]*
8. *Distributed systems [4]*
   - **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]**
9. *Architectures [1]*

17

Organization & Contents

Topics

1. *Concurrency [3]*
2. *Mutual exclusion [2]*
3. *Condition synchronization [4]*
4. *Non-determinism [2]*
5. *Data Parallelism [1]*
6. *Scheduling [2]*
7. *Safety and liveness [2]*
8. *Distributed systems [4]*
9. *Architectures [1]*

9.1. Hardware architecture
- From switches to registers and adders
- CPU architecture
- Hardware concurrency

9.2. Language architecture
- Chapel
- Occam
- Rust
- Ada
- C++

18

Organization & Contents

24 Lectures

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]
- Basic definitions
- Process states
- Implementations

2. Mutual exclusion [2]
2.1. by shared variables [1]
- Failure possibilities
- Dekker's algorithm

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

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

3. Communication & Synchronization [4]
3.1. Shared memory synchronization [2]
- Semaphores
- Cond. variables
- Conditional critical regions
- Monitors
- Protected objects

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

4. Non-determinism [2]
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]
- Forms of non-deterministic message reception

5. Data Parallelism [1]
5.1. Data-Parallelism
- Vectorization
- Reduction
- General data-parallelism

5.2. Examples
- Image processing
- Cellular automata

6. Scheduling [2]
6.1. Problem definition and design space [1]
- Which problems are addressed / solved by scheduling?

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

7. Safety and liveness [2]
7.1. Safety properties
- Essential time-independent safety properties

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

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

7.4. Failure modes

7.5. Idempotent & atomic operations
- Definitions

8. Distributed systems [4]
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]

9. Architectures [1]
9.1. Hardware architecture
- From switches to registers and adders
- CPU architecture
- Hardware concurrency

9.2. Language architecture
- Chapel
- Occam
- Rust
- Ada
- C++

19

Organization & Contents

Laboratories & Assignments

Laboratories [11]

1. Structured Programming [2]
- Program structures
- Data structures

2. Tasks [1]
- Generics
- Abstract types

3. Protection [1]
- Memory based synchronization

4. Task Lifetimes [1]
- Creation
- Termination

5. Communicating Tasks [1]
- Rendezvous

6. Distributing Server [1]
- Entry families
- Requeue facility

7. Implicit Concurrency [1]

8. Synchronized Data [1]

9. Distribution [1]
- Multi-core process creation, termination
- Multi-core process communication

10. Pipelines [1]

Assignments [2]

1. Concurrent programming [15%]

Programming task involving:
- Mutual exclusion
- Synchronization
- Message passing

2. Concurrent programming in multi-core systems [15%]

Multi-core programming task involving:
- Process communication

Examinations [3]

1. Hurdle check [5%]
- Week 4 lab exam

2. Mid-semester check [15%]
- Exam or Self-test

3. Final exam [50%]
- Examining the complete course

Marking

The final mark is based on
the assignments [30%]
plus the examinations [65%]
plus the lab mark [5%]

20

Systems, Networks & Concurrency 2020

Language refresher / introduction course

Uwe R. Zimmer - The Australian National University

21

Language refresher / introduction course

References for this chapter

[Ada 2012 Language Reference Manual]
see course pages or http://www.ada-auth.org/standards/ada12.html

[Chapel 1.13 Language Specification Version 0.981]
see course pages or
http://chapel.cray.com/docs/latest/_downloads/chapelLanguageSpec.pdf
released on 7. April 2016

22

Language refresher / introduction course

Languages explicitly supporting concurrency: e.g. Ada

Ada is an ISO standardized (ISO/IEC 8652:201x(E)) 'general purpose' language with focus on "program reliability and maintenance, programming as a human activity, and efficiency".

It provides core language primitives for:

- Strong typing, contracts, separate compilation (specification and implementation), abstract data types, generics, object-orientation.
- Concurrency, message passing, synchronization, monitors, rpcs, timeouts, scheduling, priority ceiling locks, hardware mappings, fully typed network communication.
- Strong run-time environments (incl. stand-alone execution).

... as well as standardized language-annexes for:

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

23

Language refresher / introduction course

Ada

A crash course

... refreshing for some, x'th-language introduction for others:

- **Specification** and **implementation** (body) parts, basic types
- **Exceptions**
- Information hiding in specifications ('**private**')
- **Contracts**
- **Generic** programming (polymorphism)
- **Tasking**
- Monitors and synchronisation ('**protected**', '**entries**', '**selects**', '**accepts**')
- **Abstract** types and **dispatching**

Not mentioned here: general object orientation, dynamic memory management, foreign language interfaces, marshalling, basics of imperative programming, …

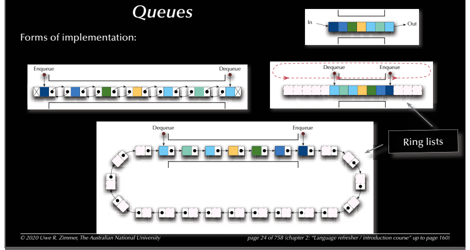
24

Language refresher / introduction course

Data structure example

Queues

Forms of implementation:



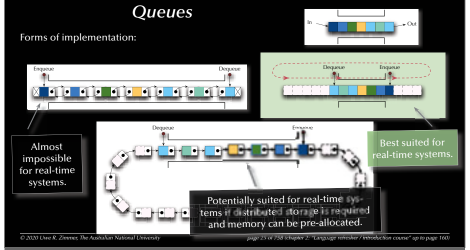
25

Language refresher / introduction course

Data structure example

Queues

Forms of implementation:



26

Language refresher / introduction course

Ada

Basics

... introducing:

- **Specification** and **implementation** (body) parts
- **Constants**
- Some **basic types** (integer specifics)
- Some **type attributes**
- **Parameter** specification

27

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


28

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


Specifications define an interface to provided types and operations.
Syntactically enclosed in a package block.

29

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


Variables should be initialized.
Constants must be initialized.

Assignments are denoted by the ":=" symbol.
... leaving the "=" symbol for comparisons.

30

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


Default initializations can be selected to be:
as is (random memory content),
initialized to **invalids**, e.g. 999
or **valid**, **predicable values**, e.g. 1_000

31

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


Numerical types can be specified by:
range, **modulo**,
number of **digits** (☞ floating point)
or **delta** increment (☞ fixed point).

Always be **as specific as the language allows**.
... and don't repeat yourself!

32

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


All types come with a long list of built-in **attributes**.
Let the compiler fill in what you already (implicitly) specified!

33

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


Parameters can be passed as 'in' (default), 'out' or 'in out'.

34

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


All specifications are used in
Code optimizations (optional),
Compile time checks (mandatory)
Run-time checks (suppressible).

35

Language refresher / introduction course

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) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
end Queue_Pack_Simple;
```


... anything on this slide still not perfectly clear?

36

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```


37

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```

Implementations are defined in a **separate** file. Syntactically enclosed in a package body block.

38

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```

Modulo type, hence no index checks required.

39

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```

Boolean expressions

40

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```

Side-effect free, **single expression functions** can be expressed without begin-end blocks.

41

Language refresher / introduction course

A simple queue implementation

```
package body Queue_Pack_Simple is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Queue.Free + 1;
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Queue.Top + 1;
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is
     (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Simple;
```

... anything on this slide still not perfectly clear?

42

Language refresher / introduction course

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);
end Queue_Test_Simple;
```


43

Language refresher / introduction course

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);
end Queue_Test_Simple;
```

Importing items from other packages is done with `with`-clauses.

use-clauses allow to use names with qualifying them with the package name.

44

Language refresher / introduction course

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);
end Queue_Test_Simple;
```

A top level procedure is read as the code which needs to be executed.

45

Language refresher / introduction course

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);
end Queue_Test_Simple;
```

Variables are declared Algol style: “`Item` is of type `Element`”.

46

Language refresher / introduction course

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);
end Queue_Test_Simple;
```

Will produce a result according to the chosen initialization:

Raises an “`invalid data`” exception if initialized to invalids.

... hmm, ok ... so this was rubbish ...

47

Language refresher / introduction course

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);
end Queue_Test_Simple;
```

... anything on this slide still not perfectly clear?

48

Language refresher / introduction course

Ada

Exceptions

... introducing:

- **Exception** handling
- **Enumeration** types
- **Type attributed** operators

49

A queue specification with proper exceptions

```
package Queue_Pack_Exceptions is
   QueueSize : constant Positive := 10;
   type Element    is (Up, Down, Spin, Turn);
   type Marker     is mod QueueSize;
   type List       is array (Marker) of Element;
   type Queue_Type  is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   Queue_overflow, Queue_underflow : exception;
end Queue_Pack_Exceptions;
```

50

A queue specification with proper exceptions

```
package Queue_Pack_Exceptions is
   QueueSize : constant Positive := 10;
   type Element    is (Up, Down, Spin, Turn);
   type Marker     is mod QueueSize;
   type List       is array (Marker) of Element;
   type Queue_Type  is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   Queue_overflow, Queue_underflow : exception;
end Queue_Pack_Exceptions;
```

Enumeration types are first-class types and can be used e.g. as array indices.

The representation values can be controlled and do not need to be continuous (e.g. for purposes like interfacing with hardware).

51

A queue specification with proper exceptions

```
package Queue_Pack_Exceptions is
   QueueSize : constant Positive := 10;
   type Element    is (Up, Down, Spin, Turn);
   type Marker     is mod QueueSize;
   type List       is array (Marker) of Element;
   type Queue_Type  is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   Queue_overflow, Queue_underflow : exception;
end Queue_Pack_Exceptions;
```

Nothing else changes in the specification.

Exceptions need to be declared.

52

A queue *specification* with proper exceptions

```
package Queue_Pack_Exceptions is
   QueueSize : constant Positive := 10;
   type Element     is (Up, Down, Spin, Turn);
   type Marker      is mod QueueSize;
   type List        is array (Marker) of Element;
   type Queue_Type  is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   Queue_overflow, Queue_underflow : exception;
end Queue_Pack_Exceptions;
```

... anything on this slide still not perfectly clear?

53

A queue *implementation* with proper exceptions

```
package body Queue_Pack_Exceptions is
   procedure Enqueue (Item : Element; Queue : in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queue_overflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free        := Marker'Succ (Queue.Free);
      Queue.Is_Empty    := False;
   end Enqueue;
   procedure Dequeue (Item : out Element; Queue : in out Queue_Type) is
   begin
      if Is_Empty (Queue) then
         raise Queue_underflow;
      end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Marker'Succ (Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
end Queue_Pack_Exceptions;
```


54

A queue *implementation* with proper exceptions

```
package body Queue_Pack_Exceptions is
   procedure Enqueue (Item : Element; Queue : in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queue_overflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free        := Marker'Succ (Queue.Free);
      Queue.Is_Empty    := False;
   end Enqueue;
   procedure Dequeue (Item : out Element; Queue : in out Queue_Type) is
   begin
      if Is_Empty (Queue) then
         raise Queue_underflow;
      end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Marker'Succ (Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
end Queue_Pack_Exceptions;
```

Raised **exceptions** break the control flow and "propagate" to the closest "exception handler" in the call-chain.

55

A queue *implementation* with proper exceptions

```
package body Queue_Pack_Exceptions is
   procedure Enqueue (Item : Element; Queue : in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queue_overflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free        := Marker'Succ (Queue.Free);
      Queue.Is_Empty    := False;
   end Enqueue;
   procedure Dequeue (Item : out Element; Queue : in out Queue_Type) is
   begin
      if Is_Empty (Queue) then
         raise Queue_underflow;
      end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Marker'Succ (Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
end Queue_Pack_Exceptions;
```

All Types come with a long list of built-in operators. Syntactically expressed as **attributes**.

Type attributes often make code more *generic*: 'Succ works for instance on enumeration types as well ... "+ 1" does not.

56

A queue *implementation* with proper exceptions

```
package body Queue_Pack_Exceptions is
   procedure Enqueue (Item : Element; Queue : in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queue_overflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free        := Marker'Succ (Queue.Free);
      Queue.Is_Empty    := False;
   end Enqueue;
   procedure Dequeue (Item : out Element; Queue : in out Queue_Type) is
   begin
      if Is_Empty (Queue) then
         raise Queue_underflow;
      end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Marker'Succ (Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
end Queue_Pack_Exceptions;
```

... anything on this slide still not perfectly clear?

57

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
exception
   when Queue_underflow => Put ("Queue underflow");
   when Queue_overflow  => Put ("Queue overflow");
end Queue_Test_Exceptions;
```


58

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
exception
   when Queue_underflow => Put ("Queue underflow");
   when Queue_overflow  => Put ("Queue overflow");
end Queue_Test_Exceptions;
```

An **exception handler** has a choice to **handle**, **pass**, or **re-raise** the same or a different exception.

Raised **exceptions** break the control flow and "propagate" to the closest "exception handler" in the call-chain.

Control flow is continued after the **exception handler** in case of a handled exception.

59

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
exception
   when Queue_underflow => Put ("Queue underflow");
   when Queue_overflow  => Put ("Queue overflow");
end Queue_Test_Exceptions;
```

... anything on this slide still not perfectly clear?

60

A queue *specification* with proper exceptions

```
package Queue_Pack_Exceptions is
   QueueSize : constant Positive := 10;
   type Element     is (Up, Down, Spin, Turn);
   type Marker      is mod QueueSize;
   type List        is array (Marker) of Element;
   type Queue_Type  is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
   procedure Enqueue (Item:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   Queue_overflow, Queue_underflow : exception;
end Queue_Pack_Exceptions;
```

This package provides access to 'internal' structures which can lead to inconsistent access.

61

Language refresher / introduction course

Ada

Information hiding

... introducing:

- **Private** declarations
  ☞ needed to compile specifications,
  yet not accessible for a user of the package.
- **Private** types ☞ assignments and comparisons are allowed
- **Limited private** types ☞ entity cannot be assigned or compared

62

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

63

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

private splits the specification into a **public** and a **private** section.

The private section is only here so that the specifications can be separately compiled.

64

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

Queue_Type can now be used outside this package **without any way to access its internal structure.**

limited **disables assignments and comparisons** for this type.

A user of this package would now e.g. not be able to make a copy of a Queue_Type value.

65

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

Queue_Type can now be used outside this package **without any way to access its internal structure.**

Alternatively '=' and ':=' operations can be replaced with type-specific versions (overloaded) or default operations can be allowed.

66

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Private;
```

... anything on this slide still not perfectly clear?

67

A queue *implementation* with proper information hiding

```
package body Queue_Pack_Private is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Marker'Pred (Queue.Free);
      Queue.Is_Empty              := False;
   end Enqueue;
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Is_Empty (Queue) then raise Queueunderflow; end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := Marker'Pred (Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;
   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Private;
```

Identical

68

A queue *implementation* with proper information hiding

```
package body Queue_Pack_Private is

   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Marker'Pred (Queue.Free);
      Queue.Is_Empty              := False;
   end Enqueue;

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

   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);

end Queue_Pack_Private;
```

Identical

... besides the implementation of the two functions which has been moved to the implementation section.

69

A queue *implementation* with proper information hiding

```
package body Queue_Pack_Private is

   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := Marker'Pred (Queue.Free);
      Queue.Is_Empty              := False;
   end Enqueue;

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

   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
     (not Queue.Is_Empty and then Queue.Top = Queue.Free);

end Queue_Pack_Private;
```

Identical

... anything on this slide still not perfectly clear?

70

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

71

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

Illegal operation on a limited type.

72

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

Parameters can be named or passed by order of definition.
(Named parameters do not need to follow the definition order.)

73

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

... anything on this slide still not perfectly clear?

74

Language refresher / introduction course

Ada

Contracts

... introducing:

- **Pre- and Post-Conditions** on methods
- **Invariants** on types
- **For all, For any** predicates

75

A contracting queue *specification*

```
package Queue_Pack_Contract is
   Queue_Size : constant Positive := 10;
   type Element is new Positive range 1 .. 1000;
   type Queue_Type is private;
   procedure Enqueue (Item :     Element; Q : in out Queue_Type) with
      Pre  => not Is_Full (Q),
      Post => not Is_Empty (Q) and then Length (Q) = Length (Q'Old) + 1
              and then Lookahead (Q, Length (Q)) = Item
              and then (for all ix in 1 .. Length (Q'Old)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix));
   procedure Dequeue (Item : out Element; Q : in out Queue_Type) with
      Pre  => not Is_Empty (Q),
      Post => not Is_Full (Q) and then Length (Q) = Length (Q'Old) - 1
              and then (for all ix in 1 .. Length (Q)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix + 1));
   function Is_Empty  (Q : Queue_Type) return Boolean;
   function Is_Full   (Q : Queue_Type) return Boolean;
   function Length    (Q : Queue_Type) return Natural;
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element;
```

76

A contracting queue *specification*

```
package Queue_Pack_Contract is
   Queue_Size : constant Positive := 10;
   type Element is new Positive range 1 .. 1000;
   type Queue_Type is private;
   procedure Enqueue (Item :     Element; Q : in out Queue_Type) with
      Pre  => not Is_Full (Q),
      Post => not Is_Empty (Q) and then Length (Q) = Length (Q'Old) + 1
              and then Lookahead (Q, Length (Q)) = Item
              and then (for all ix in 1 .. Length (Q'Old)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix));
   procedure Dequeue (Item : out Element; Q : in out Queue_Type) with
      Pre  => not Is_Empty (Q),
      Post => not Is_Full (Q) and then Length (Q) = Length (Q'Old) - 1
              and then (for all ix in 1 .. Length (Q)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix + 1));
   function Is_Empty  (Q : Queue_Type) return Boolean;
   function Is_Full   (Q : Queue_Type) return Boolean;
   function Length    (Q : Queue_Type) return Natural;
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element;
```

Pre- and **Post-predicates** are checked before and after each execution resp.

Original (Pre) values can still be referred to.

∀ and ∃ quantifiers are expressed as "for all" and "for some" expressions resp.

77

A contracting queue *specification*

```
package Queue_Pack_Contract is
   Queue_Size : constant Positive := 10;
   type Element is new Positive range 1 .. 1000;
   type Queue_Type is private;
   procedure Enqueue (Item :     Element; Q : in out Queue_Type) with
      Pre  => not Is_Full (Q),
      Post => not Is_Empty (Q) and then Length (Q) = Length (Q'Old) + 1
              and then Lookahead (Q, Length (Q)) = Item
              and then (for all ix in 1 .. Length (Q'Old)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix));
   procedure Dequeue (Item : out Element; Q : in out Queue_Type) with
      Pre  => not Is_Empty (Q),
      Post => not Is_Full (Q) and then Length (Q) = Length (Q'Old) - 1
              and then (for all ix in 1 .. Length (Q)
                          => Lookahead (Q, ix) = Lookahead (Q'Old, ix + 1));
   function Is_Empty  (Q : Queue_Type) return Boolean;
   function Is_Full   (Q : Queue_Type) return Boolean;
   function Length    (Q : Queue_Type) return Natural;
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element;
```

... anything on this slide still not perfectly clear?

78

A contracting queue *specification* (cont.)

```
private
   type Marker is mod Queue_Size;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List; -- will be initialized to invalids
   end record with Type_Invariant
      => (not Queue_Type.Is_Empty or else Queue_Type.Top = Queue_Type.Free)
        and then (for all ix in 1 .. Length (Queue_Type)
                           => Lookahead (Queue_Type, ix)'Valid);
   function Is_Empty (Q : Queue_Type) return Boolean is (Q.Is_Empty);
   function Is_Full (Q : Queue_Type)  return Boolean is
     (not Q.Is_Empty and then Q.Top = Q.Free);
   function Length (Q : Queue_Type) return Natural is
     (if Is_Full (Q) then Queue_Size else Natural (Q.Free - Q.Top));
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element is
     (Q.Elements (Q.Top + Marker (Depth - 1)));
end Queue_Pack_Contract;
```

79

A contracting queue *specification* (cont.)

```
private
   type Marker is mod Queue_Size;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List; -- will be initialized to invalids
   end record with Type_Invariant
      => (not Queue_Type.Is_Empty or else Queue_Type.Top = Queue_Type.Free)
        and then (for all ix in 1 .. Length (Queue_Type)
                           => Lookahead (Queue_Type, ix)'Valid);
   function Is_Empty (Q : Queue_Type) return Boolean is (Q.Is_Empty);
   function Is_Full (Q : Queue_Type)  return Boolean is
     (not Q.Is_Empty and then Q.Top = Q.Free);
   function Length (Q : Queue_Type) return Natural is
     (if Is_Full (Q) then Queue_Size else Natural (Q.Free - Q.Top));
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element is
     (Q.Elements (Q.Top + Marker (Depth - 1)));
end Queue_Pack_Contract;
```

Type-Invariants are checked on return from any operation defined in the public part.

80

A contracting queue *specification* (cont.)

```
private
   type Marker is mod Queue_Size;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker  := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List; -- will be initialized to invalids
   end record with Type_Invariant
      => (not Queue_Type.Is_Empty or else Queue_Type.Top = Queue_Type.Free)
        and then (for all ix in 1 .. Length (Queue_Type)
                           => Lookahead (Queue_Type, ix)'Valid);
   function Is_Empty (Q : Queue_Type) return Boolean is (Q.Is_Empty);
   function Is_Full (Q : Queue_Type)  return Boolean is
     (not Q.Is_Empty and then Q.Top = Q.Free);
   function Length (Q : Queue_Type) return Natural is
     (if Is_Full (Q) then Queue_Size else Natural (Q.Free - Q.Top));
   function Lookahead (Q : Queue_Type; Depth : Positive) return Element is
     (Q.Elements (Q.Top + Marker (Depth - 1)));
end Queue_Pack_Contract;
```

... anything on this slide still not perfectly clear?

81

A contracting queue *implementation*

```
package body Queue_Pack_Contract is

   procedure Enqueue (Item : Element; Q : in out Queue_Type) is
   begin
      Q.Elements (Q.Free) := Item;
      Q.Free              := Q.Free + 1;
      Q.Is_Empty          := False;
   end Enqueue;

   procedure Dequeue (Item : out Element; Q : in out Queue_Type) is
   begin
      Item       := Q.Elements (Q.Top);
      Q.Top      := Q.Top + 1;
      Q.Is_Empty := Q.Top = Q.Free;
   end Dequeue;

end Queue_Pack_Contract;
```

Identical

No checks in the implementation part, as all required conditions have been guaranteed via the specifications.

82

A contracting queue test *program*

```
with Ada.Text_IO;         use Ada.Text_IO;
with Exceptions;          use Exceptions;
with Queue_Pack_Contract; use Queue_Pack_Contract;
with System.Assertions;   use System.Assertions;
procedure Queue_Test_Contract is
   Queue : Queue_Type;
   Item  : Element;
begin
   Enqueue (Item => 1, Q => Queue);
   Enqueue (Item => 2, Q => Queue);
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); -- will produce an Assert_Failure
   Put (Element'Image (Item));
   Put ("Queue is empty on exit: "); Put (Boolean'Image (Is_Empty (Queue)));
exception
   when Exception_Id : Assert_Failure => Show_Exception (Exception_Id);
end Queue_Test_Contract;
```

83

A contracting queue test *program*

```
with Ada.Text_IO;         use Ada.Text_IO;
with Exceptions;          use Exceptions;
with Queue_Pack_Contract; use Queue_Pack_Contract;
with System.Assertions;   use System.Assertions;
procedure Queue_Test_Contract is
   Queue : Queue_Type;
   Item  : Element;
begin
   Enqueue (Item => 1, Q => Queue);
   Enqueue (Item => 2, Q => Queue);
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); -- will produce an Assert_Failure
   Put (Element'Image (Item));
   Put ("Queue is empty on exit: "); Put (Boolean'Image (Is_Empty (Queue)));
exception
   when Exception_Id : Assert_Failure => Show_Exception (Exception_Id);
end Queue_Test_Contract;
```

Violated Pre-condition will raise an assert failure exception.

84

A contracting queue test program

```
with Ada.Text_IO;            use Ada.Text_IO;
with Exceptions;             use Exceptions;
with Queue_Pack_Contract;    use Queue_Pack_Contract;
with System.Assertions;      use System.Assertions;

procedure Queue_Test_Contract is
   Queue : Queue_Type;
   Item  : Element;
begin
   Enqueue (Item => 1, Q => Queue);
   Enqueue (Item => 2, Q => Queue);
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); Put (Element'Image (Item));
   Dequeue (Item, Queue); -- will produce an Assert_Failure

   Put (Element'Image (Item));
   Put ("Queue is empty on exit: "); Put (Boolean'Image (Is_Empty (Queue)));
exception
   when Exception_Id : Assert_Failure => Show_Exception (Exception_Id);
end Queue_Test_Contract;
```

... anything on this slide still not perfectly clear?

85

A contracted queue

```
package Queue_Pack_Contract is
  (...)
  procedure Enqueue (Item : Element; Q : in out Queue_Type) with
    Pre  => not Is_Full  (Q), -- could also be "=> True" according to specifications
    Post => not Is_Empty (Q) and then Length (Q) = Length (Q'Old) + 1
                and then Lookahead (Q, Length (Q)) = Item
                and then (for all ix in 1 .. Length (Q'Old)
                             => Lookahead (Q, ix) = Lookahead (Q'Old, ix));

   procedure Dequeue (Item : out Element; Q : in out Queue_Type) with
    Pre  => not Is_Empty (Q), -- could also be "=> True" according to specifications
    Post => not Is_Full  (Q) and then Length (Q) = Length (Q'Old) - 1
                and then (for all ix in 1 .. Length (Q)
                             => Lookahead (Q, ix) = Lookahead (Q'Old, ix + 1));
  (...)
   type Queue_Type is record
      Top, Free : Marker    := Marker'First;

   end record with Type_Invariant =>
      (not Queue_Type.Is_Empty or else Queue_Type.Top = Queue_Type.Free)
      and then (for all ix in 1 .. Length (Queue_Type)
                                      => Lookahead (Queue_Type, ix)'Valid);
  (...)
```

Exceptions are commonly preferred to handle rare, yet valid situations.

Contracts are commonly used to test program correctness with respect to its specifications.

Those contracts can be used to fully specify operations and types. Specifications should be complete, consistent and canonical, while using as little implementation details as possible.

86

Language refresher / introduction course

Ada

Generic (polymorphic) packages

... introducing:

- Specification of **generic** packages
- Instantiation of **generic** packages

87

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker   := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

88

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker   := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

The type of Element now becomes a parameter of a generic package.

No restrictions (private) have been set for the type of Element.

Haskell syntax: enqueue :: a -> Queue a -> Queue a

89

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker   := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

Generic aspects can include:

- Type categories
- Incomplete types
- Constants
- Procedures and functions
- Other packages
- Objects (interfaces)

Default values can be provided (making those parameters optional)

90

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker   := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

... anything on this slide still not perfectly clear?

91

A generic queue implementation

```
package body Queue_Pack_Generic is
   procedure Enqueue (Item: Element; Queue: in out Queue_Type) is
   begin
      if Is_Full (Queue) then
         raise Queueoverflow;
      end if;
      Queue.Elements (Queue.Free) := Item;
      Queue.Free                  := [illegible]Queue.Free);
      Queue.Is_Empty              := False;
   end Enqueue;

   procedure Dequeue (Item: out Element; Queue: in out Queue_Type) is
   begin
      if Is_Empty (Queue) then raise Queueunderflow; end if;
      Item           := Queue.Elements (Queue.Top);
      Queue.Top      := [illegible](Queue.Top);
      Queue.Is_Empty := Queue.Top = Queue.Free;
   end Dequeue;

   function Is_Empty (Queue : Queue_Type) return Boolean is (Queue.Is_Empty);
   function Is_Full  (Queue : Queue_Type) return Boolean is
      (not Queue.Is_Empty and then Queue.Top = Queue.Free);
end Queue_Pack_Generic;
```

Identical

92

A generic queue test program

```
with Queue_Pack_Generic; -- cannot apply 'use' clause here
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; -- 'use' clause can be applied to instantiated package
   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;
```

93

A generic queue test program

```
with Queue_Pack_Generic; -- cannot apply 'use' clause here
with Ada.Text_IO       ; use Ada.Text_IO;
procedure Queue_Test_Generic is
   package Queue_Pack_Positive is
     new Queue_Pack_Generic ([illegible]);
   use Queue_Pack_Positive; -- 'use' clause can be applied to instantiated package
   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;
```

Instantiate generic package

94

A generic queue test program

```
with Queue_Pack_Generic; -- cannot apply 'use' clause here
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; -- 'use' clause can be applied to instantiated package
   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;
```

... anything on this slide still not perfectly clear?

95

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:     Element; Queue: in out Queue_Type);
   procedure Dequeue (Item: out Element; Queue: in out Queue_Type);
   function Is_Empty (Queue : Queue_Type) return Boolean;
   function Is_Full  (Queue : Queue_Type) return Boolean;
   Queueoverflow, Queueunderflow : exception;
private
   type Marker is mod QueueSize;
   type List is array (Marker) of Element;
   type Queue_Type is record
      Top, Free : Marker   := Marker'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Generic;
```

None of the packages so far can be used in a concurrent environment.

96

Language refresher / introduction course

Ada

Access routines for concurrent systems

... introducing:

- **Protected objects**
- **Entry guards**
- **Side-effecting (mutually exclusive) entry and procedure calls**
- **Side-effect-free (concurrent) function calls**

97

A generic protected queue specification

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```


98

A generic protected queue specification

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

Generic components of the package:
Element can be anything while the Index need to be a modulo type.

99

A generic protected queue specification

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

Queue is protected for safe concurrent access.

Three categories of a access routines are distinguished by the keywords: entry, procedure, function

100

A generic protected queue *specification*

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

Procedures are **mutually exclusive** to all other access routines.

Rationale:
Procedures can modify the protected data.
Hence they need a guarantee for exclusive access.

101

A generic protected queue *specification*

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

Functions are **mutually exclusive** to procedures and entries, yet **concurrent** to other functions.

Rationale:
The compiler enforces those functions to be side-effect-free with respect to the protected data.
Hence concurrent access can be granted among functions without risk.

102

A generic protected queue *specification*

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

Entries are **mutually exclusive** to all other access routines and also provide one **guard** per entry which need to evaluate to True before entry is granted.
The **guard expressions** are defined in the implementation part.

Rationale:
Entries can be blocking even if the protected object itself is unlocked.
Hence a separate task waiting queue is provided per entry.

103

A generic protected queue *specification*

```
generic
   type Element is private;
   type Index   is mod <>;  -- Modulo defines size of the queue.
package Queue_Pack_Protected_Generic is
   type Queue_Type is limited private;
   protected type Protected_Queue is
      entry Enqueue (Item :     Element);
      entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   type List is array (Index) of Element;
   type Queue_Type is record
      Top, Free : Index   := Index'First;
      Is_Empty  : Boolean := True;
      Elements  : List;
   end record;
end Queue_Pack_Protected_Generic;
```

… anything on this slide still not perfectly clear?

104

A generic protected queue *implementation*

```
package body Queue_Pack_Protected_Generic is
   protected body Protected_Queue is
      entry Enqueue (Item : Element) when not Is_Full is
      begin
         Queue.Elements (Queue.Free) := Item; Queue.Free := Index'Succ (Queue.Free);
         Queue.Is_Empty := False;
      end Enqueue;
      entry Dequeue (Item : out Element) when not Is_Empty is
      begin
         Item := Queue.Elements (Queue.Top); Queue.Top := Index'Succ (Queue.Top);
         Queue.Is_Empty := Queue.Top = Queue.Free;
      end Dequeue;
      procedure Empty_Queue is
      begin
         Queue.Top := Index'First; Queue.Free := Index'First; Queue.Is_Empty := True;
      end Empty_Queue;
      function Is_Empty return Boolean is (Queue.Is_Empty);
      function Is_Full  return Boolean is
        (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   end Protected_Queue;
end Queue_Pack_Protected_Generic;
```


105

A generic protected queue *implementation*

```
package body Queue_Pack_Protected_Generic is
   protected body Protected_Queue is
      entry Enqueue (Item : Element) when not Is_Full is
      begin
         Queue.Elements (Queue.Free) := Item; Queue.Free := Index'Succ (Queue.Free);
         Queue.Is_Empty := False;
      end Enqueue;
      entry Dequeue (Item : out Element) when not Is_Empty is
      begin
         Item := Queue.Elements (Queue.Top); Queue.Top := Index'Succ (Queue.Top);
         Queue.Is_Empty := Queue.Top = Queue.Free;
      end Dequeue;
      procedure Empty_Queue is
      begin
         Queue.Top := Index'First; Queue.Free := Index'First; Queue.Is_Empty := True;
      end Empty_Queue;
      function Is_Empty return Boolean is (Queue.Is_Empty);
      function Is_Full  return Boolean is
        (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   end Protected_Queue;
end Queue_Pack_Protected_Generic;
```

Guard expressions follow after when in the implementation of entries.

Tasks are automatically blocked or released depending on the state of the guard.
Guard expressions are re-evaluated on exiting an entry or procedure
(no point to re-check them at any other time).
Exactly one waiting task on one entry is released.

106

A generic protected queue *implementation*

```
package body Queue_Pack_Protected_Generic is
   protected body Protected_Queue is
      entry Enqueue (Item : Element) when not Is_Full is
      begin
         Queue.Elements (Queue.Free) := Item; Queue.Free := Index'Succ (Queue.Free);
         Queue.Is_Empty := False;
      end Enqueue;
      entry Dequeue (Item : out Element) when not Is_Empty is
      begin
         Item := Queue.Elements (Queue.Top); Queue.Top := Index'Succ (Queue.Top);
         Queue.Is_Empty := Queue.Top = Queue.Free;
      end Dequeue;
      procedure Empty_Queue is
      begin
         Queue.Top := Index'First; Queue.Free := Index'First; Queue.Is_Empty := True;
      end Empty_Queue;
      function Is_Empty return Boolean is (Queue.Is_Empty);
      function Is_Full  return Boolean is
        (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   end Protected_Queue;
end Queue_Pack_Protected_Generic;
```

… anything on this slide still not perfectly clear?

107

A generic protected queue test *program*

```
with Ada.Task_Identification;     use Ada.Task_Identification;
with Ada.Text_IO;                 use Ada.Text_IO;
with Queue_Pack_Protected_Generic;
procedure Queue_Test_Protected_Generic is
   type Queue_Size is mod 3;
   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character, Index => Queue_Size);
   use Queue_Pack_Protected_Character;
   Queue : Protected_Queue;
   type Task_Index is range 1 .. 3;
   task type Producer;
   task type Consumer;
   Producers : array (Task_Index) of Producer;
   Consumers : array (Task_Index) of Consumer;
(…)
begin
   null;
end Queue_Test_Protected_Generic;
```


108

A generic protected queue test *program*

```
with Ada.Task_Identification;     use Ada.Task_Identification;
with Ada.Text_IO;                 use Ada.Text_IO;
with Queue_Pack_Protected_Generic;
procedure Queue_Test_Protected_Generic is
   type Queue_Size is mod 3;
   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character, Index => Queue_Size);
   use Queue_Pack_Protected_Character;
   Queue : Protected_Queue;
   type Task_Index is range 1 .. 3;
   task type Producer;
   task type Consumer;
   Producers : array (Task_Index) of Producer;
   Consumers : array (Task_Index) of Consumer;
(…)
begin
   null;
end Queue_Test_Protected_Generic;
```

If more than one instance of a specific task is to be run then a **task type** (as opposed to a concrete task) is declared.

109

A generic protected queue test *program*

```
with Ada.Task_Identification;     use Ada.Task_Identification;
with Ada.Text_IO;                 use Ada.Text_IO;
with Queue_Pack_Protected_Generic;
procedure Queue_Test_Protected_Generic is
   type Queue_Size is mod 3;
   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character, Index => Queue_Size);
   use Queue_Pack_Protected_Character;
   Queue : Protected_Queue;
   type Task_Index is range 1 .. 3;
   task type Producer;
   task type Consumer;
   Producers : array (Task_Index) of Producer;
   Consumers : array (Task_Index) of Consumer;
(…)
begin
   null;
end Queue_Test_Protected_Generic;
```

Multiple instances of a task can be instantiated e.g. by declaring an array of this task type.

Tasks are started right when such an array is created.

110

A generic protected queue test *program*

```
with Ada.Task_Identification;     use Ada.Task_Identification;
with Ada.Text_IO;                 use Ada.Text_IO;
with Queue_Pack_Protected_Generic;
procedure Queue_Test_Protected_Generic is
   type Queue_Size is mod 3;
   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character, Index => Queue_Size);
   use Queue_Pack_Protected_Character;
   Queue : Protected_Queue;
   type Task_Index is range 1 .. 3;
   task type Producer;
   task type Consumer;
   Producers : array (Task_Index) of Producer;
   Consumers : array (Task_Index) of Consumer;
(…)
begin
   null;
end Queue_Test_Protected_Generic;
```

These declarations spawned off all the production code.

Often there are no statements for the "main task" (here explicitly stated by a null statement).

This task is prevented from terminating though until all tasks inside its scope terminated.

111

A generic protected queue test *program*

```
with Ada.Task_Identification;     use Ada.Task_Identification;
with Ada.Text_IO;                 use Ada.Text_IO;
with Queue_Pack_Protected_Generic;
procedure Queue_Test_Protected_Generic is
   type Queue_Size is mod 3;
   package Queue_Pack_Protected_Character is
      new Queue_Pack_Protected_Generic (Element => Character, Index => Queue_Size);
   use Queue_Pack_Protected_Character;
   Queue : Protected_Queue;
   type Task_Index is range 1 .. 3;
   task type Producer;
   task type Consumer;
   Producers : array (Task_Index) of Producer;
   Consumers : array (Task_Index) of Consumer;
(…)
begin
   null;
end Queue_Test_Protected_Generic;
```

… anything on this slide still not perfectly clear?

112

A generic protected queue test *program*

```
subtype Some_Characters is Character range 'a' .. 'f';
task body Producer is
begin
   for Ch in Some_Characters loop
      Put_Line ("Task " & Image (Current_Task) & " finds the queue to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " and prepares to add: " & Character'Image (Ch) &
                 " to the queue.");
      Queue.Enqueue (Ch); -- task might be blocked here!
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) & " terminates.");
end Producer;
```


113

A generic protected queue test *program*

```
subtype Some_Characters is Character range 'a' .. 'f';
task body Producer is
begin
   for Ch in Some_Characters loop
      Put_Line ("Task " & Image (Current_Task) & " finds the queue to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " and prepares to add: " & Character'Image (Ch) &
                 " to the queue.");
      Queue.Enqueue (Ch); -- task might be blocked here!
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) & " terminates.");
end Producer;
```

The executable code for a task is provided in its body.

114

A generic protected queue test *program*

```
subtype Some_Characters is Character range 'a' .. 'f';
task body Producer is
begin
   for Ch in Some_Characters loop
      Put_Line ("Task " & Image (Current_Task) & " finds the queue to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " and prepares to add: " & Character'Image (Ch) &
                 " to the queue.");
      Queue.Enqueue (Ch); -- task might be blocked here!
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) & " terminates.");
end Producer;
```

There are three of those tasks and they are all 'hammering' the queue at full CPU speed.

115

A generic protected queue test *program*

```
subtype Some_Characters is Character range 'a' .. 'f';
task body Producer is
begin
   for Ch in Some_Characters loop
      Put_Line ("Task " & Image (Current_Task) & " finds the queue to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " and prepares to add: " & Character'Image (Ch) &
                 " to the queue.");
      Queue.Enqueue (Ch); -- task might be blocked here!
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) & " terminates.");
end Producer;
```

Tasks automatically terminate once they reach their end declaration (and once all inner tasks are terminated).

116

A generic protected queue test program

```
subtype Some_Characters is Character range 'a' .. 'f';

task body Producer is
begin
   for Ch in Some_Characters loop
      Put_Line ("Task " & Image (Current_Task) & " finds the queue to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " and prepares to add: " & Character'Image (Ch) &
                 " to the queue.");
      Queue.Enqueue (Ch); -- task might be blocked here!
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) & " terminates.");
end Producer;
```

... anything on this slide still not perfectly clear?

117

A generic protected queue test program

```
task body Consumer is
   Item    : Character;
   Counter : Natural := 0;
begin
   loop
      Queue.Dequeue (Item); -- task might be blocked here!
      Counter := Natural'Succ (Counter);
      Put_Line ("Task " & Image (Current_Task) &
                 " received: " & Character'Image (Item) &
                 " and the queue appears to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " afterwards.");
      exit when Item = Some_Characters'Last;
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) &
               " terminates and received" & Natural'Image (Counter) & " items.");
end Consumer;
```


118

A generic protected queue test program

```
task body Consumer is
   Item    : Character;
   Counter : Natural := 0;
begin
   loop
      Queue.Dequeue (Item); -- task might be blocked here!
      Counter := Natural'Succ (Counter);
      Put_Line ("Task " & Image (Current_Task) &
                 " received: " & Character'Image (Item) &
                 " and the queue appears to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " afterwards.");
      exit when Item = Some_Characters'Last;
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) &
               " terminates and received" & Natural'Image (Counter) & " items.");
end Consumer;
```

Another three tasks and are all 'hammering' the queue at this end and at full CPU speed.

119

A generic protected queue test program

```
task body Consumer is
   Item    : Character;
   Counter : Natural := 0;
begin
   loop
      Queue.Dequeue (Item); -- task might be blocked here!
      Counter := Natural'Succ (Counter);
      Put_Line ("Task " & Image (Current_Task) &
                 " received: " & Character'Image (Item) &
                 " and the queue appears to be " &
                (if Queue.Is_Empty then "EMPTY" else "not empty") &
                 " and " &
                (if Queue.Is_Full  then "FULL" else "not full") &
                 " afterwards.");
      exit when Item = Some_Characters'Last;
   end loop;
   Put_Line ("<---- Task " & Image (Current_Task) &
               " terminates and received" & Natural'Image (Counter) & " items.");
end Consumer;
```

... anything on this slide still not perfectly clear?

120

A generic protected queue test program

```
Task producers(1) finds the queue to be EMPTY and not full and prepares to add: 'a' to the queue.
Task producers(1) finds the queue to be not empty and not full and prepares to add: 'b' to the queue.
Task producers(1) finds the queue to be not empty and not full and prepares to add: 'c' to the queue.
Task producers(1) finds the queue to be not empty and FULL and prepares to add: 'd' to the queue.
Task producers(2) finds the queue to be not empty and FULL and prepares to add: 'a' to the queue.
Task producers(3) finds the queue to be not empty and FULL and prepares to add: 'a' to the queue.
Task consumers(1) received: 'a' and the queue appears to be not empty and FULL afterwards.
Task consumers(1) received: 'b' and the queue appears to be not empty and FULL afterwards.
Task consumers(1) received: 'c' and the queue appears to be not empty and FULL afterwards.
Task consumers(1) received: 'd' and the queue appears to be not empty and not full afterwards.
Task consumers(1) received: 'a' and the queue appears to be not empty and not full afterwards.
..
<---- Task producers(1) terminates.
..
Task consumers(3) received: 'b' and the queue appears to be EMPTY and not full afterwards.
<---- Task consumers(2) terminates and received 1 items.
..
<---- Task producers(2) terminates.
..
<---- Task producers(3) terminates.
..
<---- Task consumers(1) terminates and received 12 items.
<---- Task consumers(3) terminates and received 5 items.
```

What is going on here?

121

A generic protected queue test program

```
Task producers(1) finds the queue to be EMPTY and not full and prepares to add: 'a' to the queue.
Task producers(2) finds the queue to be EMPTY and not full and prepares to add: 'a' to the queue.
Task producers(1) finds the queue to be not empty and not full and prepares to add: 'b' to the queue.
Task consumers(1) received: 'a' and the queue appears to be EMPTY and not full afterwards.
Task producers(3) finds the queue to be EMPTY and not full and prepares to add: 'a' to the queue.
Task producers(1) finds the queue to be EMPTY and not full and prepares to add: 'c' to the queue.
Task producers(2) finds the queue to be EMPTY and not full and prepares to add: 'b' to the queue.
Task consumers(2) received: 'a' and the queue appears to be EMPTY and not full afterwards.
Task consumers(3) received: 'b' and the queue appears to be EMPTY and not full afterwards.
..
<---- Task producers(1) terminates.
Task producers(2) finds the queue to be not empty and FULL and prepares to add: 'f' to the queue.
Task consumers(2) received: 'f' and the queue appears to be not empty and not full afterwards.
Task consumers(3) received: 'e' and the queue appears to be EMPTY and not full afterwards.
Task producers(3) finds the queue to be not empty and not full and prepares to add: 'f' to the queue.
Task consumers(1) received: 'd' and the queue appears to be not empty and not full afterwards.
<---- Task producers(2) terminates.
<---- Task consumers(2) terminates and received 5 items.
Task consumers(3) received: 'e' and the queue appears to be not empty and not full afterwards.
<---- Task producers(3) terminates.
Task consumers(1) received: 'f' and the queue appears to be not empty and not full afterwards.
Task consumers(3) received: 'f' and the queue appears to be EMPTY and not full afterwards.
<---- Task consumers(1) terminates and received 6 items.
<---- Task consumers(3) terminates and received 7 items.
```

Does this make any sense?

122

Language refresher / introduction course

Ada

Abstract types & dispatching

... introducing:

- **Abstract tagged types & subroutines (Interfaces)**
- Concrete implementation of abstract types
- **Dynamic dispatching** to different packages, tasks, protected types or partitions.
- **Synchronous message passing**.

123

Language refresher / introduction course

Ada

Abstract types & dispatching

... introducing:

- **Abstract tagged types & subroutines (Interfaces)**
- Concrete implementation of abstract types
- **Dynamic dispatching** to different packages, tasks, protected types or partitions.
- **Synchronous message passing**.

– Advanced topic –

Proceed with caution!

124

An abstract queue specification

```
generic
   type Element is private;
package Queue_Pack_Abstract is
   type Queue_Interface is synchronized interface;
   procedure Enqueue (Q : in out Queue_Interface; Item :     Element) is abstract;
   procedure Dequeue (Q : in out Queue_Interface; Item : out Element) is abstract;
end Queue_Pack_Abstract;
```

125

An abstract queue specification

```
generic
   type Element is private;
package Queue_Pack_Abstract is
   type Queue_Interface is synchronized interface;
   procedure Enqueue (Q : in out Queue_Interface; Item :     Element) is abstract;
   procedure Dequeue (Q : in out Queue_Interface; Item : out Element) is abstract;
end Queue_Pack_Abstract;
```

Motivation:
Different, derived implementations (potentially on different computers) can be passed around and referred to with the same common interface as defined here.

126

An abstract queue specification

```
generic
   type Element is private;
package Queue_Pack_Abstract is
   type Queue_Interface is synchronized interface;
   procedure Enqueue (Q : in out Queue_Interface; Item :     Element) is abstract;
   procedure Dequeue (Q : in out Queue_Interface; Item : out Element) is abstract;
end Queue_Pack_Abstract;
```

synchronized means that this interface can only be implemented by **synchronized entities** like **protected objects** (as seen above) or **synchronous message passing**.

Abstract, empty type definition which serves to define interface templates.

127

An abstract queue specification

```
generic
   type Element is private;
package Queue_Pack_Abstract is
   type Queue_Interface is synchronized interface;
   procedure Enqueue (Q : in out Queue_Interface; Item :     Element) is abstract;
   procedure Dequeue (Q : in out Queue_Interface; Item : out Element) is abstract;
end Queue_Pack_Abstract;
```

Abstract methods need to be **overridden** with concrete methods when a new type is derived from it.

128

An abstract queue specification

```
generic
   type Element is private;
package Queue_Pack_Abstract is
   type Queue_Interface is synchronized interface;
   procedure Enqueue (Q : in out Queue_Interface; Item :     Element) is abstract;
   procedure Dequeue (Q : in out Queue_Interface; Item : out Element) is abstract;
end Queue_Pack_Abstract;
```

... this does not require an implementation package (as all procedures are abstract)

... anything on this slide still not perfectly clear?

129

A concrete queue specification

```
with Queue_Pack_Abstract;
generic
   with package Queue_Instance is new Queue_Pack_Abstract (<>);
   type Index is mod <>; -- Modulo defines size of the queue.
package Queue_Pack_Concrete is
   use Queue_Instance;
   type Queue_Type is limited private;
   protected type Protected_Queue is new Queue_Interface with
      overriding entry Enqueue (Item :     Element);
      overriding entry Dequeue (Item : out Element);
      not overriding procedure Empty_Queue;
      not overriding function Is_Empty return Boolean;
      not overriding function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   (...) -- as all previous private queue declarations
end Queue_Pack_Concrete;
```

130

A concrete queue specification

```
with Queue_Pack_Abstract;
generic
   with package Queue_Instance is new Queue_Pack_Abstract (<>);
   type Index is mod <>; -- Modulo defines size of the queue.
package Queue_Pack_Concrete is
   use Queue_Instance;
   type Queue_Type is limited private;
   protected type Protected_Queue is new Queue_Interface with
      overriding entry Enqueue (Item :     Element);
      overriding entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   (...) -- as all previous private queue declarations
end Queue_Pack_Concrete;
```

A generic package which takes another **generic package as a parameter**.

131

A concrete queue specification

```
with Queue_Pack_Abstract;
generic
   with package Queue_Instance is new Queue_Pack_Abstract (<>);
   type Index is mod <>; -- Modulo defines size of the queue.
package Queue_Pack_Concrete is
   use Queue_Instance;
   type Queue_Type is limited private;
   protected type Protected_Queue is new Queue_Interface with
      overriding entry Enqueue (Item :     Element);
      overriding entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   (...) -- as all previous private queue declarations
end Queue_Pack_Concrete;
```

A synchronous implementation of the abstract type Queue_Interface

All abstract methods are **overridden** with concrete implementations.

A concrete queue *specification*

```
with Queue_Pack_Abstract;
generic
   with package Queue_Instance is new Queue_Pack_Abstract (<>);
   type Index is mod <>; -- Modulo defines size of the queue.
package Queue_Pack_Concrete is
   use Queue_Instance;
   type Queue_Type is limited private;
   protected type Protected_Queue is new Queue_Interface with
      overriding entry Enqueue (Item :     Element);
      overriding entry Dequeue (Item : out Element);
      not overriding procedure Empty_Queue;
      not overriding function Is_Empty return Boolean;
      not overriding function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   (...) -- as all previous private queue declarations
end Queue_Pack_Concrete;
```

Other (not-overriding) methods can be added.

A concrete queue *specification*


```
with Queue_Pack_Abstract;
generic
   with package Queue_Instance is new Queue_Pack_Abstract (<>);
   type Index is mod <>; -- Modulo defines size of the queue.
package Queue_Pack_Concrete is
   use Queue_Instance;
   type Queue_Type is limited private;
   protected type Protected_Queue is new Queue_Interface with
      overriding entry Enqueue (Item :     Element);
      overriding entry Dequeue (Item : out Element);
      procedure Empty_Queue;
      function Is_Empty return Boolean;
      function Is_Full  return Boolean;
   private
      Queue : Queue_Type;
   end Protected_Queue;
private
   (...) -- as all previous private queue declarations
end Queue_Pack_Concrete;
```


... anything on this slide still not perfectly clear?

A concrete queue *implementation*

```
package body Queue_Pack_Concrete is
   protected body Protected_Queue is
      entry Enqueue (Item : Element) when not Is_Full is
      begin
         Queue.Elements (Queue.Free) := Item; Queue.Free := Index'Succ (Queue.Free);
         Queue.Is_Empty := False;
      end Enqueue;
      entry Dequeue (Item : out Element) when not Is_Empty is
      begin
         Item := Queue.Elements (Queue.Top); Queue.Top := Index'Succ (Queue.Top);
         Queue.Is_Empty := Queue.Top = Queue.Free;
      end Dequeue;
      procedure Empty_Queue is
      begin
         Queue.Top := Index'First; Queue.Free := Index'First; Queue.Is_Empty := True;
      end Empty_Queue;
      function Is_Empty return Boolean is (Queue.Is_Empty);
      function Is_Full  return Boolean is
        (not Queue.Is_Empty and then Queue.Top = Queue.Free);
   end Protected_Queue;
end Queue_Pack_Concrete;
```

Identical

A dispatching test *program*

```
with Ada.Text_IO;         use Ada.Text_IO;
with Queue_Pack_Abstract;
with Queue_Pack_Concrete;
procedure Queue_Test_Dispatching is
   package Queue_Pack_Abstract_Character is
      new Queue_Pack_Abstract (Character);
   use Queue_Pack_Abstract_Character;
   type Queue_Size is mod 3;
   package Queue_Pack_Character is
      new Queue_Pack_Concrete (Queue_Pack_Abstract_Character, Queue_Size);
   use Queue_Pack_Character;
   type Queue_Class is access all Queue_Interface'class;
   task Queue_Holder; -- could be on an individual partition / separate computer
   task Queue_User is -- could be on an individual partition / separate computer
      entry Send_Queue (Remote_Queue : Queue_Class);
   end Queue_User;
(...)
begin
   null;
end Queue_Test_Dispatching;
```


A dispatching test *program*


```
with Ada.Text_IO;         use Ada.Text_IO;
with Queue_Pack_Abstract;
with Queue_Pack_Concrete;
procedure Queue_Test_Dispatching is
   package Queue_Pack_Abstract_Character is
      new Queue_Pack_Abstract (Character);
   use Queue_Pack_Abstract_Character;
   type Queue_Size is mod 3;
   package Queue_Pack_Character is
      new Queue_Pack_Concrete (Queue_Pack_Abstract_Character, Queue_Size);
   use Queue_Pack_Character;
   type Queue_Class is access all Queue_Interface'class;
   task Queue_Holder; -- could be on an individual partition / separate computer
   task Queue_User is -- could be on an individual partition / separate computer
      entry Send_Queue (Remote_Queue : Queue_Class);
   end Queue_User;
(...)
begin
   null;
end Queue_Test_Dispatching;
```


Sequence of instantiations

A dispatching test *program*


```
with Ada.Text_IO;         use Ada.Text_IO;
with Queue_Pack_Abstract;
with Queue_Pack_Concrete;
procedure Queue_Test_Dispatching is
   package Queue_Pack_Abstract_Character is
      new Queue_Pack_Abstract (Character);
   use Queue_Pack_Abstract_Character;
   type Queue_Size is mod 3;
   package Queue_Pack_Character is
      new Queue_Pack_Concrete (Queue_Pack_Abstract_Character, Queue_Size);
   use Queue_Pack_Character;
   type Queue_Class is access all Queue_Interface'class;
   task Queue_Holder; -- could be on an individual partition / separate computer
   task Queue_User is -- could be on an individual partition / separate computer
      entry Send_Queue (Remote_Queue : Queue_Class);
   end Queue_User;
(...)
begin
   null;
end Queue_Test_Dispatching;
```


Type which can refer to any instance of Queue_Interface

A dispatching test *program*


```
with Ada.Text_IO;         use Ada.Text_IO;
with Queue_Pack_Abstract;
with Queue_Pack_Concrete;
procedure Queue_Test_Dispatching is
   package Queue_Pack_Abstract_Character is
      new Queue_Pack_Abstract (Character);
   use Queue_Pack_Abstract_Character;
   type Queue_Size is mod 3;
   package Queue_Pack_Character is
      new Queue_Pack_Concrete (Queue_Pack_Abstract_Character, Queue_Size);
   use Queue_Pack_Character;
   type Queue_Class is access all Queue_Interface'class;
   task Queue_Holder; -- could be on an individual partition / separate computer
   task Queue_User is -- could be on an individual partition / separate computer
      entry Send_Queue (Remote_Queue : Queue_Class);
   end Queue_User;
(...)
begin
   null;
end Queue_Test_Dispatching;
```


Declaring two concrete tasks.
(Queue_User has a synchronous message passing entry)

A dispatching test *program*


```
with Ada.Text_IO;         use Ada.Text_IO;
with Queue_Pack_Abstract;
with Queue_Pack_Concrete;
procedure Queue_Test_Dispatching is
   package Queue_Pack_Abstract_Character is
      new Queue_Pack_Abstract (Character);
   use Queue_Pack_Abstract_Character;
   type Queue_Size is mod 3;
   package Queue_Pack_Character is
      new Queue_Pack_Concrete (Queue_Pack_Abstract_Character, Queue_Size);
   use Queue_Pack_Character;
   type Queue_Class is access all Queue_Interface'class;
   task Queue_Holder; -- could be on an individual partition / separate computer
   task Queue_User is -- could be on an individual partition / separate computer
      entry Send_Queue (Remote_Queue : Queue_Class);
   end Queue_User;
(...)
begin
   null;
end Queue_Test_Dispatching;
```


... anything on this slide still not perfectly clear?

A dispatching test *program* (cont.)

```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


A dispatching test *program* (cont.)


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


Declaring local queues in each task.

A dispatching test *program* (cont.)


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


Handing over the Holder's queue via synchronous message passing.

A dispatching test *program* (cont.)


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


Adding to both queues

A dispatching test *program* (cont.)

Tasks could run on separate computers


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


These two calls can be very different in nature:

The first call is potentially **tunneled through a network** to another computer and thus uses a **remote data structure**.

The second call is always a **local call** and using a **local data-structure**.

A dispatching test *program* (cont.)


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


Reading out 'r'

Reading out 'l'

A dispatching test *program* (cont.)


```
task body Queue_Holder is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   Queue_User.Send_Queue (Local_Queue);
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (Holder): " & Character'Image (Item));
end Queue_Holder;

task body Queue_User is
   Local_Queue : constant Queue_Class := new Protected_Queue;
   Item        : Character;
begin
   accept Send_Queue (Remote_Queue : Queue_Class) do
      Remote_Queue.all.Enqueue ('r'); -- potentially a remote procedure call!
      Local_Queue.all.Enqueue  ('l');
   end Send_Queue;
   Local_Queue.all.Dequeue (Item);
   Put_Line ("Local dequeue (User)  : " & Character'Image (Item));
end Queue_User;
```


... anything on this slide still not perfectly clear?

Language refresher / introduction course

Ada

Ada language status

Boeing 787 cockpit (press release photo)

- Established language standard with free and professionally supported compilers available for all major OSs and platforms.
- Emphasis on maintainability, high-integrity and efficiency.
- Stand-alone runtime environments for embedded systems.
- High integrity, real-time profiles part of the standard ☞ e.g. Ravenscar profile.

☞ Used in many large scale and/or high integrity projects

- Commonly used in aviation industry, high speed trains, metro-systems, space programs and military programs.
- … also increasingly on small platforms / micro-controllers.

TGV, Renaud Chodkowski 2012

Language refresher / introduction course

Chapel

Currently under development at Cray.
(originally for the DARPA High Productivity Computing Systems initiative.)

☞ Targeted at massively parallel computers

Language primitives for …

- Data parallelism:
  - ☞ Distributed data storage with fine grained control (“domains”).
  - ☞ Concurrent map operations (`forall`).
  - ☞ Concurrent fold operations (`scan, reduce`).
- Task parallelism:
  - ☞ concurrent loops and blocks (`cobegin, coforall`).
- Synchronization:
  - ☞ Task synchronization, synchronized variables, atomic sections.

A data-parallel stencil program

```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


A data-parallel stencil program


```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


Configuration constants can be set via command line options:
`./Stencil --n=500`

A data-parallel stencil program


```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


Defining **domains** to be used for multi-dimensional array declarations and assignments.

A data-parallel stencil program


```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


Declaring matrices of different, yet related dimensions.

A data-parallel stencil program


```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


Note the index type

Function which calculates a “stencil” value at a spot inside a given matrix

A data-parallel stencil program


```
config const n              = 100,
             max_iterations = 50,
             epsilon        = 1.0E-5,
             initial_border = 1.0;

const Matrix_w_Borders = {0 .. n + 1, 0 .. n + 1, 0 .. n + 1},
      Matrix           = Matrix_w_Borders [1 .. n, 1 .. n, 1 .. n],
      Single_Border    = Matrix.exterior (1, 0, 0);

var Field      : [Matrix_w_Borders] real,
    Next_Field : [Matrix]           real;

proc Stencil (M : [/* Matrix_w_Borders */] real, (i, j, k) : index (Matrix)) : real {
  return (M [i - 1, j, k]
        + M [i + 1, j, k]
        + M [i, j - 1, k]
        + M [i, j + 1, k]
        + M [i, j, k + 1]
        + M [i, j, k - 1]) / 6;
}
```


… anything on this slide still not perfectly clear?

A data-parallel stencil program (cont.)

```
Field [Single_Border] = initial_border;

for l in 1 .. max_iterations {

  forall Matrix_Indices in Matrix do
    Next_Field (Matrix_Indices) = Stencil (Field, Matrix_Indices);

  const delta = max reduce abs (Field [Matrix] - Next_Field);

  Field [Matrix] = Next_Field;

  if delta < epsilon then break;
}
```


A data-parallel stencil program (cont.)


```
Field [Single_Border] = initial_border;

for l in 1 .. max_iterations {

  forall Matrix_Indices in Matrix do
    Next_Field (Matrix_Indices) = Stencil (Field, Matrix_Indices);

  const delta = max reduce abs (Field [Matrix] - Next_Field);

  Field [Matrix] = Next_Field;

  if delta < epsilon then break;
}
```


Scalar to 2-d array-slice assignment
(Technically a 3-d domain with two degenerate dimensions)

3-d array to 3-d array-slice assignment

A data-parallel stencil program (cont.)


```
Field [Single_Border] = initial_border;

for l in 1 .. max_iterations {

  forall Matrix_Indices in Matrix do
    Next_Field (Matrix_Indices) = Stencil (Field, Matrix_Indices);

  const delta = max reduce abs (Field [Matrix] - Next_Field);

  Field [Matrix] = Next_Field;

  if delta < epsilon then break;
}
```


Data parallel application of the `Stencil` function to the whole 3-d matrix

A data-parallel stencil program (cont.)


```
Field [Single_Border] = initial_border;

for l in 1 .. max_iterations {

  forall Matrix_Indices in Matrix do
    Next_Field (Matrix_Indices) = Stencil (Field, Matrix_Indices);

  const delta = max reduce abs (Field [Matrix] - Next_Field);

  Field [Matrix] = Next_Field;

  if delta < epsilon then break;
}
```


Data parallel (divide-and-conquer) application of the `max` function to the component-wise differences.

“3-d data-parallel version” of (Haskell):
`foldr max minBound $ zipWith (-) field next_field`

A data-parallel stencil program (cont.)


```
Field [Single_Border] = initial_border;

for l in 1 .. max_iterations {

  forall Matrix_Indices in Matrix do
    Next_Field (Matrix_Indices) = Stencil (Field, Matrix_Indices);

  const delta = max reduce abs (Field [Matrix] - Next_Field);

  Field [Matrix] = Next_Field;

  if delta < epsilon then break;
}
```


… anything on this slide still not perfectly clear?

Language refresher / introduction course

Summary

Language refresher / introduction course

- Specification and implementation (body) parts, basic types
- Exceptions & Contracts
- Information hiding in specifications (‘private’)
- Generic programming
- Tasking
- Monitors and synchronisation (‘protected’, ‘entries’, ‘selects’, ‘accepts’)
- Abstract types and dispatching
- Data parallel operations

161

Systems, Networks & Concurrency 2020

1

Introduction to Concurrency

Uwe R. Zimmer - The Australian National University

162

Introduction to Concurrency

References for this chapter

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

163

Introduction to Concurrency

Forms of concurrency

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]

164

Introduction to Concurrency

Forms of concurrency

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.

165

Introduction to Concurrency

Forms of concurrency

Why do we need/have concurrency?

- Physics, engineering, electronics, biology, …

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

- Sequential processing is suggested by most core computer architectures
  … yet (almost) *all* current processor architectures have **concurrent elements**
  … and *most* computer systems are part of a **concurrent network**.

- Strict sequential processing is suggested by widely used programming languages.

☞ Sequential programming delivers some *fundamental components* for concurrent programming

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

166

Introduction to Concurrency

Forms of concurrency

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* when sequential and/or concurrent programming is **required**
  … or: to understand when sequential or concurrent programming can be **chosen freely**
☞ … to *enhance* the **reactivity** of a system
☞ … to enhance the **performance** of a system
☞ … to be able to design **embedded** systems
☞ …

167

Introduction to Concurrency

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

168

Introduction to Concurrency

Forms of concurrency

A computer scientist's view on concurrency

Terminology for physically concurrent machines architectures:

- SISD
  [singe instruction, single data]
  ☞ Sequential processors
- SIMD
  [singe instruction, multiple data]
  ☞ Vector processors
- MISD
  [multiple instruction, single data]
  ☞ Pipelined processors
- MIMD
  [multiple instruction, multiple data]
  ☞ Multi-processors or computer networks

169

Introduction to Concurrency

Forms of concurrency

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.

170

Introduction to Concurrency

Forms of concurrency

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-reproducible** ☞ debugging?

171

Introduction to Concurrency

Forms of concurrency

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-reproducible** ☞ 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 …

172

Introduction to Concurrency

Models and Terminology

Concurrency on different abstraction levels/perspectives

☞ Networks
- Large scale, high bandwidth interconnected nodes ("supercomputers")
- Networked computing nodes
- Standalone computing nodes – including local buses & interfaces sub-systems
- Operating systems (& distributed operating systems)

☞ Implicit concurrency
☞ Explicit concurrent programming (message passing and synchronization)
☞ Assembler level concurrent programming
- Individual concurrent units inside one CPU
- Individual electronic circuits
- …

173

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

1. What appears sequential on a higher abstraction level, is usually concurrent at a lower abstraction level:
   ☞ e.g. Concurrent operating system or hardware components, which might not be visible at a higher programming level
2. What appears concurrent on a higher abstraction level, might be sequential at a lower abstraction level:
   ☞ e.g. Multi-processing system, which are executed on a single, sequential computing node

174

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

- *'concurrent'* is technically 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 and logic:

  "Concurrent programming abstraction **is the study of interleaved execution sequences of the atomic instructions of sequential processes."**
  (Ben-Ari)

175

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

Concurrent program ::=
Multiple sequential programs (processes or threads) which are executed *concurrently*.

P.S. it is generally assumed that concurrent execution means that there is one execution unit (processor) per sequential program
- even though this is usually not technically correct, it is still an often valid, conservative assumption in the context of concurrent programming.

176

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

☞ No interaction between concurrent system parts means that we can analyze them individually as pure sequential programs [end of course].

177

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

☞ No interaction between concurrent system parts means that we can analyze them individually as pure sequential programs [end of course].

☞ **Interaction** occurs in form of:

- **Contention** (implicit interaction):
  Multiple concurrent execution units compete for one shared resource.
- **Communication** (explicit interaction):
  Explicit passing of information and/or explicit synchronization.

178

Introduction to Concurrency

Models and Terminology

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 ☞ stay in your seat

179

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

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

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

☞ holds true for **all possible sequences of interaction points (interleavings)**

180

Introduction to Concurrency

Models and Terminology

The concurrent programming abstraction

Correctness vs. testing in concurrent systems:

Slight changes in external triggers may (and usually does) result in completely different schedules (interleaving):

☞ Concurrent programs which depend in any way on external influences cannot be tested without modelling and embedding those influences into the test process.

☞ Designs which are provably correct with respect to the specification and are **independent** of the *actual timing behavior* are essential.

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

181

Introduction to Concurrency

Models and Terminology

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.

182

Introduction to Concurrency

Models and Terminology

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?

183

Introduction to Concurrency

Models and Terminology

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

184

Introduction to Concurrency

Models and Terminology

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)

185

Introduction to Concurrency

Models and Terminology

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)
and S is the current state of the concurrent system

Examples:

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

☞ Interesting *liveness* properties can be very hard to prove

186

Introduction to Concurrency

Introduction to processes and threads

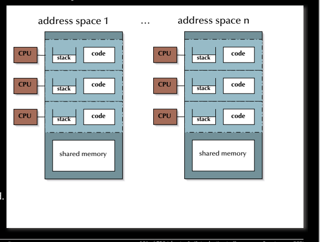
1 CPU per control-flow

Specific configurations only, e.g.:

- Distributed µcontrollers.
- Physical process control systems:
  1 cpu per task, connected via a bus-system.

☞ **Process management** (scheduling) not required.

☞ **Shared memory access** need to be coordinated.



187

Introduction to Concurrency

Introduction to processes and threads

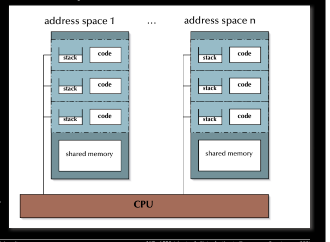
1 CPU for all control-flows

- OS: emulate one CPU for every control-flow:
  Multi-tasking operating system

☞ Support for **memory protection** essential.

☞ **Process management** (scheduling) required.

☞ **Shared memory access** need to be coordinated.



188

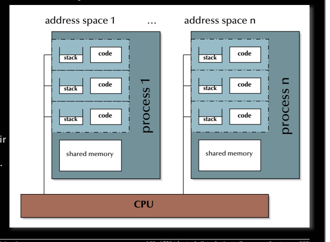
Introduction to Concurrency

Introduction to processes and threads

Processes

Process ::=
Address space
+ Control flow(s)

☞ Kernel has full knowledge about all processes as well as their **states, requirements** and currently held **resources.**



189

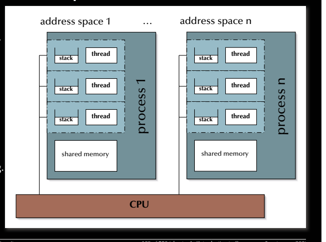
Introduction to Concurrency

Introduction to processes and threads

Threads

Threads (individual control-flows) can be handled:

- *Inside* the OS:
  ☞ Kernel scheduling.
  - Thread can easily be connected to external events (I/O).
- *Outside* the OS:
  ☞ User-level scheduling.
  - Threads may need to go through their parent process to access I/O.



190

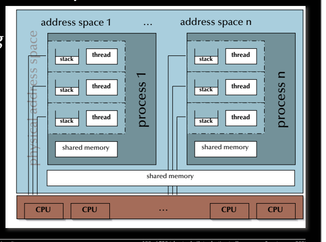
Introduction to Concurrency

Introduction to processes and threads

Symmetric Multiprocessing (SMP)

All CPUs share the same physical address space (and access to resources).

☞ Any process / thread can be executed on any available CPU.



191

Introduction to Concurrency

Introduction to processes and threads

Processes ↔ Threads

Also processes can share memory and the specific definition of threads is different in different operating systems and contexts:

☞ 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 communication can be more efficient than switching on 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.

192

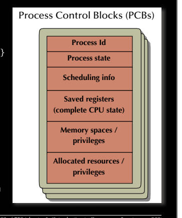
Introduction to Concurrency

Introduction to processes and threads

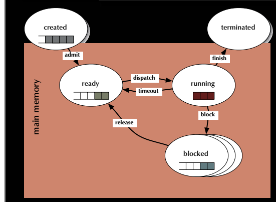
Process Control Blocks

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

… PCBs (links thereof) are commonly enqueued at a certain state or condition (awaiting access or change in state)



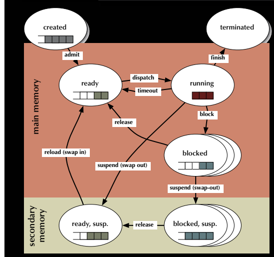
Introduction to Concurrency



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

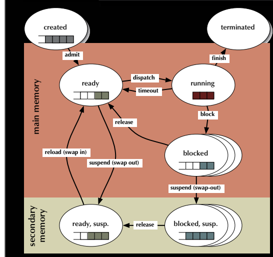
Introduction to Concurrency



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
  (none time critical processes)
  ☞ waiting for main memory space (and other resources)

Introduction to Concurrency



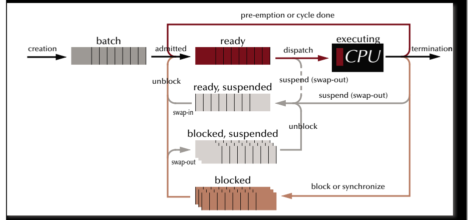
Process states

- **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
  (none time critical processes)
  ☞ waiting for main memory space (and other resources)

☞ dispatching and suspending can now be independent modules

Introduction to Concurrency

Process states



Introduction to Concurrency

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 returning **'-1'** as C-style indication of a failure (in void of actual exception handling)

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 */
}
```


Introduction to Concurrency

UNIX processes

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 ();
}
```


Introduction to Concurrency

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, …)

Introduction to Concurrency

Concurrent programming languages

Language candidates

☞ **Explicit concurrency**

- Ada, C++, Rust
- Chill
- Erlang
- Go
- Chapel, X10
- Occam, CSP
- All .net languages
- Java, Scala, Clojure
- Algol 68, Modula-2, Modula-3
- …

☞ **Implicit (potential) concurrency**

- Lisp, Haskell, Caml, Miranda, and any other functional language
- Smalltalk, Squeak
- Prolog
- Esterel, Lustre, Signal

☞ **Wannabe concurrency**

- Ruby, Python [mostly broken due to global interpreter locks]

☞ No support:

- Eiffel, Pascal
- C
- Fortran, Cobol, Basic…

☞ Libraries & interfaces (outside language definitions)

- POSIX
- MPI (Message Passing Interface)
- …

Introduction to Concurrency

Languages with implicit concurrency: e.g. functional programming

Implicit concurrency in some programming schemes

Quicksort in a functional language (here: Haskell):

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

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

☞ Parameters can be evaluated independently ☞ *could* run 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 then the evaluation of `g(n)` and `h(n)` can be stopped (or not even be started).

☞ Concurrent program parts **should be interruptible** in this case.

Short-circuit evaluations in imperative languages assume explicit sequential execution:

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


Introduction to Concurrency

Summary

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
- **Concurrent programming languages:**
  - Explicit concurrency: e.g. Ada, Chapel
  - Implicit concurrency: functional programming – e.g. Haskell, Caml

203

Systems, Networks & Concurrency 2020

2

Mutual Exclusion

Uwe R. Zimmer - The Australian National University

204

Mutual Exclusion

References for this chapter

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

205

Mutual Exclusion

Problem specification

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 in the first place.

206

Mutual Exclusion

Problem specification

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.

207

Mutual Exclusion

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;
```

☞ What is the value of G?

208

Mutual Exclusion

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 **almost any value** between 0 and 24
☞ After the first global initialisation, G will have **exactly one** value between 0 and 24
☞ After all tasks terminated, G will have **exactly one** value between 2 and 24

209

Mutual Exclusion

Mutual exclusion: First attempt

```
type Task_Token is mod 2;
Turn: Task_Token := 0;

task body P0 is
begin
  loop
    ------ non_critical_section_0;
    loop exit when Turn = 0; end loop;
      ------ critical_section_0;
    Turn := Turn + 1;
  end loop;
end P0;

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

☞ Mutual exclusion?
☞ Deadlock?
☞ Starvation?
☞ Work without contention?

210

Mutual Exclusion

Mutual exclusion: First attempt

```
type Task_Token is mod 2;
Turn: Task_Token := 0;

task body P0 is
begin
  loop
    ------ non_critical_section_0;
    loop exit when Turn = 0; end loop;
      ------ critical_section_0;
    Turn := Turn + 1;
  end loop;
end P0;

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

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

211

Mutual Exclusion

Mutual exclusion: First attempt

Patch

```
type Task_Token is mod 2;
Turn: Task_Token := 0;

task body P0 is
begin
  loop
    ------ non_critical_section_0;
    loop exit when Turn = 0; end loop;
      ------ critical_section_0;
    Turn := Turn + 1;
  end loop;
end P0;

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

☞ Mutual exclusion!
☞ No deadlock!
☞ No starvation!
☞ Inefficient!

scatter:

```
if Turn = myTurn then
  Turn := Turn + 1;
end if
```

into the non-critical sections

212

Mutual Exclusion

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;
```

☞ Any better?

213

Mutual Exclusion

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!

214

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;
```

☞ Any better?

215

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!
☞ Potential deadlock!

216

Mutual Exclusion

Mutual exclusion: Forth 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;
```

☞ Making any progress?

217

Mutual Exclusion

Mutual exclusion: Forth 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!
☞ Potential starvation! ☞ Potential global livelock!

218

Mutual Exclusion

Mutual exclusion: Decker's Algorithm

```
type Task_Range is mod 2;
type Critical_Section_State is (In_CS, Out_CS);
CSS : array (Task_Range) of Critical_Section_State := (others =>  Out_CS);
Turn : Task_Range := Task_Range'First;

task type One_Of_Two_Tasks
       (this_Task  : Task_Range);

task body One_Of_Two_Tasks is
  other_Task : Task_Range
                    := this_Task + 1;
  begin
    ------ non_critical_section
      CSS (this_Task) := In_CS;
      loop
        exit when
          CSS (other_Task) = Out_CS;
        if Turn = other_Task then
          CSS (this_Task) := Out_CS;
          loop
            exit when Turn = this_Task;
          end loop;
          CSS (this_Task) := In_CS;
        end if;
      end loop;
      ------ critical section
      CSS (this_Task) := Out_CS;
      Turn := other_Task;
    end One_Of_Two_Tasks;
```

219

Mutual Exclusion

Mutual exclusion: Decker's Algorithm

☞ Two tasks only!

```
type Task_Range is mod 2;
type Critical_Section_State is (In_CS, Out_CS);
CSS : array (Task_Range) of Critical_Section_State := (others =>  Out_CS);
Turn : Task_Range := Task_Range'First;

task type One_Of_Two_Tasks
            (this_Task   : Task_Range);

task body One_Of_Two_Tasks is
  other_Task : Task_Range
                  := this_Task + 1;
  begin
   ------ non_critical_section
   CSS (this_Task) := In_CS;
   loop
     exit when
       CSS (other_Task) = Out_CS;
     if Turn = other_Task then
       CSS (this_Task) := Out_CS;
       loop
         exit when Turn = this_Task;
       end loop;
       CSS (this_Task) := In_CS;
     end if;
   end loop;
   ------ critical section
   CSS (this_Task) := Out_CS;
   Turn := other_Task;
 end One_Of_Two_Tasks;
```

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

220

Mutual Exclusion

Mutual exclusion: Peterson's Algorithm

```
type Task_Range is mod 2;
type Critical_Section_State is (In_CS, Out_CS);
CSS : array (Task_Range) of Critical_Section_State := (others =>  Out_CS);
Last : Task_Range := Task_Range'First;

task type One_Of_Two_Tasks
            (this_Task   : Task_Range);

task body One_Of_Two_Tasks is
  other_Task : Task_Range
                  := this_Task + 1;
  begin
   ------ non_critical_section
   CSS (this_Task) := In_CS;
   Last := this_Task;
   loop
     exit when
       CSS (other_Task) = Out_CS
         or else Last /= this_Task;
   end loop;
   ------ critical section
   CSS (this_Task) := Out_CS;
 end One_Of_Two_Tasks;
```


221

Mutual Exclusion

Mutual exclusion: Peterson's Algorithm

☞ Two tasks only!

```
type Task_Range is mod 2;
type Critical_Section_State is (In_CS, Out_CS);
CSS : array (Task_Range) of Critical_Section_State := (others =>  Out_CS);
Last : Task_Range := Task_Range'First;

task type One_Of_Two_Tasks
            (this_Task   : Task_Range);

task body One_Of_Two_Tasks is
  other_Task : Task_Range
                  := this_Task + 1;
  begin
   ------ non_critical_section
   CSS (this_Task) := In_CS;
   Last := this_Task;
   loop
     exit when
       CSS (other_Task) = Out_CS
         or else Last /= this_Task;
   end loop;
   ------ critical section
   CSS (this_Task) := Out_CS;
 end One_Of_Two_Tasks;
```

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

222

Mutual Exclusion

Problem specification

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.

223

Mutual Exclusion

Mutual exclusion: Bakery Algorithm

The idea of the Bakery Algorithm

A set of N Processes $P_1 \dots P_N$ competing for mutually exclusive execution of their critical regions. Every process P_i out of $P_1 \dots P_N$ 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 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?

224

Mutual Exclusion

Mutual exclusion: Bakery Algorithm

```
No_Of_Tasks : constant Positive := …;
type Task_Range is mod No_Of_Tasks;
Choosing : array (Task_Range) of Boolean  := (others => False);
Ticket   : array (Task_Range) of Natural  := (others => 0);

task type P (this_id: Task_Range);
task body P is
 begin
  loop
   ------ non_critcal_section_1;
   Choosing (this_id) := True;
   Ticket (this_id) := Max (Ticket) + 1;
   Choosing (this_id) := False;
   for id in Task_Range loop
    if id /= this_id then
     loop
      exit when not Choosing (id);
     end loop;
      loop
       exit when
        Ticket (id) = 0
       or else
        Ticket (this_id) < Ticket (id)
       or else
        (Ticket (this_id) = Ticket (id)
         and then this_id < id);
      end loop;
     end if;
    end loop;
    ------ critical_section_1;
    Ticket (this_id) := 0;
   end loop;
  end P;
```


225

Mutual Exclusion

Mutual exclusion: Bakery Algorithm

```
No_Of_Tasks : constant Positive := …;
type Task_Range is mod No_Of_Tasks;
Choosing : array (Task_Range) of Boolean  := (others =
Ticket   : array (Task_Range) of Natural  := (others =

task type P (this_id: Task_Range);
task body P is
 begin
  loop
   ------ non_critcal_sec
   Choosing (this_id) :=
   Ticket (this_id) := Ma
   Choosing (this_id) :=
   for id in Task_Range loop
    if id /= this_id then
     loop
      exit when not Choosing (id);
     end loop;
      loop
       exit
        Tic
       or else
        Ticket (this_id) < Ticket (id)
          this_id) = Ticket (id)
          this_id < id);
      end loop;
    ------ critical_section_1;
    Ticket (this_id) := 0;
   end loop;
  end P;
```

☞ Mutual exclusion!
☞ No deadlock!
☞ No starvation!
☞ No livelock!
☞ Works for N processes!

☞ Extensive and communication intensive protocol (even if there is no contention)

226

Mutual Exclusion

Beyond atomic memory access

Realistic hardware support

Atomic **test-and-set** operations:

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

Atomic **exchange** operations:

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

Memory cell **reservations:**

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

227

Mutual Exclusion

Mutual exclusion: atomic test-and-set operation

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

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

☞ Does that work?

228

Mutual Exclusion

Mutual exclusion: atomic test-and-set operation

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

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

☞ Mutual exclusion!, No deadlock!, No global live-lock!

☞ Works for any dynamic number of processes.

☞ Individual starvation possible! Busy waiting loops!

229

Mutual Exclusion

Mutual exclusion: atomic exchange operation

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

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

☞ Does that work?

230

Mutual Exclusion

Mutual exclusion: atomic exchange operation

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

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

☞ Mutual exclusion!, No deadlock!, No global live-lock!

☞ Works for any dynamic number of processes.

☞ Individual starvation possible! Busy waiting loops!

231

Mutual Exclusion

Mutual exclusion: memory cell reservation

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

task body Pi is                      task body Pj is
L : Flag;                            L : Flag;
begin                                begin
 loop                                 loop
  loop                                 loop
   L :R= C; C :T= 1;                    L :R= C; C :T= 1;
   exit when Untouched and L = 0;       exit when Untouched and L = 0;
   ------ change process                ------ change process
  end loop;                            end loop;
  ------ critical_section_i;           ------ critical_section_j;
  C := 0;                              C := 0;
 end loop;                            end loop;
end Pi;                              end Pj;
```

☞ Does that work?

232

Mutual Exclusion

Mutual exclusion: memory cell reservation

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

task body Pi is                      task body Pj is
L : Flag;                            L : Flag;
begin                                begin
 loop                                 loop
  loop                                 loop
   L :R= C; C :T= 1;                    L :R= C; C :T= 1;
   exit when Untouched and L = 0;       exit when Untouched and L = 0;
   ------ change process                ------ change process
  end loop;                            end loop;
  ------ critical_section_i;           ------ critical_section_j;
  C := 0;                              C := 0;
 end loop;                            end loop;
end Pi;                              end Pj;
```

Any context switch needs to clear reservations

☞ Mutual exclusion!, No deadlock!, No global live-lock!

☞ Works for any dynamic number of processes.

☞ Individual starvation possible! Busy waiting loops!

233

Mutual Exclusion

Mutual exclusion … or the lack thereof

```
Count : Integer := 0;

task body Enter is                   task body Leave is
begin                                begin
 for i := 1 .. 100 loop               for i := 1 .. 100 loop
  Count := Count + 1;                  Count := Count - 1;
 end loop;                            end loop;
end Enter;                           end Leave;
```

☞ What is the value of Count after both programs complete?

234

```
Count:    .word 0x00000000

   ldr    r4, =Count                 ldr    r4, =Count
   mov    r1, #1                     mov    r1, #1
for_enter:                         for_leave:
   cmp    r1, #100                   cmp    r1, #100
   bgt    end_for_enter              bgt    end_for_leave

              Negotiate who goes first

   ldr    r2, [r4]                   ldr    r2, [r4]
   add    r2, #1   Critical section  sub    r2, #1   Critical section
   str    r2, [r4]                   str    r2, [r4]

              Indicate critical section completed

   add    r1, #1                     add    r1, #1
   b      for_enter                  b      for_leave
end_for_enter:                     end_for_leave:
```

235

```
Count:  .word 0x00000000
Lock:   .word 0x00000000 ; #0 means unlocked

    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
fail_enter:
    ldr   r0, [r3]
    cbnz  r0, fail_enter  ; if locked

    ldr   r2, [r4]
    add   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
fail_leave:
    ldr   r0, [r3]
    cbnz  r0, fail_leave  ; if locked

    ldr   r2, [r4]
    sub   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_leave
end_for_leave:
```

Critical section

Critical section

236

```
Count:  .word 0x00000000
Lock:   .word 0x00000000 ; #0 means unlocked

    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
fail_enter:
    ldr   r0, [r3]
    cbnz  r0, fail_enter  ; if locked
    mov   r0, #1          ; lock value
    str   r0, [r3]        ; lock

    ldr   r2, [r4]
    add   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
fail_leave:
    ldr   r0, [r3]
    cbnz  r0, fail_leave  ; if locked
    mov   r0, #1          ; lock value
    str   r0, [r3]        ; lock

    ldr   r2, [r4]
    sub   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_leave
end_for_leave:
```

Critical section

Critical section

237

```
Count:  .word 0x00000000
Lock:   .word 0x00000000 ; #0 means unlocked

    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
fail_enter:
    ldrex r0, [r3]
    cbnz  r0, fail_enter  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_enter  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    add   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
fail_leave:
    ldrex r0, [r3]
    cbnz  r0, fail_leave  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_leave  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    sub   r2, #1
    str   r2, [r4]

    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Critical section

Critical section

238

```
Count:  .word 0x00000000
Lock:   .word 0x00000000 ; #0 means unlocked

    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
fail_enter:
    ldrex r0, [r3]
    cbnz  r0, fail_enter  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_enter  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    add   r2, #1
    str   r2, [r4]
    dmb                   ; sync memory
    mov   r0, #0          ; unlock value
    str   r0, [r3]        ; unlock
    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
fail_leave:
    ldrex r0, [r3]
    cbnz  r0, fail_leave  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_leave  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    sub   r2, #1
    str   r2, [r4]
    dmb                   ; sync memory
    mov   r0, #0          ; unlock value
    str   r0, [r3]        ; unlock
    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Critical section

Critical section

239

```
Count:  .word 0x00000000
Lock:   .word 0x00000000 ; #0 means unlocked

    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
fail_enter:
    ldrex r0, [r3]
    cbnz  r0, fail_enter  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_enter  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    add   r2, #1
    str   r2, [r4]
    dmb                   ; sync memory
    mov   r0, #0          ; unlock value
    str   r0, [r3]        ; unlock
    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Lock
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
fail_leave:
    ldrex r0, [r3]
    cbnz  r0, fail_leave  ; if locked
    mov   r0, #1          ; lock value
    strex r0, [r3]        ; try lock
    cbnz  r0, fail_leave  ; if touched
    dmb                   ; sync memory
    ldr   r2, [r4]
    sub   r2, #1
    str   r2, [r4]
    dmb                   ; sync memory
    mov   r0, #0          ; unlock value
    str   r0, [r3]        ; unlock
    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Asks for permission

Critical section

Critical section

240

Mutual Exclusion

Mutual exclusion

```
Count: .word 0x00000000

    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
enter_strex_fail:
    ldrex r2, [r4] ; tag [r4] as exclusive
    add   r2, #1
    strex r2, [r4] ; only if untouched
    cbnz  r2, enter_strex_fail
    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
leave_strex_fail:
    ldrex r2, [r4] ; tag [r4] as exclusive
    sub   r2, #1
    strex r2, [r4] ; only if untouched
    cbnz  r2, leave_strex_fail
    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Asks for forgiveness

☞ Light weight solution – sometimes referred to as "lock-free" or "lockless".

241

Mutual Exclusion

Beyond atomic hardware operations

Semaphores

Basic definition (Dijkstra 1968)

Assuming the following three conditions on a shared memory cell between processes:

- a set of processes agree on a variable **S** operating as a flag to indicate synchronization conditions
- an atomic operation **P** on S — for 'passeren' (Dutch for 'pass'):
  P(S): `[as soon as S > 0 then S := S - 1]` ☞ this is a potentially delaying operation
- an atomic operation **V** on S — for 'vrygeven' (Dutch for 'to release'):
  V(S): `[S := S + 1]`

☞ *then* the variable **S** is called a **Semaphore**.

242

Mutual Exclusion

Beyond atomic hardware operations

Semaphores

… as supplied by operating systems and runtime environments

- a set of processes $P_1 \ldots P_N$ agree on a variable **S** operating as a flag to indicate synchronization conditions
- an atomic operation **Wait** on S: (aka '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: (aka 'Set_True', 'sem_post', …)
  Process P_i : **Signal** (S):
  `[if` $\exists P_j$ `suspended on S then release` P_j
  `else S := S + 1]`

☞ *then* the variable **S** is called a **Semaphore** in a scheduling environment.

243

Mutual Exclusion

Beyond atomic hardware operations

Semaphores

Types of semaphores:

- **Binary semaphores:** restricted to [0, 1] or [False, True] resp. Multiple V (Signal) calls have the same effect than a single call.
  - Atomic hardware operations support binary semaphores.
  - Binary semaphores are sufficient to create all other semaphore forms.
- **General semaphores** (counting semaphores): non-negative number; (range limited by the system) P and V increment and decrement the semaphore by one.
- **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: often the number of processes which are allowed inside a critical section, i.e. '1'.

244

```
Count:  .word 0x00000000
Sema:   .word 0x00000001

    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
wait_1:
    ldr   r0, [r3]
    cbz   r0, wait_1 ; if Semaphore = 0

    …

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
wait_2:
    ldr   r0, [r3]
    cbz   r0, wait_2 ; if Semaphore = 0

    …

    add   r1, #1
    b     for_leave
end_for_leave:
```

Critical section

Critical section

245

```
Count:  .word 0x00000000
Sema:   .word 0x00000001

    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
wait_1:
    ldr   r0, [r3]
    cbz   r0, wait_1 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    str   r0, [r3]   ; update

    …

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
wait_2:
    ldr   r0, [r3]
    cbz   r0, wait_2 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    str   r0, [r3]   ; update

    …

    add   r1, #1
    b     for_leave
end_for_leave:
```

Critical section

Critical section

246

```
Count:  .word 0x00000000
Sema:   .word 0x00000001

    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
wait_1:
    ldrex r0, [r3]
    cbz   r0, wait_1 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_1 ; if touched
    dmb              ; sync memory
    …

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
wait_2:
    ldrex r0, [r3]
    cbz   r0, wait_2 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_2 ; if touched
    dmb              ; sync memory
    …

    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Critical section

Critical section

247

```
Count:  .word 0x00000000
Sema:   .word 0x00000001

    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
wait_1:
    ldrex r0, [r3]
    cbz   r0, wait_1 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_1 ; if touched
    dmb              ; sync memory
    …
    ldr   r0, [r3]
    add   r0, #1        ; inc Semaphore
    str   r0, [r3]      ; update

    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
wait_2:
    ldrex r0, [r3]
    cbz   r0, wait_2 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_2 ; if touched
    dmb              ; sync memory
    …
    ldr   r0, [r3]
    add   r0, #1        ; inc Semaphore
    str   r0, [r3]      ; update

    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Critical section

Critical section

248

```
Count:  .word 0x00000000
Sema:   .word 0x00000001

    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_enter:
    cmp   r1, #100
    bgt   end_for_enter
wait_1:
    ldrex r0, [r3]
    cbz   r0, wait_1 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_1 ; if touched
    dmb              ; sync memory
    …
signal_1:
    ldrex r0, [r3]
    add   r0, #1       ; inc Semaphore
    strex r0, [r3]     ; try update
    cbnz  r0, signal_1 ; if touched
    dmb                ; sync memory
    add   r1, #1
    b     for_enter
end_for_enter:
```

```
    ldr   r3, =Sema
    ldr   r4, =Count
    mov   r1, #1
for_leave:
    cmp   r1, #100
    bgt   end_for_leave
wait_2:
    ldrex r0, [r3]
    cbz   r0, wait_2 ; if Semaphore = 0
    sub   r0, #1     ; dec Semaphore
    strex r0, [r3]   ; try update
    cbnz  r0, wait_2 ; if touched
    dmb              ; sync memory
    …
signal_2:
    ldrex r0, [r3]
    add   r0, #1       ; inc Semaphore
    strex r0, [r3]     ; try update
    cbnz  r0, signal_2 ; if touched
    dmb                ; sync memory
    add   r1, #1
    b     for_leave
end_for_leave:
```

Any context switch needs to clear reservations

Critical section

Critical section

249

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;
```

☞ Works?

250

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!
☞ Works for any dynamic number of processes
☞ Individual starvation possible!

Mutual Exclusion

Semaphores

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

task body Pi is                        task body Pj is
begin                                  begin
 loop                                   loop
  ------ non_critical_section_i;         ------ non_critical_section_j;
  wait (S1);                             wait (S2);
  wait (S2);                             wait (S1);
   ------ critical_section_i;             ------ critical_section_j;
  signal (S2);                           signal (S1);
  signal (S1);                           signal (S2);
 end loop;                              end loop;
end Pi;                                end Pj;
```

☞ Works too?

Mutual Exclusion

Semaphores

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

task body Pi is                        task body Pj is
begin                                  begin
 loop                                   loop
  ------ non_critical_section_i;         ------ non_critical_section_j;
  wait (S1);                             wait (S2);
  wait (S2);                             wait (S1);
   ------ critical_section_i;             ------ critical_section_j;
  signal (S2);                           signal (S1);
  signal (S1);                           signal (S2);
 end loop;                              end loop;
end Pi;                                end Pj;
```

☞ Mutual exclusion!, No global live-lock!

☞ Works for any dynamic number of processes.

☞ Individual starvation possible!

☞ Deadlock possible!

Mutual Exclusion

Summary

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

254

Systems, Networks & Concurrency 2020

3

Communication & Synchronization

Uwe R. Zimmer - The Australian National University

255

References for this chapter

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

[Barnes2006]
Barnes, John
Programming in Ada 2005
Addison-Wesley, Pearson education, ISBN-13 978-0-321-34078-8, Harlow, England, 2006

[Gosling2005]
Gosling, James, Joy, B, Steele, Guy & Bracha, Gilad
The Java™ Language Specification - third edition
2005

[AdaRM2012]
Ada Reference Manual - Language and Standard Libraries;
ISO/IEC 8652:201x (E)

[Chapel 1.11.0 Language Specification Version 0.97]
see course pages or http://chapel.cray.com/spec/spec-0.97.pdf released on 2. April 2015

[Saraswat2010]
Saraswat, Vijay
Report on the Programming Language X10 Version 2.01
Draft — January 13, 2010

256

Overview

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, C#, …
- Protected objects ☞ Ada
- Atomic blocks ☞ Chapel, X10

Message based synchronization

- Asynchronous messages ☞ e.g. POSIX, …
- Synchronous messages ☞ e.g. Ada, CHILL, Occam2, …
- Remote invocation, remote procedure call ☞ e.g. Ada, …

257

Motivation

Side effects

Operations have side effects which are visible …

either

☞ … **locally only**

(and protected by runtime-, os-, or hardware-mechanisms)

or

☞ … **outside the current process**

☞ If side effects transcend the local process then all forms of access need to be synchronized.

258

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
              i++;              if i > n {i=0;}
              {in one thread}   {in another thread}
```

What's the worst that can happen?

259

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
              i++;              if i > n {i=0;}
              {in one thread}   {in another thread}
```

☞ Handling a 64-bit integer on a 8- or 16-bit controller will not be atomic

… yet perhaps it is an 8-bit integer.

☞ Unaligned manipulations on the main memory will usually not be atomic

… yet perhaps it is a aligned.

☞ Broken down to a load-operate-store cycle, the operations will usually not be atomic

… yet perhaps the processor supplies atomic operations for the actual case.

☞ Many schedulers interrupt threads irrespective of shared data operations

… yet perhaps this scheduler is aware of the shared data.

☞ Local caches might not be coherent

… yet perhaps they are.

260

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
              i++;              if i > n {i=0;}
              {in one thread}   {in another thread}
```

☞ Handling a 64-bit integer on a 8- or 16-bit controller will not be atomic

… yet perhaps it is an 8-bit integer.

☞ Unaligned manipulations on the main memory will usually not be atomic

… yet perhaps it is a aligned.

☞ Broken down to a load-operate-store cycle, the operations will usually not be atomic

… yet perhaps the processor supplies atomic operations for the actual case.

☞ Many schedulers interrupt threads irrespective of shared data operations

… yet perhaps this scheduler is aware of the shared data.

☞ Local caches might not be coherent

… yet perhaps they are.

Even if all assumptions hold:

How to expand this code?

261

Sanity check

Do we need to? – really?

```
int i; {declare globally to multiple threads}
              i++;              if i > n {i=0;}
              {in one thread}   {in another thread}
```

☞ 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, yet often disastrous.)

☞ On assembler level on very simple CPU architectures: synchronization by employing knowledge about the atomicity of CPU-operations and interrupt structures is nevertheless possible and utilized in practice.

In anything higher than assembler level on single core, predictable μ-controllers:

☞ Measures for synchronization are required!

262

Towards synchronization

Condition synchronization by flags

Assumption: word-access atomicity:

i.e. assigning two values (not wider than the size of a 'word') to an aligned memory cell concurrently:

```
x := 0   |   x := 500
```

will result in *either* `x = 0` *or* `x = 500` – and no other value is ever observable

263

Towards synchronization

Condition synchronization by flags

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

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

264

Towards synchronization

Condition synchronization by flags

```
var Flag : boolean := false;

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

Sequence of operations: $A \rightarrow B; [X \mid A] \rightarrow Y; [X, Y \mid B]$

265

Towards synchronization

Condition synchronization by flags

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

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

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

266

Basic synchronization

by Semaphores

Basic definition (Dijkstra 1968)

Assuming the following three conditions on a shared memory cell between processes:

- a set of processes agree on a variable **S** operating as a flag to indicate synchronization conditions
- an atomic operation **P** on S — for 'passeren' (Dutch for 'pass'):
  P(S): `[as soon as S > 0 then S := S - 1]` ☞ this is a potentially delaying operation
  aka: 'Wait', 'Suspend_Until_True', 'sem_wait', …
- an atomic operation **V** on S — for 'vrygeven' (Dutch for 'to release'):
  V(S): `[S := S + 1]`
  aka 'Signal', 'Set-True', 'sem_post', …

☞ *then* the variable **S** is called a **Semaphore**.

267

Towards synchronization

Condition synchronization by semaphores

```
var sync : semaphore := 0;

process P1;                    process P2;
  statement X;                   statement A;
  wait (sync)                    signal (sync);
  statement Y;                   statement B;
end P1;                        end P2;
```

Sequence of operations: $A \rightarrow B; [X \mid A] \rightarrow Y; [X, Y \mid B]$

268

Towards synchronization

Mutual exclusion by semaphores

```
var mutex : semaphore := 1;

process P1;                    process P2;
  statement X;                   statement A;
  wait (mutex);                  wait (mutex);
    statement Y;                   statement B;
  signal (mutex);                signal (mutex);
  statement Z;                   statement C;
end P1;                        end P2;
```

Sequence of operations:
$A \rightarrow B \rightarrow C; X \rightarrow Y \rightarrow Z; [X, Z \mid A, B, C]; [A, C \mid X, Y, Z]; \neg[B \mid Y]$

269

Towards synchronization

Semaphores in Ada

```
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;
```

☞ This is "queueless" and can translate into a single machine instruction.

only one task can be blocked at `Suspend_Until_True`!
(`Program_Error` will be raised with a second task trying to suspend itself)

☞ no queues! ☞ minimal run-time overhead

270

Communication & Synchronization

Towards synchronization

Semaphores in Ada

```
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;
```

☞ for special cases only … otherwise:

medieval

only one task can be blocked at Suspend_Until_True!
(Program_Error will be raised with a second task trying to suspend itself)

☞ no queues! ☞ minimal run-time overhead

271

Communication & Synchronization

Towards synchronization

Malicious use of "queueless semaphores"

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

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

☞ Could raise a Program_Error as multiple tasks potentially suspend on the same semaphore (occurs only with high efficiency semaphores which do not provide process queues)

272

Communication & Synchronization

Towards synchronization

Malicious use of "queueless semaphores"

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

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

☞ Will result in a deadlock (assuming no other Set_True calls)

273

Communication & Synchronization

Towards synchronization

Malicious use of "queueless semaphores"

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

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

☞ Will potentially result in a deadlock (with general semaphores) or a Program_Error in Ada.

274

Communication & Synchronization

Towards synchronization

Semaphores in POSIX

pshared is actually a Boolean indicating whether the semaphore is to be shared between processes

```
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);
```

*value indicates the number of waiting processes as a negative integer in case the semaphore value is zero

275

Communication & Synchronization

Towards synchronization

Semaphores in POSIX

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

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);
} } }
```

Deadlock?
Livelock?
Mutual exclusion?

276

Communication & Synchronization

Towards synchronization

Semaphores in Java (since 2004)

```
Semaphore (int permits, boolean fair)
          void    acquire                 ()
          void    acquire                 (int permits)
          void    acquireUninterruptibly  (int permits)
          boolean tryAcquire              ()
          boolean tryAcquire              (int permits, long timeout, TimeUnit unit)
          int     availablePermits        ()
protected void    reducePermits           (int reduction)
          int     drainPermits            ()
          void    release                 ()
          void    release                 (int permits)
protected Collection <Thread> getQueuedThreads ()
          int     getQueueLength          ()
          boolean hasQueuedThreads        ()
          boolean isFair                  ()
          String  toString                ()
```

wait

check and manipulate

signal

administration

277

Communication & Synchronization

Towards synchronization

Review of semaphores

- Semaphores are **not bound to any resource or method or region**
  ☞ Compiler has no idea what is supposed to be protected by a semaphore.
- Semaphores are **scattered all over the code**
  ☞ Hard to read and highly error-prone.
  ☞ Adding or deleting a single semaphore operation usually stalls a whole system.

☞ Semaphores are generally considered inadequate for non-trivial systems.

(all concurrent languages and environments offer efficient and higher-abstraction synchronization methods)

☞ Special (usually close-to-hardware) applications exist.

278

Communication & Synchronization

Distributed synchronization

Conditional Critical Regions

Basic idea:

- Critical regions are a *set of associated 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 to false, the process is suspended / delayed.
- Generally, no access order can be assumed ☞ potential livelocks

279

Communication & Synchronization

Distributed synchronization

Conditional Critical Regions

```
buffer : buffer_t;
resource critial_buffer_region : buffer;

process producer;                          process consumer;
  loop                                       loop
    region critial_buffer_region               region critial_buffer_region
      when buffer.size < N do                    when buffer.size > 0 do
        ------ place in buffer etc.                ------ take from buffer etc.
    end region;                                end region;
  end loop;                                  end loop;
end producer;                              end consumer;
```


280

Communication & Synchronization

Distributed synchronization

Review of Conditional Critical Regions

- Well formed synchronization blocks and synchronization conditions.
- Code, data and synchronization primitives are associated (known to compiler and runtime).
- 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
- Condition synchronisation inside the critical code sections requires to leave and re-enter a critical region.
- As with semaphores the conditional critical regions are distributed all over the code.
  ☞ on a larger scale: same problems as with semaphores.

(The language Edison (Per Brinch Hansen, 1981) uses conditional critical regions for synchronization in a multiprocessor environment (each process is associated with exactly one processor).)

281

Communication & Synchronization

Centralized synchronization

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.

282

Communication & Synchronization

Centralized synchronization

Monitors

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

How to implement conditional synchronization?

283

Communication & Synchronization

Centralized synchronization

Monitors with condition synchronization

(Hoare '74)

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.

284

Communication & Synchronization

Centralized synchronization

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; …
```


285

Communication & Synchronization

Centralized synchronization

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!

286

Communication & Synchronization

Centralized synchronization

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 re-gain access to the monitor.

287

Communication & Synchronization

Centralized synchronization

Monitors in Modula-1

- `procedure wait (s, r)`:
  delays the caller until condition variable s is true (r is the rank (or 'priority') of the caller).
- `procedure 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).
- `function awaited (s) return integer`:
  check for waiting processes on s.

288

Communication & Synchronization

Centralized synchronization

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.
```


289

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
…
```


290

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
…
```

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
- …

291

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
…
```

Undefined while locked

Undefined while threads are waiting

292

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
```

unblocks *'at least one'* thread

unblocks *all* threads

293

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
```

undefined

if called 'out of order' i.e. mutex is not locked

294

Communication & Synchronization

Centralized synchronization

Monitors in POSIX ('C')

(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);
```

can be called

- any time
- anywhere
- multiple times

295

Communication & Synchronization

Centralized synchronization

```
#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;

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;
}
```


296

Communication & Synchronization

Centralized synchronization

```
#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;

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;
}
```

need to be called with a locked mutex

better to be called *after* unlocking all mutexes (as it is itself potentially blocking)

297

Communication & Synchronization

Centralized synchronization

Monitors in C#

```
using System;
using System.Threading;

static long data_to_protect = 0;

static void Reader()
  { try {
      Monitor.Enter (data_to_protect);
      Monitor.Wait  (data_to_protect);
      … read out protected data
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  }

static void Writer()
  { try {
      Monitor.Enter (data_to_protect);
      … write protected data
      Monitor.Pulse (data_to_protect);
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  }
```


298

Communication & Synchronization

Centralized synchronization

Monitors in Visual C++

```
using namespace System;
using namespace System::Threading

private: integer data_to_protect;

void Reader()
  { try {
      Monitor::Enter (data_to_protect);
      Monitor::Wait  (data_to_protect);
      … read out protected data
    }
    finally {
      Monitor::Exit  (data_to_protect);
    }
  };

void Writer()
  { try {
      Monitor::Enter (data_to_protect);
      … write protected data
      Monitor::Pulse (data_to_protect);
    }
    finally {
      Monitor.Exit  (data_to_protect);
    }
  };
```


299

Communication & Synchronization

Centralized synchronization

Monitors in Visual Basic

```
Imports System
Imports System.Threading

Private Dim data_to_protect As Integer = 0

Public Sub Reader
  Try
    Monitor.Enter (data_to_protect)
    Monitor.Wait  (data_to_protect)
    … read out protected data
  Finally
    Monitor.Exit  (data_to_protect)
  End Try
End Sub

Public Sub Writer
  Try
    Monitor.Enter (data_to_protect)
    … write protected data
    Monitor.Pulse (data_to_protect)
  Finally
    Monitor.Exit  (data_to_protect)
  End Try
End Sub
```


300

Communication & Synchronization

Centralized synchronization

Monitors in Java

```
Monitor mon = new Monitor();
Monitor.Condition Condvar = mon.new Condition();

public void reader
  throws InterruptedException {
    mon.enter();
    Condvar.await();
    … read out protected data
    mon.leave();
  }

public void writer
  throws InterruptedException {
    mon.enter();
    … write protected data
    Condvar.signal();
    mon.leave();
  }
```

… the Java library monitor connects data or condition variables to the monitor by convention only!

301

Communication & Synchronization

Centralized synchronization

Monitors in Java

(by means of language primitives)

Java provides two mechanisms to construct a monitors-like structure:

- **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.

Communication & Synchronization

Centralized synchronization

Monitors in Java

(by means of language primitives)

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 a Java monitor and enter at any time.
- Methods outside the monitor-object can synchronize at this object.
  ☞ it is impossible to analyse a Java 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.

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

Communication & Synchronization

Centralized synchronization

Monitors in Java

(by means of language primitives)

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 associated with the monitor or data.
  ☞ notified threads need to wait for the lock to be released **and** to re-evaluate its entry condition.

Communication & Synchronization

Centralized synchronization

Monitors in Java

(by means of language primitives)

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 *adequate* 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 or interfering with this monitor-object in any way ☞ by convention.

Communication & Synchronization

Centralized synchronization

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 ();
…
```


Communication & Synchronization

Centralized synchronization

Monitors in Java

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

```
… 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 ();
     }
  } …
```


Communication & Synchronization

Centralized synchronization

Monitors in Java

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

```
… 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;
              }
  } } } } …
```


Communication & Synchronization

Centralized synchronization

Monitors in Java

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

```
… 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 ();
     }
  } …
```


Communication & Synchronization

Centralized synchronization

Monitors in Java

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

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


Communication & Synchronization

Centralized synchronization

Monitors in Java

Per Brinch Hansen (1938-2007) in 1999:

> *Java's most serious mistake was the decision to use the sequential part of the language to implement the run-time support for its parallel features. It strikes me as absurd to write a compiler for the sequential language concepts only and then attempt to skip the much more difficult task of implementing a secure parallel notation. This wishful thinking is part of Java's unfortunate inheritance of the insecure C language and its primitive, error-prone library of threads methods.*

"Per Brinch Hansen is one of a handful of computer pioneers who was responsible for advancing both operating systems development and concurrent programming from ad hoc techniques to systematic engineering disciplines." (from his IEEE 2002 Computer Pioneer Award)

Communication & Synchronization

Centralized synchronization

Object-orientation and synchronization

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

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

Re-usage concepts of object-oriented programming do not translate to synchronized classes (e.g. monitors) and thus 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, yet they are complex and not offered in any concurrent programming language.
Alternatively, inheritance can be banned in the context of synchronization (e.g. Ada).

Communication & Synchronization

Centralized synchronization

Monitors in POSIX, Visual C++, C#, Visual Basic & Java

☞ All provide lower-level primitives for the construction of monitors.
☞ All rely on **convention** rather than compiler checks.
☞ Visual C++, C+ & Visual Basic offer data-encapsulation and connection to the monitor.
☞ Java offers data-encapsulation (yet not with respect to a monitor).
☞ POSIX (being a collection of library calls) does not provide any data-encapsulation by itself.

☞ Extreme care must be taken when employing object-oriented programming and synchronization (incl. monitors)

Communication & Synchronization

Centralized synchronization

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 monitor calls: e.g. Modula-1
- Provide constructs which specify the release of a monitor lock for remote calls, e.g. Ada

Communication & Synchronization

Centralized synchronization

Criticism of monitors

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

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

Communication & Synchronization

Centralized synchronization

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**.
- Operations are **mutual exclusive** (with exceptions for read-only operations).
- **Guards** (predicates) are **syntactically attached** to entries.
- **No** protected data is accessible (other than by the defined operations).
- **Fairness** inside operations is guaranteed by **queuing** (according to their priorities).
- **Fairness** across all operations is guaranteed by the "internal progress first" rule.
- Re-blocking provided by **re-queuing** to entries (no internal condition variables).

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Simultaneous read-access)

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

```
protected type Shared_Data (Initial : Data_Item) is
   function  Read return Data_Item;
   procedure Write (New_Value : 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 Ada.

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Condition synchronization: entries & barriers)

Condition synchronization is realized in the form of **protected procedures** combined with boolean predicates (**barriers**): ☞ called **entries** in Ada:

```
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 :     Data_Item);
private
   First  : Index := Index'First;
   Last   : Index := Index'Last;
   Num    : Count := 0;
   Buffer : Buffer_T;
end Bounded_Buffer;
```

318

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Condition synchronization: entries & 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 : Data_Item) when Num < Buffer_Size is
      begin
         Last          := Last + 1;
         Buffer (Last) := Item;
         Num           := Num + 1;
      end Put;
end Bounded_Buffer;
```


319

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Withdrawing entry calls)

```
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;
```


320

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Withdrawing entry calls)

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

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


321

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Barrier evaluation)

Barrier in protected objects need to be evaluated only on two occasions:

- on *creating a protected object*,
  all barrier are evaluated according to the initial values of the internal, protected data.
- on *leaving a protected procedure or entry*,
  all potentially altered barriers are re-evaluated.

Alternatively an implementation may choose to evaluate barriers on those two occasions:

- on *calling a protected entry*,
  the one associated barrier is evaluated.
- on *leaving a protected procedure or entry*,
  all potentially altered barriers with tasks queued up on them are re-evaluated.

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

322

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Operations on entry queues)

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

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

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


323

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(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:     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: Message) is
   begin
     New_Message := M;
     Arrived     := Receive'count > 0;
   end Send;
end Broadcast;
```


324

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

Additional, essential primitives for concurrent control flows:

- **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: external tasks are only considered for queuing on barriers once no internally requeued task can be progressed any further!

- **Private entries:**
  Protected entries which are not accessible from outside the protected object, but can be employed as destinations for requeue operations.

325

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Entry families)

```
package Modes is
  type Mode_T is
    (Takeoff, Ascent, Cruising,
     Descent, Landing);
  protected Mode_Gate is
   procedure Set_Mode (Mode: 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: 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;
```


326

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

How to moderate the flow of incoming calls to a busy server farm?

```
type Urgency     is (urgent, not_so_urgent);
type Server_Farm is (primary, secondary);
protected Pre_Filter is
   entry Reception (U : Urgency);
private
   entry Server (Server_Farm) (U : Urgency);
end Pre_Filter;
```


327

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Entry families, requeue & private entries)

```
protected body Pre_Filter is
   entry Reception (U : Urgency)
     when Server (primary)'count = 0 or else Server (secondary)'count = 0 is
   begin
      If U = urgent and then Server (primary)'count = 0 then
         requeue Server (primary);
      else
         requeue Server (secondary);
      end if;
   end Reception;
   entry Server (for S in Server_Farm) (U : Urgency) when True is
   begin null; -- might try something even more useful
   end Server;
end Pre_Filter;
```


328

Communication & Synchronization

Centralized synchronization

Synchronization by protected objects

(Restrictions for protected operations)

All code inside a protected procedure, function or entry is bound to non-blocking operations.

Thus the following operations are prohibited:

- entry call statements
- delay statements
- task creations or activations
- select statements
- accept statements
- … as well as calls to sub-programs which contain any of the above

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

329

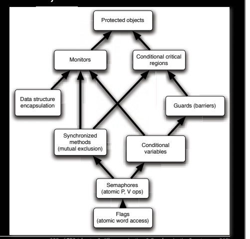
Communication & Synchronization

Shared memory based synchronization

General

Criteria:

- *Levels of abstraction*
- *Centralized versus distributed*
- *Support for automated (compiler based) consistency and correctness validation*
- *Error sensitivity*
- *Predictability*
- *Efficiency*



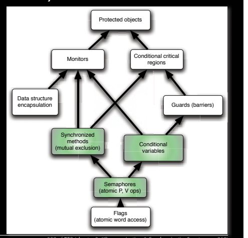
330

Communication & Synchronization

Shared memory based synchronization

POSIX

- *All low level constructs available*
- *Connection with the actual data-structures by means of convention only*
- *Extremely error-prone*
- *Degree of non-determinism introduced by the 'release some' semantic*
- *'C' based*
- *Portable*



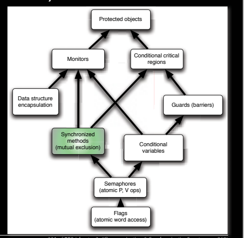
331

Communication & Synchronization

Shared memory based synchronization

Java

- *Mutual exclusion available.*
- *General notification feature (not connected to other locks, hence not a conditional variable)*
- *Universal object orientation makes local analysis hard or even impossible*
- *Mixture of high-level object oriented features and low level concurrency primitives*



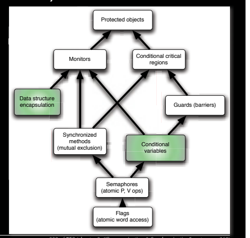
332

Communication & Synchronization

Shared memory based synchronization

C#, Visual C++, Visual Basic

- *Mutual exclusion via library calls (convention)*
- *Data is associated with the locks to protect it*
- *Condition variables related to the data protection locks*
- *Mixture of high-level object oriented features and low level concurrency primitives*



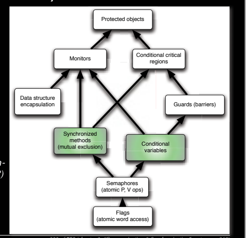
333

Communication & Synchronization

Shared memory based synchronization

C++14

- *Mutual exclusion in scopes*
- *Data is not strictly associated with the locks to protect it*
- *Condition variables related to the mutual exclusion locks*
- *Set of essential primitives without combining them in a syntactically strict form (yet?)*

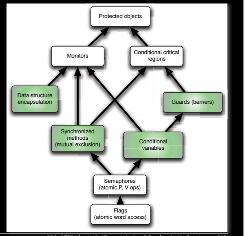


Communication & Synchronization

Shared memory based synchronization

Rust

- *Mutual exclusion in scopes*
- *Data is strictly associated with locks to protect it*
- *Condition variables related to the mutual exclusion locks*
- *Combined with the message passing semantics already a power set of tools.*
- *Concurrency features migrated to a standard library.*



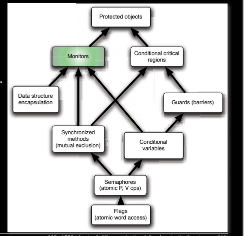
Communication & Synchronization

Shared memory based synchronization

Modula-1, Chill, Parallel Pascal, …

- *Full implementation of the Dijkstra / Hoare monitor concept*

*The term **monitor** appears in many other concurrent languages, yet it is usually not associated with an actual language primitive.*



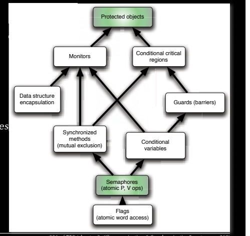
Communication & Synchronization

Shared memory based synchronization

Ada

- *High-level synchronization support which scales to large size projects.*
- *Full compiler support incl. potential deadlock analysis*
- *Low-Level semaphores for very special cases*

Ada has still no mainstream competitor in the field of explicit concurrency. (2018)



Communication & Synchronization

High Performance Computing

Synchronization in large scale concurrency

High Performance Computing (HPC) emphasizes on keeping as many CPU nodes busy as possible:

☞ Avoid contention on sparse resources.

☞ Data is assigned to individual processes rather than processes synchronizing on data.

☞ Data integrity is achieved by keeping the CPU nodes in approximate "lock-step", yet there is still a need to re-sync concurrent entities.

Traditionally this has been implemented using the Message Passing Interface (MPI) while implementing separate address spaces.

☞ Current approaches employ partitioned address spaces, i.e. memory spaces can overlap and be re-assigned. ☞ Chapel, Fortress, X10.

☞ Not all algorithms break down into independent computation slices and so there is a need for memory integrity mechanisms in shared/partitioned address spaces.

Communication & Synchronization

Current developments

Atomic operations in X10

X10 offers only atomic blocks in unconditional and conditional form.

- Unconditional atomic blocks are guaranteed to be non-blocking, which means that they cannot be nested and need to be implemented using roll-backs.
- Conditional atomic blocks can also be used as a pure notification system (similar to the Java notify method).
- Parallel statements (incl. parallel, i.e. unrolled 'loops').
- Shared variables (and their access mechanisms) are not defined.
- The programmer does not specify the scope of the locks (atomic blocks) but they are managed by the compiler/runtime environment.

☞ Code analysis algorithms are required in order to provide efficiently, otherwise the runtime environment needs to associate every atomic block with a *global* lock.

Communication & Synchronization

Current developments

Synchronization in Chapel

Chapel offers a variety of concurrent primitives:

- Parallel operations on data (e.g. concurrent array operations)
- Parallel statements (incl. parallel, i.e. unrolled 'loops')
- Parallelism can also be explicitly limited by serializing statements
- Atomic blocks for the purpose to construct atomic transactions
- Memory integrity needs to be programmed by means of synchronization statements (waiting for one or multiple control flows to complete) and/or atomic blocks

Further Chapel semantics are still forthcoming … so there is still hope for a stronger shared memory synchronization / memory integrity construct.

Communication & Synchronization

Synchronization

Message-based synchronization

Synchronization model

- Asynchronous
- Synchronous
- Remote invocation

Addressing (name space)

- direct communication
- mail-box communication

Message structure

- arbitrary
- restricted to 'basic' types
- restricted to un-typed communications

Communication & Synchronization

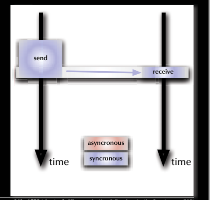
Message-based synchronization

Message protocols

Synchronous message (sender waiting)

Delay the sender process until

- Receiver becomes available
- Receiver acknowledges reception



Communication & Synchronization

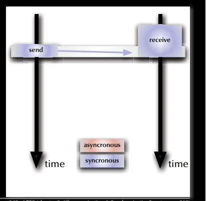
Message-based synchronization

Message protocols

Synchronous message (receiver waiting)

Delay the receiver process until

- Sender becomes available
- Sender concludes transmission



Communication & Synchronization

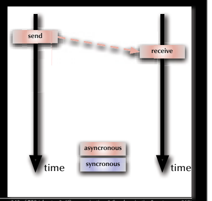
Message-based synchronization

Message protocols

Asynchronous message

Neither the sender nor the receiver is blocked:

- Message is not transferred directly
- A buffer is required to store the messages
- Policy required for buffer sizes and buffer overflow situations



Communication & Synchronization

Message-based synchronization

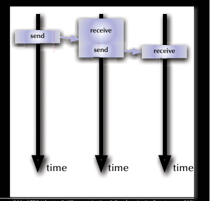
Message protocols

Asynchronous message (simulated by synchronous messages)

Introducing an intermediate process:

- Intermediate needs to be accepting messages at all times.
- Intermediate also needs to send out messages on request.

☞ While processes are blocked in the sense of synchronous message passing, they are not actually delayed as the intermediate is always ready.



Communication & Synchronization

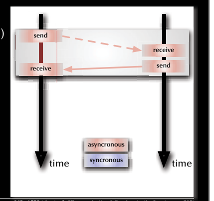
Message-based synchronization

Message protocols

Synchronous message (simulated by asynchronous messages)

Introducing two asynchronous messages:

- Both processes voluntarily suspend themselves until the transaction is complete.
- As no immediate communication takes place, the processes are never actually synchronized.
- The sender (but not the receiver) process knows that the transaction is complete.



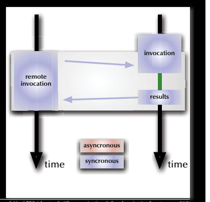
Communication & Synchronization

Message-based synchronization

Message protocols

Remote invocation

- Delay sender or receiver until the first rendezvous point
- Pass parameters
- Keep sender blocked while receiver executes the local procedure
- Pass results
- Release both processes out of the rendezvous



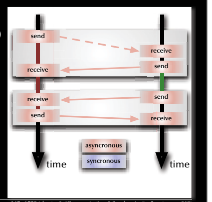
Communication & Synchronization

Message-based synchronization

Message protocols

Remote invocation (simulated by asynchronous messages)

- Simulate two synchronous messages
- Processes are never actually synchronized



Communication & Synchronization

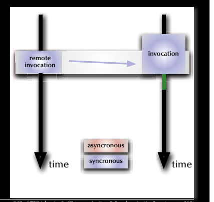
Message-based synchronization

Message protocols

Remote invocation (no results)

Shorter form of remote invocation which does not wait for results to be passed back.

- Still both processes are actually synchronized at the time of the invocation.



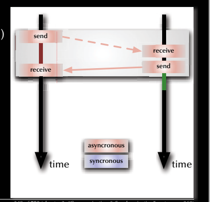
Communication & Synchronization

Message-based synchronization

Message protocols

Remote invocation (no results) (simulated by asynchronous messages)

- Simulate one synchronous message
- Processes are never actually synchronized



Communication & Synchronization

Message-based synchronization

Synchronous vs. asynchronous communications

Purpose '**synchronization**': ☞ synchronous messages / remote invocations
Purpose '**last message(s) only**': ☞ asynchronous messages

☞ Synchronous message passing in distributed systems requires hardware support.
☞ Asynchronous message passing requires the usage of buffers and overflow policies.

Can both communication modes emulate each other?

Communication & Synchronization

Message-based synchronization

Synchronous vs. asynchronous communications

Purpose '**synchronization**': ☞ synchronous messages / remote invocations
Purpose '**last message(s) only**': ☞ asynchronous messages

☞ Synchronous message passing in distributed systems requires hardware support.
☞ Asynchronous message passing requires the usage of buffers and overflow policies.

Can both communication modes emulate each other?

- *Synchronous communications* are emulated by a combination of asynchronous messages in some systems (not identical with hardware supported synchronous communication).
- *Asynchronous communications* can be emulated in synchronized message passing systems by introducing a 'buffer-task' (de-coupling sender and receiver as well as allowing for broadcasts).

Communication & Synchronization

Message-based synchronization

Addressing (name space)

Direct versus 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

Communication & Synchronization

Message-based synchronization

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

Communication & Synchronization

Message-based synchronization

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)
… semi-automatic (CORBA)
… automatic (compiler-generated) and typed-persistent (Ada, CHILL, Occam2)

Communication & Synchronization

Message-based synchronization

Message structure (Ada)

```
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;
```


Communication & Synchronization

Message-based synchronization

Message structure (Ada)

Reading and writing values of any subtype S of a specific type T 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 subtype S of a specific type T 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;
```


Communication & Synchronization

Message-based synchronization

Message-passing systems examples:

POSIX: "**message queues**":
☞ ordered indirect [asymmetrical | symmetrical] asynchronous byte-level many-to-many message passing

MPI: "**message passing**":
☞ ordered [direct | indirect] [asymmetrical | symmetrical] asynchronous memory-block-level [one-to-one | one-to-many | many-to-one | 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**":
☞ ordered indirect symmetrical synchronous fully-typed one-to-one message passing

Ada: "**(extended) rendezvous**":
☞ ordered direct asymmetrical [synchronous | asynchronous] fully-typed many-to-one remote invocation

Java: ☞ no message passing system defined

Communication & Synchronization

Message-based synchronization

Message-passing systems examples:

	ordered	symmetrical	asymmetrical	synchronous	asynchronous	direct	indirect	contents	one-to-one	many-to-one	many-to-many	method
POSIX:	✔	✔	✔		✔		✔	byte-stream			✔	message queues
MPI:	✔	✔	✔	✔	✔	✔	✔	memory-blocks	✔	✔	✔	message passing
CHILL:	✔	✔	✔	✔	✔		✔	basic types		✔	✔	message passing
Occam2:	✔	✔		✔			✔	fully typed	✔			message passing
Ada:	✔		✔	✔	✔	✔		fully typed		✔		remote invocation
Go:	✔	✔		✔	✔	✔		fully typed	✔			channels
Erlang:	✔	✔			✔	✔		fully typed	✔			message passing

Java: ☞ no message passing system defined

Communication & Synchronization

Message-based synchronization

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
```

concurrent entities are synchronized at these points

Communication & Synchronization

Message-based synchronization

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
```

Essential Occam2 keywords

```
ALT PAR SEQ PRI
ANY CHAN OF
DATA TYPE RECORD OFFSETOF PACKED
BOOL BYTE INT REAL
CASE IF ELSE FOR FROM WHILE
FUNCTION RESULT PROC IS
PROCESSOR PROTOCOL TIMER
SKIP STOP VALOF
```

☞ *Concurrent, distributed, real-time programming language!*

Communication & Synchronization

Message-based synchronization

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;

…                                       receive case
send SensorBuffer (reading);               (SensorBuffer in data) : …
                                        esac;

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


Communication & Synchronization

Message-based synchronization

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;

…                                            receive case
send SensorBuffer (reading) —asynchronous→ (SensorBuffer in data) : …
                                             esac;

signal SensorChannel = (int) to consumertype;
…
send SensorChannel (reading)                 receive case
   to consumer      —synchronous→          (SensorChannel in data): …
                                             esac;
```


Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

Ada 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 then:
☞ 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**')

Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

(Rendezvous)

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

time time

Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

(Extended rendezvous)

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

time time

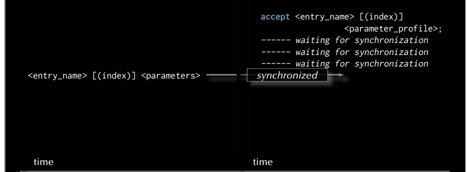
366

Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

(Rendezvous)



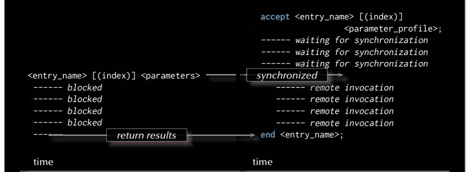
367

Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

(Extended rendezvous)



368

Communication & Synchronization

Message-based synchronization

Message-based synchronization in Ada

Some things to consider for task-entries:

- In contrast to protected-object-entries, task-entry bodies *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 which owns the entry.
- **Entry families** (arrays of entries) are supported.
- **Private entries** (accessible for internal tasks) are supported.

369

Communication & Synchronization

Summary

Communication & 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

370

Systems, Networks & Concurrency 2020

4

Non-determinism

Uwe R. Zimmer - The Australian National University

371

Non-determinism

References for this chapter

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

[Barnes2006]
Barnes, John
Programming in Ada 2005
Addison-Wesley, Pearson education, ISBN-13 978-0-321-34078-8, Harlow, England, 2006

[AdaRM2012]
Ada Reference Manual - Language and Standard Libraries;
ISO/IEC 8652:201x (E)

372

Non-determinism

Definitions

Non-determinism *by design*:

A property of a computation which may have more than one result.

Non-determinism *by interaction*:

A property of the operation environment which may lead to different sequences of (concurrent) stimuli.

373

Non-determinism

Non-determinism by design

Dijkstra's **guarded commands** (non-deterministic case statements):

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

Selection is non-deterministc for x=y

☞ 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

All true case statements in any language are potentially concurrent and non-deterministic.

374

Non-determinism

Non-determinism by design

Dijkstra's **guarded commands** (non-deterministic case statements):

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

Selection is non-deterministc for x=y

☞ 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

All true case statements in any language are potentially concurrent and non-deterministic.

Numerical non-determinism in **concurrent statements** (Chapel):

```
writeln (* reduce [i in 1..10] exp (i));
writeln (+ reduce [i in 1..1000000] i ** 2.0);
```

Results may be non-deterministc depending on numeric type

☞ The programmer needs to understand the numerical implications of out-of-order expressions.

375

Non-determinism

Non-determinism by design

Motivation for non-deterministic design

By explicitly leaving the sequence of evaluation or execution undetermined:

☞ The compiler / runtime environment can directly (i.e. without any analysis) translate the source code into a concurrent implementation.

☞ The implementation gains potentially significantly in performance

☞ The programmer does not need to handle any of the details of a concurrent implementation (access locks, messages, synchronizations, …)

A programming language which allows for those formulations is required!

☞ current language support: Ada, X10, Chapel, Fortress, Haskell, OCaml, …

376

Non-determinism

Non-determinism by interaction

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).

377

Non-determinism

Non-determinism by interaction

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 (channels are directed in Occam2):
  ☞ to initiate the sending of data (Take ! Buffer [Base]), a request need to be made first which triggers the condition: (Request ? ANY)

CSP (Communicating Sequential Processes, Hoare 1978) also supports non-deterministic selective waiting

378

Non-determinism

Non-determinism by interaction

Select function in POSIX

```
int pselect(int n, fd_set *readfds, fd_set *writefds, fd_set *exceptfds,
            const struct timespec *ntimeout, sigset_t *sigmask);
```

with:

- n being one more than the maximum of any file descriptor in any of the sets.
- after return the sets will have been reduced to the channels which have been triggered.
- the return value is used as success / failure indicator.

The POSIX select function implements parts of general selective waiting:

- pselect returns if one or multiple I/O channels have been triggered or an error occured.

¬ Branching into individual code sections is not provided.

¬ Guards are not provided.

After return it is required that the following code implements a *sequential* testing of *all* channels in the sets.

379

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

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

380

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

```
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;

accept_statement ::= accept entry_direct_name [(entry_index)] parameter_profile [do
                        handled_sequence_of_statements
                     end [entry_identifier]];
delay_statement  ::= delay until delay_expression; | delay delay_expression;
```


381

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-accept)

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

- *If none of the entries have waiting calls*
  ☞ **the process is suspended** until a call arrives.
- *If exactly one of the entries has waiting calls*
  ☞ **this entry is selected.**
- *If multiple entries have waiting calls*
  ☞ **one of those is selected** (non-deterministically). The selection can be prioritized by means of the real-time-systems annex.

The code following the selected entry (if any) is executed and the select statement completes.

382

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept)

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

- *If all conditions are* 'true'
  ☞ **identical to the previous form.**
- *If some condition evaluate to* 'true'
  ☞ **the accept statement after those conditions are treated like in the previous form.**
- *If all conditions evaluate to* 'false'
  ☞ Program_Error **is raised.**
  Hence it is important that the set of conditions covers all possible states.

This form is identical to Dijkstra's guarded commands.

383

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-else)

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

- *If all currently open entries have no waiting calls or all entries are closed*
  ☞ **The else alternative is chosen**, the associated statements executed and the select statement completes.
- Otherwise ☞ **one of the open entries with waiting calls is chosen as above.**

This form never suspends the task.

This enables a task to *withdraw* its offer to accept a set of calls if no tasks are currently waiting.

384

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-delay)

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

- *If none of the open entries have waiting calls before the deadline specified by the earliest open* **delay** *alternative*
  ☞ **This earliest delay alternative is chosen** and the statements associated with it executed.
- *Otherwise* ☞ **one of the open entries with waiting calls is chosen as above.**

This enables a task to *withdraw* its offer to accept a set of calls if no other task is calling after some time.

385

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-terminate)

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

terminate cannot be mixed with else or delay

- *If none of the open entries have waiting calls and none of them can ever be called again*
  ☞ **The terminate alternative is chosen, i.e. the task is terminated.**

This situation occurs if:

☞ … all tasks which can possibly call on any of the open entries are terminated.

☞ or … all remaining tasks which can possibly call on any of the open entries are waiting on select-terminate statements themselves and none of their open entries can be called either. In this case all those waiting-for-termination tasks are terminated as well.

386

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

Forms of selective waiting:

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

… underlying concept: Dijkstra’s guarded commands

`conditional_entry_call` and `timed_entry_call` implements …

… the possibility to withdraw an outgoing call.

… this might be restricted if calls have already been partly processed.

387

Non-determinism

Selective Synchronization

Conditional entry-calls

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

Example:

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

- *If the call is not accepted immediately*
  ☞ **The `else` alternative is chosen.**

This is e.g. useful to probe the state of a server before committing to a potentially blocking call.

Even though it is tempting to use this statement in a “busy-waiting” semantic, there is usually no need to do so, as better alternatives are available.

There is only *one* entry-call and *one* else alternative.

388

Non-determinism

Selective Synchronization

Timed entry-calls

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

Example:

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

- *If the call is not accepted before the deadline specified by the* `delay` *alternative*
  ☞ **The `delay` alternative is chosen.**

This is e.g. useful to withdraw an entry call after some specified time-out.

There is only *one* entry-call and *one* `delay` alternative.

389

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

Forms of selective waiting:

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

… underlying concept: Dijkstra’s guarded commands

`asynchronous_select` implements …

… the possibility to escape a running code block due to an event from outside this task.
(outside the scope of this course ☞ check: Real-Time Systems)

390

Non-determinism

Non-determinism

Sources of Non-determinism

As concurrent entities are not in “lockstep” synchronization, they “overtake” each other and arrive at synchronization points in non-deterministic order, due to (just a few):

- Operating systems / runtime environments:
  ☞ Schedulers are often non-deterministic.
  ☞ System load will have an influence on concurrent execution.
  ☞ Message passing systems react load depended.
- Networks & communication systems:
  ☞ Traffic will arrive in an unpredictable way (non-deterministic).
  ☞ Communication systems congestions are generally unpredictable.
- Computing hardware:
  ☞ Timers drift and clocks have granularities.
  ☞ Processors have out-of-order units.
- … basically: **Physical systems** (and **computer systems connected to the physical world**) are *intrinsically non-deterministic*.

391

Non-determinism

Non-determinism

Correctness of non-deterministic programs

Partial correctness:

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

Total correctness:

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

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

392

Non-determinism

Non-determinism

Correctness of non-deterministic programs

☞ Correctness predicates need to hold true *irrespective* of the actual sequence of interaction points.

or

☞ Correctness predicates need to hold true *for all possible* sequences of interaction points.

Therefore correctness predicates need to be based on **invariants**, i.e. **invariant** predicates which are *independent* of the potential execution sequences, *yet* support the overall correctness predicates.

393

Non-determinism

Non-determinism

Correctness of non-deterministic programs

For example (in verbal form):
“Mutual exclusion accessing a specific resource holds true, *for all possible* numbers, sequences or interleavings of requests to it”

An **invariant** would for instance be that the number of writing tasks inside a protected object is less or equal to one.

☞ Those **invariants** are the only practical way to guarantee (in a logical sense) correctness in concurrent / non-deterministic systems.

(as enumerating all possible cases and proving them individually is in general not feasible)

394

Non-determinism

Non-determinism

Correctness of non-deterministic programs

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

Concrete:

☞ Every time you formulate a non-determinstic statement like the one on the left you need to formulate an **invariant** which holds true whichever alternative will actually be chosen.

This is very similar to finding **loop invariants** in sequential programs

395

Non-determinism

Summary

Non-Determinism

- **Non-determimism by design:**
  - Benefits & considerations
- **Non-determinism by interaction:**
  - Selective synchronization
  - Selective accepts
  - Selective calls
- **Correctness of non-deterministic programs:**
  - Sources of non-determinism
  - Predicates & invariants

Systems, Networks & Concurrency 2020

5

Data Parallelism

Uwe R. Zimmer - The Australian National University

Data Parallelism

References

[Bacon98]
J. Bacon
Concurrent Systems
1998 (2nd Edition) Addison Wesley Longman Ltd, ISBN 0-201-17767-6

[Ada 2012 Language Reference Manual]
see course pages or http://www.ada-auth.org/standards/ada12.html

[Chapel 1.13 Language Specification Version 0.981]
see course pages or
http://chapel.cray.com/docs/latest/_downloads/chapelLanguageSpec.pdf
released on 7. April 2016

Data Parallelism

Vector Machines

Vectorization

```
type Real_Precision = Float
type Scalar = Real_Precision
type Vector = [Real_Precision]
scale :: Scalar -> Vector -> Vector
scale scalar vector = map (scalar *) vector
```


Data Parallelism

Vector Machines

Vectorization

Potentially concurrent, yet:

Executed sequentially.

```
type Real_Precision = Float
type Scalar = Real_Precision
type Vector = [Real_Precision]
scale :: Scalar -> Vector -> Vector
scale scalar vector = map (scalar *) vector
```


Data Parallelism

Vector Machines

Vectorization

```
import Control.Parallel.Strategies
type Real_Precision = Float
type Scalar = Real_Precision
type Vector = [Real_Precision]
scale :: Scalar -> Vector -> Vector
scale scalar vector = parMap rpar (scalar *) vector
```

Executed in parallel.

This **may be faster or slower** than a sequential execution.

Data Parallelism

Vector Machines

Vectorization

```
type Real    is digits 15;
type Vectors is array (Positive range <>) of Real;
function Scale (Scalar : Real; Vector : Vectors) return Vectors is
    Scaled_Vector : Vectors (Vector'Range);
  begin
    for i in Vector'Range loop
      Scaled_Vector (i) := Scalar * Vector (i);
    end loop;
    return Scaled_Vector;
  end Scale;
```


Data Parallelism

Vector Machines

Vectorization

Buzzword collection:
AltiVec, SPE, MMX, SSE, NEON, SPU, AVX, …

Translates into
CPU-level vector operations

```
type Real    is digits 15;
type Vectors is array (Positive range <>) of Real;
function Scale (Scalar : Real; Vector : Vectors) return Vectors is
    Scaled_Vector : Vectors (Vector'Range);
  begin
    for i in Vector'Range loop
      Scaled_Vector (i) := Scalar * Vector (i);
    end loop;
    return Scaled_Vector;
  end Scale;
```

Combined with
in-lining, **loop unrolling** and **caching**
this is as fast as a single CPU will get.

Data Parallelism

Vector Machines

Vectorization

Function is **“promoted”**

```
const Index = {1 .. 100000000},
      Vector   : [Index] real = 1.0,
      Scale    : real = 5.1,
      Scaled   : [Vector] real = Scale * Vector;
```


Data Parallelism

Vector Machines

Vectorization

Function is **“promoted”**

```
const Index = {1 .. 100000000},
      Vector   : [Index] real = 1.0,
      Scale    : real = 5.1,
      Scaled   : [Vector] real = Scale * Vector;
```

Translates into **CPU-level vector operations**
as well as **multi-core** or
fully distributed operations

Data Parallelism

Vector Machines

Reduction

```
type Real_Precision = Float
type Vector = [Real_Precision]
equal :: Vector -> Vector -> Bool
equal v_1 v_2 = foldr (&&) True $ zipWith (==) v_1 v_2
```


Data Parallelism

Vector Machines

Reduction

```
type Real_Precision = Float
type Vector = [Real_Precision]
equal :: Vector -> Vector -> Bool
equal v_1 v_2 = foldr (&&) True $ zipWith (==) v_1 v_2
```

Potentially concurrent, yet:

Executed lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
type Real_Precision = Float
type Vector = [Real_Precision]
equal :: Vector -> Vector -> Bool
equal = (==)
```

Potentially concurrent, yet:

Executed lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function "=" (Vector_1, Vector_2 : Vectors) return Boolean is
    (for all i in Vector_1'Range => Vector_1 (i) = Vector_2 (i));
```


Data Parallelism

Vector Machines

Reduction

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function "=" (Vector_1, Vector_2 : Vectors) return Boolean is
    (for all i in Vector_1'Range => Vector_1 (i) = Vector_2 (i));
```

Translates into
CPU-level vector operations

$\wedge$-chain is evaluated lazy sequentially.

Data Parallelism

Vector Machines

Reduction

Infinite recursion

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function "=" (Vector_1, Vector_2 : Vectors) return Boolean is (Vector_1 = Vector_2);
```

Translates into
CPU-level vector operations

$\wedge$-chain is evaluated lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function Equal (Vector_1, Vector_2 : Vectors) return Boolean is (Vector_1 = Vector_2);
```

Translates into
CPU-level vector operations

$\wedge$-chain is evaluated lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function Equal (Vector_1, Vector_2 : Vectors) return Boolean renames "=";
```

Translates into **CPU-level vector operations**

∧-chain is evaluated lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function "=" (Vector_1, Vector_2 : Vectors) return Boolean is
     (for all i in Vector_1'Range => Vector_1 (i) = Vector_2 (i));
```

Translates into **CPU-level vector operations**

∧-chain is evaluated lazy sequentially.

Data Parallelism

Vector Machines

Reduction

```
const Index = {1 .. 100000000},
      Vector_1, Vector_2 : [Index] real = 1.0;
proc Equal (v1, v2) : bool
   {return && reduce (v1 == v2);}
```

Function is **"promoted"**

Data Parallelism

Vector Machines

Reduction

```
const Index = {1 .. 100000000},
      Vector_1, Vector_2 : [Index] real = 1.0;
proc Equal (v1, v2) : bool
   {return && reduce (v1 == v2);}
```

-operations are evaluated in a **concurrent divide-and-conquer** (binary tree) structure.

Function is **"promoted"**

Translates into **CPU-level vector operations** *as well as* **multi-core** or **fully distributed operations**

Data Parallelism

Vector Machines

Reduction

```
const Index = {1 .. 100000000},
      Vector_1, Vector_2 : [Index] real = 1.0;
proc Equal (v1, v2) : bool
   {return v1 == v2;}
writeln (Equal (Vector_1, Vector_2));
```

Type mismatch

Data Parallelism

Vector Machines

General Data-parallelism

Data Parallelism

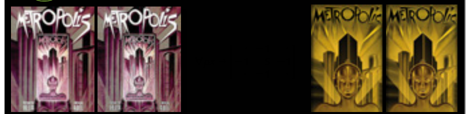
Vector Machines

General Data-parallelism

Data Parallelism

Vector Machines

General Data-parallelism



```
const Mask : [1 .. 3, 1 .. 3] real = ((0, -1, 0), (-1, 5, -1), (0, -1, 0));
```


Data Parallelism

Vector Machines

General Data-parallelism

```
const Mask : [1 .. 3, 1 .. 3] real = ((0, -1, 0), (-1, 5, -1), (0, -1, 0));
proc Unsharp_Mask (P, (i, j) : index (Image)) : real
   {return + reduce (Mask * P [i - 1 .. i + 1, j - 1 .. j + 1]);}
```


Data Parallelism

Vector Machines

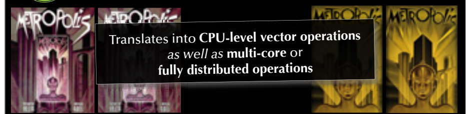
General Data-parallelism

```
const Mask : [1 .. 3, 1 .. 3] real = ((0, -1, 0), (-1, 5, -1), (0, -1, 0));
proc Unsharp_Mask (P, (i, j) : index (Image)) : real
   {return + reduce (Mask * P [i - 1 .. i + 1, j - 1 .. j + 1]);}
const Sharpened_Picture = forall px in Image do Unsharp_Mask (Picture, px);
```


Data Parallelism

Vector Machines

General Data-parallelism



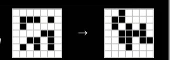
Translates into **CPU-level vector operations** *as well as* **multi-core** or **fully distributed operations**

```
const Mask : [1 .. 3, 1 .. 3] real = ((0, -1, 0), (-1, 5, -1), (0, -1, 0));
proc Unsharp_Mask (P, (i, j) : index (Image)) : real
   {return + reduce (Mask * P [i - 1 .. i + 1, j - 1 .. j + 1]);}
const Sharpened_Picture = forall px in Image do Unsharp_Mask (Picture, px);
```


Data Parallelism

Vector Machines

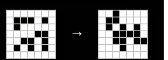
General Data-parallelism



Data Parallelism

Vector Machines

General Data-parallelism

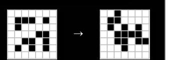


Cellular automaton transitions from a state S into the next state S':
$S \rightarrow S' \Leftrightarrow \forall c \in S: c \rightarrow c' = r(S, c)$, i.e. all cells of a state transition *concurrently* into new cells by following a rule r.

Data Parallelism

Vector Machines

General Data-parallelism



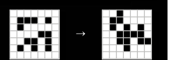
Cellular automaton transitions from a state S into the next state S':
$S \rightarrow S' \Leftrightarrow \forall c \in S: c \rightarrow c' = r(S, c)$, i.e. all cells of a state transition *concurrently* into new cells by following a rule r.

```
Next_State = forall World_Indices in World do Rule (State, World_Indices);
```


Data Parallelism

Vector Machines

General Data-parallelism



Cellular automaton transitions from a state S into the next state S':
$S \rightarrow S' \Leftrightarrow \forall c \in S: c \rightarrow c' = r(S, c)$, i.e. all cells of a state transition *concurrently* into new cells by following a rule r.

```
Next_State = forall World_Indices in World do Rule (State, World_Indices);
```

John Conway's **Game of Life** rule:

```
proc Rule (S, (i, j) : index (World)) : Cell {
  const Population : index ({0 .. 9}) =
                + reduce Count (Cell.Alive, S [i - 1 .. i + 1, j - 1 .. j + 1]);
  return (if Population == 3
         || (Population == 4 && S [i, j] == Cell.Alive) then Cell.Alive
                                                         else Cell.Dead);
}
```


Data Parallelism

Summary

Data Parallelism

- **Data-Parallelism**
  - Vectorization
  - Reduction
  - General data-parallelism
- **Examples**
  - Image processing
  - Cellular automata

Systems, Networks & Concurrency 2020

6

Scheduling

Uwe R. Zimmer - The Australian National University

Scheduling

References for this chapter

[Ben2006]
Ben-Ari, M
Principles of Concurrent and Distributed Programming
second edition, Prentice-Hall 2006

[AdaRM2012]
Ada Reference Manual - Language and Standard Libraries;
ISO/IEC 8652:201x (E)

[Stallings2001]
Stallings, William
Operating Systems
Prentice Hall, 2001

Scheduling

Motivation and definition of terms

Purpose of scheduling

Scheduling

Motivation and definition of terms

Purpose of scheduling

Two scenarios for scheduling algorithms:

1. Ordering resource assignments (CPU time, network access, …).
   ☞ live, on-line application of scheduling algorithms.
2. Predicting system behaviours under anticipated loads.
   ☞ simulated, off-line application of scheduling algorithms.

Predictions are used:

- *at compile time:* to confirm the feasibility of the system, or to predict resource needs, …
- *at run time:* to permit admittance of new requests or for load-balancing, …

Scheduling

Motivation and definition of terms

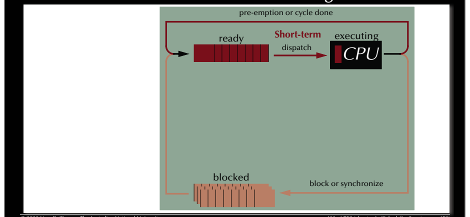
Criteria

	Performance criteria:	Predictability criteria:
Process / user perspective:		
	minimize the …	minimize *deviation* from given …
Waiting time	minima / maxima / average / variance	value / minima / maxima
Response time	minima / maxima / average / variance	value / minima / maxima / deadlines
Turnaround time	minima / maxima / average / variance	value / minima / maxima / deadlines
System perspective:		
	maximize the …	
Throughput	minima / maxima / average	
Utilization	CPU busy time	

Scheduling

Definition of terms

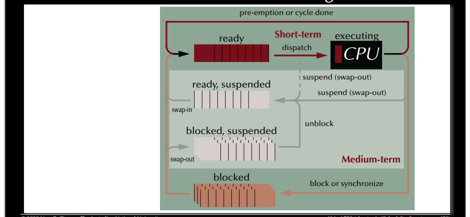
Time scales of scheduling



Scheduling

Definition of terms

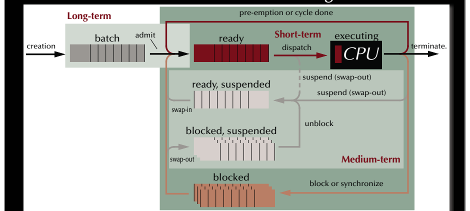
Time scales of scheduling



Scheduling

Definition of terms

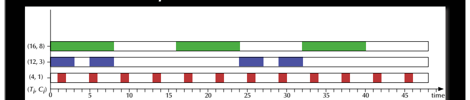
Time scales of scheduling



Scheduling

Performance scheduling

Requested resource times

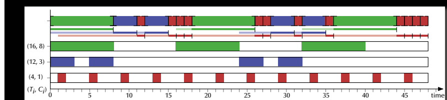


Tasks have an **average time between instantiations** of
and a constant **computation time** of

Scheduling

Performance scheduling

First come, first served (FCFS)



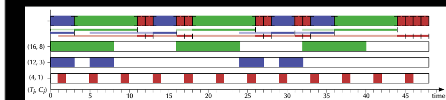
Waiting time: 0..11, average: 5.9 – **Turnaround time**: 3..12, average: 8.4

As tasks apply *concurrently* for resources, the actual sequence of arrival is non-deterministic.
☞ hence even a deterministic scheduling schema like FCFS can lead to different outcomes.

Scheduling

Performance scheduling

First come, first served (FCFS)



Waiting time: 0..11, average: 5.4 – **Turnaround time**: 3..12, average: 8.0

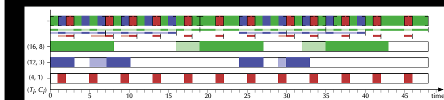
☞ In this example:
the average waiting times vary between 5.4 and 5.9
the average turnaround times vary between 8.0 and 8.4

☞ **Shortest possible maximal turnaround time!**

Scheduling

Performance scheduling

Round Robin (RR)



Waiting time: 0..5, average: 1.2 – **Turnaround time**: 1..20, average: 5.8

☞ Optimized for swift initial responses.
☞ "Stretches out" long tasks.

☞ **Bound maximal waiting time!** (depended only on the number of tasks)

Scheduling

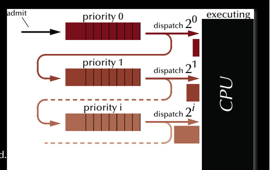
Performance scheduling

Feedback with 2^i pre-emption intervals

- 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**.

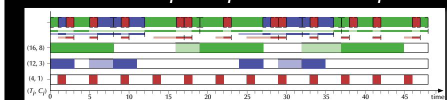
☞ New and short tasks will be preferred.



Scheduling

Performance scheduling

Feedback with 2^i pre-emption intervals - sequential



Waiting time: 0..5, average: 1.5 – **Turnaround time**: 1..21, average: 5.7

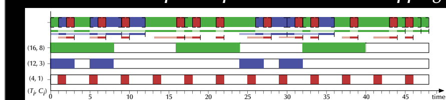
☞ Optimized for swift initial responses.
☞ Prefers short tasks and long tasks can suffer starvation.

☞ **Very short initial response times!** and good average turnaround times.

Scheduling

Performance scheduling

Feedback with 2^i pre-emption intervals - overlapping



Waiting time: 0..3, average: 0.9 – **Turnaround time**: 1..45, average: 7.7

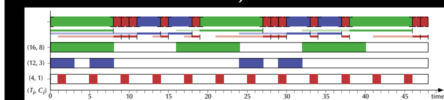
☞ Optimized for swift initial responses.
☞ Prefers short tasks and long tasks can suffer **starvation**.

☞ **Long tasks are delayed until all queues run empty!**

Scheduling

Performance scheduling

Shortest job first



Waiting time: 0..11, average: 3.7 – **Turnaround time**: 1..14, average: 6.3

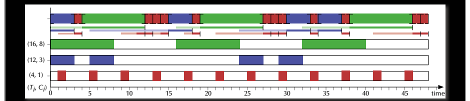
☞ Optimized for good average performance with minimal task-switches.
☞ Prefers short tasks but all tasks will be handled.

☞ **Good choice if computation times are known and task switches are expensive!**

Scheduling

Performance scheduling

Shortest job first



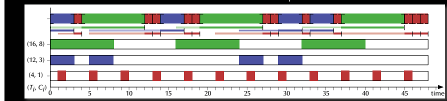
Waiting time: 0..10, average: 3.4 – **Turnaround time:** 1..14, average: 6.0

☞ Can be sensitive to non-deterministic arrival sequences.

Scheduling

Performance scheduling

Highest Response Ration $\frac{W_i + C_i}{C_i}$ First (HRRF)



Waiting time: 0..9, average: 4.1 – **Turnaround time:** 2..13, average: 6.6

☞ Blend between Shortest-Job-First and First-Come-First-Served.

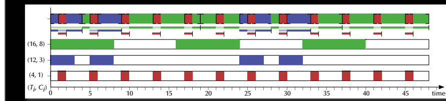
☞ Prefers short tasks but long tasks gain preference over time.

☞ **More task switches and worse averages than SJF but better upper bounds!**

Scheduling

Performance scheduling

Shortest Remaining Time First (SRTF)



Waiting time: 0..6, average: 0.7 – **Turnaround time:** 1..21, average: 4.4

☞ Optimized for good averages.

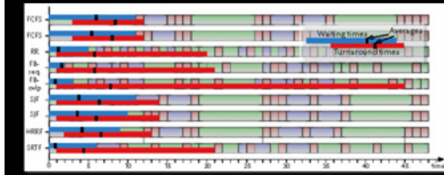
☞ Prefers short tasks and long tasks can suffer starvation..

☞ **Better averages than Feedback scheduling but with longer absolute waiting times!**

Scheduling

Performance scheduling

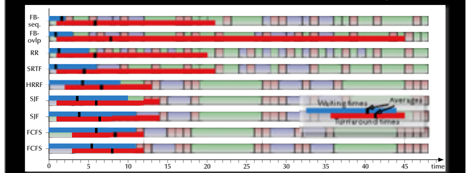
Comparison (in order of appearance)



Scheduling

Performance scheduling

Comparison by shortest maximal waiting

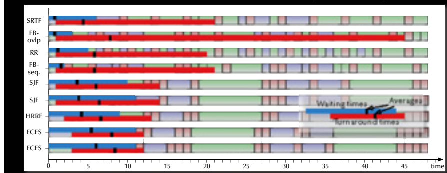


☞ Providing upper bounds to waiting times ☞ Swift response systems

Scheduling

Performance scheduling

Comparison by shortest average waiting

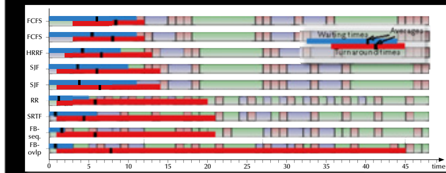


☞ Providing short average waiting times ☞ Very swift response in most cases

Scheduling

Performance scheduling

Comparison by shortest maximal turnaround

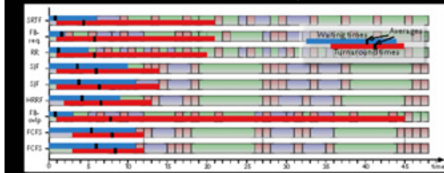


☞ Providing upper bounds to turnaround times ☞ No tasks are left behind

Scheduling

Performance scheduling

Comparison by shortest average turnaround



☞ Providing good average performance ☞ High throughput systems

Scheduling

Performance scheduling

Comparison overview

	Selection	Pre-emption	Waiting	Turnaround	Preferred jobs	Starvation possible?
Methods without any knowledge about the processes						
FCFS	$\max(W_i)$	no	long	long average & short maximum	equal	no
RR	equal share	yes	bound	good average & large maximum	short	no
FB	priority queues	yes	very short	short average & long maximum	short	no
Methods employing computation time C_i and elapsed time E_i						
SJF	$\min(C_i)$	no	medium	medium	short	yes
HRRF	$\max(\frac{W_i + C_i}{C_i})$	no	controllable compromise	controllable compromise	controllable	no
SRTF	$\min(C_i - E_i)$	yes	very short	wide variance	short	yes

Scheduling

Predictable scheduling

Towards predictable scheduling …

Task requirements (Quality of service):

☞ Guarantee **data flow** levels

☞ Guarantee **reaction** times

☞ Guarantee **deadlines**

☞ Guarantee **delivery** times

☞ Provide **bounds** for the **variations** in results

Examples:

- Streaming media broadcasts, playing HD videos, live mixing audio/video, …
- Reacting to users, Reacting to alarm situations, …
- Delivering a signal to the physical world at the required time, …

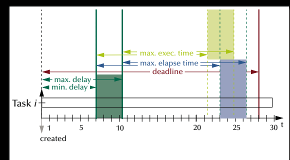
Scheduling

Predictable scheduling

Temporal scopes

Common attributes:

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



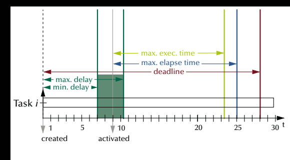
Scheduling

Predictable scheduling

Temporal scopes

Common attributes:

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



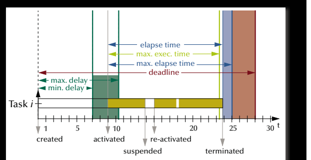
Scheduling

Predictable scheduling

Temporal scopes

Common attributes:

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



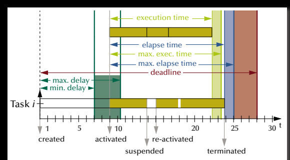
Scheduling

Predictable scheduling

Temporal scopes

Common attributes:

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



Scheduling

Predictable scheduling

Common temporal scope attributes

Temporal scopes can be:

Periodic	☞ controllers, routers, schedulers, streaming processes, …
Aperiodic	☞ periodic 'on average' tasks, i.e. regular but not rigidly timed, …
Sporadic / Transient	☞ user requests, alarms, I/O interaction, …

Deadlines can be:

Semantics defined by application

"Hard"	☞ single failure leads to severe malfunction and/or disaster
"Firm"	☞ results are meaningless after the deadline
	☞ only multiple or permanent failures lead to malfunction
"Soft"	☞ results are still useful after the deadline

Scheduling

Summary

Scheduling

- **Basic performance scheduling**
  - Motivation & Terms
  - Levels of knowledge / assumptions about the task set
  - Evaluation of performance and selection of appropriate methods
- **Towards predictable scheduling**
  - Motivation & Terms
  - Categories & Examples

460

Systems, Networks & Concurrency 2020

7

Safety & Liveness

Uwe R. Zimmer - The Australian National University

461

Safety & Liveness

References for this chapter

[Ben2006]
Ben-Ari, M
Principles of Concurrent and Distributed Programming
second edition, Prentice-Hall 2006

[Chandy1983]
Chandy, K, Misra, Jayadev & Haas, Laura
Distributed deadlock detection
Transactions on Computer Systems (TOCS) 1983 vol. 1 (2)

[Silberschatz2001]
Silberschatz, Abraham, Galvin, Peter & Gagne, Greg
Operating System Concepts
John Wiley & Sons, Inc., 2001

462

Safety & Liveness

Repetition

Correctness concepts 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

463

Safety & Liveness

Repetition

Correctness concepts 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 to complete eventually.
- The state of the system needs to be displayed eventually.
- No part of the system is to be delayed forever (fairness).

☞ Interesting *liveness* properties can become very hard to proof

464

Safety & Liveness

Liveness

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): Resources will be granted …

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

465

Safety & Liveness

Revisiting

Correctness concepts 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) ☞ *has been addressed*
- *Absence of deadlocks* ☞ *to be addressed now* (and other forms of 'silent death' and 'freeze' conditions)
- *Specified responsiveness* or free capabilities ☞ *Real-time systems* (typical in real-time / embedded systems or server applications)

466

Safety & Liveness

Deadlocks

Most forms of synchronization may lead to

Deadlocks

(Avoidance / prevention of deadlocks is one central safety property)

☞ How to predict them?
☞ How to find them?
☞ How to resolve them?
☞ … or are there structurally dead-lock free forms of synchronization?

467

Safety & Liveness

Towards synchronization

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 all resources
  signal (reserve_2);
  signal (reserve_1);

  statement Z;
end P1;

process P2;
  statement A;

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

  statement C;
end P2;
```

Sequence of operations: $A \rightharpoonup B \rightharpoonup C; X \rightharpoonup Y \rightharpoonup Z; [X,Z \mid A,B,C]; [A,C \mid X,Y,Z]; \neg[B \mid Y]$
or: $[A \mid X]$ followed by a deadlock situation.

468

Safety & Liveness

Towards synchronization

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: $A \rightharpoonup B \rightharpoonup C; X \rightharpoonup Y \rightharpoonup Z; K \rightharpoonup L \rightharpoonup M;$
$[X,Z \mid A,B,C \mid K,M]; [A,C \mid X,Y,Z \mid K,M]; [A,C \mid K,L,M \mid X,Z]; \neg[B \mid Y \mid L]$

or: $[A \mid X \mid K]$ followed by a deadlock situation.

469

Safety & Liveness

Deadlocks

Necessary deadlock conditions:

1. **Mutual exclusion:**
   resources cannot be used simultaneously.

470

Safety & Liveness

Deadlocks

Necessary deadlock conditions:

1. **Mutual exclusion:**
   resources cannot be used simultaneously.
2. **Hold and wait:**
   a process applies for a resource, while it is holding another resource (sequential requests).

471

Safety & Liveness

Deadlocks

Necessary deadlock conditions:

1. **Mutual exclusion:**
   resources cannot be used simultaneously.
2. **Hold and wait:**
   a process applies for a resource, while it is holding another resource (sequential requests).
3. **No pre-emption:**
   resources cannot be pre-empted; only the process itself can release resources.

472

Safety & Liveness

Deadlocks

Necessary deadlock conditions:

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

473

Safety & Liveness

Deadlocks

Necessary deadlock conditions:

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

☞ A system *may* become deadlocked, if *all* these conditions apply!

474

Safety & Liveness

Deadlocks

Deadlock strategies:

- Ignorance & restart
  ☞ Kill or restart unresponsive processes, power-cycle the computer, …
- Deadlock detection & recovery
  ☞ find deadlocked processes and recover the system in a coordinated way
- Deadlock avoidance
  ☞ the resulting system state is checked before any resources are actually assigned
- Deadlock prevention
  ☞ the system prevents deadlocks by its structure

475

Safety & Liveness

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

1. *Break* **Mutual exclusion:**

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

476

Safety & Liveness

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).
2. *Break* **Hold and wait**:

477

Safety & Liveness

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).
2. *Break* **Hold and wait**:
   Allocation of all required resources in one request.
   Processes can either hold *none* or *all* of their required resources.
3. *Introduce* **Pre-emption**: :

478

Safety & Liveness

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).
2. *Break* **Hold and wait**:
   Allocation of all required resources in one request.
   Processes can either hold none or all of their required resources.
3. *Introduce* **Pre-emption**:
   Provide the additional infrastructure to allow for pre-emption of resources. Mind that re-sources cannot be pre-empted, if their states cannot be fully stored and recovered.
4. *Break* **Circular waits**:

479

Safety & Liveness

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).
2. *Break* **Hold and wait**:
   Allocation of all required resources in one request.
   Processes can either hold none or all of their required resources.
3. *Introduce* **Pre-emption**:
   Provide the additional infrastructure to allow for pre-emption of resources. Mind that re-sources cannot be pre-empted, if their states cannot be fully stored and recovered.
4. *Break* **Circular waits**:
   E.g. order all resources globally and restrict processes to request resources in that order only.

480

Safety & Liveness

Deadlocks

Resource Allocation Graphs

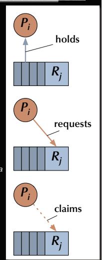
(Silberschatz, Galvin & Gagne)

$RAG = \{V,E\}$; Resource allocation graphs consist of vertices V and edges E.

$V = P \cup R$; Vertices V can be processes P or Resource types R.
with processes $P = \{P_1,\ldots,P_n\}$
and resources types $R = \{R_1,\ldots R_k\}$

$E = E_c \cup E_r \cup E_a$; Edges E can be “claims” E_c, “requests” E_r or “assignments” E_a
with claims E = { → ,…}
requests E = { → ,…}
and assignments E_a = { → ,…}

Note: any resource type can have more than one instance of a resource.



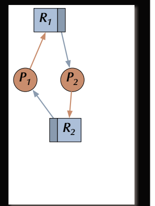
481

Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



482

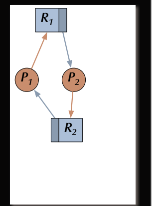
Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Two process, reverse allocation deadlock:



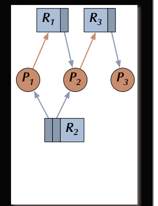
483

Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



484

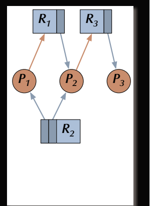
Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ No circular dependency ☞ no deadlock:



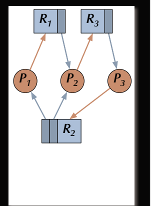
485

Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



486

Safety & Liveness

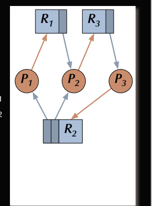
Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Two circular dependencies ☞ deadlock:
1 → 1 → 2 → 3 → 3 → 2 → 1
as well as: 2 → 3 → 3 → 2 → 2

Derived rule:
If some processes are deadlocked **then** there are cycles in the resource allocation graph.



487

Safety & Liveness

Deadlocks

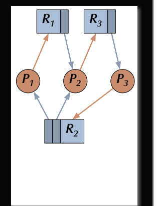
Edge Chasing

(for the distributed version see Chandy, Misra & Haas)

blocking processes:
☞ Send a probe to all requested yet unassigned resources con-taining ids of: [the blocked, the sending, the targeted node].

nodes on probe reception:
☞ Propagate the probe to all processes holding the critical resources or to all requested yet unassigned resources – while updating the second and third entry in the probe.

a process receiving its own probe:
(blocked-id = targeted-id)
☞ *Circular dependency detected.*



488

Safety & Liveness

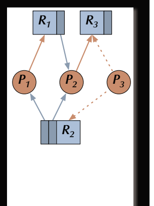
Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Knowledge of claims:

Claims are potential future requests which have no blocking ef-fect on the claiming process – while actual *requests* are blocking.



489

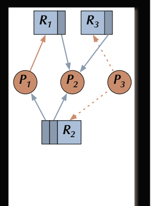
Safety & Liveness

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Assignment of resources such that circular dependencies are avoided:



490

Safety & Liveness

Deadlocks

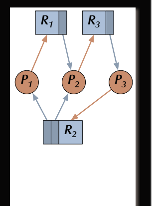
Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Earlier derived rule:
If some processes are deadlocked
then there are cycles in the resource allocation graph.

☞ Reverse rule for multiple instances:
If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Reverse rule for single instances:
If there are cycles in the resource allocation graph
and there is *exactly one* instance per resource
then the involved processes are deadlocked.



491

Safety & Liveness

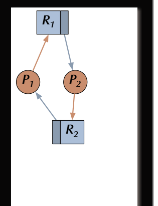
Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Reverse rule for single instances:
If there are cycles in the resource allocation graph
and there is *exactly one* instance per resource
then the involved processes are deadlocked.

☞ Actual deadlock identified



492

Safety & Liveness

Deadlocks

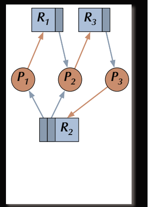
Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Reverse rule for multiple instances:

If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Potential deadlock identified



493

Safety & Liveness

Deadlocks

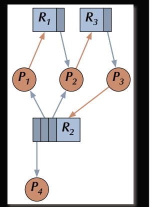
Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Reverse rule for multiple instances:

If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Potential deadlock identified
– yet clearly not an actual deadlock here



494

Safety & Liveness

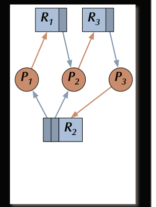
Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

How to detect actual deadlocks in the general case?

(multiple instances per resource)



495

Safety & Liveness

Deadlocks

Banker's Algorithm

There are processes $P_i \in \{P_1, \dots, P_n\}$ and resource types $R_j \in \{R_1, \dots, R_m\}$ and data structures:

- `Allocated [i, j]`
  ☞ the number of resources of type `j` *currently* allocated to process `i`.
- `Free [j]`
  ☞ the number of *currently* available resources of type `j`.
- `Claimed [i, j]`
  ☞ the number of resources of type `j` required by process `i` *eventually*.
- `Requested [i, j]`
  ☞ the number of *currently* requested resources of type `j` by process `i`.
- `Completed [i]`
  ☞ boolean vector indicating processes which may complete.
- `Simulated_Free [j]`

☞ Number of available resources assuming that complete processes deallocate their resources.

496

Safety & Liveness

Deadlocks

Banker's Algorithm

1. `Simulated_Free` ⇐ `Free`; ∀`i`: `Completed [i]` ⇐ `False`;
2. **While** ∃`i`: ¬`Completed [i]`
   and ∀`j`: `Requested [i, j] < Simulated_Free [j]` **do**:
   ∀`j`: `Simulated_Free [j]` ⇐ `Simulated_Free [j]` + `Allocated [i, j]`;
   `Completed [i]` ⇐ `True`;
3. **If** ∀`i`: `Completed [i]` **then** the system is currently **deadlock-free!**
   else all processes `i` with ¬`Completed [i]` are involved in a **deadlock!**.

497

Safety & Liveness

Deadlocks

Banker's Algorithm

1. `Simulated_Free` ⇐ `Free`; ∀`i`: `Completed [i]` ⇐ `False`;
2. **While** ∃`i`: ¬`Completed [i]`
   and ∀`j`: `Claimed [i, j] < Simulated_Free [j]` **do**:
   ∀`j`: `Simulated_Free [j]` ⇐ `Simulated_Free [j]` + `Allocated [i, j]`;
   `Completed [i]` ⇐ `True`;
3. **If** ∀`i`: `Completed [i]` **then** the system is **safe!**

A **safe** system is a system in which future deadlocks can be avoided assuming the current set of available resources.

498

Safety & Liveness

Deadlocks

Banker's Algorithm

Check potential future system safety by simulating a granted request:
(**Deadlock avoidance**)

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

   if System_is_safe (checked by e.g. Banker's algorithm) then
                      ☞ Grant request
   else
         ☞ Restore former system state: (Free, Claimed, Allocated)
   end if;
end if;
```


499

Safety & Liveness

Deadlocks

Distributed deadlock detection

Observation: Deadlock detection methods like Banker's Algorithm are too communication intensive to be commonly applied in full and at high frequency in a distributed system.

☞ Therefore a distributed version needs to:

☞ **Split** the system into nodes of reasonable locality
(keeping most processes close to the resources they require).

☞ **Organize** the nodes in an adequate topology (e.g. a tree).

☞ **Check** for deadlock inside nodes
with blocked resource requests and detect/avoid **local deadlock** *immediately*.

☞ **Exchange** resource status information
between nodes occasionally and detect **global deadlocks** *eventually*.

500

Safety & Liveness

Deadlocks

Deadlock recovery

A deadlock has been detected ☞ now what?

Breaking the circular dependencies can be done by:

☞ Either *pre-empt* an assigned **resource** which is part of the deadlock.
☞ or *stop* a **process** which is part of the deadlock.

Usually neither choice can be implemented 'gracefully' and deals only with the symptoms.

Deadlock recovery does not address the reason for the problem!
(i.e. the deadlock situation can re-occur again immediately)

501

Safety & Liveness

Deadlocks

Deadlock strategies:

- Deadlock prevention
  System prevents deadlocks by its structure or by full verification
  ☞ The best approach if applicable.
- Deadlock avoidance
  System state is checked with every resource assignment.
  ☞ More generally applicable, yet computationally very expensive.
- Deadlock detection & recovery
  Detect deadlocks and break them in a 'coordinated' way.
  ☞ Less computationally expensive (as lower frequent), yet usually 'messy'.
- Ignorance & random kill
  Kill or restart unresponsive processes, power-cycle the computer, …
  ☞ More of a panic reaction than a method.

502

Safety & Liveness

Atomic & idempotent operations

Atomic operations

Definitions of atomicity:

An operation is atomic if the processes performing it …

- **(by 'awareness')** … 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 atomic operation.
- **(by communication)** … do not communicate with other processes while the atomic operation is performed.
- **(by means of states)** … cannot detect any outside state change and do not reveal their own state changes until the atomic operation is complete.

Short:

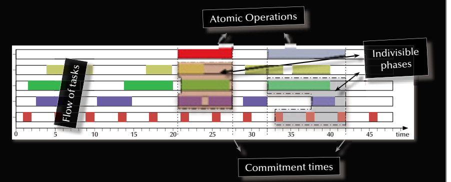
An atomic operation can be considered to be
indivisible and **instantaneous.**

503

Safety & Liveness

Atomic & idempotent operations

Atomic operations



504

Safety & Liveness

Atomic & idempotent operations

Atomic operations

Important implications:

1. An atomic operation is either performed *in full* **or** *not at all*.
2. A failed atomic operation cannot have any impact on its surroundings (must keep or re-instantiate the full initial state).
3. If any part of an atomic operation fails, then the whole atomic operation is declared failed.
4. All parts of an atomic operations (including already completed parts) must be prepared to declare failure until the final global commitment.

505

Safety & Liveness

Atomic & idempotent operations

Idempotent operations

Definition of idempotent operations:

An operation is idempotent if the observable effect of the operation are identical for the cases of executing the operation:

- once,
- multiple times,
- infinitely often.

Observations:

- Idempotent operations are often atomic, but do not need to be.
- Atomic operations do not need to be idempotent.
- Idempotent operations can ease the requirements for synchronization.

506

Safety & Liveness

Reliability, failure & tolerance

'Terminology of failure' or 'Failing terminology'?

Reliability ::= measure of success
with which a system conforms to its *specification*.
::= low failure rate.

Failure ::= a deviation of a system from its *specification*.

Error ::= the system state which leads to a failure.

Fault ::= the reason for an error.

507

Safety & Liveness

Reliability, failure & tolerance

Faults during different phases of design

- Inconsistent or inadequate specifications
  ☞ frequent source for disastrous faults
- Software design errors
  ☞ frequent source for disastrous faults
- Component & communication system failures
  ☞ rare and mostly predictable

508

Reliability, failure & tolerance

Faults in the logic domain

- Non-termination / -completion
  Systems 'frozen' in a deadlock state, blocked for missing input, or in an infinite loop
  ☞ Watchdog timers required to handle the failure
- Range violations and other inconsistent states
  ☞ Run-time environment level exception handling required to handle the failure
- Value violations and other wrong results
  ☞ User-level exception handling required to handle the failure

509

Reliability, failure & tolerance

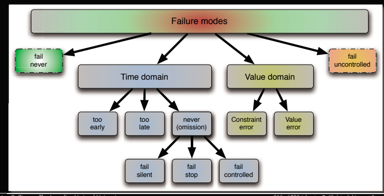
Faults in the time domain

- Transient faults
  ☞ Single 'glitches', interference, … very hard to handle
- Intermittent faults
  ☞ Faults of a certain regularity … require careful analysis
- Permanent faults
  ☞ Faults which stay … the easiest to find

510

Reliability, failure & tolerance

Observable failure modes



511

Reliability, failure & tolerance

Fault prevention, avoidance, removal, …

and / or

☞ **Fault tolerance**

512

Reliability, failure & tolerance

Fault tolerance

- Full fault tolerance
  the system continues to operate in the presence of 'foreseeable' error conditions , **without any significant loss of functionality or performance**
  — even though this might reduce the achievable total operation time.
- Graceful degradation (fail soft)
  the system continues to operate in the presence of 'foreseeable' error conditions, **while 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.

513

Summary

Safety & Liveness

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

514

Systems, Networks & Concurrency 2020

8

Distributed Systems

Uwe R. Zimmer - The Australian National University

515

Distributed Systems

References for this chapter

[Bacon1998]
Bacon, J
Concurrent Systems
Addison Wesley Longman
Ltd (2nd edition) 1998

[Ben2006]
Ben-Ari, M
Principles of Concurrent and Distributed Programming
second edition, Prentice-Hall 2006

[Schneider1990]
Schneider, Fred
Implementing fault-tolerant services using the state machine approach: a tutorial
ACM Computing Surveys 1990
vol. 22 (4) pp. 299-319

[Tanenbaum2001]
Tanenbaum, Andrew
Distributed Systems: Principles and Paradigms
Prentice Hall 2001

[Tanenbaum2003]
Tanenbaum, Andrew
Computer Networks
Prentice Hall, 2003

516

Distributed Systems

Network protocols & standards

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

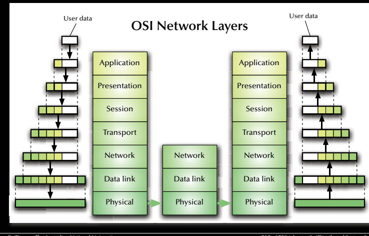
Hardy implemented anywhere in full …

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

517

Distributed Systems

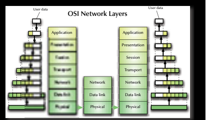
Network protocols & standards



518

Distributed Systems

Network protocols & standards



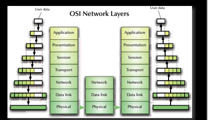
1: Physical Layer

- *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)

519

Distributed Systems

Network protocols & standards



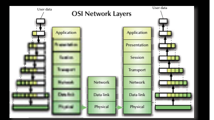
2: Data Link Layer

- *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), …

520

Distributed Systems

Network protocols & standards



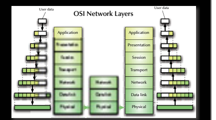
3: Network Layer

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

521

Distributed Systems

Network protocols & standards



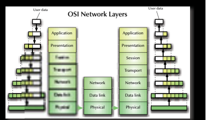
4: Transport Layer

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

522

Distributed Systems

Network protocols & standards



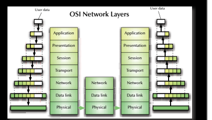
5: Session Layer

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

523

Distributed Systems

Network protocols & standards



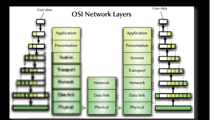
6: Presentation Layer

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

524

Distributed Systems

Network protocols & standards



7: Application Layer

- *Service*: Network access for application programs
- *Functions*: Application/OS specific
- *Examples*: APIs for mail, ftp, ssh, scp, discovery protocols …

525

Distributed Systems

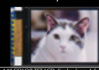
Network protocols & standards

Serial Peripheral Interface (SPI)

☞ Used by gazillions of devices … and it’s not even a formal standard!

☞ Speed only limited by what both sides can survive.

☞ Usually push-pull drivers, i.e. fast and reliable, yet not friendly to wrong wiring/programming.



1.8″ COLOR TFT LCD display from Adafruit

SanDisk marketing photo

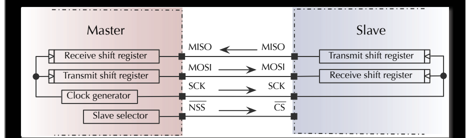
526

Distributed Systems

Network protocols & standards

Serial Peripheral Interface (SPI)

Full Duplex, 4-wire, flexible clock rate

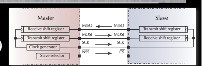


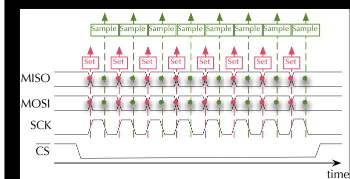
527

Distributed Systems

Network protocols & standards

Serial Peripheral Interface (SPI)





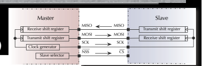
Clock phase and polarity need to be agreed upon

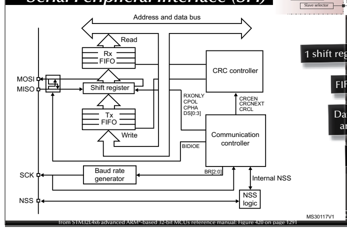
528

Distributed Systems

Network protocols & standards (SPI)

Serial Peripheral Interface (SPI)





from STM32L4x6 advanced ARM®-based 32-bit MCUs reference manual: Figure 420 on page 1291

1 shift register?

FIFOs?

CRC?

Data connected to an internal bus?

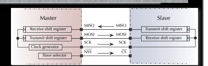
DMA?

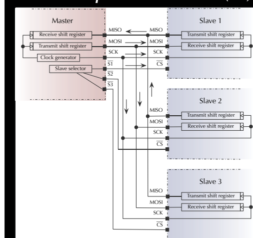
Speed?

529

Distributed Systems

Network protocols & standards (SPI)

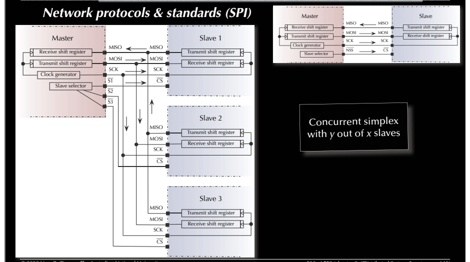




Full duplex with 1 out of x slaves

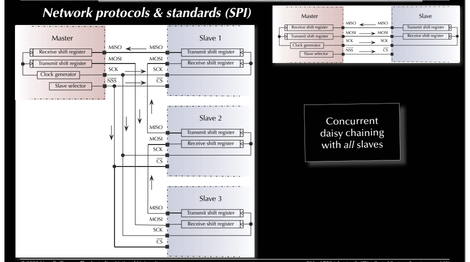
Distributed Systems

Network protocols & standards (SPI)



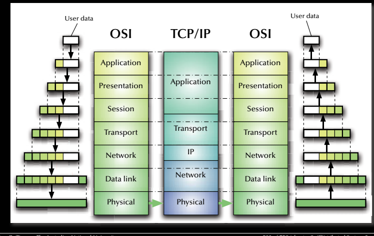
Distributed Systems

Network protocols & standards (SPI)



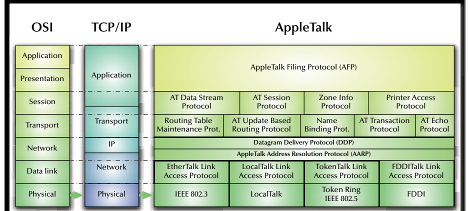
Distributed Systems

Network protocols & standards



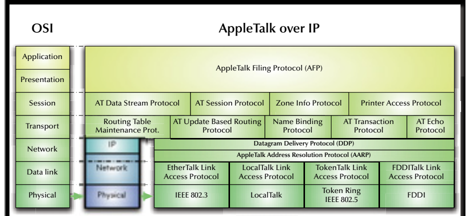
Distributed Systems

Network protocols & standards



Distributed Systems

Network protocols & standards



Distributed Systems

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.
- First standard as IEEE 802.3 in 1983 (10 Mbps over thick co-ax cables).
- currently 1 Gbps (802.3ab) copper cable ports used in most desktops and laptops.
- currently standards up to 100 Gbps (IEEE 802.3ba 2010).
- more than 85 % of current LAN lines worldwide (according to the International Data Corporation (IDC)).

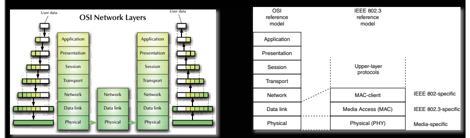
☞ **Carrier Sense Multiple Access** with **Collision Detection (CSMA/CD)**

Distributed Systems

Network protocols & standards

Ethernet / IEEE 802.3

OSI relation: PHY, MAC, MAC-client

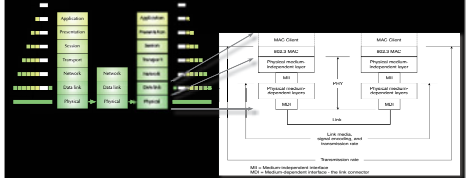


Distributed Systems

Network protocols & standards

Ethernet / IEEE 802.3

OSI relation: PHY, MAC, MAC-client



Distributed Systems

Network protocols & standards

Ethernet / IEEE 802.11

Wireless local area network (WLAN) developed in the 90's

- First standard as IEEE 802.11 in 1997 (1-2 Mbps over 2.4 GHz).
- Typical usage at 54 Mbps over 2.4 GHz carrier at 20 MHz bandwidth.
- Current standards up to 780 Mbps (802.11ac) over 5 GHz carrier at 160 MHz bandwidth.
- Future standards are designed for up to 100 Gbps over 60 GHz carrier.
- Direct relation to IEEE 802.3 and similar OSI layer association.

☞ **Carrier Sense Multiple Access** with **Collision Avoidance (CSMA/CA)**
☞ **Direct-Sequence Spread Spectrum (DSSS)**

Distributed Systems

Network protocols & standards

Bluetooth

Wireless local area network (WLAN) developed in the 90's with different features than 802.11:

- Lower power consumption.
- Shorter ranges.
- Lower data rates (typically < 1 Mbps).
- Ad-hoc networking (no infrastructure required).

☞ Combinations of 802.11 and Bluetooth OSI layers are possible to achieve the required features set.

Distributed Systems

Network protocols & standards

Token Ring / IEEE 802.5 / Fibre Distributed Data Interface (FDDI)

- "Token Ring " 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
- Fibre Distributed Data Interface combines a token ring architecture with a dual-ring, fibre-optical, physical network.

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

☞ **FDDI** is **deterministic** and **failure resistant**

☞ None of the above is currently used in performance oriented applications.

Distributed Systems

Network protocols & standards

Fibre Channel

- Developed in the late 80's.
- ANSI standard since 1994.
- Current standards allow for 16 Gbps per link.
- Allows for three different topologies:

☞ **Point-to-point**: 2 addresses
☞ **Arbitrated loop** (similar to token ring): 127 addresses ☞ deterministic, real-time capable
☞ **Switched fabric**: 2^{24} addresses, many topologies and concurrent data links possible

- Defines OSI equivalent layers up to the session level.

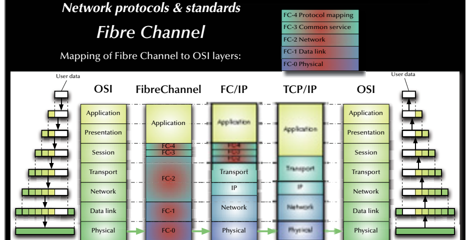
☞ Mostly used in storage arrays, but applicable to super-computers and high integrity systems as well.

Distributed Systems

Network protocols & standards

Fibre Channel

Mapping of Fibre Channel to OSI layers:



Distributed Systems

Network protocols & standards

InfiniBand

- Developed in the late 90's
- Defined by the InfiniBand Trade Association (IBTA) since 1999.
- Current standards allow for 25 Gbps per link.
- Switched fabric topologies.
- Concurrent data links possible (commonly up to 12 ☞ 300 Gbps).
- Defines only the *data-link layer* and parts of the *network layer*.
- Existing devices use copper cables (instead of optical fibres).

☞ Mostly used in super-computers and clusters but applicable to storage arrays as well.
☞ Cheaper than Ethernet or FibreChannel at high data-rates.
☞ Small packets (only up to 4 kB) and no session control.

Distributed Systems

Distributed Systems

Distribution!

Motivation

Possibly …

☞ … fits an **existing physical distribution** (e-mail system, devices in a large craft, …).
☞ … **high performance** due to potentially high degree of parallel processing.
☞ … **high reliability/integrity** due to redundancy of hardware and software.
☞ … **scalable**.
☞ … **integration** of heterogeneous devices.

Different specifications will lead to substantially different distributed designs.

Distributed Systems

Distributed Systems

What can be distributed?

- **State** ☞ *Common* operations on *distributed* data
- **Function** ☞ *Distributed* operations on *central* data
- **State & Function** ☞ Client/server clusters
- **none of those** ☞ Pure replication, redundancy

Distributed Systems

Distributed Systems

Common design criteria

☞ Achieve **De-coupling** / high degree of local autonomy
☞ **Cooperation** rather than central control
☞ Consider **Reliability**
☞ Consider **Scalability**
☞ Consider **Performance**

Distributed Systems

Distributed Systems

Some common phenomena in distributed systems

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

Distributed Systems

Distributed Systems

Time in distributed systems

Two alternative strategies:

Based on a shared time ☞ **Synchronize clocks!**

Based on sequence of events ☞ **Create a virtual time!**

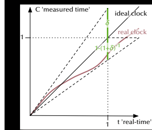
Distributed Systems

Distributed Systems

'Real-time' clocks

are:

- **discrete** – i.e. time is *not* dense and there is a minimal granularity
- **drift affected:**



Maximal clock drift δ defined as:

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

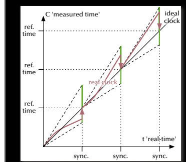
often specified as PPM (Parts-Per-Million)
(typical ≈ 20 PPM in computer applications)

Distributed Systems

Distributed Systems

Synchronize a 'real-time' clock (bi-directional)

Resetting the clock drift by regular reference time re-synchronization:



Maximal clock drift δ defined as:

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

'real-time' clock is adjusted *forwards & backwards*

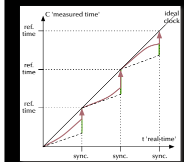
☞ **Calendar time**

Distributed Systems

Distributed Systems

Synchronize a 'real-time' clock (forward only)

Resetting the clock drift by regular reference time re-synchronization:



Maximal clock drift δ defined as:

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

'real-time' clock is adjusted *forwards only*

☞ **Monotonic time**

Distributed Systems

Distributed Systems

Distributed critical regions with synchronized clocks

- ∀ times:
  ∀ received *Requests*: **Add** to local *RequestQueue* (ordered by time)
  ∀ received *Release messages*:
  Delete *corresponding Requests* in local *RequestQueue*

1. **Create** *OwnRequest* and **attach** current time-stamp.
   Add *OwnRequest* to local *RequestQueue* (ordered by time).
   Send *OwnRequest* to *all* processes.
2. **Delay** by $2L$ (L being the time it takes for a message to reach all network nodes)
3. **While** Top (*RequestQueue*) ≠ *OwnRequest*: **delay** until new message
4. **Enter** and **leave** critical region
5. **Send** *Release*-message to *all* processes.

Distributed Systems

Distributed Systems

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 request: $2(N-1)$ messages
  (can be significantly improved by employing broadcast mechanisms).
- Clock drifts affect fairness, but not integrity of the critical region.

Assumptions:
- L is known and constant ☞ violation leads to loss of mutual exclusion.
- No messages are lost ☞ violation leads to loss of mutual exclusion.

Distributed Systems

Distributed Systems

Virtual (logical) time [Lamport 1978]

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

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

$a \rightarrow b$ iff:

- a happens **earlier than** b in the *same sequential* control-flow or
- a denotes the **sending event** of message m,
  while b denotes the **receiving event** of the *same message* m or
- there is a **transitive causal relation** between a and b: $a \rightarrow e_1 \rightarrow \ldots \rightarrow e_n \rightarrow b$

Notion of concurrency:

$$a \parallel b \Rightarrow \neg(a \rightarrow b) \wedge \neg(b \rightarrow a)$$

Distributed Systems

Distributed Systems

Virtual (logical) time

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

Implications:

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

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

$$C(a) = C(b) < C(c) \Rightarrow ?$$

$$C(a) < C(b) < C(c) \Rightarrow ?$$

Distributed Systems

Distributed Systems

Virtual (logical) time

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

Implications:

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

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

$$C(a) = C(b) < C(c) \Rightarrow ?$$

$$C(a) < C(b) < C(c) \Rightarrow ?$$

Distributed Systems

Distributed Systems

Virtual (logical) time

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

Implications:

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

$$C(a) = C(b) \Rightarrow a \parallel b = \neg(a \rightarrow b) \wedge \neg(b \rightarrow a)$$

$$C(a) = C(b) < C(c) \Rightarrow ?$$

$$C(a) < C(b) < C(c) \Rightarrow ?$$

Distributed Systems

Distributed Systems

Virtual (logical) time

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

Implications:

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

$$C(a) = C(b) \Rightarrow a \parallel b = \neg(a \rightarrow b) \wedge \neg(b \rightarrow a)$$

$$C(a) = C(b) < C(c) \Rightarrow \neg(c \rightarrow a)$$

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

Distributed Systems

Distributed Systems

Virtual (logical) time

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

Implications:

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

$$C(a) = C(b) \Rightarrow a \parallel b = \neg(a \rightarrow b) \wedge \neg(b \rightarrow a)$$

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

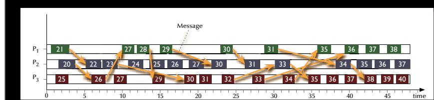
$$C(a) < C(b) < C(c) \Rightarrow \neg(c \rightarrow a) = (a \rightarrow c) \vee (a \parallel c)$$

Distributed Systems

Distributed Systems

Virtual (logical) time

Time as derived from causal relations:



☞ Events in concurrent control flows are not ordered.
☞ No global order of time.

Distributed Systems

Distributed Systems

Implementing a virtual (logical) time

1. $\forall P_i: C_i = 0$
2. $\forall P_i$:
   ∀ local events: $C_i = C_i + 1$;
   ∀ send events: $C_i = C_i + 1$; Send (message, C_i);
   ∀ receive events: Receive (message, C_m); $C_i = \max(C_i, C_m) + 1$;

Distributed Systems

Distributed Systems

Distributed critical regions with logical clocks

- ∀ times: ∀ received *Requests*:
  Add to local *RequestQueue* (ordered by time)
  Reply with *Acknowledge* or *OwnRequest*
- ∀ times: ∀ received *Release messages*:
  Delete *corresponding Requests* in local *RequestQueue*

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

Distributed Systems

Distributed Systems

Distributed critical regions with logical clocks

Analysis

- No deadlock, no individual starvation, no livelock.
- Minimal request delay: $N-1$ *requests* (1 broadcast) + $N-1$ *replies*.
- Minimal release delay: $N-1$ *release* messages (or 1 broadcast).
- Communications requirements per request: $3(N-1)$ messages (or $N-1$ messages + 2 broadcasts).
- Clocks are kept recent by the exchanged messages themselves.

Assumptions:
- No messages are lost ☞ violation leads to stall.

Distributed Systems

Distributed Systems

Distributed critical regions with a token ring structure

1. **Organize** all processes in a logical or physical **ring** topology
2. **Send** one *token* message to one process
3. ∀ times, ∀processes: **On receiving** the *token* message:
   1. If required the process
      enters and **leaves** a critical section (while holding the token).
   2. The *token* is **passed** along to the next process in the ring.

Assumptions:
- Token is not lost ☞ violation leads to stall.

(a lost token can be recovered by a number of means – e.g. the 'election' scheme following)

Distributed Systems

Distributed Systems

Distributed critical regions with a central coordinator

A global, static, central coordinator
☞ Invalidates the idea of a distributed system
☞ Enables a very simple mutual exclusion scheme

Therefore:

- A global, central coordinator is employed in some systems … yet …
- … if it fails, a system to come up with a new coordinator is provided.

Distributed Systems

Distributed Systems

Electing a central coordinator (the Bully algorithm)

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

1. *P* **sends** an *Election*-message
   to all processes with *higher* process numbers.
2. *P* **waits** for response messages.
   ☞ 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.
   ☞ If any process responds,
   then the election activity for *P* is over and *P* waits for a *Coordinator*-message

All processes P_i perform at all times:

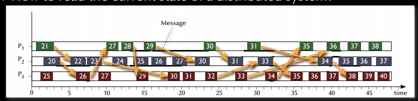
- If P_i **receives** a *Election*-message from a process with a *lower* process number, it **responds** to the originating process and starts an election process itself (if not running already).

Distributed Systems

Distributed Systems

Distributed states

☞ How to read the current state of a distributed system?



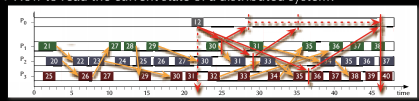
This "god's eye view" does in fact not exist.

Distributed Systems

Distributed Systems

Distributed states

☞ How to read the current state of a distributed system?



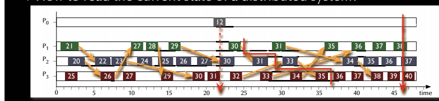
Instead: some entity probes and collects local states.
☞ What state of the global system has been accumulated?

Distributed Systems

Distributed Systems

Distributed states

☞ How to read the current state of a distributed system?



Instead: some entity probes and collects local states.
☞ What state of the global system has been accumulated?
☞ Connecting all the states to a global state.

Distributed Systems

Distributed Systems

Distributed states

A consistent global state (snapshot) is define by a unique division into:

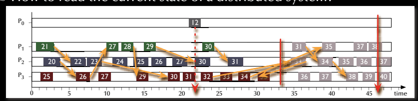
- "The Past" *P* (events before the snapshot):
  $(e_2 \in P) \wedge (e_1 \rightarrow e_2) \Rightarrow e_1 \in P$
- "The Future" *F* (events after the snapshot):
  $(e_1 \in F) \wedge (e_1 \rightarrow e_2) \Rightarrow e_2 \in F$

Distributed Systems

Distributed Systems

Distributed states

☞ How to read the current state of a distributed system?



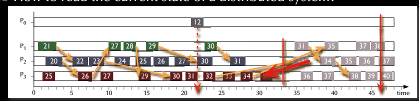
Instead: some entity probes and collects local states.
☞ What state of the global system has been accumulated?
☞ Sorting the events into past and future events.

Distributed Systems

Distributed Systems

Distributed states

☞ How to read the current state of a distributed system?



Instead: some entity probes and collects local states.
☞ What state of the global system has been accumulated?
☞ Event in the past receives a message from the future!
Division not possible ☞ Snapshot inconsistent!

Distributed Systems

Distributed Systems

Snapshot algorithm

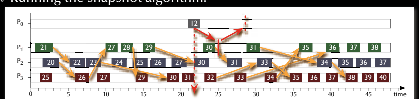
- Observer-process P_0 (any process) **creates** a snapshot token t_s and **saves** its local state s_0.
- P_0 **sends** t_s to all other processes.
- $\forall P_i$ which **receive** t_s (as an individual token-message, or as part of another message):
  - **Save** local state s_i and **send** s_i to P_0.
  - **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_0 (this message belongs to the snapshot).

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



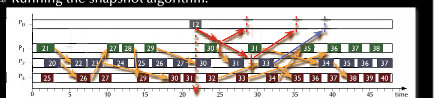
- Observer-process P_0 (any process) **creates** a snapshot token t_s and **saves** its local state s_0.
- P_0 **sends** t_s to all other processes.

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



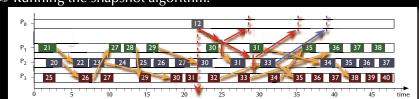
- $\forall P_i$ which **receive** t_s (as an individual token-message, or as part of another message):
  - **Save** local state s_i and **send** s_i to P_0.
  - **Attach** t_s to all further messages, which are to be sent to other processes.
  - **Save** t_s and **ignore** all further incoming t_s's.

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



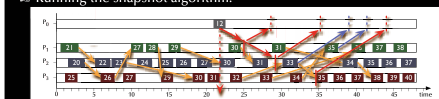
- $\forall P_i$ which previously received t_s and **receive** a message *m* without t_s:
  - **Forward** *m* to P_0 (this message belongs to the snapshot).

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



- $\forall P_i$ which **receive** t_s (as an individual token-message, or as part of another message):
  - **Save** local state s_i and **send** s_i to P_0.
  - **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.

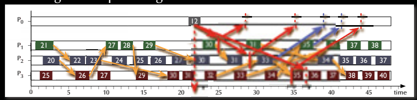
578

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



- **Save** t_s and **ignore** all further incoming t_s's.

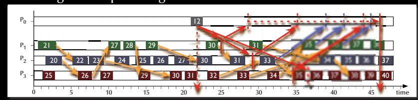
579

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



- **Finalize** snapshot

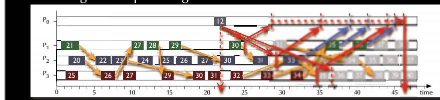
580

Distributed Systems

Distributed Systems

Distributed states

☞ Running the snapshot algorithm:



☞ Sorting the events into past and future events.

☞ Past and future events uniquely separated ☞ Consistent state

581

Distributed Systems

Distributed Systems

Snapshot algorithm

Termination condition?

Either

- Make assumptions about the communication 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.

582

Distributed Systems

Distributed Systems

Consistent distributed states

Why would we need that?

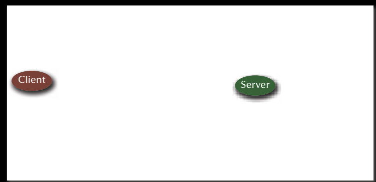
- Find deadlocks.
- Find termination / completion conditions.
- … any other global safety of liveness property.
- Collect a consistent system state for system backup/restore.
- Collect a consistent system state for further processing (e.g. distributed databases).
- …

583

Distributed Systems

Distributed Systems

A distributed server (load balancing)

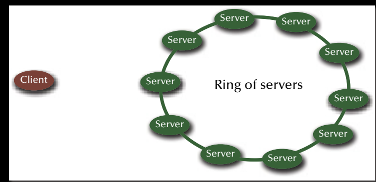


584

Distributed Systems

Distributed Systems

A distributed server (load balancing)

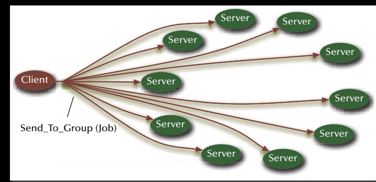


585

Distributed Systems

Distributed Systems

A distributed server (load balancing)

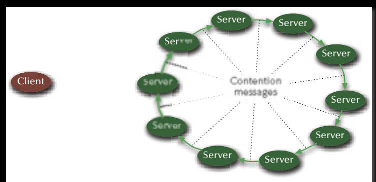


586

Distributed Systems

Distributed Systems

A distributed server (load balancing)

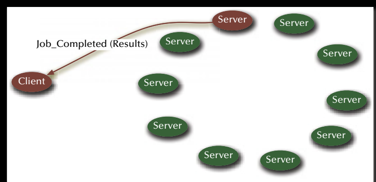


587

Distributed Systems

Distributed Systems

A distributed server (load balancing)



588

Distributed Systems

Distributed Systems

A distributed server (load balancing)

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

task type Print_Server is

   entry Send_To_Server (Print_Job : in Job_Type; Job_Done  : out Boolean);
   entry Contention     (Print_Job : in Job_Type; Server_Id : in  Task_Id);

end Print_Server;
```


589

Distributed Systems

Distributed Systems

A distributed server (load balancing)

```
task body Print_Server is
   begin
      loop
         select
            accept Send_To_Server (Print_Job : in Job_Type; Job_Done : out Boolean) do
               if not Print_Job in Turned_Down_Jobs then
                  if Not_Too_Busy then
                     Applied_For_Jobs := Applied_For_Jobs + Print_Job;
                     Next_Server_On_Ring.Contention (Print_Job, Current_Task);
                     requeue Internal_Print_Server.Print_Job_Queue;
                  else
                     Turned_Down_Jobs := Turned_Down_Jobs + Print_Job;
                  end if;
               end if;
            end Send_To_Server;
```

(…)

590

Distributed Systems

```
         or
            accept Contention (Print_Job : in Job_Type; Server_Id : in Task_Id) do
               if Print_Job in AppliedForJobs then
                  if Server_Id = Current_Task then
                     Internal_Print_Server.Start_Print (Print_Job);
                  elsif Server_Id > Current_Task then
                     Internal_Print_Server.Cancel_Print (Print_Job);
                     Next_Server_On_Ring.Contention (Print_Job; Server_Id);
                  else
                     null; -- removing the contention message from ring
                  end if;
               else
                  Turned_Down_Jobs := Turned_Down_Jobs + Print_Job;
                  Next_Server_On_Ring.Contention (Print_Job; Server_Id);
               end if;
            end Contention;
         or
            terminate;
         end select;
      end loop;
   end Print_Server;
```


591

Distributed Systems

Distributed Systems

Transactions

☞ Concurrency and distribution in systems with multiple, interdependent interactions?

☞ Concurrent and distributed client/server interactions beyond single remote procedure calls?

592

Distributed Systems

Distributed Systems

Transactions

Definition (ACID properties):

- **Atomicity**: **All** or **none** of the sub-operations are **performed**. Atomicity helps achieve crash resilience. If a crash occurs, then it is possible to roll back the system to the state before the transaction was invoked.
- **Consistency**: Transforms the system from one **consistent** state to another **consistent** state.
- **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.

593

Distributed Systems

Distributed Systems

Transactions

Definition (ACID properties):

Atomic operations spanning multiple processes?

How to ensure consistency in a distributed system?

- **Atomicity**: **All** or **none** of the sub-operations are **performed**. Atomicity helps achieve crash resilience. If a crash occurs, then it is possible to roll back the system to the state before the transaction was invoked.
- **Consistency**: Transforms the system from one **consistent** state to another **consistent** state.
- **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.

Shadow copies?

What hardware do we need to assume?

Actual isolation and efficient concurrency?

Actual isolation or the appearance of isolation?

594

Distributed Systems

Distributed Systems

Transactions

A closer look *inside* transactions:

- **Transactions** consist of a sequence of **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.
- **Idempotent** and **side-effect free** operations are by definition *commutative*.
- *All non-commutative operations* are considered **critical operations**.
- Two *critical operations* as part of two different transactions while affecting the same object are called a **conflicting pair of operations**.

595

Distributed Systems

Distributed Systems

Transactions

A closer look at *multiple* transactions:

- Any *sequential* execution of multiple transactions *will fulfil* the ACID-properties, by definition of a single transaction.
- A *concurrent* execution (or 'interleavings') of multiple transactions *might fulfil* the ACID-properties.

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

☞ If a concurrent execution ('interleaving') ensures that no transaction ever encounters an inconsistent state then it is said to ensure the **appearance of isolation**.

596

Distributed Systems

Distributed Systems

Achieving serializability

☞ For the **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.

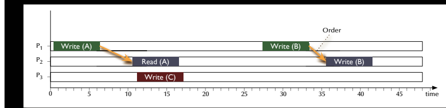
(Determining order in distributed systems requires logical clocks.)

597

Distributed Systems

Distributed Systems

Serializability



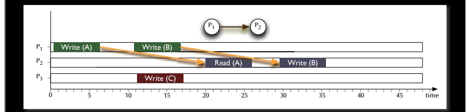
- Two conflicting pairs of operations with the same order of execution.

598

Distributed Systems

Distributed Systems

Serializability



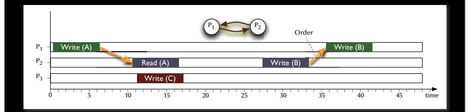
☞ Serializable

599

Distributed Systems

Distributed Systems

Serializability



- Two conflicting pairs of operations with different orders of executions.

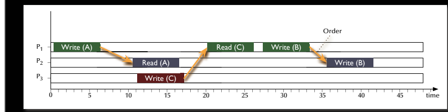
☞ Not serializable.

600

Distributed Systems

Distributed Systems

Serializability



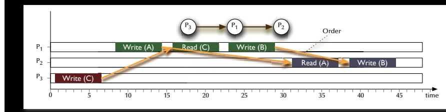
- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).
- The order between processes also leads to a global order of processes.

601

Distributed Systems

Distributed Systems

Serializability



- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).
- The order between processes also leads to a global order of processes.

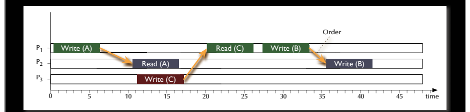
☞ Serializable

602

Distributed Systems

Distributed Systems

Serializability



- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).
- The order between processes also leads to a global order of processes.

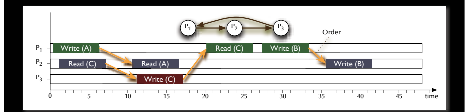
☞ Serializable

603

Distributed Systems

Distributed Systems

Serializability



- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).
- The order between processes *does no longer lead to a global order* of processes.

☞ Not serializable

604

Distributed Systems

Distributed Systems

Achieving serializability

☞ For the **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.

- Define: **Serialization graph**: A directed graph;
  Vertices *i* represent transactions T_i;
  Edges $T_i \rightarrow T_j$ represent an established global order dependency between all conflicting pairs of operations of those two transactions.

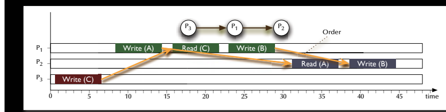
☞ For the **serializability** of multiple transactions it is **necessary** and **sufficient** that the serialization graph is *acyclic*.

605

Distributed Systems

Distributed Systems

Serializability



- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).

☞ Serialization graph is acyclic.

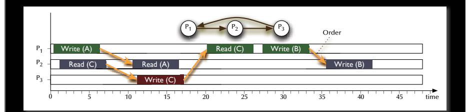
☞ Serializable

606

Distributed Systems

Distributed Systems

Serializability



- Three conflicting pairs of operations with the same order of execution (pair-wise between processes).

☞ Serialization graph is cyclic.

☞ Not serializable

607

Distributed Systems

Distributed Systems

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.

608

Distributed Systems

Distributed Systems

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 anytime*, but not acquired (two phase locking) or locks are released *on commit only* (*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)

609

Distributed Systems

Distributed Systems

Transaction schedulers – Time stamp ordering

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

☞ Collision detection rather than collision avoidance
☞ No isolation ☞ Cascading aborts possible.

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

610

Distributed Systems

Distributed Systems

Transaction schedulers – Optimistic control

Three sequential phases:

1. **Read & execute**:
   Create a shadow copy of all involved objects and
   perform all required operations *on the shadow copy* and *locally* (i.e. in isolation).
2. **Validate**:
   After local commit, **check** all occurred interleavings **for serializability**.
3. **Update or abort**:
   3a. If serializability could be ensured in step 2 then all results of involved transactions are **written** to all involved objects – *in dependency order of the transactions*.
   3b. Otherwise: **destroy** shadow copies and **start over** with the failed transactions.

611

Distributed Systems

Distributed Systems

Transaction schedulers – Optimistic control

Three sequential phases:

How to create a consistent copy?

1. **Read & execute**:
   Create a shadow copy of all involved objects and
   perform all required operations *on the shadow copy* and *locally* (i.e. in isolation).

Full isolation and maximal concurrency!

2. **Validate**:
   After local commit, **check** all occurred interleavings **for serializability**.
3. **Update or abort**:
   3a. If serializability could be ensured in step 2 then all results of involved transactions are **written** to all involved objects – *in dependency order of the transactions*.
   3b. Otherwise: **destroy** shadow copies and **start over** with the failed transactions.

How to update all objects consistently?

Aborts happen after everything has been committed locally.

612

Distributed Systems

Distributed Systems

Distributed transaction schedulers

Three major designs:

- **Locking methods**: ☞ no aborts
  Impose strict mutual exclusion on all critical sections.
- **Time-stamp ordering**: ☞ potential aborts along the way
  Note relative starting times and keep order dependencies consistent.
- **"Optimistic" methods**: ☞ aborts or commits at the very end
  Go ahead until a conflict is observed – then roll back.

☞ How to implement "commit" and "abort" operations in a distributed environment?

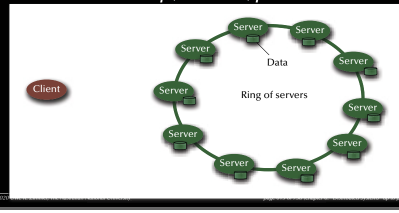
613

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



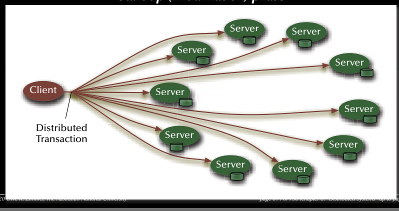
614

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



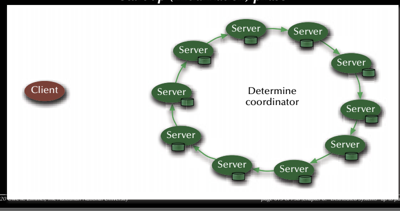
615

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



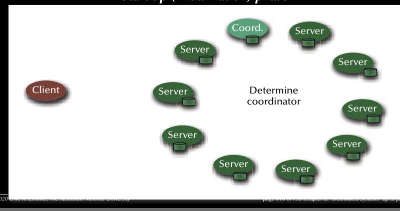
616

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



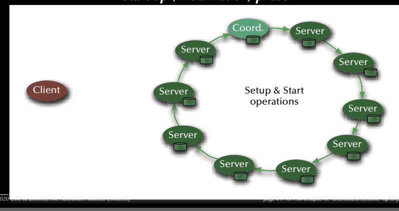
617

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



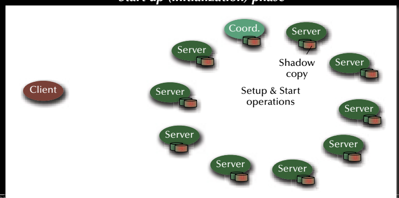
618

Distributed Systems

Distributed Systems

Two phase commit protocol

Start up (initialization) phase



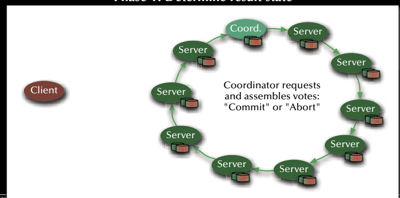
619

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 1: Determine result state



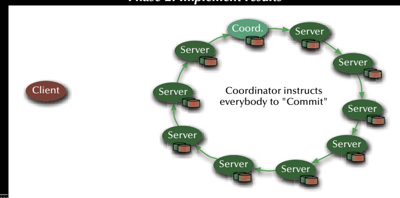
620

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 2: Implement results



621

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 2: Implement results

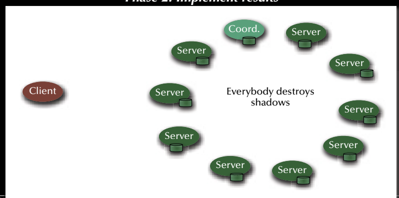
622

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 2: Implement results



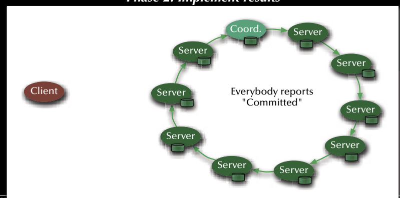
623

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 2: Implement results



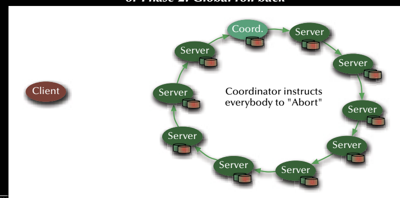
624

Distributed Systems

Distributed Systems

Two phase commit protocol

or Phase 2: Global roll back



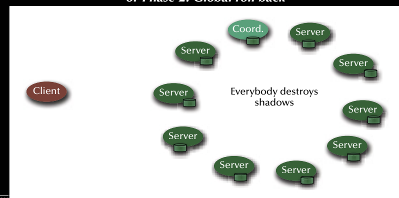
625

Distributed Systems

Distributed Systems

Two phase commit protocol

or Phase 2: Global roll back



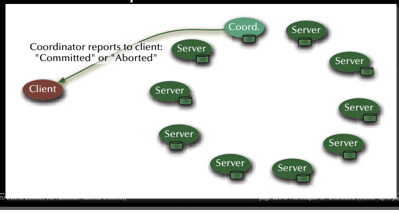
626

Distributed Systems

Distributed Systems

Two phase commit protocol

Phase 2: Report result of distributed transaction



627

Distributed Systems

Distributed Systems

Distributed transaction schedulers

Evaluating the three major design methods in a distributed environment:

- **Locking methods**: ☞ No aborts.
  Large overheads; Deadlock detection/prevention required.
- **Time-stamp ordering**: ☞ Potential aborts along the way.
  Recommends itself for distributed applications, since decisions are taken locally and communication overhead is relatively small.
- **"Optimistic" methods**: ☞ Aborts or commits at the very end.
  Maximizes concurrency, but also data replication.

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

628

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Premise:

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

Assumptions & Means:

- 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, dynamic 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).

[Schneider1990]

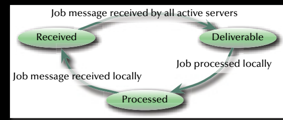
629

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Stages of each server:



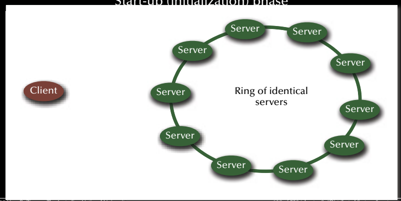
630

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Start-up (initialization) phase



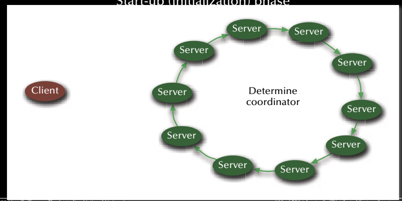
631

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Start-up (initialization) phase



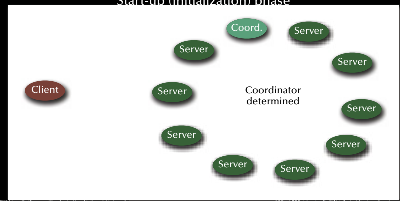
632

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Start-up (initialization) phase



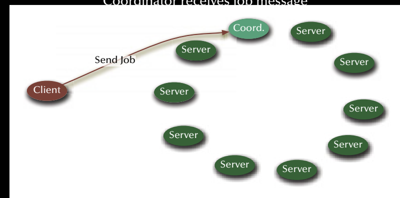
633

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Coordinator receives job message



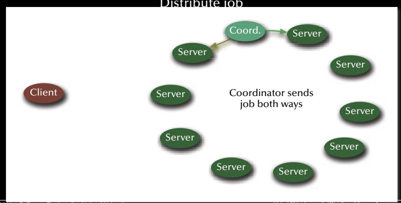
634

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Distribute job



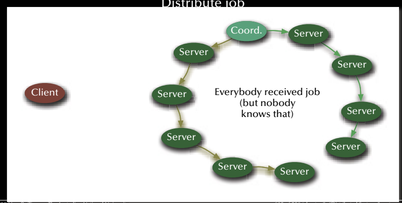
635

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Distribute job



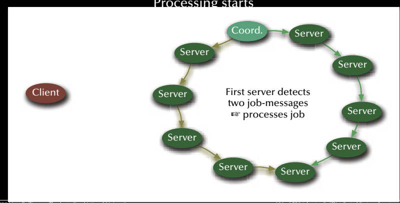
636

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Processing starts



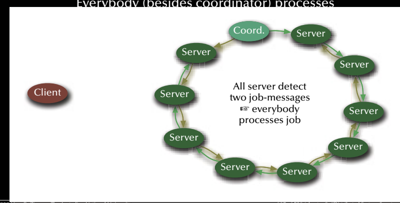
637

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Everybody (besides coordinator) processes



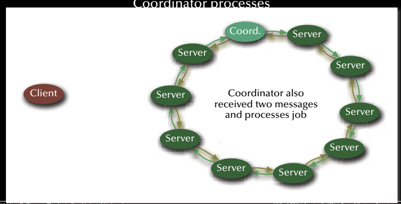
638

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Coordinator processes



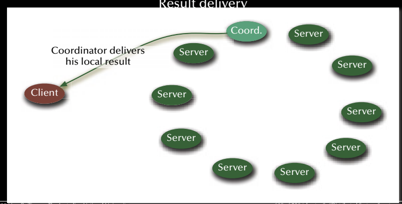
639

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Result delivery



640

Distributed Systems

Distributed Systems

Redundancy (replicated servers)

Event: Server crash, new servers joining, or current servers leaving.

☞ Server re-configuration is triggered by a message to all
(this is assumed to be supported by the distributed operating system).

Each server on reception of a re-configuration message:

1. Wait for local job 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 then $S_i \Leftarrow S_j$
5. Elect coordinator
6. Enter 'Coordinator-' or 'Replicate-mode'

641

Distributed Systems

Summary

Distributed Systems

- **Networks**
  - OSI, topologies
  - Practical network 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)

Systems, Networks & Concurrency 2020

9

Architectures

Uwe R. Zimmer - The Australian National University

Architectures

References

[Bacon98]
J. Bacon
Concurrent Systems
1998 (2nd Edition) Addison Wesley Longman Ltd, ISBN 0-201-17767-6

[Stallings2001]
Stallings, William
Operating Systems
Prentice Hall, 2001

[Intel2010]
Intel® 64 and IA-32 Architectures Optimization Reference Manual
http://www.intel.com/products/processor/manuals/

Architectures

In this chapter

Hardware architectures:

☞ From simple logic to multi-core CPUs
☞ Concurrency on different levels

Software architectures:

☞ Languages of Concurrency
☞ Operating systems and libraries

Architectures

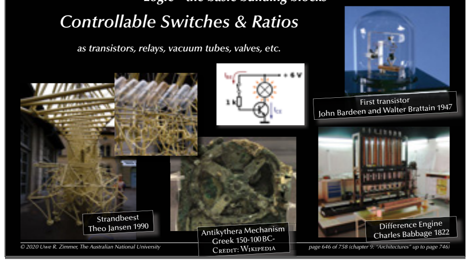
Abstraction Layer	Form of concurrency
Application level (user interface, specific functionality...)	Distributed systems, servers, web services, "multitasking" (popular understanding)
Language level (data types, tasks, classes, API, ...)	Process libraries, tasks/threads (language), synchronisation, message passing, intrinsic, ...
Operating system (HAL, processes, virtual memory)	OS processes/threads, signals, events, multitasking, SMP, virtual parallel machines,...
CPU / instruction level (assembly instructions)	Logically sequential: pipelines, out-of-order, etc. logically concurrent: multicores, interrupts, etc.
Device / register level (arithmetic units, registers,...)	Parallel adders, SIMD, multiple execution units, caches, prefetch, branch prediction, etc.
Logic gates ('and', 'or', 'not', flip-flop, etc.)	Inherently massively parallel, synchronised by clock; or: asynchronous logic
Digital circuitry (gates, buses, clocks, etc.)	Multiple clocks, peripheral hardware, memory, ...
Analog circuitry (transistors, capacitors, ...)	Continuous time and inherently concurrent

Architectures

Logic - the basic building blocks

Controllable Switches & Ratios

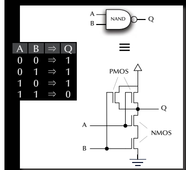
as transistors, relays, vacuum tubes, valves, etc.



Architectures

Logic - the basic building blocks for digital computers

Constructing logic gates – for instance NAND in CMOS:

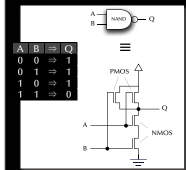


A	B	⇒	Q
0	0	⇒	1
0	1	⇒	1
1	0	⇒	1
1	1	⇒	0

Architectures

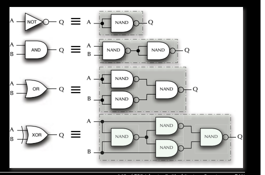
Logic - the basic building blocks for digital computers

Constructing logic gates – for instance NAND in CMOS:



A	B	⇒	Q
0	0	⇒	1
0	1	⇒	1
1	0	⇒	1
1	1	⇒	0

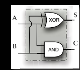
... and subsequently all other logic gates:



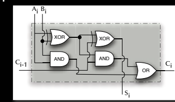
Architectures

Logic - the basic building blocks

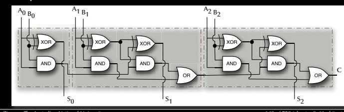
Half adder:



Full adder:



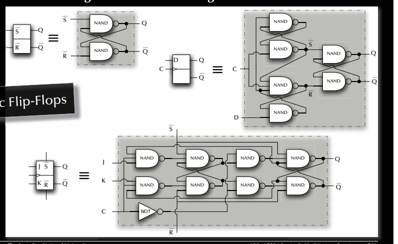
Ripple carry adder:



Architectures

Logic - the basic building blocks

Basic Flip-Flops

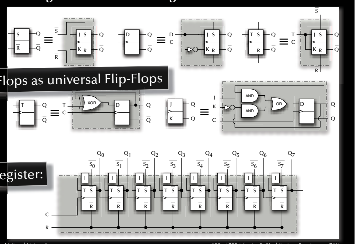


Architectures

Logic - the basic building blocks

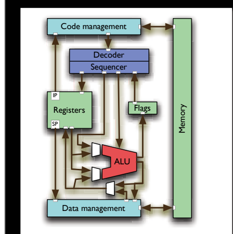
JK- and D- Flip-Flops as universal Flip-Flops

Counting register:



Architectures

Processor Architectures

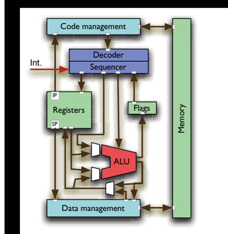


A simple CPU

- **Decoder/Sequencer**
  Can be a machine in itself which breaks CPU instructions into *concurrent* micro code.
- **Execution Unit** / Arithmetic-Logic-Unit (**ALU**)
  A collection of transformational logic.
- **Memory**
- **Registers**
  Instruction pointer, stack pointer, general purpose and specialized registers
- **Flags**
  Indicating the states of the latest calculations.
- **Code/Data management**
  Fetching, Caching, Storing

Architectures

Processor Architectures



Interrupts

- One or multiple lines wired directly into the sequencer

☞ *Required for*:
Pre-emptive scheduling, **Timer driven actions**, **Transient hardware interactions**, …

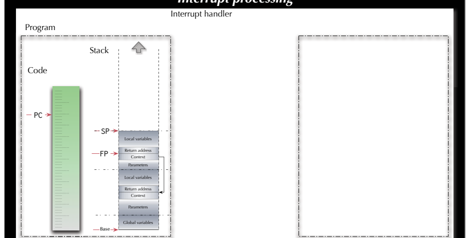
☞ Usually preceded by an external logic ("interrupt controller") which accumulates and encodes all external requests.

On interrupt (if unmasked):

- CPU stops normal sequencer flow.
- Lookup of interrupt handler's address
- Current IP and state pushed onto stack.
- IP set to interrupt handler.

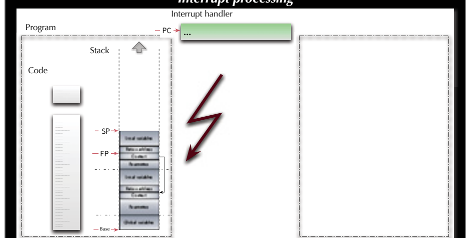
Architectures

Interrupt processing



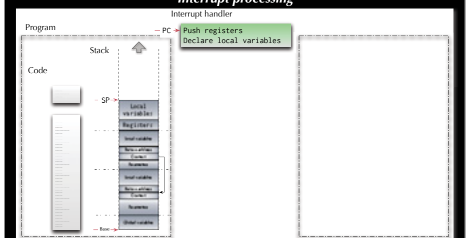
Architectures

Interrupt processing

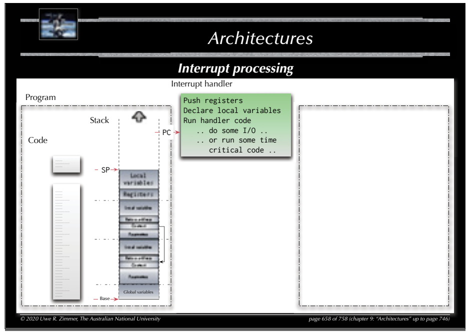


Architectures

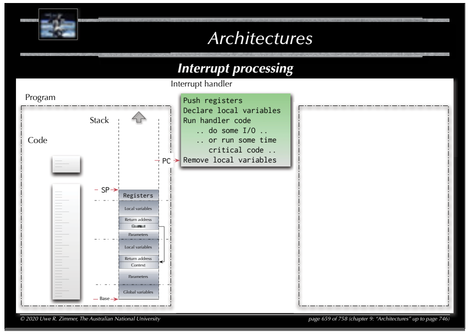
Interrupt processing



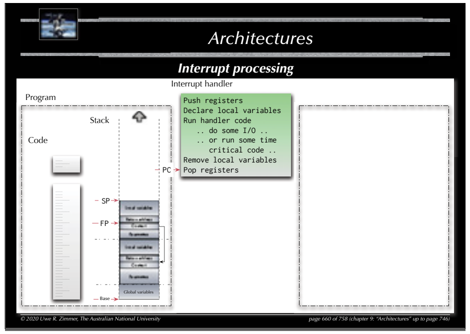
658



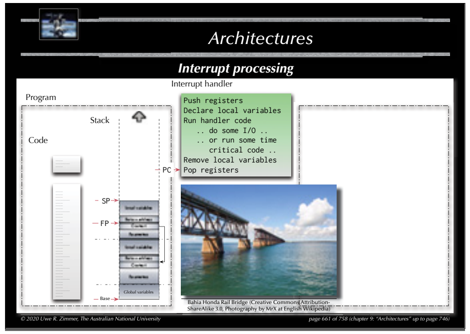
659



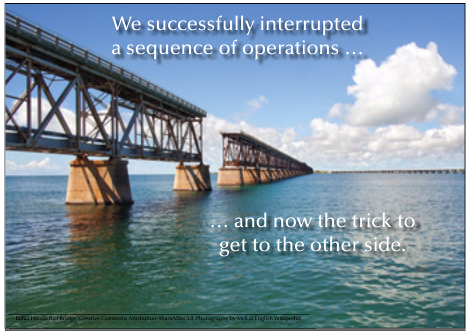
660



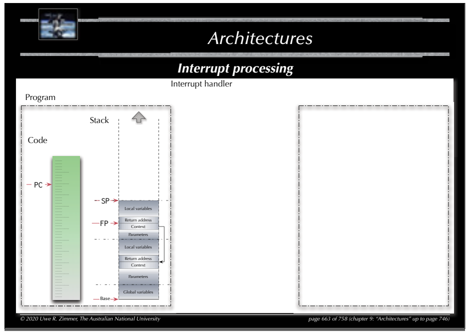
661



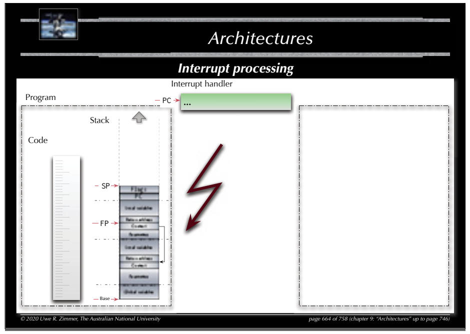
662



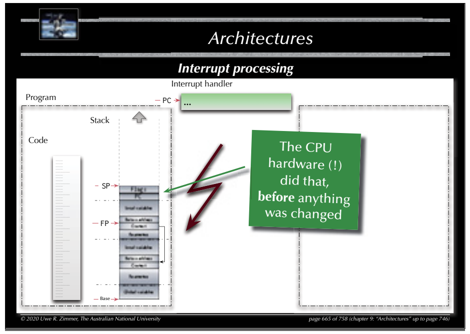
663



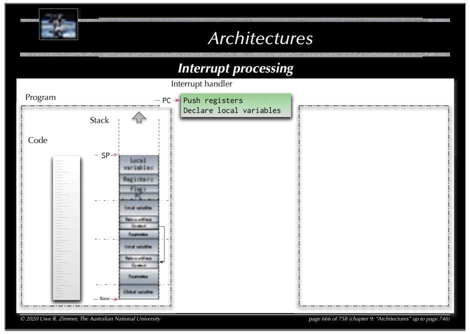
664



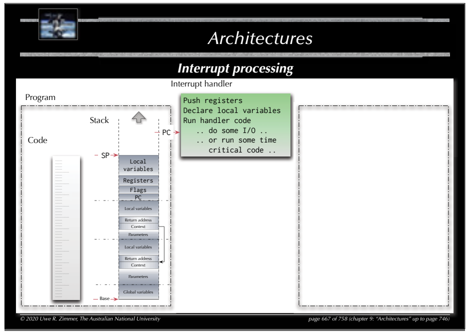
665



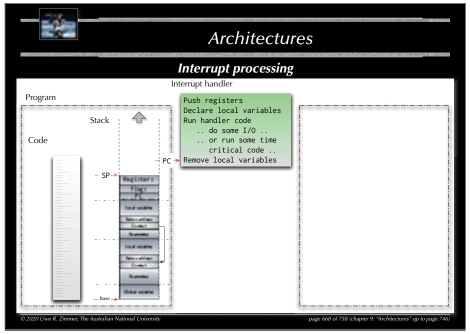
666



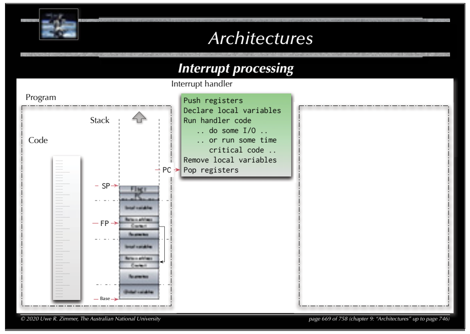
667



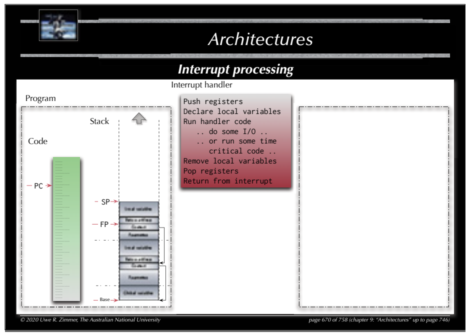
668



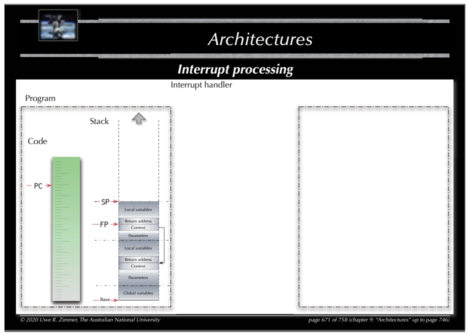
669



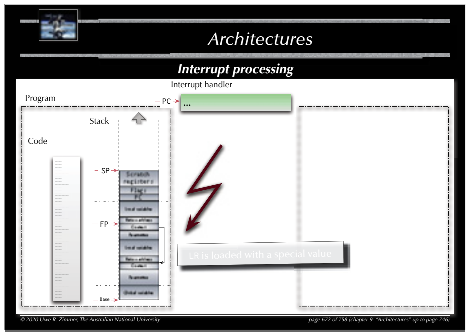
670



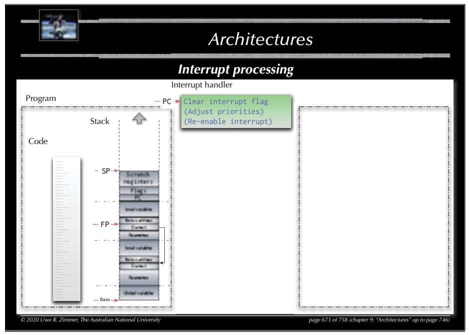
671



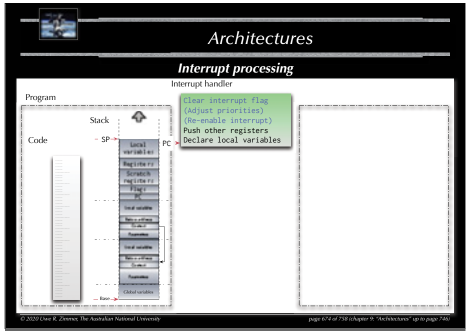
672



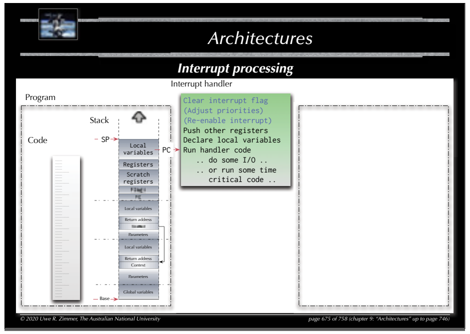
673



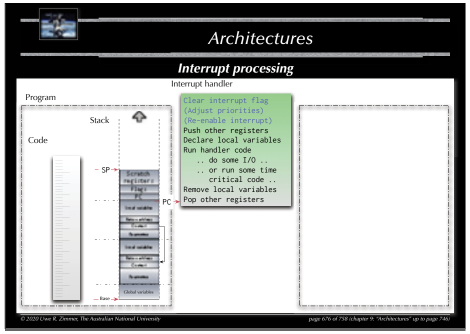
674



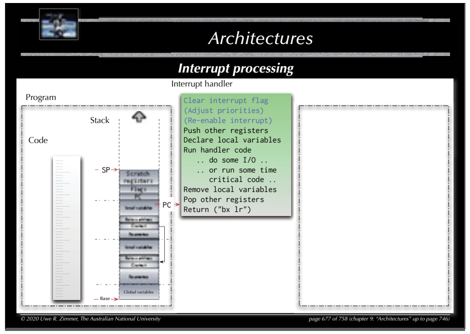
675



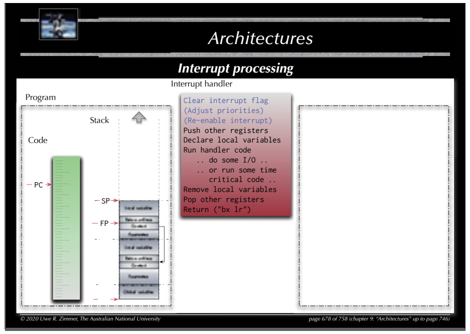
676



677



678



679

Architectures

Interrupt handler

Things to consider

- ☞ Interrupt handler code can be interrupted as well.
- ☞ Are you allowing to interrupt an interrupt handler with an interrupt on the same priority level (e.g. the same interrupt)?
- ☞ Can you overrun a stack with interrupt handlers?

680

Architectures

Interrupt handler

Things to consider

- ☞ Interrupt handler code can be interrupted as well.
- ☞ Are you allowing to interrupt an interrupt handler with an interrupt on the same priority level (e.g. the same interrupt)?
- ☞ Can you overrun a stack with interrupt handlers?

- ☞ Can we have one of those? Busy! Do Not Disturb!

681

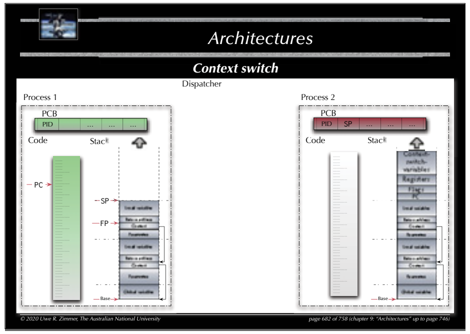
Architectures

Multiple programs

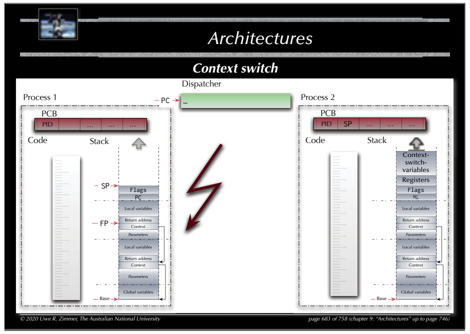
If we can execute interrupt handler code "concurrently" to our "main" program:

☞ Can we then also have multiple "main" programs?

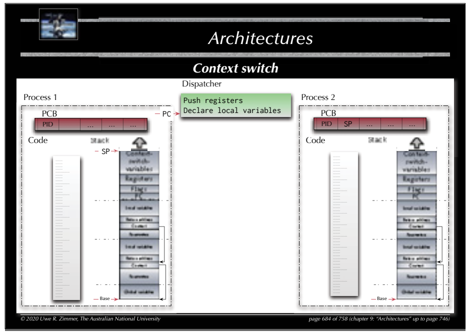
682



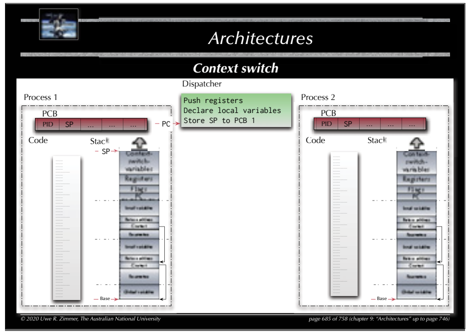
683



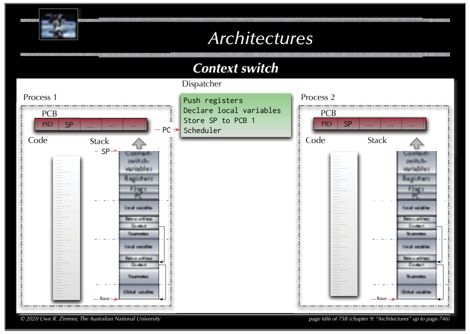
684



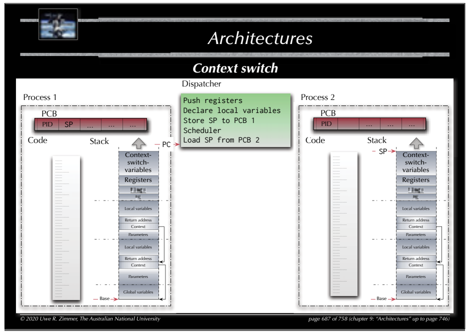
685



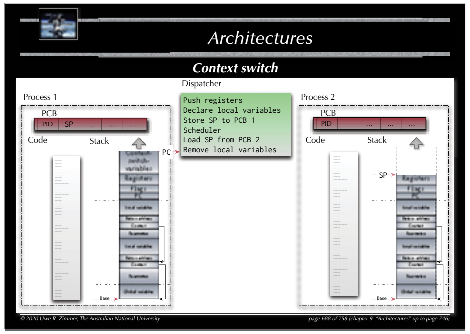
686



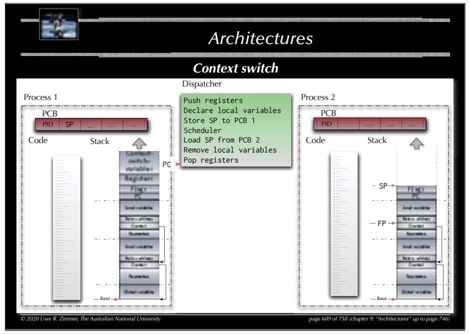
687



688



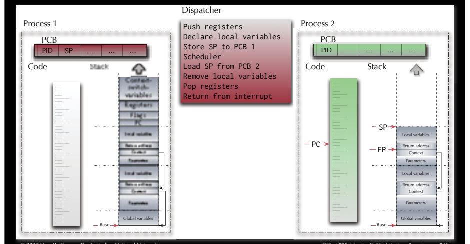
689



690

Architectures

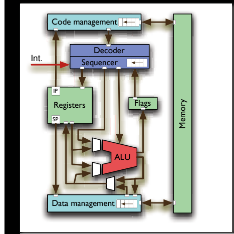
Context switch



691

Architectures

Processor Architectures



Pipeline

Some CPU actions are naturally sequential (e.g. instructions need to be first loaded, then decoded before they can be executed).

More fine grained sequences can be introduced by breaking CPU instructions into micro code.

☞ Overlapping those sequences in time will lead to the concept of pipelines.

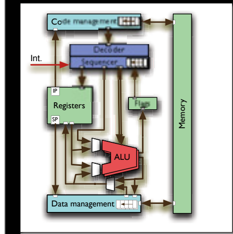
☞ Same latency, yet higher throughput.

☞ (Conditional) branches might break the pipelines
☞ Branch predictors become essential.

692

Architectures

Processor Architectures



Parallel pipelines

Filling parallel pipelines (by alternating incoming commands between pipelines) may employ multiple ALU's.

☞ (Conditional) branches might again break the pipelines.

☞ Interdependencies might limit the degree of concurrency.

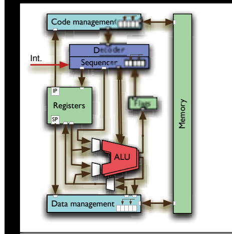
☞ Same latency, yet even higher throughput.

☞ Compilers need to be aware of the options.

693

Architectures

Processor Architectures



Out of order execution

Breaking the sequence inside each pipeline leads to 'out of order' CPU designs.

☞ Replace pipelines with hardware scheduler.

☞ Results need to be "re-sequentialized" or possibly discarded.

☞ "Conditional branch prediction" executes the most likely branch or multiple branches.

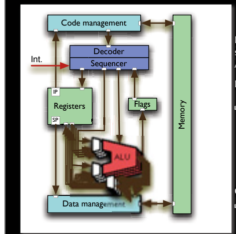
☞ Works better if the presented code sequence has more independent instructions and fewer conditional branches.

☞ This hardware will require (extensive) code optimization to be fully utilized.

694

Architectures

Processor Architectures



SIMD ALU units

Provides the facility to apply the same instruction to multiple data concurrently. Also referred to as "vector units".

Examples: Altivec, MMX, SSE[2|3|4], …

☞ **Requires specialized compilers or programming languages with implicit concurrency.**

GPU processing

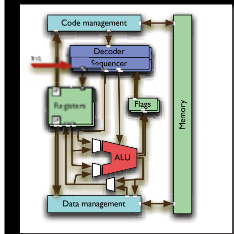
Graphics processor as a vector unit.

☞ Unifying architecture languages are used (OpenCL, CUDA, GPGPU).

695

Architectures

Processor Architectures



Hyper-threading

Emulates multiple virtual CPU cores by means of replication of:

- Register sets
- Sequencer
- Flags
- Interrupt logic

while keeping the "expensive" resources like the ALU central yet accessible by multiple hyper-threads concurrently.

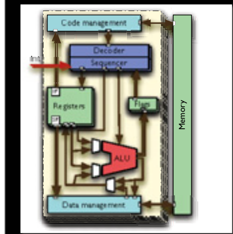
☞ **Requires programming languages with implicit or explicit concurrency.**

Examples: Intel Pentium 4, Core i5/i7, Xeon, Atom, Sun UltraSPARC T2 (8 threads per core)

696

Architectures

Processor Architectures



Multi-core CPUs

Full replication of multiple CPU cores on the same chip package.

- Often combined with hyper-threading and/or multiple other means (as introduced above) on each core.
- Cleanest and most explicit implementation of concurrency on the CPU level.

☞ **Requires synchronized atomic operations.**

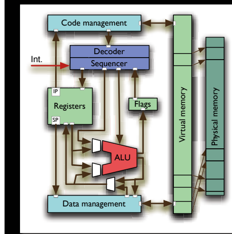
☞ **Requires programming languages with implicit or explicit concurrency.**

Historically the introduction of multi-core CPUs ended the "GHz race" in the early 2000's.

697

Architectures

Processor Architectures



Virtual memory

Translates logical memory addresses into physical memory addresses and provides memory protection features.

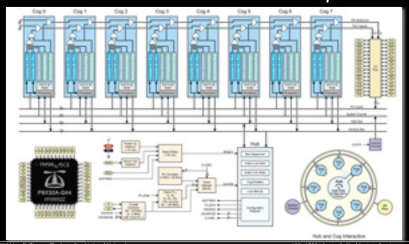
- Does not introduce concurrency by itself.

☞ Is still essential for concurrent programming as hardware memory protection guarantees memory integrity for individual processes / threads.

698

Architectures

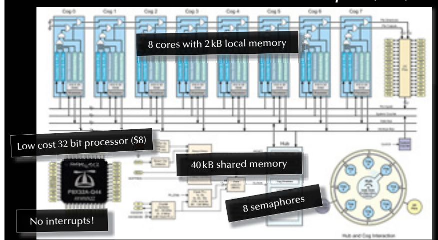
Alternative Processor Architectures: Parallax Propeller



699

Architectures

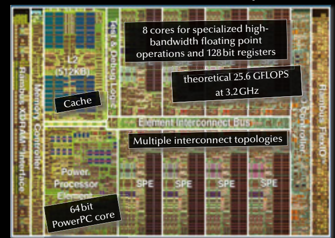
Alternative Processor Architectures: Parallax Propeller (2006)



700

Architectures

Alternative Processor Architectures: IBM Cell processor (2001)



701

Architectures

Multi-CPU systems

Scaling up:

- Multi-CPU on the same memory
  multiple CPUs on same motherboard and memory bus, e.g. servers, workstations
- Multi-CPU with high-speed interconnects
  various supercomputer architectures, e.g. Cray XE6:
  - 12-core AMD Opteron, up to 192 per cabinet (2304 cores)
  - 3D torus interconnect (160 GB/sec capacity, 48 ports per node)
- Cluster computer (Multi-CPU over network)
  multiple computers connected by network interface,
  e.g. Sun Constellation Cluster at ANU:
  - 1492 nodes, each: 2x Quad core Intel Nehalem, 24 GB RAM
  - QDR Infiniband network, 2.6 GB/sec

702

Architectures

Vector Machines

Vectorization

Buzzword collection: AltiVec, SPE, MMX, SSE, NEON, SPU, AVX, …

$$a \cdot \vec{v} = a \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a \cdot x \\ a \cdot y \\ a \cdot z \end{pmatrix}$$

Translates into **CPU-level vector operations**

```
type Real    is digits 15;
type Vectors is array (Positive range <>) of Real;
function Scale (Scalar : Real; Vector : Vectors) return Vectors is
     Scaled_Vector : Vectors (Vector'Range);
  begin
     for i in Vector'Range loop
        Scaled_Vector (i) := Scalar * Vector (i);
     end loop;
     return Scaled_Vector;
  end Scale;
```

Combined with **in-lining, loop unrolling** and **caching** this is as fast as a single CPU will get.

703

Architectures

Vector Machines

Vectorization

$$a \cdot \vec{v} = a \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a \cdot x \\ a \cdot y \\ a \cdot z \end{pmatrix}$$

Function is **"promoted"**

```
const Index = {1 .. 100000000},
      Vector_1 : [Index] real = 1.0,
      Scale    : real = 5.1,
      Scaled   : [Vector] real = Scale * Vector_1;
```

Translates into **CPU-level vector operations** *as well as* **multi-core** or **fully distributed operations**

704

Architectures

Vector Machines

Reduction

$$\vec{v_1} = \vec{v_2} \Rightarrow \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} \Rightarrow (x_1 = x_2) \wedge (y_1 = y_2) \wedge (z_1 = z_2)$$

```
type Real is digits 15;
type Vectors is array (Positive range <>) of Real;
function "=" (Vector_1, Vector_2 : Vectors) return Boolean is
    (for all i in Vector_1'Range => Vector_1 (i) = Vector_2 (i));
```

Translates into **CPU-level vector operations**

$\wedge$-chain is evaluated lazy sequentially.

705

Architectures

Vector Machines

Reduction

$$\vec{v_1} = \vec{v_2} \Rightarrow \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} \Rightarrow (x_1 = x_2) \wedge (y_1 = y_2) \wedge (z_1 = z_2)$$

```
const Index = {1 .. 100000000},
      Vector_1, Vector_2 : [Index] real = 1.0;
proc Equal (v1, v2) : bool
   {return && reduce (v1 == v2);}
```

$\wedge$-operations are evaluated in a **concurrent divide-and-conquer** (binary tree) structure.

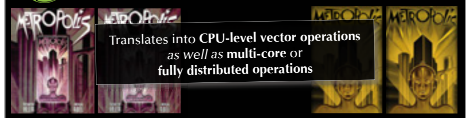
Function is **"promoted"**

Translates into **CPU-level vector operations** *as well as* **multi-core** or **fully distributed operations**

Architectures

Vector Machines

General Data-parallelism

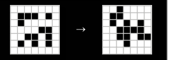



```
const Mask : [1 .. 3, 1 .. 3] real = ((0, -1, 0), (-1, 5, -1), (0, -1, 0));
proc Unsharp_Mask (P, (i, j) : index (Image)) : real
   {return + reduce (Mask * P [i - 1 .. i + 1, j - 1 .. j + 1]);}
const Sharpened_Picture = forall px in Image do Unsharp_Mask (Picture, px);
```


Architectures

Vector Machines

General Data-parallelism



Cellular automaton transitions from a state into the next state ′:
→ ′ ⇔ ∀ ∈ : → ′ = (,), i.e. all cells of a state transition *concurrently* into new cells by following a rule .

```
Next_State = forall World_Indices in World do Rule (State, World_Indices);
```

John Conway's **Game of Life** rule:

```
proc Rule (S, (i, j) : index (World)) : Cell {
  const Population : index ({0 .. 9}) =
                + reduce Count (Cell.Alive, S [i - 1 .. i + 1, j - 1 .. j + 1]);
  return (if Population == 3
        || (Population == 4 && S [i, j] == Cell.Alive) then Cell.Alive
                                                        else Cell.Dead);
}
```


Architectures

Operating Systems

What is an operating system?

Architectures

What is an operating system?

1. A virtual machine!

... offering a more comfortable and safer environment

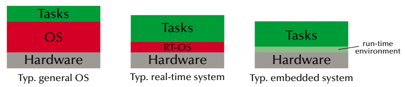
(e.g. memory protection, hardware abstraction, multitasking, ...)

Architectures

What is an operating system?

1. A virtual machine!

... offering a more comfortable and safer environment



Architectures

What is an operating system?

2. A resource manager!

... coordinating access to hardware resources

Architectures

What is an operating system?

2. A resource manager!

... coordinating access to hardware resources

Operating systems deal with

- processors
- memory
- mass storage
- communication channels
- devices (timers, special purpose processors, peripheral hardware, ...

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

Architectures

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 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)

Architectures

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)

Current standard consumer computers might come with:

- High speed network connectors (e.g. GB-Ethernet)
- Wireless LAN (e.g. IEEE802.11g, ...)
- Local device bus-system (e.g. Firewire 800, Fibre Channel or USB 3.0)
- Wireless local device network (e.g. Bluetooth)
- Infrared communication (e.g. IrDA)
- Modem/ADSL

Architectures

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, like for instace:

- 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 a proprietary user-interface)

- Multiprocessing is supported by all these OSs to some extent.
- None of these OSs are suitable for embedded systems, although trials have been performed.
- None of these OSs are suitable for distributed or real-time systems.

Architectures

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.

Architectures

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)

Architectures

Types of current operating systems

Real-time operating systems

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

Architectures

Types of current operating systems

Real-time operating systems

- ~~Fast context switches?~~ should be fast anyway
- ~~Small size?~~ should be small anyway
- ~~Quick response to external interrupts?~~ not 'quick', but predictable
- ~~Multitasking?~~ often, not always
- ~~'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!

Architectures

Types of current operating systems

Real-time operating systems need to provide...
☞ 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

Architectures

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!

722

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

723

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

☞ **no:**
the term 'operating system' covers 4 kB microkernels,
as well as > 1 GB installations of desktop general purpose operating systems.

724

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

☞ **no:**
the term 'operating system' covers 4 kB microkernels,
as well as > 1 GB installations of desktop general purpose operating systems.

Is there a minimal set of features?

725

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

☞ **no:**
the term 'operating system' covers 4 kB microkernels,
as well as > 1 GB installations of desktop general purpose operating systems.

Is there a minimal set of features?

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

726

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

☞ **no:**
the term 'operating system' covers 4 kB microkernels,
as well as > 1 GB installations of desktop general purpose operating systems.

Is there a minimal set of features?

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

Is there always an explicit operating system?

727

Architectures

What is an operating system?

Is there a standard set of features for operating systems?

☞ **no:**
the term 'operating system' covers 4 kB microkernels,
as well as > 1 GB installations of desktop general purpose operating systems.

Is there a minimal set of features?

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

Is there always an explicit operating system?

☞ **no:**
some languages and development systems operate with standalone runtime environments

728

Architectures

Typical features of operating systems

Process management:

- Context switch
- Scheduling
- Book keeping (creation, states, cleanup)

☞ context switch:

☞ needs to...
- 'remove' one process from the CPU while preserving its state
- choose another process (scheduling)
- 'insert' the new process into the CPU, restoring the CPU state

Some CPUs have hardware support for context switching, otherwise:

☞ use interrupt mechanism

729

Architectures

Typical features of operating systems

Memory management:

- Allocation / Deallocation
- Virtual memory: logical vs. physical addresses, segments, paging, swapping, etc.
- Memory protection (privilege levels, separate virtual memory segments, ...)
- Shared memory

Synchronisation / Inter-process communication

- semaphores, mutexes, cond. variables, channels, mailboxes, MPI, etc. (chapter 4)

☞ tightly coupled to scheduling / task switching!

Hardware abstraction

- Device drivers
- API
- Protocols, file systems, networking, everything else...

730

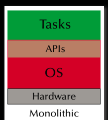
Architectures

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)

☞ but: may reach high efficiency



e.g. most early UNIX systems,
MS-DOS (80s), Windows (all non-NT based versions)
MacOS (until version 9), and many others...

731

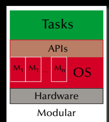
Architectures

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 high efficiency



e.g. current Linux versions

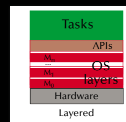
732

Architectures

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



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

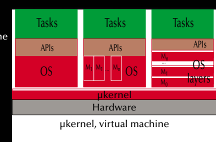
733

Architectures

Typical structures of operating systems

μKernels & 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 needs to be ported.
- possibly reduced efficiency through increased communications



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

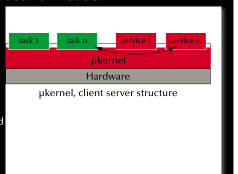
734

Architectures

Typical structures of operating systems

μKernels & client-server models

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



e.g. current research projects, L4, etc.

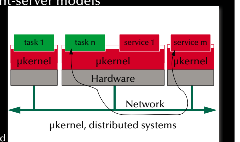
735

Architectures

Typical structures of operating systems

μKernels & client-server models

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



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

736

Architectures

UNIX

UNIX features

- Hierarchical file-system (maintained via 'mount' and 'unmount')
- 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,** OPEN-STEP, **OpenBSD, Darwin, QNX/Neutrino, OS X, QNX RTOS,** ... .

737

Architectures

UNIX

Dynamic process creation

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

resulting a *duplication of the current process*

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

738

UNIX

Dynamic process creation

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

resulting a *duplication of the current process*

- returning 0 to the newly created 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 */
}
```


739

UNIX

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 ();
}
```


740

UNIX

Message passing in UNIX ☞ Pipes

```
int data_pipe [2], c, rc;
if (pipe (data_pipe) == -1) {
  perror ("no pipe"); exit (1);
}
if (fork () == 0) { // child
  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 { // parent
  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 ();
}
```


741

UNIX

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 synchronisation

Pipes:

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

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

742

UNIX

Sockets in BSD UNIX

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

Connectionless 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]`

743

POSIX

Portable **O**perating **S**ystem **I**nterface for Uni**x**

- IEEE/ANSI Std 1003.1 and following.
- Library Interface (API)
  [C Language calling conventions – types exit mostly in terms of (open) lists of pointers and integers with overloaded meanings].
- More than 30 different POSIX standards (and growing / changing).
  ☞ a system is 'POSIX compliant', if it implements parts of one of them!
  ☞ a system is '100% POSIX compliant', if it implements one of them!

744

POSIX - some of the 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

745

POSIX - 1003.1b/c

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

746

Summary

Architectures

- **Hardware architectures - from simple logic to supercomputers**
  - logic, CPU architecture, pipelines, out-of-order execution, multithreading, ...
- **Data-Parallelism**
  - Vectorization, Reduction, General data-parallelism
- **Concurrency in languages**
  - Some examples: Haskell, Occam, Chapel
- **Operating systems**
  - Structures: monolithic, modular, layered, μkernels
  - UNIX, POSIX

747

Systems, Networks & Concurrency 2020

10

Summary

Uwe R. Zimmer - The Australian National University

748

Summary

Summary

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
- **Concurrent programming languages:**
  - Explicit concurrency: e.g. Ada, Chapel
  - Implicit concurrency: functional programming – e.g. Haskell, Caml

749

Summary

Summary

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

750

Summary

Summary

Communication & 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

751

Summary

Summary

Non-Determinism

- **Non-determimism by design:**
  - Benefits & considerations
- **Non-determinism by interaction:**
  - Selective synchronization
  - Selective accepts
  - Selective calls
- **Correctness of non-deterministic programs:**
  - Sources of non-determinism
  - Predicates & invariants

752

Summary

Summary

Data Parallelism

- **Data-Parallelism**
  - Vectorization
  - Reduction
  - General data-parallelism
- **Examples**
  - Image processing
  - Cellular automata

753

Summary

Summary

Scheduling

- **Basic performance scheduling**
  - Motivation & Terms
  - Levels of knowledge / assumptions about the task set
  - Evaluation of performance and selection of appropriate methods
- **Towards predictable scheduling**
  - Motivation & Terms
  - Categories & Examples

754

Summary

Summary

Safety & Liveness

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

755

Summary

Summary

Distributed Systems

- **Networks**
  - OSI, topologies
  - Practical network 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)

756

Summary

Summary

Architectures

- **Hardware architectures - from simple logic to supercomputers**
  - logic, CPU architecture, pipelines, out-of-order execution, multithreading, …
- **Data-Parallelism**
  - Vectorization, Reduction, General data-parallelism
- **Concurrency in languages**
  - Some examples: Haskell, Occam, Chapel
- **Operating systems**
  - Structures: monolithic, modular, layered, µkernels
  - UNIX, POSIX

757

Summary

Exam preparations

Helpful

- **Distinguish** central aspects from excursions, examples & implementations.
- **Gain** full understanding of all central aspects.
- Be able to **categorize** any given example under a general theme discussed in the lecture.
- **Explain** to and **discuss** the topics with other (preferably better) students.
- Try whether you can **connect** aspects from different parts of the lecture.

Not helpful

- Remembering the slides word by word.
- Learn the Chapel / Unix / Posix / Occam / sockets reference manual page by page.

758