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Systems, Networks & Concurrency 2020

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Mutual Exclusion

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Mutual Exclusion

References for this chapter

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

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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.

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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.

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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          task body P2 is          task body P3 is
begin                    begin                    begin
  G := 1                   G := 2                   G := 3
  G := G + G;              G := G + G;              G := G + G;
end P1;                  end P2;                  end P3;
```

☞ What is the value of G?

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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          task body P2 is          task body P3 is
begin                    begin                    begin
  G := 1                   G := 2                   G := 3
  G := G + G;              G := G + G;              G := G + G;
end P1;                  end P2;                  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

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Mutual Exclusion

Mutual exclusion: First attempt

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

task body P0 is                                task body P1 is
begin                                          begin
  loop                                           loop
    ------ non_critical_section_0;                 ------ non_critical_section_1;
    loop exit when Turn = 0; end loop;             loop exit when Turn = 1; end loop;
      ------ critical_section_0;                     ------ critical_section_1;
    Turn := Turn + 1;                              Turn := Turn + 1;
  end loop;                                      end loop;
end P0;                                        end P1;
```

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

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Mutual Exclusion

Mutual exclusion: First attempt

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

task body P0 is                                task body P1 is
begin                                          begin
  loop                                           loop
    ------ non_critical_section_0;                 ------ non_critical_section_1;
    loop exit when Turn = 0; end loop;             loop exit when Turn = 1; end loop;
      ------ critical_section_0;                     ------ critical_section_1;
    Turn := Turn + 1;                              Turn := Turn + 1;
  end loop;                                      end loop;
end P0;                                        end P1;
```

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

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Mutual Exclusion

Mutual exclusion: First attempt

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

task body P0 is                                task body P1 is
begin                                          begin
  loop                                           loop
    ------ non_critical_section_0;                 ------ non_critical_section_1;
    loop exit when Turn = 0; end loop;             loop exit when Turn = 1; end loop;
      ------ critical_section_0;                     ------ critical_section_1;
    Turn := Turn + 1;                              Turn := Turn + 1;
  end loop;                                      end loop;
end P0;                                        end P1;
```

Patch

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

scatter:

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

into the non-critical sections

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?

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!

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?

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!

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?

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!

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;
```


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!

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;
```

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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!

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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.

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Mutual Exclusion

Mutual exclusion: Bakery Algorithm

The idea of the Bakery Algorithm

A set of N Processes $P_1 \ldots P_N$ competing for mutually exclusive execution of their critical regions. Every process P_i out of $P_1 \ldots P_N$ supplies: a globally readable number t_i ('ticket') (initialized to '0').

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

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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;
```


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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)
                                   or else
                                         this_id) = Ticket (id)
                                     and then 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)

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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

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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?

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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!

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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?

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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!

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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?

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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!

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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?

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```
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:
```


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

    ldr   r3, =Lock                     ldr   r3, =Lock
    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
fail_enter:                         fail_leave:
    ldr   r0, [r3]                      ldr   r0, [r3]
    cbnz  r0, fail_enter ; if locked    cbnz  r0, fail_leave ; if locked

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

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


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

    ldr   r3, =Lock                       ldr   r3, =Lock
    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
fail_enter:                           fail_leave:
    ldr   r0, [r3]                        ldr   r0, [r3]
    cbnz  r0, fail_enter ; if locked      cbnz  r0, fail_leave ; if locked
    mov   r0, #1         ; lock value     mov   r0, #1         ; lock value
    str   r0, [r3]       ; lock           str   r0, [r3]       ; lock

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

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


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

    ldr   r3, =Lock                       ldr   r3, =Lock
    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
fail_enter:                           fail_leave:
    ldrex r0, [r3]                        ldrex r0, [r3]
    cbnz  r0, fail_enter ; if locked      cbnz  r0, fail_leave ; if locked
    mov   r0, #1         ; lock value     mov   r0, #1         ; lock value
    strex r0, [r3]       ; try lock       strex r0, [r3]       ; try lock
    cbnz  r0, fail_enter ; if touched     cbnz  r0, fail_leave ; if touched
    dmb                  ; sync memory    dmb                  ; sync memory

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

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

Any context switch needs to clear reservations

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

    ldr   r3, =Lock                       ldr   r3, =Lock
    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
fail_enter:                           fail_leave:
    ldrex r0, [r3]                        ldrex r0, [r3]
    cbnz  r0, fail_enter ; if locked      cbnz  r0, fail_leave ; if locked
    mov   r0, #1         ; lock value     mov   r0, #1         ; lock value
    strex r0, [r3]       ; try lock       strex r0, [r3]       ; try lock
    cbnz  r0, fail_enter ; if touched     cbnz  r0, fail_leave ; if touched
    dmb                  ; sync memory    dmb                  ; sync memory

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

    dmb             ; sync memory         dmb             ; sync memory
    mov   r0, #0    ; unlock value        mov   r0, #0    ; unlock value
    str   r0, [r3]  ; unlock              str   r0, [r3]  ; unlock

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

Any context switch needs to clear reservations

```
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

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".

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**.

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.

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'.


```
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


```
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


```
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


```
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

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```
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

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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?

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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!

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Mutual Exclusion

Semaphores

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

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

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

☞ Works too?

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Mutual Exclusion

Semaphores

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

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

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

☞ Mutual exclusion!, No global live-lock!
☞ Works for any dynamic number of processes.
☞ Individual starvation possible!
☞ Deadlock possible!

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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