2

Mutual Exclusion

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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

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.

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.

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`?

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`

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?

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!

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!
- ☞ Inefficient!

scatter:

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

into the non-critical sections

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: Second attempt

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

```
task body P1 is

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

```
task body P2 is

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

☞ No mutual exclusion!

Mutual exclusion: Third attempt

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

```
task body P1 is

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

```
task body P2 is

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

☞ Any better?

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: 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: 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: 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: 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: 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;
```

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!

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':

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

The idea of the Bakery Algorithm

A set of N Processes $P_1 \dots P_N$ 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?

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;
```

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;
```

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

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

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

Mutual exclusion: atomic test-and-set operation

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

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

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

☞ Does that work?

Mutual exclusion: atomic test-and-set operation

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

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

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

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

Mutual exclusion: atomic exchange operation

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

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

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

☞ Does that work?

Mutual exclusion: atomic exchange operation

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

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

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

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

Mutual exclusion: memory cell reservation

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

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

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

☞ Does that work?

Mutual exclusion: memory cell reservation

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

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

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

Mutual exclusion … or the lack thereof

```
Count : Integer := 0;
```

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

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

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

```
Count:    .word 0x00000000
```

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

    Negotiate who goes first

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

    Indicate critical section completed

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

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

    Negotiate who goes first

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

    Indicate critical section completed

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

```
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:
```

Critical section

```
    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

```
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:
```

Critical section

```
    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

```
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

```
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

```
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

```
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".

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**.

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 Pi on S]
```

- an atomic operation **Signal** on S: (aka 'Set_True', 'sem_post', …)

  Process P_i : **Signal** (S):

```
[if ∃ Pj suspended on S then release Pj
                        else S := S + 1]
```

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

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:
```

Critical section

```
    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

```
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

      …                  Critical section

      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

      …                  Critical section

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

```
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:
```

Any context switch needs to clear reservations

Critical section

```
    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:
```

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
    …
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:
```

Any context switch needs to clear reservations

Critical section

```
    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:
```

Critical section

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?

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
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?

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!

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