ETH Zürich
Chair of Software Engineering

Concepts of Concurrent Computation

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Lecture 5: Monitors

Today's lecture

In this lecture you will learn about:

- the type of monitors, an important synchronization mechanism that separates the issues of mutual exclusion and condition synchronization,
- implementation variants of monitors, in particular various signaling disciplines,
- uses of monitors, in particular the readers-writers problem and the sleeping barber problem.

The monitor type

Why semaphores are not good enough

- We have seen that semaphores provide a simple yet powerful synchronization primitive: they are conceptually simple, efficient, and versatile
- However, one can argue that semaphores provide "too much" flexibility:
  - We cannot determine the correct use of a semaphore from the piece of code where it occurs; potentially the whole program need be considered
  - Forgetting or misplacing a *down* or *up* operation compromises correctness
  - It is easy to introduce deadlocks into programs
- We would like an approach that supports programmers better in these respects, enabling them to apply synchronization in a more *structured* manner

Monitors

- Monitors are an approach to providing synchronization that is based in object-oriented principles, especially the notions of *class* and *encapsulation*
- *A monitor class* fulfills the following conditions:
  - All its attributes are private
  - Its routines execute with mutual exclusion
- *A monitor* is an object instantiating a monitor class
- Intuition:
  - Attributes correspond to shared variables, i.e. threads can only access them via the monitor
  - Routine bodies correspond to critical sections, as at most one routine is active inside a monitor at any time

Notation

```
monitor class MONITOR_NAME
   feature
      -- attribute declarations
      a1 : TYPE1
        . . .

      -- routine declarations
      r1 (arg1, ..., argk) do ... end
        . . .

   invariant
      -- monitor invariant
end
```

Ensuring mutual exclusion in monitors (1)

- The condition that at most one routine is active inside a monitor at any time is ensured by the implementation of monitors (not burdened on the programmer)
- We show an implementation based on semaphores – other implementation variants exist
- With every monitor, associate a strong semaphore as the monitor's lock:

```
entry : SEMAPHORE
```

Ensuring mutual exclusion in monitors (2)

- The semaphore entry is initialized to 1
- Any monitor routine must acquire the semaphore before executing its body:

```
r (arg₁, ..., argₖ)
    do
        entry.down
        body_r
        entry.up
    end
```

- The process queue entry.blocked of the semaphore entry is also called the *entry queue* of the monitor

Solution to the mutual exclusion problem (1)

```
monitor class CS
   feature
      x_1 : TYPE_1   . . .   x_m : TYPE_m  -- shared data
      critical_1
         do
            critical section_1
         end
       . . .
      critical_n
         do
            critical section_n
         end
end
```

Solution to the mutual exclusion problem (2)

- As shown on the previous slide, the critical sections of the n threads are taken as the bodies of routines critical_1, ..., critical_n
- Then the mutual exclusion problem is solved as

create cs.make
P_i

while true loop
    cs.critical_i
    non-critical section
end

where cs is an instance of the monitor class CS

- Mutual exclusion and starvation freedom follow from the properties of a strong semaphore

Condition variables (1)

- We have seen how monitors can provide mutual exclusion
- What about other forms of synchronization, e.g. condition synchronization?
- For this monitors offer condition variables, which can be compared to semaphores as used for condition synchronization
- However, their semantics is much different from semaphores and deeply intertwined with the monitor concept

Condition variables (2)

- A *condition variable* consists of a queue blocked and three (atomic) operations:
  - wait releases the lock on the monitor, blocks the executing thread and appends it to blocked
  - signal has no effect if blocked is empty; otherwise it unblocks a thread, but can have other side effects that depend on the *signaling discipline* used
  - is_empty returns true if blocked is empty, false otherwise
- The operations wait and signal can only be called from the body of a monitor routine

Implementation of condition variables

```
class CONDITION_VARIABLE
feature
   blocked: QUEUE
   wait
      do
         entry.up            -- release the lock on the monitor
         blocked.add(P)      -- P is the current process
         P.state := blocked  -- block process P
      end
   signal deferred end      -- behavior depends on signaling discipline
   is_empty: BOOLEAN
      do
         result := blocked.is_empty
      end
end
```

Signaling disciplines

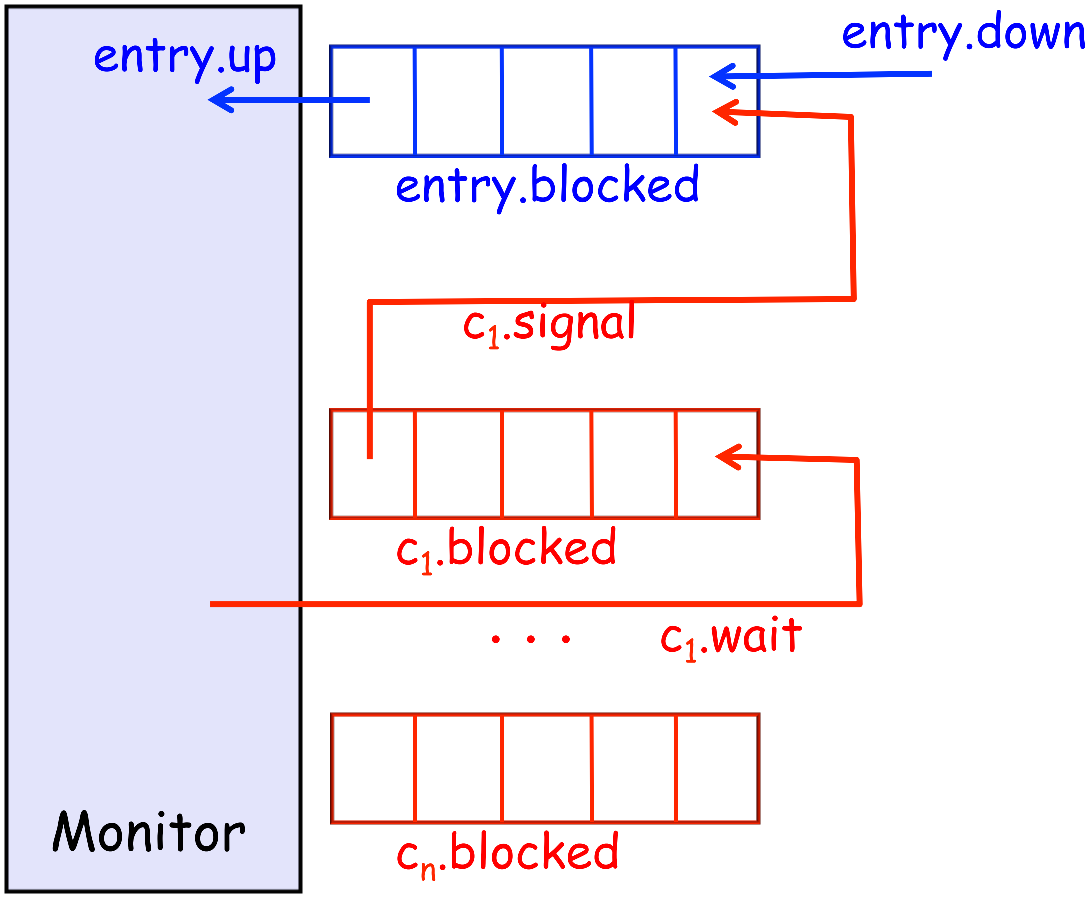
- When a process signals on a condition variable, it still executes inside the monitor
- As only one process may execute within a monitor at any time, an unblocked process cannot enter the monitor immediately
- Two main choices for continuation:
  - the signaling process continues, and the signaled process is moved to the entry of the monitor
  - the signaling process leaves the monitor, and lets the signaled process continue
- The decision of the behavior of signal is expressed in *signaling disciplines*

Signaling disciplines: Signal and Continue (1)

- Signal and Continue signaling discipline:
  - the signaling process continues
  - the signaled process is moved to the entry queue of the monitor

```
signal
    do
        if not blocked.is_empty then
            Q := blocked.remove
            entry.blocked.add(Q)
        end
    end
```

Signaling disciplines: Signal and Continue (2)

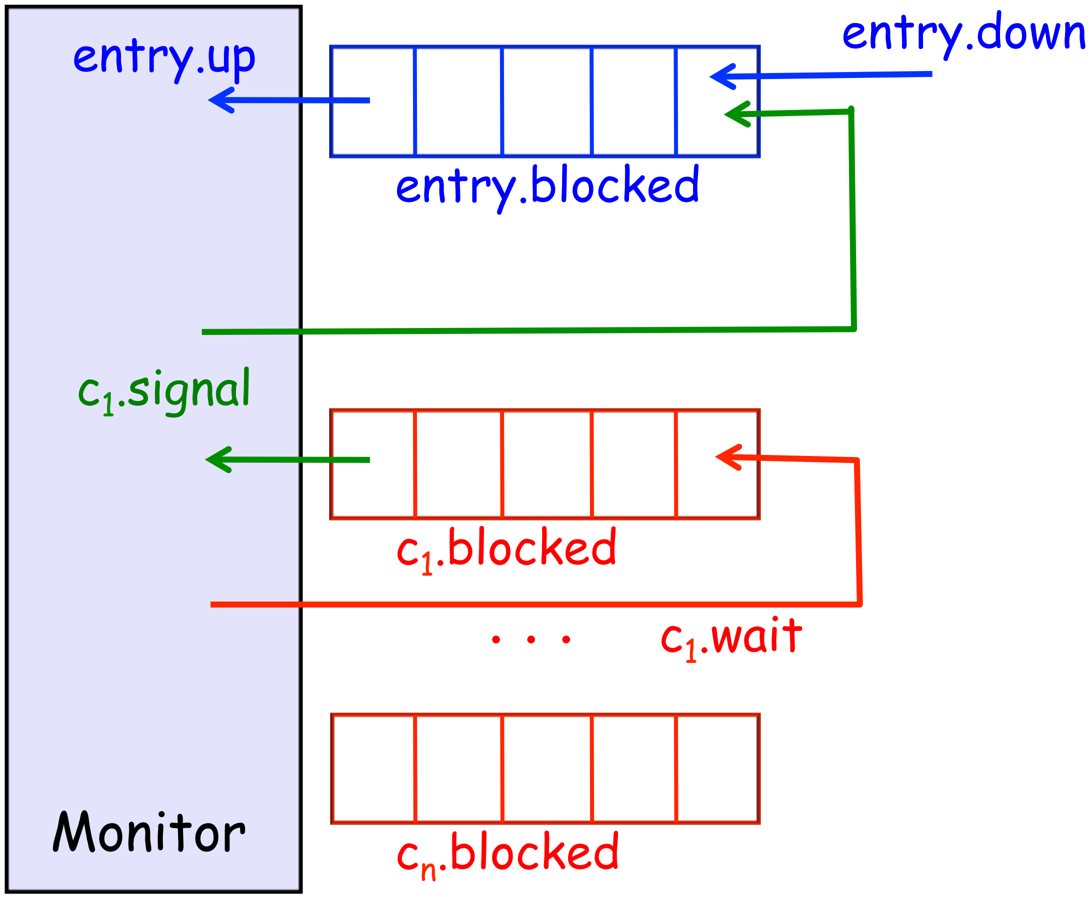


Signaling disciplines: Signal and Wait (1)

- Signal and Wait signaling discipline:
  - the signaler is moved to the entry queue of the monitor
  - the signaled process continues (the monitor's lock is silently passed on)

```
signal
  do
    if not blocked.is_empty then
      entry.blocked.add(P)  -- P is the current process
      Q := blocked.remove
      Q.state := ready        -- unblock process Q
      P.state := blocked      -- block process P
    end
  end
```

Signaling disciplines: Signal and Wait (2)



"Signal and Continue" vs. "Signal and Wait"

- If a thread executes a 'Signal and Wait' signal to indicate that a certain condition is true, this condition will be true for the signaled process
- This is not the case for 'Signal and Continue', where the signal is only a "hint" that a condition might be true now – other threads might enter the monitor beforehand and make the condition false
- In monitors with a 'Signal and Continue' also an operation

  signal_all

is offered, to wake all waiting processes, i.e.

  while not blocked.is_empty **do** signal **end**

- signal_all is typically inefficient, for many threads the signaled condition might not be true any more

Other signaling disciplines

- Urgent Signal and Continue: special case of Signal and Continue, where a thread unblocked by a signal operation is given priority over threads already waiting in the entry queue
- Signal and Urgent Wait: special case of Signal and Wait, where a signaler is given priority over threads already waiting in the entry queue

- To implement these signaling disciplines a queue urgent_entry can be introduced which has priority over the standard entry queue

Summary: signaling disciplines

- We can classify three sets of threads:
  - S Signaling threads
  - U Threads unblocked on the condition
  - B Threads blocked on the entry
- Write X > Y to mean that threads in set X have priority over threads in set Y
- Then we can express the signaling disciplines concisely as follows:
  - Signal and Continue: S > U = B
  - Urgent Signal and Continue: S > U > B
  - Signal and Wait: U > S = B
  - Signal and Urgent Wait: U > S > B

Monitors can simulate semaphores (1)

- Nobody should want to implement semaphores using monitors
- The result is important theoretically: we don't lose expressivity by using monitors instead of semaphores
- However, this does not mean that we don't have to pay more in terms of computational resources
- In the following implementation, we assume a Signal and Continue signaling discipline
- By comparing with the definition of a strong semaphore, it is easy to show that the code provides a correct simulation

Monitors can simulate semaphores (2)

```
monitor class STRONG_SEMAPHORE
feature
    count : INTEGER
    count_positive : CONDITION_VARIABLE
    down
        do
            if count > 0 then count := count - 1
            else count_positive.wait end
        end
    up
        do
            if count_positive.is_empty then count := count + 1
            else count_positive.signal end
        end
end
```

Side remark: Monitors in Java (1)

- Each object in Java has a mutex lock that can be acquired and released within **synchronized** blocks:

```
Object lock = new Object();

synchronized (lock) {
    // critical section
}
```

- The following are equivalent:

```
synchronized type m(args) {

    // body

}
```

```
type m(args) {
    synchronized (this) {
        // body
    }
}
```

Side remark: Monitors in Java (2)

- With synchronized methods, monitors can be emulated
- However not the same protection from accidental errors as in the original monitor idea is provided
- Condition variables are not explicitly available, but the following methods can be called on any synchronized object:

```
wait()
notify()        // signal
notifyAll()     // signal_all
```

- The Signal and Continue signaling discipline is used
- Java "monitors" are not starvation-free – when notify() is invoked, an *arbitrary* process is unblocked

Uses of monitors

The readers-writers problem

- **Motivation:** ensure data consistency under read and write accesses
- Relevant for databases, shared files, heap structures
- Consider shared data which can be accessed by two kinds of processes:
  - *Readers:* Processes that may execute concurrently with other readers, but need to exclude writers
  - *Writers:* Processes that have to exclude both readers and other writers

The readers-writers problem consists in providing an algorithm such that

- the access requirements are observed
- the solution is starvation-free

Towards a solution

- We cannot use monitors in the classical way, i.e. encapsulating the shared data as attributes of the monitor
- Since all monitor routines execute under mutual exclusion, we couldn't have multiple readers
- We use the monitor only to coordinate access; shared data accesses are enclosed by calls to monitor routines:

Readers: rw.read_entry
read access to shared data
rw.read_exit

Writers: rw.write_entry
write access to shared data
rw.write_exit

Monitor solution of the readers-writers problem (1)

```
monitor class READERS_WRITERS
   feature
      num_readers : INTEGER
      num_writers : INTEGER
      ok_to_read : CONDITION_VARIABLE
                     -- signal if num_writers = 0
      ok_to_write : CONDITION_VARIABLE
                     -- signal if num_readers = 0

        . . .

   invariant
      num_writers = 0 or (num_writers = 1 and num_readers = 0)
end
```

Monitor solution of the readers-writers problem (2)

- The routines follow a simple scheme:
  - entry routines
    - increment the number of readers (writers)
    - potentially block the executing process on ok_to_read or ok_to_write
  - exit routines
    - decrement the number of readers (writers)
    - potentially signal waiting readers and writers
- Checking on ok_to_write.is_empty in read_entry gives priority to writers over readers
- Checking on ok_to_read.is_empty in write_exit gives priority to readers over writers
- Together: starvation-freedom for both readers and writers

Monitor solution of the readers-writers problem (3)

```
read_entry
        do
           if num_writers > 0 or not ok_to_write.is_empty do
              ok_to_read.wait
           end
           num_readers := num_readers + 1
           ok_to_read.signal
        end
read_exit
        do
           num_readers := num_readers - 1
           if num_readers = 0 then
              ok_to_write.signal
           end
         end
```

Monitor solution of the readers-writers problem (4)

```
write_entry
        do
            if num_writers > 0 or num_readers > 0 do
                ok_to_write.wait
            end
            num_writers := num_writers + 1
        end
write_exit
        do
            num_writers := num_writers - 1
            if ok_to_read.is_empty then
                ok_to_write.signal
            else
                ok_to_read.signal
            end
        end
```

Other access strategies for readers-writers

- Instead of going for starvation-freedom for all processes, it might be beneficial in certain applications to give preference to either readers or writers
- We have three strategies:
  - *R = W:* Readers and writers have equal priority
  - *R > W:* Readers have higher priority than writers
  - *W > R:* Writers have higher priority than readers
- It is easy to derive implementations for the last two strategies from the first, which we have implemented

The sleeping barber problem (1)

- A barbershop has n chairs for waiting customers and the barber's chair. Rules of the barbershop:
  - If there are no customers waiting to be served, the barber goes to sleep
  - If a customer enters the barbershop and finds the barber sleeping, the customer wakes up the barber and then gets a haircut
  - If the barber is busy but there are waiting chairs available, the customer sits in one of the free chairs until called to the barber's chair by the barber
  - If all chairs are occupied, then the customer leaves the shop
- The problem consists in finding a starvation-free algorithm that observes these rules

The sleeping barber problem (2)

- **Motivation:** client-server relationships between operating system processes
- Generalization of a barrier:
  - two parties must arrive before any can proceed
  - however the second party is not predetermined: the barber can serve any customer

Monitor solution to the sleeping barber problem

```
monitor class SLEEPING_BARBER
   feature
      num_free_chairs : INTEGER
      barber_available : CONDITION_VARIABLE
      customer_available : CONDITION_VARIABLE

      get_haircut
         do
            if num_free_chairs > 0 then
               num_free_chairs :=
                  num_free_chairs - 1
               customer_available.signal
               barber_available.wait
               get a haircut
            end
         end

      do_haircut
         do
            while num_free_chairs = n do
               customer_available.wait
            end
            barber_available.signal
            num_free_chairs :=
               num_free_chairs + 1
            do a haircut
         end

end
```

Monitors: benefits

- Benefits of monitors:
  - *Structured approach*: programmer does not have to remember to follow a wait with a signal just to implement mutual exclusion
  - *Separation of concerns*: mutual exclusion for free, for condition synchronization we have condition variables

Monitors: problems

- Problems of monitors:
  - *Performance concerns*: trade-off between programmer support and performance
  - *Signaling disciplines*: source of confusion; Signal and Continue problematic as condition can change before a waiting process enters the monitor
  - *Nested monitor calls*: Consider that routine r1 of monitor M1 makes a call to routine r2 of monitor M2. If routine r2 contains a wait operation, should mutual exclusion be released for both M1 and M2, or only for M2?