Concepts of Concurrent Computation

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Lecture 5: Monitors

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The monitor type

The trouble with semaphores

- Semaphores provide a conceptually simple, efficient, and versatile synchronization primitive
- However, semaphores can provide “too much” flexibility
  - We cannot determine their correct use from a single piece of code, potentially the whole program needs to be considered
  - Forgetting or misplacing a down or up operation compromises correctness
  - It is easy to introduce deadlocks into programs
- How to support programmers better in using synchronization in a more structured manner?

Monitors

- Monitors are an approach to providing synchronization that is based on 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
```

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
- 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
```

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 CRITICAL_SECTION
    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 monitor class `CRITICAL_SECTION`

- 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

The sleeping barber problem

- A barbershop has *n* chairs for waiting customers and the barber's chair
  - 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: Motivation

- 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 for sleeping barber

```
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
                end
            end
            -- get a haircut

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

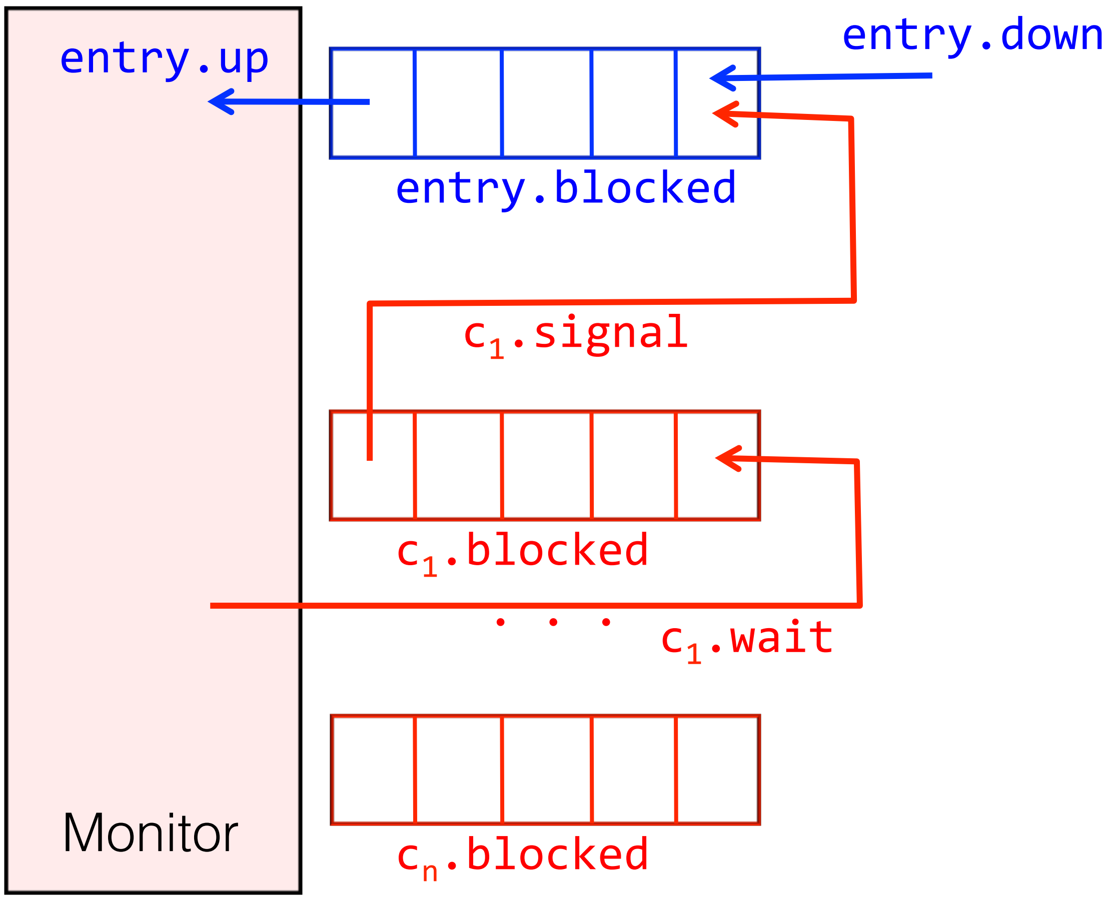
Implementation of condition variables

```
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)

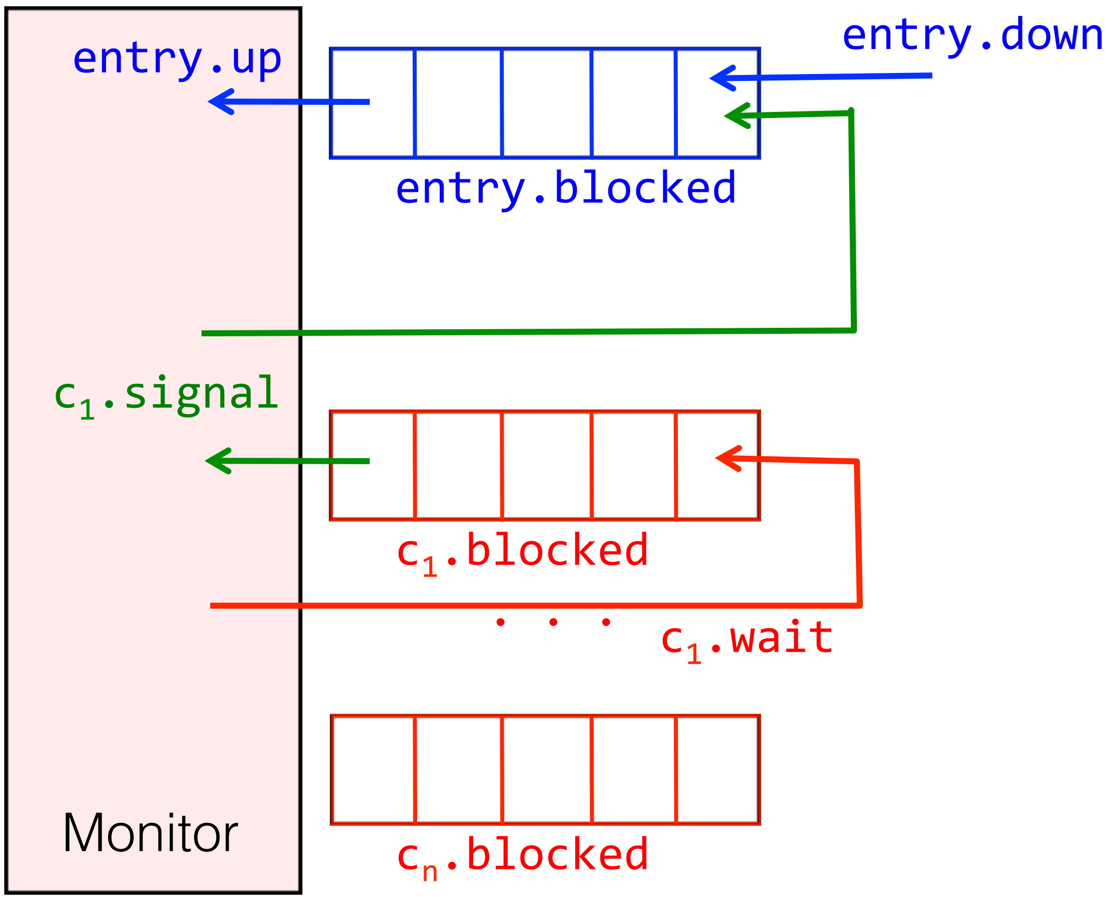


Signaling disciplines: Signal and Continue (2)

- Signal and Continue
  - 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 Wait (1)



Signaling disciplines: Signal and Wait (2)

- Signal and Wait
  - 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
```

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 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
  - 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
  - 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
  - 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, we may still 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
```

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
    }
}
```

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 for readers-writers (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 for readers-writers (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 for readers-writers (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 for readers-writers (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

Monitors: Benefits

- Structured approach
  - Programmer should have fewer troubles to implement mutual exclusion
- Separation of concerns
  - Mutual exclusion for free, condition variables for condition synchronization

Monitors: Problems

- Performance concerns
  - Trade-off between programmer support and performance
- Signaling disciplines
  - A 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?