Monitors

Ch 7 [BenA 06]

Monitors
Condition Variables
BACI and Java Monitors
Protected Objects
Monitor Concept

- High level concept
  - Semaphore is low level concept
- Want to encapsulate
  - Shared data and access to it
  - Operations on data
  - Mutex and synchronization
- Problems solved by Monitor:
  - Which data is shared?
  - Which semaphore is used to synchronize processes?
  - Which mutex is used to control critical section?
  - How to use shared resources?
  - How to maximize parallelizable work?
- Other approaches to the same (similar) problems
  - Conditional critical regions, protected objects, path expressions, communicating sequential processes, synchronizing resources, guarded commands, active objects, rendezvous, Java object, Ada package, …
Monitor (Hoare 1974)

- Encapsulated data and operations for it
  - Abstract data type, object
  - Public methods are the only way to manipulate data
  - Monitor methods can manipulate only monitor or parameter data
    - Global data outside monitor is not accessible
  - Monitor data structures are initialized at creation time and are permanent
  - Concept ”data” denotes here often to synchronization data only
    - Actual computational data processing usually outside monitor
    - Concurrent access possible to computational data
      - More possible parallelism in computation

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Monitor

- Automatic mutex for monitor methods
  - Only one method active at a time (invoked by some process)
    - May be a problem: limits possible concurrency
    - Monitor should not be used for work, but just for synchroniz.
  - Other processes are waiting
    - To enter the monitor (in mutex), or
    - Inside the monitor in some method
      - waiting for a monitor condition variable become true
      - waiting for mutex after release from condition variable or losing execution turn when signaling to condition variable
  - No queue, just set of competing processes
    - Implementation may vary

- Monitor is passive
  - Does not do anything by itself
    - No own executing threads
    - Exception: code to initialize monitor data structures (?)
  - Methods can be active only when processes invoke them
**Algorithm 7.1: Atomicity of monitor operations**

```plaintext
monitor CS
    integer n ← 0

    operation increment
        integer temp
        temp ← n
        n ← temp + 1
```

<table>
<thead>
<tr>
<th></th>
<th>p</th>
<th>q</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1:</td>
<td>CS.increment</td>
<td>q1:</td>
</tr>
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</table>

- **Automatic mutex solution**
  - Solution with busy-wait, disable interrupts, or suspension!
  - Internal to monitor, user has no handle on it, might be useful to know
  - Only one procedure active at a time – which one?

- **No ordered queue to enter monitor**
  - Starvation is possible, if many processes continuously trying to get in
Monitor Condition
Variables

- For synchronization inside the monitor
  - Must be hand-coded
  - Not visible to outside
  - Looks simpler than really is
- Condition CV
- WaitC (CV)
- SignalC (CV)

(Fig. 5.15 [Stal05])
Declaration and WaitC

- Condition CV
  - Declare new condition variable
  - No value, just fifo queue of waiting processes
- WaitC( CV )
  - Always suspends, process placed in queue
  - Unlocks monitor mutex
    - Allows someone else into monitor?
    - Allows another process awakened from (another?) WaitC to proceed?
    - Allows process that lost mutex in SignalC to proceed?
  - When awakened, waits for mutex lock to proceed
    - Not really ready-to-run yet
SignalC

- Wakes up **first** waiting process, if any
  - Which one continues execution in monitor (in mutex)?
    - The process doing the signalling?
    - The process just woken up?
    - Some other processes trying to get into monitor? **No.**
  - Two signalling disciplines (**two semantics**)
    - Signal and continue - signalling process keeps mutex
    - Signal and wait - signalled process gets mutex
- **If no one was waiting, signal is lost** (no memory)
  - Advanced signalling (with memory) must be handled in some other manner
Signaling Semantics

- **Signal and Continue** \( \text{SignalC( CV )} \)
  - Signaller process continues
    - Mutex can not terminate at signal operation
  - Awakened (signalled) process will wait in mutex lock
    - With other processes trying to enter the semaphore
    - May not be the next one active
      - Many control variables signalled by one process?
    - Condition waited for may not be true any more once awaked process resumes (becomes active again)
    - No priority or priority over arrivals for sem. mutex?
Signaling Semantics

- **Signal and Wait**  \textit{SignalC (CV )}
  - Awakened (signalled) process executes immediately
    - Mutex baton passing
      - No one else can get the mutex lock at this time
    - Condition waited for is certainly true when process resumes execution
  - Signaller waits in mutex lock
    - With other processes trying to enter the semaphore
    - No priority, or priority over arrivals for mutex?
    - Process may lose mutex at any signal operation
      - But does not lose, if no one was waiting!
      - Problem, if critical section would continue over SignalC
ESW-Priorities in Monitors

- Another way to describe signaling semantics
  - Define priority order for monitor mutex
- Processes in 3 dynamic groups
  - Priority depends on what they are doing in monitor
    - $E$ = priority of processes entering the monitor
    - $S$ = priority of a process signalling in SignalC
    - $W$ = priority of a process waiting in WaitC

- $E < S < W$ (highest pri), i.e., IRR
  - Processes waiting in WaitC have highest priority
  - Entering new process have lowest priority
  - **IRR** – immediate resumption requirement
  - **Signal and urgent wait**
  - Classical, usual semantics
  - New arrivals can not starve those inside
Algorithm 7.2: Semaphore simulated with a monitor

```c
monitor Sem
    integer s ← 1 (mutex sem)
    condition notZero
    operation wait
        if s = 0
            waitC(notZero)
        s ← s − 1
    operation signal
        s ← s + 1
        signalC(notZero)

No need for “if anybody waiting…”
What if signalC comes 1st?
```

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<tr>
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<tr>
<td>p2: Sem.signal</td>
<td>q2: Sem.signal</td>
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Problem with/without IRR

• No IRR, e.g., E=S=W or E<W<S
  – Process P waits in WaitC()
  – Process P released from WaitC, but is not executed right away
    • Waits in monitor mutex (semaphore?)
  – Signaller or some other process changes the state that P was waiting for
  – P is executed in wrong state

• IRR
  – Signalling process may lose mutex!
Algorithm 7.2: Semaphore simulated with a monitor (2)

No immediate resumption requirement, \( E = S = W \)

```
monitor Sem
    integer s ← 1
    condition notZero
    operation wait
        while (s = 0)
            waitC(notZero)
            s ← s - 1
    operation signal
        s ← s + 1
    signalC(notZero)
```

a) P & Q1 compete, Q1 wins, Q1 enters CS, s=0, P waits
b) Q1 signals P, s=1
c) P waits for mutex here
d) Q2 gets in, finds s=1, sets s=0, enters CS
e) P advances, sets s = -1, enters CS

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Algorithm 7.2: Semaphore simulated with a monitor (1/3)

No immediate resumption requirement, \( E = S = W \)

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a) P & Q1 compete, Q1 wins, Q1 enters CS, \( s=0 \), P waits
b) Q1 signals P, \( s=1 \)
c) P waits for mutex here
d) Q2 gets in, finds \( s=1 \), sets \( s=0 \), enters CS
e) P advances, sets \( s=-1 \), enters CS

monitor Sem
integer s ← 1
condition notZero
operation wait
if \( s = 0 \)
   waitC(notZero)
s ← s − 1
operation signal
s ← s + 1
signalC(notZero)
Algorithm 7.2: Semaphore simulated with a monitor (2/3)

No immediate resumption requirement, \( E = S = W \)

```plaintext
monitor Sem
    integer s ← 1
    condition notZero
    operation wait
        if s = 0
            waitC(notZero)
            s ← s - 1
    operation signal
        s ← s + 1
    signalC(notZero)
```

- **a)** P & Q1 compete, Q1 wins, Q1 enters CS, s=0, P waits
- **b)** Q1 signals P, s=1
- **c)** P waits for mutex here
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- **e)** P advances, sets s = -1, enters CS

FIX: must test for condition again

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No immediate resumption requirement, E = S = W

monitor Sem
  integer s ← 1
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  operation wait
    while (s = 0)
      waitC(notZero)
      s ← s − 1
  operation signal
    s ← s + 1
    signalC(notZero)

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a) P & Q1 compete, Q1 wins, Q1 enters CS, s=0, P waits
b) Q1 signals P, s=1
c) P waits for mutex here
d) Q2 gets in, finds s=1, sets s=0, enters CS
e) P advances, sets s = -1, enters CS

FIX: must test for condition again
Algorithm 7.3: Producer-consumer (finite buffer, monitor)

monitor PC
bufferType buffer ← empty
condition notEmpty
condition notFull

operation append(datatype V)
  if buffer is full
    waitC(notFull)
  append_tail(V, buffer) ; typo in book
  signalC(notEmpty)

operation take()
  datatype W
  if buffer is empty
    waitC(notEmpty)
  W ← head(buffer)
  signalC(notFull)
  return W

producer
  datatype D
  loop forever
  p1: D ← produce
  p2: PC.append(D)

consumer
  datatype D
  loop forever
  q1: D ← PC.take
  q2: consume(D)

buffer hidden, synchronization hidden (easy-to-write code)
internal procedures in monitor, no waitC in them (important design feature)

IRR semantics (important assumption)
Other Monitor Internal Operations

- **Empty( CV )**
  - Returns TRUE, iff CV-queue is empty
  - Might do something else than wait for your turn ….

- **Wait( CV, rank )**
  - Priority queue, release in priority order
  - Small rank number, high priority

- **Minrank( CV )**
  - Return **rank** for first waiting process (or 0 or whatever?)

- **Signal_all( CV )**
  - Wake up **everyone** waiting
    - If IRR, who gets mutex turn? Highest rank?
    - 1st in queue? Last in queue?
Readers and Writers with Monitor

Readers
- Many can read concurrently
- No writers allowed with readers

Writers
- Only one can write at a time
- No readers allowed at that time

<table>
<thead>
<tr>
<th>reader</th>
<th>writer</th>
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<tbody>
<tr>
<td>p1: RW.StartRead</td>
<td>q1: RW.StartWrite</td>
</tr>
<tr>
<td>p2: read the database</td>
<td>q2: write to the database</td>
</tr>
<tr>
<td>p3: RW.EndRead</td>
<td>q3: RW.EndWrite</td>
</tr>
</tbody>
</table>

outside monitor!
Algorithm 7.4: Readers and writers with a monitor

```
monitor RW
    integer readers ← 0
    integer writers ← 0
    condition OKtoRead, OKtoWrite

operation StartRead
    if writers ≠ 0 or not empty(OKtoWrite)
        waitC(OKtoRead)
    readers ← readers + 1
    signalC(OKtoRead)

operation EndRead
    readers ← readers - 1
    if readers = 0
        signalC(OKtoWrite)

operation StartWrite
    if writers ≠ 0 or readers ≠ 0
        waitC(OKtoWrite)
    writers ← writers + 1

operation EndWrite
    writers ← writers - 1
    if empty(OKtoRead)
        then signalC(OKtoWrite)
    else signalC(OKtoRead)
```

- 3 processes waiting in OKtoRead. Who is next?
- 3 processes waiting in OKtoWrite. Who is next?
- If writer finishing, and 1 writer and 2 readers waiting, who is next?
Algorithm 7.5: Dining philosophers with a monitor

monitor ForkMonitor
    integer array[0..4] fork ← [2, ..., 2]
    condition array[0..4] OKtoEat
    operation takeForks(integer i)
        if fork[i] ≠ 2
            waitC(OKtoEat[i])
        fork[i+1] ← fork[i+1] − 1
        fork[i−1] ← fork[i−1] − 1
    operation releaseForks(integer i)
        fork[i+1] ← fork[i+1] + 1
        fork[i−1] ← fork[i−1] + 1
        if fork[i+1] = 2
            signalC(OKtoEat[i+1])
        if fork[i−1] = 2
            signalC(OKtoEat[i−1])

Number of forks available to philosopher i
philosopher i
    loop forever
    p1: think
    p2: takeForks(i)
    p3: eat
    p4: releaseForks(i)


Signaling semantics? IRR → mutex will break here!

When executed? Much later? Semantics?

Is order important?

What changes were needed, if E=S=W semantics were used?

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BACI Monitors

- waitc
  - IRR
  - Queue not FIFO
  - Baton passing

- Also
  - waitc() with priority: `waitc ( OKtoWrite, 1 );`
  - Default priority = 10 (big number, high priority ??)
Readers and Writers in C++

```c++
monitor RW {
    int readers = 0, writing = 0; (typo fix)
    condition OKtoRead, OKtoWrite;

    void StartRead() {
        if (writing || !empty(OKtoWrite))
            waitc(OKtoRead);
        readers = readers + 1;
        signalc(OKtoRead);
    }

    void EndRead() {
        readers = readers - 1;
        if (readers == 0)
            signalc(OKtoWrite);
    }

    void StartWrite() {
        if (writing || (readers != 0))
            waitc(OKtoWrite);
        writing = 1;
    }

    void EndWrite() {
        writing = 0;
        if (empty(OKtoRead))
            signalc(OKtoWrite);
        else
            signalc(OKtoRead);
    }
}
```

readers have priority, writer may starve
Java Monitors

- No real support
- Emulate monitor with normal object with all methods synchronized
- Emulate monitor condition variables operations with Java wait(), notifyAll(), and try/catch.
  - Generic wait-operation
- “E = W < S” signal semantics
  - No IRR, use while-loops
- notifyAll() will wake-up all waiting processes
  - Must check the conditions again
  - No order guaranteed – starvation is possible
Producer-Consumer in Java

class PCMonitor {
    final int N = 5;
    int Oldest = 0, Newest = 0;
    volatile int Count = 0;
    int Buffer[] = new int[N];

    synchronized void Append(int V) {
        while (Count == N)
            try {
                wait();
            } catch (InterruptedException e) {
        }
        Buffer[Newest] = V;
        Newest = (Newest + 1) % N;
        Count = Count + 1;
        notifyAll();
    }

    synchronized int Take() {
        int temp;
        while (Count == 0)
            try {
                wait();
            } catch (InterruptedException e) {
        }
        temp = Buffer[Oldest];
        Oldest = (Oldest + 1) % N;
        Count = Count - 1;
        notifyAll();
        return temp;
    }
}
PlusMinus with Java Monitor

• Simple Java solution with monitor-like code
  – Plusminus_mon.java

  vera: javac Plusminus_mon.java
  vera: java Plusminus_mon

  http://www.cs.helsinki.fi/u/kerola/rio/Java/examples/Plusminus_mon.java

  – Better: make data structures visible only to ”monitor” methods?
Monitor Summary

+ Automatic Mutex
+ Hides complexities from monitor user
- Internal synchronization with semantically complex condition variables
  - With IRR semantics, try to place signalC at the end of the method
  - With IRR, mutex ends with signalC
- Does not allow for any concurrency inside monitor

– Monitor should be used only to control concurrency
– Actual work should be done outside the monitor
Protected Objects

- Like monitor, but condition variable definitions implicit and coupled with *when-expression* on which to wait
  - Automatic mutex control for operations (as in monitor)
- **Barrier, fifo queue**
  - Evaluated only (always!) when some operation terminates within mutex
    - Signaller is exiting
  - Implicit signalling
  - Do not confuse with barrier synchronization!

---

```
condition OKtoWrite;
void StartWrite() {
    if (writing || (readers != 0))
        waitc(OKtoWrite);
    writing = 1;
}
```

(operation StartWrite when not writing and readers = 0
writing ← true)
Algorithm 7.6: Readers and writers with a protected object

protected object RW

integer readers ← 0
boolean writing ← false

operation StartRead when not writing
    readers ← readers + 1

operation EndRead
    readers ← readers − 1

operation StartWrite when not writing and readers = 0
    writing ← true

operation EndWrite
    writing ← false

reader

loop forever
    RW.StartRead
    read the database
    RW.EndRead

writer

loop forever
    RW.StartWrite
    write to the database
    RW.EndWrite

• Mutex semantics?
  – What if many barriers become true? Which one resumes?

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Readers and Writers as ADA Protected Object

Continuous flow of readers will starve writers.

How would you change it to give writers priority?

```ada
package RW is
  entry StartRead;
  procedure EndRead;
  entry StartWrite;
  procedure EndWrite;
private
  Readers: Natural := 0;
  Writing: Boolean := false;
end RW;

protected body RW is
  entry StartRead
    when not Writing is
    begin
      Readers := Readers + 1;
    end StartRead;

  procedure EndWrite is
    begin
      Writing := false;
    end EndWrite;

  entry StartWrite
    when not Writing and Readers = 0 is
    begin
      Writing := true;
    end StartWrite;
end RW;
```
Summary

- **Monitors**
  - Automatic mutex, no concurrent work inside monitor
  - Need concurrency – do actual work outside monitor
  - Internal synchronization with condition variables
    - Similar but different to semaphores
  - Signalling semantics varies
  - No need for shared memory areas
    - Enough to invoke monitor methods in (prog. lang.) library

- **Protected Objects**
  - Avoids some problems with monitors
  - Automatic mutex and signalling
    - Can signal only at the end of method
    - Wait only in barrier at the beginning of method
    - No mutex breaks in the middle of method
  - Barrier evaluation may be costly – all tested with every signal?
  - No concurrent work inside protected object
  - Need concurrency – do actual work outside protected object