Lesson 8

Monitors

Ch 7 [BenA 06]

Monitors

Condition Variables

BACI and Java Monitors

Protected Objects

Monitor Concept (monitori)

- 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
  - 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, …

Semaphore problems
- forget P or V
- extra P or V
- wrong semaphore
- forget to use mutex
- used for mutex and for synchronization

Monitor (Hoare 1974)

- *Elliot*
- *Algol-60*
- *Sir Charles*

C.A.R. (Tony) Hoare

- 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 often outside monitor
    - Concurrent access possible to computational data
      - More possible parallelism in computation

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 preferably just for synchronization
  - 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
  - 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

```
monitor CS
  integer n ← 0

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

declarations, initialization code

procedures

p	q
p1: CS.increment	q1: CS.increment

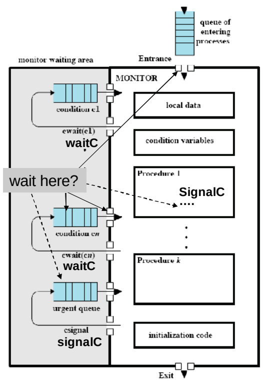
- Automatic mutex solution
  - Solution with busy-wait, disable interrupts, or suspension!
  - Internal to monitor, user has no handle on it, might be useful to know
  - Only one procedure active at a time – which one?
- No ordered queue to enter monitor
  - Starvation is possible, if many processes continuously trying to get in

Monitor Condition Variables

(ehtomuuttuja)

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

ready queue?
mutex queue?



(Fig. 5.15 [Stal05])

Declaration and WaitC

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

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SignalC

- Wakes up <u>first</u> 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? <u>No</u>.
  - Two signalling disciplines (<u>two semantics</u>)
    - Signal and continue - signalling process keeps mutex
    - Signal and wait - signalled process gets mutex
- If no one was waiting, <u>signal is lost</u> (no memory)
  - Advanced signalling (with memory) must be handled in some other manner

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Signaling Semantics

- <u>Signal and Continue</u> *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?

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Signaling Semantics

- <u>Signal and Wait</u> *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

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ESW-Priorities in Monitors

- Another way to describe signal/wait semantics
  - Instead of fifo, signal-and-continue, signal-and-wait
- Processes in 3 dynamic groups
  - Priority depends on what they are doing in monitor
    - E = priority of processes <u>e</u>ntering the monitor
    - S = priority of a process <u>s</u>ignalling in SignalC
    - W = priority of a process <u>w</u>aiting in WaitC
- <u>E < S < W</u> (highest pri), i.e., IRR
  - Processes waiting in WaitC have highest priority
  - Entering new process have lowest priority
  - <u>IRR</u> – *immediate resumption requirement*
  - *<u>Signal and urgent wait</u>*
  - Classical, usual semantics
  - New arrivals can not starve those inside

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Algorithm 7.2: Semaphore simulated with a monitor

Mutex

```
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)
```

semaphore counter kept separately, initialized before any process active

No need for "if anybody waiting…" What if signalC comes 1st?

p	q
loop forever	loop forever
non-critical section	non-critical section
p1: Sem.wait	q1: Sem.wait
critical section	critical section
p2: Sem.signal	q2: Sem.signal

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Problem with/without IRR

- No IRR, e.g., E=S=W or E<W<S
  - Prosess 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 (3)

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

FIX: must test for condition again

P p	Q1, Q2 q
loop forever	loop forever
non-critical section	non-critical section
p1: Sem.wait	q1: Sem.wait
critical section	critical section
p2: Sem.signal	q2: Sem.signal

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

No immediate resumption requirement, E = S = W

```
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

d) Q2 gets in, finds s=1, sets s=0, enters CS

e) P advances, sets s = -1, enters CS

P p	Q1, Q2 q
loop forever	loop forever
non-critical section	non-critical section
p1: Sem.wait	q1: Sem.wait
critical section	critical section
p2: Sem.signal	q2: Sem.signal

Algorithm 7.2: Semaphore simulated with a monitor(2/3)

No immediate resumption requirement, E = S = W

```
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

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

P p	Q1, Q2 q
loop forever	loop forever
non-critical section	non-critical section
p1: Sem.wait	q1: Sem.wait
critical section	critical section
p2: Sem.signal	q2: Sem.signal

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

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

FIX: must test for condition again

P p	Q1, Q2 q
loop forever	loop forever
non-critical section	non-critical section
p1: Sem.wait	q1: Sem.wait
critical section	critical section
p2: Sem.signal	q2: Sem.signal

Algorithm 7.3: Producer-consumer (finite buffer, monitor)

IRR semantics (important assumption)

```
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
```

void append_tail()
bufferType head()

internal procedures in monitor, no waitC in them (important design feature)

producer

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

buffer hidden, synchronization hidden (easy-to-write code)

consumer

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

Discussion

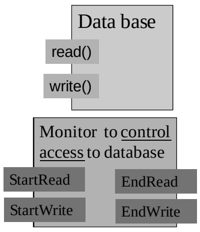
- Look at previous slide, Alg. 7.3
- Assume now: no IRR
  - What does it mean?
  - Do you need to change the code? How?
    - Changes in monitor (”server”)?
    - Changes in producer/consumer (”clients”)?
  - Will it work with multiple producers/consumers?
  - Exactly where can any producer/consumer process be suspended?

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



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

reader		writer
p1: RW.StartRead		q1: RW.StartWrite
p2: read the database	← outside monitor! →	q2: write to the database
p3: RW.EndRead		q3: RW.EndWrite

Algorithm 7.4: Readers and writers with a monitor

IRR semantics

Compare to Lesson 7, slide 26

```
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])
```

```
philosopher i
    loop forever
p1:   think
p2:   takeForks(i)
p3:   eat
p4:   releaseForks(i)
```

Number of forks available to philosopher i

IRR?

Both at once!

Deadlock free? Why? Starvation possible.

Is order Important?

Signaling semantics? IRR → mutex will break here!

When executed? Much later? Semantics?

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

BACI Monitors

```
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);
  }
```

No need for counts dr, dw

- 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--

```
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);
}
```

```
RW.StartRead();
… read data base ..
RW.EndRead();
```

```
RW.StartWrite();
… write data base ..
RW.EndWrite();
```

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
  - Without 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

suojattu objekti

Ada95?

- 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!

puomi, ehto

```
condition OKtoWrite;

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

(monitor)

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

(protected object)

Algorithm 7.6: Readers and writers with a protected object

E<W semantics

```
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?

Readers and Writers as ADA Protected Object

Continuous flow of readers will starve writers.

How would you change it to give writers priority?

```
protected 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 EndRead is
   begin
      Readers := Readers − 1;
   end EndRead;

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

   procedure EndWrite is
   begin
      Writing := false ;
   end EndWrite;
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
  - No concurrent work inside protected object
  - Need concurrency – do actual work outside protected object