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 <u>not</u> 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	
p	**q**
p1: CS.increment	q1: CS.increment

declarations, initialization code

procedures

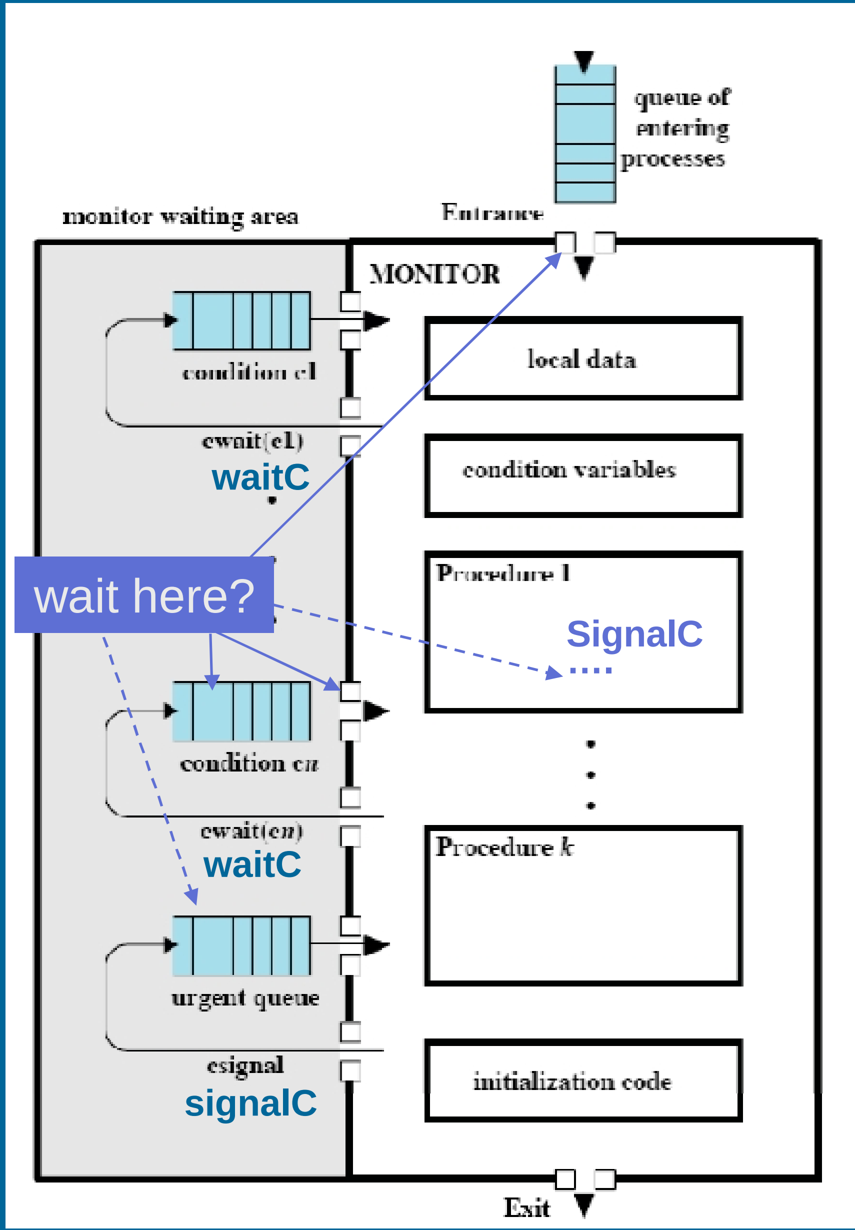
- Automatic mutex solution
  - Solution with busy-wait, disable interrupts, or suspension!
  - Internal to monitor, user has no handle on it, might be useful to know
  - Only one procedure active at a time – which one?
- No ordered queue to enter monitor
  - Starvation is possible, if many processes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

Monitor Condition Variables

(ehtomuuttuja)

- For synchronization <u>inside</u> the monitor
  - Must be <u>hand-coded</u>
  - 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 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?
  - 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 *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

- <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

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 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: $\underbrace{\text{Semaphore}}_{\text{Mutex}}$ simulated with a monitor

```
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

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

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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?

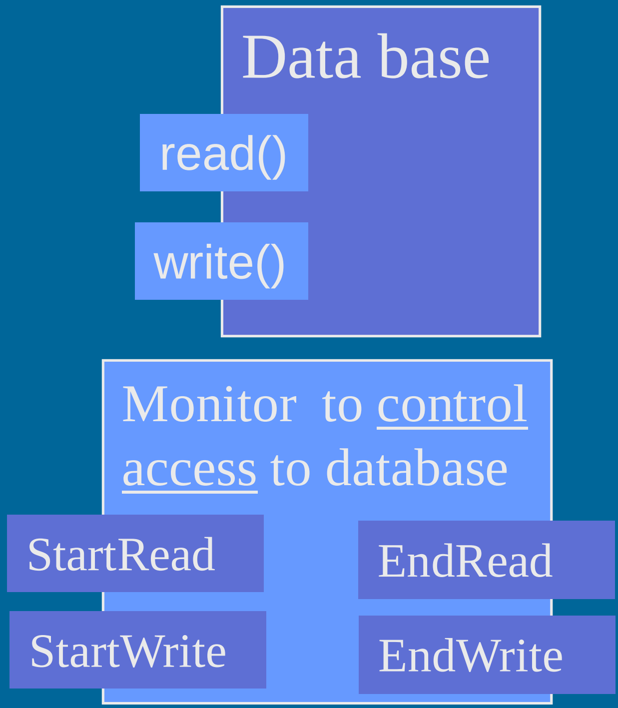
Other Monitor Internal Operations

- 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 <u>rank</u> for first waiting process (or 0 or whatever?)
- Signal_all(CV)
  - Wake up <u>everyone</u> 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	
p1:	RW.StartRead
p2:	read the database
p3:	RW.EndRead

outside monitor!

writer	
q1:	RW.StartWrite
q2:	write to the database
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])
```

Number of forks available to philosopher i

IRR?

philosopher i

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

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() <u>with priority</u>: 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 <u>all</u> methods <u>synchronized</u>
- 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 <u>inside</u> monitor
  – Monitor should be used only to <u>control</u> concurrency
  – Actual <u>work</u> 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

```
protected RW is
    entry StartRead;
    procedure EndRead;
    entry Startwrite ;
    procedure EndWrite;
private
    Readers: Natural :=0;
    Writing: Boolean := false ;
end RW;
```

Continuous flow of readers will starve writers.

How would you change it to give writers priority?

```
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