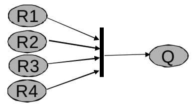
Lesson 7

Semaphore Use In Synchronization

Ch 6 [BenA 06]

Consumer Producer Revisited
Readers and Writers
Baton Passing
Private Semaphores
Resource Management

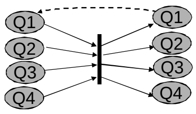
Synchronization with Semaphores




```
sem gate = -3;   # must know number of R's (!)

Process R[i = 1 to 4]
….
V(gate);  # signal Q
…

Process Q
….
P (gate)
…
# how to prepare for next time?
# sem_set (gate, -3) ??
```

```
sem g[i = 1 to 4] = 0;

Process R[i = 1 to 4]
….
V(g[i]);  # signal Q
…

Process Q
….
P(g[1]); P(g[2]); P(g[3]); P(g[4]);
…
# Q must know number of R's
```


Barrier Synchronization with Semaphores

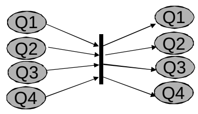



```
sem g[i = 1 to 4] = 0;
    cont = 0;

Process Q[i = 1 to 4]
….
V(g[i]);  # signal others
P(cont); # wait for others
…

Process Barrier
….
P(g[1]); P(g[2]); P(g[3]); P(g[4]);  #wait for all
V(cont); V(cont); V(cont); V(cont); #signal all
…
# Barrier must know number of Q's
```

- Barrier is implemented as separate *process*
  - This is just one possibility to implement the barrier
  - Cost of process switches?
  - How many process switches?

compare costs to using *barrier_wait* instruction ?

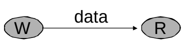
Barrier Synchronization with Barrier OS-Primitive



- Specific synchronization primitive in OS
  - Implemented with semaphores…
  - No need for extra process – less process switches

```
barrier br;

barrier_init (br, 4);       # must be done before use

process Q[i = 1 to 4]
  ….
  barrier_wait (br)         # wait until all have reached this point
  if (pid==1)               # is this ok? is this done in time?
        barrier_init (br, 4)
  …
```


Communication with Semaphores



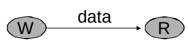

```
Sem mutex=1, data_ready = 0;
Int buffer;  # one data item buffer

Process W
….
P(mutex)
   write_buffer(data)
V(mutex)
V(data_ready);  # signal Q
…

Process R
….
P(data_ready);  # wait for data
P(mutex)
   read_buffer(data)
V(mutex)
….
```

- What is wrong?

W might rewrite data buffer before R reads it

  - Might have extra knowledge that avoids the problem

Communication with Semaphores Correctly




```
Sem mutex=1, data_ready = 0, buffer_empty=1;
Int buffer

Process W
….
P(buffer_empty);
P(mutex)
   write_buffer(data)
V(mutex)
V(data_ready);  # signal Q

Process R
….
P(data_ready);  # wait for data
P(mutex)
   read_buffer(data)
V(mutex)
V(buffer_empty)
```

- Fast W can not overtake R now
- One reader R, one writer W, binary semaphores
- Actual communication with buffer in shared memory
  - Use model: 1 producer – 1 consumer – size 1 buffer

Producer-Consumer with Binary Semaphores (Liisa Marttinen)

- Binary semaphore has values 0 and 1
  - OS or programming language library
- Semaphore does not keep count
  - Must have own variable *count* (nr of elements in buffer)
    - Protect it with critical section — mutex
- Two important state changes
  - Empty buffer becomes not empty
    - Consumer may need to be awakened — items
  - Full buffer becomes not full
    - Producer may need to be awakened — space

4.2.2011 Copyright Teemu Kerola 2011 7

Simple Solution #1

(Producer-Consumer with Binary Semaphores)

```
typeT buf[n];        /* n element buffer */
int front=0,         /* read from here */
    rear=0,          /* write to this one */
    count=0;         /* nr of items in buf */
sem space=1,         /* need this to write */
     items=0,        /* need this to read */
     mutex=1;        /* need this to update count */
```

4.2.2011 Copyright Teemu Kerola 2011 8

Sol. #1

```
process Producer [i=1 to M] {
while(true) {
  … produce data …
  P(space);      /* wait until space to write*/
  P(mutex);
    buf[rear] = data; rear = (rear+1) %n; count++;
    if (count == 1) V(items);  /* first item to empty buffer */
    if (count < n) V(space);   /* still room for next producer */
  V(mutex);
  }
}
```

```
process Consumer [i=1 to N] {
while(true) {
  P(items);      /* wait until items to consume */
  P(mutex);
    data=buf[front]; front = (front+1) %n; count--;
    if (count == n-1) V(space);  /* buffer was full */
    if (count > 0) V(items);     /* still items for next consumer */
  V(mutex);
  … consume data …
  }
}
```

4.2.2011 Copyright Teemu Kerola 2011 9

Evaluate Solution #1

- Simple solution
  - Mutex and synchronization ok
  - Mutex inside space or items
    - Get space first and then mutex
- Buffer reserved for one producer/consumer at a time
  - Does not allow for simultaneous buffer use — Not good
    - Producer inserts item to "rear"
    - Consumer removes item from "front" — Simulta-neously?
- First waiting producer/consumer advances when signalled
  - Queued in semaphores

4.2.2011 Copyright Teemu Kerola 2011 10

Better Solution #2

(Producer-Consumer with Binary Semaphores)

```
typeT buf[n];        /* n element buffer */
int front=0,         /* read from here */
    rear=0,          /* write to this one */
    count=0;         /* nr of items in buf */
sem space=1,         /* need this to write */
     items=0,        /* need this to read */
     mutex=1;        /* need this to update count */
```

4.2.2011 Copyright Teemu Kerola 2011 11

Sol. #2

```
process Producer [i=1 to M] {
while(true) {
  … produce data …
  P(space);      /* wait until space to write*/
  buf[rear] = data; rear = (rear+1) %n; /* outside mutex, ok? */
  P(mutex);
    count++;                  /* all of this must be in mutex */
    if (count == 1) V(items);      /* first item to empty buffer */
    if (count < n) V(space);  /* still room for next producer */
  V(mutex);
} }
```

```
process Consumer [i=1 to N] {
while(true) {
  P(items);      /* wait until items to consume */
  data=buf[front]; front = (front+1) %n; /* outside mutex, ok? */
  P(mutex);
    count--;                  /* all of this must be in mutex */
    if (count == n-1) V(space);        /* buffer was full */
    if (count > 0) V(items);  /* still items for next consumer */
  V(mutex);
  … consume data …
} }
```

4.2.2011 Copyright Teemu Kerola 2011 12

Evaluate Solution #2

- Relatively simple solution
  - Data copying (insert, remove) outside critical section
    - Protected by a semaphore (*items* and *space*)
- Simultaneous insert and remove ops
  - Producer inserts item to "rear"
  - Consumer removes item from "front"
- First waiting producer/consumer advances when signalled
  - Queued in semaphores

Another Solution #3

(Producer-Consumer with Binary Semaphores)

Ehto-synkro-nointi

- Use condition synchronization
  - Do P(space) or P(items) only when needed
    - Expensive op?
    - Requires execution state change (kernel/user)?

```
typeT buf[n];     /* n element buffer */
int front=0,      /* read from here */
    rear=0,       /* write to this one */
    count=0,      /* nr of items in buf */
    cwp=0,        /* nr of waiting producers */
    cwc=0;        /* nr of waiting consumers */
sem space=1,      /* need this to write */
    items=0,      /* need this to read */
    mutex=1;      /* need this to update count */
```


Sol. #3

```
process Producer [i=1 to M] {
while(true) {
   ... produce data ...
   P(mutex);
     while (count == n)   /* usually not true? while, not if !*/
        { cwp++; V(mutex); P(space); P(mutex); cwp-- }
     buf[rear] = data; rear = (rear+1) %n;  count++;
     if (count == 1 && cwc>0) V(items);
     if (count < n && cwp>0) V(space);
   V(mutex);
}  }
```

do not wait (suspend) while holding mutex!

```
process Consumer [i=1 to N] {
while(true) {
   P(mutex);
     while (count == n)    /* while, not if !*/
        { cwc++; V(mutex); P(items); P(mutex); cwc-- }
     data=buf[front]; front = (front+1) %n; count--;
     if (count == n-1 && cwp>0) V(space);
     if (count > 0 && cwc > 0) V(items);
   V(mutex);
   ... consume data ...
}  }
```


Evaluate Solution #3

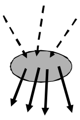
- No simultaneous insert and remove ops
  - Data copying inside critical section
- In general case, only mutex semaphore operations needed
  - Most of the time?
  - Can they be busy-wait semaphores?
- First waiting producer/consumer does not necessarily advance when signalled
  - Someone else may get mutex first
    - E.g., consumer signals V(space), another producer gets (entry) mutex and places its data in buffer.
    - Need "while" loop in waiting code
  - Unfair solution even with strong semaphores?
    - How to fix?
    - Baton passing (pass critical section to next process)?
      - Not shown now

Solutions #1, #2, and #3

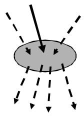
- Which one is best? Why? When?
- How to maximise concurrency?
  - Separate data transfer (insert, remove) from permission to do it
    - Allow obtaining permission (e.g., code with *P(space)* and updating *count*) for one process run concurrently with data transfer for another process (e.g., code with *buf[rear] = data; …*)
    - Need new mutexes to protect data transfers and index (*rear*, *front*) manipulation
  - Problem: signalling to other producers/consumers should happen in same critical section with updating count, but should happen only after data transfer is completed (i.e., in different critical section …)

Readers and Writers Problem

- Shared data structure or data base
- Two types of users: readers and writers
- Readers
  - Many can read at the same time
  - Can not write when someone reads
  - Can not read when someone writes



- Writers
  - Read and modify data
  - Only one can be active at the same time
  - Can be active only when there are no readers



Jeff Magee example (Imperial College, London)

http://www.doc.ic.ac.uk/~jnm/book/book_applets/ReadersWriters.html


```
sem rw = 1;
process Reader[i = 1 to M] {
  while (true) {
    ...
    P(rw);        # grab exclusive access lock
    read the database;
    V(rw);        # release the lock
  }
}
process Writer[j = 1 to N] {
  while (true) {
    ...
    P(rw);        # grab exclusive access lock
    write the database;
    V(rw);        # release the lock
  }
}
```

reader entry protocol → P(rw)

reader exit protocol → V(rw)

writer entry protocol → P(rw)

writer exit protocol → V(rw)

(Fig 4.8 [Andr00])

- Simple solution
  - Only one reader or writer at a time (not good)


```
int nr = 0;       # number of active readers
sem rw = 1;       # lock for reader/writer synchronization
process Reader[i = 1 to M] {
  while (true) {
    ...
    ⟨ nr = nr+1;
      if (nr == 1) P(rw);  # if first, get lock
    ⟩
    read the database;
    ⟨ nr = nr-1;
      if (nr == 0) V(rw);  # if last, release lock
    ⟩
  }
}
process Writer[j = 1 to N] {
  while (true) {
    ...
    P(rw);
    write the database;
    V(rw);
  }
}
```

std mutex

Only the first reader waits here

Release mutex before P(rw)? (no need, why?)

Writers may starve – not good.
Writers have no chance to cut in between readers.

Jeff Magee example

How should you adjust the readers to not starve writers?

(Fig 4.9 [Andr00])

Discuss

Readers and Writers with Baton Passing Split Binary Semaphores

- Component semaphores e, r, w — $0 \le e+r+w \le 1$ — perm. to advance in only one
  - Mutex wait in P(e), initially 1
  - Readers wait in P(r) if needed, initially 0 (Fig 4.13 [Andr00])
  - Writers wait in P(w) if needed, initially 0 (Alg. 6.21 [BenA06])
- In critical control areas only one process advances at a time
  - Wait in e, r, or w
- One advances, others wait in e, r or w
  - New reader/writer: wait in P(e)
  - Waiting for read turn: V(e); P(r)
    - Wait while not holding mutex
  - Waiting for write turn: V(e); P(w)
    - Wait while not holding mutex
  - When done, pass the baton (turn) to next one

P(e) … V(e)

P(e) … V(r)

P(e) … V(w)

P(r) … V(r)

P(r) … V(w)

…

P(w) … V(e)

…


```
int nr = 0,   ## RW: (nr == 0 or nw == 0) and nw <= 1
    nw = 0;
sem e = 1,    # controls entry to critical sections
    r = 0,    # used to delay readers
    w = 0;    # used to delay writers
              # at all times 0 <= (e+r+w) <= 1
int dr = 0,   # number of delayed readers
    dw = 0;   # number of delayed writers
```

Andrews Fig. 4.12: Outline of readers and writers with passing the baton.

```
process Reader[i = 1 to M] {
  while (true) {
    # ⟨await (nw == 0) nr = nr+1;⟩
    P(e);
    if (nw > 0)
      { dr = dr+1; V(e); P(r); }
    nr = nr+1;
    SIGNAL;
    read the database;
    # ⟨nr = nr-1;⟩
    P(e);
    nr = nr-1;
    SIGNAL;
  }
}
```

(rStart) (rExit)

```
process Writer[j = 1 to N] {
  while (true) {
    # ⟨await (nr == 0 and nw == 0) nw = nw+1;⟩
    P(e);
    if (nr > 0 or nw > 0)
      { dw = dw+1; V(e); P(w); }
    nw = nw+1;
    SIGNAL;
    write the database;
    # ⟨nw = nw-1;⟩
    P(e);
    nw = nw-1;
    SIGNAL;
  }
}
```

(wStart) (wExit)

??

~~P(e) … V(w) ?~~

~~P(r) … V(w) ?~~

P(e) … V(e) ?

P(r) … V(e) ?

P(e) … V(w) ?

Baton passing = "do not just release CS, give it to someone special…"

Baton passing

- When done your own mutex zone, wake up next … (one or more semaphores control the same mutex)

SIGNAL()

- If reader waiting and no writers: V(r)
  - Do not release mutex (currently reserved e, r, or w)
  - New reader will continue with mutex already locked "pass the mutex baton to next reader"
    - No one else can come to mutex zone in between
  - Last waiting reader will close the mutex with V(e)
  - Can happen concurrently when reading database
- Else if writer waiting and no readers: V(w)
  - Do not release mutex, pass baton to writer
- Else (let new process to compete with old ones): V(e)
  - Release mutex to let new process in the game (to execute entry or exit protocols)
  - New process gets in mutex only when no old one can be advance
  - Can happen concurrently when reading database

Baton Passing with SIGNAL

SIGNAL – CS baton passing, priority on readers

```
if (nw == 0  and  dr > 0) {
   dr = dr -1;
   V(r);                    # wake up waiting reader
}
else if  (nr == 0  and nw == 0  and  dw > 0) {
   dw = dw -1;
   V(w);                    # wake up waiting writer
}
else
   V(e);                    # let new process to mix
```

not possible in wStart, rExit

not possible in rStart

"pass the baton within CS"

"just complete CS"

4.2.2011 Copyright Teemu Kerola 2011 25

```
process Reader[i = 1 to M] {
  while (true) {
    # ⟨await (nw == 0) nr = nr+1;⟩
      P(e);
      if (nw > 0) { dr = dr+1; V(e); P(r);}
      nr = nr+1;
      if (dr > 0) { dr = dr-1; V(r);}
      else V(e);
    read the database;
    # ⟨nr = nr-1;⟩
      P(e);
      nr = nr-1;
      if (nr == 0 and dw > 0)
        { dw = dw-1; V(w); }
      else V(e);
  }
}
```

```
process Writer[j = 1 to N] {
  while (true) {
    # ⟨await (nr==0 and nw==0) nw = nw+1;⟩
      P(e);
      if (nr > 0 or nw > 0)
        { dw = dw+1; V(e); P(w); }
      nw = nw+1;
      V(e);
    write the database;
    # ⟨nw = nw-1;⟩
      P(e);
      nw = nw-1;
      if (dr > 0) { dr = dr-1; V(r); }
      elseif (dw > 0) { dw = dw-1; V(w); }
      else V(e);
  }
}
```

next reader

1st reader

1st writer

next writer

Fig. 4.13 [Andr00]: readers / writers solution using passing the baton (with SIGNAL code)

Still readers first

Unnecessary parts of *SIGNAL* code was removed

Modify to give writers priority?

Discuss

4.2.2011 Copyright Teemu Kerola 2011 26

Resource Management

- Problem
  - Many types of resources
  - N units of given resource
  - Request allocation: K units
    - Wait suspended until resource available
- Solution
  - Semaphore mutex (init 1)
  - Semaphore Xavail
    - init N – wait for available resource
    - init 0 - wait for permission to continue

use printer
use webcam
access database
access CS
allocate memory
allocate buffer
use comm port
get user focus
etc. etc.

4.2.2011 Copyright Teemu Kerola 2011 27

Simple Very Bad Solution

```
sem Xmutex = 1, Xavail = N

Xres_request()  # one unit at a time
   P(Xmutex)
   P(Xavail)  # ok if always
              # allocate just 1 unit
   take 1 unit  # not simple,
                # may take long time?
   V(Xmutex);

Xres_release()
   P(Xmutex)
   return 1 unit
   V(Xavail);
   V(Xmutex);
```

- What is wrong?
  - everything
- Mutex?
- Deadlock?
- Unnecessary delays?
  - Each P() may result in (long) delay?
  - Hold mutex while waiting for resource
    - Very, very bad
    - Others can not get mutex to release resources…

4.2.2011 Copyright Teemu Kerola 2011 28

Another Not So Good Solution

```
sem Xmutex = 1, Xavail = N

Xres_request()   # one unit at a time
   P(Xavail)     # ok if always
                 # allocate just 1 unit
   P(Xmutex)
   take 1 unit   # not simple,
                 # may take long time?
   V(Xmutex);

Xres_release()
   P(Xmutex)
      return 1 unit
   V(Xmutex);
   V(Xavail);
```

- What is wrong?
  - Works only for resources allocated and freed one unit at a time
- Mutex?
  - Mutex of control data?
  - Mutex of resource allocation data structures?

4.2.2011 Copyright Teemu Kerola 2011 29

Resource Management with Baton Passing Split Semaphore

sem Xmutex = 1, Xavail = 0 (not N) ; split semaphore
; (short wait) (long wait)

Xres_request(K) – request K units of given resource
   P(Xmutex)
   if "not enough free units" {V(Xmutex); P(Xavail);}
   take K units ; assume short time
   if "requests pending and enough free units" {V(Xavail); }
   else V(Xmutex);

Xres_release(K)
   P(Xmutex)
   return K units
   if "requests pending and enough free units" {V(Xavail);}
   else V(Xmutex);

if ok? yes.

CS

CS

baton passing

baton passing

4.2.2011 Copyright Teemu Kerola 2011 30

Problems with Resource Management

- Need strong semaphores
- Strong semaphores are FIFO
  - What if 1st in line want 6 units, 2nd wants 3 units, and there are 4 units left?
  - What about priorities?
    - Each priority class has its own semaphore
    - Baton passing within each priority class?
  - How to release just some specific process?
    - Strong semaphore releases 1st in line
    - Answer: private semaphores

Private Semaphore

yksityinen semafori

- Semaphore, to which only one process can ever make a P-operation
  - Initialized to 0, belongs to that process
- Usually part of PCB (process control block) for the process
  - Can create own semaphore arrays for this purpose
- Process makes demands, and then waits in private semaphore for turn
- Most often just one process at a time
  - Usually P(mutex) does not lead to process switches
- Usually still need to wait in private semaphore

Process User

```
P(mutex)
   set up resource demands
V(mutex)
P(me.PrivSem)
```

Process Server

```
P(mutex)
   locate next process Q to release
   V(Q.PrivSem)
V(mutex)
```

order?

Shortest Job Next (Private Semaphore Use Example)

- Common resource allocation method
  - Here: *time = amount of resource requested*
  - Here: just select next job (with shortest time)
  - Here: just one job (at most) holding the resource at a time
- Use private semaphores

```
request(time,id):  # requested time, user id
    P(e);
CS  if (!free) DELAY();  # wait for your turn
    free = false;        # got it!
    V(e);                # not SIGNAL(), only 1 at a time
```

```
release():    ??
    P(e);
CS  free = true;
    SIGNAL();            # who gets the next one?
                         # pass baton, or release mutex
```


- DELAY:
  - Place delayed process in queue PAIRS (ordered in ascending requested resource amount order) in correct place
  - V(e) – release mutex
  - Wait for your turn in private semaphore P(b[ID])
    - Each process has private semaphore, where only that process waits (initial value 0)
    - PAIRS queue determines order, one always wakes up the process at the head of the queue
      - Priority: smallest resource request first
- SIGNAL (in Release)
  - If someone waiting, take first one (time, ID), and wake up that process: V(b[ID]);
  - o/w V(e)

PAIRS:					
	P2	P15	P3	P1	ID
	3	6	17	64	time

request(26, P11)

Queue can be ordered according to requested cpu-time
(requested cpu-time is the resource in this example)

	0	1	2	3	…	n-1
b[n]		P1		P3	…	

Private semaphore b[ID] for each process ID: 0 ..n-1

Process release is dependent on its location in PAIRS. When resource becomes free, the 1st process in line may advance.


```
bool free = true;
sem e = 1, b[n] = ([n] 0);  # for entry and delay
typedef Pairs = set of (int, int);
Pairs pairs = ∅;
## SJN:  pairs is an ordered set ∧ free ⇒ (pairs == ∅)
request(time,id):
  P(e);
  if (!free) {
    insert (time,id) in pairs;
    V(e);          # release entry lock
    P(b[id]);      # wait to be awakened
  }
  free = false;
  V(e);    # optimized since free is false here
release():
  P(e);
  free = true;
  if (P != ∅) {
    remove first pair (time,id) from pairs;
    V(b[id]);  # pass baton to process id
  }
  else V(e);
```

CS

CS

Andr00 Fig. 4.14 Shortest job next (cpu scheduling policy) allocation using semaphores.

Semaphore Feature Summary

- Many implementations and semantics
  - Be careful to use
  - E.g., is the (process) scheduler called after each V()?
    - Which one continues with processor, the process executing V() or the process just woken up?
    - Can critical section continue after V()?
  - Busy wait vs. suspend state?
- Hand coded synchronization solutions
  - Can solve almost any synchronization problem
  - Baton passing is useful and tricky
    - Explicit handover of some resource
  - Be careful to use
    - Do not leave mutex'es open
    - Do not suspend inside mutex
    - Avoid deadlocks
    - Do (multiple) P's and V's in correct order

4.2.2011 37