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

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

```
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 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)
```

Q1
Q2
Q3
Q4

Q1
Q2
Q3
Q4
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
- Two important state changes
  - Empty buffer becomes not empty
    - Consumer may need to be awakened
  - Full buffer becomes not full
    - Producer may need to be awakened

Simple Solution #1
(Producer-Consumer with Binary Semaphores)

```c
typedef typeT buf[n]; /* n element buffer */
int front=0, /* read from here */
    rear=0, /* write to this one */
    count=0;
sem space=1, /* nr of items in buf */
    items=0, /* need this to write */
    mutex=1; /* need this to update count */
```
process Producer \([i=1 \text{ to } M]\) {
    while(true) {
        ... produce data ...
        P\(\text{space}\); /* wait until space to write*/
        P\(\text{mutex}\);
        \(\text{buf}\[\text{rear}\] = \text{data};\) \(\text{rear} = (\text{rear}+1) \mod n;\) \(\text{count}++;\)
        if (\(\text{count} == 1\)) V\(\text{items}\); /* first item to empty buffer */
        if (\(\text{count} < n\)) V\(\text{space}\); /* still room for next producer */
        V\(\text{mutex}\);
    }
}
process Consumer \([i=1 \text{ to } N]\) {
    while(true) {
        P\(\text{items}\); /* wait until items to consume */
        P\(\text{mutex}\);
        \(\text{data} = \text{buf}\[\text{front}\];\) \(\text{front} = (\text{front}+1) \mod n;\) \(\text{count}--;\)
        if (\(\text{count} == n-1\)) V\(\text{space}\); /* buffer was full */
        if (\(\text{count} > 0\)) V\(\text{items}\); /* still items for next consumer */
        V\(\text{mutex}\);
        ... consume data ...
    }
}

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” Simultaneously?
    - Consumer removes item from “front”
- First waiting producer/consumer advances when signalled
  - Queued in semaphores
Better Solution #2
(Producer-Consumer with Binary Semaphores)

Better Solution #2
(Producer-Consumer with Binary Semaphores)

```c
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 */
```

```c
#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 …
}
```
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)

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

```c
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 */
```
process Producer \([i=1 \text{ to } M]\) {
    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); } } 

process Consumer \([i=1 \text{ to } N]\) {
    while(true) {
        P(mutex);
        while (count == n) /* while, not if !!!*/
            { cwc++; V(mutex); P(space); 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 ...
    } } 

do not wait (suspend) while holding mutex!

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 ...)

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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

Simple solution
- Only one reader or writer at a time (not good)
Readers and Writers with Baton Passing Split Binary Semaphores

- **Component** semaphores e, r, w
  - Mutex wait in P(e), initially 1
  - Readers wait in P(r) if needed, initially 0
  - Writers wait in P(w) if needed, initially 0
- 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

```
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);
    }
}
```

![Diagram](image-url)
Baton passing

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

"pass the baton within CS"

"just complete CS"

Still readers first

Unnecessary parts of *SIGNAL* code was removed

Modify to give writers priority?
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

Simple Very Bad Solution

```c
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…
Another Not So Good Solution

\[
\text{sem Xmutex = 1, Xavail = N}
\]

\[
\text{Xres\_request ():} \quad \# \text{one unit at a time}
\]

\[
\text{P(Xavail) \quad \# \text{ok if always}}
\]

\[
\text{\# allocate just one unit}
\]

\[
\text{P(Xmutex)}
\]

\[
\text{take 1 unit \quad \# \text{not simple,}}
\]

\[
\text{\# may take long time?}
\]

\[
\text{V(Xmutex);}
\]

\[
\text{Xres\_release ():}
\]

\[
\text{P(Xmutex)}
\]

\[
\text{return 1 unit}
\]

\[
\text{V(Xmutex);}
\]

\[
\text{V(Xavail);}
\]

- 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?

Resource Management with Baton Passing Split Semaphore

\[
\text{sem Xmutex = 1, Xavail = 0 (not N) \quad \text{; split semaphore}}
\]

\[
\text{; (short wait) (long wait)}
\]

\[
\text{Xres\_request (K) – request K units of given resource}
\]

\[
\text{P(Xmutex)}
\]

\[
\text{if \text{"not enough free units"} \{ V(Xmutex); P(Xavail); \}}
\]

\[
\text{take K units \quad \text{; assume short time}}
\]

\[
\text{if \text{"requests pending and enough free units"} \text{\quad else \quad V(Xmutex);}}
\]

\[
\text{Xres\_release (K)}
\]

\[
\text{P(Xmutex)}
\]

\[
\text{return K units}
\]

\[
\text{if \text{"requests pending and enough free units"} \text{\quad else \quad V(Xmutex);}}
\]

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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

- 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 \textbf{not} lead to process switches
- Usually still need to wait in private semaphore

\begin{itemize}
  \item \texttt{P(mutex)} set up resource demands
  \item \texttt{V(mutex)}
  \item \texttt{P(me.PrivSem)}
  \item \texttt{P(mutex)} locate next process Q to release
  \item \texttt{V(Q.PrivSem)}
  \item \texttt{V(mutex)}
\end{itemize}
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);
    if (!free) 
    DELAY(); # wait for your turn
    free = false;
    # not SIGNAL(), only 1 at a time
    V(e);
  - release():
    P(e);
    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)
Queue can be ordered according to requested cpu-time (requested cpu-time is the resource in this example)

Private semaphore $b[ID]$ for each process ID: $0 \ldots n-1$

Process release is dependent on its location in PAIRS. When resource becomes free, the 1st process in line may advance.
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 mutex handover of some type of resource use
  - Private semaphores
    - Explicit signal to some specific process
  - 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