Lesson 6

Semaphores

Ch 6 [BenA 06]

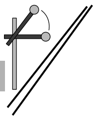
Semaphores
Producer-Consumer Problem
Semaphores in C--, Java, Linux

Synchronization with HW support

- Disable interrupts
  - Good for short time wait, not good for long time wait
  - Not good for multiprocessors
    - Interrupts are disabled only in the processor used
- Test-and-set instruction (etc)
  - Good for short time wait, not good for long time wait
  - Nor so good in single processor system
    - May reserve CPU, which is needed by the process holding the lock
  - Waiting is usually "busy wait" in a loop
- Good for mutex, not so good for general synchronization
  - E.g., "wait until process P34 has reached point X"
  - No support for long time wait (in suspended state)
- Barrier wait in HW in some multicore architectures
  - Stop execution until all cores reached *barrier_wait* instruction
  - No busy wait, because execution pipeline just stops
  - Not to be confused with barrier_wait thread operation

Semaphores


Edsger W. Dijkstra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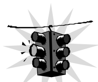
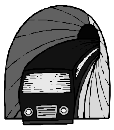
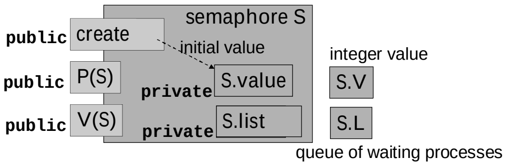




http://en.wikipedia.org/wiki/THE_operating_system

- Dijkstra, 1965, THE operating system
- Protected variable, abstract data type (object)
  - Allows for concurrency solutions if used properly
- Atomic operations
  - Create (SemaName, InitValue)
  - P, *down, wait, take, pend, passeren, proberen, try, prolaad, try to decrease*
  - V, *up, signal, release, post, vrijgeven, verlagen, verhoog, increase*

(Basic) Semaphore



- P(S) WAIT(S), Down(S)
  - If value > 0, deduct 1 and proceed
  - o/w, wait suspended in list (queue?) until released
- V(S) SIGNAL(S), Up(S)
  - If someone in queue, release one (first?) of them
  - o/w, increase value by one

General vs. Binary Semaphores

- General Semaphore
  - Value range: 0, 1, 2, 3, ….
    - nr processes doing P(S) and advancing without delay
    - Value: "Nr of free units", "nr of advance permissions"
- Binary semaphore (or "*mutex*")
  - Value range: 0, 1
    - Mutex lock (with suspended wait)
    - V(S) can (should!) be called only when value = 0
      - By process in critical section (CS)
  - Many processes can be in suspended in list
  - At most one process can proceed at a time

Algorithm 6.1: Critical section with semaphores (N processes)

binary semaphore S ← $(1, \emptyset)$

p	q
loop forever	loop forever
p1: non-critical section	q1: non-critical section
p2: wait(S)	q2: wait(S)
p3: critical section	q3: critical section
p4: signal(S)	q4: signal(S)

- Someone must create S
  - Value initialized to 1
- Possible wait in suspended state
  - Long time, hopefully at least 2 process switches

Some (operating) systems have "semaphores" with (optional) busy wait (i.e., busy-wait semaphore).
Beware of busy-wait locks hidden in such semaphores!

General Semaphore Implementation

- P(S)

```
if (S.value > 0)
   S.value = S.value - 1
else
   suspend calling process P
   place P (last?) in S.list
   call scheduler()
```

go to sleep …
… wake up here

Atomic operations! How? Use HW mutex support!

Tricky part: section of CS is in operating system scheduler?

- V(S)

```
if (S.list == empty)
   S.value = S.value + 1
else
   take arbitrary (or 1st ?) process Q
                               from S.list
   move Q to ready-to-run list
   call scheduler()
```


Semaphore Implementation

- Use HW-supported busy-wait locks to solve mutex-problem for semaphore operations
  - Short waiting times, a few machine instructions
- Use OS suspend operation to solve semaphore synchronization problem
  - Possibly very long, unlimited waiting times
  - Implementation at process control level in OS
  - This is the resume point for suspended process
    - Deep inside in privileged OS-module

Semaphore Implementation Variants

- Take first process in S.list in V(S)?
  - Important semantic change, affects applications
  - Fairness
  - Strong semaphore (vs. weak semaphore with no order in S.list)
- Add to/subtract from S.value first in P(S) and in V(S)?
  - Just another way to write code
- Scheduler call every time or sometimes at P or V end?
  - Semantic change, may affect applications
  - Execution turn may (likely) change with P even when process is not suspended in wait
  - Signalled process may start execution immediately

Semaphore Implementation Variants

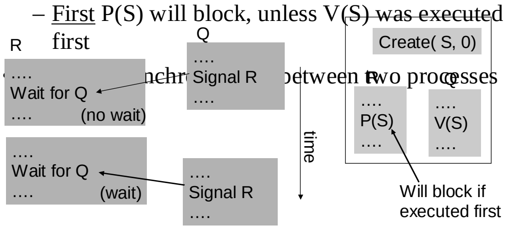
- S.value can be negative
  - Negative S.value gives the number of waiting processes?
  - Makes it easier to poll number of waiting processes
    - New user interface to semaphore object

n = value(s);

- Busy-wait semaphore
  - Wait in busy loop instead of in suspended state
  - Really a busy-wait lock that looks like a semaphore
  - Important semantic change, affects applications

Blocking Semaphore

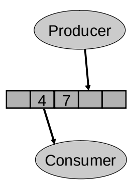
- Blocking
  - Normal (counting) semaphore with initial value = 0
  - First P(S) will block, unless V(S) was executed first
  - Synchronization between two processes



Producer-Consumer Problem

Tuottaja-kuluttaja -ongelma

- Synchronization problem
- Correct execution order
- Producer places data in buffer
  - Waits if finite size buffer full
- Consumer takes data from buffer
  - Same order as they were produced
  - Waits if no data available
- Variants
  - Cyclic finite buffer – usual case
  - Infinite buffer
    - Realistic sometimes!
      - External conditions rule out buffer overflow?
      - Can be implemented with finite buffer!
  - Many producers and/or many consumers



Algorithm 6.6: Producer-consumer (infinite buffer)

infinite queue of dataType buffer ← empty queue
semaphore notEmpty ← (0, ∅)

producer	consumer
dataType d	dataType d
loop forever	loop forever
p1: d ← produce	q1: wait(notEmpty)
p2: append(d, buffer)	q2: d ← take(buffer)
p3: signal(notEmpty)	q3: consume(d)

(no wait!)

- Synchronization only one way (producer never waits)
  - Synchronization from producer to consumer
- Counting split semaphore notEmpty
  - Split = "different processes doing waits and signals"
  - Value = nr of data items in buffer
- Append/take might need to be indivisible operations
  - Protect with semaphores or busy-wait locks?
  - Not needed now? Maybe not? (only one producer/consumer)

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Algorithm 6.8: Producer-consumer (finite buffer, semaphores)

finite queue of dataType buffer ← empty queue
semaphore notEmpty ← (0, ∅)
semaphore notFull ← (N, ∅)

producer	consumer
dataType d	dataType d
loop forever	loop forever
p1: d ← produce	q1: wait(notEmpty)
p2: wait(notFull)	q2: d ← take(buffer)
p3: append(d, buffer)	q3: signal(notFull)
p4: signal(notEmpty)	q4: consume(d)

- Synchronization both ways, both can wait
- New semaphore notFull: value = nr of free slots in buffer
- Split semaphore notEmpty & notFull
  - notEmpty.value + notFull.value = N in (p1, q4, …)
    - When both at the beginning of loop, outside wait-signal area
  - wait(notFull)…signal(notEmpty), wait(notEmpty)…signal(notFull)

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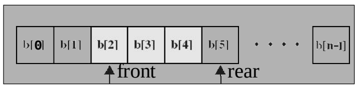
Size N buffer
One producer
One consumer




```
typeT buf[n];
int front = 0, rear = 0;
sem empty = n, full = 0;
```

```
process Producer {
  while (true) {
    ...
    produce message data
    P(empty);
    buf[rear] = data;
    rear = (rear+1) % n;
    V(full);
  }
}
```

```
process Consumer {
  while (true) {
    fetch and consume
    P(full);
    result = buf[front];
    front = (front+1) % n;
    V(empty);
    ...
  }
}
```

Does it work with one producer and one consumer? Yes.
Mutex problem? No. Why not?

Does it work with many producers or consumers? No.

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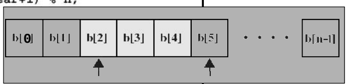
Prod/Consumers
Size N buffer
Many producers
Many consumers

```
typeT buf[n];      /* an array of some type T */
int front = 0, rear = 0;
sem empty = n, full = 0;      /* n-2 <= empty+full <= n */
sem mutexD = 1, mutexF = 1;  /* for mutual exclusion   */
process Producer[i = 1 to M] {
  while (true) {
    ...
    produce message data and deposit it in the buffer;
    P(empty);
    P(mutexD);
    buf[rear] = data; rear = (rear+1) % n;
    V(mutexD);
    V(full);
  }
}
process Consumer[j = 1 to N] {
  while (true) {
    fetch message result and consume it;
    P(full);
    P(mutexF);
    result = buf[front]; front = (front+1) % n;
    V(mutexF);
    V(empty);
    ...
  }
}
```

Need mutexes!
Semaphores or busy wait?



Semaphore *full* for synchronization

Semaphore *mutexF* for mutex problem

Why separate mutexD and mutexF?

(Andrews, Fig. 4.5)

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Barz's General Semaphore Simulation

- Starting point
  - Have binary semaphore
  - Need counting semaphore
  - Realistic situation
    - Operating system or programming language library may have only binary semaphores

k = 4
4 in CS, 2 in gate
1 completes CS
What now?

2 complete CS?

binary semaphore S ← 1
binary semaphore gate ← 1
integer count ← k

loop forever
  non-critical section
p1: wait(gate)
p2: wait(S)
p3: count ← count − 1
p4: if count > 0 then
p5:   signal(gate)
p6: signal(S)
  critical section
p7: wait(S)
p8: count ← count + 1
p9: if count = 1 then
p10:   signal(gate)
p11: signal(S)

P

V

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Udding's No-Starvation Critical Section with Weak Split Binary Semaphores

- Weak semaphore
  - Set, not a queue in wait
- Split binary semaphore
  - 0 ≤ gate1+ gate2 ≤ 1
- Batch arrivals
  - Start service only when no more arrivals
  - Close gate1 during service
- No starvation
  - gate1 opened again only after whole batch in gate2 is serviced

semaphore gate1 ← 1, gate2 ← 0
integer numGate1 ← 0, numGate2 ← 0

p1: $\boxed{\text{wait(gate1)}}$
p2: numGate1 ← numGate1 + 1
p3: signal(gate1)
p4: $\boxed{\text{wait(gate1)}}$
p5: numGate2 ← numGate2 + 1
numGate1 ← numGate1 − 1 (typo in book)
p6: if numGate1 > 0 someone in p4?
p7:   signal(gate1)
p8: else signal(gate2) last in batch
p9: $\boxed{\text{wait(gate2)}}$
p10: numGate2 ← numGate2 − 1
others in "batch"
p11: if numGate2 > 0
p12:   signal(gate2)
p13: else signal(gate1) last in batch

(Alg 6.14)

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Semaphore Features

- Utility provided by operating system or programming language library
- Can be used solve almost any synchronization problem
- Need to be used carefully
  - Easy to make profound errors
    - Forget V
    - Suspend process in critical section
      - No one can get CS to resume suspended process
      - Someone may be waiting in busy-wait loop
    - Deadlock
  - Need strong coding discipline

(Fig. 6.12 [Stal06]) (Alg. 6.10 [BenA06])

Trivial Solution #1

```
/* program     diningphilosophers */
semaphore fork [5] = {1}; /* mutex, one at a time */
int i;
void philosopher (int i)
{
     while (true)
     {
          think();
          wait (fork[i]);               /* left fork */
          wait (fork [(i+1) mod 5]);/* right fork */
          eat();
          signal(fork [(i+1) mod 5]);
          signal(fork[i]);
     }
}
void main()
{
     parbegin (philosopher (0), philosopher (1), philosopher (2),
          philosopher (3), philosopher (4));
     }
```

- Possible deadlock – not good
  - All 5 grab left fork "at the same time"

(Fig. 6.13 [Stal06]) (Alg. 6.11 [BenA06])

Trivial Solution #2

```
/* program diningphilosophers */
semaphore fork[5] = {1};
semaphore room = {4}; /* only 4 at a time, 5th waits */
int i;
void philosopher (int I)
{
    while (true)
    {
     think();
     wait (room);
     wait (fork[i]);
     wait (fork [(i+1) mod 5]);
     eat();
     signal (fork [(i+1) mod 5]);
     signal (fork[i]);
     signal (room);
    }
}
void main()
{
    parbegin (philosopher (0), philosopher (1), philosopher (2),
         philosopher (3), philosopher (4));
}
```

- No deadlock, no starvation
- Waiting when resources are available – which scenario? – not good

Algorithm AS : Dining philosophers (good solution)

semaphore array [0..4] fork ← [1,1,1,1,1]

```
    loop forever
p1:     think
p2:     wait(fork[i])
p3:     wait(fork[i+1])
p4:     eat
p5:     signal(fork[i])
p6:     signal(fork[i+1])
```

philosopher 4

```
    loop forever
p1:     think
p2:     wait(fork[0])
p3:     wait(fork[4])
p4:     eat
p5:     signal(fork[0])
p6:     signal(fork[4])
```

Even numbered philosophers?
or
This way with 50% chance?
or
This way with 20% chance?

Etc. etc.

- No deadlock, no starvation
- No extra blocking
- Asymmetric solution – not so nice…
  - All processes should execute the same code
- Simple primitives, must be used properly

Minix Semaphore

```
void semaphore_server( ) {
  message m;
  int result;
  /* Initialize the semaphore server. */
  initialize( );
  /* Main loop of server. Get work and process it. */
  while(TRUE) {
    /* Block and wait until a request message arrives. */
    ipc_receive(&m);
    /* Caller is now blocked. Dispatch based on message type. */
    switch(m.m_type) {
      case UP:     result = do_up(&m);      break;
      case DOWN:   result = do_down(&m);    break;
      default:     result = EINVAL;
    }
    /* Send the reply, unless the caller must be blocked. */
    if (result != EDONTREPLY) {
      m.m_type = result;
      ipc_reply(m.m_source, &m);
    }
  }
}
```

http://www.usenix.org/publications/login/2006-04/openpdfs/herder.pdf

Minix Semaphore P

```
int do_down(message *m_ptr) {
    /* Resource available. Decrement semaphore and reply. */
    if (s > 0) {
       s = s – 1;                    /* take a resource */
       return(OK);                   /* let the caller continue */
    }
    /* Resource taken. Enqueue and block the caller. */
    enqueue(m_ptr->m_source);  /* add process to queue */
    return(EDONTREPLY);            /* do not reply in order to block the caller */
  }
```

Suspend in message queue!

Minix Semaphore V

Mutex?

```
int  do_up(message *m_ptr) {
message m;                      /* place to construct reply message */
   /* Add resource, and return OK to let caller continue. */
   s = s + 1;                   /* add a resource */

   /* Check if there are processes blocked on the semaphore. */
   if (queue_size() > 0) {      /* are any processes blocked? */
      m.m_type = OK;
      m.m_source = dequeue();   /* remove process from queue */
      s = s – 1;                /* process takes a resource */
      ipc_reply(m.m_source, m); /* reply to unblock the process */
   }
   return(OK);                  /* let the caller continue */
}
```

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Semaphores in Linux

http://fxr.watson.org/fxr/source/include/asm-sh/semaphore.h?v=linux-2.4.22

- semaphore.h
- Low level process/thread control
- In assembly language, in OS kernel
- struct semaphore {
  atomic_t count;
  int sleepers;
  wait_queue_head_t wait;
  }
- sema_init(s, val)
- init_MUTEX(s), init_MUTEX_LOCKED(s)
- down(s), int down_interruptible(s), int down_trylock(s)
- up(s)

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Semaphores in BACI with C--

- Weak semaphore
  - S.list is a set, not a queue
  - Awakened process chosen in random
- Counting semaphore: *semaphore count;*
- Binary semaphore: *binarysem mutex;*
- Operations
  - *Initialize (count, 0);*
  - *P()* and *V()*
  - Also *wait()* and *signal()* in addition to *P()* and *V()*
  - Value can be used directly: n = *count*; cout *count*;

current value of semaphore count

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C- - Semaphore Example *semexample.cm*

```
semaphore count;    // a "general" semaphore
binarysem output;   // a binary (0 or 1) semaphore for unscrambling output
main()
{
   initialsem(count,0);
   initialsem(output,1);
   cobegin {
      decrement(); increment();
   }
}  // main

void increment()
{
   p(output);         // obtain exclusive access to standard output
   cout << "before v(count) value of count is " << count << endl;
   v(output);
   v(count);          // increment the semaphore
}  // increment

void decrement()
{
   p(output);         // obtain exclusive access to standard output
   cout << "before p(count) value of count is " << count << endl;
   v(output);
   p(count);          // decrement the semaphore (or stop -- see manual text)
}  // decrement
```

(BACI C- - User's Guide)

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C- - Semaphore Example

- 3 possible outcomes
  - how?
    ```
    Executing PCODE ...
    before v(count) value of count is 0
    before p(count) value of count is 1
    ```
  - how?
    ```
    Executing PCODE ...
    before p(count) value of count is 0
    before v(count) value of count is 0
    ```
  - how?
    ```
    Executing PCODE ...
    before v(count) value of count is 0
    before p(count) value of count is 0
    ```
  - Why no other possible outcome?

(BACI C- - User's Guide)

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Semaphores in Java

- Class *Semaphore* in package *java.util.concurrent*
  http://java.sun.com/j2se/1.5.0/docs/api/java/util/concurrent/Semaphore.html
- S.value is *S.permits* in Java
  - Permit value can be positive and negative
- Permits can be initialized to negative numbers
- Semaphore type
  - fair (= strong) & nonfair (≈ busy-wait ??), default)
- Wait(S):
  ```
  try {
     s.acquire();
  }
  catch (InterruptedException e) {}
  ```
- Signal(S): `s.release();`
- Many other features

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Java Example

- Simple Java-solution with semaphore

```
vera: javac Plusminus_sem.java
vera: java Plusminus_sem
```

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

- Still fairly complex
  - Not as streamlined as P() and V()
- How does it *really* work?
  - Busy wait or suspended wait?
  - Fair queueing?
  - Overhead when no competition for CS?

Semaphore Summary

- Most important synchronization primitive
  - Implementation needs OS assistance
- Can do anything
  - Just like assembly language coding…
- Many variants
  - Counting, binary, split, neg. values, mutex
- Programming language interfaces vary