Lesson 6

Semaphores

Ch 6 [BenA 06]

Semaphores

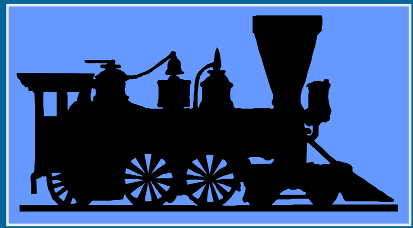
Producer-Consumer Problem

Semaphores in C--, Java, Linux, Minix

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

Edsger W. Dijkstra



Semaphores

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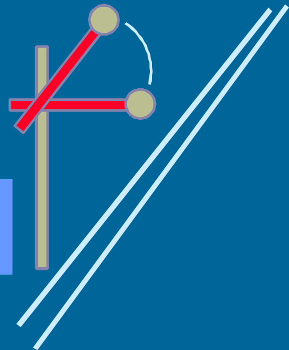
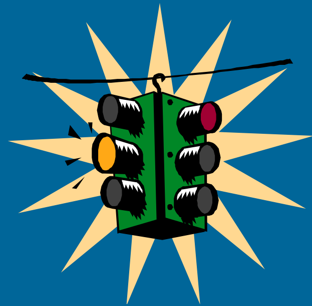
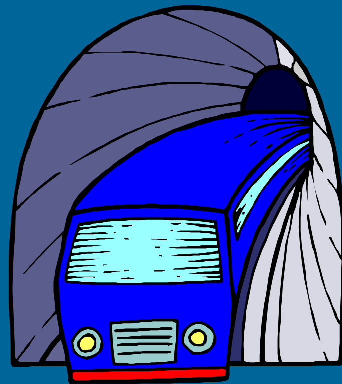


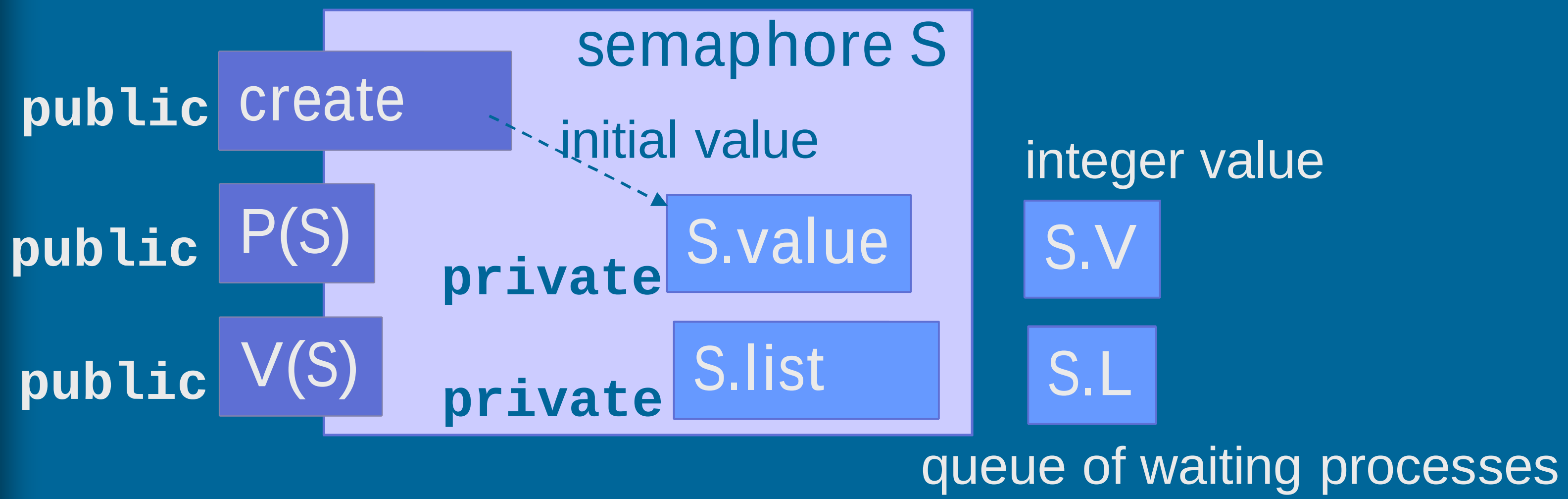




http://en.wikipedia.org/wiki/THE_operating_system

- Dijkstra, 1965, THE operating system
- Protected variable, abstract data type (object)
  – Allows for concurrency solutions <u>if</u> used properly
- <u>Atomic operations</u>
  – Create (SemaName, InitValue)
  – P, *<u>down</u>*, *<u>wait</u>*, *take*, *pend*,
    <u>p</u>asseren, *proberen*, *try*, *prolaad*, *try to decrease*
  – V, *<u>up</u>*, *<u>signal</u>*, *release*, *post*,
    <u>v</u>rijgeven, *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)
    - Usually initial value 1
    - 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, ∅)

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 (and just one!) must create S
  - Value initialized to 1 (in this example)
- 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
  - Process waits in suspended waiting state
  - 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 or V even when calling process is not suspended in wait
  - Signalled process may start execution immediately

Semaphore Implementation Variants

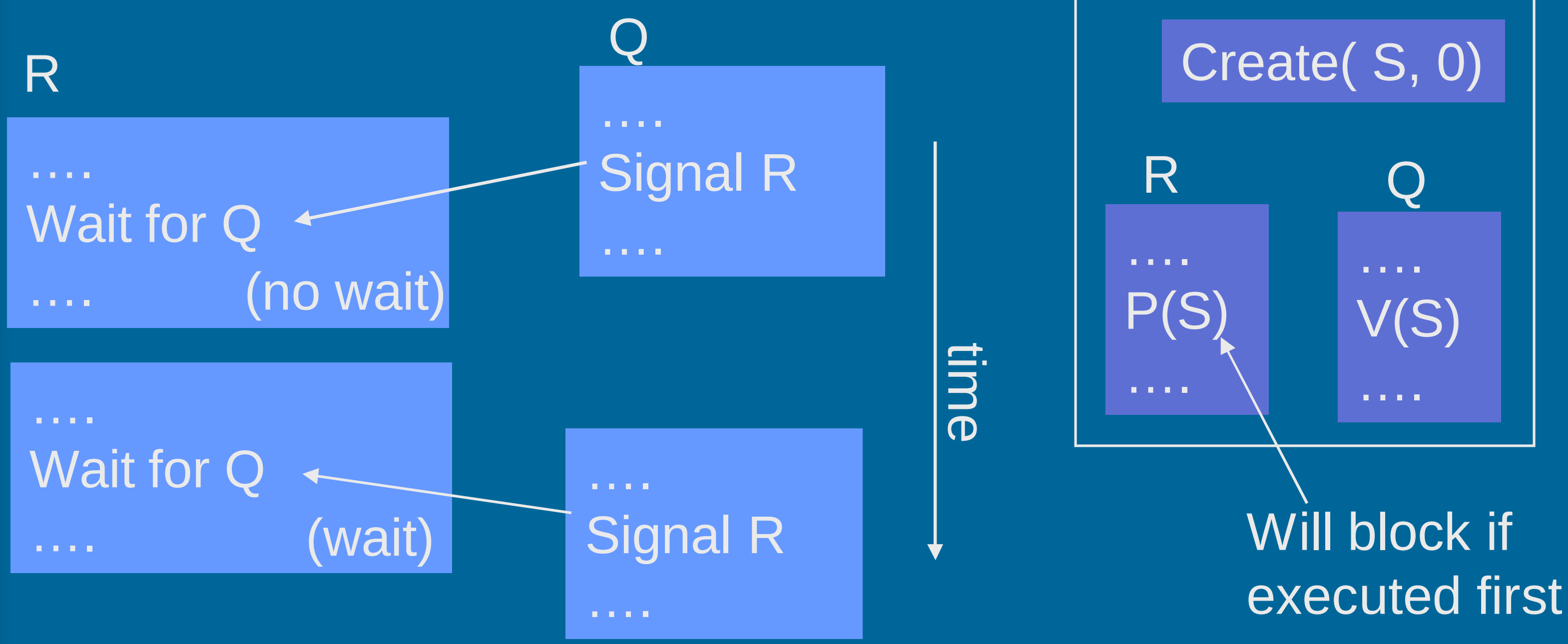
- S.value can be negative
  - P(S) always deducts 1 from S.value
  - Negative S.value gives the number of waiting processes?
  - Makes it easier to poll number of waiting processes
    - New user interface to semaphore object?

```
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

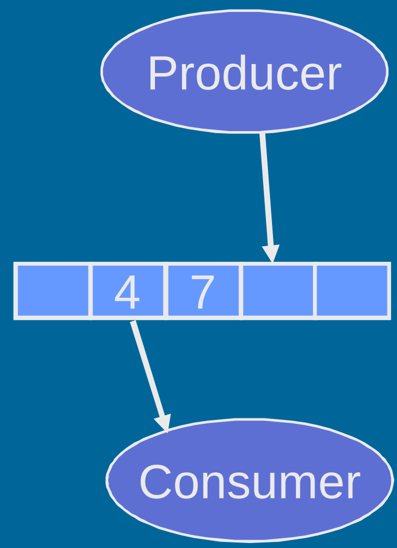
- "Blocking"
  - Normal (counting) semaphore with initial value = 0
  - First P(S) will block, unless V(S) was executed first
- Example: synchronization between two processes



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 – producer can not wait
      - 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 waiting ever)

- Synchronization only one way (producer never waits)
  - Synchronization from producer to consumer
- Counting semaphore notEmpty
  - 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)

Discuss

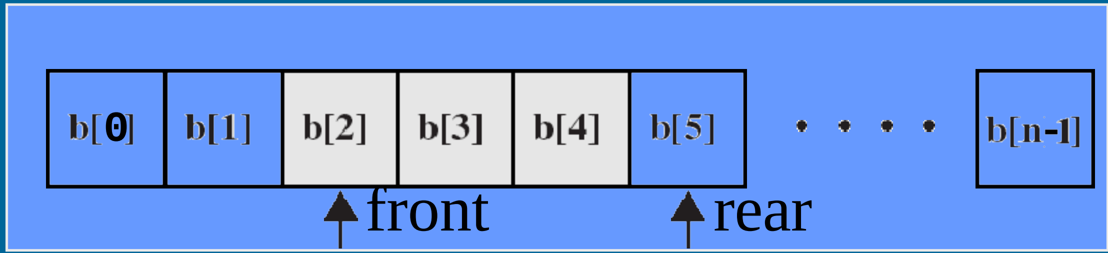
Algorithm 6.8: Producer-consumer (finite buffer, semaphores)

finite queue of dataType buffer ← empty queue
semaphore notEmpty ← $(0, \emptyset)$
semaphore notFull ← $(N, \emptyset)$

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)

Size N buffer
<u>One</u> producer
<u>One</u> 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);
    ...
  }
}
```

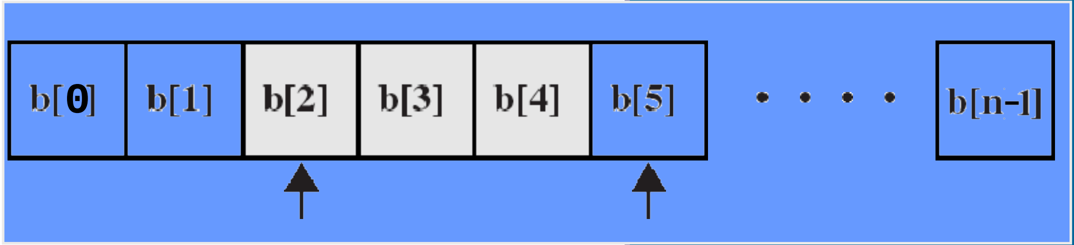
Does it work with one producer and one consumer? Yes.
Mutex problem? No. Why not?

Does it work with many producers or consumers? No.

```
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);
    ...
  }
}
```

Prod/Consumers
Size N buffer
Many producers
Many consumers

Need mutexes!
Semaphores or busy wait?



Semaphore *full* for synchronization

Semaphore *mutexF* for mutex problem

Why separate mutexD and mutexF?

(Andrews, Fig. 4.5)

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

```
binary semaphore S ← 1          mutex
binary semaphore gate ← 1
integer count ← k               nr  of permissions
```

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

critical section to implement V

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

2 complete CS?

Udding's No-Starvation Critical Section with <u>Weak</u> <u>Split</u> <u>Binary</u> Semaphores

- Weak semaphore
  - Set, not a queue in wait
- Split binary semaphore

  $0 \leq \text{gate1} + \text{gate2} \leq 1$
- Batch arrivals
  - Start service only when no more arrivals
  - Close gate1 during service
- No starvation
  - gate1 opened again only after <u>whole batch</u> in gate2 is serviced

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

p1:   wait(gate1)
p2:   numGate1 ← numGate1 + 1
p3:   signal(gate1)
p4:   wait(gate1)
p5:   numGate2 ← numGate2 + 1
      numGate1 ← numGate1 − 1
p6:   if numGate1 > 0
p7:      signal(gate1)
p8:   else signal(gate2)
p9:   wait(gate2)
p10:  numGate2 ← numGate2 − 1
      critical section
p11:  if numGate2 > 0
p12:     signal(gate2)
p13:  else signal(gate1)
```

(typo in book) [beside the line "numGate1 ← numGate1 − 1"]

someone in p4? [beside p6–p7]

last in batch [beside p8, arrow to p9]

others in "batch" [arrow from p12 to p9]

last in batch [beside p13]

(Alg 6.14)

Discuss

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 (with P)
      - 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])

```
/* 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])
```

Symmetric solutions?

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

x
ore

```
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 */
}
```

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)

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

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)

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)

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

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 high level synchr. primitive
  - Implementation needs OS assistance
  - Wait in suspended state
  - Should wait relatively long time
    - Costs 2 process switches (wait – resume)
- Can do anything
  - Just like assembly language coding…
- Many variants
  - Counting, binary, split, blocking, neg. values, mutex
- Programming language interfaces vary
- No need for shared memory areas
  - Enough to invoke semaphore operations in OS or programming language libraries

Summary

- Semaphore structure, implementation, and use
  - "Busy wait semaphores"
- Producer-Consumer problem and its variants
  - Semaphores for synchronization and for mutex
- Emulate advanced semaphores with simpler ones
  - Barz, Udding
- Semaphores in Linux (C), C--, Java