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
  – Not 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

- Dijkstra, 1965, THE operating system
- Protected variable, abstract data type (object)
  - Allows for concurrency solutions if used properly
- Atomic operations
  - Create (SemName, 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)
  - If value > 0, deduct 1 and proceed
  - o/w, wait suspended in list (queue?) until released
- V(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)

<table>
<thead>
<tr>
<th>p</th>
<th>q</th>
</tr>
</thead>
<tbody>
<tr>
<td>loop forever</td>
<td>loop forever</td>
</tr>
<tr>
<td>q1: non-critical section</td>
<td>q2: wait(S)</td>
</tr>
<tr>
<td>q3: critical section</td>
<td>q4: signal(S)</td>
</tr>
</tbody>
</table>

• 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()

- **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
  - $n = \text{value}(s)$;
- 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

![Diagram of a blocking semaphore](image)

**Example:** synchronization between two processes

- Wait for $Q$
- ... 
- Signal $R$
- ... 
- Wait for $Q$
- ... 
- Signal $R$
- ... 

(time)

- **Create** $(S, 0)$
- Will block if executed first

---

**Producer-Consumer Problem**

- **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

![Diagram of a producer-consumer problem](image)
Algorithm 6.6: Producer-consumer (infinite buffer)

- 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)

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

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

Does it work with many producers or consumers? No.

Semaphore full for synchronization
Semaphore mutexF for mutex problem

Prod/Consumers
Size N buffer
Many producers
Many consumers

Need mutexes!
Semaphores or busy wait?

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 N) {
    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);
        ... 
    }
}
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?

Udding’s No-Starvation Critical Section with Weak Split Binary 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 whole batch in gate2 is serviced

\[ \text{semaphore gate1} \leftarrow 1, \text{gate2} \leftarrow 0 \]
\[ \text{integer numGate1} \leftarrow 0, \text{numGate2} \leftarrow 0 \]

1. \[ \text{wait}(\text{gate1}) \]
2. \[ \text{numGate1} \leftarrow \text{numGate1} + 1 \]
3. \[ \text{signal}(\text{gate1}) \]
4. \[ \text{wait}(\text{gate1}) \]
5. \[ \text{numGate2} \leftarrow \text{numGate2} + 1 \]

\[ \text{numGate1} \leftarrow \text{numGate1} - 1 \]
6. \[ \text{if numGate1} > 0 \]
7. \[ \text{signal}(\text{gate1}) \]
8. \[ \text{else signal}(\text{gate2}) \]
9. \[ \text{wait}(\text{gate2}) \]
10. \[ \text{numGate2} \leftarrow \text{numGate2} - 1 \]

(Semaphore opened again only after whole batch in gate2 is serviced)
Semaphore Features

• Utility provided by operating system or programming language library
• Can be used to 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

/ * 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 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”
Lecture 6: Semaphores

// 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]);
        eat();
        signal (fork [(i+1) mod 5]);
        signal (fork[i]);
        signal (fork [(i+1) mod 5]);
    }
}
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] |

philosopher 4*

loop forever
p1: think
p2: wait(fork[i])

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

p3: wait(fork[i+1])

Etc. etc.

p4: eat
p5: signal(fork[i])

• 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

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Minix Semaphore

```c
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);
        }
    }
}
```


Minix Semaphore P

```c
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

```c
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

- semaphore.h
- Low level process/thread control
- In assembly language, in OS kernel
- struct `semaphore`
  ```c
  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)`

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

```c--
semaphore count; // a "general" semaphore
binarysem output; // a binary (0 or 1) semaphore for unscrambling output
main()
{
    initialize(count, 0);
    initialize(output, 0);
    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
```

(CACI 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?

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 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