Semaphores and Monitors

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Summer 2009

From locks and barriers...

- Are busy-waiting protocols complex?
- No clear distinction between variables used:
  - for synchronization
  - for computing results
- Busy-waiting is often inefficient
  - Usually more processes/threads than processors
  - Processor executing a spinning process can be more productively employed to execute another process

Semaphores

First synchronisation tool (and remains one of the most important).
⇒ Easy to protect critical sections.
⇒ Included in (almost) all parallel programming libraries.

Semaphore

Shared variable with 2 methods:

```
down(Semaphore s) {
        ▷Probeer (try) / Passeren (pass) / Pakken (grab)
        < wait until c > 0, then c := c-1; >
        ▷must be atomic once c > 0 is detected
}
```

```
up(Semaphore s) {
        ▷Verhoog (increase)
        < c = c + 1; >   ▷must be atomic
}
```

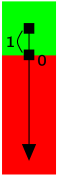
Init(*Semaphore* s, *Integer* i){ c := i; }

Semaphores, what for?

- Critical section: Mutual exclusion
- Barriers: Signaling events
- Producers and Consumers
- Bounded buffers: Resource counting

Critical section

sem mutex; Init(sem,1);



while (true) { ▷*Process 1*

____

Critical section

NON-Critical section

____

}

while (true) { ▷*Process 2*

____

Critical section

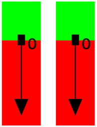
NON-Critical section

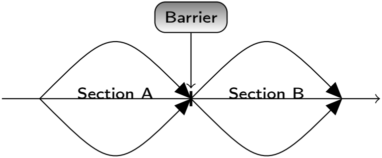
____

}

Barriers: Signaling events

sem arrive1, arrive2;
Init(arrive1,0); Init(arrive2,0);





. . . ▷*process 1 in section A*

▷*signal arrival*

▷*Wait for the other process*

. . . ▷*process 1 in section B*

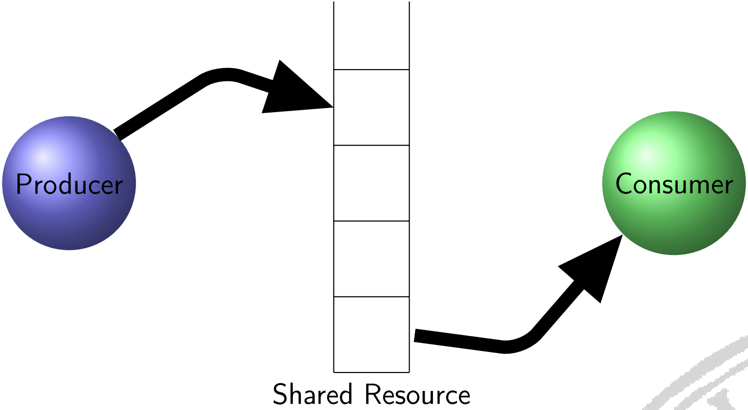
. . . ▷*process 2 in section A*

▷*signal arrival*

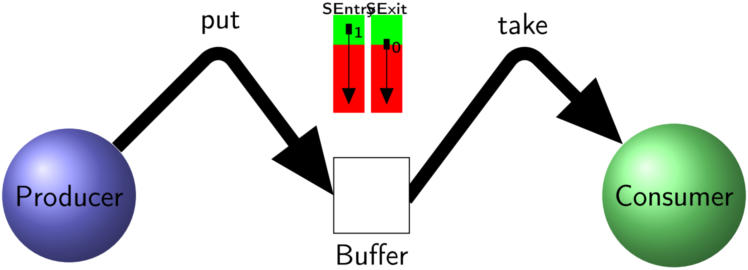
▷*Wait for the other process*

. . . ▷*process 2 in section B*

Semaphores: Procuders and Consumers



Semaphores: Procuders and Consumers

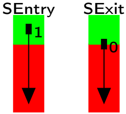


Split Binary Semaphore

Both are *binary semaphores*

Semaphores: Procuders and Consumers

```
typeT buf;   ▷Buffer of some type T
sem sEntry, sExit;
Init(sEntry,1); Init(sExit,0);
```



```
while (true) {   ▷Producer
    ...

    buf = data;

    ...
}
```

```
while (true) {   ▷Consumer
    ...

    result = buf;

    ...
}
```

In the last example...

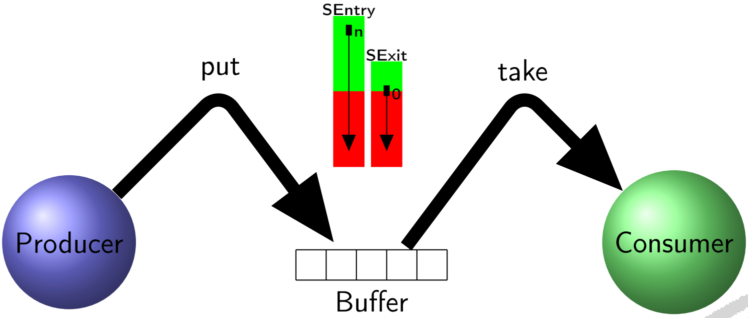
- Single communication buffer
- No waiting if data are produced+consumed at the same rate
- But in general, producer/consumer execution is bursty

Example

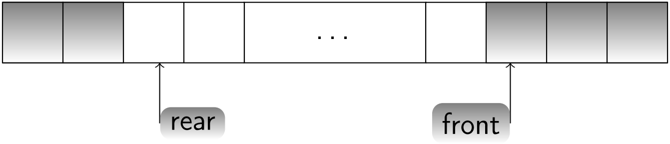
- producer produces several items in a quick succession
- does more computation
- produces another set of items

- Solution: Increase the buffer capacity

Bounded buffer: Resource counting

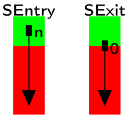


The Buffer



- Put: buf[rear] = data; rear = (rear + 1) %n
- Take: result = buf[front]; front = (front + 1) %n

Bounded buffer: Resource counting

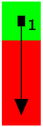


```
typeT buf[n];   ▷Array of some type T
int front=0, rear=0;
sem sEntry, sExit;
Init(sEntry,n); Init(sExit,0);
  sem mutexP, mutexT; Init(mutexP,1), Init(mutexT,1);
```

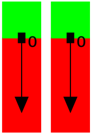
```
while (true) {   ▷Producer
    ...


    buf[rear] = data;
    rear = (rear+1) %n;


    ...
}
```

```
while (true) {   ▷Consumer
    ...


    result = buf[front];
    front = (front+1) %n;


    ...
}
```

Semi-Conclusion

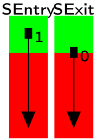


Critical Section

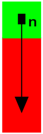


Blocking semaphore

Barriers/Signaling



Split Binary semaphore

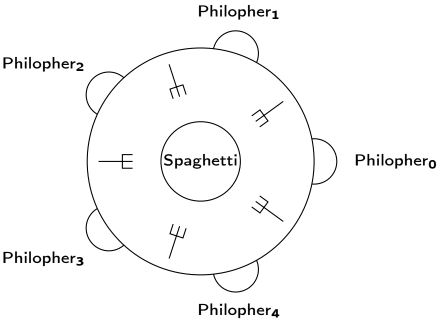


Resource Counting

Dining Philosophers Problem

Five philosophers sit around a circular table. Each philosopher spends his life alternately thinking and eating. In the center of the table is a large patter of spaghetti. Because the spaghetti is long and tangled – and the philosophers are not mechanically adept – a philosopher must use two forks to eat a helping. Unfortunately, the philosophers can afford only five forks. One fork is placed between each pair of philosophers. And they agree that each will use only the forks to the immediate left and right. The problem is to write a program to simulate the behavior of the philosophers. The program must avoid the unfortunate (and eventually fatal) situation in which all philosophers are hungry but non is able to acquire both forks – for example, each holds one fork and refuses to give it up.

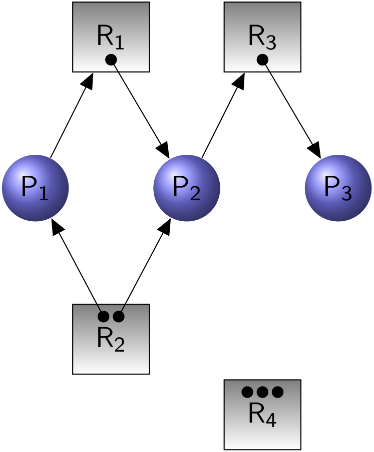
Dining Philosophers Problem



```
while (true) {   ▷Philosopher$_i$
        think;
        acquire forks;
        eat;
        release forks;
}
```

```
sem fork[5] = {1,1,1,1,1}
while (true) {   ▷Philosopher$_{0,1,2,3,4}$
        think;
        down(fork[i]);down(fork[i+1]);
        eat;
        up(fork[i]);up(fork[i+1]);
}
```

Deadlocks: Resource Allocation Graph



Deadlock?

- No cycle ⇒
  No process is deadlocked
- If cycle,
  deadlock may exist

Cycle in the Graph?

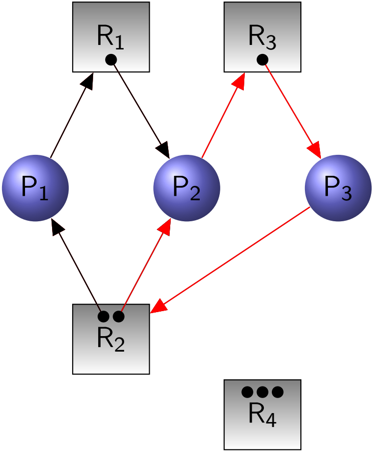
If each resource has ONE instance

-
- Each process involved in the cycle is deadlocked
- Both necessary and sufficient condition for deadlock

If each resource has SEVERAL instance

-
- Necessary but not sufficient condition for deadlock

RAG example



- $P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$
- $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

P_1, P_2, P_3 are deadlocked

Conditions

Mutual exclusion

At least one resource must be nonsharable
(only one process can use it)

Hold and wait

At least one process holds at least one resource and waits for more resources which are held by other processes

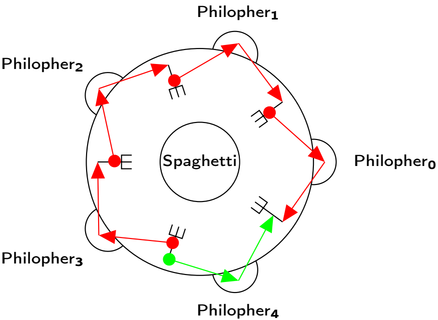
No preemption

Only the process holding a resource can release it.

Circular wait

A set of processes are waiting for resources held by others in a circular manner
$< P_0, ..., P_n >$ where P_i waits for a resource held by $P_{(i+1)\%n}$

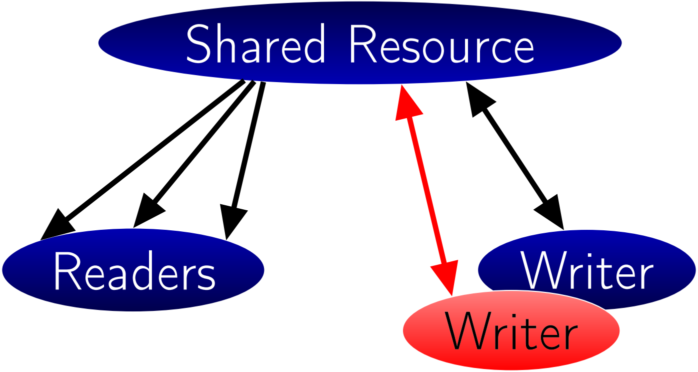
Dining Philosophers Starvation ...solved



```
while (true) {   ▷Philosopher_{0,1,2,3}
        think;
        down(fork[i]);down(fork[i+1]);
        eat;
        up(fork[i]);up(fork[i+1]);
}
```

```
while (true) {   ▷Philosopher_4
        think;
        down(fork[0]);down(fork[4]);
        eat;
        up(fork[0]);up(fork[4]);
}
```

Readers/Writers



- Example of selective mutual exclusion
- Example of general condition synchronization

Readers/Writers as an Exclusion Problem

- First Solution:
  1. the problem
  2. the constraints
- Let rw be a mutual exclusion semaphore⇒ Init(rw,1);

Readers $_{1,..,M}$

```
while (true) {
    ...
    down(rw);  ▷grab exclusive access lock
    Read the database
    up(rw);  ▷release the lock
    ...
}
```

Writers $_{1,..,N}$

```
while (true) {
    ...
    down(rw);  ▷grab exclusive access lock
    Write the database
    up(rw);  ▷release the lock
    ...
}
```

- Readers – as a group – need to lock out writers
- but only the *first* needs to grab the lock (i.e. down(rw))
- Subsequent readers can directly access the database

Relaxing constraints

```
int nr = 0;                        ▷number of active readers
sem rw; Init(rw,1);                ▷lock for reader/writer exclusion
sem mutexR; Init(mutexR,1);        ▷lock for reader access to nr
```

Readers $_{1,..,M}$

```
while (true) {
    ...
    down(mutexR);
    nr = nr + 1;  ▷if first, get lock
    if (nr == 1) down(rw);
    up(mutexR);
    Read the database
    down(mutexR);
    nr = nr - 1;  ▷if last, release lock
    if (nr == 0) up(rw);
    up(mutexR);
    ...
}
```

Writers $_{1,..,N}$

```
while (true) {
    ...
    down(rw);  ▷grab exclusive access lock
    Write the database
    up(rw);  ▷release the lock
    ...
}
```

Readers/Writers using Condition Synchronization

- Second Solution:
  1. Count the number of each kind of processes trying to access the database
  2. Constrain the values of the counters
- Let nr and nw be nonnegative counters;
- BAD: $(nr > 0 \wedge nw > 0) \vee nw > 1$
- Symmetrically, good states, $RW = \overline{BAD}$
  RW: $(nr == 0 \vee nw == 0) \wedge nw \leq 1$

Coarse-grained solution using Condition Synchronization

```
int nr = 0, nw = 0;
 ▷RW: $(nr == 0 \vee nw == 0) \wedge nw \leq 1$
```

Readers $_{1,..,M}$

```
while (true) {
  ...
  <await(nw == 0)nr=nr+1;>
  Read the database
  <nr=nr−1;>
  ...
}
```

Writers $_{1,..,N}$

```
while (true) {
  ...
  <await(nr == 0 and nw == 0)nw=nw+1;>
  Write the database
  <nw=nw−1;>
  ...
}
```

So ... semaphores, really?

- Common use in programming languages that do not intrinsically support other forms of synchronization.
- They are the primitive synchronization mechanism in many operating systems.

The trend in programming language development, though, is towards more structured forms of synchronization, such as *monitors*.

- Inadequacies in dealing with (multi-resource) deadlocks
- Do not protect the programmer from the easy mistakes of taking a semaphore that is already held by the same process, and forgetting to release a semaphore that has been taken.

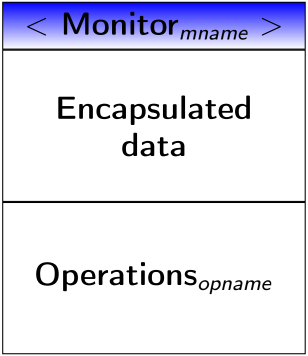
Outline

1. Semaphores

2. **Monitors**
   - ADT
   - Mutual Exclusion
   - Condition Variables
   - Bounded Buffer
   - Readers/Writers

3. Conclusion

Monitor – an abstract data type

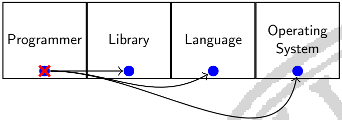


< Monitor$_{mname}$ >

Encapsulated data

Operations$_{opname}$

- Mutual exclusion is provided implicitly by ensuring that procedures in the same monitor are not executed concurrently
- Easier programming
- `call mname.opname(args)`
- Designed in isolation
- Maintain the



Programmer

Library

Language

Operating System

Mutual exclusion

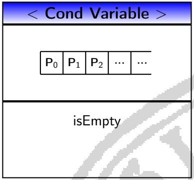
Monitor procedures *by definition* execute with

Condition Variables

- used to delay a process that cannot safely continue executing until the monitor's state satisfies some boolean condition.
- used to awaken delayed processes when the condition becomes true.

```
cond cv;
```

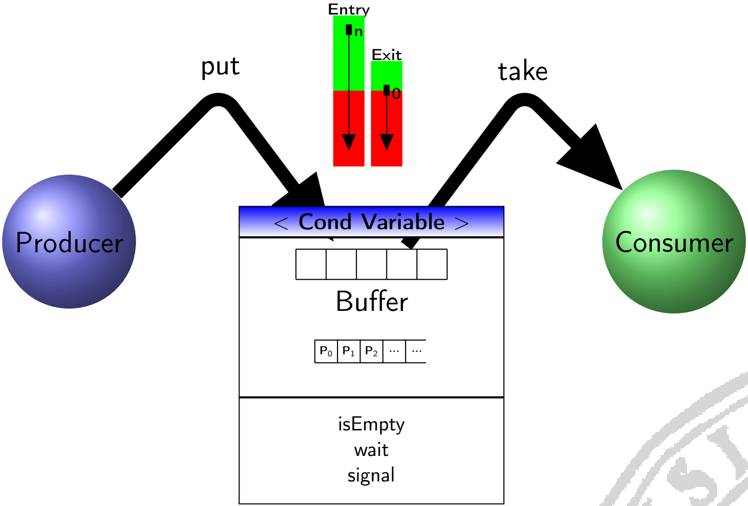
- The value of the condition variable cv is a FIFO queue of delayed processes.
- Hidden to the programmer.
- Somebody is waiting? → Check `isEmpty(cv);`
- A process blocks on a condition variable by executing `wait(cv);`
- `signal(cv);` awakens the front of the queue



Signaling and waking up...Dilemma

- Signal and (non-preemptive)
  → The signaler continues and the signaled process executes at some later time.
- Signal and (preemptive)
  → The signaler waits until some later time and the signaled process executes now.

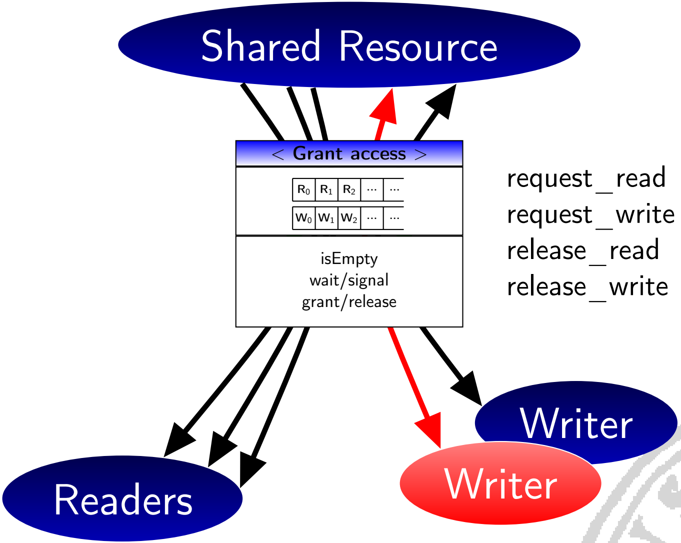
Bounded buffer with Monitors



Bounded Buffer – Code

```
monitor Bounded_Buffer {

    typeT buf[n]
    int front=0, rear=0, count=0;  ▷ rear = (front+count)%n

    cond not_full,      ▷ signaled when count < n
         not_empty;     ▷ signaled when count > 0



     procedure put(typeT data) {
         while(count == n)wait(not_full);
         buf[rear] = data; rear=(rear+1)%n; count=count+1;
         signal(not_empty);
    }



     procedure take(typeT &result) {
         while(count == 0)wait(not_empty);
         result = buf[front]; front=(front+1)%n; count=count-1;
         signal(not_full);
    }

}
```

Readers/Writers



request_read
request_write
release_read
release_write

Readers/Writers – Code

```
monitor RW_Controller  {

      int nr=0, nw=0;  ▷RW: (nr == 0 v nw == 0 ) ∧ nw ≤ 1
      cond oktoread,    ▷ signaled when nw == 0
      cond oktowrite,   ▷ signaled when nr == 0 and nw == 0

        procedure request_read()  {
              while(nw > 0) wait(oktoread);
              nr = nr + 1;
      }

        procedure release_read()  {
              nr = nr - 1;
              if(nr == 0) signal(oktowrite);  ▷ awaken one writer
      }

        procedure request_write()  {
              while(nr > 0 || nw > 0) wait(oktowrite);
              nw = nw + 1;
      }

        procedure release_write()  {
              nw = nw - 1;
              signal(oktowrite);       ▷ awaken one writer
              signal_all(oktoread);    ▷ and all readers
      }

}
```

Conclusion

- Semaphore
    - Fundamental
    - Easy to program mutual exclusion and signaling
    - Easy to make errors
    - Global to all processes:
      ⇒ Hard to understand the program
- Monitors
    - Data structure abstraction
    - Operations are the *only* means to manipulate data
    - Implicit mutual exclusion (*Not* the programmer's task)
    - Condition variables (FIFO queue)
    - Awaking disciplines