Sistemas de Operação

Semaphores and shared memory

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3. Unix IPC primitives for shared memory
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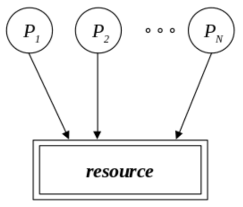
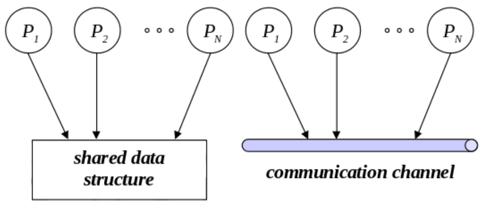
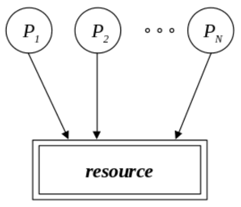
Key concepts
Independent and interacting processes

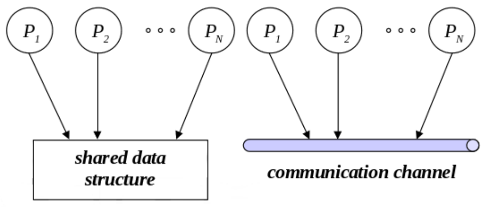
- In a multiprogrammed environment, two or more processes can be:
  - independent – if they, from their creation to their termination, never explicitly interact
    - actually. there is an implicit interaction, as they compete for system resources
    - ex: jobs in a batch system; processes from different users
  - interactive – if they share information or explicitly communicate
    - the sharing requires a common address space
    - communication can be done through a common address space or a communication channel connecting them





Key concepts
Independent and interacting processes (2)



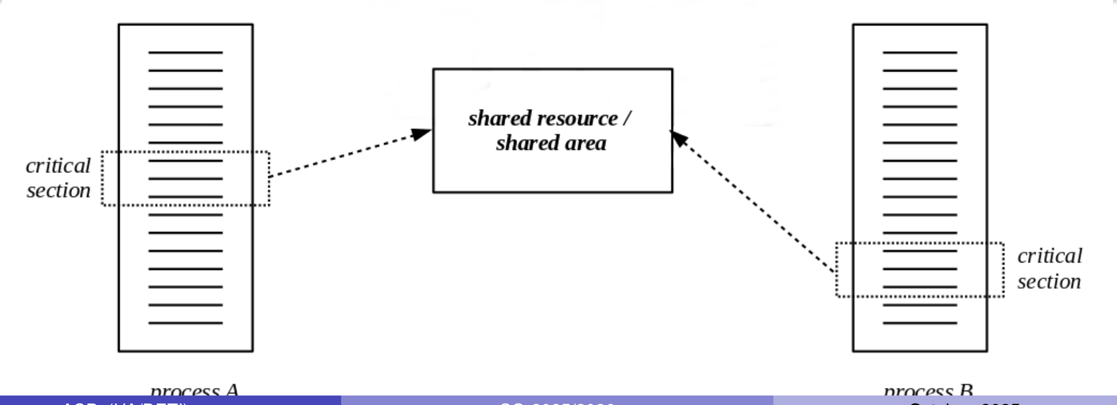


- Independent processes competing for a resource
- It is the responsibility of the OS to ensure the assignment of resources to processes is done in a controlled way, such that no information lost occurs
- In general, this imposes that only one process can use the resource at a time – mutual exclusive access
- The communication channel is typically a system resource, so processes compete for it

- Interacting processes sharing information or communicating
- It is the responsibility of the processes to ensure that access to the shared area is done in a controlled way, such that no information lost occurs
- In general, this imposes that only one process can access the shared area at a time – mutual exclusive access
- The communication channel is typically a system resource, so processes compete for it

Key concepts
Critical section

- Having access to a resource or to a shared area actually means executing the code that does the access
- This section of code, called critical section , if not properly protected, can result in race conditions
- A race condition is a condition where the behaviour (output, result) depends on the sequence or timing of other (uncontrollable) events, and can lead to undesirable behaviour
- Critical sections should execute in mutual exclusion

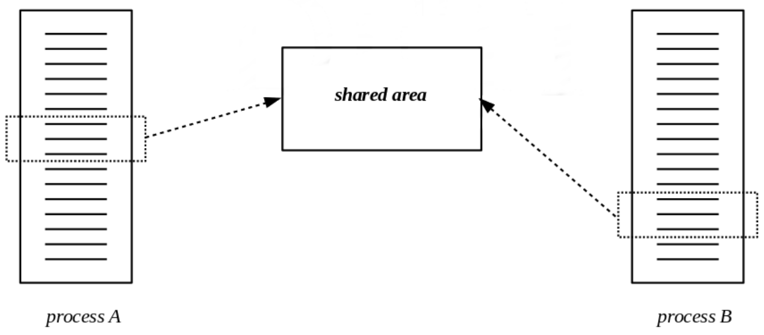


Key concepts
Deadlock and starvation

- Mutual exclusion in the access to a resource or shared area can result in
  - deadlock – when two or more processes are forever barred from accessing their respective critical section, waiting for events that can be demonstrated will never happen
    - operations are blocked
  - starvation – when one or more processes compete for access to a critical section and, due to a conjunction of circumstances in which new processes that exceed them continually arise, access is successively deferred
    - operations are continuously postponed

Shared memory
Shared memory as a resource

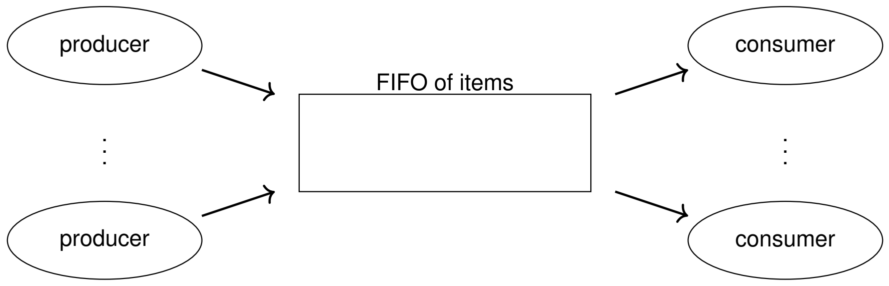
- Address spaces of processes are independent
- But address spaces are virtual
- Two or more virtual regions can be mapped to the same physical region (the physical region is shared)
- Shared memory is managed as a resource by the operating system
- Two actions are required:
  - Requesting a segment of shared memory to the OS
  - Maping a region of the process' address space to that segment



Unix IPC primitives
Shared memory

- System V shared memory
  - creation – `shmget`
  - mapping and unmapping – `shmat`, `shmdt`
  - other operations – `shmctl`
  - execute `man 7 sysvipc` for an overview description
  - execute `man shmget`, `man shmat` `man shmdt` or `man shmctl` for specific descriptions
- POSIX shared memory
  - creation - `shm_open`, `ftruncate`
  - mapping and unmapping - `mmap`, `munmap`
  - other operations - `close`, `shm_unlink`, `fchmod`, ···
  - execute `man shm_overview` for an overview description
  - execute `man shm_open`, `man mmap`, `man munmap`, `man shm_close`,... for specific descriptions

Illustration example
Bounded-buffer problem – problem statement



- In this problem, a number of entities (producers) produce information that is consumed by a number of different entities (consumers)
- Communication is carried out through a buffer with bounded capacity, shared by all intervening entities

- Assume that every producer and every consumer run as a different process
  - Hence the FIFO must be implemented in shared memory so the different processes can access it
- Let look at an implementation...

Illustration example
Bounded-buffer problem – fifo definition

```
#define N 100

struct FIFO
{
    bool full;
    uint32_t size; // effective size of the FIFO
    uint32_t in, out;
    uint32_t dummyDelay; // added to enhance the probability of occurrence of race conditions
    struct item
    {
        uint32_t id; // id of the producer
        uint32_t v1; // a general purpose value
        uint32_t v2; // another general purpose value
    } data[N];
};

void fifoInit(FIFO *f, uint32_t sz, uint32_t delay);

bool fifoIsFull(FIFO *f);

bool fifoIsEmpty(FIFO *f);

void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2);

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p);

void fifoDestroy(FIFO *f);
```

Illustration example
Bounded-buffer problem – unsafe implementation of the fifo

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* wait until fifo is not full */
    while (fifoIsFull(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);
}

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* wait until fifo is not empty */
    while (fifoIsEmpty(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;
}
```

- How to guarantee absence of race conditions?
  - enforcing mutual exclusion

Semaphores
Definition

- A semaphore is a synchronization mechanism, defined by a data type plus two atomic operations, down and up
- Data type:

```
typedef struct
{
   unsigned int val;     /* can not be negative */
   PROCESS *queue;       /* queue of waiting blocked processes */
} SEMAPHORE;
```

- Operations:
  - down
    - block and queue process if `val` is zero
    - decrement `val` otherwise
  - up
    - increment `val`
    - if `queue` is not empty, wake up one waiting process (accordingly to a given policy)
- Note that `val` can only be manipulated through these operations
  - It is not possible in general to check the value of `val`

Semaphores
A possible implementation of semaphores

```
/* array of semaphores defined in kernel */
#define  R   ... /* semid = 0, 1, ..., R-1 */

static SEMAPHORE sem[R];

void sem_down(unsigned int semid)
{
    disable_interruptions;
    if (sem[semid].val == 0)
        block_on_sem(getpid(), semid);
    sem[semid].val -= 1;
    enable_interruptions;
}

void sem_up(unsigned int semid)
{
    disable_interruptions;
    sem[semid].val += 1;
    if (sem[sem_id].queue != NULL)
        wake_up_one_on_sem(semid);
    enable_interruptions;
}
```

- This implementation is typical of uniprocessor systems. Why?

- Semaphores can be binary or not binary

- How to implement mutual exclusion using semaphores?
  - Using a binary semaphore

Unix IPC primitives
Semaphores

- System V semaphores
  - creation: `semget` (actually creates an array of semaphores)
  - down and up: `semop`
  - other operations: `semctl`
  - execute `man semget`, `man semop` or `man semctl` for a description
- POSIX semaphores
  - Two types: named and unnamed semaphores
  - Named semaphores
    - `sem_open`, `sem_close`, `sem_unlink`
    - created in a virtual filesystem (e.g., /dev/sem)
  - unnamed semaphores – memory based
    - `sem_init`, `sem_destroy`
  - down and up
    - `sem_wait`, `sem_trywait`, `sem_timedwait`, `sem_post`
  - execute `man sem_overview` for an overview description
  - execute `man sem_open`, `man sem_wait`, ..., for a specific description

Illustration example
Bounded-buffer problem – making the implementation safe

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* wait until fifo is not full */
    while (fifoIsFull(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);
}

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* wait until fifo is not empty */
    while (fifoIsEmpty(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;
}
```

Illustration example
Bounded-buffer problem – making the implementation safe

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* wait until fifo is not full */

    reserve a slot, waiting if necessary

    lock
    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);
}   unlock
    make an item available
void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* wait until fifo is not empty */

    reserve an item, waiting if necessary

    lock
    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;
}   unlock
    make a slot available
```

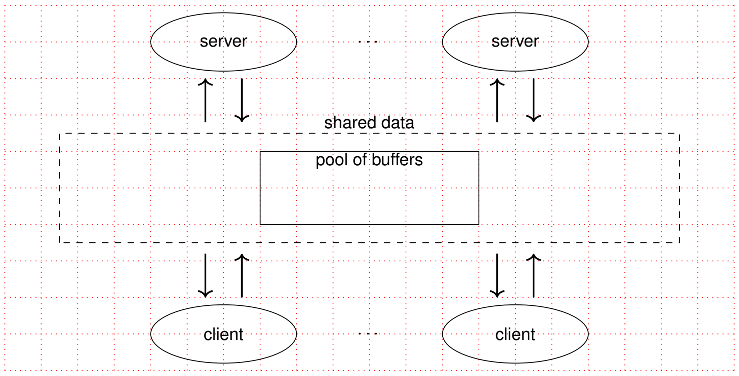
Illustration example
Bounded-buffer problem – fifo definition

```
#define N 100

#define ACCESS 0
#define SLOTS 1
#define ITEMS 2

struct FIFO
{
    bool full;
    uint32_t size; // effective size of the FIFO
    uint32_t in, out;
    uint32_t dummyDelay; // added to enhance the probability of occurrence of race conditions
    struct item
    {
        uint32_t id; // id of the producer
        uint32_t v1; // a general purpose value
        uint32_t v2; // another general purpose value
    } data[N];

    /* support for safeness, not used in the unsafe implementation */
    int sem;
};

void fifoInit(FIFO *f, uint32_t sz, uint32_t delay);

bool fifoIsFull(FIFO *f);

bool fifoIsEmpty(FIFO *f);

void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2);

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p);

void fifoDestroy(FIFO *f);
```

Illustration example
Bounded-buffer problem – safe implementation using semaphores

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* reserve a slot, waiting if necessary */
    psem_down(f->sem, SLOTS);

    /* lock access to fifo */
    psem_down(f->sem, ACCESS);

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);

    /* release access to fifo */
    psem_up(f->sem, ACCESS);

    /* notify there is one more item available */
    psem_up(f->sem, ITEMS);
}

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* reserve an item, waiting if necessary */
    psem_down(f->sem, ITEMS);

    /* lock access to fifo */
    psem_down(f->sem, ACCESS);

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;

    /* release access to fifo */
    psem_up(f->sem, ACCESS);

    /* notify there is one more slot available */
    psem_up(f->sem, SLOTS);
}
```

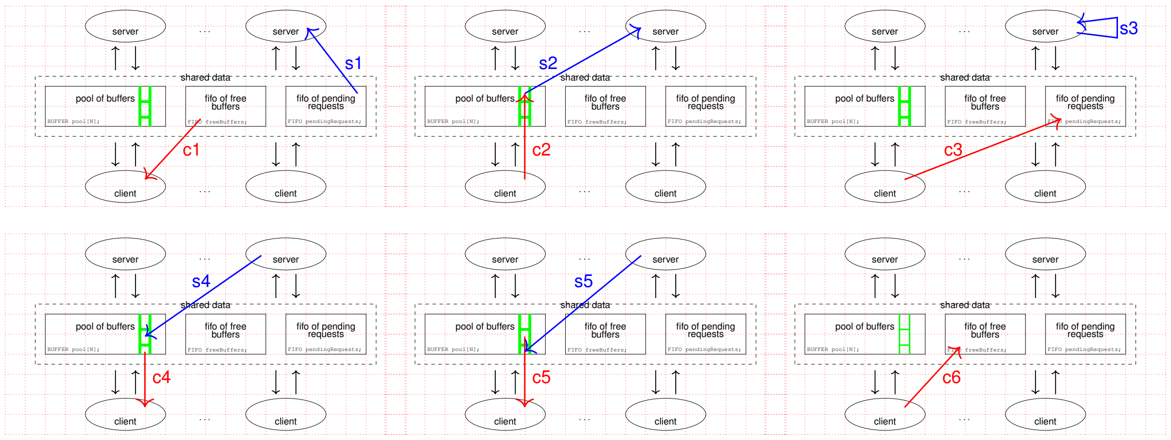
Illustration example
Client-server example – problem statement



- In this problem, a number of entities (clients) interact with a number of other entities (servers) to request a service
- Communication is carried out through a pool of buffers shared by all

- Every producer and consumer must run as a different process
  - Hence the data structure must be implemented in shared memory so the different processes can access it

Illustration example
Client-server example – interaction cycles



client interaction cycle	**server interaction cycle**
c1: tk = getFreeBuffer()	**s1:** tk = getPendingRequest()
c2: putRequestData(data, tk)	**s2:** req = getRequestData(tk)
c3: submitRequest(tk)	**s3:** resp = produceResponse(req)
c4: waitForResponse(tk)	**s4:** putResponse(resp, tk)
c5: resp = getResponseData(tk)	**s5:** notifyClient(tk)
c6: releaseBuffer(tk)	