Inter-Process Communication

Inter-Process Communication

- Mechanisms for processes to communicate with each other

- UNIX IPC
  - ✓ pipes
  - ✓ FIFOs
  - ✓ message queue
  - ✓ shared memory
  - ✓ sockets

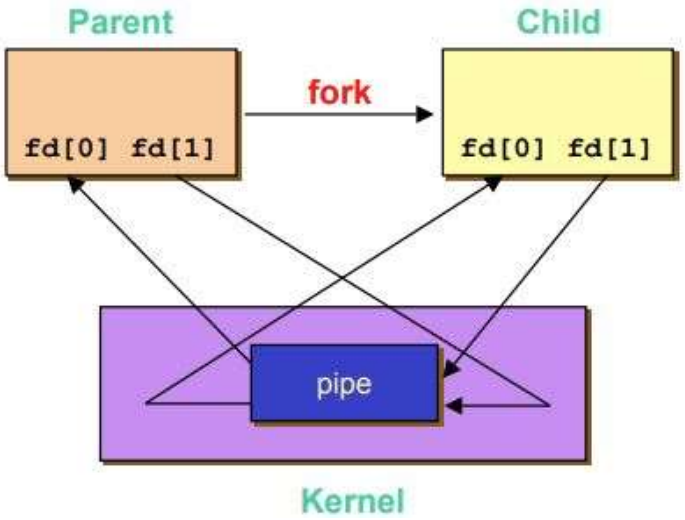
Pipes

- The oldest form of UNIX IPC
  - ✓ Half-duplex
  - ✓ Between processes that have a common ancestor

- Pipe

```
#include <unistd.h>
int pipe(int fd[2]);
return: 0 if OK, -1 on error
```

- Half-duplex pipe after a fork



- IPC through pipes
  - ✓ Once we have created a pipe using pipe
  - ✓ We can use the normal file I/O functions (e.g., read, write)

Exercise

- Send data from parent to child over a pipe

```
$arm-linux-gnueabihf-gcc –o pipe pipe.c (or make pipe)
$./pipe
```

- Synchronization between parent and child using pipe

```
$ arm-linux-gnueabihf-gcc –o sync sync.c synchlib.c (or make sync)
$./sync
```

FiFOs

- Named pipes
  - ✓ Full-duplex
  - ✓ Between unrelated processes that don't have a common ancestor

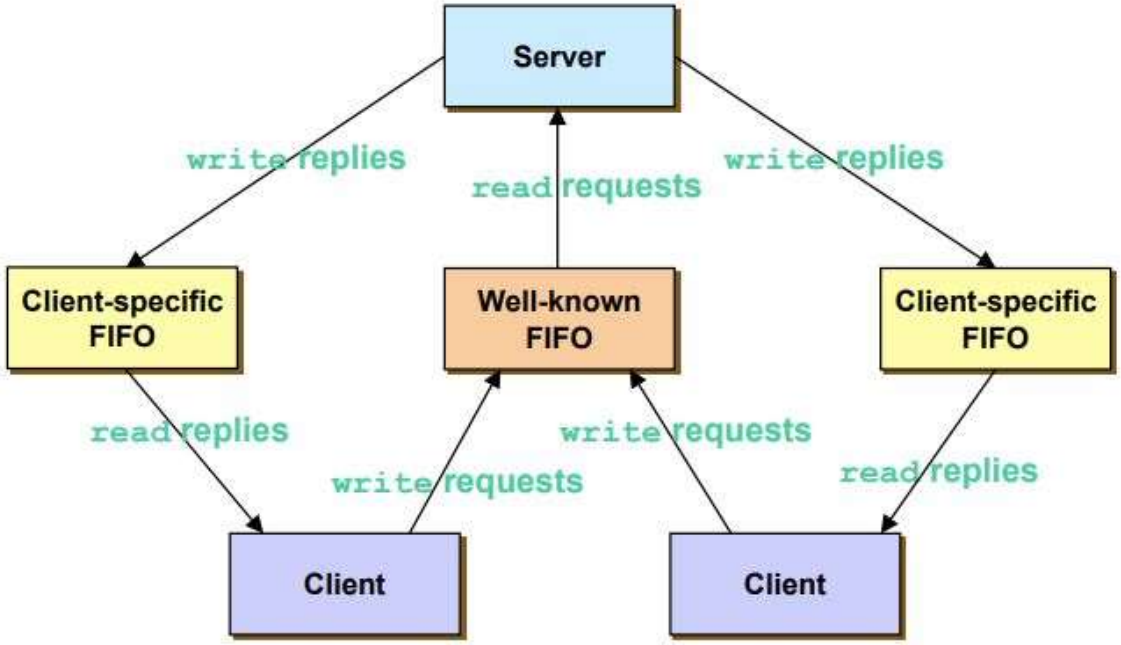
- Create a FIFO

```
#include <sys/types.h>
#include <sys/stat.h>
int mkfifo(char *pathname, mode_t mode);
return: 0 if OK, -1 on error
```

- IPC through FIFOs
  - ✓ Once we have created a FIFO using `mkfifo`,
  - ✓ We can use the normal file I/O functions (e.g., `open, read, write, close`)

FIFOs

- Client-server communication using FIFOs



Exercise

- Client-server communication using FIFOs

```
$arm-linux-gnueabihf-gcc -o fifos fifos.c (or make fifos)
$arm-linux-gnueabihf-gcc -o fifoc fifoc.c (or make fifoc)
$./fifos

$./fifoc
```

Message Queues

- A linked list of messages stored within the kernel

- A message consists of
  - ✓A long integer that have the positive integer message type
  - ✓Message data

```
struct mymsg {
    long mtype;     /* positive message type
*/
    char mtext[512];   /* message data */
};
```

- IPC through message queues
  - ✓ msgget : Open an existing queue or create a new one
  - ✓ msgsnd : Place a message onto the queue
  - ✓ msgrcv : Fetch a message from the queue

System Calls for Message Queues

- Obtain a message queue ID

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgget(key_t key, int flag);
return: message queue ID if OK, -1 on error
```

- Message queue control operations

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgctl(int msqid, int cmd, struct msqid_ds *buf);
return: 0 if OK, -1 on error
```

System Calls for Message Queues

- Message queue control operations
  - ✓ The second argument, `cmd`
    - ➢ `IPC_STAT` : fetch the `msqid_ds` structure for this queue
    - ➢ `IPC_SET` : set the part of `msqid_ds` structure
    - ➢ `IPC_RMID` : remove the message queue from the system
  - ✓ The third argument, `buf`

```
struct msqid_ds {
   struct ipc_perm    msg_perm;      //IPC structure: permission and owner
   struct msg     *msg_first;    //ptr to first message on queue
   struct msg     *msg_last;     //ptr to last message on queue
   ulong          msg_cbytes;    //current # of bytes on queue
   ulong          msg_qnum;      //# of messages on queue
   ulong          msg_qbytes;    //max. # of bytes on queue
   pid_t          msg_lspid;     //pid of last msgsnd()
   pid_t          msg_lrpid;     //pid of last msgrcv()
   time_t         msg_stime;     //last-msgsnd() time
   time_t         msg_rtime;     //last-msgrcv() time
   time_t         msg_ctime;     //last-change time
};
```

System Calls for Message Queues

- Send a message

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgsnd(int msqid, void *ptr, size_t nbytes, int flag);
return: 0 if OK, -1 on error
the fourth argument, flag: IPC_NOWAIT
```

- Receive a message

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgrcv(int msqid, void *ptr, size_t nbytes, long type, int flag);
return: size of data portion of message if OK, -1 on error
the fifth argument, flag: IPC_NOWAIT
```

System Calls for Message Queues

- Receive a message
  - ✓ If `type` == 0,
    - ➢ The first message on the queue is returned
  - ✓ If `type` 〉 0,
    - ➢ The first message on the queue whose message type equals `type` is returned
  - ✓ If `type` 〈 0,
    - ➢ The first message on the queue whose message type is the lowest value less than or equal to the absolute value of `type` is returned
  - ✓ If `IPC_NOWAIT` is specified in `flag`,
    - ➢ Return is made with an error of `EAGAIN`

Exercise

- IPC between two processes using message queue

```
$arm-linux-gnueabihf-gcc -o msgq1 msgq1.c (or make msgq1)
$arm-linux-gnueabihf-gcc -o msgq2 msgq2.c (or make msgq2)
$./msgq1

$./msgq2
```

- Note:
  - ✓ If a process creates a message queue, its data structure remains in the kernel even though the process has terminated
  - ✓ You have to remove it through `msgctl()` with `IPC_RMID` parameter (or, reboot the system !!)

Shared Memory

- Allows two or more processes to share a given region of memory
  - ✓ The fastest form of IPC because data does not need to be copied between them
  - ✓ Need to synchronize shared memory access
    - ➢ Semaphores are used often

- IPC through shared memory
  - ✓ `shmget`
    - ➢ Obtain a shared memory identifier
    - ➢ Open an existing segment or create a new one
  - ✓ `shmat`
    - ➢ Attach a shared memory segment to the process' address space
  - ✓ `shmdt`
    - ➢ Detach a shared memory segment
    - ➢ `shmdt` does not remove the identifier and its associated data structure from the system

System Calls for Shared Memory

- Obtain a shared memory ID

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
int shmget(key_t key, int size, int flag);
return: shared memory ID if OK, -1 on error
```

  - ✓ The second argument, `size`
    - ➢ If a new segment is being created, we must specify its minimum size, `size`
    - ➢ If we are referencing an existing segment, we can specify `size` as 0

- Shared memory control operations

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
int shmctl(int shmid, int cmd, struct shmid_ds *buf);
return: 0 if OK, -1 on error
```

System Calls for Shared Memory

- Shared memory control operations
  - ✓The second argument, cmd

```
IPC_STAT        :fetch the shmid_ds structure for this shared memory
IPC_SET     :set the part of shmid_ds structure
IPC_RMID        :remove the shared memory segment from the system
SHM_LOCK        :lock the shared memory in memory
SHM_UNLOCK  :unlock the shared memory segment
```

  - ✓The third argument, buf

```
 struct shmid_ds {
    struct ipc_perm    shm_perm;      //IPC structure: permission and
owner
    struct anon_map    *shm_amp;      //pointer in kernel
    int             shm_segsz;     //size of segment in bytes
    ushort          shm_lkcnt;     //# of times segment is being locked
    pid_t           shm_lpid;      //pid of last shmop()
    pid_t           shm_cpid;      //pid of creator
    ulong           shm_nattch;    //# of current attaches
    ulong           shm_cnattch;       //used only for shminfo
    time_t          shm_atime;     //last-attach time
    time_t          shm_dtime;     //last-detach time
    time_t          shm_ctime;     //last-chang time
 };
```

System Calls for Shared Memory

- Attach a shared memory segment

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
int *shmat(int shmid, void *addr, int flag);
return: pointer to shared memory segment if OK, -1 on error
```

✓ The fourth argument, `flag`
  - ➢ `SHM_RND, SHM_RDONLY`

✓ If `addr` == 0, (Recommended)
  - ➢ The segment is attached at the first available address selected by the kernel

✓ If `add` != 0 and `SHM_RND` is not specified,
  - ➢ The segment is attached at the address given by `addr`

✓ If `addr` != 0 and `SHM_RND` is specified,
  - ➢ The segment is attached at the address given by (`addr`−(`addr` modulus `SHMLBA`))

✓ If `SHM_RDONLY` is specified,
  - ➢ The segment is attached read-only

System Calls for Shared Memory

- Detach a shared memory segment

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
int shmdt(void *addr);
return: 0 if OK, -1 on error
```

Exercise

- Shared memory example (&memory map)

```
$arm-linux-gnueabihf-gcc –o shm shm.c (or make shm)
$./shm
```

- IPC between two processes using shared memory

```
$arm-linux-gnueabihf-gcc –o sipc1 sipc1.c (or make sipc1)
$arm-linux-gnueabihf-gcc –o sipc2 sipc2.c (or make sipc2)
$./sipc1

$./sipc2
```

- Note:
  - ✓ If a process creates a shared memory, its data structure remains in the kernel even though the process has terminated
  - ✓ You have to remove it through `shmctl()` with `IPC_RMID` parameter (or, reboot the system !!)

Synchronization

Synchronization

- Thread cooperate in multithreaded programs
  - ✓ To share resources, access shared data structures
  - ✓ Also, to coordinate their execution

- For correctness, we have to control this cooperation
  - ✓ Must assume threads interleave executions arbitrarily and at different rates
  - ✓ We control cooperation using synchronization
    - ➢ Enables us to restrict the interleaving of execution
  - ✓ (Note) This also applies to processes, not just threads
    - ➢ And it also applies across machines in a distributed system

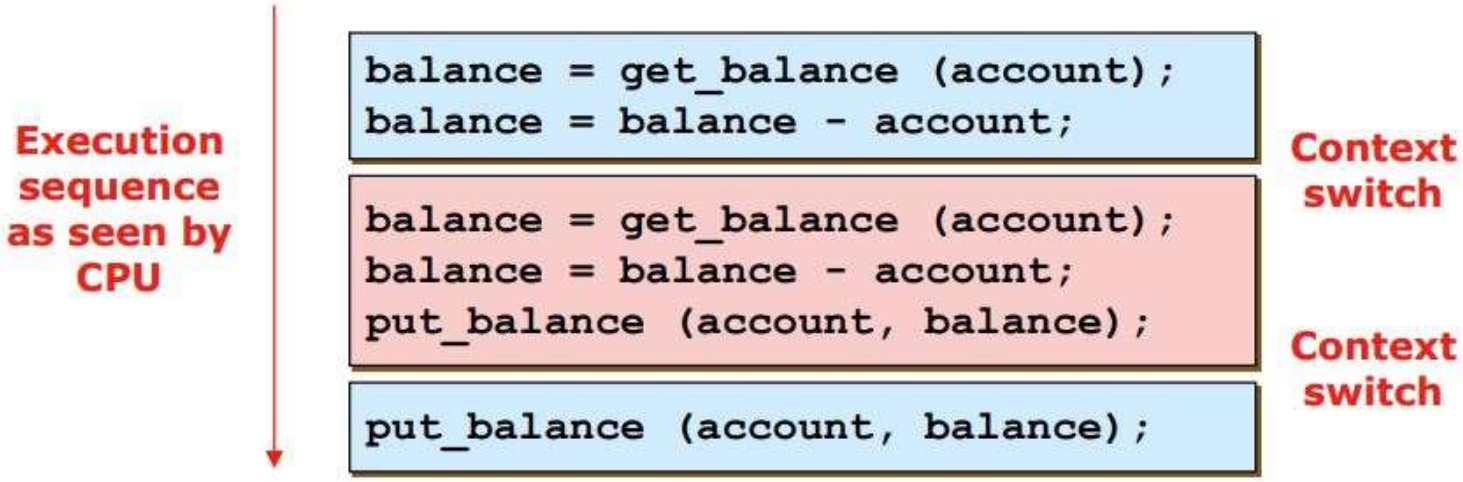
An Example

- Withdraw money from a back account
  - ✓ Suppose you and your friend share a back account with a balance of 1,000,000 won
  - ✓ What happens if both go to separate ATM machines, and simultaneously withdraw 100,000 won from the account?

```
int withdraw (account, amount)
{
   balance = get_balance (account);
   balance = balance - amount;
   put_balance (account, balance);
   return balance;
}
```

An Example

- Interleaved schedules
  - ✓ Represent the situation by creating a separate thread for each person to do the withdrawals
  - ✓ The execution of the two threads can be interleaved, assuming preemptive scheduling:



Synchronization Problem

- Two concurrent threads (or processes) access a shared resource without any synchronization
- Creates a race condition
  - ✓The situation where several processes access and manipulate shared data concurrently
  - ✓The result is non-deterministic and depends on timing
- Critical section
  - ✓Code segment in which the shared data is accessed
- We need mechanisms for controlling access to critical sections in the face of concurrency
  - ✓So that we can reason about the operation programs
- Synchronization is necessary for any shared data structure
  - ✓Buffers, queues, lists, etc.

Another Example: Bounded Buffer

- No synchronization

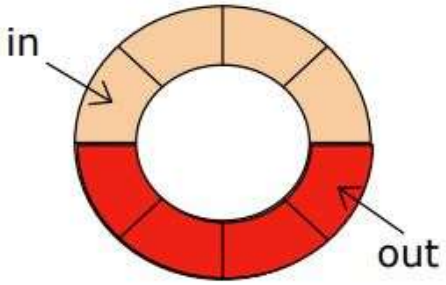
Producer

```
void producer(data)
{

 while (count==N) ;
 buffer[in] = data;
 in = (in+1) % N;
 count++;

}
```

```
int count;
struct item buffer[N];
int in, out;
```



Consumer

```
void consumer(data)
{

 while (counter==0) ;
 data = buffer[out];
 out = (out+1) % N;
 count--;

}
```

Exercise

- Producer & Consumer sharing bounded buffer

```
$ arm-linux-gnueabihf-gcc -o producer producer.c (or make producer)
$ arm-linux-gnueabihf-gcc -o consumer consumer.c (or make consumer)
$ ./producer
$ ./consumer
```

- Synchronization problem
  - ✓ The statement "`count++`" may be implemented in machine language as:

```
register1 = counter
register1 = register1 + 1
counter = register1
```

  - ✓ The statement "`count--`" may be implemented as:

```
register2 = counter
register2 = register2 + 1
counter = register2
```

Exercise

- Synchronization problem (cont'd)
  - ✓ Assume `counter` is initially 5. One interleaving of statements is:

```
producer: register1 = counter        (register1 = 5)
producer: register1 = register1 + 1  (register1 = 6)
consumer: register2 = counter        (register2 = 5)
consumer: register2 = register2 - 1  (register2 = 4)
producer: counter = register1        (counter = 6)
consumer: counter = register2        (counter = 4)
```

  - ✓ The value of `counter` may be either 4 or 6, where the correct result should be 5

Synchronization Mechanisms

- Semaphores
  - ✓ Basic, easy to get the hang of, hard to program with
  - ✓ Binary semaphore = mutex (lock)
  - ✓ Counting semaphore
- Monitors
  - ✓ High-level, requires language support, implicit operations
  - ✓ Each to program with: Java “synchronized”
- Mutex + Condition variables
  - ✓ Pthreads

Semaphores

- Semaphore
  - ✓ A counter used to provide access to a shared data object for multiple processes or threads
  - ✓ Two operations
    - ➢ Wait or P
    - ➢ Signal or V

- Synchronization procedure using semaphores
  - ✓ Test the semaphore that controls the resource
  - ✓ If the value of the semaphore is positive, the process can use the resource
    - ➢ The process decrements the semaphore value by 1, indicating that is has used on unit of the resource
  - ✓ If the value of the semaphore is 0, the process goes to sleep until the semaphore value is greater than 0
    - ➢ When the process wakes up, it returns to above step

Semaphore Implementations

- System V semaphore
  - ✓ Named semaphore → between processes
  - ✓ Shared key (number) between processes
  - ✓ Serviced by kernel

- POSIX semaphore
  - ✓ Unnamed semaphore → between threads or related processes
  - ✓ Shared variable in `sem_t` type between threads or related processes
  - ✓ Serviced by libraries or kernel
  - ✓ Most implementation doesn't support synchronization between processes yet, including Solaris and Linux

System calls for System V Semaphores

- Obtain a semaphore set ID

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

int semget(key_t key, int nsems, int flag);
return: semaphore ID if OK, -1 on error
```

- Semaphore control operations

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

int semctl(int semid, int semnum, int cmd, union semun arg);
return: non-negative value depending on cmd if OK, -1 on error
```

System calls for System V Semaphores

- Semaphore control operations
  - ✓The third argument, cmd

```
IPC_STAT: fetch the semid_ds structure for this semaphore set
IPC_SET : set the part of semid_ds structure
IPC_RMID: remove the semaphore set from the system
GETVAL  : return the semaphore value
SETVAL  : set the semaphore value
GETPID  : get pid of the process which do the last access to the semaphore
GETNCNT : return the number of processes which wait for the semaphore to increase
GETZCNT : return the number of processes which wait for the semaphore to be zero
GETALL  : fetch all the semaphore values in the set
SETALL  : set all the semaphore values in the set
```

  - ✓The fourth argument, arg

```
union semun {
   int              val;      /* for SETVAL */
   struct semid_ds  *buf;     /* for IPC_STAT and IPC_SET */
   ushort           *array;   /* for GETALL and SETALL */
};
```

System calls for System V Semaphores

- Semaphore operations

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
int semop(int semid, struct sembuf semop[], size_t nops);
return: 0 if OK, -1 on error

The second argument, semop
 struct sembuf {
    ushort sem_num;  // member # in set (0, 1, …, nsems-1)
    short  sem_op;   // operation (negative, 0, or positive)
    short  sem_flg;  // IPC_NOWAIT, SEM_UNDO
 };
```

System calls for System V Semaphores

- Semaphore operations
  - ✓ If `sem_op` 〉0,
    - ➢ The value of `sem_op` is added to the semaphore's value
  - ✓ If `sem_op` 〈 0 and the semaphore's value 〉= the value of `sem_op`,
    - ➢ The value of `sem_op` is added to the semaphore's value
  - ✓ If `sem_op` 〈 0 and the semaphore's value 〈 the value of `sem_op`,
    - ➢ If `IPC_NOWAIT` is not specified, the calling process is suspended until the semaphore's value 〉= the absolute value of `sem_op`
    - ➢ If `IPC_NOWAIT` is specified, return is made with an error of `EAGAIN`
  - ✓ If `sem_op` == 0 and the semaphore's value is not zero
    - ➢ If `IPC_NOWAIT` is not specified, the calling process is suspended until the semaphore's value becomes zero
    - ➢ If `IPC_NOWAIT` is specified, return is made with an error of `EAGAIN`
- Semaphore adjustment on `exit`
  - ✓ What happens if a process terminates while it has resources allocated through a semaphore?
  - ✓ Use `SEM_UNDO` flags

POSIX Semaphores

- POSIX semaphore libraries

```
#include <semaphore.h>
int sem_init(sem_t *sem, int pshared, unsigned int value);
int sem_wait(sem_t *sem);
int sem_trywait(sem_t *sem);
int sem_post(sem_t *sem);
int sem_getvalue(sem_t *sem, int *sval);
int sem_destroy(sem_t *sem);
return: 0 if OK, non-zero value on error
```

- Note: link option (dependent on semaphore packages)
  - ✓ Solaris

    `-lposix4`
  - ✓ Linux

    `-lpthread`

Exercise

- Implementation of semaphores similar to POSIX semaphores using System V semaphores & shared memory

```
$arm-linux-gnueabihf-gcc semlib.c (or make semlib.o)
```

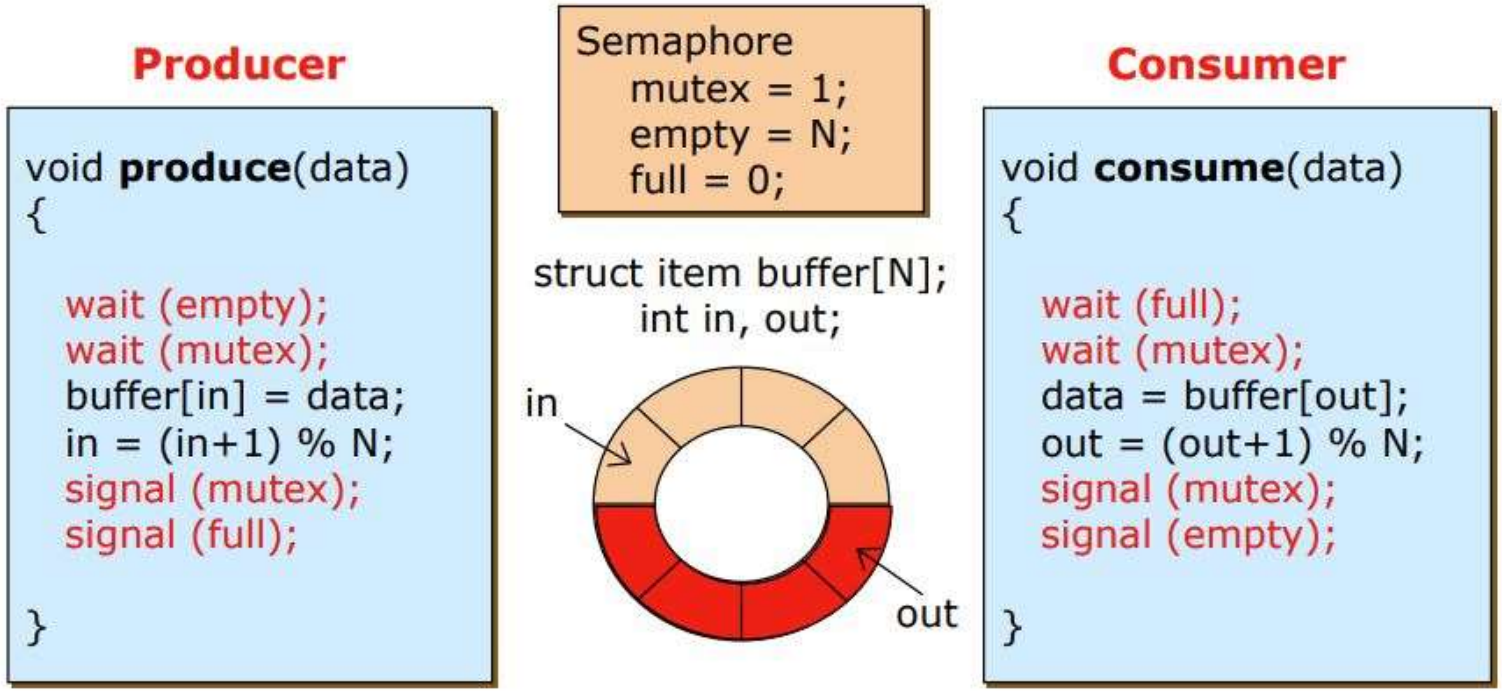
- Producer & Consumer example using `semlib` library

```
$arm-linux-gnueabihf-gcc -o producer_s producer_s.c semlib.c (or make producer_s)
$arm-linux-gnueabihf-gcc -o consumer_s consumer_s.c semlib.c (or make consumer_s)
$./producer_s
$./consumer_s
```

- Note:
  - ✓ If a process creates a system V semaphore, its data structure remains in the kernel even though the process has terminated
  - ✓ You have to remove it through `semctl()` with `IPC_RMID` parameter (or, reboot the system !!!)

Exercise

- Bounded buffer implementation with semaphores



Exercise

- Producer & consumer example using pthreads & POSIX semaphores

```
$arm-linux-gnueabihf-gcc –o prodcons prodcons.c –lposix4 –lpthread
  (or make prodcons)
$./prodcons
```

Mutexes

- Mutexes
  - ✓ Mutual exclusive locks for threads
  - ✓ Serviced by Pthread libraries
  - ✓ Similar to binary semaphore

- Pthread libraries for mutexes

```
#include <pthread.h>
int pthread_mutex_init(pthread_mutex_t *mutex, pthread_mutexattr_t *mattr);
int pthread_mutex_destroy(pthread_mutex_t *mutex);
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
return: 0 if OK, non-zero value on error
```

Condition Variables

- Condition variables
  - ✓ A synchronization device that allows threads to suspend and resume execution until some predicate on shared data is satisfied
  - ✓ Serviced by Pthread libraries
  - ✓ Associated with a mutex, to avoid the race condition

- Pthread libraries for condition variables

```
#include <pthread.h>
int pthread_cond_init(pthread_cond_t *cond, pthread_condattr_t *cattr);
int pthread_cond_destroy(pthread_cond_t *cond);
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
return: 0 if OK, non-zero value on error
```

Exercise

- Producer & Consumer example using mutexes and condition variables

```
$arm-linux-gnueabihf-gcc -o prodcons_m prodcons_m.c -lpthread
 (or make prodcons_m)
$./prodcons_m
```

- Implementation of POSIX semaphores using mutexes and condition variables

```
$arm-linux-gnueabihf-gcc semlib2.c (or make semlib2.o)
```

- Producer & Consumer example using `semlib2` library

```
$arm-linux-gnueabihf-gcc -o prodcons_s prodcons_s.c semlib2.c -lpthread
 (or make prodcons_s)
$./prodcons_s
```

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