Inter-Process Communications (IPCs): Message Queues, Shared Memory, Semaphores & File Locking

May 2017

IPCs (System V)

- Three types of IPCs:
  - Message Queues
  - Shared Memory
  - Semaphores
- Each IPC structure is referred to by a non-negative integer identifier.
  - When an IPC is created, the program responsible for this creation provides a key of type `key_t`.
  - The Operating System converts this key into an IPC identifier.

Keys in the IPC Client-Server Paradigm

$\Rightarrow$ Keys can be created in three ways:

1. The "server" program creates a new structure by specifying a private key that is `IPC_PRIVATE`.
   - Client has to become explicitly aware of this private key.
   - This is often accomplished with the help of a file generated by the server and then looked-up by the client.
2. Server and client do agree on a key value (often defined and hard-coded in the header).
3. Server and client can agree on a pathname to an existing file in the file system `AND` a project-ID (0..255) and then call `ftok()` to convert these two values into a unique key!

Keys

- Keys help identify resources and offer access to the internal structures of the 3 IPC mechanisms (through systems calls):

```
struct msqid_ds   // for message queues
struct shmid_ds   // for shared segments
struct semid_ds   // for semaphores
```

- Wrongly accessing resources returns -1
- Access rights for IPC mechanisms: read/write stored in `struct ipc_perm`
- Included header files:

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

The `ftok()` system call

- converts a pathname and a project identifier to a (System V) IPC-key
- ```
  key_t ftok(const char *pathname, int proj_id)
  ```
- Calling the `ftok()`:

```
if ( (thekey=ftok("/tmp/ad.tempfile", 23)) == -1)
    perror("Cannot create key from /tmp/ad.tempfile");
```

- The file `/tmp/ad.tempfile` must be accessible by the invoking process.
```

Message Queues

- Message queues allow for the exchange of messages between processes.
- The dispatching process sends a specific type of message and the receiving process may request the specific type of message.
- Each message consists of its *"type"* and the *"payload"*.
- Messages are pointers to stuctures:

```
struct message{
        long type;
        char messagetext[MESSAGESIZE];
    };
```

- Header needed:

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

The system call msgget() - creating/using a queue

```
int msgget(key_t key, int msgflg)
```

- returns (creates) a message queue identifier associated with the value of the key argument.
- A new message queue is created, if key has the value IPC_PRIVATE.
- If key isn't IPC_PRIVATE and no message queue with the given key exists, the msgflg must be specified to IPC_CREAT (to create the queue).
- If a queue with key key exists and both IPC_CREAT and IPC_EXCL are specified in msgflg, then msgget fails with errno set to EEXIST.
  - IPC_EXCL is used with IPC_CREAT to ensure failure if the segment already exists.

Use-cases of `msgflg`

- Upon creation, the least significant bits of `msgflg` define the permissions of the message queue.
- These permission bits have the same format and semantics as the permissions specified for the mode argument of `open()`.
- The various use-cases of `msgflg` are:

	PERMS	PERMS | IPC_CREAT	PERMS | IPC_CREAT | IPC_EXCL
resource exists	use resource	use resource	error
resource does not exist	error	create and use new resource	create and use new resource

msgsnd() - sending a message to a queue

```
int msgsnd(int msqid, const void *msgp,
           size_t msgsz, int msgflg);
```

- send msgp (pointer to a record – see below) to message queue with id msqid.
- ```
  struct msgbuf {
        long mtype;         /* msg type-must be>0 */
        char mtext[MSGSZ]; /* msg data           */
        };
  ```
- sender must have write-access permission on the message queue to send a message.
  ```

`msgrcv()` – fetching a message from a queue

```
ssize_t msgrcv(int msqid, void *msgp,  size_t msgsz,
               long msgtyp, int msgflg);
```

- receive a message `msgp` from a message queue with id `msqid`
- `msgtyp` is an integer value.
- if `msgtyp` is zero, the first message is retrieved regardless its type.
  - This value can be used by the receiving process for designating message selection (see below).
- `mesgsz` specifies the size of the field `mtext`.
- By and large, `msgflg` is set to 0.

The role of `msgtyp` in `msgrcv()`

`msgtyp` specifies the type of message requested as follows:

- if `msgtyp=0` then the first message in the queue is read.
- if `msgtyp` $>$ `0` then the first message in the queue of type `msgtyp` is read.
- if `msgtyp` $<$ `0` then the first message in the queue with the lowest type value is read.
  - Assume a queue has 3 messages with `mtype` 1, 40, 554 and and `msgtyp` is set to -554; If `msgrcv` is called three times, the messages will be received in the following order: 1, 40, 554.

msgctl() - controling a queue

```
int msgctl(int msqid, int cmd, struct msqid_ds *buf)
```

- performs the control operation specified by cmd on the message queue with identifier msqid
- The msqid_ds structure is defined in <sys/msg.h> as:

```
struct msqid_ds {
    struct ipc_perm msg_perm; /* Ownership and permissions */
    time_t  msg_stime;        /* Time of last msgsnd(2) */
    time_t  msg_rtime;        /* Time of last msgrcv(2) */
    time_t  msg_ctime;        /* Time of last change    */
    unsigned long  __msg_cbytes; /* Current number of bytes
                                    in queue (non-standard)*/
    msgqnum_t msg_qnum;       /* Current number of
                                       messages in queue */
    msglen_t msg_qbytes;      /* Maximum number of bytes
                                       allowed in queue */
    pid_t  msg_lspid;         /* PID of last msgsnd(2)  */
    pid_t  msg_lrpid;         /* PID of last msgrcv(2)  */
};
```

Operating with `msgctl()` on message queues

Some values for `cmd`:

- `IPC_STAT`: Copy information from the kernel data structure associated with `msqid` into the `msqid_ds` structure pointed to by `buf`.
- `IPC_SET`: Write the values of some members of the `msqid_ds` structure pointed to by `buf` to the kernel data structure associated with this message queue, updating also its `msg_ctime` element.
- `IPC_RMID`: Immediately remove the message queue, awakening all waiting reader and writer processes (with an `error` return and `errno` set to `EIDRM`).

The server in a message-queue communication

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

#define MSGSIZE 128
#define PERMS 0666
#define SERVER_MTYPE 27L
#define CLIENT_MTYPE 42L

struct message{
    long mtype;
    char mtext[MSGSIZE];
    };

main(){
    int qid;
    struct message sbuf, rbuf;
    key_t the_key;

    the_key = ftok("/home/ad/SysProMaterial/Set008/src/fileA", 226);

    if ( (qid = msgget(the_key, PERMS | IPC_CREAT)) < 0 ){
        perror("megget"); exit(1);
        }
    printf("Creating message queue with identifier %d \n",qid);
```

The server in a message-queue communication

```
    sbuf.mtype = SERVER_MTYPE;
    strcpy(sbuf.mtext,"A message from server");
    if (msgsnd(qid, &sbuf, strlen(sbuf.mtext)+1, 0) < 0){
        perror("msgsnd"); exit(1);
        }
    printf("Sent message: %s\n",sbuf.mtext);

    if ( msgrcv(qid, &rbuf, MSGSIZE, CLIENT_MTYPE, 0) < 0){
        perror("msgrcv"); exit(1);}
    printf("Received message: %s\n",rbuf.mtext);

    if ( msgrcv(qid, &rbuf, MSGSIZE, CLIENT_MTYPE, 0) < 0){
        perror("msgrcv"); exit(1);}
    printf("Received message: %s\n",rbuf.mtext);

    if (msgctl(qid, IPC_RMID, (struct msqid_ds *)0) < 0){
        perror("msgctl"); exit(1);}
    printf("Removed message queue with identifier %d\n",qid);

}
```

Client (1) in the message-queue communication

```
....
#define MSGSIZE 128
#define PERMS 0666
#define SERVER_MTYPE 27L
#define CLIENT_MTYPE 42L

struct message{
    long mtype;
    char mtext[MSGSIZE]; };

main(){
    int qid; struct message sbuf, rbuf; key_t the_key;

        the_key = ftok("/home/ad/SysProMaterial/Set008/src/fileA", 226);
    if ( (qid = msgget(the_key, PERMS)) < 0 ){
        perror("megget"); exit(1); }
    printf("Accessing message queue with identifier %d \n",qid);
    if ( msgrcv(qid, &rbuf, MSGSIZE, SERVER_MTYPE, 0) < 0){
        perror("msgrcv"); exit(1);}
    printf("Received message: %s\n",rbuf.mtext);
    sbuf.mtype = CLIENT_MTYPE;
    strcpy(sbuf.mtext,"A message from client 1");
    if (msgsnd(qid, &sbuf, strlen(sbuf.mtext)+1, 0) < 0){
        perror("msgsnd"); exit(1);
        }
    printf("Sent message: %s\n",sbuf.mtext);
}
```

Client (2) in the message-queue communication

```
......
#define MSGSIZE 128
#define PERMS 0666
#define SERVER_MTYPE 27L
#define CLIENT_MTYPE 42L

struct message{
    long mtype;
    char mtext[MSGSIZE]; };

main(){
    int qid; struct message sbuf, rbuf; key_t the_key;

        the_key = ftok("/home/ad/SysProMaterial/Set008/src/fileA", 226);
    if ( (qid = msgget(the_key, PERMS)) < 0 ){
        perror("megget"); exit(1); }
    printf("Accessing message queue with identifier %d \n",qid);
    sbuf.mtype = CLIENT_MTYPE;
    strcpy(sbuf.mtext,"A message from client 2");
    if (msgsnd(qid, &sbuf, strlen(sbuf.mtext)+1, 0) < 0){
        perror("msgsnd"); exit(1);
        }
    printf("Sent message: %s\n",sbuf.mtext);
}
```

Running the application

The server:

```
ad@haiku:~/src$ ./msg-server
Creating message queue with identifier 0
Sent message: A message from server
```

Client 1:

```
ad@haiku:~/src$ ./msg-client1
Accessing message queue with identifier 0
Received message: A message from server
Sent message: A message from client 1
ad@haiku:~/src$
```

Server status:

```
ad@haiku:~/src$ ./msg-server
Creating message queue with identifier 0
Sent message: A message from server
Received message: A message from client 1
```

Running the application

Client 2:

```
ad@haiku:~/src$ ./msg-client2
Accessing message queue with identifier 0
Sent message: A message from client 2
ad@haiku:~/src$
```

Server:

```
ad@haiku:~/src$ ./msg-server
Creating message queue with identifier 0
Sent message: A message from server
Received message: A message from client 1
Received message: A message from client 2
Removed message queue with identifier 0
ad@haiku:~/src$
```

Developing a Priority Queue

- Implement a Queue in which Jobs have Priorities
- A server gets the items from the queue and and in some way (pick one) “processes” these items.

q.h

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

#define QKEY          (key_t) 108
#define QPERM         0660
#define MAXOBN        50
#define MAXPRIOR      10

struct q_entry{
    long mtype;
    char mtext[MAXOBN+1];
    };
```

init_queue.c

```c
#include <stdio.h>
#include <stdlib.h>
#include "q.h"

int init_queue(void){
    int queue_id;

    if ( (queue_id = msgget(QKEY, IPC_CREAT | QPERM)) == -1 )
        perror("msgget failed");
    return(queue_id);
}
```

myqueue.c

```
#include <stdio.h>
#include <stdlib.h>
#include "q.h"

int myenter(char *objname, int priority){
        int len, s_qid;
        struct q_entry s_entry;

        if ( (len=strlen(objname)) > MAXOBN){
                printf("name too long\n"); exit(1); }
        if ( priority > MAXPRIOR || priority < 0 ){
                printf("invalid priority level"); return(-1); }
        if ( (s_qid = init_queue()) == -1 ) return(-1);
        else    printf("Entering Queue with ID: %d \n",s_qid);

        s_entry.mtype= (long)priority;
        strncpy(s_entry.mtext, objname, MAXOBN);

        if (msgsnd(s_qid, &s_entry, len, 0) == -1 ){
                perror("msgsnd failed"); return(-1);}
        else    {
                printf("Object %s With Priority %ld has been Enqueued
                     Successfully \n",\
                        s_entry.mtext, s_entry.mtype);
                return(0);
                }
}
```

myqueue.c

```
main(int argc, char *argv[]){
        int priority;

        if ( argc!= 3){
                fprintf(stderr,"usage: %s objname priority\n",argv[0]);
                }
        if ((priority = atoi(argv[2])) <=0 || priority > MAXPRIOR){
                printf("invalid priority");
                exit(2);
                }

        if ( myenter(argv[1], priority) < 0 ){
                printf("enter failure");
                exit(3);
                }
        exit(0);
}
```

dequeue.c

```
#include <stdio.h>
#include <stdlib.h>
#include "q.h"

int proc_obj(struct q_entry *msg){
        printf("Retrieved Object with Priority: %ld and Text: %s\n", \
                        msg->mtype, msg->mtext);
        }

int myserve(void){
        int mlen, r_qid;
        struct q_entry r_entry;

        if ( (r_qid=init_queue()) == -1)
                return(-1);
        else    printf("Accessing Queue with ID: %d\n",r_qid);

        for(;;){
                if ( (mlen=msgrcv(r_qid, &r_entry, MAXOBN,
                        (-1 * MAXPRIOR) , MSG_NOERROR) ) == -1 ){
                        perror("mesgrcv failed"); return(-1);
                        }
                else {
                        r_entry.mtext[mlen]='\0';
                        proc_obj(&r_entry);
                        }
                }
}
```

dequeue.c

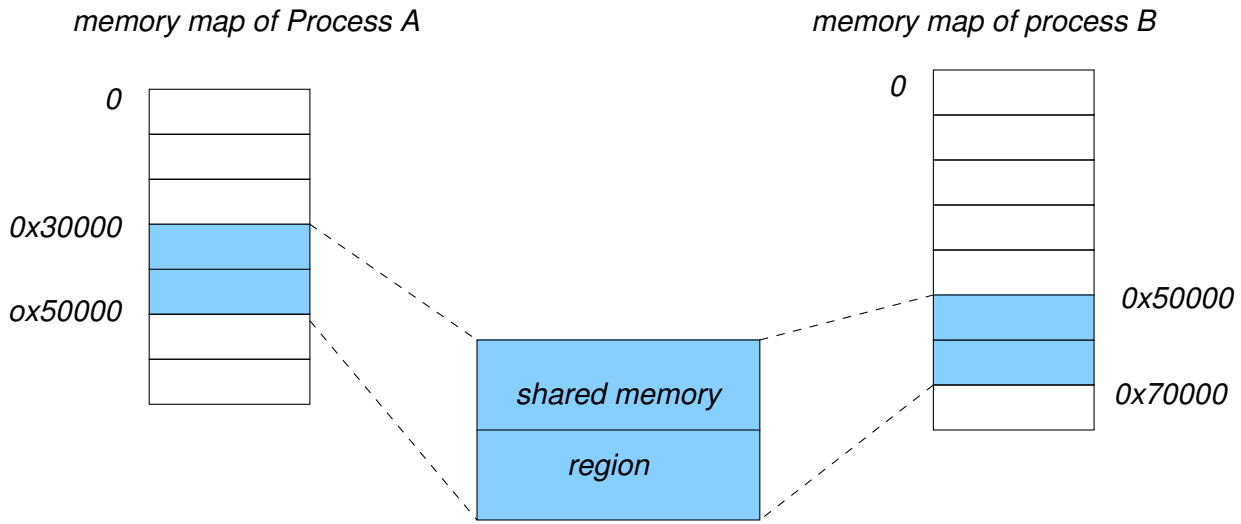
```
main(){
        pid_t pid;

        switch (pid=fork()){
        case 0: // child
                myserve();
                break;
        case -1:
                printf("fork to start the server failed");
                break;
        default:
                printf("server process pid is %d \n", pid);
        }
exit(pid != 1 ? 0 : 1);
}
```

Running the priority queue program(s)

```
ad@haiku:~/PriorityQueue$ ./enqueue object123 2
Entering Queue with ID: 262144
Object object123 With Priority 2 has been Enqueued Successfully
ad@haiku:~/PriorityQueue$ ./enqueue object111 5
Entering Queue with ID: 262144
Object object111 With Priority 5 has been Enqueued Successfully
ad@haiku:~/PriorityQueue$ ./enqueue object133 4
Entering Queue with ID: 262144
Object object133 With Priority 4 has been Enqueued Successfully
ad@haiku:~/PriorityQueue$ ./enqueue object321 9
Entering Queue with ID: 262144
Object object321 With Priority 9 has been Enqueued Successfully
ad@haiku:~/PriorityQueue$ ./enqueue object311 7
Entering Queue with ID: 262144
Object object311 With Priority 7 has been Enqueued Successfully
ad@haiku:~/PriorityQueue$ ./dequeue
server process pid is 4569
Accessing Queue with ID: 262144
Retrieved Object with Priority: 2 and Text: object123
Retrieved Object with Priority: 4 and Text: object133
Retrieved Object with Priority: 5 and Text: object111
Retrieved Object with Priority: 7 and Text: object311
Retrieved Object with Priority: 9 and Text: object321
ad@haiku:~/PriorityQueue$ ./dequeue
server process pid is 4571
Accessing Queue with ID: 262144
ad@haiku:~/PriorityQueue$
```

Shared Memory

- A shared memory region is a portion of physical memory that is shared by multiple processes.



- In this region, structures can be set up by processes and others may read/write on them.
- Synchronization among processes using the segment (if required) is achieved with the help of semaphores.

Creating a shared segment with `shmget()`

```
#include <sys/ipc.h>
#include <sys/shm.h>

int shmget(key_t key, size_t size, int shmflg)
```

- returns the identifier of the shared memory segment associated with the value of the argument `key`.
- the returned size of the segment is equal to `size` rounded up to a multiple of `PAGE_SIZE`.
- `shmflg` helps designate the access rights for the segment (`IPC_CREAT` and `IPC_EXCL` are used in a way similar to that of message queues).
- If `shmflg` specifies *both* `IPC_CREAT` and `IPC_EXCL` and a shared memory segment already exists for `key`, then `shmget()` fails with `errno` set to `EEXIST`.

Attach- and Detach-ing a segment: `shmat()/shmdt()`

```
void *shmat(int shmid, const void *shmaddr, int shmflg)
```

- attaches the shared memory segment identified by `shmid` to the address space of the calling process.
- If `shmaddr` is NULL, the OS chooses a suitable (unused) address at which to attach the segment (frequent choice).
- Otherwise, `shmaddr` must be a page-aligned address at which the attach occurs.

```
int shmdt(const void *shmaddr)
```

- detaches the shared memory segment located at the address specified by `shmaddr` from the address space of the calling process.

The system call `shmctl()`

```
int shmctl(int shmid, int cmd, struct shmid_ds *buf)
```

- performs the control operation specified by `cmd` on the shared memory segment whose identifier is given in `shmid`.
- The `buf` argument is a pointer to a `shmid_ds` structure:

```
struct shmid_ds {
    struct ipc_perm shm_perm;    /* Ownership and permissions */
    size_t          shm_segsz;   /* Size of segment (bytes) */
    time_t          shm_atime;   /* Last attach time */
    time_t          shm_dtime;   /* Last detach time */
    time_t          shm_ctime;   /* Last change time */
    pid_t           shm_cpid;    /* PID of creator */
    pid_t           shm_lpid;    /* PID of last shmat(2)/shmdt(2) */
    shmatt_t        shm_nattch;  /* No. of current attaches */
    ...
};
```

The system call `shmctl()`

Usual values for `cmd` are:

- `IPC_STAT`: copy information from the kernel data structure associated with `shmid` into the `shmid_ds` structure pointed to by `buf`.
- `IPC_SET`: write the value of some member of the `shmid_ds` structure pointed to by `buf` to the kernel data structure associated with this shared memory segment, updating also its `shm_ctime` member.
- `IPC_RMID`: mark the segment to be destroyed. The segment will be destroyed after the last process detaches it (i.e., `shm_nattch` is zero).

Use Cases of Calls

- Only one process creates the segment:

```
int id;
id = shmget(IPC_PRIVATE, 10, 0666);
if ( id == -1 ) perror("Creating");
```

- Every (interested) process attaches the segment:

```
int *mem;
mem = (int *) shmat (id, (void *)0, 0);
if ( (int)mem == -1 ) perror("Attachment");
```

- Every process detaches the segment:

```
int err;
err = shmdt((void *)mem);
if ( err == -1 ) perror("Detachment");
```

- Only one process has to remove the segment:

```
int err;
err = shmctl(id, IPC_RMID, 0);
if ( err == -1 ) perror("Removal");
```

Creating and accessing shared memory (shareMem1.c)

```c
#include <stdio.h>
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

int main(int argc, char **argv){
    int id=0, err=0;
    int *mem;

    id = shmget(IPC_PRIVATE,10,0666);  /* Make shared memory segment */
    if (id == -1) perror ("Creation");
    else printf("Allocated. %d\n",(int)id);

    mem = (int *) shmat(id, (void*)0, 0); /* Attach the segment */
    if (*(int *) mem == -1) perror("Attachment.");
    else printf("Attached. Mem contents %d\n",*mem);

    *mem=1; /* Give it initial value */
    printf("Start other process. >"); getchar();

    printf("mem is now %d\n", *mem); /* Print out new value */

    err = shmctl(id, IPC_RMID, 0); /* Remove segment */
    if (err == -1) perror ("Removal.");
    else printf("Removed. %d\n", (int)(err));
    return 0;
}
```

Creating and accessing shared memory (shareMem2.c)

```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

int main(int argc, char **argv) {
    int id, err;
    int *mem;

    if (argc <= 1) { printf("Need shared memory id. \n"); exit(1); }

    sscanf(argv[1], "%d", &id); /* Get id from command line. */
    printf("Id is %d\n", id);

    mem = (int *) shmat(id, (void*) 0,0); /* Attach the segment */
    if ((int) mem == -1) perror("Attachment.");
    else printf("Attached. Mem contents %d\n",*mem);

    *mem=2; /* Give it a different value */
    printf("Changed mem is now %d\n", *mem);

    err = shmdt((void *) mem); /* Detach segment */
    if (err == -1) perror ("Detachment.");
    else printf("Detachment %d\n", err);
    return 0;
}
```

Running the two programs:

- Starting off with executing "shareMem1":

```
ad@haiku:~/SharedSegments$ ./shareMem1
Allocated. 1769489
Attached. Mem contents 0
Start other process. >
```

- Executing "shareMem2":

```
ad@haiku:~/SharedSegments$ ./shareMem2 1769489
Id is 1769489
Attached. Mem contents 1
Changed mem is now 2
Detachment 0
ad@haiku:~/SharedSegments$
```

- Providing the final input to "shareMem1":

```
Start other process. >s
mem is now 2
Removed. 0
ad@haiku:~/SharedSegments$
```

Semaphores

- Fundamental mechanism that facilitates synchronization and coordinated accessing of resources placed in shared memory.
- A semaphore is an integer whose value is never allowed to fall below zero.
- *Two operations* can be atomically performed on a semaphore:
  - increment the semaphore value by one (`UP` or `V()` ala Dijkstra).
  - decrement a semaphore value by one (`DOWN` or `P()` ala Dijkstra).
    If the value of semaphore is currently zero, then the invoking process will block until the value becomes greater than zero.

System-V Semaphores

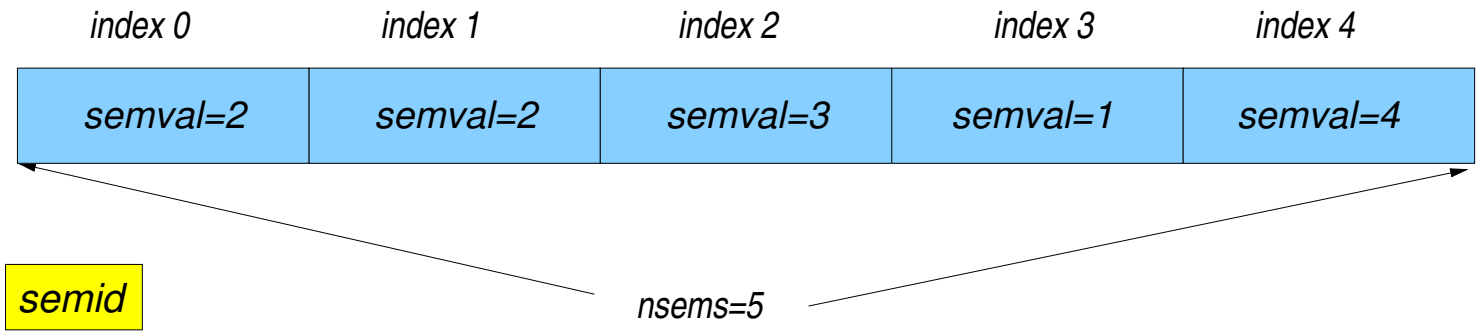
- In general, (System-V) system calls create sets of semaphores:
  - The kernel warrants atomic operations on these sets.
  - Should we have more than one resources to protect, we can "lock" all of them simultaneously.

Creating a set of Semaphores

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

int semget(key_t key, int nsems, int semflg)
```

- returns the semaphore set identifier associated with the argument `key`.
- A new set of `nsems` semaphores is created if `key` has the value `IPC_PRIVATE` **OR** if no existing semaphore set is associated with `key` and `IPC_CREAT` is specified in `semflg`.
- `semflg` helps set the access right for the semaphore set.
- If `semflg` specifies both `IPC_CREAT` and `IPC_EXCL` and a semaphore set already exists for `key`, then `semget()` fails with `errno` set to `EEXIST`.

Structure of a Semaphore Set



Associated with each (single) semaphore in the set are the following values:

- `semval`: the semaphore value, always a positive number.
- `sempid`: *pid* of the process that last "acted" on semaphore.
- `semcnt`: number of processes waiting for the semaphore to reach value greater that its current one.
- `semzcnt`: number of processes waiting for the semaphore to reach value zero.

Operating on a Set of Semaphores

```
int semop(int semid, struct sembuf *sops, unsigned nsops)
```

- performs operations on *selected* semaphores in the set indicated by `semid`.
- each of the `nsops` elements in the array pointed to by `sops` specifies an operation to be performed on a single semaphore on the set.

Operating on a Set of Semaphores

- The elements of the `struct sembuf` have as follows:

```
struct sembuf{
    unsigned short sem_num;   /* semaphore number */
    short          sem_op;    /* semaphore operation */
    short          sem_flg;   /* operation flags */
    };
```

- In the above:
  - `sem_num` identifies the ID of the specific semaphore on the set on which `sem_op` operates.
  - The value of `sem_op` is set to:
    - < 0 for locking
    - > 0 for unlocking
  - `sem_flg` often set to 0.

The semctl() system call

```
int semctl(int semid, int semnum, int cmd,
           [union semun arg])
```

- performs the control operation specified by cmd on the semnum-th semaphore of the set identified by semid.
- The 4th parameter above –if it exists– has the following layout:

```
union semun {
    int               val;    /* Value for SETVAL */
    struct semid_ds  *buf;    /* Buffer for IPC_STAT, IPC_SET */
    unsigned short   *array;  /* Array for GETALL, SETALL */
    struct seminfo   *__buf;  /* Buffer for IPC_INFO (Linux-specific) */
};
```

The semid_ds structure

- The semaphore data structure semid_ds, is as follows:

```
struct semid_ds {
     struct ipc_perm sem_perm;  /* Ownership and permissions */
     time_t          sem_otime; /* Last semop time */
     time_t          sem_ctime; /* Last change time */
     unsigned short  sem_nsems; /* No. of semaphores in set */
     };
```

semctl()

Values for the cmd parameter:

- IPC_STAT: copy information from the kernel data structure associated with semid into the semid_ds structure pointed to by arg.buf.
- IPC_SET: write the value of some member of the semid_ds structure pointed to by arg.buf to the kernel data structure associated with this semaphore set; its sem_ctime member gets updated as well.
- IPC_SETALL: Set semval for all semaphores of the set using arg.array, updating also the sem_ctime member of the semid_ds structure associated with the set.
- IPC_GETALL: Return to semval the current values of all semaphores of the set arg.array.
- IPC_RMID: remove the semaphore set while awakening all processes blocked by the respective semop().

A server program using Semaphores

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
#include <sys/sem.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define SHMKEY (key_t)4321
#define SEMKEY (key_t)9876
#define SHMSIZE 256
#define PERMS 0600

union semnum{
    int val;
    struct semid_ds *buff;
    unsigned short *array; };

main(){
    int shmid, semid; char line[128], *shmem;
    struct sembuf oper[1]={0,1,0};
    union semnum arg;

    if ((shmid = shmget (SHMKEY, SHMSIZE, PERMS | IPC_CREAT)) < 0) {
        perror("shmget"); exit(1); }
    printf("Creating shared memory with ID: %d\n",shmid);
    /* create a semaphore */
    if ((semid = semget(SEMKEY, 1, PERMS| IPC_CREAT)) <0) {
        perror("semget"); exit(1); }
    printf("Creating a semaphore with ID: %d \n",semid);
    arg.val=0;
```

A server program using Semaphores (continued)

```
/* initialize semaphore for locking */
if (semctl(semid, 0, SETVAL, arg) <0) {
    perror("semctl");
    exit(1);
    }
printf("Initializing semaphore to lock\n");

if ( (shmem = shmat(shmid, (char *)0, 0)) == (char *) -1) {
    perror("shmem");
    exit(1);
    }
printf("Attaching shared memory segment \nEnter a string: ");
fgets(line, sizeof(line), stdin);
line[strlen(line)-1]='\0';

/* Write message in shared memory */
strcpy(shmem, line);

printf("Writing to shared memory region: %s\n", line);

/* Make shared memory available for reading */
if ( semop(semid, &oper[0], 1) < 0 ) {
    perror("semop");
    exit(1);
    }
shmdt(shmem);
printf("Releasing shared memory region\n");
}
```

A client program using semaphore

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
#include <sys/sem.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define SHMKEY (key_t)4321
#define SEMKEY (key_t)9876
#define SHMSIZE 256
#define PERMS 0600

main(){
    int shmid, semid;
    char *shmem;
    struct sembuf oper[1]={0,-1,0};

    if ((shmid = shmget (SHMKEY, SHMSIZE, PERMS )) < 0) {
        perror("shmget"); exit(1); }
    printf("Accessing shared memory with ID: %d\n",shmid);

    /* accessing a semaphore */
    if ((semid = semget(SEMKEY, 1, PERMS )) <0) {
        perror("semget"); exit(1); }
    printf("Accessing semaphore with ID: %d \n",semid);
```

A client program using semaphore (continued)

```
if ( (shmem = shmat(shmid, (char *) 0, 0)) == (char *) -1 ) {
    perror("shmat"); exit(1); }
printf("Attaching shared memory segment\n");

printf("Asking for access to shared memory region \n");
if (semop(semid, &oper[0], 1) <0)  {
    perror("semop"); exit(1); }
printf("Reading from shared memory region: %s\n", shmem);

/* detach shared memeory */
shmdt(shmem);

/* destroy shared memory */
if (shmctl(shmid, IPC_RMID, (struct shmid_ds *)0 ) <0) {
    perror("semctl"); exit(1); }
printf("Releasing shared segment with identifier %d\n", shmid);

/* destroy semaphore set */
if (semctl(semid, 0, IPC_RMID, 0) <0 ) {
    perror("semctl"); exit(1); }
printf("Releasing semaphore with identifier %d\n", semid);
}
```

Running the server and the client

The server:

```
ad@ad-desktop:~/SysProMaterial/Set008/src/V-Sems$ ./sem-server
Creating shared memory with ID: 22511641
Creating a semaphore with ID: 327688
Initializing semaphore to lock
Attaching shared memory segment
Enter a string:
```

The client:

```
ad@ad-desktop:~/SysProMaterial/Set008/src/V-Sems$ ./sem-client
Accessing shared memory with ID: 22511641
Accessing semaphore with ID: 327688
Attaching shared memory segment
Asking for access to shared memory region
```

Running the programs

- Server:

```
ad@ad-desktop:~/src/V-Sems$ ./sem-server
Creating shared memory with ID: 22511641
Creating a semaphore with ID: 327688
Initializing semaphore to lock
Attaching shared memory segment
Enter a string: THIS IS A TEST ONLY A TEST
Writing to shared memory region: THIS IS A TEST ONLY A TEST
Releasing shared memory region
ad@ad-desktop:~/src/V-Sems$
```

- Client:

```
ad@ad-desktop:~/src/V-Sems$ ./sem-client
Accessing shared memory with ID: 22511641
Accessing semaphore with ID: 327688
Attaching shared memory segment
Asking for access to shared memory region
Reading from shared memory region: THIS IS A TEST ONLY A TEST
Releasing shared segment with identifier 22511641
Releasing semaphore with identifier 327688
ad@ad-desktop:~/src/V-Sems$
```

Access to Critical Section

```c
#include <stdio.h> /* Example code using semaphores and shared memory */
#include <stdlib.h>
#include <sys/types.h>
#include <sys/shm.h>
#include <sys/sem.h>
#include <sys/ipc.h>

/* Union semun */
union semun {
   int val;                    /* value for SETVAL */
   struct semid_ds *buf;       /* buffer for IPC_STAT, IPC_SET */
   unsigned short *array;      /* array for GETALL, SETALL */
};

void free_resources(int shm_id, int sem_id) {
   /* Delete the shared memory segment */
   shmctl(shm_id,IPC_RMID,NULL);
   /* Delete the semaphore */
   semctl(sem_id,0,IPC_RMID,0);
}

int sem_P(int sem_id) {      /* Semaphore P - down operation, using semop */
   struct sembuf sem_d;

   sem_d.sem_num = 0;
   sem_d.sem_op = -1;
   sem_d.sem_flg = 0;
   if (semop(sem_id,&sem_d,1) == -1) {
       perror("# Semaphore down (P) operation "); return -1; }
   return 0;
}
```

Access to Critical Section

```
/* Semaphore V - up operation, using semop */
int sem_V(int sem_id) {
   struct sembuf sem_d;

   sem_d.sem_num = 0;
   sem_d.sem_op = 1;
   sem_d.sem_flg = 0;
   if (semop(sem_id,&sem_d,1) == -1) {
       perror("# Semaphore up (V) operation "); return -1; }
   return 0;
}

/* Semaphore Init - set a semaphore's value to val */
int sem_Init(int sem_id, int val) {
   union semun arg;

   arg.val = val;
   if (semctl(sem_id,0,SETVAL,arg) == -1) {
       perror("# Semaphore setting value "); return -1; }
   return 0;
}
```

Access to Critical Section

```
int main () {
   int shm_id; int sem_id; int t = 0; int *sh; int pid;

   /* Create a new shared memory segment */
   shm_id = shmget(IPC_PRIVATE,sizeof(int),IPC_CREAT | 0660);
   if (shm_id == -1) {
       perror("Shared memory creation"); exit(EXIT_FAILURE); }

   /* Create a new semaphore id */
   sem_id = semget(IPC_PRIVATE,1,IPC_CREAT | 0660);
   if (sem_id == -1) {
       perror("Semaphore creation ");
       shmctl(shm_id,IPC_RMID,(struct shmid_ds *)NULL);
       exit(EXIT_FAILURE);
   }

   /* Set the value of the semaphore to 1 */
   if (sem_Init(sem_id, 1) == -1) {
       free_resources(shm_id,sem_id);
       exit(EXIT_FAILURE);
   }

   sh = (int *)shmat(shm_id,NULL,0);  /* Attach the shared memory segment */
   if (sh == NULL) {
       perror("Shared memory attach ");
       free_resources(shm_id,sem_id);
       exit(EXIT_FAILURE);
   }
   /* Setting shared memory to 0 */
   *sh = 0;
```

Access to Critical Section

```
/* New process */
if ((pid = fork()) == -1) {
     perror("fork");
     free_resources(shm_id,sem_id);
     exit(EXIT_FAILURE);
}

if (pid == 0) {
    /* Child process */
    printf("# I am the child process with process id: %d\n", getpid());
} else {
    /* Parent process */
    printf("# I am the parent process with process id: %d\n", getpid());
    sleep(2);
}

printf("(%d): trying to access the critical section\n", getpid());
sem_P(sem_id);
printf("(%d): accessed the critical section\n", getpid());

(*sh)++;
printf("(%d): value of shared memory is now: %d\n", getpid(), *sh);

printf("(%d): getting out of the critical section\n", getpid());
sem_V(sem_id);

printf("(%d): got out of the critical section\n", getpid());
```

Access to Critical Section

```
    /* Child process */
    if (!pid)
      exit(EXIT_SUCCESS);

    /* Wait for child process */
    wait(NULL);

    /* Clear recourses */
    free_resources(shm_id,sem_id);
    return 0;
}
```

→ outcome of execution:

```
ad@ad-desktop:~/src/V-Sems$ ./access-criticalsection
# I am the parent process with process id: 9256
# I am the child process with process id: 9257
(9257): trying to access the critical section
(9257): accessed the critical section
(9257): value of shared memory is now: 1
(9257): getting out of the critical section
(9257): got out of the critical section
(9256): trying to access the critical section
(9256): accessed the critical section
(9256): value of shared memory is now: 2
(9256): getting out of the critical section
(9256): got out of the critical section
ad@ad-desktop:~/src/V-Sems$
```

POSIX Semaphores

```
#include <semaphore.h>
```

- `sem_init`, `sem_destroy`, `sem_post`, `sem_wait`, `sem_trywait`

```
int sem_init(sem_t *sem, int pshared, unsigned int value);
```

- The above initializes a semaphore.
- Compile either with `-lrt` or `-lpthread`
- `pshared` indicates whether this semaphore is to be shared between the threads of a process, or between processes:
  - zero: semaphore is shared between the **threads of a process**; should be located at an address visible to **all threads**.
  - non-zero: semaphore is shared **among processes**.

POSIX Semaphore Operations

- `sem_wait()`, `sem_trywait()`
  - ```
    int sem_wait(sem_t *sem);
    ```
  - ```
    int sem_trywait(sem_t *sem);
    ```
  - Perform $\mathrm{P}(\mathrm{s})$ operation.
  - `sem_wait` blocks; `sem_trywait` will fail rather than block.
- `sem_post()`
  - ```
    int sem_post(sem_t *sem)
    ```
  - Performs $\mathrm{V}(\mathrm{s})$ operation.
- `sem_destroy()`
  - ```
    int sem_destroy(sem_t *sem);
    ```
  - Destroys a semaphore.

Creating and using a POSIX Semaphore

```c
#include <stdio.h>
#include <stdlib.h>
#include <semaphore.h>
#include <sys/types.h>
#include <sys/ipc.h>

extern int errno;

int main(int argc, char **argv)
{
    sem_t sp; int retval;

    /* Initialize the semaphore. */
    retval = sem_init(&sp,1,2);
    if (retval != 0) {
        perror("Couldn't initialize."); exit(3); }

    retval = sem_trywait(&sp);
    printf("Did trywait. Returned %d >\n",retval); getchar();

    retval = sem_trywait(&sp);
    printf("Did trywait. Returned %d >\n",retval); getchar();

    retval = sem_trywait(&sp);
    printf("Did trywait. Returned %d >\n",retval); getchar();

    sem_destroy(&sp);
    return 0;
}
```

Executing the Program

```
ad@ad-desktop:~/src/PosixSems$ ./semtest
Did trywait. Returned 0 >

Did trywait. Returned 0 >

Did trywait. Returned -1 >

ad@ad-desktop:~/src/PosixSems$
```

Initialize and Open a **named** *Semaphore*

```
sem_t *sem_open(const char *name, int oflag);
sem_t *sem_open(const char *name, int oflag,
                mode_t mode, unsigned int value);
```

- creates a new POSIX semaphore OR opens an existing semaphore whose name is `name`.
- `oflag` specifies flags that control the operation of the call
  - `O_CREAT` creates the semaphore;
  - provided that both `O_CREAT` and `O_EXCL` are specified, an `error` is returned if a semaphore with `name` already exists.
- if `oflag` is `O_CREAT` then 2 more arguments have to be used:
  - `mode` specifies the permissions to be placed on the new semaphore.
  - `value` specifies the initial value for the new semaphore.

More on Named POSIX Semaphores

- A named semaphore is identified by a (persistent) name that has the form `/this_is_a_sample_named_semaphore`.
  - consists of an initial slash followed by a (large) number of character (but no slashes).
- If you want to "see" (list) all named sempahores in your (Linux) system look at directory `/dev/shm`

More on Named POSIX Semaphores

```
int sem_close(sem_t *sem)
```

- closes the named semaphore referred to by *sem* freeing the system resources the invoking process has used.

```
int sem_unlink(const char *name)
```

- removes the named semaphore in question.

```
int sem_getvalue(sem_t *sem, int *sval)
```

- obtains the current value of semaphore..
- the cheater API-call!

Named POSIX Semaphore

```
#include        <stdio.h>
...
#include        <sys/stat.h>
#include        <semaphore.h>

int main(int argc, char *argv[]){
const char *semname;
int op=0; int val=0;

if (argc==3)  {
        semname=argv[1]; op=atoi(argv[2]);
        }
else    {
        printf("usage: nameSem nameOfSem Operation\n"); exit(1);
        }

sem_t *sem=sem_open(semname, O_CREAT|O_EXCL, S_IRUSR|S_IWUSR, 0);

if (sem!= SEM_FAILED)
        printf("created new semaphore!\n");
else if (errno== EEXIST ) {
        printf("semaphore appears to exist already!\n");
        sem = sem_open(semname, 0);
        }
else ;

assert(sem != SEM_FAILED);
sem_getvalue(sem, &val);
printf("semaphore's before action value is %d\n",val);
```

Named Posix Semaphore

```
if ( op == 1 ) {
        printf("incrementing semaphore\n");
        sem_post(sem);
        }
else if ( op == -1 ) {
        printf("decrementing semaphore\n");
        sem_wait(sem);
        }
else if ( op == 2 ){
        printf("clearing up named semaphore\n");
        sem_close(sem);  // close the sem
        sem_unlink(semname); // remove it from system
        exit(1);
        }
else    printf("not defined operation! \n");

sem_getvalue(sem, &val);
printf("semaphore's current value is %d\n",val);
sem_close(sem);
return(0);
}
```

Execution Outcome

```
ad@serifos:~/PosixSems$ ls /dev/shm/
pulse-shm-1024070233  pulse-shm-1294442337  pulse-shm-2927836935
pulse-shm-1274848112  pulse-shm-2305588894  pulse-shm-3888866544
ad@serifos:~/PosixSems$ ./namedSem /delis 1
created new semaphore!
semaphore's before action value is 0
incrementing semaphore
semaphore's current value is 1
ad@serifos:~/PosixSems$ ls /dev/shm/
pulse-shm-1024070233  pulse-shm-1294442337  pulse-shm-2927836935  sem.delis
pulse-shm-1274848112  pulse-shm-2305588894  pulse-shm-3888866544
ad@serifos:~/PosixSems$ ./namedSem /delis -1
semaphore appears to exist already!
semaphore's before action value is 1
decrementing semaphore
semaphore's current value is 0
ad@serifos:~/PosixSems$ ./namedSem /delis 2
semaphore appears to exist already!
semaphore's before action value is 0
clearing up named semaphore
ad@serifos:~/PosixSems$ ls /dev/shm/
pulse-shm-1024070233  pulse-shm-1294442337  pulse-shm-2927836935
pulse-shm-1274848112  pulse-shm-2305588894  pulse-shm-3888866544
ad@serifos:~/PosixSems$ ./namedSem /delis 1
created new semaphore!
semaphore's before action value is 0
incrementing semaphore
semaphore's current value is 1
```

Execution Outcome

```
ad@serifos:~/PosixSems$ ./namedSem /delis 1
semaphore appears to exist already!
semaphore's before action value is 1
incrementing semaphore
semaphore's current value is 2
ad@serifos:~/PosixSems$ ls /dev/shm/
pulse-shm-1024070233  pulse-shm-1294442337  pulse-shm-2927836935  sem.delis
pulse-shm-1274848112  pulse-shm-2305588894  pulse-shm-3888866544
ad@serifos:~/PosixSems$ ./namedSem /delis -1
semaphore appears to exist already!
semaphore's before action value is 2
decrementing semaphore
semaphore's current value is 1
ad@serifos:~/PosixSems$ ./namedSem /delis -1
semaphore appears to exist already!
semaphore's before action value is 1
decrementing semaphore
semaphore's current value is 0
ad@serifos:~/PosixSems$ ./namedSem /delis 2
semaphore appears to exist already!
semaphore's before action value is 0
clearing up named semaphore
ad@serifos:~/PosixSems$ ls /dev/shm/
pulse-shm-1024070233  pulse-shm-1294442337  pulse-shm-2927836935
pulse-shm-1274848112  pulse-shm-2305588894  pulse-shm-3888866544
ad@serifos:~/PosixSems$
```

Locking a file

- Imposing read/write locks on files (or sections of files) is essential at times.

- ```
  #include <fnctl.h>

  int fnctl(int filedes, int cmd, struct flock *ldata)
  ```

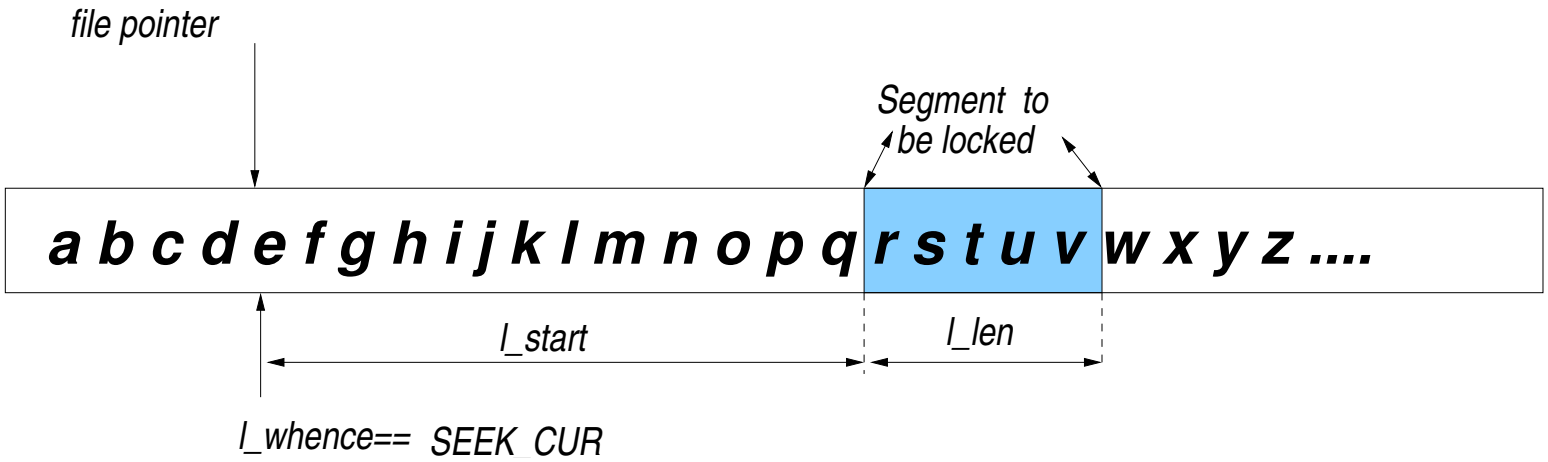
- File `filedes` must be opened with `O_RDONLY` or `O_WRONLY`.
- The `cmd` can be one of the three ("advisory locking"):
  - `F_GETLK`: get lock from data returned from `ldata`
  - `F_SETLK`: apply lock to a file; *return immediately* if this is not feasible.
  - `F_SETLKW`: apply lock to a file. However *wait*, if lock is blocked by a previous lock owned by another process.
  ```

The flock structure

- The `flock` structure is defined in `<fnctl.h>` and includes:

```
struct flock {
    ...
    short l_type;    /* Type of lock: F_RDLCK, F_WRLCK,
                        F_UNLCK                          */
    short l_whence;  /* How to interpret l_start: SEEK_SET,
                        SEEK_CUR, SEEK_END               */
    off_t l_start;   /* Starting offset for lock         */
    off_t l_len;     /* Number of bytes to lock          */
    pid_t l_pid;     /* PID of process blocking
                        our lock (F_GETLK only)          */
    ...
};
```

Locking a file



- `l_whence`: can be `SEEK_SET`, `SEEK_CUR` or `SEEK_END`.
  `l_start`: start position of the segment.
  `l_len`: segment in bytes.
- The `l_type` (lock type) can be:
  - `F_RDLCK`: lock to be applied is *read*
  - `F_WRLCK`: lock to be applied is *write*
  - `F_UNLCK`: lock on specified segment to be removed.

Locking a file

```
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>

main( ){
    int fd;
    struct flock my_lock;

    my_lock.l_type = F_WRLCK;
    my_lock.l_whence =  SEEK_SET;
    my_lock.l_start = 0 ;
    my_lock.l_len= 10;

    fd=open("locktest", O_RDWR);

    // lock first 10 bytes
    if ( fcntl(fd, F_SETLKW, &my_lock) == -1 ){
        perror("parent: locking");
            exit(1);
            }

    printf("parent: locked record \n");
```

Locking a file

```
    switch(fork()){
        case -1:
            perror("fork"); exit(1);
        case 0:
            printf("child: trying to lock file \n");
            my_lock.l_len = 5 ;
            if ( (fcntl(fd, F_SETLKW, &my_lock)) == -1 ){
                perror("child: problem in locking");
                exit(1);
                }
            printf("child: locked \n"); sleep(1);
            printf("child: exiting \n");
            fflush(stdout); fflush(stderr); exit(1);
        default:
            printf("parent: just about unlocking now \n");
            sleep(5);
            my_lock.l_type = F_UNLCK;
            printf("parent: unlocking -now- \n");
            if ( fcntl(fd, F_SETLK, &my_lock) == -1 ){
                perror("parent: problem in unlocking! \n");
                exit(1); }
            printf("parent: has unlocked and is now exiting \n");
            fflush(stdout); fflush(stderr); wait(NULL);
    }
    sleep(2);
}
```

Execution Outcome

```
ad@ad-desktop:~/Filelocking$ ./lockit
parent: locked record
child: trying to lock file
parent: just about unlocking now
parent: unlocking -now-
parent: has unlocked and is now exiting
child: locked
child: exiting
ad@ad-desktop:~/Filelocking$
```

Possible Deadlock

```
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>

main( ){
    int fd;
    struct flock first_lock;
    struct flock second_lock;

    first_lock.l_type = F_WRLCK;
    first_lock.l_whence =  SEEK_SET;
    first_lock.l_start = 0 ;
    first_lock.l_len= 10;

    second_lock.l_type = F_WRLCK;
    second_lock.l_whence =  SEEK_SET;
    second_lock.l_start = 10;
    second_lock.l_len= 5;


    fd=open("locktest", O_RDWR);

    if ( fcntl(fd, F_SETLKW, &first_lock) == -1 )
        perror("-A:");
    printf("A: lock obtained by processs %d \n",getpid());

    switch(fork()) {
        case -1:
            perror("error on fork");
            exit(1);
```

Possible Deadlock

```
        case 0: /* child */
            if ( fcntl(fd, F_SETLKW, &second_lock) == -1 )
                perror("-B:");
            printf("B: lock obtained by process %d\n",getpid());

            if ( fcntl(fd, F_SETLKW, &first_lock) == -1 ){
                perror("-C:");
                printf("Process %d terminating\n",getpid());
                     exit(1);
                }
            else printf("C: lock obtained by process %d\n",getpid());
            printf("Process %d successfully acquired BOTH locks \n",getpid());
            exit(0);
        default: /* parent */
            printf("Parent process %d sleeping \n",getpid());
            sleep(10);
            if ( fcntl(fd, F_SETLK, &second_lock) == -1 ){
                perror("--D:");
                printf("Process %d about to terminate\n",getpid());
                }
            else printf("D: lock obtained by process %d\n",getpid());
            sleep(1);
            printf("Process %d on its way out of here \n",getpid());
    }
}
```

Execution Outcome

```
ad@ad-desktop:~/Filelocking$ ./deadlock
A: lock obtained by processs 10822
Parent process 10822 sleeping
B: lock obtained by process 10823
--D:: Resource temporarily unavailable
Process 10822 about to terminate
Process 10822 on its way out of here
C: lock obtained by process 10823
Process 10823 successfully acquired BOTH locks
ad@ad-desktop:~/Filelocking$
```