Programmation Systèmes
Cours 9 — System V IPC

Stefano Zacchiroli
zack@pps.univ-paris-diderot.fr

Laboratoire PPS, Université Paris Diderot

2012–2013

Outline

1. Introduction to System V IPC
2. System V Message Queues
   - Client/server message queues
3. System V Semaphores
4. System V Shared Memory
   - Data structures in shared memory

Outline

1. Introduction to System V IPC

2. System V Message Queues
   - Client/server message queues

3. System V Semaphores

4. System V Shared Memory
   - Data structures in shared memory

System V IPC

The expression "System V IPC" (or "SysV IPC", for short) refers to 3 distinct IPC mechanisms:

1. SysV message queues — used to pass messages between processes
   - boundary management, i.e. message granularity
   - messages are typed with integer values, allowing to cherry pick messages of a specific type

System V IPC

The expression "System V IPC" (or "SysV IPC", for short) refers to 3 distinct IPC mechanisms:

1. SysV message queues — used to pass messages between processes
   - boundary management, i.e. message granularity
   - messages are typed with integer values, allowing to cherry pick messages of a specific type
2. SysV semaphores — used for process synchronization
   - kernel-maintained integers that can be atomically tested & decremented (or tested & incremented)
   - "taking" a unit of a semaphore value indicates that the taker is working on a shared resource

System V IPC

The expression "System V IPC" (or "SysV IPC", for short) refers to 3 distinct IPC mechanisms:

1. SysV message queues — used to pass messages between processes
   - boundary management, i.e. message granularity
   - messages are typed with integer values, allowing to cherry pick messages of a specific type
2. SysV semaphores — used for process synchronization
   - kernel-maintained integers that can be atomically tested & decremented (or tested & incremented)
   - "taking" a unit of a semaphore value indicates that the taker is working on a shared resource
3. SysV shared memory – used to share memory regions
   - similar to shared `mmap` mappings, but with kernel persistence

Why together?

System V IPCs are quite different in function.
Why discuss them together?

- history

late 70s they first appear together in *Columbus UNIX*, a Bell UNIX for database and efficient transaction processing

1983 they land together in *System V* that made them popular in mainstream UNIX-es, hence the name

2001 SUSv3 is published and require implementation of all of them for XSI conformance, hence they are also called XSI IPC

- uniformity
  - System V IPC mechanisms share many API traits (persistence, namespace, protocol, etc.)

Overview of System V IPC APIs

System V IPC mechanisms at a glance:

aspect	msg queues	semaphores	shared memory
header	`<sys/msg.h>`	`<sys/sem.h>`	`<sys/shm.h>`
data type	msqid_ds	semid_ds	shmid_ds
get object	`msgget`	`semget`	`shmget` / `shmat`
close object	—	—	`shmdt`
manipulation	`msgctl`	`semctl`	`shmctl`
communicate	`msgsnd` / `msgrcv`	`semop`	memory access

Note the uniformity in naming and operations, to the extent of what's possible for different communication primitives.

System V IPC concepts

object instance of the IPC mechanism that can be used for communication

- e.g.:
  - a specific message queue
  - a (set of) semaphores
  - a shared memory region
- each object defines a communication context

identifier unique identifier for an IPC object

key name used by processes to *rendez-vous* on a common object, to ensure they communicate in the same context

System V IPC protocol

The usage of all System V IPC mechanisms goes through a common "protocol":

1. obtain a key
2. get an object
3. store its identifier
4. communicate through the object

Steps (1) and (2) are optional: object identifiers are stable integers that can be stored and passed around as processes see fit.

System V IPC protocol

The usage of all System V IPC mechanisms goes through a common "protocol":

1. obtain a key
   - *mechanism-independent*
2. get an object
   - passing the key to a *mechanism-specific* syscall
3. store its identifier
   - *mechanism-independent*
4. communicate through the object
   - passing the identifier to *mechanism-specific* syscalls

Steps (1) and (2) are optional: object identifiers are stable integers that can be stored and passed around as processes see fit.

System V IPC vs file-based communication

At a macro level, using System V IPC is similar to communicate via shared files:

file	⟷	**System V IPC**
file name	⟷	key
file	⟷	object
FD	⟷	identifier

Notable differences between object identifiers and FDs:

- IPC identifiers are kernel-persistent; FDs are process-persistent
- IPC identifiers are globally visible; FDs are restricted to related processes

Getting IPC object

Each mechanism provide a get syscall to get an IPC object

- `msgget`, `semget`, `shmget`

Similarly to open for files, get syscalls are used to either:

1. create a new IPC object and return its identifier; or
2. return the identifier of a preexisting IPC object.

Either way, get syscalls receive as arguments:[1]

- the key for the object we want to get
- a set of flags that always support:

IPC_CREAT	request object creation, if needed
IPC_EXCL	request object creation, fail if already exists
S_IRUSR, S_IWUSR, ...	permission mask

the analogy with open continues...

[1] additional, mechanism-specific args and flags are used by specific syscalls

Getting IPC object — example

```
int id;

/* ... */

/* get message queue for key */
if ((id = msgget(key, IPC_CREAT | S_IRUSR | S_IWUSR)) < 0)
    err_sys("msgget error");
```

Notes:

- the message queue will be created if it doesn’t exist, otherwise the existing one corresponding to *key* will be returned
- if created, the message queue will be readable and writable only by processes belonging to the owner of the current process

System V object persistence

System V IPC objects have kernel persistence: they remain available, no matter the number of “users” they have, until kernel shutdown or explicit deletion.

Advantages

- processes can access the object, change its state, and then exit without having to wait; other processes can come up later and check the (modified) state
  - i.e. System V IPC objects are stateful and connectionless

Disadvantages

- IPC objects consume system resources and cannot be automatically garbage collected
  - hence the need of enforcing limits on their quantity
- it’s hard to determine when it is safe to delete an object

System V object deletion

Each System V IPC offers a control syscall for generic object manipulation

- msgctl, semctl, shmctl

IPC control syscalls are typical dispatcher syscalls that expect an object identifier, a command, and extra command-specific arguments.

Among other things, IPC control syscalls are used to delete IPC objects:

- passing the IPC_RMID command
- and no extra arguments (i.e. a trailing NULL)

Example

```
/* delete shared memory region */
if (shmctl(id, IPC_RMID, NULL) < 0)
        err_sys("shmctl error");
```

Shell manipulation of IPC objects

Shell utilities are available to manipulate System V IPC objects:

- **ipcs** lists available System V IPC objects
  - *which* objects are shown (i.e. all we can read, all we are owner of, etc.) is implementation dependent
  - provide extra info: key, id, owner, permissions, etc.
  - `ipcs -l` show system limits on IPC object counts
- **ipcrm** allows to delete IPC objects (we own)
- **ipcmk** (non portable) allows to create IPC objects

On Linux, `/proc/sysvipc/` provides a view on *all* existing IPC objects, in a format easier to parse than `ipcs`.

Shell manipulation of IPC objects

Shell utilities are available to manipulate System V IPC objects:

ipcs lists available System V IPC objects

- *which* objects are shown (i.e. all we can read, all we are owner of, etc.) is implementation dependent
- provide extra info: key, id, owner, permissions, etc.
- `ipcs -l` show system limits on IPC object counts

ipcrm allows to delete IPC objects (we own)

ipcmk (non portable) allows to create IPC objects

On Linux, `/proc/sysvipc/` provides a view on *all* existing IPC objects, in a format easier to parse than `ipcs`.

Demo

System V IPC keys

System V IPC keys are represented as key_t integer values. They get translated to *unique* object identifiers by get syscalls.

The kernel maintains a key↔identifier association and guarantees that processes getting IPC objects with the same key:

- will get the same identifier
- will not clash with identifiers returned for other keys

But we have just *shifted* the problem!
A related problem is: how can processes choose a common key, so that they don't end up obtaining the identifier of an IPC object used by other applications?

Assigning System V IPC keys

There are three main strategies to assign IPC keys to applications:

1. choose an arbitrary key value once and for all and distribute it via a common header file

Assigning System V IPC keys

There are three main strategies to assign IPC keys to applications:

1. choose an arbitrary key value once and for all and distribute it via a common header file
2. pass the special constant IPC_PRIVATE as key to get syscalls, which always result in the creation of a fresh IPC object
   - e.g. id = msgget(IPC_PRIVATE, S_IRUSR | S_IWUSR);
   - the creating process will then need to transmit the object identifier to collaborating processes by other means

ftok

3. use the ftok syscall to generate a unique key from the name of an existing file and an arbitrary integer
   - i.e. delegate uniqueness guarantees to the filesystem namespace

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

key_t ftok(char *pathname, int proj);
```

Returns: *key value if OK, -1 on error*

- pathname points to a file that will be subject to stat
- proj allows to have different contexts for the same file

Behind the scenes, the 8 least significant bits of proj and of the file i-node will be used to build a unique key.

ftok — example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/ipc.h>
#include "helpers.h"

int main(int argc, char **argv) {
        key_t key;

        if (argc != 3)
                err_quit("Usage: ftok PATH PROJNO");
        if ((key = ftok(argv[1], atoi(argv[2]))) < 0)
                err_sys("ftok error");
        printf("key=%d\n", key);

        exit(EXIT_SUCCESS);
} /* ftok.c */
```

ftok — example

Demo

Notes:

- ftok is a function in the mathematical sense: equal values map to equal results
  - the function is not 100% granted to be injective though, as only the least significant bits are considered
- the key depends on the i-node, i.e. we can't cheat with links
- directory traversal permissions can be used to enforce private contexts via keys that can't be obtained by 3rd party programs that lack the appropriate permissions

POSIX IPC

POSIX.1b introduced 3 IPC mechanisms equivalent to System V IPC: *POSIX* message queues, semaphores, and shared memory.

pros

- simpler API than System V IPC
- consistent naming and usage of IPC objects
  - `/foo/bar/baz` instead of `ftok` paraphernalia
  - open-, `close`-, `unlink`-like syscalls
- reference counting for IPC objects
  - ease garbage collection

cons

- less portability:
  - POSIX IPC are optional SUSv3 features
    - *all* implemented in Linux since 2004 "only"
  - non portable object creation (e.g. would `/object` work?)
  - no portable cmdline tools to list/remove IPC objects

Outline

1. Introduction to System V IPC

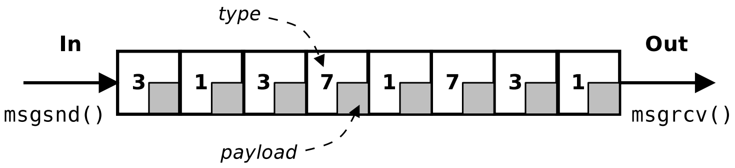
2. System V Message Queues
   - Client/server message queues

3. System V Semaphores

4. System V Shared Memory
   - Data structures in shared memory

System V message queues

System V message queues are IPC objects used for data transfer among unrelated processes.



- communication granularity are individual messages
  - no need to handle message boundaries explicitly as it happened with byte stream
- communication discipline is first-in, first-out ...
- ...but messages are typed with integer values and can be extracted using type predicates
  - i.e. a queue can be seen as multiple independent queues, one per message type, as well as a priority queue
- each message carries a payload of arbitrary data

Message queues limits & blocking behavior

Message queues are limited: in their total number, in message size, and in the number of messages.

```
$ ipcs -l -q
------ Messages Limits --------
max queues system wide = 7786
max size of message (bytes) = 8192
default max size of queue (bytes) = 16384
$
```

By default:

- sending a message is *not blocking* unless the queue is full, otherwise it's blocking
- receiving a message is *blocking* unless a message for the receiver is already available

Overview of System V Message Queue API

header file	<sys/msg.h>	
get queue	msgget	
send message	msgsnd	
receive message	msgrcv	
data structure	msqid_ds	note the “q”
control	msgctl	

msgget

An existing message queue can be opened or a new one created using the message queue get syscall msgget:

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

int msgget(key_t key, int flags);
```

Returns: *message queue ID if OK, -1 on error*

- flags supports IPC_CREAT, IPC_EXCL, and permissions as usual
- the return message queue ID should be stored and used for subsequent usage of the message queue

Reminder: as with all other System V IPC objects, get is not mandatory; message queue IDs are stable and can be passed around by other means.

Messages

A message is a structure conforming to the following structure:

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

- the payload size is arbitrary: all message exchanges will specify a (maximum) size
  - generally, applications decide on a specific message structure and all involved programs stick to it
- as a consequence, extra trailing payload fields can be added
- also, `mtext` can have size 0
  - e.g. payload-less messages where all conveyed information is the message type

msgsnd

Once you have a message msgp, you can send it through a given message queue msqid using msgsnd:

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

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

Returns: *0 if OK, -1 on error*

- msgsz is the *size of the payload* (i.e. what follows mtype)
  - it will depend on your specific *instantiation* of the msg. struct
- msgflg supports a single flag:

IPC_NOWAIT	non-blocking send

  if given, IPC_NOWAIT will have msgsnd fail with EAGAIN if the target queue is full, instead of blocking

msgrcv

The dual of msgsnd is msgrcv, that is used to receive a message from the queue msqid and copy it to msgp:

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

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

Returns: *0 if OK, -1 on error*

- maxmsgsz is the maximum payload size
- msgtyp is the type predicate that identifies the message we want to receive

$\texttt{msgtyp} == 0$	first message in the queue
$\texttt{msgtyp} > 0$	first message $\texttt{mtype} == \texttt{msgtyp}$
$\texttt{msgtyp} < 0$	first message with the lowest $\texttt{mtype} < abs(\texttt{msgtyp})$

msgrcv (cont.)

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

int msgrcv(**int** msqid, **void** *msgp, size_t maxmsgsz, **long** msgtyp,
            int msgflg);

Returns: *0 if OK, -1 on error*

- `msgflg` support the following flags:

IPC_NOWAIT	non-blocking receive
MSG_EXCEPT	complement message selection for `msgtyp` > 0
MSG_NOERROR	allow to remove over-size messages

Message queue associated data structure

To each System V IPC object, the kernel associates a data structure that can be retrieved and set using the appropriate control syscall.

For message queues the data structure is msqid_ds, which contains a lot of accounting information as well as common properties such as permissions:

```
struct msqid_ds {
    struct ipc_perm msg_perm;     /* ownership and permissions */
    time_t          msg_stime;    /* time of last msgsnd() */
    time_t          msg_rtime;    /* time of last msgrcv() */
    time_t          msg_ctime;    /* time of last change */
    unsigned long   __msg_cbytes; /* n. of bytes in queue */
    msgqnum_t       msg_qnum;     /* n. of messages in queue */
    msglen_t        msg_qbytes;   /* max n. of bytes in queue */
    pid_t           msg_lspid;    /* PID of last msgsnd() */
    pid_t           msg_lrpid;    /* PID of last msgrcv() */
};
```

msgctl

The control syscall of message queues is msgctl, a typical dispatcher syscall:

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

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

Returns: *0 if OK, -1 on error*

Allowed commands for cmd are:

IPC_RMID	destroy queue; all pending messages are lost
IPC_STAT	get queue data structure into buf
IPC_SET	set queue data structure from buf

Outline

1. Introduction to System V IPC

2. System V Message Queues
   - Client/server message queues

3. System V Semaphores

4. System V Shared Memory
   - Data structures in shared memory

Client/server message queues

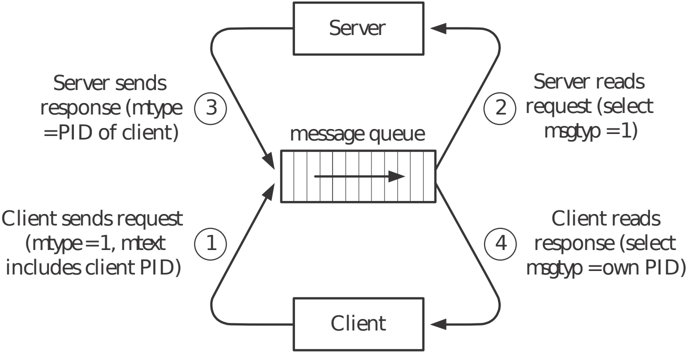
Message queues can be used to implement host-local client/server architectures.

Several arrangements are possible:

1. one request/response queue
   - this was not possible with FIFO-based client/server architectures, as there was no way to route responses to the appropriate client
2. one request queue + one response queue
3. one request queue + one response queue *per-client*

Single request/response queue

- we use a single message queue
  - all clients send requests there
  - the server send there responses to all clients
- then, to ensure proper message routing:
  - requests have type 1 and contain client PID
  - responses have type equal to the PID of the target client


Server
Server sends response (mtype =PID of client)
3
message queue
2
Server reads request (select msgtyp =1)
Client sends request (mtype=1, mtext includes client PID)
1
4
Client reads response (select msgtyp =own PID)
Client

TLPI, Fgure 46-2

Single request/response queue — discussion

- it is usually safe to use 1 (or 0) as server message type (it's `init`'s PID)
  - alternatively we can use server's PID, but it is difficult for client to get to know it

- queue limited capacity might cause denial of service (DoS):
  1. many clients might fill the queue blocking the system, as not even the server will be able to write responses
  2. a malicious/misbehaving client might fail to retrieve its response; many will block the system

One request queue + one response queue

As a first improvement, we can use two queues:

- client send their requests to a single request queue
- server send responses for all clients to a single response queue

This arrangement solves problem (1)—many clients blocking the queue:

- when the request queue is full, new client will block, but the server will still be able to process requests and send responses without blocking

It does not solves problem (2)—clients failing to retrieve responses.

Per client response queue

To improve over problem (2) we need a more complex arrangement.

- a single request queue, as before
- one response queue per client
  - a client creates its own private message queue
  - the client queue identifier is included in requests
  - the server retrieves the queue identifier and write responses to the corresponding queue

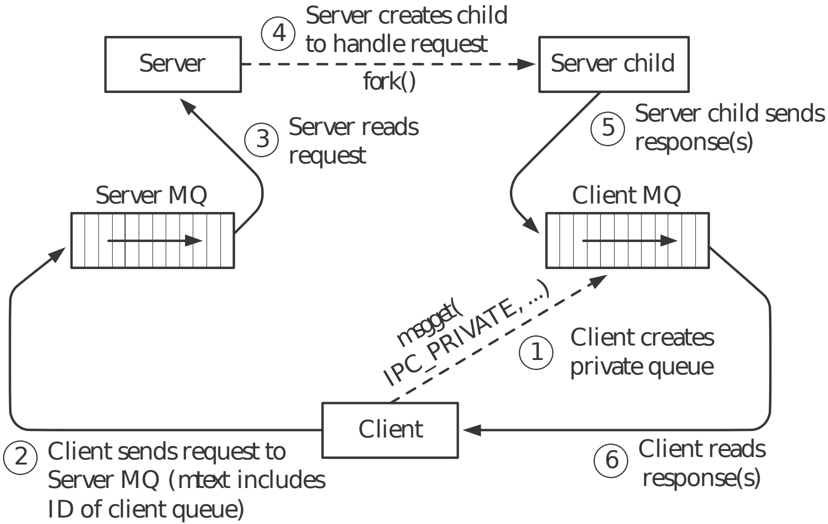
Per client response queue

To improve over problem (2) we need a more complex arrangement.

- a single request queue, as before
- one response queue per client
    - a client creates its own private message queue
    - the client queue identifier is included in requests
    - the server retrieves the queue identifier and write responses to the corresponding queue

- to avoid blocking on full response queues (e.g. created on purpose by malicious clients), the server fork a child to handle each request

Per client response queue (cont.)



TLPI, Fgure 46-3

Per client response queue — example

As an example of the per client response queue architecture we provide an implementation of a:

Example (stat server)

- clients send to the server a pathname of a file they want to be stat-ed
  - possibly, the file is accessible to the server but not to the clients
- the server stat the file and return its information to the client
  - in the example, we return only file size

We will use one shared queue for requests + one private queue per client for responses.

Per client response queue — example (protocol)

```
#include <errno.h>
#include <limits.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sys/msg.h>
#include <sys/stat.h>
#include <unistd.h>
#include "helpers.h"

#define SRV_FTOK_PATH   "/tmp/stat-server" /* dummy value */
#define SRV_FTOK_PROJ   1

#define RES_OK          1       /* OK, checksum returned */
#define RES_ERR         2       /* error, no checksum */
```

Per client response queue — example (protocol) (cont.)

```
struct request_msg {
        long mtype;                 /* not used */
        int cli_id;                 /* client queue id */
        char pathname[PATH_MAX];
};

struct response_msg {
        long mtype;         /* one of RES_* values */
        size_t size;        /* size (if mtype==RES_OK) */
        /* ... */
};

#define REQ_SIZ (sizeof(struct request_msg) - sizeof(long))
#define RES_SIZ (sizeof(struct response_msg) - sizeof(long))

/* stat-common.h */
```

Per client response queue — example (server)

```
#include "stat-common.h"

static int srv_id;
int handle_request(const struct request_msg *req);
void rm_queue(int signo) {
        msgctl(srv_id, IPC_RMID, NULL);
}
void dezombie(int signo) {
        waitpid(-1, NULL, WNOHANG);
}
int main(void) {
        int msglen;
        key_t srv_key;
        pid_t pid;
        struct request_msg req;

        if ((srv_key = ftok(SRV_FTOK_PATH, SRV_FTOK_PROJ)) < 0)
                err_sys("ftok error");
        if ((srv_id = msgget(srv_key, IPC_CREAT | IPC_EXCL
                             | S_IRUSR | S_IWUSR | S_IWGRP)) < 0)
                err_sys("msgget error");
        if (signal(SIGCHLD, dezombie) == SIG_ERR /* better cleanup needed...
            || signal(SIGINT, rm_queue) == SIG_ERR)
                err_sys("signal error");
```

Per client response queue — example (server) (cont.)

```
        for (;;) {
                if ((msglen = msgrcv(srv_id, &req, REQ_SIZ, 0, 0)) < 0) {
                        if (errno == EINTR)
                                continue;
                        break;
                }

                if ((pid = fork()) < 0)
                        err_sys("fork error");
                if (pid == 0) { /* child */
                        if (handle_request(&req) < 0)
                                err_msg("handle_request error");
                        exit(EXIT_SUCCESS);
                }
                /* parent continues to handle next request */
        }


        rm_queue(-1);
        exit(EXIT_SUCCESS);
}
```

Per client response queue — example (server) (cont.)

```
int handle_request(const struct request_msg *req) {
        struct stat finfo;
        struct response_msg res;

        if (stat(req->pathname, &finfo) < 0) {
                res.mtype = RES_ERR;
        } else {
                res.mtype = RES_OK;
                res.size = finfo.st_size;
        }
        return msgsnd(req->cli_id, &res, RES_SIZ, 0);
}

/* stat-server.c */
```

Per client response queue — example (client)

```
#include "stat-common.h"
static int cli_id;
void rm_queue(void) {
        msgctl(cli_id, IPC_RMID, NULL);
}

int main(int argc, char **argv) {
        int srv_id;
        key_t srv_key;
        struct request_msg req;
        struct response_msg res;

        if (argc != 2)
                err_quit("Usage: stat-client PATH");

        if ((srv_key = ftok(SRV_FTOK_PATH, SRV_FTOK_PROJ)) < 0)
                err_sys("ftok error");
        if ((srv_id = msgget(srv_key, 0)) < 0)
                err_sys("msgget error (server queue)");
        if ((cli_id = msgget(IPC_PRIVATE,
                             S_IRUSR | S_IWUSR | S_IWGRP)) < 0)
                err_sys("msgget error (client queue)");
        if (atexit(rm_queue) != 0)
                err_sys("atexit error");
```

Per client response queue — example (client) (cont.)

```c
        req.mtype = 1;  /* unused */
        req.cli_id = cli_id;
        strncpy(req.pathname, argv[1], sizeof(req.pathname) - 1);
        req.pathname[sizeof(req.pathname) - 1] = '\0'; /* safeguard */
        if (msgsnd(srv_id, &req, REQ_SIZ, 0) < 0)
                err_sys("msgsnd error");

        if (msgrcv(cli_id, &res, RES_SIZ, 0, 0) < 0)
                err_sys("msgrcv error");
        if (res.mtype == RES_ERR)
                exit(EXIT_FAILURE);
        else {
                printf("%ld\n", res.size);
                exit(EXIT_SUCCESS);
        }
} /* stat-client.c */
```

Per client response queue — example

Demo

Notes:

- clients cannot DoS the server queue
  - they can still DoS the system by filling up the number of available queues; this is an intrinsic problem of System V IPC
- clients and servers take good care of queue cleanup
- we don't use message types, but they can be used to provide Quality of Service (QoS), by prioritizing requests

Per client response queue — example

Demo

Notes:

- clients cannot DoS the server queue
  - they can still DoS the system by filling up the number of available queues; this is an intrinsic problem of System V IPC
- clients and servers take good care of queue cleanup
- we don't use message types, but they can be used to provide Quality of Service (QoS), by prioritizing requests

Exercise

Adapt the example to become a file server, where the server sends to clients the content of the requested file.

Disadvantages of System V message queues

Common System V IPC issues:

- object identifiers, rather than FDs
- keys, rather than filenames
- no accounting of object users; hard to delete safely
- limits

Outline

1 Introduction to System V IPC

2 System V Message Queues
- Client/server message queues

3 System V Semaphores

4 System V Shared Memory
- Data structures in shared memory

Semaphores

A semaphore is an abstract data type whose instances can be used by processes that want to coordinate access to shared resources.
A semaphore is equipped with operations that allow coordination without race conditions between testing the value of the semaphore and changing it.

In its general form, a semaphore is an integer variable that can never descend below 0.
Intuitively, such a semaphore counts the number of available units of a shared resource.

A special, yet very common, case is that of a binary semaphore used to guarantee mutual exclusion when accessing a single shared resource. A binary semaphore has only two possible values:

1 the resource is available

0 the resource is taken

Semaphores essential bibliography

Edsger W. Dijkstra
Cooperating Sequential Processes
Programming Languages, Academic Press, New York. 1968
http://www.cs.utexas.edu/~EWD/transcriptions/EWD01xx/EWD123.html

Semaphore operations

Two operations are defined on a semaphore:

- P (for *probeer te verlagen*, “try to decrease” in Dutch)
  try to decrease semaphore value and blocks if that would result in a negative value; when the operation returns the semaphore value has been decreased by one
  intuition: ask for exclusive access to a resource unit
- V (for *verhogen*, “increase” in Dutch)
  increase semaphore value
  intuition: signal that a resource unit has been made available to others who are waiting for it

Semaphore — example

You want to coordinate access to a shared memory area among multiple processes ensuring memory coherence.

More precisely, each process wants to perform an increment action on the `int counter` variable stored into shared memory. The increment operation is defined as: read `counter` and write it back incremented by one (i.e. `counter++`). The desired property is that if n processes perform a total of k increment operations, the counter is incremented exactly by k.

Due to the race condition between reading `counter` value and writing it back incremented, it is not enough for each process to simply do `counter++`

- with more complex data structure, the race condition can also cause data corruption that makes impossible to read the value

Semaphore — example (cont.)

With a binary semaphore S we can solve the problem and avoid race conditions. We assume that the semaphore is initialized with $S \leftarrow 1$. Each process will implement increment as follows:

1. $P(S)$
2. `counter++`
3. $V(S)$

The P call would block if someone else is incrementing `counter`. Within the $P \ldots V$ window a process knows that—as long as all other processes follow the same protocol—he will execute its critical section without interference from others.

For semaphores to work, it is essential that $P(S)$ atomically test & decrement (if possible) the semaphore value.
Only the kernel can guarantee that.

General semaphores

In the example, there is a single resource available (the counter global variable), hence a binary semaphore is enough.

- the scheme can be generalized to n available resources using $S \leftarrow n$ as semaphore initialization
- we then generalize P and V to take arbitrary integer parameters
    - $V(S, n)$ increment semaphore value by n
    - $P(S, n)$ try to decrease semaphore value by n and block if that is not possible
        - note: until the decrease is possible, semaphore value remains unchanged, i.e. no partial decrease is possible

Example

A TP room at the UFR has n available machines. In the morning, the room opens with $S \leftarrow n$. A student arrives at the door and does $P(S, 1)$ to enter. A group of m students working together on a project does $P(S, m)$. Each student leaving the room does $V(S, 1)$.

System V Semaphores

The traditional implementation of semaphores by UNIX kernels are System V semaphores.

- they belong to System V IPC mechanisms; the IPC object is a *set of semaphores*
- all semaphores in the set are generalized semaphores with arbitrary (non-negative) integer values
- each semaphore in a set support the following operations:
  1. add a (positive) value to semaphore value (generalized V)
  2. subtract a (positive) number from semaphore value (generalized P)
  3. set semaphore value to an arbitrary (non-negative) value (initialization)
  4. wait for semaphore value to become 0

Overview of System V semaphore API

header file	<sys/sem.h>
get semaphore set	semget
semaphore action	semop
data structure	semid_ds
control	semctl

semget

To obtain a semaphore set corresponding to a given key, the get syscall semget should be used:

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

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

Returns: *semaphore set ID if OK, -1 on error*

- nsems specifies the number of semaphores in the set
  - 1 is a common choice
- semflg supports IPC_CREAT, IPC_FLAGS, and permissions as usual

semop

All semaphore operations are requested via the semop syscall. The fact that the object granularity is the semaphore *set*, makes it rather cumbersome to use. . .

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

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

Returns: *0 if OK, -1 on error*

- semid is the semaphore set identifier
- sops points to a (non-empty) array of operations to be performed on individual semaphores

```
struct sembuf {
        unsigned short sem_num;      /* semaphore number, 0-based */
        short          sem_op;       /* operation to be performed */
        short          sem_flg;      /* operation flags */
};
```

- nsops is the number of operations in the sops array

semop (cont.)

#include <sys/sem.h>

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

Returns: *0 if OK, -1 on error*

```
struct sembuf {
    unsigned short sem_num;    /* semaphore number, 0-based */
    short          sem_op;     /* operation to be performed */
    short          sem_flg;    /* operation flags */
};
```

Operations are interpreted as follows:

$$\begin{array}{lcl} \mathtt{sem\_op} > 0 & \longrightarrow & V(S_{\mathtt{sem\_num}}, \mathtt{sem\_op}) \\ \mathtt{sem\_op} < 0 & \longrightarrow & P(S_{\mathtt{sem\_num}}, |\mathtt{sem\_op}|) \\ \hline \mathtt{sem\_op} = 0 & \longrightarrow & \text{test \& wait until } S_{\mathtt{sem\_num}} = 0 \end{array}$$

operation flags support IPC_NOWAIT with the usual semantics

Semaphore associated data structure

As with all System V IPC objects, a kernel data structure is associated to each semaphore set:

```
struct semid_ds {
    struct ipc_perm msg_perm;     /* ownership and permissions */
    time_t          sem_otime;    /* time of last semop() */
    time_t          sem_ctime;    /* time of last change */
    unsigned long   sem_nsems;    /* n. of semaphores in set */
};
```

It allows to access IPC object permissions and also provides the usual accounting information.

semctl

The semaphore set control syscall is semctl. Contrary to other control syscalls, semctl is overloaded for two different purposes:

1. generic control operations (access to semid_ds, deletion)
2. semaphore initialization & reset

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

int semctl(int semid, int semnum, int cmd, ... /*union semun arg */);
```

Returns: *non-negative integer if OK, -1 on error*

Generic control operations are as usual according to cmd:

- IPC_RMID to delete the semaphore set
- IPC_STAT/IPC_SET to get/set the associated data structure

semctl (cont.)

#include <sys/sem.h>

int semctl(**int** semid, **int** semnum, **int** cmd, ... */*union semun arg */*);

Returns: *non-negative integer if OK, -1 on error*

Semaphore initialization / reset uses the following cmd-s:

- GETVAL/SETVAL: get/set the value of the setnum-th semaphore
- GETALL/SETALL: as above, but for *all* semaphores at once

Arguments and return values for all semctl commands are conveyed by semun, that must be defined by your programs as follows:

```
union semun {
    int                 val;      /* individual semaphore value */
    struct semid_ds    *buf;      /* semaphore data structure */
    unsigned short     *array;    /* multiple semaphore values */
};
```

Semaphore initialization

- according to SUSv3, semaphores are not initialized to any specific value when created with semget+IPC_CREAT
  - Linux initializes semaphores to 0, but it's not portable
- therefore, semaphores must be explicitly initialized *after* creation with semctl

If multiple processes attempt to create & initialize a common semaphore you get a race condition for semaphore initialization.

Semaphore initialization

- according to SUSv3, semaphores are not initialized to any specific value when created with `semget+IPC_CREAT`
  - Linux initializes semaphores to 0, but it's not portable
- therefore, semaphores must be explicitly initialized *after* creation with `semctl`

If multiple processes attempt to create & initialize a common semaphore you get a race condition for semaphore initialization.

Solutions:

1. avoidance: ensure that a single process is in charge of creating & initializing the semaphore, e.g.:
   - creation at (application) boot time, possibly using `ipcmk`
   - have a parent create & initialize before spawning children
2. the `sem_otime` trick based on the historical (and now standard) fact that the field is set to 0 upon creation

Semaphore — example

```
#include <stdio.h>
#include <sys/sem.h>
#include <sys/stat.h>
#include <unistd.h>
#include "helpers.h"

union semun {   /* SUSv3 mandates definition in user programs */
        int             val;
        struct semid_ds *buf;
        unsigned short  *array;
};
```

Semaphore — example (cont.)

```
int main(int argc, char **argv) {
        int semid;

        if (argc < 2 || argc > 3)
                err_quit("Usage: svsem_demo [ SEM_ID ] SEM_OP");

        if (argc == 2) {        /* create & init semaphore */
                union semun arg;

                if ((semid = semget(IPC_PRIVATE, 1,
                                    S_IRUSR | S_IWUSR)) < 0)
                        err_sys("semid error");
                arg.val = atoi(argv[1]);

                if (semctl(semid, 0, SETVAL, arg) < 0)
                        err_sys("semctl error");

                printf("semaphore ID = %d\n", semid);
        }
```

Semaphore — example (cont.)

```
        else {              /* act on first semaphore */
                struct sembuf sop;

                semid = atoi(argv[1]);
                sop.sem_num = 0;            /* act on first semaphore */
                sop.sem_op = atoi(argv[2]);
                sop.sem_flg = 0;            /* no special flags */

                printf("%d: about to semop\n", getpid());
                if (semop(semid, &sop, 1) < 0)
                        err_sys("semop error");

                printf("%d: semop completed\n", getpid());
        }

        exit(EXIT_SUCCESS);
}
/* svsem_demo.c. Based on TLPI's svsem_demo.c.
   Copyright (C) Michael Kerrisk, 2010. License: GNU AGPL-3+ */
```

Semaphore — example (cont.)

Demo

Semaphore limits

As other System V IPC objects, semaphores are limited along many traits, many of which can be customized:

```
$ ipcs -l -s
------ Semaphore Limits --------
max number of arrays = 128
max semaphores per array = 250
max semaphores system wide = 32000
max ops per semop call = 32
semaphore max value = 32767
$
```

Disadvantages of System V semaphores

Common System V IPC issues:

- object identifiers, rather than FDs
- keys, rather than filenames
- no accounting of object users; hard to delete safely
- limits

Semaphore-specific issues:

- initialization race condition
- overly complex API, “thanks” to the set granularity

Outline

1. Introduction to System V IPC

2. System V Message Queues
   - Client/server message queues

3. System V Semaphores

4. System V Shared Memory
   - Data structures in shared memory

System V Shared Memory

System V shared memory is an IPC mechanism that allows unrelated processes to share memory areas. In the System V shared memory jargon, shared memory areas are called segments.

As with other System V IPC mechanisms, segments are kernel-persistent and should be explicitly created and destroyed.

System V Shared Memory

System V shared memory is an IPC mechanism that allows unrelated processes to share memory areas. In the System V shared memory jargon, shared memory areas are called segments.

As with other System V IPC mechanisms, segments are kernel-persistent and should be explicitly created and destroyed.

For many purposes, System V shared memory is similar to memory mappings that we already discussed:

- different processes access virtual pages pointing to the same memory frames
- communication happens via direct memory access
- however, segments can be shared among unrelated processes without a file as backing store
  - with memory mappings either you map a file, or you can share only among related processes (via anonymous mappings)

Shared memory protocol

The "protocol" to use shared memory segments, unlike other System V mechanisms, require more than one step before actual IPC.

1. obtain the identifier of a shared memory segment
   - this can happen via a get syscall (`shmget`) that either create a segment or retrieve its identifier
   - or via communication of the identifier by other means
2. attach the segment to the process address space
   - as a result of attaching, the caller obtain the starting memory address of the shared segment
3. use the attached segment, as if it were native process memory
   - no mediation by the syscall API is needed
   - as with memory mappings, synchronization among sharing processes is an important concern here

Shared memory protocol (cont.)

4. once a process is done using shared memory, it should detach the segment from its address space
   - once detached, access to the memory corresponding to the (now detached) segment will cause SIGSEGV

5. once all processes are done using shared memory, a process should delete the segment using the control syscall with `IPC_RMID`
   - until this step is done, the shared memory segment will continue to exist (and to occupy system resources)

Overview of System V Shared Memory API

header file	<sys/shm.h>
get segment	shmget
attach segment	shmat
detach segment	shmdt
data structure	shmid_ds
control	shmctl

shmget

shmget is the get syscall for shared memory segments:

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

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

Returns: *shared memory segment id if OK, -1 on error*

- key is the System V key, obtained by the usual means
- size is the size of the desired memory segment, in bytes
  - the kernel will return a segment of size multiple to system page size, roundup to the next such multiple will happen
- shmflg is a bitwise OR of the usual System V IPC flags: IPC_CREAT, IPC_EXCL, permission bits
- on success, shmget returns a shared memory segment identifier that can be stored and passed to others

shmat

Once a process has obtained a segment identifier, it should use it to attach the segment to its address space using shmat, which behaves similarly to mmap:

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

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

Returns: *base address of the attached segment if OK, -1 on error*

- shmid is the identifier of the segment to attach
- shmaddr is the address where to attach the segment
  - it is optional, if omitted the kernel will choose a suitable address
  - contrary to mmap, it is *not* a hint
    - either attachment at shmadrr is possible
    - or shmat will fail with EINVAL
- on success, shmat will return the starting address of the attached segment

Where to attach segments?

The main reason to force attachment at a specific address is to ensure consistency throughout all processes that share the segment.

Example

A group of processes want to collaborate on a big array of `struct mystruct` in shared memory.
To do so, they all attach a suitably-sized segment starting at address 0x6ed000.
Once done, all processes know that the 1234-th array entry can be found at address:

$$0x6ed000 + \mathit{sizeof}(\texttt{struct mystruct}) * (1234 - 1)$$

Otherwise, addresses pointing to specific array entries in different processes might be different.

Where to attach segments? (cont.)

Attaching segments at fixed addresses using shmaddr comes with its own problems though

- at compile time, when we write the program, we often don't know if shmaddr will be available at runtime for attaching the segment; in particular:
  - we don't know if another segment will be attached at shmaddr
  - we don't know if at shmaddr there will be enough available contiguous memory to fit the segment+roundup
- it reduces portability, as an address valid on some UNIX machine will not necessarily be valid on different UNIX-es
- shmaddr is less flexible than mmap's addr hint, as mmap is able to fallback to a difference address
  - unless you requested MAP_FIXED

As a best practice, *never* use shmaddr and rely on the kernel to find a suitable address for you.
(Stay tuned for how to solve the uniform memory address problem.)

shmat (cont.)

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

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

Returns: *base address of the attached segment if OK, -1 on error*

Flags is a bitwise OR of flags that include:

- SHM_RDONLY: attach segment read-only
- SHM_REMAP: replace already existing mapping at shmaddr

shmdt

Once done working on a shared memory segment, a process can detach it from its address space using shmdt:

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

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

Returns: *0 if OK, -1 on error*

Note that detaching is different than deleting. Once detached, the memory segment (and its content) will still exist in kernel space until explicitly deleted.

Segment inheritance

Attached memory segments are automatically detached upon process termination.

Attached memory segments are inherited through fork— as it happens with memory mappings. That provides a(nother) handy way to do IPC between parent and child

1. parent creates shared memory segment using key IPC_PRIVATE
2. parent fork-s a child
3. child and parent can now transfer data via shared memory

Note: the same is neither possible via regular memory due to address space copying (on write), nor via vfork as parent is blocked until child "reset".

Shared memory — example

As an example, we will develop a simple command line toolkit to transfer data across processes with the mediation of the kernel and without relying on the filesystem. It will work as follows:

- we create shared memory segments using `ipcmk`, and note down the shared memory identifier (`shmid`) that it returns
- we copy data from standard input to shared memory with the custom program `stdin2shm`
- we copy data from shared memory to stdout with the custom program `shm2stdout`
  - for both programs we will need to specify on the cmdline shared memory segment identifier and size
- once done, we use `ipcrm` to free the used segment

For simplicity, copied data (in both directions) will be trimmed to

$$\min(\textit{stdin size}, \textit{segment size})$$

Shared memory — example (protocol)

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/shm.h>
#include <unistd.h>
#include "helpers.h"

#define min(x,y)        (x > y ? y : x)

static int shmid = -1;
static int shmsize = -1;

struct shmseg {
        int size;       /* used data in buf */
        char buf[];     /* actual data */
};
```

Shared memory — example (protocol) (cont.)

```
/* parse cmdline and fill: shmid, shmsize */
void parse_cmdline(int argc, char **argv) {
        char msg[1024] = "";

        if (argc != 3) {
                snprintf(msg, 1024, "Usage: %s SHMID SIZE", argv[0])
                err_quit(msg);
        }
        shmid = atoi(argv[1]);
        shmsize = atoi(argv[2]);
}

/* shm-common.h */
```

Shared memory — example (stdin2shm)

```
#include "shm−common.h"

int main(int argc, char **argv) {
        int n, bufsize;
        struct shmseg *shmp;
        parse_cmdline(argc, argv);

        if ((shmp = shmat(shmid, NULL, 0)) < 0)
                err_sys("shmat error");
        fprintf(stderr, "attached segment at: %p\n", shmp);

        bufsize = shmsize − sizeof(int);
        shmp−>size = 0; /* running count of read bytes */
        while (bufsize − shmp−>size >= 0
               && (n = read(STDIN_FILENO, shmp−>buf + shmp−>size,
                            bufsize − shmp−>size)) > 0)
                shmp−>size += n;
        if (n < 0)  err_sys("read error");
        fprintf(stderr, "stdin −> shm: copied %d bytes\n", shmp−>size
        exit(EXIT_SUCCESS);
} /* stdin2shm.c */
```

Shared memory — example (shm2stdout)

```
#include "shm-common.h"
int main(int argc, char **argv) {
        int n, done, rem;
        struct shmseg *shmp;
        parse_cmdline(argc, argv);

        if ((shmp = shmat(shmid, NULL, 0)) < 0)
                err_sys("shmat error");
        fprintf(stderr, "attached segment at: %p\n", shmp);

        done = 0;                               /* written bytes */
        rem = min(shmp->size, shmsize); /* todo bytes */
        while(rem > 0
          && (n = write(STDOUT_FILENO, shmp->buf + done, rem)) > 0)
                done += n;
                rem -= n;
        }
        if (n < 0) err_sys("write error");
        fprintf(stderr, "shm -> stdout: copied %d bytes\n", done);
        exit(EXIT_SUCCESS);
} /* shm2stdout.c */
```

Shared memory — example (cont.)

Demo

Notes:

- shared memory segments are stable, content copied there persists beyond the life of processes accessing it
- shared memory identifiers are stable (and readable), we can create and pass them around between different programs
- setup and tear-down are delegated to `ipcmk` and `ipcrm`
- we do no synchronization whatsoever

Exercise

Can we avoid specifying segment size on the cmdline?

Shared memory synchronization — example

Any “real” use of shared resources memory needs synchronization to avoid race conditions and memory corruptions. Consider the following use case:

Example (efficient process-to-process data transfer)

We want to transfer a big amount of data among two unrelated processes.

For maximum efficiency:

- we want to minimize the amount of memory copies and of context switches between user space and kernel space
- we do not want to use the filesystem

System V shared memory offers an interesting solution.

Shared memory synchronization — example (cont.)

- we use a shared memory segment as a buffer for data exchange among two processes
- two processes are involved: a writer (reading from stdin and writing to shared memory) + a reader (reading from shared memory and writing to stdout)

- as the buffer is in general not enough to hold the entire amount of data to be transferred we do several iterations of (i) *writer writes*, (ii) reader reads
- therefore we need to ensure proper synchronization:
  1. *mutual exclusion*: the reader does not act when the writer does and vice-versa
  2. reader and writer *alternates* in accessing data
     - ⋆ i.e. each written chunk is read exactly once

Shared memory synchronization — example (cont.)

To do so we use an array of 2 System V semaphores:

1. a write semaphore W
   - intuition: when the semaphore is taken, writing is happening
2. a read semaphore R
   - intuition: when the semaphore is taken, reading is happening

At system bootstrap, we initialize the semaphores so that only writing can happen:

- write semaphore is initialized $W \leftarrow 1$ (available)
- read semaphore is initialized $R \leftarrow 0$ (not available)

Shared memory synchronization — example (cont.)

```
writer()
  while true do
    1. $P(W)$
    2. $shmem \leftarrow stdin$
    3. $V(R)$
```

```
reader()
  while true do
    1. $P(R)$
    2. $stdout \leftarrow shmem$
    3. $V(W)$
```

Discussion:

- at bootstrap: reader is blocked at (1); writer do a full iteration
- when writer does (3), reader is unblocked;
  when writer does (1) (again), it blocks (sides exchanged)
- reader do a full iteration, unblocks writer at (3), and blocks when doing (1) again (sides exchanged again, loop)

Shared memory sync. — example (protocol)

```
#include <sys/sem.h>
#include <sys/shm.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>
#include "helpers.h"

#define SHM_KEY         0x1234  /* shmem key */
#define SEM_KEY         0x5678  /* semaphore set key */
#define OBJ_PERMS       (S_IRUSR | S_IWUSR | S_IRGRP | S_IWGRP)
#define WRITE_SEM       0       /* write index in semaphore set */
#define READ_SEM        1       /* read index in semaphore set */
#define BUF_SIZE        10240   /* transfer buffer size */

union semun {   /* SUSv3 forces definition in user programs */
        int             val;
        struct semid_ds *buf;
        unsigned short  *array;
};

struct shmseg {
    int cnt;                    /* bytes used in 'buf' */
    char buf[BUF_SIZE];         /* data */
};
```

Shared memory sync. — example (library)

```
/* init semaphore to 1 */
int sem_init_avail(int semid, int semno) {
        union semun arg;

        arg.val = 1;
        return semctl(semid, semno, SETVAL, arg);
}

/* init semaphore to 0 */
int sem_init_taken(int semid, int semno) {
        union semun arg;

        arg.val = 0;
        return semctl(semid, semno, SETVAL, arg);
}
```

Shared memory sync. — example (library) (cont.)

```c
int sem_p(int semid, int semno) { /* reserve semaphore (P) */
        struct sembuf sop;

        sop.sem_num = semno;
        sop.sem_op = -1;
        sop.sem_flg = 0;
        return semop(semid, &sop, 1);
}

int sem_v(int semid, int semno) { /* release semaphore (V) */
    struct sembuf sop;

    sop.sem_num = semno;
    sop.sem_op = 1;
    sop.sem_flg = 0;
    return semop(semid, &sop, 1);
}

/* svshm-xfr.h, based on svshm_xfr.h
   Copyright (C) Michael Kerrisk 2010, License: GNU AGPL-3+ */
```

Shared memory sync. — example (writer)

```c
#include "svshm-xfr.h"

int main(int argc, char **argv) {
        int semid, shmid, bytes, xfrs;
        struct shmseg *shmp;
        union semun dummy;

        if ((semid = semget(SEM_KEY, 2, IPC_CREAT | OBJ_PERMS)) < 0)
                err_sys("semget error");
        if (sem_init_avail(semid, WRITE_SEM) < 0)
                err_sys("semctl error (sem_init_avail)");
        if (sem_init_taken(semid, READ_SEM) < 0)
                err_sys("semctl error (sem_init_taken)");

        if ((shmid = shmget(SHM_KEY, sizeof(struct shmseg),
                            IPC_CREAT | OBJ_PERMS)) < 0)
                err_sys("shmget error");
        if ((shmp = shmat(shmid, NULL, 0)) < 0)
                err_sys("shmat error");
```

Shared memory sync. — example (writer) (cont.)

```
for (xfrs = 0, bytes = 0; ; xfrs++, bytes += shmp->cnt) {
        if (sem_p(semid, WRITE_SEM) < 0)
                err_sys("semop error (sem_p)");
        if ((shmp->cnt = read(STDIN_FILENO, shmp->buf,
                              BUF_SIZE)) < 0)
                err_sys("read error");
        if (sem_v(semid, READ_SEM) < 0)
                err_sys("semop error (sem_v)");

        /* Test for EOF after reader turn so that
           it can see the 0 value in shmp->cnt. */
        if (shmp->cnt == 0)
                break;
}

if (sem_p(semid, WRITE_SEM) < 0)
        err_sys("semop error (sem_p)");
```

Shared memory sync. — example (writer) (cont.)

```
        if (semctl(semid, 0, IPC_RMID, dummy) < 0)
                err_sys("semctl error");
        if (shmdt(shmp) < 0)
                err_sys("shmdt error");
        if (shmctl(shmid, IPC_RMID, 0) < 0)
                err_sys("shmctl error");

        fprintf(stderr, "sent %d bytes (%d xfrs)\n", bytes, xfrs);
        exit(EXIT_SUCCESS);
}

/* svshm-writer.c, based on svshm_xfr_writer.c
   Copyright (C) Michael Kerrisk 2010, License: GNU AGPL-3+ */
```

Shared memory sync. — example (reader)

```c
#include "svshm-xfr.h"

int main(int argc, char **argv) {
        int semid, shmid, xfrs, bytes;
        struct shmseg *shmp;

        if ((semid = semget(SEM_KEY, 0, 0)) < 0)
                err_sys("semget error");
        if ((shmid  = shmget(SHM_KEY, 0, 0)) < 0)
                err_sys("shmget error");

        if ((shmp = shmat(shmid, NULL, SHM_RDONLY)) < 0)
                err_sys("shmat error");
```

Shared memory sync. — example (reader) (cont.)

```c
for (xfrs = 0, bytes = 0; ; xfrs++) {
        if (sem_p(semid, READ_SEM) < 0)
                err_sys("semop error (sem_p)");

        if (shmp->cnt == 0)     /* writer EOF */
                break;
        bytes += shmp->cnt;

        if (write(STDOUT_FILENO, shmp->buf, shmp->cnt)
            != shmp->cnt)
                err_quit("partial/failed write");

        if (sem_v(semid, WRITE_SEM) < 0)
                err_sys("semop error (sem_v)");
}
```

Shared memory sync. — example (reader) (cont.)

```
        if (shmdt(shmp) < 0)
                err_sys("shmdt error");

        /* one more writer turn to cleanup */
        if (sem_v(semid, WRITE_SEM) < 0)
                err_sys("releaseSem");

        fprintf(stderr,
                "received %d bytes (%d xfrs)\n", bytes, xfrs);
        exit(EXIT_SUCCESS);
}

/* svshm-reader.c, based on svshm_xfr_reader.c
   Copyright (C) Michael Kerrisk 2010, License: GNU AGPL-3+ */
```

Shared memory sync. — example (cont.)

Demo

Notes:

- semaphore initialization is delegated to writer
  - it should start first, otherwise reader won't find the shared memory segment (and fail)
- we need a way to inform reader of EOF; to do so we let reader read `cnt == 0`
- before writer termination (that will destroy the shared memory segment), we wait for the last reader turn to happen
  - after it, reader liberates writer using `sem_v` one last time

Shared memory associated data structure

As all System V IPC mechanisms, each shared memory segment is associated to a specific data structure, shmid_ds in this case:

```
struct shmid_ds {
    struct   ipc_perm msg_perm;         /* ownership and permissions */
    size_t   shm_segsz;                 /* size of segment (bytes) */
    time_t   shm_atime;                 /* time of last shmat() */
    time_t   shm_dtime;                 /* time of last shmdt() */
    time_t   shm_ctime;                 /* time of last change */
    pid_t    shm_cpid;                  /* PID of creator */
    pid_t    shm_lpid;                  /* PID of last shmat/shmdt() */
    shmatt_t shm_nattach; shm_lpid;     /* n. of attached processes */
}
```

It contains the usual ownership and accounting information.

shmctl

The control syscall for shared memory segments is shmctl:

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

shmctl(int shmid, int cmd, struct shmid_ds *buf);
                                        Returns: 0 if OK, -1 on error
```

It supports the usual operations: IPC_RMID (removal), IPC_STAT (retrieve shmid_ds), IPC_SET (update shmid_ds).

Segment removal semantics

To avoid disruptions in process address spaces, a shared memory segment is *not* removed immediately after IPC_RMID.
Instead, the kernel does reference counting on the number of attached processes and destroys the segment only when the number reaches 0.

- we can ensure proper segment cleanup by removing the segment right after attaching it
- . . . but whether new attaches are allowed or not after IPC_RMID is implementation dependent
  - Linux allows it

Shared memory limits

Like other System V IPC mechanisms, shared memory segments are limited:

```
$ ipcs -l -q
------ Shared Memory Limits --------
max number of segments = 4096
max seg size (kbytes) = 32768
max total shared memory (kbytes) = 8388608
min seg size (bytes) = 1
$
```

Outline

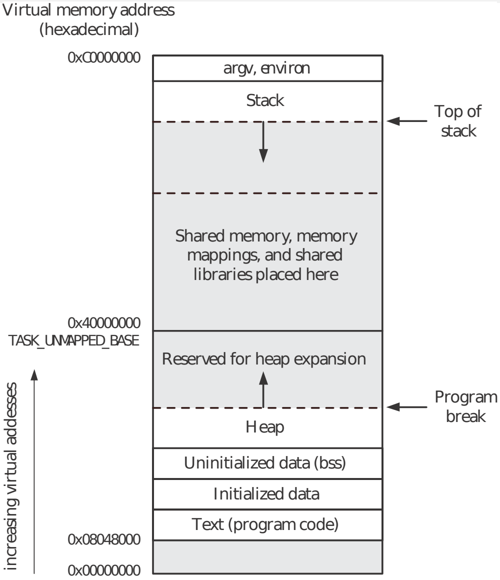
1 Introduction to System V IPC

2 System V Message Queues
- Client/server message queues

3 System V Semaphores

4 System V Shared Memory
- Data structures in shared memory

Shared memory location



TLPI, Fgure 48-2

If we let the kernel choose, all shared memory areas—memory mappings, System V shared segments, and shared libraries—will be located in a common memory area between the stack and the heap.

- on Linux, the starting address for shared memory areas is the compile-time constant TASK_UNMAPPED_BASE

Shared memory areas are per-process. There is no guarantee that co-operating processes will attach a shared area at the same address.

Data structures in shared memory

At the conceptual level, most non-trivial data structures are interlinked, i.e. parts of the structure *refers to* other parts of it.

At the physical memory level, we have memory cells that contains parts of a data structure (say, p) that points to other parts of it (say, `target`).

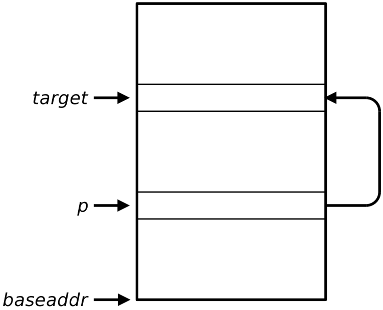


Figure: conceptual memory layout of data structure in shared memory

Data structures in shared memory (cont.)

For a memory part to reference another, we usually store the absolute memory address of the destination as part of the source. In presence of shared memory regions that might be attached at different addresses this is wrong:

- the absolute address of `target` might be different from process to process
  - it *might* happen that the address is the same, but there is no guarantee of it
- also, there is no way of knowing where other processes have attached a shared memory area

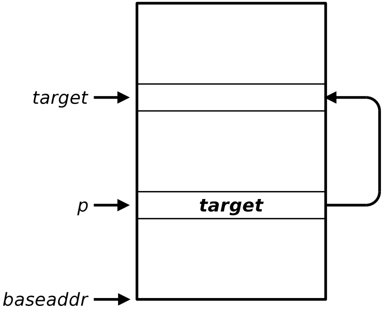


Figure: wrong/risky with shared memory

Data structures in shared memory

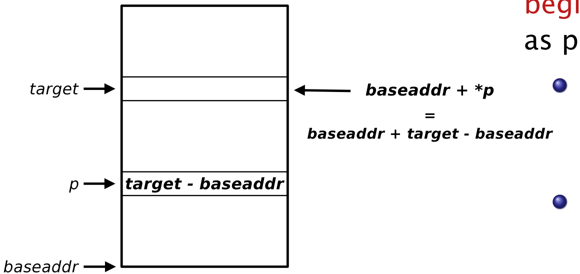


Figure: shared memory safe

The solution is to use addresses relative to the beginning of the shared area as pointers.

- keep around baseaddr, as returned by mmap or shmat
- to store a pointer to shared memory:
  `*p = (target - baseaddr)`
- to dereference a pointer:
  `target = baseaddr + *p;`

Data structures in shmem — example

Let's reconsider the ad-hoc memory allocation mechanism we implemented using mmap (shared + anonymous). That example had no problem with absolute addressing:

- the memory mapping was created by a common ancestor before fork
- due to address space copy, the absolute addresses were granted to be the same for all involved processes

We want to do the same, but this time among unrelated processes that cooperate on a linked list:

- shm-list-writer sets up a linked list in a shared memory segment
- shm-list-reader visit the list printing its content

Data structures in shmem — example (protocol)

```
#include <errno.h>
#include <stdio.h>
#include <sys/shm.h>
#include <sys/stat.h>
#include <unistd.h>
#include "helpers.h"

#define SHM_KEY         0x1234  /* shmem key */
#define OBJ_PERMS       (S_IRUSR | S_IWUSR | S_IRGRP | S_IWGRP)

struct list {
        int val;
        struct list *next;
};

static struct list *list_bot;
static struct list *list_top;
static long list_siz;
```

Data structures in shmem — example (library)

```c
struct list *list_get(void) {
        int shmid;
        if ((shmid = shmget(SHM_KEY, 0, 0)) < 0)
                return ((void *) -1);
        list_bot = shmat(shmid, NULL, 0);
        printf("list attached at %p\n", list_bot);
        return list_bot;
}

int list_init(long len) {
        int shmid;
        if ((shmid = shmget(SHM_KEY, len * sizeof(struct list),
                            IPC_CREAT | OBJ_PERMS)) < 0)
                return (-1);
        if ((list_top = shmat(shmid, NULL, 0)) < 0)
                return (-1);
        printf("list attached at %p\n", list_top);
        list_bot = list_top;
        list_siz = len;
        printf("list_init: top=%p, len=%ld\n", list_top, len);
        return 0;
```

Data structures in shmem — example (library) (cont.)

```c
struct list *list_alloc() {
        long siz = list_top - list_bot;
        if (siz >= list_siz) {
                errno = ENOMEM;
                return NULL;
        }
        list_top->next = NULL;
        printf("allocated %p (length: %ld)\n", list_top, siz + 1);
        return list_top++;
}

struct list *list_free() {
        /* left as an exercise */
        return NULL;
}
```

Data structures in shmem — example (library) (cont.)

```
struct list *list_append(struct list *l, int val) {
        struct list *elt;
        if ((elt = list_alloc()) == NULL)
                return NULL;
        elt->val = val;
        l->next = (void *) ((long) elt - (long) list_bot);
        return elt;
}

void visit_list(const char *label, struct list *l) {
        printf("[%s] visit list: ", label);
        while (l != NULL) {
                printf("%d ", l->val);
                if (l->next == NULL)
                        l = NULL;
                else
                        l = (void *) ((long) list_bot + (long) l->ne
        }
        printf("\n");
}
```

Data structures in shmem — example (writer)

```c
#include "shm-list-common.h"

int main(void) {
        struct list *head, *l = NULL;

        if (list_init(1000) < 0)  err_sys("list_init error");
        if ((l = list_alloc()) == NULL)
                err_sys("list_alloc");
        l->val = 13;
        head = l;
        if ((l = list_append(l, 17)) == NULL
            || (l = list_append(l, 42)) == NULL)
                err_sys("list_append");
        visit_list("common", head);

        exit(EXIT_SUCCESS);
} /* shm-list-writer.c */
```

Data structures in shmem — example (reader)

```
#include "shm-list-common.h"

int main(void) {
        struct list *l = NULL;

        if ((l = list_get()) < 0)
                err_sys("list_get error");

        visit_list("common", l);

        exit(EXIT_SUCCESS);
} /* shm-list-reader.c */
```

Data structures in shmem — example (cont.)

Demo

Notes:

- we have switched from a cons semantics to an append semantics
  - otherwise the head pointer would be lost in the data structure
  - alternatively: we could have stored a pointer to the head in `struct list` and kept it up to date
- shared memory segments are attached to different addresses on a regular basis!
- we need quite a bit of (scary) cast gymnastics to make the compiler happy (i.e. we really are on our own, beware!)