Classical Inter-Process Communication

Pipes

- Pipes
  - oldest UNIX IPC
  - half duplex
    - modern system has full duplex pipe
    - not suggest to use because of portability
  - can be used only between processes have common ancestor
  - normal steps
    - process create pipe
    - process calls `fork(2)`
    - pipe then can be used between parent and child
- `pipe(2)`: `int pipe(int pipefd[2]);`
  - return: 0 OK, -1 error
  - `pipefd[0]` is opened for reading
  - `pipefd[1]` is opened for writing
  - a pipe in a single process is useless
  - as the pipe is half duplex, the following actions may apply
    - child send to parent
      - parent close `pipefd[1]`
      - child close `pipefd[0]`
    - parent send to child
      - parent close `pipefd[0]`
      - child close `pipefd[1]`
  - example

```
int fd[2];
if (pipe(fd) < 0) {
  printf("err\n");
}
if ((pid = fork()) < 0) {
  printf("err\n");
} else if (pid > 0) {
  close(fd[0]);
```

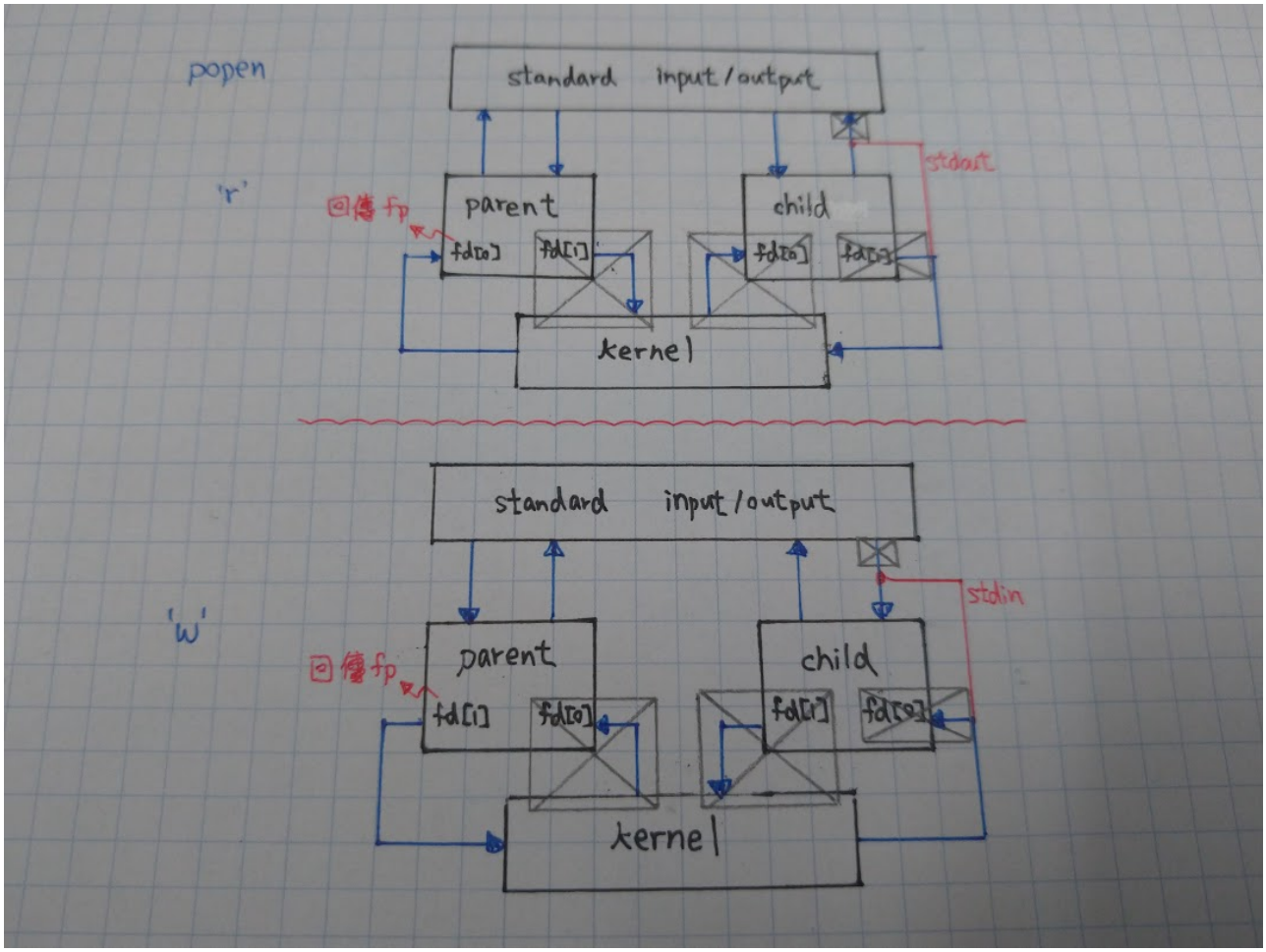
```
    write(fd[1], "hello world\n", 12);
  } else {
    close(fd[1]);
    n = read(fd[0], line, 256);
    write(STDOUT_FILENO, line, n);
  }
```

- can be used for process synchronization

```
  static int pfd1[2];

  void TELL_WAIT() {
    if (pipe(pfd1) < 0)
      printf("err");
  }

  void WAIT_PARENT() {
    char c;
    if (read(pfd1[0]), &c, 1) != 1)
      printf("err");
    if (c != 'p')
      printf("incorrect data");
  }

  void TELL_CIHLD(pid_t pid) {
    if (write(pfd1[1], "p", 1) != 1)
      printf("err");
  }
```

- `popen(3)`: `FILE *popen(const char *command, const char *type);`
  - return: file pointer if OK, `NULL` on error
  - execute `command` and access it standard I/O
  - read from its `stdout` or write to its `stdin`
  - half-duplex, cannot read/write at the same time
  - internal implementation
    - check `type[0]` is `'r'` or `'w'`
    - `calloc(3)`: create buffer for `popen(2)` children PIDs
    - `pipe(2)`: create pipe
    - `fork(2)`: fork child
    - child
      - `close(2)`: close unused file descriptor
      - `dup2(2)`: configure the descriptor to standard I/O
        - `'r'`: `close(pfd[0])`, `dup2(pfd[1], STDOUT_FILENO);`, `close(pfd[1])`
        - `'w'`: `close(pfd[1])`, `dup2(pfd[0], STDIN_FILENO);`, `close(pfd[0])`
      - `exec(3)`: execute `command`

    - parent
        - `close(2)`: close unused file descriptor
        - `fdopen(3)`: open another file descriptor
            - `'r'`: `close(pfd[1])`, `fdopen(pfd[0], 'r');`
            - `'w'`: `close(pfd[0])`, `fdopen(pfd[1], 'w');`
        - set the buffer to remember child pid for the file descriptor
        - return file pointer



- `pclose(3)`: `int pclose(FILE *stream);`
    - return: exit status, -1 error
    - internal implementation
        - `fileno(3)`: get file descriptor from file pointer
        - get `pid` from the buffer, set that element to zero
        - `fclose(3)`: close file pointer
        - `waitpid(2)`: wait for `pid` and store status
        - return status

- `popen(2)` Example

```
int main() {
  int c;
  while ((c = getchar()) != EOF) {
    if (isupper(c)) c = tolower(c);
    if (putchar(c) == EOF) printf("err");
```

```
    if (c == '\n') fflush(stdout);
  }
}
```

```
int main() {
  char line[MAXLINE];
  FILE *fpin;
  if ((fpin = popen("./myuclc", "r")) == NULL)
    printf("err");
  while (1) {
    fputs("prompt> ", stdout);
    fflush(stdout);
    if (fgets(line, MAXLINE, fpin) == NULL)
      break;
    if (fputs(line, stdout) == EOF)
      printf("err");
  }
  if (pclose(fpin) == -1)
    printf("err");
  putchar('\n');
}
```

```
$ ./filter
prompt> abcdEFGH
abcdefgh
prompt> ^C
$
```

- Coprocess
  - input and output are associated with the same program
  - two pipes are needed
  - cannot use `popen(3)`, need to `fork(2)`, `close(2)`, `dup2(2)` from scratch

```
int main(void) {
  int n, fd1[2], fd2[2];
  pid_t pid;
  char line[MAXLINE];
  if (signal(SIGPIPE, sig_pipe) == SIG_ERR) err_sys("signal error");
  if (pipe(fd1) < 0 || pipe(fd2) < 0) err_sys("pipe error");
  if ((pid = fork()) < 0) {
    err_sys("fork error");
  } else if (pid > 0) { /* parent */
    close(fd1[0]);
    close(fd2[1]);
    while (fgets(line, MAXLINE, stdin) != NULL) {
      n = strlen(line);
```

```
        if (write(fd1[1], line, n) != n) err_sys("write error to pipe");
        if ((n = read(fd2[0], line, MAXLINE)) < 0)
          err_sys("read error from pipe");
        if (n == 0) {
          err_msg("child closed pipe");
          break;
        }
        line[n] = 0; /* null terminate */
        if (fputs(line, stdout) == EOF) err_sys("fputs error");
      }
      if (ferror(stdin)) err_sys("fgets error on stdin");
      exit(0);
    } else { /* child */
      close(fd1[1]);
      close(fd2[0]);
      if (fd1[0] != STDIN_FILENO) {
        if (dup2(fd1[0], STDIN_FILENO) != STDIN_FILENO)
          err_sys("dup2 error to stdin");
        close(fd1[0]);
      }
      if (fd2[1] != STDOUT_FILENO) {
        if (dup2(fd2[1], STDOUT_FILENO) != STDOUT_FILENO)
          err_sys("dup2 error to stdout");
        close(fd2[1]);
      }
      if (execl("./add2", "add2", (char *)0) < 0) err_sys("execl
error");
    }
    exit(0);
}
```

- if coprocess is implemented using standard I/O?
  - not work
  - because of I/O buffering mode
    - when standard I/O are not terminal devices, they are fully buffered
  - solution: need pseudo-terminals devices to emulate the line buffer or unbuffered channel

FIFOs

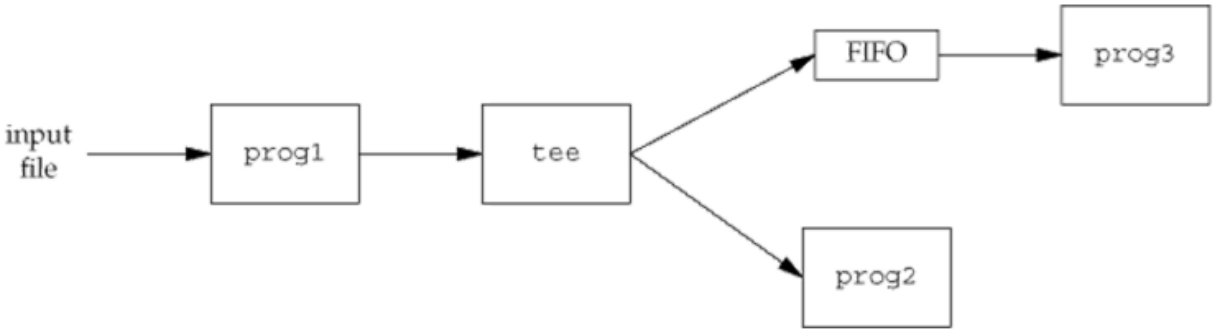
- First In First Out
  - sometimes called named pipes
  - pipes can be only used between processes of a common ancestor
  - but FIFO can used between unrelated processes
  - `mkfifo(3)`: `int mkfifo(const char *pathname, mode_t mode);`
    - return: 0 OK, -1 error
    - if `O_NONBLOCK` is not specified (normal case)
      - open for read-only blocks until others write
      - open for write-only blocks until others read
    - if `O_NONBLOCK` is specified

    - open for read-only returns immediately
    - open for write-only returns -1 with errno `ENXIO` if no others read

- Data Passing

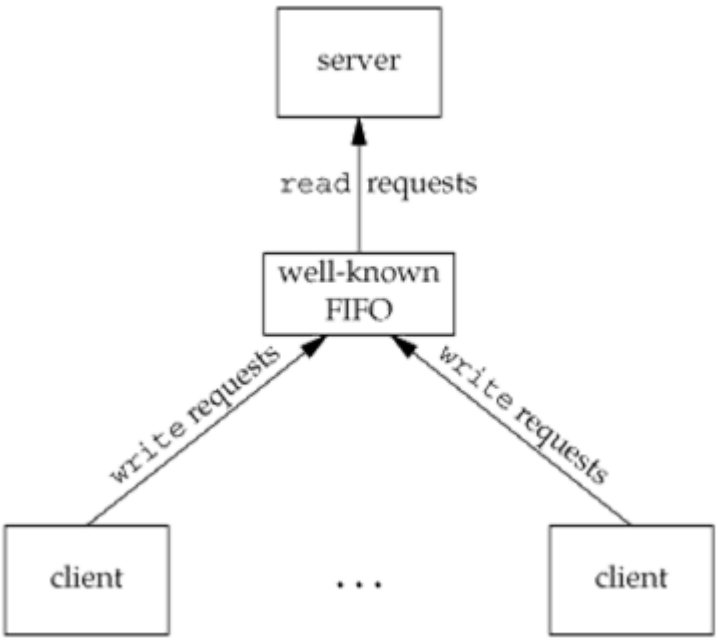
    - `tee`: read from standard input and write to standard output and files

    ```
    $ mkfifo fifo1
    $ prog3 < fifo1 &
    $ prog1 < infile | tee fifo1 | prog2
    ```

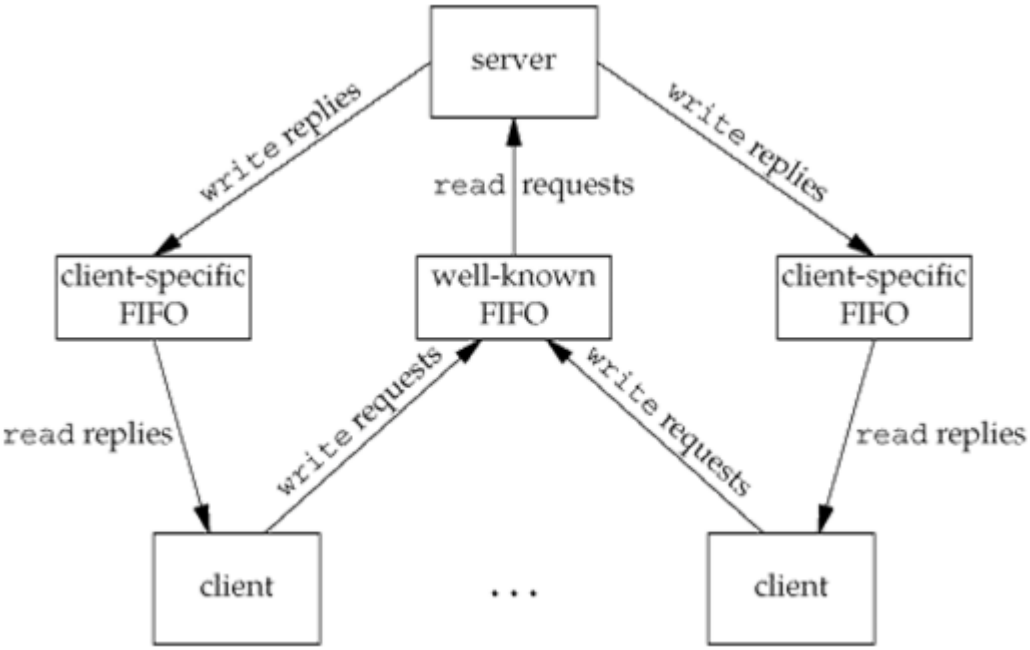


- Client-Server Communication

    - one-way communication



    - two-way communication



XSI (SysV) IPC

- XSI: X/Open System Interface
  - three types of XSI IPC
    - message queue
    - semaphore
    - shared memory
  - common user commands
    - `ipcs`: show information on IPC facilities
    - `ipcrm`: remove certain IPC resources
  - IPC identifiers
    - each IPC structure is referred to non-negative integer
    - but the identifier is an internal name for an IPC object
      - naming scheme is needed to refer the same IPC object - the IPC keys
    - IPC keys
      - a key must be specified whenever IPC object is being created
      - datatype `key_t`
      - then, the identifier of the referred IPC object is returned
  - share of IPC objects
    - server creates an IPC object with a key of `PIC_PRIVATE`
      - the identifier can be passed by storing in a file, or
      - fork a child which inherits the identifier
    - server and client can agree on a key by defining the key in a common header
    - server and client can agree on a pathname and a project ID
      - generate key by `ftok(3)`
      - `key_t ftok(const char *pathname, int proj_id);`
        - return: key OK, -1 error
        - `pathname` must be an existing file
        - `id` is a 8-bit non-zero number
- Advantages

    - reliable
    - support flow control
    - record based
    - can be processed in other than FIFO order
- Disadvantages
    - IPC data may left in the system even if no one refers to it
    - different from file system objects, i.e. no descriptors
    - need a different set of system calls to manipulate them

Message Queues

- Message Queues
    - linked list of messages
    - `msgget(2)`: `int msgget(key_t key, int msgflg);`
        - return: message queue identifier, -1 error
        - creating or opening a message queue
        - upon creating, least significant 9 bits of `msgflg` define the permissions
        - `msgflg` can be combination of `IPC_CREAT` and `IPC_EXCL`
- System Limitations

```
$ ipcs -l  # ipcs -Q on BSD and MAC OS X
------ Messages Limits --------
max queues system wide = 32000
max size of message (bytes) = 8192
default max size of queue (bytes) = 16384
...
```

- Controlling a Message Queue
    - `msgctl(2)`: `int msgctl(int msqid, int cmd, struct msqid_ds *buf);`
        - return: 0 OK, -1 error
        - `cmd`
            - `IPC_STAT`: retrieve the internal data
            - `IPC_SET`: set the internal data
                - only superuser is able to increase `msg_qbytes`
            - `IPC_RMID`: remove the queue immediately

```
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 (nonstandard) */
  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) */
};

struct ipc_perm {
  key_t          __key;       /* Key supplied to msgget(2) */
  uid_t          uid;         /* Effective UID of owner */
  gid_t          gid;         /* Effective GID of owner */
  uid_t          cuid;        /* Effective UID of creator */
  gid_t          cgid;        /* Effective GID of creator */
  unsigned short mode;        /* Permissions */
  unsigned short __seq;       /* Sequence number */
};
```

- Send a Message into Queue
  - `msgsnd(2)`: `int msgsnd(int msqid, const void *msgp, size_t msgsz, int msgflg);`
    - return: 0 OK, -1 error
    - `msgp` point to `struct msgbuf`

      ```
      struct msgbuf {
        long mtype;       /* message type, must be > 0 */
        char mtext[1];    /* message data */
      };
      ```

    - `msgflg`
      - `IPC_NOWAIT`: non-blocking access to the queue
      - if the queue is full and `IPC_NOWAIT` is specified
        - it returns error with `errno` set to `EAGAIN`
- Receive a Message from Queue
  - `msgrcv(2)`: `ssize_t msgrcv(int msqid, void *msgp, size_t msgsz, long msgtyp, int msgflg);`
    - return: number of bytes copied into `mtext` array, -1 error
    - `msgtype`
      - 0: the first message is returned
      - >0: the first message whose type equals `msgtype` is returned
      - <0: the first message whose type is the lowest value less than or equal to `abs(msgtype)` is returned
    - `msgflg`
      - `IPC_NOWAIT`: non-blocking access to the queue

    - `MSG_EXCEPT`: `msgtype` >0, the first message whose type has a non-equal type is returned
    - `MSG_NOERROR`: if received message has a longer size than n bytes, it is truncated and returned

- Example

```
#define MESSAGE "hello, world!"

struct msgbuf {
  long mtype;    /* message type, must be > 0 */
  char mtext[0]; /* message data */
};

int main() {
  int qid = -1, rlen, wlen;
  char buf[1024];
  pid_t pid;
  struct msgbuf *msg = (struct msgbuf *)buf;
  if ((qid = msgget(IPC_PRIVATE, IPC_CREAT | IPC_EXCL | 0660)) < 0)
    err_sys("msgget");
  if ((pid = fork()) < 0) err_sys("fork");
  if (pid == 0) {
    msg->mtype = 0;
    if ((rlen = msgrcv(qid, msg, sizeof(buf) - sizeof(*msg), 0, 0)) <
0)
      err_sys("msgrcv");
    printf("[%ld] %s (%u bytes)\n", msg->mtype, msg->mtext, rlen);
  } else {
    msg->mtype = 1024;
    wlen = snprintf(msg->mtext, sizeof(buf) - sizeof(*msg), "%s",
MESSAGE);
    if (msgsnd(qid, msg, wlen + 1, 0) < 0)
      perror("msgsnd");
    else if (wait(&wlen) < 1)
      perror("wait");
    if (qid >= 0)
      if (msgctl(qid, IPC_RMID, NULL) < 0) err_sys("msgctl(RMID)");
  }
  return 0;
}
```

Semaphores

- Semaphores
    - shared counter
    - procedures
        1. test the semaphore
        2. if positive, the process can use the resource -> decrements the semaphore value by 1

3. if the value of the semaphore is 0 -> process goes to sleep until value is positive

- independent of semaphore creation (`semget(2)`) and initialization (`semctl(2)`)
  - may be a problem as we cannot atomically create a new semaphore set and initialize them
- all XSI IPC objects are not release automatically
  - need to worry about termination without releasing semaphores
  - this can be solved by the semaphore `SEM_UNDO` feature

- `semget(2)`: `int semget(key_t key, int nsems, int semflg);`
  - return: semaphore set identifier, -1 error
  - upon creating, the least significant 9 bits of `semflg` define the permissions
  - `semflg` can be combination of `IPC_CREAT` and `IPC_EXCL`

- System Limitations

```
$ ipcs -l  # ipcs -Q on BSD and MAC OS X
...
------ Semaphore Limits --------
max number of arrays = 32000
max semaphores per array = 32000
max semaphores system wide = 1024000000
max ops per semop call = 500
semaphore max value = 32767
```

- Controlling Semaphores
  - `semctl(2)`: `int semctl(int semid, int semnum, int cmd, ...)`
    - return: depends on commands, -1 error
    - kernel maintains member in semaphore set

Name	Description
`semval`	semaphore value, always >= 0
`sempid`	pid for last operation
`semncnt`	# of processes waiting for the `semval` to increase
`semzcnt`	# of processes waiting for the `semval` to be zero

```
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) */
};

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 long   sem_nsems; /* No. of semaphores in set */
};

struct ipc_perm {
  key_t          __key;       /* Key supplied to msgget(2) */
  uid_t          uid;         /* Effective UID of owner */
  gid_t          gid;         /* Effective GID of owner */
  uid_t          cuid;        /* Effective UID of creator */
  gid_t          cgid;        /* Effective GID of creator */
  unsigned short mode;        /* Permissions */
  unsigned short __seq;       /* Sequence number */
};
```

- `cmd`

Command	Description
`IPC_STAT`	Retrieve the internal `semid_ds` data structure and stores in `arg.buf`
`IPC_SET`	Set the internal `semid_ds` data structure by `arg.buf`
`IPC_RMID`	Remove the semaphore (immediately)
`GETVAL`	Return the value of semnum-th member
`SETVAL`	Set the value of semnum-th member by `arg.val`
`GETPID`	Return the value of `sempid` for the semnum-th member
`GETNCNT`	Return the value of `semncnt` for the semnum-th member
`GETZCNT`	Return the value of `semzcnt` for the semnum-th member
`GETALL`	Retrieve all semaphore values, returned by `arg.array`
`SETALL`	Set all semaphore values by `arg.array`

- Semaphore Operations
  - `semop(2)`: `int semop(int semid, struct sembuf *sops, size_t nsops);`
    - return: 0 OK, -1 error

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

- `sem_op` is positive, added to the semaphore's value

        - if `SEM_UNDO` is specified, `sem_op` is subtracted from the semaphore's adjustment value for this process
    - `sem_op` is negative
        - if resources are available (|`sem_op`| >= `sem_val`)
            - |`sem_op`| is subtracted from the semaphore's value
            - if `SEM_UNDO` is specified, |`sem_op`| is added to the semaphore's adjustment value for this process
        - if resources are not available (|`sem_op`| < `sem_val`)
            - if `IPC_NOWAIT` is specified, `semop(2)` returns an error of `EAGAIN`
            - if `IPC_NOWAIT` is not specified
                - the `semncnt` value for this semaphore is increased
                - the process is suspended until
                    - the semaphore's value becomes greater or equal to the |`sem_op`|, the `semncnt` should be increased
                    - the semaphore is removed from the system: `semop(2)` returns an error of `EIDRM`
                    - it is interrupted by a signal: `semop(2)` returns an error of `EINTR`
    - `sem_op` is zero
        - wait until the semaphore's value becomes 0
        - if the value is currently 0, the function returns immediately, otherwise
        - if `IPC_NOWAIT` is specified, return is made with an error of `EAGAIN`
        - if `IPC_NOWAIT` is not specified
            - the `semzcnt` value for this semaphore is incremented
            - the process is suspended until
                - the semaphore's value becomes 0, the `semzcnt` should be increased
                - the semaphore is removed from the system: `semop(2)` returns an error of `EIDRM`
                - it is interrupted by a signal: `semop(2)` returns an error of `EINTR`

- Semaphore Adjustment on Terminating a Process

    - a program's termination without releasing semaphores may block future access
    - the problem can be solved by the `SEM_UNDO` feature
        - When we specify the `SEM_UNDO` flag for a semaphore operation
        - the kernel remembers how many resources we allocated from that particular semaphore
        - when the process terminates, the kernel checks whether the process has any outstanding semaphore adjustments, i.e., the value is > 0
        - if so, applies the adjustment to the corresponding semaphore
            - `semval` is increased by the adjustments

Shared Memory

- Shared Memory

    - fastest form of IPC
        - data does not to be copied
        - but need to synchronize access to a given region
        - synchronizing can be done by semaphores

- Creating or Opening a Shared Memory
  - `shmget(2)`: `int shmget(key_t key, size_t size, int shmflg);`
    - return: shared memory identifier, -1 error
    - upon creating, the lease significant 9 bits of `shmflg` define the permissions
    - `shmflg` can be combination of `IPC_CREAT` and `IPC_EXCL`
    - actual size is round up to multiples of `PAGE_SIZE`
    - when created, it's content initialized to all zero
- System Limitations

```
$ ipcs -l  # ipcs -Q on BSD and MAC OS X
...
------ Shared Memory Limits --------
max number of segments = 4096
max seg size (kbytes) = 262144
max total shared memory (kbytes) = 18014398509481980
min seg size (bytes) = 1
...
```

- Controlling Shared Memory
  - `shmctl(2)`: `int shmctl(int shmid, int cmd, struct shmid_ds *buf);`
    - return: 0 OK, -1 error

```
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 */
  ...
};

struct ipc_perm {
  key_t          __key;    /* Key supplied to shmget(2) */
  uid_t          uid;      /* Effective UID of owner */
  gid_t          gid;      /* Effective GID of owner */
  uid_t          cuid;     /* Effective UID of creator */
  gid_t          cgid;     /* Effective GID of creator */
  unsigned short mode;     /* Permissions + SHM_DEST and
SHM_LOCKED flags */
  unsigned short __seq;    /* Sequence number */
};
```

        - `cmd`
            - `IPC_STAT`: Retrieve the internal `shmid_ds` data structure
            - `IPC_SET`: Set the internal `shmid_ds` data structure
            - `IPC_RMID`: Remove the shared memory, but it is actually removed until the last process using the segment terminates or detaches it
            - `SHM_LOCK`: Make the shared memory not swappable
            - `SHM_UNLOCK`: Make the shared memory swappable
                - the two commands can be only used y superuser

- Attach a Shared Memory

    - `shmat(2)`: `void *shmat(int shmid, const void *shmaddr, int shmflg);`
        - return: address of the attached shared memory, (void *)-1 error
        - `shmaddr`
            - `NULL`
                - the segment is attached at the first available address selected by the kernel (recommended)
            - not `NULL` and `SHM_RND` is not specified
                - the segment is attached at the address given by `addr`
            - not `NULL` and `SHM_RND` is specified
                - the segment is attached at the address given by `addr` - `addr modulus SHMLBA` (round down to the multiples of `SHMLBA`)
        - `flag`
            - if the `SHM_RDONLY` bit is specified in `flag`, the segment is attached read-only

- Detach a Shared Memory

    - `shmdt(2)`: `int shmdt(void *addr)`
        - return: 0 OK, -1 error