CS162
Operating Systems and Systems Programming
Lecture 4

Fork (con't), Introduction to I/O (Everything is a File!)

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Recall: Process Creating New Processes

- `pid_t fork()` – copy the current process
  - New process has different pid
  - New process contains a single thread
- Return value from **`fork()`**: pid (like an integer)
  - When > 0:
    - » Running in (original) Parent process
    - » return value is pid of new child
  - When = 0:
    - » Running in new Child process
  - When < 0:
    - » Error! Must handle somehow
    - » Running in original process
- State of original process duplicated in *both* Parent and Child!
  - Address Space (Memory), File Descriptors (covered later), etc…

Recall: fork1.c

c p

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                  /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {          /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```


Recall: fork1.c

p c

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char *argv[]) {
  pid_t cpid, mypid;
  pid_t pid = getpid();            /* get current processes PID */
  printf("Parent pid: %d\n", pid);
  cpid = fork();
  if (cpid > 0) {                  /* Parent Process */
    mypid = getpid();
    printf("[%d] parent of [%d]\n", mypid, cpid);
  } else if (cpid == 0) {          /* Child Process */
    mypid = getpid();
    printf("[%d] child\n", mypid);
  } else {
    perror("Fork failed");
  }
}
```

Mystery: fork_race.c

```
int i;
pid_t cpid = fork();
if (cpid > 0) {
  for (i = 0; i < 10; i++) {
    printf("Parent: %d\n", i);
    // sleep(1);
  }
} else if (cpid == 0) {
  for (i = 0; i > -10; i--) {
    printf("Child: %d\n", i);
    // sleep(1);
  }
}
```

Recall: a process consists of one or more threads executing in an address space

- Here, each process has a single thread
- These threads execute concurrently

- What does this print?
- Would adding the calls to `sleep()` matter?

Process Management API

- `exit` – terminate a process
- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

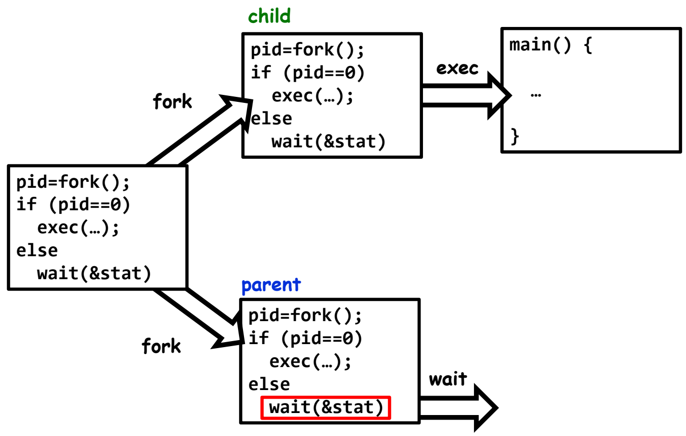
Starting new Program: variants of exec

```
…
cpid = fork();
if (cpid > 0) {               /* Parent Process */
  tcpid = wait(&status);
} else if (cpid == 0) {      /* Child Process */
  char *args[] = {"ls", "-l", NULL};
  execv("/bin/ls", args);

  /* execv doesn't return when it works.
     So, if we got here, it failed! */

  perror("execv");
  exit(1);
}
…
```


fork2.c – parent waits for child to finish

```
int status;
pid_t tcpid;
…
cpid = fork();
if (cpid > 0) {               /* Parent Process */
  mypid = getpid();
  printf("[%d] parent of [%d]\n", mypid, cpid);
  tcpid = wait(&status);
  printf("[%d] bye %d(%d)\n", mypid, tcpid, status);
} else if (cpid == 0) {      /* Child Process */
  mypid = getpid();
  printf("[%d] child\n", mypid);
  exit(42);
}
…
```

Process Management: The Shell pattern



Process Management API

- `exit` – terminate a process
- `fork` – copy the current process
- `exec` – change the *program* being run by the current process
- `wait` – wait for a process to finish
- `kill` – send a *signal* (interrupt-like notification) to another process
- `sigaction` – set handlers for signals

inf_loop.c

```
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>
#include <unistd.h>
#include <signal.h>

void signal_callback_handler(int signum) {
  printf("Caught signal!\n");
  exit(1);
}
int main() {
  struct sigaction sa;
  sa.sa_flags = 0;
  sigemptyset(&sa.sa_mask);
  sa.sa_handler = signal_callback_handler;
  sigaction(SIGINT, &sa, NULL);
  while (1) {}
}
```

Q: What would happen if the process receives a SIGINT signal, but does not register a signal handler?
A: The process dies!

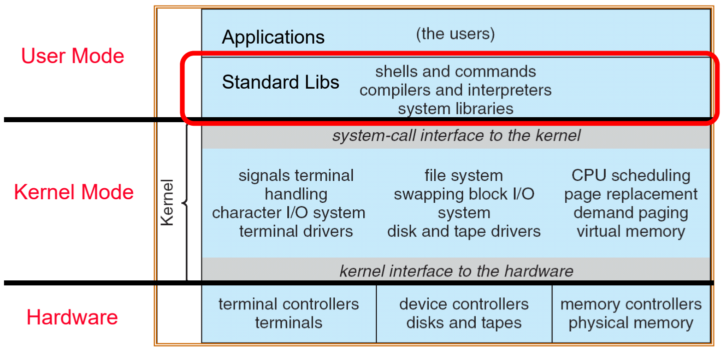
For each signal, there is a default handler defined by the system

Common POSIX Signals

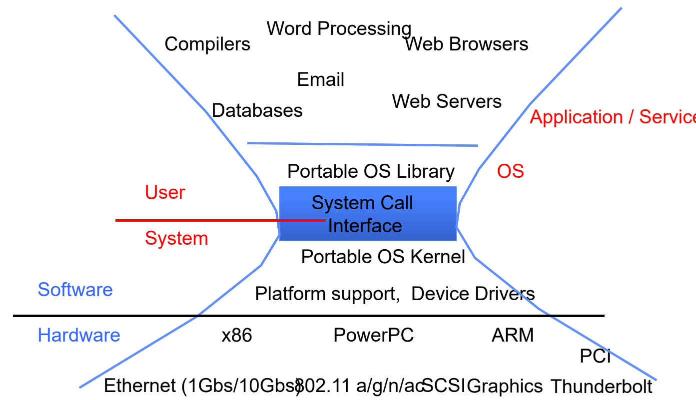
- `SIGINT` – control-C
- `SIGTERM` – default for `kill` shell command
- `SIGSTP` – control-Z (default action: stop process)

- `SIGKILL`, `SIGSTOP` – terminate/stop process
  - Can't be changed with `sigaction`
  - Why?

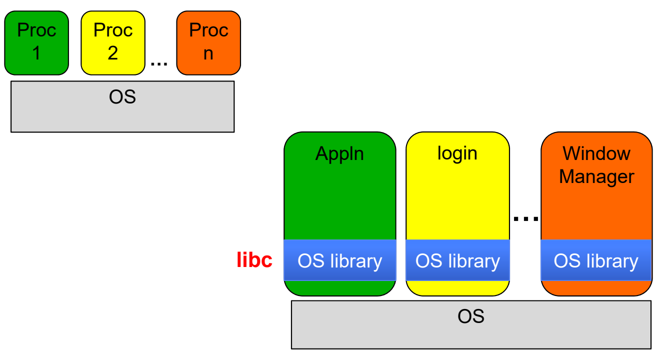
Recall: UNIX System Structure



A Kind of Narrow Waist



Recall: OS Library (libc) Issues Syscalls



- OS Library: Code linked into the user-level application that provides a clean or more functional API to the user than just the raw syscalls
  – Most of this code runs at user level, but makes syscalls (which run at kernel level)

Unix/POSIX Idea: Everything is a “File”

- Identical interface for:
  – Files on disk
  – Devices (terminals, printers, etc.)
  – Regular files on disk
  – Networking (sockets)
  – Local interprocess communication (pipes, sockets)
- Based on the system calls **`open()`**, **`read()`**, **`write()`**, and **`close()`**
- Additional: **`ioctl()`** for custom configuration that doesn’t quite fit
- Note that the “Everything is a File” idea was a radical idea when proposed
  – Dennis Ritchie and Ken Thompson described this idea in their seminal paper on UNIX called “The UNIX Time-Sharing System” from 1974
  – I posted this on the resources page if you are curious

Aside: POSIX interfaces

- POSIX: Portable Operating System Interface (for uniX?)
  - Interface for application programmers (mostly)
  - Defines the term "Unix," derived from AT&T Unix
  - Created to bring order to many Unix-derived OSes, so applications are portable
    - » Partially available on non-Unix OSes, like Windows
  - Requires standard system call interface

The File System Abstraction

- File
  - Named collection of data in a file system
  - POSIX File data: sequence of bytes
    - » Could be text, binary, serialized objects, …
  - File Metadata: information about the file
    - » Size, Modification Time, Owner, Security info, Access control
- Directory
  - "Folder" containing files & directories
  - Hierachical (graphical) naming
    - » Path through the directory graph
    - » Uniquely identifies a file or directory
      - /home/ff/cs162/public_html/fa14/index.html
  - Links and Volumes (later)

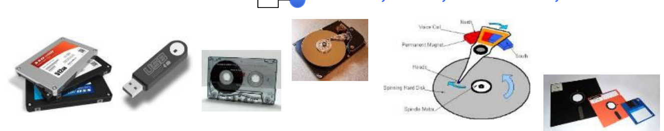
Connecting Processes, File Systems, and Users

- **Every process has a *current working directory* (CWD)**
  - Can be set with system call:
    ```
    int chdir(const char *path); //change CWD
    ```
- Absolute paths ignore CWD
  - /home/oski/cs162
- Relative paths are relative to CWD
  - index.html, ./index.html
    - » Refers to index.html in current working directory
  - ../index.html
    - » Refers to index.html in parent of current working directory
  - ~/index.html, ~cs162/index.html
    - » Refers to index.html in the home directory

I/O and Storage Layers

Application / Service

High Level I/O	***Streams (buffered I/O)***
Low Level I/O	***File Descriptors***
Syscall	***open(), read(), write(), close(), …***
	Open File Descriptions
File System	***Files/Directories/Indexes***
I/O Driver	***Commands and Data Transfers***
	Disks, Flash, Controllers, DMA



C High-Level File API – Streams

- Operates on "streams" – unformatted sequences of bytes (wither text or binary data), with a position: 

```
#include <stdio.h>
FILE *fopen( const char *filename, const char *mode );
int fclose( FILE *fp );
```

Mode Text	Binary	Descriptions
r	rb	Open existing file for reading
w	wb	Open for writing; created if does not exist
a	ab	Open for appending; created if does not exist
r+	rb+	Open existing file for reading & writing.
w+	wb+	Open for reading & writing; truncated to zero if exists, create otherwise
a+	ab+	Open for reading & writing. Created if does not exist. Read from beginning, write as append

- Open stream represented by pointer to a FILE data structure
  – Error reported by returning a NULL pointer

C API Standard Streams – `stdio.h`

- Three predefined streams are opened implicitly when the program is executed.
  - `FILE *stdin` – normal source of input, can be redirected
  - `FILE *stdout` – normal source of output, can too
  - `FILE *stderr` – diagnostics and errors
- STDIN / STDOUT enable composition in Unix
- All can be redirected
  - `cat hello.txt | grep "World!"`
  - **`cat`**'s **`stdout`** goes to **`grep`**'s **`stdin`**

C High-Level File API

```
// character oriented
int fputc( int c, FILE *fp );              // rtn c or EOF on err
int fputs( const char *s, FILE *fp );      // rtn > 0 or EOF

int fgetc( FILE * fp );
char *fgets( char *buf, int n, FILE *fp );

// block oriented
size_t fread(void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);
size_t fwrite(const void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);

// formatted
int fprintf(FILE *restrict stream, const char *restrict format, ...);
int fscanf(FILE *restrict stream, const char *restrict format, ... );
```


C Streams: Char-by-Char I/O

```
int main(void) {
  FILE* input = fopen("input.txt", "r");
  FILE* output = fopen("output.txt", "w");
  int c;

  c = fgetc(input);
  while (c != EOF) {
    fputc(output, c);
    c = fgetc(input);
  }
  fclose(input);
  fclose(output);
}
```

C High-Level File API

```
// character oriented
int fputc( int c, FILE *fp );       // rtn c or EOF on err
int fputs( const char *s, FILE *fp );      // rtn > 0 or EOF

int fgetc( FILE * fp );
char *fgets( char *buf, int n, FILE *fp );

// block oriented
size_t fread(void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);
size_t fwrite(const void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);

// formatted
int fprintf(FILE *restrict stream, const char *restrict format, ...);
int fscanf(FILE *restrict stream, const char *restrict format, ... );
```


C Streams: Block-by-Block I/O

```
#define BUFFER_SIZE 1024
int main(void) {
  FILE* input = fopen("input.txt", "r");
  FILE* output = fopen("output.txt", "w");
  char buffer[BUFFER_SIZE];
  size_t length;
  length = fread(buffer, BUFFER_SIZE, sizeof(char), input);
  while (length > 0) {
    fwrite(buffer, length, sizeof(char), output);
    length = fread(buffer, BUFFER_SIZE, sizeof(char), input);
  }
  fclose(input);
  fclose(output);
}
```


Aside: Check your Errors!

- Systems programmers should always be paranoid!
  - Otherwise you get intermittently buggy code
- We should really be writing things like:

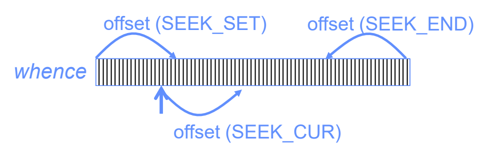
```
FILE* input = fopen(“input.txt”, “r”);
if (input == NULL) {
  // Prints our string and error msg.
  perror(“Failed to open input file”)
}
```

- Be **thorough about checking return values!**
  - Want failures to be systematically caught and dealt with
- I may be a bit loose with error checking for examples in class (to keep short)
  - Do as I say, not as I show in class!

C High-Level File API: Positioning The Pointer

```
int fseek(FILE *stream, long int offset, int whence);
long int ftell (FILE *stream)
void rewind (FILE *stream)
```

- For `fseek()`, the `offset` is interpreted based on the `whence` argument (constants in `stdio.h`):
  - `SEEK_SET`: Then offset interpreted from beginning (position 0)
  - `SEEK_END`: Then offset interpreted backwards from end of file
  - `SEEK_CUR`: Then offset interpreted from current position



- Overall preserves high-level abstraction of a uniform stream of objects

I/O and Storage Layers

Application / Service

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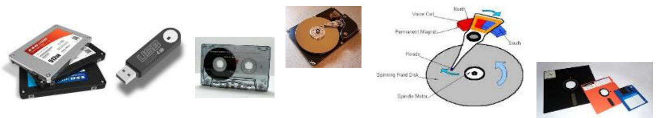


Low-Level File I/O: The RAW system-call interface

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int creat (const char *filename, mode_t mode)
int close (int filedes)
```

Bit vector of:
- **Access modes (Rd, Wr, …)**
- **Open Flags (Create, …)**
- **Operating modes (Appends, …)**

Bit vector of Permission Bits:
- **User|Group|Other X R|W|X**

- Integer return from `open()` is a *file descriptor*
  - *Error indicated by return < 0:* the global `errno` variable set with error (see man pages)
- Operations on *file descriptors*:
  - Open system call created an *open file description* entry in system-wide table of open files
  - *Open file description* object in the kernel represents an instance of an open file
  - Why give user an integer instead of a pointer to the file description in kernel?

C Low-Level (pre-opened) Standard Descriptors

```
#include <unistd.h>
STDIN_FILENO -  macro has value 0
STDOUT_FILENO - macro has value 1
STDERR_FILENO - macro has value 2

// Get file descriptor inside FILE *
int fileno (FILE *stream)

// Make FILE * from descriptor
FILE * fdopen (int filedes, const char *opentype)
```


Low-Level File API

- Read data from open file using file descriptor:

```
ssize_t read (int filedes, void *buffer, size_t maxsize)
```

  – Reads up to `maxsize` bytes – **might actually read less!**
  – returns bytes read, 0 => EOF, -1 => error

- Write data to open file using file descriptor

```
ssize_t write (int filedes, const void *buffer, size_t size)
```

  – returns number of bytes written

- Reposition file offset within kernel (this is independent of any position held by high-level FILE descriptor for this file!

```
off_t lseek (int filedes, off_t offset, int whence)
```

Example: `lowio.c`

```
int main() {
  char buf[1000];
  int     fd = open("lowio.c", O_RDONLY, S_IRUSR | S_IWUSR);
  ssize_t rd = read(fd, buf, sizeof(buf));
  int    err = close(fd);
  ssize_t wr = write(STDOUT_FILENO, buf, rd);
}
```

- How many bytes does this program read?

POSIX I/O: Design Patterns

- Open before use
  - Access control check, setup happens here
- Byte-oriented
  - Least common denominator
  - OS responsible for hiding the fact that real devices may not work this way (e.g. hard drive stores data in blocks)
- Explicit close

POSIX I/O: Kernel Buffering

- Reads are buffered inside kernel
  - Part of making everything byte-oriented
  - Process is **blocked** while waiting for device
  - Let other processes run while gathering result
- Writes are buffered inside kernel
  - Complete in background (more later on)
  - Return to user when data is “handed off” to kernel

- This buffering is part of global buffer management and caching for block devices (such as disks)
  - Items typically cached in quanta of disk block sizes
  - We will have many interesting things to say about this buffering when we dive into the kernel

Low-Level I/O: Other Operations

- Operations specific to terminals, devices, networking, …
  - e.g., `ioctl`
- Duplicating descriptors
  - `int dup2(int old, int new);`
  - `int dup(int old);`
- Pipes – channel
  - `int pipe(int pipefd[2]);`
  - `Writes to pipefd[1] can be read from pipefd[0]`
- File Locking
- Memory-Mapping Files
- Asynchronous I/O

High-Level vs. Low-Level File API

High-Level Operation:

```
size_t fread(…) {
  Do some work like a normal fn…

  asm code … syscall # into %eax
  put args into registers %ebx, …
  special trap instruction
      Kernel:
        get args from regs
        dispatch to system func
        Do the work to read from the file
        Store return value in %eax
  get return values from regs
  Do some more work like a normal fn…
};
```

Low-Level Operation:

```
ssize_t read(…) {

  asm code … syscall # into %eax
  put args into registers %ebx, …
  special trap instruction
      Kernel:
        get args from regs
        dispatch to system func
        Do the work to read from the file
        Store return value in %eax
  get return values from regs

};
```


High-Level vs. Low-Level File API

- Streams are buffered in user memory:

```
printf("Beginning of line ");
sleep(10); // sleep for 10 seconds
printf("and end of line\n");
```

Prints out everything at once

- Operations on file descriptors are visible immediately

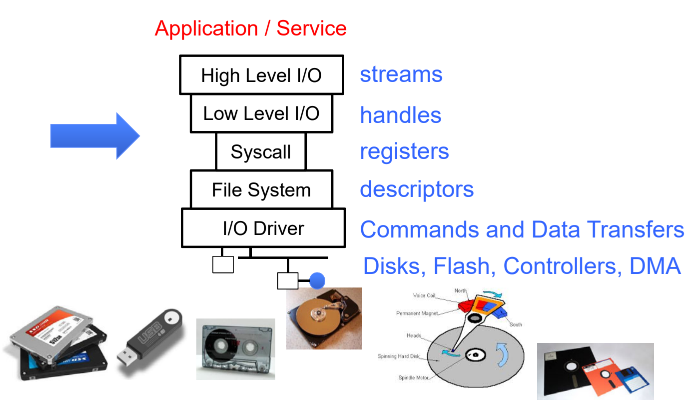
```
write(STDOUT_FILENO, "Beginning of line ", 18);
sleep(10);
write("and end of line \n", 16);
```

Outputs "Beginning of line" 10 seconds earlier than “and end of line”

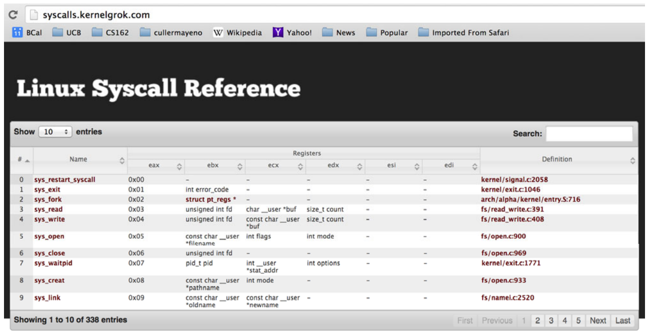
Administrivia

- Kubiatowicz Office Hours:
  – 1-2pm, Tuesday & Wednesday
- No one left on WaitList! Everyone left is in the class.
- TOMORROW (Friday) is Drop Deadline!
  VERY HARD TO DROP LATER!
- Recommendation: Read assigned readings *before* lecture
- You should be going to sections now – Important information covered in section
  – Any section will do until groups assigned
- Group sign up is operational now!
- Get finding groups of 4 people ASAP
  – Priority for same section; if cannot make this work, keep same TA
  – Remember: Your TA needs to see you in section!
- Midterm 1 conflicts
  – We will handle these conflicts next week

What’s below the surface ??



Recall: SYSCALL



Linux Syscall Reference

Show 10 entries Search:

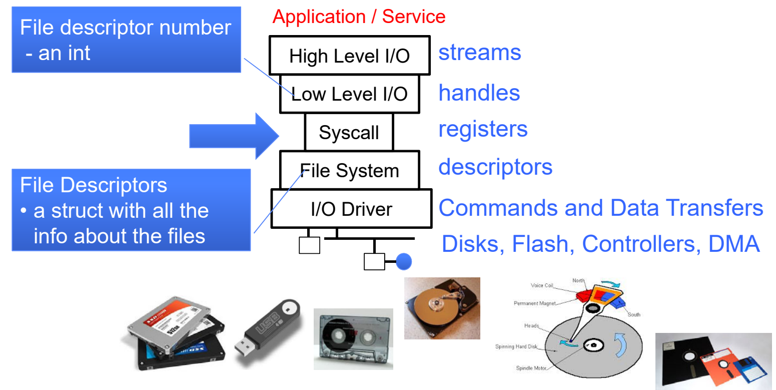
#	Name	Registers: eax	ebx	ecx	edx	esi	edi	Definition
0	sys_restart_syscall	0x00	-	-	-	-	-	kernel/signal.c:2058
1	sys_exit	0x01	int error_code	-	-	-	-	kernel/exit.c:1046
2	sys_fork	0x02	struct pt_regs *	-	-	-	-	arch/alpha/kernel/entry.S:716
3	sys_read	0x03	unsigned int fd	char __user *buf	size_t count	-	-	fs/read_write.c:391
4	sys_write	0x04	unsigned int fd	const char __user *buf	size_t count	-	-	fs/read_write.c:408
5	sys_open	0x05	const char __user *filename	int flags	int mode	-	-	fs/open.c:900
6	sys_close	0x06	unsigned int fd	-	-	-	-	fs/open.c:969
7	sys_waitpid	0x07	pid_t pid	int __user *stat_addr	int options	-	-	kernel/exit.c:1771
8	sys_creat	0x08	const char __user *pathname	int mode	-	-	-	fs/open.c:933
9	sys_link	0x09	const char __user *oldname	const char __user *newname	-	-	-	fs/namei.c:2520

Showing 1 to 10 of 338 entries

Generated from Linux kernel 2.6.35.4 using Exuberant Ctags, Python, and DataTables. Project on GitHub. Hosted on GitHub Pages.

- Low level lib parameters are set up in registers and syscall instruction is issued
  - A type of synchronous exception that enters well-defined entry points into kernel

What's below the surface ??



What's in an Open File Description?

Inside Kernel!

For our purposes, the two most important things are:

- Where to find the file data on disk
- The current position within the file

lxr.free-electrons.com/source/include/linux/fs.h#L747

```
struct file {
        union {
                struct llist_node       fu_llist;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
        struct inode            *f_inode;       /* cac
        const struct file_operations    *f_op;

        /*
         * Protects f_ep_links, f_flags.
         * Must not be taken from IRQ context.
         */
        spinlock_t              f_lock;
        atomic_long_t           f_count;
        unsigned int            f_flags;
        fmode_t                 f_mode;
        struct mutex            f_pos_lock;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        const struct cred       *f_cred;
        struct file_ra_state    f_ra;

        u64                     f_version;
#ifdef CONFIG_SECURITY
        void                    *f_security;
#endif
        /* needed for tty driver, and maybe others */
        void                    *private_data;

#ifdef CONFIG_EPOLL
        /* Used by fs/eventpoll.c to link all the hook
        struct list_head        f_ep_links;
        struct list_head        f_tfile_llink;
#endif /* #ifdef CONFIG_EPOLL */
        struct address_space    *f_mapping;
} __attribute__((aligned(4)));  /* lest something weir
```


File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return
  if (!file->f_op || (!file->f_op->read &&
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, bu
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Read up to "count" bytes from "file" starting from "pos" into "buf".
- Return error or number of bytes read.

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Make sure we are allowed to read this file

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check if file has read methods

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Check whether we can write to buf (e.g., buf is in the user space range)
- unlikely(): hint to branch prediction this condition is unlikely

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check whether we read from a valid range in the file.

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

If driver provide a read function (f_op->read) use it; otherwise use do_sync_read()

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->re
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Notify the parent of this file that the file was read (see http://www.fieldses.org/~bfields/kernel/vfs.txt)

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, po
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Update the number of bytes read by "current" task (for scheduling purposes)

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Update the number of read syscalls by "current" task (for scheduling purposes)

Lower Level Driver

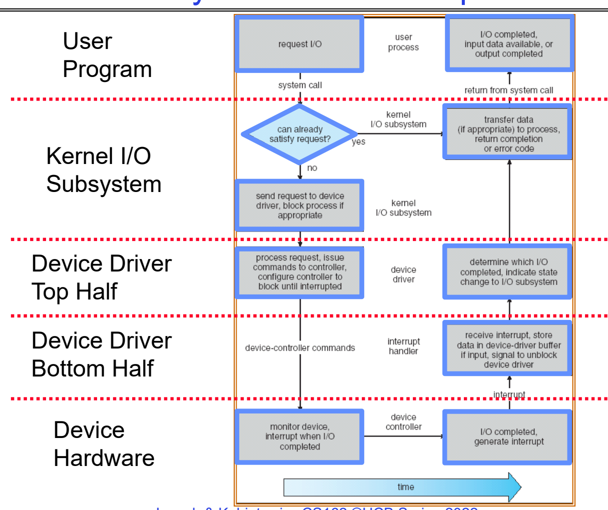
- Associated with particular hardware device
- Registers / Unregisters itself with the kernel
- Handler functions for each of the file operations

```
struct file_operations {
    struct module *owner;
    loff_t (*llseek) (struct file *, loff_t, int);
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    int (*readdir) (struct file *, void *, filldir_t);
    unsigned int (*poll) (struct file *, struct poll_table_struct *);
    int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);
    int (*mmap) (struct file *, struct vm_area_struct *);
    int (*open) (struct inode *, struct file *);
    int (*flush) (struct file *, fl_owner_t id);
    int (*release) (struct inode *, struct file *);
    int (*fsync) (struct file *, struct dentry *, int datasync);
    int (*fasync) (int, struct file *, int);
    int (*flock) (struct file *, int, struct file_lock *);
    [...]
};
```


Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - » implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - » This is the kernel's interface to the device driver
    - » Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - » Gets input or transfers next block of output
    - » May wake sleeping threads if I/O now complete

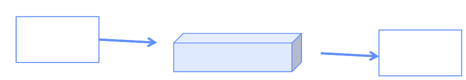
Life Cycle of An I/O Request



Communication between processes

- Can we view files as communication channels?

```
write(wfd, wbuf, wlen);
```

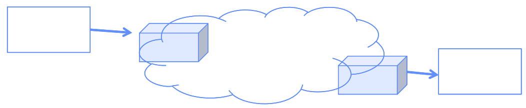


```
n = read(rfd,rbuf,rmax);
```

- Producer and Consumer of a file may be distinct processes
  - May be separated in time (or not)
- However, what if data written once and consumed once?
  - Don't we want something more like a queue?
  - Can still look like File I/O!

Communication Across the world looks like file IO!

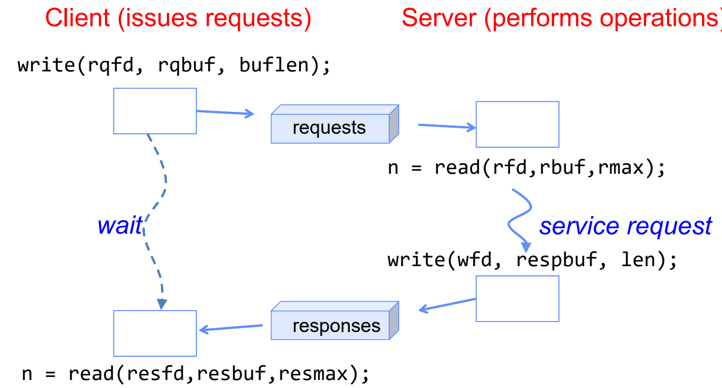
`write(wfd, wbuf, wlen);`



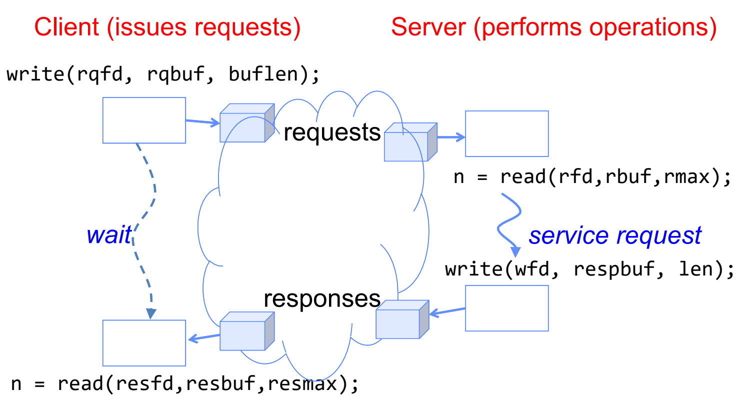
`n = read(rfd,rbuf,rmax);`

- Connected queues over the Internet
  - But what's the analog of open?
  - What is the namespace?
  - How are they connected in time?

Request Response Protocol



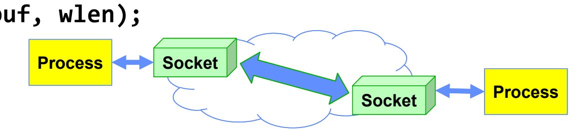
Request Response Protocol: Across Network



The Socket Abstraction: Endpoint for Communication

- **Key Idea:** Communication across the world looks like File I/O

`write(wfd, wbuf, wlen);`



`n = read(rfd, rbuf, rmax);`

- Sockets: Endpoint for Communication
  - Queues to temporarily hold results
- Connection: Two Sockets Connected Over the network ⇒ IPC over network!
  - How to **open()**?
  - What is the namespace?
  - How are they connected in time?

Sockets: More Details

- **Socket:** An abstraction for one endpoint of a network connection
  - Another mechanism for **inter-process communication**
  - Most operating systems (Linux, Mac OS X, Windows) provide this, even if they don't copy rest of UNIX I/O
  - Standardized by POSIX
- First introduced in 4.2 BSD (Berkeley Standard Distribution) Unix
  - This release had some huge benefits (and excitement from potential users)
  - Runners waiting at release time to get release on tape and take to businesses
- Same abstraction for any kind of network
  - Local (within same machine)
  - The Internet (TCP/IP, UDP/IP)
  - Things "no one" uses anymore (OSI, Appletalk, IPX, …)

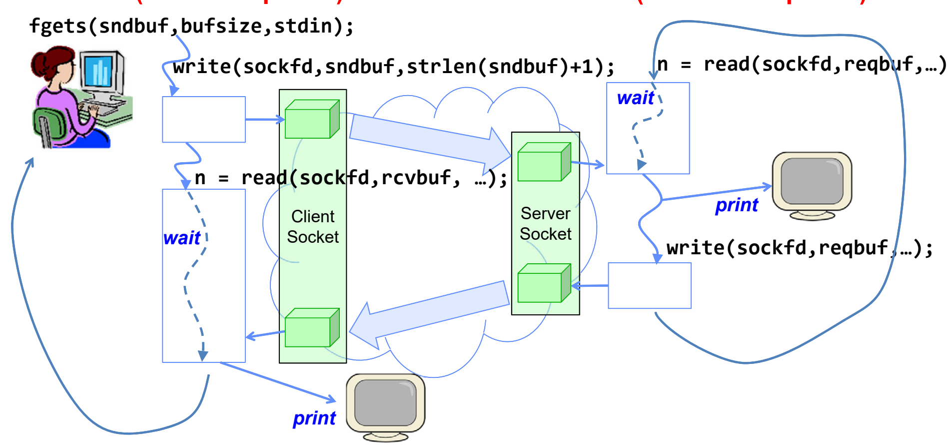
Sockets: More Details

- Looks just like a file with a **file descriptor**
  - Corresponds to a network connection (*two* queues)
  - **`write`** adds to output queue (queue of data destined for other side)
  - **`read`** removes from it input queue (queue of data destined for this side)
  - Some operations do not work, e.g. **`lseek`**
- How can we use sockets to support real applications?
  - A bidirectional byte stream isn't useful on its own…
  - May need messaging facility to partition stream into chunks
  - May need RPC facility to translate one environment to another and provide the abstraction of a function call over the network

Simple Example: Echo Server

Simple Example: Echo Server

Client (issues requests) **Server (services requests)**



Echo client-server example

```
void client(int sockfd) {
  int n;
  char sndbuf[MAXIN]; char rcvbuf[MAXOUT];
  while (1) {
    fgets(sndbuf,MAXIN,stdin);                /* prompt */
    write(sockfd, sndbuf, strlen(sndbuf)+1); /* send (including null terminator) */
    memset(rcvbuf,0,MAXOUT);                  /* clear */
    n=read(sockfd, rcvbuf, MAXOUT);           /* receive */
    write(STDOUT_FILENO, rcvbuf, n);          /* echo */
}
```

```
void server(int consockfd) {
  char reqbuf[MAXREQ];
  int n;
  while (1) {
    memset(reqbuf,0, MAXREQ);
    len = read(consockfd,reqbuf,MAXREQ); /* Recv */
    if (n <= 0) return;
    write(STDOUT_FILENO, reqbuf, n);
    write(consockfd, reqbuf, n); /* echo*/
  }
}
```


What Assumptions are we Making?

- Reliable
  - Write to a file => Read it back. Nothing is lost.
  - Write to a (TCP) socket => Read from the other side, same.
- In order (sequential stream)
  - Write X then write Y => read gets X then read gets Y
- When ready?
  - File read gets whatever is there at the time
    - » Actually need to loop and read until we receive the terminator ('\0')
  - Assumes writing already took place
  - Blocks if nothing has arrived yet

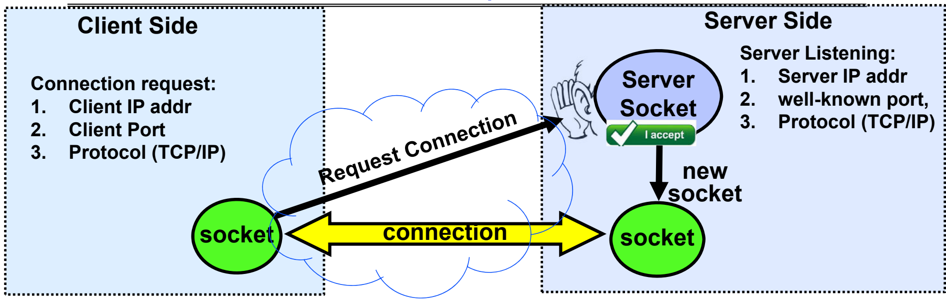
Socket Creation

- File systems provide a collection of permanent objects in a structured name space:
  - Processes open, read/write/close them
  - Files exist independently of processes
  - Easy to name what file to `open()`
- Pipes: one-way communication between processes on same (physical) machine
  - Single queue
  - Created transiently by a call to `pipe()`
  - Passed from parent to children (descriptors inherited from parent process)
- Sockets: two-way communication between processes on same or different machine
  - Two queues (one in each direction)
  - Processes can be on separate machines: no common ancestor
  - How do we *name* the objects we are opening?
  - How do these completely independent programs know that the other wants to "talk" to them?

Namespaces for Communication over IP

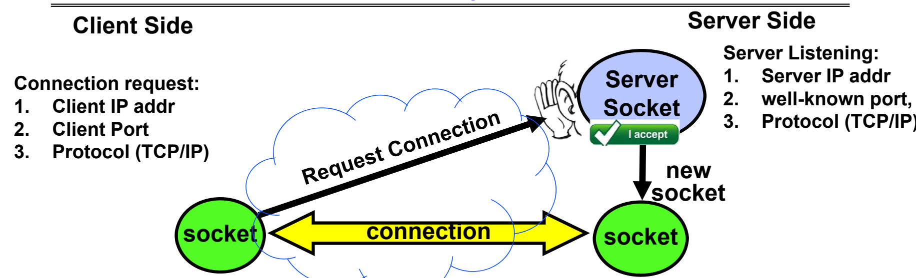
- Hostname
  - www.eecs.berkeley.edu
- IP address
  - 128.32.244.172 (IPv4, 32-bit Integer)
  - 2607:f140:0:81::f (IPv6, 128-bit Integer)
- Port Number
  - 0-1023 are "well known" or "system" ports
    - » Superuser privileges to bind to one
  - 1024 – 49151 are "registered" ports (registry)
    - » Assigned by IANA for specific services
  - 49152–65535 ($2^{15}+2^{14}$ to $2^{16}-1$) are "dynamic" or "private"
    - » Automatically allocated as "ephemeral ports"

Connection Setup over TCP/IP



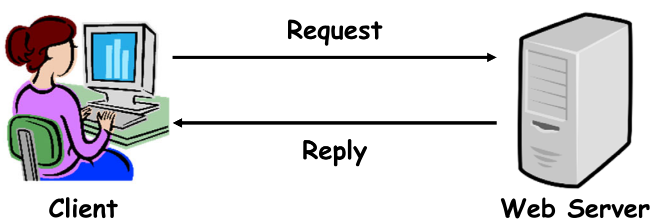
- Special kind of socket: **server socket**
  – Has file descriptor
  – Can't read or write
- Two operations:
  1. **listen()**: Start allowing clients to connect
  2. **accept()**: Create a *new socket* for a *particular* client

Connection Setup over TCP/IP

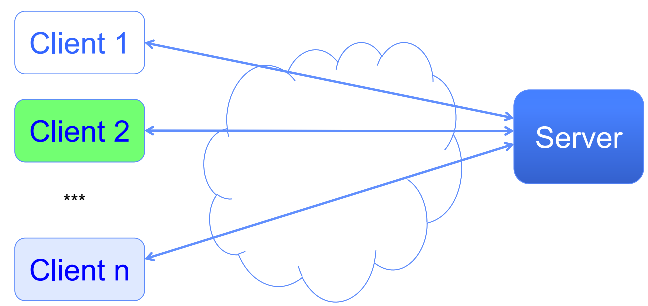


- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port "randomly" assigned
  – Done by OS during client socket setup
- Server Port often "well known"
  – 80 (web), 443 (secure web), 25 (sendmail), etc
  – Well-known ports from 0—1023

Web Server

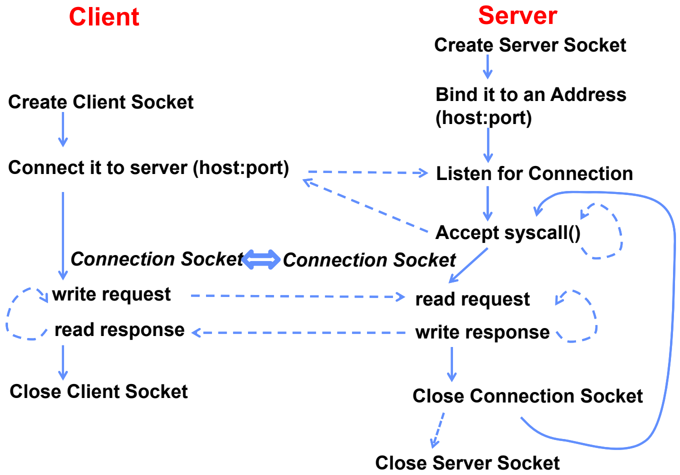


Client-Server Models



- File servers, web, FTP, Databases, …
- Many clients accessing a common server

Sockets in concept



Client Protocol

```
char *host_name, *port_name;

// Create a socket
struct addrinfo *server = lookup_host(host_name, port_name);
int sock_fd = socket(server->ai_family, server->ai_socktype,
                     server->ai_protocol);

// Connect to specified host and port
connect(sock_fd, server->ai_addr, server->ai_addrlen);

// Carry out Client-Server protocol
run_client(sock_fd);

/* Clean up on termination */
close(sock_fd);
```


Server Protocol (v1)

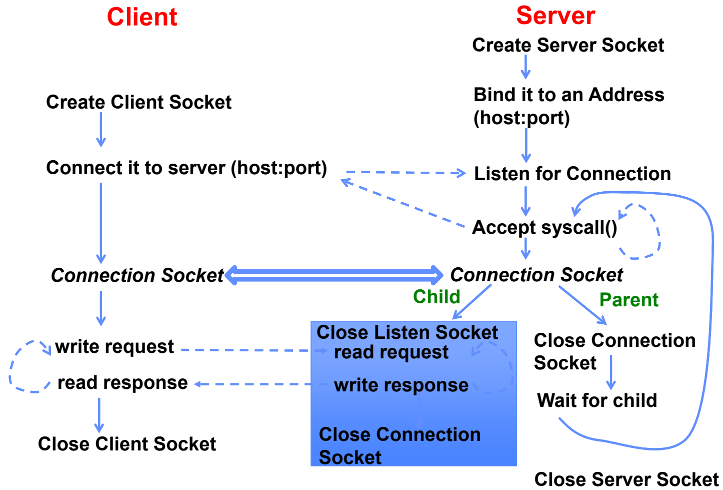
```
// Create socket to listen for client connections
char *port_name;
struct addrinfo *server = setup_address(port_name);
int server_socket = socket(server->ai_family,
      server->ai_socktype, server->ai_protocol);
// Bind socket to specific port
bind(server_socket, server->ai_addr, server->ai_addrlen);
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  serve_client(conn_socket);
  close(conn_socket);
}
close(server_socket);
```


How Could the Server Protect Itself?

- Handle each connection in a separate process
  - This will mean that the logic serving each request will be “sandboxed” away from the main server process

Sockets With Protection (each connection has own process)



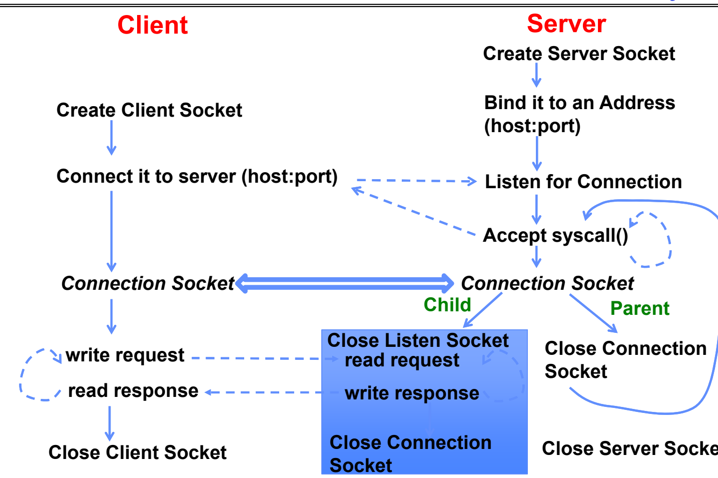
Server Protocol (v2)

```
// Socket setup code elided…
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    wait(NULL);
  }
}
close(server_socket);
```


Concurrent Server

- So far, in the server:
  - Listen will queue requests
  - Buffering present elsewhere
  - But server waits for each connection to terminate before servicing the next
- A concurrent server can handle and service a new connection before the previous client disconnects

Sockets With Protection and Concurrency



Server Protocol (v3)

```
// Socket setup code elided…
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    //wait(NULL);
  }
}
close(server_socket);
```


Server Address: Itself

```
struct addrinfo *setup_address(char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;
  hints.ai_socktype = SOCK_STREAM;
  hints.ai_flags = AI_PASSIVE;
  getaddrinfo(NULL, port, &hints, &server);
  return server;
}
```

- Accepts any connections on the specified port

Client: Getting the Server Address

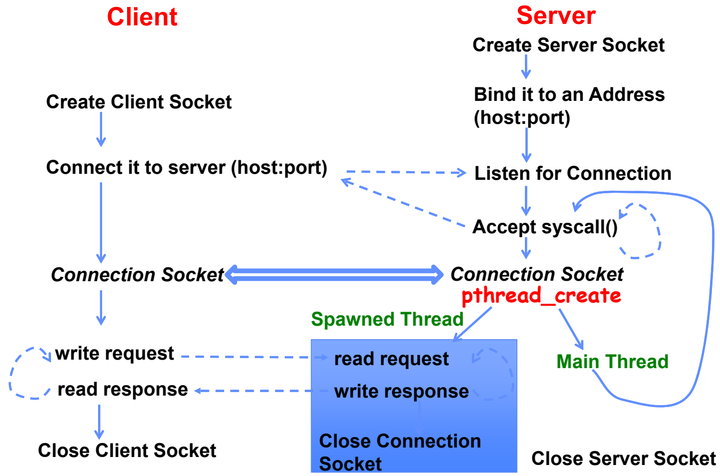
```
struct addrinfo *lookup_host(char *host_name, char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;
  hints.ai_socktype = SOCK_STREAM;

  int rv = getaddrinfo(host_name, port_name,
                       &hints, &server);
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```


Concurrent Server without Protection

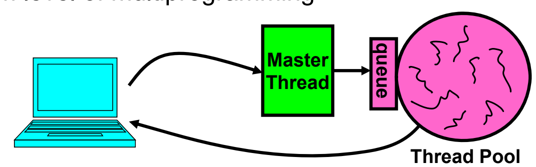
- Spawn a new thread to handle each connection
- Main thread initiates new client connections without waiting for previously spawned threads
- Why give up the protection of separate processes?
  - More efficient to create new threads
  - More efficient to switch between threads

Sockets with Concurrency, without Protection



Thread Pools: More Later!

- Problem with previous version: Unbounded Threads
  – When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming




```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```


Conclusion (I)

- System Call Interface is "narrow waist" between user programs and kernel
- Streaming IO: modeled as a stream of bytes
  – Most streaming I/O functions start with "f" (like "`fread`")
  – Data buffered automatically by C-library functions
- Low-level I/O:
  – File descriptors are integers
  – Low-level I/O supported directly at system call level
- `STDIN` / `STDOUT` enable composition in Unix
  – Use of pipe symbols connects `STDOUT` and `STDIN`
    » `find | grep | wc …`

Conclusion (II)

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  – Supports a standard, internal interface
  – Same kernel I/O system can interact easily with different device drivers
- File abstraction works for inter-processes communication (local or Internet)
- Socket: an abstraction of a network I/O queue
  – Mechanism for inter-process communication