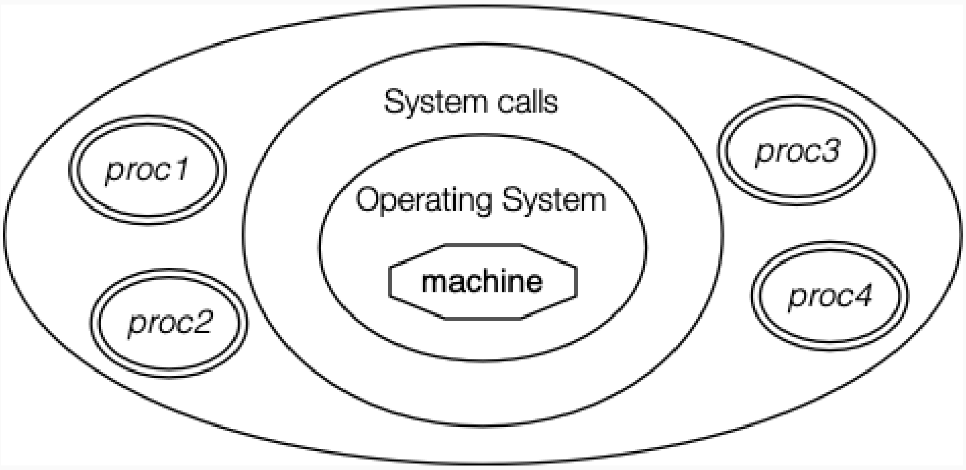
COMP1521 24T1 — Processes

https://www.cse.unsw.edu.au/~cs1521/24T1/

Processes

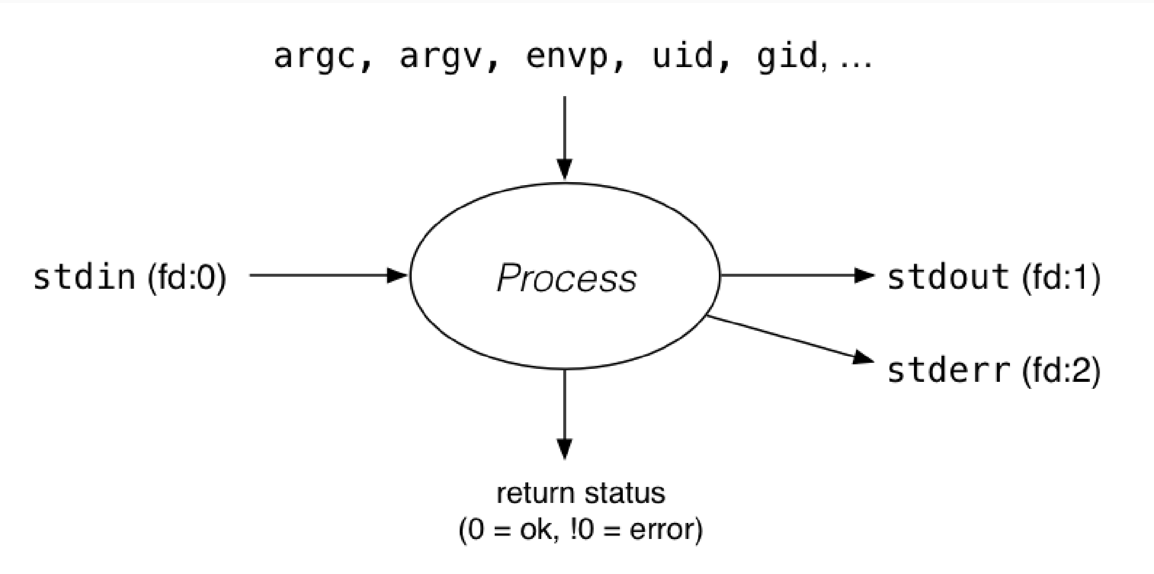
A *process* is a program executing in an environment



The operating system manages processes (create, finish, pre-empt)

Unix/Linux Processes

Environment for processes running on Unix/Linux systems



Processes

A *process* is an instance of an executing program.

Each process has an *execution state*, defined by...

- current values of CPU registers
- current contents of its memory
- information about open files (and other results of system calls)

On Unix/Linux:

- each process has a unique process ID, or PID: a positive integer, type **`pid_t`**, defined in `<unistd.h>`
- PID 1: ***init***, used to boot the system.
- low-numbered processes usually system-related, started at boot
  - ... but PIDs are recycled, so this isn't *always* true
- some parts of the operating system may appear to run as processes
  - many Unix-like systems use PID 0 for the operating system

Parent Processes

Each process has a *parent process*.

- initially, the process that created it;
- if a process' parent terminates, its parent becomes *init* (PID 1)

A process may have *child processes*

- these are processes that it created

Unix Tools

Unix provides a range of tools for manipulating processes

Commands:

- `sh` ... creating processes via object-file name
- `ps` ... showing process information
- `w` ... showing per-user process information
- `top` ... showing high-cpu-usage process information
- `kill` ... sending a signal to a process

System Calls to Get information about a process

`pid_t getpid()`

- requires `#include <sys/types.h>`
- returns the process ID of the current process

`pid_t getppid()`

- requires `#include <sys/types.h>`
- returns the parent process ID of the current process

For more details: `man 2 getpid`

There is also one we don't use in this course called:

- `getpgid()` ... get process group ID

System Calls to Get information about a process

Minimal example for `getpid() and getppid()`:

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

int main(void){
   printf("My PID is (%d)\n", getpid());
   printf("My parent's PID is (%d)\n", getppid());
   return 0;
}
```


Environment Variables

- When run, a program is passed a set of *environment variables* an array of strings of the form **`name=value`**, terminated with `NULL`.
- access via global variable **`environ`**
  - many C implementations also provide as 3rd parameter to `main`:

    ```
    int main(int argc, char *argv[], char *env[])
    ```

```
// print all environment variables
extern char **environ;
for (int i = 0; environ[i] != NULL; i++) {
    printf("%s\n", environ[i]);
}
```

source code for environ.c

- Recommended you use **`getenv()`** and **`setenv()`** to access environment variables

- Unix-like shells have simple syntax to set environment variables
  - common to set environment in startup files (e.g `.profile`)
  - then passed to any programs they run
- Almost all program pass the environment variables they are given to any programs they run
  - perhaps adding/changing the value of specific environment variables
- Provides simple mechanism to pass settings to all programs, e.g
  - timezone (TZ)
  - user's prefered language (LANG)
  - directories to search for promrams (PATH)
  - user's home directory (HOME)

`getenv()` — get an environment variable

```
#include <stdlib.h>

char *getenv(const char *name);
```

- search environment variable array for **`name=value`**
- returns **`value`**
- returns **`NULL`** if **`name`** not in environment variable array

```
int main(void) {
    // print value of environment variable STATUS
    char *value = getenv("STATUS");
    printf("Environment variable 'STATUS' has value '%s'\n", value);
```

source code for get_status.c

`setenv()` — set an environment variable

```
#include <stdlib.h>

int setenv(const char *name, const char *value, int overwrite);
```

- adds **`name=value`** to environment variable array
- if **`name`** in array, value changed if **`overwrite`** is non-zero

Multi-Tasking

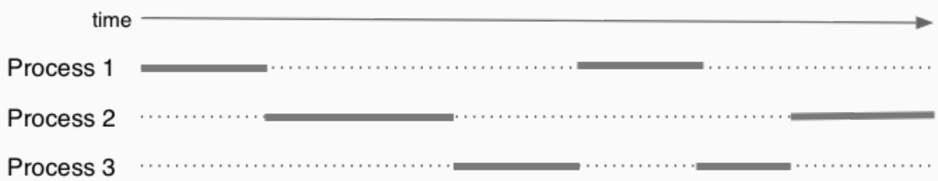
On a typical modern operating system...

- multiple processes are active "simultaneously" (*multi-tasking*)
- operating systems provides a virtual machine to each process:
  - each process executes as if the only process running on the machine
  - e.g. each process has its own address space (N bytes, addressed 0..N-1)

When there are multiple processes running on the machine,

- a process uses the CPU, until it is *preempted* or exits;
- then, another process uses the CPU, until it too is preempted.
- eventually, the first process will get another run on the CPU.

Multi-tasking



Overall impression: three programs running simultaneously. (In practice, these time divisions are imperceptibly small!)

Preemption — When? How?

What can cause a process to be preempted?

- it ran "long enough", and the OS replaces it by a waiting process
- it needs to wait for input, output, or other some other operation

On preemption...

- the process's entire state is saved
- the new process's state is restored
- this change is called a ***context switch***
- context switches are *very* expensive!

Which process runs next? The *scheduler** answers this. The operating system's process scheduling attempts to:

- fairly sharing the CPU(s) among competing processes,
- minimize response delays (lagginess) for interactive users,
- meet other real-time requirements (e.g. self-driving car),
- minimize number of expensive context switches

Process-related Unix/Linux Functions/System Calls

Creating processes:

- `system()`, `popen()` ... create a new process via a shell - convenient but major security risk
- `posix_spawn()` ... create a new process.
- `fork()` `vfork()` ... duplicate current process. (do not use in new code)
- `exec()` family ... replace current process.

Destroying processes:

- `exit()` ... terminate current process, see also
  - `_exit()` ... terminate *immediately*
    atexit functions not called, stdio buffers not flushed
- `waitpid()` ... wait for state change in child process

exec() family - replace yourself

```
#include <unistd.h>
int execv(const char *file, char *const argv[]);
int execvp(const char *file, char *const argv[]);
```

- Run another program in place of the current process:
  - `file`: an executable — either a binary, or script starting with `#!`
  - `argv`: arguments to pass to new program
- Most of the current process is re-initialized:
  - e.g. new address space is created - all variables lost
- open file descriptors survive
  - e.g, stdin & stdout remain the same
- PID unchanged
- if successful, exec does not return ... where would it return *to*?
- on error, returns -1 and sets `errno`

Example: using `exec()`

```
int main(void) {
    char *echo_argv[] = {"/bin/echo","good-bye","cruel","world",NULL};
    execv("/bin/echo", echo_argv);
    // if we get here there has been an error
    perror("execv");
```

source code for exec.c

```
$ dcc exec.c
$ a.out
good-bye cruel world
$
```

fork() — clone yourself (OBSOLETE)

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

pid_t fork(void);
```

Creates new process by duplicating the calling process.

- new process is the *child*, calling process is the *parent*

Both child and parent return from `fork()` call... how do we tell them apart?

- in the child, `fork()` returns 0
- in the parent, `fork()` returns the pid of the child
- if the system call failed, `fork()` returns -1

Child inherits copies of parent's address space, open file descriptors, ...

Do not use in new code! Use *`posix_spawn()`* instead.

`fork()` appears simple, but is prone to subtle bugs

Example: using fork() (OBSOLETE)

```
// fork creates 2 identical copies of program
// only return value is different
pid_t pid = fork();
if (pid == -1) {
     perror("fork");  // print why the fork failed
} else if (pid == 0) {
    printf("I am the child because fork() returned %d.\n", pid);
} else {
    printf("I am the parent because fork() returned %d.\n", pid);
}
```

source code for fork.c

```
$ dcc fork.c
$ a.out
I am the parent because fork() returned 2884551.
I am the child because fork() returned 0.
$
```


waitpid() — wait for a process to change state

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

pid_t waitpid(pid_t pid, int *wstatus, int options);
```

- **`waitpid`** pauses current process until process **`pid`** changes state
    - where state changes include finishing, stopping, re-starting, ...
- ensures that child resources are released on exit
- special values for **`pid`** ...
    - if `pid` = -1, wait on any child process
    - if `pid` = 0, wait on any child in process group
    - if `pid` > 0, wait on specified process

```
pid_t wait(int *wstatus);
```

- equivalent to `waitpid(-1, &status, 0)`

`waitpid()` — wait for a process to change state

```
pid_t waitpid(pid_t pid, int *wstatus, int options);
```

`status` is set to hold info about `pid`.

- e.g., exit status if `pid` terminated
- macros allow precise determination of state change (e.g. `WIFEXITED(`*status*`)`, `WCOREDUMP(`*status*`)`)

`options` provide variations in `waitpid()` behaviour

- default: wait for child process to terminate
- `WNOHANG`: return immediately if no child has exited
- `WCONTINUED`: return if a stopped child has been restarted

For more information, `man 2 waitpid`.

Example: Using `fork()` and `exec()` to run `/bin/date`

```
pid_t pid = fork();
if (pid == -1) {
     perror("fork"); // print why fork failed
} else if (pid == 0) { // child
    char *date_argv[] = {"/bin/date", "--utc", NULL};
    execv("/bin/date", date_argv);
    perror("execvpe"); // print why exec failed
} else { // parent
    int exit_status;
    if (waitpid(pid, &exit_status, 0) == -1) {
        perror("waitpid");
        exit(1);
    }
    printf("/bin/date exit status was %d\n", exit_status);
}
```

source code for fork_exec.c

Example: one of the dangers of fork - a fork bomb

```
#include <stdio.h>
#include <unistd.h>
int main(void) {
    // creates 2 ** 10 = 1024 processes
    // which all print fork bomb then exit
    for (int i = 0; i < 10; i++) {
        fork();
    }
    printf("fork bomb\n");
    return 0;
}
```

source code for fork_bomb.c

`system()` — convenient but unsafe way to run another program

```c
#include <stdlib.h>

int system(const char *command);
```

Runs **command** via **/bin/sh**.

Waits for **command** to finish and returns exit status

Convenient ... but **extremely dangerous** —
very brittle; highly vulnerable to security exploits

- use for quick debugging and throw-away programs only

```c
// run date --utc to print current UTC
int exit_status = system("/bin/date --utc");
printf("/bin/date exit status was %d\n", exit_status);
return 0;
```

source code for system.c

Making Processes

Old-fashioned way **fork()** then **exec()**

- fork() duplicates the current process (parent+child)
- exec() "overwrites" the current process (run by child)

New, standard way **posix_spawn()**

`posix_spawn()` — Run a new process

```c
#include <spawn.h>

int posix_spawn(
    pid_t *pid, const char *path,
    const posix_spawn_file_actions_t *file_actions,
    const posix_spawnattr_t *attrp,
    char *const argv[], char *const envp[]);
```

Creates a new process. - **path**: path to the program to run - **argv**: arguments to pass to new program - **envp**: environment to pass to new program - **pid**: returns process id of new program - **file_actions**: specifies *file actions* to be performed before running program - can be used to redirect *stdin*, *stdout* to file or pipe - **attrp**: specifies attributes for new process (not used/covered in COMP1521)

Example: using `posix_spawn()` to run /bin/date

```c
pid_t pid;
extern char **environ;
char *date_argv[] = {"/bin/date", "--utc", NULL};
// spawn "/bin/date" as a separate process
int ret = posix_spawn(&pid, "/bin/date", NULL, NULL, date_argv, environ);
if (ret != 0) {
    errno = ret;   //posix_spawn returns error code, does not set errno
    perror("spawn");
    exit(1);
}
// wait for spawned processes to finish
int exit_status;
if (waitpid(pid, &exit_status, 0) == -1) {
    perror("waitpid");
    exit(1);
}
printf("/bin/date exit status was %d\n", exit_status);
```


Example: `posix_spawn()` versus `system()`

Running `ls -ld` via `posix_spawn()`

```c
char *ls_argv[2] = {"/bin/ls", "-ld", NULL};
pid_t pid; int ret;
extern char **environ;
if((ret = posix_spawn(&pid, "/bin/ls", NULL, NULL, ls_argv, environ)) != 0) {
    errno = ret; perror("spawn"); exit(1);
}
int exit_status;
if (waitpid(pid, &exit_status, 0) == -1) {
    perror("waitpid");
    exit(1);
}
```

Running `ls -ld` via `system()`

```c
system("ls -ld");
```


Example: Setting and environment Variable in a child process

```c
// set environment variable STATUS
setenv("STATUS", "great", 1);
char *getenv_argv[] = {"./get_status", NULL};
pid_t pid;
extern char **environ;
int ret = posix_spawn(&pid, "./get_status", NULL, NULL,
          getenv_argv, environ);
if (ret != 0) {
    errno = ret;
    perror("spawn");
    return 1;
}
int exit_status;
if (waitpid(pid, &exit_status, 0) == -1) {
    perror("waitpid");
    exit(1);
```

source code for set_status.c

Example: Changing behaviour with an environment variable

```
pid_t pid;
char *date_argv[] = { "/bin/date", NULL };
char *date_environment[] = { "TZ=Australia/Perth", NULL };
// print time in Perth
int ret = posix_spawn(&pid, "/bin/date", NULL, NULL, date_argv,
          date_environment);
if (ret != 0) {
    errno = ret;
    perror("spawn");
    return 1;
}
int exit_status;
if (waitpid(pid, &exit_status, 0) == -1) {
    perror("waitpid");
    return 1;
}
printf("/bin/date exit status was %d\n", exit_status);
```


Aside: Zombie Processes (advanced)

A process cannot terminate until its parent is notified. - notification is via wait/waitpid or `SIGCHLD` signal

Zombie process = exiting process waiting for parent to handle notification

- parent processes which don't handle notification create long-term zombie processes
  - wastes some operating system resources

Orphan process = a process whose parent has exited

- when parent exits, orphan assigned PID 1 (*init*) as its parent
- *init* always accepts notifications of child terminations

`exit()` — terminate yourself

```
#include <stdlib.h>

void exit(int status);
```

- triggers any functions registered as `atexit()`
- flushes stdio buffers; closes open `FILE *`'s
- terminates current process
- a `SIGCHLD` signal is sent to parent
- returns `status` to parent (via `waitpid()`)
- any child processes are inherited by `init` (pid 1)

```
void _exit(int status);
```

- terminates current process without triggering functions registered as `atexit()`
- stdio buffers not flushed

pipe() — stream bytes between processes

```
#include <unistd.h>

int pipe(int pipefd[2]);
```

A **pipe** is a unidirectional byte stream provided by the operating system.

- **pipefd[0]**: set to file descriptor of *read* end of pipe
- **pipefd[1]**: set to file descriptor of *write* end of pipe
- bytes written to **pipefd[1]** will be read from **pipefd[0]**

Child processes (by default) inherits file descriptors including for pipe

Parent can send/receive bytes (not both) to child via pipe

- parent and child should both close the pipe file descriptor they are not using
  - e.g if bytes being written (sent) parent to child
    - parent should close read end **pipefd[0]**
    - child should close write end **pipefd[1]**

Pipe file descriptors can be used with stdio via **fdopen**.

popen() — a convenient but unsafe way to set up pipe

```
#include <stdio.h>
FILE *popen(const char *command, const char *type);
int pclose(FILE *stream);
```

- runs **command** via **/bin/sh**
- if **type** is "w" pipe to stdin of **command** created
- if **type** is "r" pipe from stdout of **command** created
- **FILE *** stream returned - get then use **fgetc**/**fputc** etc
- **NULL** returned if error
- close stream with **pclose** (not **fclose**)
  - **pclose** waits for **command** and returns exit status

Convenient, but brittle and highly vulnerable to security exploits ...
use for quick debugging and throw-away programs only

Example: capturing process output with popen()

```
// popen passes string to a shell for evaluation
// brittle and highly-vulnerable to security exploits
// popen is suitable for quick debugging and throw-away programs only
FILE *p = popen("/bin/date --utc", "r");
if (p == NULL) {
    perror("");
    return 1;
}
char line[256];
if (fgets(line, sizeof line, p) == NULL) {
    fprintf(stderr, "no output from date\n");
    return 1;
}
printf("output captured from /bin/date was: '%s'\n", line);
pclose(p); // returns command exit status
```

source code for read_popen.c

Example: sending input to a process with **popen()**

```c
int main(void) {
    // popen passes command to a shell for evaluation
    // brittle and highly-vulnerable to security exploits
    // popen is suitable for quick debugging and throw-away programs only
    //
    // tr a-z A-Z - passes stdin to stdout converting lower case to upper case
    FILE *p = popen("tr a-z A-Z", "w");
    if (p == NULL) {
        perror("");
        return 1;
    }
    fprintf(p, "plz date me - I know every SPIM system call\n");
    pclose(p); // returns command exit status
    return 0;
}
```

source code for write_popen.c

posix_spawn and pipes (advanced topic)

```c
int posix_spawn_file_actions_destroy(
    posix_spawn_file_actions_t *file_actions);
int posix_spawn_file_actions_init(
    posix_spawn_file_actions_t *file_actions);
int posix_spawn_file_actions_addclose(
    posix_spawn_file_actions_t *file_actions, int fildes);
int posix_spawn_file_actions_adddup2(
    posix_spawn_file_actions_t *file_actions, int fildes, int newfildes);
```

- functions to combine file operations with posix_spawn process creation
- awkward to understand and use — but robust

Example: capturing output from a process:

source code for spawn_read_pipe.c

Example: sending input to a process:

source code for spawn_write_pipe.c