COMP1521 21T2 — Processes

https://www.cse.unsw.edu.au/~cs1521/21T2/

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 (virtual) memory
- information about open files, sockets, etc.

On Unix/Linux:

- each process had 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 *nix-like systems use PID 0 for the operating system

Process Parents

Each process has a *parent process*.

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

Unix provides a range of commandss for manipulating processes, e.g.:

- `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

Aside: Zombie Process

Zombie Process?

Photo credit: Kenny Louie, Flickr.com

Aside: Zombie Processes

A process cannot terminate until its parent is notified.

- if `exit()` called, operating system sends `SIGCHLD` signal to parent
- `exit()` will not return until parent handles `SIGCHLD`

Zombie process = exiting process waiting for parent to handle `SIGCHLD`

- all processes become zombies until `SIGCHLD` handled
- bug in parent that ignores `SIGCHLD` creates 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* should always handles `SIGCHLD` when process exits

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

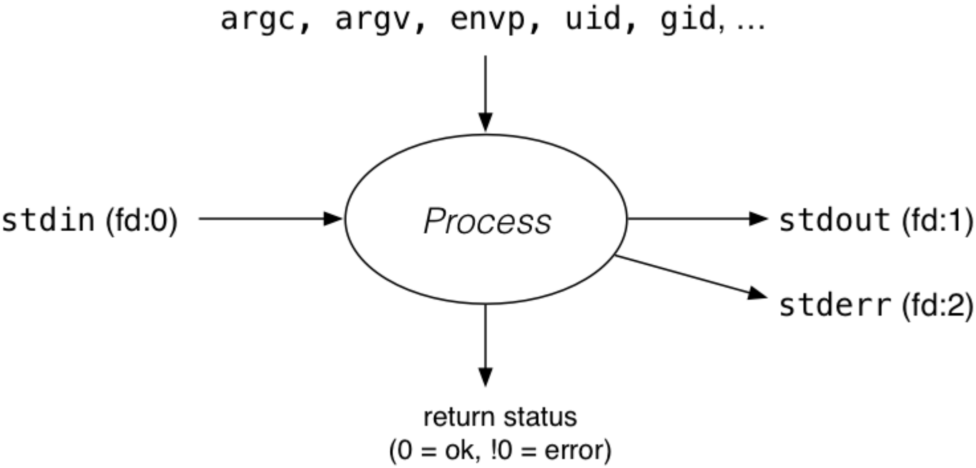
On preemption...

- 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

Environment for processes running on Unix/Linux systems



Process-related Unix/Linux Functions/System Calls

Process information:

- `getpid()` ... get process ID
- `getppid()` ... get parent process ID
- `getpgid()` ... get process group ID

Creating processes:

- `posix_spawn()` ... create a new process.
- `fork()` ... duplicate current process. (do not use in new code)
- `vfork()` ... duplicate current process. (do not use in new code)
- `execvp()` ... replace current process.
- `system()`, `popen()` ... create a new process via a shell (*unsafe*)

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

posix_spawn() — Run a new process

```
#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 process 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

```
pid_t pid;
extern char **environ;
char *date_argv[] = {"/bin/date", "--utc", NULL};
// spawn "/bin/date" as a separate process
if (posix_spawn(&pid, "/bin/date", NULL, NULL, date_argv, environ) != 0) {
    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);
```

source code for spawn.c

fork() — clone yourself

```c
#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()

```c
// 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.
$
```

execvp() - replace yourself

```
#include <unistd.h>

int execvp(const char *file, char *const argv[]);
```

Replace the program in the currently-executing process.

- `file`: an executable — either a binary, or script starting with `#!`
- `argv`: arguments to pass to new program

Most of the current process is reset:

- e.g., new virtual address space is created; signal handlers reset

New process inherits open file descriptors from original process.

- on error, returns -1 and sets `errno`
- if successful, does not return ... where would it return *to*?

Example: using exec()

```
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
$
```

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

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

```
#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

```
// 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

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

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

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

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

`getpid()`, `getppid()` — get process IDs

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

pid_t getpid(void);
pid_t getppid(void);
```

`getpid` returns the process ID of the current process.

`getppid` returns the process ID of the current process' parent.

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)`
- pauses until any child processes terminates.

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`.

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 implementation also provide as 3rd parameter to main:

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

  - but in practice this is extremely hard to get right

```
// 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

- Most programs instead use **getenv()** and **setenv()** to access environment variables

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

```
// 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

```
// set environment variable STATUS
setenv("STATUS", "great", 1);
char *getenv_argv[] = {"./get_status", NULL};
pid_t pid;
extern char **environ;
if (posix_spawn(&pid, "./get_status", NULL, NULL,
    getenv_argv, environ) != 0) {
    perror("spawn");
    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
if (posix_spawn(&pid, "/bin/date", NULL, NULL, date_argv,
                date_environment) != 0) {
    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);
```

source code for spawn_environment.c

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[1]**

Child processes (by default) inherit 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()

```c
// 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()

```
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\n");
    pclose(p); // returns command exit status
    return 0;
}
```

source code for write_popen.c

posix_spawn and pipes (advanced topic)

```
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