posix_spawn() ... create a new process, see also
- clone() ... duplicate current process
  address space can be shared to implement threads
  only use clone if posix_spawn can’t do what you want
- fork() ... duplicate current process - don’t use
- execve() ... replace current process - don’t use
- exit() ... terminate current process, see also
  _exit() ... terminate current process immediately
  stdio buffers won’t be flushed
  atexit functions won’t be called
- getpid() ... get process ID
- getpgid() ... get process group ID
- waitpid() ... wait for state change in child process

Unix/Linux system calls:
- kill() ... send a signal to a process
- sigaction() ... specify behaviour on receiving a signal
  signal() simpler version of sigaction, hard to use safely
- sleep() ... suspend execution for specified time

Minimal example for posix_spawn()

```c
int main(void) {
    pid_t pid;
    extern char **environ;
    char *spawn_argv[] = {"/bin/date", "--utc", NULL};
    if (posix_spawn(&pid, "/bin/date", NULL, NULL, spawn_argv, environ) != 0) {
        perror("spawn");
        return 1;
    }
    int exit_status;
    if (waitpid(pid, &exit_status, 0) != 0) {
        perror("waitpid");
        return 1;
    }
    printf("date exit status was %d\n", exit_status);
}
```
fork()

(pid_t) fork()
  - requires #include <unistd.h>
  - creates new process by duplicating the calling process
  - new process is the child, calling process is the parent
  - child has a different process ID (pid) to the parent
  - in the child, fork() returns 0
  - in the parent, fork() returns the pid of the child
  - if the system call fails, fork() returns -1
  - child inherits copies of parent’s address space and open file descriptors

Minimal example for fork

```c
#include <stdio.h>
#include <unistd.h>

int main(void) {
    pid_t pid = fork();
    if (pid == -1) {
        // the fork failed, perror will print why
        perror("fork");
    } else if (pid == 0) {
        printf("child: fork() returned %d.\n", pid);
    } else {
        printf("parent: fork() returned %d.\n", pid);
    }
}
```

execvp

(int) execvp(char *Path, char *Argv[])
  - transforms current process by executing Path object
    - Path must be an executable, binary or script (starting with #!)
  - passes arrays of strings to new process
    - both arrays terminated by a NULL pointer element
  - much of the state of the original process is lost, 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

exit()

(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 wait())
  - any child processes are inherited by init (pid 1)

Also void _exit(int status)
  - terminates current process without triggering functions registered as
    _atexit()
  - stdio buffers not flushed
void abort(void)

- generates SIGABRT signal which by default terminates process
- closes and flushes stdio streams
- used by the assert() macro

Zombie Process?

Photo credit: Kenny Louie, Flickr.com

Process-related System Calls

When a process finishes, sends SIGCHLD signal to parent

**Zombie process** = a process which has exited but signal not handled
- all processes become zombie until SIGCHLD handled
- parent may be delayed e.g. slow i/o, but usually resolves quickly
- bug in parent that ignores SIGCHLD creates long-term zombies
- note that zombies occupy a slot in the process table

**Orphan process** = a process whose parent has exited
- when parent exits, orphan is assigned pid=1 as its parent
- pid=1 always handles SIGCHLD when process exits

getpid & getppid

Getting 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
**Process Groups**

Processes belong to *process groups*

- a signal can be sent to all processes in a process group

```c
pid_t getpgid(pid_t pid)
```
- returns the process group ID of specified process
- if `pid` is zero, use get PGID of current process

```c
int setpgid(pid_t pid, pid_t pgid)
```
- set the process group ID of specified process

Both return -1 and set `errno` on failure.

For more details: `man 2 getpgid`

**waitpid**

```c
pid_t waitpid(pid_t pid, int *status, int options)
```
- pause 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 the specified process

```c
int wait(int *status)
```
- equivalent to `waitpid(-1, &status, 0)`
- pauses until one of the child processes terminates

For more information: `man 2 waitpid`

**Processes: review**

Process = instance of an executing program

- defined by execution state (incl. registers, address space, ...)

Operating system shares CPU among many active processes

On Unix/Linux:

- each process had a unique process ID (pid)
- `posix_spawn()` creates a copy of current process
- `wait()` parent process waits for child to change state

More on `waitpid(pid, &status, 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`
**kill()**

```c
int kill(pid_t ProcID, int SigID)
```

- requires `#include <signal.h>`
- send signal `SigID` to process `ProcID`
- various signals (POSIX) e.g.
  - `SIGHUP` ... hangup detected on controlling terminal/process
  - `SIGINT` ... interrupt from keyboard (control-C)
  - `SIGKILL` ... kill signal (e.g. `kill -9`)
  - `SIGILL` ... illegal instruction
  - `SIGFPE` ... floating point exception (e.g. divide by zero)
  - `SIGSEGV` ... invalid memory reference
  - `SIGPIPE` ... broken pipe (no processes reading from pipe)
- if successful, return 0; on error, return -1 and set `errno`

**Signals**

Signals can be generated from a variety of sources
- from another process via `kill()`
- from the operating system (e.g. timer)
- from within the process (e.g. system call)
- from a fault in the process (e.g. div-by-zero)

Processes can define how they want to handle signals
- using the `signal()` library function (simple)
- using the `sigaction()` system call (powerful)

**Signals**

Signals from internal process activity, e.g.
- `SIGILL` ... illegal instruction  (Term by default)
- `SIGABRT` ... generated by `abort()`  (Core by default)
- `SIGFPE` ... floating point exception  (Core by default)
- `SIGSEGV` ... invalid memory reference  (Core by default)

Signals from external process events, e.g.
- `SIGINT` ... interrupt from keyboard  (Term by default)
- `SIGPIPE` ... broken pipe  (Term by default)
- `SIGCHLD` ... child process stopped or died  (Ignored by default)
- `SIGTSTP` ... stop typed at tty (control-Z)  (Stop by default)

Processes can choose to ignore most signals.
If not ignored, signals can be handled in several default ways
- Term ... terminate the process
- Core ... terminate the process, dump core
- Stop ... stop the process
- Cont ... continue the process if currently stopped

Or you can write your own `signal` handler

See `man 7 signal` for details of signals and default handling.
**Signal Handlers**

**Signal Handler** = a function invoked in response to a signal

- knows which signal it was invoked by
- needs to ensure that invoking signal (at least) is blocked
- carries out appropriate action; may return

---

**SigHnd signal(int SigID, SigHnd Handler)**

- define how to handle a particular signal
- requires `<signal.h>` (library function, not syscall)
- SigID is one of the OS-defined signals
  - e.g. SIGHUP, SIGCHLD, SIGSEGV, ... but not SIGHUP, SIGSTOP
- Handler can be one of ...
  - SIG_IGN ... ignore signals of type SigID
  - SIG_DFL ... use default handler for SigID
  - a user-defined function to handle SigID signals
- note: typedef void (*SigHnd)(int);
- returns previous value of signal handler, or SIG_ERR

---

**Details on struct sigaction ...**

- void (*sa_handler)(int)
  - pointer to a handler function, or SIG_IGN or SIG_DFL
- void (*sa_sigaction)(int, siginfo_t *, void *)
  - pointer to handler function; used if SA_SIGINFO flag is set
  - allows more context info to be passed to handler
- sigset_t sa_mask
  - a mask, where each bit specifies a signal to be blocked
- int sa_flags
  - flags to modify how signal is treated
    (e.g. don't block signal in its own handler)

---

### C Function Declarations:

```c
int sigaction(int sigID, struct sigaction *newAct, struct sigaction *oldAct);
```
Signal Handlers

Details on `siginfo_t` ...

- `si_signo` ... signal being handled
- `si_errno` ... any `errno` value associated with signal
- `si_pid` ... process ID of sending process
- `si_uid` ... user ID of owner of sending process
- `si_status` ... exit value for process termination
- etc. etc. etc.

For more details: `bits/types/siginfo_t.h` (system-dependent)

Processes

A process is an instance of an executing program

Each process has an execution state, defined by

- current execution point (PC register)
- current values of CPU registers
- current contents of its virtual address space
- information about open files, sockets, etc.

To manage processes, the operating system also maintains

- process page table (i.e. virtual memory mapping)
- process metadata (e.g. execution time, priority, ...)

Processes

On a typical modern operating system

- multiple processes are active "simultaneously" (multi-tasking)

The operating system provides each process with

- control-flow independence
  - each process executes as if the only process running on the machine
- private address space
  - each process has its own address space (N bytes, addressed 0..N-1)

*Process management* is a critical OS functionality

Processes

Control-flow independence ("I am the only process, and I run until I finish")

When there are multiple processes running on the machine

- each process uses the CPU until pre-empted or exits
- then another process uses the CPU until it too is pre-empted
- eventually, the first process will get another run on the CPU

Overall impression: three programs running simultaneously
Processes

What can cause a process to be pre-empted?
• it runs "long enough" and the OS replaces it by a waiting process
• it attempts to perform a long-duration task, like input/output

On pre-emption ...
• the process’s entire dynamic state must be saved (incl PC)
• the process is flagged as temporarily suspended
• it is placed on a process (priority) queue for re-start

On resuming, the state is restored and the process starts at saved PC

Overall impression: I ran until I finished all my computation

Process Management

How does the OS manage multiple simultaneous processes?
For each process, maintains context (or state)
• static information: program code and constant data
• dynamic state: heap, stack, registers, program counter
• OS-supplied state: environment variables, stdin, stdout

At pre-emption, performs a context switch
• save context for one process
• restore context for another process

Non-static process context is held in a process control block

Typical contents of process control block (PCB)
• identifier: unique process ID (int)
• status: running, ready, suspended, exited
  • if suspended, event being waited for
• state: registers (including PC)
• privileges: owner, group
• memory management info: (reference to) page table
• accounting: CPU time used, amount of I/O done
• I/O: open file descriptors

The operating system maintains a table of PCBs
• one for each currently active process (indexed by process ID?)

The OS scheduler
• maintains a queue of runnable processes
• ordered based on information in the PCBs

When current process is pre-empted or suspends, the scheduler
• saves state of process, updates PCB entry
• selects next process to run, and re-starts it
Unix/Linux Processes

Environment for processes running on Unix/Linux systems

![Diagram of process with stdin, stdout, stderr, and return status]

Unix provides a range of tools for manipulating processes

Commands:
- `sh` ... for creating processes via object-file name
- `ps` ... show process information
- `w` ... show per-user process information
- `top` ... show high-cpu-usage process information
- `kill` ... send a signal to a process

System calls:
- `fork()`, `execve()`, `_exit()`, etc.

Exercise: Process Information
How can I find out...
- what processes I currently have running
- what are all of the processes running on the system

Information associated with processes (PCB):
- `pid` ... process id
- `ruid`, `euid` ... real and effective user id
- `rgid`, `egid` ... real and effective group id
- current working directory
- accumulated execution time (user/kernel)
- user file descriptor table
- information on how to react to signals
- pointer to process page table
- process state ... running, suspended, asleep, etc.

Process info is split across process table entry and user structure

**Process table** = kernel data structure describing all processes
- memory-resident since very heavily used
- contains PCB info as described above
- content of PCB entries is critical for scheduler

**User structure** = kernel data structure describing run-time state
- holds info not needed when process swapped out
- e.g. execution state (registers, signal handlers, file descriptors, ...)
Every process in Unix/Linux is allocated a process ID (PID)
- a +ve integer, unique among currently executing processes
- with type `pid_t` (defined in `<unistd.h>>)
- process 0 is the `idle` process (always runnable)
- process 1 is `init` ("the system")
- low-numbered processes are typically system-related

Process 0 is not a real process (it’s a kernel artefact)
- it exists to ensure that there is always at least one process to run

On older Unix systems, process 0 was called `ached`

Each process has a `parent process`
- typically, the process that created the current process

A process may have `child processes`
- any processes that it created

Process 1 is created at system startup
If a process’ parent dies, it is inherited by process 1

Processes are collected into `process groups`
- each group is associated with a unique PGID
- with type `pid_t` (defined in `<unistd.h>>)
- a child process belongs to the process group of its parent
- a process can create its own process group,
  or can move into another process group

Process groups allow
- OS to keep track of groups of processes working together
- distribution of signals to a set of related processes
- management of processes for job control (control-Z)
- management of processes within pipelines

Reminder ...
System calls are requests for the OS to do something, e.g.
- create a new process, send a signal, read some data, etc.

Sometimes the request cannot be completed, e.g.
- invalid PID or file descriptor, resources exhausted, etc.

In such cases
- the system call returns -1
- the value of the global variable `errno` is set

In many (most?) cases, a failed system call is a fatal error.
How to deal with failed system calls?

Generally, print an error and terminate the process.

A useful strategy: a wrapper function

- with same arguments/returns as system call
- catches and reports the error
- only ever returns with a valid result

Not always appropriate, e.g.

- failure of `open()` best handled by caller

Example: a wrapper function for `read()`

```c
size_t read1(int fd, void *buf, size_t nbytes) {
    ssize_t nread = read(fd, buf, nbytes);
    if (nread < 0) {
        perror("read() failed");
        exit(1);
    }
    return nread;
}
```

Use like `read()` but only get non-negative returns.