Process-related Linux Functions/System Calls

- `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

Process-related Linux Functions/System Calls

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

posix_spawn()

```
posix_spawn(pid_t *pid, char *path, ..., char *argv[],
char *envp)
```

- creates new process running program at *path*
- argv specifies argv of new program
- envp specifies environment of new program
- *pid set to process id of new program

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

```
#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

abort()

`void abort(void)`

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

Zombie Process

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

`pid_t getpgid(pid_t pid)`

- returns the process group ID of specified process
- if `pid` is zero, use get PGID of current process

`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

`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

`pid_t wait(int *status)`

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

waitpid

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`

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

kill()

`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)

Signals

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

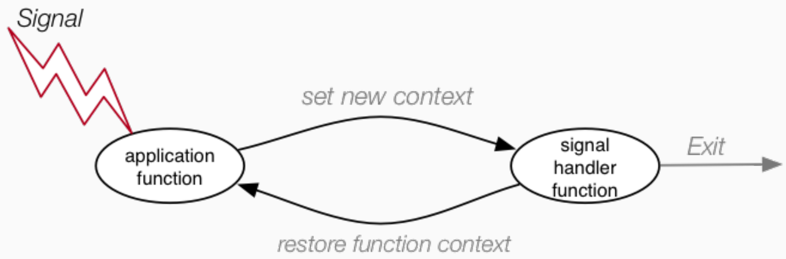
Or you can write your own *signal handler*

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



Signal Handlers

`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 `SIGKILL`, `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`

Signal Handlers

`int sigaction(int sigID, struct sigaction *newAct, struct sigaction *oldAct)`

- `sigID` is one of the OS-defined signals
  - e.g. `SIGHUP`, `SIGCHLD`, `SIGSEGV`, ... but not `SIGKILL`, `SIGSTOP`
- `newAct` defines how signal should be handled
- `oldAct` saves a copy of how signal was handled
- if `newAct.sa_handler == SIG_IGN`, signal is ignored
- if `newAct.sa_handler == SIG_DFL`, default handler is used
- on success, returns 0; on error, returns -1 and sets `errno`

For much more information: `man 2 sigaction`

Signal Handlers

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)

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)

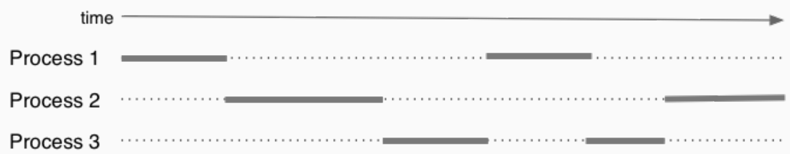
Process management is a critical OS functionality

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*

Process Management

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

Process Management

The operating system maintains a table of PCBs

- one for each currently active process (indexed by process ID?)

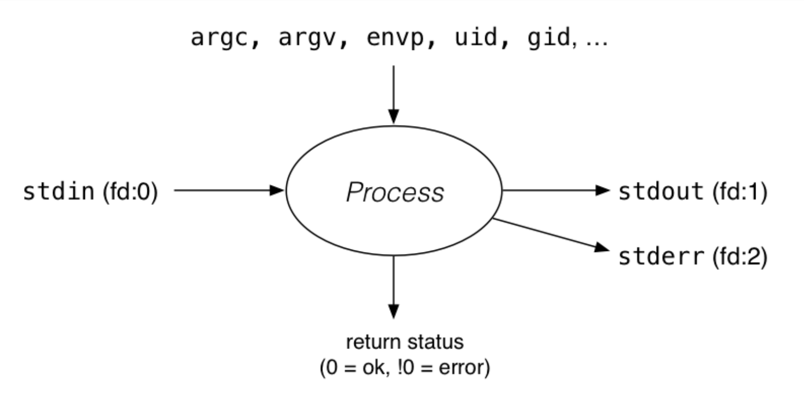
The OS *scheduler*

- 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

Environment for processes running on Unix/Linux systems



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, ...)

Unix/Linux Processes

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 `sched`

Unix/Linux Processes

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

Unix/Linux Processes

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

System Calls (and Failure)

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.

System Calls (and Failure)

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

System Calls (and Failure)

Example: a wrapper function for **`read()`**

```
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.