What is an Operating System?

- Software that abstracts the computer hardware
  - Hides the messy details of the underlying hardware
  - Presents users with a resource abstraction that is easy to use
  - Extends or virtualizes the underlying machine
- Manages the resources
  - Processors, memory, timers, disks, mice, network interfaces, printers, displays, …
  - Allows multiple users and programs to share the resources and coordinates the sharing, provides protection

9/6/2012 CSC 2/456 1

Operating Systems Concepts/Components

- Processes/process management
- Memory management
- I/O device management
- File systems/storage management
- Network/communication management
- Security/protection

9/6/2012 CSC 2/456 2

Process Management

- A *process* is a program in execution
  - Unit of work – A process needs certain resources, including CPU time, memory, files, and I/O devices, to accomplish its task
  - Protection domain
- OS responsibilities for process management:
  - Process creation and deletion
  - Process scheduling, suspension, and resumption
  - Process synchronization, inter-process communication

9/6/2012 CSC 2/456 3

Memory Management

- Memory
  - A large array of addressable words or bytes.
  - A data repository shared by the CPU and I/O devices.
- OS responsibility for memory management:
  - Allocate and deallocate memory space as requested
  - Efficient utilization when the memory resource is heavily contended
  - Keep track of which parts of memory are currently being used and by whom

9/6/2012 CSC 2/456 4

I/O System Management

- A computer needs I/O to interact with the outside world:
  - Console/terminal
  - Non-volatile secondary storage – disks
  - Networking
- The I/O system consists of:
  - A buffer-caching system
  - A general device-driver interface
  - Drivers for specific hardware devices

File and Secondary Storage Management

- A file is a collection of information defined by its user. Commonly, both programs and data are stored as files
- OS responsibility for file management:
  - Manipulation of files and directories
  - Map files onto (nonvolatile) secondary storage - disks
- OS responsibility for disk management:
  - Free space management and storage allocation
  - Disk scheduling
- They are not all always together
  - Not all files are mapped to secondary storage!
  - Not all disk space is used for the file system!

Networking and Communication

- A *distributed* system
  - A collection of processors that do not share memory
  - Processors are connected through a communication network
  - Communication takes place using a *protocol*
  - *OS provides communication end-points or sockets*
- Inter-process communication (msg, shm, sem, pipes)

System Calls and Interfaces/Abstractions

- Examples: Win32, POSIX, or Java APIs
- Process management
  - fork, waitpid, execve, exit, kill
- File management
  - open, close, read, write, lseek
- Directory and file system management
  - mkdir, rmdir, link, unlink, mount, umount
- Inter-process communication
  - sockets, ipc (msg, shm, sem, pipes)

Today

- Process management
  - Process concept
  - Operations on processes
- Signals
- Pipes

Assignment #1

- Exclusively outside of the OS
- Part I: observing the OS through the /proc virtual file system
- Part II: building a shell (command-line interpreter)
  - Support foreground/background executions
  - Support pipes

User Operating-System Interface

- Command interpreter – special program initiated when a user first logs on
- Graphical user interface
  - Common desktop environment (CDE)
  - K desktop environment (KDE)
  - GNOME desktop (GNOME)
  - Aqua (MacOS X)

System Boot

- How does the hardware know where the kernel is or how to load that kernel?
  - Use a *bootstrap* program or loader
  - Execution starts at a predefined memory location in ROM (read-only memory)
  - Read a single block at a fixed location on disk and execute the code from that boot block
  - Easily change operating system image by writing new versions to disk

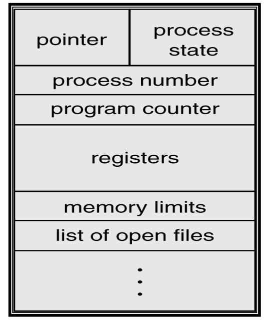
Processes

- Def: A *process* is an instance of a running program.
  - One of the most profound ideas in computer science.
  - Not the same as “program” or “processor”
- Process provides each program with two key abstractions:
  - Logical control flow
    - Each program seems to have exclusive use of the CPU.
  - Private address space
    - Each program seems to have exclusive use of main memory.
- How are these Illusions maintained?
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system

Process Control Block (PCB)

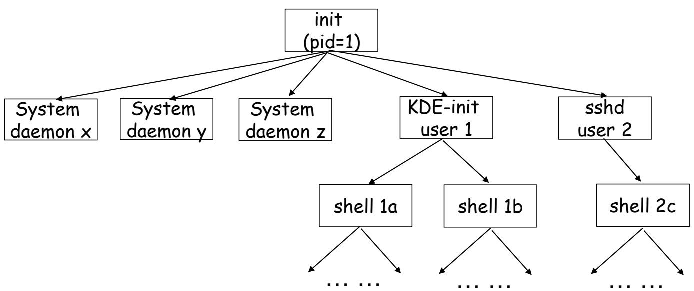
OS data structure (in kernel memory) maintaining information associated with each process.

- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- Information about open files
- maybe kernel stack?



Process Tree on a Linux System

- Parent process creates children processes, which, in turn create other processes, forming a tree of processes.



Unix: fork, exec; Win32API: CreateProcess

Process Creation

- When a process (parent) creates a new process (child)
  - Execution sequence?
  - Address space sharing?
  - Open files inheritance?
  - … …
- UNIX examples
  - **fork** system call creates new process with a duplicated copy of everything.
  - **exec** system call used after a **fork** to replace the process’ memory space with a new program.
  - child and parent compete for CPU like two normal processes.
- Copy-on-write

fork: Creating new processes

- `int fork(void)`
  - creates a new process (child process) that is identical to the calling process (parent process)
  - returns 0 to the child process
  - returns child's `pid` to the parent process

```
if (fork() == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Fork is interesting (and often confusing) because it is called *once* but returns *twice*

exec: Running new programs

- `int execl(char *path, char *arg0, char *arg1, …, 0)`
  - loads and runs executable at `path` with args `arg0`, `arg1`, …
    - `path` is the complete path of an executable
    - `arg0` becomes the name of the process
      - typically `arg0` is either identical to `path`, or else it contains only the executable filename from `path`
    - "real" arguments to the executable start with `arg1`, etc.
    - list of args is terminated by a `(char *)0` argument
  - returns `-1` if error, otherwise doesn't return!

```
main() {
   if (fork() == 0) {
      execl("/usr/bin/cp", "cp", "foo", "bar", 0);
   }
   wait(NULL);
   printf("copy completed\n");
   exit();
}
```


exit: Destroying Process

- `void exit(int status)`
  - exits a process
    - Normally return with status 0
  - `atexit()` registers functions to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork6() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

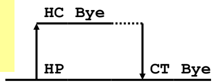

wait: Synchronizing with children

- `int wait(int *child_status)`
  - suspends current process until one of its children terminates
  - return value is the `pid` of the child process that terminated
  - if `child_status != NULL`, then the object it points to will be set to a status indicating why the child process terminated

wait: Synchronizing with children

```
void fork9() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   }
   else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
   exit();
}
```



Waitpid

- waitpid(pid, &status, options)
  - Can wait for specific process
  - Various options

```
void fork11()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
       if ((pid[i] = fork()) == 0)
           exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
       pid_t wpid = waitpid(pid[i], &child_status, 0);
       if (WIFEXITED(child_status))
           printf("Child %d terminated with exit status %d\n",
                  wpid, WEXITSTATUS(child_status));
       else
           printf("Child %d terminated abnormally\n", wpid);
    }
```

Simple Shell eval Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* argv for execve() */
    int bg;              /* should the job run in bg or fg? */
    pid_t pid;           /* process id */

    bg = parseline(cmdline, argv);
    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        if (!bg) {   /* parent waits for fg job to terminate */
           int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else         /* otherwise, don't wait for bg job */
            printf("%d %s", pid, cmdline);
    }
}
```

Problem with Simple Shell Example

- Shell correctly waits for and reaps foreground jobs.
- But what about background jobs?
  - Will become zombies when they terminate.
  - Will never be reaped because shell (typically) will not terminate.
  - Creates a memory leak that will eventually crash the kernel when it runs out of memory.
- Solution: Reaping background jobs requires a mechanism called a *signal*.

Signals

- A *signal* is a small message that notifies a process that an event of some type has occurred in the system.
  - Kernel abstraction for exceptions and interrupts.
  - Sent from the kernel (sometimes at the request of another process) to a process.
  - Different signals are identified by small integer ID's
  - The only information in a signal is its ID and the fact that it arrived.

ID	Name	Default Action	Corresponding Event
2	`SIGINT`	Terminate	Interrupt from keyboard (`ctl-c`)
9	`SIGKILL`	Terminate	Kill program (cannot override or ignore)
11	`SIGSEGV`	Terminate & Dump	Segmentation violation
14	`SIGALRM`	Terminate	Timer signal
17	`SIGCHLD`	Ignore	Child stopped or terminated

Signal Concepts

- Sending a signal
  - Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process.
  - Kernel sends a signal for one of the following reasons:
    - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
    - Another process has invoked the `kill` system call to explicitly request the kernel to send a signal to the destination process.

Signal Concepts (cont)

- Receiving a signal
  - A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal.
  - Three possible ways to react:
    - Ignore the signal (do nothing)
    - Terminate the process.
    - *Catch* the signal by executing a user-level function called a signal handler.
      - Akin to a hardware exception handler being called in response to an asynchronous interrupt.

Signal Concepts (cont)

- A signal is *pending* if it has been sent but not yet received.
  - There can be at most one pending signal of any particular type.
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded.
- A process can *block* the receipt of certain signals.
  - Blocked signals can be delivered, but will not be received until the signal is unblocked.
- A pending signal is received at most once.

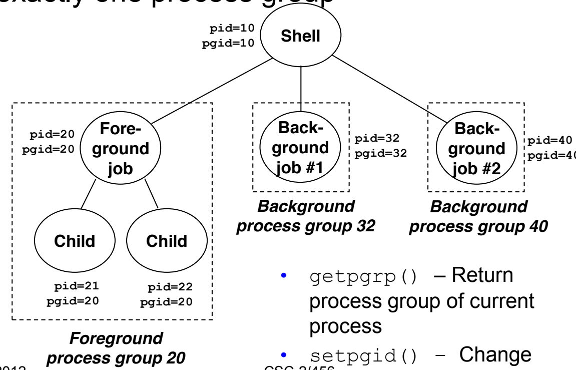
Signal Concepts (contd)

- Kernel maintains `pending` and `blocked` bit vectors in the context of each process.
  - `pending` – represents the set of pending signals
    - Kernel sets bit k in `pending` whenever a signal of type k is delivered.
    - Kernel clears bit k in `pending` whenever a signal of type k is received
  - `blocked` – represents the set of blocked signals
    - Can be set and cleared by the application using the `sigprocmask` function.

9/6/2012 CSC 2/456 29

Process Groups

- Every process belongs to exactly one process group



- `getpgrp()` – Return process group of current process
- `setpgid()` – Change process group of a process

9/6/2012 CSC 2/456 30

Sending Signals with `kill` Program

- `kill` program sends arbitrary signal to a process or process group
- Examples
  - `kill –9 24818`
    - `Send SIGKILL to process 24818`
  - `kill –9 –24817`
    - `Send SIGKILL to every process in process group 24817.`

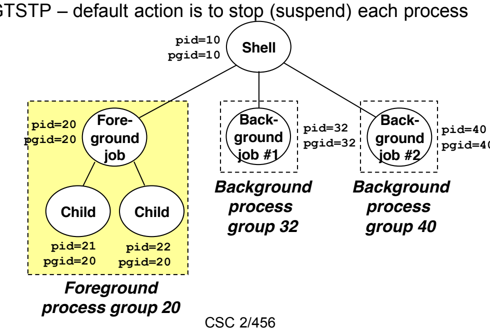
```
linux> ./forks 16
linux> Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```

9/6/2012 CSC 2/456 31

Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) to every job in the foreground process group.
  - SIGTERM – default action is to terminate each process
  - SIGTSTP – default action is to stop (suspend) each process



9/6/2012 CSC 2/456 32

Example of `ctrl-c` and `ctrl-z`

```
linux> ./forks 17
Child: pid=24868 pgrp=24867
Parent: pid=24867 pgrp=24867
 <typed ctrl-z>
Suspended
linux> ps a
  PID TTY      STAT   TIME COMMAND
24788 pts/2    S      0:00 -usr/local/bin/tcsh -i
24867 pts/2    T      0:01 ./forks 17
24868 pts/2    T      0:01 ./forks 17
24869 pts/2    R      0:00 ps a
bass> fg
./forks 17
<typed ctrl-c>
linux> ps a
  PID TTY      STAT   TIME COMMAND
24788 pts/2    S      0:00 -usr/local/bin/tcsh -i
24870 pts/2    R      0:00 ps a
```

Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Receiving Signals

- Suppose kernel is returning from exception handler and is ready to pass control to process *p*.
- Kernel computes `pnb = pending & ~blocked`
  - The set of pending nonblocked signals for process *p*
- If (`pnb == 0`)
  - Pass control to next instruction in the logical flow for *p*.
- Else
  - Choose least nonzero bit *k* in `pnb` and force process *p* to receive signal *k*.
  - The receipt of the signal triggers some *action* by *p*
  - Repeat for all nonzero *k* in `pnb`.
  - Pass control to next instruction in logical flow for *p*.

Default Actions

- Each signal type has a predefined *default action*, which is one of:
  - The process terminates
  - The process terminates and dumps core.
  - The process stops until restarted by a SIGCONT signal.
  - The process ignores the signal.

Installing Signal Handlers

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
  - `handler_t *signal(int signum, handler_t *handler)`
- Different values for `handler`:
  - SIG_IGN: ignore signals of type `signum`
  - SIG_DFL: revert to the default action on receipt of signals of type `signum`.
  - Otherwise, handler is the address of a *signal handler*
    - Called when process receives signal of type `signum`
    - Referred to as "*installing*" the handler.
    - Executing handler is called "*catching*" or "*handling*" the signal.
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal.

9/6/2012 CSC 2/456 37

Signal Handling Example

```
void int_handler(int sig)
{
    printf("Process %d received signal %d\n",
           getpid(), sig);
    exit(0);
}

void fork13()
{
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);

    . . .
}
```

```
linux> ./forks 13
Killing process 24973
Killing process 24974
Killing process 24975
Killing process 24976
Killing process 24977
Process 24977 received signal 2
Child 24977 terminated with exit status 0
Process 24976 received signal 2
Child 24976 terminated with exit status 0
Process 24975 received signal 2
Child 24975 terminated with exit status 0
Process 24974 received signal 2
Child 24974 terminated with exit status 0
Process 24973 received signal 2
Child 24973 terminated with exit status 0
linux>
```

Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    printf("Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Exit */
            exit(0);
        }
    while (ccount > 0)
        pause();/* Suspend until signal occurs */
}
```

- Pending signals are not queued
  - For each signal type, just have single bit indicating whether or not signal is pending
  - Even if multiple processes have sent this signal

Living With Nonqueuing Signals

- Must check for all terminated jobs
  - Typically loop with `wait`

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    while ((pid = wait(&child_status)) > 0) {
       ccount--;
       printf("Received signal %d from process %d\n",
sig, pid);
    }
}

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
```

A Program That Reacts to Externally Generated Events (ctrl-c)

```
#include <stdlib.h>
#include <stdio.h>
#include <signal.h>

void handler(int sig) {
  printf("You think hitting ctrl-c will stop the bomb?\n");
  sleep(2);
  printf("Well...");
  fflush(stdout);
  sleep(1);
  printf("OK\n");
  exit(0);
}

main() {
  signal(SIGINT, handler); /* installs ctl-c handler */
  while(1) {
  }
}
```

A Program That Reacts to Internally Generated Events

```
#include <stdio.h>
#include <signal.h>

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
  printf("BEEP\n");
  fflush(stdout);

  if (++beeps < 5)
    alarm(1);
  else {
    printf("BOOM!\n");
    exit(0);
  }
}
```

```
main() {
  signal(SIGALRM, handler);
  alarm(1); /* send SIGALRM in
               1 second */

  while (1) {
    /* handler returns here */
  }
}
```

```
linux> a.out
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```

Interprocess Communication: Pipes

- Conduit allowing two processes to communicate
  - Unidirectional or bidirectional
  - Full-duplex or half-duplex two-way communication
  - Is parent-child relationship required?
  - Is communication across a network allowed?

Unix Pipes

- A unidirectional data channel that can be used for interprocess communication
- Treated as a special type of file, accessed using read() and write()
- Cannot be accessed from outside the process that created it unless inherited (by a child)
- Pipe ceases to exist once closed or when process terminates
- System calls
  - pipe (int fd[])
  - dup2

Example

- pipe(int fd[]) – fd[0] = read_end, fd[1]=write_end

```
    int fd[2];
pid_t pid;

pipe(fd);
pid = fork();
if (pid > 0) {/* parent process */
    close(fd[0]);
    write(fd[1], write_msg, strlen(write_msg)+1);
    close(fd[1]);
}
else {/* child process */
    close(fd[1]);
    read(fd[0], read_msg, BUFFER_SIZE);
    printf("read %s", read_msg);
    close(fd[0];
}
```

9/6/2012 CSC 2/456 45

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9/6/2012 CSC 2/456 68