Process Management: Fork-Exec Model

CS 0449: Introduction to System Software

CS0449 Teaching Assistants

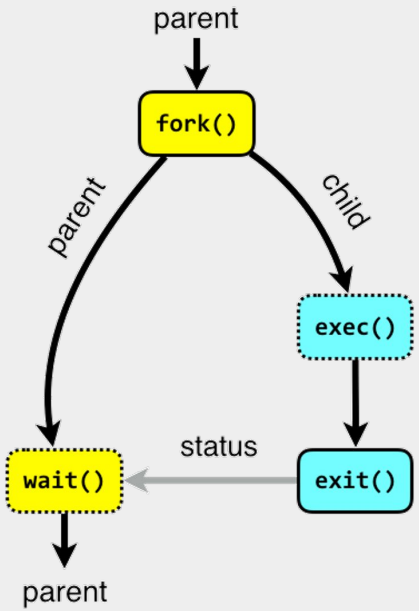
University of Pittsburgh | School of Computing and Information

Process Management

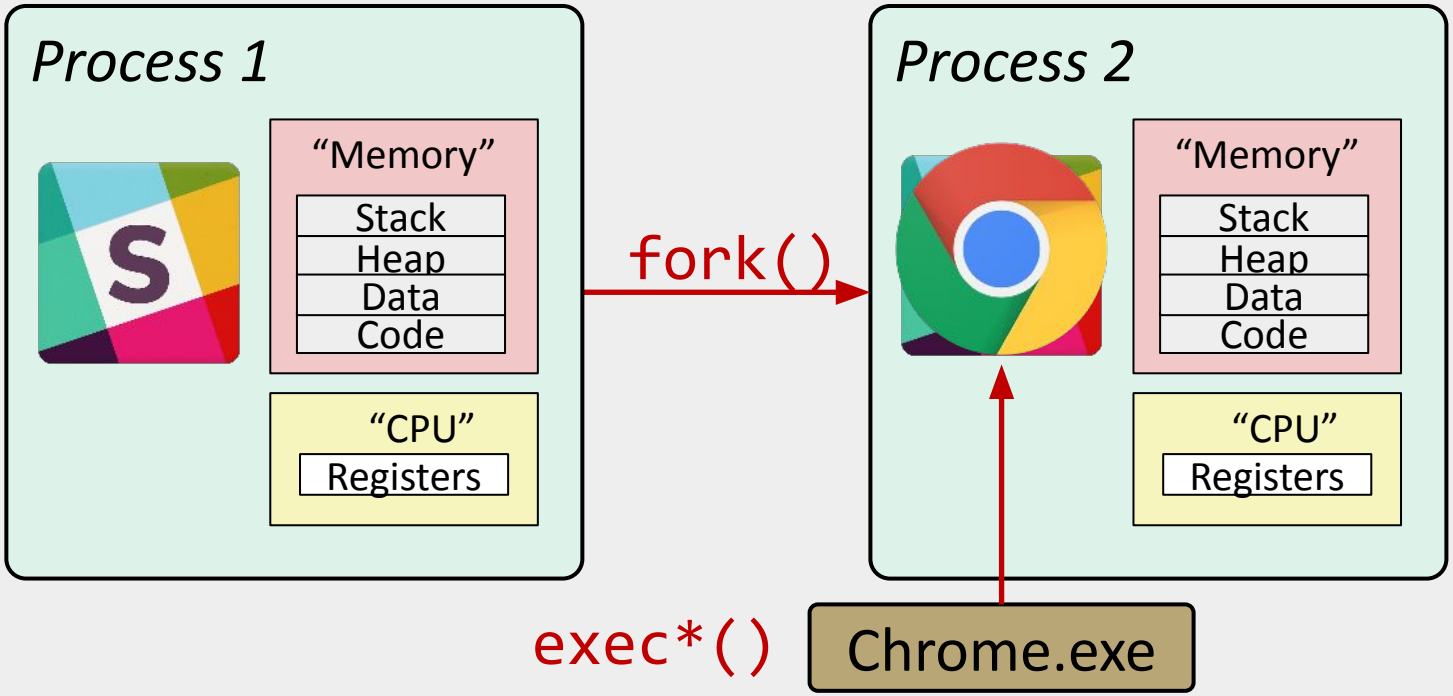
The Linux Fork-Exec model

Creating new processes & programs

- `fork-exec` model (Linux)
  - `fork()` copies the current process
    - Creating a “child” process that is a duplicate of the memory and state of its parent process
  - `exec*()` replaces the current process’s code and address space with the code for a different program
    - Family: `execv`, `execl`, `execve`, `execle`, `execvp`, `execlp`
  - `fork()` and `exec()` are system calls
- Other system calls for process management
  - `getpid()` gets process id
  - `exit(int)` ends the current process
    - Argument is known as the **exit code**
    - We can have processes that are no longer running, but not yet deallocated (Zombie processes)
  - `wait()` yields the process and returns only when the child process ends
    - Return value of `wait()` is the process id of the child that exited
    - Specify which child to wait for using `waitpid(pid_t)`



Creating new processes & programs



`fork()`: creating new processes

- `pid_t fork(void)`
  - **Returns 0 to the child process**
  - **Returns child's process ID (PID) to the parent process**
- Child is almost identical to parent:
  - Child gets an identical (but separate) copy of the parent's address space
  - Child has a different PID than the parent
- fork is unique (and often confusing) because it is called **once** but returns "**twice**"

Understanding fork()

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

Understanding fork

Process X

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

Process Y (child)

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

Understanding fork

Process X (parent)

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

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

Process Y (child)

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

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

`hello from parent`

`hello from child`

Which one appears first?

Modeling `fork()` with process graphs

- A **process graph** is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex is the execution of a statement
  - a → b means a happens before b
  - Edges can be labeled with current value of variables
  - `printf` vertices can be labeled with output
  - Each graph begins with a vertex with no in edges

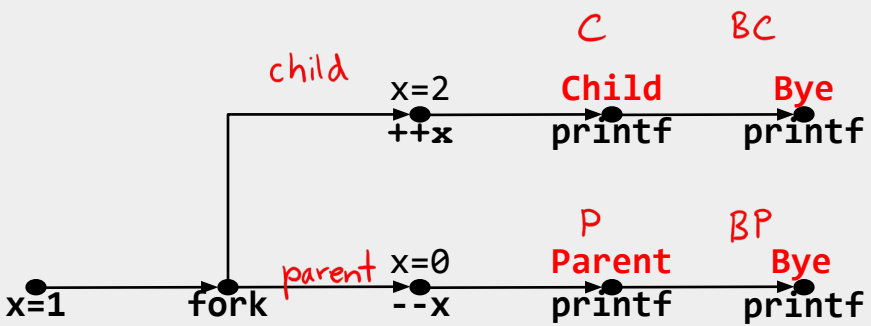
Fork example

```
void fork1() {
    int x = 1;
    pid_t pid = fork();
    if (pid == 0)
      printf("Child has x = %d\n", ++x); // child only
    else
      printf("Parent has x = %d\n", --x); // parent only
    printf("Bye from process %d with x = %d\n", getpid(), x); // both
}
```

- Both processes continue/start execution after fork
  - Child starts at instruction after the call to fork (storing into pid)
- Can't predict execution order of parent and child
- Both processes start with x=1
  - Subsequent changes to x are independent

Modeling `fork()` with process graphs

```
void fork1() {
    int x = 1;
    pid_t pid = fork();
    if (pid == 0)     printf("Child has x = %d\n", ++x);
    else              printf("Parent has x = %d\n", --x);
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



C BC P BP
P BP C BP
C P BC BP
C P BP BC
C BC BP P
P BC C BP

As long as C comes before BC and P comes before BP

} Not possible!

PEV: Is the following sequence of outputs possible?

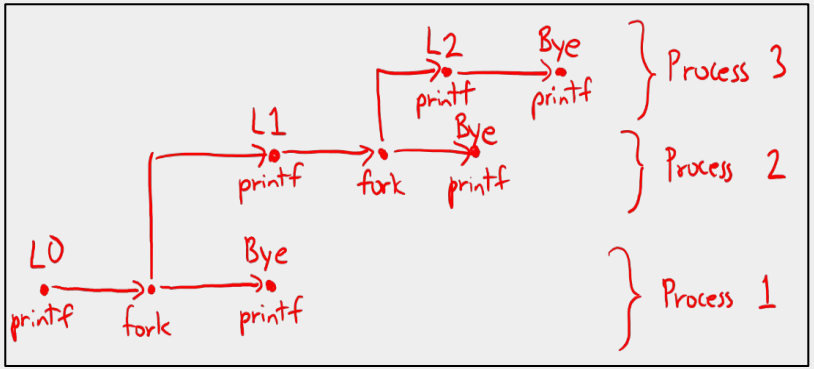
```
void nestedfork() {
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

```
Seq 1:
L0
L1
Bye
Bye
Bye
L2
```

Are the following sequences of outputs possible?

```
void nestedfork() {
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

Seq 1:
L0
L1
Bye
Bye
Bye
L2 *NO!*



Fork bombs 💣

- A Fork bomb (AKA rabbit virus, or wabbit)
  - is a denial-of-service attack
  - wherein a process continually replicates itself to deplete available system resources
  - `while(true) { fork(); }`
- `:(){ :|:& };:` ← This is all you need for a fork bomb
  - https://en.wikipedia.org/wiki/Fork_bomb
- Try experimenting on your own machine
  - Preferably on a virtual machine
  - Worst case scenario, you just reboot your machine!
- That being said, if you fork bomb Thoth, your access to it will be revoked
  - *And you will need access for other courses (e.g., 1550)*

Lab 5: Loading & Forking

Executables and Plugins

Now, it's your turn!

- In lab 5, you will practice:
  a. Learn how libraries are loaded dynamically
  b. Learn how processes are created
     - Using `fork()`, `exec()`
     - And `wait()`
- Three parts
  a. Plugging your code!
  b. FORK!
  c. Gradescope Questions

Collaboration on this lab is allowed and encouraged!

Part A: Plugging your code!

- Read the handout on how *function pointers* work
  - A function pointer is a variable that stores the address of a function that can later be called through that function pointer.
- `return_type (*pointer_name)(list,of,argument,types);`
  - `long int (*f_ptr)(int, int);`
  - Really useful for general purpose functions!
    - A sort function that can work on any data type
      - Works as long you pass in a function that can *compare* two values of that type

```
void qsort(void *base, size_t n_elem, size_t elem_size, int(*compare)(const void *, const void *));
```

If I want to use `qsort()` on a different data type (e.g., Strings), all I need to do is, swap out the comparison function!

```
int compare_ascending(const void *val1, const void *val2) {  // Compares integers
       return *(const int *)val1-*(const int *)val2;
}
```

Part A: Plugging your code!

- Build a program that accepts a *plugin name* as a parameter and executes that plugin.
  - Plugin file will have the name `plugin-name.so`
  - All Plugin support
    - `int initialize()`
    - `int run()`
    - `int cleanup()`
  - Your program should be run as
    - `$ ./program plugin-name`
- Create `plugin_manager.c` that
  - reads the first argument - `you may need to format your argument (e.g., "plugin" → ./plugin.so)`
  - Loads the shared object
  - Runs `initialize()`, `run()`, and `cleanup()` in that order

```c
/* Sample Plugin */
int initialize() {
    printf("Initializing plugin\n");
}

int run() {
    printf("Running plugin\n");
}

int cleanup() {
    printf("Cleaning plugin\n");
}
```

```
// Create a shared object
gcc plugin.c -o plugin.so -shared
```

To dynamically link libraries you will need to get familiar with `dlfcn.h` functions (see lecture slides for examples)

Dynamic linking requires the -ldl flag when compiling with gcc

(gcc plugin_manager.c … -ldl)

Part B: FORK!

- Forking allows us to expand our programs to multiple processes
  - But how can processes communicate with one another?
    - That is, how do we **synchronize** processes? ←`This is often known as interprocess communication`
- Signals are primitive standards that can be sent to processes
  - By other processes, the OS, etc.0
- For example, when you kill a program with `ctrl + c`, the shell sends the `SIGINT` signal to that process
  - Which usually terminates the program
- When you get a *segmentation fault*, the OS usually sends the `SIGSEGV` signal to the process
- However, we can *capture* the signals to do something else
  - For example, on when the user tries to kill the process (`SIGINT`) print “No!” and keep running

Part B: FORK!

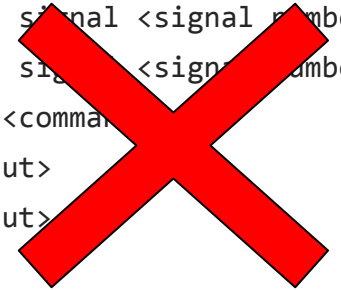
- Create a program `run_on_demand.c` that:
  - When it receives signal `SIGUSR1`,
    - Fork-execs `ls`
  - When it receives signal `SIGUSR2`,
    - Fork-execs `ls -l a`
- When `CTRL + c` is pressed, the program should print
  - `"Leaving gracefully"`
  - Then exit
- Remember to synchronize the processes
  - Printing order should be respected
  - *The process should "wait" until the `ls` is complete*

Sample Output

```
Received signal <signal number>.
Running <command>.
<ls output>
Done!
```

Sample Output

```
Received signal <signal number>.
Received signal <signal number>.
Running <command>.
<ls output>
<ls output>
Done!
Done!
```



Testing with signals

- How can we test signals?
- Signals are sent by *processes*…so we can create a wrapper program that tests our `run_on_demand` program
  - For example:

This is pseudo-code

```
pid_t pid = fork();
if (pid == 0) // child process
   exec("./run_on_demand");
else // parent process
   kill(pid, SIGUSR1); //send
SIGUSR1 to child
```

- Or we can do so manually:
  - Open up two terminals
  - In terminal 1, run `run_on_demand`
  - In terminal 2, manually send signals
    - `$ kill -s SIGUSR1 pid`
    - How do we know `pid`?
    - `$ ps ux` gets you the pid of all process (that you are running)

Part C: Gradescope Questions

- Fork tracing questions + extra
- Good exam practice!

Collaboration on this lab is allowed and encouraged!

⇒ You must submit:

1. `plugin_manager.c`
2. `run_on_demand.c`
3. Answer questions on Gradescope

Project IV

Writing Your Own Shell

`man strtok` abridged

- The `strtok()` function can help tokenize strings
- `#include <string.h>`
- `char *strtok(char *str, const char *delim);`
  - Breaks string `str` into a series of tokens using the delimiter `delim`.
  - Returns a pointer to the next token, or NULL if there are no more tokens.
- Called in one of two ways:
  1. `strtok(str, d) // starts processing a new string`
  2. `strtok(NULL, d) // continue processing a string`

A strtok() example

```c
#include <stdio.h>
#include <string.h>
int main(){
   char str[] = "I:love-programming";
   char delim[] = "-:";
   char *token;
   token = strtok(str, delim);
   printf("%s\n", token);
   return 0;
}
```

```
$ ./strtok_example
I
```

What will be printed?

A `strtok()` example

```c
#include <stdio.h>
#include <string.h>
int main(){
   char str[] = "I:love-programming";
   char delim[] = "-:";
   char *token;
   token = strtok(str, delim);
   printf("%s\n", token);
   token = strtok(str, delim);
   printf("%s\n", token);
   return 0;
}
```

What will be printed?

```
$ ./strtok_example
I
I   🤔 But the second token should be "love"
```

A strtok() example

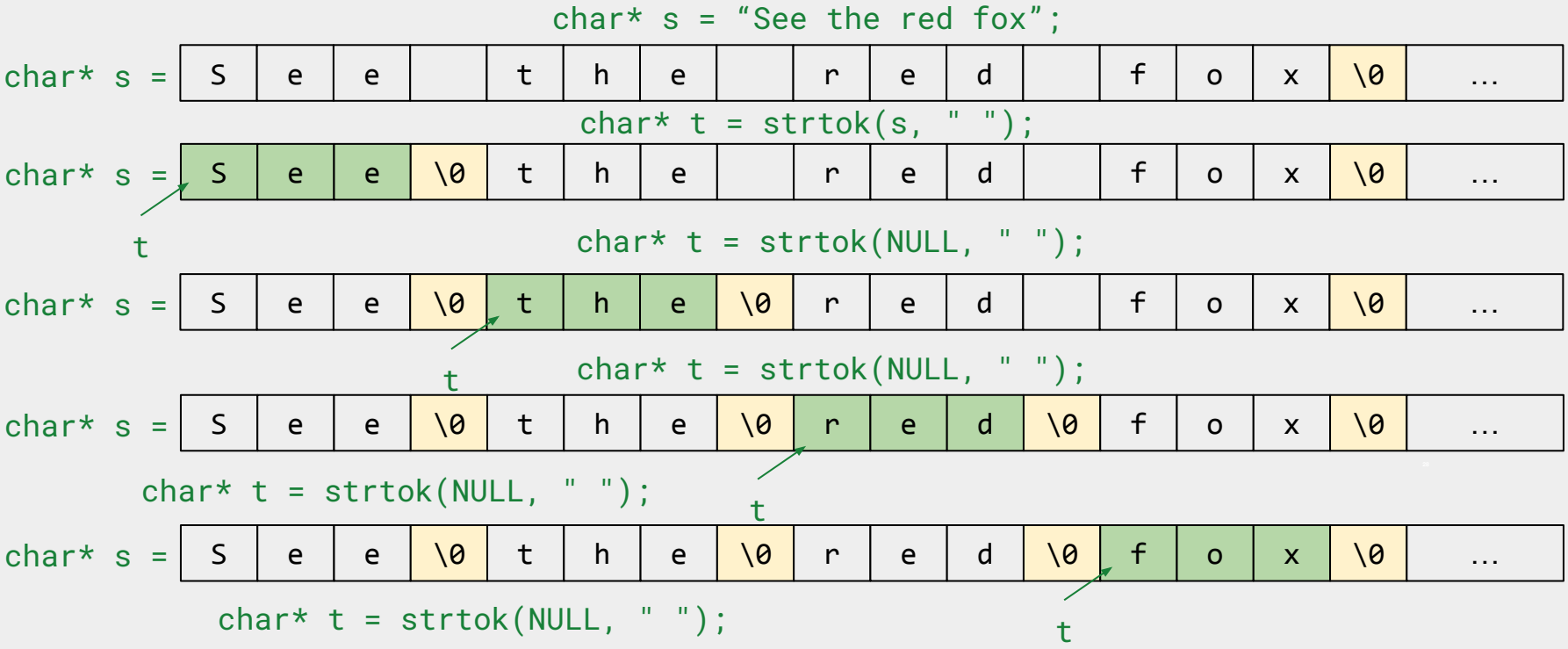
```c
#include <stdio.h>
#include <string.h>
int main(){
   char str[] = "I:love-programming";
   char delim[] = "-:";
   char *token;
   token = strtok(str, delim);
   printf("%s\n", token);
   token = strtok(NULL, delim);
   printf("%s\n", token);
   return 0;
}
```

What will be printed?

```
$ ./strtok_example
I
love
```

How can we print the remaining tokens?

A `strtok()` example



- `strtok()` changes the string that has been parsed!

`t` → NULL

idem·po·tent

- The `strtok()` function exhibits some weird behavior
  - `strtok()` changes the string that has been parsed
  - Replacing the character in place with a null terminator (`'\0'`)
- `strtok()` produces different results when called multiple times
  - It's a **non-idempotent** function
    - Which has ***side effects***.
- In comparison, functions that have no side effects are called **idempotent**.

```
x = 2; // Assignment operations are
x = 2; // idempotent
x = 2;
x = 2; // Calling it multiple times
x = 2; // always produces the same result
```

`man strtok` #NOTES-AND-BUGS

- Be cautious when using these functions. If you do use them, note that:
  - These functions modify their first argument.
  - These functions cannot be used on constant strings.
  - The identity of the delimiting byte is lost.
- For instance, if you try
  - `strtok("String Constant", delim)`
  - Segmentation fault! (attempting to write to a literal)

Still unsure? Read the man pages!

```
$ man strtok
```

- What arguments does the function take?
  - read **SYNOPSIS**
- What does the function do?
  - read **DESCRIPTION**
- What does the function return?
  - read **RETURN VALUES**
- What errors can the function fail with?
  - read **ERRORS**
- Is there anything I should watch out for?
  - read **NOTES**
- I want an example
  - read **EXAMPLES**
  - https://pitt.edu/~shk148/teaching/CS0449-2234/code/strtok.c.html

TopHat Questions