Part II
Processes and Threads

Process Basics

Program testing can be used to show the presence of bugs, but never to show their absence

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From Compilation to Execution

- A compiler compiles source files to `.o` files.
- A linker links `.o` files and other libraries together, producing a binary executable (e.g., `a.out`).
- A loader loads a binary executable into memory for execution.
What Is a Process?

- When the OS runs a program (i.e., a binary executable), this program is loaded into memory and the control is transferred to this program’s first instruction. Then, the program runs.

- **A process is a program in execution.**

- A process is more than a program, because a process has a program counter, stack, data section, code section, etc (i.e., the runtime stuffs).

- Moreover, multiple processes may be associated with one program (e.g., run the same program, say `a.out`, multiple times at the same time).
Process Space

The diagram illustrates the different sections of process space:

- **text/code**: Contains the program code.
- **data**: Stores global data.
- **heap**: Used for dynamic allocations with `malloc()`.
- **stack**: Contains local data and the stack top.

Out of memory occurs if the program counter points to an instruction and these two pointers cross each other. The stack top is indicated with an arrow and the maximum stack size is marked as `max`. The block diagram visually represents the process space layout.
Process States

At any moment, a process can be in one of the five states: new, running, waiting, ready and terminated.

- **New**: The process is being created
- **Running**: The process is executing on a CPU
- **Waiting**: The process is waiting for some event to occur (e.g., waiting for I/O completion)
- **Ready**: The process has everything but the CPU. It is waiting to be assigned to a processor.
- **Terminated**: The process has finished execution.
Process State Diagram

new

ready

running

waiting

terminated

converting to process

reclaim resource

destroy process

admitted

scheduler dispatch

interrupt

waiting for CPU

I/O or event completion

I/O or event wait

waiting for I/O or event

exit
Process Representation in OS

- Each process is assigned a unique number, the **process ID**.
- Process info are stored in a table, the **process control block (PCB)**.
- These PCBs are chained into a number of lists. For example, all processes in the ready state are in the **ready queue**.

<table>
<thead>
<tr>
<th>pointer</th>
<th>process state</th>
</tr>
</thead>
<tbody>
<tr>
<td>process ID</td>
<td></td>
</tr>
<tr>
<td>program counter</td>
<td></td>
</tr>
<tr>
<td>registers</td>
<td></td>
</tr>
<tr>
<td>scheduling info</td>
<td></td>
</tr>
<tr>
<td>memory limits</td>
<td></td>
</tr>
<tr>
<td>list of open files</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Process Scheduling: 1/2

- Since the number of processes may be larger than the number of available CPUs, the OS must maintain **maximum CPU utilization**.
- To determine which process can do what, processes are chained into a number of **scheduling queues**.
- For example, in addition to the ready queue, each event may have its own scheduling queue (*i.e.*, waiting queue).
Process Scheduling: 2/2

- The ready queue, which may be organized into several sub-queues, has all processes ready to run.
- The OS has a **CPU scheduler**.
- When a CPU is free, the CPU scheduler looks at the ready queue, picks a process, and resumes it.
- The way of picking a process from the ready queue is referred to as **scheduling policy**.
- Scheduling policy is unimportant to this course because we **cannot make any assumption** about it.
Context Switch: 1/2

- What is a process context? The context of a process includes process ID, process state, the values of CPU registers, the program counter, and other memory/file management information (i.e., execution environment).

- What is a context switch? After the CPU scheduler selects a process and before allocates CPU to it, the CPU scheduler must
  - save the context of the currently running process,
  - put it back to the ready queue or waiting state,
  - load the context of the selected process, and
  - go to the saved program counter.
  
  mode switching may be needed
**Context Switch: 2/2**

always remember mode switch
Operations on Processes

- There are three commonly seen operations:
  - **Process Creation**: Create a new process. The newly created is the child of the original. Unix uses `fork()` to create new processes.
  - **Process Termination**: Terminate the execution of a process. Unix uses `exit()`.
  - **Process Join**: Wait for the completion of a child process. Unix uses `wait()`.

- `fork()`, `exit()` and `wait()` are system calls.
Some Required Header Files

- Before you use processes, include header files `sys/types.h` and `unistd.h`.
- `sys/types.h` has all system data types, and `unistd.h` declares standard symbolic constants and types.

```c
#include <sys/types.h>
#include <unistd.h>
```
The fork() System Call

- The purpose of fork() is to create a child process. The creating and created processes are the parent and child, respectively.
- fork() does not require any argument!
- If the call to fork() is successful, Unix creates an identical but separate address space for the child process to run.
- Both processes start running with the instruction following the fork() system call.
**fork() Return Values**

- A negative value means the creation of a child process was unsuccessful.
- A zero means the process is a child.
- Otherwise, `fork()` returns the process ID of the child process. The ID is of type `pid_t`.
- Function `getpid()` returns the process ID of the caller.
- Function `getppid()` returns the parent’s process ID. If the calling process has no parent, `getppid()` returns 1.
Before the Execution of `fork()`

```c
parent

main()
{
    int a, b;
    pid_t pid
    fork();
    pid = ...;
    ......
}
```
After the Execution of `fork()`

in different address spaces

two independent and separate address spaces
Example 1: 1/2

#include <stdio.h>
#include <string.h>
#include <sys/types.h>
#include <unistd.h>

void main(void)
{
    pid_t MyID, ParentID;
    int i;
    char buf[100];

    fork();              // create a child process
    MyID     = getpid(); // get my process ID
    ParentID = getppid(); // get my parent’s process ID
    for (i = 1; i <= 200; i++) {
        sprintf(buf, "From MyID=%ld, ParentID=%ld, i=%3d\n", 
                MyID, ParentID, i);
        write(1, buf, strlen(buf)); // why don’t we
    } // why don’t we
} // use printf?

fork-1.c

this is stdout
Example 1: 2/2

Processes 19087 and 19088 run concurrently

Parent 19087’s parent is 19004, the shell that executes fork-1

Parent: 19087
Child : 19088

19004
19087
19088
fork(): A Typical Use

main(void)
{
    pid_t pid;

    pid = fork();
    if (pid < 0)
        printf(“Oops!”);
    else if (pid == 0)
        child();
    else // pid > 0
        parent();
}

void child(void)
{
    int i;
    for (i=1; i<=10; i++)
        printf(“Child:%d\n”, i);
    printf(“Child done\n”);
}

void parent(void)
{
    int i;
    for (i=1; i<=10; i++)
        printf(“Parent:%d\n”, i);
    printf(“Parent done\n”);
}

we use printf here to save space.
Before the Execution of `fork()`

```c
int main(void) {
    int pid = fork();
    if (pid == 0) {
        child();
    } else {
        parent();
    }
}

void child(void) {
    ...... }

void parent(void) {
    ...... }
```
After the Execution of \texttt{fork()}\footnote{1/2}

\begin{minipage}[t]{0.49\linewidth}
\textbf{parent}

\begin{verbatim}
main(void)
{
    pid = fork();
    if (pid == 0)
        child();
    else
        parent();
}

void child(void)
{   ......   }

void parent(void)
{   ......   }
\end{verbatim}
\end{minipage} \hspace{1cm}

\begin{minipage}[t]{0.49\linewidth}
\textbf{child}

\begin{verbatim}
main(void)
{
    pid = fork();
    if (pid == 0)
        child();
    else
        parent();
}

void child(void)
{   ......   }

void parent(void)
{   ......   }
\end{verbatim}
\end{minipage}

\textit{in two different address spaces}
After the Execution of `fork()` 2/2

**parent**

```c
main(void) { pid = fork();
    if (pid == 0)
        child();
    else
        parent();
}

void child(void)
{
    // ...
}

void parent(void)
{
    // ...
}
```

**child**

```c
main(void) { pid = fork();
    if (pid == 0)
        child();
    else
        parent();
}

void child(void)
{
    // ...
}

void parent(void)
{
    // ...
}
```
```c
#include ………  // child exits first 

void main(void)
{
    pid_t pid;

    pid = fork();
    if (pid == 0) {  // child here
        printf("From child %ld: my parent is %ld\n", 
            getpid(), getppid());
        sleep(5);
        printf("From child %ld 5 sec later: parent %ld\n", 
            getpid(), getppid());
    } else {  // parent here
        sleep(2);
        printf("From parent %ld: child %ld, parent %ld\n", 
            getpid(), pid, getppid());
        printf("From parent: done!\n");
    }
}
```
Example 2: 2/2

while parent is still running
  19004
  ↓
  parent 19291
  ↓
  child 19292

parent terminated
  1
  ↓
  child 19292

19004 is the shell process that executes 19291

Orphan children have a new parent \texttt{init}, the Unix process that spawns all processes

1 is the ID of \texttt{init}, the Unix process that spawns all processes
Example 3: 1/2

```c
#include ...... // separate address spaces

void main(void)
{
    pid_t pid;
    char out[100];
    int i = 10, j = 20;

    if ((pid = fork()) == 0) { // child here
        i = 1000; j = 2000; // child changes values
        sprintf(out, "From child: i=%d, j=%d\n", i, j);
        write(1, out, strlen(out));
    }
    else { // parent here
        sleep(3);
        sprintf(out, "From parent: i=%d, j=%d\n", i, j);
        write(1, out, strlen(out));
    }
}
```

This is equivalent to

```c
pid = fork();
if (pid == 0) ...
```

force the parent to print after the child terminated
Example 3: 2/2

child changes $i$ and $j$ to 1000 and 2000 from 10 and 20, respectively

parent’s $i$ and $j$ are not affected because parent and child have independent and separate address space
The `wait()` System Call

- The `wait()` system call blocks the caller until one of its child processes exits or a signal is received.
- `wait()` takes a pointer to an integer variable and returns the process ID of the completed process. If no child process is running, `wait()` returns `-1`.
- Some flags that indicate the completion status of the child process are passed back with the integer pointer.
How to Use `wait()`?

- Wait for an unspecified child process:
  
  ```c
  wait(&status);
  ```

- Wait for a number, say $n$, of unspecified child processes:
  
  ```c
  for (i = 0; i < n; i++)
      wait(&status);
  ```

- Wait for a specific child process whose ID is known:
  
  ```c
  while (pid != wait(&status))
      ;
  ```
wait() System Call Example

```c
void main(void)
{
    pid_t pid, pid_child;
    int status;

    if ((pid = fork()) == 0) // child here
        child();
    else { // parent here
        parent();
        pid_child = wait(&status);
    }
}
```
The exec() System Calls

- A newly created process may run a different program rather than that of the parent.
- This is done using the `exec` system calls. We will only discuss `execvp()`:

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

- **file** is a `char` array that contains the name of an executable file. Depending on your system settings, you may need the `. /` prefix for files in the current directory.
- **argv[]** is the argument passed to your main program
- **argv[0]** is a pointer to a string that contains the program name
- **argv[1]**, **argv[2]**, … are pointers to strings that contain the arguments
execvp() : An Example 1/2

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

void main(void)
{
    char prog[] = { "cp" };  
    char in[]   = { "this.c" }; 
    char out[]  = { "that.c" }; 
    char *argv[4];
    int status;
    pid_t pid;

    argv[0] = prog;  argv[1] = in;

    // see next slide
```
```c
if ((pid = fork()) < 0) {
    printf("fork() failed\n");
    exit(1);
}
else if (pid == 0)
    if (execvp(prog, argv) < 0) {
        printf("execvp() failed\n");
        exit(1);
    }
    else
        wait(&status);
else
    wait(&status);
```
A Mini-Shell: 1/3

void parse(char *line, char **argv)
{
    while (*line != ' \0') { // not EOLN
        while (*line == ' ' || *line == ' \n' || *line == ' \t')
            *line++ = ' \0'; // replace white spaces with 0
        *argv++ = line; // save the argument position
        while (*line != ' \0' && *line != ' \t' && *line != ' \n')
            line++;
    } // skip the argument until ...

    *argv = ' \0'; // mark the end of argument list
}

line[]

```c
cp this.c that.c \0
```

argv[]

```c
line[]

```

```c
cp \0 this.c \0 that.c \0
```
void execute(char **argv)
{
    pid_t pid;
    int status;
    if ((pid = fork()) < 0) { // fork a child process
        printf("*** ERROR: forking child process failed\n");
        exit(1);
    }
    else if (pid == 0) { // for the child process:
        if (execvp(*argv, argv) < 0) { // execute the command
            printf("*** ERROR: exec failed\n");
            exit(1);
        }
    }
    else { // for the parent:
        while (wait(&status) != pid) // wait for completion
            ;
    }
}
A Mini-Shell: 3/3

void main(void)
{
    char line[1024];       // the input line
    char *argv[64];        // the command line argument

    while (1) {             // repeat until done ....
        printf("Shell > ");  // display a prompt
        gets(line);          // read in the command line
        printf("\n");       // read in the command line
        parse(line, argv);   // parse the line
        if (strcmp(argv[0], "exit") == 0)  // is it an "exit"
            exit(0);          // exit if it is
        execute(argv);       // otherwise, execute the command
    }
}

Don’t forget that gets() is risky! Use fgets() instead.
What is Shared Memory?

- The parent and child processes are run in independent and separate address spaces. All processes, parent and children included, do not share anything.
- A shared memory segment is a piece of memory that can be allocated and attached to an address space. Processes that have this memory segment attached will have access to it.
- But, race conditions can occur!
Procedure for Using Shared Memory

- Find a **key**. Unix uses this key for identifying shared memory segments.
- Use `shmget()` to allocate a shared memory.
- Use `shmat()` to attach a shared memory to an address space.
- Use `shmdt()` to detach a shared memory from an address space.
- Use `shmctl()` to deallocate a shared memory.
To use shared memory, include the following:

```c
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
```

A key is a value of type `key_t`. There are three ways to generate a key:

- Do it yourself
- Use function `ftok()`
- Ask the system to provide a private key.
**Keys: 2/2**

- **Do it yourself:**
  
  ```c
  key_t    SomeKey;
  SomeKey = 1234;
  ```

- **Use `ftok()` to generate one for you:**
  
  ```c
  key_t = ftok(char *path, int ID);
  ```
  
  - `path` is a path name (e.g., `"./"`)  
  - `ID` is an integer (e.g., `'a'`)  
  - Function `ftok()` returns a key of type `key_t`:
    ```c
    SomeKey = ftok("./", 'x');
    ```

- **Keys are global entities.** If other processes know your key, they can access your shared memory.

- **Ask the system to provide a private key with `IPC_PRIVATE`.**
Ask for a Shared Memory: 1/4

- Include the following:
  
  ```c
  #include <sys/types.h>
  #include <sys/ipc.h>
  #include <sys/shm.h>
  ```

- Use `shmget()` to request a shared memory:
  
  ```c
  shm_id = shmget(
  key_t key,    /* identity key    */
  int size,   /* memory size     */
  int flag);  /* creation or use */
  ```

- `shmget()` returns a shared memory ID.

- The flag, for our purpose, is either `0666` (rw) or `IPC_CREAT | 0666`. Yes, `IPC_CREAT`.

The following creates a shared memory of size

```
struct Data { int a; double b; char x; };
int ShmID;
```

```
ShmID = shmget(
    IPC_PRIVATE, /* private key */
    sizeof(struct Data), /* size */
    IPC_CREAT | 0666); /* cr & rw */
```
Ask for a Shared Memory: 3/4

- The following creates a shared memory with a key based on the current directory:

```c
struct Data { int a; double b; char x;};
int    ShmID;
key_t  Key;

Key = ftok("./", 'h');
ShmID = shmget(
    Key,    /* a key */
    sizeof(struct Data),
    IPC_CREAT | 0666);
```
Ask for a Shared Memory: 4/4

- When asking for a shared memory, the process that creates it uses `IPC_CREAT | 0666` and processes that access a created one use `0666`.

- If the return value is negative (Unix convention), the request was unsuccessful, and no shared memory is allocated.

- **Create a shared memory before its use!**
After the Execution of `shmget()`

Shared memory is allocated; but, is not part of the address space
Attaching a Shared Memory: 1/3

- Use `shmat()` to attach an existing shared memory to an address space:

  
  ```c
  shm_ptr = shmat(
    int  shm_id, /* ID from shmget() */
    char *ptr,   /* use NULL here */
    int  flag);  /* use 0 here */
  ```

- `shm_id` is the shared memory ID returned by `shmget()`.

- Use `NULL` and `0` for the second and third arguments, respectively.

- `shmat()` returns a `void` pointer to the memory. If unsuccessful, it returns a negative integer.
struct Data { int a; double b; char x;};
int    ShmID;
key_t   Key;
struct Data *p;

Key = ftok("./", ‘h’);
ShmID = shmget(Key, sizeof(struct Data),
IPC_CREAT | 0666);
p = (struct Data *) shmat(ShmID, NULL, 0);
if ((int) p < 0) {
    printf("shmat() failed\n"); exit(1);
}
p->a = 1; p->b = 5.0; p->x = ‘.’;
Attaching a Shared Memory: 3/3

Now processes can access the shared memory.
Detaching/Removing Shared Memory

- To detach a shared memory, use
  ```c
  shmdt(shm_ptr);
  ```
  `shm_ptr` is the pointer returned by `shmat()`.

- After a shared memory is detached, it is still there. You can attach and use it again.

- To remove a shared memory, use
  ```c
  shmctl(shm_ID, IPC_RMID, NULL);
  ```
  `shm_ID` is the shared memory ID returned by `shmget()`. After a shared memory is removed, it no longer exists.
void main(int argc, char *argv[]) {
    int ShmID, *ShmPTR, status;
    pid_t pid;

    ShmID = shmget(IPC_PRIVATE, 4 * sizeof(int), IPC_CREAT|0666);
    ShmPTR = (int *) shmat(ShmID, NULL, 0);
    ShmPTR[0] = getpid();       ShmPTR[1] = atoi(argv[1]);
    if ((pid = fork()) == 0) {
        Child(ShmPTR);
        exit(0);
    }
    wait(&status);
    shmdt((void *) ShmPTR);    shmctl(ShmID, IPC_RMID, NULL);
    exit(0);
}
Communicating with a Child: 2/2

Why are `shmget()` and `shmat()` not needed in the child process?
Define the structure of a shared memory segment as follows:

```c
#define NOT_READY (-1)
#define FILLED (0)
#define TAKEN (1)

struct Memory {
    int status;
    int data[4];
};
```
Communicating Among Separate Processes: 2/5

The “Server”

```c
int main(int argc, char *argv[]) {
    key_t          ShmKEY;
    int            ShmID, i;
    struct Memory  *ShmPTR;

    ShmKEY = ftok("./", 'x');
    ShmID = shmget(ShmKEY, sizeof(struct Memory),
                   IPC_CREAT | 0666);
    ShmPTR = (struct Memory *) shmat(ShmID, NULL, 0);
}
```

Prepare for a shared memory.
Communicating Among Separate Processes: 3/5

```c
ShmPTR->status = NOT_READY;

ShmPTR->data[0] = getpid();
for (i = 1; i < 4; i++)
    ShmPTR->data[i] = atoi(argv[i]);

ShmPTR->status = FILLED;
while (ShmPTR->status != TAKEN)
    sleep(1); /* sleep for 1 second */
printf("My buddy is %ld\n", ShmPTR->data[0]);
shmdt((void *) ShmPTR);
shmctl(ShmID, IPC_RMID, NULL);
exit(0);
```
int main(void)
{
    key_t          ShmKEY;
    int            ShmID;
    struct Memory  *ShmPTR;

    ShmKEY=ftok(“./”, ‘x’);
    ShmID = shmget(ShmKEY, sizeof(struct Memory), 0666);
    ShmPTR = (struct Memory *) shmat(ShmID, NULL, 0);
    while (ShmPTR->status != FILLED)
    {
        printf(“%d %d %d %d
”, ShmPTR->data[0],
                     ShmPTR->data[1], ShmPTR->data[2], ShmPTR->data[3]);
        ShmPTR->data[0] = getpid();
        ShmPTR->status = TAKEN;
        shmdt((void *) ShmPTR);
    }
    exit(0);
}

The “Client”

prepare for shared memory
Communicating Among Separate Processes: 5/5

- The “server” must run first to prepare a shared memory.
- Run the server in one window, and run the client in another a little later.
- Or, run the server as a background process. Then, run the client in the foreground later:
  
  server 1 3 5 &
  client

- This version uses busy waiting.
- One may use Unix semaphores for mutual exclusion.
Important Notes: 1/3

- If you do not remove your shared memory segments (e.g., program crashes before the execution of `shmctl()`), they will be in the system forever until the system is shut down. This will degrade the system performance.
- Use the `ipcs` command to check if you have shared memory segments left in the system.
- Use the `ipcrm` command to remove your shared memory segments.
Important Notes: 2/3

- To see existing shared memory segments in the system, use `ipcs -m`, where `m` means shared memory.
- The following is a snapshot on `wopr`:

```
[shene@wopr ~]$ ipcs -m

------- Shared Memory Segments -------
key    shmid     owner     perms  bytes  nattch  status
0x78181367 1573912576 machoudh  666    12     0
0x7817433c 1336737793 hyunjik     666   204     0
0x78181363 1575583746 machoudh     666    12     0
0x7818132a 1577582595 machoudh     666    12     0
0x781813da 1579515908 machoudh     666    12     0
0x6b179e35 1612414981 mswillia     666    20     0
0x6b18b8b0 1909686278 machoudh     666    40     0
0x7918299c 1910013959 machoudh     666    92     0
[shene@wopr ~]$
```
Important Notes: 3/3

- To remove a shared memory, use the `ipcrm` command as follows:
  - `ipcrm -M shm-key`
  - `ipcrm -m shm-ID`

- You have to be the owner (or super user) to remove a shared memory.
The End