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., running the same program, say `a.out`, multiple times at the same time).
Process Space

- **Stack**: Local data, stack top.
- **Heap**: Dynamic allocations with `malloc()` obtain space here.
- **Data**: Global data.
- **Text/Code**: Program code.

Program counter points to an instruction.

Out of memory if these two pointers cross each other.
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**

**Transitions:**
- Converting to process
- Admitted
- Scheduler dispatch
- Interrupt
- Wait for I/O or event completion
- Exit
- I/O or event wait

**Actions:**
- Reclaim resource
- Destroy process
- Waiting for CPU
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**.
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 (i.e., all CPU’s being as busy as possible).
- 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*
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
main()
{
    int a, b;
    pid_t pid
    fork();
    pid = ...;
    ......
}
```
After the Execution of `fork()`

```c
parent
main()
{
    int a, b;
    pid_t pid;
    fork();
    pid = ...;
    ......
}

child
main()
{
    int a, b;
    pid_t pid;
    fork();
    pid = ...;
    ......
}
```

in different address spaces

two independent and separate address spaces
#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?
}
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
fork(): A Typical Use

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

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

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

**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)
{ ...... }
```

in two different address spaces

pid = 123

pid = 0
After the Execution of `fork()`
Example 2: 1/2

```c
#include .......... // child exits first
define fork-2.c

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");
    }
}
```

force the child to print after the parent terminates
Example 2: 2/2

while parent is still running

19004

<table>
<thead>
<tr>
<th>parent 19291</th>
</tr>
</thead>
<tbody>
<tr>
<td>child 19292</td>
</tr>
</tbody>
</table>

parent terminated

<table>
<thead>
<tr>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 is the ID of init, the Unix process that spawns all processes</td>
</tr>
</tbody>
</table>

19004 is the shell process that executes 19291

Orphan children have a new parent 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 \textit{wait()} System Call

- The \textit{wait()} system call blocks the caller until \textbf{one of its child processes} exits or a signal is received.

- \textit{wait()} takes a pointer to an integer variable and returns the process ID of the completed process. If no child process is running, \textit{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()`:

```
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

#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
execvp() : An Example 2/2

```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);
```

Execute program `cp`

```
cp
that.c
this.c
argv[]
```
void parse(char *line, char **argv)
{
    while (*line != '\0') { // not EOLN
        while (*line == ' ' || *line == '	' || *line == '
')
            *line++ = '0'; // replace white spaces with 0
        *argv++ = line; // save the argument position
        while (*line != '\0' && *line != ' ' && *line != '
')
            line++;
        // skip the argument until ...
    }
    *argv = '\0'; // mark the end of argument list
}

line[]
c p t h i s . c t h a t . 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
        {
        }
    }
}
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");
        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:

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

- Use `shmget()` to request a shared memory:

  ```
  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 means permission, which is either 0666 (you and your group can read and write) or `IPC_CREAT` | 0666.
The following creates a shared memory of size

struct Data with a private key

IPC_PRIVATE. This is a creation

(IPC_CREAT) with read and write permission

(0666).

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);
```
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 \texttt{shmget()}

Process 1

\texttt{shmget(...,IPC_CREAT|0666);}

Process 2

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
"); 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.
Communicating with a Child: 1/2

```c
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);
}
```
void Child(int SharedMem[]) {
    printf("%d %d %d %d\n", SharedMem[0], SharedMem[1], SharedMem[2], SharedMem[3]);
}

- **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];
};
```
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);
```
Communicating Among Separate Processes: 4/5

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\n", 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`:
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