OPERATING SYSTEM CONCEPTS

Chapter 3. Processes

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Warm-up

What Is the Output?

```c
/* cpu.c */
int main(int argc, char *argv[]) {
        if (argc != 2) {
                fprintf(stderr, "usage: cpu <string>\n");
                exit(1);
        }
        char *str = argv[1];
        while (1) {
                spin(1);
                printf("%s\n", str);
        }
        return 0;
}
```

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu A
```

Warm-up

What Is the Output?

```
1   /* cpu.c */
2   int main(int argc, char *argv[]) {
3           if (argc != 2) {
4                   fprintf(stderr, "usage: cpu <string>\n");
5                   exit(1);
6           }
7           char *str = argv[1];
8           while (1) {
9                   spin(1);
10                  printf("%s\n", str);
11          }
12          return 0;
13  }
```

```
1   prompt> gcc -o cpu cpu.c -Wall
2   prompt> ./cpu A
```
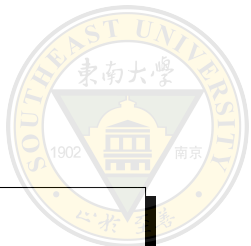
```
1   A
2   A
3   A
4   A
5   ^C
6   prompt>
```

Warm-up
What Is the Output? (contd.)

```c
/* cpu.c */
int main(int argc, char *argv[]) {
        if (argc != 2) {
                fprintf(stderr, "usage: cpu <string>\n");
                exit(1);
        }
        char *str = argv[1];
        while (1) {
                spin(1);
                printf("%s\n", str);
        }
        return 0;
}
```

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu A & ; ./cpu B & ; ./cpu C & ; ./cpu D &
```

Warm-up
What Is the Output? (contd.)

```
1  prompt> gcc -o cpu cpu.c -Wall
2  prompt> ./cpu A & ; ./cpu B & ; ./cpu C & ; ./cpu D &
```

```
1   [1] 7353
2   [2] 7354
3   [3] 7355
4   [4] 7356
5   A
6   B
7   D
8   C
9   A
10  B
11  D
12  C
13  A
14  C
15  B
16  D
17  ...
```

Warm-up

- How to implement virtualization of the CPU? — The OS will need both some low-level machinery (mechanisms) as well as some high-level intelligence (policies).

- The time-sharing mechanism (context switch) + scheduling policy — By running one process, then stopping it and running another, and so forth.

- The **process** (or job) is one of the most fundamental abstractions that the OS provides to users.

Objectives

- To introduce the notion of a process – a program in execution, which forms the basis of all computation.

- To describe the various features of processes, including scheduling, creation and termination, and communication.

- To explore interprocess communication using shared memory and message passing.

- To describe communication in client-server systems.

Contents

Contents

Process Concept

- An operating system executes a variety of programs:
  - Batch system — jobs
  - Time-shared systems — user programs or tasks

- Textbook uses the terms *job* and *process* almost interchangeably

- **Process** — a program in execution; process execution must progress in sequential fashion

- Multiple parts (machine state of the running program)
  - The program code, also called text section
  - Current activity including program counter, processor registers
  - Stack containing temporary data
    - » Function parameters, return addresses, local variables
  - Data section containing global variables
  - Heap containing memory dynamically allocated during run time
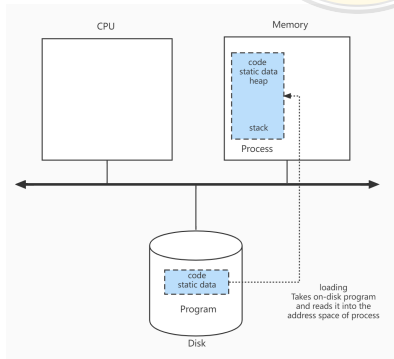
Process Concept
Process Vs. Program

- Program is *passive* entity stored on disk (executable file), process is *active*
  - Program becomes process when executable file loaded into memory
- Execution of program started via GUI mouse clicks, command line entry of its name, etc
- One program can be several processes
  - Consider multiple users executing the same program

Process Concept
Loading: From Program To Process

- How programs are transformed into processes?

  - *Loading* (*eagerly* or *lazily*)
  - *Paging* and *swapping*
  - Allocation of stack and heap
  - IO initialization
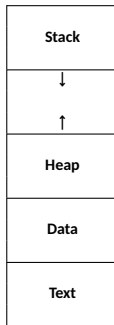
Process Concept

Process in Memory

```
1   /* main.c */
2   int a = 0;
3   char *p1;
4   int main(int argc, char *argv[]) {
5           int b;
6           char s[] = "abc";
7           char *p2;
8           char *p3 = "123456";
9           p1 = (char *)malloc(10);
10          p2 = (char *)malloc(20);
11          return 0;
12  }
```

max

| Stack |
| ↓ |
| ↑ |
| Heap |
| Data |
| Text |

0

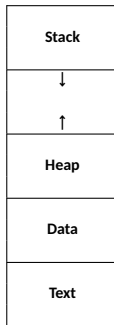# Process Concept
Process in Memory

```c
/* main.c */
int a = 0; // data
char *p1;
int main(int argc, char *argv[]) {
        int b;
        char s[] = "abc"; // stack
        char *p2;
        char *p3 = "123456"; // stack
        p1 = (char *)malloc(10); // heap
        p2 = (char *)malloc(20); // heap
        return 0;
}
```

max

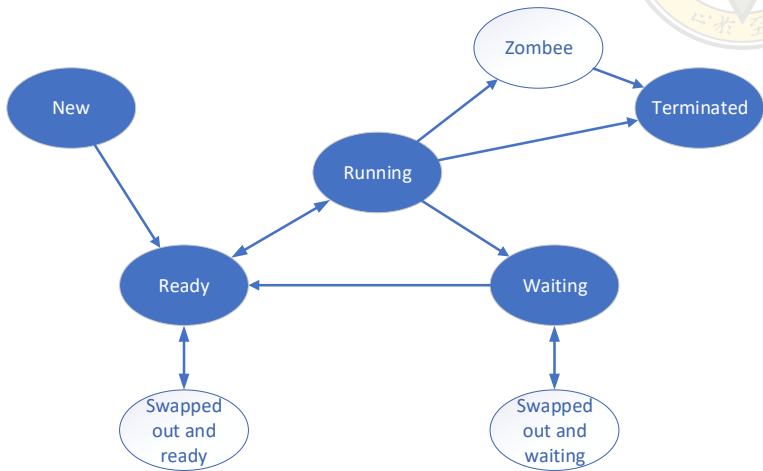| Stack |
| :---: |
| ↓ |
| ↑ |
| Heap |
| Data |
| Text |

0

Process Concept
Process State

- **new**: The process is being created
- **running**: Instructions are being executed
- **waiting**: The process is waiting for some event to occur
- **ready**: The process is waiting to be assigned to a processor
- **terminated**: The process has finished execution

Process Concept

Diagram of Process State

Process Concept
Process Data Structure

- Review: Motivating processes, why not programs?

  - Can a program be stopped and then be run again?

    » No, unless we can record the machine state of the running program.

    » A process can be viewed as a running program with machine states.

- OS is a program, so it has some key data structures that *track the state of each process*.

  - Process lists for all ready / running / waiting processes.

  - What else? — Types of information an OS needs to track processes.

- **Process Control Block** — An example: xv6 kernel
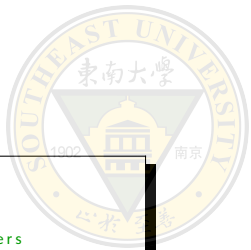
Process Concept

Process Control Block

```
1   // the registers
2   struct context {
3           int eip; // Program counter / instruction pointer
4           int esp, ebx, ecx, edx, esi, edi, ebp; // Other registers
5   };
6
7   // the different states a process can be in
8   enum proc_state { UNUSED, EMBRYO, SLEEPING, RUNNABLE, RUNNING, ZOMBIE };
9
10  // the information xv6 tracks about each process
11  struct proc {
12          char *mem; // Start of process memory
13          uint sz; // Size of process memory
14          char *kstack; // Bottom of kernel stack for this process
15          enum proc_state state; // Process state
16          int pid; // Process ID
17          struct proc *parent; // Parent process
18          void *chan; // If non-zero, sleeping on chan
19          int killed; // If non-zero, have been killed
20          struct file *ofile[NOFILE]; // Open files
21          struct inode *cwd; // Current directory
22          struct context context; // Switch here to run process
23          struct trapframe *tf; // Trap frame for the current interrupt
24  };
```

Process Concept
Process Execution — Direct Execution

- Suppose the following direct execution protocol.

- Any problem?

OS	Program
(kernel mode)	
create entry for process list	
allocate memory for program	
load program into memory	
set up stack with argc/argv	
clear registers	
execute call *main*()	
	run *main*()
	execute return from main
free memory of process	
remove from process list	

Process Concept
Process Execution — Limited Direct Execution

- Direct execution is fast, but
- Two problems with direct execution
- Protection
  - How can the OS make sure the program doesn't do anything that we don't want it to do?
  - Protection via dual mode and system call.
- Time sharing
  - How does the operating system stop it from running and switch to another process?
  - Time sharing via context switch.

Process Concept

Process Execution — Limited Direct Execution

OS @boot (kernel mode)	Hardware
initialize *trap table*	
	remember addresses of ...
	system call handler
	timer handler
	illegal instruction handler
start interrupt timer	
	start timer; interrupt after *X* ms

Process Concept
Process Execution — Protection

OS @run (kernel mode)	Hardware	Program (user mode)
create entry for process list		
allocate memory for program		
load program into memory		
set up user stack with argv		
fill kernel stack with reg/PC		
return-from-trap		
	move to *user mode*	
		run main()
		...
		call *system call* *trap* into OS
		to be contd.

Process Concept
Process Execution — Protection (contd.)

OS @run (kernel mode)	Hardware	Program (user mode)
		call *system call*
		trap into OS
	save regs to kernel stack	
	move to *kernel mode*	
	jump to *system call handler*	
handle *trap*		
return-from-trap		
	restore regs from kernel stack	
	move to *user mode*	
	jump to PC after trap	
		...
		return from main
		trap (via exit())
free memory of process		
remove from *process list*		

Process Concept
Process Execution — Time-sharing

- Switching Between Processes

    - OS regains control of the CPU via the timer interrupt.
    - Discussion: why hardware interrupt instead of software trap?

- Whether to switch is decided by the scheduler in OS.

- Context switch — saving and restoring context.

Process Concept
Process Execution — Time-sharing (contd.)

OS @boot (kernel mode)	Hardware
initialize *trap table*	
	remember addresses of ...
	system call handler
	timer handler
	illegal instruction handler
start interrupt timer	
	start timer
	interrupt CPU in *X* ms

Process Concept

Process Execution — Time-sharing (contd.)

OS @run (kernel mode)	Hardware	Program (user mode)
		Process *A*
		...
	timer interrupt	
	save regs(*A*)	
	from CPU to k-stack(*A*)	
	move to *kernel mode*	
	jump to *timer handler*	
handle *trap*		
call switch() routine		
save regs(*A*)		
from k-stack(*A*) to PCB(*A*)		
restore regs(*B*) from PCB(*B*)		
from PCB(*B*) to k-stack(*B*)		
switch to k-stack(*B*)		
return-from-trap (into *B*)		
	restore regs(*B*)	
	from k-stack(*B*) to CPU	
	move to *user mode*	
	jump to *B*'s PC	
		Process *B*
		...

Process Concept
Register Saves/Restores

- Where is the context stored in a context switch?
    - Somewhere in the memory
- Two types of register saves/restores:
- When the (timer) interrupt occurs
    - User registers are implicitly saved by the hardware, into the kernel stack of the process.
- When the OS decides to switch
    - Kernel registers are explicitly saved by the OS, into the PCB in memory.

Process Concept
Some Details

- What if one interrupt occurs during another interrupt or trap handling?
    - Especially when the kernel stack is not saved into PCB in memory.
    - If you understand this problem, you are now thinking about **concurrency** issues.
- Basically, disable interrupts during interrupt processing.
    - More details? In future lectures on concurrency.

Process Concept
Threads

- So far, process has a single thread of execution
- Consider having multiple program counters per process
  - Multiple locations can execute at once
  - Multiple threads of control → **threads**
- Must then have storage for thread details, multiple program counters in PCB
- Will be detailed in Ch4

Contents

Process Scheduling

- Maximize CPU use, quickly switch processes onto CPU for time sharing

- Process scheduler selects among available processes for next execution on CPU

- Maintains **scheduling queues** of processes
    - **Job queue** — set of all processes in the system
    - **Ready queue** — set of all processes residing in main memory, ready and waiting to execute
    - **Device queues** — set of processes waiting for an I/O device
    - Processes migrate among the various queues

Process Scheduling
Schedulers — Short-term Scheduler

- **Short-term scheduler** (or **CPU scheduler**) – selects which process should be executed next and allocates CPU
    - Sometimes the only scheduler in a system
    - Short-term scheduler is invoked frequently (milliseconds) → (must be fast)
- Will be detailed in Chapter 5

Process Scheduling

Schedulers — Long-term scheduler

- **Long-term scheduler** (or **job scheduler**) — selects which processes should be brought into the ready queue

    – Long-term scheduler is invoked infrequently (seconds, minutes) → (may be slow)

    – The long-term scheduler controls the degree of multiprogramming

- Processes can be described as either:

    – **I/O-bound process** — spends more time doing I/O than computations, many short CPU bursts

    – **CPU-bound process** — spends more time doing computations; few very long CPU bursts

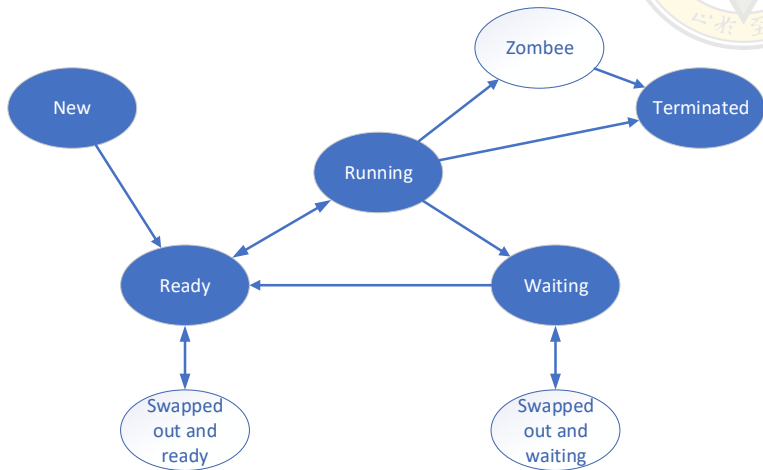- Long-term scheduler strives for good process mix

Process Scheduling
Schedulers — Medium-term scheduler

- **Medium-term scheduler** can be added if degree of multiple programming needs to decrease
  - Remove process from memory, store on disk, bring back in from disk to continue execution: **swapping**

Process Scheduling

Diagram of Process State with Schedulers

Contents

Operations on Processes

- System must provide mechanisms for:
  - process creation,
  - process termination,
  - and so on as detailed next
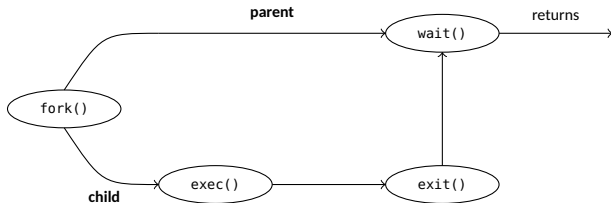
Operations on Processes
Process Creation

- Parent process creates children processes, which, in turn create other processes, forming a tree of processes
- Generally, process identified and managed via a **process identifier** (**pid**)
- Resource sharing options
  - Parent and children share all resources
  - Children share subset of parent's resources
  - Parent and child share no resources
- Execution options
  - Parent and children execute concurrently
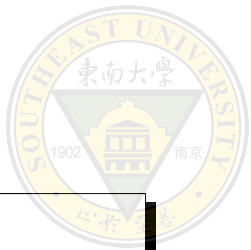 - Parent waits until children terminate

Operations on Processes
Process Creation (contd.)

- Address space
  - Child duplicate of parent
  - Child has a program loaded into it

- UNIX examples
  - *fork*() system call creates new process
  - *exec*() system call used after a *fork*() to replace the process' memory space with a new program

Operations on Processes

C Program Forking Separate Process

```c
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[]) {
        pid_t pid;
        pid = fork();
        if (pid < 0) { // error occurred
                fprintf(stderr, "Fork Failed");
                return 1;
        }
        else if (pid == 0) { // child process
                execlp("/bin/ls", "ls", NULL);
        }
        else { // parent process
                wait(NULL);
                printf("Child Complete");
        }
        return 0;
}
```

Operations on Processes
Process Termination

- Process executes the last statement and then asks the operating system to delete it using the *exit*() system call.
    - Returns status data from child to parent (via *wait*())
    - Process' resources are deallocated by operating system
- Parent may terminate the execution of children processes using the *abort*() system call. Some reasons for doing so:
    - Child has exceeded allocated resources
    - Task assigned to child is no longer required
    - The parent is exiting and the operating systems does not allow a child to continue if its parent terminates

Operations on Processes
Process Termination (contd.)

- Some operating systems do not allow child to exists if its parent has terminated. If a process terminates, then all its children must also be terminated.
  - cascading termination. All children, grandchildren, etc. are terminated.
  - The termination is initiated by the operating system.
- The parent process may wait for termination of a child process by using the *wait*()system call. The call returns status information and the pid of the terminated process

```
1      pid = wait(&status);
```

- If no parent waiting (did not invoke *wait*()), process is a zombie
- If parent terminated without invoking *wait*(), process is an orphan

Operations on Processes

In Class Exercise

```c
/* exercise.c */
int value = 5;
int main(int argc, char *argv[]) {
        pid_t pid;
        pid = fork();
        if (pid == 0) {
                printf("child process, value1 : %d\n", value);
                value += 15;
                printf("child process, value2 : %d\n", value);
        }
        else if (pid > 0) {
                printf("parent process, value3 : %d\n", value);
                wait(NULL);
                printf("parent process, value4 : %d\n", value);
        }
        exit(0);
}
```

- What is the output?

Key

```
1  prompt> ./exercise
2  child process, value1 : 5
3  child process, value2 : 20
4  parent process, value3 : 5
5  parent process, value4 : 5
6  prompt>
```

```
1  prompt> ./exercise
2  parent process, value3 : 5
3  child process, value1 : 5
4  child process, value2 : 20
5  parent process, value4 : 5
6  prompt>
```

Operations on Processes

Motivating the APIs

```c
1   /* p1.c */
2   int main(int argc, char *argv[]) {
3           printf("hello world (pid:%d)\n", (int) getpid());
4           int rc = fork();
5           if (rc < 0) {
6                   fprintf(stderr, "fork failed\n");
7                   exit(1);
8           }
9           else if (rc == 0) {
10                  printf("hello, I am child (pid:%d)\n", (int) getpid());
11                  char *myargs[3];
12                  myargs[0] = strdup("wc");
13                  myargs[1] = strdup("p1.c");
14                  myargs[2] = NULL;
15                  execvp(myargs[0], myargs);
16                  printf("this shouldn't print out");
17          }
18          else {
19                  int wc = wait(NULL);
20                  printf("hello, I am parent of %d (wc:%d) (pid:%d)\n", rc, wc
                           , (int) getpid());
21          }
22          return 0;
23  }
```

Operations on Processes
Motivating the APIs (contd.)

```
1   prompt> ./p1
2   hello world (pid:29383)
3   hello, I am child (pid:29384)
4         29      107     1030    p1.c
5   hello, I am parent of 29384 (wc:29384) (pid:29383)
6   prompt>
```

- Motivating The API

- Available to run code after the call to fork() but before the call to *exec*().

```
1   prompt> wc p2.c > newfile
```

Operations on Processes

Redirection

```
1   /* p2.c */
2   int main(int argc, char *argv[]) {
3           printf("hello world (pid:%d)\n", (int) getpid());
4           int rc = fork();
5           if (rc < 0) {
6                   fprintf(stderr, "fork failed\n");
7                   exit(1);
8           }
9           else if (rc == 0) {
10                  /********** from here **********/
11                  close(STDOUT_FILENO);
12                  open("./p2.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);
13                  /**********  to here  **********/
14                  char *myargs[3];
15                  myargs[0] = strdup("wc");
16                  myargs[1] = strdup("p2.c");
17                  myargs[2] = NULL;
18                  execvp(myargs[0], myargs);
19                  printf("this shouldn't print out");
20          }
21          else {
22                  int wc = wait(NULL);
23          }
24          return 0;
25  }
```

Contents

Interprocess Communication

- Processes within a system may be independent or cooperating

- Cooperating process can affect or be affected by other processes, including sharing data

- Reasons for cooperating processes: (pp.122)

    – Information sharing
    – Computation speedup
    – Modularity
    – Convenience

- Cooperating processes need **interprocess communication** (**IPC**)

- Two models of IPC

    – **Shared memory**
    – **Message passing**

Interprocess Communication
Message Passing & Shared Memory
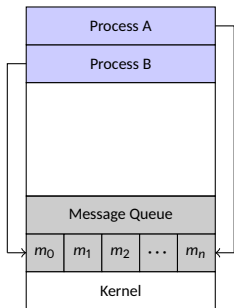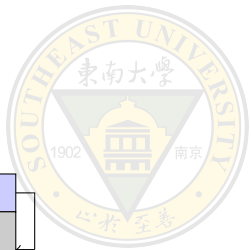
**Message Passing**
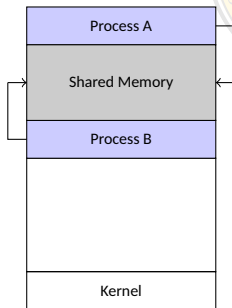
Shared Memory

- In the **message-passing** model, communication takes place by means of messages exchanged between the cooperating processes.

- In the **shared-memory** model, a region of memory that is shared by cooperating processes is established. Processes can then exchange information by reading and writing data to the shared region.

Interprocess Communication
Producer-Consumer Problem

- A common paradigm for cooperating processes.

- A producer process produces information that is consumed by a consumer process.

  - A compiler may produce assembly code that is consumed by an assembler.
  - The assembler, in turn, may produce object modules that are consumed by the loader.
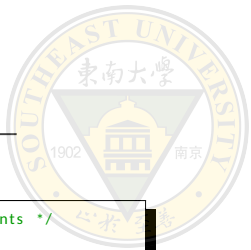
Interprocess Communication

Producer-Consumer Problem — Bounded Buffer —
Shared-Memory Solution

```
1   /* Solution is correct, but can only use BUFFER_SIZE – 1 elements */
2   #define BUFFER_SIZE 10
3   typedef struct { ... } item;
4   item buffer[BUFFER_SIZE];
5   int in = 0;
6   int out = 0;
```

```
1   /* producer */
2   item next_produced;
3   while (true) {
4           while (((in + 1) % BUFFER_SIZE) == out) ;
5           buffer[in] = next_produced;
6           in = (in + 1) % BUFFER_SIZE;
7   }
```

```
1   /* consumer */
2   item next_consumed;
3   while (true) {
4           while (in == out) ;
5           next_consumed = buffer[out];
6           out = (out + 1) % BUFFER_SIZE;
7   }
```

Interprocess Communication

Producer-Consumer Problem — Bounded Buffer — Shared-Memory Solution

| *in* = | 0 |
| *out* = | 0 |

| *i* = | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

buffer

- An exercise for you to provide a solution in which *BUFFER_SIZE* items can be in the buffer at the same time.
- *in* indicates the next production, and
- *out* indicates the next consumption.
- What if *i* == *out*?
  - *buffer* is empty, or
  - *buffer* is full.

Interprocess Communication

Producer-Consumer Problem — Bounded Buffer — Shared-Memory Solution

in =	1										
out =	0										
i =	0	1	2	3	4	5	6	7	8	9	
buffer	*										

- An exercise for you to provide a solution in which *BUFFER_SIZE* items can be in the buffer at the same time.
- *in* indicates the next production, and
- *out* indicates the next consumption.
- What if *i* == *out*?
  - *buffer* is empty, or
  - *buffer* is full.

Interprocess Communication

Producer-Consumer Problem — Bounded Buffer —
Shared-Memory Solution

in =			2								
out =		0									

i =	0	1	2	3	4	5	6	7	8	9
buffer	*	*								

- An exercise for you to provide a solution in which *BUFFER_SIZE* items can be in the buffer at the same time.
- *in* indicates the next production, and
- *out* indicates the next consumption.
- What if *i* == *out*?
    - *buffer* is empty, or
    - *buffer* is full.

Interprocess Communication

Producer-Consumer Problem — Bounded Buffer — Shared-Memory Solution

in =			3							
out =	0									

i =	0	1	2	3	4	5	6	7	8	9
buffer	*	*	*							

- An exercise for you to provide a solution in which *BUFFER_SIZE* items can be in the buffer at the same time.
- *in* indicates the next production, and
- *out* indicates the next consumption.
- What if *i* == *out*?
    - *buffer* is empty, or
    - *buffer* is full.

Interprocess Communication

Producer-Consumer Problem — Bounded Buffer — Shared-Memory Solution

| *in* = | | | | | | | | | | 9 |

| *out* = | 0 | | | | | | | | | |

i =	0	1	2	3	4	5	6	7	8	9
buffer	*	*	*	*	*	*	*	*	*	

- An exercise for you to provide a solution in which *BUFFER_SIZE* items can be in the buffer at the same time.
- *in* indicates the next production, and
- *out* indicates the next consumption.
- What if *i* == *out*?
  - *buffer* is empty, or
  - *buffer* is full.

Interprocess Communication
Shared Memory

- An area of memory shared among the processes that wish to communicate

- The communication is under the control of the users processes not the operating system.

- Major issues is to provide mechanism that will allow the user processes to synchronize their actions when they access shared memory.

- **Synchronization** will be discussed in great details in Chapter 5.

Interprocess Communication
Message Passing

- Mechanism for processes to communicate and to synchronize their actions

- Message system — processes communicate with each other without resorting to shared variables

- IPC facility provides two operations:
  - *send*(*message*)
  - *receive*(*message*)

- The *message* size is either fixed or variable

Interprocess Communication

Message Passing — Naming

- Under direct communication, each process that wants to communicate must explicitly name the recipient or sender of the communication.
    - *Symmetric* addressing: both the sender process and the receiver process must name the other to communicate.
        » *send*(*P, message*) — Send a message to process P.
        » *receive*(*Q, message*) — Receive a message from process Q.
    - *Asymmetric* addressing: only the sender names the recipient; the recipient is not required to name the sender.
        » *send*(*P, message*) — Send a message to process P.
        » *receive*(*id, message*) — Receive a message from any process.
    - Properties:
        » A link is established automatically between every pair of processes that want to communicate.
        » A link is associated with exactly two processes.
        » Between each pair of processes, there exists exactly one link.

Interprocess Communication
Message Passing — Naming (Contd.)

- With Indirect communication, the messages are sent to and received from *mailboxes*, or *ports*
  - A mailbox can be viewed abstractly as an object into which messages can be placed by processes and from which messages can be removed.
    - » *send*(*A, message*) — Send a message to mailbox A.
    - » *receive*(*A, message*) — Receive a message from mailbox A.
  - Properties:
    - » A link is established between a pair of processes only if both members of the pair have a shared mailbox.
    - » A link may be associated with more than two processes.
    - » Between each pair of communicating processes, a number of different links may exist, with each link corresponding to one mailbox.

Interprocess Communication
Message Passing — Synchronization

- Message passing may be either blocking or non-blocking

- **Blocking** is considered **synchronous**

    - Blocking send — the sender is blocked until the message is received
    - Blocking receive — the receiver is blocked until a message is available

- **Non-blocking** is considered **asynchronous**

    - Non-blocking send — the sender sends the message and continue
    - Non-blocking receive — the receiver receives:
        - » A valid message, or
        - » Null message

- Different combinations possible

    - If both send and receive are blocking, we have a rendezvous

Interprocess Communication
Message Passing — Buffering

- Whether communication is direct or indirect, messages exchanged by communicating processes reside in a temporary queue, which can be implemented in three ways:
    - Zero capacity. The sender must block until the recipient receives the message
    - Bounded capacity.
    - Unbounded capacity.

Interprocess Communication

Producer-Consumer Problem — Message Passing Solution

```
1   /* producer */
2   message next_produced;
3   while (true) {
4            /* produce an item in next produced */
5            send(next_produced);
6   }
```

```
1   /* consumer */
2   item next_consumed;
3   while (true) {
4            receive(next_consumed);
5            /* consume the item in next consumed */
6   }
```

Interprocess Communication
Message Passing Vs. Shared Memory

- Which is better?
- Message passing is useful for exchanging smaller amounts of data, because no conflicts need be avoided.
- Message passing is easier to implement in a distributed system than shared memory.
- Shared memory can be faster than message passing
  - Message-passing systems are typically implemented using system calls and thus require the more time-consuming task of kernel intervention.
  - In shared-memory systems, system calls are required only to establish shared memory regions.
- Message passing provides better performance than shared memory in multi-processing systems
  - Shared memory suffers from cache coherency issues
- As the number of processing cores on systems increases, it is possible that we will see message passing as the preferred mechanism for IPC.

Contents

Communication in Client-Server Systems
Sockets

- A socket is defined as an endpoint for communication
- Concatenation of IP address and port — a number included at start of message packet to differentiate network services on a host
- The socket 161.25.19.8 : 1625 refers to port 1625 on host 161.25.19.8
- Communication consists between a pair of sockets
- All ports below 1024 are well known, used for standard services
- Special IP address 127.0.0.1 (loopback) to refer to system on which process is running

Communication in Client-Server Systems
Remote Procedure Calls

- Remote procedure call (RPC) abstracts procedure calls between processes on networked systems
- Again uses ports for service differentiation
- Stubs — client-side proxy for the actual procedure on the server
- The client-side stub locates the server and marshalls the parameters
- The server-side stub receives this message, unpacks the marshalled parameters, and performs the procedure on the server
- On Windows, stub code compile from specification written in Microsoft Interface Definition Language (MIDL)

Communication in Client-Server Systems
Pipes

- UNIX pipes are implemented in a similar way, but with the pipe() system call.

  - The output of one process is connected to an in-kernel pipe.
  - The input of another process is connected to that same pipe.

```
1   prompt> ls |wc
```

- Ordinary pipes — cannot be accessed from outside the process that created it. Typically, a parent process creates a pipe and uses it to communicate with a child process that it created.

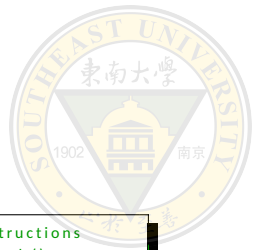- Named pipes — can be accessed without a parent-child relationship.

Exercise
Exercise

- Including the initial parent process, how many processes are created by the following program.

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

int main() {
        int i;
        for (i = 0; i < 4; i++)
                fork();
        return 0;
}
```
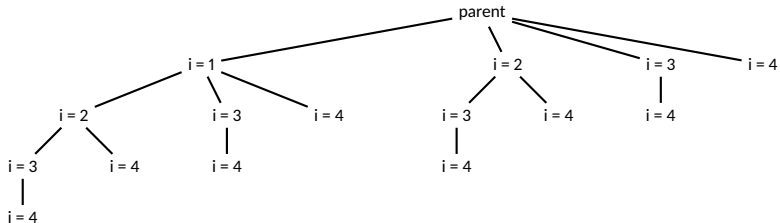
Exercise

Key to

```
1  int i;
2  for (i = 0; i < 4; i ++)
3    fork ();
4  return 0;
```

```
1  0x1024 ···; some instructions
       implementing fork()
2  0x2028 incl %eax
3  0x202c cmpl $0x0004, %eax
4  0x2030 jne 0x1024
5  0x2032 retn
```

Exercise

Exercise 3.2

- Draw the diagram of process state.