CS370 Operating Systems

Colorado State University

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Fall 2025 Lecture 6

Processes

Slides based on

- **Text by Silberschatz, Galvin, Gagne**
- **Various sources**

We have seen

- When does the child process begin execution? fork ( ).
- What does fork( ) return?
  - It returns the value 0 in the child process. Child's PID is not zero
  - In the parent fork( ) returns the PID of the child.
- Fork is not a branch or a function call like the ordinary programs you have worked with in the past. The child process is a separate process.
- getpid(), getppid( )
- rv = wait(&wstatus);
  - Caller will block until the child exits or finishes.
  - on success, returns PID of the terminated child; on error, -1 is returned.
  - Status in wstatus variable, extracted using WEXITSTATUS(wstatus)
- **Self exercise 3**: Examine, compile and and run programs.

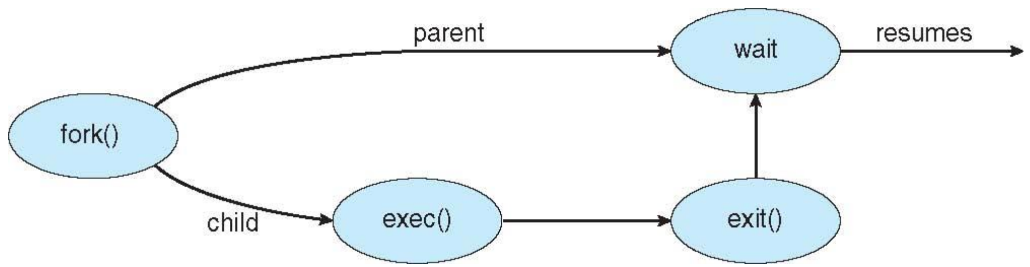
Forking PIDs

```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>
int main(){
        pid_t cid;

        /* fork a child process */
        cid = fork();
        if (cid < 0) { /* error occurred */
            fprintf(stderr, "Fork Failed\n");
           return 1;
        }
        else if (cid == 0) { /* child process */
            printf("I am the child %d, my PID is %d\n", cid, getpid());
             execlp("/bin/ls","ls",NULL);
        }
        else { /* parent process */
             /* parent will wait for the child to complete */
             printf("I am the parent with PID %d, my parent is %d, my child is %d\n",getpid(), getppid(), cid);
             wait(NULL);

             printf("Child Complete\n");
        }

  return 0;
}
```



Parent and the child processes run concurrently.

Producer-Consumer Problem

- Common paradigm for cooperating processes, *producer* process produces information that is consumed by a *consumer* process
  - **unbounded-buffer** places no practical limit on the size of the buffer
  - **bounded-buffer** assumes that there is a fixed buffer size

Why do we need a buffer (shared memory region)?
- The producer and the consumer process operate at their own speeds. Items wait in the buffer when consumer is slow.

Where does the bounded buffer "start"?
- It is circular

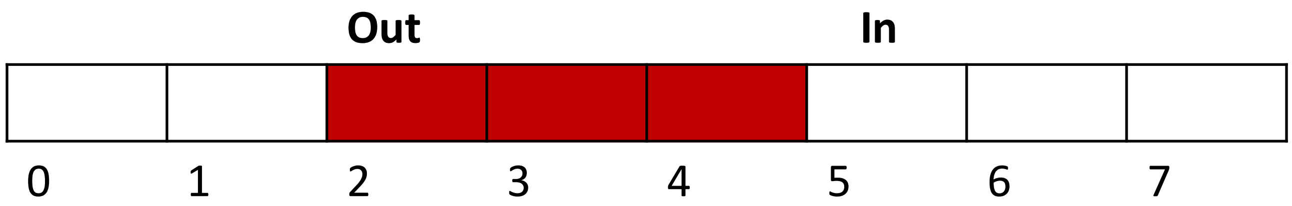
Bounded-Buffer – Shared-Memory Solution

- Shared data

```
#define BUFFER_SIZE 8
typedef struct {
   . . .
} item;

item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

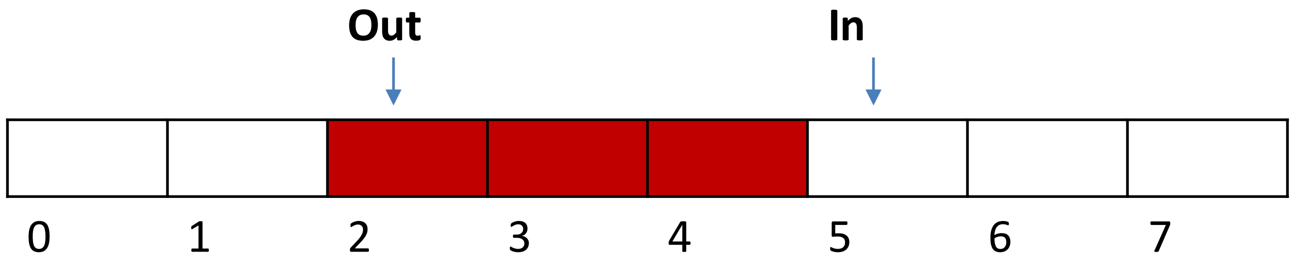
- **in** points to the **next free position** in the buffer
- **out** points to the **first full position** in the buffer.
- Buffer is empty when **in == out**;
- Buffer is full when
  ((in + 1) % BUFFER SIZE) == out. (Circular buffer)
- This scheme can only use BUFFER_SIZE-1 elements



(2+1)%8 =3 but   (7+1)%8 =0

Bounded-Buffer – Producer

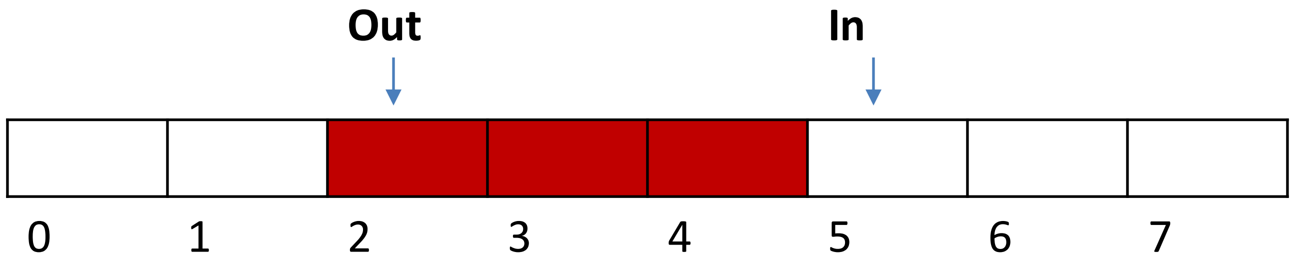
```
item next_produced;
while (true) {
        /* produce an item in next produced */
        while (((in + 1) % BUFFER_SIZE) == out)
                ; /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
}
```



Bounded Buffer – Consumer

```
item next_consumed;
while (true) {
        while (in == out)
                ; /* do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;

        /* consume the item in next consumed */
}
```



Interprocess Communication – Shared Memory

- Each process has its own private address space.
- An area of memory shared among the processes that wish to communicate
- The communication is under the control of the user processes, not the operating system.
- Major issue is to provide mechanism that will allow the user processes to synchronize their actions when they access shared memory.
  - Synchronization is discussed in great details in a later Chapter.
- Example soon.

Only one process may access shared memory at a time

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

Message Passing (Cont.)

- If processes *P* and *Q* wish to communicate, they need to:
  - Establish a ***communication link*** between them
  - Exchange messages via send/receive
- Implementation issues:
  - How are links established?
  - Can a link be associated with more than two processes?
  - How many links can there be between every pair of communicating processes?
  - What is the capacity of a link?
  - Is the size of a message that the link can accommodate fixed or variable?
  - Is a link unidirectional or bi-directional?

Message Passing (Cont.)

- Implementation of communication link
  - Physical:
    - Shared memory
    - Hardware bus
    - Network
  - Logical: Options (details next)
    - Direct (process to process) or indirect (mail box)
    - Synchronous (blocking) or asynchronous (non-blocking)
    - Automatic or explicit buffering

Direct Communication

- Processes must name each other explicitly:
  - **`send`** (*P, message*) – send a message to process P
  - **`receive`**(*Q, message*) – receive a message from process Q
- Properties of communication link
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link
  - The link may be unidirectional, but is usually bi-directional

Indirect Communication

- Messages are directed and received from mailboxes (also referred to as ports)
  - Each mailbox has a unique id
  - Processes can communicate only if they share a mailbox
- Properties of communication link
  - Link established only if processes share a common mailbox
  - A link may be associated with many processes
  - Each pair of processes may share several communication links
  - Link may be unidirectional or bi-directional

Indirect Communication

- Operations
  - create a new mailbox (port)
  - send and receive messages through mailbox
  - destroy a mailbox
- Primitives are defined as:

  `send`(*A, message*) – send a message to mailbox A

  `receive`(*A, message*) – receive a message from mailbox A

Indirect Communication

- Mailbox sharing
  - P_1, P_2, and P_3 share mailbox A
  - P_1, sends; P_2 and P_3 receive
  - Who gets the message?
- Possible Solutions
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation
  - Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was.

Synchronization*(blocking or not)*

- Message passing may be either blocking or non-blocking
- Blocking is termed **synchronous**
  - **Blocking send** -- sender is blocked until message is received
  - **Blocking receive** -- receiver is blocked until a message is available
- Non-blocking is termed **asynchronous**
  - **Non-blocking send** -- sender sends message and continues
  - **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.**
  - Producer-Consumer problem: Easy if both block

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Examples of IPC Systems

OSs support many different forms of IPC*. We will look at two of them

- Shared Memory
- Pipes

* **Linux kernel supports**: Signals, **Anonymous Pipes**, Named Pipes or FIFOs, SysV Message Queues, POSIX Message Queues, SysV Shared memory, **POSIX Shared memory**, SysV semaphores, POSIX semaphores, FUTEX locks, File-backed and anonymous shared memory using mmap, UNIX Domain Sockets, Netlink Sockets, Network Sockets, Inotify mechanisms, FUSE subsystem, D-Bus subsystem

Ex. POSIX Shared Memory (1)

- Older scheme (System V) us3d shmget(), shmat(), shmdt(), shmctl()
- POSIX Shared Memory
  - First process first creates shared memory segment

    ```
    shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);
    ```
    - Returns file descriptor (int)
    - Identified by name (string)
    - Also used to open an existing segment to share it
  - Set the size of the object

    ```
    ftruncate(shm_fd, 4096);
    ```
  - map the shared memory segment in the address space of the process

    ```
    ptr = mmap(0,SIZE, PROT_READ | PROT_WRITE,
               MAP_SHARED, shm_fd, 0);
    ```
  - Now the process could write to the shared memory

    ```
    sprintf(ptr, "Writing to shared memory");
    ```

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Ex. POSIX Shared memory (2)

- POSIX Shared Memory
  - Other process opens shared memory object name
    ```
    shm_fd = shm_open(name, O_RDONLY, 0666);
    ```
    - Returns file descriptor (int) which identifies the file
  - map the shared memory object
    ```
    ptr = mmap(0,SIZE, PROT_READ, MAP_SHARED,
             shm_fd, 0);
    ```
    - Now the process can read from to the shared memory object
  - `printf(“%s”, (char *)ptr);`
  - remove the shared memory object
    ```
    shm_unlink(name);
    ```

Please remember to unlink, name persists in OS.

IPC POSIX Producer

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <fcntl.h>
#include <sys/shm.h>
#include <sys/stat.h>

int main()
{
   /* the size (in bytes) of shared memory object */
   const int SIZE = 4096;

   /* name of the shared memory object */
   const char* name = "OS";

   /* strings written to shared memory */
   const char* message_0 = "Hello";
   const char* message_1 = "World!";

   /* shared memory file descriptor */
   int shm_fd;

   /* pointer to shared memory object */
   char* ptr;

   /* create the shared memory object */
   shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);

   /* configure the size of the shared memory object */
   ftruncate(shm_fd, SIZE);

   /* memory map the shared memory object */
   ptr = mmap(0, SIZE, PROT_WRITE, MAP_SHARED, shm_fd, 0);

   /* write to the shared memory object */
   sprintf(ptr, "%s", message_0);

   ptr += strlen(message_0);
   sprintf(ptr, "%s", message1);
   ptr += strlen(message_1);
   return 0;
```

See Self Exercises

IPC POSIX Producer (details)

```
/* create the shared memory segment */
shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);

/* configure the size of the shared memory segment */
ftruncate(shm_fd,SIZE);

/* now map the shared memory segment in the address space of the process */
ptr = mmap(0,SIZE, PROT_READ | PROT_WRITE, MAP_SHARED, shm_fd, 0);
if (ptr == MAP_FAILED) {
        printf("Map failed\n");
        return -1;
}

/**
 * Now write to the shared memory region.
 *
 * Note we must increment the value of ptr after each write.
 */
sprintf(ptr,"%s",message0);
ptr += strlen(message0);
sprintf(ptr,"%s",message1);
ptr += strlen(message1);
sprintf(ptr,"%s",message2);
ptr += strlen(message2);

return 0;
}
```

File descriptor FD: int that uniquely identifies a file.

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IPC POSIX Consumer

```
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <sys/shm.h>
#include <sys/stat.h>

int main()
{
   /* the size (in bytes) of shared memory object */
   const int SIZE = 4096;

   /* name of the shared memory object */
   const char* name = "OS";

   /* shared memory file descriptor */
   int shm_fd;

   /* pointer to shared memory object */
   char *ptr;

   /* open the shared memory object */
   shm_fd = shm_open(name, O_RDONLY, 0666);

   /* memory map the shared memory object */
   ptr = mmap(0, SIZE, PROT_READ, MAP_SHARED, shm_fd, 0);

   /* read from the shared memory object */
   printf("%s", (char*)ptr);

   /* remove the shared memory object */
   shm_unlink(name);
   return 0;
}
```

IPC POSIX Consumer (details)

```
/* open the shared memory segment */
        shm_fd = shm_open(name, O_RDONLY, 0666);
        if (shm_fd == -1) {
                printf("shared memory failed\n");
                exit(-1);
        }

        /* now map the shared memory segment in the address space of the process
*/
        ptr = mmap(0,SIZE, PROT_READ, MAP_SHARED, shm_fd, 0);
        if (ptr == MAP_FAILED) {
                printf("Map failed\n");
                exit(-1);
        }

        /* now read and print from the shared memory region */
        printf("%s",ptr);

        /* remove the shared memory segment */
        if (shm_unlink(name) == -1) {
                printf("Error removing %s\n",name);
                exit(-1);
        }
```

Bit mask created by ORing flags

Mode

Memory protection

Flag

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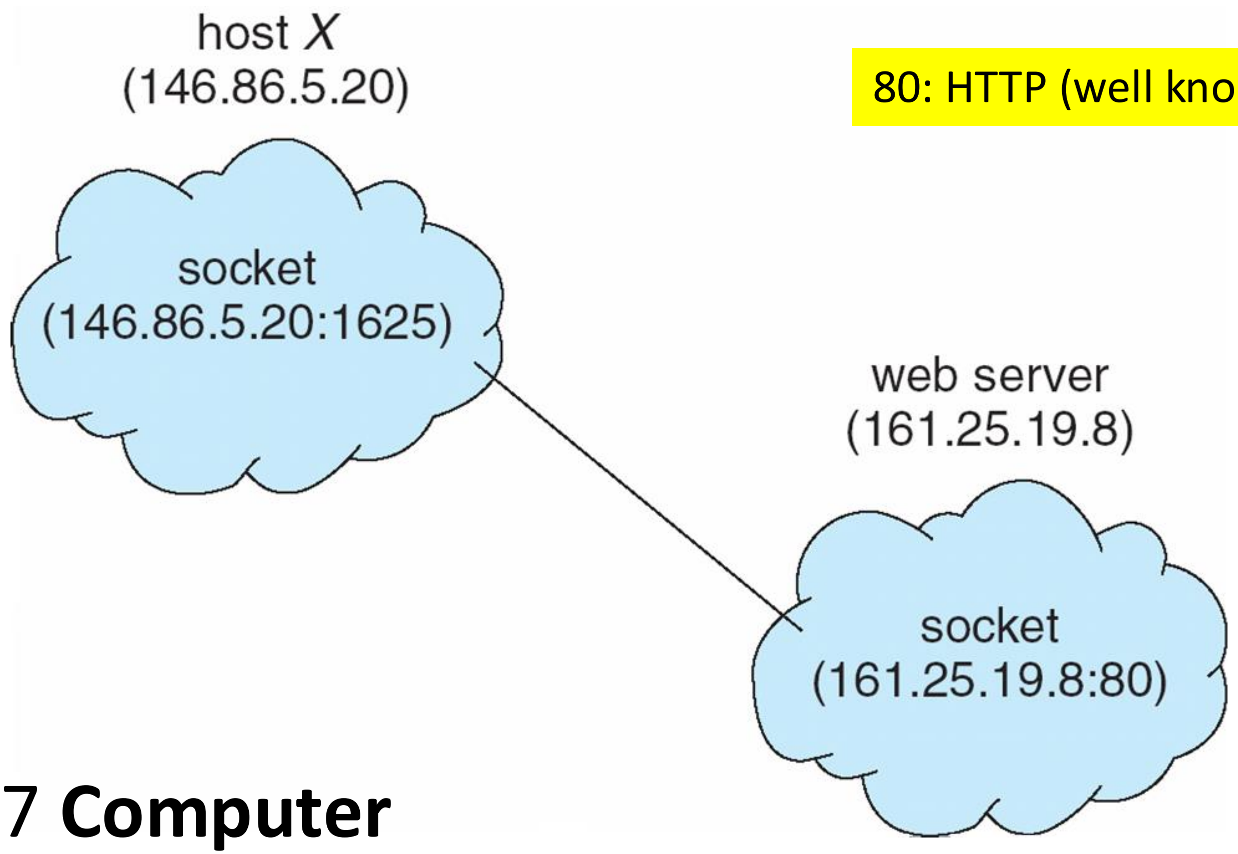
Communications in Client-Server Systems

- Sockets
- Pipes
- Remote Procedure Calls
  - Calling a function on another machine through the network.
- Remote Method Invocation (Java)
  - Object oriented version of RPC

Socket Communication



80: HTTP (well known)

- CS457 **Computer Networks and the Internet**

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Pipes

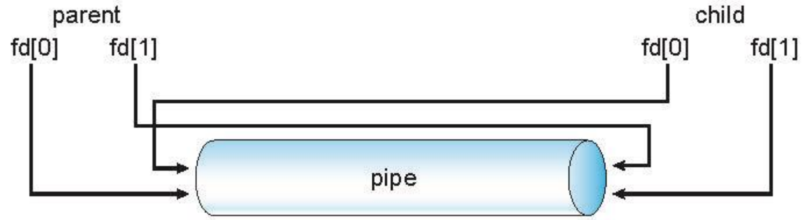
Conduit allowing two processes to communicate

- **Ordinary ("anonymous") pipes** –Typically, a parent process creates a pipe and uses it to communicate with a child process that it created.
  - Cannot be accessed from outside the process that created it.
  - Created using *pipe( )* in Linux.
- **Named pipes ("FIFO")** – can be accessed without a parent-child relationship.
  - *Created using fifo( ) in Linux.*

Ordinary Pipes

Ordinary Pipes allow communication in standard producer-consumer style

- Producer writes to one end (the **write-end** of the pipe)
- Consumer reads from the other end (the **read-end** of the pipe)
- Ordinary pipes are therefore **unidirectional** (half duplex)
- **Require parent-child relationship** between communicating processes
- pipe (int fd[]) to create pipe, fd[0] is the read-end, fd[1] is the write-end



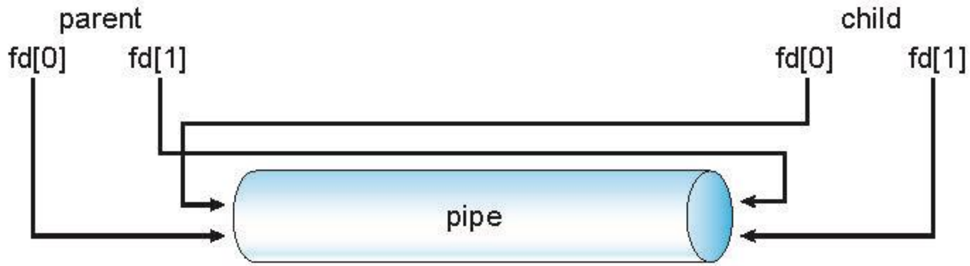
Arrows do not Show direction of transfer
Right: write-end for parent or child

- Windows calls these **anonymous pipes**

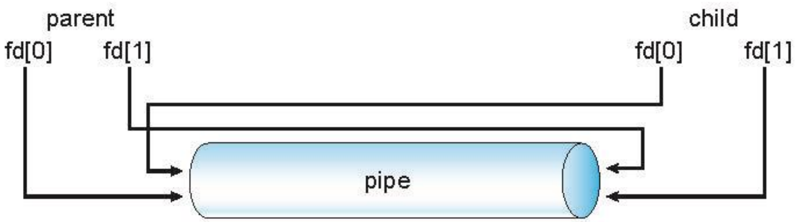
For a process the *file descriptors* identify specific files.

Ordinary Pipes

- Pipe is a special type of file.
  - Ends identified by file descriptors (FDs).
- Inherited by the child as FDs
- Flow: from Write End of P/C to Read End of C/P
  - Must close unused portions of the the pipe
- Next example: Parent to child information flow



UNIX pipe example 1/2 (parent)



Direction of flow

```
#define READ_END    0
#define WRITE_END   1

        int fd[2];
```

create the pipe:

```
        if (pipe(fd) == -1) {
                fprintf(stderr,"Pipe failed");
                return 1;
```

fork a child process:

```
        pid = fork();
```

Child inherits the pipe

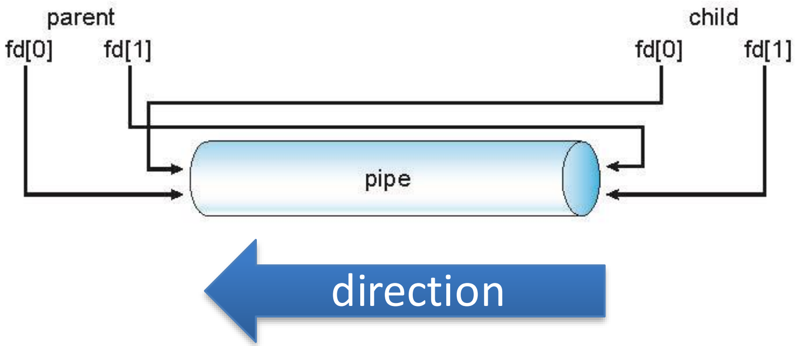
parent process:

```
                /* close the unused end of the pipe */
                close(fd[READ_END]);

                /* write to the pipe */
                write(fd[WRITE_END], write_msg, strlen(write_msg)+1);

                /* close the write end of the pipe */
                close(fd[WRITE_END]);
```

UNIX pipe example 2/2 (child)



child process:

```
/* close the unused end of the pipe */
close(fd[WRITE_END]);

/* read from the pipe */
read(fd[READ_END], read_msg, BUFFER_SIZE);
printf("child read %s\n",read_msg);

/* close the write end of the pipe */
close(fd[READ_END]);
```

See Self Exercises

Named Pipes

- Named Pipes (termed FIFO) are more powerful than ordinary pipes
- Communication is bidirectional
- No parent-child relationship is necessary between the communicating processes
- Several processes can use the named pipe for communication
- Provided on both UNIX and Windows systems

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Threads

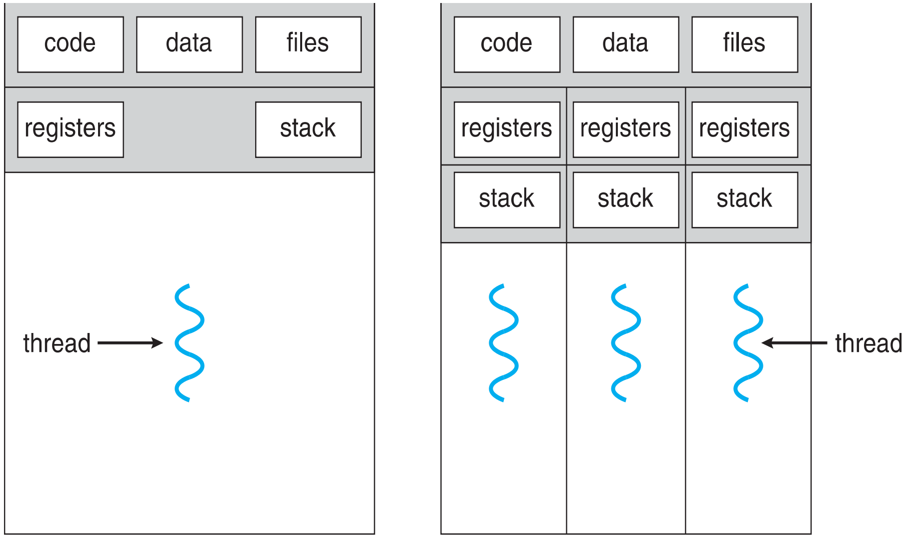
Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Chapter 4: Threads

Objectives:

- Thread—basis of multithreaded systems
- APIs for the Pthreads and Java thread libraries
- implicit threading, multithreaded programming
- OS support for threads



single-threaded process   multithreaded process

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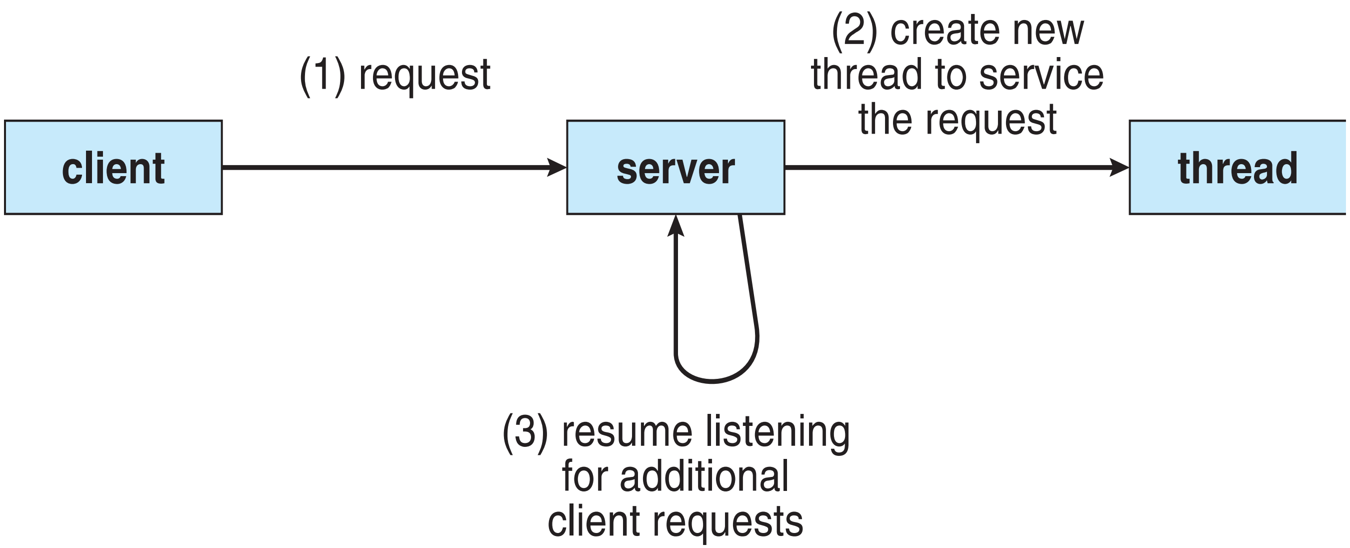
Chapter 4: Threads

- Overview
- Multicore Programming
- Multithreading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Operating System Examples

Modern applications are multithreaded

- Most modern applications are multithreaded
  - Became common with GUI
- Threads run within application
- Multiple tasks with the application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request
- Process creation is heavy-weight while thread creation is light-weight
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

Multithreaded Server Architecture



Benefits

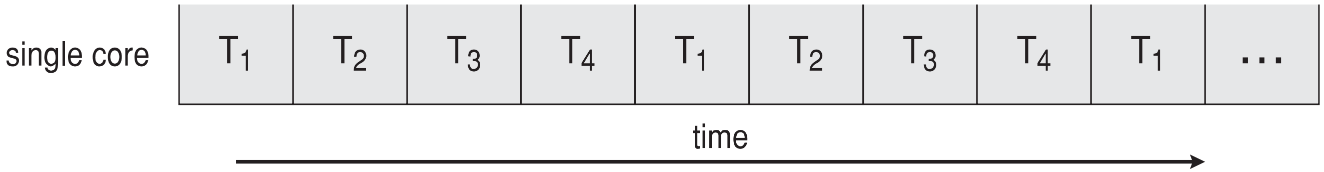
- **Responsiveness –** may allow continued execution if part of process is blocked, especially important for user interfaces
- **Resource Sharing –** threads share resources of process, easier than shared memory or message passing
- **Economy –** cheaper than process creation (10-100 times), thread switching lower overhead than context switching
- **Scalability –** process can take advantage of multiprocessor architectures

Multicore Programming

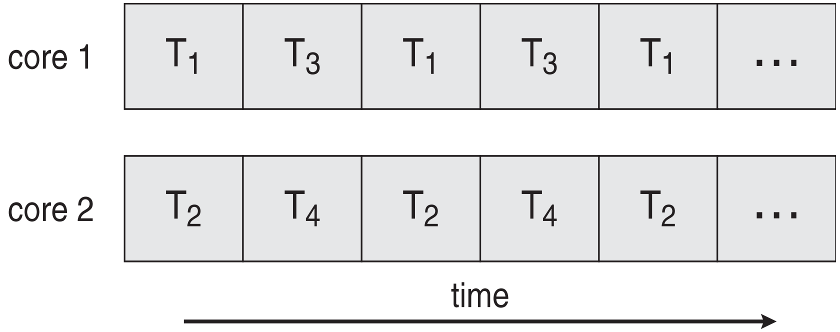
- **Multicore** or **multiprocessor** systems putting pressure on programmers, challenges include:
  - **Dividing activities**
  - **Balance**
  - **Data splitting**
  - **Data dependency**
  - **Testing and debugging**
- ***Parallelism*** implies a system can perform more than one task simultaneously
  - Extra hardware needed for parallel execution
- ***Concurrency*** supports more than one task *making progress*
  - Single processor / core: scheduler providing concurrency

Concurrency vs. Parallelism

- **Concurrent execution on single-core system:**



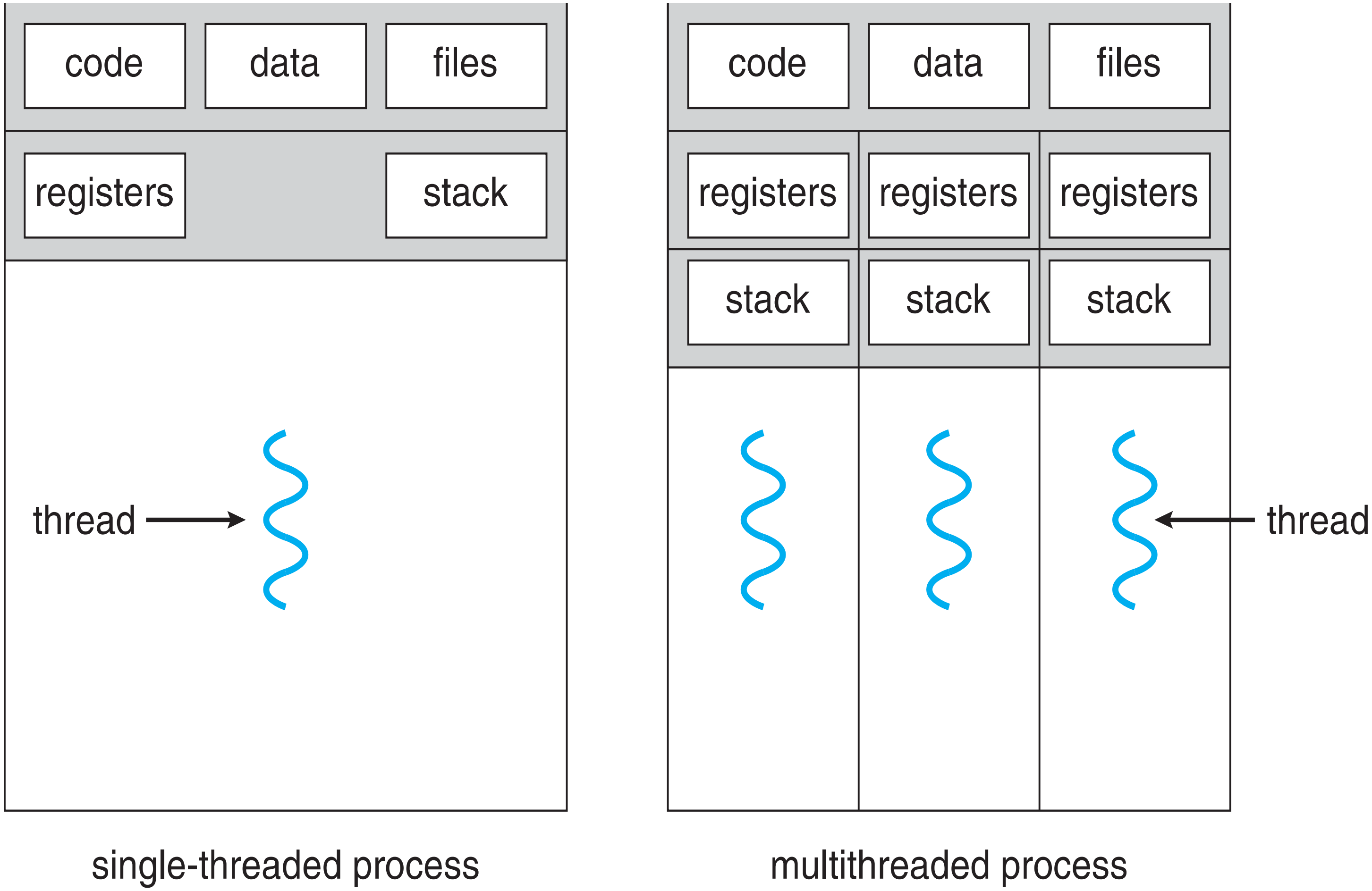
- **Parallelism on a multi-core system:**



Multicore Programming (Cont.)

- Types of parallelism
  - **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
  - **Task parallelism** – distributing threads across cores, each thread performing unique operation
- As # of threads grows, so does architectural support for threading
  - CPUs have cores as well as ***hardware threads***
    - ***e.g. hyper-threading***
  - Oracle SPARC T4 with 8 cores, and 8 hardware threads per core (total 64 threads)
  - AMD Ryzen 7 with 4 cores and 8 threads

Single and Multithreaded Processes



Process vs Thread

- All threads in a process have same address space (text, data, open files, signals etc.), same global variables
- *Each thread has its own*
  - *Thread ID*
  - *Program counter*
  - *Registers*
  - *Stack: execution trail, local variables*
  - *State (running, ready, blocked, terminated)*
- *Thread is also a schedulable entity*