



# **Inter-Process Communications (IPC)**

**ICS332  
Operating Systems**

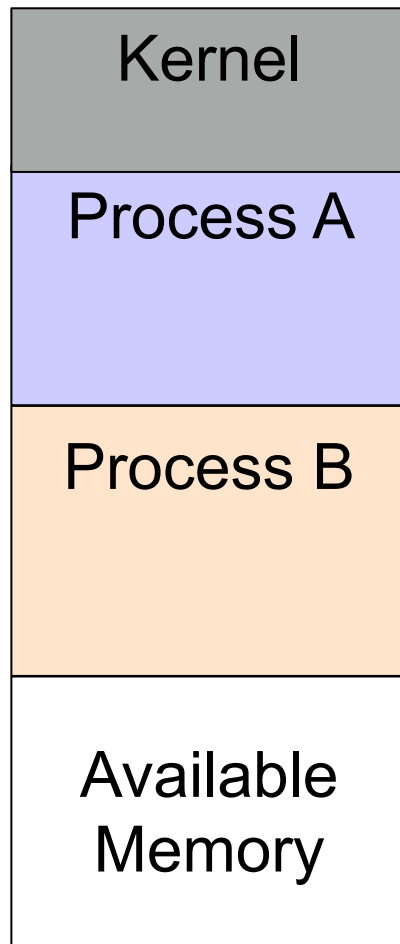
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# Communicating Processes?

- So far we have seen independent processes
  - Each process runs code independently
  - Parents and aware of their children, and children are aware of their parents, but they do not interact
    - Besides the ability to wait for a child to terminate and to kill another process
- But often we need processes to cooperate
  - To share information (e.g., access to common data)
  - To speed up computation (e.g., to use multiple cores)
  - Because it's convenient (e.g., some applications are naturally implemented as sets of interacting processes)
- But, processes cannot see each other's address spaces!
- In general, the means of communication between cooperating processes is called **Inter-Process Communication (IPC)**

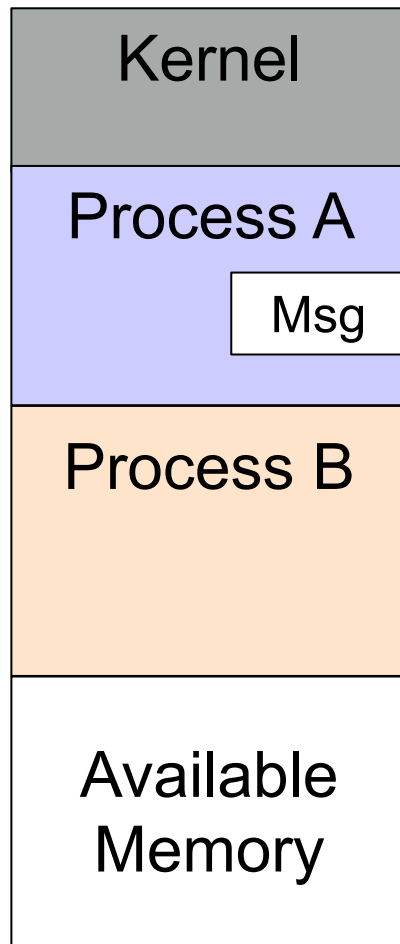
# Communication Models

- Process A needs to communicate with Process B



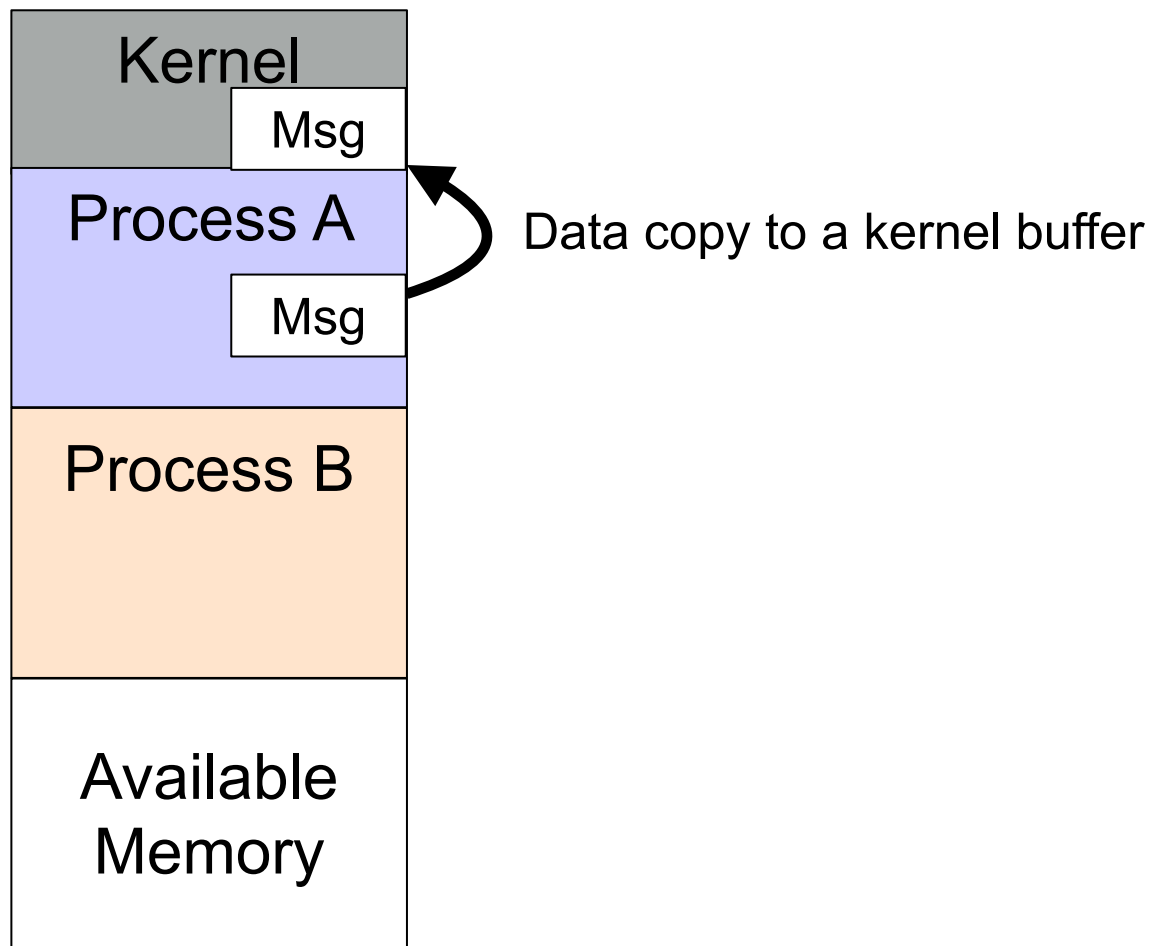
# Message Passing

- Option #1: Message Passing



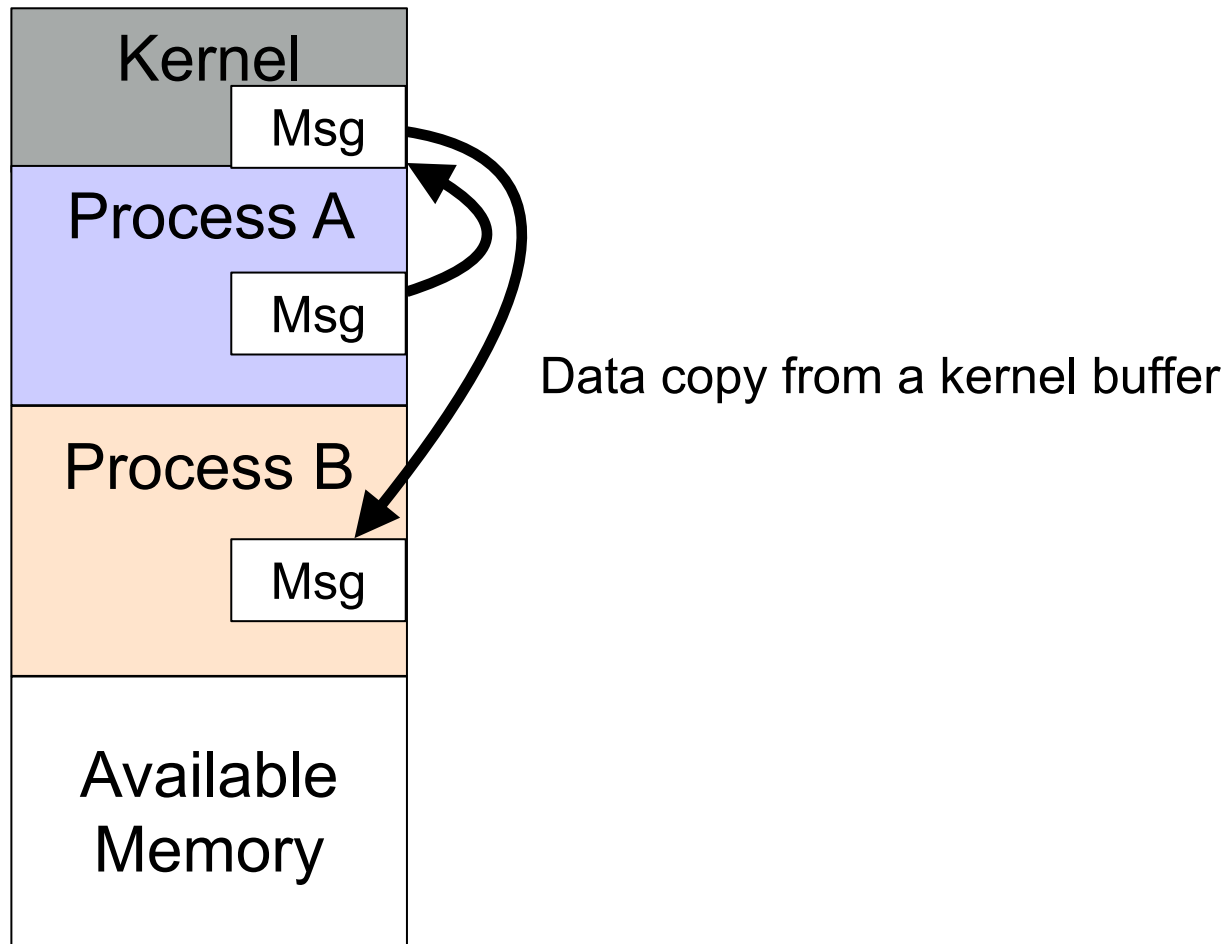
# Message Passing

- Option #1: **Message Passing**



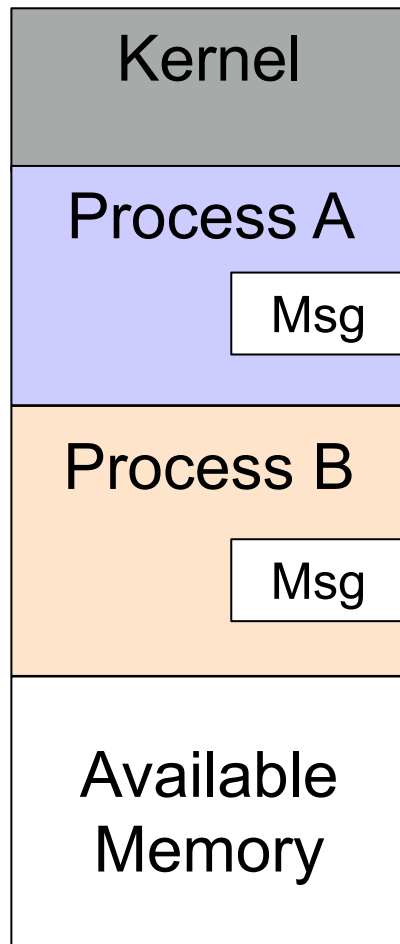
# Message Passing

- Option #1: **Message Passing**



# Message Passing

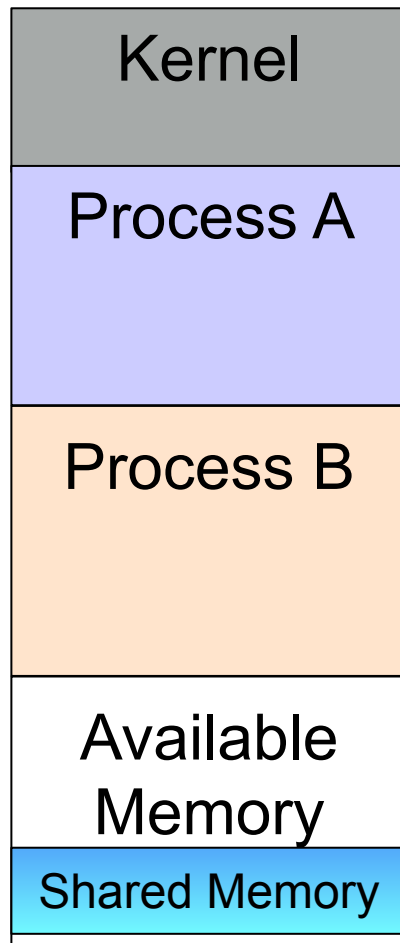
- Option #1: **Message Passing**



Process B has now the message in its address space

# Message Passing

- Option #2: **Shared Memory**



A zone of memory that “belongs” to both processes’s address space, so that each can read/write at will it it and the other can “see” it all



# Pros and Cons

## ■ Message Passing

- 😊 Simple to implement in the kernel
- 😡 Limited by kernel size: small messages
- 😡 One syscall per operation (send / receive): high overhead
- 😡 Cumbersome for users as code can be hard to read with sends/receives everywhere

## ■ Shared memory

- 😡 Not as easy to implement in the kernel (stay tuned...)
- 😊 Large messages allowed
- 😊 Low overhead: a few syscalls to set it up, and then no kernel involvement thereafter
- 😊 Convenient for users (after setup, just normal memory reads/writes)
- 😡 Violates the principle of memory protection between processes, which can lead to horrible bugs

# Message Passing

- All OSes provide several IPC abstractions and API
  - And so do many user-level libraries
- In your careers you will have to define abstraction and APIs for all kinds of purposes
- Abstraction and API design choices often seem innocuous but can have huge impact
  - Good choices can lead to awesome success, bad choices can lead to abject failures/rewrites
- Making good Abstraction/API choices is hard:
  - Sufficiently expressive (can users do anything they might want to do with it?)
  - Sufficiently convenient (can users do what they want easily?)
  - Not too hard for you to implement/maintain/evolve
- **Pedagogic challenge:** Conveying to college students how important/crucial this is, when it all seems like a bunch of pointless nitpicking
  - You wouldn't believe the number of hours spent daily on minuscule API details in the software industry
  - Because you haven't yet experienced the above "snowball effect" of your poorly designed Abstractions/API

# POSIX Message Queue

- A standard message passing scheme supported by UNIX-like systems are POSIX Message Queues
  - There is a message queue “object” that has a name, a maximum msg size, and a maximum number of msg in the queue
  - Both processes create their own queue object using the same name (meaning they both have a reference to the same queue)
  - The queue object supports send/receive operations
- This Abstraction/API makes several design choices
  - One option called “direct communication” would have been “I am process A and I send a message to process B”, which requires that process B is created/known when A does the send
  - Instead, this API uses “indirect communication” by using a message queue object, which is more flexible
- Just for kicks let’s look at a hello world example...

# POSIX MQ Hello World

```
pid_t pid = fork();

if (pid) { // parent

    mqd_t queue = mq_open("mq", O_CREAT | O_WRONLY, 0664, NULL);
    char msg[MSG_SIZE] = "Hello!";
    mq_send(queue, msg, MSG_SIZE, 1);
    waitpid(pid, NULL, 0);
    mq_close(queue);
    mq_unlink(MQ_NAME);

} else { // child

    mqd_t queue = mq_open("mq", O_CREAT | O_RDONLY, 0664, NULL);
    char msg[MSG_SIZE];
    mq_receive(queue, msg, MSG_SIZE, NULL);
    mq_close(queue);
    mq_unlink(MQ_NAME);

}
```

- Let's look at and run the real/full code in [posix\\_mq\\_example.c](#)
- **Conceptually** this is just like network communication, but within a machine
- There are SO many abstractions/implementations of message passing for all kinds of scenarios/purposes, each with slight differences

# POSIX Shared Memory Segments

- Like there is a POSIX MQ API, there is a POSIX SHM (Shared Memory) API
- The abstraction is that of a “shared memory segment” with a simple API
- One process can create a shared memory segment
- Multiple processes can then attach it to their address spaces
  - Bye bye memory protection
  - It's the processes' (i.e., the developer's) responsibility to make sure that processes are not stepping on each other's toes
- Once the setup is done, the OS is not involved
  - What happens in shared memory stays in shared memory
- At some point, the shared memory segment is freed by the requester
- Let's look at a Hello World example...

# POSIX SHM Hello World

```
int segment_id = shmget(IPC_PRIVATE, 10*sizeof(char), SHM_R | SHM_W);

pid = fork();
if (pid) { // parent

    char *shared_memory = (char *)shmat(segment_id, NULL, 0);
    sprintf(shared_memory, "hello");
    waitpid(pid, NULL, 0);
    shmdt(shared_memory);
    shmctl(segment_id, IPC_RMID, NULL);

} else { // child

    char *shared_memory = (char *)shmat(segment_id, NULL, 0);
    fprintf(stdout, "Child: read '%s' in SHM\n", shared_memory);
    shmdt(shared_memory);

}
```

- Let's look at and run the real/full code in [posix\\_shm\\_example.c](#)

# POSIX SHM Hello World

```
int segment_id = shmget(IPC_PRIVATE, 10*sizeof(char), SHM_R | SHM_W);
```

```
pid = fork();  
if (pid) {
```

```
    char *shared_memory = (char *)shmget(segment_id, 10*sizeof(char), SHM_R | SHM_W);  
    sprintf(shared_memory, "Parent: read '%s' in SHM\n", "Parent");  
    waitpid(pid, NULL, 0);  
    shmdt(shared_memory);  
    shmctl(segment_id, IPC_RMID, 0);  
}
```

```
} else { //
```

```
    char *shared_memory = (char *)shmget(segment_id, 10*sizeof(char), SHM_R | SHM_W);  
    fprintf(stdout, "Child: read '%s' in SHM\n", shared_memory);  
    shmdt(shared_memory);  
}
```

Note that the child needs the `segment_id`. In this case, we're ok because `shmget()` is called before `fork()`. But if the child was a different program (e.g., after an `exec()`), then the `segment_id` would need to be communicated to the child (e.g., via message passing!!)

- Let's look at and run the real/full code in [posix\\_shm\\_example.c](#)

# The IPC Zoo

- There are many IPC abstractions that fall into the message passing or the shared memory category, or blur the lines
  - Signals, sockets, message queues, pipes, shared memory segments, files, ...
- Several abstractions share common characteristics but have a few key differences (e.g., a message queue and a socket)
- There is a distinction between the abstraction that's exposed by the API and the implementation of this API
- In fact, many abstractions can be implemented on top of others
  - message queues on top of shared memory segments
  - message queues on top of files
  - message queues on top of sockets
  - shared memory segments on top of message passing
  - ...
- Some implementations are only for IPCs within a machine, some implementations are also for across machines over a network
- Let's now talk about a very, very commonplace abstraction: pipes





# Pipes

- One of the most ancient, yet simple, useful, and powerful IPC mechanism provided by OSes is typically called **pipes**
- We explore this in a programming assignment, so it's a good idea to pay close attention
- But first, let's take a little detour about UNIX file descriptors and output redirection...

# stdin, stdout, stderr

- In UNIX, every process comes with 3 already opened “files”
  - Not real files, but in UNIX “everything looks like a file”
- These files, or streams, are:
  - stdin: the **standard input** stream
  - stdout: the **standard output** stream
  - stderr: the **standard error** stream
- You’ve encountered these when developing code (C/C++, Java, Python, etc.)
  - e.g., printf writes to stdout
- Each file in UNIX is associated to an integer **file descriptor**
  - An index into some “this process’ open files” table
- By convention, the file descriptors for each standard stream are (see /usr/include/unistd.h):
  - stdin: STDIN\_FILENO = **0**
  - stdout: STDOUT\_FILENO = **1**
  - stderr: STDERR\_FILENO = **2**

# Re-directing output

- Perhaps some of you have wondered how come something like `ls > file.txt` can work?
- After all, `ls` has code that looks like:

```
fprintf(stdout, "%s", filename);
```
- So how can this code magically know to write to a file instead of to `stdout`???
- This is one of the famous UNIX “tricks”
- In UNIX, when I open a new file, this file gets the first available file descriptor number
- So, if I close `stdout`, and open a file right after, this file will have file descriptor 1
- Therefore, `printf()` will write to it as if it were `stdout`
  - Because `fprintf(stdout, ...)` really means “write to file descriptor 1”
- And I don’t need to change the code of `ls` at all!!!
- Let’s see an example program...

# Output Redirect Example

## Example program fragment

```
...
pid_t pid = fork();
if (!pid) { // child
    // close stdout
    close(1);
    // open a new file, which gets file descriptor 1
    FILE *file = fopen("/tmp/stuff", "w");
    // exec the "ls -la" program
    char* const arguments[] = {"ls", "-la", NULL};
    execv("ls", arguments);
}
...
```

- This program will run `ls -la` and write its output to file `/tmp/stuff`
- Let's look at [output\\_redirect\\_example1.c](#)

# UNIX Pipes

- A **pipe** is a simple IPC mechanism between two processes
- One can create a pipe so that process A can write to it and process B reads from it and B can read from the pipe
- Available in the shell with the **|** symbol: the output of a process becomes the input of other(s)
  - Just like a file indirection, but to another process' input stream
- Example: Count the files whose names contain foo but not bar in the /tmp directory
  - List all files in /tmp: `find /tmp -type f`
  - Keep those with foo: `grep foo`
  - Remove those with bar: `grep -v bar`
  - Count the lines that remain: `wc -l`

Putting everything together: `find /tmp -type f | grep foo | grep -v bar | wc -l`

# **popen(): fork() with a pipe!**

- Very convenient library functions are popen() and pclose()
- Sounds like “pipe open” and “pipe close”, but it’s MUCH more than that
- **popen()** does:
  - Creates a (bi-directional) pipe, and we have to specify whether we’re going to read (“r”) or write (“w”) to it
  - Forks and execs a child process (e.g., “ls -a”)
  - Returns the pipe, which is in fact a file (FILE \*)
  - Both the parent and the child can “talk” through the pipe!
- **pclose()** does:
  - Waits for the child process to complete
  - Closes the pipe
- These are implemented with several system calls: fork, waitpid, pipe (which creates a pipe), close, open, dup
- Re-implementing popen/pclose would be a bit too much here, but let’s just see an example program that uses it...

# popen() / pclose() Example

## Example program fragment

```
// fork/exec a child process and get a pipe to READ from
FILE *pipe = popen("/usr/bin/ls -la", "r");

// Get lines of output from the pipe, which is just a FILE *,
// until EOF is reached
char buffer[2048];
while (fgets(buffer, 2048, pipe)) {
    fprintf(stderr, "LINE: %s", buffer);
}

// Wait for the child process to terminate
pclose(pipe);
```

- This program prints all the output produced by `ls -la`
- Almost all languages provide something like this: Python's subprocess module, Java's ProcessBuilder class, etc.
- Let's look at and run [popen\\_example1.c](#)
- And then let's look at and run [popen\\_example2.c](#), which opens a pipe to **write** to

# Higher-Level IPC?

- What we've seen so far are IPC abstractions for processes to exchange, essentially, bytes
- With that one can do everything of course, since the bytes can be encoded/interpreted in arbitrary ways
- Often IPC is used to ask another process to do something for us and send us back the result
- This is conceptually like calling a method/function on the other process
- A powerful abstraction has been proposed to do this more easily than with just byte messages: **Remote Procedure Call (RPC)**



# RPC

- RPC provides a procedure invocation abstraction across processes (and actually across machines)
- A client invokes a procedure in another process (almost) as it would invoke it directly itself
- RPC has a lot of usages, of course for client-server applications (and microkernels!)
- The “magic” is performed through a client stub (one stub for each RPC):
  - **Marshal** the parameters (converts structured data to bytes)
  - **Send** the data over to the server
  - **Wait** for the server’s answer
  - **Unmarshal** the returned values (convert bytes to structured data)
- A lot of different implementations exist... including in Java

# Java Remote Method Invocation (RMI)

- RPC in Java: **Remote Method Invocation (RMI)**
- A process in a JVM can invoke a method of an object living in another JVM
- Marshalling/Unmarshalling of data is performed by the JVM
  - Each object must be from a class that implements the `java.io.Serializable` interface
- RMI hides all the gory details of RPC/IPC
- See this [Java RMI Tutorial](#) for more info



# Conclusion

- We've seen two kinds of mechanisms for processes to communicate:
  - **Message Passing:** Within the kernel Space
  - **Shared Memory:** Outside the kernel Space
- Both kinds of mechanisms are implemented in all mainstream OS and **many** variants and abstractions exist
  - Message Queues, Shared Memory Segments, Files, Signals, Sockets, Pipes, RPC
- The line between message passing and shared memory is often blurred by abstractions, and abstractions of one kind can be implemented on top of abstractions of the other kind