

3.4 Interprocess Communication

Processes executing concurrently in the operating system may be either independent processes or cooperating processes. A process is *independent* if it does not share data with any other processes executing in the system. A process is *cooperating* if it can affect or be affected by the other processes executing in the system. Clearly, any process that shares data with other processes is a cooperating process.

There are several reasons for providing an environment that allows process cooperation:

- **Information sharing.** Since several applications may be interested in the same piece of information (for instance, copying and pasting), we must provide an environment to allow concurrent access to such information.
- **Computation speedup.** If we want a particular task to run faster, we must break it into subtasks, each of which will be executing in parallel with the others. Notice that such a speedup can be achieved only if the computer has multiple processing cores.
- **Modularity.** We may want to construct the system in a modular fashion, dividing the system functions into separate processes or threads, as we discussed in Chapter 2.

Cooperating processes require an **interprocess communication (IPC)** mechanism that will allow them to exchange data— that is, send data to and receive data from each other. There are two fundamental models of interprocess communication: **shared memory** and **message passing**. In the shared-memory model, a region of memory that is shared by the cooperating processes is established. Processes can then exchange information by reading and writing data to the shared region. In the message-passing model,

MULTIPROCESS ARCHITECTURE—CHROME BROWSER

Many websites contain active content, such as JavaScript, Flash, and HTML5 to provide a rich and dynamic web-browsing experience. Unfortunately, these web applications may also contain software bugs, which can result in sluggish response times and can even cause the web browser to crash. This isn't a big problem in a web browser that displays content from only one website. But most contemporary web browsers provide tabbed browsing, which allows a single instance of a web browser application to open several websites at the same time, with each site in a separate tab. To switch between the different sites, a user need only click on the appropriate tab. This arrangement is illustrated below:



A problem with this approach is that if a web application in any tab crashes, the entire process—including all other tabs displaying additional websites—crashes as well.

Google's Chrome web browser was designed to address this issue by using a multiprocess architecture. Chrome identifies three different types of processes: browser, renderers, and plug-ins.

- The **browser** process is responsible for managing the user interface as well as disk and network I/O. A new browser process is created when Chrome is started. Only one browser process is created.
- **Renderer** processes contain logic for rendering web pages. Thus, they contain the logic for handling HTML, Javascript, images, and so forth. As a general rule, a new renderer process is created for each website opened in a new tab, and so several renderer processes may be active at the same time.
- A **plug-in** process is created for each type of plug-in (such as Flash or QuickTime) in use. Plug-in processes contain the code for the plug-in as well as additional code that enables the plug-in to communicate with associated renderer processes and the browser process.

The advantage of the multiprocess approach is that websites run in isolation from one another. If one website crashes, only its renderer process is affected; all other processes remain unharmed. Furthermore, renderer processes run in a **sandbox**, which means that access to disk and network I/O is restricted, minimizing the effects of any security exploits.

communication takes place by means of messages exchanged between the cooperating processes. The two communications models are contrasted in Figure 3.11.

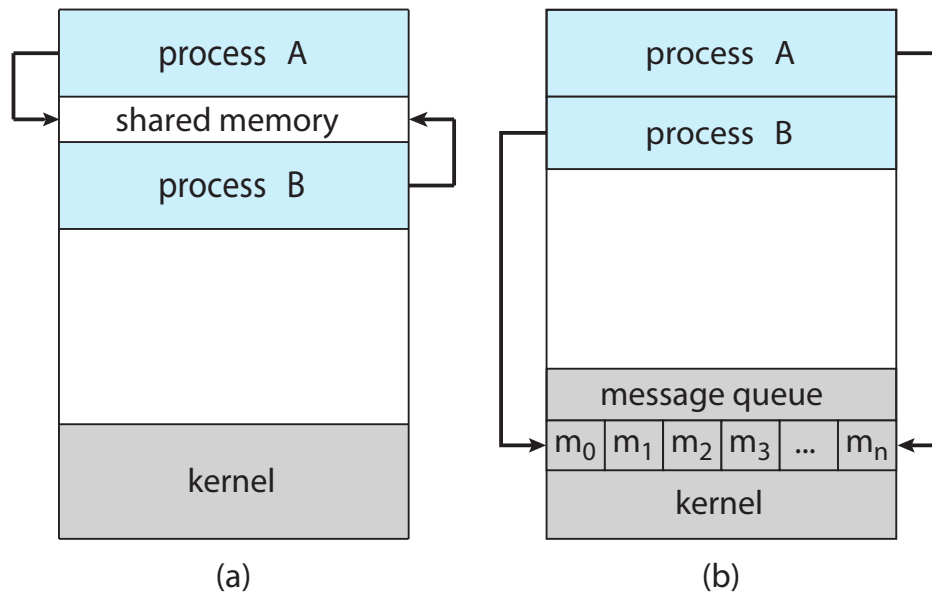


Figure 3.11 Communications models. (a) Shared memory. (b) Message passing.

Both of the models just mentioned are common in operating systems, and many systems implement both. Message passing is useful for exchanging smaller amounts of data, because no conflicts need be avoided. Message passing is also easier to implement in a distributed system than shared memory. (Although there are systems that provide distributed shared memory, we do not consider them in this text.) Shared memory can be faster than message passing, since 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. Once shared memory is established, all accesses are treated as routine memory accesses, and no assistance from the kernel is required.

In Section 3.5 and Section 3.6 we explore shared-memory and message-passing systems in more detail.

3.5 IPC in Shared-Memory Systems

Interprocess communication using shared memory requires communicating processes to establish a region of shared memory. Typically, a shared-memory region resides in the address space of the process creating the shared-memory segment. Other processes that wish to communicate using this shared-memory segment must attach it to their address space. Recall that, normally, the operating system tries to prevent one process from accessing another process's memory. Shared memory requires that two or more processes agree to remove this restriction. They can then exchange information by reading and writing data in the shared areas. The form of the data and the location are determined by these processes and are not under the operating system's control. The processes are also responsible for ensuring that they are not writing to the same location simultaneously.

To illustrate the concept of cooperating processes, let's consider the producer–consumer problem, which is a common paradigm for cooperating processes. A **producer** process produces information that is consumed by a **consumer** process. For example, 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. The producer–consumer problem also provides a useful metaphor for the client–server paradigm. We generally think of a server as a producer and a client as a consumer. For example, a web server produces (that is, provides) web content such as HTML files and images, which are consumed (that is, read) by the client web browser requesting the resource.

One solution to the producer–consumer problem uses shared memory. To allow producer and consumer processes to run concurrently, we must have available a buffer of items that can be filled by the producer and emptied by the consumer. This buffer will reside in a region of memory that is shared by the producer and consumer processes. A producer can produce one item while the consumer is consuming another item. The producer and consumer must be synchronized, so that the consumer does not try to consume an item that has not yet been produced.

Two types of buffers can be used. The **unbounded buffer** places no practical limit on the size of the buffer. The consumer may have to wait for new items, but the producer can always produce new items. The **bounded buffer** assumes a fixed buffer size. In this case, the consumer must wait if the buffer is empty, and the producer must wait if the buffer is full.

Let's look more closely at how the bounded buffer illustrates interprocess communication using shared memory. The following variables reside in a region of memory shared by the producer and consumer processes:

```
#define BUFFER_SIZE 10

typedef struct {
    . . .
} item;

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

The shared buffer is implemented as a circular array with two logical pointers: `in` and `out`. The variable `in` points to the next free position in the buffer; `out` points to the first full position in the buffer. The buffer is empty when `in == out`; the buffer is full when `((in + 1) % BUFFER_SIZE) == out`.

The code for the producer process is shown in Figure 3.12, and the code for the consumer process is shown in Figure 3.13. The producer process has a local variable `next_produced` in which the new item to be produced is stored. The consumer process has a local variable `next_consumed` in which the item to be consumed is stored.

This scheme allows at most `BUFFER_SIZE - 1` items in the buffer at the same time. We leave it as an exercise for you to provide a solution in which `BUFFER_SIZE` items can be in the buffer at the same time. In Section 3.7.1, we illustrate the POSIX API for shared memory.

```
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;
}
```

Figure 3.12 The producer process using shared memory.

One issue this illustration does not address concerns the situation in which both the producer process and the consumer process attempt to access the shared buffer concurrently. In Chapter 6 and Chapter 7, we discuss how synchronization among cooperating processes can be implemented effectively in a shared-memory environment.

3.6 IPC in Message-Passing Systems

In Section 3.5, we showed how cooperating processes can communicate in a shared-memory environment. The scheme requires that these processes share a region of memory and that the code for accessing and manipulating the shared memory be written explicitly by the application programmer. Another way to achieve the same effect is for the operating system to provide the means for cooperating processes to communicate with each other via a message-passing facility.

```
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 */
}
```

Figure 3.13 The consumer process using shared memory.

Message passing provides a mechanism to allow processes to communicate and to synchronize their actions without sharing the same address space. It is particularly useful in a distributed environment, where the communicating processes may reside on different computers connected by a network. For example, an Internet chat program could be designed so that chat participants communicate with one another by exchanging messages.

A message-passing facility provides at least two operations:

```
        send(message)
and
        receive(message)
```

Messages sent by a process can be either fixed or variable in size. If only fixed-sized messages can be sent, the system-level implementation is straightforward. This restriction, however, makes the task of programming more difficult. Conversely, variable-sized messages require a more complex system-level implementation, but the programming task becomes simpler. This is a common kind of tradeoff seen throughout operating-system design.

If processes P and Q want to communicate, they must send messages to and receive messages from each other: a **communication link** must exist between them. This link can be implemented in a variety of ways. We are concerned here not with the link's physical implementation (such as shared memory, hardware bus, or network, which are covered in Chapter 19) but rather with its logical implementation. Here are several methods for logically implementing a link and the `send()`/`receive()` operations:

- Direct or indirect communication
- Synchronous or asynchronous communication
- Automatic or explicit buffering

We look at issues related to each of these features next.

3.6.1 Naming

Processes that want to communicate must have a way to refer to each other. They can use either direct or indirect communication.

Under **direct communication**, each process that wants to communicate must explicitly name the recipient or sender of the communication. In this scheme, the `send()` and `receive()` primitives are defined as:

- `send(P, message)` — Send a message to process P .
- `receive(Q, message)` — Receive a message from process Q .

A communication link in this scheme has the following properties:

- A link is established automatically between every pair of processes that want to communicate. The processes need to know only each other's identity to communicate.

- A link is associated with exactly two processes.
- Between each pair of processes, there exists exactly one link.

This scheme exhibits *symmetry* in addressing; that is, both the sender process and the receiver process must name the other to communicate. A variant of this scheme employs *asymmetry* in addressing. Here, only the sender names the recipient; the recipient is not required to name the sender. In this scheme, the `send()` and `receive()` primitives are defined as follows:

- `send(P, message)` — Send a message to process P.
- `receive(id, message)` — Receive a message from any process. The variable `id` is set to the name of the process with which communication has taken place.

The disadvantage in both of these schemes (symmetric and asymmetric) is the limited modularity of the resulting process definitions. Changing the identifier of a process may necessitate examining all other process definitions. All references to the old identifier must be found, so that they can be modified to the new identifier. In general, any such *hard-coding* techniques, where identifiers must be explicitly stated, are less desirable than techniques involving indirection, as described next.

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. Each mailbox has a unique identification. For example, POSIX message queues use an integer value to identify a mailbox. A process can communicate with another process via a number of different mailboxes, but two processes can communicate only if they have a shared mailbox. The `send()` and `receive()` primitives are defined as follows:

- `send(A, message)` — Send a message to mailbox A.
- `receive(A, message)` — Receive a message from mailbox A.

In this scheme, a communication link has the following 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.

Now suppose that processes P_1 , P_2 , and P_3 all share mailbox A. Process P_1 sends a message to A, while both P_2 and P_3 execute a `receive()` from A. Which process will receive the message sent by P_1 ? The answer depends on which of the following methods we choose:

- Allow a link to be associated with two processes at most.

- Allow at most one process at a time to execute a `receive()` operation.
- Allow the system to select arbitrarily which process will receive the message (that is, either P_2 or P_3 , but not both, will receive the message). The system may define an algorithm for selecting which process will receive the message (for example, *round robin*, where processes take turns receiving messages). The system may identify the receiver to the sender.

A mailbox may be owned either by a process or by the operating system. If the mailbox is owned by a process (that is, the mailbox is part of the address space of the process), then we distinguish between the owner (which can only receive messages through this mailbox) and the user (which can only send messages to the mailbox). Since each mailbox has a unique owner, there can be no confusion about which process should receive a message sent to this mailbox. When a process that owns a mailbox terminates, the mailbox disappears. Any process that subsequently sends a message to this mailbox must be notified that the mailbox no longer exists.

In contrast, a mailbox that is owned by the operating system has an existence of its own. It is independent and is not attached to any particular process. The operating system then must provide a mechanism that allows a process to do the following:

- Create a new mailbox.
- Send and receive messages through the mailbox.
- Delete a mailbox.

The process that creates a new mailbox is that mailbox's owner by default. Initially, the owner is the only process that can receive messages through this mailbox. However, the ownership and receiving privilege may be passed to other processes through appropriate system calls. Of course, this provision could result in multiple receivers for each mailbox.

3.6.2 Synchronization

Communication between processes takes place through calls to `send()` and `receive()` primitives. There are different design options for implementing each primitive. Message passing may be either **blocking** or **nonblocking**—also known as **synchronous** and **asynchronous**. (Throughout this text, you will encounter the concepts of synchronous and asynchronous behavior in relation to various operating-system algorithms.)

- **Blocking send.** The sending process is blocked until the message is received by the receiving process or by the mailbox.
- **Nonblocking send.** The sending process sends the message and resumes operation.
- **Blocking receive.** The receiver blocks until a message is available.
- **Nonblocking receive.** The receiver retrieves either a valid message or a null.

```
message next_produced;

while (true) {
    /* produce an item in next_produced */

    send(next_produced);
}
```

Figure 3.14 The producer process using message passing.

Different combinations of `send()` and `receive()` are possible. When both `send()` and `receive()` are blocking, we have a **rendezvous** between the sender and the receiver. The solution to the producer–consumer problem becomes trivial when we use blocking `send()` and `receive()` statements. The producer merely invokes the blocking `send()` call and waits until the message is delivered to either the receiver or the mailbox. Likewise, when the consumer invokes `receive()`, it blocks until a message is available. This is illustrated in Figures 3.14 and 3.15.

3.6.3 Buffering

Whether communication is direct or indirect, messages exchanged by communicating processes reside in a temporary queue. Basically, such queues can be implemented in three ways:

- **Zero capacity.** The queue has a maximum length of zero; thus, the link cannot have any messages waiting in it. In this case, the sender must block until the recipient receives the message.
- **Bounded capacity.** The queue has finite length n ; thus, at most n messages can reside in it. If the queue is not full when a new message is sent, the message is placed in the queue (either the message is copied or a pointer to the message is kept), and the sender can continue execution without

```
message next_consumed;

while (true) {
    receive(next_consumed);

    /* consume the item in next_consumed */
}
```

Figure 3.15 The consumer process using message passing.

waiting. The link's capacity is finite, however. If the link is full, the sender must block until space is available in the queue.

- **Unbounded capacity.** The queue's length is potentially infinite; thus, any number of messages can wait in it. The sender never blocks.

The zero-capacity case is sometimes referred to as a message system with no buffering. The other cases are referred to as systems with automatic buffering.

3.7 Examples of IPC Systems

In this section, we explore four different IPC systems. We first cover the POSIX API for shared memory and then discuss message passing in the Mach operating system. Next, we present Windows IPC, which interestingly uses shared memory as a mechanism for providing certain types of message passing. We conclude with pipes, one of the earliest IPC mechanisms on UNIX systems.

3.7.1 POSIX Shared Memory

Several IPC mechanisms are available for POSIX systems, including shared memory and message passing. Here, we explore the POSIX API for shared memory.

POSIX shared memory is organized using memory-mapped files, which associate the region of shared memory with a file. A process must first create a shared-memory object using the `shm_open()` system call, as follows:

```
fd = shm_open(name, O_CREAT | O_RDWR, 0666);
```

The first parameter specifies the name of the shared-memory object. Processes that wish to access this shared memory must refer to the object by this name. The subsequent parameters specify that the shared-memory object is to be created if it does not yet exist (`O_CREAT`) and that the object is open for reading and writing (`O_RDWR`). The last parameter establishes the file-access permissions of the shared-memory object. A successful call to `shm_open()` returns an integer file descriptor for the shared-memory object.

Once the object is established, the `ftruncate()` function is used to configure the size of the object in bytes. The call

```
ftruncate(fd, 4096);
```

sets the size of the object to 4,096 bytes.

Finally, the `mmap()` function establishes a memory-mapped file containing the shared-memory object. It also returns a pointer to the memory-mapped file that is used for accessing the shared-memory object.

The programs shown in Figure 3.16 and Figure 3.17 use the producer-consumer model in implementing shared memory. The producer establishes a shared-memory object and writes to shared memory, and the consumer reads from shared memory.

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

#include <sys/mman.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 fd;
    /* pointer to shared memory object */
    char *ptr;

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

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

    /* memory map the shared memory object */
    ptr = (char *)
        mmap(0, SIZE, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);

    /* write to the shared memory object */
    sprintf(ptr,"%s",message_0);
    ptr += strlen(message_0);
    sprintf(ptr,"%s",message_1);
    ptr += strlen(message_1);

    return 0;
}
```

Figure 3.16 Producer process illustrating POSIX shared-memory API.

The producer, shown in Figure 3.16, creates a shared-memory object named OS and writes the infamous string "Hello World!" to shared memory. The program memory-maps a shared-memory object of the specified size and allows writing to the object. The flag `MAP_SHARED` specifies that changes to the shared-memory object will be visible to all processes sharing the object. Notice that we write to the shared-memory object by calling the `sprintf()` function and writing the formatted string to the pointer `ptr`. After each write, we must increment the pointer by the number of bytes written.

```

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

#include <sys/mman.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 fd;
    /* pointer to shared memory object */
    char *ptr;

    /* open the shared memory object */
    fd = shm.open(name, O_RDONLY, 0666);

    /* memory map the shared memory object */
    ptr = (char *)
        mmap(0, SIZE, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);

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

    /* remove the shared memory object */
    shm.unlink(name);

    return 0;
}

```

Figure 3.17 Consumer process illustrating POSIX shared-memory API.