

threads running on other processors. Such instructions are known as **memory barriers** or **memory fences**. When a memory barrier instruction is performed, the system ensures that all loads and stores are completed before any subsequent load or store operations are performed. Therefore, even if instructions were reordered, the memory barrier ensures that the store operations are completed in memory and visible to other processors before future load or store operations are performed.

Let's return to our most recent example, in which reordering of instructions could have resulted in the wrong output, and use a memory barrier to ensure that we obtain the expected output.

If we add a memory barrier operation to Thread 1

```
while (!flag)
    memory_barrier();
print x;
```

we guarantee that the value of `flag` is loaded before the value of `x`.

Similarly, if we place a memory barrier between the assignments performed by Thread 2

```
x = 100;
memory_barrier();
flag = true;
```

we ensure that the assignment to `x` occurs before the assignment to `flag`.

With respect to Peterson's solution, we could place a memory barrier between the first two assignment statements in the entry section to avoid the reordering of operations shown in Figure 6.4. Note that memory barriers are considered very low-level operations and are typically only used by kernel developers when writing specialized code that ensures mutual exclusion.

6.4.2 Hardware Instructions

Many modern computer systems provide special hardware instructions that allow us either to test and modify the content of a word or to swap the contents of two words **atomically**—that is, as one uninterruptible unit. We can use these special instructions to solve the critical-section problem in a relatively simple manner. Rather than discussing one specific instruction for one specific machine, we abstract the main concepts behind these types of instructions by describing the `test_and_set()` and `compare_and_swap()` instructions.

```
boolean test_and_set(boolean *target) {
    boolean rv = *target;
    *target = true;

    return rv;
}
```

Figure 6.5 The definition of the atomic `test_and_set()` instruction.

```

do {
    while (test_and_set(&lock))
        ; /* do nothing */

    /* critical section */

    lock = false;

    /* remainder section */
} while (true);

```

Figure 6.6 Mutual-exclusion implementation with `test_and_set()`.

The `test_and_set()` instruction can be defined as shown in Figure 6.5. The important characteristic of this instruction is that it is executed atomically. Thus, if two `test_and_set()` instructions are executed simultaneously (each on a different core), they will be executed sequentially in some arbitrary order. If the machine supports the `test_and_set()` instruction, then we can implement mutual exclusion by declaring a boolean variable `lock`, initialized to `false`. The structure of process P_i is shown in Figure 6.6.

The `compare_and_swap()` instruction (CAS), just like the `test_and_set()` instruction, operates on two words atomically, but uses a different mechanism that is based on swapping the content of two words.

The CAS instruction operates on three operands and is defined in Figure 6.7. The operand `value` is set to `new_value` only if the expression `(*value == expected)` is true. Regardless, CAS always returns the original value of the variable `value`. The important characteristic of this instruction is that it is executed atomically. Thus, if two CAS instructions are executed simultaneously (each on a different core), they will be executed sequentially in some arbitrary order.

Mutual exclusion using CAS can be provided as follows: A global variable (`lock`) is declared and is initialized to 0. The first process that invokes `compare_and_swap()` will set `lock` to 1. It will then enter its critical section,

```

int compare_and_swap(int *value, int expected, int new_value) {
    int temp = *value;

    if (*value == expected)
        *value = new_value;

    return temp;
}

```

Figure 6.7 The definition of the atomic `compare_and_swap()` instruction.

```

while (true) {
    while (compare_and_swap(&lock, 0, 1) != 0)
        ; /* do nothing */

    /* critical section */

    lock = 0;

    /* remainder section */
}

```

Figure 6.8 Mutual exclusion with the compare_and_swap() instruction.

because the original value of `lock` was equal to the expected value of 0. Subsequent calls to `compare_and_swap()` will not succeed, because `lock` now is not equal to the expected value of 0. When a process exits its critical section, it sets `lock` back to 0, which allows another process to enter its critical section. The structure of process P_i is shown in Figure 6.8.

Although this algorithm satisfies the mutual-exclusion requirement, it does not satisfy the bounded-waiting requirement. In Figure 6.9, we present

```

while (true) {
    waiting[i] = true;
    key = 1;
    while (waiting[i] && key == 1)
        key = compare_and_swap(&lock, 0, 1);
    waiting[i] = false;

    /* critical section */

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j + 1) % n;

    if (j == i)
        lock = 0;
    else
        waiting[j] = false;

    /* remainder section */
}

```

Figure 6.9 Bounded-waiting mutual exclusion with compare_and_swap().

MAKING COMPARE-AND-SWAP ATOMIC

On Intel x86 architectures, the assembly language statement `cpxchq` is used to implement the `compare_and_swap()` instruction. To enforce atomic execution, the `lock` prefix is used to lock the bus while the destination operand is being updated. The general form of this instruction appears as:

```
lock cpxchq <destination operand>, <source operand>
```

another algorithm using the `compare_and_swap()` instruction that satisfies all the critical-section requirements. The common data structures are

```
boolean waiting[n] ;
int lock;
```

The elements in the `waiting` array are initialized to `false`, and `lock` is initialized to 0. To prove that the mutual-exclusion requirement is met, we note that process P_i can enter its critical section only if either `waiting[i] == false` or `key == 0`. The value of `key` can become 0 only if the `compare_and_swap()` is executed. The first process to execute the `compare_and_swap()` will find `key == 0`; all others must wait. The variable `waiting[i]` can become `false` only if another process leaves its critical section; only one `waiting[i]` is set to `false`, maintaining the mutual-exclusion requirement.

To prove that the progress requirement is met, we note that the arguments presented for mutual exclusion also apply here, since a process exiting the critical section either sets `lock` to 0 or sets `waiting[j]` to `false`. Both allow a process that is waiting to enter its critical section to proceed.

To prove that the bounded-waiting requirement is met, we note that, when a process leaves its critical section, it scans the array `waiting` in the cyclic ordering $(i + 1, i + 2, \dots, n - 1, 0, \dots, i - 1)$. It designates the first process in this ordering that is in the entry section (`waiting[j] == true`) as the next one to enter the critical section. Any process waiting to enter its critical section will thus do so within $n - 1$ turns.

Details describing the implementation of the `atomic test_and_set()` and `compare_and_swap()` instructions are discussed more fully in books on computer architecture.

6.4.3 Atomic Variables

Typically, the `compare_and_swap()` instruction is not used directly to provide mutual exclusion. Rather, it is used as a basic building block for constructing other tools that solve the critical-section problem. One such tool is an **atomic variable**, which provides atomic operations on basic data types such as integers and booleans. We know from Section 6.1 that incrementing or decrementing an integer value may produce a race condition. Atomic variables can be used in to ensure mutual exclusion in situations where there may be a data race on a single variable while it is being updated, as when a counter is incremented.

Most systems that support atomic variables provide special atomic data types as well as functions for accessing and manipulating atomic variables.