Lecture 13 — Semaphores

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Mutual Exclusion through Messages

The earlier definition of mutual exclusion was informal.

There are additional desirable properties that will be used to evaluate any solution:

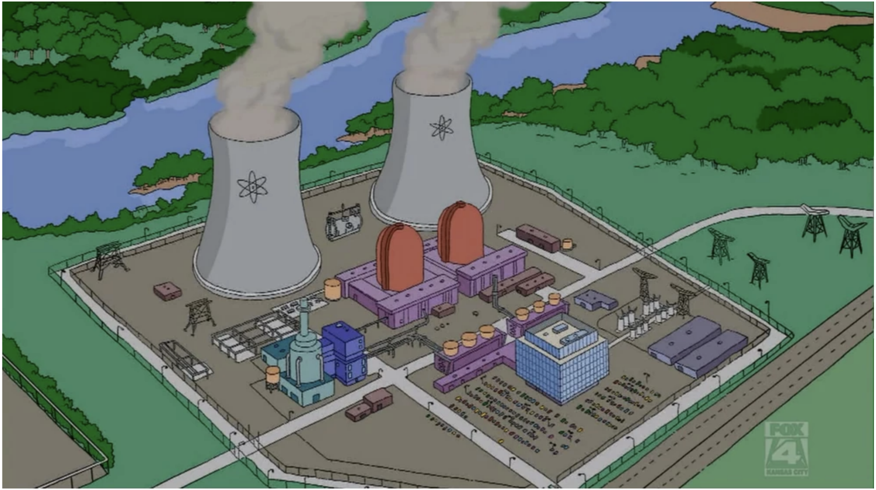
- Mutual exclusion must apply.
- A thread that halts outside the critical section must not interfere with other threads.
- It must not be possible for a thread requiring access to a critical section to be delayed indefinitely.

Mutual Exclusion through Messages

There are additional desirable properties that will be used to evaluate any solution:

- When no thread is in the critical section, a thread that requests access should be allowed to enter right away.
- No assumptions are made about what the threads will do or the number of processors in the system.
- A thread remains inside the critical section for a finite time only.

Back to Springfield



Back to Springfield

Recall from earlier the example of the employees Alice and Bob who worked at the Springfield Nuclear Power Plant in Sector 7G.

Suppose there is a third employee at the power plant, Charlie, who works on the day shift at the same time as Alice.

Safety rules say that at least one of them has to monitor the safety of the reactor at all times and therefore they cannot both take lunch at the same time.

If we cannot predict when lunch begins or how long it will last, how can Alice and Charlie co-ordinate to make sure they don’t take lunch at the same time?

At the Power Plant

Before Alice gets up from her desk to go for lunch, she calls Charlie.

If he does answer, she may proceed.

If Charlie does not answer, Alice will know he is not at his desk.
Therefore she cannot leave at the moment.

At the Power Plant

She can call again, constantly, until she reaches Charlie (busy-waiting), but this ties up a phone line nonstop and is effort intensive for Alice.

If she doesn't want to do that, at this point she has two options:
- Wait some period of time (perhaps 15 minutes) and call again. Or
- Leave a message in Charlie's voice mail box, asking him to call her back.

Then Alice can go about her work until she gets a call from Charlie and as soon as that happens, she may step out for lunch.

Busy waiting has already been found inadequate as a solution.

It wastes CPU time that another thread could be putting to productive use.

The approach of “wait 15 minutes and try again” might be adequate for Alice as a human, but for the computer it is not ideal.

If *A* fails to get in, then sleeps for 2000 ms before trying again, if *B* is finished after 20 ms, then thread *A* waits unnecessarily for 1980 ms.

What we want is something that resembles the call-when-finished semantics of Alice leaving a message and Charlie calling her back.

Semaphore

A semaphore is a system of signals used for communication.

Before ships had radios, when two friendly ships were in visual range, they would communicate with one another through flag semaphores.

Each ship had someone holding certain flags in a specific position.

Thus, the two ships could co-ordinate at (visual range) distance.

This worked dramatically better than many alternatives (e.g., shouting).

Semaphore

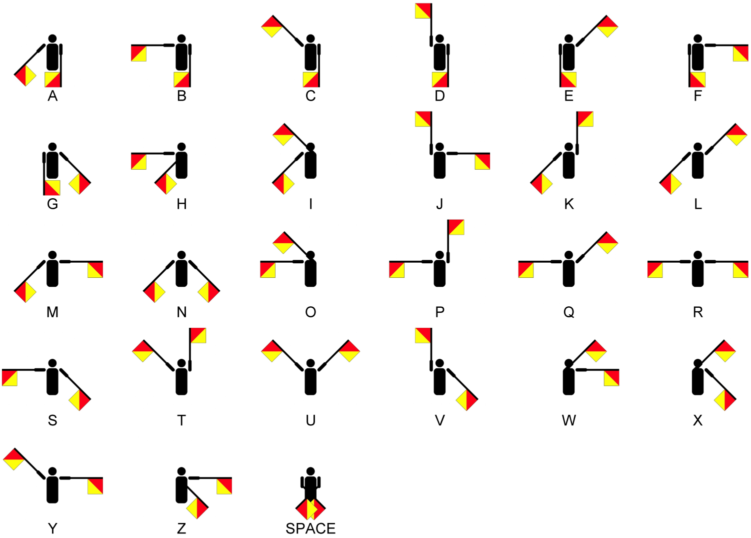


Image Credit: Wikipedia user Denelson83

The Computer Semaphore

The computer semaphore was invented in 1965 by Edsger Dijkstra.

He described a data structure that can be used to solve synchronization problems via messages.

Although the version we use now is not exactly the same as the original description, even 50 years later, the core idea is unchanged.

Semaphore

Semaphore is a non-negative integer variable.

It can be initialized to 0 or a positive integer.

The semaphore has two operations: `wait` and `post`.

In the original paper, `wait` was called `P` and `post` was called `V`, but the names in common usage have become a little more descriptive.

Note: `post` is also called `signal` in many textbooks.

Semaphore: Wait

When `wait` is called, if the semaphore value is positive, it is decremented, and the calling thread may continue.

If the semaphore is 0, the current thread must *wait* its turn.

The thread that called `wait` will be blocked by the operating system, just as if it asked for memory or a disk operation.

This is sometimes referred to as *decrementing* the semaphore.

Semaphore: Post

The `post` (or signal) operation is how a thread *signals* the waiting thread(s).

When this is called, if the semaphore is 0 and there is at least one other thread blocked awaiting that semaphore, one of the blocked threads may be unblocked.

Otherwise, the semaphore value is incremented.

This is also sometimes called *incrementing* the semaphore.

Mutal Exclusion with (Binary) Semaphore

Initialize the semaphore to 1.

The `wait` operation is how a thread tries to enter the critical section.

When `wait` is called, if the semaphore value is 1, it is set to 0, allowing the thread to enter the critical section and continue. Otherwise, the current thread is blocked.

The `post` operation is how a thread exits the critical section.

When `post` is called, if the semaphore is 0 and there is at least one other thread blocked, one of the blocked threads may be unblocked. Otherwise, the semaphore is incremented.

Image Credit: Brandt Kofton

Analogy: you like coffee, and going to a particular coffee shop because there you can get your drink exactly the way you like it.

“Half caf, no whip, extra hot, extra foam, two shot, soy milk latte.”

Delicious Coffee

After this beverage it may be the case that you need to use the washroom.

The washroom may be locked at such places (usually because they are worried homeless people or non-customers may use the facilities).

So to get in you will need the key, which is available by asking one of the employees.

Programmers Convert Caffeine into Code

If nobody is currently in the washroom, you will get the key and can proceed.

If it is currently occupied, you will have to wait.

When the key is returned, if anyone is waiting, the employee will give the key to the first person in line for the washroom.

Otherwise, they will put the key away behind the counter.

Semaphores: OS Support

Observe that the operating system is needed to make this work.

If thread *A* attempts to wait on a semaphore that some other thread already has, it will be blocked.

The operating system knows not to schedule it to run until it is unblocked.

When thread *B* is finished and signals the semaphore it is holding, that will unblock *A* and allow it to run again.

No Checking

The semaphore does not provide any facility to “check” the current value.

A thread doesn’t know in advance if it will block when it waits on a semaphore.

It can only give it a shot. Either it will be blocked or proceed directly.

Post

When a thread posts on a semaphore, it likewise does not know if any other thread(s) are waiting on that semaphore.

There is no facility to check this, either.

When thread *A* signals a semaphore, we don’t know what thread will continue execution.

Semaphore: Bad Behaviour

Nothing in the semaphore as defined protects against certain bad behaviour.

Suppose thread *C* would like to enter the critical section.

The programmer of this task is malicious as well as impatient: “my task is FAR too important to wait for those other processes and threads,” he says.

He implements his code: before he waits on the semaphore, he posts on it.

Even though *A* or *B* might be in the critical section, the semaphore is incremented.

So he is fairly certain that his program will now get to enter the critical section.

Semaphore: Bad Behaviour

It's not foolproof: if there are other threads waiting, they might get woken up to proceed instead of C; much depends on the scheduler.

Nevertheless, this is really bad: one process can wreak all kinds of havoc by letting another process into the critical section.

Though the example here makes the author of thread C a scheming villain, such a situation may occur if it is simply the result of a programming error.

Semaphore Example: Linked List Integrity

```
typedef struct single_node {
  void *element;
  struct single_node *next;
} single_node_t;

typedef struct single_list {
  single_node_t *head;
  single_node_t *tail;
  int size;
} single_list_t;


void single_list_init( single_list_t *list ) {
  list->head = NULL;
  list->tail = NULL;
  list->size = 0;
}
```

Semaphore Example: Linked List Integrity

```
bool push_front( single_list_t *list, void *obj ) {
  single_node_t *tmp = malloc( sizeof( single_node_t ) );

  if ( tmp == NULL ) {
    return false;
  }

  tmp->element = obj;
  tmp->next = list->head;
  list->head = tmp;

  if ( list->size == 0 ) {
     list->tail = tmp;
  }

  ++( list->size );
  return true;
}
```

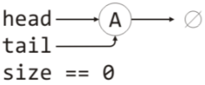
Using the Linked List

If only one thread access this data structure, we do not have a problem.

Suppose a thread tries to add an element *A* to the list using `push_front`.

Right before the increment of the `size` field there is a process switch.

At this point, the new node has been allocated and initialized, the pointers of `head` and `tail` have been updated, but `size` is 0.

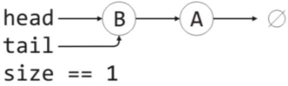


Using the Linked List

Now, the second thread executes and wants to add *B* to the linked list.

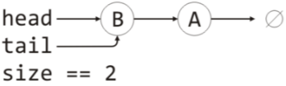
In the conditional statement, `list->size == 0` evaluates to true.

Thus, the `tail` pointer is updated.



When the first thread gets to run again, it will resume where it left off.

It increments the `size` integer, leaving the final state: `head` and `tail` both point to element *B*, even though there is element *A* in the list.



Inconsistent State

This is an inconsistent state.

The linked list has two elements in it but the `tail` pointer is wrong.

An attempt to remove an element from the list will reveal the problem.

Remove the front element? Check if `head` and `tail` are equal. That may give the mistaken impression that *B* is the last element in the list. We lost *A*!

Or the `head` pointer will be updated but `tail` will still point to *B* even after it has been freed, which can result in a segmentation fault or invalid access.

Semaphore Syntax

The syntax we will use is as follows:

```
sem_init( sem_t* semaphore, int shared, int initial_value);
sem_destroy( sem_t* semaphore )
sem_wait( sem_t* semaphore )
sem_post( sem_t* semaphore )
```

Applying the Semaphore to the Linked List

```
typedef struct single_node {
  void *element;
  struct single_node *next;
} single_node_t;

typedef struct single_list {
  single_node_t *head;
  single_node_t *tail;
  int size;
  sem_t sem;
} single_list_t;

void single_list_init( single_list_t *list ) {
  list->head = NULL;
  list->tail = NULL;
  list->size = 0;

  sem_init( &( list->sem ), 0, 1 );
}
```

Applying the Semaphore to the Linked List

```
bool push_front( single_list_t *list, void *obj ) {
  single_node_t *tmp = malloc( sizeof( single_node_t ) );

  if ( tmp == NULL ) { return false; }
  tmp->element = obj;

  sem_wait( &( list->sem ) ); {
    tmp->next = list->head;
    list->head = tmp;

    if ( list->size == 0 ) {
       list->tail = tmp;
    }
    ++( list->size );

  } sem_post( &( list->sem ) );
  return true;
}
```

Applying the Semaphore to the Linked List

The critical section here just encloses the modification of the shared linked list.

In theory one might put the wait and signal operations at the start and end of the entire function, respectively.

This is, however, suboptimal: it forces unnecessary waiting.

Including the call to `malloc` is especially bad; the memory allocation itself can block if insufficient memory is available.