The Critical Section Problem

Problem Description

Informally, a critical section is a code segment that accesses shared variables and has to be executed as an atomic action.

The critical section problem refers to the problem of how to ensure that at most one process is executing its critical section at a given time.

Important: Critical sections in different threads are not necessarily the same code segment!

Problem Description

Formally, the following requirements should be satisfied:

- Mutual exclusion: When a thread is executing in its critical section, no other threads can be executing in their critical sections.
- Progress: If no thread is executing in its critical section, and if there are some threads that wish to enter their critical sections, then one of these threads will get into the critical section.
- Bounded waiting: After a thread makes a request to enter its critical section, there is a bound on the number of times that other threads are allowed to enter their critical sections, before the request is granted.

Problem Description

In discussion of the critical section problem, we often assume that each thread is executing the following code.

It is also assumed that (1) after a thread enters a critical section, it will eventually exit the critical section; (2) a thread may terminate in the non-critical section.

```
while (true) {
    entry section
    critical section
    exit section
    non-critical section
}
```

Solution 1

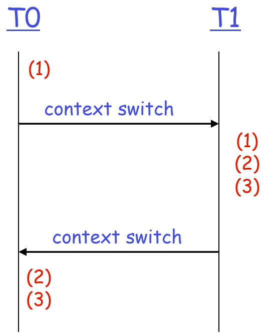
In this solution, *lock* is a global variable initialized to *false*. A thread sets *lock* to *true* to indicate that it is entering the critical section.

```
boolean lock = false;
```

```
T0:
while (true) {
    while (lock) { ; }        (1)
    lock = true;              (2)
    critical section          (3)
    lock = false;             (4)
    non-critical section      (5)
}
```

```
T1:
while (true) {
    while (lock) { ; }        (1)
    lock = true;              (2)
    critical section          (3)
    lock = false;             (4)
    non-critical section      (5)
}
```

Solution 1 is incorrect!



Comments

T0 exits the while loop

T1 exits the while loop
lock is set to true
T1 enters the critical section

lock is set to true
T0 enters the critical section

Solution 2

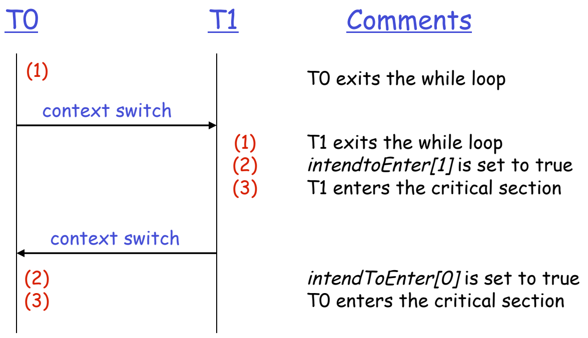
The threads use a global array *intendToEnter* to indicate their intention to enter the critical section.

```
boolean intendToEnter[] = {false, false};
```

```
T0:
while (true) {
   while (intendToEnter[1]) { ; }  (1)
   intendToEnter[0] = true;        (2)
   critical section                (3)
   intendToEnter[0] = false;       (4)
   non-critical section            (5)
}
```

```
T1:
while (true) {
   while (intendToEnter[0]) { ; }  (1)
   intendToEnter[1] = true;        (2)
   critical section                (3)
   intendToEnter[1] = false;       (4)
   non-critical section            (5)
}
```

Solution 2 is incorrect!



T0: (1) — T0 exits the while loop

T1: (1) — T1 exits the while loop
(2) — *intendtoEnter[1]* is set to true
(3) — T1 enters the critical section

T0: (2) — *intendToEnter[0]* is set to true
(3) — T0 enters the critical section

Solution 3

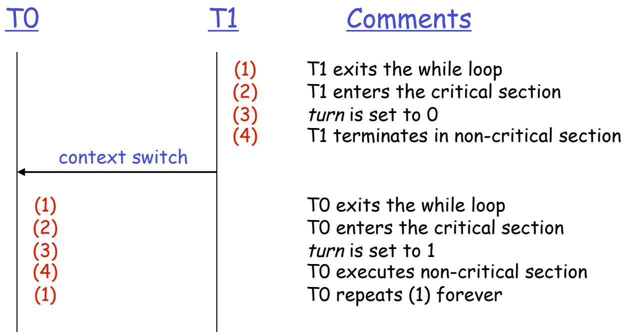
The global variable *turn* is used to indicate the next process to enter the critical section. The initial value of *turn* can be 0 or 1.

```
int turn = 1;
```

```
T0:
while (true) {
   while (turn != 0) { ; }          (1)
   critical section                 (2)
   turn = 1;                        (3)
   non-critical section             (4)
}
```

```
T1:
while (true) {
   while (turn != 1) { ; }          (1)
   critical section                 (2)
   turn = 0;                        (3)
   non-critical section             (4)
}
```

Solution 3 is incorrect!



T0	T1	Comments
	(1)	T1 exits the while loop
	(2)	T1 enters the critical section
	(3)	*turn* is set to 0
	(4)	T1 terminates in non-critical section
context switch		
(1)		T0 exits the while loop
(2)		T0 enters the critical section
(3)		*turn* is set to 1
(4)		T0 executes non-critical section
(1)		T0 repeats (1) forever

Solution 4

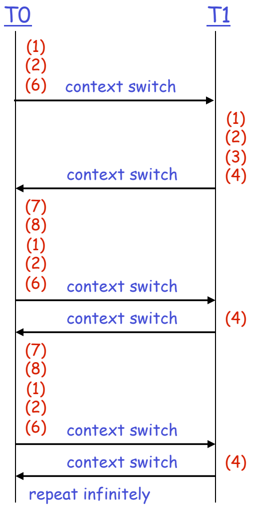
When a thread finds that the other thread also intends to enter its critical section, it sets its own *intendToEnter* flag to false and waits until the other thread exits its critical section.

`boolean intendToEnter[] = {false, false};`

```
T0:
while (true) {
   intendToEnter[0] = true;          (1)
   while (intendToEnter[1]) {        (2)
      intendToEnter[0] = false;      (3)
      while (intendToEnter[1]) {;}   (4)
      intendToEnter[0] = true;       (5)
   }
   critical section                  (6)
   intendToEnter[0] = false;         (7)
   non-critical section              (8)
}
```

```
T1:
while (true) {
   intendToEnter[1] = true;          (1)
   while (intendToEnter[0]) {        (2)
      intendToEnter[1] = false;      (3)
      while (intendToEnter[0]) {;}   (4)
      intendToEnter[1] = true;       (5)
   }
   critical section                  (6)
   intendToEnter[1] = false;         (7)
   non-critical section              (8)
}
```

Solution 4 is incorrect!



T0	T1	Comments
(1)		*intendToEnter*[0] is set to true
(2)		T0 exits *while* loop
(6) context switch		T0 enters critical section; intendToEnter[0] is true
	(1)	*intendToEnter*[1] is set to true
	(2)	T1 enters while (*intendToEnter*[0]) loop
	(3)	*intendToEnter*[1] is set to false
context switch	(4)	T1 enters second while(*intendToEnter*[0]) loop
(7)		*intendToEnter*[0] is set to false
(8)		T0 executes the non-critical section
(1)		*intendToEnter*[0] is set to true
(2)		T0 exits while loop
(6) context switch		T0 enters critical section; intendToEnter[0] is true
context switch	(4)	T1 is still waiting for *intendToEnter*[0] to be false
(7)		*intendToEnter*[0] is set to false
(8)		T0 executes the non-critical section
(1)		*intendToEnter*[0] is set to true
(2)		T0 exits while loop
(6) context switch		T0 enters critical section; intendToEnter[0] is true
context switch	(4)	T1 is still waiting for *intendToEnter*[0] to be false
repeat infinitely		

How to check a solution

Informally, we should consider three important cases:

1. One thread intends to enter its critical section, and the other thread is not in its critical section or in its entry section.
2. One thread intends to enter its critical section, and the other thread is in its critical section.
3. Both threads intend to enter their critical sections.

Peterson's algorithm

Peterson's algorithm is a combination of solutions (3) and (4).

```
boolean intendToEnter[]= {false, false};
int turn; // no initial value for turn is needed.
```

```
T0:
while (true) {
  intendToEnter[0] = true;          (1)
  turn = 1;                         (2)
  while (intendToEnter[1]
         && turn == 1) { ; }        (3)
  critical section                  (4)
  intendToEnter[0] = false;         (5)
  non-critical section              (6)
}
```

```
T1:
while (true) {
  intendToEnter[1] = true;          (1)
  turn = 0;                         (2)
  while (intendToEnter[0]
         && turn == 0) { ; }        (3)
  critical section                  (4)
  intendToEnter[1] = false;         (5)
  non-critical section              (6)
}
```

Peterson's algorithm

Informally, we consider the following cases:

1. Assume that one thread, say T0, intends to enter its critical section and T1 is not in its critical section or its entry-section. Then intendToEnter[0] is true and intendToEnter[1] is false and T0 will enter the critical section immediately.

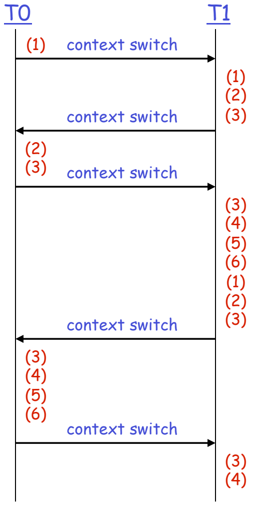
Peterson's algorithm

2. Assume that thread T0 intends to enter its critical section and T1 is in its critical section. Since turn = 1, T0 loops at statement (3). After the execution of (5) by T1, if T0 resumes execution before T1 intends to enter again, T0 enters its critical section immediately; otherwise, see case (3).

Peterson's algorithm

3. Assume both threads intend to enter the critical section, i.e. both threads have set their *intendToEnter* flags to true. The thread that first executes "*turn* = ...;" waits until the other thread executes "*turn* = ...;" and then enters its critical section. The other thread will be the next thread to enter the critical section.

Peterson's algorithm



T0		T1	Comments
(1)	context switch		*intendToEnter*[0] is set to true
		(1)	*intendToEnter*[1] is set to true
		(2)	*turn* is set to 0
	context switch	(3)	T1 enters the *while* loop
(2)			*turn* is set to 1
(3)	context switch		T0 enters the *while* loop
		(3)	T1 exits *while* loop
		(4)	T1 enters the critical section
		(5)	*intendToEnter*[1] is set to false
		(6)	T1 executes the non-critical section
		(1)	*intendToEnter*[1] is set to true
		(2)	*turn* is set to 0
	context switch	(3)	T1 enters *while* loop
(3)			T0 exits *while* loop
(4)			T0 enters critical section
(5)			*intendToEnter*[0] is set to false
(6)	context switch		T0 executes the non-critical section
		(3)	T1 exits the *while* loop
		(4)	T1 enters critical section

Bakery algorithm

Bakery algorithm is used to solve the n-process critical section problem. The main idea is the following:

- ❑ When a thread wants to enter a critical section, it gets a ticket. Each ticket has a number.
- ❑ Threads are allowed to enter the critical section in ascending order of their ticket numbers.

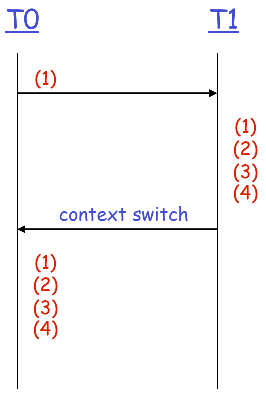
Version 1

```
int number[n]; // array of ticket numbers, initially all elements of number is 0
```

```
while (true) {
  number[i] = max(number) + 1;                              (1)
  for (int j = 0; j < n; j ++) {                            (2)
    while (j != i && number[j] != 0 &&
           (number[j], j) < (number[i], i)) { ;}             (3)
  }
  critical section                                          (4)
  number[i] = 0;                                            (5)
  non-critical section                                      (6)
}
```

- (a, b) < (c, d) if a < c or (a == c and b < d)
- max(number) is the max value of all the elements in number

Version 1 is incorrect!



Comments

T0 executes max(number) + 1, switch
occur before 1 is assigned to number[0]

T1 sets number[1] to 1
T1 starts for loop
T1 exits while and for loop
T1 enters critical section

T0 assigns 1 (not 2) to number[0]
T0 starts for loop
To exits the while and for loops
T0 enters critical section

Bakery algorithm

int number[n]; // array of ticket numbers, initially all elements of *number* is 0

boolean choosing[n]; // initially all elements of *choosing* is false

```
while (true) {
  choosing[i] = true;                                  (1)
  number[i] = max(number) + 1;                         (2)
  choosing[i] = false;                                 (3)
  for (int j = 0; j < n; j ++) {                       (4)
    while (choosing[j]) { ; }                          (5)
    while (j != i && number[j] != 0 &&
          (number[j], j) < (number[i], i)) { ;}        (6)
  }
  critical section                                     (7)
  number[i] = 0;                                       (8)
  non-critical section                                 (9)
}
```

- (a, b) < (c, d) if a < c or (a == c and b < d)
- max(*number*) is the max value of all the elements in *number*

UTA

Bakery algorithm

Let us consider the following cases:

1. One thread, say Ti, intends to enter its critical section and no other thread is in its critical section or entry section. Then number[i] = 1 and number[j], where j ≠ i, is 0. Thus, Ti enters its critical section immediately.
2. One thread, say Ti, intends to enter its critical section and Tk, k ≠ i, is in its critical section. Then at (6), when j = k, number[j] < number[i]. Thus, Ti is delayed at (6) until Tk executes (8).

UTA

Bakery algorithm

3. Two or more threads intend to enter their critical sections and no other threads is in its critical section. Assume that Tk and Tm, where k < m, intend to enter. Consider the possible relationships between *number*[k] and *number*[m]:
   - number[k] < number[m]. Tk enters its critical section since (number[m], m) > (number[k], k).
   - number[k] == number[m]. Tk enters its critical section since (number[m], m) > (number[k], k).
   - number[k] > number[m]. Tm enters its critical section since (number[k], k) > (number[m], m).