CSMC 412

Operating Systems

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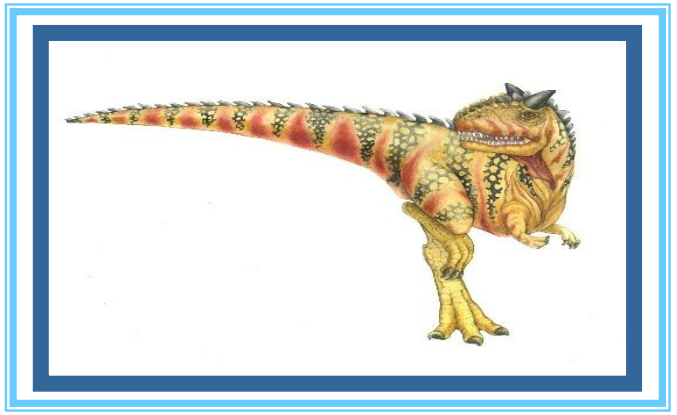
Synchronization Tools

Set 8

Synchronization Tools



Objectives

- To present the concept of process synchronization.
- To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data
- To present both software and hardware solutions of the critical-section problem
- To examine several classical process-synchronization problems
- To explore several tools that are used to solve process synchronization problems

Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

Systems = Objects + Activities

- Safety is a property of objects, and groups of objects, that participate across multiple activities.
  - Can be a concern at many different levels: objects, composites, components, subsystems, hosts, …
- Liveness is a property of activities, and groups of activities, that span across multiple objects.
  - Levels: Messages, call chains, threads, sessions, scenarios, scripts workflows, use cases, transactions, data flows, mobile computations, …

Violating Safety

- Data can be shared by threads
  - Scheduler can interleave or overlap threads arbitrarily
  - Can lead to *interference*
    - Storage corruption (e.g., a *data race*/*race condition)*
    - Violation of representation invariant
    - Violation of a protocol (e.g., *A* occurs before *B*)

How does this apply to OSs?

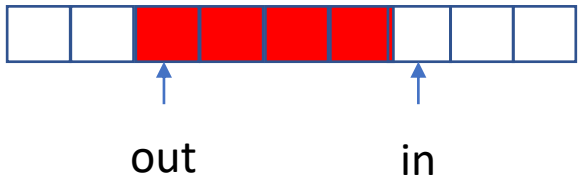
- Any resource that is shared could be accessed inappropriately
  - Shared memory
    - Kernel threads
    - Processes (shared memory set up by kernel)
  - Shared resources
    - Printer, Video screen, Network card, …
- OS must protect shared resources
  - And provide processes a means to protect their own abstractions

Illustration of the problem:

- Suppose that we wanted to provide a solution to the consumer-producer problem that fills ***all*** the buffers. We can do so by having an integer **`counter`** that keeps track of the number of full buffers. Initially, **`counter`** is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer

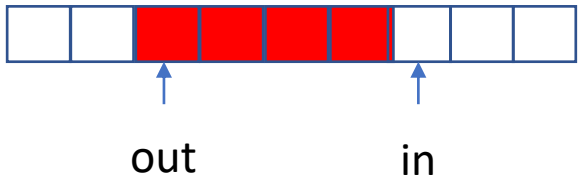
```
while (true) {
        /* produce an item in next produced */

        while (counter == BUFFER_SIZE) ;
                /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
}
```



counter = 9

Consumer

```
while (true) {
        while (counter == 0)
               ; /* do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
         counter--;
        /* consume the item in next consumed */
}
```



counter = 9

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

Start: both threads ready to run. Each will increment the global count.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

y = 0

T1 executes, grabbing the global counter value into y.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

y = 0

y = 0

T1 is pre-empted. T2 executes, grabbing the global counter value into y.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state **cnt = 1**

y = 0

y = 0

T2 executes, storing the incremented cnt value.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state **cnt = 1**

y = 0

y = 0

T2 completes. T1 executes again, storing the old counter value (1) rather than the new one (2)!

But When I Run it Again?

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

Start: both threads ready to run. Each will increment the global count.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

y = 0

T1 executes, grabbing the global counter value into y.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state **cnt = 1**

y = 0

T1 executes again, storing the counter value

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 1

y = 0

y = 1

T1 finishes. T2 executes, grabbing the global counter value into y.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state **cnt = 2**

y = 0

y = 1

T2 executes, storing the incremented cnt value.

What happened?

- In the first example, **t1** was preempted after it read the counter but before it stored the new value.
  - Depends on the idea of an *atomic action*
  - Violated an object invariant
- A particular way in which the execution of two threads is interleaved is called a *schedule*. We want to prevent this undesirable schedule.
- Undesirable schedules can be hard to reproduce, and so hard to debug.

Race Condition

- **`counter++`** could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

- **`counter--`** could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

- Consider this execution interleaving with "count = 5" initially:

S0: producer execute `register1 = counter` {register1 = 5}
S1: producer execute `register1 = register1 + 1` {register1 = 6}
S2: consumer execute `register2 = counter` {register2 = 5}
S3: consumer execute `register2 = register2 – 1` {register2 = 4}
S4: producer execute `counter = register1` {counter = 6 }
S5: consumer execute `counter = register2` {counter = 4}

Question

- If you run a program with a race condition, will you always get an unexpected result?

Answer

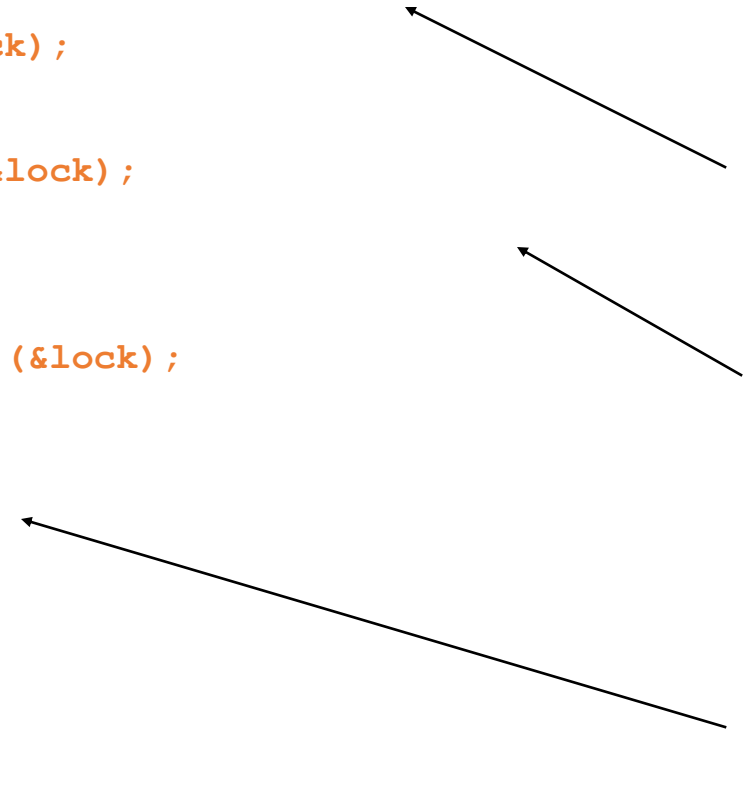
- If you run a program with a race condition, will you always get an unexpected result?
  - No! It depends on the scheduler
  - ...and on the other threads/processes/etc that are running on the same CPU
- Race conditions are hard to find

Disabling Interrupts

- Doesn’t work for multiprocessors
- Doesn’t permit different groups of critical sections

Synchronization

```
static int cnt = 0;
struct Mutex lock;
Mutex_Init(&lock);
void run() {
  Mutex_Lock (&lock);
  int y = cnt;
  cnt = y + 1;
  Mutex_Unlock (&lock);
}
```



***Lock**, for protecting The shared state*

***Acquires** the lock; Only succeeds if not held by another thread*

***Releases** the lock*

Java-style `synchronized` block

```
static int cnt = 0;
struct Mutex lock;
Mutex_Init(&lock);
void run() {
  synchronized (lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

***Lock**, for protecting The shared state*

***Acquires** the lock; Only succeeds if not held by another thread*

***Releases** the lock*

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 0

T1 acquires the lock

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 0

y = 0

T1 reads cnt into y

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

y = 0

Shared state cnt = 0

T1 is pre-empted.
T2 attempts to
acquire the lock but fails
because it's held by
T1, so it blocks

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

y = 0

Shared state **cnt = 1**

T1 runs, assigning to cnt

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

y = 0

Shared state cnt = 1

T1 releases the lock and terminates

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

y = 0

Shared state cnt = 1

T2 now can acquire the lock.

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state cnt = 1

y = 0

T2 reads cnt into y.

y = 1

Applying synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = cnt;
    cnt = y + 1;
  }
}
```

Shared state **cnt = 2**

y = 0

T2 assigns cnt,
then releases the lock

y = 1

Critical Section

- A critical section is a piece of code that should not be interleaved with code from another thread
- Mutually Exclusive Execution

ATOMIC ACTION

Thread A
.
Non CS.

CS

Non CS

Thread B
.
Non CS.

CS

Non CS

- Locks
- Only one thread can “acquire” a mutex
  - Other threads block until they can acquire it
  - Used for implementing critical sections

Mutex (Lock) Policies

- What if a thread already holds the mutex it's trying to acquire?
  - Re-entrant mutexes: The thread can reacquire the same lock many times. Lock is released when object unlocked the corresponding number of times
    - This is the case for Java
  - Non-reentrant: Deadlock! (defined soon.)
    - This is the case in GeekOS
- What happens if a thread is killed while holding a mutex? Or if it just forgets to release it
  - Could lead to deadlock

Java Synchronized statement

- **synchronized (obj) {** *statements* **}**
- Obtains the lock on **obj** before executing statements in block
  - **obj** can be any Object
- Releases the lock when the statement block completes
  - Either normally, or due to a return, break, or exception being thrown in the block
- Can’t forget to release the lock!

Synchronization not a Panacea

- Two threads can block on locks held by the other; this is called *deadlock*

```
Object A = new Object();
Object B = new Object();
T1.run() {
  synchronized (A) {
    synchronized (B) {
      …
    }
  }
}
```

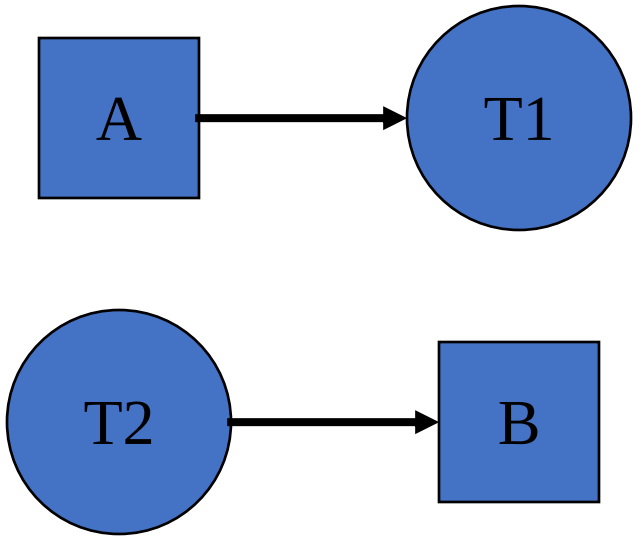
```
T2.run() {
  synchronized (B) {
    synchronized (A) {
      …
    }
  }
}
```

Deadlock

- Quite possible to create code that deadlocks
  - Thread 1 holds lock on **A**
  - Thread 2 holds lock on **B**
  - Thread 1 is trying to acquire a lock on **B**
  - Thread 2 is trying to acquire a lock on **A**
  - Deadlock!
- Not easy to detect when deadlock has occurred
  - other than by the fact that nothing is happening

```
Object A = new Object();
Object B = new Object();
T1.run() {
  synchronized (A) {
    synchronized (B) {
      …
    }
  }
}

T2.run() {
  synchronized (B) {
    synchronized (A) {
      …
    }
  }
}
```

Deadlock: Wait graphs

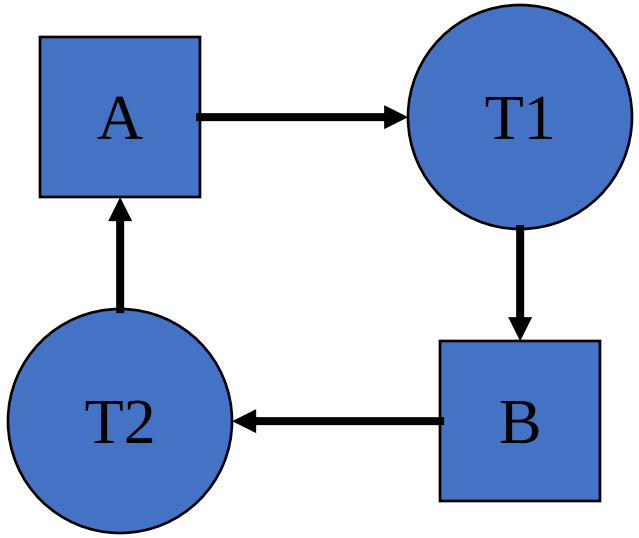


Thread T1 holds lock A

Thread T2 attempting to acquire lock B

Deadlock occurs when there is a cycle in the graph

Wait graph example



T1 holds lock on **A**

T2 holds lock on **B**

T1 is trying to acquire a lock on **B**

T2 is trying to acquire a lock on **A**

Critical Section Problem

- Consider system of ***n*** processes {p_0, p_1, … p_{n-1}}
- Each process has a **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process is in its critical section, no other may be in its critical section
- ***Critical section problem*** is to design protocol to solve this

- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**

Critical Section

- General structure of process P_i

```
do {
        entry section
            critical section
        exit section
            remainder section
} while (true);
```

Solution to Critical-Section Problem

1. Mutual Exclusion - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3. Bounded Waiting - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a nonzero speed
   - No assumption concerning relative speed of the N processes

Two-task Solution

- Two tasks, T_0 and T_1 (T_i and T_j)
- Three solutions presented.

Algorithm 1

- Threads share a common integer variable turn
  - Turn takes values 0 and 1
- Initialize turn to 0
- Entry Section for thread i
  - If turn==i, thread i is allowed to proceed, else yield
- Exit Section for thread I
  - turn== (1-i)

Algorithm 1

- Satisfies mutual exclusion but not progress.
  - Processes are forced to enter their critical sections alternately.
  - One process not in its critical section thus prevents the other from entering its critical section.

Algorithm 2

- Boolean flags to indicate thread's interest in entering critical section
- Entry Code

```
if (t == 0) {
        flag0 = true;
        while(flag1 == true)
            Thread.yield();
    }
    else {
        flag1 = true;
        while (flag0 == true)
            Thread.yield();
```

- Exit Code

```
if (t == 0)
    flag0 = false;
else
    flag1 = false;
```

- Initialize
  - Both flags to false

Algorithm 2

- Satisfies mutual exclusion, but not progress requirement.
  - Both processes can end up setting their flag[] variable to true, and thus neither process enters its critical section!

Algorithm 3 Peterson's Solution

- Combine ideas from 1 and 2

Peterson's Solution

- Good algorithmic description of solving the problem
- Two process solution
- Assume that the `load` and `store` machine-language instructions are atomic; that is, cannot be interrupted
- The two processes share two variables:
  - `int turn;`
  - `Boolean flag[2]`
- The variable `turn` indicates whose turn it is to enter the critical section
- The `flag` array is used to indicate if a process is ready to enter the critical section. `flag[i] = true` implies that process P_i is ready!

Algorithm for Process P_i

```
do {
        flag[i] = true;
        turn = j;
        while (flag[j] && turn = = j);

                critical section

        flag[i] = false;

                remainder section

} while (true);
```

Peterson's Solution (Cont.)

- Provable that the three CS requirement are met:
  1. Mutual exclusion is preserved
     P_i enters CS only if:
     either **`flag[j] = false`** or **`turn = i`**
  2. Progress requirement is satisfied
  3. Bounded-waiting requirement is met

Algorithm 3

- Meets all three requirements; solves the critical-section problem for two processes.
  - One process is always guaranteed to get into its critical section.
  - Processes are forced to take turns when they both want to get in.

Bakery Algorithm

Critical section for n processes

- Before entering its critical section, process receives a number. Holder of the smallest number enters the critical section.
- If processes P_i and P_j receive the same number, if $i < j$, then P_i is served first; else P_j is served first.
- The numbering scheme always generates numbers in increasing order of enumeration; i.e., 1,2,3,3,3,3,4,5...

Bakery Algorithm

- Notation <≡ lexicographical order (ticket #, process id #)
  - $(a,b) < c,d)$ if $a < c$ or if $a = c$ and $b < d$
  - max $(a_0,\ldots, a_{n-1})$ is a number, k, such that $k \geq a_i$ for i - 0, …, $n - 1$
- Shared data

  boolean choosing[n];

  int number[n];

  Data structures are initialized to **false** and **0** respectively

Bakery Algorithm

```
do {
   choosing[i] = true;
   number[i] = max(number[0], number[1], …, number [n – 1])+1;
   choosing[i] = false;
   for (j = 0; j < n; j++) {
            while (choosing[j]) ;
            while ((number[j] != 0) && (number[j,j] < number[i,i])) ;
   }
      critical section
   number[i] = 0;
      remainder section
} while (1);
```

Critical-Section Handling in OS

Two approaches depending on if kernel is preemptive or non- preemptive

- **Preemptive** – allows preemption of process when running in kernel mode
- **Non-preemptive** – runs until exits kernel mode, blocks, or voluntarily yields CPU
  - Essentially free of race conditions in kernel mode

Synchronization Hardware

- Many systems provide hardware support for implementing the critical section code.
- All solutions below based on idea of **locking**
  - Protecting critical regions via locks
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally, too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special atomic hardware instructions
    - **Atomic** = non-interruptible
  - Either test memory word and set value
  - Or swap contents of two memory words

Solution to Critical-section Problem Using Locks

```
do {
        acquire lock
                critical section
        release lock
                remainder section
} while (TRUE);
```

test_and_set Instruction

Definition:

```
boolean test_and_set (boolean *target)
{
    boolean rv = *target;
    *target = TRUE;
    return rv:
}
```

1. Executed atomically
2. Returns the original value of passed parameter
3. Set the new value of passed parameter to “TRUE”.

4. In x86 the instruction is BTS
    1. Specify the bit in a string which is SET and its old value is stored in CF flag

Solution using test_and_set()

- Shared Boolean variable lock, initialized to FALSE
- Solution:

```
do {
        while (test_and_set(&lock))
           ; /* do nothing */
                /* critical section */
        lock = false;
                /* remainder section */

    } while (true);
```

compare_and_swap Instruction

Definition:

```
int compare _and_swap(int *value, int expected, int new_value) {
     int temp = *value;

     if (*value == expected)
        *value = new_value;
  return temp;
 }
```

1. Executed atomically
2. Returns the original value of passed parameter “value”
3. Set the variable “value” the value of the passed parameter “new_value” but only if “value” ==“expected”. That is, the swap takes place only under this condition.

Solution using compare_and_swap

- Shared integer “lock” initialized to 0;
- Solution:

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

   /* critical section */

   lock = 0;

   /* remainder section */

} while (true);
```

Bounded waiting mutual exclusion

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

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 */
}
```

- P_i can enter its CS only if
  - Either waiting [i] is false, or
  - Key =0
- Key can become 0 only if compare and swap is executed
- First process to execute compare and swap will find Key = 0, all others must wait.
- Variable waiting [i] becomes false only if another process leaves its CS
  - Only one waiting[i] is set to false