CSCI [4|6] 730
Operating Systems

Synchronization Part 1 : The Basics

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Chapter 6: Process *[& Thread]* Synchronization

- Why is synchronization needed?
- Synchronization Language/Definitions:
  - » What are race conditions?
  - » What are critical sections?
  - » What are atomic operations?
- How are locks implemented?

Why does cooperation require synchronization?

- **Example**: Two threads: `Maria` and `Tucker` share an account with **shared** variable ‘`balance`’ in memory.
- **Code to `deposit()`:**

```
void deposit( int amount )
{
balance = balance + amount;
}
```

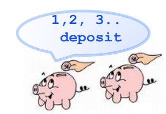
- **Compiled to assembly:**

```
deposit:
  load  RegisterA, balance
  add   RegisterA, amount
  store RegisterA, balance
```

- **Both Maria & Tucker deposit money into account:**
  - » Initialization: `balance = 100`
  - » Maria: `deposit( 200 )`
  - » Tucker: `deposit( 10 )`

Which variables are shared? Which are private?

Example Execution



`deposit(amount) { balance = balance + amount; }`

1. Initialization: `balance = 100`
2. Maria: `deposit( 200 )`
3. Tucker: `deposit( 10 )`

```
deposit:
  load  RegisterA, balance
  add   RegisterA, amount
  store RegisterA, balance
```

```
Memory:
  balance = 310
  RegisterA = 310
```

Time

```
deposit (Maria):
  load  RegisterA, 100
  add   RegisterA, 200
  store RegisterA, balance
```

```
deposit (Tucker):
  load  RegisterA, 300
  add   RegisterA, 10
  store RegisterA, balance
```

Concurrency

```
4. Memory:
  balance = 300
  RegisterA = 300
```

```
3..
110?
```

```
4. Memory:
  balance = 110
  RegisterA = 110
```

- What happens if M & T deposit the funds "concurrently"? `deposit(amount) { balance = balance + amount; }`
  - » Strategy:
    - – Assume that any interleaving is possible
  - » No assumption about scheduler
  - » Observation: When a thread is interrupted content of registers are saved (and restored) by interrupt handlers (dispatcher/context switcher)
    - – Initialization: balance = 100
    - – Maria: deposit(200)
    - – Tucker: deposit(10)

```
deposit:
  load  RegisterA, balance
  add   RegisterA, amount
  store RegisterA, balance
```

Time

```
deposit (Maria):
  load  RegisterA, balance

  add   RegisterA, 200

  store RegisterA, balance
```

M T M T M T

```
deposit (Tucker):

  load  RegisterA, balance

  add   RegisterA, 10

  store RegisterA, balance
```


What program data is (or is not) shared?

- Local variables are not shared (private)
  - » Each thread has its own stack
  - » Local variables are allocated on private stack
- Global variables and static objects are shared
  - » Stored in the static data segment, accessible by any threads
  - » Pass by (variable) 'reference' : &data1
- Dynamic objects and other heap objects are shared
  - » Allocated from heap with `malloc/free` or `new/delete`

Beware of Weird Bugs: Never pass, share, or store a pointer * to a local variable on another threads stack

Race Condition

- Results depends on the order of execution
  - » Result in non-deterministic bugs, these are hard to find!
    - – Deterministic : Input alone determines results, i.e., the same inputs always produce the same results:
      - Example: Sqrt (4) = 2
- Intermittent –
  - » A time dependent `bug'
  - » a small change may hide the real bug (e.g., print statements can hide the real bug because they slow down processing time and consequently impacts the timing of the threads).

How to avoid race conditions

- Idea: Prohibit one or more threads from reading and writing *shared* data at the same time! ⇒ Provide Mutual Exclusion (what?)
- Critical Section: Part of program (or 'slice") where shared memory is accessed

Critical Section

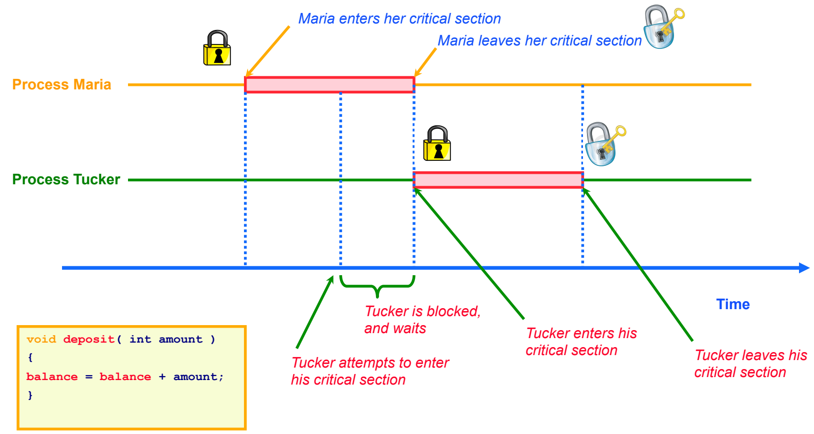
```
void credit( int amount )
{
int x = 5;
printf( "Adding money" );
balance = balance + amount;
}
```

```
void debit( int amount )
{
int i;
balance = balance - amount;
for( i = 0; i < 5; i++ );
}
```

THE Critical Section Problem?

- **Problem**: Avoiding race conditions (i.e., provide mutual exclusion) is **not sufficient** for having threads cooperate ***correctly (no progress)*** and ***efficiently:***
  - » What about if **no one** gets into the critical section even if several threads wants to get in? (No progress at ALL!)
  - » What about if someone waits outside the critical section and never gets a turn? (starvation, NOT FAIR!)

What We Want: *Mutual Exclusion (!)*



Critical Section Problem: Properties

Memorize

Required Properties:

- **Mutual Exclusion**:
  - » Only **one** thread in the critical section at a time
- **Progress (e.g., someone gets the CS):**
  - » Not block others out: if there are requests to enter the CS must allow one to proceed
  - » Must not depend on threads outside critical section
    - – If no one is in CS then someone must be let in…
      - We take no reservations!

- **Bounded waiting (starvation-free):**
  - » Must eventually allow each waiting thread
  - » to enter

Solve: THE Critical Section Problem: "Proper" Synchronization

Required "Proper"ties :

- Mutual Exclusion
- Progress (someone gets the CS)
- Bounded waiting (starvation-free, eventually you will run)

Desirable Properties:

- **Efficient**:
  - » Don't consume substantial resources while waiting.
    - – Example : Do not busy wait (i.e., spin wait)
- **Fair**:
  - » Don't make some processes wait longer than others
- **Simple**: Should be easy to reason about and use

Critical Section Problem: Need *Atomic* Operations

- **Basics**: Need atomic operations:
  - » No other instructions can be interleaved (low level)
  - » Completed in its entirety without interruption (no craziness)
- **Examples** of atomic operations:
  - » Loads and stores of words
    - `load register1, B`
    - `store register2, A`
  - » Idea: : Code between interrupts on uniprocessors
    - Disable timer interrupts, don't do any I/O
  - » Special hardware instructions (later)
    - "load, store" in one instruction
    - Test&Set
    - Compare&Swap

Disabling Interrupts

- Kernel provides two system calls:
  - » `Acquire()` and
  - » `Release()`
- No preemption when interrupts are off!
  - » No clock interrupts can occur
- Disadvantage:
  - » unwise to give processes power to turn of interrupts
    - Never turn interrupts on again!
  - » Does not work on multiprocessors
- When to use?:
  - » But it may be good for kernel itself to disable interrupts for a few instructions while it is updating variables or lists

```
void Aquire()
{
disable interrupts
}
```

```
void Release()
{
enable interrupts
}
```

Who do you trust?
Do you trust your kernel?
Do you trust your friend's kernel?
Do you trust your kernel's friends?

Software Solutions

- **Assumptions:**
  - » We have an atomic load operation (read)
  - » We have an atomic store operation (assignment)
- **Notation** [lock=true, lock=false]
  - » True: means un-available (lock is set, someone has the lock)
  - » False: means available (e.g., lock is not set, as the CS is available, no one is in the CS)

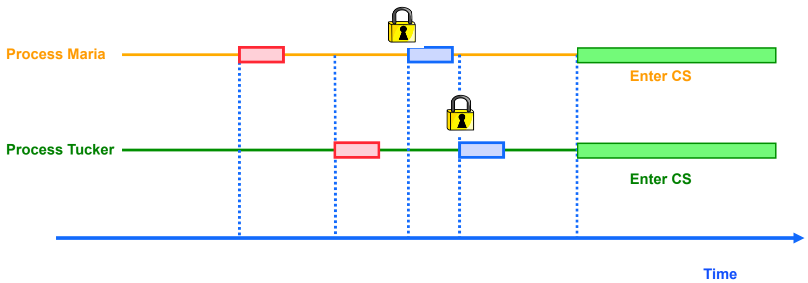
Attempt 1: Shared Lock Variable

- Single shared `lock` variable

```
boolean lock = false; // lock available shared variable
void deposit(int amount)
  {
  while( lock == true ) {} /* while lock is set :  wait */ ;   // Entry CS
  lock = true; /* gets the lock */                             // Entry CS

  balance += amount; // critical section                       // CS

  lock = false; /* release the lock */                         // Exit CS
  }
```

- Uses busy waiting
- Does this work?
  - » Are any of the principles violated (i.e., does it ensure mutual, progress and bounded waiting)?

Attempt 1: Shared Variable




```
boolean lock = false; // shared variable
void deposit(int amount)
  {
  while( lock == true ) {} /* wait */ ;
  lock = true;
  balance += amount; // critical section
  lock = false;
  }
```

- M reads lock sees that it is false
- T reads lock sets it as false
- M sets the lock
- T sets the lock

Two threads in critical section

Attempt 1: Lock Variable Problem & Lesson

- **Problems**:
  - » No mutual exclusion: Both processes entered the CS.
- **Lesson learned**: Failed because two threads read the lock variable simultaneously and both thought it was its 'turn' to get into the critical section

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation
Shared Lock Variable	X		

```
Idea: Take Turns:
    Add a variable that determine if it
    is its turn or not!
```


Attempt 2: Alternate (we want to be fair)

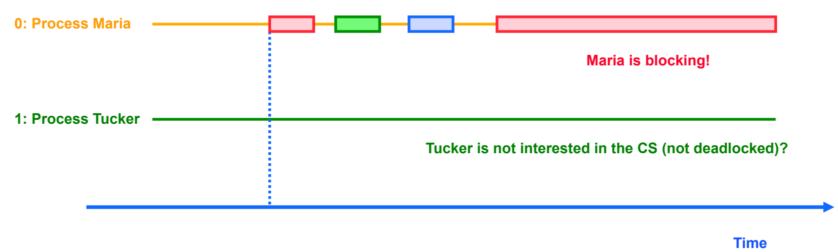
- **Idea**: Take turns (alternate) via a `turn` variable that determines which thread's turn it is to be in the CS
  - » (set to thread ID's: `0` or `1`). We are assuming only 2 threads!

Entry CS: / CS: / Exit CS:

```
int turn = 0; // shared variable
void deposit( int amount )
  {
  while( turn == 1-tid ) {} /* wait */ ; [me=0; 0 == 1]

  balance += amount; // critical section

  turn = 1-tid;
  }
```

- **Does this work?**
  - » Mutual exclusion?
  - » Progress (someone gets the CS if empty)
  - » Bounded waiting… it will become next sometime?

Attempt 2: Alternate – Does it work?




```
int turn = 0; // shared variable
void deposit( int amount )
  {
  while( turn == 1-tid ) {} /* wait */ ;

  balance += amount; // critical section

  turn = 1-tid;
  }
```

- Initialize: Maria is '0' & Tucker is '1'
- M reads turn sees that it is her turn
- M done and change turn to other
- M want to deposit more money…
- T never requests CS no money!

No progress!

Attempt 2: Strict Alternation

- **Problems**:
  - » **No progress**:
    - – if no one is in a critical section and a thread wants in -- it should be allowed to enter
  - » **Also not efficient**:
    - – Pace of execution: Dictated by the slower of the two threads. IF Tucker uses its CS only one per hour while Maria would like to use it at a rate of 1000 times per hour, then Maria has to adapt to Tucker's slow speed.

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation
Shared Lock Variable	No		
Strict Alteration	Yes	No	No

Pace limited to slowest process

Lessons: Attempt 2: Strict Alternation

- **Problem: Need to fix the problem of progress!**
- **Lesson: Why did strict alternation fail?**
  - » *Pragmatically*: Problem with the turn variable is that we need state information about BOTH processes.
    - – We need to know if the other thread is interested in the CS, and [of-course]:
    - – We should not wait for a thread that is not interested!
- **Idea**:
  - » We need *to know the needs of others*!
  - » Check to see if other needs it.
    - – Don't get the lock until the 'other' is done with it.

Attempt 3: Check "other thread's" state/interest then Lock

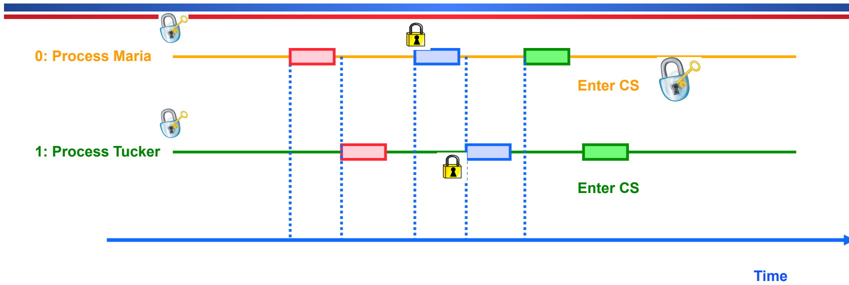
- **Idea: Each thread has its own lock; lock indexed by tid (0, 1). Check other's needs**

```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  while( lock[1-tid] == true ) {} /* wait for other */ ;
  lock[tid] = true;

  balance += amount; // critical section

  lock[tid] = false;
  }
```

Entry CS: `while( lock[1-tid] == true ) {} /* wait for other */ ;` and `lock[tid] = true;`
CS: `balance += amount; // critical section`
Exit CS: `lock[tid] = false;`

- **Does this work? Mutual exclusion? Progress (someone gets the CS if empty, no deadlock)? Bounded Waiting (no starvation)?**

Attempt 3: Check then Lock




```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  while( lock[1-tid] == true ) {} /* wait */;

  lock[tid] = true;

  balance += amount; // critical section

  lock[tid] = false;
  }
```

- M checks if Tucker is interested and he isn't
- T checks if Maria is interested and she isn't
- Switch back to Maria she now sets his lock
- Switch Back to Tucker he sets his lock

Attempt 3: Check then Lock

- **Problems**:
  - » No Mutual Exclusion
- **Lesson**: Process locks the critical section AFTER the process has checked it is available but before it enters the section.
- **Idea**: Lock the section first! then lock…

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation
Shared Lock Variable	No		
Strict Alteration	Yes	No	No
Check then Lock	No		

Pace limited to slowest process

Attempt 4: Lock then Check

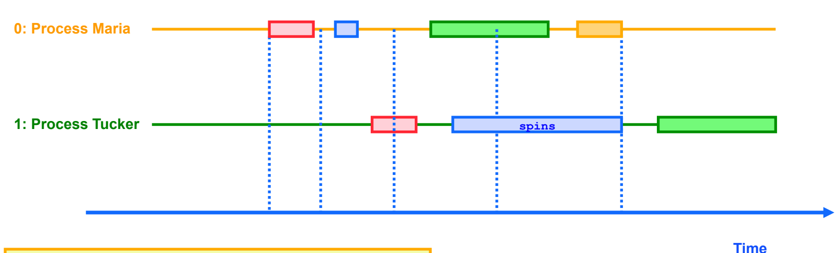
- **Idea**: Each thread has its own lock; lock indexed by tid (0, 1). Check other's needs

Entry CS:, CS:, Exit CS:

```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  lock[tid] = true; /* express interest */      // Entry CS
  while( lock[1-tid] == true ) {} /* wait */ ;  // Entry CS

  balance += amount; // critical section        // CS

  lock[tid] = false;                            // Exit CS
  }
```

- Does this work? Mutual exclusion? Progress (someone gets the CS if empty, no deadlock)? Bounded Waiting (no starvation)?

Attempt 4: Lock then Check



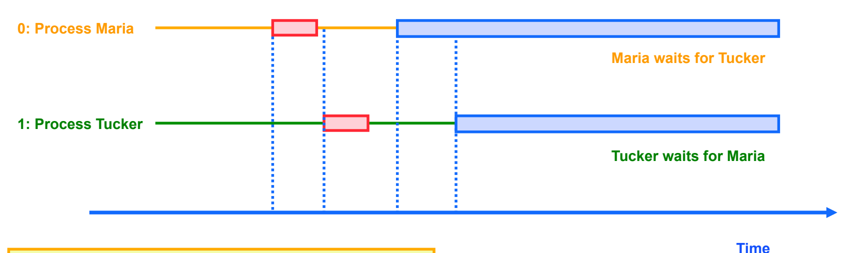

```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  lock[tid] = true;

  while( lock[1-tid] == true ) {} /* wait */;

  balance += amount; // critical section

  lock[tid] = false;
  }
```

Mutual Exclusion?

- Maria's View: Once Maria sets her lock:
  - » Tucker cannot enter until Maria is done
  - » Tucker already in CS, then Maria blocks until Tucker leaves the CS (someone always spins)
- Tucker's View: Same thing

So YES it Provided for Mutual Exclusion

Attempt 4: Lock then Check




```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  lock[tid] = true;

  while( lock[1-tid] == true ) {} /* wait */;

  balance += amount; // critical section

  lock[tid] = false;
  }
```

- Mutual Exclusion: Yes
- **Deadlock**: Each thread waits for the other. Each one thinks that the other is in the critical section

Attempt 4: Lock then Check

- **Problems**:
  - » No one gets the critical section!
  - » Each thread 'insisted' on its right to get the CS and did not back off from this position.
- **Lesson**: Again a 'state' problem, a thread misunderstood the state of the other thread
- **Idea**: Allow a thread to back off to give the other a chance to enter its critical section.

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation
Shared Lock Variable	No		
Strict Alteration	Yes	No	No
Check then Lock	No		
Lock then Check	Yes	No (deadlock)	

Pace limited to slowest process

Attempt 5: Defer, back-off lock

- **Idea**: Add an delay

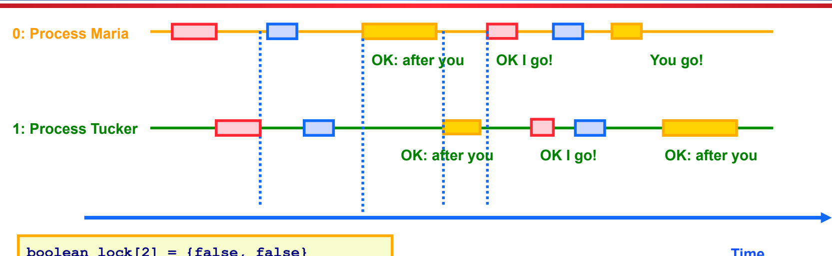
Entry CS: (lines from `lock[tid] = true;` to the closing `}` of the while loop)

CS: `balance += amount;`

Exit CS: `lock[tid] = false;`

```
boolean lock[2] = {false, false} // shared
void deposit( int amount )
  {
  lock[tid] = true;
  while( lock[1-tid] == true ) /* spin for other to finish */
    {
     lock[tid] = false;
     delay;
     lock[tid] = true;
    }

  balance += amount; // critical section

  lock[tid] = false;
  }
```


Attempt 5: Deferral




```
boolean lock[2] = {false, false}
void deposit( int amount )
  {
  lock[tid] = true;

  while( lock[1-tid] == true )
     lock[tid] = false;
     delay;
     lock[tid] = true;

  balance += amount; //critical section

  lock[tid] = false;
  }
```

- Mutual Exclusion: Yes
- Live Lock: sequence can be broken if you are lucky!
  - » Not really a deadlock (guaranteed not to be able to proceed)
  - » Not starvation - threads starves when a process repeatedly loose to the other threads, here both loose

Attempt 5: Deferral

- **Problems:**

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation
Shared Lock Variable	No		
Strict Alteration	Yes	No	No
Check then Lock	No		
Lock then Check	Yes	No (deadlock)	
Deferral	Yes	No (not deadlock)	Not really

Pace limited to slowest process

Lessons

- We need to be able to observe the state of both processes
  - » Simple lock is not enough
- We most impose an order to avoid this 'mutual courtesy'; i.e., after you-after you phenomena
- **Idea**:
  - » If both threads attempt to enter CS at the same time let only one thread it.
  - » Use a turn variable to avoid mutual courtesy
    - – Indicates who has the right to insist on entering his critical section.

Attempt 6: Careful Turns

```
boolean lock[2] = {false, false} // shared
int turn = 0; // shared variable – arbitrarily set
void deposit( int amount )
  {
  lock[tid] = true;              // I am interested in the lock take my lock.
  while( lock[1-tid] == true )   // *IS* the OTHER interested? If not get in!
    {                            //* WE know he is interested! (we both are)
     if( turn == 1-tid )         // if it is it OTHER's turn then *I* SPIN/DEFER
        {                        // NOTE if it is MY turn keep the lock
        lock[tid] = false;       // it is – so I will LET him get the lock.
          while( turn == 1 - tid ) {};  // wait to my turn
        lock[tid] = true;               // my turn – still wants the lock
        }
    } /* while */
  balance += amount; // critical section
  turn = 1 - tid;    // Set it to the other's turn so he stops spinning */
  lock[tid] = false;
  }
```


Dekker's Algorithm

https://en.wikipedia.org/wiki/Dekker%27s_algorithm

- **Mutual Exclusion**: Two threads cannot be in the critical region simultaneously – prove by contraction.
  - » Suppose they are then locks are set according the time line for each point of view (P0, P1).
  - » P_0 :
    - – 1. lock[0] = true (sets the lock, then)
    - – 2. lock[1] = false (see that lock 1 is false)
  - » P_1 :
    - – 3. lock[1] = true
    - – 4. lock[0] = false
- Suppose P_0 enters CS no later than P1
  - » t2 < t4 (so P0 checks lock[1] is false just before entering its CS).
  - » t2 ? t3
    - – after 3. lock[1] = true it remains true so t2 < t3
  - » So: t1 < t2 < t3 < t4
  - » But lock[0] cannot become false until P0 exits and we assumed that both P0 and P1 were in the CS at the same time. Thus it is impossible to have checked flag as false at t4.

```
boolean lock[2] = {false, false}
int turn = 0;
void deposit( int amount )
  {
  lock[tid] = true;
  while( lock[1-tid] == true )
    {
     if( turn == 1-tid )
       lock[tid] = false;
         while( turn == 1 - tid ){};
       lock[tid] = true;
    }
  balance += amount; // CS
  turn = 1 - tid;
  lock[tid] = false;
  }
```


Attempt 6: Dekker's Algorithm (before 1965)

- Peterson's Solution: Change order – A process sets the turn to the other process right away

```
boolean lock[2] = {false, false} // shared
int turn = 0; // shared variable
void deposit( int amount )
  {
  lock[tid] = true;
  while( lock[1-tid] == true ) // check other
    {
     if( turn == 1-tid )        // Whose turn?
       lock[tid] = false;       // then I defer
         while( turn == 1 - tid ) {};
       lock[tid] = true;
    }
  balance += amount; // critical section
  turn = 1 - tid;
  lock[tid] = false;
  }
```

Attempt 7: Peterson's Simpler Lock Algorithm

- **Idea**: combines turn and separate locks (recall turn taking avoids the deadlock)

```
boolean lock[2] = {false, false} // shared
int turn = 0; // shared variable
void deposit( int amount )
  {
  lock[tid] = true;
  turn = 1-tid; // set turn to other process
  while( lock[1-tid] == true && turn == 1-tid ) {};
  balance += amount; // critical section
  lock[tid] = false;
  }
```

- When 2 processes enters simultaneously, setting turn to the other releases the 'other' process from the while loop (one write will be last).
- **Mutual Exclusion**: Why does it work?
  - » The Key Observation: Turn cannot be both 0 and 1 at the same time

Peterson's Algorithm Intuition (1981)

- **Mutual exclusion**: Enter critical section if and only if
  - » Other thread does not want to enter
  - » Other thread wants to enter, but your turn
- **Progress**: Both threads cannot wait forever at while() loop
  - » Completes if other process does not want to enter
  - » Other process (matching turn) will eventually finish
- **Bounded waiting**
  - » Each process waits at most one critical section

```
boolean lock[2] = {false, false} // shared
int turn = 0; // shared variable
void deposit( int amount )
  {
  lock[tid] = true;
  turn = 1-tid;
  while( lock[1-tid] == true && turn == 1-tid ) {};
  balance += amount; // critical section
  lock[tid] = false;
  }
```


Summary: Software Solutions

	Mutual Exclusion	Progress someone gets the CS	Bounded Waiting No Starvation	
Shared Lock Variable	No			
Strict Alteration	Yes	No	No	*Pace limited to slowest process*
Check then Lock	No			
Lock then Check	Yes	No (deadlock)		
Deferral	Yes	No (not deadlock)	Not really	
Dekker	Yes	Yes	Yes	
Peterson	Yes	Yes	Yes	*Simpler*

2 Processes

- So far, only 2 processes and it was tricky!
- How about more than 2 processes?
  - » Enter Leslie's Lamport's Bakery Algorithm

Lamport's Bakery Algorithm (1974)

https://en.wikipedia.org/wiki/Lamport%27s_bakery_algorithm

- Idea: Bakery -- each thread picks next highest ticket (may have ties –ties broken by a thread's priority number)
- A thread enters the critical section when it has the lowest ticket.
- Data Structures (size `N`):
  - » `choosing[i]` : true iff P_i in the entry protocol
  - » `number[i]` : value of 'ticket', one more than max
  - » Threads may share the same number
- Ticket is a pair: `( number[tid], i )`
- Lexicographical order:
  - » `(a, b) < (c, d) :`
    `if( a < c) or if( a == c AND b < d )`
  - » `(number[j],j) < (number[tid],tid))`

Bakery Algorithm

- Pick next highest ticket (may have ties)
- Enter CS when my ticket is the lowest (combination of number and my tid)

```
choosing[tid] = true;  // Enter bakery shop and get a number
(initialized to false)
number[tid] = max( number[0], … , number[n-1] ) + 1; /*starts at
0 */
choosing[tid] = false;
for( j = 0; j < n; j++ ) /* checks all threads */
  {
  while( choosing[j] ){};  // wait until j receives its number

  // iff j has a lower number AND is interested then WAIT
  while( number[j]!= 0 && ( (number[j],j) < (number[tid],tid)) );
  }
balance += amount;
number[tid] = 0;  /    //* unlocks
```


Baker's Algorithm Intuition

- **Mutual exclusion**:
  - » Only enters CS if thread has *smallest* number
- **Progress**:
  - » Entry is guaranteed, so deadlock is not possible
- **Bounded waiting**
  - » Threads that re-enter CS will have a higher number than threads that are already waiting, so fairness is ensured (no starvation)

```
choosing[tid] = true;
number[tid] = max( number[0], … , number[n-1] ) + 1;
choosing[tid] = false;
for(j = 0; j < n; j++)
  while( choosing[j] ){};  // wait until j is done choosing
  // wait until number[j] = 0 (not interested) or me smallest number
  while( number[j]!= 0 && ( (number[j],j) < (number[tid],tid)) );
balance += amount;
number[tid] = 0;
```