Part III
Synchronization
Software and Hardware Solutions

Computers are useless. They can only give answers.

Pablo Picasso

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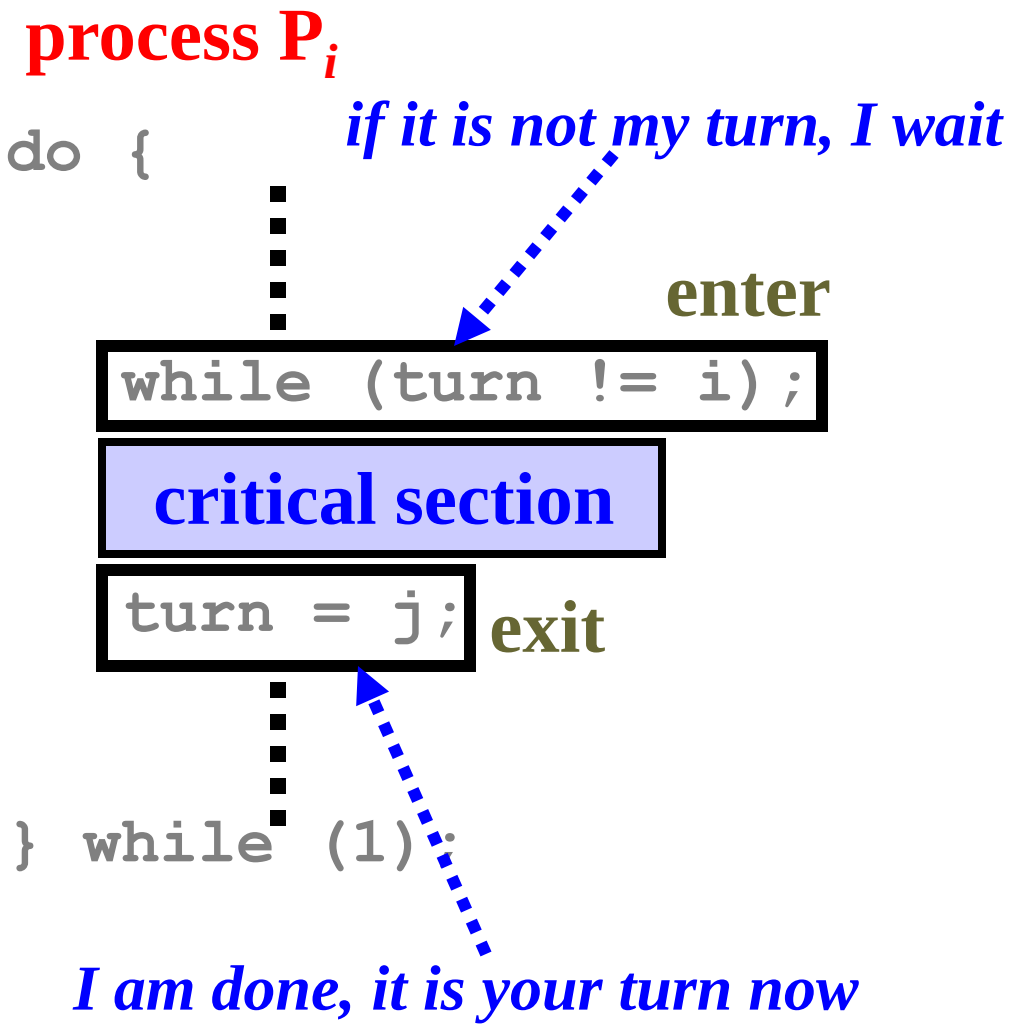
Software Solutions for Two Processes

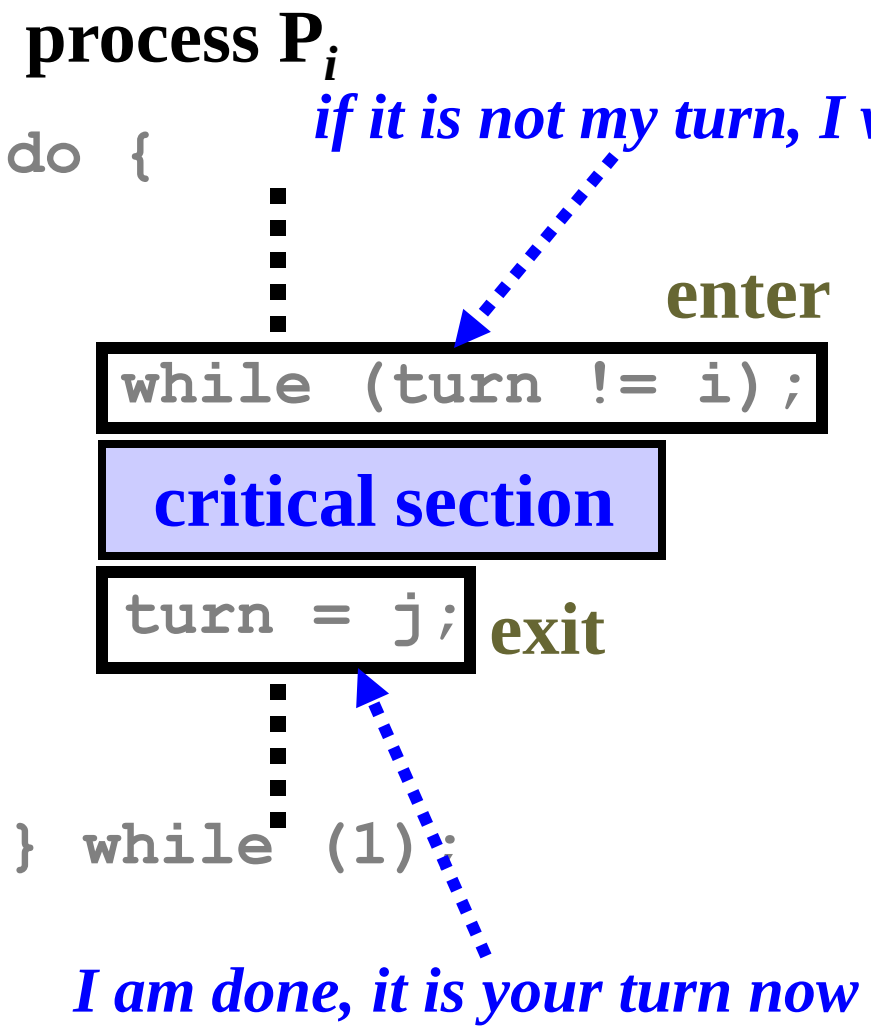
- Suppose we have two processes P_0 and P_1.
- Let one process be P_i and the other be P_j, where $j = 1- i$. Thus, if $i = 0$, then $j = 1$ and if $i = 1$, then $j = 0$.
- We wish to design an enter-exit protocol for a critical section to ensure mutual exclusion.
- We will go through a few unsuccessful attempts and finally obtain a correct one.
- These solutions are pure software-based.

Attempt I: 1/3



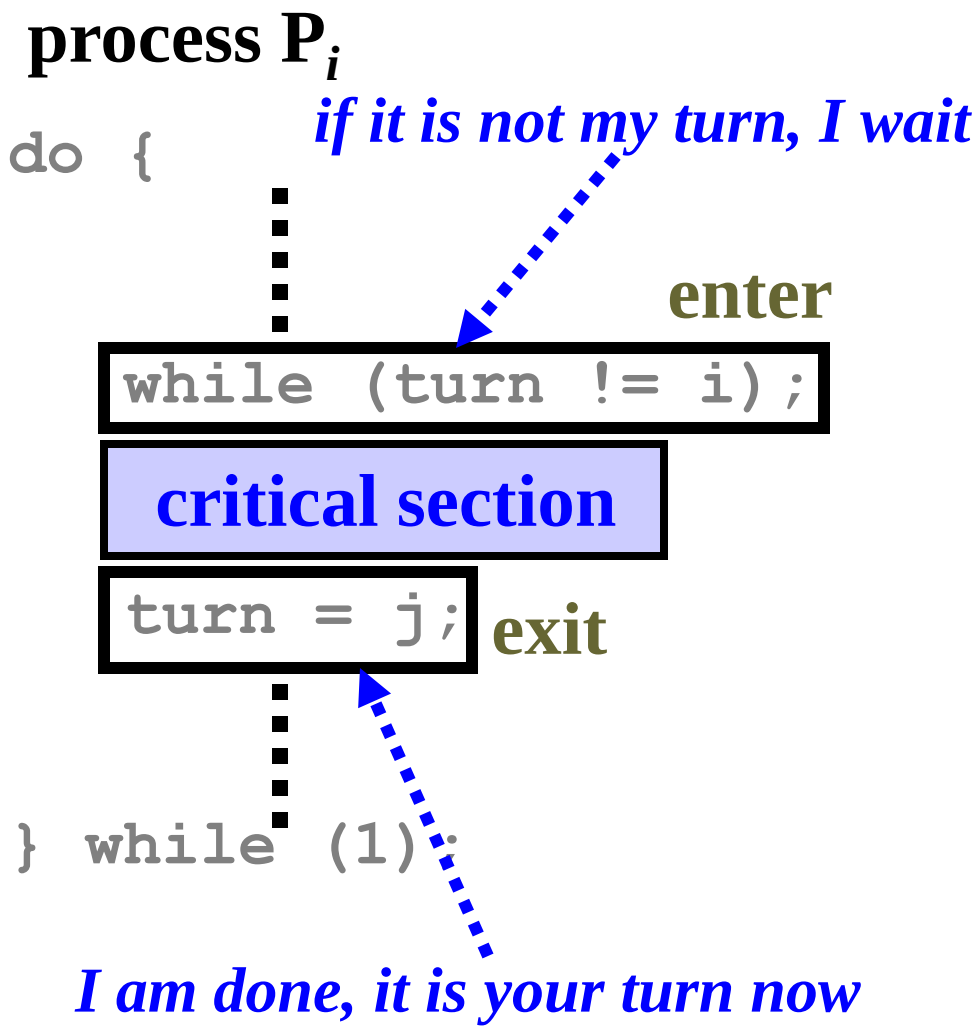
- Shared variable `turn` controls who can enter the critical section.
- Since `turn` is either 0 or 1, only one can enter.
- However, processes are forced to run in an *alternating* way.
- **Not good!**

Attempt I: 2/3



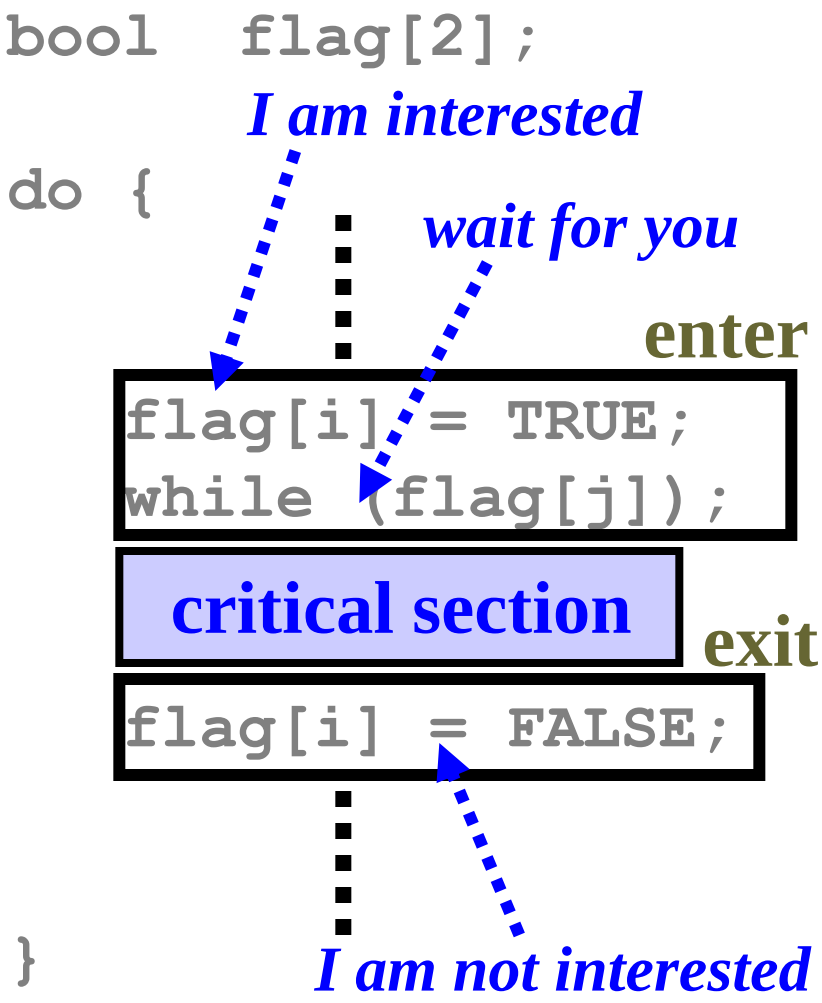
- **Mutual Exclusion**
- P_0 in its CS if `turn=0`.
- P_1 in its CS if `turn=1`.
- If P_0 and P_1 are **BOTH** in their CS, then `turn=0` and `turn=1` must **BOTH** be true.
- This is absurd, because a variable can only hold one and only one value (i.e., cannot hold both 0 and 1).

Attempt I: 3/3



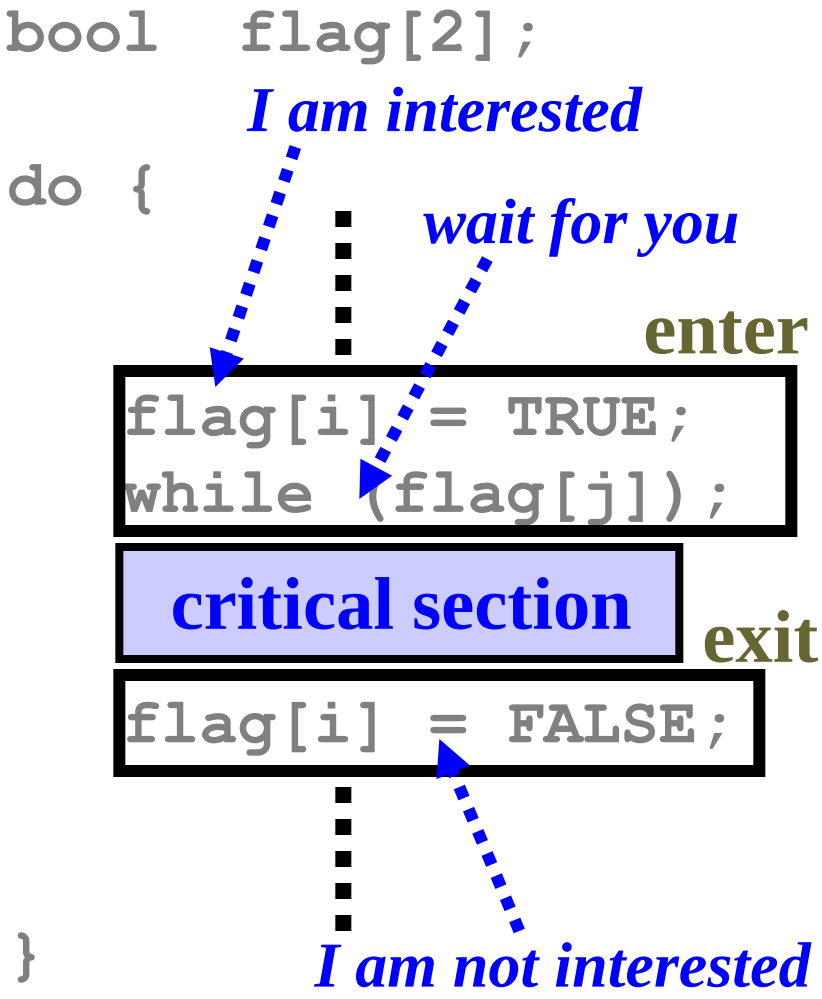
- **Progress**
- If P_i sets `turn` to j and never uses the critical section again, P_j can enter but cannot enter again.
- Thus, an irrelevant process blocks other processes from entering a critical section. **Not good!**
- Does bounded waiting hold? **Exercise!**

Attempt II: 1/5



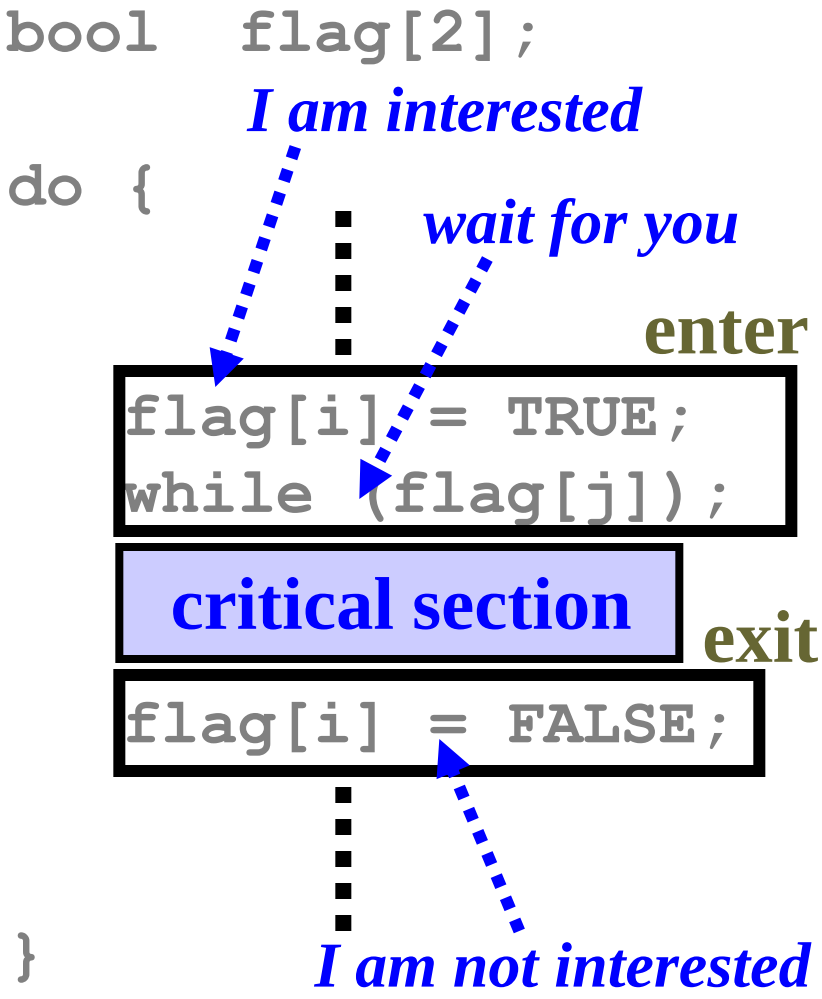
- Shared variable `flag[i]` is the "state" of process P_i: *interested* or *not-interested*.
- P_i indicates its intention to enter, waits for P_j to exit, enters its section, and, finally, changes to "*I am out*" upon exit.

Attempt II: 2/5



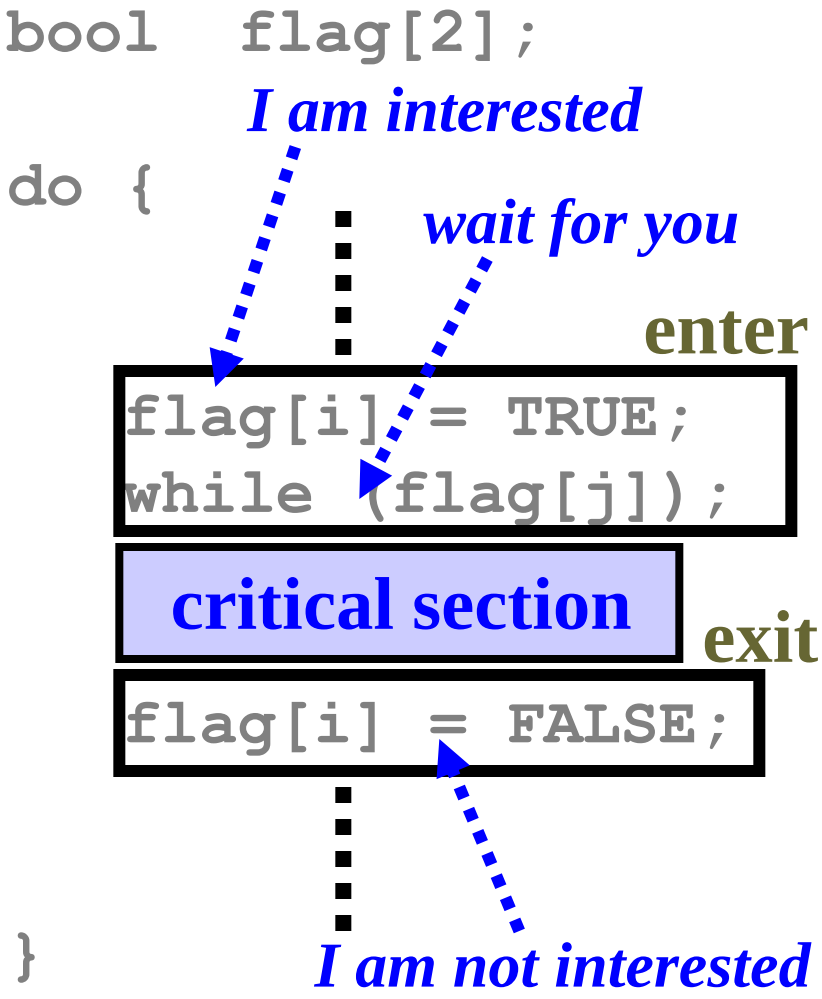
- **Mutual Exclusion**
- P_0 is in CS if `flag[0]` is `TRUE` **AND** `flag[1]` is `FALSE`.
- P_1 is in CS if `flag[1]` is `TRUE` **AND** `flag[0]` is `FALSE`.
- If both are in their CS, `flag[0]` must be both `TRUE` and `FALSE`.
- This is absurd.

Attempt II: 3/5



- **Progress**
- **If both P_0 and P_1 set `flag[0]` and `flag[1]` to `TRUE` at the same time, then both will loop at the `while` forever and no one can enter.**
- **A decision cannot be made in finite time.**

Attempt II: 4/5



- **Bounded Waiting**
- P_0 is in the enter section but switched out before setting `flag[0]` to `TRUE`.
- P_1 reaches its CS and sees `flag[0]` being not `TRUE`. P_1 enters.
- P_1 can enter and exit in this way repeatedly. Thus, P_0 cannot enter forever (i.e., unbounded).

Attempt II: 5/5

```
bool   flag[2];

do {
        flag[i] = TRUE;
        while (flag[j]);

        critical section

        flag[i] = FALSE;

}
```

I am interested

wait for you

enter

exit

I am not interested

no change to continue

P_0	P_1	flag[0]	flag[1]
LOAD #0		F	F
	flag[1]=T	F	T
	while ..	F	T
	in CS		
	flag[i]=F	F	F
	loop back		

```
flag[i] = LOAD i
          LOAD address flag[i]
          MOVE T or F to flag[i]
```

Attempt III/A Combination: 1/12
Peterson's Algorithm

```
bool flag[2] = FALSE;  // process Pi
int  turn;

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

        critical section

        flag[i] = FALSE;

}
```

I am interested

yield to you first

enter

I am done

wait while you are interested and it is your turn.

exit

Attempt III: Mutual Exclusion 2/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- If P_i is in its critical section, then it sets
  - `flag[i]` to `TRUE`
  - `turn` to `j` (but `turn` may not be `j` after this point because P_j **may** set it to `i` later).
  - and waits until `flag[j] && turn == j` becomes `FALSE`

Attempt III: Mutual Exclusion 3/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- If P_j is in its critical section, then it sets
  - `flag[j]` to `TRUE`
  - `turn` to `i` (but `turn` may not be `i` after this point because P_i **may** set it to `j` later).
  - and waits until `flag[i] && turn == i` becomes `FALSE`

Attempt III: Mutual Exclusion 4/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- If processes P_i and P_j are both in their critical sections, then we have:
  - `flag[i]` and `flag[j]` are both `TRUE`.
  - `flag[i] && turn == i` and `flag[j] && turn == j` are both `FALSE`.
  - Therefore, `turn == i` and `turn == j` must both be `FALSE`.

they are both `TRUE`

Attempt III: Mutual Exclusion 5/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- Since `turn == i` and `turn == j` are both `FALSE` and since `turn` is set to `j` (by P_i) or `i` (by P_j) before entering the critical section, only one of `turn == i` and `turn == j` can be `FALSE` but not both.
- Therefore, we have a contradiction.
- Of course, mutual exclusion holds.

Attempt III: Mutual Exclusion 6/12

- We normally use the proof by contradiction technique to establish the mutual exclusion condition.
- To do so, follow the procedure below:
  - Find the condition C_0 for P_0 to enter its CS
  - Find the condition C_1 for P_1 to enter its CS
  - If P_0 and P_1 are in their critical sections, C_0 and C_1 will both be true.
  - From C_0 and C_1 being true, we should be able to derive an absurd result.
  - Therefore, mutual exclusion holds.

Attempt III: Mutual Exclusion 7/12

- **We care about the conditions C_0 and C_1. The way of reaching these conditions via instruction execution is un-important.**
- **Never use an execution sequence to prove mutual exclusion. In doing so, you make a serious mistake, which is usually referred to as proof by example.**
- **You may use a single example to show a proposition being false. But, you cannot use a single example to show a proposition being true. That is, $3^2 + 4^2 = 5^2$ cannot be used to prove $a^2 + b^2 = c^2$ for a right triangles.**

Attempt III: Progress 8/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- If P_i and P_j are both waiting to enter their critical sections, since the value of `turn` can only be *i* or *j* but not both, one process can pass its `while` loop (*i.e.*, decision time is finite).
- Suppose P_i is waiting and P_j is not in its CS:
  - Since P_j is not interested in entering, `flag[j]` was set to `FALSE` when P_j exits and P_i enters.
  - Thus, the process that is not entering does not influence the decision.

Attempt III: Bounded Waiting 9/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- If P_i wishes to enter, we have three cases:
  1. P_j is *outside* of its critical section.
  2. P_j is *in* its critical section.
  3. P_j is *in the entry section*.

Attempt III: Bounded Waiting 10/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- **CASE I**: If P_j is *outside* of its critical section, P_j sets `flag[j]` to `FALSE` when it exits its critical section, and P_i may enter.
- In this case, P_i does not wait.

Attempt III: Bounded Waiting 11/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- **CASE 2**: If P_j is *in the entry section*, depending on the value of `turn`, we have two cases:
  - If `turn` is `i` (e.g., P_i sets `turn` to `j` before P_j sets `turn` to `i`), P_i enters immediately.
  - Otherwise, P_j enters and P_i stays in the `while` loop, and we have **CASE 3**.

Attempt III: Bounded Waiting 12/12

process P_i

```
flag[i] = TRUE;
turn = j;
while (flag[j] && turn == j);
```

process P_j

```
flag[j] = TRUE;
turn = i;
while (flag[i] && turn == i);
```

- **CASE 3**: If P_j is *in* its critical section, `turn` must be `j` and P_i waits for at most one round.

P_i	P_j	flag[i]	flag[j]	turn	Comments
flag[i]=T	flag[j]=T	TRUE	TRUE	?	
while (…)		TRUE	TRUE	j	P_j enters
	Critical Sec				P_j in CS
	flag[j]=F	TRUE	FALSE	j	P_j exits
	flag[j]=T	TRUE	TRUE	j	P_j returns
	turn = i	TRUE	TRUE	i	P_j yields
	while (…)	TRUE	TRUE	i	P_j loops
Critical Sec					P_i enters

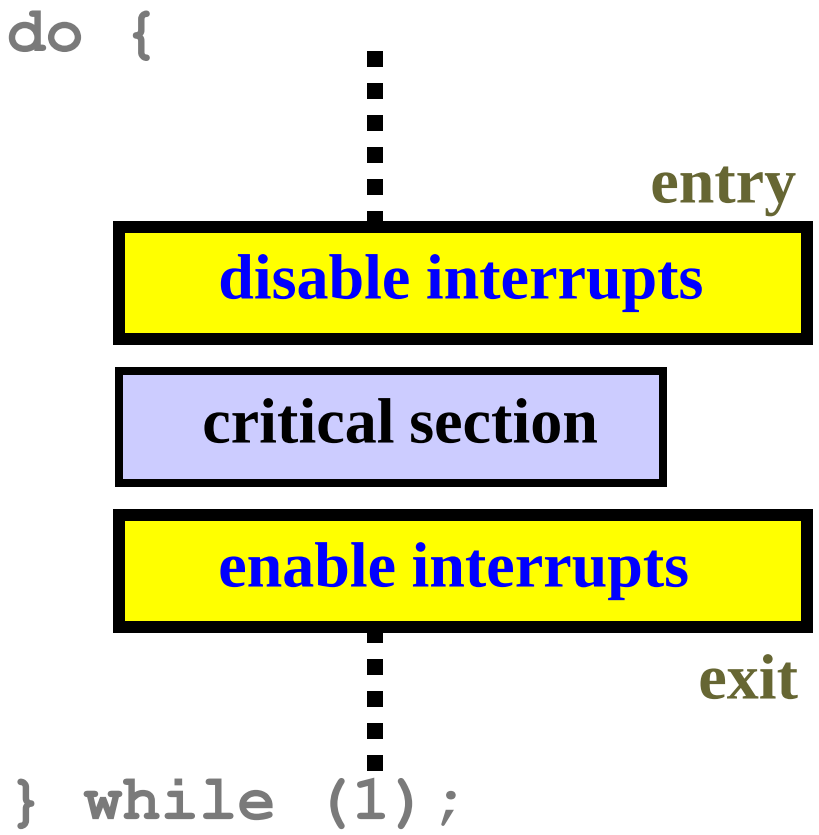
P_i has a chance to enter here.

if P_j comes back fast

Hardware Support

- **There are two types of hardware synchronization supports:**
  - **Disabling/Enabling interrupts: This is slow and difficult to implement on multiprocessor systems.**
  - **Special *privileged*, actually *atomic*, machine instructions:**
    - ✓ **Test and set (`TS`)**
    - ✓ **Swap**
    - ✓ **Compare and Swap (`CS`)**

Interrupt Disabling



- Because interrupts are disabled, no context switch can occur in a critical section (why?).
- Infeasible in a multiprocessor system because all CPUs/cores must be informed.
- Some features that depend on interrupts (*e.g.*, clock) may not work properly.

Test-and-Set Instruction: 1/2

```
bool TS(bool *key)
{
    bool save = *key;
    *key = TRUE;
    return save;
}
```

```
bool  lock = FALSE;

do {
        ⋮
                                  entry
   while (TS(&lock));
   critical section
   lock = FALSE;                  exit
        ⋮
} while (1);
```

- `TS` is atomic.
- **Mutual exclusion** is met as the `TS` instruction is atomic. **See next slide.**
- However, **bounded waiting** may not be satisfied. **Progress?**

Test-and-Set Instruction: 2/2

- A process is in its critical section if the `TS` instruction returns `FALSE`.
- If two processes P_0 and P_1 are in their critical sections, they both got the `FALSE` return value from `TS`.
- P_0 and P_1 cannot execute their `TS` instructions at the same time because `TS` is atomic.
- Hence, one of them, say P_0, executes the `TS` instruction before the other.
- Once P_0 finishes its `TS`, the value of `lock` becomes `TRUE`.
- P_1 cannot get a `FALSE` return value and cannot enter its CS.
- We have a contradiction!

```
bool  lock = FALSE;

do {
        ⋮
    while (TS(&lock));
    critical section
    lock = FALSE;
        ⋮
} while (1);
```

Problems with Software and Hardware Solutions

- All of these solutions use **busy waiting**.
- **Busy waiting** means a process waits by executing a tight loop to check the status/value of a variable.
- Busy waiting may be needed on a multiprocessor system; however, it wastes CPU cycles that some other processes may use productively.
- Even though some systems may allow users to use some atomic instructions, unless the system is lightly loaded, CPU and system performance can be low, although a programmer may "think" his/her program looks more efficient.
- So, we need better solutions.

The End