Operating Systems and Concurrency

Lecture 8: Concurrency

G52OSC/COMP2007

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- 25/10/2018, 16:00 - 17:00 will be revision
  - Please send me an email with topics that you would like to re-visit
  - We will go through past exam questions
- Make sure you download the last version of the slides before the lectures

Recap
Last Lecture

- Examples of **concurrency issues** (e.g. `counter++`)
- Root causes of **concurrency issues** (parallel code, race conditions, registers vs. variables)
- **Critical sections**, **mutual exclusion**, and **deadlocks**

- **Software based**: Peterson's solution
- **Hardware based**: disable **interrupts**, `test_and_set()`, `swap_and_compare()`

- **OS based**:
  - Mutexes
  - Semaphores

- **Monitors:** software construct within the programming languages

Peterson's Solution
Software Solution

- Peterson's solution is a **software based solution** which worked well on **older machines**
- Two **shared variables** are used:
  - `turn`: indicates **which process is next** to enter its critical section
  - `boolean flag[2]`: indicates that a **process is ready** to enter its critical section
- Can be **generalised to multiple processes**
- Peterson's solution for two processes **satisfies all "critical section requirements"** (mutual exclusion, progress, fairness)

Peterson’s Solution

Software Solution

```
do {
    flag[i] = true; // i wants to enter critical section
    turn = j;       // allow j to access first
    while (flag[j] && turn == j);
    // whilst j wants to access critical section
    // and its j's turn, apply busy waiting

    // CRITICAL SECTION, e.g. counter++

    flag[i] = false;

    // remainder section
} while (...);
```

Figure: Peterson’s solution for process *i*

Peterson’s Solution
Software Solution

```
do {
      flag[j] = true; // j wants to enter critical section
      turn = i;       // allow i to access first
      while (flag[i] && turn == i);
      // whilst i wants to access critical section
      // and its i’s turn, apply busy waiting

      // CRITICAL SECTION, e.g. counter++

      flag[j] = false;

      // remainder section
} while (...);
```

Figure: Peterson’s solution for process *j*

Peterson’s Solution
Software Solution

```
flag[i] = false;                    flag[j] = false;
...                                 ...
do {                                do {
   flag[i] = true;                     flag[j] = true;
   turn = j;                           turn = i;
   while (flag[j] && turn == j);       while (flag[i] && turn == i);
   counter++;                          counter++;
   flag[i] = false;                    flag[j] = false;
} while (...);                      } while (...);
```

Process i   *Process j*

Peterson’s Solution
Software Solution

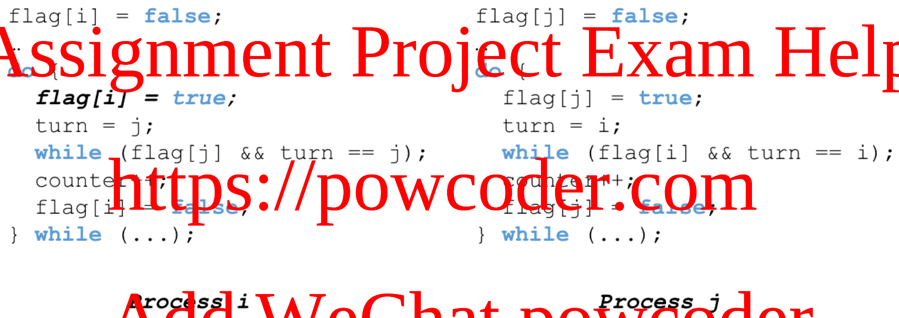
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Software Solution



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Process j

Peterson’s Solution
Software Solution

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Process j

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Software Solution

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Process i

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Process j

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Software Solution

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Process j

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Software Solution

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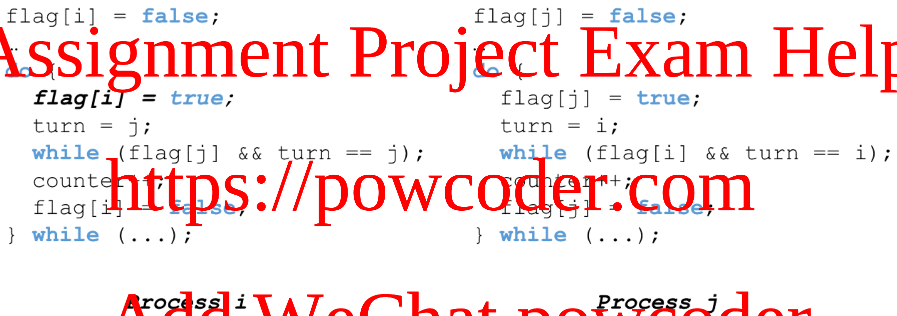
Process j

Peterson’s Solution
Software Solution



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Process i

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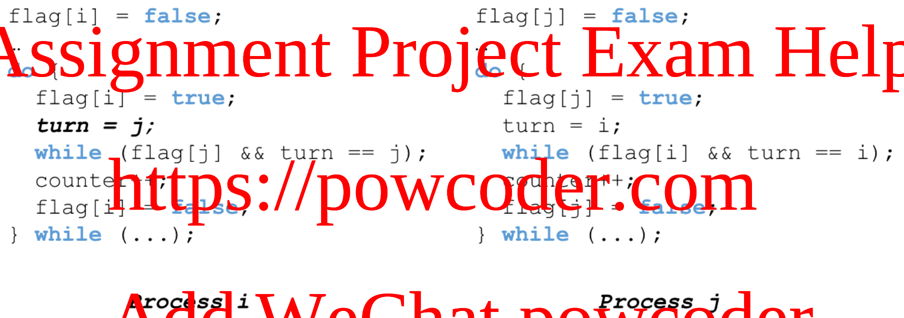
Process j

Peterson's Solution

Software Solution



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Process i

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Process j

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Process j

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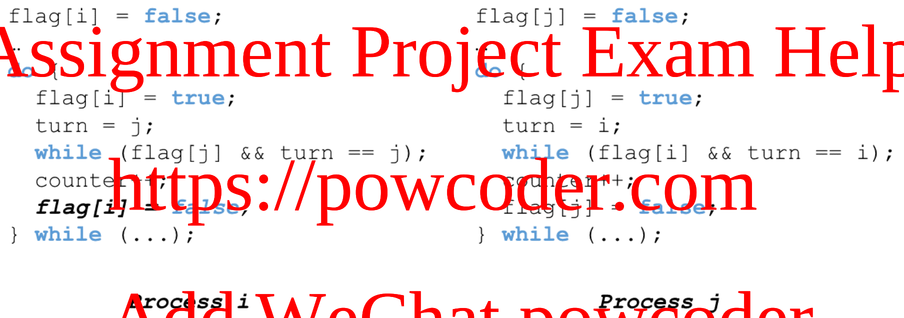

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Software Solution

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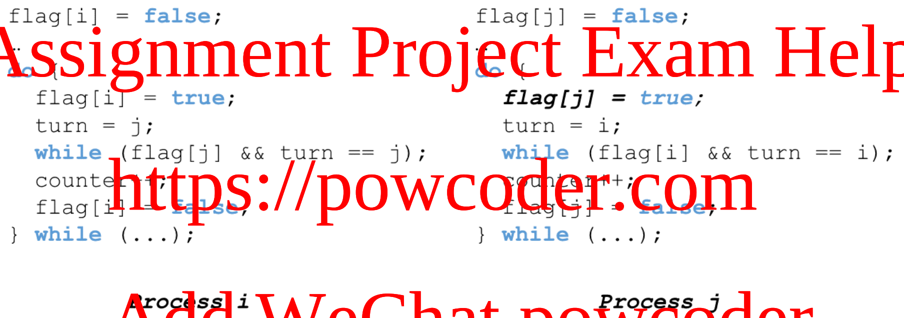
Process j

Peterson’s Solution
Software Solution



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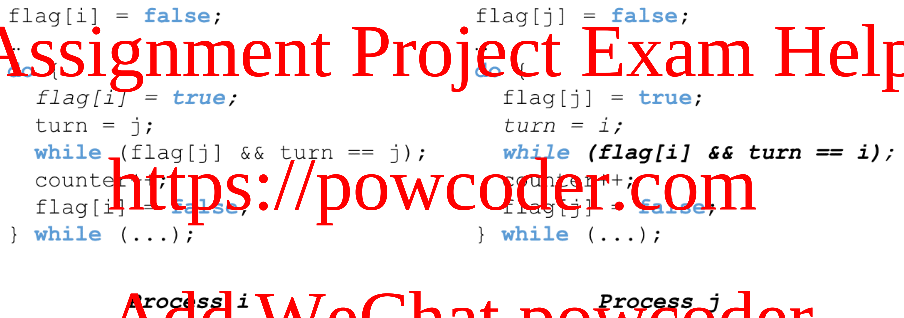
Peterson’s Solution

Software Solution



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Process j

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Process j

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Software Solution

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} while (...);
```

Process j

Peterson's Solution
Mutual exclusion requirement

- **Mutual exclusion requirement:** the variable turn can have **at most one value at a time**
  - Both `flag[i]` and `flag[j]` are `true` when they want to enter their critical section
  - Turn is a **singular variable** that can store **only one value**
  - Hence, either `while(flag[i] && turn == i)` or `while(flag[j] && turn == j)` is true and at most **one process can enter its critical section** (mutual exclusion)

Peterson's Solution

Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
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Process i

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flag[j] = false;
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   flag[j] = true;
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   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Mutual Exclusion Requirement

```
flag[i] = false;                        flag[j] = false;
...                                     ...
do {                                    do {
   flag[i] = true;                         flag[j] = true;
   turn = j;                               turn = i;
   while (flag[j] && turn == j);           while (flag[i] && turn == i);
   counter++;                              counter++;
   flag[i] = false;                        flag[j] = false;
} while (...);                          } while (...);
```

Process i   *Process j*

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;
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do {
   flag[i] = true;
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Process j

Peterson’s Solution
Mutual Exclusion Requirement

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Process j

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Mutual Exclusion Requirement

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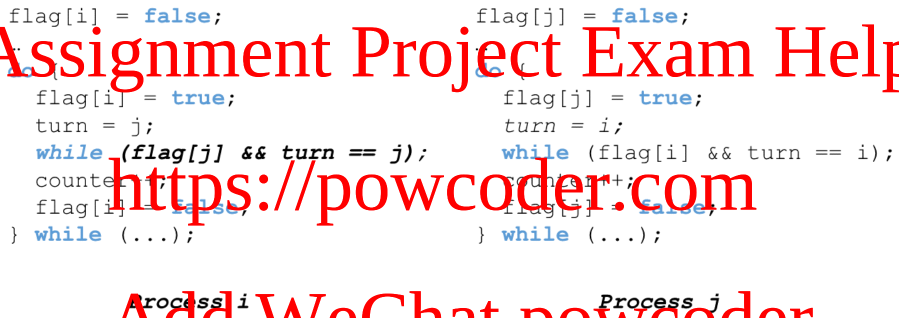
Process j

Peterson’s Solution

Mutual Exclusion Requirement



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Process *i*

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Process *j*

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Mutual Exclusion Requirement

```
flag[i] = false;                     flag[j] = false;
...                                  ...
do {                                 do {
   flag[i] = true;                      flag[j] = true;
   turn = j;                            turn = i;
   while (flag[j] && turn == j);        while (flag[i] && turn == i);
   counter++;                           counter++;
   flag[i] = false;                     flag[j] = false;
} while (...);                       } while (...);
```

Process i *Process j*

Peterson’s Solution

Mutual Exclusion Requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

- **Progress**: any process must be able to enter its critical section at some point in time
  - Processes/threads in the “**remaining code**” **do not influence** access to critical sections
  - If process *j* does **not want to enter** its critical section

    ⇒ `flag[j] == false`

    ⇒ `while(flag[j] && turn == j)` will terminate for process *i*

    ⇒ *i* enters critical section

Peterson’s Solution
Progress requirement

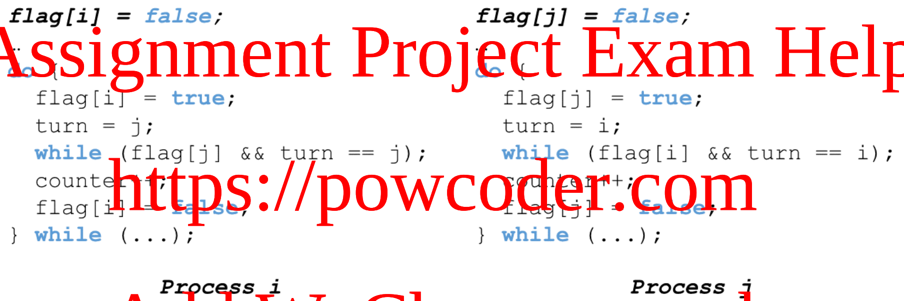
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Progress requirement



```
flag[i] = false;                     flag[j] = false;
...                                  ...
do {                                 do {
   flag[i] = true;                      flag[j] = true;
   turn = j;                            turn = i;
   while (flag[j] && turn == j);        while (flag[i] && turn == i);
   counter++;                           counter++;
   flag[i] = false;                     flag[j] = false;
} while (...);                       } while (...);

          Process i                            Process j
```

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

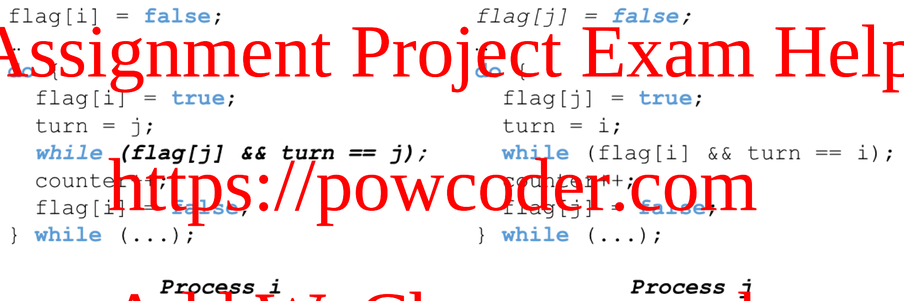
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);

            Process i
```

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);

            Process j
```

Peterson’s Solution
Progress requirement



```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

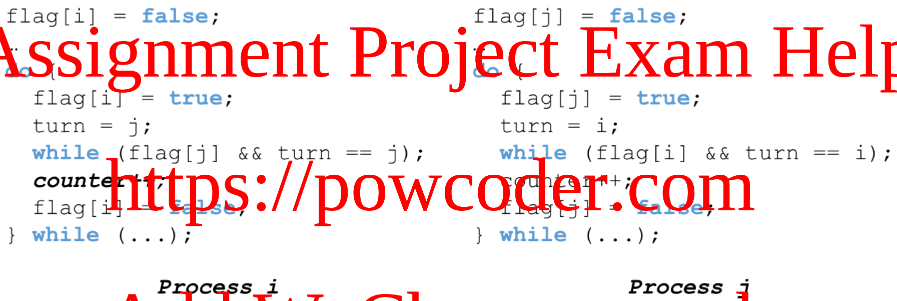
Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement



```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

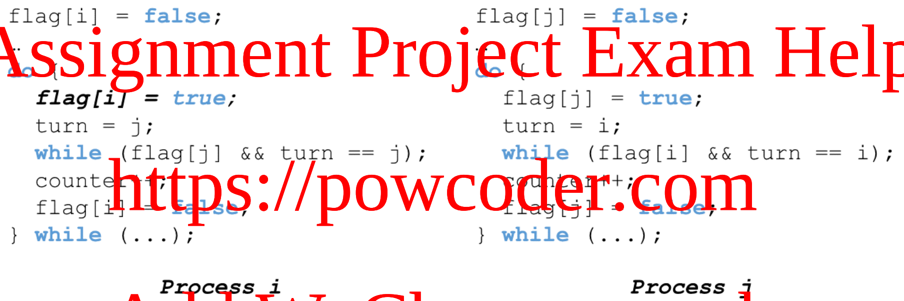
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Progress requirement



```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution

Progress requirement

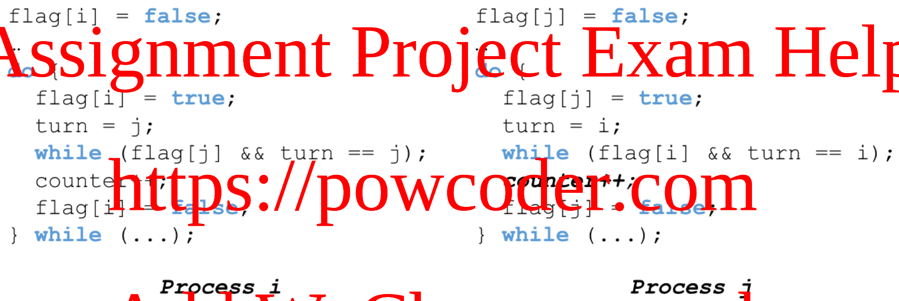
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement



```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;                        flag[j] = false;
...                                     ...
do {                                    do {
  flag[i] = true;                         flag[j] = true;
  turn = j;                               turn = i;
  while (flag[j] && turn == j);           while (flag[i] && turn == i);
  counter++;                              counter++;
  flag[i] = false;                        flag[j] = false;
} while (...);                          } while (...);
```

Process i ***Process j***

Peterson's Solution

Fairness/bounded waiting requirement

- **Fairness/bounded waiting**: fairly distributed waiting times/processes cannot be made to wait indefinitely
  - If P_i and P_j both want to enter their critical section
    ⇒ `flag[i] == flag[j] = true`
    ⇒ `turn` is either *i* or *j* ⇒ assuming that `turn == i` ⇒
    `while(flag[j] && turn == j)` terminates and *i* enters section
    ⇒ *i* finishes critical section ⇒ `flag[i] = false` ⇒
    `while(flag[i] && turn == i)` terminates and *j* enters critical section

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Progress requirement

```
flag[i] = false;
...
do {
  flag[i] = true;
  turn = j;
  while (flag[j] && turn == j);
  counter++;
  flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
  flag[j] = true;
  turn = i;
  while (flag[i] && turn == i);
  counter++;
  flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;                      flag[j] = false;
...                                   ...
do {                                  do {
   flag[i] = true;                       flag[j] = true;
   turn = j;                             turn = i;
   while (flag[j] && turn == j);         while (flag[i] && turn == i);
   counter++;                            counter++;
   flag[i] = false;                      flag[j] = false;
} while (...);                        } while (...);

            Process i                             Process j
```

Peterson’s Solution
Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson's Solution
Progress requirement

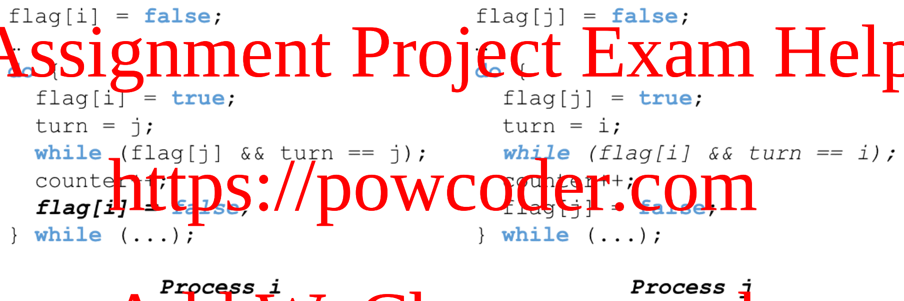
```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement



```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);

              Process i
```

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);

              Process j
```

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
   counter++;
   flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
   flag[j] = true;
   turn = i;
   while (flag[i] && turn == i);
   counter++;
   flag[j] = false;
} while (...);
```

Process j

Peterson’s Solution
Progress requirement

```
flag[i] = false;                          flag[j] = false;
...                                       ...
do {                                      do {
  flag[i] = true;                           flag[j] = true;
  turn = j;                                 turn = i;
  while (flag[j] && turn == j);             while (flag[i] && turn == i);
  counter++;                                counter++;
  flag[i] = false;                          flag[j] = false;
} while (...);                            } while (...);

              Process i                                 Process j
```

Peterson’s Solution

Progress requirement

```
flag[i] = false;
...
do {
  flag[i] = true;
  turn = j;
  while (flag[j] && turn == j);
  counter++;
  flag[i] = false;
} while (...);
```

Process i

```
flag[j] = false;
...
do {
  flag[j] = true;
  turn = i;
  while (flag[i] && turn == i);
  counter++;
  flag[j] = false;
} while (...);
```

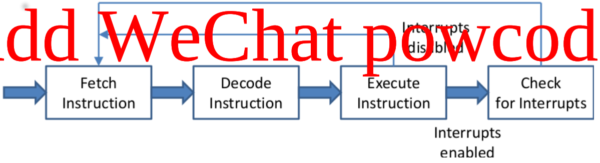
Process j

Disabling Interrupts

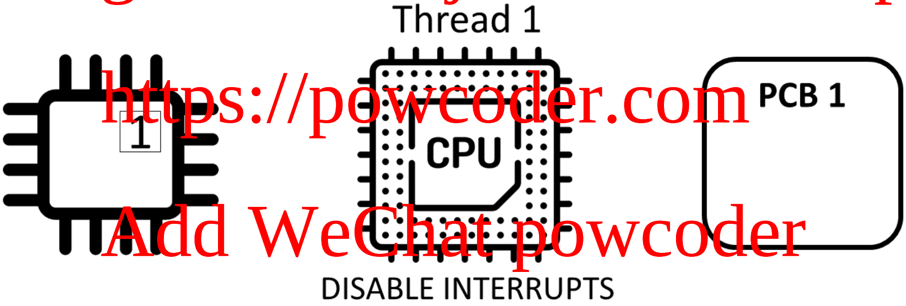
Hardware Approaches

- **Disable interrupts** whilst **executing a critical section** and prevent interruption (i.e., interrupts from timers, I/O devices, etc.)
    - Think of the `counter++` example

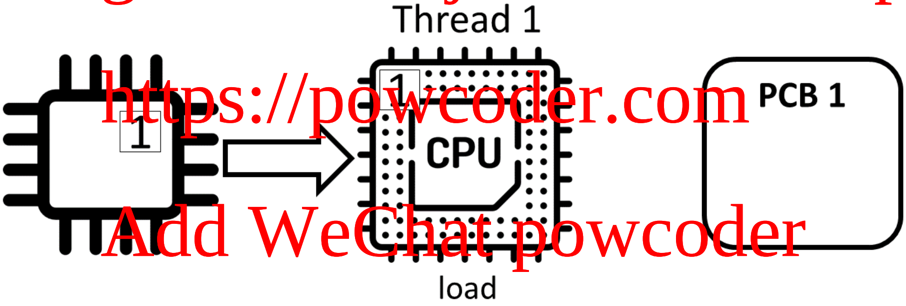
```
register = counter;
register = register + 1
counter = register;
```



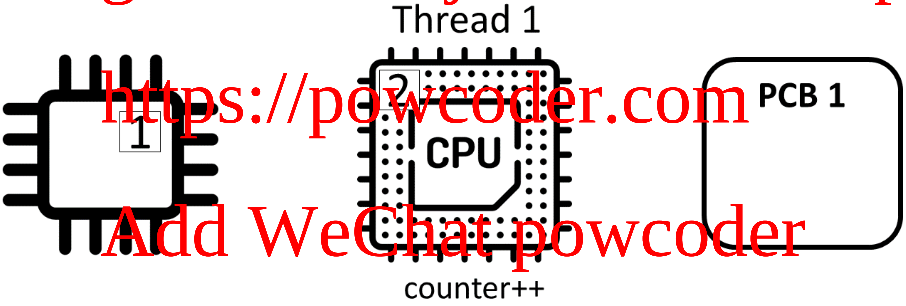
Disabling Interrupts
Hardware Approaches



Disabling Interrupts
Hardware Approaches



Disabling Interrupts
Hardware Approaches



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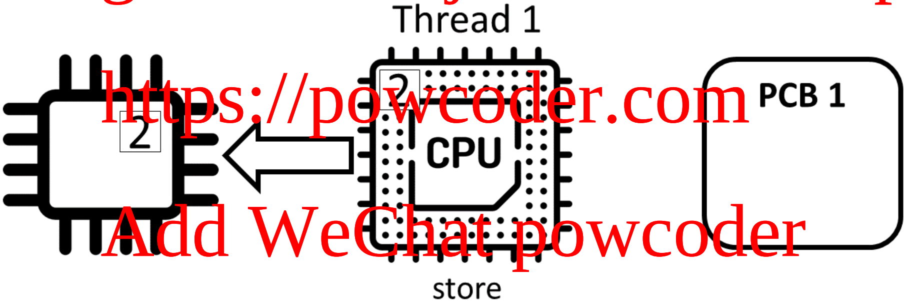

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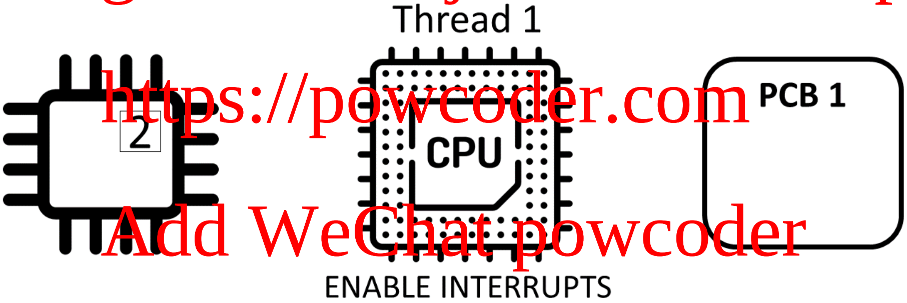

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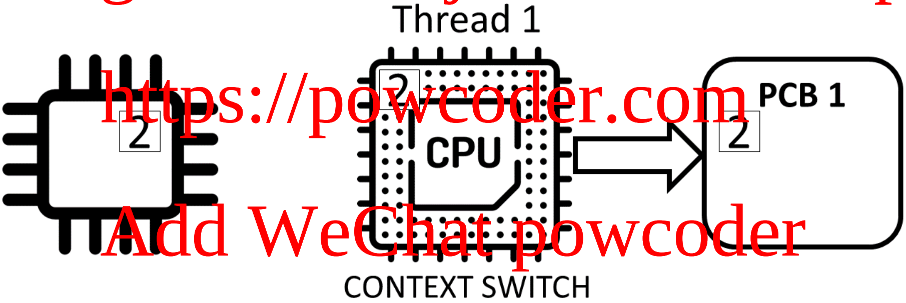

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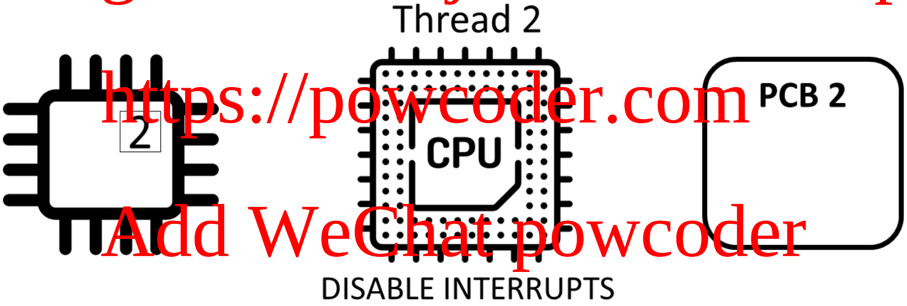

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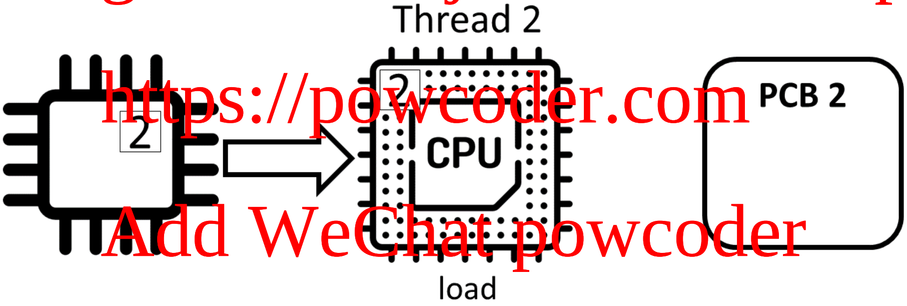

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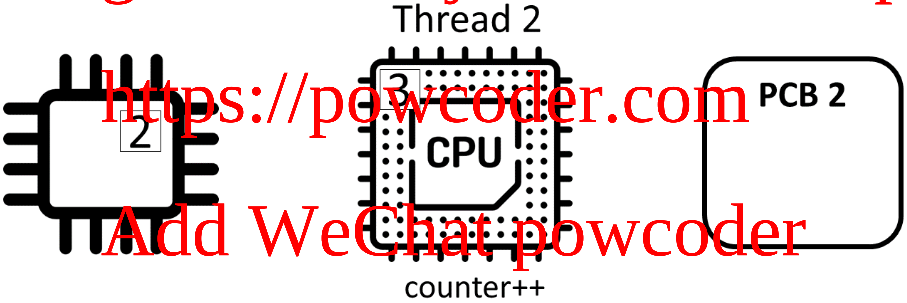

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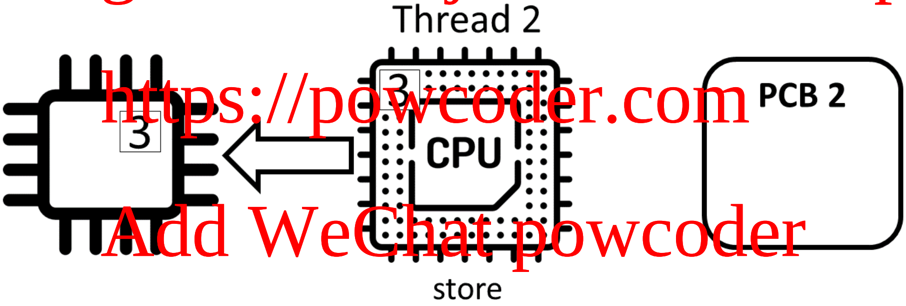

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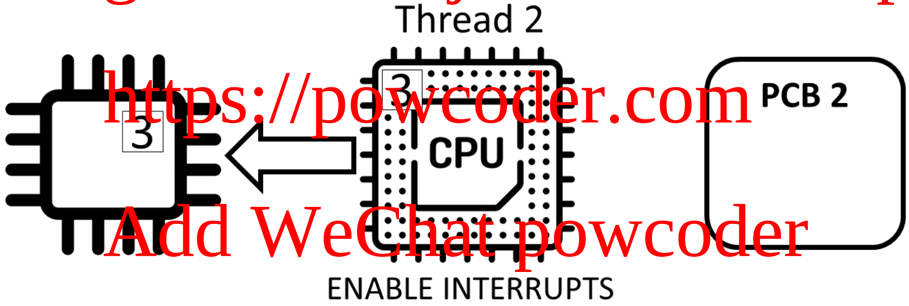

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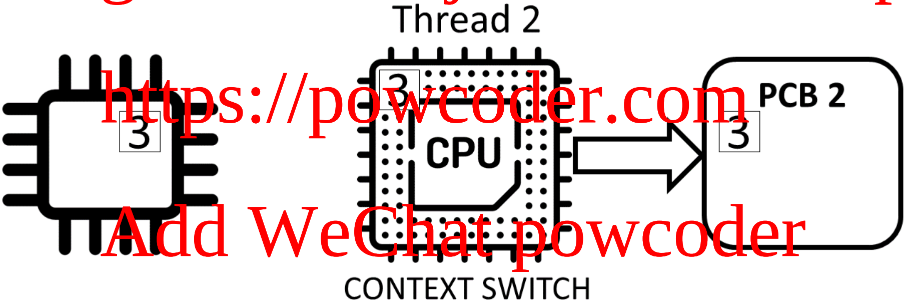
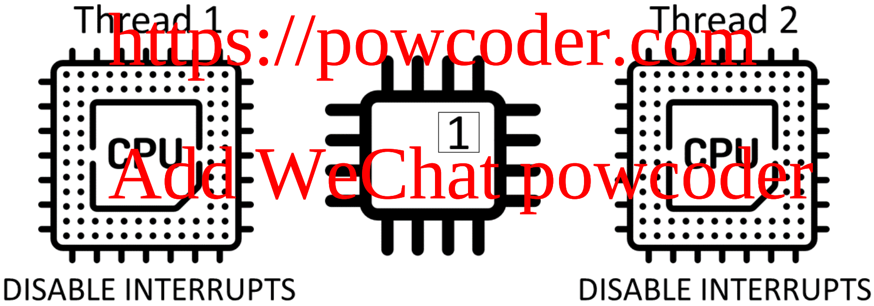


Disabling Interrupts
Hardware Approaches

- Disabling interrupts “may” be appropriate on a **single CPU machine**
- This **is insufficient on modern multi-core/multi-processor machines**



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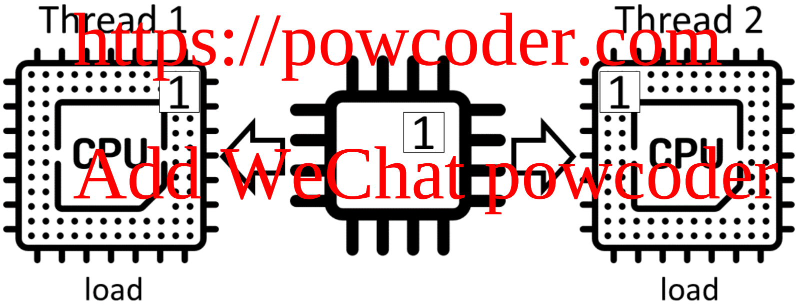

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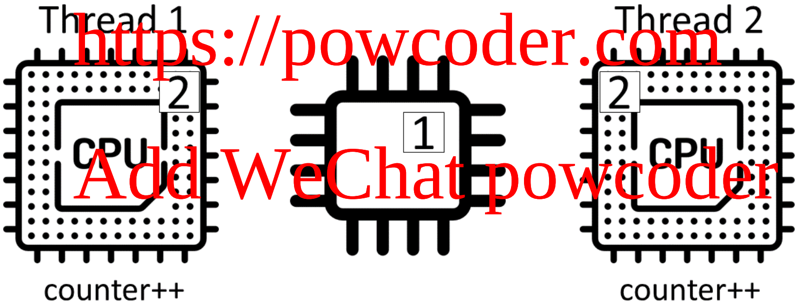

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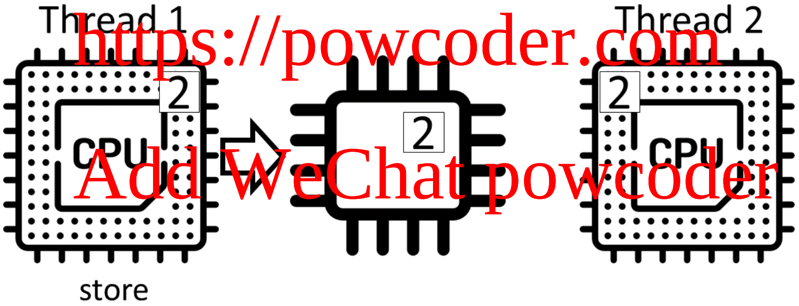

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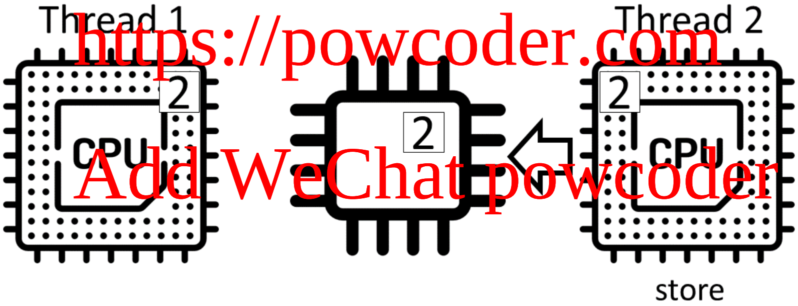

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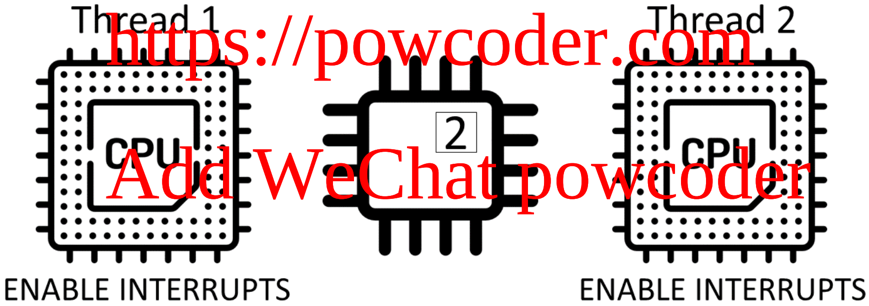

Atomic Instructions

Hardware approaches

- Implement `test_and_set()` and `swap_and_compare()` instructions as a **set of atomic (= uninterruptible) instructions**
  - Reading and setting the variable(s) is done as **one "complete" set of instructions**
  - If `test_and_set()` / `compare_and_swap()` are **called simultaneously**, they will be **executed sequentially**
- They are used in in combination with **global lock variables**, assumed to be `true (1)` if the lock is **in use**

Atomic Instructions

Hardware approaches

```
// Test and set method
boolean test_and_set(boolean * bIsLocked) {
    boolean rv = *bIsLocked;
    *bIsLocked = true;
    return rv;
}
```

```
// Example of using test and set method
do {
        // WHILE the lock is in use, apply busy waiting
        while (test_and_set(&bIsLocked));
        // Lock was false, now true

        // CRITICAL SECTION
        ...
        lock = false;
        ...
        // remainder section
} while (...)
```

Atomic Instructions

Hardware approaches: test_and_set() and compare_and_swap()

- Test and set must be **atomic/UN-interruptable**

```
THREAD 1                           THREAD 2
...                                ...
boolean rv = *bIsLocked;           ...
...                                boolean rv = *bIsLocked;
*bIsLocked = true;                 ...
return rv;                         ...
...                                *bIsLocked = true;
...                                return rv;


---                                ---

while (test_and_set(&bIsLocked));  while (test_and_set(&bIsLocked));
```

Atomic Instructions

Hardware approaches: test_and_set() and compare_and_swap()

- Test and set must be **atomic/UN-interruptable**

```
THREAD 1                            THREAD 2
...                                 ...
boolean rv = *bIsLocked;            ...
*bIsLocked = true;                  ...
return rv;                          ...
...                                 boolean rv = *bIsLocked;
...                                 *bIsLocked = true;
...                                 return rv;


---                                 ---

while (test_and_set(&bIsLocked));   while (test_and_set(&bIsLocked));
```

Atomic Instructions

Hardware approaches: compare_and_swap()

```
// Compare and swap method
int compare_and_swap(int* iIsLocked, int expected, int new_value) {
  int temp = *iIsLocked;
  if(*iIsLocked == expected)
    *iIsLocked = new_value;
  return temp;
}
```

```
 // Example using compare and swap method
 do {
         // While the lock is in use (i.e. == 1), apply busy waiting
         while (compare_and_swap(&iIsLocked, 0, 1) != 0);
         // Lock was false, now true

         // CRITICAL SECTION
         ...
         lock = 0;
         ...
         // remainder section
 } while (...);
```

- `test_and_set()` and `compare_and_swap()` are **hardware instructions** and (usually) **not directly accessible** to the user
  - Rembember, the OS hides the "bare metal" from the user

- Other disadvantages include:
  - **Busy waiting** is used
  - **Deadlock** is possible, e.g. when two locks are requested in opposite orders in different threads

- The **OS uses the hardware instructions** to implement **higher level mechanisms/instructions** for mutual exclusion, i.e. **mutexes** and **semaphores**

Mutex Locks
OS approaches

- **Mutexes** are an approach for mutual exclusion **provided by the operating system** containing a **boolean** lock variable to indicate availability
  - The lock variable is set to **true** if the lock **is available** (process can enter critical section), **false** if **not**

- Two **atomic functions** are used to **manipulate the mutex**:
  - `acquire()`: called **before entering** a critical section, boolean set to **false**
  - `release()`: called **after exiting** the critical section, boolean set to **true** again

Mutex Locks
OS approaches

```
acquire() {
   while (!available)
      ;   // busy wait
   available = false;
}
```

Figure: Conceptual implementation of acquire()

```
release() {
   available = true;
}
```

Figure: Conceptual implementation of release()

Mutex Locks
OS approaches (Cont'ed)

- `acquire()` and `release()` must be **atomic instructions**
  - No **interrupts** should occur between reading and setting the lock
  - If interrupts can occur, the follow sequence could occur:

```
T_i => lock available
...                                T_j => lock available
...                                T_j sets lock
T_i sets lock                      ...
```

- The **process that acquires** the lock **must release** the lock (in contrast to semaphores – see later)

- The key **disadvantage** of mutex locks is that calls to `acquire()` result in **busy waiting** (although this appears to be OS dependent)
  - **Detrimental for performance** on single CPU systems

- The key **advantages** of mutex locks include:
  - **Context switches** can be avoided (short critical sections)
  - **Efficient on multi-core/multi-processor** systems when **locks are held for a short time** only

Mutex Locks in Linux
Example

```
//includes here
int sum = 0;
pthread_mutex_t lock;

void * calc(void * number_of_increments)
{ int i;
  for(i = 0; i < *((int*) number_of_increments);i++)
  { pthread_mutex_lock(&lock);
    sum++;
    pthread_mutex_unlock(&lock);
  }
}
int main()
{ int iterations = 50000000;
  pthread_t tid1,tid2;
  pthread_mutex_init(&lock,NULL);
  // no error checking for clarity/brevity
  pthread_create(&tid1, NULL, calc, (void *) &iterations);
  pthread_create(&tid2, NULL, calc, (void *) &iterations);
  pthread_join(tid1,NULL);
  pthread_join(tid2,NULL);
  printf("the value of sum is: %d\n", sum);
}
```

Mutex Locks in Linux
Example

```
THREAD 1                 THREAD 2

...                      ...
mutex_lock               ...
sum++                    mutex_lock
mutex_unlock             // busy wait
mutex_lock               sum++
// busy_wait             mutex_unlock
sum++                    mutex_lock
mutex_unlock             // busy wait
mutex_lock               sum++
...                      ...
```

- Software based approach: **Peterson's** solution (software)
- Hardware based approaches:
  - disabling interrupts
  - atomic instructions: (`test_and_set`, `compare_and_swap`)
- OS based approach: **Mutexes**