# Synchronization

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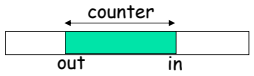
## Bounded Buffer

- Shared data

```
typedef struct { ... } item;
item buffer[BUFFER_SIZE];
int in = 0, out = 0;
int counter = 0;
```




- Producer task

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

- Consumer task

```
item nextConsumed;
while (1) {
   while (counter==0)
        ; /* do nothing */
   nextConsumed = buffer[out];
   out = (out+1) % BUFFER_SIZE;
   counter--;
}
```

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## Bounded Buffer

- The statement "`counter++`" may be compiled into the following instruction sequence:

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

- The statement "`counter--`" may be compiled into:

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

- The following statements must be performed *atomically*:

```
counter++;
counter--;
```

- Atomic operation means an operation that completes in its entirety without interruption.

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## Race Condition

- **Race condition**:
  - The situation where several tasks access and manipulate shared data concurrently.
  - The final value of the shared data and/or effects on the participating tasks depends upon the order of task execution – nondeterminism.
- To prevent race conditions, concurrent tasks must be **synchronized**.

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## Synchronization Principles

- Background
  - Concurrent access to shared data may result in data inconsistency.
  - Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating tasks.
- The Critical-Section Problem
  - Pure software solution
  - With help from the hardware
- Synchronization that coordinates with process/thread scheduler (when waiting, we can yield the CPU instead of busy noop loop)
  - Semaphore
  - Mutex lock
  - Condition variables

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## The Critical-Section Problem

- Problem context:
  - *n* tasks all competing to use some shared data
  - Each task has a code segment, called *critical section*, in which the shared data is accessed.
- Find a solution that satisfies the following:
  1. **Mutual Exclusion**. No two tasks simultaneously in the critical section.
  2. **Progress**. No task running outside its critical section may block other tasks.
  3. **Bounded Waiting/Fairness**. Given the set of concurrent tasks, a bound must exist on the number of times that other tasks are allowed to enter their critical sections after a task has made a request to enter its critical section and before that request is granted.

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## Critical Section for Two Tasks

- Only 2 tasks, $P_0$ and $P_1$
- General structure of task $P_i$ (other task $P_j$)

**do** {
*entry section*
critical section
*exit section*
remainder section
} **while (1)**;

- Tasks may share some common variables to synchronize their actions.
- Assumption: instructions are atomic and no re-ordering of instructions.

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## Algorithm 1

- Shared variables:
  - `int turn;` initially `turn = 0;`
  - `turn==i` $\Rightarrow P_i$ can enter its critical section
- Task $P_i$

```
do {
   while (turn != i) ;
      critical section
   turn = j;
      remainder section
} while (1);
```

- Satisfies mutual exclusion, but not progress

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## Algorithm 2

- Shared variables:
  - `boolean flag[2];` initially `flag[0] = flag[1] = false;`
  - `flag[i]==true` ⇒ $P_i$ ready to enter its critical section
- Task $P_i$

```
do {
   flag[i] = true;
   while (flag[j]) ;
      critical section
   flag[i] = false;
      remainder section
} while (1);
```

- Satisfies mutual exclusion, but may lead to deadlock.

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## Algorithm 3

- Combine shared variables of algorithms 1 and 2.
- Task $P_i$

```
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn==j) ;
      critical section
   flag[i] = false;
      remainder section
} while (1);
```

- Meets all three requirements; solves the critical-section problem for two tasks. ⇒ called Peterson's algorithm.

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## Synchronization Using Special Instruction: TSL (test-and-set)

```
entry_section:
   TSL R1, LOCK        | copy lock to R1 and set lock to 1
   CMP R1, #0          | was lock zero?
   JNE entry_section   | if it wasn't zero, lock was set, so loop
   RET                 | return; critical section entered

exit_section:
   MOV LOCK, #0        | store 0 into lock
   RET                 | return; out of critical section
```

- Solve the synchronization problem
- Work for multiple (>2) tasks
- Instruction atomicity and ordering only necessary on **`TSL`**
- What if you have special instruction **`SWP`** (swap the value of a register and a memory word)?

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## Solving Critical Section Problem with Busy Waiting

- In all our solutions, a task enters a loop until the entry is granted ⇒ busy waiting (or spin waiting).
- Problems with busy waiting:
  - Waste of CPU time
  - If a task is switched out of CPU during critical section
    - other tasks may have to waste a whole CPU quantum
    - may even deadlock with strictly prioritized scheduling
- Solution
  - Avoid busy wait as much as possible (yield the processor instead).
  - If you can't avoid busy wait, you must prevent context switch during critical section (disable interrupts while in the OS kernel)

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## Semaphore

- Synchronization tool that does not require busy waiting.
- Semaphore *S* – integer variable which can only be accessed via two atomic operations
- Semantics (roughly) of the two operations:

```
wait(S) or P(S):
    wait until S>0;
    S--;

signal(S) or V(S):
    S++;
```

- Solving the critical section problem:

Shared data:

```
semaphore mutex=1;
```

Task *Pi:*

```
wait(mutex);
    critical section
signal(mutex);
    remainder section
```

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## Mutex Lock (Binary Semaphore)

- Mutex lock – a semaphore with only two state: locked/unlocked
- Semantics of the two (atomic) operations:

```
lock(mutex):
    wait until mutex==unlocked;
    mutex=locked;

unlock(mutex):
    mutex=unlocked;
```

- Can you implement mutex lock using semaphore?
- How about the opposite?

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## Implement Semaphore Using Mutex Lock

- Data structures:

```
mutex_lock L1, L2;
int C;
```

- Initialization:

```
L1 = unlocked;
L2 = locked;
C = initial value of semaphore;
```

- *wait* operation:

```
lock(L1);
C --;
if (C < 0) {
    unlock(L1);
    lock(L2);
}
unlock(L1);
```

- *signal* operation:

```
lock(L1);
C ++;
if (C <= 0)
    unlock(L2);
else
    unlock(L1);
```

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## Classic Synchronization Problem: Bounded Buffer Problem

- Shared data

```
buffer;
```

- Producer task

```
while (1) {
    ...
    produce an item in nextp;
    ...
    add nextp to buffer;
    ...
}
```

- Consumer task

```
while (1) {
    ...
    remove an item from buffer to nextc;
    ...
    consume nextc;
    ...
}
```

- Protecting the critical section for safe concurrent execution.
- Synchronizing producer and consumer when buffer is empty/full.

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## Bounded Buffer Solution

- Shared data

```
buffer;
semaphore full=0;
semaphore empty=n;
semaphore mutex=1;
```

- Producer task

```
while (1) {
    ...
    produce an item in nextp;
    ...
    wait(empty);
    wait(mutex);
    add nextp to buffer;
    signal(mutex);
    signal(full);
    ...
}
```

- Consumer task

```
while (1) {
    ...
    wait(full);
    wait(mutex);
    remove an item from buffer to nextc;
    signal(mutex);
    signal(empty);
    ...
    consume nextc;
    ...
}
```

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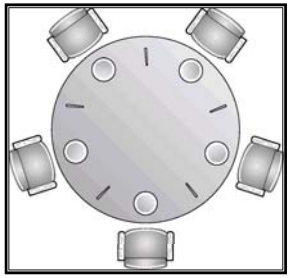
## Dining-Philosophers Problem



- Philosopher i (1 ≤ i ≤ 5):

```
while (1) {
    ...
    eat;
    ...
    think;
    ...
}
```

- Eating needs both chopsticks (the left and the right one).

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## Dining-Philosophers Solution

- Shared data:

```
semaphore chopstick[5];
```

Initially all values are 1;

- Philosopher i:

```
while(1) {
    ...
    wait(chopstick[i]);
    wait(chopstick[(i+1) % 5]);
    eat;
    signal(chopstick[i]);
    signal(chopstick[(i+1) % 5]);
    ...
    think;
    ...
};
```

Deadlock?

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## Thread Synchronization In Practice

- All threads share the same address space
- When only need to protect a short critical section (busy waiting is OK)
  - software/hardware spin locks
  - still has the risk of context switch in the middle of critical section
- For complex synchronization (busy waiting is not OK)
  - semaphore, mutex lock, condition variable, …
  - cost is higher (may involve operating system)

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## Synchronization Primitives in Pthreads

- Mutex lock
  - `pthread mutex init`
  - `pthread_mutex_destroy`
  - `pthread_mutex_lock`
  - `pthread_mutex_unlock`
- Condition variable (used in conjunction with a mutex lock)
  - `pthread_cond_init`
  - `pthread_cond_destroy`
  - `pthread_cond_wait`
  - `pthread_cond_signal`
  - `pthread_cond_broadcast`

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## Condition Variables

- To allow a task to wait, a condition variable must be declared, as

```
condition x, y;
```

- Condition variable can only be used with the operations wait and signal.
  - The operation

```
x.wait();
```

    means that the task invoking this operation is suspended until another task invokes

```
x.signal();
```

  - The x.signal operation resumes exactly one suspended task. If no task is suspended, then the signal operation has no effect.
- Unlike semaphore, there is no counting in condition variables

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## Process Synchronization

- Processes naturally do not share the same address space
- Process synchronization:
  - semaphore
  - shared memory
  - messages

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