Operating Systems

Thread Synchronization Primitives

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2022

Agenda

- Week 42: Synchronization primitives
- Week 43: Synchronization implementation [+ **First Midterm Exam**]
- Week 44: **Vacation**
- Week 45: **Second Midterm Exam** + Advanced Synchronization Techniques
- Week 46: CPU Scheduling + I/O and Disks
- Week 47: File Systems

References

The content of these lectures is inspired by:

- The lecture notes of Prof. André Schiper.
- The lecture notes of Prof. David Mazières.
- *Operating Systems: Three Easy Pieces* by R. Arpaci-Dusseau and A. Arpaci-Dusseau

Other references:

- *Modern Operating Systems* by A. Tanenbaum
- *Operating System Concepts* by A. Silberschatz et al.

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Goals of the lecture

A Multi-Threaded Application

Mutual Exclusion

Locks

Semaphores

The Producer-Consumer Problem

Condition Variables

Monitors

Other synchronization problems

Seen previously

Threads

- Schedulable execution context
- Multi-threaded program = multiple threads in the same process address space
- Allow a process to use several CPUs
- Allow a program to overlap I/O and computation

Implementation

- Kernel-level threads
- User-level threads
- Preemptive vs non-preemptive

Seen previously

POSIX threads API (`pthreads`) – pseudo API:

- `tid thread_create(void (*fn)(void *), void *arg);`
- `void thread_exit();`
- `void thread_join(tid thread);`

Data sharing

- Threads share the data of the enclosing process

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Motivation

Observations

- Multi-thread programming is used in many contexts.
  - It is also called concurrent programming.
- Shared memory is the inter-thread communication medium.

Is it easy to use shared memory to cooperate?

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Observations

- Multi-thread programming is used in many contexts.
  - It is also called concurrent programming.
- Shared memory is the inter-thread communication medium.

Is it easy to use shared memory to cooperate?

NO

The problem:

A set of threads executing on a shared-memory (multi-)processor is an asynchronous system.

- A thread can be preempted at any time.
- Reading/writing a data in memory incurs unpredictable delays (data in L1 cache vs page fault).

Cooperating in an asynchronous system

Example

2 threads have access to a shared memory

- A data structure (including multiple fields) is stored in shared memory
- Both threads need to update the data structure
- The system is asynchronous

How can B know:

- whether A is currently modifying the data structure?
- whether A has updated all the fields it wanted it update?

High-level goals of the lecture

- Start thinking like a concurrent programmer
- Learn to identify concurrency problems
- Learn to cooperate through shared memory
  - Synchronization
  - Communication
- Think about the correctness of an algorithm

Content of this lecture

Classical concurrent programming problems

- Mutual exclusion
- Producer-consumer

Concepts related to concurrent programming

- Critical section
- Busy waiting
- Deadlock

Synchronization primitives

- Locks
- Semaphores
- Condition variables

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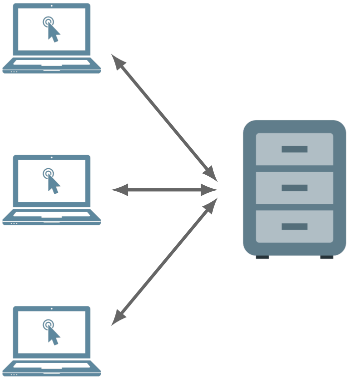
Example: A chat server

Single-threaded version

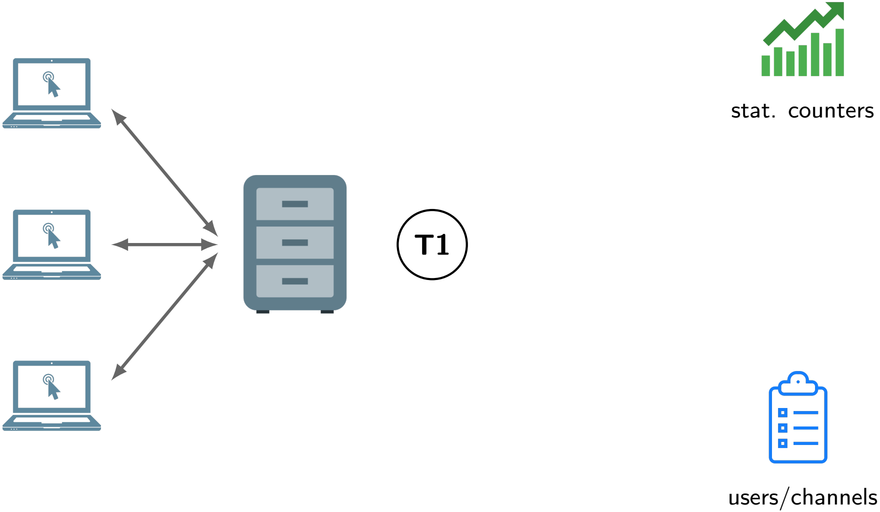


stat. counters

users/channels

Example: A chat server

Single-threaded version



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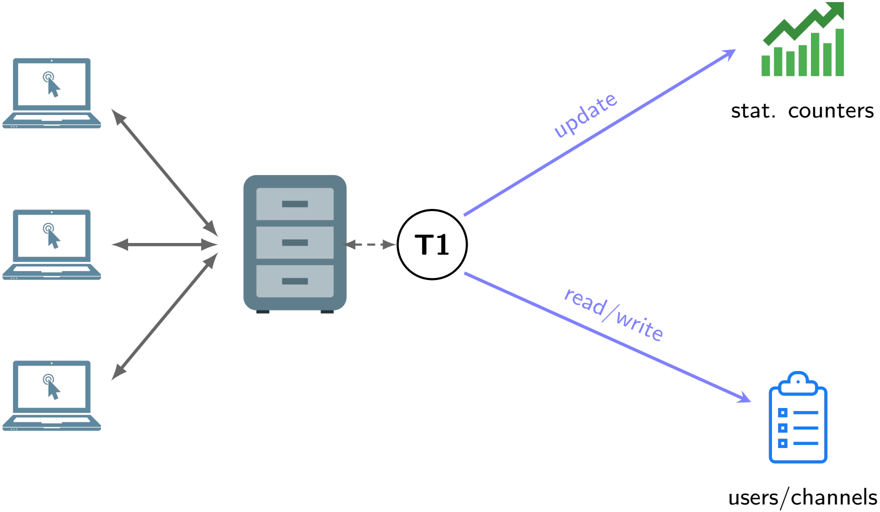
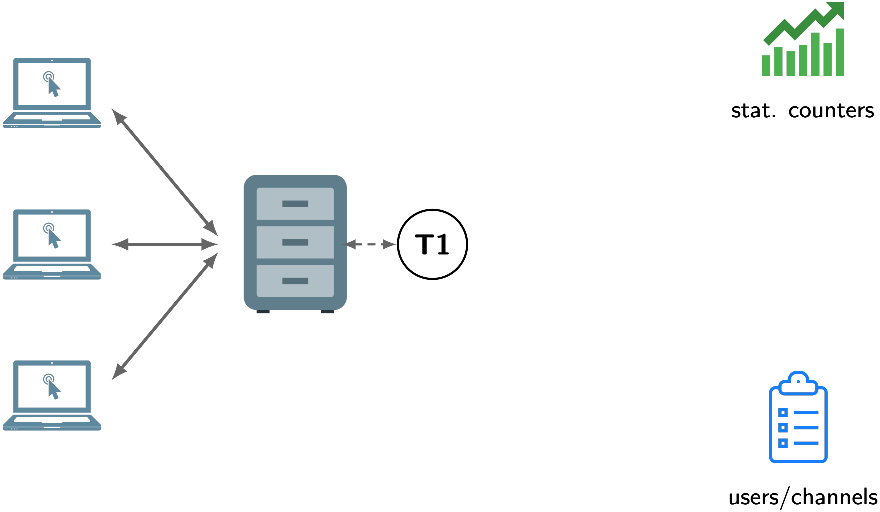


Example: A chat server

First multi-threaded version



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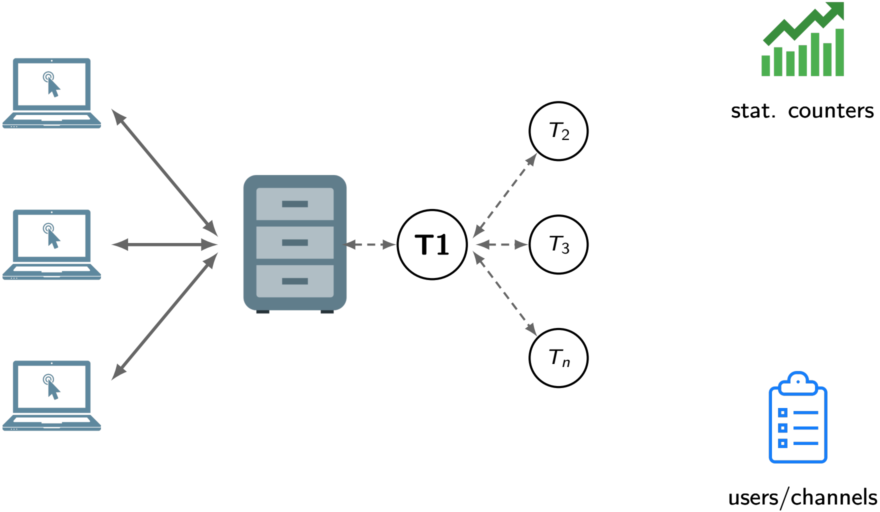

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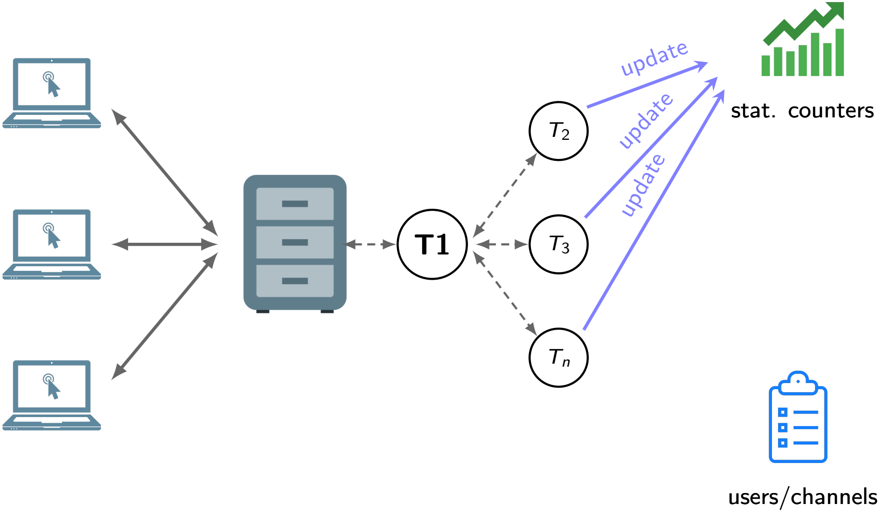

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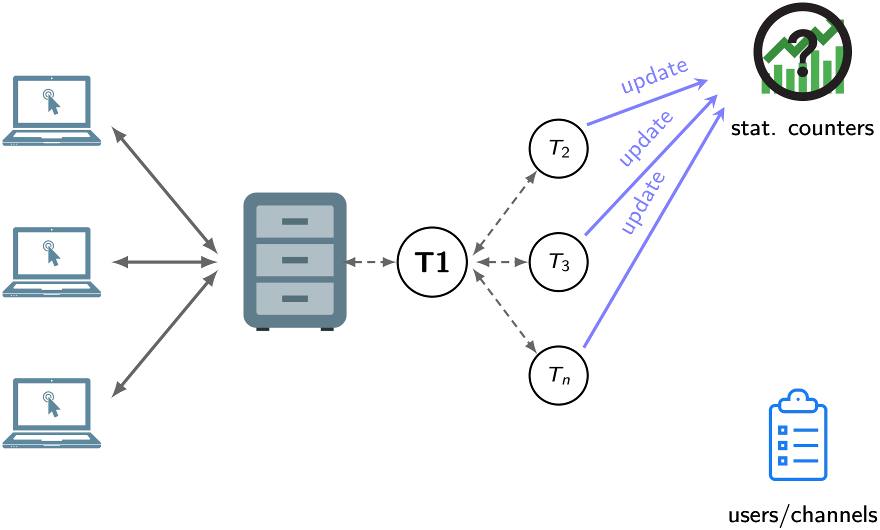

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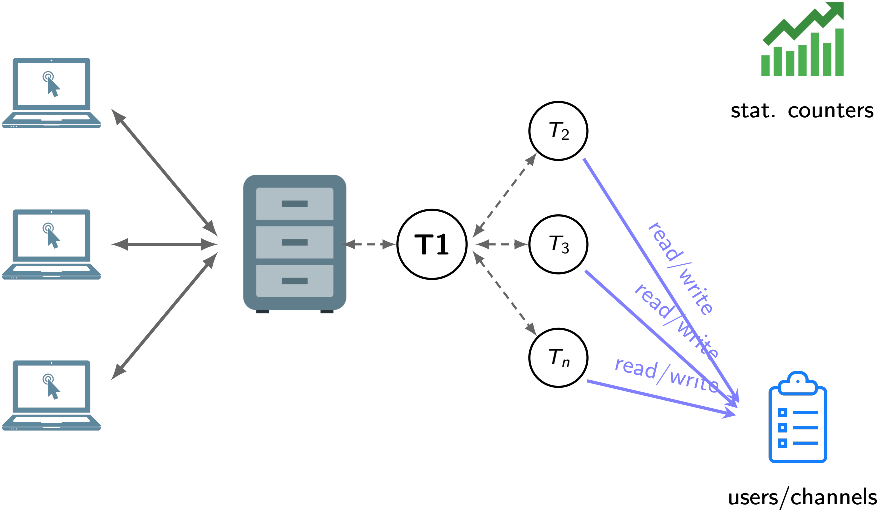

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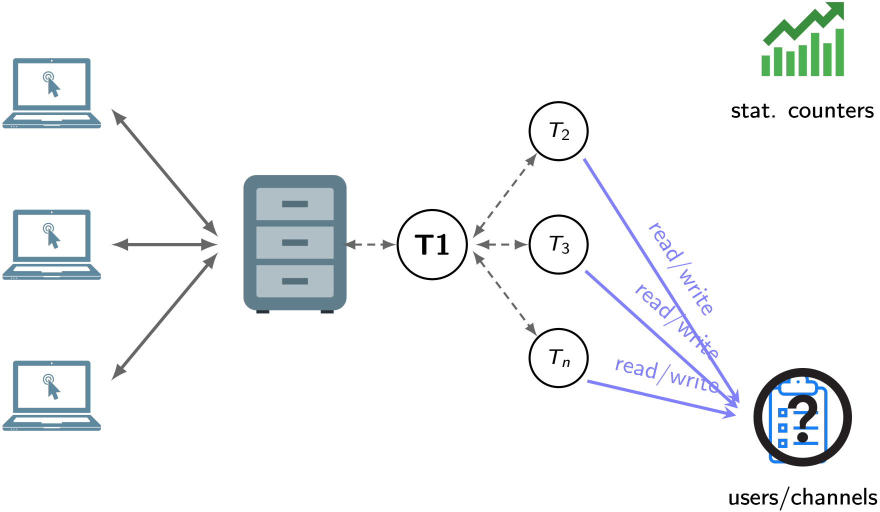
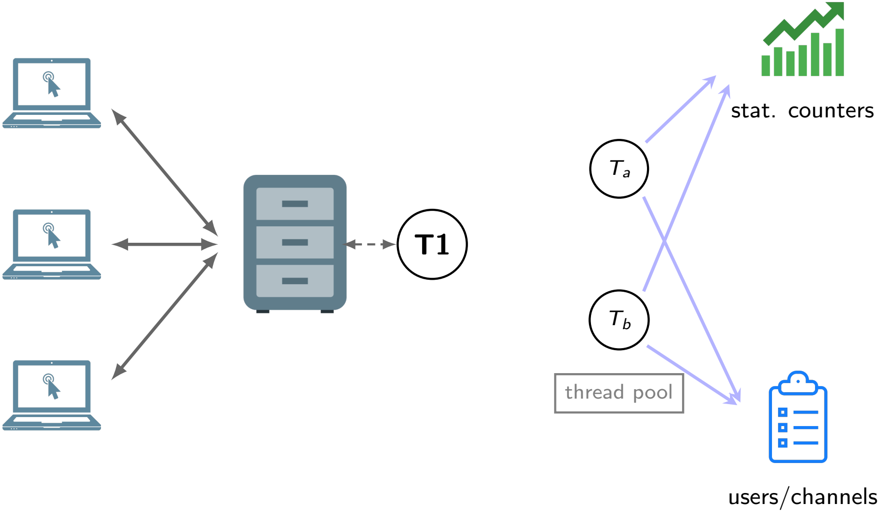


Example: A chat server

Second multi-threaded version



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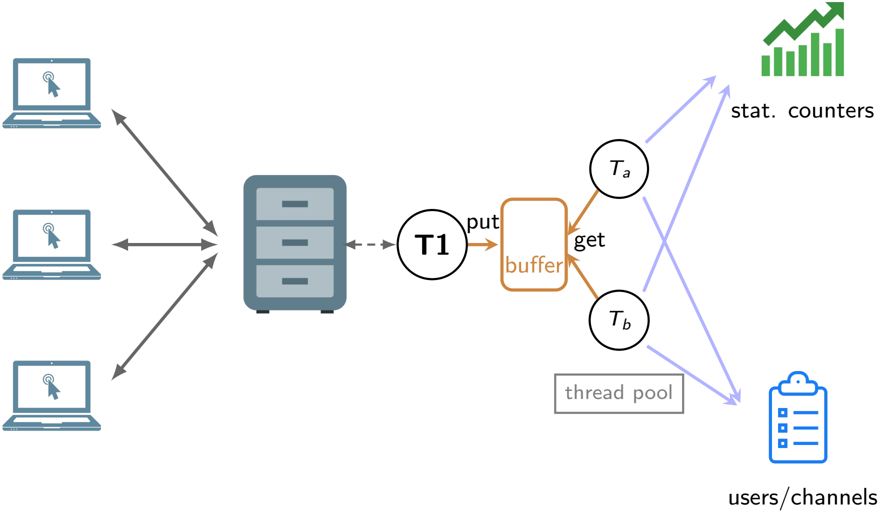

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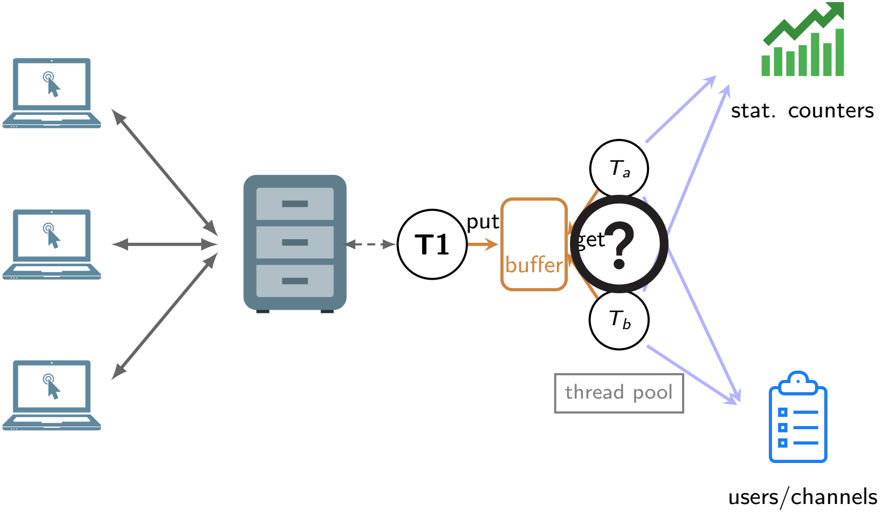

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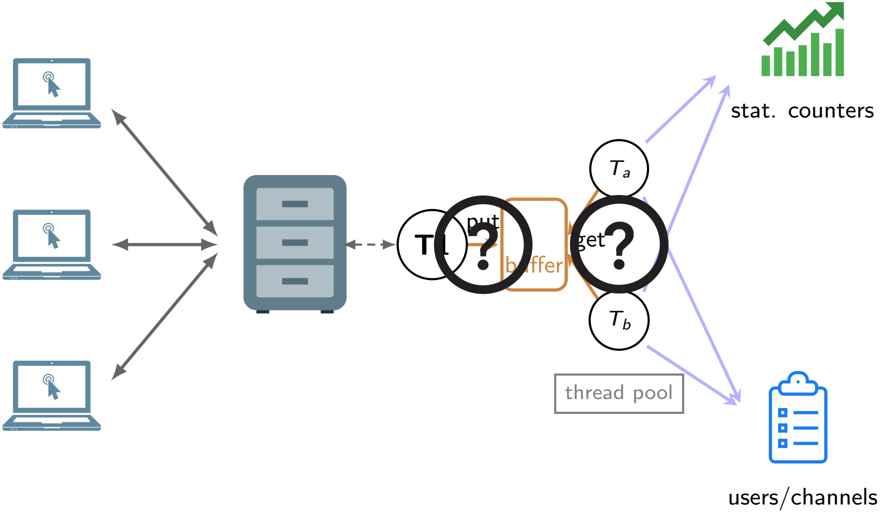

Classical problems

Synchronization

Mutual exclusion

- Avoid that multiple threads execute operations on the same data concurrently (*critical sections*)
- Example: Update data used for statistics

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- Example: Update data used for statistics

Reader-Writer

- Allow multiple readers or a single writer to access a data
- Example: Access to list of users and channels

Classical problems

Cooperation

Producer-Consumer

- Some threads *produce* some data that are *consumed* by other threads
- Example: A queue of tasks

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Other synchronization problems

A shared counter

```
int count = 0;
```

Thread 1:

```
for(i=0; i<10; i++){
  count++;
}
```

Thread 2:

```
for(i=0; i<10; i++){
  count++;
}
```

What is the final value of `count`?

A shared counter

```
int count = 0;
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Thread 1:

```
for(i=0; i<10; i++){
  count++;
}
```

Thread 2:

```
for(i=0; i<10; i++){
  count++;
}
```

What is the final value of `count`?

- A value between 2 and 20

A shared counter: Explanation

Let's have a look at the (pseudo) assembly code for `count++`:

```
mov   count, register
add   $0x1, register
mov   register, count
```

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A possible interleave (for one iteration on each thread)

mov count, register	
add \$0x1, register	
	mov count, register
	add \$0x1, register
mov register, count	
	mov register, count

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A possible interleave (for one iteration on each thread)

Thread 1	Thread 2
mov count, register	
add $0x1, register	
	mov count, register
	add $0x1, register
mov register, count	
	mov register, count

At the end, `count=1` :-(

A shared counter

This may happen:

- When threads execute on different processor cores
- When *preemptive* threads execute on the same core
    - A thread can be preempted at any time in this case

Critical section

Critical resource

A critical resource should not be accessed by multiple threads at the same time. It should be accessed in mutual exclusion.

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Critical section (CS)

A critical section is a part of a program code that accesses a critical resource.

Critical section: Definition of the problem

Safety

- Mutual exclusion: At most one thread can be in CS at a time

Liveness

- Progress: If no thread is currently in CS and threads are trying to access, one should eventually be able to enter the CS.
- Bounded waiting: Once a thread T starts trying to enter the CS, there is a bound on the number of times other threads get in.

Critical section: About liveness requirements

Liveness requirements are mandatory for a solution to be useful

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Liveness requirements are mandatory for a solution to be useful

Progress vs. Bounded waiting

- Progress: If no thread can enter CS, we don't have progress.
- Bounded waiting: If thread A is waiting to enter CS while B repeatedly leaves and re-enters C.S. ad infinitum, we don't have bounded waiting

Shared counter: New version

Thread 1:

```
Enter CS;
count++;
Leave CS;
```

Thread 2:

```
Enter CS;
count++;
Leave CS;
```

Shared counter: New version

Thread 1:

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Enter CS;
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Thread 2:

```
Enter CS;
count++;
Leave CS;
```

How to implement Enter CS and Leave CS?

Implementation: First try using busy waiting

Shared variables:

```
int count=0;
int busy=0;
```

Thread 1:

```
while(busy){;}
busy=1;
count++;
busy=0;
```

Thread 2:

```
while(busy){;}
busy=1;
count++;
busy=0;
```

Exercise

Show through an example that the solution violates safety.

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Thread 1	Thread 2
while(busy){;}	
	while(busy){;}
	busy = 1
busy = 1	
count++	
	count++

- The 2 threads access `count` **at the same time**.

Exercise

Show through an example that the solution violates liveness.

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Show through an example that the solution violates liveness.

```
while(busy){;}
busy = 1
count++
                    while(busy){;}
busy = 0
while(busy){;}
busy = 1
                    while(busy){;}
count++
...
```

- With a bad interleaving of threads, Thread 2 never gets access to count.

Synchronization primitives

To implement mutual exclusion, we need help from the hardware (and the operating system).

- Implementing mutual exclusion is the topic of next course.

Threading libraries provide synchronization primitives:

- A set of functions that allow synchronizing threads
  - Locks
  - Semaphores
  - Condition variables

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Locks

A lock provides a means to achieve mutual exclusion.

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A *lock* is defined by a lock variable and two methods: `lock()` and `unlock()`.

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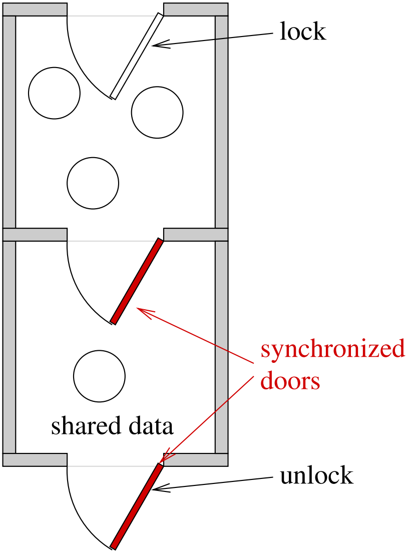
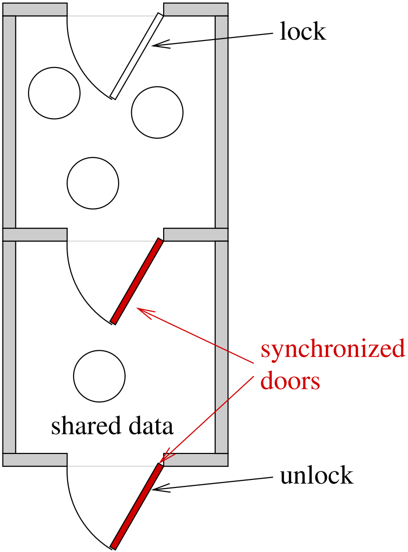
- lock(): If the lock is free, the calling thread acquires the lock and enters the CS. Otherwise the thread is blocked until the lock becomes free.
- unlock(): Releases the lock. It has to be called by the thread currently holding the lock.
- At any time, at most one thread can hold the lock.

Locks: Analogy

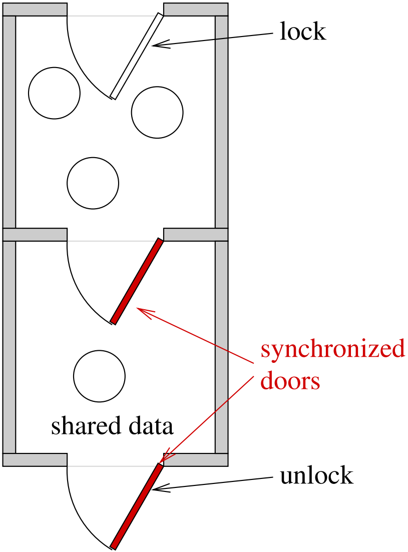


Locks: Analogy



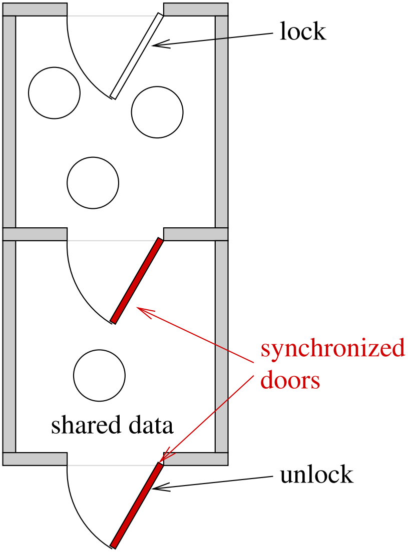
- Calling lock, a thread enters a waiting room

Locks: Analogy



- Calling lock, a thread enters a waiting room
- A single thread can be in the *CS* room (hosting the shared data)

Locks: Analogy



- Calling lock, a thread enters a waiting room
- A single thread can be in the *CS* room (hosting the shared data)
- When the thread in the CS room calls unlock, it leaves the CS room, and lets one thread from the waiting room enter (opens the doors of the CS room)

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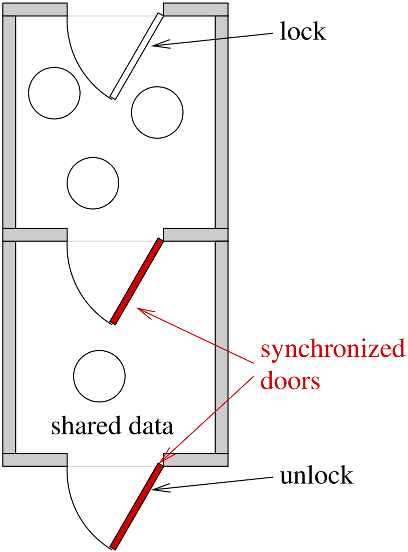

- Calling lock, a thread enters a waiting room
- A single thread can be in the *CS* room (hosting the shared data)
- When the thread in the CS room calls unlock, it leaves the CS room, and lets one thread from the waiting room enter (opens the doors of the CS room)
  - The doors of the CS room are initially opened.

Programming with locks

All critical data should be protected by a lock!

- Critical = accessed by more than one thread, at least one write
- It is the responsibility of the application writer to correctly use locks

- Exception is initialization, before data is exposed to other threads

Pthread locks: Mutexes

- `mutex`: variable of type `pthread_mutex_t`
- `pthread_mutex_init(&mutex, ...)`: initialize the mutex
  - The macro `PTHREAD_MUTEX_INITIALIZER` can be used to initialize a mutex allocated statically with the default options
- `pthread_mutex_destroy(&mutex)`: destroy the mutex
- `pthread_mutex_lock(&mutex)`
- `pthread_mutex_unlock(&mutex)`
- `pthread_mutex_trylock(&mutex)`: is equivalent to lock(), except that if the mutex is held, it returns immediately with an error code

Pthread locks: Example

```
#include <pthread.h>

int count=0;
pthread_mutex_t count_mutex = PTHREAD_MUTEX_INITIALIZER;


void* thread_routine(void *arg){

      /* ... */
      pthread_mutex_lock(&count_mutex);
      count++;
      pthread_mutex_unlock(&count_mutex);
      /* ... */

}
```

Pthread locks attributes

`man pthread_mutex_lock`

Several attributes of a lock can be configured at initialization among which:

- `type`
  - `NORMAL`: Deadlock on *relock*[1]
  - `RECURSIVE`: Allows relocking. A *lock count* is implemented (as many lock() as unlock() calls required).
  - `ERRORCHECK`: Error returned on relock.
  - `DEFAULT`: Usually maps to `NORMAL`.

- `robust`: Defines what happens if a thread terminates without releasing a lock, and if a non-owner thread calls unlock().

- Other attributes are related to priority management and visibility of the lock.

[1] A thread calls lock() on a lock it already locked.

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Semaphores

- Locks ensure mutual exclusion.
- A semaphore is another mechanism that allows controlling access to shared variables but is more powerful than a lock.
- Semaphores were proposed by Dijkstra in 1968

Semaphores

A semaphore is initialized with an integer value N and can be manipulated with two operations P and V.

About the interface

- P stands for Proberen (Dutch) – try
- V stands for Verhogen (Dutch) – increment

POSIX interface

- P $\rightarrow$ `int sem_wait(sem_t *s)`
- V $\rightarrow$ `int sem_post(sem_t *s)`
  - Other interfaces call it `sem_signal()`

Semaphores

When a tread calls sem_wait():

```
N = N - 1;
if( N < 0 )
   Calling thread is blocked
```

When a tread calls sem_post():

```
N = N +1;
if( N <= 0 )
   One blocked thread is unblocked
```

About the value of N:

Semaphores

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```

When a tread calls sem_post():

```
N = N +1;
if( N <= 0 )
    One blocked thread is unblocked
```

About the value of N:

- If $N > 0$, N is the *capacity* of the semaphore
- if $N < 0$, N is the number of blocked threads
  - **Warning:** The programer cannot read the value of the semaphore

Mutual exclusion with semaphores

Mutual exclusion with semaphores

- Initializing a semaphore with value N can be seen as providing it with N *tokens*
- To implement critical sections, a semaphore should be initialized with $N = 1$
  - Warning: A semaphore with $N = 1$ and a lock are not equivalent

Example

```
#include <semaphore.h>

int count=0;
sem_t count_mutex;

sem_init(&count_mutex, 0, 1);
/* ... */
sem_wait(&count_mutex);
count++;
sem_post(&count_mutex);
```

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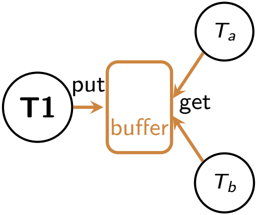
Specification of the problem

Recall



Specification

- A buffer of fixed size
- Producer threads put items into the buffer. The *put* operation blocks if the buffer is full
- Consumer threads get items from the buffer. The *get* operation blocks if the buffer is empty

Producer-Consumer

```
void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */


    while (count == BUFFER_SIZE) {

      /* Do nothing */

    }

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;

  }
}
```

```
void consumer (void *ignored) {
  for (;;) {

    while (count == 0) {

      /* Do nothing */

    }

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;


    /* consume the item in
       nextConsumed */
  }
}
```

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    out = (out + 1) % BUFFER_SIZE;
    count--;


    /* consume the item in
       nextConsumed */
  }
}
```

Not correct: shared data are not protected

- `count` can be accessed by the prod. and the cons.
- With multiple prod./cons., concurrent accesses to `in`, `out`, `buffer`

Producer-Consumer with Locks

```
mutex_t mutex = MUTEX_INITIALIZER;

void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */

    mutex_lock (&mutex);
    while (count == BUFFER_SIZE) {

      thread_yield (); // Release CPU

    }

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
    mutex_unlock (&mutex);
  }
}
```

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    }

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
    mutex_unlock (&mutex);

    /* consume the item in
       nextConsumed */
  }
}
```

Not correct: If a thread enters a `while` loop, all threads are blocked forever (deadlock)

- yield() does not release the lock

Producer-Consumer with Locks

```
mutex_t mutex = MUTEX_INITIALIZER;

void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */

    mutex_lock (&mutex);
    while (count == BUFFER_SIZE) {
      mutex_unlock (&mutex);
      thread_yield ();
      mutex_lock (&mutex);
    }

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
    mutex_unlock (&mutex);
  }
}
```

```
void consumer (void *ignored) {
  for (;;) {
    mutex_lock (&mutex);
    while (count == 0) {
      mutex_unlock (&mutex);
      thread_yield ();
      mutex_lock (&mutex);
    }

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
    mutex_unlock (&mutex);

    /* consume the item in
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}
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```
mutex_t mutex = MUTEX_INITIALIZER;

void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */

    mutex_lock (&mutex);
    while (count == BUFFER_SIZE) {
      mutex_unlock (&mutex);
      thread_yield ();
      mutex_lock (&mutex);
    }

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
    mutex_unlock (&mutex);
  }
}
```

```
void consumer (void *ignored) {
  for (;;) {
    mutex_lock (&mutex);
    while (count == 0) {
      mutex_unlock (&mutex);
      thread_yield ();
      mutex_lock (&mutex);
    }

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
    mutex_unlock (&mutex);

    /* consume the item in
       nextConsumed */
  }
}
```

Correct ... but busy waiting

- **We don't want busy waiting**

About Busy Waiting

Busy waiting

Waiting for some condition to become true by repeatedly checking (spinning) the value of some variable.

Why is it bad?

- Waste of CPU cycles
  - Use CPU cycles to check the value of a variable while there is no evidence that this value has changed.
  - Follows from previous comment: Using `sleep` is still busy waiting.
- On a single processor: Wasted cycles could have been used by other threads.
- On a multi-processor: Repeatedly reading a variable that is used by other threads can slow down these threads.
  - In specific cases, with a careful design, busy waiting can be efficient.

Cooperation

Cooperation = Synchronization + Communication

- Synchronization: Imposing an order on the execution of instructions
- Communication: Exchanging information between threads

Semaphores allow cooperation between threads

Producer-Consumer with semaphores

- Initialize `fullCount` to 0 (block consumer on empty buffer)
- Initialize `emptyCount` to N (block producer when buffer full)

```
void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */

    sem_wait(&emptyCount);

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    /*count++;*/

    sem_post(&fullCount)
  }
}
```

```
void consumer (void *ignored) {
  for (;;) {
    sem_wait(&fullCount);

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    /*count--;*/

    sem_post(&emptyCount);

    /* consume the item in
       nextConsumed */
  }
}
```

Producer-Consumer with semaphores

- Initialize `fullCount` to 0 (block consumer on empty buffer)
- Initialize `emptyCount` to N (block producer when buffer full)
- An additional semaphore (initialized to 1) should be used for mutual exclusion (a lock could be used instead)

```
void producer (void *ignored) {
  for (;;) {
    /* produce an item and put in
       nextProduced */

    sem_wait(&emptyCount);
    sem_wait(&mutex)
    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    /*count++;*/
    sem_post(&mutex)
    sem_post(&fullCount)
  }
}
```

```
void consumer (void *ignored) {
  for (;;) {
    sem_wait(&fullCount);
    sem_wait(&mutex)
    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    /*count--;*/
    sem_post(&mutex)
    sem_post(&emptyCount);

    /* consume the item in
       nextConsumed */
  }
}
```

Comments on semaphores

- Semaphores allow elegant solutions to some problems (producer-consumer, reader-writer)
- However they are quite error prone:
  - If you call `wait` instead of `post`, you'll have a deadlock
  - If you forget to protect parts of your code, you might violate mutual exclusion
  - You have "tokens" of different types, which may be hard to reason about

This is why other constructs have been proposed

Agenda

Goals of the lecture

A Multi-Threaded Application

Mutual Exclusion

Locks

Semaphores

The Producer-Consumer Problem

Condition Variables

Monitors

Other synchronization problems

Condition variables (pthreads)

A condition variable is a *special shared variable*.

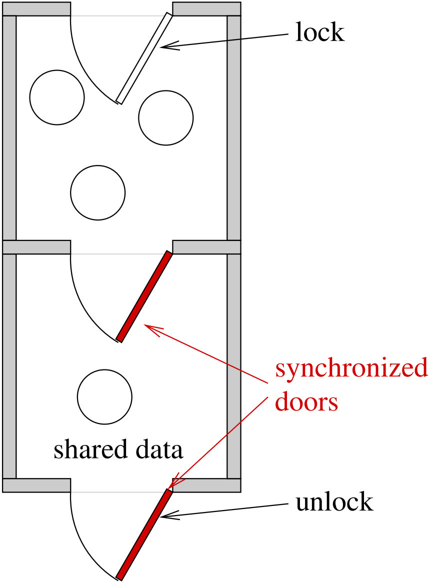
- It allows a thread to explicitly put itself to *wait*.
  - The condition variable can be seen as a container of waiting threads.
  - As such, this variable does not have a value.
- It is used together with a mutex:
  - When a thread puts itself to wait, the corresponding mutex is released.
- It is often associated to a *logical condition* (reason for this name)

Condition variables (pthreads)

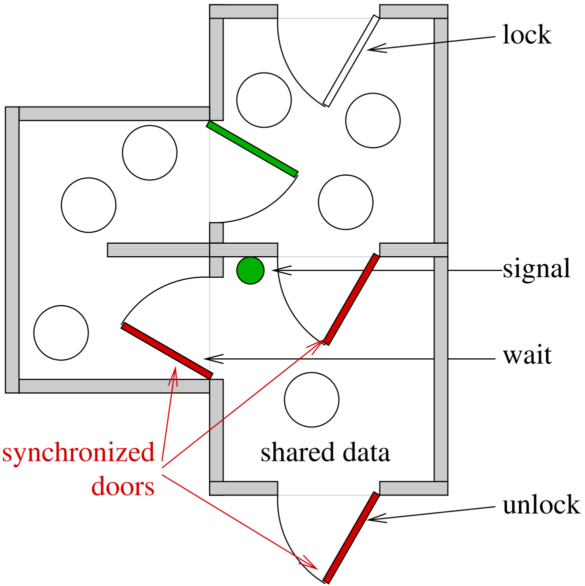
Interface

- `cond`: variable of type `pthread_cond_t`
- `pthread_cond_init(&cond, ...)`: initialize the condition
  - The macro `PTHREAD_COND_INITIALIZER` can be used to initialize a condition variable allocated statically with the default options
- `void pthread_cond_wait(&cond, &mutex)`: atomically unlock `mutex` and put the thread to wait on `cond`.
- `void pthread_cond_signal(&cond)` and `pthread_cond_broadcast(&cond)`: Wake one/all the threads waiting on `cond`.

Condition variable: Analogy



Condition variable: Analogy



On the semantic of the operations

- Calling `wait()` releases the lock similarly to `unlock()`.
- When a thread is woken up by a call to `signal()` (or `broadcast()`), it is guaranteed that at the time it returns from `wait()`, it owns the corresponding lock again.
  - However, it has to compete with other threads to acquire that lock before returning from `wait()`.
- On a call to `signal()`, any of the waiting threads might be the one that is woken up.
- Calling functions `signal()` and `broadcast()` does not require owning the lock.
  - However in most cases the lock should be held for the application logic to be correct.

Producer-Consumer with condition variables

```
mutex_t mutex = MUTEX_INITIALIZER;
cond_t nonempty = COND_INITIALIZER;
cond_t nonfull = COND_INITIALIZER;

void producer (void *ignored) {
  for (;;) {
    /* produce an item and
       put in nextProduced */

    mutex_lock (&mutex);
    while (count == BUFFER_SIZE)
      cond_wait (&nonfull, &mutex);

    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
    cond_signal (&nonempty);
    mutex_unlock (&mutex);
  }
}
```

```
void consumer (void *ignored) {
  for (;;) {
    mutex_lock (&mutex);
    while (count == 0)
      cond_wait (&nonempty, &mutex);

    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
    cond_signal (&nonfull);
    mutex_unlock (&mutex);

    /* consume the item
       in nextConsumed */
  }
}
```

Beware: this solution does not warrant First Come First Served!

More on condition variables

Why must `cond_wait` both release mutex and sleep? Why not separate mutexes and condition variables?

```
while (count == BUFFER_SIZE) {
  mutex_unlock (&mutex);
  cond_wait(&nonfull);
  mutex_lock (&mutex);
}
```

More on condition variables

Why must `cond_wait` both release mutex and sleep? Why not separate mutexes and condition variables?

```
while (count == BUFFER_SIZE) {
  mutex_unlock (&mutex);
  cond_wait(&nonfull);
  mutex_lock (&mutex);
}
```

A thread could end up stuck waiting because of a bad interleaving

- A condition variable has no associated state

PRODUCER	CONSUMER
`while (count == BUFFER_SIZE){`	
`  mutex_unlock (&mutex);`	
	`mutex_lock (&mutex);`
	`...`
	`count--;`
	`cond_signal (&nonfull);`
`  cond_wait (&nonfull);`	
`}`	

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Other synchronization problems

Monitors

- A monitor is a synchronization construct
- It provides synchronization mechanisms similar to mutex + condition variables. (Some people call both "monitors")

Definition

- A monitor is an object/module with a set of methods.
- Each method is executed in mutual exclusion
- Condition variables (or simply "*conditions*") are defined with the same semantic as defined previously

Comments on monitors

- Proposed by Brinch Hansen (1973) and Hoare (1974)
- Possibly less error prone than raw mutexes
- Basic synchronization mechanism in Java
- Different *flavors* depending on the semantic of signal:
  - Hoare-style: The signaled thread get immediately access to the monitor. The signaling thread waits until the signaled threads leaves the monitor.
  - Mesa-style (java): The signaling thread stays in the monitor.
- Semaphores can be implemented using monitors and monitors can be implemented using semaphores

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The Reader-Writer problem

Problem statement

- Several threads try to access the same shared data, some reading, other writing.
- Either a single writer or multiple readers can access the shared data at any time

Different flavors

- Priority to readers
- Priority to writers

The Dining Philosophers problem

Proposed by Dijkstra

Problem statement

5 philosophers spend their live alternatively thinking and eating. They sit around a circular table. The table has a big plate of rice but only 5 chopsticks, placed between each pair of philosophers. When a philosopher wants to eat, he has to peak the chopsticks on his left and on his right. Two philosophers can't use a chopstick at the same time. How to ensure that no philosopher will starve?

Goals

- Avoid deadlocks: Each philosopher holds one chopstick
- Avoid starvation: Some philosophers never eat