CS 4504
Parallel and Distributed Computing

Lock

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https://kevinsuo.github.io/

Outline

- Start from examples
- Concurrency and synchronization
  - Race condition
  - Critical section
- Mutual exclusion
  - Spinlock
  - Mutex lock
  - Semaphore
  - Deadlock and priority inversion

Concurrency Example

https://github.com/kevinsuo/CS3502/blob/master/threads.c

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        counter++;
    }
    return NULL;
}

int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, "usage: threads <value>\n");
        exit(1);
    }
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", counter);

    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", counter);
    return 0;
}
```

- thread.c (What does this program do?)

pthread_create() function starts a new thread in the calling process.
pthread_join() function shall suspend execution of the calling thread until the target thread terminates

Expected output?

```
prompt> gcc -o thread thread.c -Wall -pthread
prompt> ./thread 1000
Initial value : 0
Final value   : 2000
```

Concurrency Example

```c
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        counter++;
    }
    return NULL;
}

int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, "usage: threads <value>\n");
        exit(1);
    }
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", counter);

    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", counter);
    return 0;
}
```

Expected output?

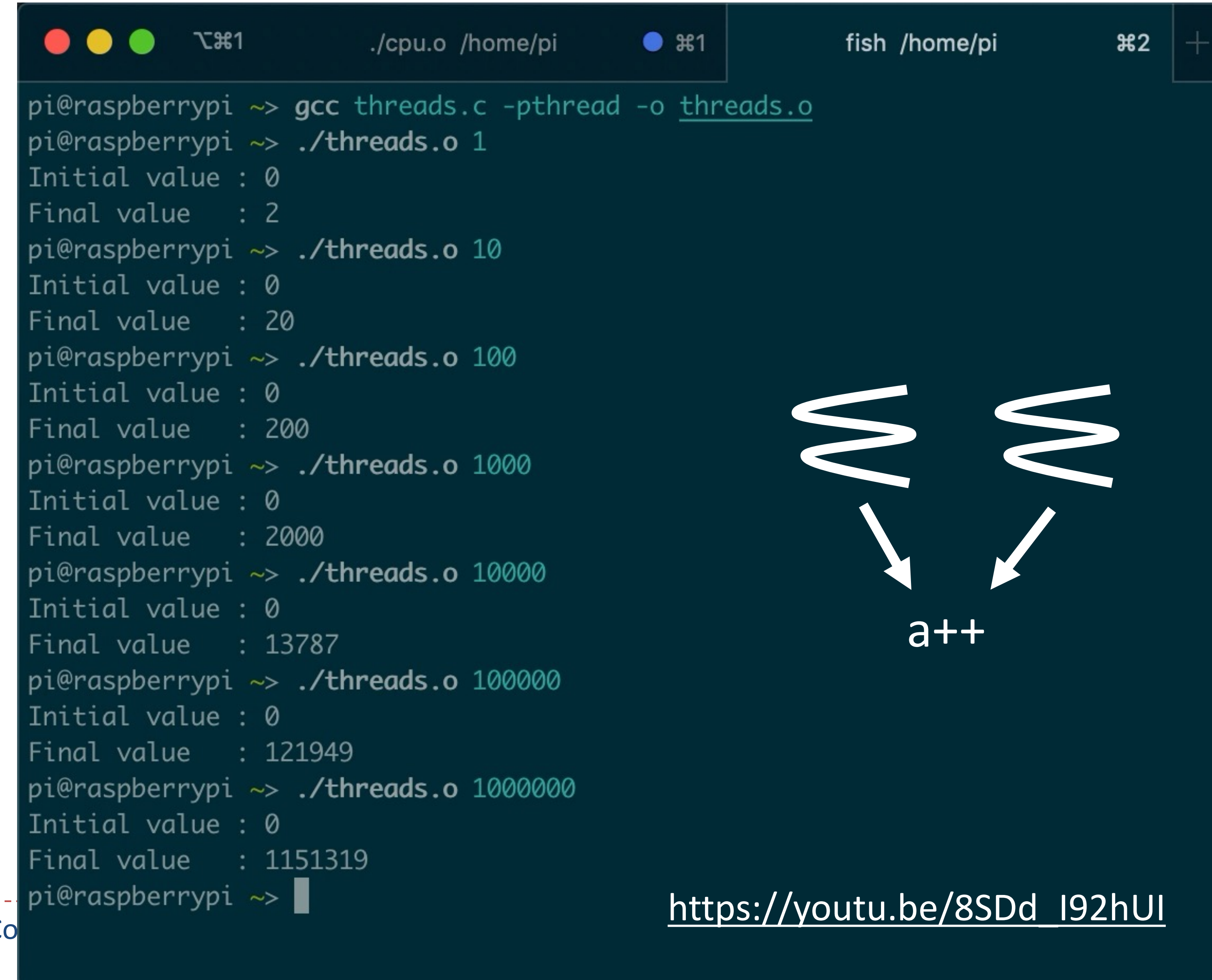
```
prompt> gcc -o thread thread.c -Wall -pthread
prompt> ./thread 1000
Initial value : 0
Final value   : 2000
```

Counter value: before

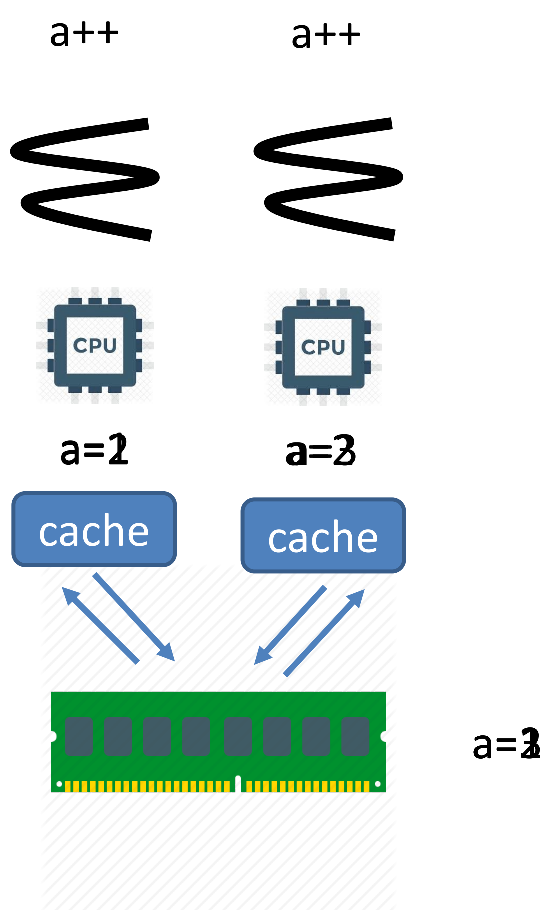
Two threads increase a counter

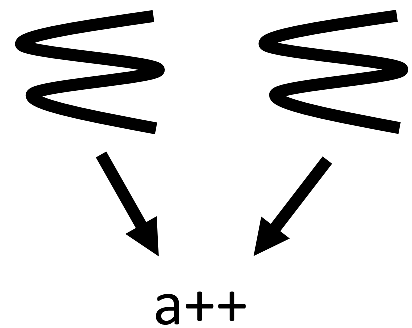
Counter value: after

Concurrency Example

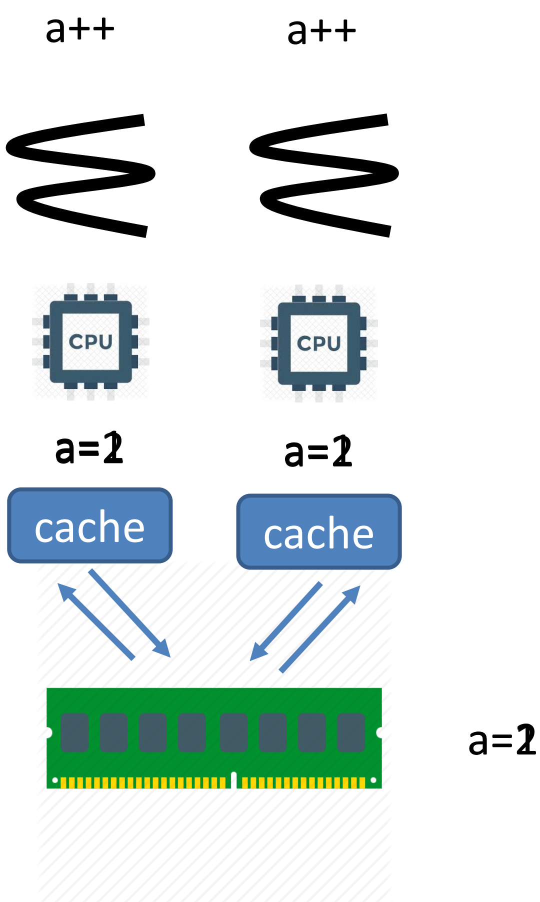


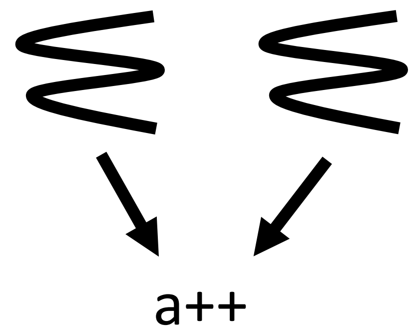
Concurrency Example





Concurrency Example





Concurrency Example

Reality?

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        counter++;
    }
    return NULL;
}

int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, "usage: threads <value>\n");
        exit(1);
    }
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", counter);

    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", counter);
    return 0;
}
```

```
prompt> ./thread 100000
Initial value : 0
Final value   : 143012     // huh??
prompt> ./thread 100000
Initial value : 0
Final value   : 137298     // what the??
```

A key part of the program above, where the shared counter is incremented, takes three instructions:

- one to load the value of the counter from memory into a register,
- one to increment it, and
- one to store it back into memory.

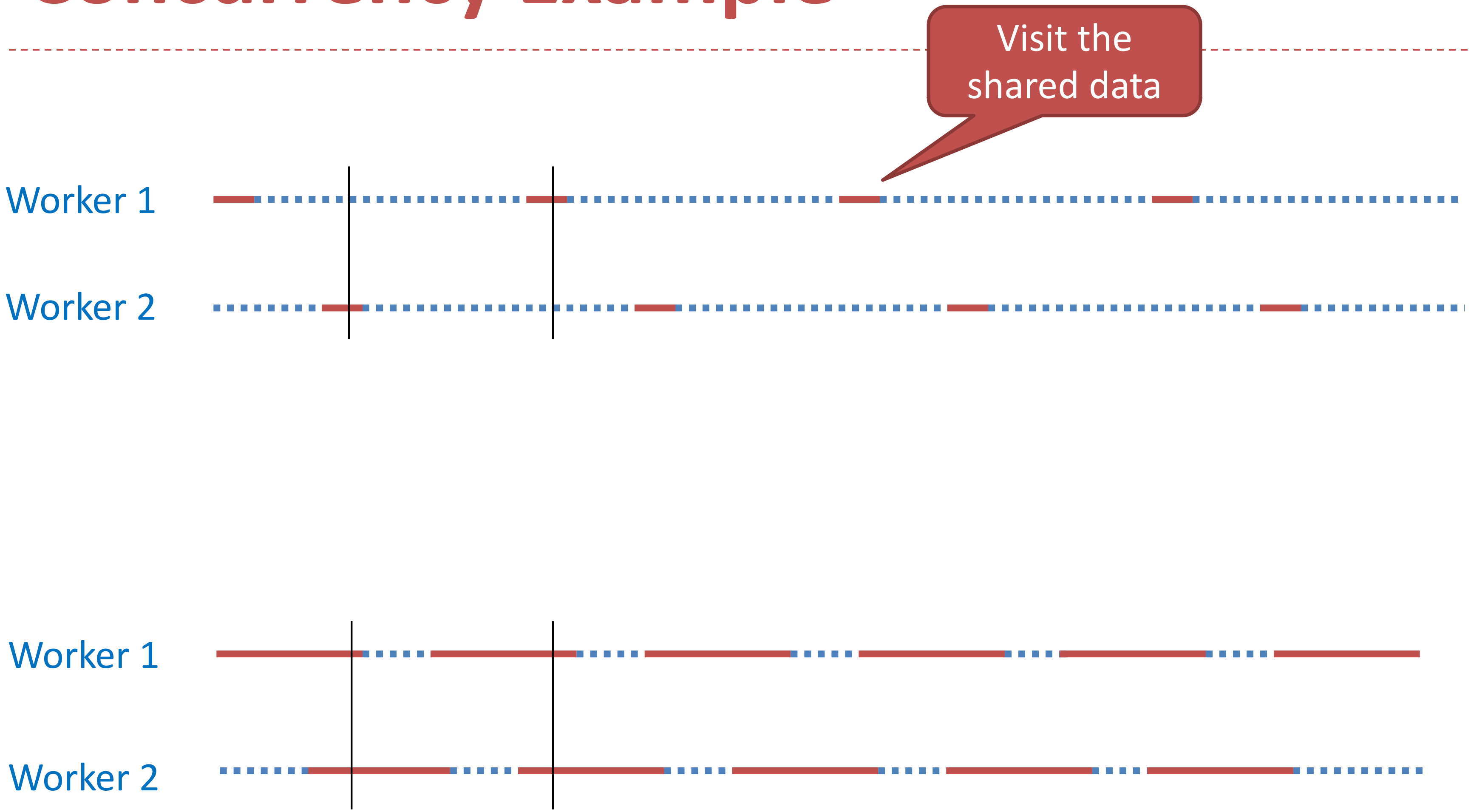
Because these three instructions do not execute **atomically** (all at once), strange things can happen.

Concurrency Example

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"
#include "common_threads.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
    int i, j;
    for (i = 0; i < loops; i++) {
        for (j = 0; j < 1000; j++) {
                counter++;
                counter--;
        }
        counter++;
    }
    return NULL;
}

int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, "usage: threads <loops>\n");
        exit(1);
    }
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", counter);
    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", counter);
    return 0;
}
```

For each iteration of i, it takes more time each round

Concurrency Example



Concurrency Example

```
fish  /home/ksuo
ksuo@ksuo-VirtualBox ~> gcc threads.c -o threads.o -pthread
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 20
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 9
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 20
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 15
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 20
ksuo@ksuo-VirtualBox ~> ./threads.o 10
Initial value : 0
Final value   : 10
ksuo@ksuo-VirtualBox ~> ./threads.o 100
Initial value : 0
Final value   : 127
ksuo@ksuo-VirtualBox ~> ./threads.o 100
Initial value : 0
Final value   : 100
ksuo@ksuo-VirtualBox ~>
```

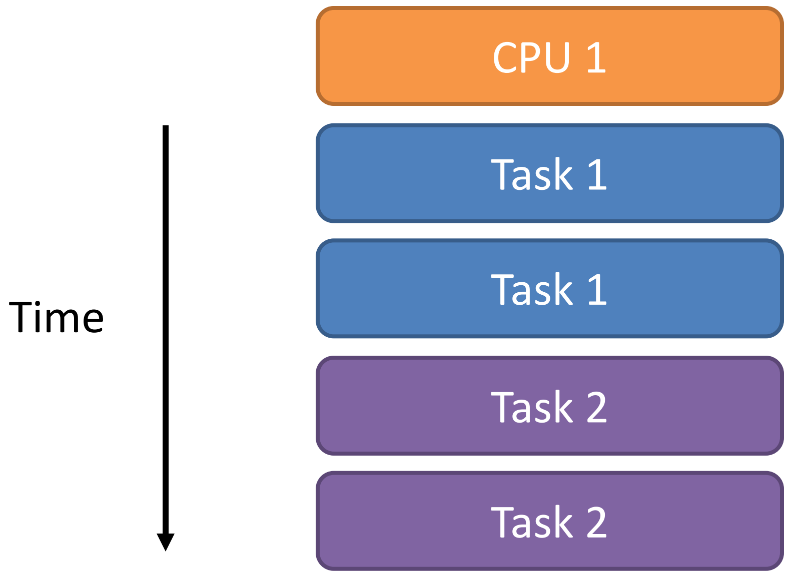
Test

```
int x = 0;

void ThreadPro ()
{
    for (int i = 1; i <= 50; i++)
        x += 1;
}
```

- When two threads finish, what is the range of x?
- [50, 100]

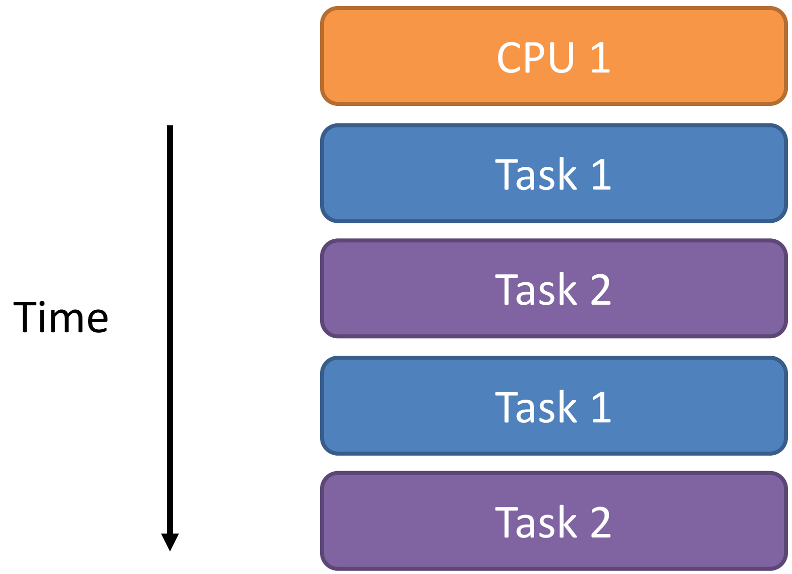
Execution models

- Sequential execution
  - Loosely, doing a lot of things, but one after another
  - E.g. Finish one assignment then another



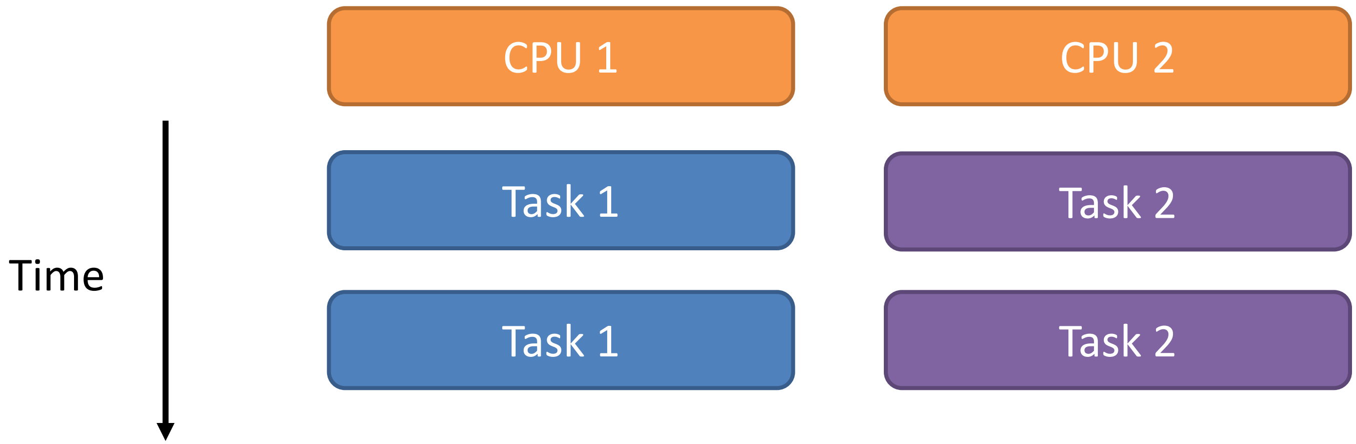
Execution models

- Concurrent execution
  - Loosely, concurrency is “juggling” many things within a time window

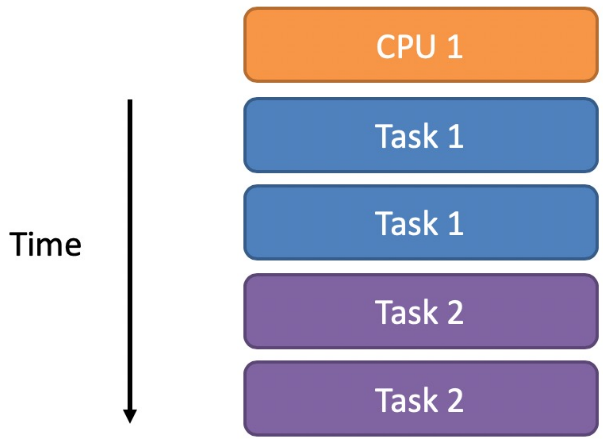


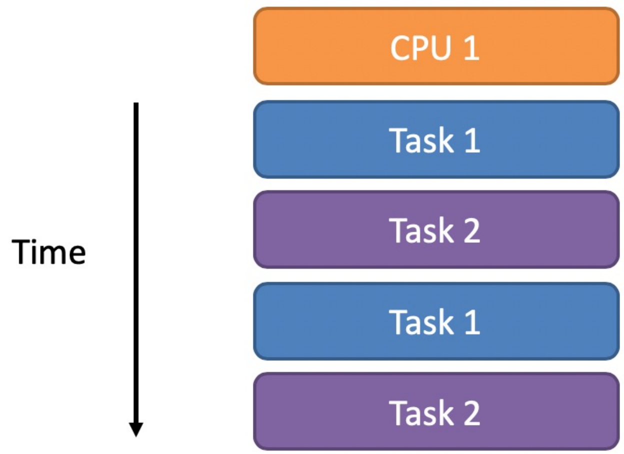
Execution models

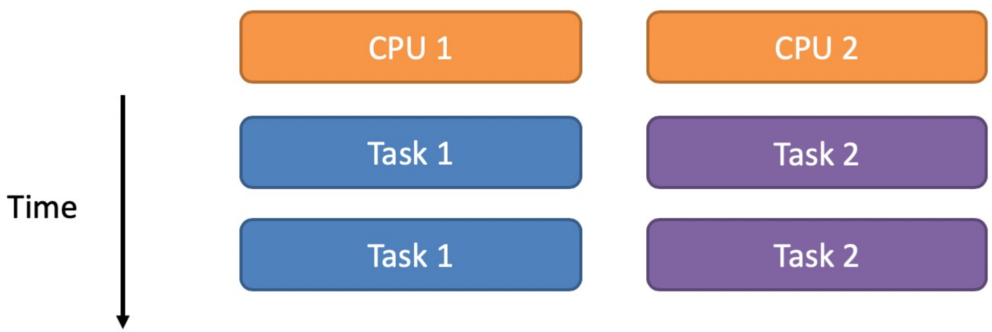
- Parallel execution
  - Loosely, parallelism is doing many things simultaneously
  - Parallel execution model is a subset of concurrency model
    - All parallelism is concurrency, but not all concurrency is parallelism



Three models: sequential, concurrent and parallel







Outline

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- Concurrency and synchronization
  - Race condition
  - Critical section
- Mutual exclusion
  - Spinlock
  - Mutex lock
  - Semaphore
  - Deadlock and priority inversion

Race condition

https://github.com/kevinsuo/CS7172/blob/master/race_condition.c

- A race condition occurs when two or more threads access shared data and they try to change it at the same time.
- The order in which the threads attempt to access the shared data makes the results unpredictable

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;

void *compute()
{
        int i = 0;
        while (i < 100) {
                counter = counter + 1;
                i++;
        }
        printf("Counter value: %d\n", counter);
}

int main()
{
        pthread_t thread1, thread2;

        pthread_create(&thread1, NULL, compute, (void *)&thread1);
        pthread_create(&thread2, NULL, compute, (void *)&thread2);

        pthread_exit(NULL);
        exit(0);
}
```

Race condition occurs for variable counter

```
pi@raspberrypi ~/Downloads> ./race_condition.o
Counter value: 100
Counter value: 200
```

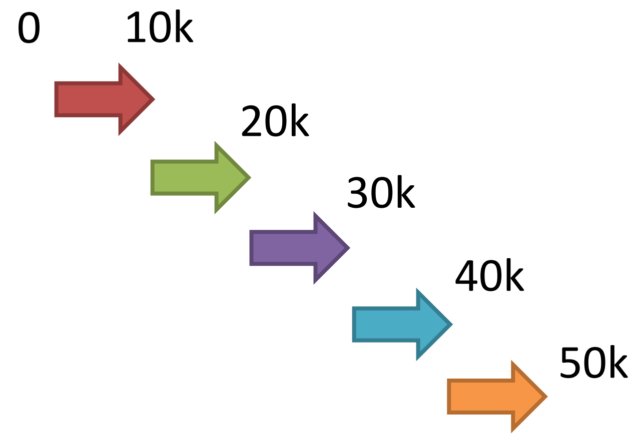
Seem nothing wrong?

Race condition example

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;

void *compute()
{
        int i = 0;
        while (i < 10000) {
                counter = counter + 1;
                i++;
        }
        printf("Counter value: %d\n", counter);
}

int main()
{
        pthread_t thread1, thread2, thread3, thread4, thread5;

        pthread_create(&thread1, NULL, compute, (void *)&thread1);
        pthread_create(&thread2, NULL, compute, (void *)&thread2);
        pthread_create(&thread3, NULL, compute, (void *)&thread3);
        pthread_create(&thread4, NULL, compute, (void *)&thread4);
        pthread_create(&thread5, NULL, compute, (void *)&thread5);

        pthread_exit(NULL);
        exit(0);
}
```

Increase the loop number

Add more threads

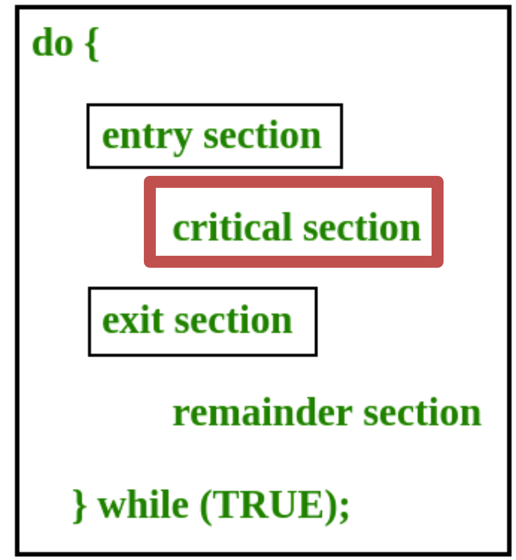



```
pi@raspberrypi ~/Downloads> ./race_condition.o
Counter value: 14467
Counter value: 10410
Counter value: 12080
Counter value: 22745
Counter value: 32725
```

Weird results!

Critical section

- A section of code in a concurrent task that modifies or accesses a resource shared with another task.



- Examples
  - A piece of code that reads from or writes to a shared memory region
  - Or a code that modifies or traverses a shared linked list.

Critical section example

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;

void *compute()
{
        int i = 0;
        while (i < 100) {
                counter = counter + 1;
                i++;
        }
        printf("Counter value: %d\n", counter);
}

int main()
{
        pthread_t thread1, thread2;

        pthread_create(&thread1, NULL, compute, (void *)&thread1);
        pthread_create(&thread2, NULL, compute, (void *)&thread2);

        pthread_exit(NULL);
        exit(0);
}
```

Critical section: All threads read and write the shared counter

Critical section vs. Race condition

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;

void *compute()
{
        int i = 0;
        while (i < 100) {
                counter = counter + 1;
                i++;
        }
        printf("Counter value: %d\n", counter);
}

int main()
{
        pthread_t thread1, thread2;

        pthread_create(&thread1, NULL, compute, (void *)&thread1);
        pthread_create(&thread2, NULL, compute, (void *)&thread2);

        pthread_exit(NULL);
        exit(0);
}
```

Critical section is where the race condition happens.

When multiple threads visit the critical section, race condition problem appears!

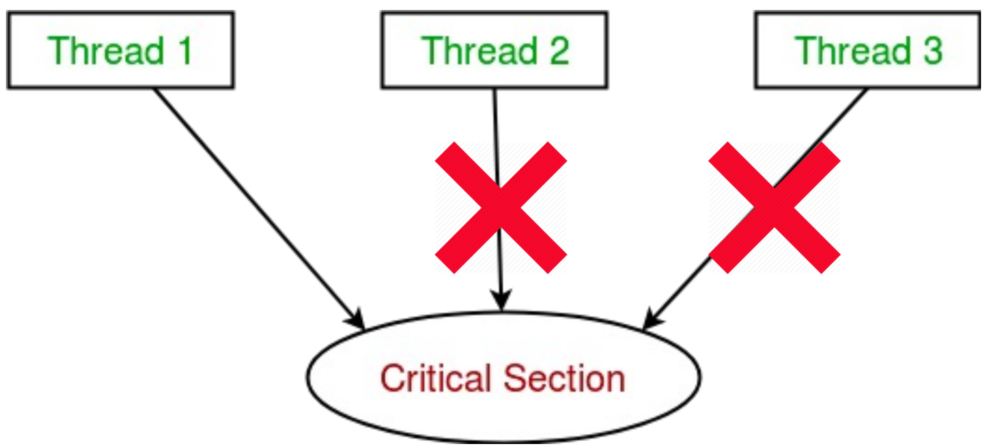
Outline

- Start from examples
- Concurrency and synchronization
  - Race condition
  - Critical section
- Mutual exclusion
  - Spinlock
  - Mutex lock
  - Semaphore
  - Deadlock and priority inversion

To avoid race condition

- Principles:

  1. No two processes are simultaneously in the critical region

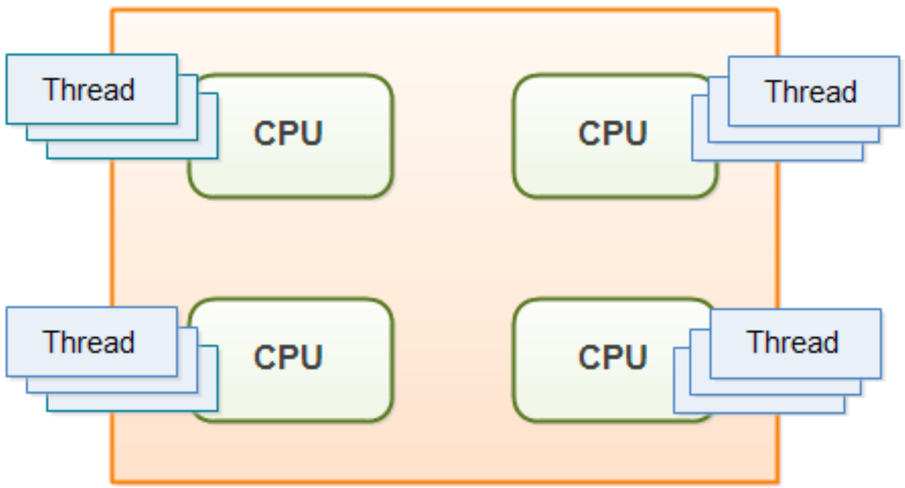


To avoid race condition

- Principles:

  2. No assumptions are made about speeds or numbers of CPUs

Thread could have varied speeds

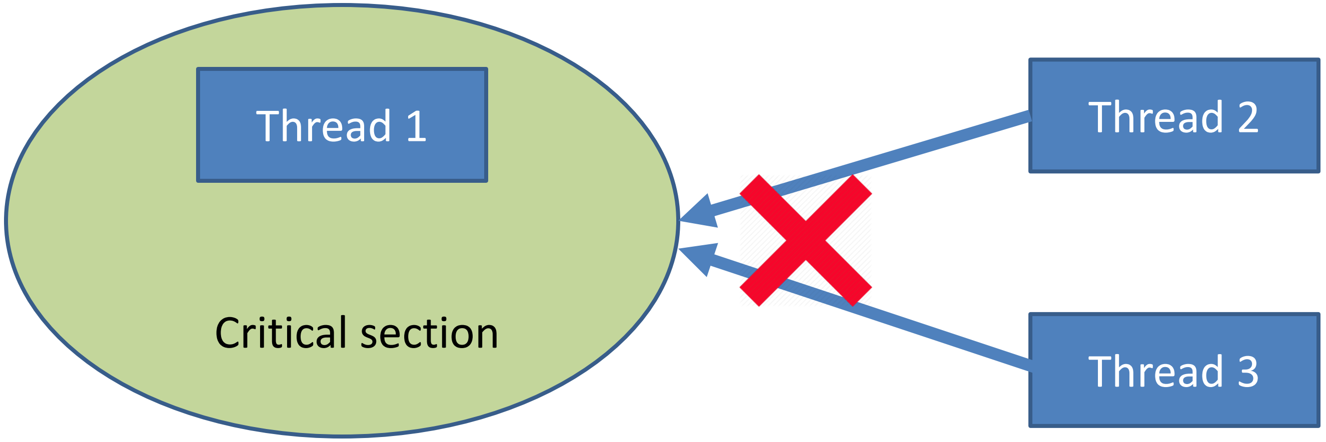


Thread could exist at each core

To avoid race condition

- Principles:

3. No process running outside its critical region may block another process running in the critical region

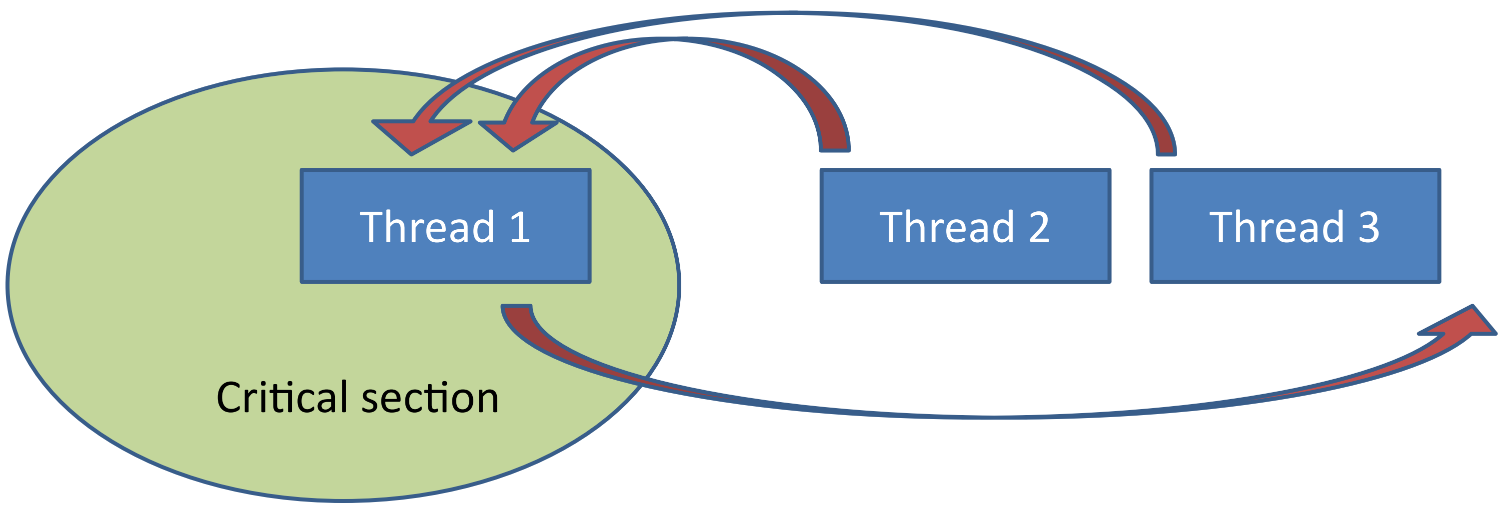


To avoid race condition

- Principles:

4. No process must wait forever to enter its critical region

  - Waiting forever indicates a deadlock



To avoid race condition

- Principles:

1. No two processes are simultaneously in the critical region
2. No assumptions are made about speeds or numbers of CPUs

OS lock

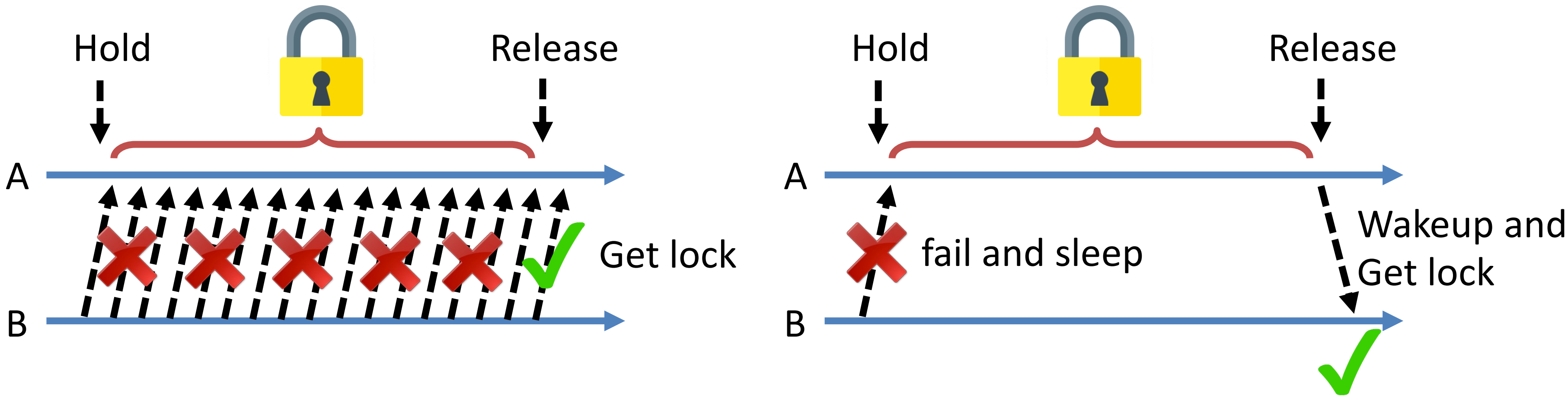
3. No process running outside its critical region may block another process running in the critical region
4. No process must wait forever to enter its critical region
    - Waiting forever indicates a deadlock

- (1) and (2) are enforced by the operating system's implementation of locks
    - Programmers assume that locks satisfy (1) and (2)
- (3) and (4) must be ensured by the programmer using the locks.
    - OS cannot enforce these.

Lock (mutual exclusion)

- A lock (mutual exclusion) is a synchronization mechanism for enforcing limits on access to a resource in an environment where there are many threads of execution

- Types of mutual mechanism:
  - Busy-waiting, e.g., spinlock
  - Sleep and wakeup



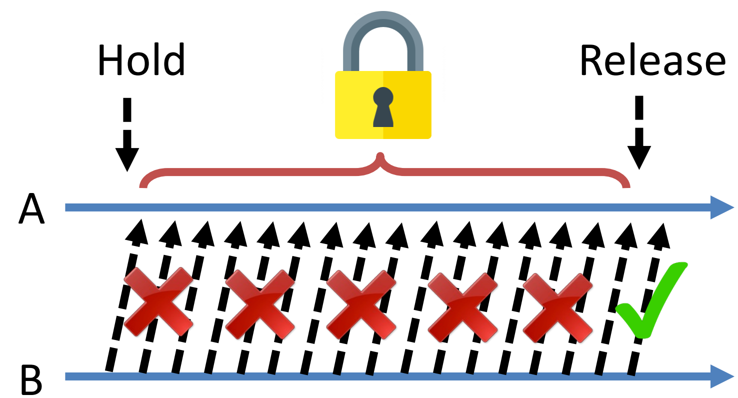
1, Spinlock: A busy-waiting lock implementation

- Don't block. Instead, constantly poll the lock for availability.
- Usage: small critical region

```
while (lock is unavailable)
    continue; // try again
return success;
```

```
SpinLock(resource);
Execute Critical Section;
SpinUnlock(resource);
```

- Advantage
  - Very efficient with short critical sections
    - if you expect a lock to be released quickly
- Disadvantage
  - Doesn't yield the CPU and burns CPU cycles
    - Bad if critical sections are long.
  - Efficient only if machine has multiple CPUs.
    - Counterproductive on uniprocessor machines



Without Spinlock example

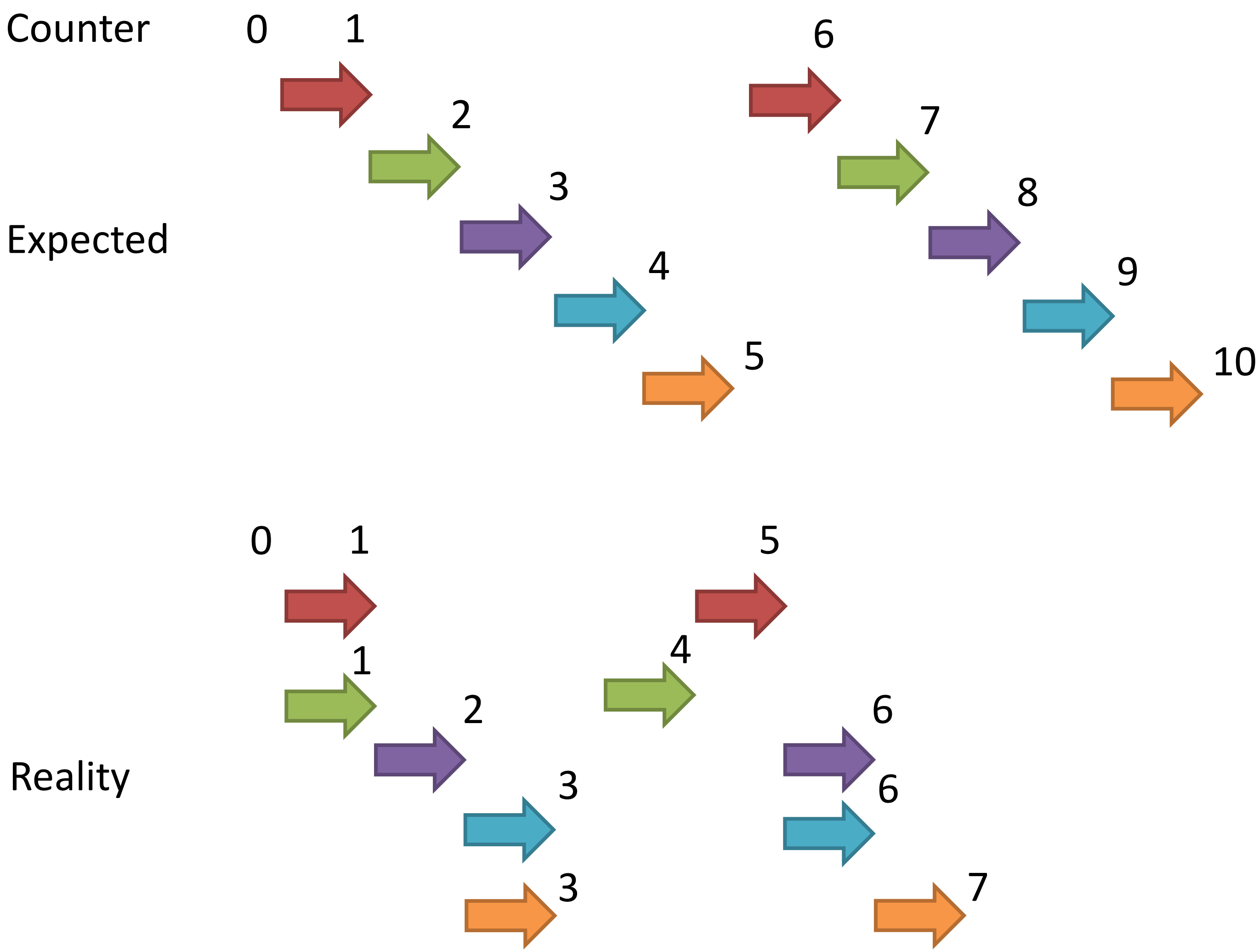
https://github.com/kevinsuo/CS3502/blob/master/spin_no_lock.c

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;
static pthread_spinlock_t splock;

void *compute()
{
    int i = 0;
    while (i < 10000) {
        counter = counter + 1;
        i++;
    }
    printf("Counter value: %d\n", counter);
}

int main()
{
    pthread_t thread1, thread2, thread3, thread4, thread5;

    pthread_create(&thread1, NULL, compute, (void *)&thread1);
    pthread_create(&thread2, NULL, compute, (void *)&thread2);
    pthread_create(&thread3, NULL, compute, (void *)&thread3);
    pthread_create(&thread4, NULL, compute, (void *)&thread4);
    pthread_create(&thread5, NULL, compute, (void *)&thread5);

    pthread_exit(NULL);
    exit(0);
}
```

```
fish  /home/ksuo                                          ⌥⌘1
Counter value: 10000
Counter value: 26973
Counter value: 30000
Counter value: 34209
Counter value: 44209
ksuo@ksuo-VirtualBox ~> ./spinlock.o
Counter value: 10000
Counter value: 20000
Counter value: 30000
Counter value: 40000
Counter value: 49841
ksuo@ksuo-VirtualBox ~> ./spinlock.o
Counter value: 14946
Counter value: 10128
Counter value: 17272
Counter value: 27272
Counter value: 30431
ksuo@ksuo-VirtualBox ~>
```

Without Spinlock example

https://github.com/kevinsuo/CS3502/blob/master/spin_no_lock.c

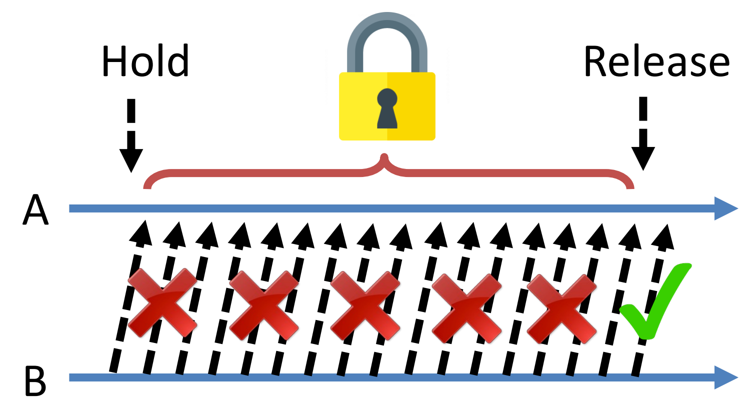


Spinlock example

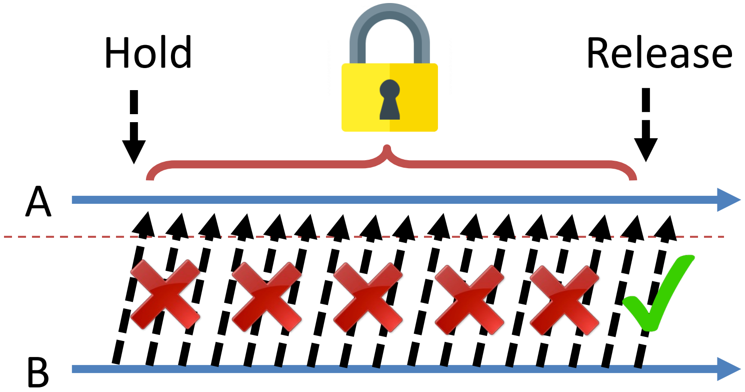
https://github.com/kevinsuo/CS7172/blob/master/spinlock.c

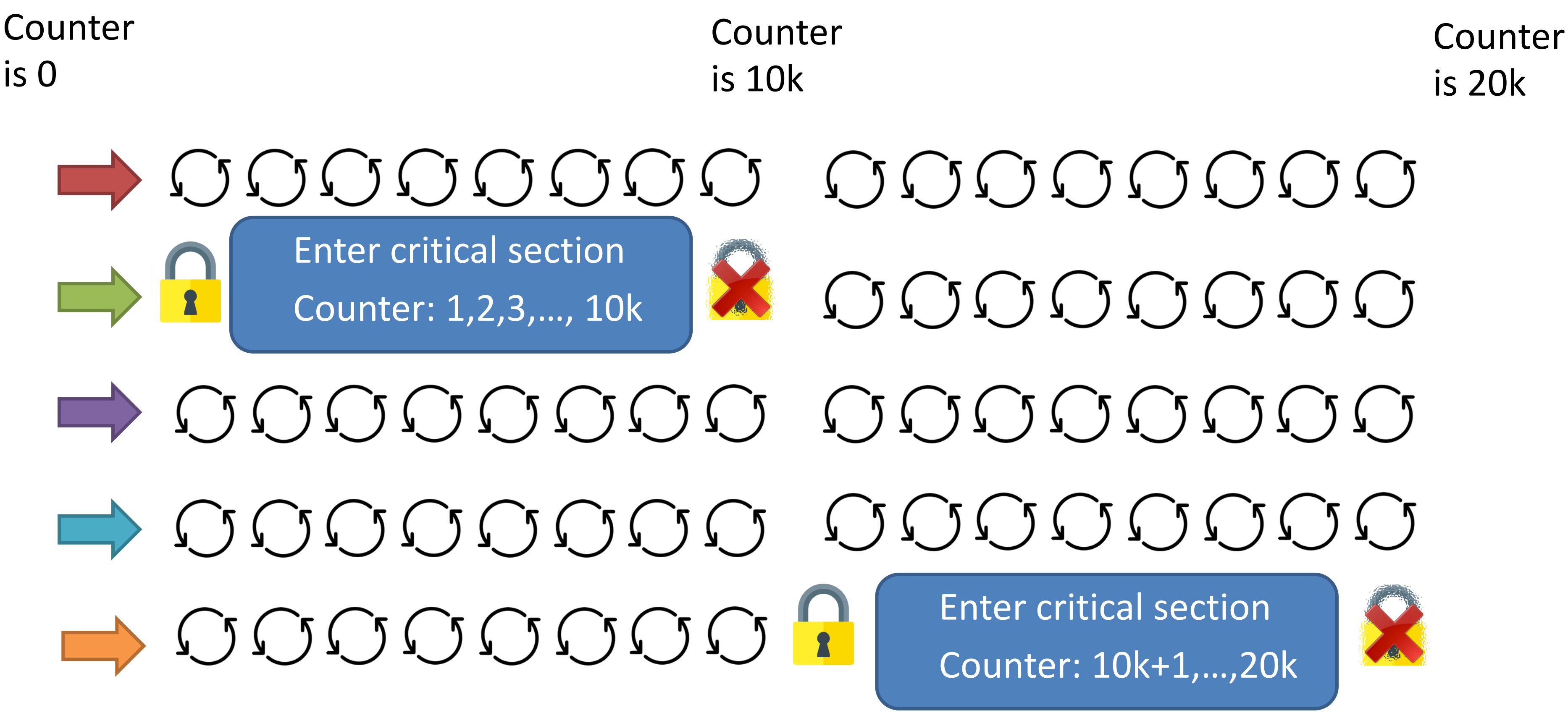
```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;
static pthread_spinlock_t splock;

void *compute()
{
    int i = 0;
    pthread_spin_lock(&splock);
    while (i < 10000) {
        counter = counter + 1;
        i++;
    }
    printf("Counter value: %d\n", counter);
    pthread_spin_unlock(&splock);
}

int main()
{
    pthread_t thread1, thread2, thread3, thread4, thread5;

    pthread_create(&thread1, NULL, compute, (void *)&thread1);
    pthread_create(&thread2, NULL, compute, (void *)&thread2);
    pthread_create(&thread3, NULL, compute, (void *)&thread3);
    pthread_create(&thread4, NULL, compute, (void *)&thread4);
    pthread_create(&thread5, NULL, compute, (void *)&thread5);

    pthread_exit(NULL);
    exit(0);
}
```

```
ksuo@ksuo-VirtualBox ~/Desktop> ./spinlock.o
Counter value: 10000
Counter value: 20000
Counter value: 30000
Counter value: 40000
Counter value: 50000
```

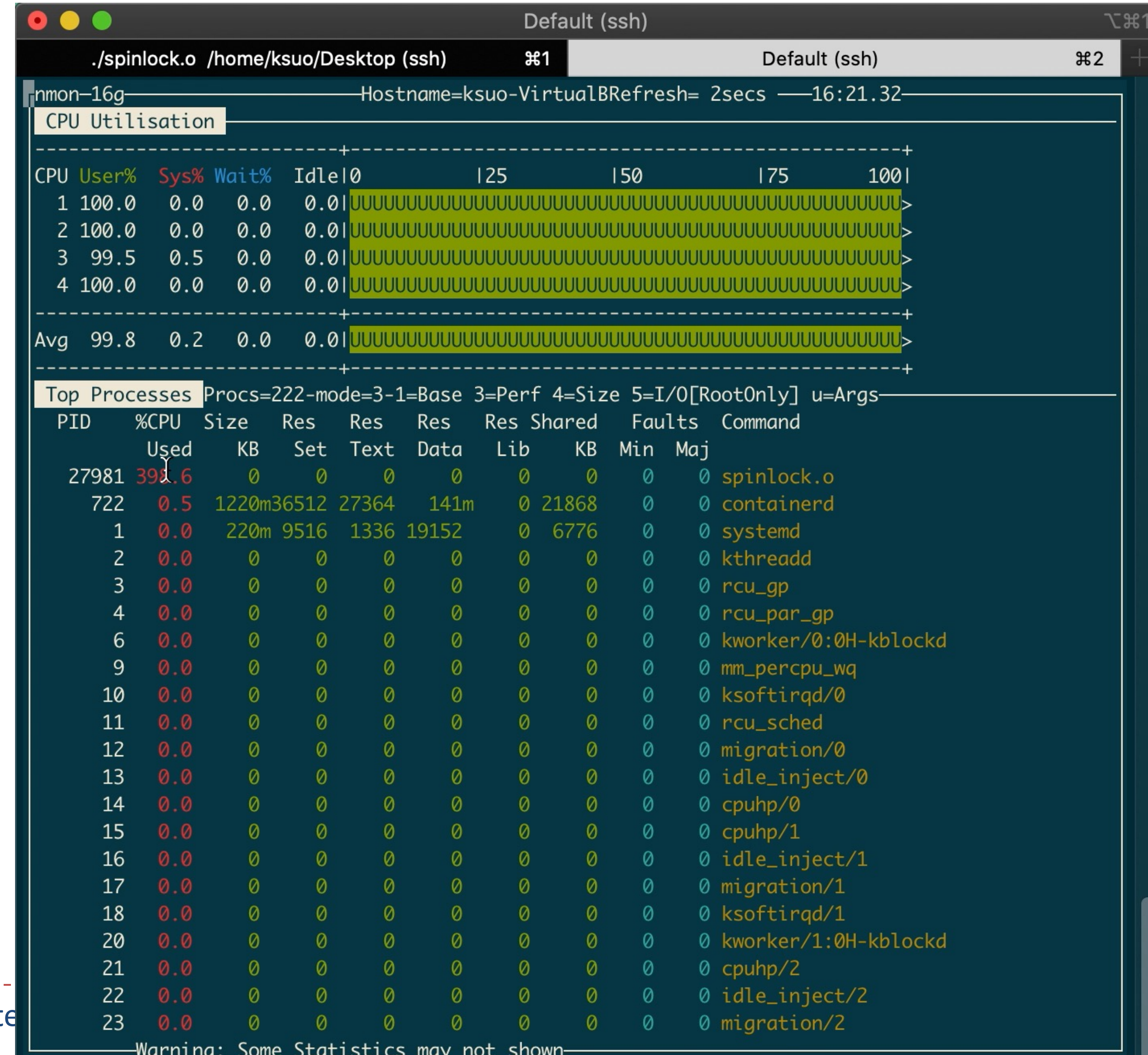


Spinlock example





Spinlock example: CPU utilization

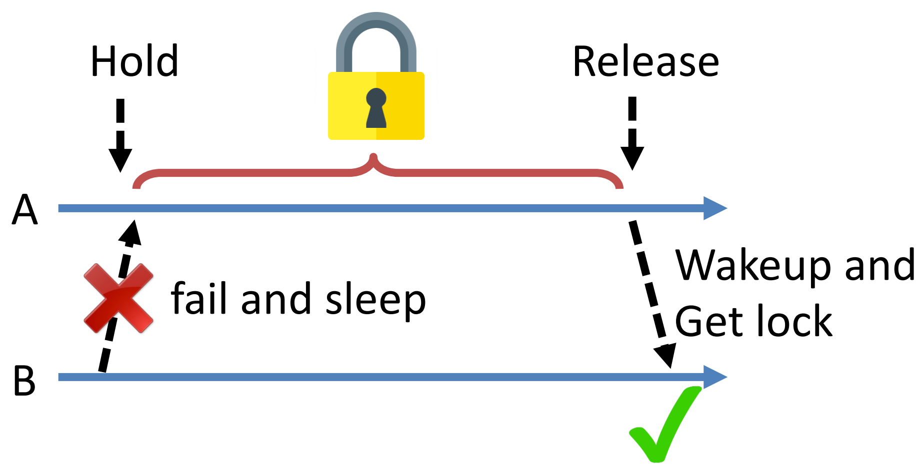


Other mutual exclusion similar as busy waiting (spinlock)

- Disabling interrupts:
  - OS technique, not users’
- Lock variables:
  - Test-and-set lock (TSL) is a two-step process, not atomic
- Peterson's algorithm
  - Does not need atomic operation and mainly used in user space application

2, Mutex lock: A sleep-and-wakeup lock implementation

- A variable that can be in one of two states: unlocked or locked
- Mutex is used as a LOCK around critical sections



Example:

Lock(mutex)
Critical Section…
Unlock(mutex)

Pro:
Better cpu utilization

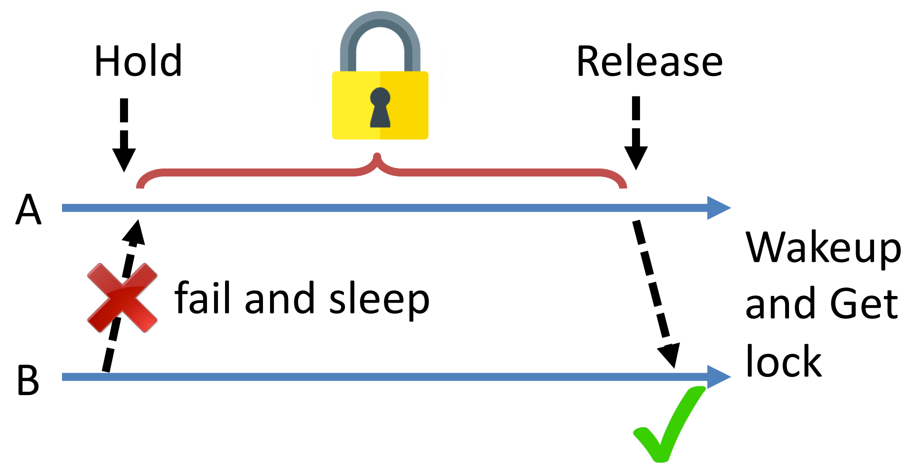
Con:
Overhead on entering sleep or wake up
Not suited for short duration of lock acquisition

Mutex lock example

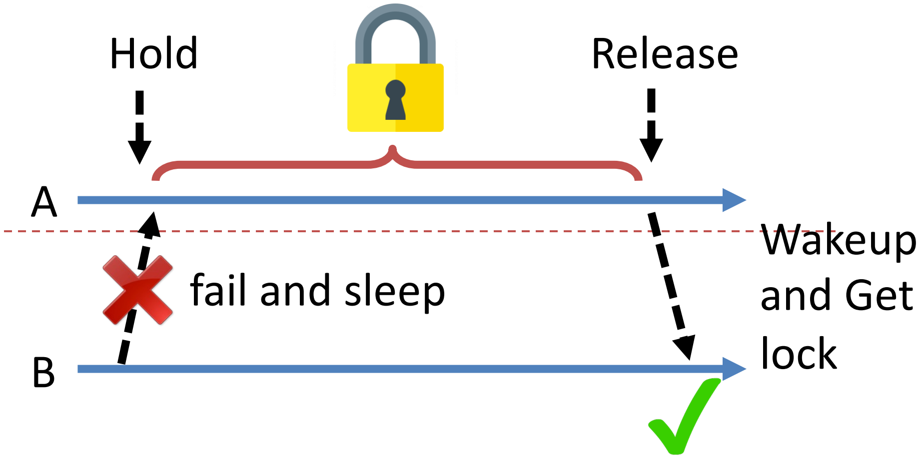
https://github.com/kevinsuo/CS7172/blob/master/mutexlock.c

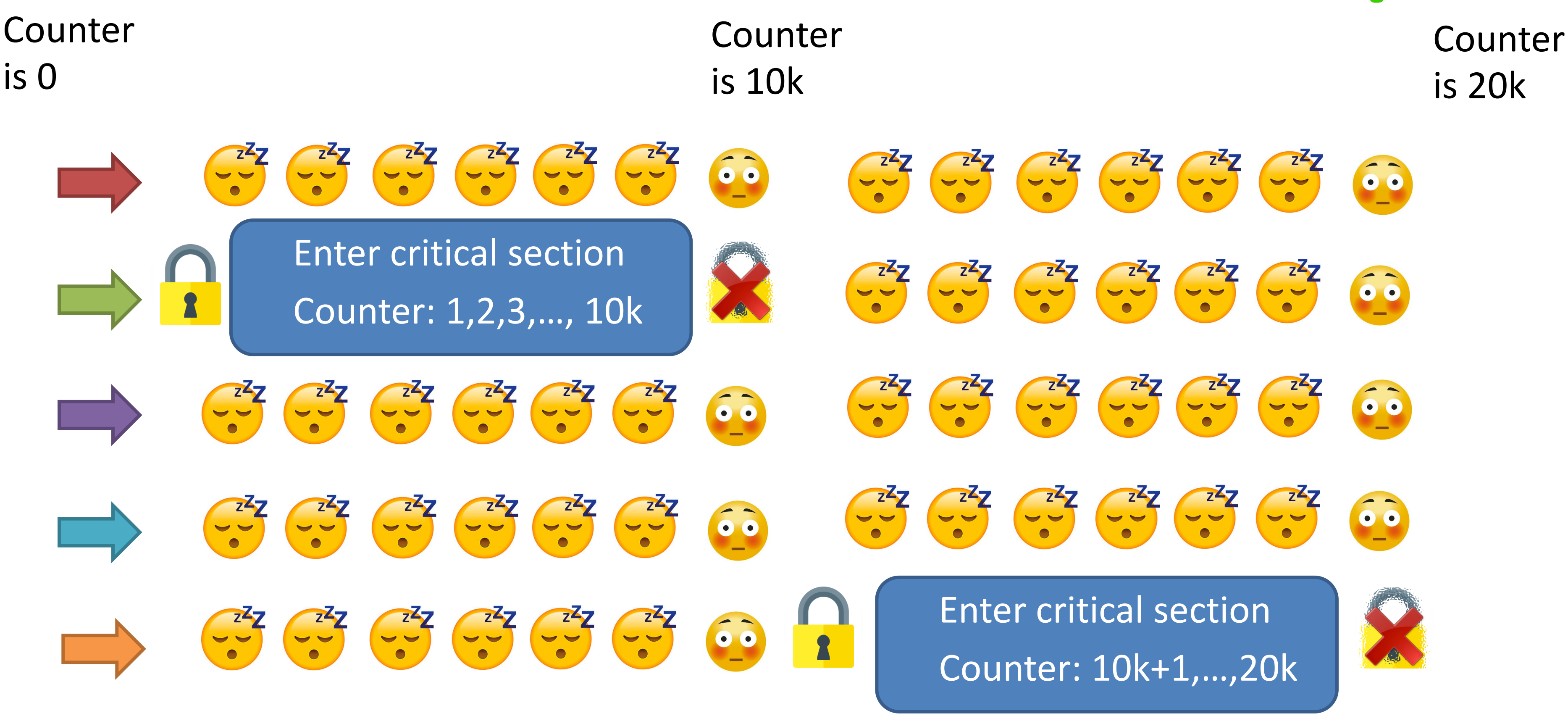
```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int counter = 0;
static pthread_mutex_t mlock;

void *compute()
{
    int i = 0;
    pthread_mutex_lock(&mlock);
    while (i < 10000) {
        counter = counter + 1;
        i++;
    }
    printf("Counter value: %d\n", counter);
    pthread_mutex_unlock(&mlock);
}

int main()
{
    pthread_t thread1, thread2, thread3, thread4, thread5;

    pthread_create(&thread1, NULL, compute, (void *)&thread1);
    pthread_create(&thread2, NULL, compute, (void *)&thread2);
    pthread_create(&thread3, NULL, compute, (void *)&thread3);
    pthread_create(&thread4, NULL, compute, (void *)&thread4);
    pthread_create(&thread5, NULL, compute, (void *)&thread5);

    pthread_exit(NULL);
    exit(0);
}
```

```
pi@raspberrypi ~/Downloads> ./mutexlock.o
Counter value: 10000
Counter value: 20000
Counter value: 30000
Counter value: 40000
Counter value: 50000
```

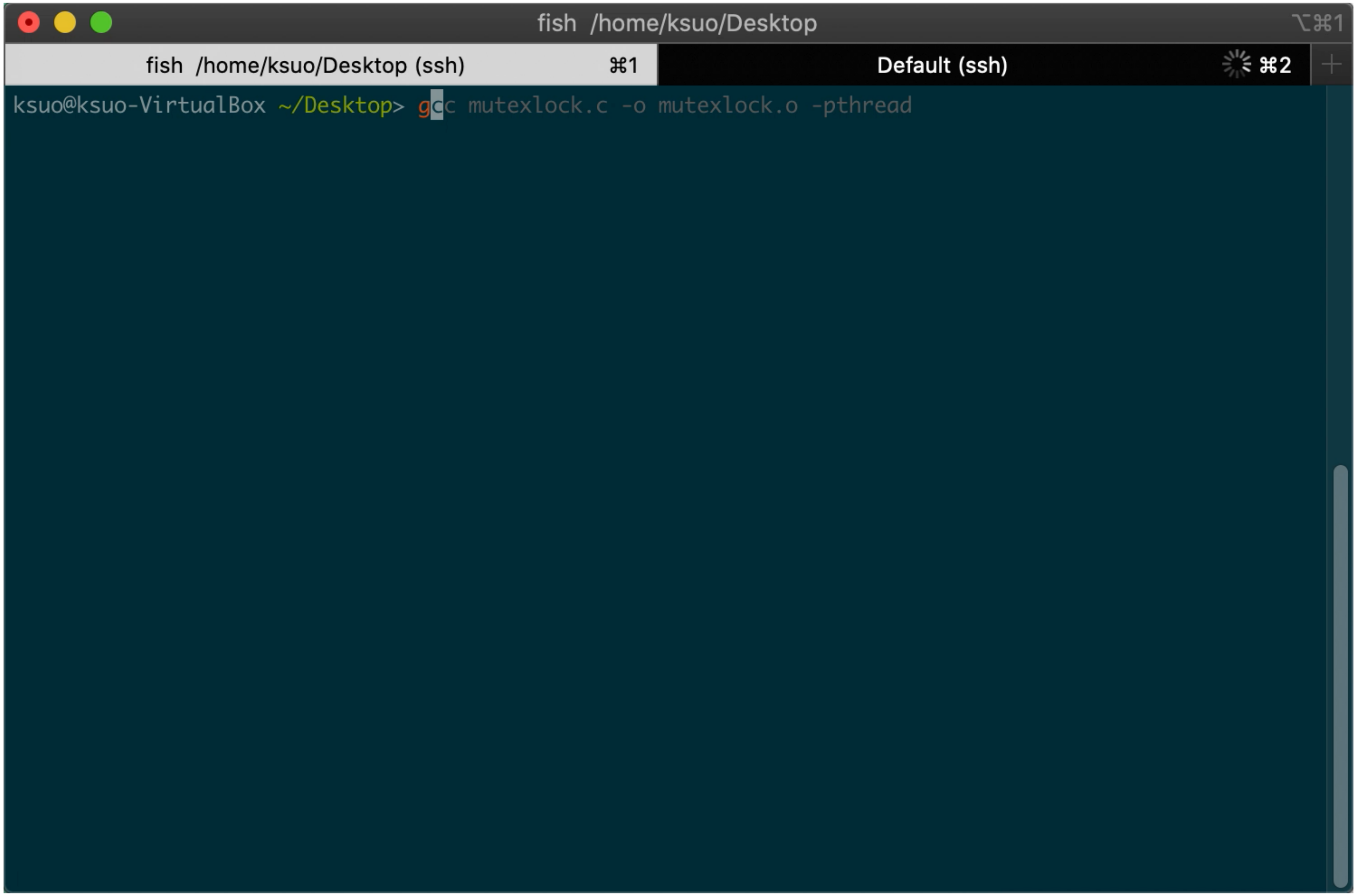


Mutex example





Mutex lock CPU utlization

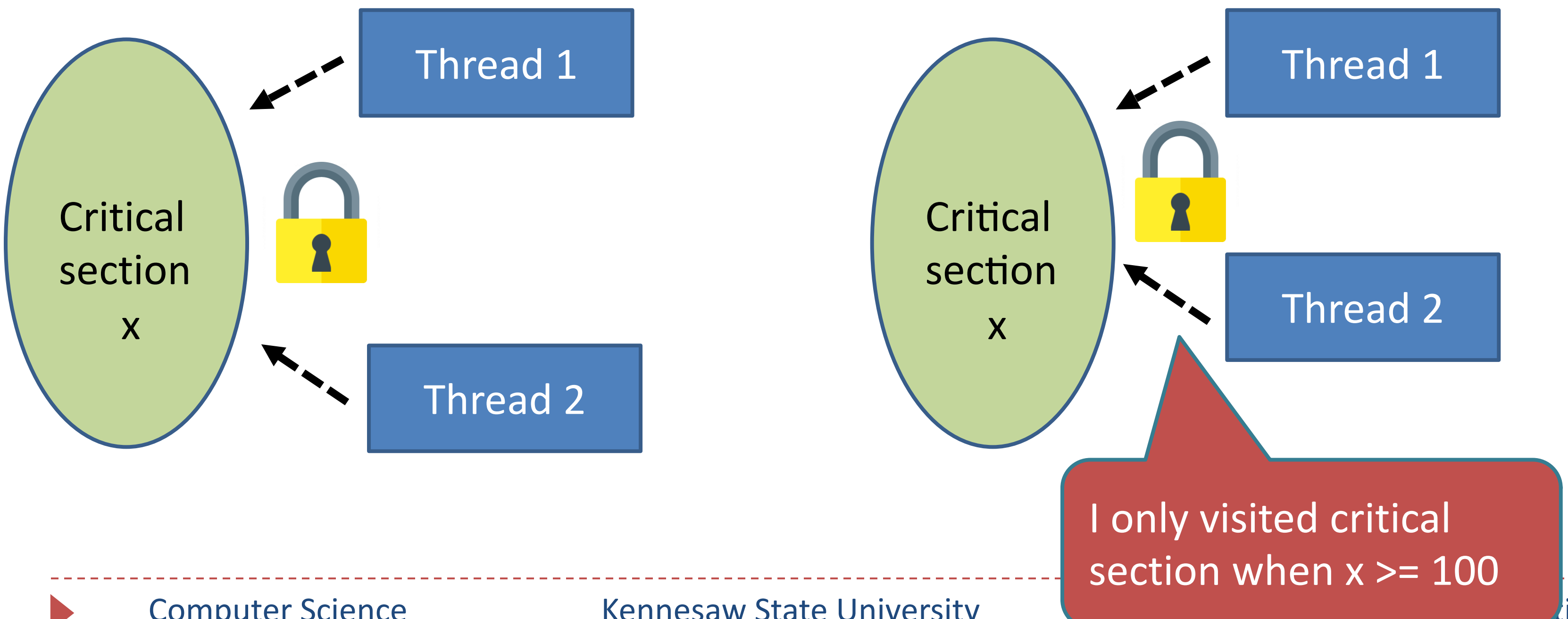


Busy waiting lock vs Sleep wake up lock

	Mechanism	Use case	Implementation	Other examples
Busy waiting lock	constantly poll the lock for availability	When the waiting time is short	Spin lock	Disabling interrupts; Lock variables; Peterson’s algorithm
Sleep wake up lock	Sleep if lock not available; wake up if available	When the waiting time is long	Mutex lock	Semaphore

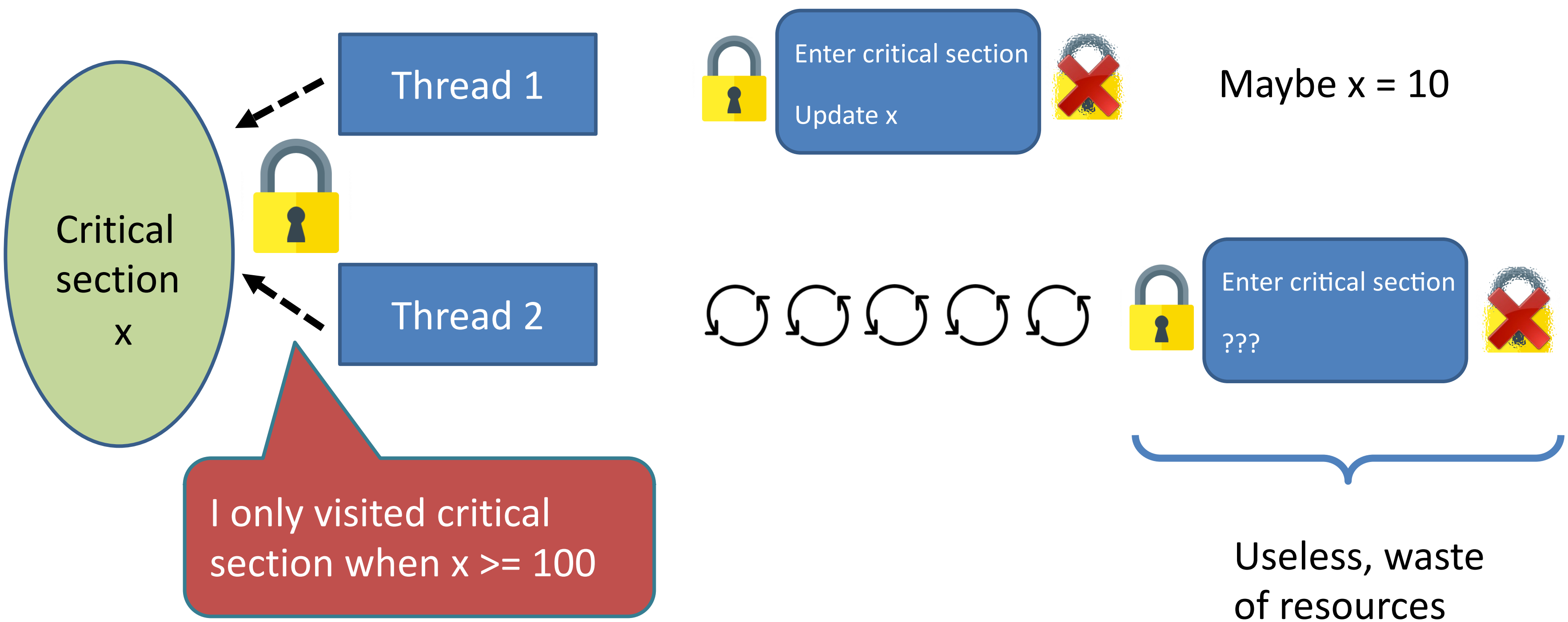
3. Mutex lock with conditions

- Mutex locks solve the competition problem of multiple threads accessing the same global variable under the shared memory space. (without conditions)
- How about competition with condition variables?



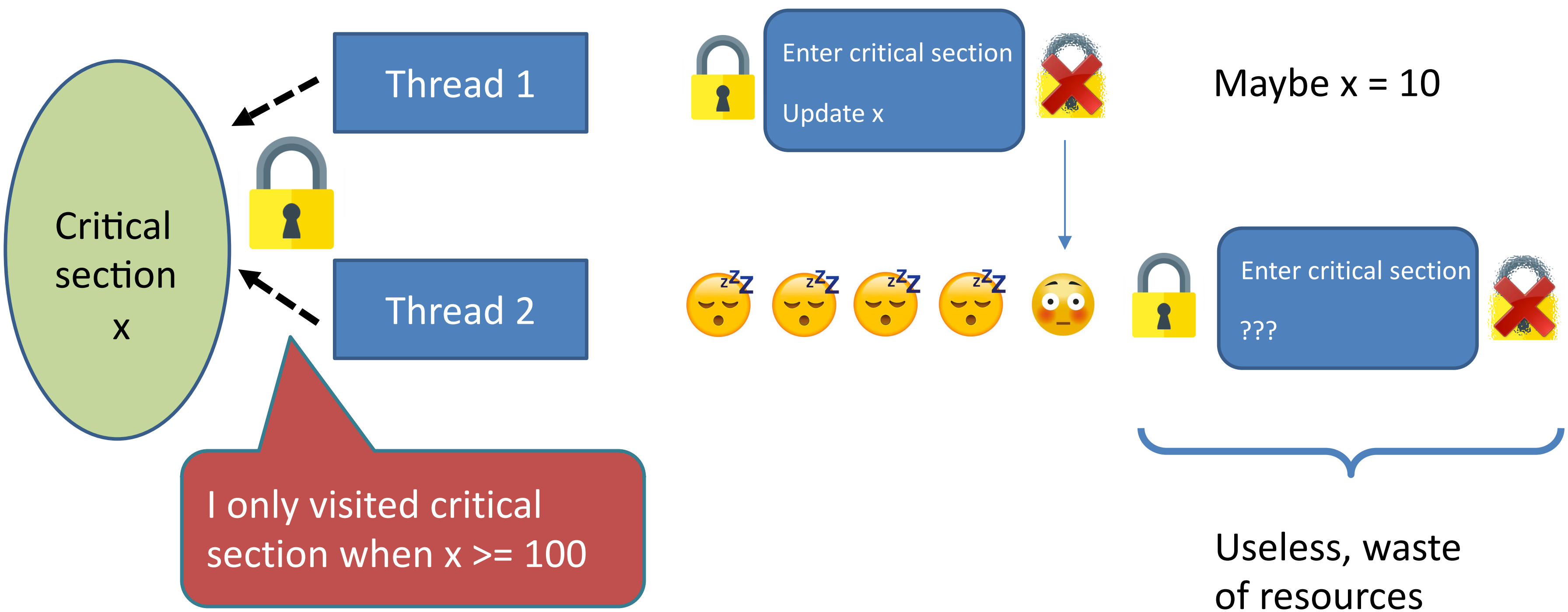
3. Mutex lock with conditions

- Can we use busy-waiting lock?



3. Mutex lock with conditions

- Can we use sleep-and-wakeup lock?



Mutex lock with conditions example

- How about competition with condition variables?
  - Example: T1: increase x every time;
  - T2: when x is larger than 99, then set x to 0;

T1 and T2 compete for variable iCount!

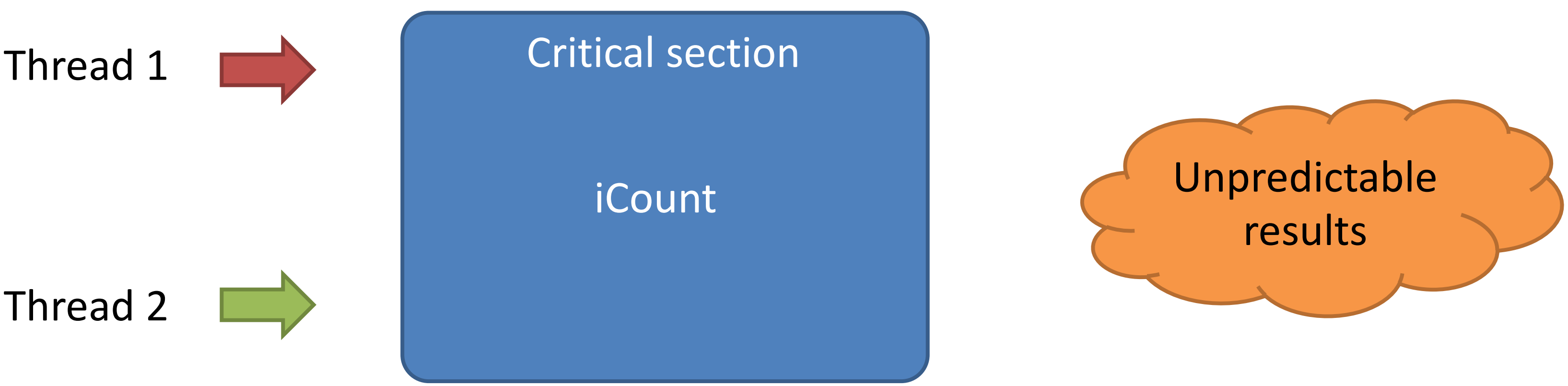
```
//thread 1:

while(true)
{

    iCount++;

}
```

```
//thread 2:
while(true)
{

    if(iCount >= 100)
    {
        iCount = 0;
    }


}
```

Mutex lock with conditions example

```
//thread 1:

while(true)
{

    iCount++;

}
```

```
//thread 2:
while(true)
{

    if(iCount >= 100)
    {
        iCount = 0;
    }


}
```



Mutex lock with conditions

- How about competition with condition variables?
  - Example: T1: increase x every time;
  - T2: when x is larger than 99, then set x to 0;

T2 needs to:
lock;
determine;
unlock;
every time to check

```
//thread 1:

while(true)
{
    pthread_mutex_lock(&mutex);
    iCount++;
    pthread_mutex_unlock(&mutex);
}
```

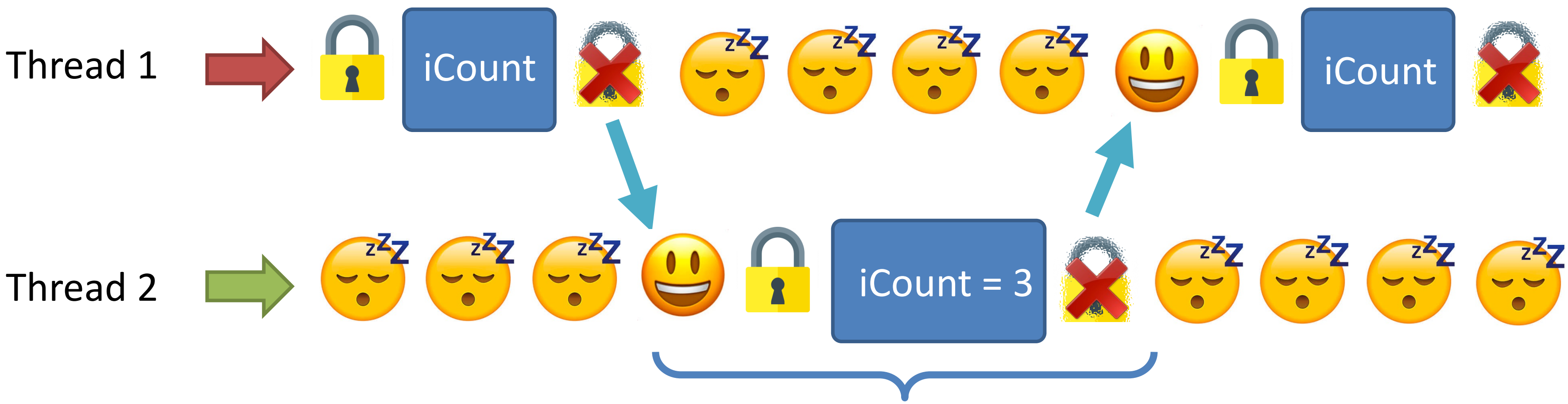
```
//thread 2:
while(true)
{
    pthread_mutex_lock(&mutex);
    if(iCount >= 100)
    {
        iCount = 0;
    }
    pthread_mutex_unlock(&mutex);

}
```

Mutex lock with conditions

```
//thread 1:

while(true)
{
    pthread_mutex_lock(&mutex);
    iCount++;
    pthread_mutex_unlock(&mutex);
}
```

```
//thread 2:
while(true)
{
    pthread_mutex_lock(&mutex);
    if(iCount >= 100)
    {
        iCount = 0;
    }
    pthread_mutex_unlock(&mutex);

}
```

Critical section



Useless, waste of resources

Examples

```c
int iCount = 0;
static pthread_mutex_t mlock;

void *thread1_work(void *id) {
	long tid = (long)id;
	while (1) {
		pthread_mutex_lock(&mlock);
		iCount++;
		printf("thread: %ld iCount: %d\n", tid, iCount);
		pthread_mutex_unlock(&mlock);
		sleep(1);
	}
}

void *thread2_work(void *id) {
	long tid = (long)id;
	while (1) {
		pthread_mutex_lock(&mlock);
		if (iCount >= 100)
			iCount = 0;
		printf("thread: %ld iCount: %d\n", tid, iCount);
		pthread_mutex_unlock(&mlock);
		sleep(1);
	}
}


int main() {
	pthread_t thread1, thread2;
	int id1=1, id2=2;
	if (pthread_mutex_init(&mlock, NULL) != 0) {
		printf("mutex init failed\n");
		return 1;
	}

	pthread_create(&thread1, NULL, thread1_work, (void *)(intptr_t)id1);
	pthread_create(&thread2, NULL, thread2_work, (void *)(intptr_t)id2);

	pthread_exit(NULL);
	pthread_mutex_destroy(&mlock);
	exit(0);
}
```

https://github.com/kevinsuo/CS3502/blob/master/lock_wo_condition.c

```c
//thread 1:

while(true)
{
    pthread_mutex_lock(&mutex);
    iCount++;
    pthread_mutex_unlock(&mutex);
}
```

```c
//thread 2:
while(true)
{
    pthread_mutex_lock(&mutex);
    if(iCount >= 100)
    {
        iCount = 0;
    }
    pthread_mutex_unlock(&mutex);

}
```

Pthread_cond_signal and Pthread_cond_wait

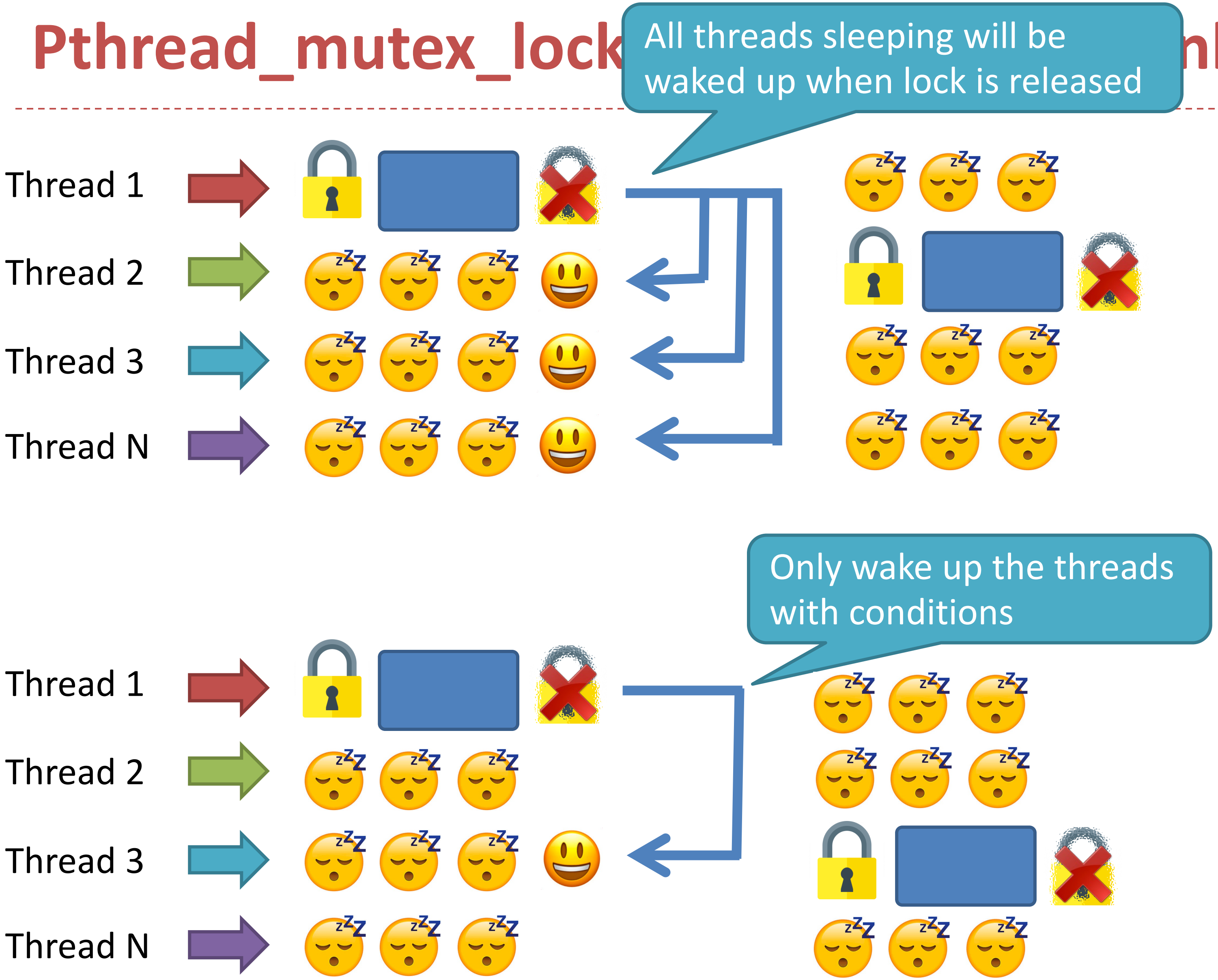
Release the lock
Sleep here until condition is reached

- Pthread_cond_wait(&condition, &lock)

- Pthread_cond_signal(&condition)

When condition is reached,
notify all threads waiting for it

Pthread_cond_signal/Pthread_cond_wait v.s. Pthread_mutex_lock nlock



Condition variable

- How about competition with condition variables?
  - Example: T1: increase x every time;
  - T2: when x is larger than 99, then set x to 0;

```
//thread1 :
while(true)
{
    pthread_mutex_lock(&mutex);
    iCount++;
    pthread_mutex_unlock(&mutex);

    pthread_mutex_lock(&mutex);
    if(iCount >= 100)
    {
        pthread_cond_signal(&cond);
    }
    pthread_mutex_unlock(&mutex);
}
```

```
//thread2:
while(1)
{
    pthread_mutex_lock(&mutex);
    while(iCount < 100)
    {
        pthread_cond_wait(&cond, &mutex);
    }
    printf("iCount >= 100\r\n");
    iCount = 0;
    pthread_mutex_unlock(&mutex);
}
```

When T2 executes here:
1: release mutex
2: blocked here
3: when waked, get mutex and execute


//thread1 :
while(true)
{
pthread_mutex_lock(&mutex);
iCount++;
pthread_mutex_unlock(&mutex);
pthread_mutex_lock(&mutex);
if(iCount >= 100)
{
pthread_cond_signal(&cond);
}
pthread_mutex_unlock(&mutex);
}
1. Get the
2. release the
3. Get the
4. release the
//thread2:
while(1)
{
pthread_mutex_lock(&mutex);
while(iCount < 100)
{
pthread_cond_wait(&cond, &mutex);
}
printf("iCount >= 100\r\n");
iCount = 0;
pthread_mutex_unlock(&mutex);
}
1. Get the
2. release the
3. Get
4. release the
3. Wake up
T2 needs to:
lock;
determine;
unlock;
every time to check
//thread 1:
while(true)
{
pthread_mutex_lock(&mutex);
iCount++;
pthread_mutex_unlock(&mutex);
}
1.
2. Release the
//thread 2:
while(true)
{
pthread_mutex_lock(&mutex);
if(iCount >= 100)
{
iCount = 0;
}
pthread_mutex_unlock(&mutex);
}

Condition variable example

https://github.com/kevinsuo/CS3502/blob/master/lock_w_condition.c

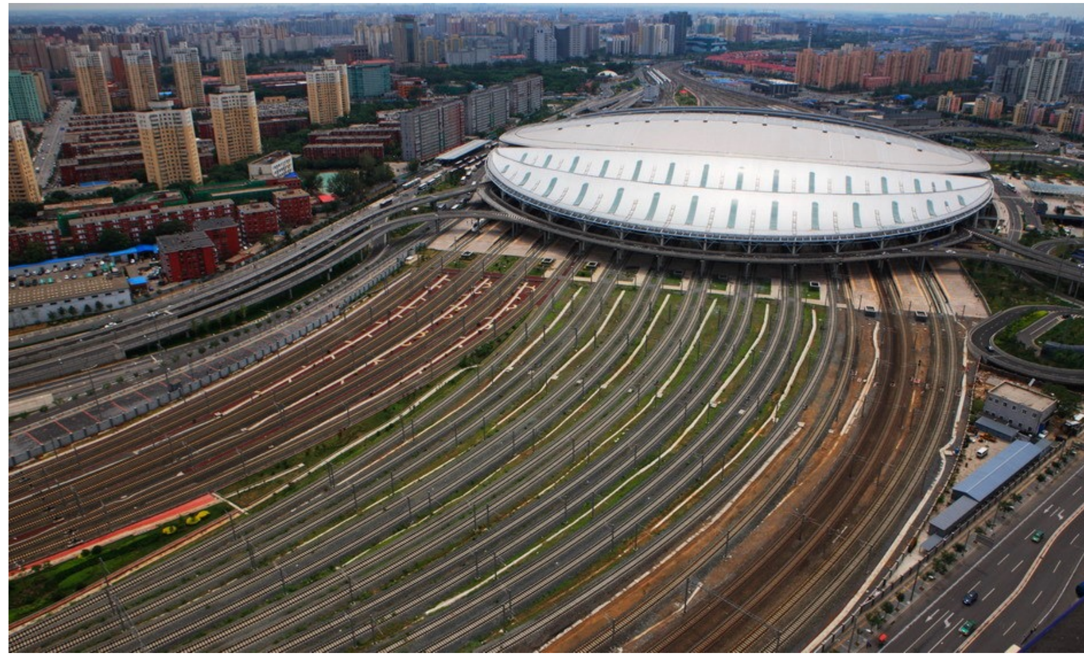
```
int iCount = 0;
static pthread_mutex_t mlock;
static pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

void *thread1_work(void *id) {
        long tid = (long)id;
        while (1) {
                pthread_mutex_lock(&mlock);
                iCount++;
                printf("thread: %ld iCount: %d\n", tid, iCount);
                pthread_mutex_unlock(&mlock);

                pthread_mutex_lock(&mlock);
                if (iCount >= 100) {
                        pthread_cond_signal(&cond);
                        printf("thread: %ld iCount: %d\n", tid, iCount);
                }
                pthread_mutex_unlock(&mlock);
                sleep(1);
        }
}

void *thread2_work(void *id) {
        long tid = (long)id;
        while (1) {
                pthread_mutex_lock(&mlock);
                if (iCount < 100) {
                        pthread_cond_wait(&cond, &mlock);
                }
                iCount = 0;
                printf("thread: %ld iCount: %d\n", tid, iCount);
                pthread_mutex_unlock(&mlock);
                sleep(1);
        }
}
```

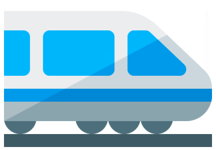
```
//thread1 :
while(true)
{
    pthread_mutex_lock(&mutex);
    iCount++;
    pthread_mutex_unlock(&mutex);

    pthread_mutex_lock(&mutex);
    if(iCount >= 100)
    {
        pthread_cond_signal(&cond);
    }
    pthread_mutex_unlock(&mutex);
}
```

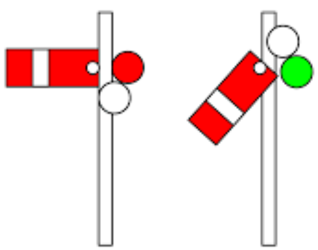
```
//thread2:
while(1)
{
    pthread_mutex_lock(&mutex);
    while(iCount < 100)
    {
        pthread_cond_wait(&cond, &mutex);
    }
    printf("iCount >= 100\r\n");
    iCount = 0;
    pthread_mutex_unlock(&mutex);
}
```

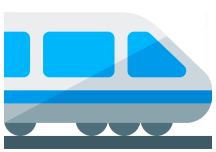
4. Semaphore

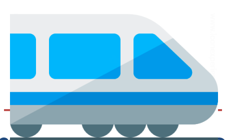
a system of sending messages by holding the arms or two flags in certain positions





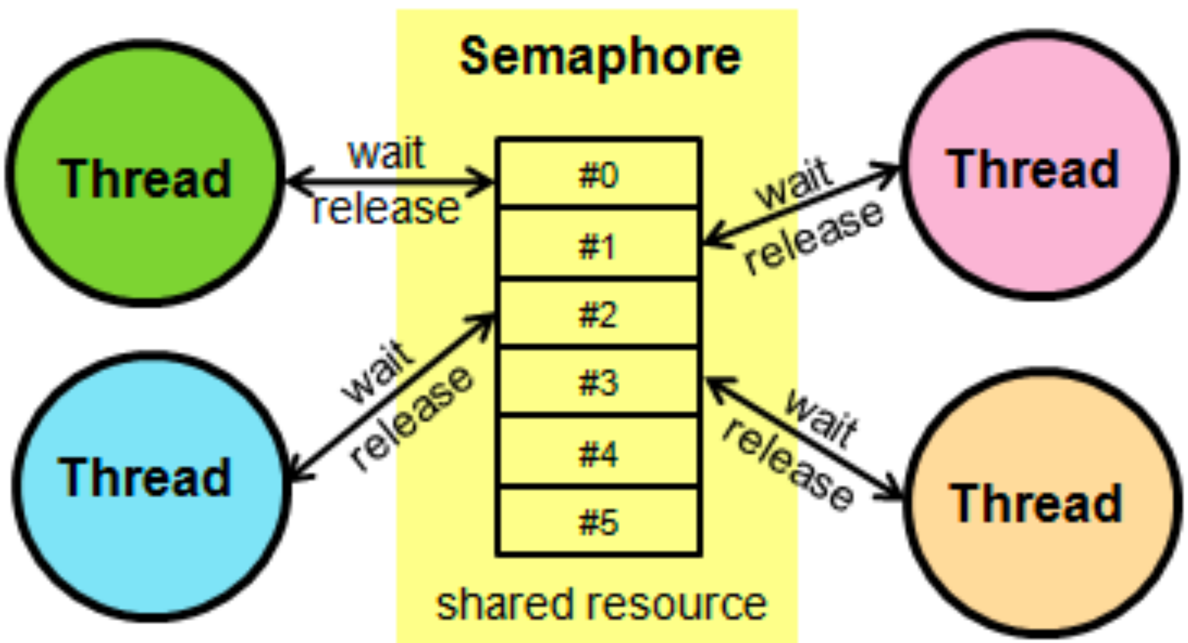






4. Semaphore

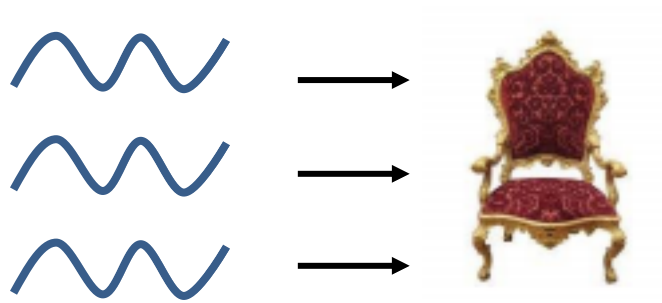
- Semaphore is a variable used to control access to shared resources by multiple processes/threads



Mutex lock and Semaphore

threads

Mutex = 0 or 1

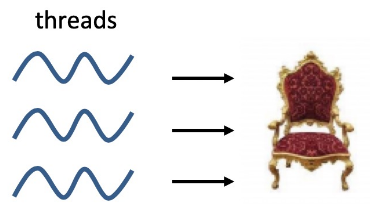


threads

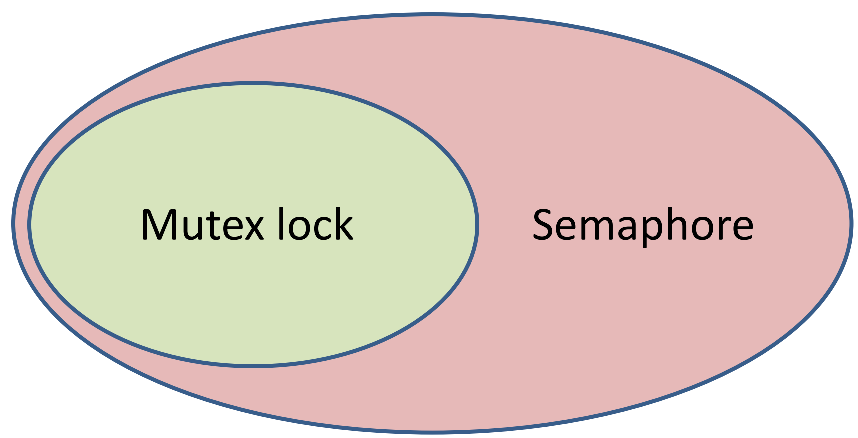
Sem = 0/1/2/3

Mutex lock and Semaphore

Mutex = 0 or 1



Sem = 0/1/2/3

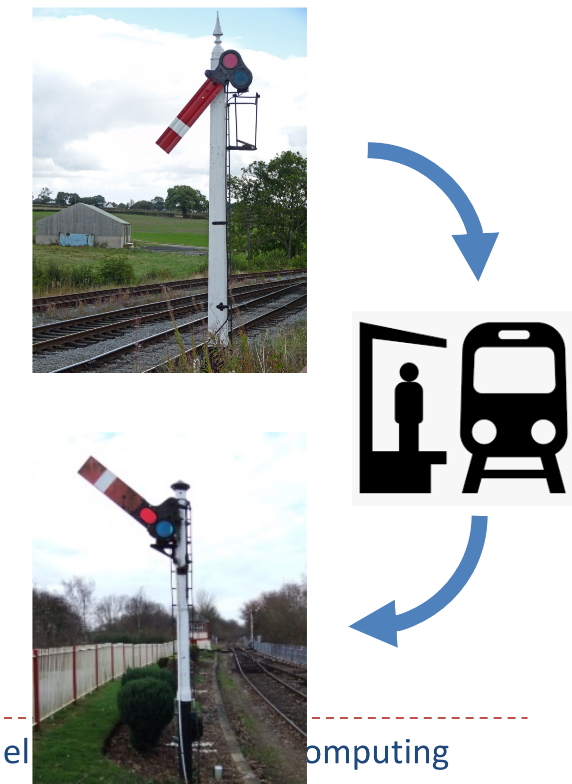


Semaphore

- A semaphore "sem" is a special integer on which only two operations can be performed.
  - DOWN(sem)
  - UP(sem)

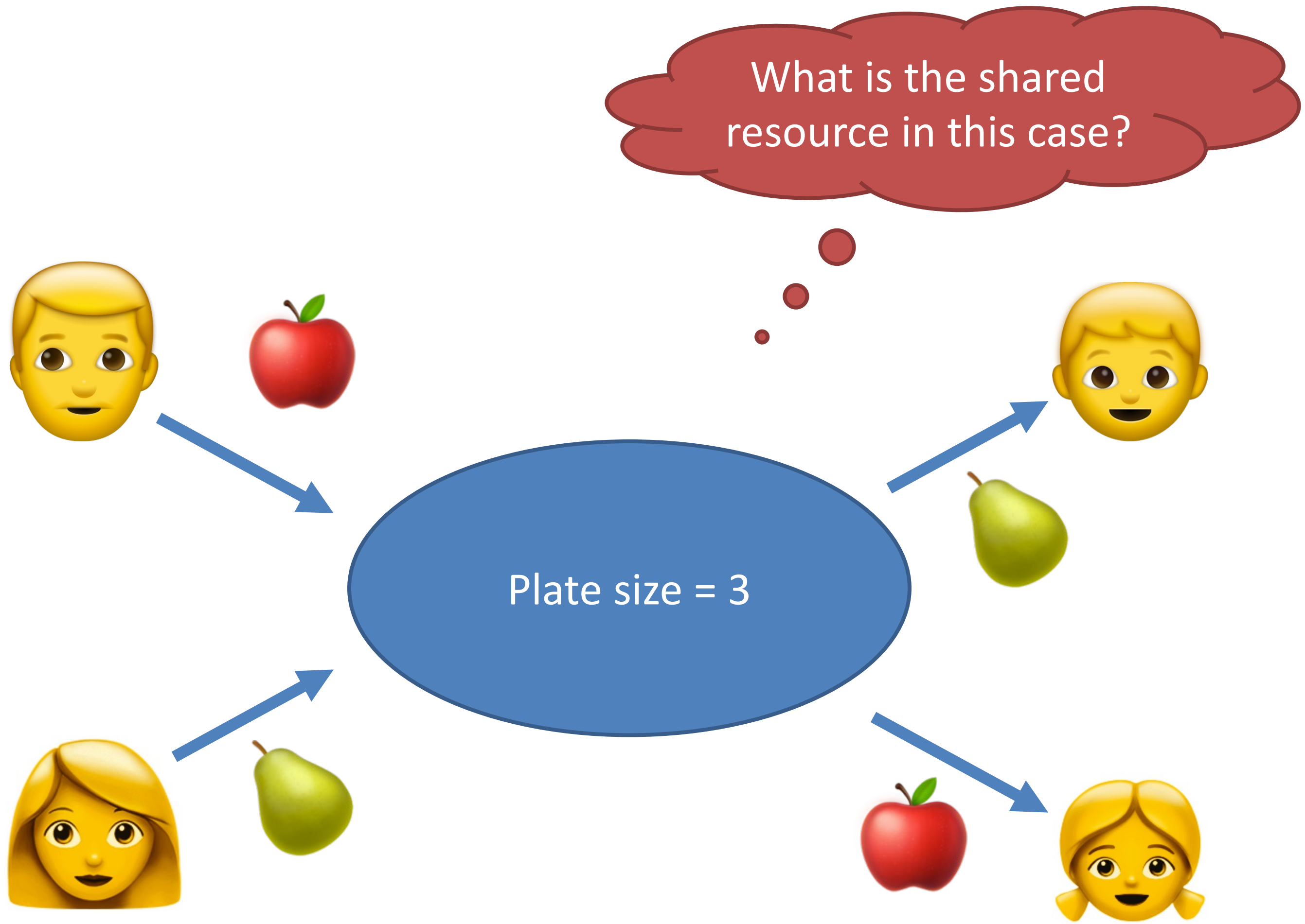
- Down operation (P; request):
  - Checks if a semaphore is > 0, sem--
    - Request one-unit resource and one process enters
  - if a semaphore <= 0, wait and sleep

- Up operation (V; release)
  - sem++
    - Release one-unit resource and one process leaves



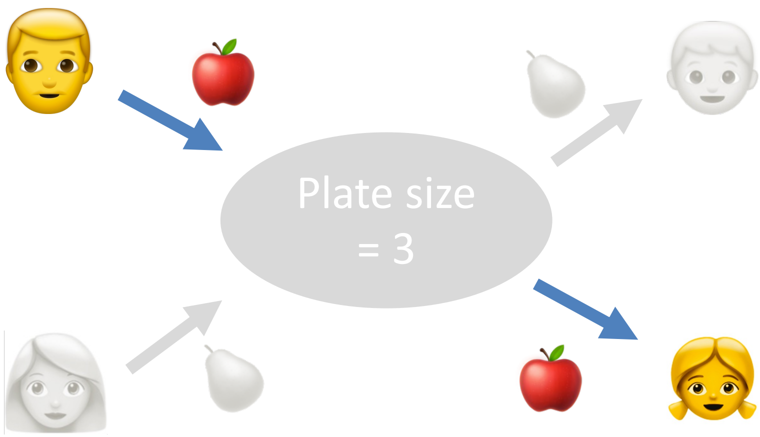
Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c



Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c



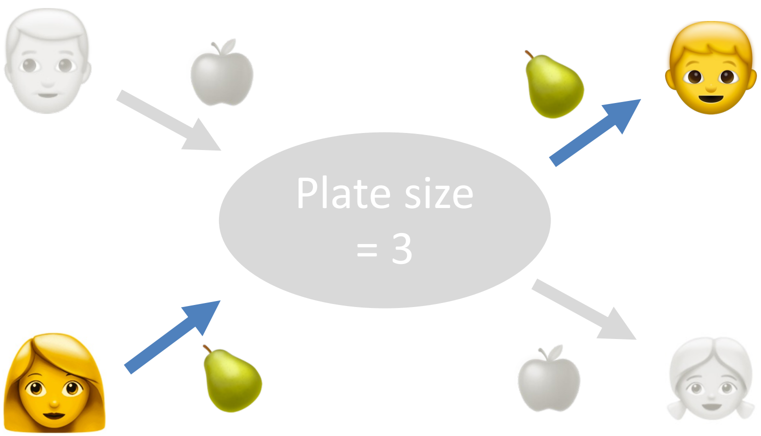
- Semaphore of apple (s2):
  - Daughter: request apple
  - Father: release the apple

Father thread:
    peel apple
    put apple
    V(s2)

Daughter thread:
    P(s2)
    get apple
    eat apple

Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c



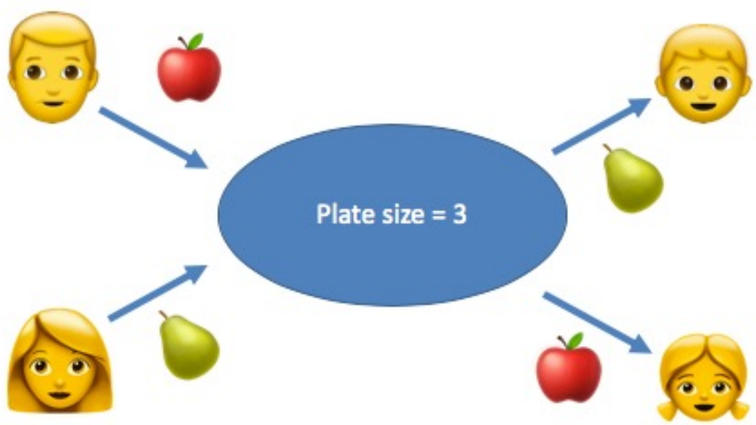
- Semaphore of pear (s1):
  - Son: request pear
  - Mather: release the pear

Mother thread:
    peel pear
    put apple
    V(s1)

Son thread:
    P(s1)
    get pear
    eat pear

Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c

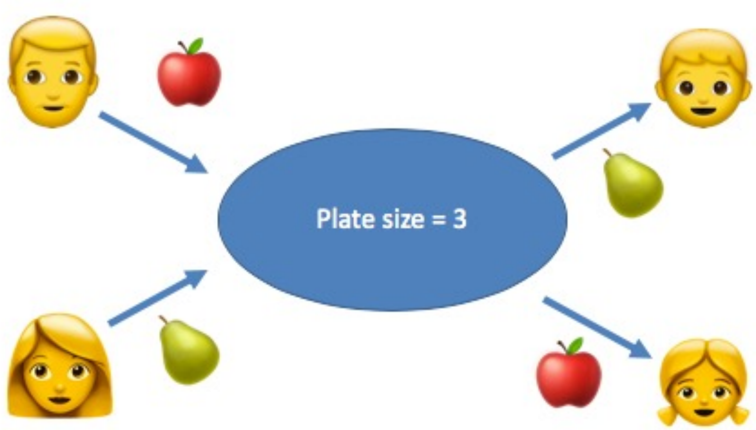


- Semaphore of plate (s3):
  - Son/Daughter: release the space
  - Father/Mother: request the space

Father thread:	Mother thread:	Son thread:	Daughter thread:
peel apple	peel pear	get pear	get apple
P(s3)	P(s3)	V(s3)	V(s3)
put apple	put apple	eat pear	eat apple

Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c



- Semaphore:
  - Son: whether there is pear, s1
  - Daughter: whether there is apple, s2
  - Father/Mother: whether there is space, s3

Father thread:
- peel apple
- P(s3)
- put apple
- V(s2)

Mother thread:
- peel pear
- P(s3)
- put apple
- V(s1)

Son thread:
- P(s1)
- get pear
- V(s3)
- eat pear

Daughter thread:
- P(s2)
- get apple
- V(s3)
- eat apple

Semaphore example

https://github.com/kevinsuo/CS7172/blob/master/semaphore.c

- Semaphore:
  - Son: whether there is pear, pear
  - Daughter: whether there is apple, apple
  - Father/Mother: whether there is space, remain

Father thread:
peel apple
P(remain)
put apple
V(apple)

Daughter thread:
P(apple)
get apple
V(remain)
eat apple

```
void *father(void *arg) {
        while(1) {
                sleep(5);  //simulate peel apple
P(s3)           sem_wait(&remain);
                sem_wait(&mutex);
                nremain--;
                napple++;
                sem_post(&mutex);
V(s2)           sem_post(&apple);
        }
}
```

```
void *daughter(void *arg) {
        while(1) {
P(s2)           sem_wait(&apple);
                sem_wait(&mutex);
                nremain++;
                napple--;
                sem_post(&mutex);
V(s3)           sem_post(&remain);
                sleep(10); //simulate eat apple
        }
}
```

Semaphore example

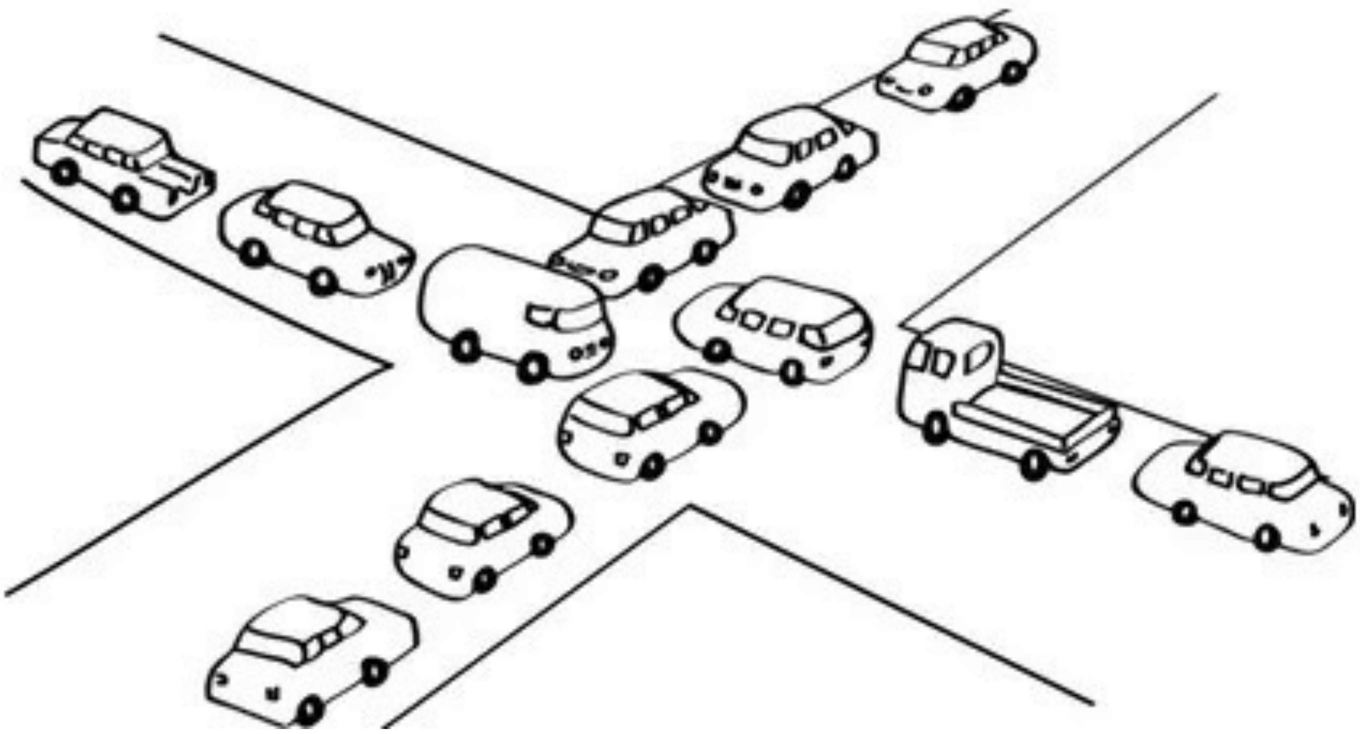
https://github.com/kevinsuo/CS7172/blob/master/semaphore.c

```
pi@raspberrypi ~/Downloads> ./semaphore.o
father  👨 before put apple, remain=3, apple🍎=0, pear🍐=0
father  👨 after  put apple, remain=2, apple🍎=1, pear🍐=0

daughter👧 before eat apple, remain=2, apple🍎=1, pear🍐=0
daughter👧 after  eat apple, remain=3, apple🍎=0, pear🍐=0

mother  👩 before put pear , remain=3, apple🍎=0, pear🍐=0
mother  👩 after  put pear , remain=2, apple🍎=0, pear🍐=1

son     👦 before eat pear , remain=2, apple🍎=0, pear🍐=1
son     👦 after  eat pear , remain=3, apple🍎=0, pear🍐=0

father  👨 before put apple, remain=3, apple🍎=0, pear🍐=0
father  👨 after  put apple, remain=2, apple🍎=1, pear🍐=0

mother  👩 before put pear , remain=2, apple🍎=1, pear🍐=0
mother  👩 after  put pear , remain=1, apple🍎=1, pear🍐=1

daughter👧 before eat apple, remain=1, apple🍎=1, pear🍐=1
daughter👧 after  eat apple, remain=2, apple🍎=0, pear🍐=1

father  👨 before put apple, remain=2, apple🍎=0, pear🍐=1
father  👨 after  put apple, remain=1, apple🍎=1, pear🍐=1

son     👦 before eat pear , remain=1, apple🍎=1, pear🍐=1
son     👦 after  eat pear , remain=2, apple🍎=1, pear🍐=0

mother  👩 before put pear , remain=2, apple🍎=1, pear🍐=0
mother  👩 after  put pear , remain=1, apple🍎=1, pear🍐=1

father  👨 before put apple, remain=1, apple🍎=1, pear🍐=1
father  👨 after  put apple, remain=0, apple🍎=2, pear🍐=1

daughter👧 before eat apple, remain=0, apple🍎=2, pear🍐=1
daughter👧 after  eat apple, remain=1, apple🍎=1, pear🍐=1
```

gcc -pthread semaphore.c -o semaphore.o

https://youtu.be/ZIWwvcuROME

Deadlocks

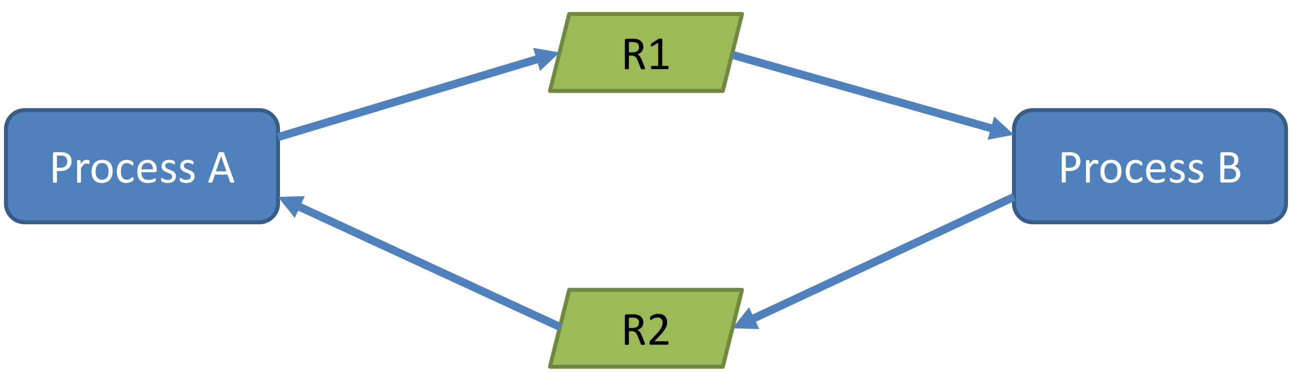


Deadlocks: philosopher dining

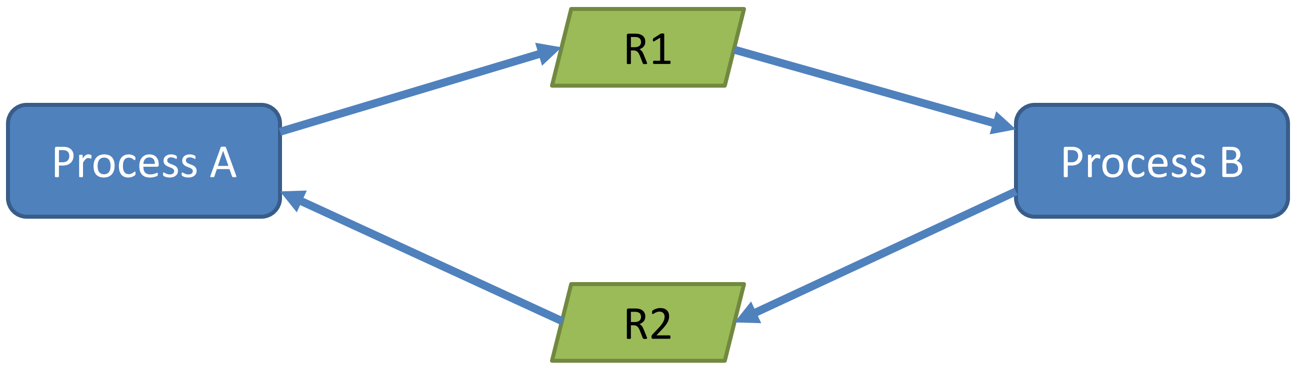
- Six people
- Three folks
- Three knives

Deadlocks

- When two or more threads stop making progress indefinitely because they are **all waiting for each other** to do something.
  - If process A waits for process B to release a resource, and
  - Process B is waiting for process A to release another resource at the same time.
  - In this case, neither A not B can proceed because both are waiting for the other to proceed.



Deadlock example



Thread 1

```
pthread_mutex_lock(&R1);
/* use resource 1 */
pthread_mutex_lock(&R2);
/* use resources 1 and 2 */
do_something();
pthread_mutex_unlock(&R2);
pthread_mutex_unlock(&R1);
```

Stuck right here

Thread 2

```
pthread_mutex_lock(&R2);
/* use resource 2 */
pthread_mutex_lock(&R1);
/* use resources 1 and 2 */
do_something();
pthread_mutex_unlock(&R1);
pthread_mutex_unlock(&R2);
```

A Joke about Deadlock

Deadlock example: Priority Inversion

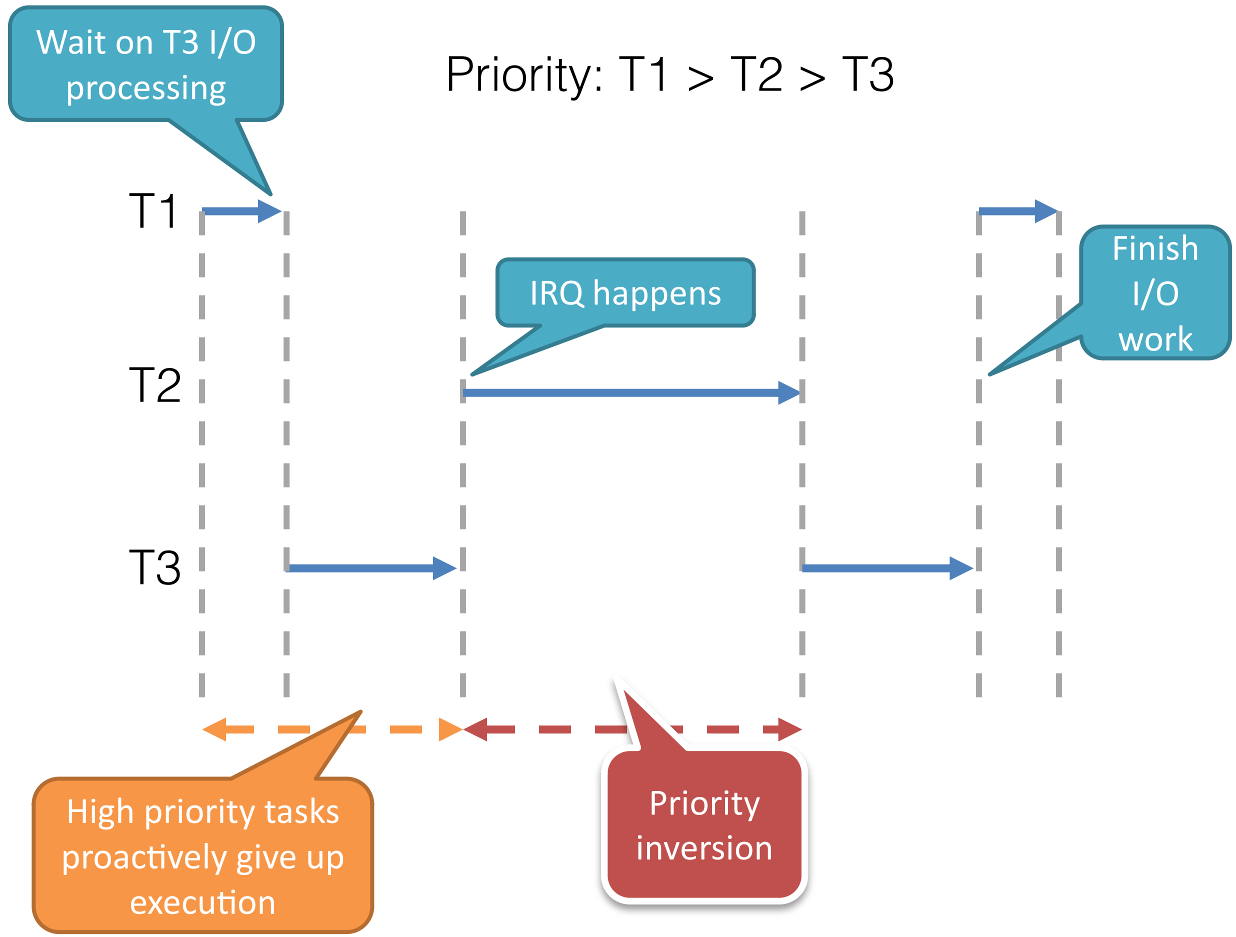
https://www.youtube.com/watch?v=lyx7kARrGeM

https://www.youtube.com/watch?v=t9RM5xcNUak

https://www.rapitasystems.com/blog/what-really-happened-to-the-software-on-the-mars-pathfinder-spacecraft

1997/07/04 Pathfinder —> Mars

Priority: T1 > T2 > T3



Conclusion

- Concurrency and synchronization
  - Execution models
  - Race condition
  - Critical section
- Mutual exclusion
  - Spinlock
  - Mutex lock
  - Semaphore
  - Deadlock and priority inversion