Lecture Notes for Lecture 11 of CS 5600 (Computer Systems) for the Fall 2019 session at the Northeastern University Silicon Valley Campus.

Threads and Concurrency

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Acknowledgements:
These slide highlight content from suggested readings.

Lecture 10 Review

- In this lecture, we explored the low-level C language *unbuffered I/O* functions that enables writing and reading information directly to and from files. Each call function is a call to the operating system.
- We also learned about a higher-level access mechanism known as *buffered I/O* that buffers information before writing or reading it to or from the file system to improve I/O efficiency.
- Next we looked at block-oriented methods of writing and reading information to and from the disk as blocks rather than streams, which enables dealing with structs and arrays.
- Finally, we will saw how to access information in specific parts of a file using random-access I/O functions.

Threads and Concurrency

- Up until now, programs we have written performed just a single task at a time and exit when the task was complete.
- Today's lecture will present a model of computing where a program can perform multiple tasks at the same time, and coordinate the actions of these tasks.
- Tasks can begin and end during the execution of a program as required, and a task that completes does not result in the program exiting.
- The mechanism we will study that accomplishes this is known as a *thread*, and each task is called a *thread of execution*. A program that operates in this way is called multi-threaded.
- In this lecture we will study how threads work, how they can be used, and how to implement them in C and C++.

Threads and Concurrency

Processes

- When a program is run, the operating system creates a process that executes the program.
- A process is like a virtual computer with its own address space, executable code, open file handles, environment variables, and other resources.
- Each process is started with a single thread of execution, often called the *main thread*. and can create additional threads from any of its threads.

Threads and Concurrency

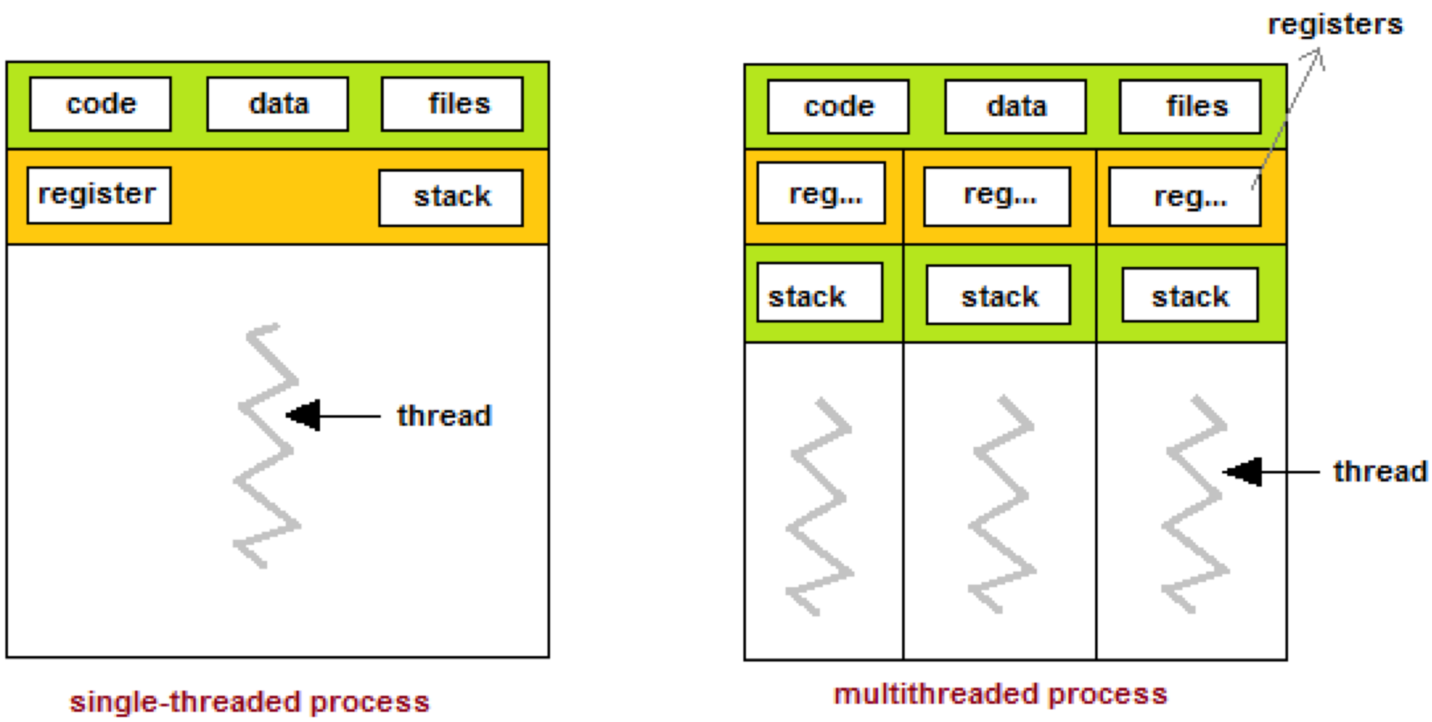
Processes

- All threads of a process share its virtual address space and system resources.
- Each thread maintains exception handlers, a scheduling priority, thread local storage, a thread ID, and structures the system uses to save the thread context until it is scheduled.
- The thread context includes the thread's machine registers, the kernel stack, a thread environment block, and a user stack in the address space of the thread's process.

Threads and Concurrency

Processes

- Here is a diagram of single- and multi-threaded processes.



Threads and Concurrency

Types of Threads

- There are two types of threads :
  - *Kernel threads* are implementation-dependent kernel resources that are entirely managed by the operating system scheduler.
  - *User threads* have a standard interface, operate entirely within a process, and are used to handle multiple flows of control within a running program.

Threads and Concurrency

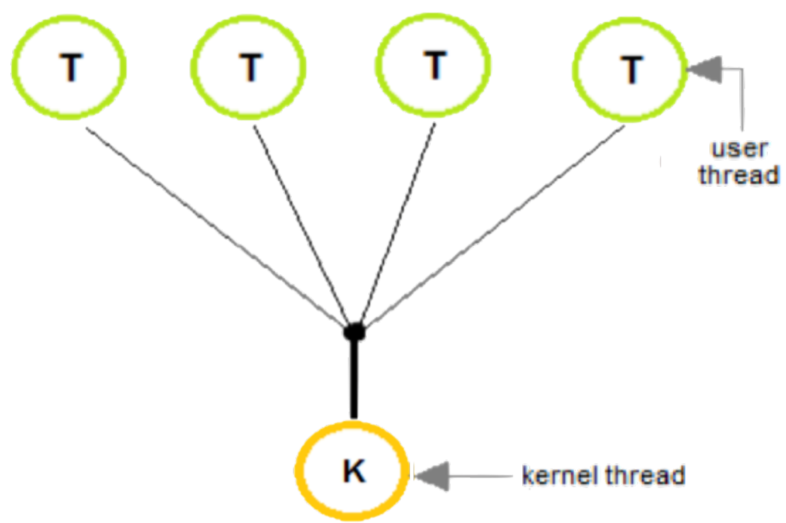
Types of Threads

- When a process needs to run a thread, it can manage the thread of execution itself, or “borrow” a kernel thread to run the process thread.
- Processes can have many threads, but kernel threads are limited, so user threads share kernel threads using one of the following strategies:
  - Many-to-One Model
  - One-to-One Model
  - Many-to-Many Model

Threads and Concurrency

Types of Threads

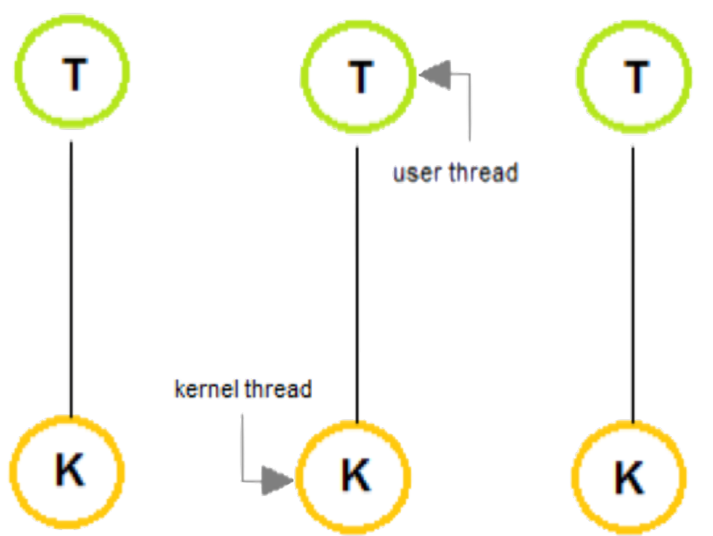
- In the many-to-one model, many user-level threads are all mapped onto a single kernel thread.
- Thread management is handled by a thread library entirely in user space, which is efficient in nature because no operating system calls are required.



Threads and Concurrency

Types of Threads

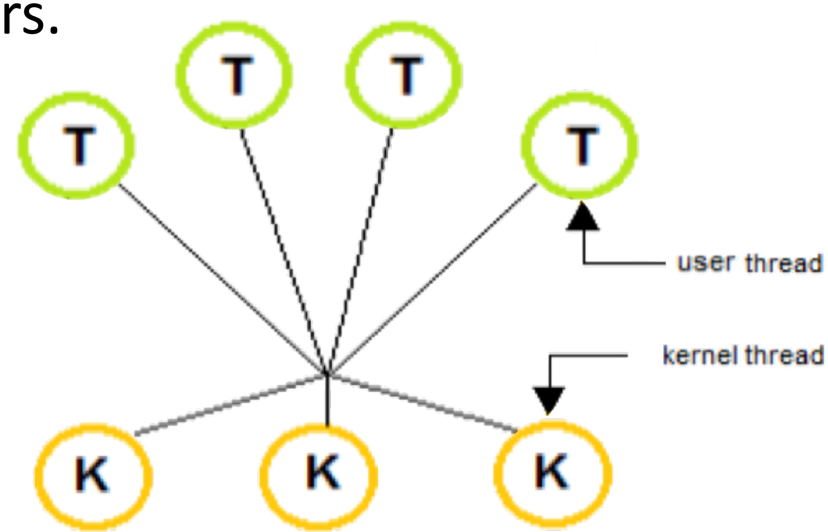
- A one-to-one model creates separate kernel thread for each and every user thread.
- Linux, and Windows from 95 to XP, implement this model. Most implementations limit how many threads can be created.



Threads and Concurrency

Types of Threads

- Multiplexes user threads onto an equal or smaller number of kernel threads, combining the best features of the one-to-one and many-to-one models.
- Users can create any number of threads. Kernel system calls do not block the entire process. Processes can be split across multiple processors.



Threads and Concurrency

Preemptive vs. Cooperative Threads

- Cooperative threads are also called non-preemptive threads. Cooperative threads have exclusive use of the CPU until they give it up. The scheduler then picks another thread to run.
- Preemptive threads can voluntarily give up the CPU but when they do not, the scheduler can take control from them and start another thread.
- Cooperative threads have greater efficiency (on single-core machines, at least) and easier handling of concurrency: it only exists when you yield control, so locking isn't required.
- Preemptive threads are more fault tolerance: failing to yield does not block other threads. They also work better on multi-core machines, and, you don't have to constantly yield.

Threads and Concurrency

Managed vs. Daemon Threads

- A thread is said to be *managed* if the state of the thread can be directly controlled either by the thread that created it or from any other thread in the process.
- Managed threads run ”in the foreground” and perform tasks in coordination with other threads in the process.
- A thread is said to be a *daemon* if the thread is *detached* or runs independently of other threads, and is not controlled by any other thread in the process.
- Daemon threads run “in the background” and once started, perform tasks that require no further external control.

Threads and Concurrency

Benefits of Multi-Threading

- Benefits of multi-threaded programs include:
  - More responsiveness because users can interact with a the program while processing also takes place
  - Better resource utilization because different parts of a program can utilize different resources concurrently.
  - Allows different threads of a program to be distributed over multiple processors.
  - Context switching is smooth because switching between threads in a process is more efficient than switching between processes.

Threads and Concurrency

Examples of Threaded Systems

- Threads play a critical role in a number of both large and small scale systems, including:
  - Producer/consumer and queueing systems
  - Data-centric systems like databases
  - Web browsers and web servers
  - Distributed and peer-to-peer systems
  - Cell phone operating systems like iOS & Android

Threads and Concurrency

User Thread Libraries

- Thread libraries provides programmers with API for creating and managing of threads.
- May be implemented either in user space or in kernel space.
  - The user space involves API functions implemented solely within user space, with no kernel support.
  - The kernel space involves system calls, and requires a kernel with thread library support.

Threads and Concurrency

User Thread Libraries

- We will study POSIX *pthreads* available on most Unix-based systems.
- Pthreads defines a set of C programming language types, functions and constants. It is implemented with a pthread.h header and a thread library.

Threads and Concurrency

User Thread Libraries

- There are around 100 pthread procedures, all prefixed by pthread_. They are categorized into four groups:
  - Thread management - creating, joining threads etc.
  - Mutexes
  - Condition variables
  - Synchronization between threads using read/write locks and barriers
- The POSIX semaphore API works with POSIX threads but is part of the POSIX.1b Real-time extensions (IEEE Std 1003.1b-1993) standard. Semaphore procedures are prefixed by sem_.

Threads and Concurrency

Example: C Posix Thread Library

```
/** data shared by the thread */
int sum;

/**
 * This function reads a non-negative value parameter
 * and runs a thread that sets global sum to the sum of
 * numbers between 1 and that value.
 */
int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, ”main(): usage: %s max_value\n", argv[0]);
        return EXIT_FAILURE;
    }
    int maxval = atoi(argv[1]);
    if (maxval < 0) {
        fprintf(stderr, ”main(): %d must be >= 0\n", maxval);
        return EXIT_FAILURE;
    }
```

Threads and Concurrency

Example: C Posix Thread Library

```
// initialize thread attributes
pthread_attr_t attr;    // set of thread attributes
pthread_attr_init(&attr);

// create the thread
pthread_t tid;
printf("main(): running thread to compute sum from 1 to %d\n", maxval);
int status = pthread_create(&tid, &attr, runner, &maxval);
if (status != 0) {
      fprintf(stderr, "thread not created: error=%d", status);
      return EXIT_FAILURE;
}
printf("main(): created thread %lu: waiting for it to exit\n", (unsigned long)tid);
```

Threads and Concurrency

Example: C Posix Thread Library

```
    // wait for thread to exit
    void *sumptr;
    status = pthread_join(tid, &sumptr);  // result also returned here
    if (status != 0) {
        fprintf(stderr, "thread exited with status %d\n", status);
        return EXIT_FAILURE;
    }

    // report sum
    printf("main(): thread %lu exited normally\n", (unsigned long)tid);
    printf(”main(): global sum = %d\n", sum);
    if (sumptr != NULL) {
        printf(”main(): thread returned sum = %d\n", *(int*)sumptr);
    }
    return EXIT_SUCCESS;
}
```

Threads and Concurrency

Example: C Posix Thread Library

```
/**
 * Thread begins control in this function, which computes the sum
 * of the integers between 1 and the value of the input parameter.
 * @param param the integer pointed to by param
 * @return pointer to result value (unused)
 */
void *runner(void *param) {
	sum = 0;  // initialize global

	int upper = *(int*)param;
	for (int i = 1; i < upper; i++) {
		sum += i;
	}

	pthread_t tid = pthread_self();
	printf("runner() [thread %lu]: sum is %d\n", (unsigned long)tid, sum);

	// return pointer to sum that pthread_join can retrieve
	pthread_exit(&sum);  // or return pointer to sum
}
```

Threads and Concurrency

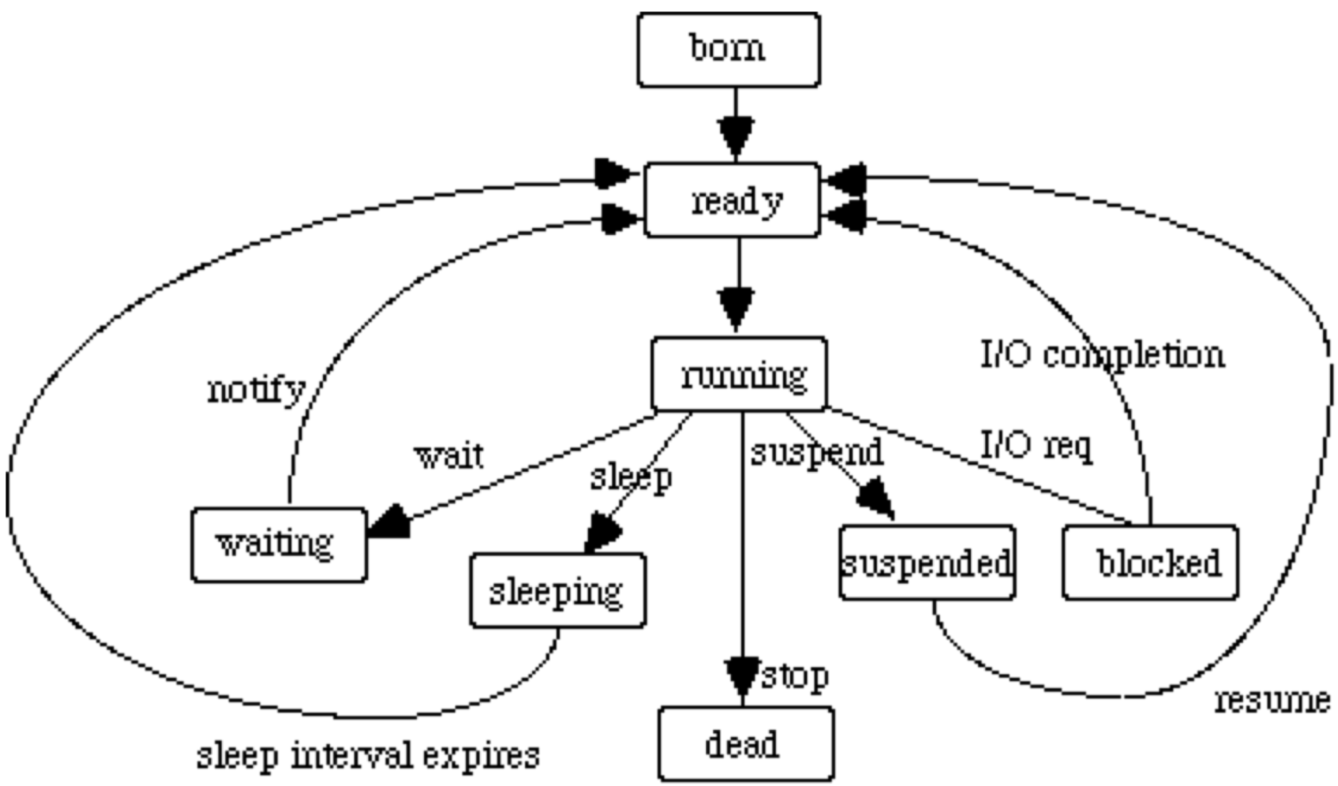
Lifecycle of a Thread

- Threads go through a number of transitions from one state to another as they are created, initialized, run, complete, and are destroyed.
- As threads to from one state to another they follow a regular set of paths that are know as *state transitions*.
- The set of states and the state transitions they follow can be represented in a graph know as a *state transition diagram*.

Threads and Concurrency

Lifecycle of a Thread

- Here is a state transition diagram for a thread's lifecycle.



Threads and Concurrency

Lifecycle of a Thread

- A thread runs until it is swapped out for another thread (going back to the ready state) or until one of the following happens:
  - If it runs to completion or a "stop" message is sent to it, then it moves to a "dead" state.
  - If it issues an I/O request, it moves to a blocked state until the I/O request is completed, and then moves to the "ready" state again.
  - If a "sleep(n)" is called on it, then it waits for at least n milliseconds, and then returns to the ready state. Used when want fixed delay time.

Threads and Concurrency

Lifecycle of a Thread

- If a "suspend" message is sent to it, then it stays in the "suspended" state until a resume message is sent to it.
- If a wait message is sent to it, then it goes into the "waiting" state where it waits in a queue.
- The first item in the wait queue goes into the "ready" state on a call to notify by another thread associated with the object.
- A call of notifyAll puts all of the threads on the wait queue in the "ready" state. Used when don't know who is waiting to proceed.

Threads and Concurrency

Lifecycle of a Thread

- Most thread systems allow a program to ask a thread if it is still alive and whether it can be joined.
- It is hard to suspend a thread if it is busy.
  - As a result, often have a method that sets a flag that can then be checked each time through the loop to see if want to suspend.
  - The thread can then suspend itself, though it will be "resumed" from outside.

Threads and Concurrency

Concurrency and Synchronization

- So far, we have seen a simple case of multi-threading where a main thread creates and runs a second thread while the main thread waits for it to complete.
- In this case, there is little need for the two threads to coordinate their execution, or guard against one thread writing data that interferes with the other one using it.
- In real-world multi-threaded programs threads must gain exclusive access to data at times, while cooperating to produce data for other threads to read.
- We will next consider the problem of concurrency and synchronization, and the tools for implementing them.

Threads and Concurrency

Concurrency and Synchronization

- *Synchronization* refers to one of two distinct but related concepts: synchronization of tasks and of data.
    - *Task synchronization* refers to multiple tasks coordinating based on some shared state, to ensure that the state of one task matches with the state of another one.
    - *Resource synchronization* refers to multiple tasks coordinating on some shared resource to ensure orderly and consistent access to the resource.

Threads and Concurrency

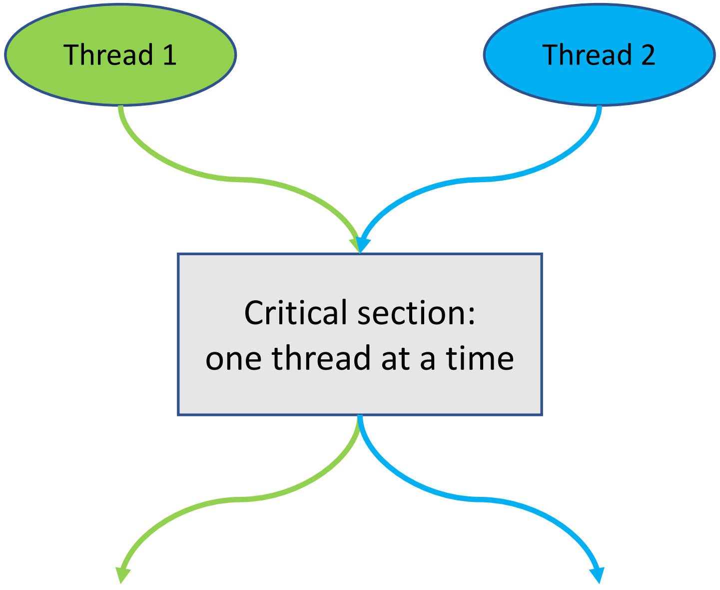
Concurrency and Synchronization

- Task synchronization is a mechanism that ensures two or more concurrent threads do not simultaneously execute a particular program segment known as *critical section*.
- When one thread starts executing the critical section (serialized segment of the program) the other thread should wait until the first thread finishes.
- A thread's access to critical section is controlled by using synchronization techniques.

Threads and Concurrency

Concurrency and Synchronization

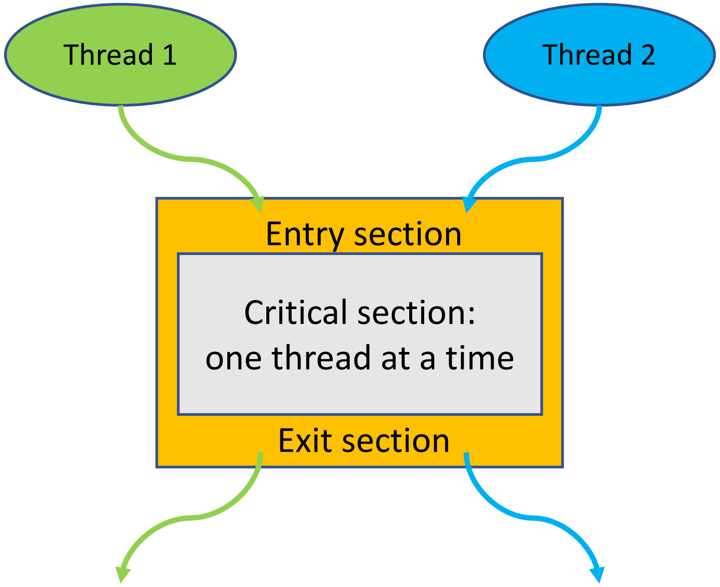
- Task synchronization: multiple threads should not be in a critical section of code at the same time.



Threads and Concurrency

Concurrency and Synchronization

- Task synchronization: multiple threads should not be in a critical section of code at the same time.



Threads and Concurrency

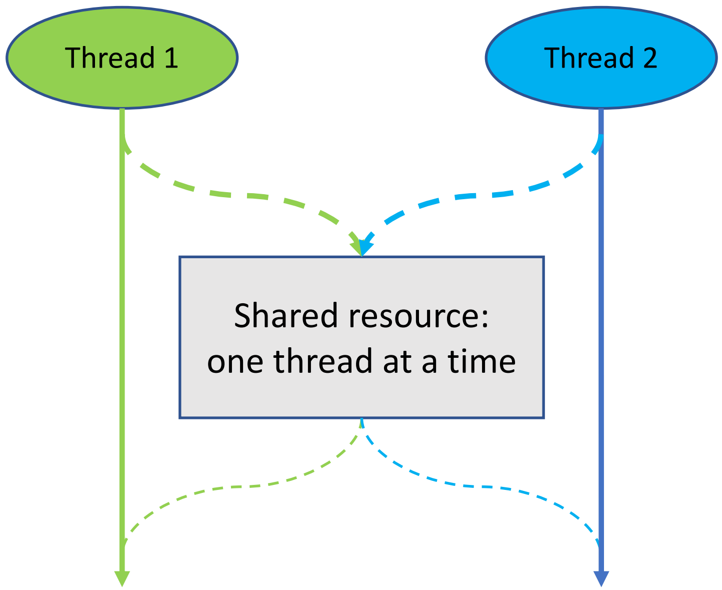
Concurrency and Synchronization

- Resource synchronization is a mechanism that ensures two or more concurrent threads do not simultaneously access a shared resource at the same time
- When one thread gains access to a shared resource, the other thread should wait until the first thread finishes before accessing it.
- A thread’s access to a shared resource is controlled by using synchronization techniques.

Threads and Concurrency

Concurrency and Synchronization

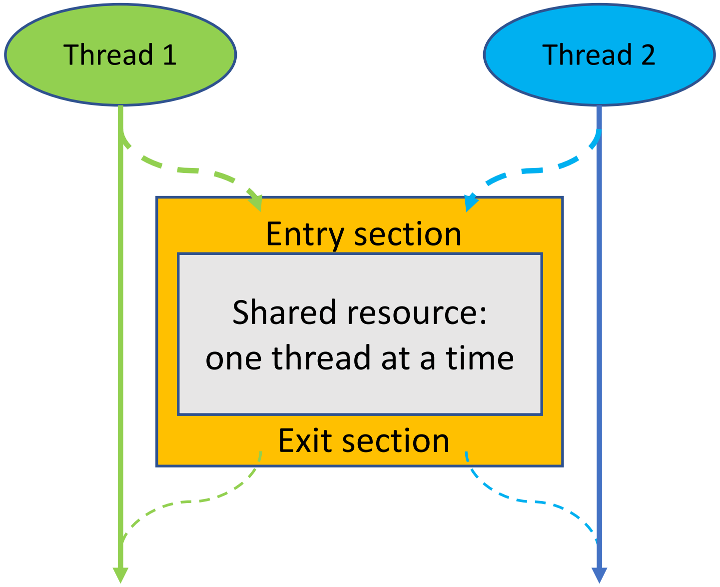
- Resource synchronization: multiple threads should not access a critical resource at the same time.



Threads and Concurrency

Concurrency and Synchronization

- Resource synchronization: multiple threads should not access a critical resource at the same time.



Threads and Concurrency

Synchronization Techniques

- Semaphores (1960s)
  - Introduced by Dutch computer scientist Edsger Dijkstra
  - Mutual exclusion primitives of early operating systems.
- Monitors (1970s)
  - Proposed independently by British computer scientist Tony Hoare and by Danish-American computer scientist Per Brinch Hansen.
  - Provides both mutual exclusion and the ability to wait (block) for a certain condition to become true.

Threads and Concurrency

Synchronization Techniques: Semaphore

- A semaphore provides mutual exclusion for executing a block of code or for locking access to a shared resource.
- A semaphore is implemented as a non-negative integer variable with two atomic and isolated operations: Passieren()/down() and Vrijgeven()/up()
  - P()/down() if semaphore value > 0, decrements semaphore and proceeds; otherwise waits until it is possible to decrement.
  - V()/up() increments semaphore; if value > 0 another waiter on P() can proceed to lock semaphore.

Threads and Concurrency

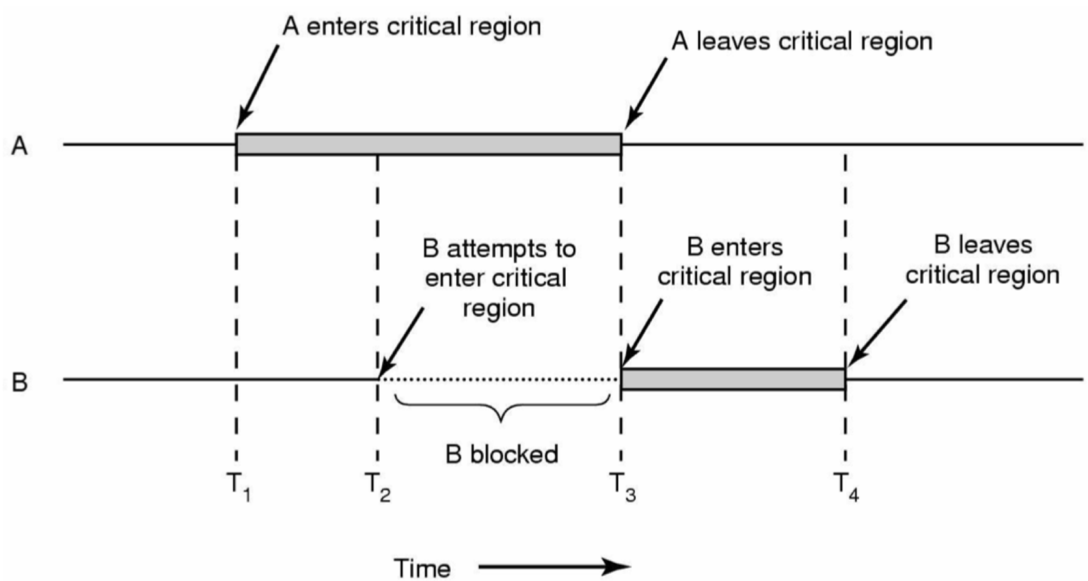
Synchronization Techniques: Semaphore

- Two types of semaphores
  - Binary semaphores: Can either be 0 or 1
  - General/Counting semaphores: any non-negative value.
  - Binary semaphores are as expressive as general semaphores (given one can implement the other)

Threads and Concurrency

Synchronization Techniques: Semaphore

- Semaphores are used both for mutual exclusion, and conditional synchronization



Mutual exclusion using critical regions

Threads and Concurrency

Synchronization Techniques: Semaphore in C

- C pthreads package includes a semaphore primitive that acts as locking mechanism for critical sections.
- **sem_t** is the type descriptor for a semaphore. It is a small integer, similar to a file descriptor for files.
- There are two kinds of semaphores:
  - Unnamed semaphores can be used only by threads belonging to the same process or by processes that share memory
  - Named semaphores has a actual name in the file system and can be shared by multiple unrelated processes.

Note: MacOS has replaced Posix unnamed semaphores with a proprietary mechanism. However, it is possible to substantially implement unnamed semaphores using named semaphores, which they still support. “semaphore.h” does this for MacOS

Threads and Concurrency

Synchronization Techniques: Semaphore in C

- Here is an example of using a semaphore to implement a producer and consumer. A *producer* and a *consumer* share a resource and must coordinate access to it.
- The consumer must wait for the producer to produce units of a resource before consuming. The producer must wait for the consumer to consume a resource before producing more.
- A semaphore is used to synchronize access to the shared resource to ensure orderly production and consumption.
- In this example, the shared resources is a message string that is written by the producer and read by the consumer.

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
#include <stdlib.h>
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <errno.h>
#include <unistd.h>
#include "semaphore.h”  // see note

/** mutual exclusion semaphore */
sem_t semaphore;

/** shared string resource */
char message[128] = "";  // no message
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
/** Creates consumer thread, runs producer, and reports results. */
int main(void) {
    pthread_t consumer_tid;  // thread for consumer

    // initialize semaphore
    If (sem_init(&semaphore, 0, 1) != 0) {
        perror("sem_init");
        return EXIT_FAILURE;
    }
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
    // create and start consumer thread
    sem_wait(&semaphore);  // lock critical section
        fprintf(stderr, "main: creating consumer\n");
        pthread_create(&consumer_tid, NULL, consumer, NULL);
        sleep(2);  // to slow things down
    sem_post(&semaphore);  // unlock critical section

    //produce messages
    const char* messages[] = {"first", "second", "third", "quit"};
    producer(4, messages);

    // wait for consumer and report count
    char *msgcount;
    pthread_join(consumer_tid, &msgcount);
    fprintf(stderr, "main: finished with msgcount %u\n", (unsigned)(msgcount – (char*)0));
}
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
/** This function produces message strings. */
void producer(int nmessages, const char *messages[]) {
    unsigned msgindex = 0;
    fprintf(stderr, "producer: beginning\n");

    while (msgindex < nmessages) {
        fprintf(stderr, "producer: waiting to lock semaphore\n");
        sem_wait(&semaphore);  // lock critical section
            fprintf(stderr, "producer: locked semaphore\n");
            if (strlen(message) == 0) {  // message consumed
                fprintf(stderr, "producer: producing message '%s'\n", messages[msgindex]);
                strcpy(message, messages[msgindex++]);
            } else {  // message not yet consumed
                fprintf(stderr, "producer: waiting to produce next message\n");
            }
            fprintf(stderr, "producer: unlocking semaphore\n");
        sem_post(&semaphore);  // unlock critical section
        sleep(3);  // sleep to give consumer time to consume message
    }
    fprintf(stderr, "producer: ending\n");
}
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
/** This function consumes message strings. */
void *consumer(void *arg) {
    unsigned int msgcount = 0;
    bool quit = false;

    fprintf(stderr, "    consumer: thread beginning\n");

    do {
        fprintf(stderr, "    consumer: waiting to lock semaphore\n");
        // If producer has monitor, thread waits; when monitor unlocks, thread continues
        sem_wait(&semaphore);  // lock critical section
            fprintf(stderr, "    consumer: locked semaphore\n");
            if (strlen(message) > 0) {  // message available
                // report and truncate message
                fprintf(stderr, "    consumer: consuming message '%s'\n", message);
                quit = (strcmp(message, "quit") == 0);
                strcpy(message,"");
                msgcount++;
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

```
            } else {  // no message yet
                fprintf(stderr, "    consumer: waiting for next message to consume\n");
            }
            fprintf(stderr, "    consumer: unlocking semaphore\n");
        sem_post(&semaphore);  // unlock critical section
        sleep(1); // sleep to give producer time to produce message
    } while (!quit);

    fprintf(stderr, "    consumer: thread finishing\n");
    return ((char*)0 + msgcount);  // pointer encoded count
}
```

Threads and Concurrency

Synchronization Techniques: Semaphore in C

- One down-side to semaphores is that if there is no message to consume, the consumer must ”busy-wait” until the next message is available
- Similarly, if the previous message has not yet been consumed, the producer must “busy-wait” until the previous message was consumed.
- Is there an alternative?

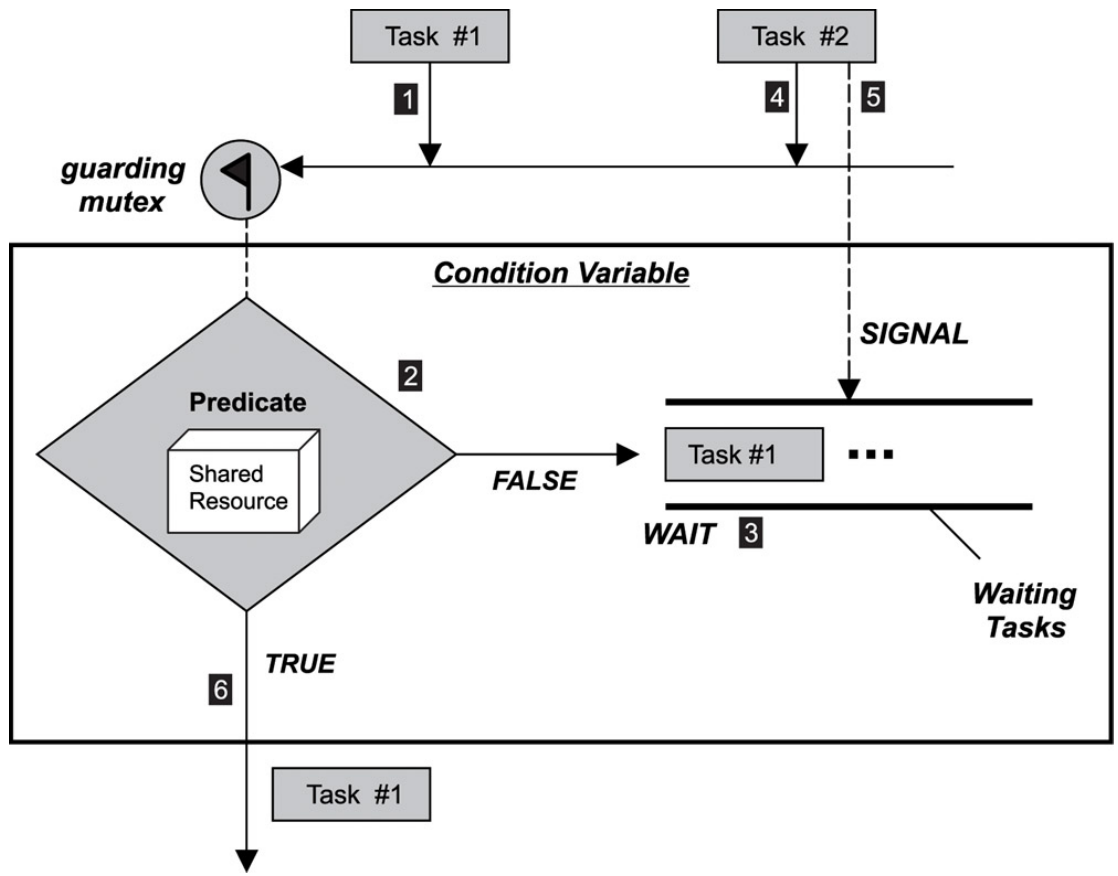
Threads and Concurrency

Synchronization Techniques: Monitor

- A monitor is a synchronization construct that allows threads to have both mutual exclusion and the ability to wait (block) for a certain condition to become true.
- A monitor consists of a *mutex* (lock) object and condition variables. A condition variable is basically a container of threads that are waiting for a certain condition.
- Monitors also have a mechanism for signaling other threads that their condition has been met.

Threads and Concurrency

Synchronization Techniques: Monitor



Threads and Concurrency

Synchronization Techniques: Monitor

- Monitors provide a mechanism for a thread to give up access temporarily to the critical section.
- The thread waits for some condition to be met, before regaining exclusive access and resuming its task.
- Monitors separate the concerns of mutual exclusion and conditional synchronization

Threads and Concurrency

Synchronization Techniques: Monitor

- Basic idea:
  - Permit access to shared resources only within a critical section
  - Maintains conditional invariant of shared resources
- General program structure
  - Entry section
    - Lock before entering critical section
    - Wait if invariant does not yet hold until it does
    - Key point: synchronization may involve wait
  - Critical section
    - Execute code that depends on invariant
  - Exit section
    - Unlock when leaving the critical section

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
#include <stdlib.h>
#include <stdio.h>
#include <pthread.h>
#include <stdbool.h>
#include <unistd.h>

/** Monitor for message string.  */
pthread_mutex_t message_lock = PTHREAD_MUTEX_INITIALIZER;

/** Condition for message state changes.*/
pthread_cond_t message_cond = PTHREAD_COND_INITIALIZER;

/** shared string resource */
char message[128] = "";  // no message
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
int main(void) {
    pthread_t consumer_tid;  // thread for consumer

    // create and start consumer thread
    pthread_mutex_lock(&message_lock); // lock message monitor to block thread
        fprintf(stderr, "main: creating consumer\n");
        pthread_create(&consumer_tid, NULL, consumer, NULL);
        sleep(2);  // to slow things down
    pthread_mutex_unlock(&message_lock);  // unlock monitor
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
    // produce messages
    const char* messages[] = {"first", "second", "third", "quit"};
    producer(4, messages);

    // wait for consumer and report count
    void *msgcount;
    pthread_join(consumer_tid, &msgcount);
    fprintf(stderr, "main: finished with msgcount %u\n", (unsigned)(msgcount – (char*)0));
}
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
/** This function produces message strings.  */
void producer(int nmessages, const char *messages[]) {
    unsigned msgindex = 0;

    fprintf(stderr, "producer: beginning\n");
    pthread_mutex_lock(&message_lock); // lock message monitor
        while (msgindex < nmessages) {
            // wait for consumer
            if (strlen(message) != 0) {
                fprintf(stderr, "producer: waiting to send next message\n");
                do {
                    pthread_cond_wait(&message_cond, &message_lock);
                } while (strlen(message) != 0);
            }
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
            // send next message
            fprintf(stderr, "producer: sending message '%s'\n", messages[msgindex]);
            strcpy(message, messages[msgindex++]);

            pthread_cond_signal(&message_cond); // signal message available
            sleep(2);  // only to slow things down for demo purposes
        }
    pthread_mutex_unlock(&message_lock);  // unlock message monitor

    fprintf(stderr, "producer: ending\n");
}
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
/** This thread function consumes message srings */
void *consumer(void *arg) {
    unsigned int msgcount = 0;
    fprintf(stderr, "    consumer: thread beginning\n");
    bool quit = false;

    // If producer has monitor, thread waits; when producer unlocks, thread continues
    fprintf(stderr, "    consumer: waiting for monitor lock\n");
    pthread_mutex_lock(&message_lock);  // lock message monitor
        do {
            fprintf(stderr, "    consumer: monitor locked\n");
            if (strlen(message) == 0) {
                fprintf(stderr, "    consumer: waiting to receive next message\n");
                do {
                    pthread_cond_wait(&message_cond, &message_lock);
                } while (strlen(message) == 0);
            }
```

Threads and Concurrency

Synchronization Techniques: Monitor in C

- Here is a version of producer/consumer using a monitor.

```
            fprintf(stderr, "    consumer: received message is '%s'\n", message);
            quit = (strcmp(message, "quit") == 0);
            strcpy(message,"");

            pthread_cond_signal(&message_cond);  // signal message received
            msgcount++;
        } while (!quit);
        fprintf(stderr, "    consumer: unlocking monitor\n");
    pthread_mutex_unlock(&message_lock); // unlock message monitor

    fprintf(stderr, "    consumer: thread finishing\n");
    return ((char*)0 + msgcount);  // pointer encoded count
}
```