

# Multithreaded programming

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Lecture 08

PRG – Programming in C

## Overview of the Lecture

### ■ Part 1 – Multithreaded Programming

Introduction

Multithreaded applications and operating system

Models of Multi-Thread Applications

Synchronization Mechanisms

POSIX Threads

C11 Threads

Debugging

## Part I

### Part 1 – Multithreaded Programming

## Terminology – Threads

- Thread is an independent execution of a sequence of instructions.
  - It is individually performed computational flow.

*Typically a small program that is focused on a particular part.*
- Thread is running within the process.
  - It shares the same memory space as the process.
  - Threads running within the same memory space of the process.
- Thread **runtime environment** – each thread has its separate space for variables.
  - Thread identifier and space for synchronization variables.
  - Program counter (PC) or Instruction Pointer (IP) – address of the performing instruction.

*Indicates where the thread is in its program sequence.*
  - Memory space for local variables **stack**.

## Where Threads Can be Used?

- Threads are lightweight variants of the processes that share the memory space.
- There are several cases where it is useful to use threads, the most typical situations are.
  - **More efficient usage of the available computational resources.**
    - When a process waits for resources (e.g., reads from a periphery), it is blocked, and control is passed to another process.
    - Thread also waits, but another thread within the same process can utilize the dedicated time for the process execution.
    - Having multi-core processors, we can speedup the computation using more cores simultaneously by **parallel algorithms**.
  - **Handling asynchronous events.**
    - During blocked i/o operation, the processor can be utilized for other computational.
    - One thread can be dedicated for the i/o operations, e.g., per communication channel, another threads for computations.

## Threads and Processes

### Process

- Computational flow.
- Has own memory space.
- Entity (object) of the OS.
- Synchronization using OS (IPC).
- CPU allocated by OS scheduler.
- Time to create a process.

### Threads of a process

- Computational flow.
- Running in the same memory space of the process.
- User or OS entity.
- Synchronization by exclusive access to variables.
- CPU allocated within the dedicated time to the process.
- + Creation is faster than creating a process.

## Examples of Threads Usage

- **Input/output operations**
  - Input operations can take significant portions of the run-time, which may be mostly some sort of waiting, e.g., for a user input.
  - During the communication, the dedicated CPU time can be utilized for computationally demanding operations.
- **Interactions with Graphical User Interface (GUI)**
  - Graphical interface requires immediate response for a pleasant user interaction with our application.
  - User interaction generates events that affect the application.
  - Computationally demanding tasks should not decrease interactivity of the application.

*Provide a nice user experience with our application.*

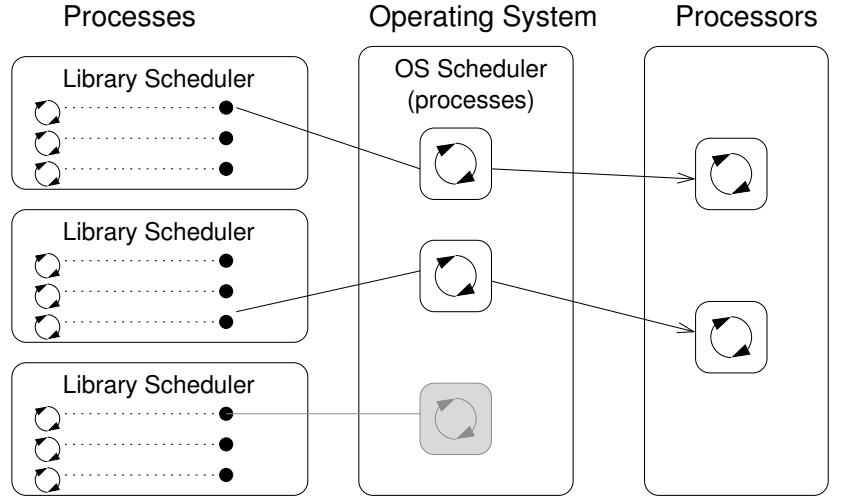
## Multi-thread and Multi-process Applications

- Multi-thread application.
  - + Application can enjoy higher degree of interactivity.
  - + Easier and faster communications between the threads using the same memory space.
  - It does not directly support scaling the parallel computation to distributed computational environment with different computational systems (computers).
- Even on single-core single-processor systems, multi-thread application may better utilize the CPU.

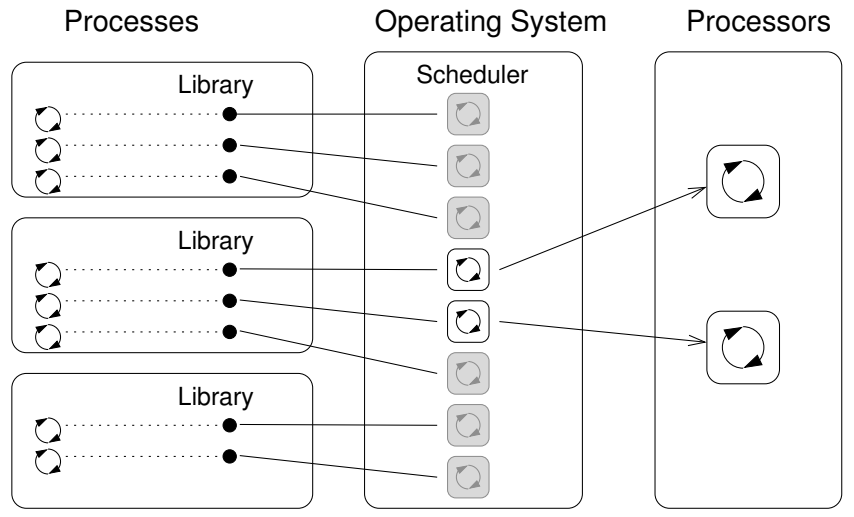
### Threads in the Operating System

- Threads are running within the process, but regarding the implementation, threads can be in user space or OS entities.
  - **User space of the process** – threads are implemented by a user specified library.
    - Threads do not need special support from the OS.
    - Threads are scheduled by the local scheduler provided by the library.
    - Threads typically cannot utilize more processors (multi-core).
  - **OS entities** that are scheduled by the system scheduler.
    - It may utilize multi-core or multi-processors computational resources.

### Threads in the User Space



### Threads as Operating System Entities



### User Threads vs Operating System Threads

#### User Threads

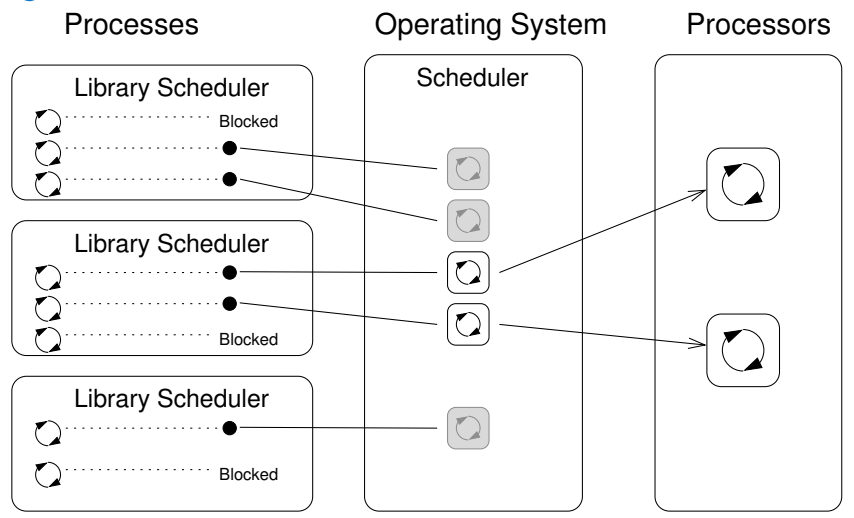
- + Do not need support of the OS.
- + Creation does not need (expensive) system call. Expensive is relative to the cost of creating thread, system thread, and process.
- Execution priority of threads is managed within the assigned process time.
- Threads cannot run simultaneously (pseudo-parallelism).

#### Operating System Threads

- + Threads can be scheduled in competition with all threads in the system.
- + Threads can run simultaneously (on multi-core or multi-processor system – true parallelism).
- Thread creation is a bit more complex (system call).

*A high number of threads scheduled by the OS may increase overhead. However, modern OS are using O(1) schedulers – scheduling a process is an independent on the number of processes. Scheduling algorithms based on complex heuristics.*

## Combining User and OS Threads



## Typical Multi-Thread Applications

- **Servers** – serve multiple clients simultaneously. It may require access to shared resources and many i/o operations.
- **Computational application** – having multi-core or multi-processor system, the application runtime can be decreased by using more processors simultaneously.
- **Real-time applications** – we can utilize specific schedulers to meet real-time requirements.

Multi-thread application can be more efficient than complex asynchronous programming; a thread waits for the event vs. explicit interrupt and context switching.

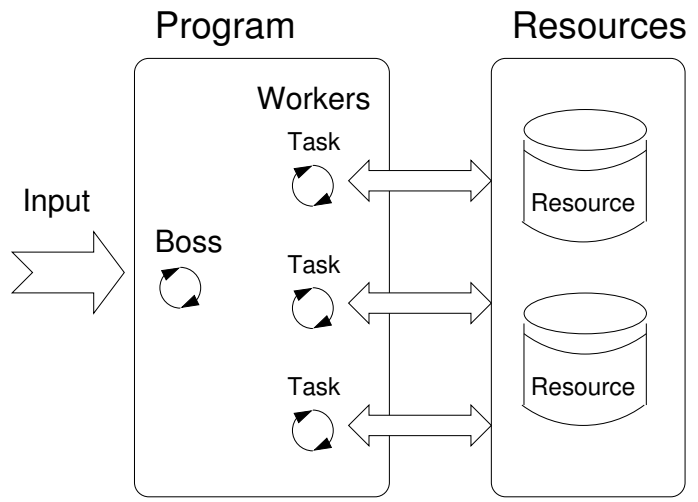
## When to use Threads?

- Threads are advantageous whenever the application meets any of the following criteria.
- It consists of several independent tasks.
- It can be blocked for a certain amount of time.
- It contains a computationally demanding part (while it is also desirable to keep interactivity).
- It has to promptly respond to asynchronous events.
- It contains tasks with lower and higher priorities than the rest of the application.
- The main computation part can be speeded up by a parallel algorithm using multi-core processors.

## Models of Multithreaded Applications

- Models address creation and division of the work to particular threads.
  - **Boss/Worker** – the main thread control division of the work to other threads.
  - **Peer** – threads run in parallel without specified manager (boss).
  - **Pipeline** – data processing by a sequence of operations.
    - It assumes a long stream of input data and particular threads works in parallel on different parts of the stream*

# Boss/Worker Model



# Example – Boss/Worker

```

1 // Boss
2 while(1) {
3     switch(getRequest()) {
4         case taskX:
5             create_thread(taskX);
6             break;
7         case taskY:
8             create_thread(taskY);
9             break;
10    }
11 }

1 // Task solvers
2 taskX()
3 {
4     solve the task // synchronized
5     usage of shared resources
6     done;
7 }
8 taskY()
9 {
10    solve the task // synchronized
11    usage of shared resources
12    done;
13 }
    
```

# Boss/Worker Model – Roles

- The main threads is responsible for managing the requests. It works in a cycle.
  1. Receive a new request.
  2. Create a thread for serving the particular request.
    - Or passing the request to the existing thread.
  3. Wait for a new request.
- The output/results of the assigned request can be controlled by particular working thread or the main thread.
  - Particular thread (worker) solving the request.
  - The main thread using synchronization mechanisms (e.g., event queue).

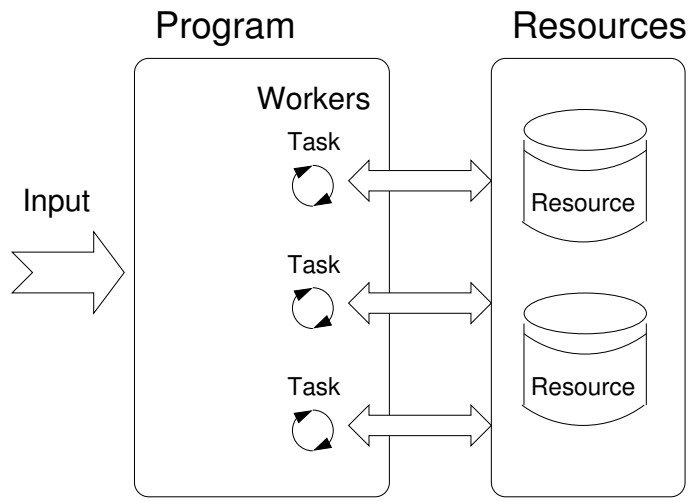
# Thread Pool

- The main thread creates threads upon new request is received.
- The overhead with creation of new threads can be decreasing using the **Thread Pool** with already created threads.
- The created threads wait for new tasks.



- Properties of the thread pool needs to consider.
  - Number of pre-created threads.
  - Maximal number of the request in the queue of requests.
  - Definition of the behavior if the queue is full and none of the threads is available.
    - E.g., block the incoming requests.

### Peer Model



### Peer Model Properties and Example

- It does not contain the main thread; the first thread creates all other threads and then:
  - It becomes one of the other threads (equivalent).
  - It suspends its execution and waits to other threads.
- Each thread is responsible for its input and output.

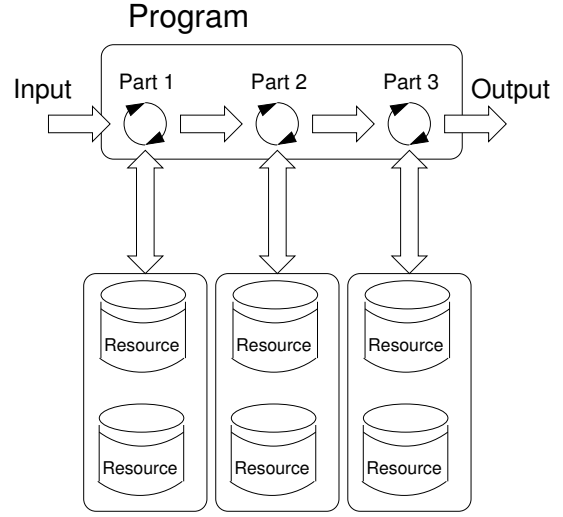
Example

```

1 // Boss
2 {
3   create_thread(task1);
4   create_thread(task2);
5   :
6   :
7   start all threads;
8   wait to all threads;
9 }

1 // Task solvers
2 task1()
3 {
4   wait to be executed
5   solve the task // synchronized usage of
6   shared resources
7   done;
8 }
9 task2()
10 {
11   wait to be executed
12   solve the task // synchronized usage of
13   shared resources
14   done;
15 }
```

### Data Stream Processing – Pipeline



### Pipeline Model – Properties and Example

- A long input stream of data with a **sequence of operations** (a part of processing) – each input data unit must be processed by all parts of the processing operations.
- At a particular time, different input data units are processed by individual processing parts – the input units must be independent.

```

main()
{
  create_thread(stage1);
  create_thread(stage2);
  ...
  wait // for all pipeline;
}

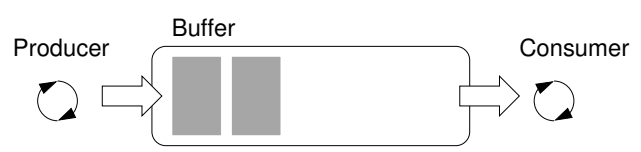
stage1()
{
  while(input) {
    get next program input;
    process input;
    pass result to next the stage;
  }
}

stage2()
{
  while(input) {
    get next input from thread;
    process input;
    pass result to the next stage;
  }
}

...
stageN()
{
  while(input) {
    get next input from thread;
    process input;
    pass result to output;
  }
}
```

## Producer-Consumer Model

- Passing data between units can be realized using a memory buffer.
  - Producer – thread that passes data to other thread.
  - Consumer – thread that receives data from other thread.
- Access to the buffer must be synchronized (exclusive access).



Using the buffer does not necessarily mean the data are copied.

## Mutex – A Locker of Critical Section

- Mutex is shared variable accessible from particular threads.
- Basic operations that threads may perform on the mutex.
  - **Lock** the mutex (acquired the mutex to the calling thread).
    - If the mutex cannot be acquired by the thread (because another thread holds it), the thread is **blocked and waits for mutex release**.
  - **Unlock** the already acquired mutex.
    - If there is one or several threads trying to acquired the mutex (by calling lock on the mutex), one of the thread is selected for mutex acquisition.

## Synchronization Mechanisms

- Synchronization of threads uses the same principles as synchronization of processes.
  - Because threads share the memory space with the process, the main communication between the threads is through the memory and (global) variables.
  - The crucial is the control of access to the same memory.
  - **Exclusive access** to the **critical section**.
- Basic synchronization primitives are **Mutexes** and **Conditional variables**.
  - **Mutex/Locker** for exclusive access to critical section (mutexes or spinlocks).
  - **Condition variable** synchronization of threads according to the value of the shared variable.

*A sleeping thread can be awakened by another signaling from other thread.*

## Example – Mutex and Critical Section

- Lock/Unlock access to the critical section via `drawingMtx` mutex

```

1 void add_drawing_event(void)
2 {
3     Tcl_MutexLock(&drawingMtx);
4     Tcl_Event * ptr = (Tcl_Event*)Tcl_Alloc(sizeof(Tcl_Event));
5     ptr->proc = MyEventProc;
6     Tcl_ThreadQueueEvent(guiThread, ptr, TCL_QUEUE_TAIL);
7     Tcl_ThreadAlert(guiThread);
8     Tcl_MutexUnlock(&drawingMtx);
9 }
    
```

*Example of using thread support from the TCL library.*

- Example of using a concept of `ScopedLock`

```

1 void CCanvasContainer::draw(cairo_t *cr)
2 {
3     ScopedLock lk(mtx);
4     if (drawer == 0) {
5         drawer = new CCanvasDrawer(cr);
6     } else {
7         drawer->setCairo(cr);
8     }
9     manager.execute(drawer);
10 }
    
```

*The ScopedLock releases (unlocks) the mutex once the local variable lk is destroyed at the end of the function call.*

# Generalized Models of Mutex

- Recursive – the mutex can be locked multiple times by the same thread.
- Try – the lock operation immediately returns if the mutex cannot be acquired.
- Timed – limit the time to acquired the mutex.
- *Spinlock* – the thread repeatedly checks if the lock is available for the acquisition.  
*Thread is not set to blocked mode if lock cannot be acquired.*

# Condition Variable

- **Condition variable** allows signaling thread from other thread.
- The concept of **condition variable** allows the following synchronization operations.
  - Wait – the variable has been changed/notified.
  - Timed waiting for signal from other thread.
  - Signaling other thread waiting for the condition variable.
  - Signaling all threads waiting for the condition variable.  
*All threads are awakened, but the access to the condition variable is protected by the mutex that must be acquired and only one thread can lock the mutex.*

# Spinlock

- Under certain circumstances, it may be advantageous to do not block the thread during acquisition of the mutex (lock), e.g.,
  - Performing a simple operation on the shared data/variable on the system with true parallelism (using multi-core CPU).
  - Blocking the thread, suspending its execution and passing the allocated CPU time to other thread may result in a significant overhead.
  - Other threads quickly perform other operation on the data and thus, the shared resource would be quickly accessible.
- During the locking, the thread actively tests if the lock is free.  
*It wastes the CPU time that can be used for productive computation elsewhere.*
- Similarly to a semaphore such a test has to be performed by TestAndSet instruction at the CPU level.
- **Adaptive mutex** combines both approaches to use the **spinlocks** to access resources locked by currently running thread and block/sleep if such a thread is not running.  
*It does not make sense to use spinlocks on single-processor systems with pseudo-parallelism.*

# Example – Condition Variable

- Example of using condition variable with lock (mutex) to allow exclusive access to the condition variable from different threads.

```

Mutex mtx; // shared variable for both threads
CondVariable cond; // shared condition variable

// Thread 1
Lock(mtx);
// Before code, wait for Thread 2
CondWait(cond, mtx); // wait for cond
... // Critical section
UnLock(mtx);

// Thread 2
Lock(mtx);
... // Critical section
// Signal on cond
CondSignal(cond, mtx);
UnLock(mtx);

```



# Parallelism and Functions

- In parallel environment, functions can be called multiple times.
- Regarding the parallel execution, functions can be **reentrant** or **thread-safe**.
  - **Reentrant** – at a single moment, the same function can be executed multiple times simultaneously.
  - **Thread-Safe** – the function can be called by multiple threads simultaneously.
- The following needs to be satisfied for achieving the properties.
  - **Reentrant function** does not write to static data and does not work with global data.
  - **Thread-safe function** strictly access to global data using synchronization primitives.

# POSIX Thread Functions (pthread)

- POSIX threads library (<pthread.h> and -lpthread) is a set of functions to support multithreaded programming.
- The basic types for threads, mutexes, and condition variables are
  - pthread\_t – type for representing a thread;
  - pthread\_mutex\_t – type for mutex;
  - pthread\_cond\_t – type for condition variable.
- The thread is created by pthread\_create() function call, which immediately executes the new thread as a function passed as a pointer to the function.
 

*The thread calling the creation continues with the execution.*
- A thread may wait for other thread by pthread\_join().
- Particular mutex and condition variables has to be initialized using the library calls.
 

*Note, initialized shared variables before threads are created.*

  - pthread\_mutex\_init() – initialize mutex variable.
  - pthread\_cond\_init() – initialize condition variable.

*Additional attributes can be set, see documentation.*

# Main Issues with Multithreaded Applications

- The main issues/troubles with multiprocessing application are related to synchronization.
  - **Deadlock** – a thread wait for a resource (mutex) that is currently locked by other thread that is waiting for the resource (thread) already locked by the first thread.
  - **Race condition** – access of several threads to the shared resources (memory/variables) and at least one of the threads does not use the synchronization mechanisms (e.g., critical section).

*A thread reads a value while another thread is writing the value. If Reading/writing operations are not atomic, data are not valid.*

# POSIX Threads – Example 1/10

- Create an application with three active threads for
  - Handling user input – function input\_thread().
    - User specifies a period output refresh of by pressing dedicated keys.
  - Refresh output – function output\_thread().
    - Refresh output only when the user interacts with the application or the alarm is signaling the period has been passed.
  - Alarm with user defined period – function alarm\_thread().
    - Refresh the output or do any other action.
- For simplicity the program uses stdin and stdout with thread activity reporting to stderr.
- Synchronization mechanisms are demonstrated using
  - pthread\_mutex\_t mtx – for exclusive access to data\_t data;
  - pthread\_cond\_t cond – for signaling threads.

*The shared data consists of the current period of the alarm (alarm\_period), request to quit the application (quit), and number of alarm invocations (alarm\_counter).*

## POSIX Threads – Example 2/10

- Including header files, defining data types, declaration of global variables.

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <stdbool.h>
4 #include <termios.h>
5 #include <unistd.h> // for STDIN_FILENO
6 #include <pthread.h>
7
8 #define PERIOD_STEP 10
9 #define PERIOD_MAX 2000
10 #define PERIOD_MIN 10
11
12 typedef struct {
13     int alarm_period;
14     int alarm_counter;
15     bool quit;
16
17     pthread_mutex_t *mtx; // avoid global variables for mutex and
18     pthread_cond_t *cond; // conditional variable
19 } data_t; // data structure shared among the threads
    
```

## POSIX Threads – Example 4/10

- Create threads and wait for terminations of all threads.

```

41 call_termios(0); // switch terminal to raw mode
42 for (int i = 0; i < NUM_THREADS; ++i) {
43     int r = pthread_create(&threads[i], NULL, thr_functions[i], &data);
44     printf("Create thread '%s' %s\r\n", threads_names[i], (r == 0 ? "OK" : "FAIL"));
45 }
46
47 int *ex;
48 for (int i = 0; i < NUM_THREADS; ++i) {
49     printf("Call join to the thread %s\r\n", threads_names[i]);
50     int r = pthread_join(threads[i], (void*)&ex);
51     printf("Joining the thread %s has been %s - exit value %i\r\n", threads_names[i], (r == 0 ?
52         "OK" : "FAIL"), *ex);
53 }
54 call_termios(1); // restore terminal settings
55 return EXIT_SUCCESS;
56 }
    
```

## POSIX Threads – Example 3/10

- Functions prototypes and initialize of variables and structures.

```

21 void call_termios(int reset); // switch terminal to raw mode
22 void* input_thread(void*);
23 void* output_thread(void*);
24 void* alarm_thread(void*);
25
26 // - main function -----
27 int main(int argc, char *argv[])
28 {
29     data_t data = { .alarm_period = 100, .alarm_counter = 0, .quit = false };
30     enum { INPUT, OUTPUT, ALARM, NUM_THREADS }; // named ints for the threads
31     const char *threads_names[] = { "Input", "Output", "Alarm" };
32     void* (*thr_functions[]) (void*) = {
33         input_thread, output_thread, alarm_thread // array of thread functions
34     };
35
36     pthread_t threads[NUM_THREADS]; // array for references to created threads
37     pthread_mutex_init(&mtx, NULL); // initialize mutex with default attributes
38     pthread_cond_init(&cond, NULL); // initialize condition variable with default attributes
39     data.mtx = &mtx; // make the mutex accessible from the shared data structure
40     data.cond = &cond; // make the cond accessible from the shared data structure
    
```

## POSIX Threads – Example 5/10 (Terminal Raw Mode)

- Switch terminal to raw mode.

```

57 void call_termios(int reset)
58 {
59     static struct termios tio, tioOld; // use static to preserve the initial settings
60     tcgetattr(STDIN_FILENO, &tio);
61     if (reset) {
62         tcsetattr(STDIN_FILENO, TCSANOW, &tioOld);
63     } else {
64         tioOld = tio; //backup
65         cfmakeraw(&tio);
66         tcsetattr(STDIN_FILENO, TCSANOW, &tio);
67     }
68 }
    
```

*The caller is responsible for appropriate calling the function, e.g., to preserve the original settings, the function must be called with the argument 0 only once.*

## POSIX Threads – Example 6/10 (Input Thread 1/2)

```

70 void* input_thread(void* d)
71 {
72     data_t *data = (data_t*)d;
73     static int r = 0;
74     int c;
75     while ((c = getchar()) != 'q') {
76         pthread_mutex_lock(data->mtx);
77         int period = data->alarm_period; // save the current period
78         // handle the pressed key detailed in the next slide
79
80         if (data->alarm_period != period) { // the period has been changed
81             pthread_cond_signal(data->cond); // signal the output thread to refresh
82         }
83         data->alarm_period = period;
84         pthread_mutex_unlock(data->mtx);
85     }
86     r = 1;
87     pthread_mutex_lock(data->mtx);
88     data->quit = true;
89     pthread_cond_broadcast(data->cond);
90     pthread_mutex_unlock(data->mtx);
91     fprintf(stderr, "Exit input thread %lu\r\n", pthread_self());
92     return &r;
93 }

```

## POSIX Threads – Example 7/10 (Input Thread 2/2)

■ `input_thread()` – handle the user request to change period.

```

79 switch(c) {
80     case 'r':
81         period -= PERIOD_STEP;
82         if (period < PERIOD_MIN) {
83             period = PERIOD_MIN;
84         }
85         break;
86     case 'p':
87         period += PERIOD_STEP;
88         if (period > PERIOD_MAX) {
89             period = PERIOD_MAX;
90         }
91         break;
92 }

```

## POSIX Threads – Example 8/10 (Output Thread)

```

94 void* output_thread(void* d)
95 {
96     data_t *data = (data_t*)d;
97     static int r = 0;
98     bool q = false;
99     pthread_mutex_lock(data->mtx);
100     while (!q) {
101         pthread_cond_wait(data->cond, data->mtx); // wait for next event
102         q = data->quit;
103         printf("\rAlarm time: %10i Alarm counter: %10i", data->alarm_period, data->
104             alarm_counter);
105         fflush(stdout);
106     }
107     pthread_mutex_unlock(data->mtx);
108     fprintf(stderr, "Exit output thread %lu\r\n", (unsigned long)pthread_self());
109     return &r;
110 }

```

## POSIX Threads – Example 9/10 (Alarm Thread)

```

111 void* alarm_thread(void* d)
112 {
113     data_t *data = (data_t*)d;
114     static int r = 0;
115     pthread_mutex_lock(data->mtx);
116     bool q = data->quit;
117     useconds_t period = data->alarm_period * 1000; // alarm_period is in ms
118     pthread_mutex_unlock(data->mtx);
119
120     while (!q) {
121         usleep(period);
122         pthread_mutex_lock(data->mtx);
123         q = data->quit;
124         data->alarm_counter += 1;
125         period = data->alarm_period * 1000; // update the period is it has been changed
126         pthread_cond_broadcast(data->cond);
127         pthread_mutex_unlock(data->mtx);
128     }
129     fprintf(stderr, "Exit alarm thread %lu\r\n", pthread_self());
130     return &r;
131 }

```

## POSIX Threads – Example 10/10

- The example program `lec08/threads.c` can be compiled and run.

```
clang -c threads.c -std=gnu99 -O2 -pedantic -Wall -o threads.o
clang threads.o -pthread -o threads
```

- The period can be changed by 'r' and 'p' keys.
- The application is terminated after pressing 'q'.

```
./threads
Create thread 'Input' OK
Create thread 'Output' OK
Create thread 'Alarm' OK
Call join to the thread Input
Alarm time:      110 Alarm counter:      20Exit input thread 750871808
Alarm time:      110 Alarm counter:      20Exit output thread 750873088
Joining the thread Input has been OK - exit value 1
Call join to the thread Output
Joining the thread Output has been OK - exit value 0
Call join to the thread Alarm
Exit alarm thread 750874368
Joining the thread Alarm has been OK - exit value 0
```

`lec08/threads.c`

## C11 Threads Example

- The previous example `lec08/threads.c` implemented with C11 threads is in `lec08/threads-c11.c`.

```
clang -std=c11 threads-c11.c -stdthreads -o threads-c11
./threads-c11
```

- Basically, the function calls are similar with different names and minor modifications.
  - `pthread_mutex_*`() → `mxt_*`().
  - `pthread_cond_*`() → `cnd_*`().
  - `pthread_*`() → `thrd_*`().
  - Thread body functions return int value.
  - There is not `pthread_self()` equivalent.
  - `thrd_t` is implementation dependent
  - Threads, mutexes, and condition variable are created/initialized without specification particular attributes.
- The program is linked with the `-lstdthreads` library.

*Simplified interface.*

`lec08/threads-c11.c`

## C11 Threads

- C11 provides a “wrapper” for the POSIX threads.

*E.g., see <http://en.cppreference.com/w/c/thread>*

- The library is `<threads.h>` and `-lstdthreads`.

- Basic types
  - `thrd_t` – type for representing a thread;
  - `mtx_t` – type for mutex;
  - `cnd_t` – type for condition variable.

- Creation of the thread is `thrd_create()` and the thread body function has to return an `int` value.

- `thrd_join()` is used to wait for a thread termination.

- Mutex and condition variable are initialized (without attributes)
  - `mtx_init()` – initialize mutex variable;
  - `cnd_init()` – initialize condition variable.

## How to Debug Multi-Thread Applications

- The best tool to debug a multi-thread application is *to do not need to debug it*.
- It can be achieved by discipline and a prudent approach to shared variables.
- Otherwise a debugger with a minimal set of features can be utilized.

## Debugging Support

- Desired features of the debugger.
  - List of running threads.
  - Status of the synchronization primitives.
  - Access to thread variables.
  - Break points in particular threads.

lldb – <http://lldb.llvm.org>; gdb – <https://www.sourceware.org/gdb>  
 cgdb, ddd, kgdb, Code::Blocks or Eclipse, Kdevelop, Netbeans, CLion

SlickEdit – <https://www.slickedit.com>; TotalView – <http://www.roguewave.com/products-services/totalview>

- **Logging** can be more efficient to debug a program than manual debugging with manually set breakpoints.
  - Deadlock is mostly related to the order of locking.
  - Logging and analyzing access to the lockers (mutex) can help to find a wrong order of the thread synchronizing operations.

## Comments – Deadlock

- Deadlocks are related to the mechanisms of synchronization.
  - Deadlock is much easier to debug than the race condition.
  - Deadlock is often the *mutex deadlock* caused by order of multiple mutex locking.
  - **Mutex deadlock can not occur** if, at any moment, each thread has (or it is trying to acquire) **at most a single mutex**.
  - It is **not recommended to call functions with a locked mutex**, especially if the function is attempting to lock another mutex.
  - **It is recommended to lock the mutex for the shortest possible time.**

## Comments – Race Condition

- Race condition is typically caused by a lack of synchronization.
- It is worth of remember the following.
  - **Threads are asynchronous!**  
*Do not rely that a code execution is synchronous on a single processor system.*
  - **When writing multi-threaded applications assume that the thread can be interrupted or executed at any time!**  
*Parts of the code that require a particular execution order of the threads needs synchronization.*
  - **Never assume that a thread waits after it is created!**  
*It can be started very soon and usually much sooner than you can expect.*
  - **Unless you specify the order of the thread execution, there is no such order!**  
*"Threads are running in the worst possible order". Bill Gallmeister"*

## Topics Discussed

## Summary of the Lecture

## Topics Discussed

- Multithreaded programming
    - Terminology, concepts, and motivations for multithreaded programming
    - Models of multi-threaded applications
    - Synchronization mechanisms
    - POSIX and C11 thread libraries
- Example of an application*
- Comments on debugging and multi-thread issues with the race condition and deadlock