

# Multithreading programming

Jan Faigl

Department of Computer Science

Faculty of Electrical Engineering

Czech Technical University in Prague

Lecture 08

**B3B36PRG – C Programming Language**

# Overview of the Lecture

- Part 1 – Multithreading Programming

Introduction

Multithreading applications and operating system

Models of Multi-Thread Applications

Synchronization Mechanisms

POSIX Threads

C11 Threads

Debugging

# Part I

## Part 1 – Multithreading 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

# 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*

# 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

# Multi-thread and Multi-process Applications

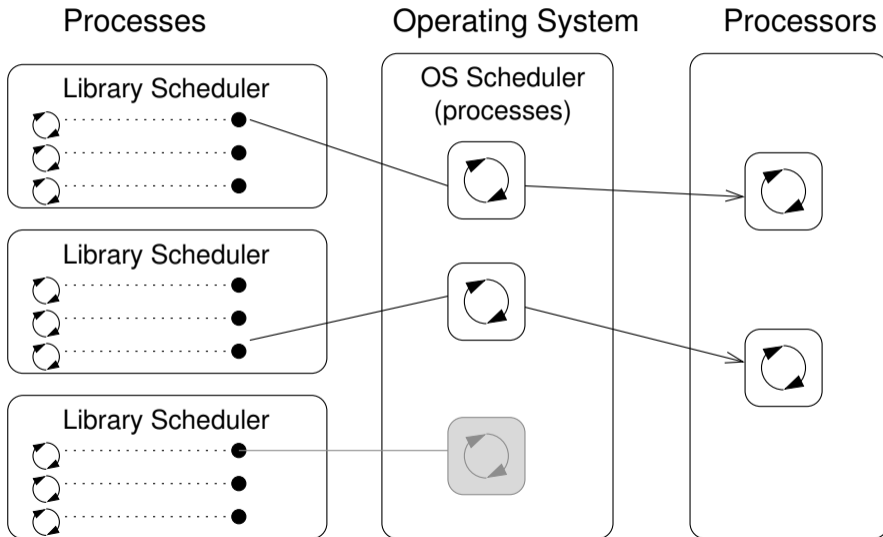
- Multi-thread application
  - + Application can enjoy higher degree of interactivity
  - + Easier and faster communications between the threads using the same memory space
  - It does not directly support scaling the parallel computation to distributed computational environment with different computational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



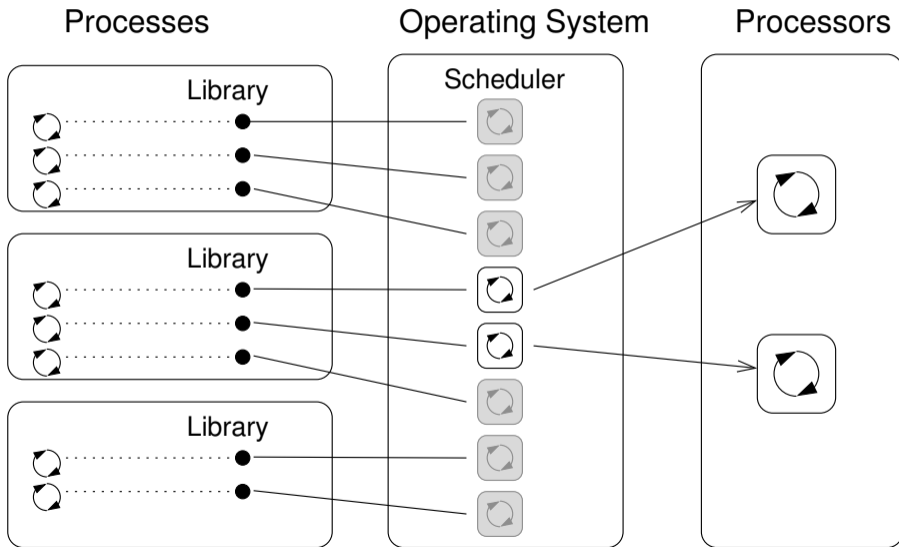
# Threads in the Operating System

- Threads are running within the process, but regarding the implementation, threads can be
  - **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 utilized 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

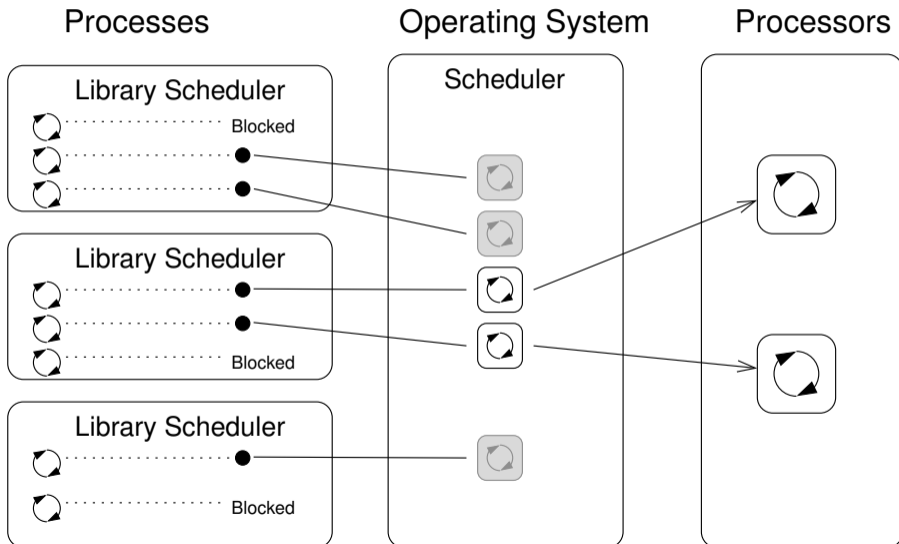
- + Do not need support of the OS
- + Creation does not need (expensive) system call
- Execution priority of threads is managed within the assigned process time
- Threads cannot run simultaneously (pseudo-parallelism)

## 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



# 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 speed by a parallel algorithm using multi-core processors

## 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

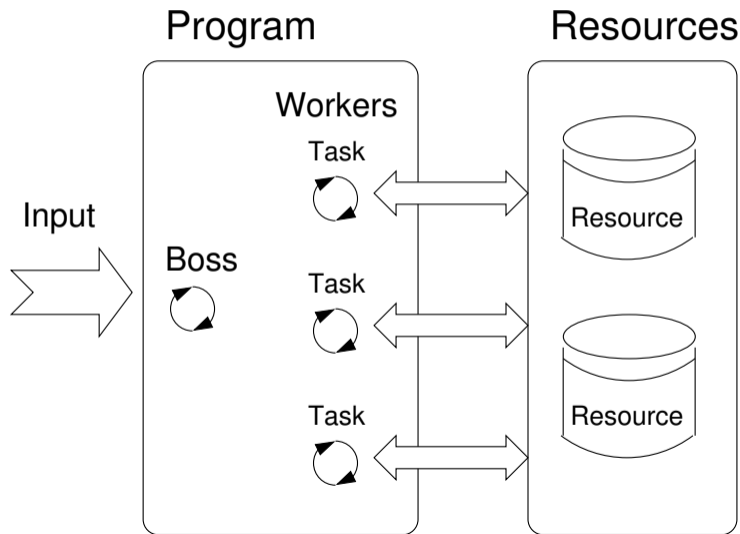
Multi-thread application can be more efficient than complex asynchronous programming; a thread waits for the event vs. explicit interrupt and context switching

# Models of Multithreading 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



## 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 thread (worker) solving the request
    - The main thread using synchronization mechanisms (e.g., event queue)

## 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 }
```

## Thread Pool

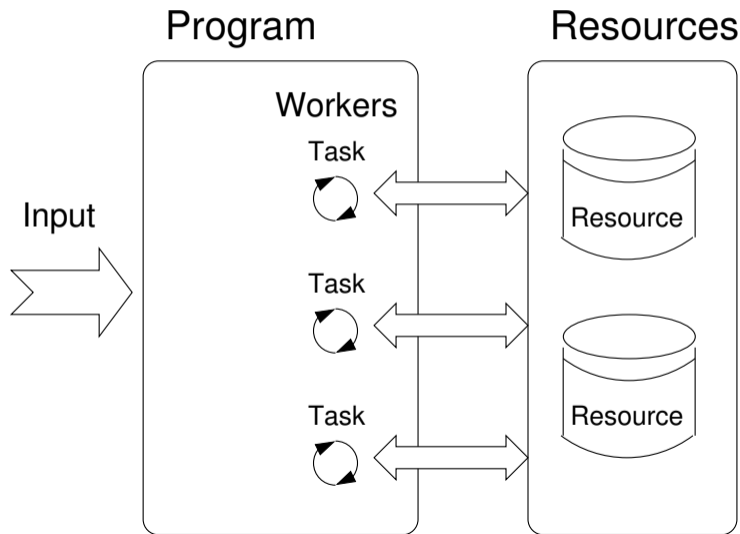
- The main thread creates threads upon new request is received
- The overhead with creation of new threads can be decreasing using the **Thread Pool** with already created threads
- The created threads wait for new tasks



- 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



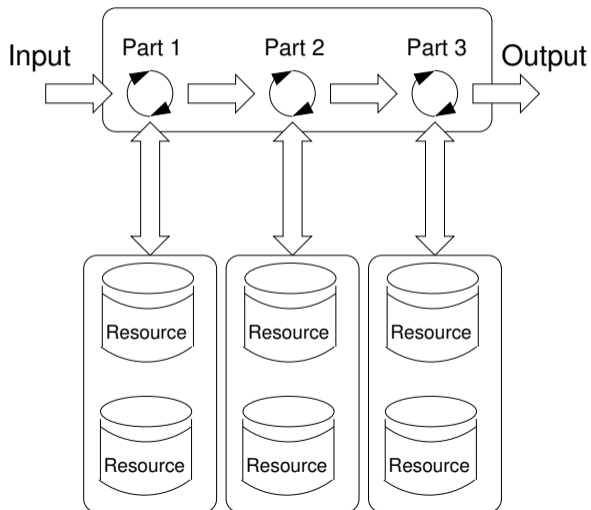
## Peer Model Properties and Example

- 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 Program



## 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
  - Or just a buffer of references (pointers) to particular data units*
  - 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.*

# 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/Lockers** 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.*

## 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.

## 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 acquire 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.*

# 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.*

# 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.*

## 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** – at a single moment, the same function can be executed multiple times simultaneously
  - **Thread-Safe** – the function can be called by multiple threads simultaneously
- To achieve these 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

# Main Issues with Multithreading 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 writting the value. If Reading/writting operations are not atomic, data are not valid.*

## POSIX Thread Functions (pthread)

- POSIX threads library (`<pthread.h>` and `-lpthread`) is a set of functions to support multithreading 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.*

## 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 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 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
55     call_termios(1); // restore terminal settings
56     return EXIT_SUCCESS;
57 }
```

## 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
93     .... if (data->alarm_period != period) { // the period has been changed
94         pthread_cond_signal(data->cond); // signal the output thread to refresh
95     }
96     data->alarm_period = period;
97     pthread_mutex_unlock(data->mtx);
98 }
99 r = 1;
100 pthread_mutex_lock(data->mtx);
101 data->quit = true;
102 pthread_cond_broadcast(data->cond);
103 pthread_mutex_unlock(data->mtx);
104 fprintf(stderr, "Exit input thread %lu\r\n", pthread_self());
105 return &r;
106 }
```

## 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 if 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 -lpthread -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

- 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

## 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 -lstdthreads -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`

# 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 – Race Condition

- Race condition is typically caused by a lack of synchronization
- It is worth of remember that
  - **Threads are asynchronous**

*Do not relay 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”*

## 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**

## Summary of the Lecture

# Topics Discussed

- Multithreading programming
  - Terminology, concepts, and motivations for multithreading 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