Multithreaded programming

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Přednáška 11

BAB36PRGA – Programování v C

Overview of the Lecture

Část 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.

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.

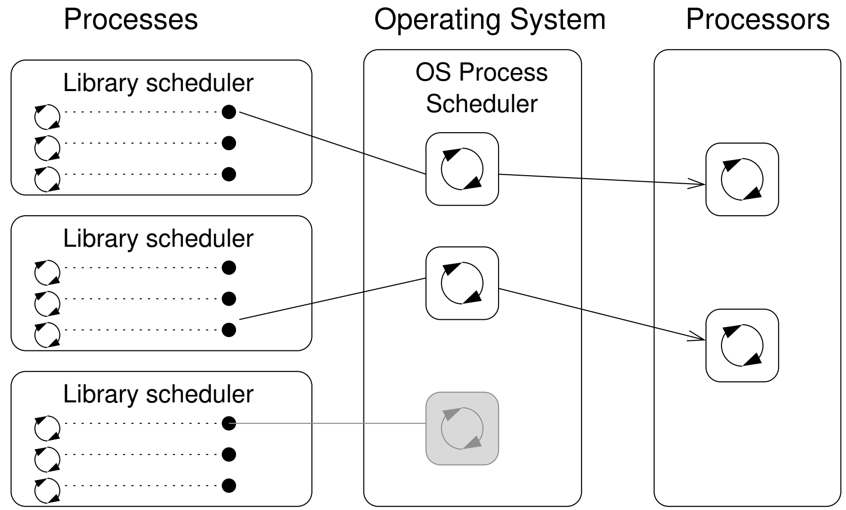
Multi-thread and Multi-process Applications

- 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.

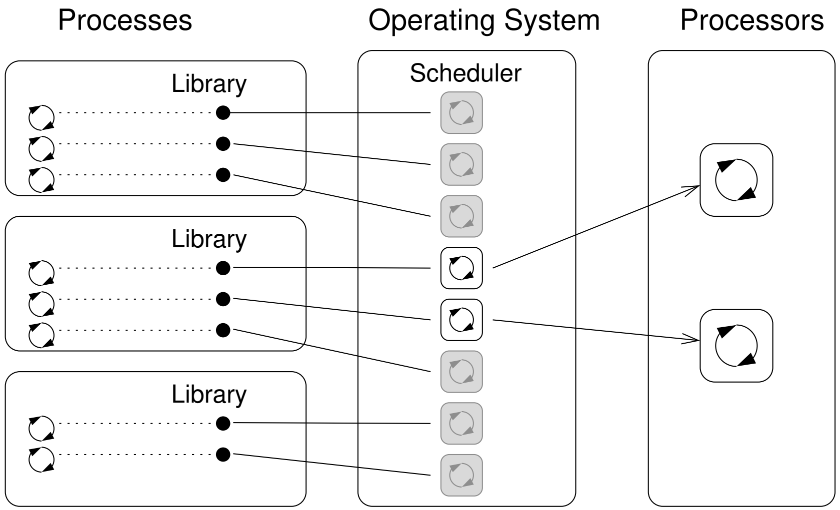
Threads in the Operating System

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

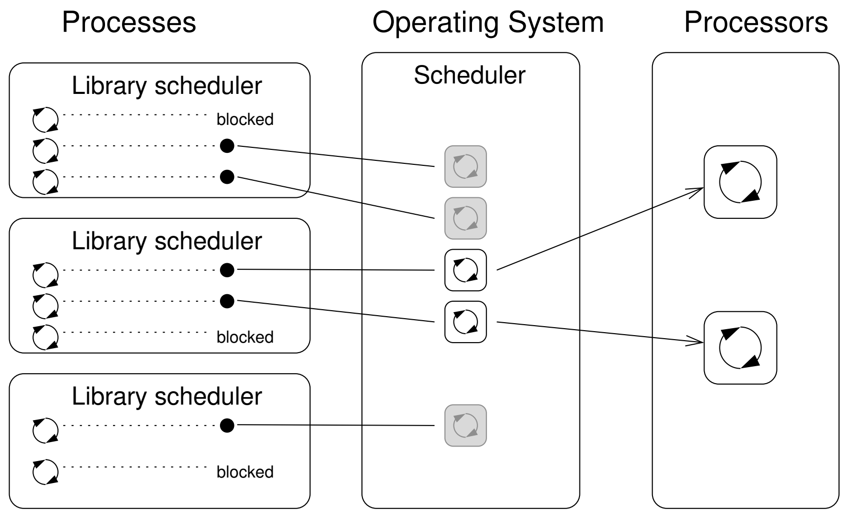
\+ Threads can be scheduled in competition with all threads in the system.

\+ 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



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.

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.

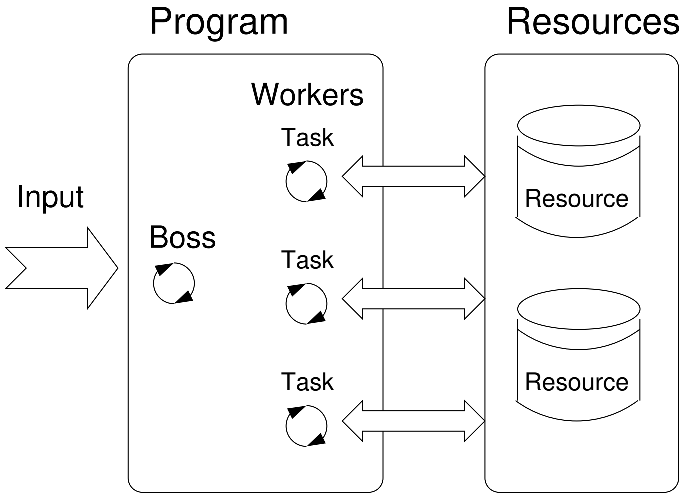
Multi-thread application can be more efficient than complex asynchronous programming; a thread waits for the event vs. explicit interrupt and context switching.

Models of 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



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).

Example – Boss/Worker

```
// Boss
while(1) {
  switch(getRequest()) {
    case taskX:
       create_thread(taskX);
       break;
    case taskY:
       create_thread(taskY);
       break;
  }
}
```

```
// Task solvers
taskX()
{
  solve the task // synchronized
    usage of shared resources
  done;
}

taskY()
{
  solve the task // synchronized
    usage of shared resources
  done;
}
```

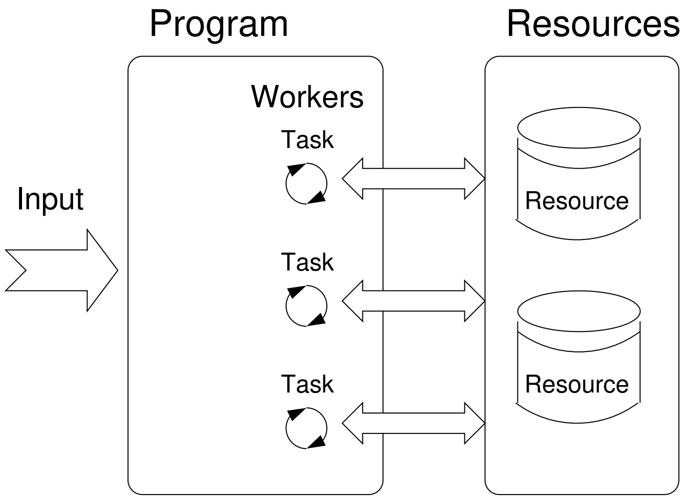

Thread Pool

- 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



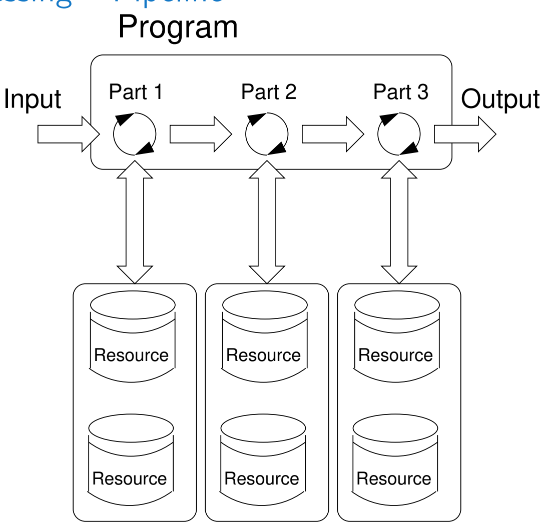
Peer Model Properties and Example

- 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

```
// Boss
{
  create_thread(task1);
  create_thread(task2);
  .
  .
  start all threads;
  wait to all threads;
}
```

```
// Task solvers
task1()
{
  wait to be exectued
  solve the task // synchronized usage of
     shared resources
  done;
}

task2()
{
  wait to be exectued
  solve the task // synchronized usage of
     shared resources
  done;
}
```


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.

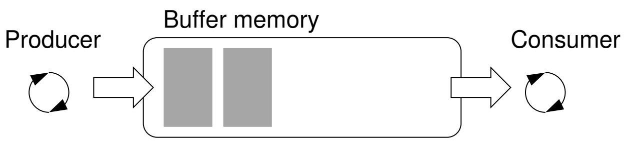
```
main()
{
  create_thread(stage1);
  create_thread(stage2);
  ...
  ...
  wait // for all pipeline;
}

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.

  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** 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.

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

```
void add_drawing_event(void)
{
   Tcl_MutexLock(&drawingMtx);
   Tcl_Event * ptr = (Tcl_Event*)Tcl_Alloc(sizeof(Tcl_Event));
   ptr->proc = MyEventProc;
   Tcl_ThreadQueueEvent(guiThread, ptr, TCL_QUEUE_TAIL);
   Tcl_ThreadAlert(guiThread);
   Tcl_MutexUnlock(&drawingMtx);
}
```

Example of using thread support from the TCL library.

- Example of using a concept of `ScopedLock`

```
void CCanvasContainer::draw(cairo_t *cr)
{
   ScopedLock lk(mtx);
   if (drawer == 0) {
      drawer = new CCanvasDrawer(cr);
   } else {
      drawer->setCairo(cr);
   }
   manager.execute(drawer);
}
```

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.

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** 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.

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 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 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.

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.

```
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <termios.h>
#include <unistd.h>  // for STDIN_FILENO
#include <pthread.h>

#define PERIOD_STEP 10
#define PERIOD_MAX 2000
#define PERIOD_MIN 10

typedef struct {
   int alarm_period;
   int alarm_counter;
   bool quit;

   pthread_mutex_t *mtx; // avoid global variables for mutex and
   pthread_cond_t *cond; // conditional variable
} data_t; // data structure shared among the threads
```


POSIX Threads – Example 3/10

- Functions prototypes and initialize of variables and structures.

```
void call_termios(int reset); // switch terminal to raw mode
void* input_thread(void*);
void* output_thread(void*);
void* alarm_thread(void*);

// - main function -----------------------------
int main(int argc, char *argv[])
{
   data_t data = { .alarm_period = 100, .alarm_counter = 0, .quit = false };
   enum { INPUT, OUTPUT, ALARM, NUM_THREADS }; // named ints for the threads
   const char *threads_names[] = { "Input", "Output", "Alarm" };
   void* (*thr_functions[])(void*) = {
      input_thread, output_thread, alarm_thread // array of thread functions
   };

   pthread_t threads[NUM_THREADS]; // array for references to created threads
   pthread_mutex_init(&mtx, NULL); // initialize mutex with default attributes
   pthread_cond_init(&cond, NULL); // initialize condition variable with default attributes
   data.mtx = &mtx;                // make the mutex accessible from the shared data structure
   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.

```
   call_termios(0); // switch terminal to raw mode
   for (int i = 0; i < NUM_THREADS; ++i) {
      int r = pthread_create(&threads[i], NULL, thr_functions[i], &data);
      printf("Create thread '%s' %s\r\n", threads_names[i], ( r == 0 ? "OK" : "FAIL") );
   }

   int *ex;
   for (int i = 0; i < NUM_THREADS; ++i) {
      printf("Call join to the thread %s\r\n", threads_names[i]);
      int r = pthread_join(threads[i], (void*)&ex);
      printf("Joining the thread %s has been %s - exit value %i\r\n", threads_names[i], (r == 0 ? "OK" : "FAIL"), *ex);
   }

   call_termios(1); // restore terminal settings
   return EXIT_SUCCESS;
}
```


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

- Switch terminal to raw mode.

```
void call_termios(int reset)
{
   static struct termios tio, tioOld; // use static to preserve the initial settings
   tcgetattr(STDIN_FILENO, &tio);
   if (reset) {
      tcsetattr(STDIN_FILENO, TCSANOW, &tioOld);
   } else {
      tioOld = tio; //backup
      cfmakeraw(&tio);
      tcsetattr(STDIN_FILENO, TCSANOW, &tio);
   }
}
```

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)

```c
void* input_thread(void* d)
{
   data_t *data = (data_t*)d;
   static int r = 0;
   int c;
   while (( c = getchar()) != 'q') {
      pthread_mutex_lock(data->mtx);
      int period = data->alarm_period; // save the current period
      // handle the pressed key detailed in the next slide
....
      if (data->alarm_period != period) { // the period has been changed
         pthread_cond_signal(data->cond); // signal the output thread to refresh
      }
      data->alarm_period = period;
      pthread_mutex_unlock(data->mtx);
   }
   r = 1;
   pthread_mutex_lock(data->mtx);
   data->quit = true;
   pthread_cond_broadcast(data->cond);
   pthread_mutex_unlock(data->mtx);
   fprintf(stderr, "Exit input thread %lu\r\n", pthread_self());
   return &r;
}
```


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

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

```c
switch(c) {
   case 'r':
      period -= PERIOD_STEP;
      if (period < PERIOD_MIN) {
         period = PERIOD_MIN;
      }
      break;
   case 'p':
      period += PERIOD_STEP;
      if (period > PERIOD_MAX) {
         period = PERIOD_MAX;
      }
      break;
}
```


POSIX Threads – Example 8/10 (Output Thread)

```c
void* output_thread(void* d)
{
   data_t *data = (data_t*)d;
   static int r = 0;
   bool q = false;
   pthread_mutex_lock(data->mtx);
   while (!q) {
      pthread_cond_wait(data->cond, data->mtx); // wait for next event
      q = data->quit;
      printf("\rAlarm time: %10i   Alarm counter: %10i", data->alarm_period, data->
     alarm_counter);
      fflush(stdout);
   }
   pthread_mutex_unlock(data->mtx);
   fprintf(stderr, "Exit output thread %lu\r\n", (unsigned long)pthread_self());
   return &r;
}
```


POSIX Threads – Example 9/10 (Alarm Thread)

```c
void* alarm_thread(void* d)
{
   data_t *data = (data_t*)d;
   static int r = 0;
   pthread_mutex_lock(data->mtx);
   bool q = data->quit;
   useconds_t period = data->alarm_period * 1000; // alarm_period is in ms
   pthread_mutex_unlock(data->mtx);

   while (!q) {
      usleep(period);
      pthread_mutex_lock(data->mtx);
      q = data->quit;
      data->alarm_counter += 1;
      period = data->alarm_period * 1000; // update the period is it has been changed
      pthread_cond_broadcast(data->cond);
      pthread_mutex_unlock(data->mtx);
   }
   fprintf(stderr, "Exit alarm thread %lu\r\n", pthread_self());
   return &r;
}
```

POSIX Threads – Example 10/10

- The example program lec11/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
```

lec11/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 lec11/threads.c implemented with C11 threads is in lec11/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. *Simplified interface.*
  - The program is linked with the -lstdthreads library.

lec11/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 the following.
  - 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

- 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