# Project Uthreads

*Due: February 7, 2018*

This assignment must be completed by all 167 students (including those who are registered for 169).

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## 1 Introduction

In this project you will develop and test your very own user-level threads package complete with thread creation/deletion/joining, mutexes, condition variables, and a priority-based scheduler. Hav-
ing completed this assignment, you should be able to write multi-threaded applications using your package instead of, say, pthreads. You can install the stencil by running /course/cs167/bin/cs1670_install uthreads in your home directory.

2 Background

A thread is a coherent sequence of instructions that are executed in order. Although the instructions in a thread must occur in order, they can be started, stopped, and run concurrently with other threads. This is determined by the operating system’s scheduler as well as other synchronization constructs such as mutexes. For this assignment, we will be writing a threads package that supports time-slicing, which means only one thread runs at a time but they are interleaved in a way such that each thread makes progress in a fair way.

How do we support this start-and-stop method of running threads? Linux (and most other operating systems) have the notion of a “machine context” which contains the complete state (at least everything viewable from user-land) of the CPU at any given time. Usually this includes a pointer to the stack, register contents, and other bookkeeping information. The idea is that since contexts contain a complete description of the CPU state, you should be able to save the current state and exchange it with another state (which has either been previously saved or constructed by hand). This enables the operating system to suspend and resume execution of programs at will, and also enables you to write a user-land threads package.

Let’s try an example. Say you have threads $T_A$, $T_B$, and $T_C$ with contexts $C_A$, $C_B$, and $C_C$ of which $T_A$ is currently running. Say $T_A$ calls $\text{swap}(C_A, C_B)$, causing the current machine state to be saved as $C_A$ and the thread $T_B$ to begin executing. $T_B$ then does a $\text{swap}(C_B, C_C)$, causing $T_C$ to start running. Eventually $T_C$ decides that, for whatever reason it wants to allow thread $T_A$ to run again. When it calls $\text{swap}(C_C, C_A)$, the machine state that was previously saved as $C_A$ is restored, and $T_A$ starts running again. From $T_A$’s perspective, the call to $\text{swap}()$ simply did nothing except pause for some period of time.

It is important to note that context and threads are fundamentally different things. A context is merely a snapshot of the CPU as it is at a point in time/code. Threads are represented by a kernel construct that contains a bunch of other information which is unimportant to the hardware (scheduling priority, thread state information, errno, signal mask, etc.). Threads contain a context, not the other way around.

The other little bit of magic that you will be (indirectly) employing is interpositioning, which Tom touched on briefly in his lectures on Linkers and Loaders in CS033. When you run an executable that is using your uthreads package, some system calls will be interposed on by our wrapper code. This is done so that we can effect the rescheduling of a thread whenever it calls a system call that would normally block. In our syscall wrapper, we will call your uthread_yield() function which will cause another, appropriately prioritized thread to begin executing.

3 The Assignment

uthreads is a user-level threading package which has been loosely based on the familiar pthreads interface. It supports the creation of threads which can be joined with or detached, a simple priority
based scheduler, mutexes and condition variables. You will be writing the majority of the uthreads code, but your generous TAs have provided you with some code for dealing with dead threads in addition to some wrappers around the Linux functions for creating and swapping contexts. The uthreads functions which we give you that you might have to call yourself are:

```
// uthread.c
char *alloc_stack();
void free_stack(char*stack);
void make_reapable(uthread_t *uth);

// uthread_ctx.c
void uthread_makecontext(uthread_ctx_t *ctx, char *stack,
                        int stacksz, void (*func)(),
                        long arg1, void *arg2);
void uthread_swapcontext(uthread_ctx_t *oldctx,
                         uthread_ctx_t *newctx);
```

as well as the functions in uthread_queue.h and the macros in list.h.

The uthreads API functions which you must implement are:

```
// uthread.c
void uthread_init();
int uthread_create(uthread_id_t *uidp, uthread_func_t func,
                    long arg1, void *arg2, int prio);
void uthread_exit(int status);
int uthread_join(uthread_id_t uid, int *return_value);
int uthread_detach(uthread_id_t uid);
uthread_id_t uthread_alloc();
void uthread_destroy (uthread_t *uth);

// uthread_sched.c
void uthread_yield();
void uthread_block();
void uthread_wake(uthread_t *uthr);
int uthread_setprio(uthread_id_t id, int prio);
void uthread_switch();
void uthread_sched_init();
void uthread_start_timer();
void clock_interrupt(int sig);
void uthread_nopreempt_reset();

// uthread_mtx.c
void uthread_mtx_init(uthread_mtx_t *mtx);
void uthread_mtx_lock(uthread_mtx_t *mtx);
int uthread_mtx_trylock(uthread_mtx_t *mtx);
void uthread_mtx_unlock(uthread_mtx_t *mtx);
```

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This may seem like a lot of work, but most of these functions are short. As a case-in-point, we are providing you with 800+ lines of stencil code and the TA implementation is less than 1000 lines total. So, while this assignment contains some concepts that you might not have been exposed to, it is mercifully short.

These functions are marked by NOT_YET_IMPLEMENTED macros found in the code. To see a list of all the functions you still need to implement, type make nyi from the command line, while in the same directory as the Makefile we have included.

### 3.1 Overview

Each of the functions mentioned above has extensive comments in the source code which explain what is expected of you, but to save you some time, we will give you a brief summary of how the system works as a whole.

The first thing that any executable that uses your threads package should call is uthread_init(). This should be called exactly once and is responsible for setting up all of your data structures such as the global utthreads array and ut_curthr (which you should make sure is always set to the thread that is currently executing). There is some special code provided for you in uthread_init() that will deal with making the currently executing context (from which the executable just called uthread_init()) a valid uthread and setting up ut_curthr. See the comments around create_first_thr() for more information, if you are interested. Once everything is initialized and uthread_init has completed, you can create threads using uthread_create().

Once you can create threads, you need to schedule them. Whenever a thread needs to temporarily yield the processor to another thread (but still remain runnable), it should call uthread_yield(). You will need to call this in your interrupt handler when preemption is enabled. The support code also uses it as a hook to invoke your scheduler inside our syscall wrappers. Threads can be put to sleep indefinitely and woken up using uthread_block() and uthread_wake() respectively. Choosing another thread to run is done inside the uthread_switch() function. Your scheduler should take thread priorities into account (which are set by uthread_setprio()). To do this, we recommend using a table of separate round-robin queues, one queue for each priority level. This data structure has been provided for you as runq_table in uthread_sched.c.

It is worth noting the difference between blocking and being preempted. A preempted thread is still runnable, and thus should be placed on a run queue before yielding the processor. However, a blocked thread is not runnable, and should not execute until it is explicitly woken back up. Another important difference is that a thread will not block arbitrarily: It does so only when uthread_block() is called. In contrast, a thread may be preempted at any time, unless preemption has been explicitly disabled using uthread_nopreempt_on().

When a thread blocks, it is important that a reference (i.e. pointer) to the thread is kept somewhere. Otherwise, there is no way to find the thread to wake it back up. A reference could be kept as an
explicit pointer, or by placing the thread on a queue. Similarly, when a thread is preempted and relinquishes the processor, a reference must also be maintained, otherwise it will never be placed back on the processor!

In general, the uthreads assignment has been designed to behave like a system you are familiar with, pthreads. As such, it has functions to create, detach, and join threads. As with pthreads, if an undetached thread finishes executing, its cleanup should be deferred until a call to uthread_join() is made. The functions for dealing with mutexes and condition variables should be pretty straightforward as you are familiar with their expected functionality from CS033.

You may find it useful throughout the assignment to reference the man pages for corresponding pthreads functions.

3.2 Thread State

A member of the uthread_t struct (ut_state) is used to store the thread’s state, which is one of the following enum values:

- UT_NO_STATE: An invalid thread state, which should only be used for a thread that has been destroyed, has not been created, or is otherwise no longer valid.
- UT_ON_CPU: A thread state indicating that the thread is currently being run.
- UT_RUNNABLE: A thread state indicating that the thread is runnable, but is not currently being run.
- UT_WAIT: A thread state indicating that the thread is currently blocked, i.e., is not runnable.
- UT_ZOMBIE: A thread state indicating that the thread has finished executing, but has not been cleaned up.
- UT_TRANSITION: A thread state that indicates that the thread is not yet available to be run.

3.3 Assumptions

A note on some of the assumptions that you may make when writing this assignment: uthreads will never have more than one thread running at any one time. Handling multiple CPUs (the ability to run more than one thread concurrently) is beyond the scope of this assignment. This means that as long as preemption is disabled (which can be done with uthread_nopreempt_on) global data structures cannot be modified by other threads.

3.4 Swapping Contexts

In uthreads, you will use uthread_makecontext() to create a machine context for a thread. When you want to change which thread is currently executing (i.e. in your scheduler), you will need to call uthread_swapcontext(). This will cause the current CPU context to be saved and a new context to begin executing. The saved context will resume at a later time when uthread_swapcontext() is called with it as the newctx argument.
3.5 Time Slicing and Preemption

Previous versions of uthreads only allowed for threads to be de-scheduled if they explicitly yielded the processor. Most interfaces for threads do not work this way; instead the execution of various processes are interleaved implicitly by the scheduler.

A common way of implementing this is by time slicing: each thread is granted a certain amount of time that it can run continuously. After this time is up, the thread is “preempted” (i.e. descheduled) and another thread allowed to run. This is typically implemented by scheduling a periodic timer interrupt, and yielding the processor in an interrupt handler.

Since we are in user space, and don’t have interrupts, you will use interval timers (see setitimer) and SIGVTALRM to simulate a timer interrupt; your signal handler will simulate an interrupt handler.

One thing to keep in mind when modifying a threads priority from a uthread’s context is that if the target thread (the thread whose priority is being modified) now has a higher priority than the calling thread, the calling thread should yield to the target thread immediately (see uthread_setprio), to ensure that threads with higher priorities run more frequently than ones with lower priority.

You do not need to worry about the order of execution of threads with the same priority. It is acceptable for your code to execute threads with the same priority in a different order than the TA solution.

3.5.1 Thinking about Preemption

When a thread is preempted (or, for that matter, any time a context switch occurs), although the stream of instructions for the processor does not stop or change, a context switch will often involve executing on a different stack, even though the instruction pointer does not immediately change. What will cause the instruction pointer to change to resume instruction of the thread’s code is the return from the context switch (which uses a return address from the stack it switched to.) In this sense, we can think of multithreaded code as being “two dimensional”, with the instruction pointer being one dimension and the stack pointer being the other dimension. Executing an instruction, jumping, and returning can be thought of as ways of travelling along the instruction dimension, and a context switch is the way to travel along the stack dimension. Think carefully about how you handle preemption when any form of context switch occurs.

3.5.2 Dangers of Preemption

Unfortunately, adding preemption to your code does not “just work.” Some routines must run to completion without yielding the processor - for example, what might happen if uthread_mtx_lock is preempted in the middle of execution? Use the uthread_NOPREEMPT_ON/OFF functions to maintain the correctness of key functions.

Relatedly, you cannot implement this assignment without considering preemption and then return to consider preemption afterwards. You should consider how preemption will affect each function when first implementing it.

\(^1\)And when they do, they often aren’t called threads; more often, they are called coroutines
3.6 Dealing with Dead Threads: The Reaper

As discussed in lecture, the reaper thread is responsible for cleaning up the resources of unused threads. It is important to note that the reaper does not fully clean up non-detached threads which have finished but not yet been joined. Rather, it leaves that work for uthread_join(). We have given you a complete reaper as reaper in uthread.c. You should look at it to understand what this means.

3.7 Error Reporting

As a rule, one should use the standard error types defined in errno.h (although it should not be necessary to include this file to use the values) as mentioned in the pthreads man page. We will follow the same convention that the pthread functions use, which is to return the proper error code.

There are two exceptions to this rule—As our uthread’s mutexes and condition variables are somewhat more well behaved, there’s not a huge necessity for error handling. If a mutex or cond function returns void, you need not return an error code.

3.8 uthread_idle()

In this assignment, you are provided with an implementation of uthread_idle(), which is used to ensure that uthread_switch() does not monopolize the processor when no runnable thread exists (i.e., when the run queue is empty.) For context, this is the same reason that we generally use pthread_cond_wait() instead of looping until a certain condition is met. However, in this assignment, the function is entirely superfluous: You should always have at least one runnable thread, assuming that the client of your library is using it in a way that is defined. You may benefit from thinking about why this is true. Nevertheless, we include the function because it will be necessary in the upcoming mthreads assignment, and because a similar design is necessary for the procs assignment in 169.

4 Compiling and Testing

Currently, it is not possible to take any (already compiled) program and have it use uthreads instead of pthreads. In order to use uthreads, you will need to add all of uthreads’s files to its project, modify it to use the uthreads API functions and recompile it.

4.1 Debugging

As always, use of gdb will make your life much easier when trying to get this assignment up and running. However, gdb can sometimes get confused in multithreaded programs, and may have trouble printing stack traces. If that happens, don’t worry; it doesn’t mean your code is broken. Also, since uthreads is built as a library, gdb won’t find the symbols in it right away, so tell it to wait for the “future shared library to load”.
Also note the variables `clock_count` and `taken_clock_count`. The variables are just debugging/informational tools. `clock_count` should be incremented on every clock interrupt, while `taken_clock_count` should only be incremented if the clock interrupt actually results in a thread switch (i.e. when preemption is allowed).

Essentially `taken_clock_count <= clock_count` and they only fall out of sync when a clock interrupt is received but is “masked”.

### 4.1.1 Core Dumps

When debugging segfaults, sometimes you may want to run the program outside of GDB, perhaps because the program runs correctly under GDB, but not when run independently. In this case, it can sometimes be useful to enable core dumps. A core dump is a copy of the program’s memory that is generated and written to disk (typically with a name like “core”) in the current working directory when the program segfaults. Then, you can attach to the core dump with GDB with `gdb path/to/program/binary path/to/core`, and GDB will tell you where your program segfaulted, and you can examine the state of your program. To enable core dumps, just type `ulimit -c unlimited`. Note that core dumps take a lot of space, so you will want to delete them after you are done with them. Also, you cannot attach to a core dump generated from an old binary; that is, if you recompile, you will not be able to attach to core dumps from a previous compilation, unless you preserve the binary somewhere, but generally, you don’t need to hold on to old cores or binaries.

### 4.1.2 GDB Init

Frequently, you may want to be able to enter a lot of commands and be able to use them every time you start GDB. In order to do this, you will need to create two files called `.gdbinit`, one in your home directory and one in your `uthreads` assignment directory. In your home directory’s `.gdbinit` file, add the following line:

```
add-auto-load-safe-path </full/path/to/uthreads/stencil/.gdbinit>
```

This will allow GDB to recognize the path to your uthreads stencil as safe. In your assignment directory’s `.gdbinit` file, add the following line to the top:

```
set breakpoint pending on
```

followed by any other commands you’d like to run on startup, including breakpoints. The above line allows GDB to automatically answer yes to all pending breakpoint requests (the default action when reading from a file is to answer “no” to all prompts.)

### 4.2 Test Code

We can’t stress enough how important test code is in an assignment like this. Without proper test code, finding bugs will be next to impossible. Make sure to test all sorts of situations with lots of threads at different priority levels. The `Makefile` included with the assignment will compile a simple test program which uses the `uthreads` functions, just to get you started (run `./test` from the directory your `uthreads` library is in). If it runs and exits cleanly, most of your basic functionality is working, but be sure to test more complicated cases.
Judicious use of `assert()` will help you both understand your threads package and debug it. This is your first real systems-level coding project, and it is highly recommended that you assert a general safe state of the system whenever you enter a function. Thinking about what a “safe state” means should lead to a greater understanding of what is happening at any given time and what could go wrong. A caveat though: if you have an `assert` that fails in `uthread_yield()`, your program will enter an infinite loop due to `assert()` calling `write()` calling `uthread_yield()` and so on.

A final warning: `printf()` is NOT thread-safe. This means that while your program may appear to be executing incorrectly, it may just be that the data structures used for buffering are getting clobbered since `printf()` makes multiple calls to `write()`, and the TA code interpositions and thus yields control around each individual call to `write()`. If you are going to write a program to test your `uthreads`, consider using a combination of `sprintf()` and `write()` like is done in the test program the TAs provide for you. As described above, however, `write()` depends on `uthread_yield` and calling it may cause your program to fail if the scheduler isn’t yet fully functional. In such a situation you will need to use `gdb` to debug your program.

5 Getting Started

In order to install the template, run `/course/cs167/bin/cs1670 install uthreads` in your home directory on a department machine.

We suggest you fill in the following files in this order:

- `uthreads.c` (contains core functions such as create, exit, join)
- `uthread_sched.c` (contains thread scheduling functions and time slicing)
- `uthread_mtx.c, uthread_cond.c` (mutexes and condition variables)

As a reminder, you must consider how preemption would affect your functions while you write them. Some routines must run to completion without being preempted by the processor.

Additionally, your functions must correctly handle errors. Refer to the man pages for pthreads when trying to determine how your functions should behave.

6 Handing In

Before submitting, please write a README that includes:

- A description of any additional tests you wrote, and how to run them.
- A description of any known bugs. (If there are none, just write “No bugs” or something similar.)

To hand in your finished assignment, please run this command while in the directory containing your code: `/course/cs167/bin/cs1670_handin uthreads`. 