ECE459: Programming for Performance Winter 2016

Lecture 5 — Creating Processes & Threads

Patrick Lam and Jeff Zarnett

Creating and Using Processes

The workflow in UNIX is as follows. First, the parent spawns the child process with the `fork` system call. If it is interested in waiting for the child process to finish, it will use the system call `wait`, in which case the parent will be awaiting the completion of the child process. When the child process is finished, it returns a value with the `exit` system call. The parent process will then get this as the return value of the `wait` call and may proceed.

What does `fork` do? It creates a new process; it makes a copy of itself. The parent and child continue execution after the `fork` statement. If `fork` returns a negative number, the `fork` system call failed. If it returns 0, the process that got the 0 back is the child. If it returns a positive value, that is the process ID of the child.

After the `fork`, one of the processes may use the `exec` system call, or one of its variants, to replace its memory space with a new program. There's no rule that says this must happen; a child can continue to be a clone of its parent if it wishes. The `exec` invocation loads the binary file into memory and starts execution [SGG13]. At this point, the programs can go their separate ways, or the parent might want to wait for the child to finish. The parent is then blocked, waiting for the child process to execute.

Let's put this all together in an actual C-code example adapted from [SGG13]:

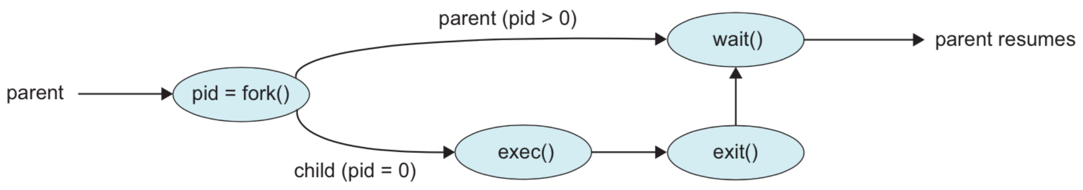
```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main()
{
  pid_t pid;
  int childStatus;

  /* fork a child process */
  pid = fork();

  if (pid < 0) {

    /* error occurred */
    fprintf(stderr, "Fork Failed");
    return 1;

 } else if (pid == 0) {

    /* child process */
    execlp("/bin/ls","ls",NULL);

  } else {

    /* parent process */
    /* parent will wait for the child to complete */
    wait(&childStatus);
    printf("Child Complete with status: %i \n", childStatus);
  }

  return 0;
}
```

When executed, this code starts up and attempts to spawn a child process. Let us assume that the `fork` command succeeds and we do not enter the error-occurred block. After the fork there are now two processes at the statement `if ( pid < 0 )` . The child process calls `execlp`, replacing itself with the `ls` (list directory contents) command. The parent process will go to the `wait` statement and wait for the child process to complete. The child process runs `ls`, listing the contents of the directory. Then it finishes. The parent process, finally, prints "Child Complete" to the console.

Thus, the output is:

```
jz@Freyja:~/fork$ ./fork
fork   fork.c
Child Complete with status: 0
jz@Freyja:~/fork$
```

Or, to represent this visually:



Process creation with the `fork` system call [SGG13].

Using Threads to Program for Performance

We'll start by seeing how to use threads on "embarrassingly parallel problems":

- mostly-independent sub-problems (little synchronization); and
- strong locality (little communication).

Later, we'll see:

- which problems are amenable to parallelization (*dependencies*)
- alternative parallelization patterns
  (right now, just use one thread per sub-problem)

About Pthreads. Pthreads stands for POSIX threads. It's available on most systems, including Pthreads Win32 (which I don't recommend). Use Linux, and our provided server, for this course. C++ 11 also includes threads in its specification.

Here's a quick `pthreads` refresher. To compile a C or C++ program with pthreads, add the `-pthread` parameter to the compiler commandline. To ensure C++11 support in GCC, use `-std=c++11`.

Starting a new thread. You can start a thread with `pthread_create()` or by creating a `std::thread`:

```
#include <pthread.h>
#include <stdio.h>

void* run(void*) {
  printf("In run\n");
}

int main() {
  pthread_t thread;
  pthread_create(&thread, NULL, &run, NULL);
  printf("In main\n");
}
```

```
#include <thread>
#include <iostream>

void run() {
  std::cout << "In run\n";
}

int main() {
  std::thread t1(run);
  std::cout << "In main\n";
  t1.join(); // see below
}
```

From the man page, here's how you use `pthread_create`:

```
int pthread_create(pthread_t* thread,
                   const pthread_attr_t* attr,
                   void* (*start_routine)(void*),
                   void* arg);
```

- **thread**: creates a handle to a thread at pointer location
- **attr**: thread attributes (NULL for defaults, more details later)
- **start_routine**: function to start execution
- **arg**: value to pass to start_routine

This function returns 0 on success and an error number otherwise (in which case the contents of *thread are undefined).

Waiting for Threads to Finish. If you want to join the threads of execution, use the `pthread_join` call. Let's improve our example.

```
#include <pthread.h>
#include <stdio.h>

void* run(void*) {
  printf("In run\n");
}

int main() {
  pthread_t thread;
  pthread_create(&thread, NULL, &run, NULL);
  printf("In main\n");
  pthread_join(thread, NULL);
}
```

The main thread now waits for the newly created thread to terminate before it terminates. (C++11 requires threads to be either joined or detached when they go out of scope; we'll see the meaning of detach below.)

Here's the syntax for `pthread_join`:

```
int pthread_join(pthread_t thread, void** retval)
```

- **thread**: wait for this thread to terminate (thread must be joinable).
- **retval**: stores exit status of thread (set by `pthread_exit`) to the location pointed by *retval. If cancelled, returns `PTHREAD_CANCELED`. `NULL` is ignored.

This function returns 0 on success, error number otherwise.

Caveat: Only call this one time per thread! Multiple calls to join on the same thread lead to undefined behaviour.

Inter-thread communication. Recall that the `pthread_create` call allows you to pass data to the new thread. Let's see how we might do that...

```
int i;
for (i = 0; i < 10; ++i)
  pthread_create(&thread[i], NULL, &run, (void*)&i);
```

Wrong! This is a *terrible* idea. Why?

1. The value of `i` will probably change before the thread executes.
2. The memory for `i` may be out of scope, and therefore invalid by the time the thread executes.

On the other hand, you can pull off something similar with C++11 threads:

```
int i;
for (i = 0; i < 10; ++i) {
  std::thread t(run, i);
  t.detach();
}
```

This is OK because we pass `i` by value, which doesn't work for Pthreads.

In Pthreads-land, this is marginally acceptable:

```
int i;
for (i = 0; i < 10; ++i)
  pthread_create(&thread[i], NULL, &run, (void*)i);

...

void* run(void* arg) {
  int id = (int)arg;
```

It's not ideal, though.

- Beware size mismatches between arguments: you have no guarantee that a pointer is the same size as an int, so your data may overflow. (C only guarantees that the difference between two pointers is an int.)
- Sizes of data types change between systems. For maximum portability, just use pointers you got `from malloc`.

The idiomatic way of returning data from threads in C++11 appears to be using futures. `std::async` provides support for this:

```
#include <thread>
#include <iostream>
#include <future>

int run() {
  return 42;
}

int main() {
  std::future<int> t1_retval = std::async(std::launch::async, run);
  std::cout << t1_retval.get();
}
```

This launches your thread for you. The `get()` call waits until the answer is ready and returns it to you.

More on inter-thread synchronization. There was a comment on `pthread_join` only working if the target thread was joinable. Joinable threads (which is the default on Linux) wait for someone to call `pthread_join` before they release their resources (e.g. thread stacks). On the other hand, you can also create *detached* threads, which release resources when they terminate, without being joined. We've seen C++11 detached threads above.

```
int pthread_detach(pthread_t thread);
```

- **thread**: marks the thread as detached

This call returns 0 on success, error number otherwise.

Calling `pthread_detach` on an already detached thread results in undefined behaviour.

Finishing a thread. A thread finishes when its `start_routine` returns. But it's also possible to explicitly end a thread from within:

```
void pthread_exit(void *retval);
```

- **retval**: return value passed to function which called `pthread_join`

Alternately, returning from the thread's `start_routine` is equivalent to calling `pthread_exit`, and `start_routine`'s return value is passed back to the `pthread_join` caller. There is no C++11 equivalent.

Attributes. Beyond being detached/joinable, threads have additional attributes. (Note, also, that even though being joinable rather than detached is the default on Linux, it's not necessarily the default everywhere). Here's a list.

- Detached or joinable state
- Scheduling inheritance
- Scheduling policy
- Scheduling parameters
- Scheduling contention scope
- Stack size

- Stack address
- Stack guard (overflow) size

Basically, you create and destroy attributes objects with `pthread_attr_init` and `pthread_attr_destroy` respectively. You can pass attributes objects to `pthread_create`. For instance,

```
size_t stacksize;
pthread_attr_t attributes;
pthread_attr_init(&attributes);
pthread_attr_getstacksize(&attributes, &stacksize);
printf("Stack size = %i\n", stacksize);
pthread_attr_destroy(&attributes);
```

Running this on a laptop produces:

```
jon@riker examples master % ./stack_size
Stack size = 8388608
```

Once you have a thread attribute object, you can set the thread state to joinable:

```
pthread_attr_setdetachstate(&attributes,
                            PTHREAD_CREATE_JOINABLE);
```

Warning about detached threads. Consider the following code.

```
#include <pthread.h>
#include <stdio.h>

void* run(void*) {
  printf("In run\n");
}

int main() {
  pthread_t thread;
  pthread_create(&thread, NULL, &run, NULL);
  pthread_detach(thread);
  printf("In main\n");
}
```

When I run it, it just prints "In main". Why?

Solution. Use `pthread_exit` to quit if you have any detached threads.

```
#include <pthread.h>
#include <stdio.h>

void* run(void*) {
  printf("In run\n");
}

int main() {
  pthread_t thread;
  pthread_create(&thread, NULL, &run, NULL);
  pthread_detach(thread);
  printf("In main\n");
  pthread_exit(NULL); // This waits for all detached
                      // threads to terminate
}
```

(There is no C++11 equivalent.)

Threading Challenges.

- Be aware of scheduling (you can also set affinity with pthreads on Linux).
- Make sure the libraries you use are **thread-safe**:
  - Means that the library protects its shared data (we'll see how, below).
- glibc reentrant functions are also safe: a program can have more than one thread calling these functions concurrently. For example, use `rand_r`, not `rand`.

References

[SGG13] Abraham Silberschatz, Peter Baer Galvin, and Greg Gagne. *Operating System Concepts (9th Edition)*. John Wiley & Sons, 2013.