Lecture 29: Concurrency with pthreads

David Hovemeyer

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601.229 Computer Systems Fundamentals

Concurrency using processes

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Scheduling a process requires switching address spaces (possibly losing useful context built up in caches and TLB)

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Compared to processes, threads are lightweight, requiring only:

- Context (memory in which to save register values when thread is suspended)
- A stack
- Thread-local storage (for per-thread variables)

Pthreads

Pthreads

Pthreads = "POSIX threads"

Standard API for using threads on Unix-like systems

Allows:

- Creating threads and waiting for them to complete
- Synchronizing threads (more on this soon)

Can be used for both concurrency and parallelism (on multicore machines, threads can execute in parallel)

Basic concepts

Some basic concepts:

`pthread_t`: the *thread id* data type, each running thread has a distinct thread id

Thread attributes: runtime characteristics of a thread

- Many programs will just create threads using the *default attributes*

Attached vs. detached: a thread is *attached* if the program will explicitly call `pthread_join` to wait for the thread to finish.

pthread_create

```
#include <pthread.h>

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

Creates a new thread. Thread id is stored in variable pointed-to by *thread* parameter. The *attr* parameter specifies attributes (NULL for default attributes.)

The created thread executes the *start_routine* function, which is passed *arg* as its parameter.

Returns 0 if successful.

pthread_join

```
#include <pthread.h>

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

Waits for specified thread to finish. Only attached threads can be waited for.

Value returned by exited thread is stored in the variable pointed-to by *retval*.

pthread_self

```
#include <pthread.h>

pthread_t pthread_self(void);
```

Allows a thread to find out its own thread id.

pthread_detach

```
#include <pthread.h>

int pthread_detach(pthread_t thread);
```

Changes the specified thread to be detached, so that its resources can be freed without another thread explicitly calling `pthread_join`.

Multithreaded web server

Third version of the example web server: `mt_webserver.zip` on course web page

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- Server will create a thread for each client connection
- Created threads are *detached*: the server program doesn't wait for them to complete
- No limit on number of threads that can be created
- Only the `main` function is different than previous versions

struct ConnInfo

`struct ConnInfo`: represents a client connection:

```
struct ConnInfo {
  int clientfd;
  const char *webroot;
};
```

It's useful to pass an object containing data about the task the thread has been assigned to the thread's start function

worker function

The `worker` function (executed by client connection threads):

```
void *worker(void *arg) {
  struct ConnInfo *info = arg;

  pthread_detach(pthread_self());

  server_chat_with_client(info->clientfd, info->webroot);
  close(info->clientfd);
  free(info);

  return NULL;
}
```

A created thread detaches itself, handles the client request, closes the client socket, frees its `ConnInfo` object, then returns

main loop

Main loop:

```
while (1) {
  int clientfd = Accept(serverfd, NULL, NULL);
  if (clientfd < 0) {
    fatal("Error accepting client connection");
  }

  struct ConnInfo *info = malloc(sizeof(struct ConnInfo));
  info->clientfd = clientfd;
  info->webroot = webroot;

  pthread_t thr_id;
  if (pthread_create(&thr_id, NULL, worker, info) != 0) {
    fatal("pthread_create failed");
  }
}
```

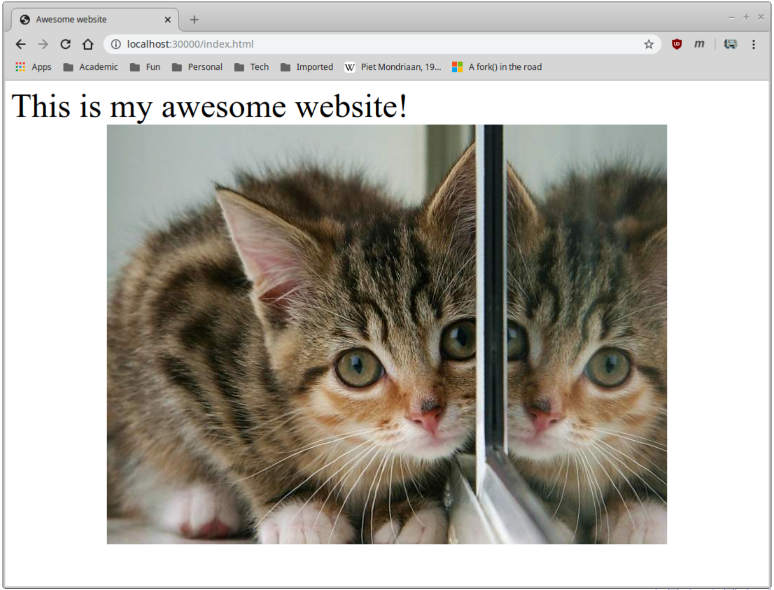
Trying it out

Compile and run the server:

```
$ gcc -o mt_webserver main.c webserver.c csapp.c -lpthread
$ ./mt_webserver 30000 ./site
```

Result

Visiting URL `http://localhost:30000/index.html`



Multithreaded programming

Shared memory

Main issue with writing multithreaded progams is that the threads execute in the *same address space*, so they share memory

A variable written by one thread may be read by another!

- Can be useful for communication between threads
- Can also be dangerous

Reentrancy

Some functions are designed to use global variables:

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"Reentrant" means function can be safely "reentered" before a currently-executing call to the same function completes

Non-reentrant functions are dangerous for multithreaded programs (and also cause issues when called from recursive functions)

Writing reentrant functions

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Tips for writing reentrant functions:

- Don't use global variables
- Memory used by a reentrant function should be limited to
  - Local variables (on stack), or
  - Heap buffers not being used by other threads
- It's a good idea to have functions receive explicit pointers to memory they should use

Example: strtok vs. strtok_r

The `strtok` function uses an implicit global variable to keep track of progress:

```
char buf[] = "foo bar baz";
printf("%s\n", strtok(buf, " "));    /* prints "foo" */
printf("%s\n", strtok(NULL, " "));   /* prints "bar" */
printf("%s\n", strtok(NULL, " "));   /* prints "baz" */
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The reentrant `strtok_r` function makes the progress variable explicit by taking a pointer to it as a parameter:

```
/* same output as code example above */
char buf[] = "foo bar baz", *save;
printf("%s\n", strtok_r(buf, " ", &save));
printf("%s\n", strtok_r(NULL, " ", &save));
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```

Always use reentrant versions of library functions, and make your own functions reentrant!

Synchronization

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Synchronization mechanisms allow multiple threads to access shared data cooperatively

- More on this eventually
- 10 second version: queues are awesome

Parallel computation

Mandelbrot set

Assume C is a complex number, and $Z_0 = 0 + 0i$

Iterate the following equation an arbitrary number of times, starting with Z_0:

$$Z_{n+1} = {Z_n}^2 + C$$

Does the magnitude of Z ever reach 2 (for any finite number of iterations)?

- No $\rightarrow$ C is in the Mandelbrot set
- Yes $\rightarrow$ C is not in the Mandelbrot set

Visualizing the Mandelbrot set

For some region of the complex plane, sample points and determine whether they are in the Mandelbrot set

Assume a point C is in the set if the equation can be iterated at large number of times without magnitude of Z reaching 2

For points C not in the set, choose a color based on number of iterations before magnitude of Z reaches 2

Complex numbers

```
typedef struct { double real, imag; } Complex;

static inline Complex complex_add(Complex left, Complex right) {
  Complex sum = { left.real+right.real, left.imag+right.imag };
  return sum;
}

static inline Complex complex_mul(Complex left, Complex right) {
  double a = left.real, b = left.imag, c = right.real, d = right.imag;
  Complex prod = { a*c - b*d, b*c + a*d };
  return prod;
}

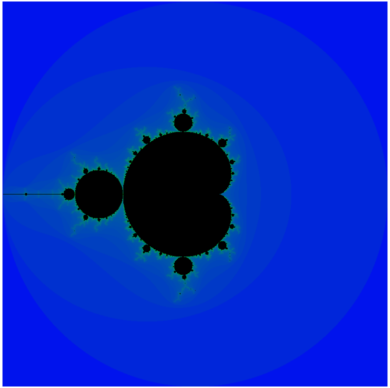
static inline double complex_mag(Complex c) {
  return sqrt(c.real*c.real + c.imag*c.imag);
}
```

Computation

Function to iterate the equation for a specific complex number, up to a maximum number of iterations

```
int mandel_num_iters(Complex c) {
  Complex z = { 0.0, 0.0 };
  int num_iters = 0;
  while (complex_mag(z) < 2.0 && num_iters < MAX_ITERS) {
    z = complex_add(complex_mul(z, z), c);
    num_iters++;
  }
  return num_iters;
}
```

Visualization



For complex numbers $a + bi$ where $-2 < a < 2$ and $-2 < b < 2$:

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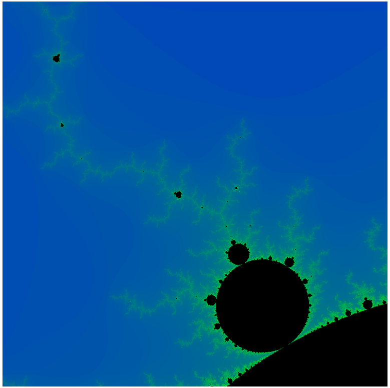


For complex numbers $a + bi$ where $-1.28667 < a < -1.066667$ and $-0.413333 < b < -0.193333$:

Observation

The computation for each point in the complex plane is completely independent

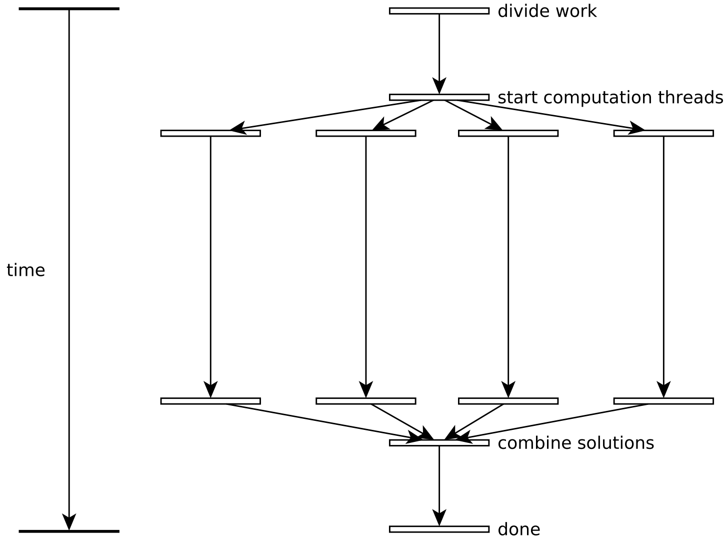
- I.e., an *embarrassingly parallel* problem

We can speed up the computation by doing the computation for different points in parallel on multiple CPU cores

Approach:

- Use an array to store iteration counts (one per complex number)
- Create fixed number of computation threads
- Assign a subset of array elements to each computation thread
- When all threads have finished, use iteration counts to render image

Fork/join parallel computation



Sequential computation

Core of the sequential Mandelbrot computation:

```
int *iters = malloc(sizeof(int) * NROWS * NCOLS);
for (int i = 0; i < NROWS; i++) {
  mandel_compute_row(iters, NROWS, NCOLS,
    xmin, xmax, ymin, ymax,
    i);
}
```

The `mandel_compute_row` function computes iteration counts for a row of complex numbers, storing them in the `iters` array

Fork/join: task struct, start func

```
typedef struct {
  double xmin, xmax, ymin, ymax;
  int *iters;
  int start_row, skip;
} Work;

void *worker(void *arg) {
  Work *work = arg;

  for (int i = work->start_row; i < NROWS; i += work->skip) {
    mandel_compute_row(work->iters, NROWS, NCOLS,
      work->xmin, work->xmax, work->ymin, work->ymax,
      i);
  }

  return NULL;
}
```

Fork/join: parallel computation

```
/* master work assignment */
Work master = { xmin, xmax, ymin, ymax, iters, 0, NUM_THREADS };

/* start threads */
pthread_t threads[NUM_THREADS];
Work work[NUM_THREADS];
for (int i = 0; i < NUM_THREADS; i++) {
  work[i] = master;
  work[i].start_row = i; /* each thread has different start row */
  pthread_create(&threads[i], NULL, worker, &work[i]);
}

/* wait for threads to complete */
for (int i = 0; i < NUM_THREADS; i++) {
  pthread_join(threads[i], NULL);
}
```

Results

Running sequential vs. 4 threads on Core i5-3470T (dual core, hyperthreaded):

```
$ time ./mandelbrot -1.286667 -1.066667 -0.413333 -0.193333
Success?

real    0m2.020s
user    0m2.012s
sys     0m0.008s
$ time ./mandelbrot_par -1.286667 -1.066667 -0.413333 -0.193333
Success?

real    0m0.815s
user    0m3.054s
sys     0m0.000s
```

Source code on web page: `mandelbrot.zip`