Multithreading

Types of parallel computations

Plan

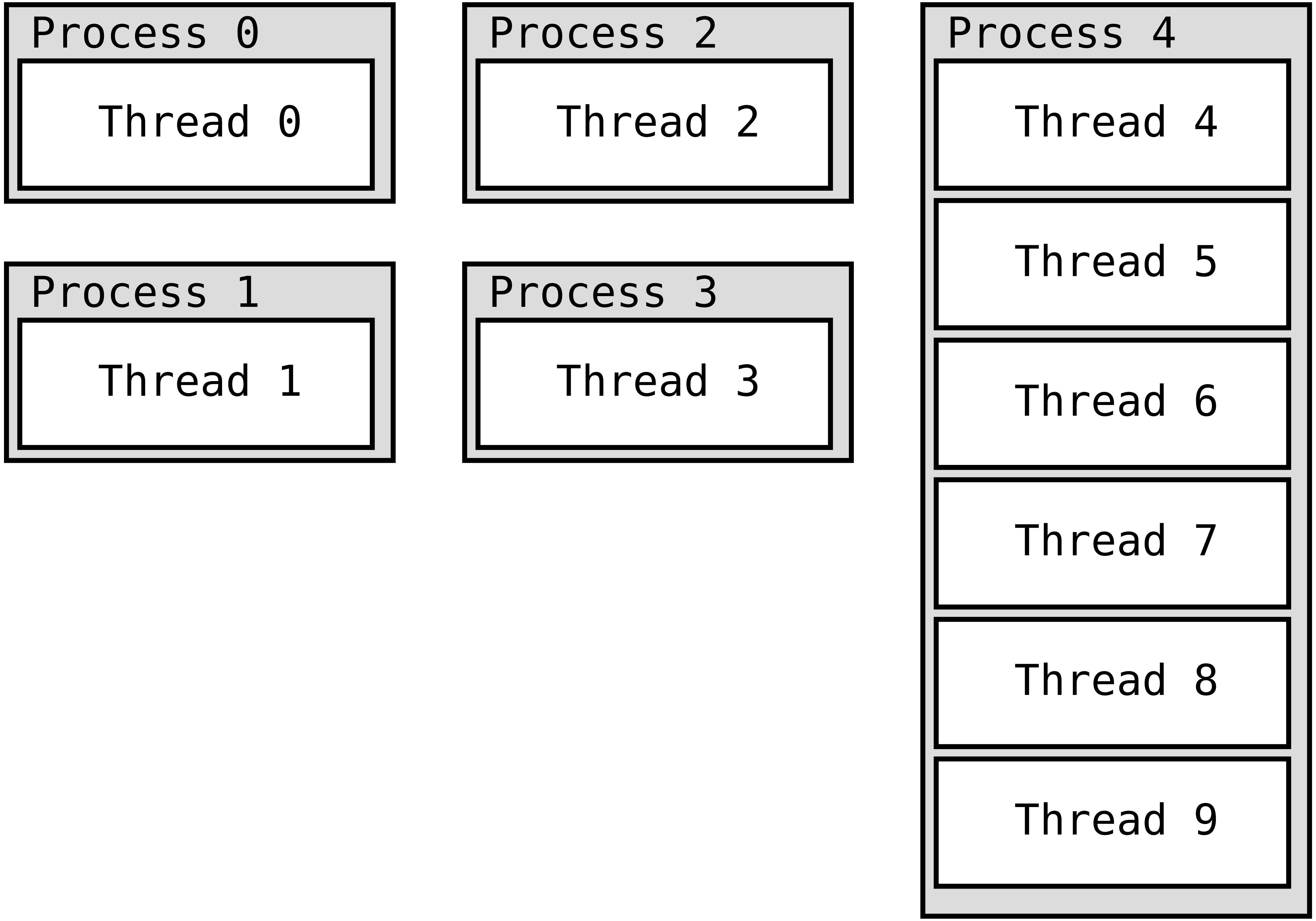
0. Parallelism that does not require programmer intervention
1. SIMD
2. Thread-level concurrency
3. Distributed computing
4. Hardware acceleration

2. Thread-level concurrency

Processes and threads

- When the OS runs an executable, it gets its own process
- A single executable (if run multiple times) can have multiple independent processes
- Memory is virtualized: each process has its own view of the memory it owns

- A process can create (“spawn”) multiple threads
- Like processes, each thread is an individual task from the point of view of the scheduler
- Within a process, threads share a same view of the process memory


Process 0
Thread 0
Process 1
Thread 1
Process 2
Thread 2
Process 3
Thread 3
Process 4
Thread 4
Thread 5
Thread 6
Thread 7
Thread 8
Thread 9

- Pro: Communication between threads is extremely efficient
    - Just write something to memory,
    - let other threads read it through the same pointer

- Con: Because memory is shared, **synchronizing** threads is very complex
    - It is difficult for humans to reason about
    - The C language was not designed for multithreading

      no semantics for concurrent read/write to shared variables until C11

Wrong code (1)

```c
int ready = 0;       //  one if there is some data in the buffer, zero otherwise
int buffer = 0;      //  data in the buffer

// Every push()ed element must be pop()ed exactly once.
// - push() will block until the buffer is empty/available/"not ready"
// - pop() will block until the buffer is nonempty/"ready"
void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    ready = 0;
    return buffer;
}
```

The C compiler is free to reorder this:

```c
void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

into this:

```c
void push(int value)
{
    buffer = value;

    while (ready == 1) {
        // wait
    }

    ready = 1;
}
```

```c
while (ready == 1) {
    // wait
}
```

The C compiler can also notice that this loop has either

- zero iterations, or
- infinitely many iterations without side effects (UB!)

thus remove the loop!

The `volatile` keyword

An object that has volatile-qualified type [C23, p119]

- may be modified in ways unknown to the implementation
- or have other unknown side effects.

Example:

```
volatile int ready = 0;      //  one if there is some data in the buffer, zero otherwise
volatile int buffer = 0;     //  data in the buffer
```

Wrong code (2)

```
volatile int ready = 0;      //  one if there is some data in the buffer, zero otherwise
volatile int buffer = 0;     //  data in the buffer

void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    ready = 0;
    return buffer;
}
```

Thread 0

```
                                  // ready = 1      buffer = 'A'
int pop()
{
    while (ready == 0) {
        // wait
    }
                                  // ready = 1      buffer = 'A'
    ready = 0;                    // ready = 0      buffer = 'A'






                                  // ready = 0      buffer = 'B'
                                  // ready = 1      buffer = 'B'


    return buffer;
}
```

Thread 1

```
void push(int value)              // push('B')
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

Wrong code (3)

```
volatile int ready = 0;       //  one if there is some data in the buffer, zero otherwise
volatile int buffer = 0;      //  data in the buffer

void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    int b = buffer;
    ready = 0;
    return b;
}
```

Thread 0

```
                                   // ready = 0      buffer = 'X'
void push(int value)  // push('A')
{
    while (ready == 1) {
        // wait
    }
                                   // ready = 0      buffer = 'X'




                                   // ready = 0      buffer = 'B'
                                   // ready = 1      buffer = 'B'


    buffer = value;                // ready = 1      buffer = 'A'
    ready = 1;                     // ready = 1      buffer = 'A'
}
```

Thread 1

```
void push(int value)    // push('B')
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

Solution

- low-level: compiler intrinsics for “**atomic**” operations:

  combined operations that are performed as a single unit

  no thread will ever see the memory in an intermediate state

- high-level: use libraries that correctly implement some primitives:

  locks, queues, etc.

  - C11 threads
  - Win32 threads (Windows)
  - Posix threads (“`pthreads`”; Linux, MacOS)
  - OpenMP (Open Multi-Processing; higher-level, portable)

C11 threads

- Introduced in C11
- Was initially defective and thus amended in C17
- Support is optional for compilers writers
- Very little documentation besides the C standard

Other multithreading APIs

- Win32 threads: official documentation.
- Posix threads: official documentation, current reference.
- OpenMP: tutorials, specification.

Posix threads

Using with `libpthread`

```c
#include <pthread.h>

...
```

Link with `-lpthread`:

```
clang -o executable obj0.o obj1.o obj2.o -lpthread
```

Creating threads

```c
#include <pthread.h>

typedef thread_fn_t(void *arg);

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

- `thread` is a pointer to a `pthread_t` (in practice: an integer of some size).
  On success, it is set to a thread identifier (for the just-created thread).
- `attr` allows overriding default parameters (stack size and address, thread priority, …).
  Set to NULL for defaults.
- `fn` is a pointer to a function that will run the thread code.
  (When the function returns, the thread terminates.)
- `arg` is a pointer passed as an argument to `fn`.
  (Allows differentiating threads if they run the same `fn`).

```c
#include <pthread.h>

typedef thread_fn_t(void *arg);

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

Example:

```c
void *thread_fn(void *arg)
{
    int data = *((int *)arg);
    printf("Thread %d\n", data);
    return NULL;
}

int main()
{
    int data0 = 0;
    int data1 = 1;
    pthread_t id0, id1;

    if (pthread_create(&id0, NULL, thread_fn, &data0))
        return 1;

    if (pthread_create(&id1, NULL, thread_fn, &data1))
        return 1;

    // ...
}
```

Terminating threads

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

- `pthread_exit()` is an alternative to returning from the thread function
- It exits as if the thread function returned `retval`

Waiting for a thread to terminate

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

We pass:

- the thread identifier `thread`, and
- a pointer to a void pointer `retval`.

  (the void pointer will be set to the return value of the thread function)

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <pthread.h>

int x = 0;

void *mythread(void *arg)
{
    x = 1;
    printf("Child process set x=1\n");
    return NULL;
}

int main(int argc, char *argv[])
{
    pthread_t tid;
    int e0 = pthread_create(&tid, NULL, mythread, NULL);

    if (e0) {
        fprintf(stderr, "pthread_create(): %s\n", strerror(e0));
        exit(EXIT_FAILURE);
    }

    void *vp;
    int e1 = pthread_join(tid, &vp);

    if (e1) {
        fprintf(stderr, "pthread_join(): %s\n", strerror(e1));
        exit(EXIT_FAILURE);
    }

    printf("Returned pointer: %p\n", vp);
    printf("Parent process sees x=%d\n", x);
    return EXIT_SUCCESS;
}
```

```
Child process set x=1
Returned pointer: (nil)
Parent process sees x=1
```

Synchronizing primitives

- mutex
- condition variable

Mutexes

Mutexes

"Mutex" stands for mutual exclusion.

Mutexes have two states:

- locked and "owned" by a specific thread
- unlocked

Attempting to lock an already-locked mutex blocks until it is unlocked first

```c
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- `pthread_mutex_lock()` locks the given mutex
  1. if `mutex` was unlocked,

     it becomes locked and owned by the calling thread

     returns immediately
  2. if `mutex` is already locked by another thread

     suspends the calling thread until `mutex` is unlocked.

     when `mutex` is unlocked, see a.

- `pthread_mutex_unlock()` unlocks the given mutex

  (currently locked and owned by the calling thread)

Both functions return zero in normal operation.

Example

```c
char shared_buffer[16777216];
pthread_mutex_t shared_buffer_mutex = PTHREAD_MUTEX_INITIALIZER;


void *thread_function(void *arg)
{
    while (1) {
        if (pthread_mutex_lock(&shared_buffer_mutex))
            abort();

        process_data(shared_buffer);

        if (pthread_mutex_unlock(&shared_buffer_mutex))
            abort();
    }

    return NULL;
}
```

Implementation of blocking functions

Busy waiting:

```
while (*mutex_locked == 0) { }
```

- Best possible latency
- Wastes resources:
  - Keeps a CPU busy, no other thread can run
  - CPU consumes power and generates heat while doing nothing

System call:

Kernel scheduler suspends thread and either puts CPU to sleep, or runs another thread

- High latency
  - direct costs: 1000+ cycles (“context switch”: restoring registers & usermode page table)
  - indirect costs: pipeline and cache invalidation

- Best resource usage (if not too frequent)

Consider the following task:

- We have a shared buffer:

```
pthread_mutex_t buff_mutex = PTHREAD_MUTEX_INITIALIZER;
char *buff_data;
size_t buff_size;
size_t buff_used;
```

- We have a thread with a single mission:
  When the buffer is full, it calls a function `buffer_flush()`

```c
pthread_mutex_t buff_mutex = PTHREAD_MUTEX_INITIALIZER;
char *buff_data;
size_t buff_size;
size_t buff_used;
```

```c
void *flusher_thread(void *arg)
{
    while (1) {
        // wait until buffer is full
        while (1) {
            if (pthread_mutex_lock(&buff_mutex))
                abort();

            if (buff_used == buff_size) {
                // stop waiting, while owning the mutex
                break;
            }

            if (pthread_mutex_unlock(&buff_mutex))
                abort();
        }

        // flush buffer (while owning the mutex)
        buffer_flush();

        // unlock mutex
        if (pthread_mutex_unlock(&buff_mutex))
            abort();
    }

    return NULL;
}
```

- This implementation has high *lock contention*:

  `flusher_thread()` will keep trying own `buff_mutex` all the time

- If it succeeds in doing so without waiting, it is essentially busy waiting.

Solution: condition variables

Condition variables

Condition variables

A **condition variable** allows efficiently blocking until an arbitrary condition becomes true.

Other threads cooperatively signal it when the condition **may** have become true.

```c
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
```

- `pthread_cond_wait()`:
  - unlocks `mutex`
  - waits for cond to be signaled
  - re-locks `mutex`

- `pthread_cond_signal()` restarts one thread waiting cond
  - if no thread is waiting, nothing happens
  - if several threads are waiting, exactly one is restarted (it is not specified which)

```c
pthread_mutex_t buff_mutex = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t buff_cond = PTHREAD_COND_INITIALIZER;
char *buff_data;
size_t buff_size;
size_t buff_used;
```

```c
void *flusher_thread(void *arg)
{
    while (1) {
        // wait until buffer is full
        if (pthread_mutex_lock(&buff_mutex))
            abort();

        while (buff_used < buff_size) {
            if (pthread_cond_wait(&buff_cond, &buff_mutex))
                abort();
        }

        // flush buffer (while owning the mutex)
        buffer_flush();

        // unlock mutex
        if (pthread_mutex_unlock(&buff_mutex))
            abort();
    }

    return NULL;
}
```

```c
void *filler_thread(void *arg)
{
    while (1) {
        // lock mutex
        if (pthread_mutex_lock(&buff_mutex))
            abort();

        // fill buffer
        size_t old_used = buff_used;

        buffer_fill();

        if (buff_used > old_used) {
            if (pthread_cond_signal(&buff_cond))
                abort();
        }

        // unlock mutex
        if (pthread_mutex_unlock(&buff_mutex))
            abort();
    }

    return NULL;
}
```

Resources

Resources

- “Perf Book”:
  Is Parallel Programming Hard, And, If So, What Can You Do About It?
  https://mirrors.edge.kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html

- Book about (among other things) concurrency:
  Operating Systems: Three Easy Pieces
  https://pages.cs.wisc.edu/~remzi/OSTEP/

- pthreads tutorial:
  https://www.cs.cmu.edu/afs/cs/academic/class/15492-f07/www/pthreads.html