Concurrency + Parallelism

- Concurrency vs Parallelism
- Flynn’s taxonomy
- Threads in C
- What can go wrong?
- Synchronisation with mutexes
- What can still go wrong?
- Atomics
- Lifetimes + Thread barriers

Concurrency? Parallelism?

Concurrency:
multiple computations in overlapping time periods ...
does not have to be simultaneous

Parallelism:
multiple computations executing simultaneously

Common classifications of types of parallelism (Flynn’s taxonomy):

- **SISD**: Single Instruction, Single Data (“no parallelism”)
  - e.g. our code in *mipsy*
- **SIMD**: Single Instruction, Multiple Data (“vector processing”):
  - multiple cores of a CPU executing (parts of) same instruction
  - e.g., GPUs rendering pixels
- **MISD**: Multiple Instruction, Single Data (“pipelining”):
  - data flows through multiple instructions; very rare in the real world
  - e.g., fault tolerance in space shuttles (task replication), sometimes A.I.
- **MIMD**: Multiple Instruction, Multiple Data (“multiprocessing”)
  - multiple cores of a CPU executing different instructions
Distributed Parallel Computing: Parallelism Across Many Computers

Parallelism can also occur between multiple computers!

Example: Map-Reduce is a popular programming model for

- manipulating very large data sets
- on a large network of computers — local or distributed
  - spread across a rack, data center or even across continents

The map step filters data and distributes it to nodes

- data distributed as (key, value) pairs
- each node receives a set of pairs with common key

Nodes then perform calculation on received data items.

The reduce step computes the final result

- by combining outputs (calculation results) from the nodes

There also needs a way to determine when all calculations completed.

Data Parallel Computing: Parallelism Across An Array

- multiple, identical processors
- each given one element of a data structure from main memory
- each performing same computation on that element: SIMD
- results copied back to data structure in main memory

- But not totally independent: need to synchronise on completion
- Graphics processing units (GPUs) provide this form of parallelism
  - used to compute the same calculation for every pixel in an image quickly
  - popularity of computer gaming has driven availability of powerful hardware
  - there are tools & libraries to run some general-purpose programs on GPUs
    - if the algorithm fits this model, it might run 5-10x faster on a GPU
    - e.g., GPUs used heavily for neural network training (deep learning)

Parallelism Across Processes

One method for creating parallelism:
create multiple processes, each doing part of a job.

- child executes concurrently with parent
- runs in its own address space
- inherits some state information from parent, e.g. open fd’s

Processes have some disadvantages:

- process switching is expensive
- each require a significant amount of state — memory usage
- communication between processes potentially limited and/or slow

But one big advantage:

- separate address spaces make processes more robust.

The web server providing the class website uses process-level parallelism

An android phone will have several hundred processes running.
Threads allow us parallelism within a process.

- Threads allow simultaneous execution.
- Each thread has its own execution state often called Thread control block (TCB).
- Threads within a process share address space:
  - threads share code: functions
  - threads share global/static variables
  - threads share heap: malloc
- But a separate stack for each thread:
  - local variables not shared
- Threads in a process share file descriptors, signals.

POSIX Threads is a widely-supported threading model.

Supported in most Unix-like operating systems, and beyond

Describes an API/model for managing threads (and synchronisation).

```c
#include <pthread.h>

More recently, ISO C2011 has adopted a pthreads-like model...
less well-supported generally, but very, very similar.
```

**pthread_create(3): create a new thread**

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

- Starts a new thread running the specified `thread_main(arg)`.
- Information about newly-created thread stored in `thread`.
- Thread has attributes specified in `attr` (NULL if you want no special attributes).
- Returns 0 if OK, -1 otherwise and sets `errno`
- analogous to `posix_spawn(3)`
**pthread_join(3): wait for, and join with, a terminated thread**

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

- waits until `thread` terminates
  - if `thread` already exited, does not wait
- thread return/exit value placed in `*retval`
- if `main` returns, or `exit(3)` called, all threads terminated
  - program typically needs to wait for all threads before exiting
- analogous to `waitpid(3)`

**pthread_exit(3): terminate calling thread**

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

- terminates the execution of the current thread (and frees its resources)
- `retval` returned — see `pthread_join(3)`
- analogous to `exit(3)`

**Example: two_threads.c — creating two threads #1**

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

// This function is called to start thread execution.
// It can be given any pointer as an argument.
void *run_thread(void *argument) {
    int *p = argument;
    for (int i = 0; i < 10; i++) {
        printf("Hello this is thread %d: i=%d\n", *p, i);
    }
    // A thread finishes when either the thread's start function
    // returns, or the thread calls `pthread_exit(3)`.
    // A thread can return a pointer of any type --- that pointer
    // can be fetched via `pthread_join(3)`
    return NULL;
}
```

Source code for two_threads.c
Example: `two_threads.c` — creating two threads

```c
int main(void) {
    // Create two threads running the same task, but different inputs.
    pthread_t thread_id1;
    int thread_number1 = 1;
    pthread_create(&thread_id1, NULL, run_thread, &thread_number1);
    pthread_t thread_id2;
    int thread_number2 = 2;
    pthread_create(&thread_id2, NULL, run_thread, &thread_number2);
    // Wait for the 2 threads to finish.
    pthread_join(thread_id1, NULL);
    pthread_join(thread_id2, NULL);
    return 0;
}
```

Example: `n_threads.c` — creating many threads

```c
int n_threads = strtol(argv[1], NULL, 0);
assert(0 < n_threads && n_threads < 100);
pthread_t thread_id[n_threads];
int argument[n_threads];
for (int i = 0; i < n_threads; i++) {
    argument[i] = i;
    pthread_create(&thread_id[i], NULL, run_thread, &argument[i]);
}

// Wait for the threads to finish
for (int i = 0; i < n_threads; i++) {
    pthread_join(thread_id[i], NULL);
}
return 0;
```

Example: `thread_sum.c` — dividing a task between threads (i)

```c
struct job {
    long start, finish;
    double sum;
};
void *run_thread(void *argument) {
    struct job *j = argument;
    long start = j->start;
    long finish = j->finish;
    double sum = 0;
    for (long i = start; i < finish; i++) {
        sum += i;
    }
    j->sum = sum;
}
```

Source code for `two_threads.c`

Source code for `n_threads.c`

Source code for `thread_sum.c`
printf("Creating %d threads to sum the first %lu integers\n", n_threads, integers_to_sum, integers_per_thread);

struct job jobs[n_threads];

for (int i = 0; i < n_threads; i++) {
    jobs[i].start = i * integers_per_thread;
    jobs[i].finish = jobs[i].start + integers_per_thread;
    if (jobs[i].finish > integers_to_sum) {
        jobs[i].finish = integers_to_sum;
    }
    // create a thread which will sum integers_per_thread integers
    pthread_create(&thread_id[i], NULL, run_thread, &jobs[i]);
}

double overall_sum = 0;

for (int i = 0; i < n_threads; i++) {
    pthread_join(thread_id[i], NULL);
    overall_sum += jobs[i].sum;
}

printf("\nCombined sum of integers 0 to %lu is %.0f\n", integers_to_sum, overall_sum);

return 0;

---

Seconds to sum the first $10^{10}$ ($10,000,000,000$) integers using double arithmetic, with $N$ threads, on some different machines…

<table>
<thead>
<tr>
<th>host</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>12</th>
<th>24</th>
<th>50</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>5800X</td>
<td>6.6</td>
<td>3.3</td>
<td>1.6</td>
<td>0.8</td>
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<td>0.6</td>
<td>0.6</td>
</tr>
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<td>0.3</td>
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<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>E7330</td>
<td>12.9</td>
<td>6.3</td>
<td>3.2</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>IIIi</td>
<td>136.6</td>
<td>68.4</td>
<td>68.6</td>
<td>68.4</td>
<td>68.5</td>
<td>68.6</td>
<td>68.6</td>
</tr>
</tbody>
</table>

5800X: AMD Ryzen 5800X; 8 cores, 16 threads, 3.8 GHz, 2020
3900X: AMD Ryzen 3900X; 12 cores, 24 threads, 3.8 GHz, 2019
i5-4590: Intel Core i5-4590; 4 cores, 4 threads, 3.3 GHz, 2014
E7330: Intel Xeon E7330; 4 sockets, 4 cores, 4 threads, 2.4 GHz, 2007
IIIi: Sun UltraSPARC IIIi; 2 sockets, 1 core, 1 thread, 1.5 GHz, 2003
Example: `two_threads_broken.c` — shared mutable state gonna hurt you

```c
int main(void) {
    pthread_t thread_id1;
    int thread_number = 1;
    pthread_create(&thread_id1, NULL, run_thread, &thread_number);
    thread_number = 2;
    pthread_t thread_id2;
    pthread_create(&thread_id2, NULL, run_thread, &thread_number);
    pthread_join(thread_id1, NULL);
    pthread_join(thread_id2, NULL);
    return 0;
}
```

- variable `thread_number` will probably change in `main`, before thread 1 starts executing...
- \[\implies\] thread 1 will probably print `Hello this is thread 2...`?

Example: `bank_account_broken.c` — unsafe access to global variables (i)

```c
int bank_account = 0;
// add $1 to Andrew's bank account 100,000 times
void *add_100000(void *argument) {
    for (int i = 0; i < 100000; i++) {
        // execution may switch threads in middle of assignment
        // between load of variable value
        // and store of new variable value
        // changes other thread makes to variable will be lost
        nanosleep((struct timespec){ .tv_nsec = 1 }, NULL);
        // RECALL: shorthand for `bank_account = bank_account + 1`
        bank_account++;
    }
    return NULL;
}
```

Example: `bank_account_broken.c` — unsafe access to global variables (ii)

```c
int main(void) {
    // create two threads performing the same task
    pthread_t thread_id1;
    pthread_create(&thread_id1, NULL, add_100000, NULL);
    pthread_t thread_id2;
    pthread_create(&thread_id2, NULL, add_100000, NULL);
    // wait for the 2 threads to finish
    pthread_join(thread_id1, NULL);
    pthread_join(thread_id2, NULL);
    // will probably be much less than $200000
    printf("Andrew's bank account has $%ld\n", bank_account);
    return 0;
}
```

Example: `bank_account_broken.c` — unsafe access to global variables (ii)
Global Variables and Race Conditions

Incrementing a global variable is not an atomic operation.

- (atomic, from Greek — “indivisible”)

```c
int bank_account;

void *thread(void *a) {
    // ...
    bank_account++;
    // ...
}
```

Oops! We lost an increment.
Threads do not share registers or stack (local variables)... but they do share global variables.

Global Variable: Race Condition

If, initially, bank_account = 42, and two threads increment simultaneously...

```assembly
la $t0, bank_account
lw $t1, ($t0)
addi $t1, $t1, 1
sw $t1, ($t0)
```

This is a critical section. We don’t want two processes in the critical section — we must establish mutual exclusion.

If, initially, bank_account = 100, and two threads change it simultaneously...

```assembly
la $t0, bank_account
lw $t1, ($t0)
addi $t1, $t1, 100
sw $t1, ($t0)
```

```assembly
la $t0, bank_account
lw $t1, ($t0)
addi $t1, $t1, -50
sw $t1, ($t0)
```

This is a critical section. We don’t want two processes in the critical section — we must establish mutual exclusion.
int pthread_mutex_lock (pthread_mutex_t *mutex);
int pthread_mutex_unlock (pthread_mutex_t *mutex);

- We associate a mutex with the resource we want to protect.
  - in the case the resources is access to a global variable
- For a particular mutex, only one thread can be running between _lock and _unlock
- Other threads attempting to pthread_mutex_lock will block (wait) until the first thread executes pthread_mutex_unlock

For example:

```c
pthread_mutex_lock (&bank_account_lock);
andrews_bank_account += 100000;
pthread_mutex_unlock (&bank_account_lock);
```

Example: bank_account_mutex.c — guard a global with a mutex

```c
int bank_account = 0;
pthread_mutex_t bank_account_lock = PTHREAD_MUTEX_INITIALIZER;
// add $1 to Andrew's bank account 100,000 times
void *add_100000(void *argument) {
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock(&bank_account_lock);
        // only one thread can execute this section of code at any time
        bank_account = bank_account + 1;
    }
    pthread_mutex_unlock(&bank_account_lock);
}
return NULL;
}
```

Mutex the world!

- Mutexes solve all our data race problems!
- So, just put a mutex around everything?
- This works, but then we lose the advantages of parallelism
- Python does this - the global interpreter lock (GIL)
  - although they are (trying to stop)[https://peps.python.org/pep-0703/]
- Linux used to do this - the Big Kernel Lock
  - removed in 2011
Deadlock

- No thread can make progress!
- The system is deadlocked

Example: `bank_account_deadlock.c` — deadlock with two resources (i)

```c
void *andrew_send_xavier_money(void *argument) {
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock(&andrews_bank_account_lock);
        pthread_mutex_lock(&xaviers_bank_account_lock);
        if (andrews_bank_account > 0) {
            andrews_bank_account--;
            xaviers_bank_account++;
        }
        pthread_mutex_unlock(&xaviers_bank_account_lock);
        pthread_mutex_unlock(&andrews_bank_account_lock);
    }
    return NULL;
}
```

Example: `bank_account_deadlock.c` — deadlock with two resources (ii)

```c
void *xavier_send_andrew_money(void *argument) {
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock(&xaviers_bank_account_lock);
        pthread_mutex_lock(&andrews_bank_account_lock);
        if (xaviers_bank_account > 0) {
            xaviers_bank_account--;
            andrews_bank_account++;
        }
        pthread_mutex_unlock(&andrews_bank_account_lock);
        pthread_mutex_unlock(&xaviers_bank_account_lock);
    }
    return NULL;
}
```
int main(void) {
    // create two threads sending each other money
    pthread_t thread_id1;
    pthread_create(&thread_id1, NULL, andrew_send_xavier_money, NULL);
    pthread_t thread_id2;
    pthread_create(&thread_id2, NULL, xavier_send_andrew_money, NULL);
    // threads will probably never finish
    // deadlock will likely likely occur
    // with one thread holding andrews_bank_account_lock
    // and waiting for xaviers_bank_account_lock
    // and the other thread holding xaviers_bank_account_lock
    // and waiting for andrews_bank_account_lock
    pthread_join(thread_id1, NULL);
    pthread_join(thread_id2, NULL);
    return 0;
}

Avoiding Deadlock

- A simple rule can avoid deadlock in many programs
- All threads should acquire locks in same order
  - also best to release in reverse order (if possible)

<table>
<thead>
<tr>
<th>THREAD 1</th>
<th>THREAD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. acquire lock_A</td>
<td>1. acquire lock_A</td>
</tr>
<tr>
<td>2. acquire lock_B</td>
<td>2. acquire lock_B</td>
</tr>
<tr>
<td>3. do_something(A, B)</td>
<td>3. do_something(A, B)</td>
</tr>
<tr>
<td>4. release lock_B</td>
<td>4. release lock_B</td>
</tr>
<tr>
<td>5. release lock_A</td>
<td>5. release lock_A</td>
</tr>
</tbody>
</table>

Previous program deadlocked because one thread executed:

```c
pthread_mutex_lock(&andrews_bank_account_lock);
pthread_mutex_lock(&xaviers_bank_account_lock);
```

and the other thread executed:

```c
pthread_mutex_lock(&xaviers_bank_account_lock);
pthread_mutex_lock(&andrews_bank_account_lock);
```

- Deadlock avoided if same order used in both threads, e.g
Atomics!

Atomic instructions allow a small subset of operations on data, that are guaranteed to execute atomically! For example,

- `fetch_add`: `n += value`
- `fetch_sub`: `n -= value`
- `fetch_and`: `n &= value`
- `fetch_or`: `n |= value`
- `fetch_xor`: `n ^= value`

`compare_exchange`:

```c
if (n == v1) {
    n = v2;
} return n;
```

Complete list: https://en.cppreference.com/w/c/atomic

• With mutexes, a program can lock mutex A, and then (before unlocking A) lock some mutex B.
  • multiple mutexes can be locked simultaneously.
• Atomic instructions are (by definition!) atomic, so there’s no equivalent to the above problem.
  • Goodbye deadlocks!
• Atomic instructions are a fundamental tool for lock-free/wait-free programming.
• Non-blocking: If a thread fails or is suspended, it cannot cause failure or suspension of another thread.
• Lock-free: non-blocking + the system (as a whole) always makes progress.
• Wait-free: lock-free + every thread always makes progress.

Example: `bank_account_atomic.c` — safe access to a global variable

```c
#include <stdatomic.h>
atomic_int bank_account = 0;
// add $1 to Andrew’s bank account 100,000 times
void *add_100000(void *argument) {
    for (int i = 0; i < 100000; i++) {
        // NOTE: This *cannot* be `bank_account = bank_account + 1`,
        // as that will not be atomic!
        // However, `bank_account++` would be okay
        // and, `atomic_fetch_add(&bank_account, 1)` would also be okay
        bank_account += 1;
    }
    return NULL;
}
```
What’s the catch with atomics?

- Specialised hardware support is required
  - essentially all modern computers provide atomic support
  - may be missing on more niche / embedded systems.
- Although faster and simpler than traditional locking, there is still a performance penalty using atomics (and increases program complexity).
- Can be incredibly tricky to write correct code at a low level (e.g. memory ordering, which we won’t cover in COMP1521).
- Some issues can arise in application; e.g. ABA problem.

Concurrency is really complex!

- This is just a taste of concurrency!
- Other fun concurrency problems/concepts: livelock, starvation, thundering herd, memory ordering, semaphores, software transactional memory, user threads, fibers, etc.
- A number of courses at UNSW offer more:
  - COMP3231/COMP3891: [Extended] operating systems e.g more on deadlock
  - COMP3151: Foundations of Concurrency
  - COMP6991: Solving Modern Programming Problems with Rust - e.g safety through types
  - and more!