COMP1521 21T2 — Concurrency, Parallelism, Threads

https://www.cse.unsw.edu.au/~cs1521/21T2/

Concurrency? Parallelism?

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

Parallelism:
multiple computations executing *simultaneously*

Parallel computations occur at different levels:

- SIMD: Single Instruction, Multiple Data ("vector processing"):
  - multiple cores of a CPU executing (parts of) same instruction
  - e.g., GPUs rendering pixels
- MIMD: Multiple Instruction, Multiple Data ("multiprocessing")
  - multiple cores of a CPU executing different instructions
- distributed: spread across computers
  - e.g., with MapReduce

Both parallelism and concurrency need to deal with *synchronisation*.

Distributed Parallel Computing: Parallelism Across Many Computers

Example: Map-Reduce is a popular programming model for

- manipulating *very large* data sets
- on a large network of computers — local or distributed

The *map* step filters data and distributes it to nodes

- data distributed as $(\text{key}, \text{value})$ pairs
- each node receives a set of pairs with common key

Nodes then perform calculation on received data items.

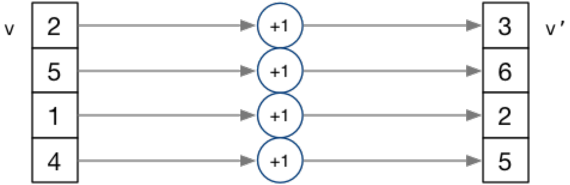
The *reduce* step computes the final result

- by combining outputs (calculation results) from the nodes

(This 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

Common use-case for GPUs, neural network processors, etc.

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:

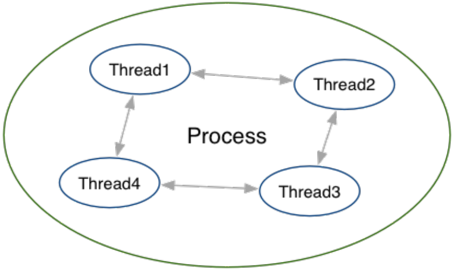
- separate address spaces make processes more robust.

(You're probably using a process-parallel program right now!)

Threads: Parallelism within Processes

Threads allow us parallelism *within* a process.

- Threads allow *simultaneous* execution.
- Each thread has its own execution state (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.



Threading with POSIX Threads (pthreads)

POSIX Threads is a widely-supported threading model.
supported in most *nix-like operating systems, and beyond

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

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

More recently, ISO C:2011 has adopted a pthreads-like model...
less well-supported generally, but very, very similar.

pthread_create(3): create a new thread

```
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` (possibly `NULL`).
- 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)*
- analagous to ***exit(3)***

Example: two_threads.c — creating two threads (i)

```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 (ii)

```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;
}
```

source code for two_threads.c

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;
}
```

source code for n_threads.c

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 thread_sum.c

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

```c
printf (
    "Creating %d threads to sum the first %lu integers\n"
    "Each thread will sum %lu integers\n",
    n_threads, integers_to_sum, integers_per_thread);
pthread_t thread_id[n_threads];
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]);
}
```

source code for thread_sum.c

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

```
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);
```

source code for thread_sum.c

`thread_sum.c` performance

Summing the first 1e+10 (10,000,000,000) integers, with N threads, on some different machines...

host	1	2	4	12	24	50	500
ceyx	6.9	3.6	1.8	0.6	0.3	0.3	0.3
lisbon	7.6	3.9	2.0	0.8	0.7	0.7	0.7

ceyx: AMD Ryzen 3900X (12c/24t), 3.8 GHz
lisbon: AMD Ryzen 4750U (8c/16t), 4.1 GHz

Example: two_threads_broken.c — shared mutable state gonna hurt you

```
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;
}
```

source code for two_threads_broken.c

- variable `thread_number` will probably change in `main`, *before* thread 1 starts executing...
- $\Longrightarrow$ 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);
        bank_account = bank_account + 1;
    }
    return NULL;
}
```

source code for bank_account_broken.c

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 $%d\n", bank_account);
    return 0;
}
```

source code for bank_account_broken.c

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++;
    // ...
}
```

```
la   $t0, bank_account
lw   $t1, ($t0)
addi $t1, $t1, 1
sw   $t1, ($t0)
.data
bank_account:  .word 0
```

Global Variables and Race Condition

If, initially, `bank_account = 42`, and two threads increment simultaneously…

```
la      $t0, bank_account
# {| bank_account = 42 |}
lw      $t1, ($t0)
# {| $t1 = 42 |}
addi    $t1, $t1, 1
# {| $t1 = 43 |}
sw      $t1, ($t0)
# {| bank_account = 43 |}
```

```
la      $t0, bank_account
# {| bank_account = 42 |}
lw      $t1, ($t0)
# {| $t1 = 42 |}
addi    $t1, $t1, 1
# {| $t1 = 43 |}
sw      $t1, ($t0)
# {| bank_account = 43 |}
```

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 = 100`, and two threads change it simultaneously…

```
la      $t0, bank_account
# {| bank_account = 100 |}
lw      $t1, ($t0)
# {| $t1 = 100 |}
addi    $t1, $t1, 100
# {| $t1 = 200 |}
sw      $t1, ($t0)
# {| bank_account = ...? |}
```

```
la      $t0, bank_account
# {| bank_account = 100 |}
lw      $t1, ($t0)
# {| $t1 = 100 |}
addi    $t1, $t1, -50
# {| $t1 = 50 |}
sw      $t1, ($t0)
# {| bank_account = 50 or 200 |}
```

This is a *critical section*.

We don't want two processes in the critical section — we must establish *mutual exclusion*.

pthread_mutex_lock(3), pthread_mutex_unlock(3): Mutual Exclusion

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

We associate a resource with a *mutex*.
For a particular mutex, only one thread can be running between `_lock` and `_unlock`.
Other threads attempting to `_lock` will block.
(Other threads attempting to `_trylock` will fail.)

For example:

```c
    pthread_mutex_lock (&bank_account_lock);
    andrews_bank_account += 1000000;
    pthread_mutex_unlock (&bank_account_lock);
```

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

```
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;
}
```

source code for bank_account_mutex.c

Semaphores

Semaphores are a more general synchronisation mechanism than mutexes.

```
#include <semaphore.h>
int sem_init(sem_t *sem, int pshared, unsigned int value);
int sem_post(sem_t *sem);
int sem_wait(sem_t *sem);
```

- *sem_init(3)* initialises `sem` to `value`.
- *sem_wait(3)* — classically **P**
  - if sem > 0, then sem $:=$ sem $- 1$ and continue...
  - otherwise, **wait** until sem > 0
- *sem_post(3)* — classically **V**, also *signal*
  - sem $:=$ sem $+ 1$ and continue...

Example: Allow *n* threads to access a resource

```
#include <semaphore.h>
sem_t sem;
sem_init (&sem, 0, n);
```

```
sem_wait (&sem);
// only n threads can be executing here simultaneously
sem_post (&sem);
```

Example: bank_account_sem.c: guard a global with a semaphore (i)

```
sem_t bank_account_semaphore;
// add $1 to Andrew's bank account 100,000 times
void *add_100000 (void *argument)
{
    for (int i = 0; i < 100000; i++) {
        // decrement bank_account_semaphore if > 0
        // otherwise wait until > 0
        sem_wait (&bank_account_semaphore);
        // only one thread can execute this section of code at any time
        // because  bank_account_semaphore was initialized to 1
        bank_account = bank_account + 1;
        // increment bank_account_semaphore
        sem_post (&bank_account_semaphore);
    }
    return NULL;
}
```

source code for bank_account_sem.c

Example: bank_account_sem.c: guard a global with a semaphore (ii)

```c
int main (void)
{
    // initialize bank_account_semaphore to 1
    sem_init (&bank_account_semaphore, 0, 1);
    // 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 always be $200000
    printf ("Andrew's bank account has $%d\n", bank_account);
    sem_destroy (&bank_account_semaphore);
    return 0;
}
```

source code for bank_account_sem.c

Concurrent Programming is Complex

Concurrency is *really complex* with many issues beyond this course:

Data races
: thread behaviour depends on unpredictable ordering; can produce difficult bugs or security vulnerabilities

Deadlock
: threads stopped because they are wait on each other

Livelock
: threads running without making progress

Starvation
: threads never getting to run

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

```
void *swap1 (void *argument)
{
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock (&bank_account1_lock);
        pthread_mutex_lock (&bank_account2_lock);
        int tmp = andrews_bank_account1;
        andrews_bank_account1 = andrews_bank_account2;
        andrews_bank_account2 = tmp;
        pthread_mutex_unlock (&bank_account2_lock);
        pthread_mutex_unlock (&bank_account1_lock);
    }
    return NULL;
}
```

source code for bank_account_deadlock.c

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

```
void *swap2 (void *argument)
{
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock (&bank_account2_lock);
        pthread_mutex_lock (&bank_account1_lock);
        int tmp = andrews_bank_account1;
        andrews_bank_account1 = andrews_bank_account2;
        andrews_bank_account2 = tmp;
        pthread_mutex_unlock (&bank_account1_lock);
        pthread_mutex_unlock (&bank_account2_lock);
    }
    return NULL;
}
```

source code for bank_account_deadlock.c

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

```c
int main (void)
{
    // create two threads performing almost the same task
    pthread_t thread_id1;
    pthread_create (&thread_id1, NULL, swap1, NULL);
    pthread_t thread_id2;
    pthread_create (&thread_id2, NULL, swap2, NULL);
    // threads will probably never finish
    // deadlock will likely likely occur
    // with one thread holding  bank_account1_lock
    // and waiting for bank_account2_lock
    // and the other  thread holding  bank_account2_lock
    // and waiting for bank_account1_lock
    pthread_join (thread_id1, NULL);
    pthread_join (thread_id2, NULL);
    return 0;
}
```

source code for bank_account_deadlock.c