COMP1521 23T2 — Concurrency, Parallelism, Threads

https://www.cse.unsw.edu.au/~cs1521/23T2/

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

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

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

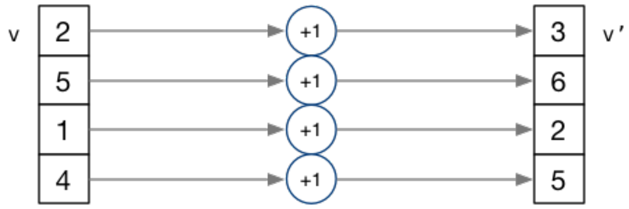
- by combining outputs (calculation results) from the nodes

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

(Beyond the scope of COMP1521!)

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 availablity 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)
- beyond the scope of COMP1521!

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.

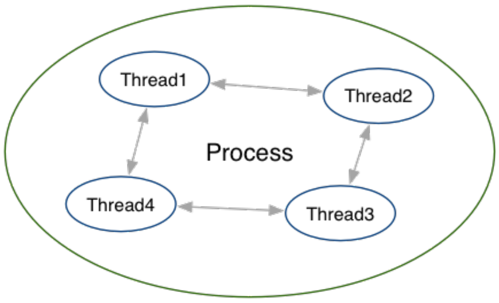
The web server providing the class website uses process-level parallelism

An android phone will have several hundred processes running.

Threads: Parallelism within Processes

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.



Threading with POSIX Threads (pthreads)

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).

```
#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` (`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

```
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

```
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 #1

```
#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 #2

```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)

```
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);
return 0;
```

source code for thread_sum.c

thread_sum.c performance

Seconds to sum the first 1e+10 (10,000,000,000) integers using double arithmetic, with N threads, on some different machines...

host	1	2	4	12	24	50	500
5800X	6.6	3.3	1.6	0.8	0.6	0.6	0.6
3900X	6.9	3.6	1.8	0.6	0.3	0.3	0.3
i5-4590	8.6	4.3	2.2	2.2	2.2	2.2	2.2
E7330	12.9	6.3	3.2	1.0	0.9	0.9	0.8
IIIi	136.6	68.4	68.6	68.4	68.5	68.6	68.6

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

```
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...
- ⟹ thread 1 will probably print **`Hello this is thread 2`** ... ?!

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

```
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;
}
```

source code for bank_account_broken.c

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

```
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

```
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:

```
    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

Mutex the world!

- Mutexes solve all our data race problems!
- Why not just protect everything with a mutex?
- Python does! The global interpreter lock (GIL).
  - Hard to exploit parallelism within Python
- mutexes are slow
- and other things can go wrong?

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

If these topics sound interesting at all to you, consider COMP3231/3891 ([Extended] Operating Systems)!

Advanced reading: cs3231 Deadlocks slides

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

```
void *andrew_send_zac_money(void *argument) {
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock(&andrews_bank_account_lock);
        pthread_mutex_lock(&zacs_bank_account_lock);
        if (andrews_bank_account > 0) {
            andrews_bank_account--;
            zacs_bank_account++;
        }
        pthread_mutex_unlock(&zacs_bank_account_lock);
        pthread_mutex_unlock(&andrews_bank_account_lock);
    }
    return NULL;
}
```

source code for bank_account_deadlock.c

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

```
void *zac_send_andrew_money(void *argument) {
    for (int i = 0; i < 100000; i++) {
        pthread_mutex_lock(&zacs_bank_account_lock);
        pthread_mutex_lock(&andrews_bank_account_lock);
        if (zacs_bank_account > 0) {
            zacs_bank_account--;
            andrews_bank_account++;
        }
        pthread_mutex_unlock(&andrews_bank_account_lock);
        pthread_mutex_unlock(&zacs_bank_account_lock);
    }
    return NULL;
}
```

source code for bank_account_deadlock.c

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

```
int main(void) {
    // create two threads sending each other money
    pthread_t thread_id1;
    pthread_create(&thread_id1, NULL, andrew_send_zac_money, NULL);
    pthread_t thread_id2;
    pthread_create(&thread_id2, NULL, zac_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 zacs_bank_account_lock
    // and the other thread holding  zacs_bank_account_lock
    // and waiting for andrews_bank_account_lock
    pthread_join(thread_id1, NULL);
    pthread_join(thread_id2, NULL);
    return 0;
}
```

source code for bank_account_deadlock.c

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)
- Previous program deadlocked because one thread executed:

```
pthread_mutex_lock(&andrews_bank_account_lock);
pthread_mutex_lock(&zacs_bank_account_lock);
```

and the other thread executed:

```
pthread_mutex_lock(&zacs_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:

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

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

Atomics!

- 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!
- Atomics 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

```
#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;
}
```

source code for bank_account_atomic.c

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.

Final issue: data lifetime

- When sharing data with a thread, we can only pass the address of our data.
- This presents a lifetime issue
  - what if by the time the thread reads the data, that data no longer exists?
- How have we avoided this so far?
- What kind of code could trigger this issue?
- How can this issue be avoided?

Data lifetime: avoiding so far

- so far we have put data in local variables in `main`
  - local variables live until their function returns
- `main` has created threads by calling ‘pthread_create
- `main` has waited for all threads to finish by calling `pthread_join`
- so `main` “outlives” all the created threads.
  - hence the local variables in `main` outlive the threads
  - so the data we pass to each thread will be valid for the entire lifetime of each thread.
- but what if we pass data with a lifetime shorter than the thread lifetime?

Data lifetime: triggering the issue

```
pthread_t create_thread(void) {
    int super_special_number = 0x42;
    pthread_t thread_handle;
    pthread_create(&thread_handle, NULL, my_thread, &super_special_number);
    // super_special_number is destroyed when create_thread returns
    // but the thread just created may still be running and access it
    return thread_handle;
}
```

source code for thread_data_broken.c

```
void *my_thread(void *data) {
    int number = *(int *)data;
    sleep(1);
    // should print 0x42, probably won't
    printf("The number is 0x%x!\n", number);
    return NULL;
}
```

source code for thread_data_broken.c

Data lifetime: solving our problem – malloc

- stack memory is automatically cleaned up when a function returns
  - in `mipsy` `$sp` returns to its orignal value
  - local variable are destroyed
  - the lifetime of a local variable ends with return
- when function `create_thread` return `super_special_number` is destroyed -which is causing us problems.
- the function `say_hello` makes this obvious
  - it changes the stack memory which used to hold `super_special_number` (by using it for `greeting`)
- we've solved this problem before in `COMP1[59]11` by using `malloc`
  - the programmer controls the lifetime of memory allocated with `malloc`
  - it lives until `free` is called
  - the thread can call free when it is finished with the data

Data lifetime: solving our problem – malloc

```c
pthread_t function_creates_thread(void) {
    int *super_special_number = malloc(sizeof(int));
    *super_special_number = 0x42;
    pthread_t thread_handle;
    pthread_create(&thread_handle, NULL, my_thread, super_special_number);
    return thread_handle;
}
```

source code for thread_data_malloc.c

```c
void *my_thread(void *data) {
    int number = *(int *)data;
    sleep(1);
    printf("The number is 0x%x!\n", number);
    free(data);
    return NULL;
}
```

source code for thread_data_malloc.c

Data lifetime: solving our problem – barriers (advanced topic)

- Another solution is to force both the calling thread and the newly created thread to wait for each other.
- The calling thread shouldn't proceed until the new thread has had a chance to read the data.
- The new thread shouldn't proceed too far before letting the calling thread keep moving – could stall performance!
- We can implement this cross-thread waiting with barriers.

Data lifetime: solving our problem – barriers (advanced topic)

```c
pthread_t function_creates_thread(void) {
    pthread_barrier_t barrier;
    pthread_barrier_init(&barrier, NULL, 2);
    struct thread_data data = {
        .barrier = &barrier,
        .number = 0x42,
    };
    pthread_t thread_handle;
    pthread_create(&thread_handle, NULL, my_thread, &data);
    pthread_barrier_wait(&barrier);
    return thread_handle;
}
```

source code for thread_data_barrier.c

Data lifetime: solving our problem – barriers (advanced topic)

```c
void *my_thread(void *data) {
    struct thread_data *thread_data = (struct thread_data *)data;
    int number = thread_data->number;
    pthread_barrier_wait(thread_data->barrier);
    sleep(1);
    printf("The number is 0x%x!\n", number);
    return NULL;
}
```

source code for thread_data_barrier.c

Aside, COMP6991

If topics such as:

- Data races (e.g. bank account without protection)
- Lifetime (e.g. the previous example)
- Safety through types (e.g. prevent accessing data without locking mutex)

sound interesting to you, you may want to consider COMP6991 (Solving Modern Programming Problems with Rust)!

Aside, pending time: Semaphores (advanced topic)

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 (advanced topic)

Common example: Web servers often launch 1 thread per incoming connection.

If a lot of connections come in all at once, the system could have huge slowdowns due to the enormous amount of threads created.

So, only allow the web server to be dealing with *n* connections at any particular time.

```
#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