Concurrency/Parallelism

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

Parallelism multiple computations executing simultaneously

Parallel computation occurs at different level:

- spread across computers (e.g., with MapReduce)
- multiple cores of a CPU executing different instructions (MIMD)
- multiple cores of a CPU executing same instruction (SIMD)
  - e.g. GPU rendering pixels

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

Parallel Computing 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 $(key, value)$ pairs
- each node receives a set of pairs with common key(s)

Nodes then perform calculation on received data items

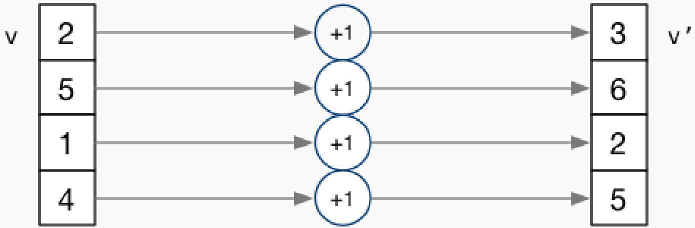
The *reduce* step computes the final result

- by combining outputs (calculation results) from the nodes

Also needs a way to determine when all calculations completed

Parallelism Across a 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

Example: GPU rendering pixels or neural network

Parallelism Across Processes

One method for creating parallelism:

Use `posix_spawn()` to create multiple processes, each does part of 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 expensive
- each require a significant amount of state (RAM)
- communication between processes limited and/or slow

One big advantage - separate address spaces make processes more robust.

Parallelism within Processes

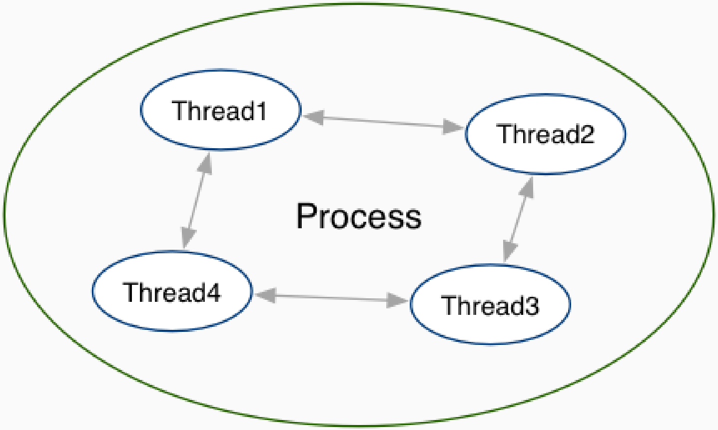
threads - mechanism for parallelism within process.

- threads allow simultaneous execution within process
- each thread has its own execution state
- threads within a process have same address space:
  - threads share code (functions)
  - threads share global & static variables
  - threads share heap (`malloc`)
- but separate stack for each thread
  - local variables not shared
- threads share file descriptor
- threads share signals

POSIX threads (pThreads)

```
// POSIX threads widely supported in Unix-like
// and other systems (Windows).  Provides functions
// to create/synchronize/destroy/... threads

#include <pthread.h>
```



Create A POSIX Thread

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

- creates a new thread with attributes specied in **`attr`**
  - **`attr`** can be `NULL`
- thread info stored in **`*thread`**
- thread starts by executing **`start_routine(arg)`**
- returns 0 if OK, -1 otherwise and sets **`errno`**
- analogous to **`posix_spawn()`**

Wait for A POSIX Thread

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

- wait until **`thread`** terminates
- **`thread`** return (or **`pthread_exit()`**) value is placed in **`*retval`**
- if **`thread`** has already exited, does not wait
- if main returns or exit called, all threads terminated
- programs typically need towait for all threads before main returns/exit called
- analogous to **`waitpid`**

Terminate A POSIX Thread

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

- terminate execution of thread (and free resources)
- **`retval`** is returned (see **`pthread_join`**)
- if **`thread`** has already exited, does not wait
- analagous to **`exit`**

Simple example - Creating Two threads

```
#include <pthread.h>
// this function is called to start thread execution
// it can be given any pointer as argument (int *) in this example
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 the function returns or  thread_exit
    // a pointer of any type can be returned
    // this can be obtained via thread_join's 2nd argument
    return NULL;
}
```

source code for two_threads.c

Simple example - Creating Two threads

```c
//create two threads performing almost the same task
pthread_t thread_id1;
int thread_number1 = 1;
pthread_create(&thread_id1, NULL, run_thread, &thread_number1);
int thread_number2 = 2;
pthread_t thread_id2;
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);
```

source code for two_threads.c

CLassic Bug - Sharing a Variable Between Threads

```
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);
```

source code for two_threads_broken.c

- variable `thread_number` will probably have changed in main before thread 1 starts executing
- so thread 1 will probably print `Hello this is thread 2`

Simple example - Creating Many threads

```
int n_threads = strtol(argv[1], NULL, 0);
assert(n_threads > 0 && 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);
}
```

source code for n_threads.c

Simple example - Dividing a task between threads

```
struct job {
    long start;
    long 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

Simple example - Dividing a task between threads

```
printf("Creating %d threads to sum the first %lu integers\n",
       n_threads, integers_to_sum);
printf("Each thread will sum %lu integers\n", 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

Simple example - Dividing a task between threads

```c
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

Simple example - Dividing a task between threads

```
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

Simple example - Dividing a task between threads

- on a AMD Ryzen 3900x which can run *24* threads simultaneously
- 1 thread takes `6.9` seconds to sum first 10000000000 integers
- 2 threads takes `3.6` seconds to sum first 10000000000 integers
- 4 threads takes `1.8` seconds to sum first 10000000000 integers
- 12 threads takes `0.6` seconds to sum first 10000000000 integers
- 24 threads takes `0.3` seconds to sum first 10000000000 integers
- 50 threads takes `0.3` seconds to sum first 10000000000 integers
- 500 threads takes `0.3` seconds to sum first 10000000000 integers

Example - Unsafe Access to Global Variable

```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 - Unsafe Access to Global Variable

```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 Variable: Race Condition

Incrementing a global variable is not an atomic (indivisible) operation.

```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 Variable: Race Condition

If `bank_account` == 42 and two threads increment simultaneously.

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

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

One increment is lost.

Note threads don't share registers or stack (local variable).

They do share global variables.

Global Variable: Race Condition

If `bank_account` == 100 and two threads change it simultaneously.

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

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

Exclude Other Threads from Code

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

- only one thread can enter a *critical section*
- establishes mutual exclusion — *mutex*
- call **`pthread_mutex_lock`** before
- call **`pthread_mutex_unlock`** after
- only 1 thread can execute in protected code
- for example:

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

Example - Protecting Access to Global Variable 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
        bank_account = bank_account + 1;
        pthread_mutex_unlock(&bank_account_lock);
    }
    return NULL;
}
```

source code for bank_account_mutex.c

Semaphores

Semaphores are special variables which provide 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` initialises `sem` to `value`
- `sem_wait` - classically called `P()`
  - if `sem` > 0, decrement `sem` and continue
  - otherwise, wait until `sem` > 0
- `sem_post` - classically called `V()`
  - increment `sem` and continue

Allow n threads access to a resource

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

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

Protecting Access to Global Variable with a Semaphore

```
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
        // 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_semaphore.c

Protecting Access to Global Variable with a Semaphore

```
// 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);
```

source code for bank_account_semaphore.c

File Locking

`int flock(int FileDesc, int Operation)`

Similar to mutexes for a file.

- controls access to shared files (**note**: files not fds)
- possible operations
  - `LOCK_SH` … acquire shared lock
  - `LOCK_EX` … acquire exclusive lock
  - `LOCK_UN` … unlock
  - `LOCK_NB` … operation fails rather than blocking
- in blocking mode, `flock()` does not return until lock available
- only works correctly if all processes accessing file use locks
- return value: 0 in success, -1 on failure

File Locking

If a process tries to acquire a *shared lock* ...

- if file not locked or other shared locks, OK
- if file has exclusive lock, blocked

If a process tries to acquire an *exclusive lock* ...

- if file is not locked, OK
- if any locks (shared or exclusive) on file, blocked

If using a non-blocking lock

- `flock()` returns 0 if lock was acquired
- `flock()` returns -1 if process would have been blocked

Concurrent Programming is Complex

Concurrency is *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 - deadlock accessing two resources

```c
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 - deadlock accessing two resources

```c
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 - deadlock accessing two resources

```
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