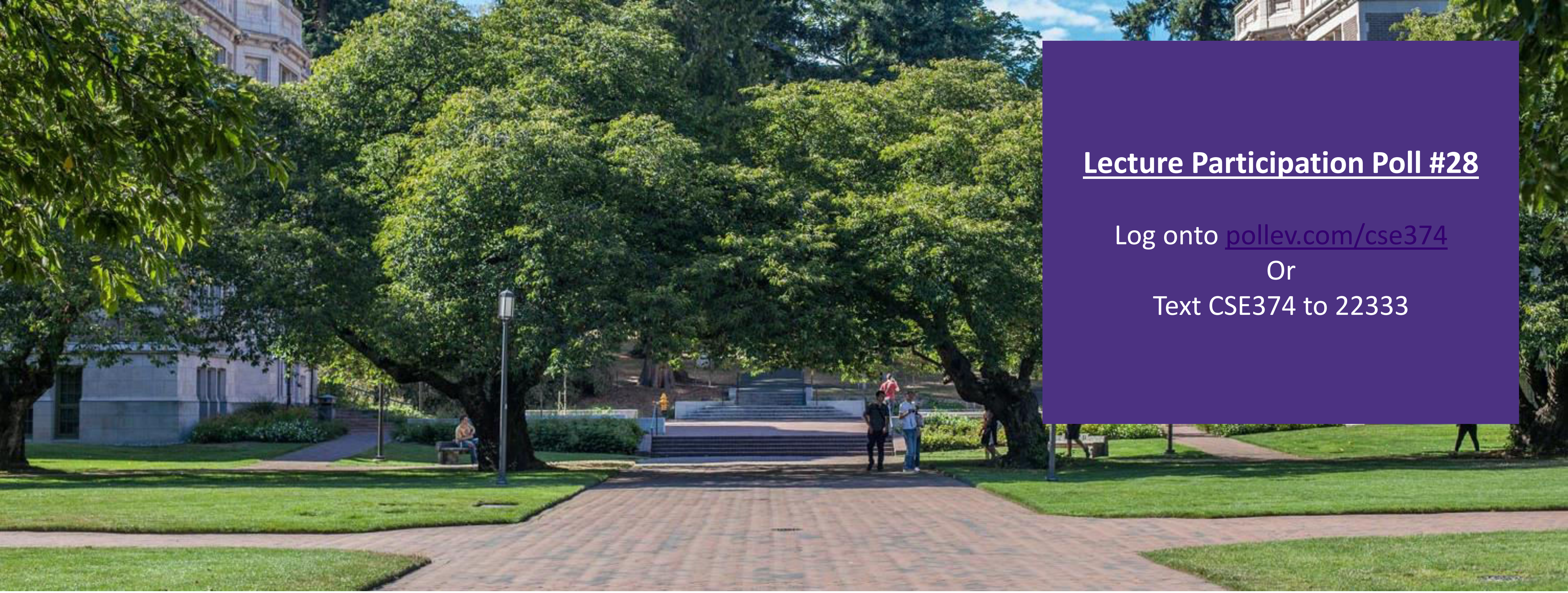


**Lecture Participation Poll #28**

Log onto pollev.com/cse374
Or
Text CSE374 to 22333

# Lecture 28: Concurrency Continued…

CSE 374: Intermediate Programming Concepts and Tools

# Administrivia

- HW 5 (final HW) posted
- Final review assignment posted!
- End of quarter due date Wednesday December 16th @ 9pm

# Concurrency vs Parallelism

- parallelism refers to running things simultaneously on **separate** resources (ex. Separate CPUs)
- concurrency refers to running multiple threads on a **shared** resources
- Concurrency is one person cooking multiple dishes at the same time.
- Parallelism is having multiple people (possibly cooking the same dish).
- Allows processes to run 'in the background'
  - Responsiveness – allow GUI to respond while computation happens
  - CPU utilization – allow CPU to compute while waiting (waiting for data, for input)
  - isolation – keep threads separate so errors in one don't affect the others

# Concurrency

- A search engine could run concurrently:
  - Example: Execute queries one at a time, but issue I/O requests against different files/disks simultaneously
    - Could read from several index files at once, processing the I/O results as they arrive
  - Example: Web server could execute multiple queries at the same time
    - While one is waiting for I/O, another can be executing on the CPU

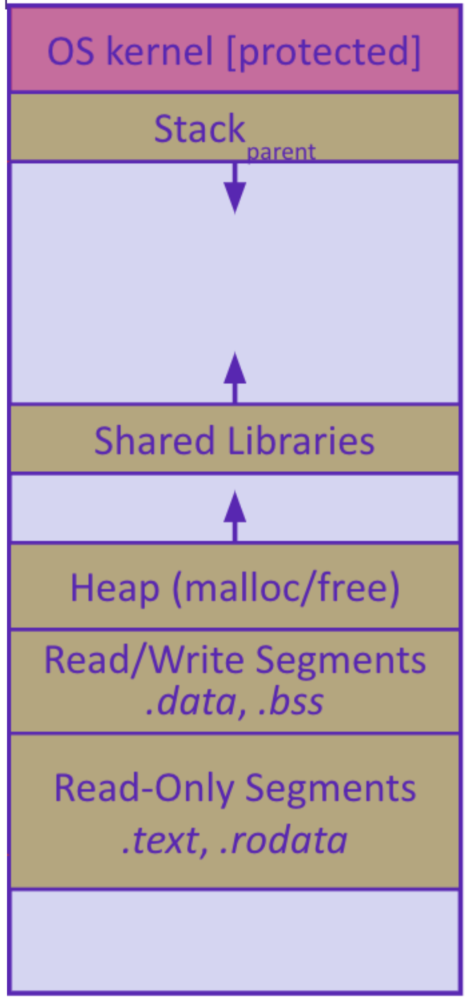
- Use multiple "workers"
  - As a query arrives, create a new "worker" to handle it
  - The "worker" reads the query from the network, issues read requests against files, assembles results and writes to the network
  - The "worker" uses blocking I/O; the "worker" alternates between consuming CPU cycles and blocking on I/O
  - The OS context switches between "workers"
  - While one is blocked on I/O, another can use the CPU
  - Multiple "workers'" I/O requests can be issued at once
  - So what should we use for our "workers"?

# Threads

- In most modern OS's threads are the *unit of scheduling*.
  - Separate the concept of a process from the "*thread of execution*"
  - Threads are contained within a process
  - Usually called a thread, this is a sequential execution stream within a process
- Cohabit the same address space
  - Threads within a process see the same heap and globals and can communicate with each other through variables and memory
  - Each thread has its own stack
  - But, they can interfere with each other – need synchronization for shared resources
- Advantages:
  - They execute concurrently like processes
  - You (mostly) write sequential-looking code
  - Threads can run in parallel if you have multiple CPUs/cores
- Disadvantages:
  - If threads share data, you need locks or other synchronization
    - Very bug-prone and difficult to debug
  - Threads can introduce overhead
    - Lock contention, context switch overhead, and other issues
  - Need language support for threads

A <u>Process</u> has a unique: address space, OS resources, and security attributes
A <u>Thread</u> has a unique: stack, stack pointer, program counter, and registers
Threads are the *unit of scheduling* and processes are their *containers*; every process has at least one thread running in it

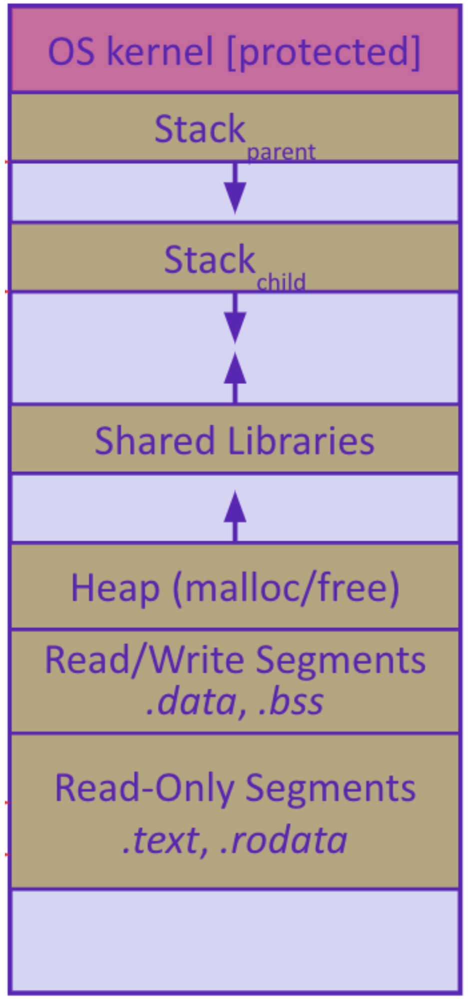
# Address Spaces




Single threaded address space

- Before creating a thread
  - One thread of execution running in the address space
    - One PC, stack, SP
  - That main thread invokes a function to create a new thread

-> pthread_create() ->




Multi-threaded address space

- After creating a thread
  - *Two* threads of execution running in the address space
    - Original thread (parent) and new thread (child)
    - New stack created for child thread
    - Child thread has its own *values* of the PC and SP
  - Both threads share the other segments (code, heap, globals)
    - They can cooperatively modify shared data

# POSIX Threads and Pthread functions

- The POSIX APIs for dealing with threads
  - Declared in pthread.h
    - Not part of the C/C++ language (cf. Java)
  - To enable support for multithreading, must include -pthread flag when compiling and linking with gcc command
  - POSIX stands for Portable Operating System Interface, pthread conforms to POSIX standard for threading

```
gcc -g -Wall -std=c11 -pthread -o main main.c
```

- Example Usage
  - `pthread_t thread ID;`
    - the threadID keeps track of to which thread we are referring
  - `pthread_create` takes a function plinter and arguments to trigger separate thread
    - `int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void *(*start routing) (void*), void *arg);`
    - note – pthread_create takes two generic (untyped) pointers
    - interprets the first as a function pointer and the second as an argument pointer
  - `int pthread_join(pthread_t thread, void **value_ptr);`
    - puts calling thread 'on hold' until 'thread' completes – useful for waiting to thread to exit

https://pubs.opengroup.org/onlinepubs/7908799/xsh/pthread.h.html

# Creating and Terminating Threads

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

- Creates a new thread into *thread, with attributes *attr (NULL means default attributes)
- Returns **0** on success and an error number on error (can check against error constants)
- The new thread runs **start_routine**(arg)

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

- Equivalent of **exit**(retval); for a thread instead of a process
- The thread will automatically exit once it returns from **start_routine**()

# Multi Threaded Example

```c
void do_one_thing(int *pnum_times) {
   int i, j, x;
   for (i = 0; i < 4; i++) {
      printf("doing one thing\n");
      for (j = 0; j < 10000; j++) x = x + i;
      (*pnum_times)++;
   }
}
```

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

void do_one_thing(int *);
void do_another_thing(int *);
void do_wrap_up(int, int);

int main() {
   pthread_t thread1, thread2;
   int r1 = 0, r2 = 0;

   pthread_create(&thread1, NULL, (void *) do_one_thing, (void *) &r1);
   pthread_create(&thread2, NULL, (void *) do_another_thing, (void *) &r2);

   pthread_join(thread1, NULL);
   pthread_join(thread2, NULL);

   do_wrap_up(r1, r2);
}
```

```c
void do_another_thing(int *pnum_times) {
   int i, j, x;
   for (i = 0; i < 4; i++) {
      printf("doing another \n");
      for (j = 0; j < 10000; j++) x = x + i;
      (*pnum_times)++;
   }
}
```

```c
void do_wrap_up(int one_times, int another_times) {
   int total;
   total = one_times + another_times; printf("All done,
           one thing %d, another %d for a total of
           %d\n", one_times, another_times, total);
}
```

# Parallel Processing

- common pattern for expensive computations (such as data processing)

1. split up the work, give each piece to a thread (fork)
2. wait until all are done, then combine answers (join)

- to avoid bottlenecks, each thread should have about the same about of work

- performance will always be less than perfect speedup

- what about when all threads need access to the same mutable memory?

# After forking threads

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

- Waits for the thread specified by thread to terminate
- The thread equivalent of **waitpid**()
- The exit status of the terminated thread is placed in *retval

```
int pthread_detach(pthread_t thread);
```

- Mark thread specified by thread as detached – it will clean up its resources as soon as it terminates

# Race Conditions

- A race condition happens when the result of a computation depends upon scheduling of multiple threads, ie the order in which the processor executes instructions.
- Bad interleavings is when the code exposes bad intermediate state.
  - example: the getBalance() -> setBalance() calls exposed intermediate state.
  - Bad interleavings are incorrect from the programmatic logical perspective:
  - in the bank example, we lost money or allowed balances to go below 0.
- Data races - Even if we can't have a line-by-line interleaving, we can still have race conditions
  - what seems like an "atomic" operation, like setting "balance_ = amount" or "return balance_", is actually NOT guaranteed to be an atomic operation at the compiled machine-code level.

whenever you have the potential to read+write or write+write on different threads, you MUST synchronize access to the shared memory (with a lock or similar).

# Data Races

- Two memory accesses form a data race if different threads access the same location, and at least one is a write, and they occur one after another
  - Means that the result of a program can vary depending on chance (which thread ran first?)
- Data races might interfere in painful, non-obvious ways, depending on the specifics of the data structure
- <u>Example</u>: two threads try to read from and write to the same shared memory location
  - Could get "correct" answer
  - Could accidentally read old value
  - One thread's work could get "lost"
- <u>Example</u>: two threads try to push an item onto the head of the linked list at the same time
  - Could get "correct" answer
  - Could get different ordering of items
  - Could break the data structure!

# A Data Race

- two threads are running at the same time, and therefore, because we cannot guarantee the exact speed at which each thread runs, we could get into a bad situation

- have a bank account x with a balance of $150
- thread T1 calls x.withdrawal(100) and thread T2 calls x.withdrawal(100) right afterwards
  - two transactions are attempting to happen on the same account
  - what SHOULD happen is that one of the transactions succeeds in withdrawing 100, and the other throws an exception because the remaining balance of $50 is insufficient
- T1 reads the balance (150) and stores it in variable b
- T2 executes completely, deducting 100 from the account to leave a balance of 50
- rest of the function on T1 executes, comparing 150 with 100 (ok) and then setting the balance to $50
- We've lost a transaction!

```
     | Thread T1:                              Thread T2:
     |
     | double b = getBalance();
     |                                         double b = getBalance();
     |                                         if (amount > b) {
     |                                           throw std::invalid_argument();
time |                                         }
 |   |                                         setBalance(b - amount);
 v   | if (amount > b) {
     |   throw std::invalid_argument();
     | }
     | setBalance(b - amount);
```

https://courses.cs.washington.edu/courses/cse374/18sp/lectures/24-concurrency-1.html

# Synchronization

- **Synchronization** is the act of preventing two (or more) concurrently running threads from interfering with each other when operating on shared data
  - Need some mechanism to coordinate the threads
    - "Let me go first, then you can go"
  - Many different coordination mechanisms have been invented
- Goals of synchronization:
  - **Liveness** – ability to execute in a timely manner (informally, "something good happens")
  - **Safety** – avoid unintended interactions with shared data structures (informally, "nothing bad happens")

# Lock Synchronization

- Use a “Lock” to grant access to a *critical section* so that only one thread can operate there at a time
  - Executed in an uninterruptible
  - an operation we want to be done all at once
  - operation must be the right size (atomic unit)
    - too big program runs sequentially
    - too small program has data races
- Lock Acquire
  - Wait until the lock is free, then take it
- Lock Release
  - Release the lock
  - If other threads are waiting, wake exactly one up to pass lock to

```
// non-critical code

lock.acquire();   loop/idle if locked
// critical section
lock.release();

// non-critical code
```

# Example

- If your fridge has no milk, then go out and buy some more
  - What could go wrong?
- If you live alone:


If you live with a roommate:


- What if we use a lock on the refrigerator?
  - Probably overkill – what if roommate wanted to get eggs?

```
fridge.lock()
if (!milk) {
  buy milk
}
fridge.unlock()
```

- For performance reasons, only put what is necessary in the critical section
  - Only lock the milk
  - But lock all steps that must run uninterrupted (i.e. must run as an atomic unit)

```
milk_lock.lock()
if (!milk) {
  buy milk
}
milk_lock.unlock()
```

# pthreads and Locks

- Another term for a lock is a mutex ("mutual exclusion")
  - pthread.h defines datatype pthread_mutex_t
- pthread_mutex_init()

```
int pthread_mutex_init(pthread_mutex_t* mutex, const pthread_mutexattr_t* attr);
```

  - Initializes a mutex with specified attributes
- pthread_mutex_lock()

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

  - Acquire the lock – blocks if already locked
- pthread_mutex_unlock()

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

  - Releases the lock
- pthread_mutex_destroy()

```
int pthread_mutex_destroy(pthread_mutex_t* mutex);
```

  - "Uninitializes" a mutex – clean up when done

# Synchronization Example

- https://courses.cs.washington.edu/courses/cse374/20sp/lectures/cppcode/BankAccountThread.h
- https://courses.cs.washington.edu/courses/cse374/20sp/lectures/cppcode/BankAccountThread.cpp

# Questions