Threads & Synchronization

Computer Operating Systems, Spring 2024

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Administrivia

- PennOS:
  - To be done in groups of 4
  - Group signup due Tuesday Tonight at midnight
    - Those who do not form a group will be randomly assigned
    - Random assignment will prefer to keep people in pairs (unless you reach out and specify otherwise)
  - Specification released earlier today

- Mid semester Survey
  - Anonymous and due Saturday @ midnight

- Checkin due before lecture today
  - (extended to be due tonight at midnight)

Administrivia

- Next lecture is TA-led pennos demo
- Lecture next week will be on Zoom (more threads stuff)

- You have the first milestone due Tuesday 3/26 @ 11:59pm
  - Your group (or at least most of your group) needs to meet with your assigned TA and display the expectations laid out in the PennOS Specfication

- No Instructor Office Hours this week, will resume next week

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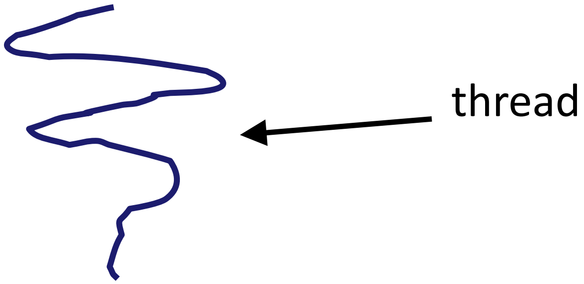
- Any questions, comments or concerns from last lecture?

Lecture Outline

- **Threads Quick Refresher**
- Shared Resources & Data Races
- Disable Interrupts
- Peterson’s Algorithm
- Mutex
- TSL

Introducing Threads

- 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

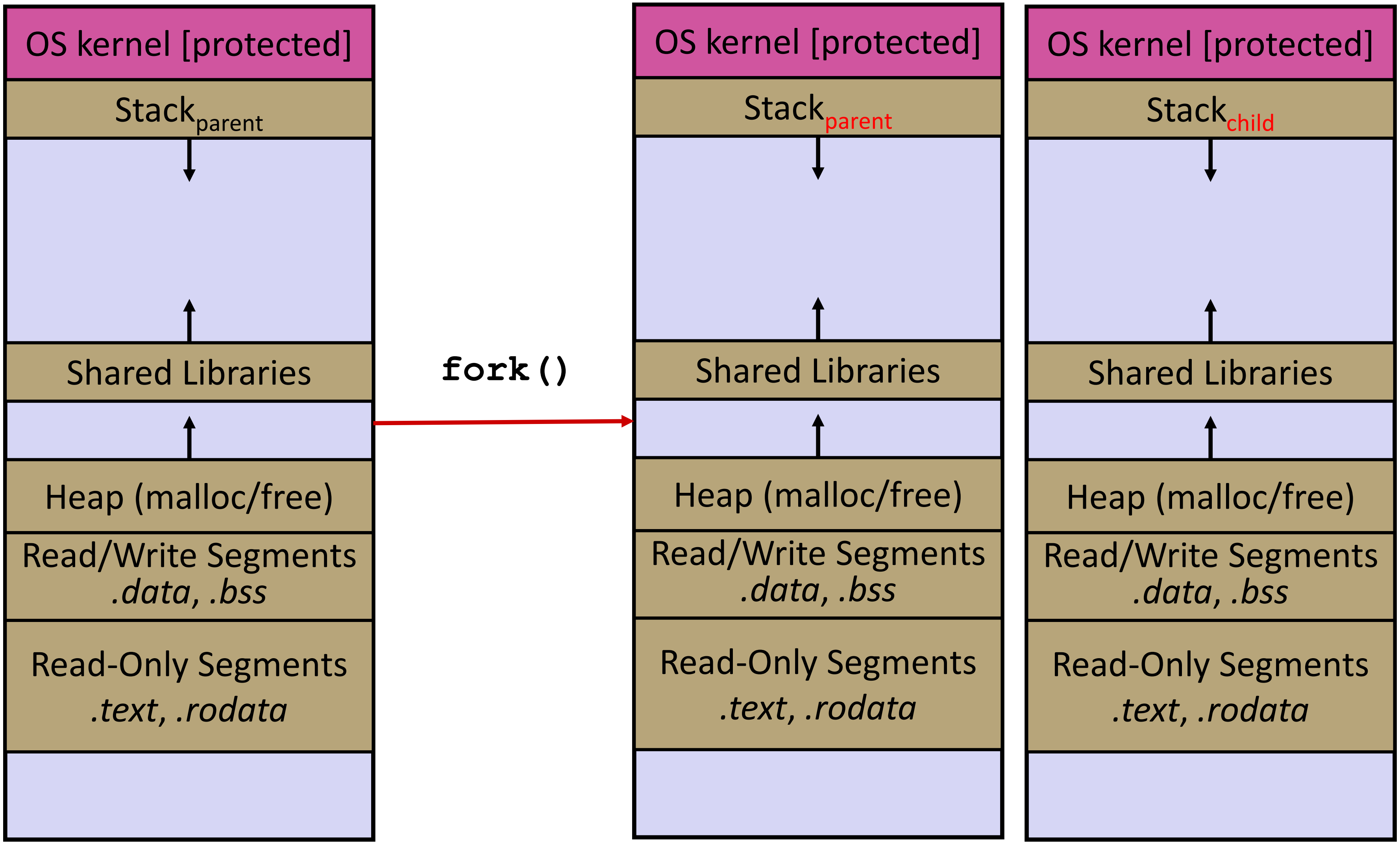


- In most modern OS's:
  - Threads are the *unit of scheduling.*

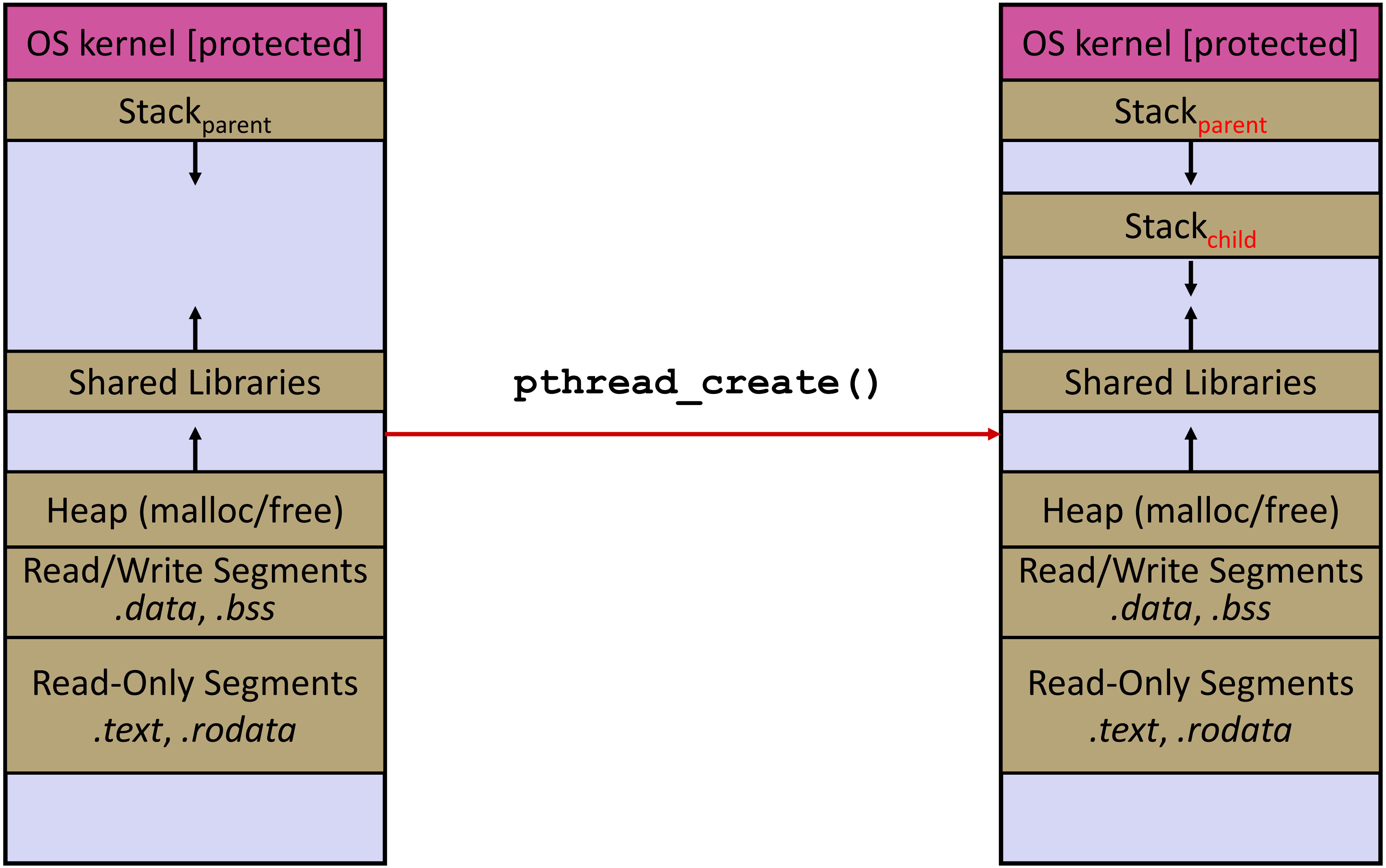
Threads vs. Processes

- In most modern OS's:
  - A Process has a unique: address space, OS resources, & security attributes
  - A Thread has a unique: stack, stack pointer, program counter, & registers
  - Threads are the *unit of scheduling* and processes are their *containers*; every process has at least one thread running in it

Threads vs. Processes



Threads vs. Processes



POSIX Threads (pthreads)

- The POSIX APIs for dealing with threads
  - Declared in `pthread.h`
    - Not part of the C/C++ language
  - To enable support for multithreading, must include `-pthread` flag when compiling and linking with `gcc` command
    - `gcc -g -Wall -pthread -o main main.c`
  - Implemented in C
    - Must deal with C programming practices and style

Creating and Terminating Threads

Output parameter.
Gives us a "thread_descriptor"

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

Argument for the thread function

Function pointer!
Takes & returns void*
to allow "generics" in C

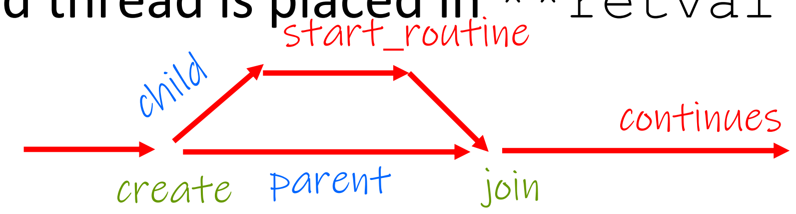
- Creates a new thread into `*thread`, with attributes `*attr` (`NULL` means default attributes)
- Returns **0** on success and an error number on error (can check against error constants)
- The new thread runs **`start_routine`**`(arg)`

pthread_create
child
start_routine
parent
continue

What To Do 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`

Parent thread waits for child thread to exit, gets the child's return value, and child thread is cleaned up



Why Threads?

- Advantages:
  - You (mostly) write sequential-looking code
  - Threads can run in parallel if you have multiple CPUs/cores
    - Takes advantage of the multiple cores
    - Can make progress on multiple tasks at once, even if only 1 core
- 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

Lecture Outline

- Threads Quick Refresher
- **Shared Resources & Data Races**
- Disable Interrupts
- Peterson's Algorithm
- Mutex
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Shared Resources

- Some resources are shared between threads and processes

- Thread Level:
  - Memory
  - Things shared by processes

- Process level
  - I/O devices
    - Files
    - terminal input/output
    - The network

Issues arise when we try to shared things

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? When did a thread get interrupted?)**

Data Race Example

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

```
if (!milk) {
  buy milk
}
```

- If you live alone:

- If you live with a roommate:

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- Idea: leave a note!
  - Does this fix the problem?

```
if (!note) {
  if (!milk) {
    leave note
    buy milk
    remove note
  }
}
```

A. Yes, problem fixed

B. No, could end up with no milk

C. No, could still buy multiple milk

D. We're lost…

Threads and Data Races

- Data races might interfere in painful, non-obvious ways, depending on the specifics of the data structure
- Example: 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"
- Example: 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! ☠

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- What does this print?

```
#define NUM_PROCESSES 50
#define LOOP_NUM 100

int sum_total = 0;

void loop_incr() {
  for (int i = 0; i < LOOP_NUM; i++) {
    sum_total++;
  }
}


int main(int argc, char** argv) {
  pid_t pids[NUM_PROCESSES];  // array of process ids

  // create processes to run loop_incr()
  for (int i = 0; i < NUM_PROCESSES; i++) {
    pids[i] = fork();
    if (pids[i] == 0) {
      // child
      loop_incr();
      exit(EXIT_SUCCESS);
    }
    // parent loops and forks more children
  }

  // wait for all child processes to finish
  for (int i = 0; i < NUM_PROCESSES; i++) {
    waitpid(pids[i], NULL, 0);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

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- What does this print?

```
#define NUM_PROCESSES 50
#define LOOP_NUM 100

int sum_total = 0;

void loop_incr() {
  for (int i = 0; i < LOOP_NUM; i++) {
    sum_total++;
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int main(int argc, char** argv) {
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  // create processes to run loop_incr()
  for (int i = 0; i < NUM_PROCESSES; i++) {
    pids[i] = fork();
    if (pids[i] == 0) {
      // child
      loop_incr();
      exit(EXIT_SUCCESS);
    }
    // parent loops and forks more children
  }

  // wait for all child processes to finish
  for (int i = 0; i < NUM_PROCESSES; i++) {
    waitpid(pids[i], NULL, 0);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

Always prints 0, the global counter is not shared across processes, so the parent's global never changes

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- What does this print?

```c
#define NUM_THREADS 50
#define LOOP_NUM 100

int sum_total = 0;

// print out a sequence of LOOP_NUM numbers with thread identifying number
void* thread_main(void* arg) {
  for (int i = 0; i < LOOP_NUM; i++) {
    sum_total++;
  }
  return NULL;  // return type is a pointer
}


int main(int argc, char** argv) {
  pthread_t thds[NUM_THREADS];  // array of thread ids

  // create threads to run thread_main()
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_create(&thds[i], NULL, &thread_main, NULL);
  }

  // wait for all child threads to finish
  // (children may terminate out of order, but cleans up in order)
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_join(thds[i], NULL);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

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- What does this print?

```
#define NUM_THREADS 50
#define LOOP_NUM 100

int sum_total = 0;

// print out a sequence of LOOP_NUM numbers with thread identifying number
void* thread_main(void* arg) {
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    sum_total++;
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}


int main(int argc, char** argv) {
  pthread_t thds[NUM_THREADS];  // array of thread ids

  // create threads to run thread_main()
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_create(&thds[i], NULL, &thread_main, NULL);
  }

  // wait for all child threads to finish
  // (children may terminate out of order, but cleans up in order)
  for (int i = 0; i < NUM_THREADS; i++) {
    pthread_join(thds[i], NULL);
  }

  printf("%d\n", sum_total);

  return EXIT_SUCCESS;
}
```

Usually 5000

Demos:

- See `total.c` and `total_processes.c`
  - Threads share an address space, if one thread increments a global, it is seen by other threads
  - Processes have separate address spaces, incrementing a global in one process does not increment it for other processes

- NOTE: sharing data between threads is actually kinda unsafe if done wrong (we are doing it wrong in this example), **more on this NOW**

Increment Data Race

- What seems like a single operation `++sum_total` is actually multiple operations in one. The increment looks something like this in assembly:

```
LOAD  sum_total into R0
ADD   R0 R0 #1
STORE R0 into sum_total
```

- What happens if we context switch to a different thread while executing these three instructions?

- **Reminder: Each thread has its own registers to work with. Each thread would have its own R0**

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

`sum_total = 0`

Thread 0 `R0 = 0`

```
LOAD  sum_total into R0
```

Thread 1

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 0

Thread 0 **R0 = 0**

```
LOAD sum_total into R0
```

Thread 1 **R0 = 0**

```
LOAD sum_total into R0
```

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 0

Thread 0 **R0 = 0**

```
LOAD   sum_total into R0
```

Thread 1 **R0 = 1**

```
LOAD   sum_total into R0
ADD    R0 R0 #1
```

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 1

Thread 0 **R0 = 0**

```
LOAD  sum_total into R0
```

Thread 1 **R0 = 1**

```
LOAD  sum_total into R0
ADD   R0 R0 #1
STORE R0 into sum_total
```

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 1

Thread 0 **R0 = 1**

```
LOAD   sum_total into R0



ADD    R0 R0 #1
```

Thread 1 **R0 = 1**

```
LOAD   sum_total into R0
ADD    R0 R0 #1
STORE  R0 into sum_total
```

Increment Data Race

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 1

Thread 0 **R0 = 1**

```
LOAD  sum_total into R0



ADD   R0 R0 #1
STORE R0 into sum_total
```

Thread 1 **R0 = 1**

```
LOAD  sum_total into R0
ADD   R0 R0 #1
STORE R0 into sum_total
```

- With this example, we could get 1 as an output instead of 2, even though we executed ++sum_total twice

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 eventually happens")
  - Safety – avoid unintended interactions with shared data structures (informally, "nothing bad happens")

Lecture Outline

- Threads Quick Refresher
- Shared Resources & Data Races
- **Disable Interrupts**
- Peterson's Algorithm
- Mutex
- TSL

Disabling Interrupts

- If data races occur when one thread is interrupted while it is accessing some shared code….

  What is we don’t switch to other threads while executing that code?

- This can be done by disabling interrupts: no interrupts means that the clock interrupt won’t go off and interrupt the currently running thread

Disabling Interrupts

- Consider that sum_total starts at 0 and two threads try to execute `++sum_total`

sum_total = 1

Thread 0

```
disable_interrupts();
++sum_total;
enable_interrupts();
```

Thread 1

```
disable_interrupts();
++sum_total;
enable_interrupts();
```

Disabling Interrupts

- Advantages:
  - This is one way to fix this issue
- Disadvantages
  - This is usually overkill
  - This can stop threads that aren't trying to access the shared resources in the critical section. May stop threads that are executing other processes entirely
  - If interrupts disabled for a long time, then other threads will starve
  - In a multi-core environment, this gets complicated

Lecture Outline

- Threads Quick Refresher
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- Disable Intertupts
- **Peterson's Algorithm**
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- Lets try a more complicated software approach..
- We create two threads running thread_code, one with **`arg = 0`**, other thread has **`arg = 1`**
- Each thread tries to increment sum_total. Does this work?

```
int sum_total = 0;
bool flag[2] = {false, false};
int turn = 0

void thread_code(int arg) {
  int me = arg;

  flag[me] = true;
  turn = 1 - me;
  while((flag[1-me] == true) && (turn != me)) { }
  ++sum_total;
  flag[me] = false;
}
```

Check the index of the other thread

Peterson's Algorithm

- What we just did was Peterson's algorithm
- Why does it work? (using an analogy)
  - Each thread first declares that they want to enter the critical section by setting their flag
  - Each thread then states (once) that the other should "go first".
    - This is done by setting the turn variable to 1 – me
    - One of these assignments to the turn variable will happen last, that is the one that decides who goes first
  - One of the thread goes first (decided by the value of turn) and accesses the critical section, before saying it is done (by changing their flag to false)

Peterson’s Algorithm

- What we just did was Peterson's algorithm
- Why does it work?
  - Case1:
    If P0 enters critical section, flag[0] = true, turn = 0. It enters the critical section successfully.
  - Case2:
    If P0 and P1 enter critical section, flag[0] and flag[1] = true

    Race condition on turn. Suppose P0 sets turn = 0 first. Final value is turn = 1. P0 will get to run first.

Explanation

TIME

Thread 0

```
flag[0] = true
```

Thread 1

```
flag[1] = true
```

RACE

Thread 0:

```
turn = 1
turn = 1
```

Thread 1:

```
turn = 0
```

turn = ?

// suppose `turn = 1` came after `turn = 0`
// the `turn` variable is set to 1

turn = 1

Thread 0:

```
while(flag[1] == true
        && turn != 0)
```

Thread 1:

```
while(flag[0] == true
        && turn != 1)
```

Thread 1:

```
++sum_total
```

```
flag[1] = false
```

Thread 0:

```
++sum_total
```

Peterson's Assumptions

- Some operations are atomic:
  - Reading from the flag and turn variables cannot be interrupted
  - Writing to the flag and turn variables cannot be interrupted
  - E.g setting turn = 1 or 0 will set turn to 0 or 1, you can be interrupted before or after, but not "during" when turn may have some intermediate value that is not 0 or 1

- That the instructions are executed in the specific order laid out in the code

Atomicity

- Atomicity: An operation or set of operations on some data are *atomic* if the operation(s) are indivisible, that no other operation(s) on that same data can interrupt/interfere.

- Aside on terminology:
  - Often interchangeable with the term "Linearizability"
  - Atomic has a different (but similar-ish) meaning in the context of data bases and ACID.

Aside: Instruction & Memory Ordering

- Do we know that **t** is set before **g** is set?

```
bool g = false;
int t = 0

void some_func(int arg) {
  t = arg;
  g = true;
}
```

Aside: Instruction & Memory Ordering

NO

- Do we know that **t** is set before **g** is set?

```
bool g = false;
int t = 0

void some_func(int arg) {
  t = arg;
  g = true;
}
```

The compiler may generate instructions that sets g first and then t
The Processor may execute these out of order or at the same time

Why? Optimizations on program performance

You can be guaranteed that `t` and `g` are set before `some_func` returns

Aside: Instruction & Memory Ordering

- The compiler may generate instructions with different ordering if it does not appear that it will affect the semantics of the function
  - Since `g = true;` is not affected by `t = arg;` then either one could execute first.

- The Processor may also execute these in a different order than what the compiler says

- Why? Optimizations on program performance
  - If you want to know more, look into "Out-of-Order Execution" and "Memory Order"

Aside: Memory Barriers

- How do we fix this?

- We can emit special instructions to the CPU and/or compiler to create a “memory barrier”
  - “all memory accesses before the barrier are guaranteed to happen before the memory accesses that come after the barrier”
  - A way to enforce an order in which memory accesses are ordered by the compiler and the CPU

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- Disable Interrupts
- Peterson's Algorithm
- **Mutex**
- TSL

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 (*i.e.* atomic) manner

- 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

- Pseudocode:

```
// non-critical code

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

// non-critical code
```

Lock API

- Locks are constructs that are provided by the operating system to help ensure synchronization
  - Often called a mutex or a semaphore
- Only one thread can acquire a lock at a time,
  No thread can acquire that lock until it has been released
- Has memory barriers built into it and usually uses TSL to ensure that acquiring the lock is atomic (more on TSL in a little bit)

Milk Example – What is the Critical Section?

- 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`

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

- Initializes a mutex with specified attributes

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

- Acquire the lock – blocks if already locked Un-blocks when lock is acquired

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

- Releases the lock

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

- "Uninitializes" a mutex – clean up when done

pthread Mutex Examples

- See `total.c`
  - Data race between threads
- See `total_locking.c`
  - Adding a mutex fixes our data race
- How does `total_locking` compare to sequential code and to `total`?
  - Likely *slower* than both– only 1 thread can increment at a time, and must deal with checking the lock and switching between threads
  - One possible fix: each thread increments a local variable and then adds its value (once!) to the shared variable at the end
    - See `total_locking_better.c`

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- Mutex
- **TSL**

TSL

- TSL stands for **T**est and **S**et **L**ock, sometimes just called **test-and-set**.

- TSL is an atomic instruction that is guaranteed to be atomic at the hardware level

- `TSL R, M`
  - Pass in a register and a memory location
  - R gets the value of M
  - M is set to 1 AFTER setting R

TSL to implement Mutex

- A mutex is pretty much this:

```
pthread_mutex_lock(lock) {
    prev_value = TSL(lock);

    // if prev_value = 1, then it was already locked
    while (prev_value == 1) {
        block();
        prev_value = TSL(lock);
    }
}

pthread_mutex_unlock(lock) {
   lock = 0;
   wakeup_blocked_threads(lock);
}
```