Threads and Synchronization

15

Introduction to
Systems Software

wilkie

Spring 2019/2020

Threads

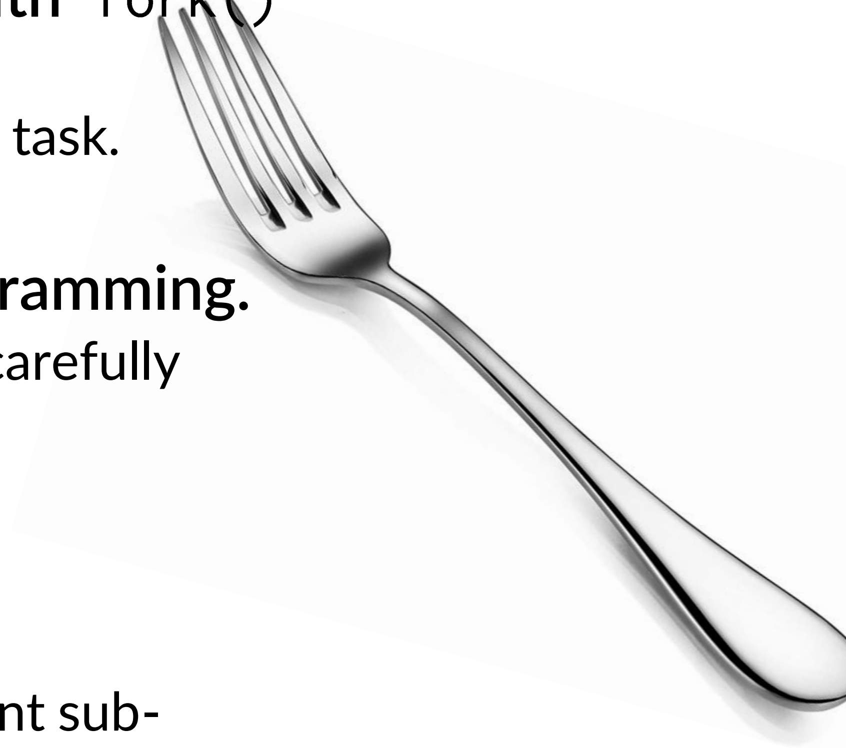
Strings? Threads?? What are we building... a loom???

Our story so far...

- **We looked at how processes reproduce with `fork()`**
  - This gave us some type of concurrency.
  - It is process-level, so the OS is scheduling each task.

- **We saw some issues with concurrent programming.**
  - Race conditions mean we have to much more carefully consider our code.

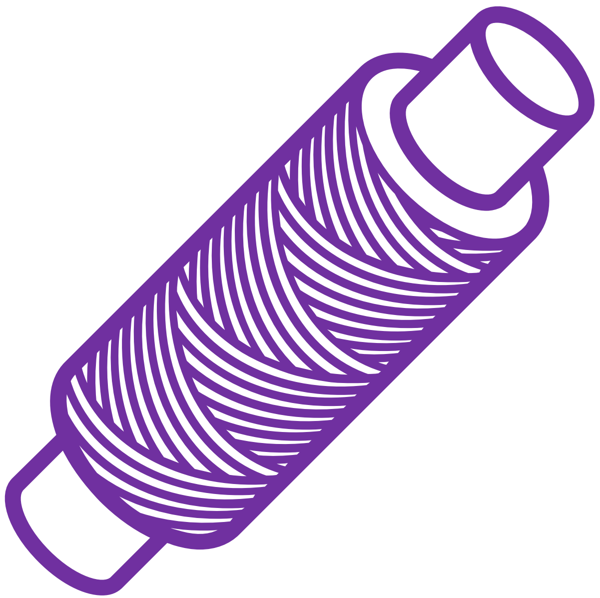
- **This time...**
  - We will look at other forms of concurrency.
  - Some new methods of coordinating the different sub-programs.
  - And some new... dreaded... types of concurrency bugs.



Threads

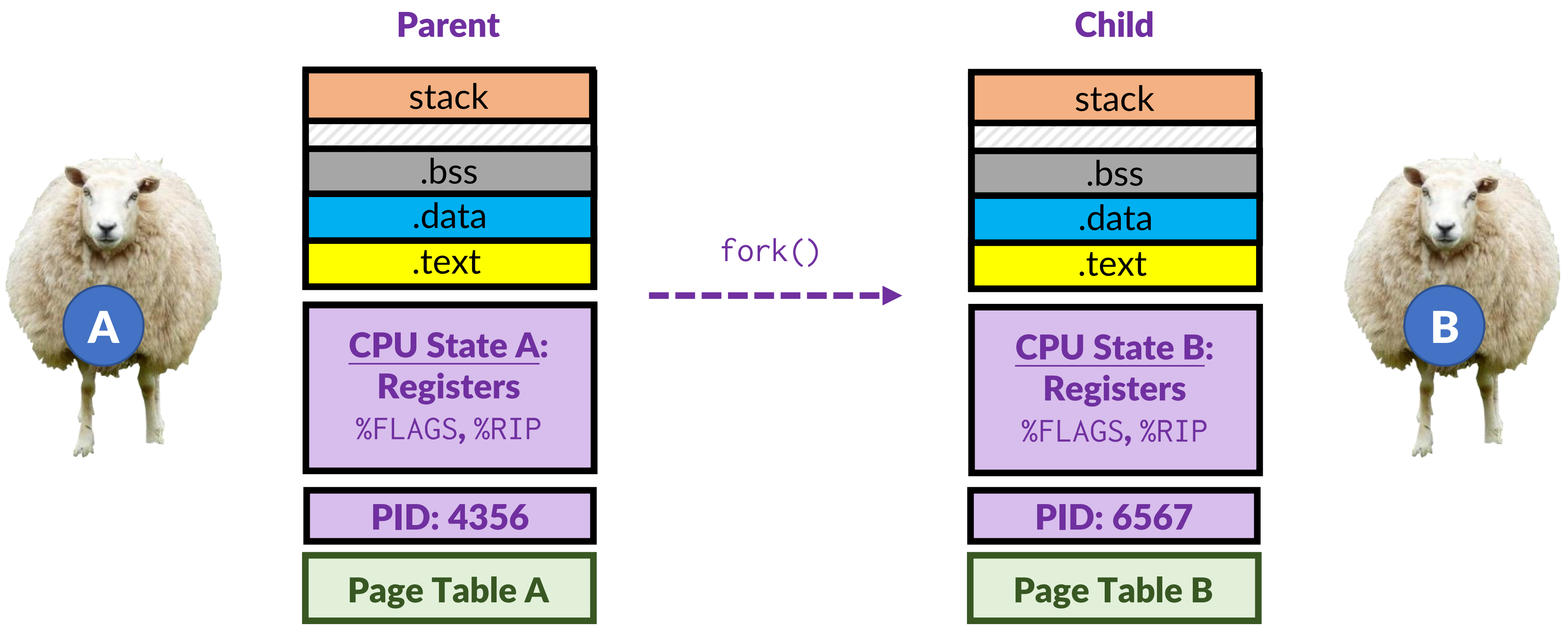
- **Process-level concurrency with `fork()` is powerful, but inflexible.**
  - The OS schedules the task, incurring context switching overhead.
  - The process memory is copied making it hard to share data among tasks.

- **A thread is a concurrency primitive that is inner-process.**
  - The program itself schedules the task as part of the same process.
  - Process memory, therefore, is shared across all threads.



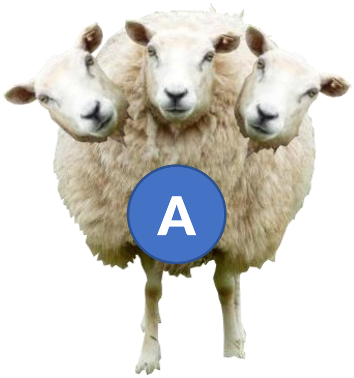
Recall our friend Dolly...

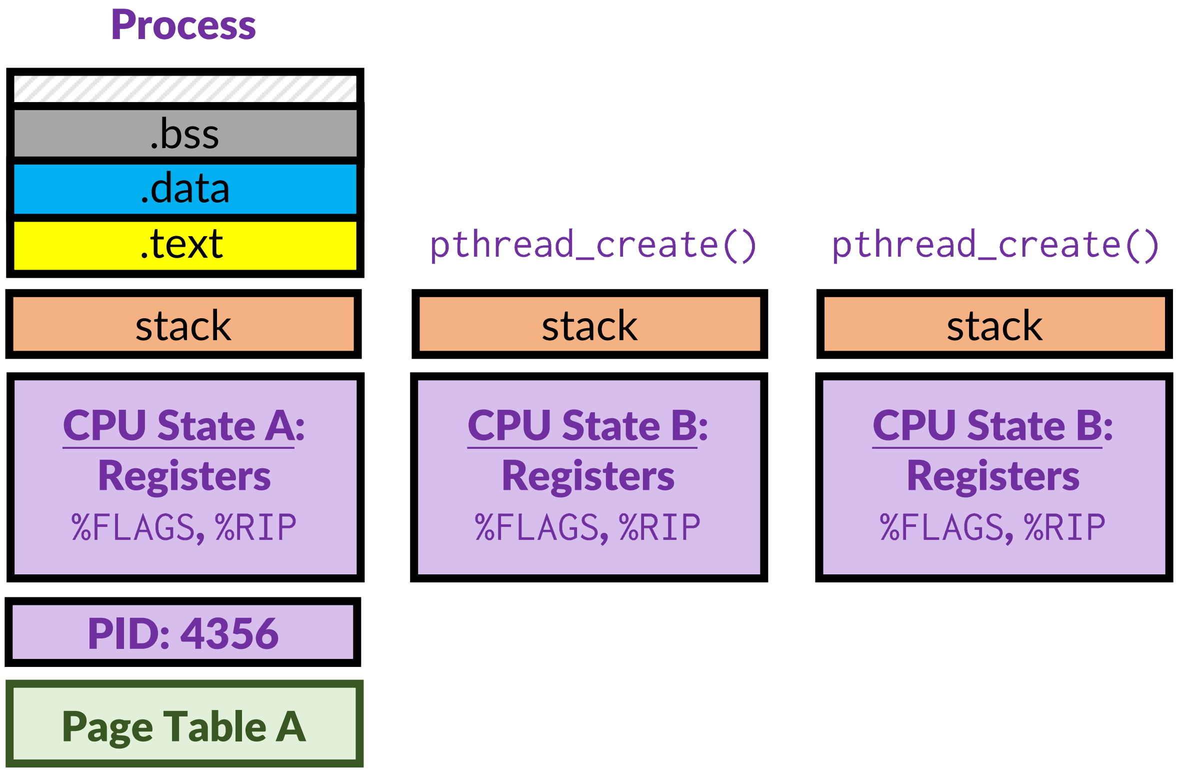
- The `fork()` system call in action:
  - Copies the memory layout.
  - Copies the process state. (but gives it a unique ID)



Dolly learned a new trick!

- **However, with threads… we retain much of the address space.**
  - Threads share code/data/etc, however they have their own stack and CPU state.
  - They execute in parallel with one another interacting directly with the same data.





`libpthread`

- **The 2011 amendment to the C standard (C11) added a threading API.**
  - However, we will still be looking at an older, more prevalent standard.

- **We will be reviewing the `pthread` standard.**
  - The C11 `threads.h` API is still very similar.
  - There are ports of the `pthread.h` interface to many OSes.
  - Lots of threading APIs in other language emulate it.

- **Still <u>very</u> useful to learn!**

POSIX

- **The "p" in pthread stands for the Portable Operating System Interface (POSIX).**
  - This is a standard for creating OS abstractions.
  - Intended to lower the burden of porting applications.
    - Most OSes conform to most POSIX standards.
    - However, very few OSes fully implement POSIX.

- **POSIX standardizes threads, but also process creation and the behavior of fork, file abstractions, and how data is shared among processes.**
  - Many OS interfaces are POSIX interfaces and remain (mostly) true across different platforms.

Creating... hmm... no... *weaving* a thread

C (`gcc -o thrd_bad thrd_bad.c -lpthread`)

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

void* thread(void* data) {
  printf("Hello, %s!\n", data);
  return NULL;
}

void main(void) {
  char* str = "wilkie";

  pthread_t tid;
  pthread_create(&tid, NULL, thread, (void*)str);

  printf("Done!\n");
}
```

This function runs in a thread

Holds the thread ID.

The thread function

Function argument

- **Here is a basic threaded program.**
  - `main()` is within the main thread.
- **The `pthread_create` function creates a second thread, which runs alongside the main thread.**
  - The first argument is the address of a variable to hold the thread ID.
  - The NULL is where you can add some flags, but the defaults are OK.
  - The thread is the function to use.
  - The last argument is passed to that function and generally an address.

The race to the finish.

C (`gcc -o thrd_bad thrd_bad.c -lpthread`)

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

void* thread(void* data) {
  printf("Hello, %s!\n", data);
  return NULL;
}

void main(void) {
  char* str = "wilkie";

  pthread_t tid;
  pthread_create(&tid, NULL, thread, (void*)str);

  printf("Done!\n");
}
```

This never happens!

```
> ./thrd_bad
Done!
```

- However, when the process exits normally, all threads are also canceled, even if they haven't completed.
- In this run, the second thread never prints its message.

In the end of the program, threads are also all exited, potentially prematurely.

Being considerate

C (`gcc -o thrd thrd.c -lpthread`)

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

void* thread(void* data) {
  printf("Hello, %s!\n", (char*)data);
  return NULL;
}

void main(void) {
  char* str = "wilkie";

  pthread_t tid;
  pthread_create(&tid, NULL, thread, (void*)str);

  pthread_join(tid, NULL); // wait for thread

  printf("Done!\n");
}
```

The "str" argument.

Waits...

Guaranteed to happen only after `thread()` completes.

```
> ./thrd
Hello, wilkie!
Done!
```

- `pthread_join()` **waits for the given thread to exit by thread ID.**
  - The NULL is, again, optional flags.
- **Here, the main thread waits until the thread function completes.**
  - It prints out the string given by the argument.

Sharing is caring

C (`gcc -o thrd_share_bad thrd_share_bad.c -lpthread`)

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

int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    printf("THREAD: %d\n", counter);
    counter++;
  }
  return NULL;
}

void main(void) {
  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    printf("MAIN: %d\n", counter);
    counter++;
  }
  printf("Done!\n");
}
```

Thread function increments

Main thread increments, too!

- **Unlike process-level concurrency using `fork()`, threads share memory.**
- **Each thread, here, shares access to the same global variable `counter`.**
  - When the main thread updates, the secondary thread sees that value.
- **Threads share the same virtual address space (and page table.)**
  - They only have their own stack and CPU state.

A problem returns with a vengeance

C (gcc -o thrd_share_bad thrd_share_bad.c -lpthread)

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

int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    printf("THREAD: %d\n", counter);
    counter++;
  }
  return NULL;
}

void main(void) {
  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    printf("MAIN: %d\n", counter);
    counter++;
  }
  printf("Done!\n");
}
```

Thread function might get interrupted before the print

Then main thread increments! :(

```
> ./thrd_share_bad
MAIN: 0
MAIN: 1
MAIN: 2
MAIN: 3
THREAD: 4
THREAD: 5
THREAD: 6
MAIN: 4
MAIN: 8
MAIN: 9
MAIN: 10
THREAD: 7
THREAD: 11
THREAD: 12
```

What happened???

C (`gcc -o thrd_share_bad thrd_share_bad.c -lpthread`)

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

int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    printf("THREAD: %d\n", counter);
    counter++;
  }
  return NULL;
}

void main(void) {
  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    printf("MAIN: %d\n", counter);
    counter++;
  }
  printf("Done!\n");
}
```

Thread function increments

Main thread increments, too!

- Since the threads share memory, access to a variable, such as this, may require extra care.
- When the main thread gets interrupted just as it was printing the value, the thread is scheduled.
  - The thread prints the value instead.
  - Then the main thread, when it continues, prints it again!
- If only we had a way to... align them in time... what's the word...

Synchronization

Stop! Hammer time!

A story about the railroad

- **Systems scientists have long been inspired by the real-world for insight on design.**
- **The rail system requires a lot of attention to detail to provide:**
  - Orderly and timely scheduling of trains.
  - Shared use of a single resource: rail.
  - Coördination with trains and competing interests.
- **In order to provide this, trains make use of signals and switching areas.**
  - Trains wait while others pass, all agreeing on the nature of signals.
  - The signals are called *semaphores*.

The seminal semaphore

- A **semaphore** is a special counter used for synchronization.
  - Invented by Dutch systems scientist Edsger Dijkstra in the early 1960s.

- The counter is a signed integer that often starts at zero or one.

- Two defined operations:
  - Up (signal/release); increments counter.
  - Down (wait/acquire); decrements counter but waits if the counter is 0.

- These operations often have different names or are abbreviated:
  - V (Based on Dutch *vrijgave* “to release”)
  - P (Based on Dutch *passering* “to pass”, *based around railroad terminology*)

Semaphores to prevent the derailing

C (`gcc -o thrd_share thrd_share.c -lpthread`)

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

sem_t lock;
int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    sem_wait(&lock); // down
    printf("THREAD: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  return NULL;
}

void main(void) {
  sem_init(&lock, 0, 1);  // create a counter starting at 1

  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    sem_wait(&lock); // down
    printf("MAIN: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  printf("Done!\n");
}
```

Critical Section

- `sem_init()` **creates a new semaphore.**
  - The first argument is an address to a variable that will hold the semaphore data.
  - The second argument, when 0, means that other threads can see the semaphore. Non-zero means other threads cannot interact with the semaphore, which is a bit more advanced.
  - The third argument is the initial value.
    - Here it is 1.
- `sem_wait()` **decrements the counter.**
  - Waits to decrement if the counter is 0.
- `sem_post()` **increments the counter.**
  - May release a thread waiting at `sem_wait`

Semaphores to prevent the derailing

C (gcc -o thrd_share thrd_share.c -lpthread)

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

sem_t lock;
int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    sem_wait(&lock); // down
    printf("THREAD: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  return NULL;
}

void main(void) {
  sem_init(&lock, 0, 1);  // create a counter starting at 1

  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    sem_wait(&lock); // down
    printf("MAIN: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  printf("Done!\n");
}
```

Critical Section

- When both threads hit `sem_wait()` at the same time, only one continues.
- When one sets the lock; other waits.
  - The other thread relies on the first to eventually release the lock using `sem_post()`
  - When this happens, the other thread can go.
- The lock/unlock pattern creates a **critical section**, a piece of code that has the guarantee that only one task can enter at a time.
  - Here, the counter is guaranteed to update at the same time as it is printed.

Semaphores to prevent the derailing

C (gcc -o thrd_share thrd_share.c -lpthread)

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

sem_t lock;
int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    sem_wait(&lock); // down
    printf("THREAD: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  return NULL;
}

void main(void) {
  sem_init(&lock, 0, 1);  // create a counter starting at 1

  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    sem_wait(&lock); // down
    printf("MAIN: %d\n", counter);
    counter++;
    sem_post(&lock); // up
  }
  printf("Done!\n");
}
```

Critical Section

```
> ./thrd_share
MAIN: 0
MAIN: 1
MAIN: 2
MAIN: 3
THREAD: 4
THREAD: 5
THREAD: 6
MAIN: 7
MAIN: 8
MAIN: 9
MAIN: 10
THREAD: 11
THREAD: 12
THREAD: 13
```

Mutex… ew… don’t like the sound of that

- As you can see, there is a common case.
  - Simple critical sections just need a counter that covers 0 and 1.
- A **mutex** is a special Boolean used for synchronization.
  - It is short for “mutual exclusion,” a term for when two things can only have one resource at a time.
- There are two defined operations:
  - lock / wait; only proceeds if the mutex is unlocked.
  - unlock / release; unlocks the mutex.
- A mutex can be created using a semaphore.
  - It provides a subset of the capabilities of the more general semaphore.

A mutex to prevent the derailing

C (`gcc -o thrd_share_mutex thrd_share_mutex.c -lpthread`)

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

pthread_mutex_t lock;
int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    pthread_mutex_lock(&lock);
    printf("THREAD: %d\n", counter);
    counter++;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}

void main(void) {
  pthread_mutex_init(&lock, NULL);

  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    pthread_mutex_lock(&lock);
    printf("MAIN: %d\n", counter);
    counter++;
    pthread_mutex_unlock(&lock);
  }
  printf("Done!\n");
}
```

Critical Section

- **Mutexes are useful for locking single resources.**
  - It follows much the same pattern as semaphores, and perhaps easier to understand.
- `pthread_mutex_init()` **creates the mutex similarly to** `sem_init()`.
- `pthread_mutex_lock()` **and** `pthread_mutex_unlock()` **do the locking and unlocking, as expected.**

A mutex to prevent the derailing

C (`gcc -o thrd_share_mutex thrd_share_mutex.c -lpthread`)

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

pthread_mutex_t lock;
int counter = 0;

void* thread(void* data) {
  while(counter < 100) {
    pthread_mutex_lock(&lock);
    printf("THREAD: %d\n", counter);
    counter++;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}

void main(void) {
  pthread_mutex_init(&lock, NULL);

  pthread_t tid;
  pthread_create(&tid, NULL, thread, NULL);

  while(counter < 100) {
    pthread_mutex_lock(&lock);
    printf("MAIN: %d\n", counter);
    counter++;
    pthread_mutex_unlock(&lock);
  }
  printf("Done!\n");
}
```

Critical Section

```
> ./thrd_share_mutex
MAIN: 0
MAIN: 1
MAIN: 2
MAIN: 3
MAIN: 4
THREAD: 5
THREAD: 6
THREAD: 7
THREAD: 8
THREAD: 9
MAIN: 10
MAIN: 11
THREAD: 12
THREAD: 13
```

Strategies

- Semaphores and mutexes are both primitives to aid in concurrent programming.

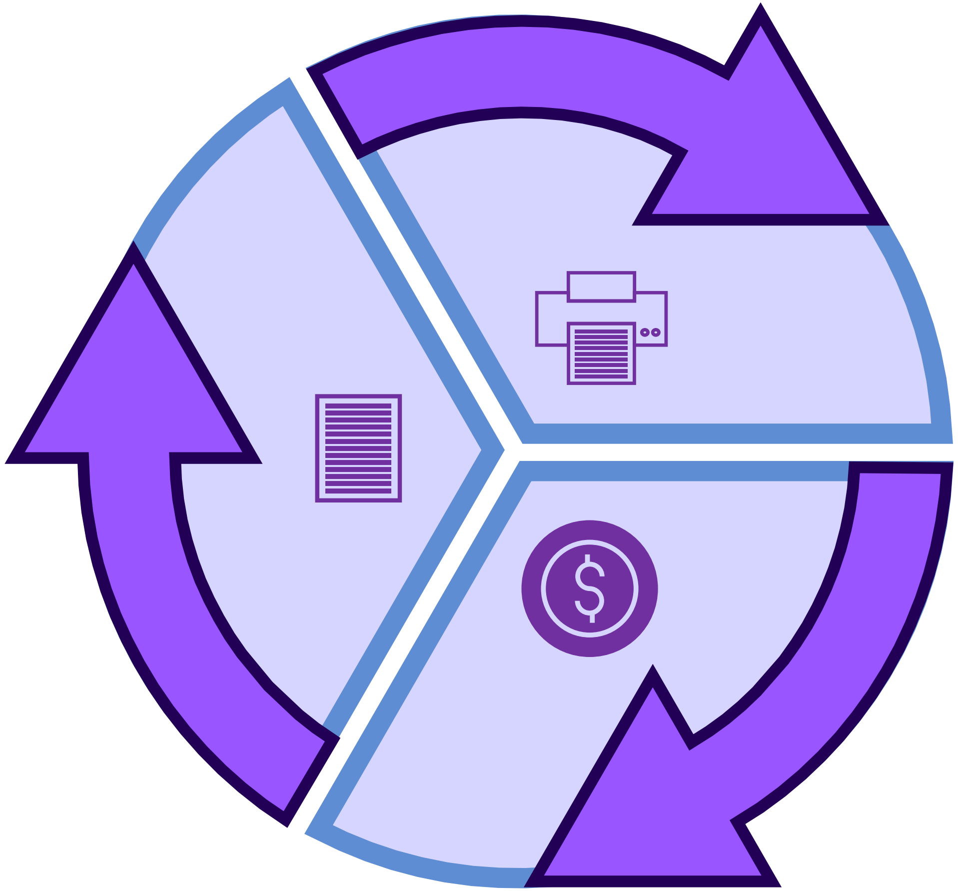
- We saw, here, another example of a **race condition**, a concurrency bug where the absence of guaranteed order can result in incorrect behavior.
  - Namely, threads being interrupted in-between operations that need to happen together and racing another thread that will incorrectly use that intermediate value.

- However, that's not the only type of concurrency bug we can have!
  - Yay! ☹

Parallel Pitfalls

This is like that time when a bird pooped on me the same time I stepped in a very muddy puddle.

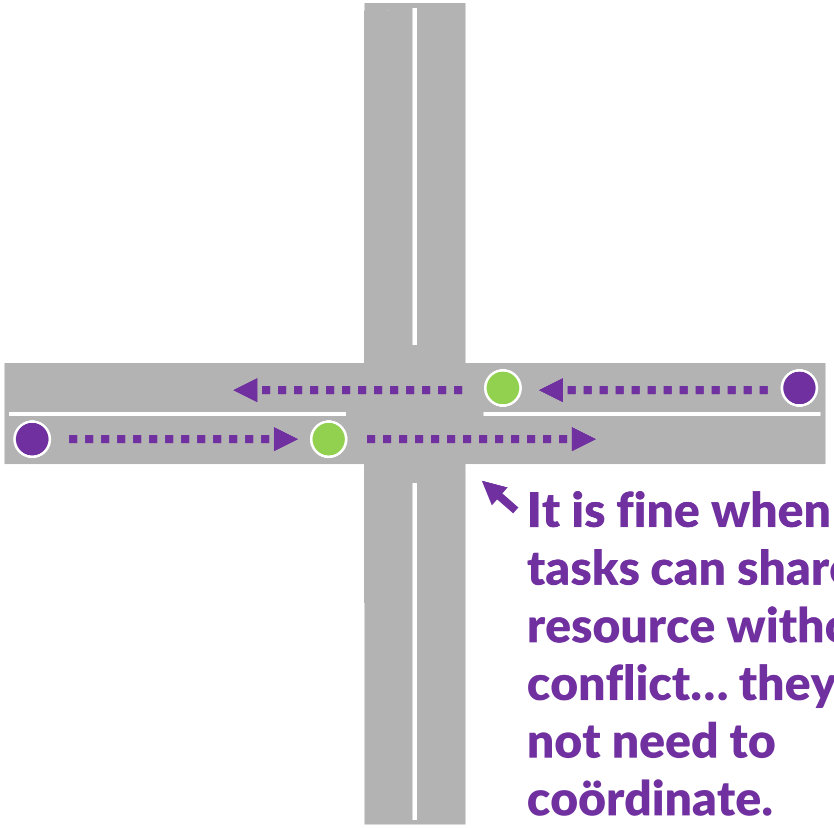
Everybody loves resources



Resource contention:

- Printer needs paper…
- You need to buy some paper…
- You need to print an order form for paper…
- Printer needs paper…

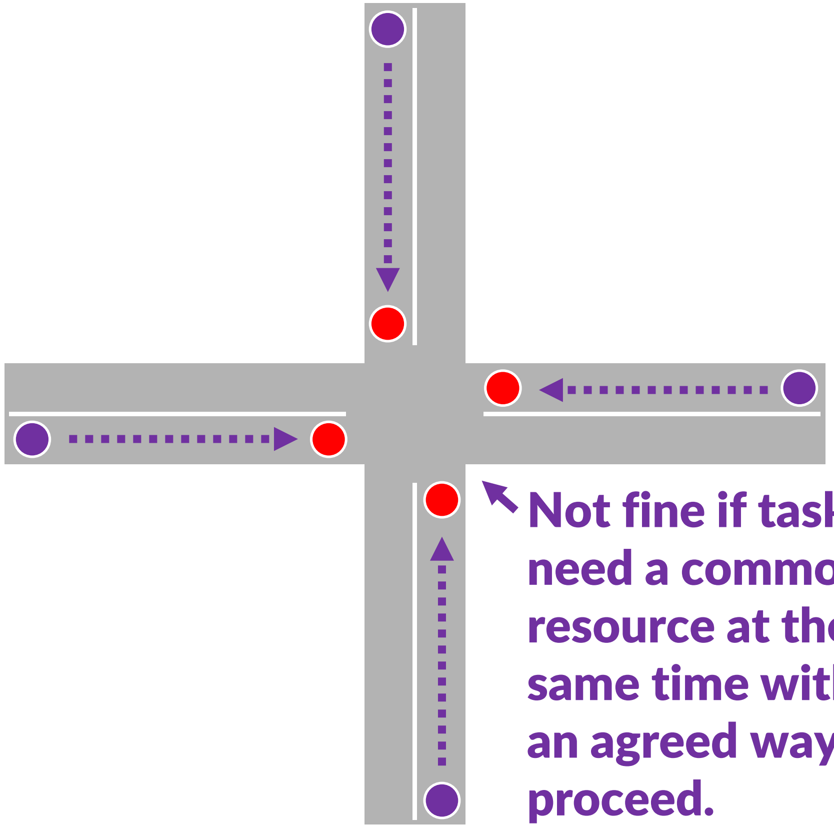
Typically...



It is fine when two tasks can share a resource without conflict... they do not need to coördinate.

- Metaphor: intersection.
- The intersection is a shared resource, much like a device or the CPU.
- Multiplexing the intersection is important to avoid crashes.
- When the streets aren't busy, cars just make it safely across.

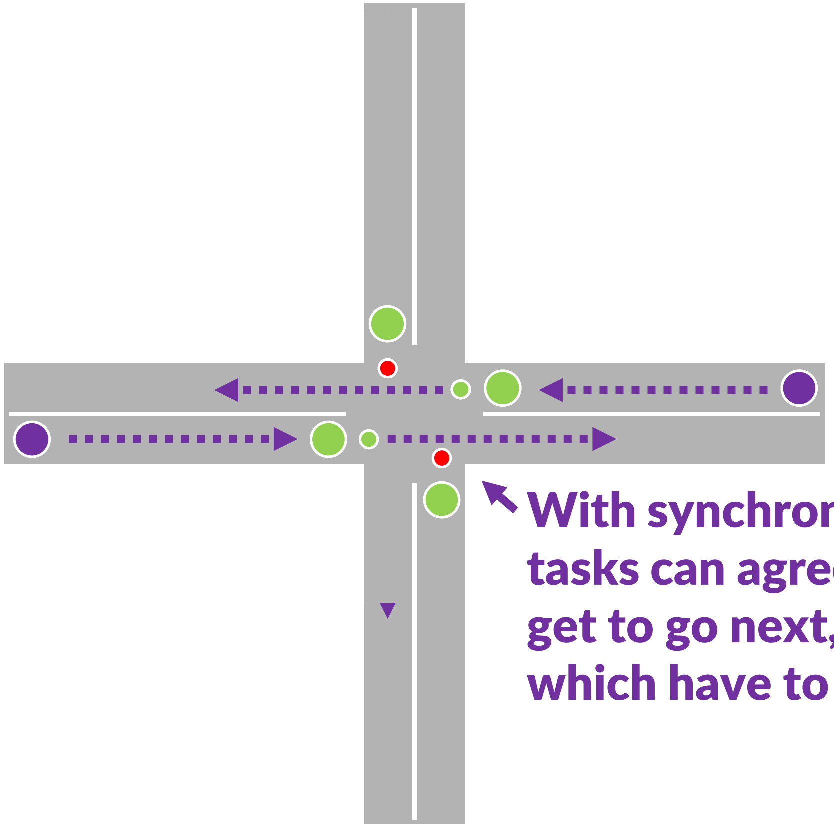
Deadlock: The traffic jam (it's not very delicious)



Not fine if tasks need a common resource at the same time without an agreed way to proceed.

- However, in some circumstances, several cars may reach the intersection at the same time.
- If there is no previously defined way to handle this, they all wait for the others to get out of the way.
  - Forever.
- **Deadlock** occurs when multiple tasks are waiting for each other, making no progress.

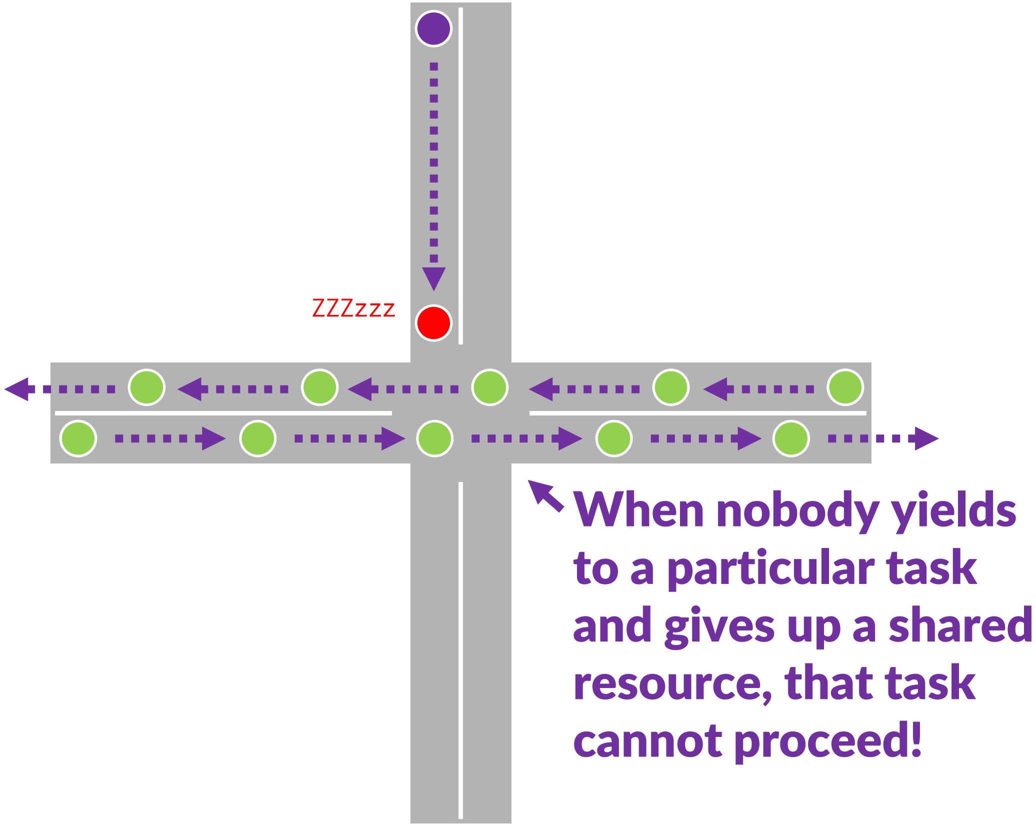
Synchronization solves deadlock



With synchronization, tasks can agree which get to go next, and which have to wait.

- Deadlock is a bug that needs extra consideration to avoid.
- In this case, you need some method of making only some of the cars (tasks) wait, while letting others go.
  - Traffic light, perhaps
- Beyond defining order, synchronization helps avoid these types of logical errors.

Starved for attention...



- Another issue, related to deadlock, is **starvation** where the system makes progress but one task is perpetually delayed.
- When some tasks have priority over resources, they may not give them up for other tasks.
  - Those tasks wait forever.
- Without a traffic light, you rely on people being nice. :(

Starvation: a matter of fairness

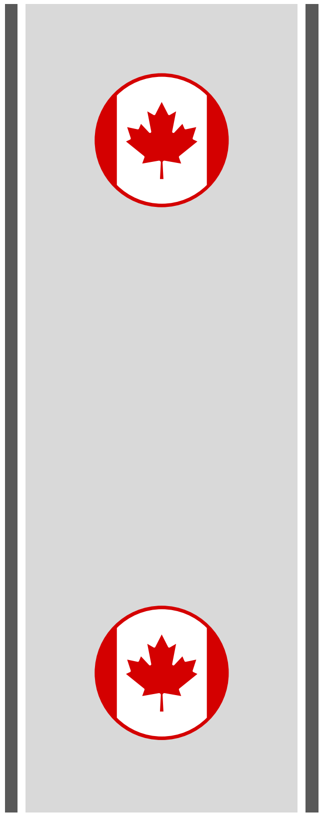
- This can happen in situations where “fairness” scheduling goes awry.

- If you have a webserver, the OS might schedule that process whenever there is some incoming requests.
  - What if you are getting a lot of traffic!
  - The OS might always schedule the webserver.
  - Important background tasks might not run!

- Preventing starvation might be keeping track of how much time a process has a resource and how long it has waited in line.
  - Low-priority tasks start at the back of the line and move up the queue the longer they wait… eventually cutting in front of high-priority tasks that start in the front.

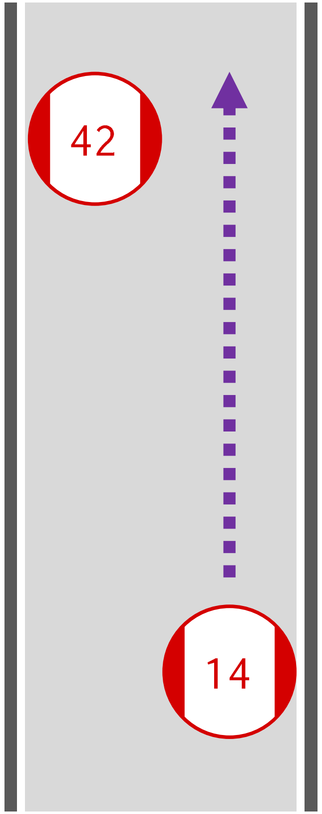
- That’s just *one* idea. Scheduling resources is a very difficult problem!

Livelock: The hallway problem



- There is a narrow hallway.
- Let's say you have two very polite people.
- They walk toward each other… and try very hard to get out of each other's way.
  - They keep insisting the other go ahead of them.
- This is **livelock**, where two tasks are actively signaling the other to go and making no progress.

Careful design works around livelock



- Livelock can be solved using a tie-breaking scheme.
  - Just find something comparable and unique among the tasks to create an arbitrary priority.

- All threads have IDs, so one easy strategy is to have the largest ID yield to the smaller.
  - This also helps starvation since livelock is starvation to the extreme: where everybody is starving.

Deadlock vs. Livelock

- In deadlock, all tasks are waiting for a signal that will never happen.
  - They are *inactively* achieving nothing. (“ZZzzzzzz”, “ZZzzzzzz”)

- In contrast, livelock occurs when each task signals the other, and they respond by signaling back. (“No, you.” “No… you!”)
  - They are *actively* achieving nothing.

- Detecting that your program has a deadlock or livelock is tricky.
  - When it does, it may only happen a small percentage of the time.
  - In your OS course, you will learn more about deadlock detection and resolution.

Solving things

- **Proper synchronization and planning can solve all these issues.**
  - Deadlock: Avoid patterns of critical sections that depend on each other.
  - Livelock: Establish a tie-breaking mechanism (thread with smallest ID goes first!)
  - Yet, it takes a good deal of programming experience to handle them.

- **The wide prevalence of multiprocessing and multithreading capable computers in the hands of average consumers is changing programming.**
  - New (and old) languages are being pushed for their better handling of concurrency issues.
  - Best-practices and frameworks continue to adapt to avoid many of the pitfalls we have discussed today.
  - Pay attention in your compilers and OS course to hone your own skill!

pthread **basic API summary**

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

- **Thread creation**
  - `int pthread_create(pthread_t*, pthread_attr_t*, void*(*)(void*), void*);`
- **Join threads (wait until complete)**
  - `pthread_join(pthread_t, void**);` Waits for the given thread to end.
- **Getting thread ID**
  - `pthread_t pthread_self();` Returns the thread ID of the current thread.
- **Thread destruction (explicit)**
  - `pthread_cancel(pthread_t);` Attempts to preemptively exit the given thread.
  - `pthread_exit(void*);` Ends current thread and returns the provided value.

pthread **synchronization API summary**

- Semaphores
  - `#include <semaphore.h>`
  - `int sem_init(sem_t*, 0, unsigned int initial_value);`
    Creates a semaphore with the given initial value. (The second argument means it the semaphore data is in shared memory. If non-zero, it can't be seen by other threads.)
  - `int sem_wait(sem_t*);` Decrements counter unless it is 0 in which case it waits.
  - `int sem_post(sem_t*);` Increments counter.

- Mutexes
  - `#include <pthread.h>`
  - `int pthread_mutex_init(pthread_mutex_t, NULL);` Creates a mutex (unlocked).
  - `int pthread_mutex_lock(pthread_mutex_t*);` Waits until it can lock the mutex.
  - `int pthread_mutex_unlock(pthread_mutex_t*);` Unlocks the mutex.

Summary

- **Threads are a different way to provide concurrency in a program.**
  - Unlike process-level concurrency, threads share memory within the process.
- **Synchronization primitives such as semaphores allow for creation of critical sections; necessary for correct concurrent code.**
- **Incorrect code may result in a new set of logical errors.**
  - Race conditions – When execution order stochastically results in wrong behavior.
  - Deadlock – When resources are contended so much the program freezes.
  - Starvation – When a resource is greedily kept by a task, certain tasks freeze.
  - Livelock – Starvation happens at every task… they all actively yield to each other.