CS 261
Fall 2021

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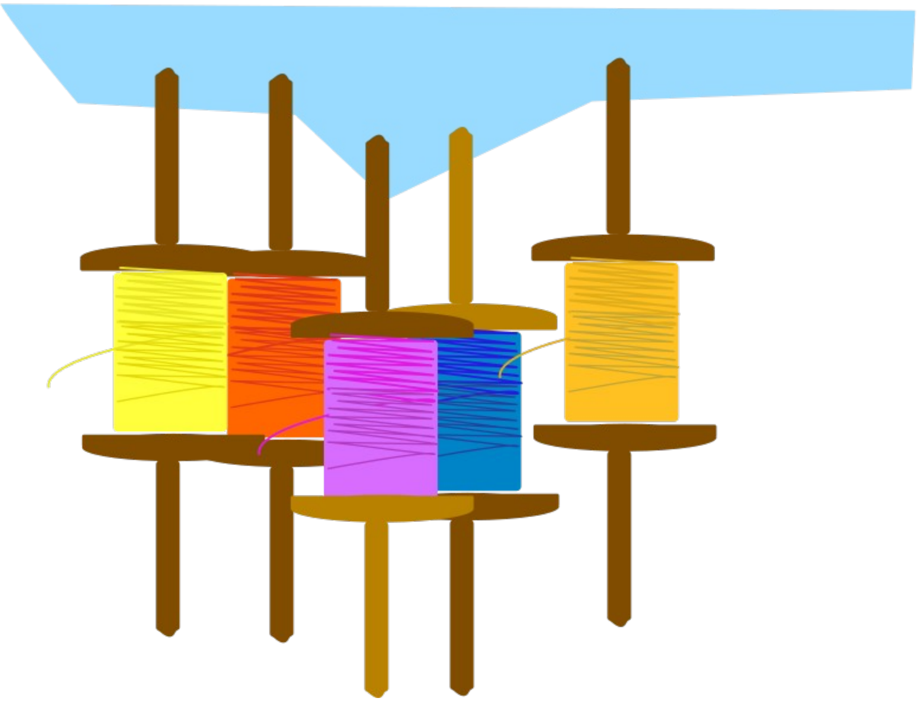


Threads

Parallel computing

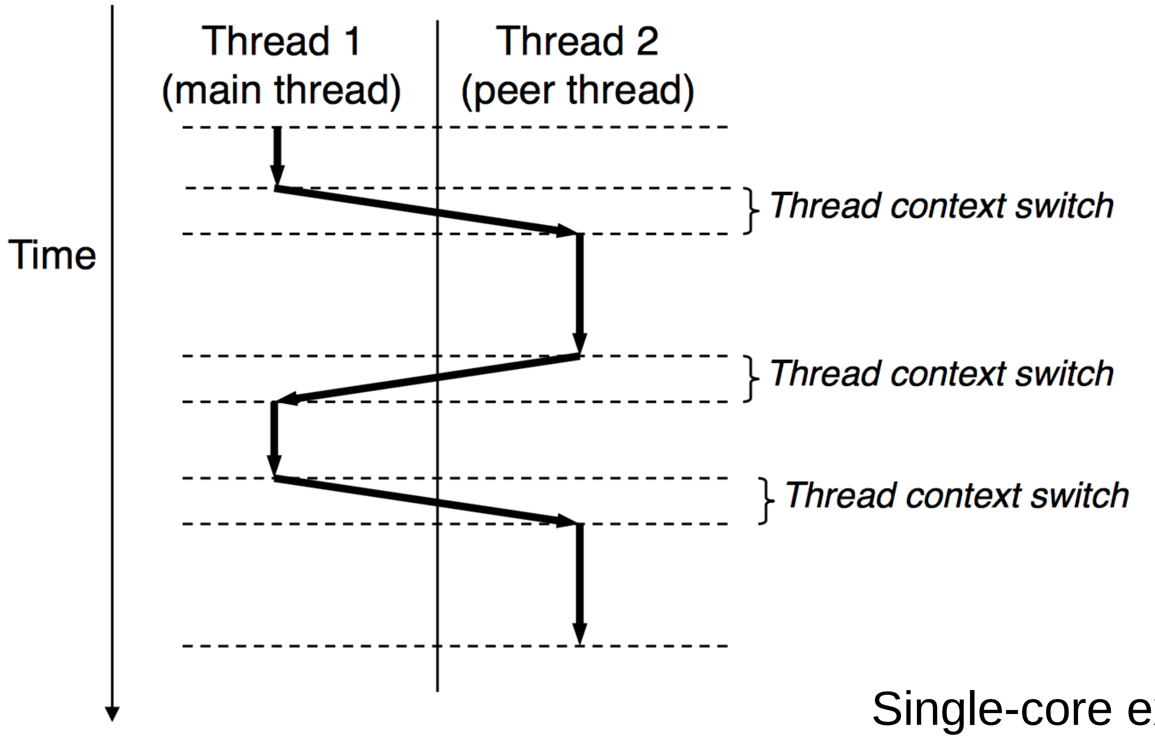
- Goal: concurrent or parallel computing
  - Take advantage of multiple hardware units to solve multiple problems simultaneously
- Motivations:
  - Maintain high utilization during slow I/O downtime
  - Maintain UI responsiveness during computation
  - Respond simultaneously to multiple realtime events
  - Split up a large problem and solve sub-pieces concurrently to achieve faster time-to-solution (strong scaling)
  - Solve larger problems by adding more hardware (weak scaling)

Parallel computing

- Process: currently-executing program
  - Code and state (PC, stack, data, heap)
  - Private address space
- Thread: unit of execution or logical flow
  - Exists within the context of a single process
  - Shares code/data/heap/files w/ other threads
  - Keeps private PC, stack, and registers
    - Stacks are technically shared, but harder to access

Threads

- One main thread for each process
  - Can create multiple peer threads



Single-core example

POSIX threads

- Pthreads – POSIX standard interface for threads in C
  - Not part of the standard library
    - Requires "`-lpthread`" flag during linking
  - `pthread_create`: spawn a new child thread
    - `pthread_t` struct for storing thread info
    - attributes (or NULL)
    - thread work routine (function pointer)
    - thread work routine parameter (void*, can be NULL)
  - `pthread_self`: get current thread ID
  - `pthread_exit`: terminate current thread
    - can also terminate implicitly by returning from the thread routine
  - `pthread_join`: wait for another thread to terminate
    - requires a `pthread_t` to wait for

Threading example

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

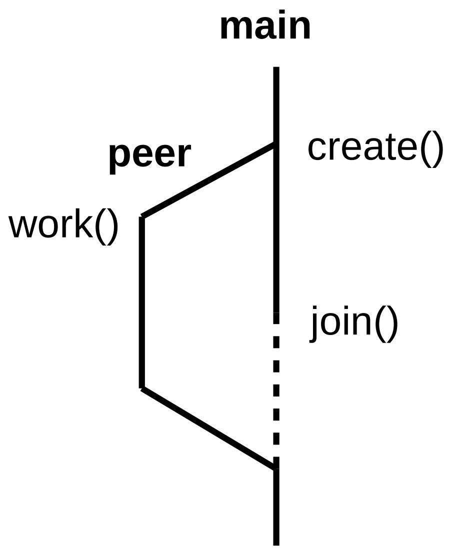
void* work (void* arg)
{
    printf("Hello from work routine!\n");
    return NULL;
}

int main ()
{
    printf("Spawning single child ...\n");

    pthread_t child;
    pthread_create(&child, NULL, work, NULL);
    pthread_join(child, NULL);

    printf("Done!\n");

    return 0;
}
```



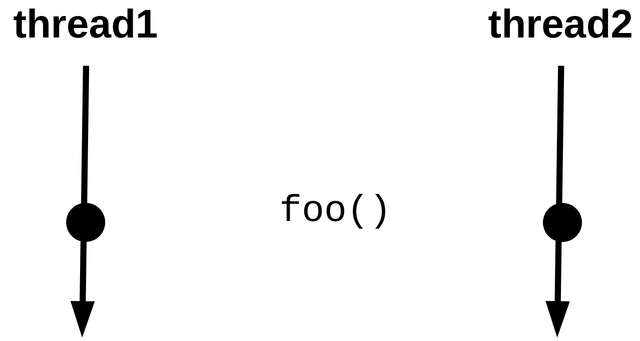
Shared memory

- **Global** variables (shared, single static copy)
  - Often used for communication between threads
  - Requires careful coordination
- **Local** “automatic” variables (multiple copies, one on each stack)
  - Technically still shared if in memory, but harder to access
  - Not shared if cached in register
  - Safer to assume they're private; this is conventional
- **Local static** variables (shared, single static copy)
  - Similar to global variables but with reduced scope
- **Heap**-allocated variables (shared, dynamic)
  - Requires coordination if threads share pointers to same memory

Issues with shared memory

```
foo:
    irmovq x, %rcx
    irmovq 7, %rax
    mrmovq (%rcx), %rdx
    addq %rax, %rdx
    rmmovq %rdx, (%rcx)
    ret

x:
    .quad 0
```




```
irmovq x, %rcx
irmovq 7, %rax
                    irmovq x, %rcx
                    irmovq 7, %rax
mrmovq (%rcx), %rdx
addq %rax, %rdx
rmmovq %rdx, (%rcx)
ret
                    mrmovq (%rcx), %rdx
                    addq %rax, %rdx
                    rmmovq %rdx, (%rcx)
                    ret
```

This interleaving is ok.

Issues with shared memory

```
foo:
    irmovq x, %rcx
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    mrmovq (%rcx), %rdx
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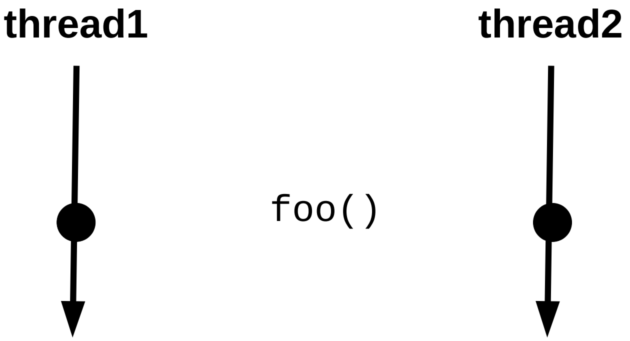


```
irmovq x, %rcx
irmovq 7, %rax
mrmovq (%rcx), %rdx
                              irmovq x, %rcx
                              irmovq 7, %rax
                              mrmovq (%rcx), %rdx
addq %rax, %rdx
rmmovq %rdx, (%rcx)
ret
                              addq %rax, %rdx
                              rmmovq %rdx, (%rcx)
                              ret
```

This one is not!

Issues with shared memory

- A program is non-deterministic when it can produce different outputs given the same inputs
- A data race occurs when correct output relies on a particular ordering during execution
- Deadlock occurs when threads or processes are blocked waiting on a condition that will never happen

Mutual exclusion

- Fixing a data race requires some form of mutual exclusion
  - Only one thread at a time should update shared memory
  - In Pthreads, this can be accomplished using either a mutex or a semaphore (more details in CS 361)
  - However, these mechanisms introduce overhead!
    - Threads must perform additional checks before updating memory
    - Some threads may have to pause and wait before they may continue
  - If not implemented carefully, the additional overhead may defeat the purpose of using multiple threads
    - Theme: Systems design requires tradeoffs
    - Theme: Details matter (a LOT!)
  - Efficient parallel and distributed computing can be very difficult

Automatic parallelism

- Wouldn't it be great if the compiler could automatically parallelize our programs?
  - This is a HARD problem
  - In some cases, it is (kind of) possible
  - Approach #1: code annotations in existing language
    - Example: OpenMP (CS 450, **CS 470**)
  - Approach #2: new language designed for parallelism
    - Example: HPF and Chapel (CS 430, **CS 470**)

```
int a[100];

#pragma omp parallel for
for (int i=0; i < 100; i++)
    a[i] = i*i;
```

OpenMP example

```
var a: [100] int;

forall i in 0..100 do
    a[i] = i*i;
```

Chapel example

Processes vs. threads

- Process: currently-executing program
  - Private code and state (PC, stack, data, heap)
  - Created via system call (`fork`); parent and child continue from call site
  - **Private address space** not shared w/ other processes
  - Advantages: isolation, safety, and mutual exclusion

- Thread: unit of execution or logical flow
  - Private PC, registers, condition codes, and stack
  - Created via library call (`pthread_create`); child runs separate routine
  - **Shared address space** w/ other threads
  - Advantages: faster context switching, more shared resources

History of parallel systems

- Uniprogramming / batch (1950s) - **CS 261**
  - One process at a time w/ complete control of CPU
  - Minimal OS (mostly for launching programs)
- Multiprogramming / multitasking / time sharing (1960s) - CS 261, **CS 450**
  - Multiple processes taking turns on a single CPU
  - Increased utilization, lower response time
  - OS handles scheduling and context switching
- (Symmetric) multiprocessing (1970s) - **CS 361**, CS 450, CS 470
  - Multiple processes share multiple CPUs or cores
  - Increased throughput, increased parallelism
  - OS handles scheduling, context switching, and communication
- Distributed processing (1980s and onward) - CS 361, **CS 470**
  - Multiple processes share multiple computers
  - Massive scaling; OS no longer sufficient (other middleware required)