CSC 252/452: Computer Organization
Fall 2025: Lecture 24

Instructor: Yanan Guo

Department of Computer Science
University of Rochester

Announcements

- Final exam: Dec. 13th, 8:30 AM -- 11:30 AM
- Open book test: any sort of paper-based product, e.g., book, **notes**, magazine, old tests.
  - **No** electronic devices
- Problem sets and previous exams are helpful.
- Course evaluation starts today.
  - If >60% students do course evaluation, two extra points are given to each student

Today

- From process to threads
  - Basic thread execution model
- Multi-threading programming
- Hardware support of threads
  - Single core
  - Multi-core
  - Hyper-threading
  - Cache coherence

Programmers View of A Process

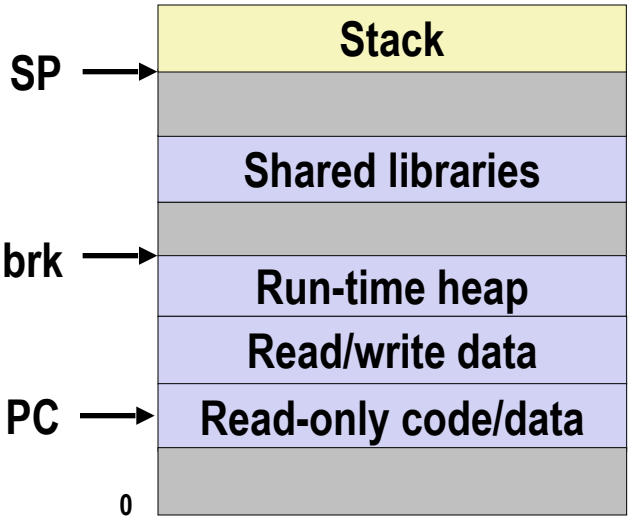
- Process = process context + code, data, and stack

Process context

Program context:
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

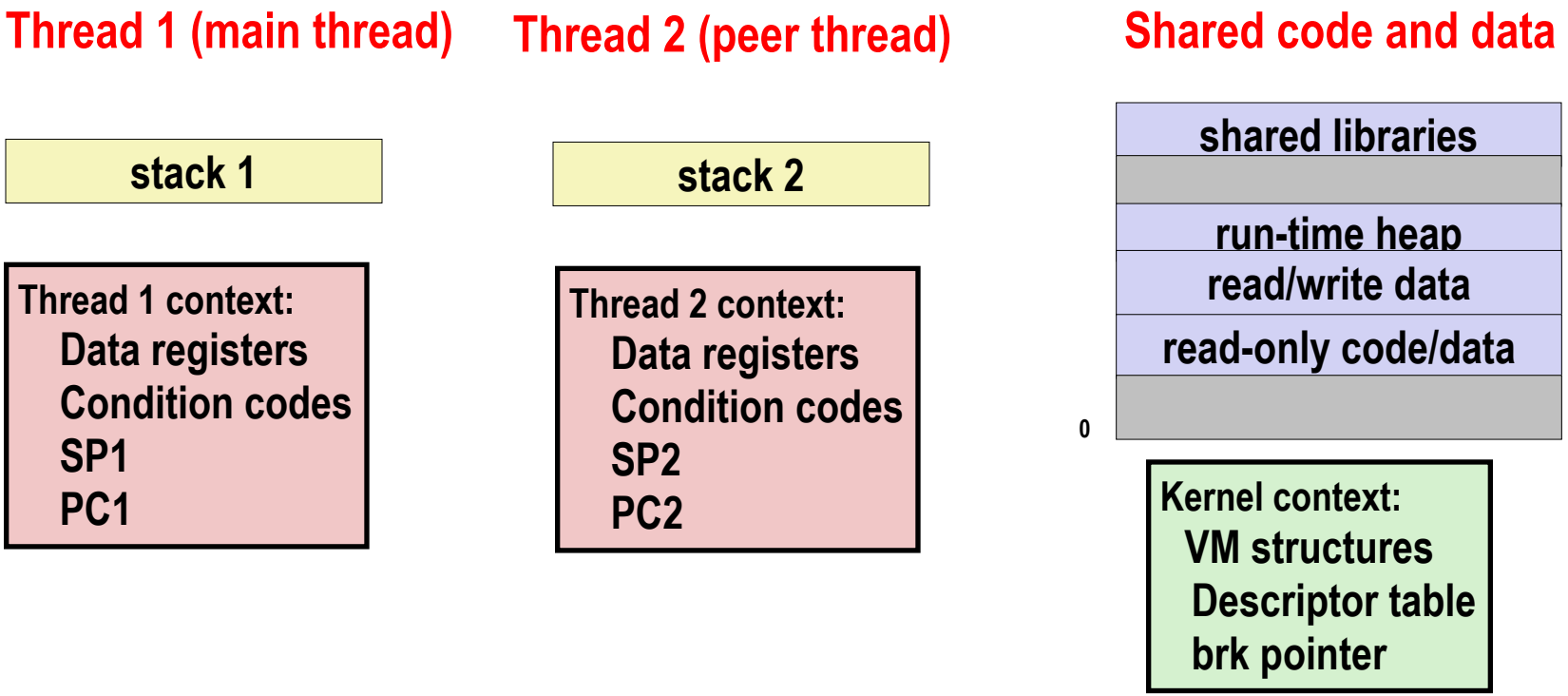
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



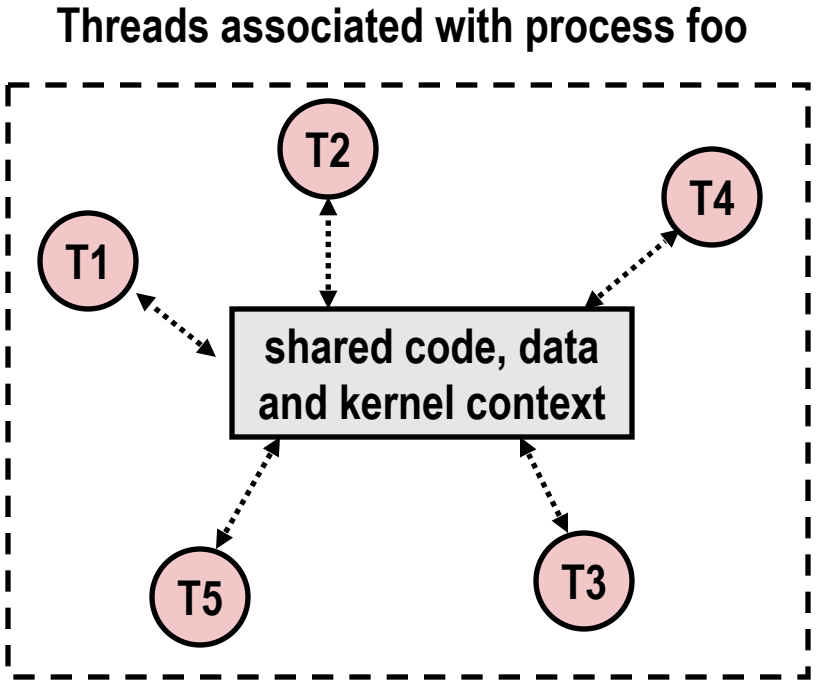
A Process With Multiple Threads

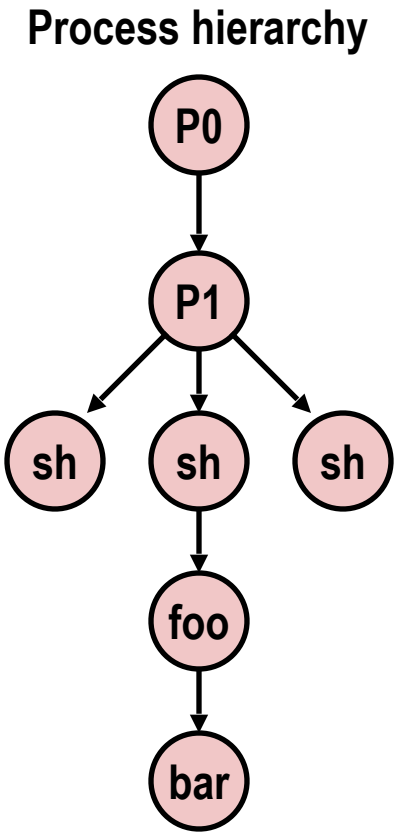
- Multiple threads can be associated with a process
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID)



Logical View of Threads

- Threads associated with process form a pool of peers
  - Unlike processes which form a tree hierarchy

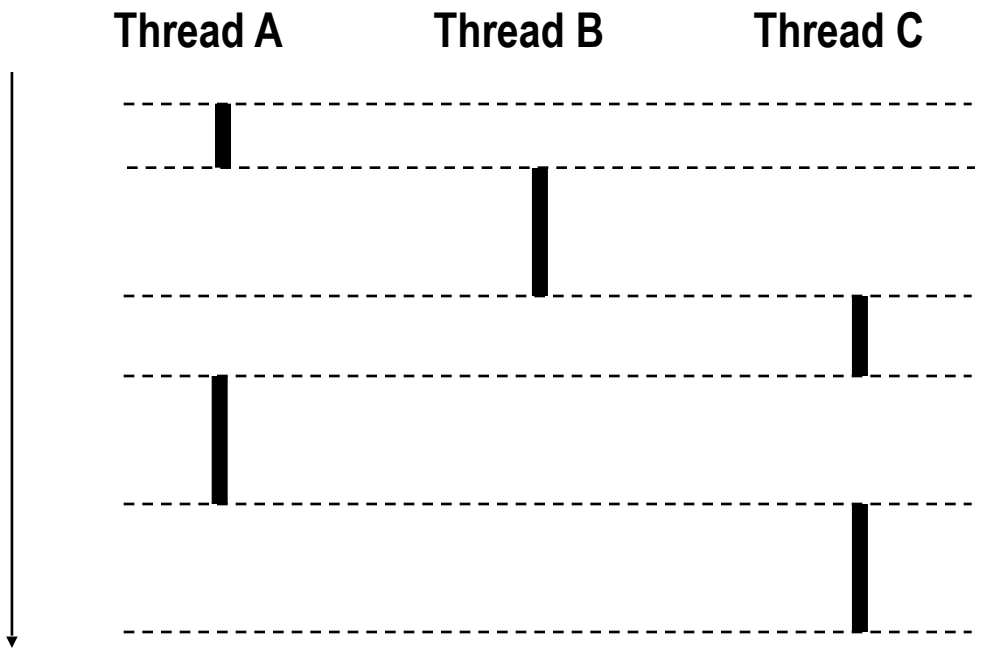




Concurrent Threads

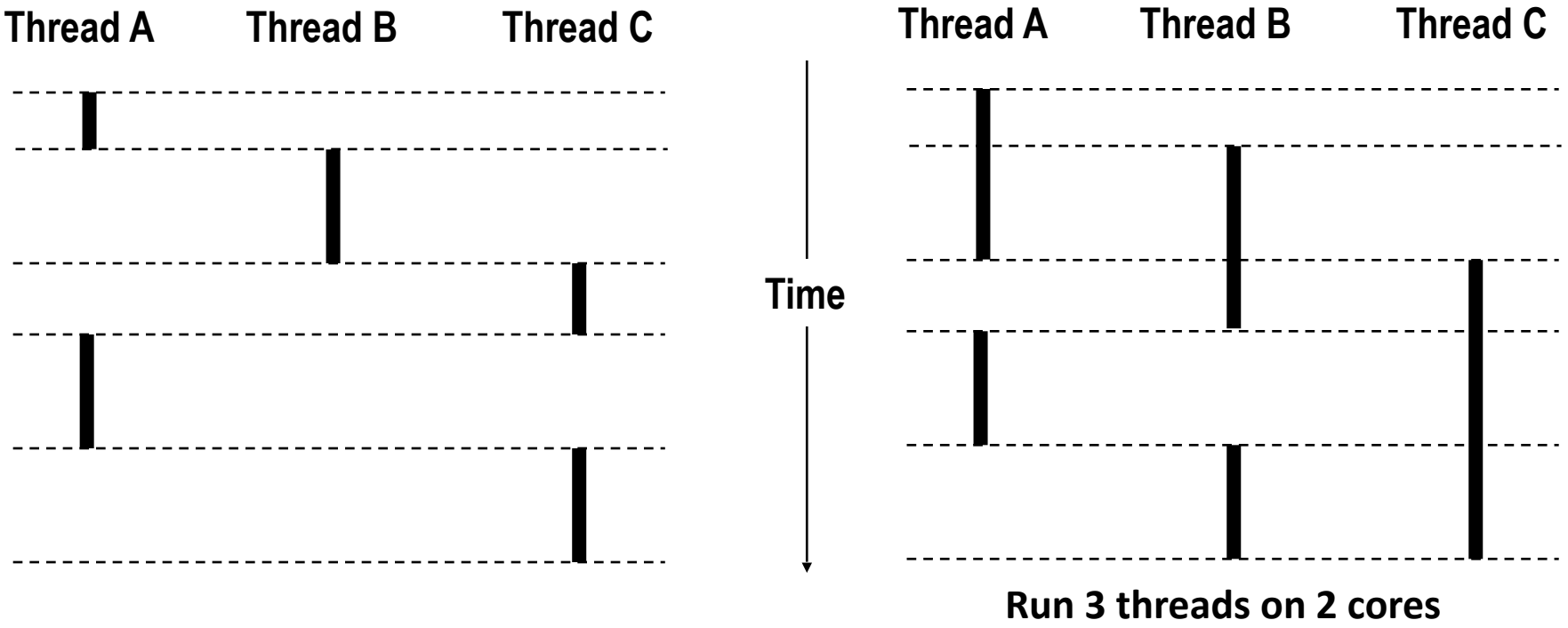
- Two threads are *concurrent* if their flows overlap in time
- Otherwise, they are sequential

- Examples:
  - Concurrent: A & B, A&C
  - Sequential: B & C



Concurrent Thread Execution

- Single Core Processor
  - Simulate parallelism by time slicing
- Multi Core Processor
  - Threads can have true parallelisms



Threads vs. Processes

- How threads and processes are similar
  - Each has its own logical control flow
  - Each can run concurrently with others (possibly on different cores)
  - Each is context switched, controlled by kernel

Threads vs. Processes

- How threads and processes are similar
  - Each has its own logical control flow
  - Each can run concurrently with others (possibly on different cores)
  - Each is context switched, controlled by kernel
- How threads and processes are different
  - Threads share all code and data (except local stacks)
    - Processes (typically) do not
  - Threads are less expensive than processes
    - Space: threads share the same virtual address space except stacks, but processes have their own virtual address space
    - Process control (creating and reaping) twice as expensive
    - Typical Linux numbers:
      - ~20K cycles to create and reap a process
      - ~10K cycles (or less) to create and reap a thread

Posix Threads (Pthreads) Interface

- *Pthreads:* Standard interface for ~60 functions that manipulate threads from C programs
  - Creating and reaping threads
    - `pthread_create()`
    - `pthread_join()`
  - Determining your thread ID
    - `pthread_self()`
  - Terminating threads
    - `pthread_cancel()`
    - `pthread_exit()`
    - `exit()` [terminates all threads] , `return()` [terminates current thread]
  - Synchronizing access to shared variables
    - `pthread_mutex_init`
    - `pthread_mutex_[un]lock`

The Pthreads "hello, world" Program

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 * hello.c - Pthreads "hello, world" program
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#include "csapp.h"
void *thread(void *vargp);

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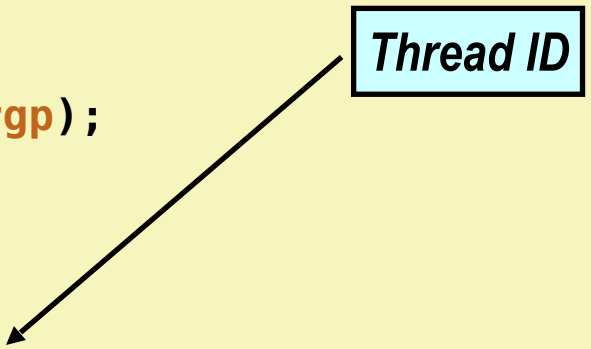

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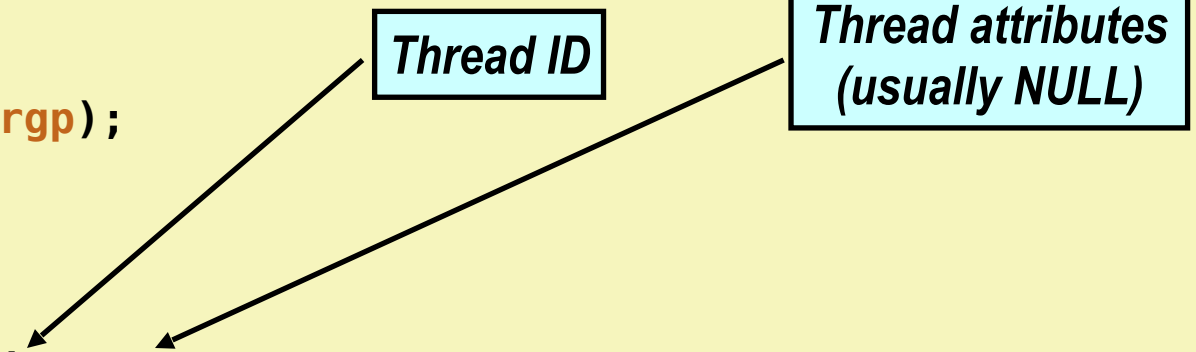


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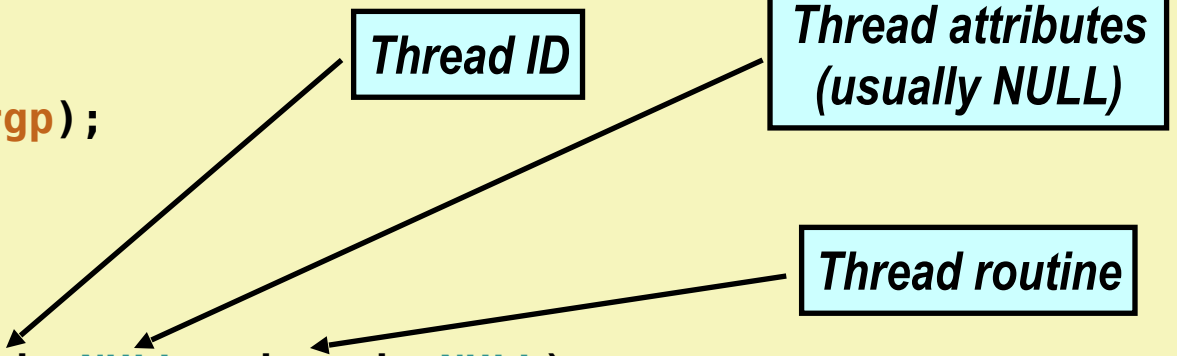


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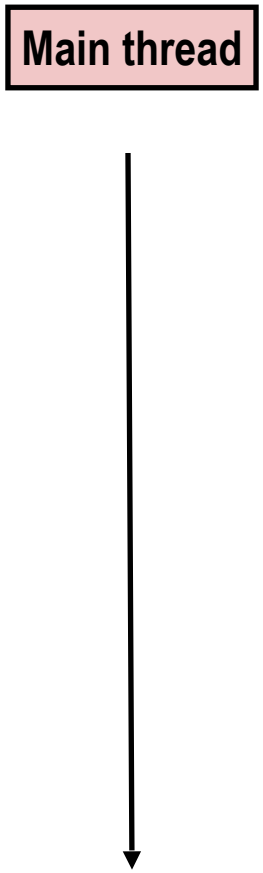
Execution of Threaded “hello, world”



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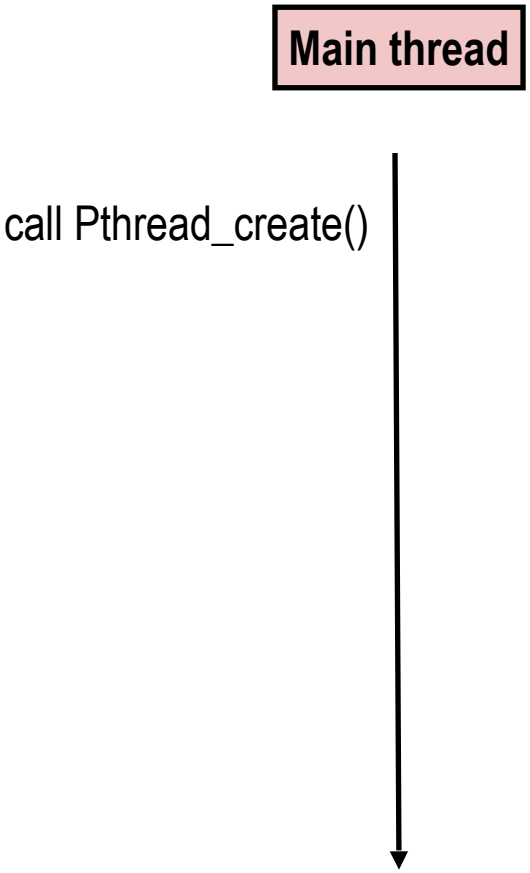

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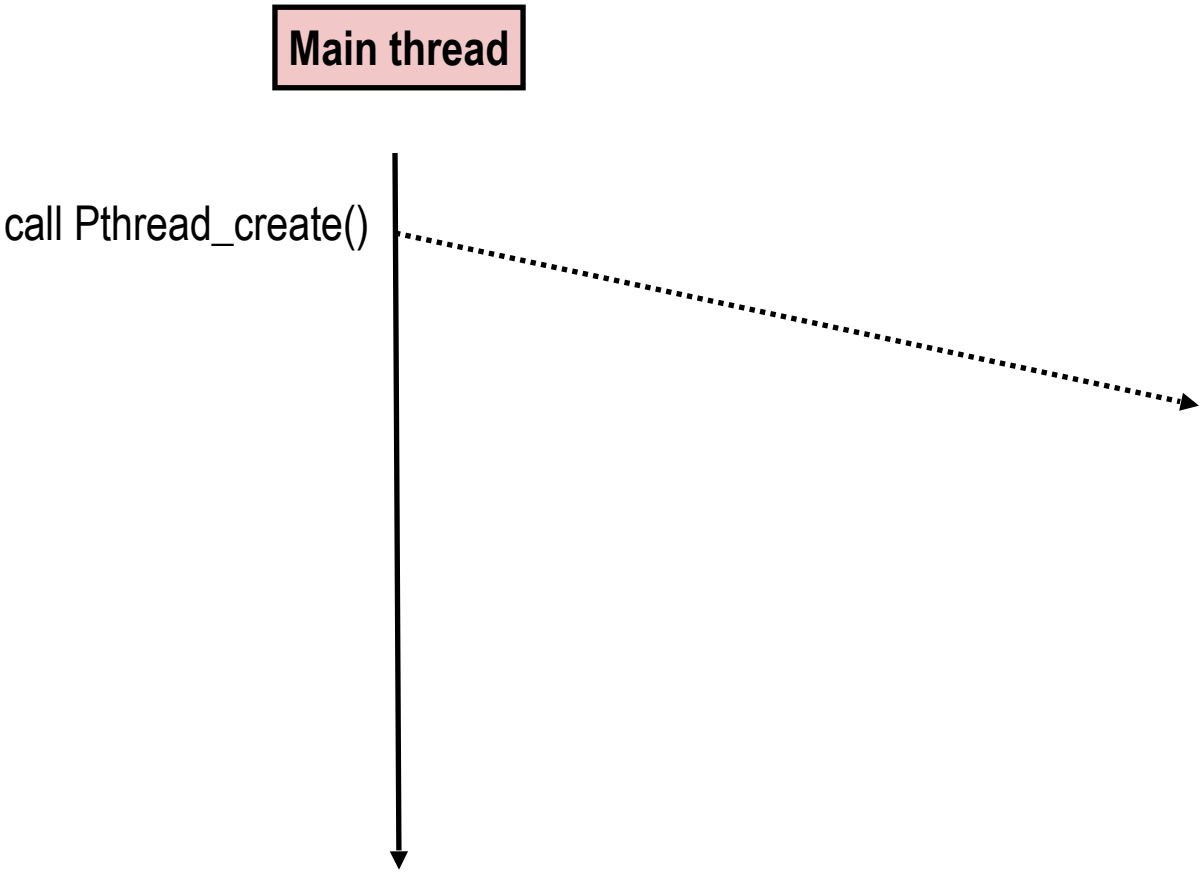

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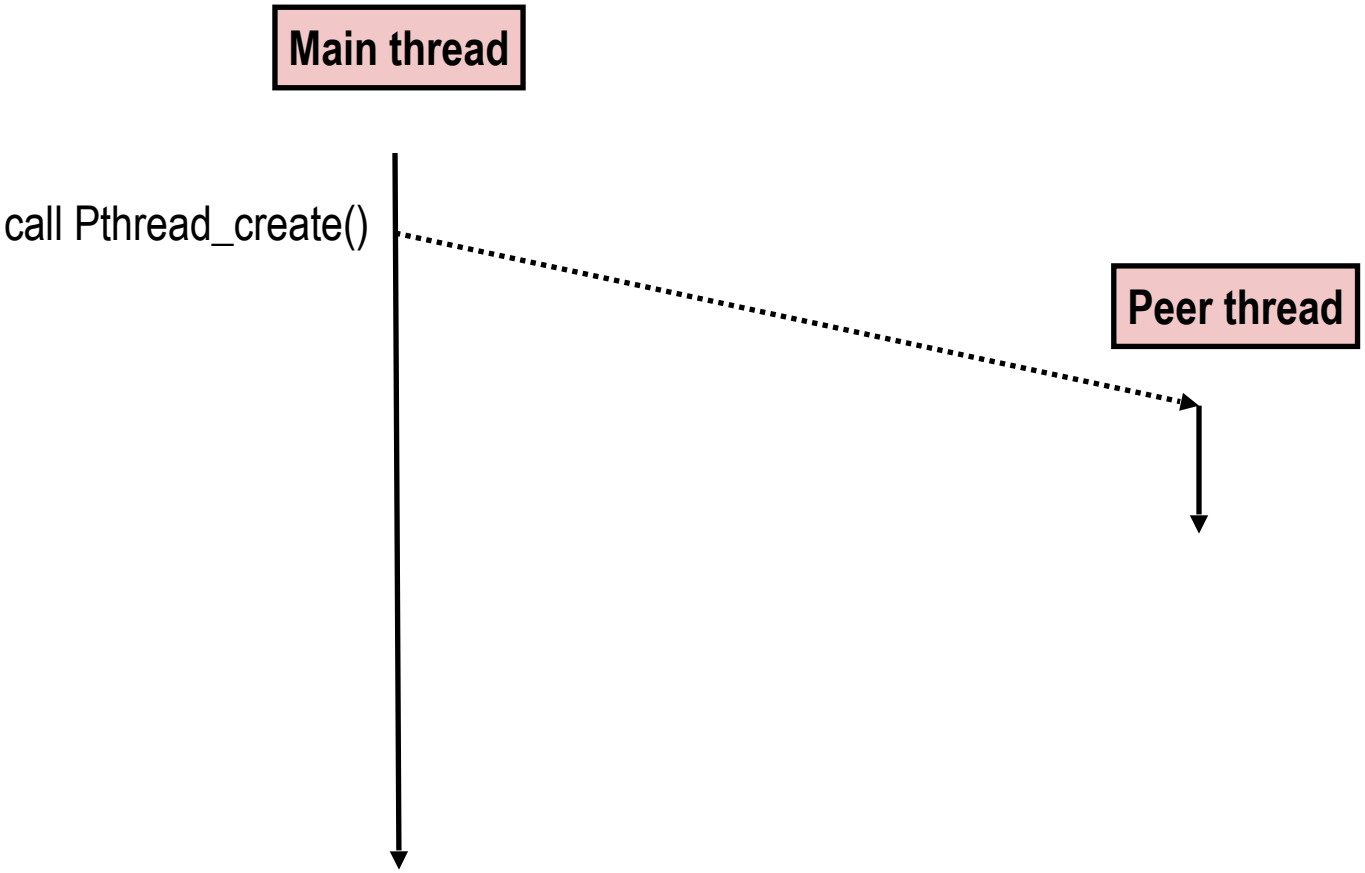

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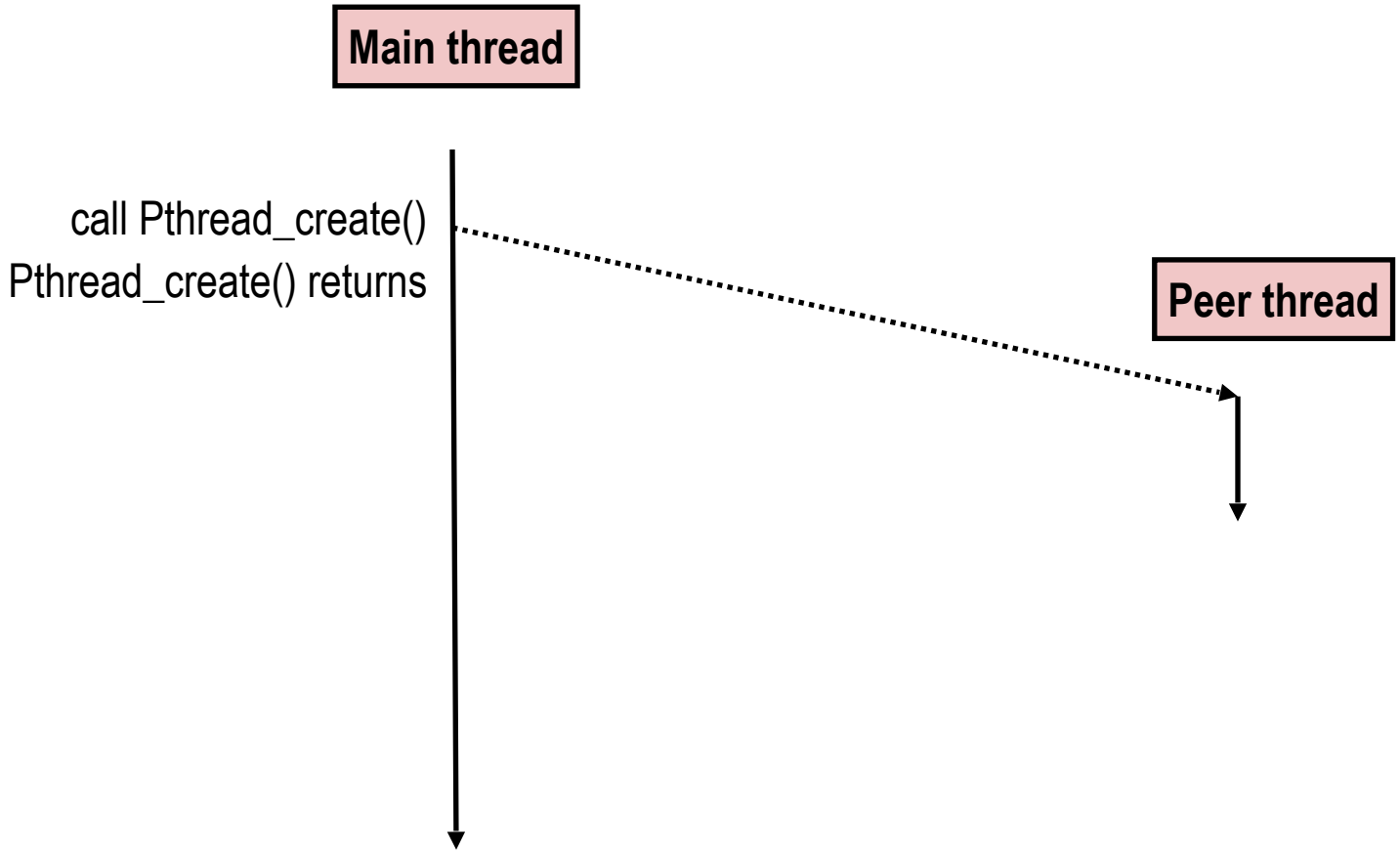

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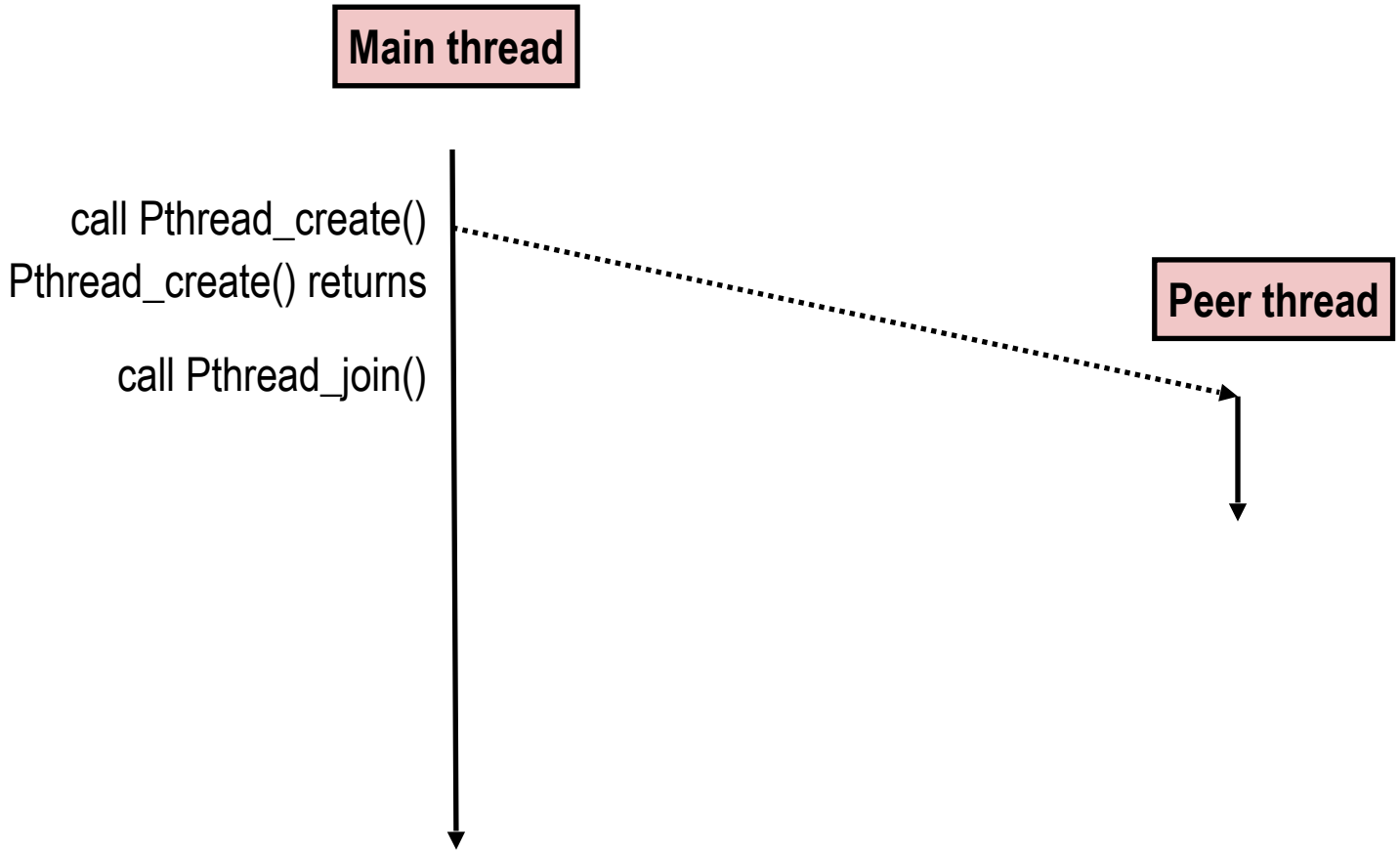

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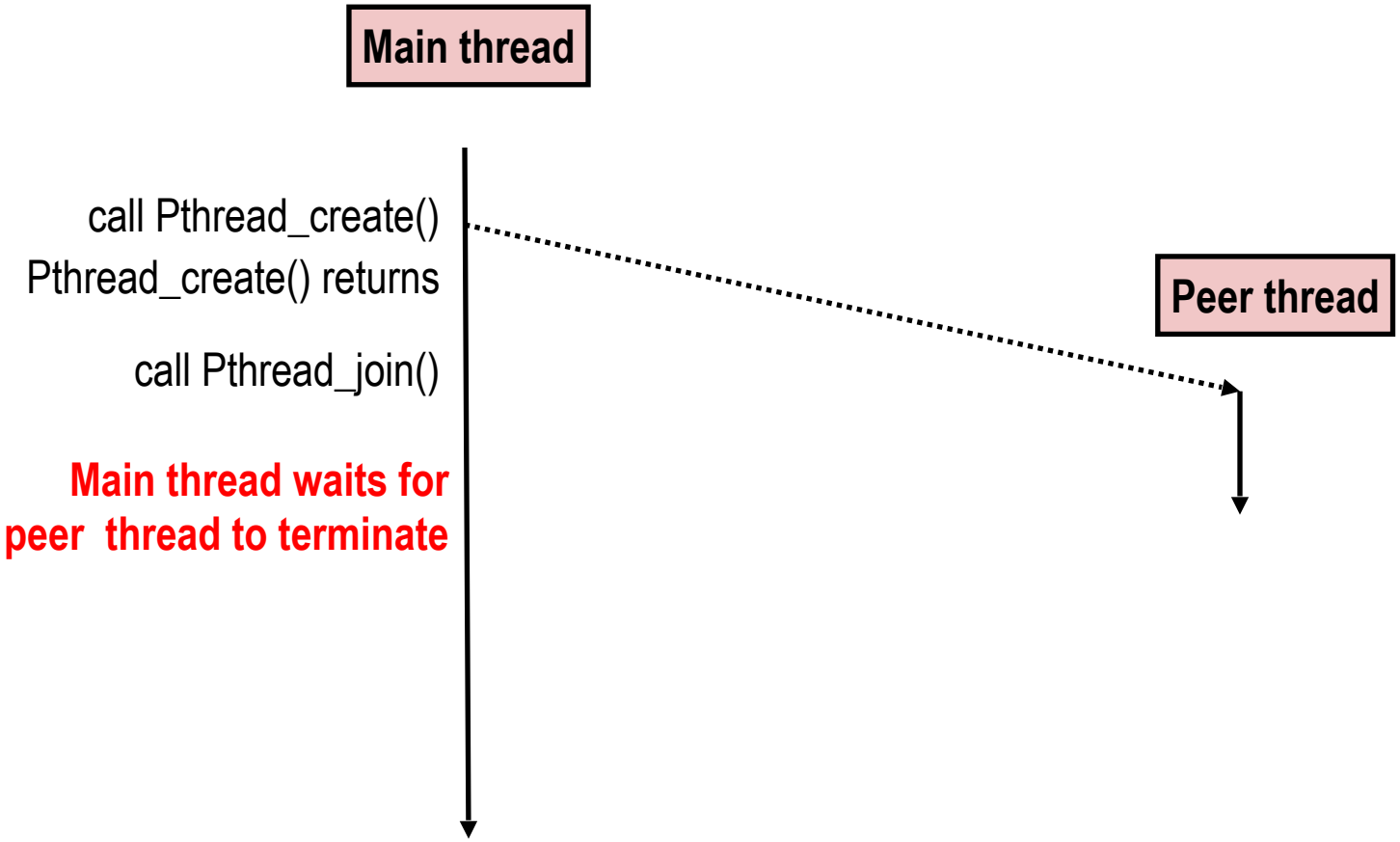

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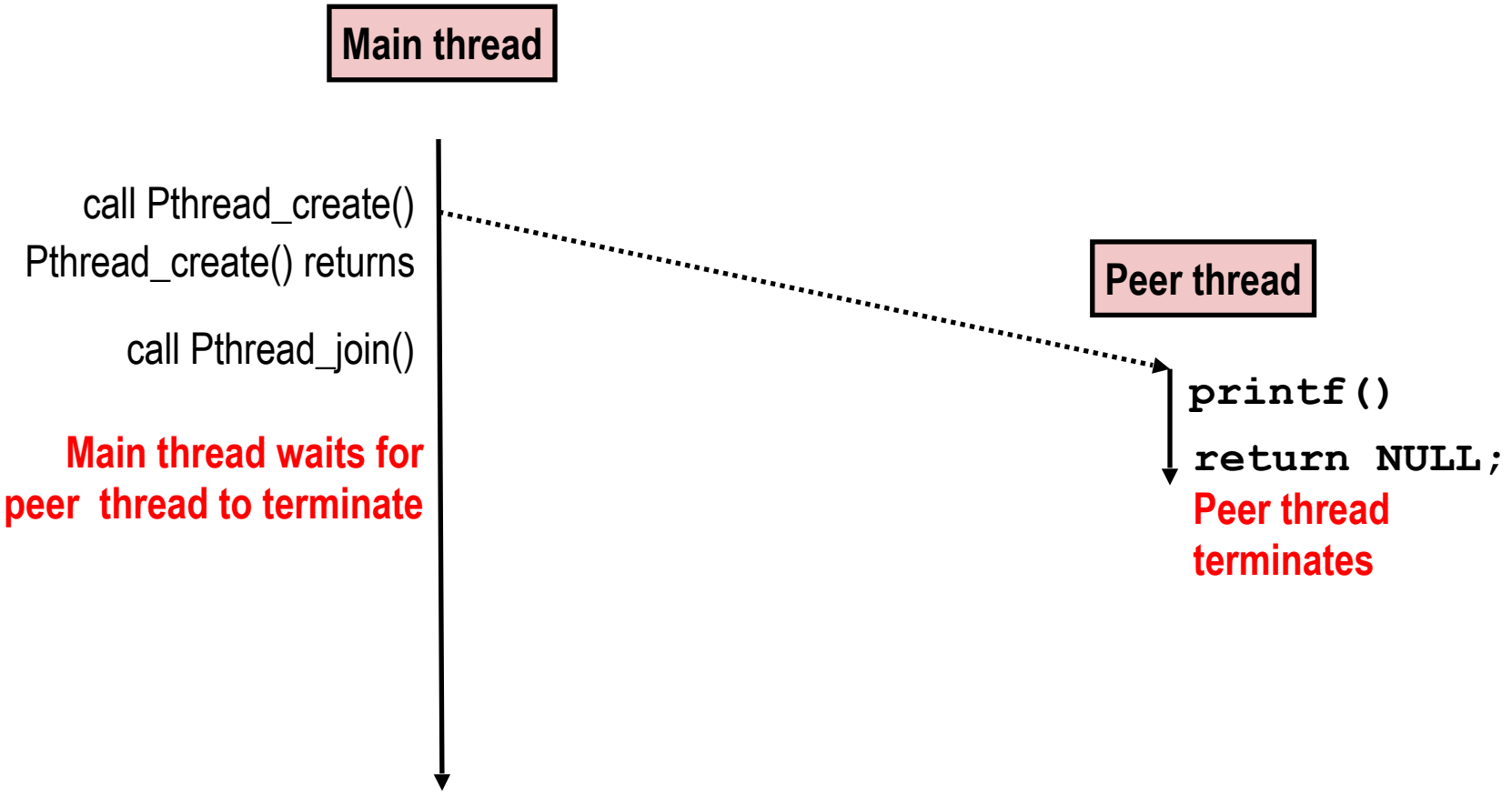

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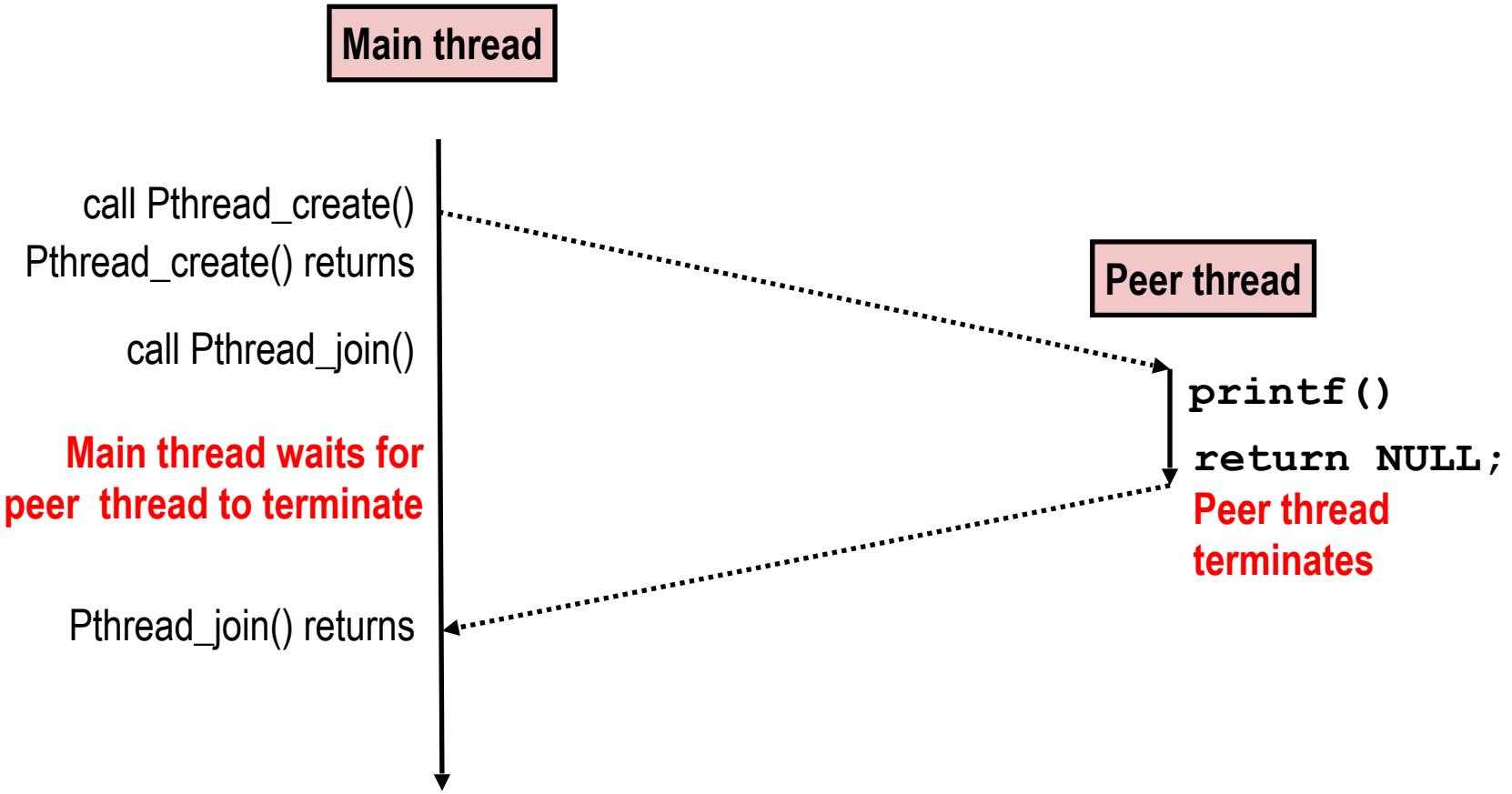

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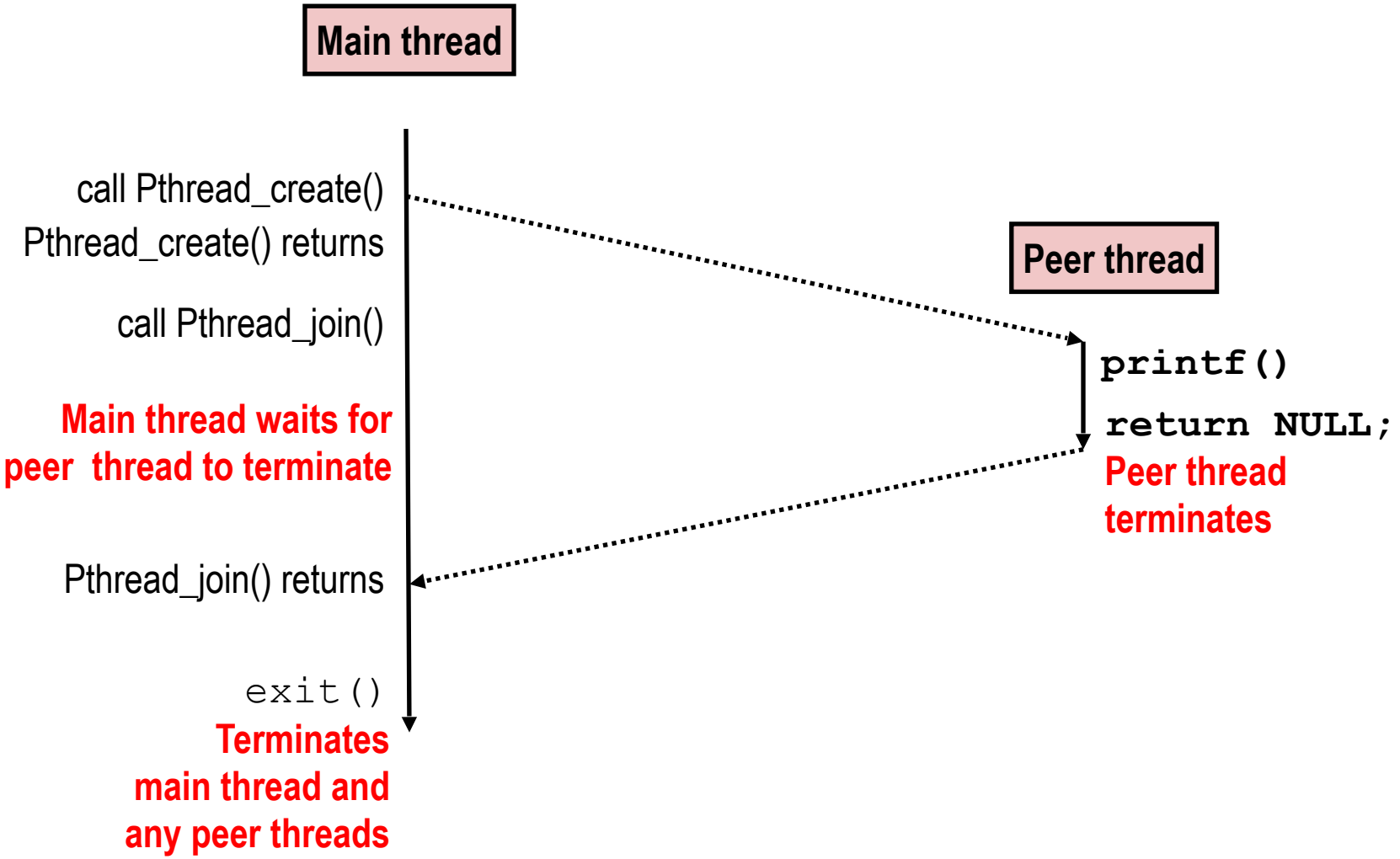

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- Multi-threading programming
- Hardware support of threads
  - Single core
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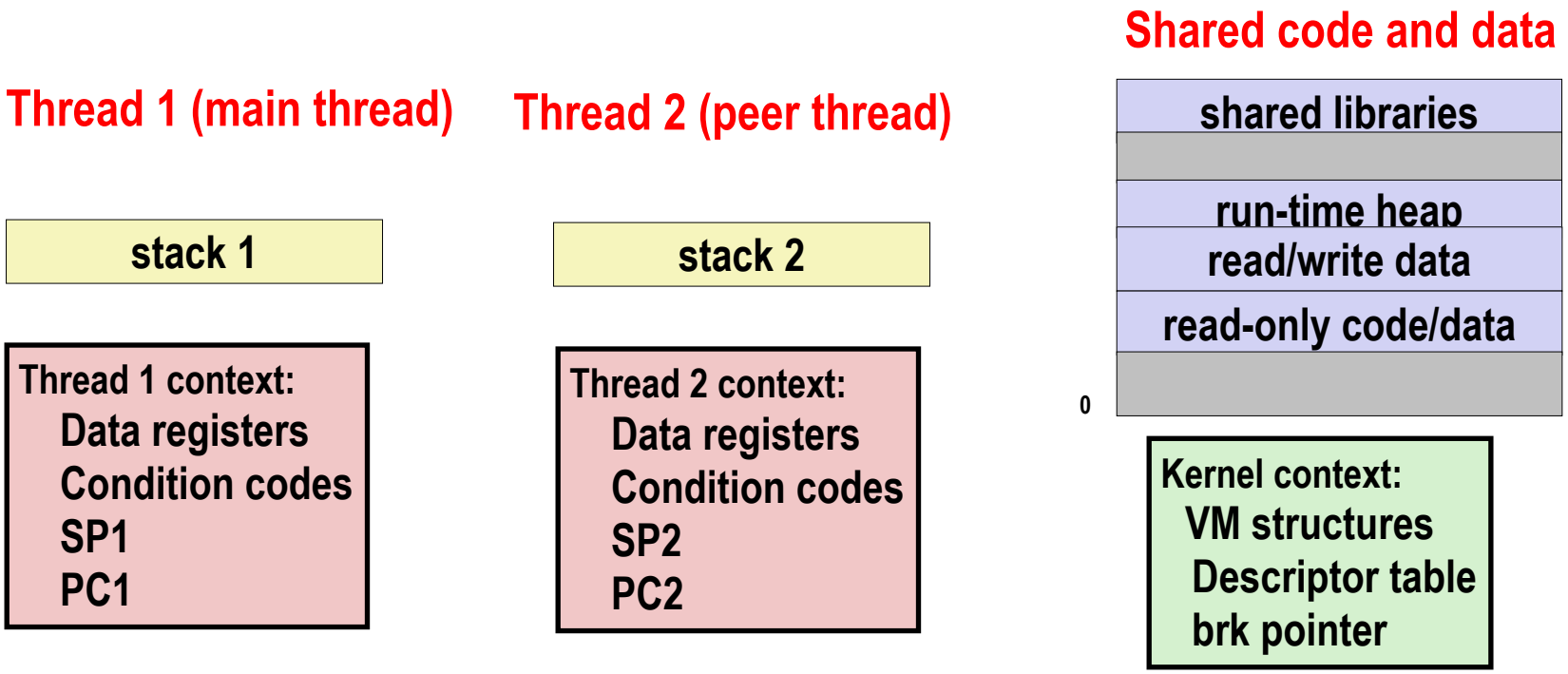
Shared Variables in Threaded C Programs

- One great thing about threads is that they can share same program variables.
- Question: Which variables in a threaded C program are shared?
- Intuitively, the answer is as simple as "*global variables are shared*" and "*stack variables are private*". Not so simple in reality.



Example Program to Illustrate Sharing

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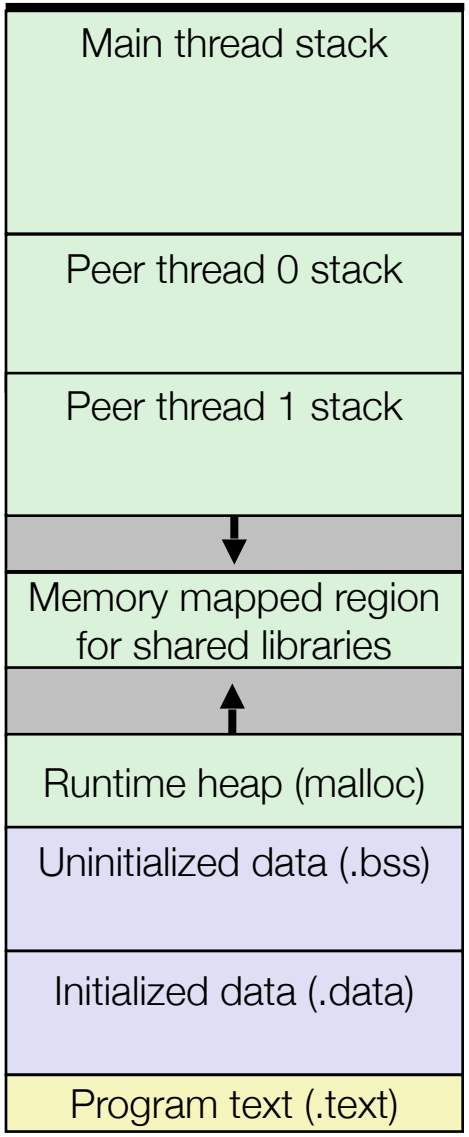
sharing.c



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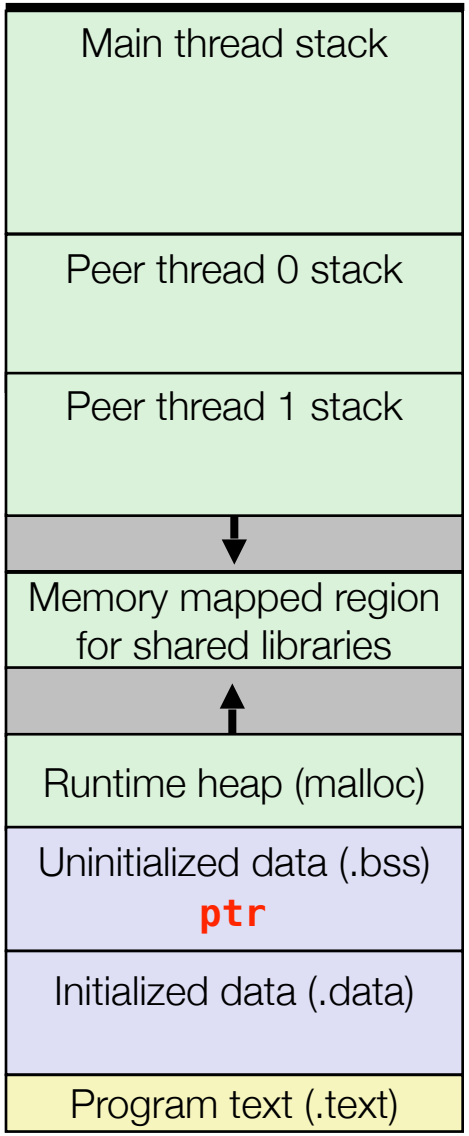

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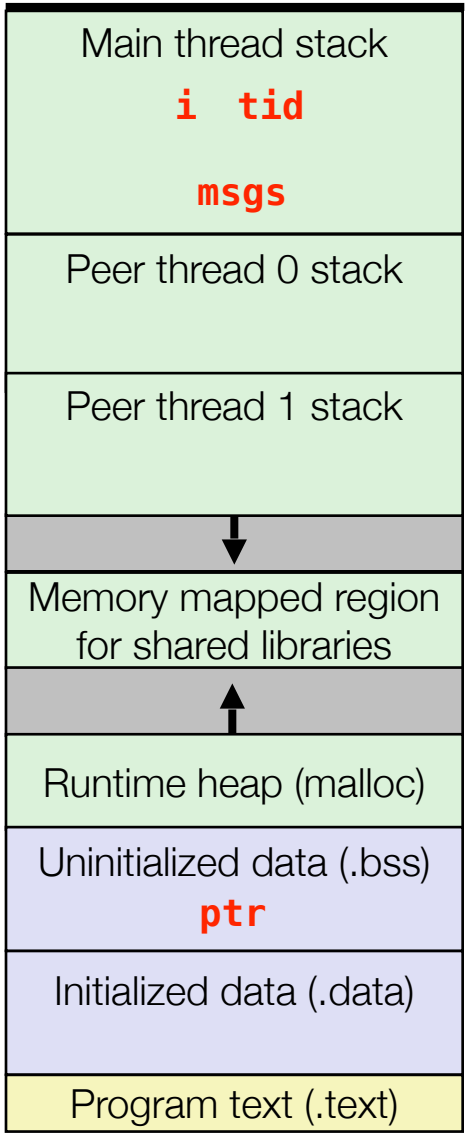

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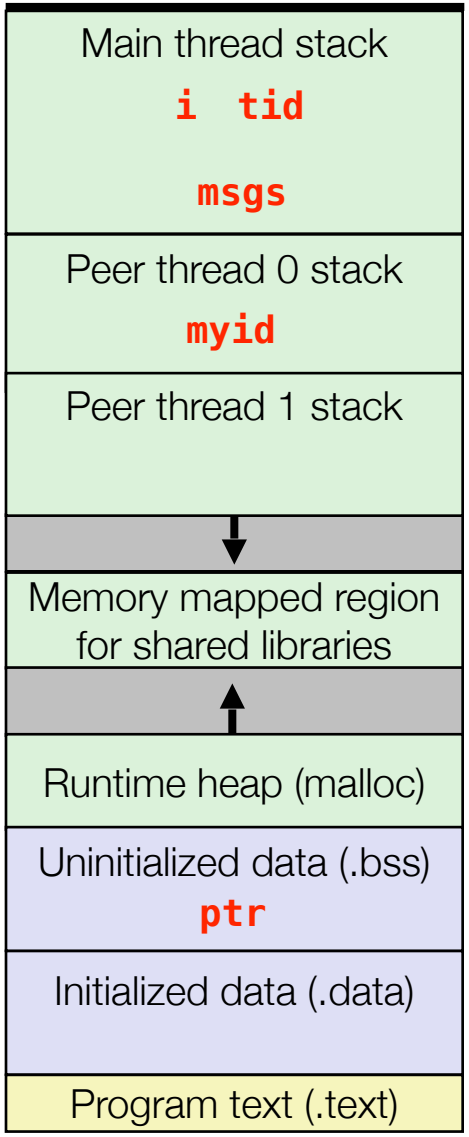

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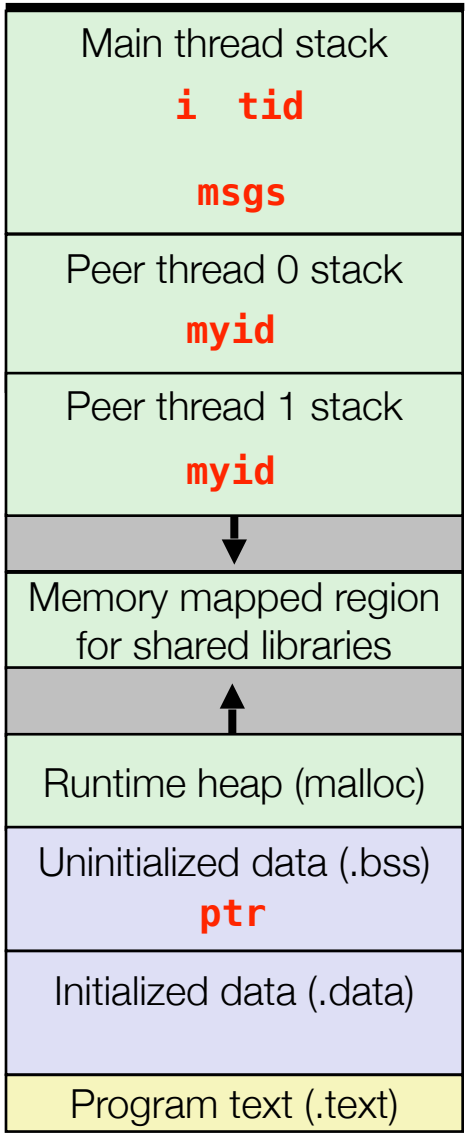

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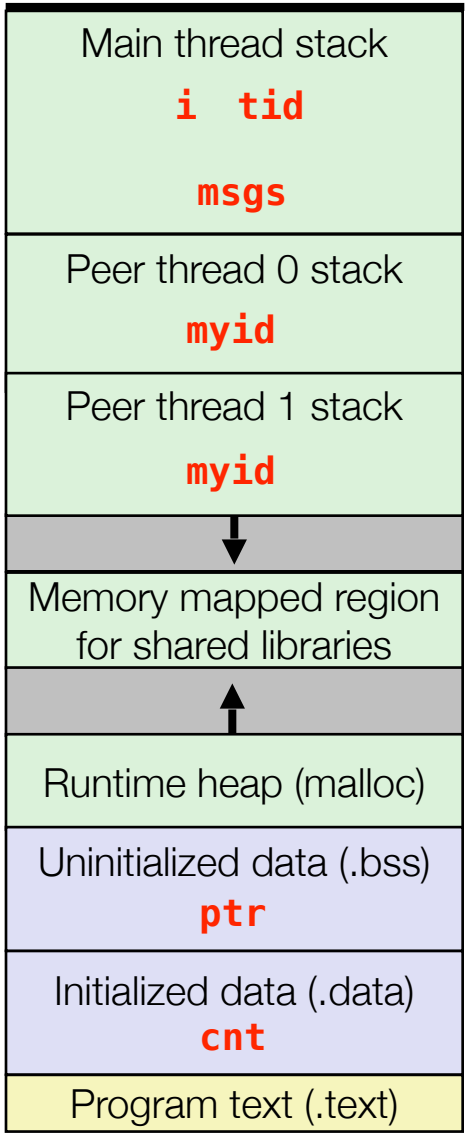

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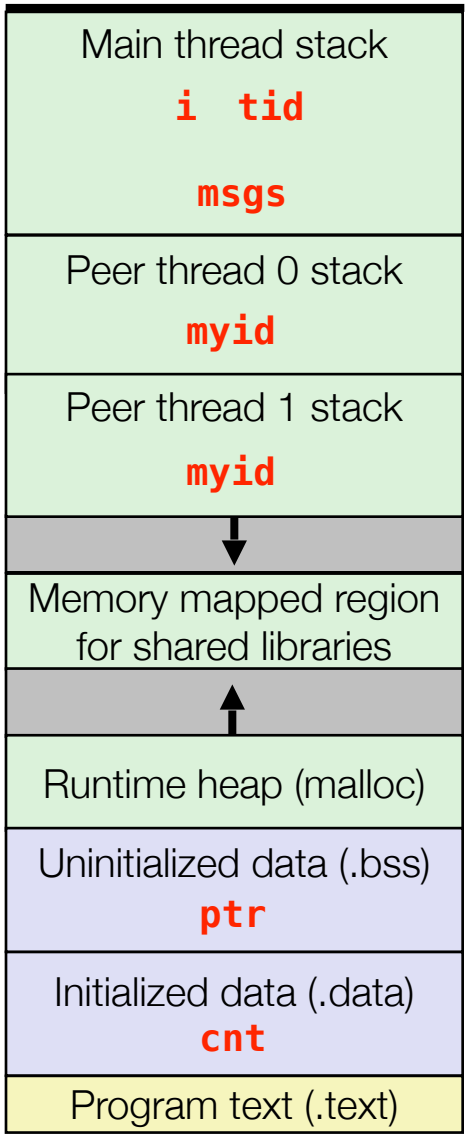

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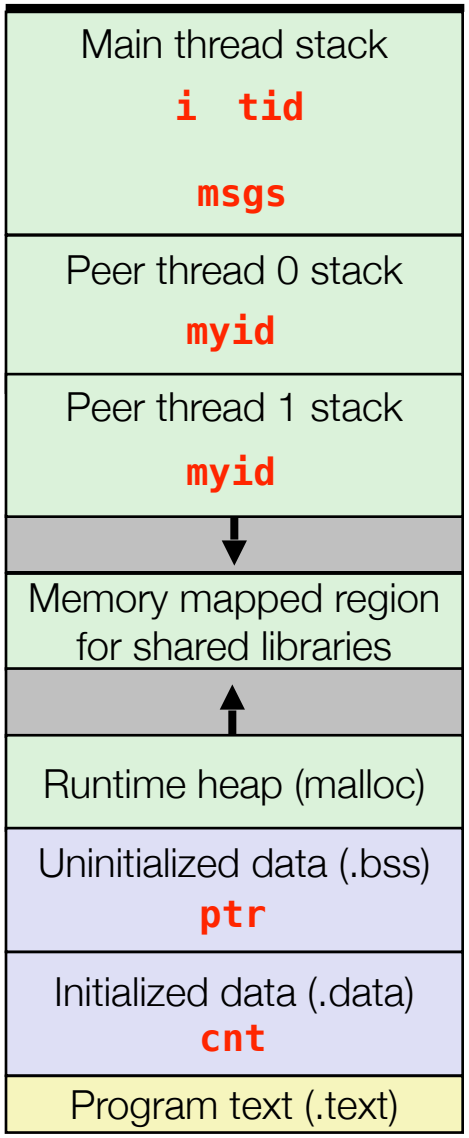

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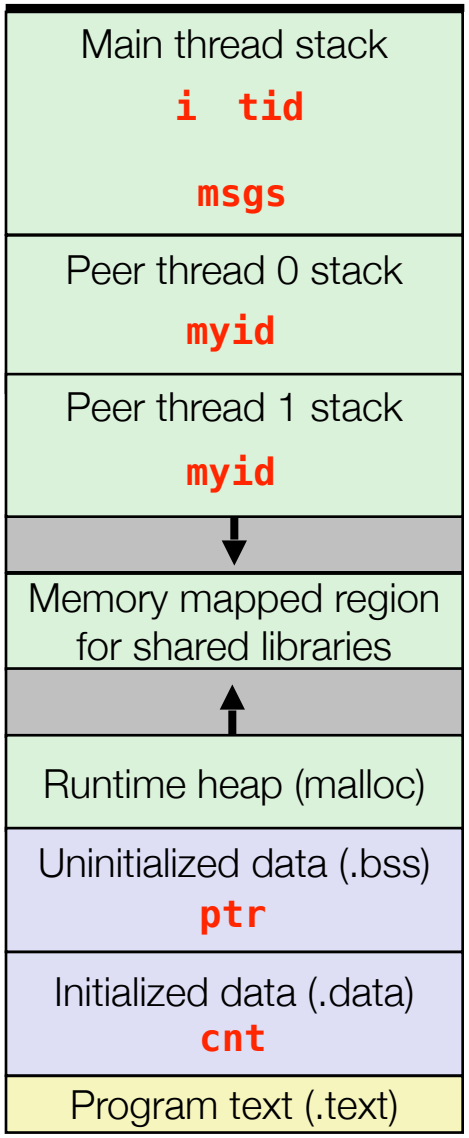

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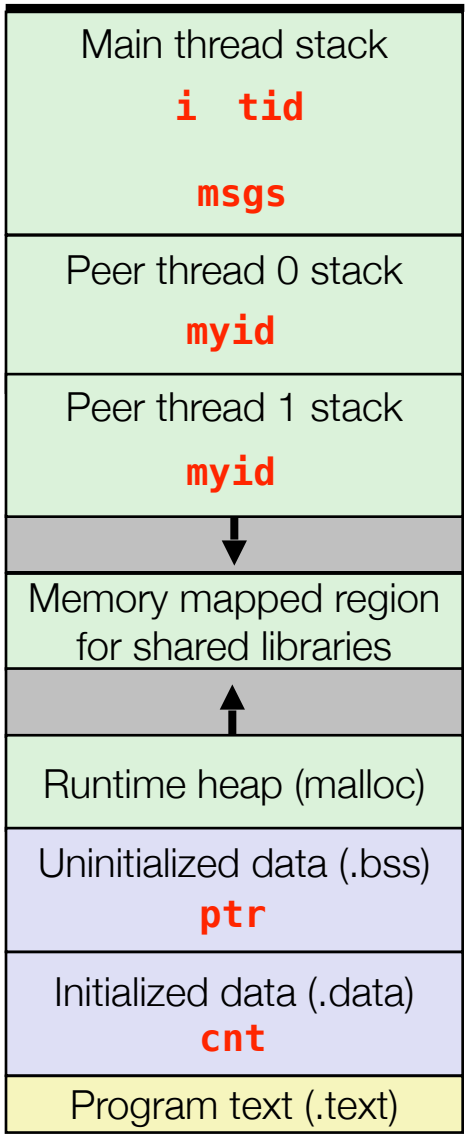
    printf("[%ld]:  %s (cnt=%d)\n",
        myid, ptr[myid], ++cnt);
    return NULL;
}

int main()
{
    long i;
    pthread_t tid;
    char *msgs[2] = {
        "Hello from foo",
        "Hello from bar"
    };
    ptr = msgs;
    for (i = 0; i < 2; i++)
        pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    pthread_exit(NULL);
}
```

sharing.c



main

p0 p1 main

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Example Program to Illustrate Sharing

```c
char **ptr;  /* global var */

void *thread(void *vargp)
{
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    printf("[%ld]:  %s (cnt=%d)\n",
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    return NULL;
}

int main()
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    };
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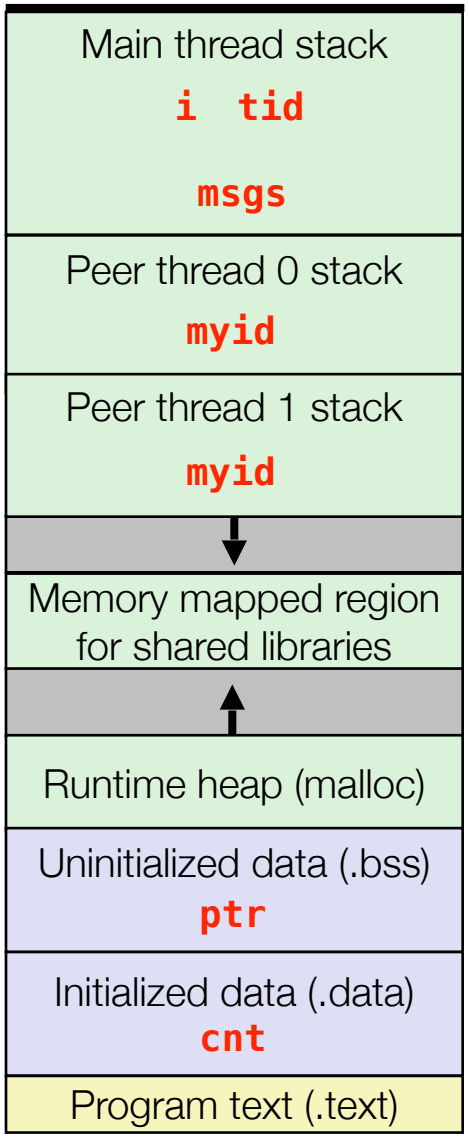
sharing.c



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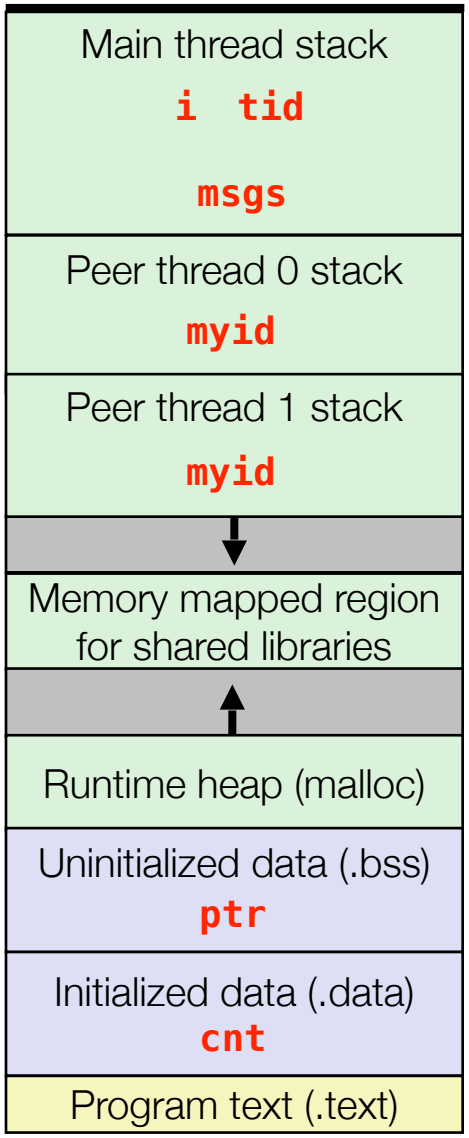

main

p0 p1 main

p0

p1

p0 p1 main

p0 p1

Synchronizing Threads

- Shared variables are handy...

- …but introduce the possibility of nasty *synchronization* errors.

Improper Synchronization

```c
/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
   pthread_t tid1, tid2;
   long niters = 10000;

   Pthread_create(&tid1, NULL,
        thread, &niters);
    Pthread_create(&tid2, NULL,
        thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * 10000))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

badcnt.c

```c
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
                *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}
```

https://www.geeksforgeeks.org/understanding-volatile-qualifier-in-c/

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badcnt.c

```c
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
                *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}
```

```
linux> ./badcnt
OK cnt=20000

linux> ./badcnt
BOOM! cnt=13051
```

`cnt` should be 20,000.

What went wrong?

https://www.geeksforgeeks.org/understanding-volatile-qualifier-in-c/

Assembly Code for Counter Loop

C code for counter loop in thread i

```
for (i = 0; i < niters; i++)
    cnt++;
```

Asm code for thread i

```
    movq   (%rdi), %rcx
    testq  %rcx,%rcx
    jle    .L2
    movl   $0, %eax
-------------------------------------
.L3:
    movq   cnt(%rip),%rdx
    addq   $1, %rdx
    movq   %rdx, cnt(%rip)
-------------------------------------
    addq   $1, %rax
    cmpq   %rcx, %rax
    jne    .L3
.L2:
```

H_i : Head

L_i : Load `cnt`

U_i : Update `cnt`

S_i : Store `cnt`

T_i : Tail

Concurrent Execution

- Key observation: In general, any sequentially consistent interleaving is possible, but some give an unexpected result!

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt (shared)
1	L_1	0	-	0
1	U_1	1	-	0
1	S_1	1	-	1
2	L_2	-	1	1
2	U_2	-	2	1
2	S_2	-	2	2

Thread 1 critical section

Thread 2 critical section

L_i	`movq cnt(%rip),%rdx`
U_i	`addq $1, %rdx`
S_i	`movq %rdx, cnt(%rip)`

Concurrent Execution (cont)

- A legal (feasible) but undesired ordering: two threads increment the counter, but the result is 1 instead of 2

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt (shared)
1	L_1	0	-	0
1	U_1	1	-	0
2	L_2	-	0	0
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.L2:
```

H_i : Head

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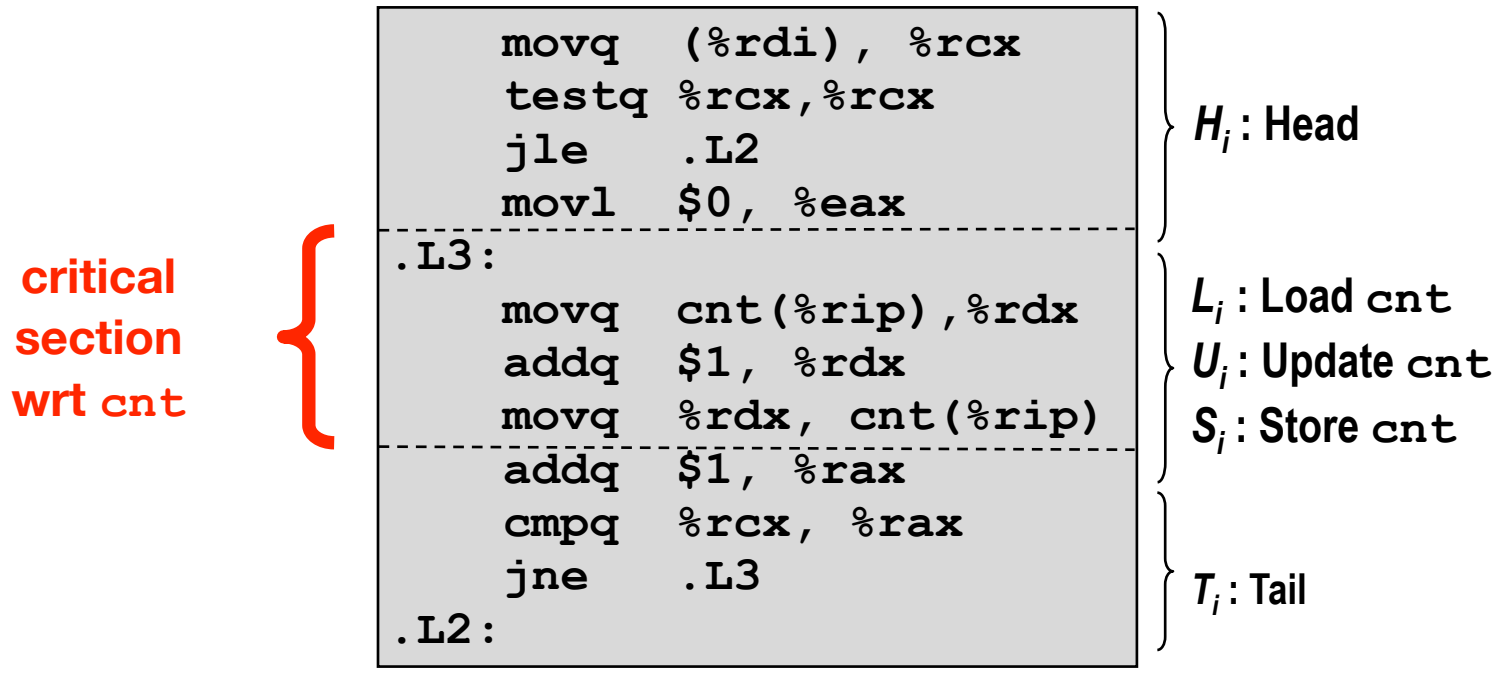
critical section wrt `cnt`

Critical Section

- Code section (a sequence of instructions) where no more than one thread should be executing concurrently.
  - Critical section refers to code, but its intention is to protect data!



Critical Section

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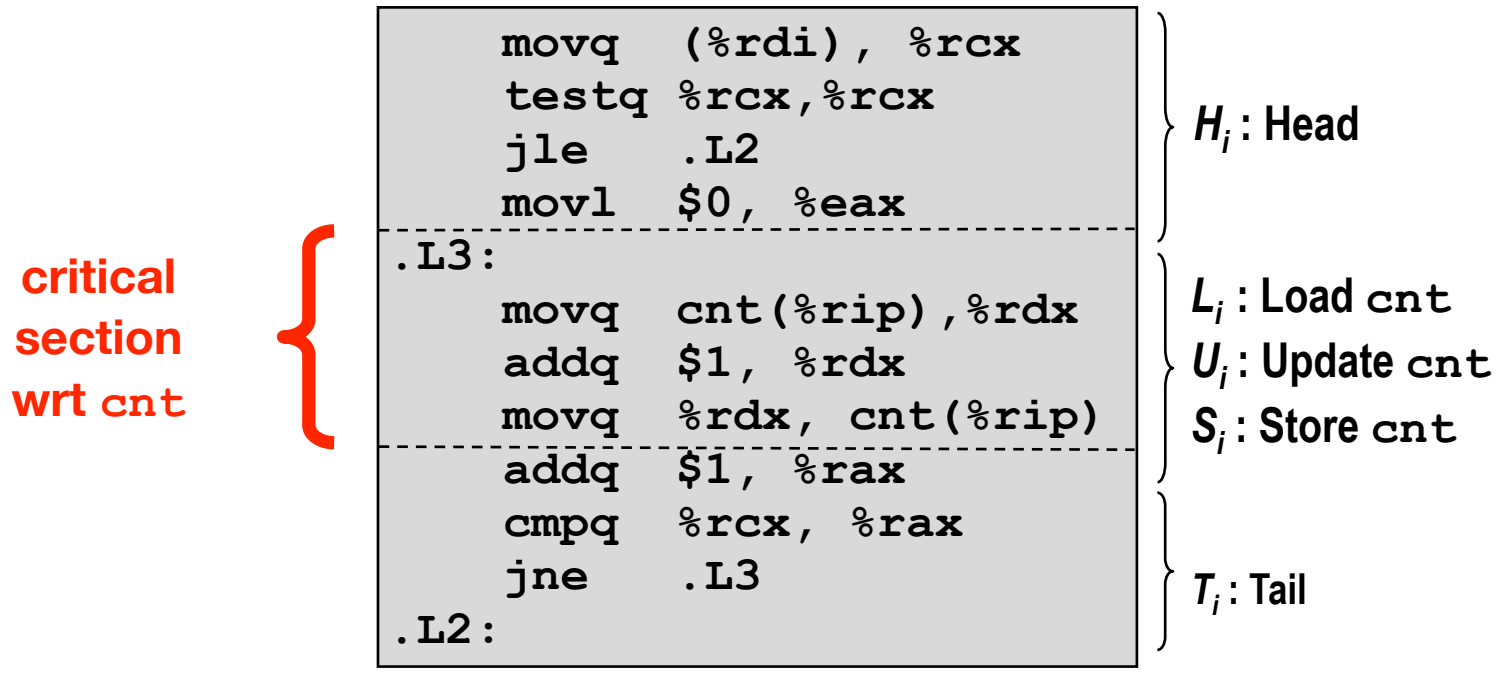
- Threads need to have ***mutually exclusive*** access to critical section. That is, the execution of the critical section must be ***atomic***: instructions in a CS either are executed entirely without interruption or not executed at all.



Enforcing Mutual Exclusion

- We must *coordinate*/*synchronize* the execution of the threads
  - i.e., need to guarantee ***mutually exclusive access*** for each critical section.

- Classic solution:
  - Semaphores/mutex (Edsger Dijkstra)

- Other approaches
  - Condition variables
  - Monitors (Java)
  - 254/258 discusses these

Using Semaphores for Mutual Exclusion

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- Terminology
  - **Binary semaphore** is also called **mutex** (i.e., the semaphore value could only be 0 or 1)
  - Think of P operation as "**locking**", and V as "**unlocking**".

Proper Synchronization

- Define and initialize a mutex for the shared variable `cnt`:

```
volatile long cnt = 0;  /* Counter */
sem_t mutex;            /* Semaphore that protects cnt */

Sem_init(&mutex, 0, 1); /* mutex = 1 */
```

- Surround critical section with P and V:

```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
 }
```

goodcnt.c

```
linux> ./goodcnt 10000
OK cnt=20000
linux> ./goodcnt 10000
OK cnt=20000
linux>
```

Warning: It's orders of magnitude slower than `badcnt.c`.

Problem?

- Wouldn't there be a problem when multiple threads access the mutex? How do we ensure exclusive accesses to mutex itself?

```
for (i = 0; i < niters; i++) {
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  - Checking mutex value and setting its value must be an atomic unit: they either are performed entirely or not performed at all.
  - on x86: the atomic test-and-set instruction.

```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
 }
```

goodcnt.c

Deadlock

- Def: A process/thread is *deadlocked* if and only if it is waiting for a condition that will never be true
- General to concurrent/parallel programming (threads, processes)
- Typical Scenario
  - Processes 1 and 2 needs two resources (A and B) to proceed
  - Process 1 acquires A, waits for B
  - Process 2 acquires B, waits for A
  - Both will wait forever!

Deadlocking With Semaphores

```c
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[id]); P(&mutex[1-id]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}

int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_1)$;
$P(s_1)$;	$P(s_0)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

Avoiding Deadlock

Acquire shared resources in same order

```
Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);
```

```
Tid[1]:
P(s1);
P(s0);
cnt++;
V(s1);
V(s0);
```

```
Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);
```

```
Tid[1]:
P(s0);
P(s1);
cnt++;
V(s1);
V(s0);
```

Summary of Multi-threading Programming

- Concurrent/parallel threads access shared variables
- Need to protect concurrent accesses to guarantee correctness
- Semaphores (e.g., mutex) provide a simple solution
- Can lead to deadlock if not careful
- Take CSC 254/258 to know more about avoiding deadlocks (and parallel programming in general)

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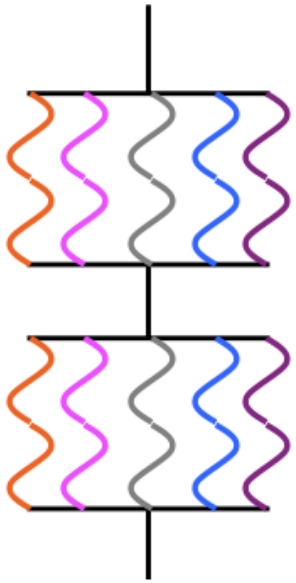
  - Sum all sub-sums in the end
- Question: if you parallel you work N ways, do you always an N times speedup?

Why the Sequential Bottleneck?



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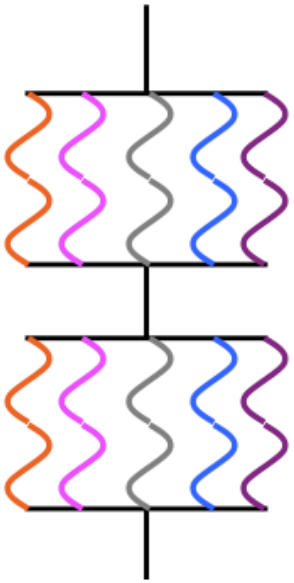

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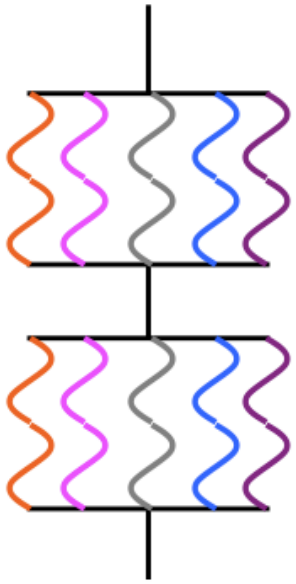

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```
Each thread:
    loop {
        Compute
        P(A)
            Update shared data
        V(A)
     }
```

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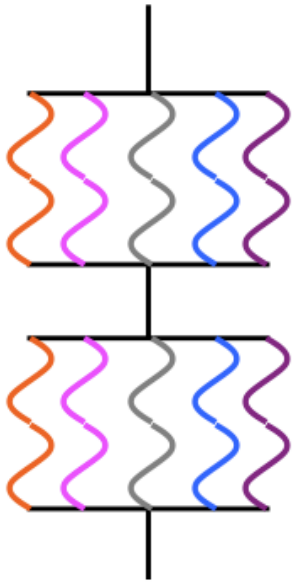

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Each thread:
    loop {
      Compute                    N
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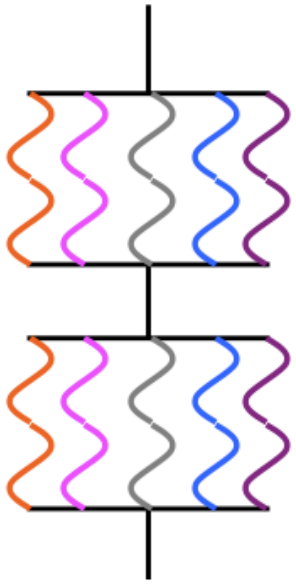

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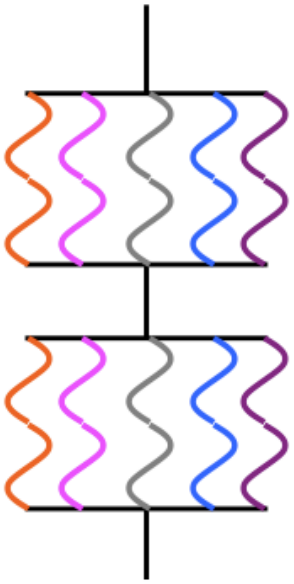

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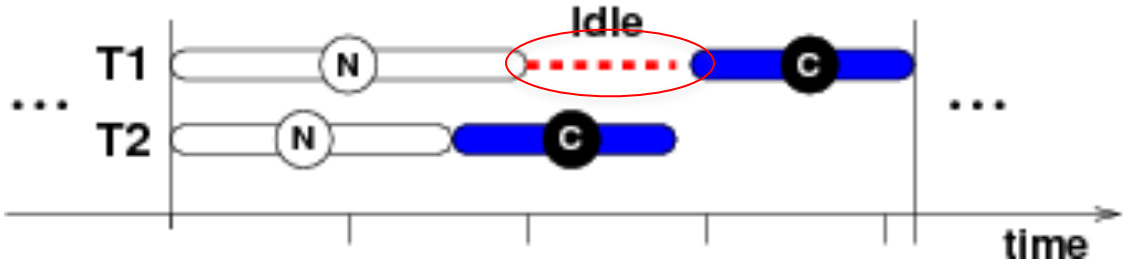

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- Gene Amdahl (1922 – 2015). Giant in computer architecture
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```
1 - f
```

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$$\frac{1}{1 - f + \frac{f}{N}}$$

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$$\text{Speedup} = \frac{1}{1 - f + \frac{f}{N}}$$

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- Completely parallelizable (f = 1): Speedup = N
- Completely sequential (f = 0): Speedup = 1
- Mostly parallelizable (f = 0.9, **N = 1000**): **Speedup = 9.9**

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Today

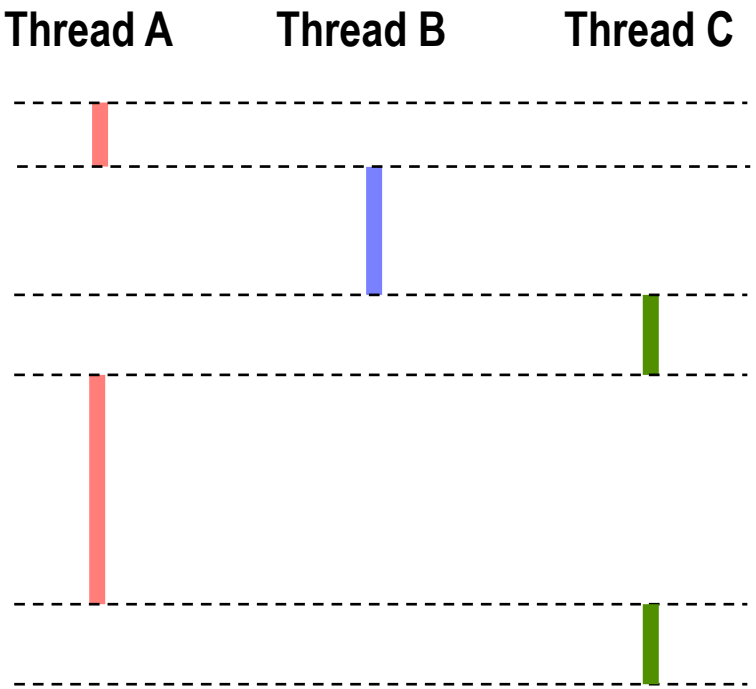
- From process to threads
  - Basic thread execution model
- Multi-threading programming
- Hardware support of threads
  - Single core
  - Multi-core
  - Cache coherence

Can A Single Core Support Multi-threading?

- Need to multiplex between different threads (time slicing)

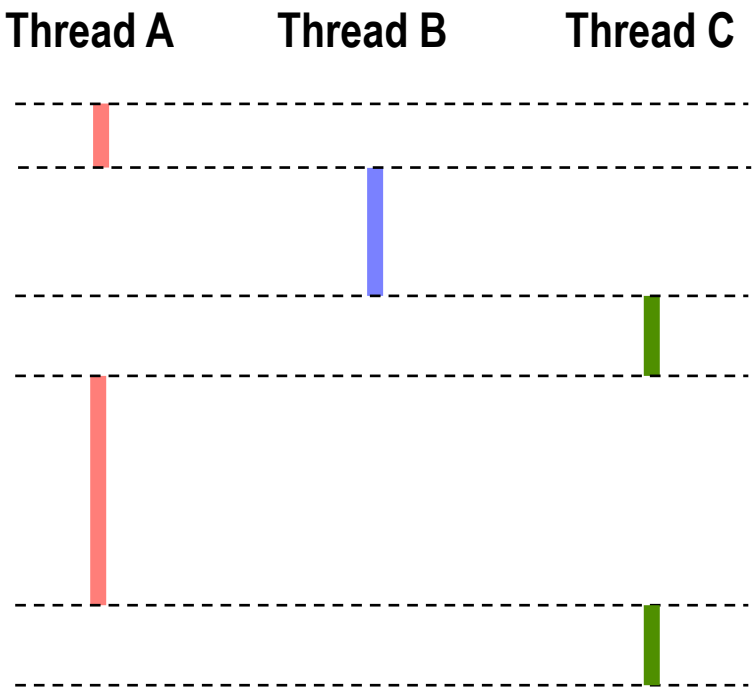
Sequential

Multi-threaded



Any benefits?

- Can single-core multi-threading provide any performance gains?



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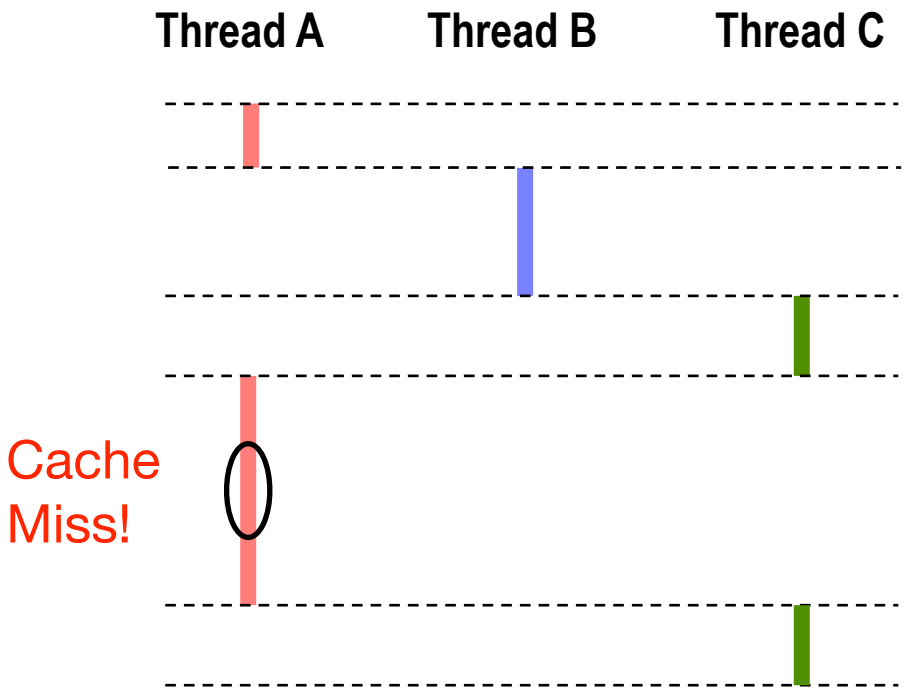

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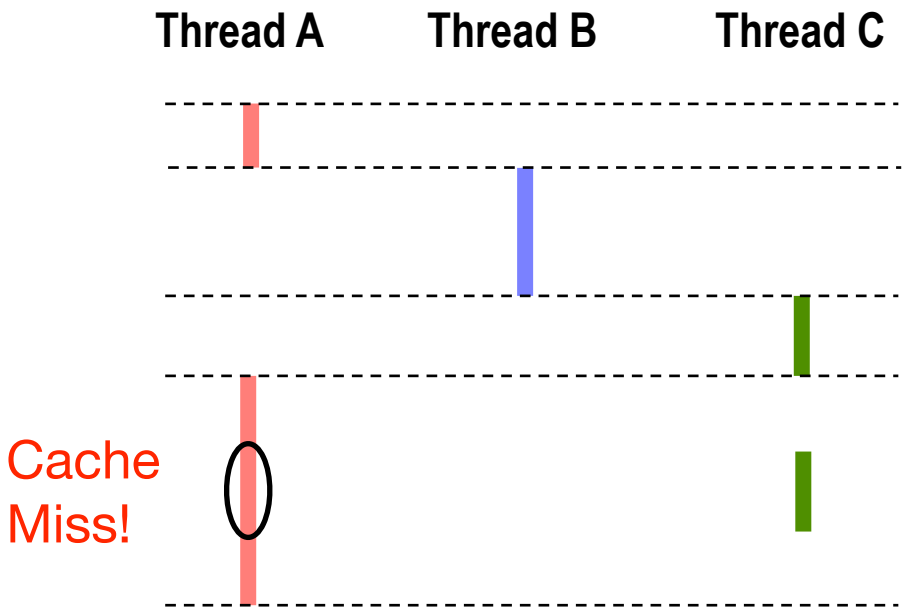
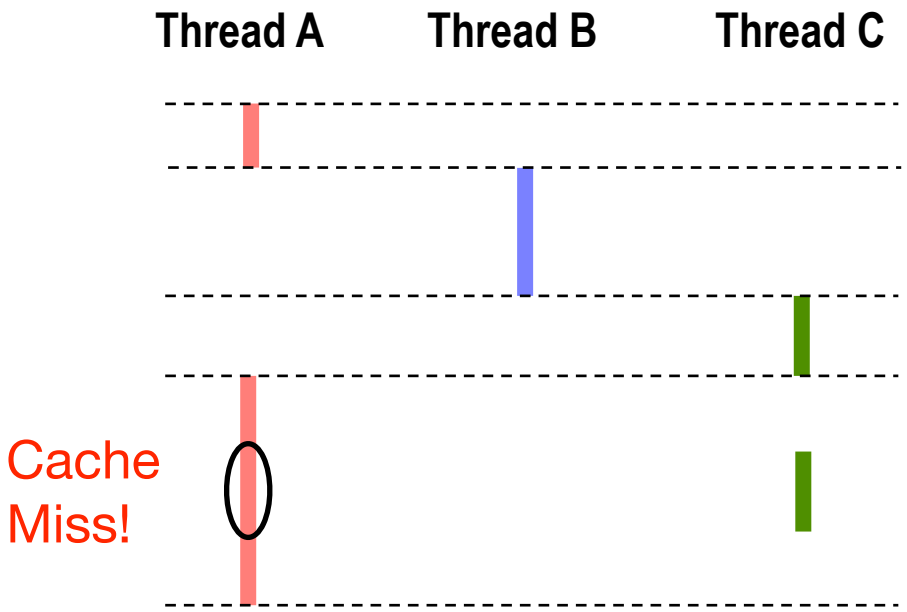


Any benefits?

- Can single-core multi-threading provide any performance gains?
- If Thread A has a cache miss and the pipeline gets stalled, switch to Thread C. Improves the overall performance.



When to Switch?

- Coarse grained
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  - Quantum based (every thousands of cycles)

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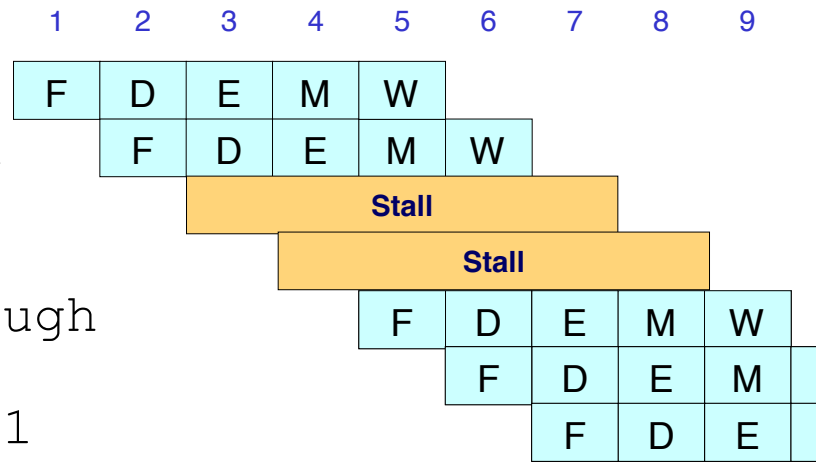
- Either way, need to save/restore thread context upon switching.

Fine-Grained Switching

- One big bonus of fine-grained switching: no need for branch predictor!!

The stalling approach

```
     xorg %rax, %rax
     jne L1                 # Not taken
     Stall
     Stall
     irmovq $1, %rax        # Fall Through
L1   irmovq $4, %rcx        # Target
     irmovq $3, %rax        # Target + 1
```



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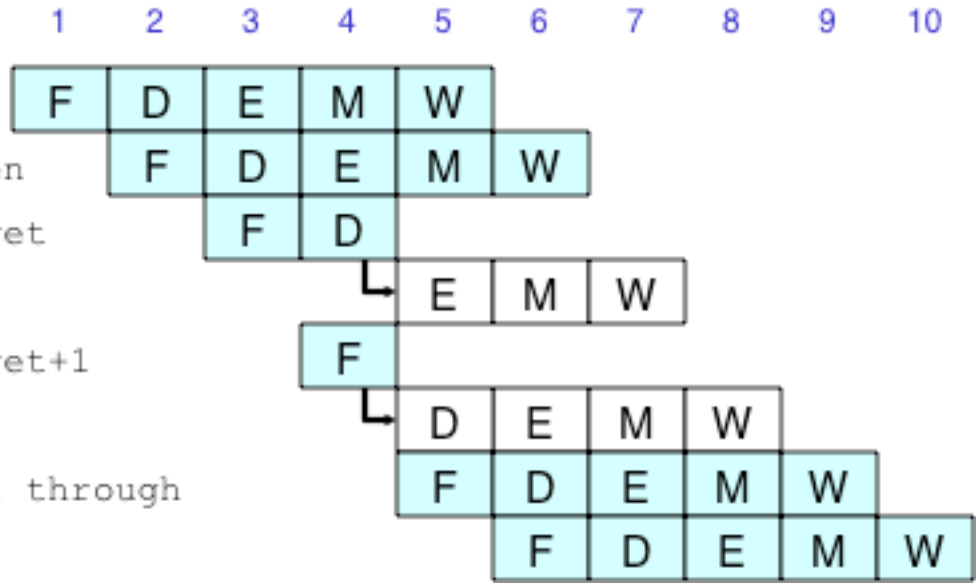
The branch prediction approach

```
# demo-j.ys
0x000: xorq %rax,%rax
0x002: jne target # Not taken
0x016: irmovq $2,%rdx # Target
       bubble
0x020: irmovq $3,%rbx # Target+1
       bubble
0x00b: irmovq $1,%rax # Fall through
0x015: halt
```



Fine-Grained Switching

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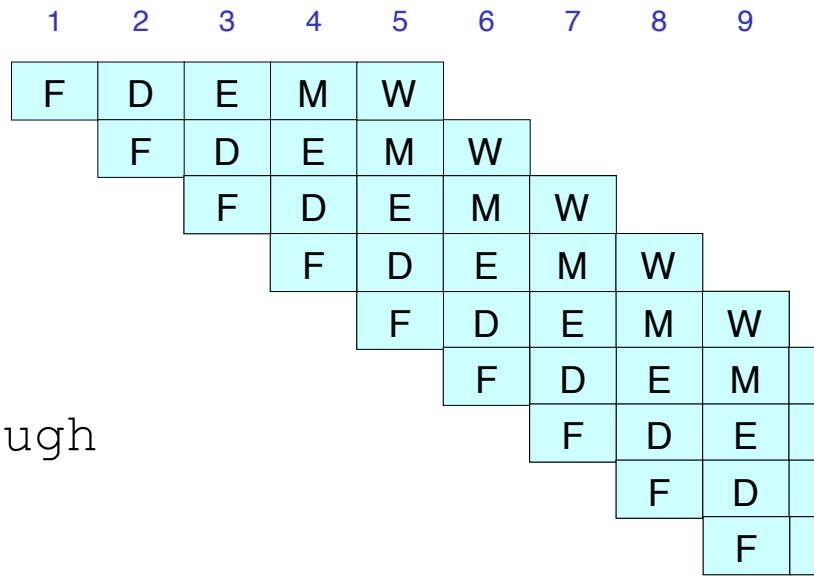
The fine-grained multi-threading approach

```
xorg %rax, %rax
Inst x from TID=1
Inst y from TID=2
jne L1                  # Not taken
Inst x+1 from TID=1
Inst y+1 from TID=2
irmovq $1, %rax         # Fall Through
Inst x+2 from TID=1
Inst y+2 from TID=2
… …
```



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  - Context switching overhead would be very high! Use separate hardware contexts for each thread (e.g., separate register files).

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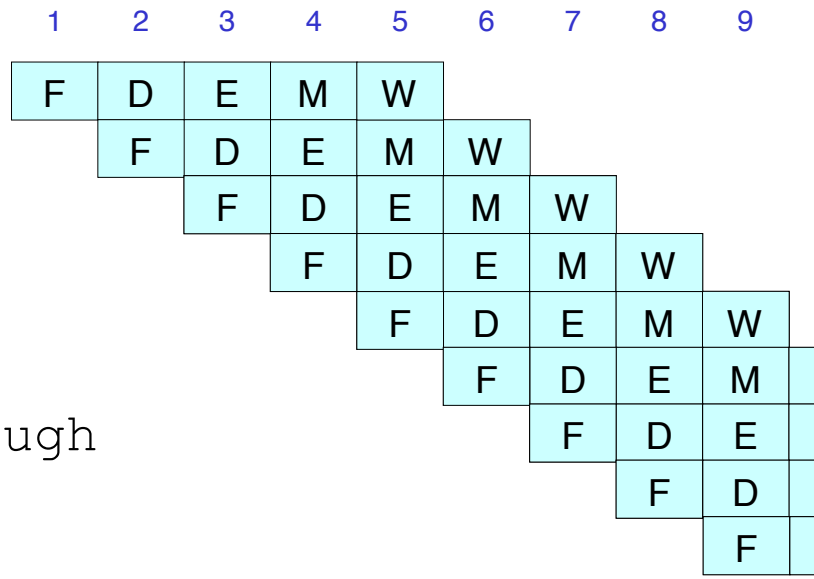

Fine-Grained Switching

- One big bonus of fine-grained switching: no need for branch predictor!!
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  - GPUs do this (among other things).

The fine-grained multi-threading approach

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