HPCSE - I

«Introduction to multithreading»

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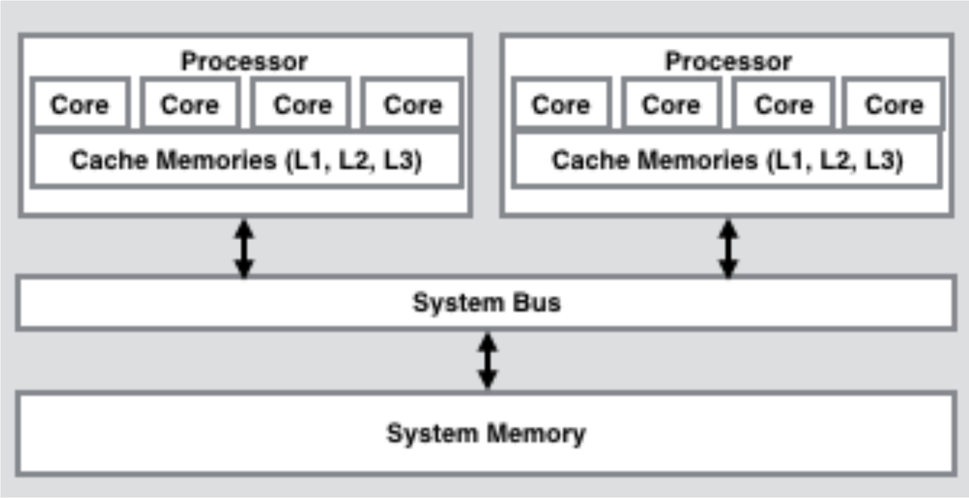
Outline

- Processes and Threads
- POSIX Threads API
  - Thread management
  - Synchronization with mutexes
- Deadlock and thread safety

Terminology

- Parallelism in Hardware:
  - multiple cores and memory
- Parallelism in Software:
  - **process**: execution sequence within the OS, a running program
  - **thread**: can execution sequence within a process, all threads of the same process share the application data (memory)



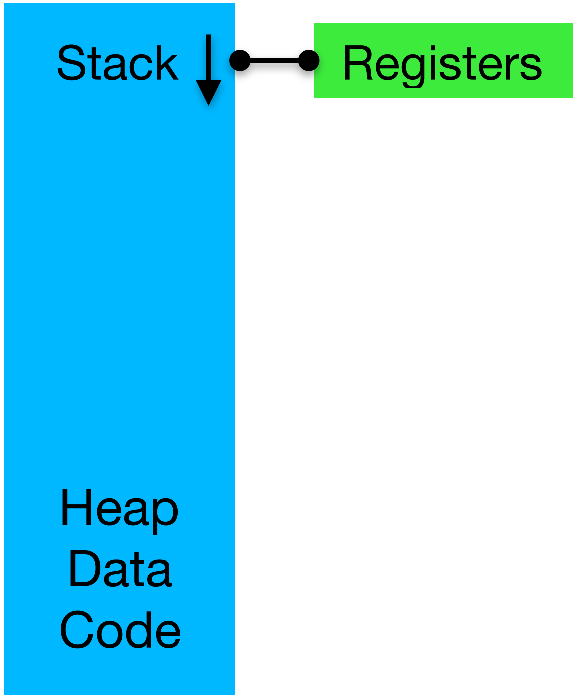

```c
int a[1000];

int main( int argc, char** argv )
{
  for(int i =   0; i <  500; i++ ) a[i] = 1;
  for(int i = 500; i < 1000; i++ ) a[i] = 2;

  return 0;
}
```

Processes

- A process consists of the following:
  - Address space: text segment (code), data segment, heap and stack
  - Information maintained by the operating system (process state, priority, resources, statistics)
- Process state: snapshot where the above information has specific values
  - Memory state: state of the address space
  - Processor state: register values



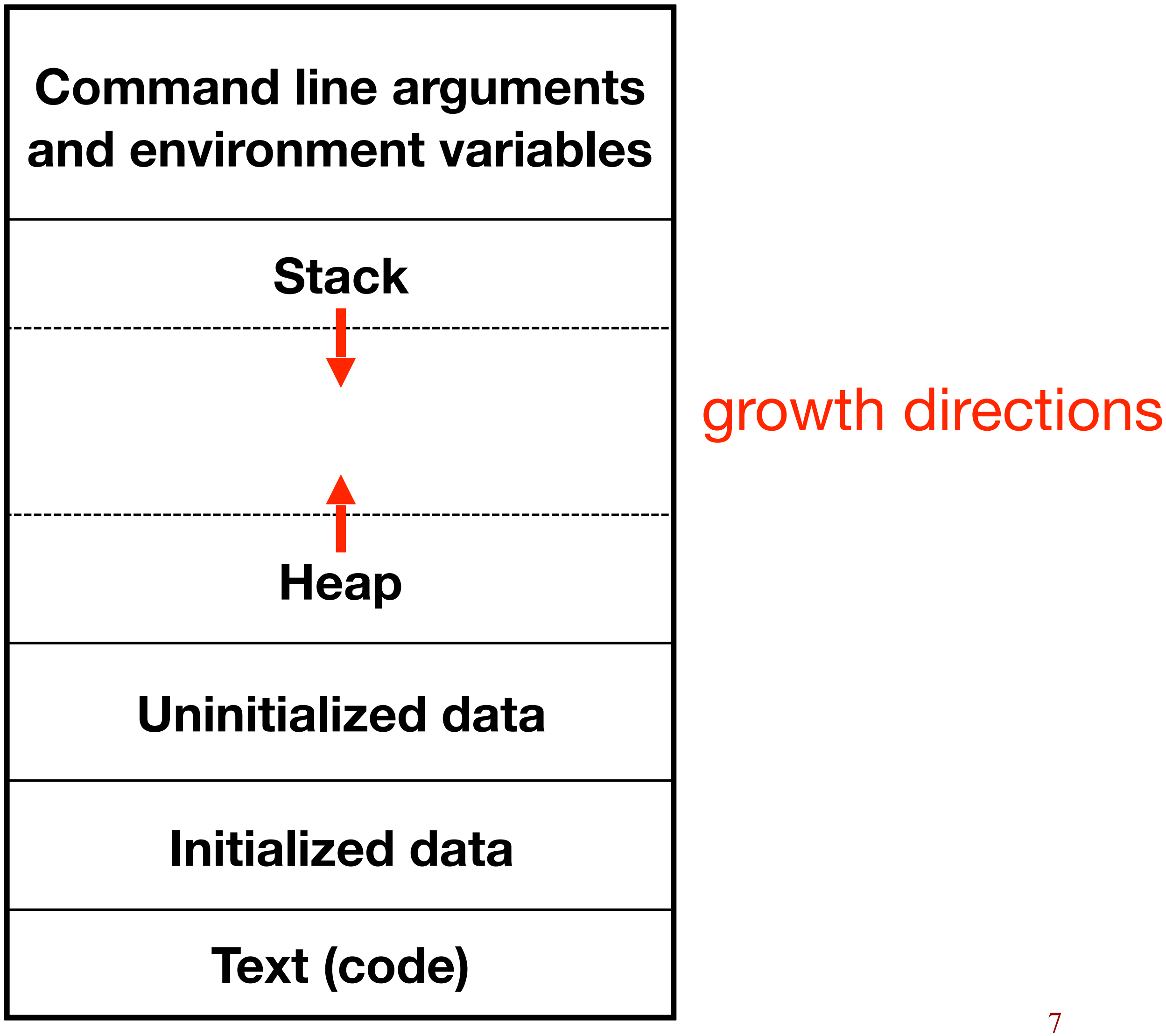
Process Switching

- Before execution, the processor state of a process must be loaded first to the specific processor
- During execution, the processor state of the process changes
- Context switching: a running process stops and another one starts (or resumes)
  - The processor state of the current process is stored
  - The processor state of the next process is loaded

Process Memory

- Each process has its own (private) memory space
  - A process cannot access the memory of another process
  - This provides basic safety in a multi-user environment
- Communication between processes is important
  - When the cooperate to solve a single problem
- Operating systems implement several mechanisms for interprocess communication
  - signals, files, pipes, sockets
  - shared memory

Process Memory Layout



Memory Organization (C/C++)

- Text segment
  - Instruction executed by the processor
  - Can be shared between multiple processes
  - Read-only segment
- Initialized data segment
  - Global variables with initial value:

```
double Pi = 3.1415;
static char message[] = "hello world!";
```

Memory Organization (C/C++)

- Uninitialized data segment
  - Global variables without initial value

```
int result;
double Matrix[512][512];
```

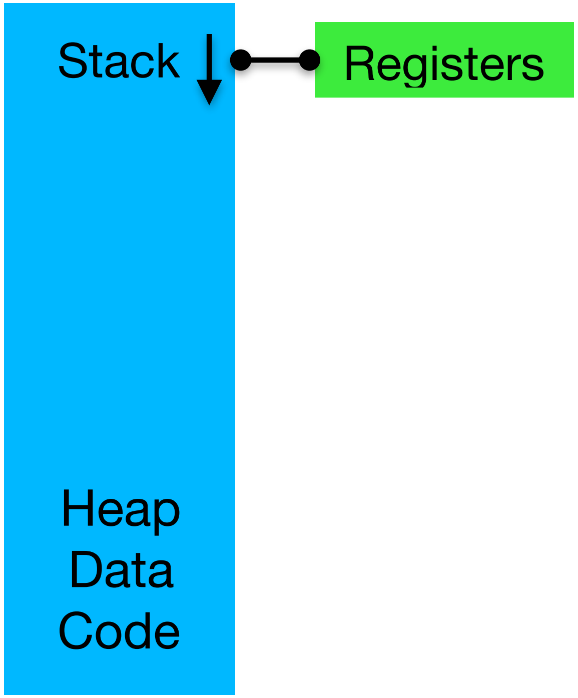
  - The operating system initializes these variables to zero before the execution of the program
- Stack
  - Local variables, function parameters
- Heap
  - Dynamic memory management (`malloc`, `new`, …)

Threads

- Thread: an independent stream of instructions that can be scheduled to run as such by the operating system
  - execution sequence within the process
- A process can create multiple threads
  - each thread executes a specific user-defined function
  - main() is the first (primary) thread
- Threads
  - share the memory space of the process they belong to
  - have their own state and some private memory (stack)
  - are cheap to create but difficult to use correctly
  - can run on different processors

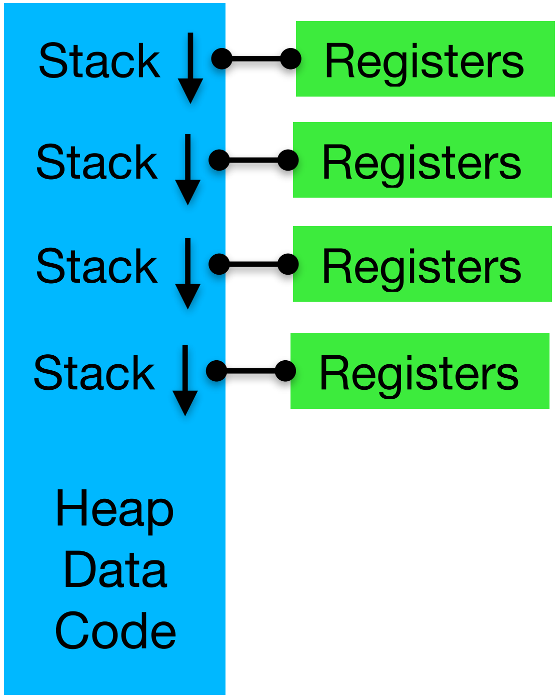
Processes and Threads

Traditional Process



Single execution flow

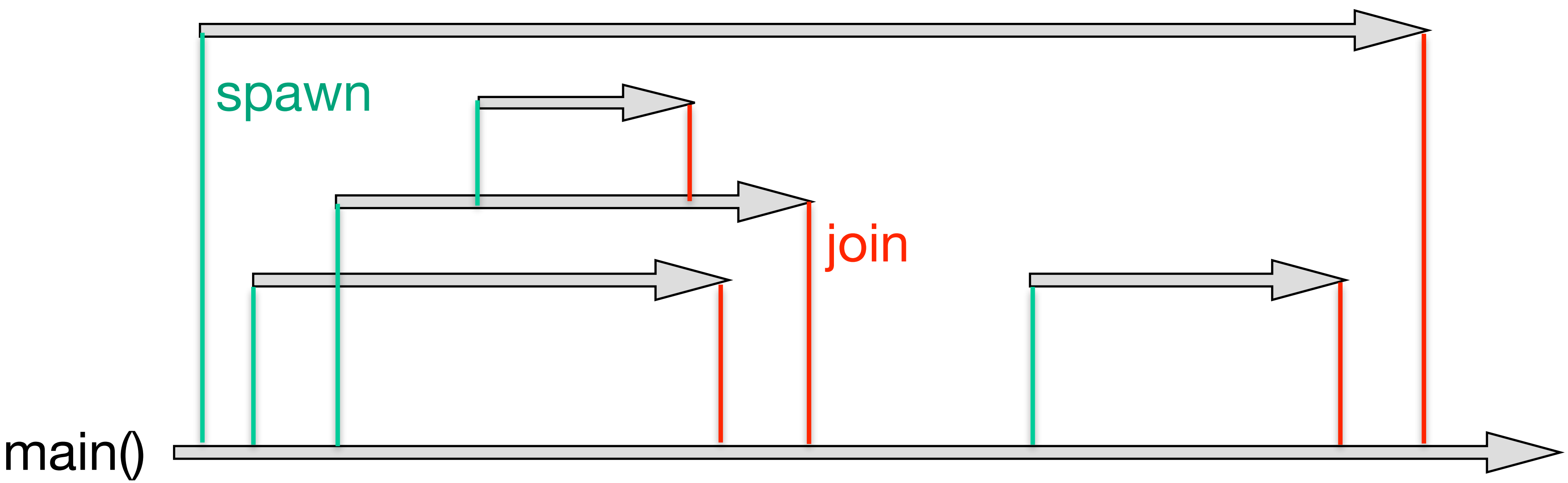
Multithreaded Process



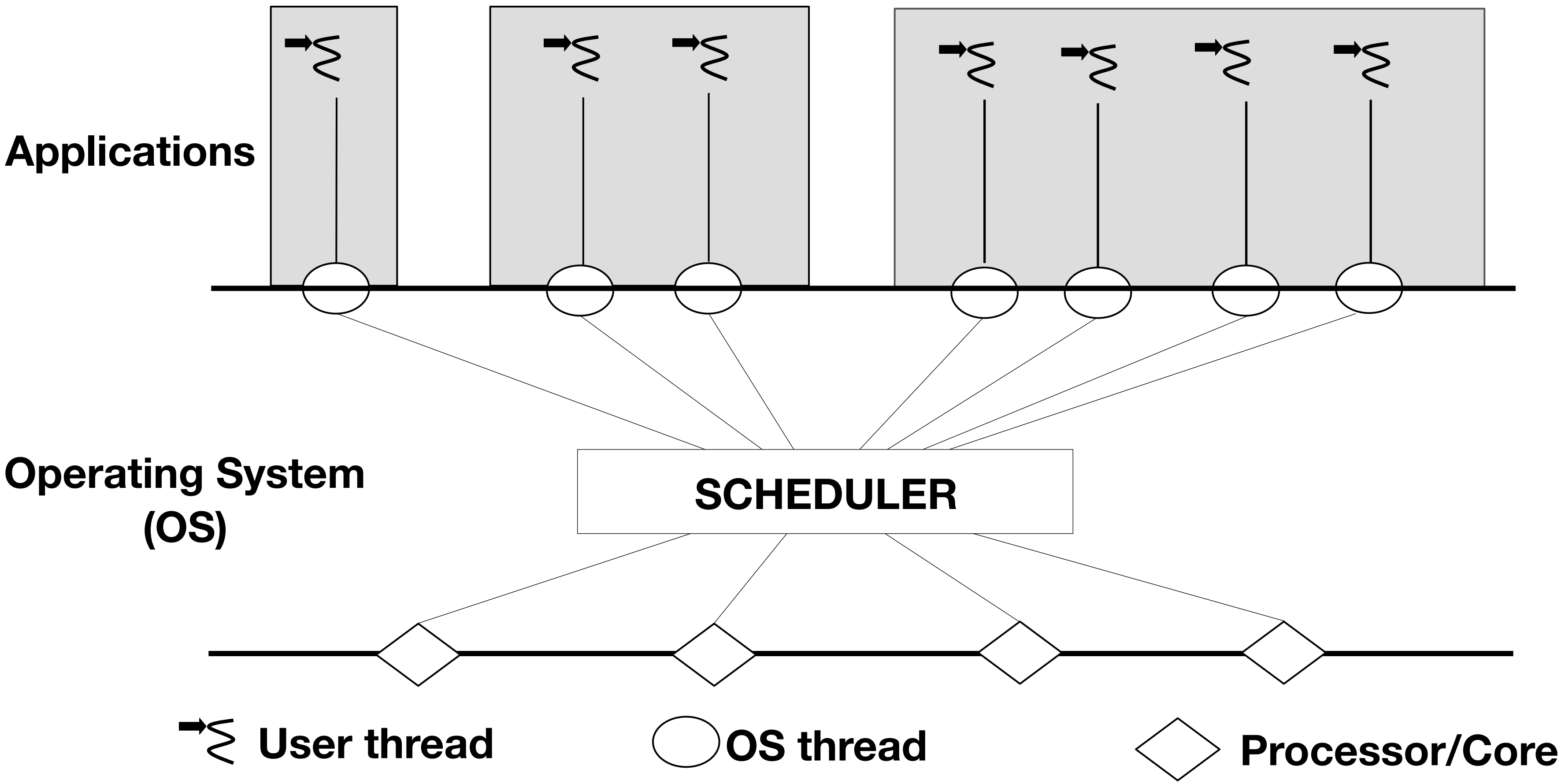
Multiple execution flows

Spawning and Joining Threads

- During execution of a multithreaded program threads get spawned and joined dynamically



General View



POSIX Threads (Pthreads)

- Standardized C language threads programming interface
  - http://pubs.opengroup.org/onlinepubs/9699919799/

- Header file:

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

- Compilation

```
$ gcc -pthread -o hello hello.c
```

- Execution

```
$ ./hello
```

Skeleton

```
void *func(void *arg)
{
   /* define local data */
   - - - - - - - - - - -
   - - - - - - - - - - -        /* function code */
   - - - - - - - - - - -
                                       equivalently:
   return (void *)&result;      pthread_exit(&result);
}

main()
{
   pthread_t tid;
   int exit_value;
   - - - - - - - - - - -
   pthread_create (&tid, NULL, func, NULL);
   - - - - - - - - - - -
   pthread_join (tid, &exit_value);
   - - - - - - - - - - -
}
```

Thread Creation

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

- `thread`: unique identifier for the new thread returned by the subroutine
- `attr`: used to set thread attributes. If NULL, the default values are used.
- `routine`: the C routine that the thread will execute once it is created.
- `arg`: single argument that may be passed to start_routine. It must be passed by reference as a pointer cast of type void. NULL may be used if no argument is to be passed.
- if there are no errors, it returns 0

pthread_create

```
#include <pthread.h>

pthread_t tid;
extern void *func(void *arg);
void *arg;

int res = pthread_create(&tid, NULL, func, arg);
```

Passing Multiple Arguments

```
struct data {
  int i;
  float f;
}

void *routine(void *arg) {
  struct data *d = (struct data *) arg;
  int local_i = d->i;
  d->f = 5.0;
  return NULL;
}

int main() {
  pthread_t tid;
  struct data main_data;
  main_data.i = 6;

  pthread_create(&tid, NULL, routine, (void *) &main_data);
  //...
}
```

Thread Joining

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

- `pthread_join()` blocks the calling thread until the specified thread terminates
- The value returned by the thread function is stored in the memory location specified by `status`
- if there are no errors, it returns 0

pthread_join

```
#include <pthread.h>

pthread_t tid;
int result;


pthread_join(tid, (void *)&result);

pthread_join(tid, NULL);
```

Hello World

ID of calling thread

```
void *work(void *arg)
{
  pthread_t me = pthread_self();
  printf("Hello world from thread %ld!\n", (long)me);
  return NULL;
}

int main(int argc, char **argv)
{
  long i = 1;
  pthread_t thread;

  printf("main thread %ld!\n", (long)pthread_self());

  pthread_create(&thread, NULL, work, (void *)i);
  pthread_join(thread, NULL);

  printf("Child ended, exiting\n");
  return 0;
}
```

Spawning and Joining Threads

```
void *func(void *arg)
{
   sleep(1);
   return NULL;
}

int main(int argc, char * argv[])
{
   pthread_t id[4];

   for (long i = 0; i < 4; i++)   {
       pthread_create(&id[i], NULL, func, NULL);
   }

   for (long i = 0; i < 4; i++)   {
       pthread_join(id[i], NULL);
    }

   return 0;
}
```

Creating and Joining Threads

```
void * func(void * arg)
{
   long sec = (long) arg + 1;
   sleep((long) sec);
   return arg;          /* pthread_exit(arg); */
}

int main(int argc, char * argv[])
{
   pthread_t id[4];
   long result;

   for (long i = 0; i < 4; i++)   {
       pthread_create(&id[i], NULL, func, (void *) i);
   }

   for (long i = 0; i < 4; i++)   {
       pthread_join(id[i], (void *) &result);
       /* result == i */;
   }

  return 0;
}
```

fix: (long) (*arg) +1;

what if we pass &i and then apply the above fix

Synchronization

- Consider the following code
  - `next_ticket` is a global variable initialized to 0
  - `ticket` is a local variable, private to each thread

```
ticket = next_ticket++;          /* 0 ⇒ 1 */
```

- In the general case, this is equivalent to the following:

```
ticket = temp = next_ticket; /* 0 */
++temp;                      /* 1 */
next_ticket = temp;          /* 1 */
```

Execution with 2 Threads

Thread 0 | Thread 1

```
tkt = tmp = n_tkt;  (0)
++tmp;              (1)
n_tkt = tmp;        (1)
```

```
                    tkt = tmp = n_tkt;  (1)
                    ++tmp;              (2)
                    n_tkt = tmp;        (2)
```

↓ time

Another Possible Case

Thread 0		Thread 1	
`tkt = tmp = n_tkt;`	(0)		
		`tkt = tmp = n_tkt;`	(0)
`++tmp;`	(1)		
		`++tmp;`	(1)
`n_tkt = tmp;`	(1)		
		`n_tkt = tmp;`	(1)

time

What we observe here is a race condition
The update of the shared variable is a critical section and must be protected

Synchronization - Mutexes

- POSIX Threads include several synchronization mechanisms
  - Mutexes, Condition variables, Semaphores, Reader-Writer locks, Spinlocks, Barriers
- A Mutex (*Mut*ual *Ex*clusion) is a mechanism that allows multiple threads to synchronize their access to shared resources (e.g. variables)
  - A mutex has two states: *locked* and *unlocked*
  - Only one thread can lock the mutex
  - Once a mutex is locked, any other thread that tries to lock that mutex will suspend its execution, until the thread unlocks the mutex
  - At that point, one of the waiting threads acquires the mutex and continues its execution

Mutex Management

- Declaration and static initialization of a mutex:

```
pthread_mutex_t mymutex = PTHREAD_MUTEX_INITIALIZER;
```

- Declaration and dynamic initialization of a mutex:

```
pthread_mutex_t mymutex;
pthread_mutex_init(&mymutex, NULL);
```

- Locking (acquiring) the mutex:

```
pthread_mutex_lock(&mymutex);
```

- Unlocking (releasing) the mutex after the critical section:

```
pthread_mutex_unlock(&mymutex);
```

Usage

```
#include <pthread.h>

pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
double global_sum = 0.0;

void *work(void *arg)
{
    ...
   pthread_mutex_lock(&mutex);
   global_sum += local_sum;
   pthread_mutex_unlock(&mutex);
    ...
}
```

Check and Lock

```
int pthread_mutex_trylock(pthread_mutex_t *m);
```

- Allows a thread to try to lock a mutex
- If the mutex is available then the thread locks the mutex
- If the mutex is locked then the function informs the user by returning a special value (EBUSY)
- This approach allows for implementations of spinlocks

```
while (pthread_mutex_trylock(&mutex) == EBUSY)
        /*sched_yield()*/;
```

Compute Pi - Sequential Version

```
long num_steps = 100000;
double step;

int main()
{
  double x, pi, sum = 0.0;

  step = 1.0/(double) num_steps;

  for (int i=0; i <num_steps; i++){
    x = (i-0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
  }

  pi = step * sum;

  return 0;
}
```

POSIX Threads Version

```
#include <pthread.h>
#define NUM_THREADS 2
pthread_t thread[NUM_THREADS];
pthread_mutex_t Mutex;
long num_steps = 100000;
double step;
double global_sum = 0.0;

void *Pi (void *arg) {
  long start;
  double x, sum = 0.0;

  start = (long) (*(int *) arg);
  step = 1.0/(double) num_steps;

  for(long i=start; i<num_steps; i+=NUM_THREADS)
  {
    x = (i+0.5)*step;
    sum = sum + 4.0/(1.0+x*x);
  }
  pthread_mutex_lock (&Mutex);
  global_sum += sum;
  pthread_mutex_unlock(&Mutex);

  return 0;
}
```

```
int main ()
{
  double pi;

  int Arg[NUM_THREADS];

  for(int i=0; i<NUM_THREADS; i++)
    Arg[i] = i;

  pthread_mutex_init(&Mutex, NULL);

  for (int i=0; i<NUM_THREADS; i++)
    pthread_create(&thread[i], NULL,
                   Pi, &Arg[i]);

  for (int i=0; i<NUM_THREADS; i++)
   pthread_join(thread[i], NULL);

  pi = global_sum * step;

  return 0;
}
```

Deadlocks

- Deadlock can occur when multiple mutexes are not locked in the same order.
- The threads cannot continue their execution:

Thread 0

```
pthread_mutex_lock(&mut1);
pthread_mutex_lock(&mut2);
```

Thread 1

```
pthread_mutex_lock(&mut2);
pthread_mutex_lock(&mut1);
```

- Deadlock can also occur if a mutex is locked twice (recursively) by the same thread

```
pthread_mutex_lock(&mut1);
pthread_mutex_lock(&mut1);
```

Thread Safety

- A function is thread-safe if it can be called safely at the same time by multiple threads
- Functions that use static variables are not thread-safe
  - `rand()`, `drand48()`
- Solutions
  - A mutex inside the function provides an easy but inefficient solution
    - already applied to the previous functions
  - Static variables must be replaced by thread private variables that are passed to the function as arguments

Example 1

- rand_r: thread-safe version of rand()
  - randp is assigned a number from 0 and RAND_MAX
  - returns 0 on success

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

int rand_r(int *ranp){
   static pthread_mutex_t = PTHREAD_MUTEX_INITIALIZER;
   int error;
   if (error = pthread_mutex_lock(&lock))
       return error;
   *ranp = rand();
   return pthread_mutex_unlock(&lock);
}
```

Example 2

- drand48() vs erand48()
  - "return non-negative, double-precision, floating-point values, uniformly distributed over the interval [0.0 , 1.0]"
  - http://pubs.opengroup.org/onlinepubs/7908799/xsh/drand48.html

```
srand48(10); // initialization
double xi = drand48();
double yi = drand48();
```

```
unsigned short buf[3];// random stream
buf[0] = 0; buf[1] = 0; buf[2] = 10; // initialization
double xi = erand48(buf);
double yi = erand48(buf);
```

References

- Advanced Programming in the Unix Environment, W. Richard Stevens
- Programming with POSIX Threads, David R. Butenhof
  - www.openmp.org
- POSIX threads tutorial at LLNL, Blaise Barney
  - https://computing.llnl.gov/tutorials/pthreads/