Concurrency, Concepts and Case Studies

Thread

- A new abstraction for a single running process

- Multi-threaded program
  - A multi-threaded program has more than one point of execution
  - Multiple PCs (Program Counter)
  - They share the same address space

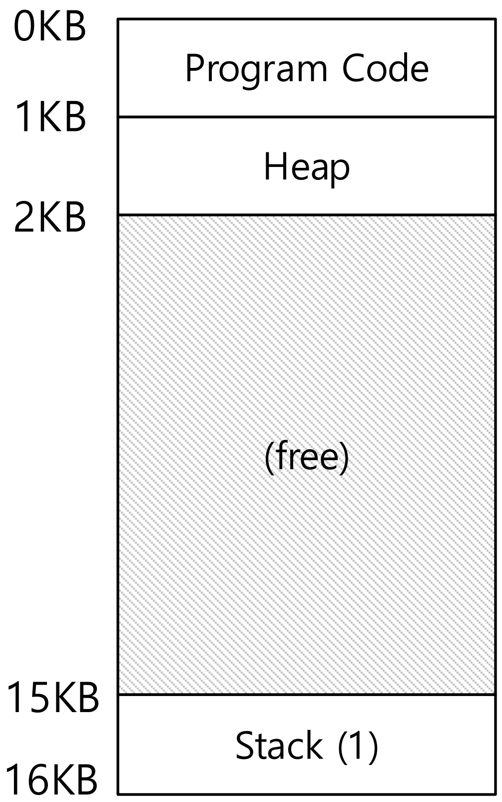
Context switch between threads

- Each thread has its own program counter and set of registers
  - One or more **thread control blocks(TCBs)** are needed to store the state of each thread

- When switching from running one (T1) to running the other (T2),
  - The register state of T1 be saved.
  - The register state of T2 restored.
  - The address space remains the same.

The stack of the relevant thread

- There will be one stack per thread

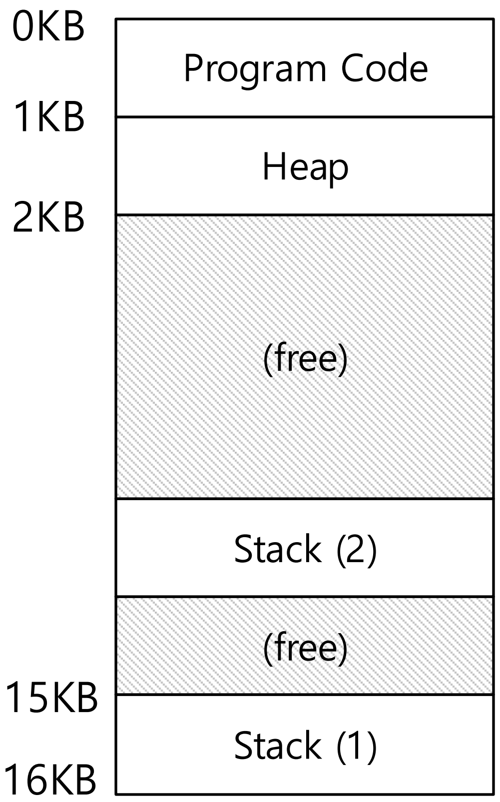


The code segment:
where instructions live

The heap segment:
contains malloc'd data
dynamic data structures
(it grows downward)

(it grows upward)
The stack segment:
contains local variables
arguments to routines,
return values, etc.

A Single-Threaded Address Space



Two threaded Address Space

Race condition

- Example with two threads
  - counter = counter + 1 (default is 50)
  - We expect the result is 52. However,

OS	Thread1	Thread2	(after instruction) PC	%eax	counter
	before critical section		100	0	50
	mov 0x8049a1c, %eax		105	50	50
	add $0x1, %eax		108	51	50
interrupt					
save T1's state					
restore T2's state			100	0	50
		mov 0x8049a1c, %eax	105	50	50
		add $0x1, %eax	108	51	50
		mov %eax, 0x8049a1c	113	51	51
interrupt					
save T2's state					
restore T1's state			108	51	50
	mov %eax, 0x8049a1c		113	51	$\boxed{\textbf{51}}$

Critical section

- A piece of code that accesses a shared variable and must not be concurrently executed by more than one thread
  - Multiple threads executing critical section can result in a race condition
  - Need to support **atomicity** for critical sections (**mutual exclusion**)

Locks

- Ensure that any such critical section executes as if it were a single atomic instruction (**execute a series of instructions atomically**)

```
lock_t mutex;
. . .
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```

Critical section

Thread Creation

- How to create and control threads?

```
#include <pthread.h>

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

- `thread`: Used to interact with this thread
- `attr`: Used to specify any attributes this thread might have
  - Stack size, Scheduling priority, …
- `start_routine`: the function this thread start running in
- `arg`: the argument to be passed to the function (`start routine`)
  - *a void pointer* allows us to pass in *any type of* argument

Thread Creation (Cont.)

- If `start_routine` instead required another type argument, the declaration would look like this:
  - An integer argument:

```
int
pthread_create(…, // first two args are the same
                    void*  (*start_routine)(int),
                    int     arg);
```

  - Return an integer:

```
int
pthread_create(…, // first two args are the same
                    int   (*start_routine)(void*),
                    void*    arg);
```

Example: Creating a Thread

```
#include <pthread.h>

typedef struct __myarg_t {
        int a;
        int b;
} myarg_t;

void *mythread(void *arg) {
        myarg_t *m = (myarg_t *) arg;
        printf("%d %d\n", m->a, m->b);
        return NULL;
}

int main(int argc, char *argv[]) {
        pthread_t p;
        int rc;

        myarg_t args;
        args.a = 10;
        args.b = 20;
        rc = pthread_create(&p, NULL, mythread, &args);
        …
}
```

Wait for a thread to complete

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

- `thread`: Specify which thread *to wait for*
- `value_ptr`: A pointer to the return value
  - Because `pthread_join()` routine changes the value, you need to pass in a pointer to that value

Example: Waiting for Thread Completion

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

typedef struct __myarg_t {
    int a;
    int b;
} myarg_t;

typedef struct __myret_t {
    int x;
    int y;
} myret_t;

void *mythread(void *arg) {
    myarg_t *m = (myarg_t *) arg;
    printf("%d %d\n", m->a, m->b);
    myret_t *r = malloc(sizeof(myret_t));
    r->x = 1;
    r->y = 2;
    return (void *) r;
}

```

Example: Waiting for Thread Completion

```
int main(int argc, char *argv[]) {
    int rc;
    pthread_t p;
    myret_t *m;

    myarg_t args;
    args.a = 10;
    args.b = 20;
    pthread_create(&p, NULL, mythread, &args);
    pthread_join(p, (void **) &m);  // this thread has been
                                     // waiting inside of the
                                     // pthread_join() routine.
    printf("returned %d %d\n", m->x, m->y);
    return 0;
}
```

Example: Dangerous code

- Be careful with how values are returned from a thread

```
void *mythread(void *arg) {
    myarg_t *m = (myarg_t *) arg;
    printf("%d %d\n", m->a, m->b);
    myret_t r; // ALLOCATED ON STACK: BAD!
    r.x = 1;
    r.y = 2;
    return (void *) &r;
}
```

  - When the variable `r` returns, it is automatically de-allocated

Example: Simpler Argument Passing to a Thread

- Just passing in a single value

```
void *mythread(void *arg) {
    int m = (int) arg;
    printf("%d\n", m);
    return (void *) (arg + 1);
}

int main(int argc, char *argv[]) {
    pthread_t p;
    int rc, m;
    pthread_create(&p, NULL, mythread, (void *) 100);
    pthread_join(p, (void **) &m);
    printf("returned %d\n", m);
    return 0;
}
```

Locks

- Provide mutual exclusion to a critical section
  - Interface

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

  - Usage (w/o *lock initialization* and *error check*)

```
pthread_mutex_t lock;
pthread_mutex_lock(&lock);
x = x + 1; // or whatever your critical section is
pthread_mutex_unlock(&lock);
```

    – No other thread holds the lock → the thread will acquire the lock and enter the critical section
    – If another thread hold the lock → the thread will not return from the call until it has acquired the lock

Locks (Cont.)

- All locks must be properly initialized
  - One way: using `PTHREAD_MUTEX_INITIALIZER`

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

  - The dynamic way: using `pthread_mutex_init()`

```
int rc = pthread_mutex_init(&lock, NULL);
assert(rc == 0); // always check success!
```

Locks (Cont.)

- Check errors code when calling lock and unlock
  - An example wrapper

```
// Use this to keep your code clean but check for failures
// Only use if exiting program is OK upon failure
void Pthread_mutex_lock(pthread_mutex_t *mutex) {
    int rc = pthread_mutex_lock(mutex);
    assert(rc == 0);
}
```

- These two calls are used in lock acquisition

```
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_timelock(pthread_mutex_t *mutex,
                           struct timespec *abs_timeout);
```

  - trylock: return failure if the lock is already held
  - timelock: return after a timeout

Condition Variables

- **Condition variables** are useful when some kind of signaling must take place between threads

```
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
```

- `pthread_cond_wait`:
  - Put the calling thread to sleep.
  - Wait for some other thread to signal it.
- `pthread_cond_signal`:
  - Unblock at least one of the threads that are blocked on the condition variable

Condition Variables (Cont.)

- A thread calling wait routine:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t init = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
        pthread_cond_wait(&init, &lock);
pthread_mutex_unlock(&lock);
```

  - The wait call releases the lock when putting said caller to sleep
  - Before returning after being woken, the wait call re-acquire the lock

- A thread calling signal routine:

```
pthread_mutex_lock(&lock);
initialized = 1;
pthread_cond_signal(&init);
pthread_mutex_unlock(&lock);
```

Condition Variables (Cont.)

- The waiting thread **re-checks** the condition in a while loop, instead of a simple if statement

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t init = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
        pthread_cond_wait(&init, &lock);
pthread_mutex_unlock(&lock);
```

  - Without rechecking, the waiting thread will continue thinking that the condition has changed *even though it has not*

Condition Variables (Cont.)

- Don't ever to this
  - A thread calling wait routine:

```
while(initialized == 0)
        ; // spin
```

  - A thread calling signal routine:

```
initialized = 1;
```

  - It performs poorly in many cases → just wastes CPU cycles
  - It is error prone

Compiling and Running

- To compile them, you must include the header `pthread.h`
  - Explicitly link with the pthreads library, by adding the `-pthread` flag

```
prompt> gcc -o main main.c -Wall -pthread
```

  - For more information,

```
man -k pthread
```