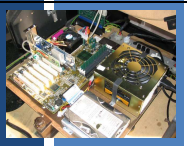
TCSS 422: OPERATING SYSTEMS



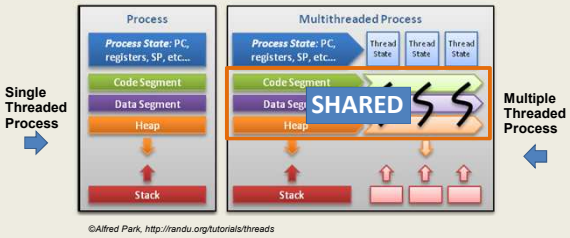
Concurrency: An Introduction

Wes J. Lloyd
Institute of Technology
University of Washington - Tacoma

OBJECTIVES

- Introduction to threads
- Race condition
- Critical section
- Thread API

THREADS



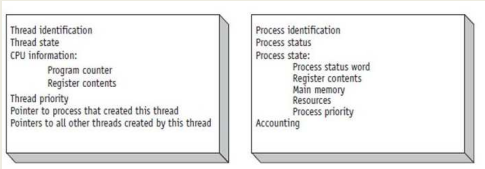
©Alfred Park, http://randu.org/tutorials/threads

THREADS - 2

- Enables a single process (program) to have multiple "workers"
- Supports independent path(s) of execution within a program
- Each thread has its own Thread Control Block (TCB)
  - PC, registers, SP, and stack
- Code segment, memory, and heap are shared

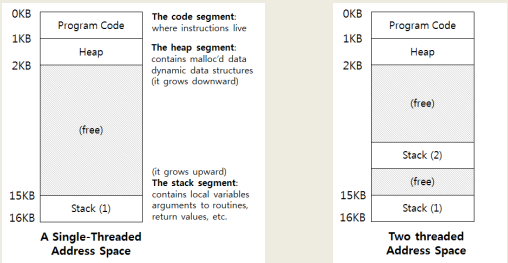
PROCESS AND THREAD METADATA

- Thread Control Block vs. Process Control Block



SHARED ADDRESS SPACE

- Every thread has it's own stack / PC



THREAD CREATION EXAMPLE

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

void *mythread(void *arg) {
    printf("%s\n", (char *) arg);
    return NULL;
}

int
main(int argc, char *argv[]) {
    pthread_t p1, p2;
    int rc;
    printf("main: begin\n");
    rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
    rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);
    // join waits for the threads to finish
    rc = pthread_join(p1, NULL); assert(rc == 0);
    rc = pthread_join(p2, NULL); assert(rc == 0);
    printf("main: end\n");
    return 0;
}
```


POSSIBLE ORDERINGS OF EVENTS

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T1		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		
		Runs
		Prints 'B'
		Returns
Prints 'main: end'		

POSSIBLE ORDERINGS OF EVENTS - 2

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
	Runs	
	Prints 'A'	
	Returns	
Creates Thread 2		
		Runs
		Prints 'B'
		Returns
Waits for T1	*Returns immediately*	
Waits for T2		*Returns immediately*
Prints 'main: end'		

POSSIBLE ORDERINGS OF EVENTS - 3

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T1		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		*Immediately returns*
Prints 'main: end'		

What if execution order of events in the program matters?

COUNTER EXAMPLE

- Show example
- A + B : ordering
- Counter: incrementing global variable by two threads

RACE CONDITION

- Example when counter=50
  - Counter = counter + 1
  - If synchronized, counter will = 52

```
                                                  (after instruction)
OS          Thread1          Thread2              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    51
```

CRITICAL SECTION

- Code that accesses a shared variable must not be ***concurrently*** executed by more than one thread
- Multiple ***active*** threads inside a critical section produces a ***race condition***.
- ***Atomicity*** of execution must be ensured in ***critical*** sections
  - These sections must be ***mutually exclusive***

LOCKS

- To demonstrate how critical section(s) can be executed "atomically" Chapter 27 & beyond introduce locks

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

Critical section

- Counter example revisited

LINUX THREAD API

THREAD CREATION

- pthread_create

```
#include <pthread.h>

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

- thread: thread struct
- attr: stack size, scheduling priority…
- start_routine: function pointer to thread routine
- arg: argument to pass to thread routine

THREAD CREATION - 2

- Casting
- Suppresses compiler warnings when passing "typed" data where (void) or (void *) is called for
- Example: uncasted capture in pthread_join

```
pthread_int.c: In function 'main':
pthread_int.c:34:20: warning: passing argument 2 of 'pthread_join'
from incompatible pointer type [-Wincompatible-pointer-types]
   pthread_join(p1, &p1val);
```

- Example: uncasted return

```
In file included from pthread_int.c:3:0:
/usr/include/pthread.h:250:12: note: expected 'void **' but argument
is of type 'int **'
 extern int pthread_join (pthread_t __th, void **__thread_return);
```


ADDING CASTS

- pthread_join

```
int * p1val;
int * p2val;
pthread_join(p1, (void *)&p1val);
pthread_join(p2, (void *)&p2val);
```

- return from thread function

```
int * counterval = malloc(sizeof(int));
*counterval = counter;
return (void *) counterval;
```

PTHREAD_CREATE – PASS ANY DATA

```
#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);
        …
}
```


WAITING FOR THREADS TO FINISH

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

- thread: which thread?
- value_ptr: pointer to return value
  type is dynamic / agnostic
- Returned values *must* be on the heap
- Thread stacks destroyed upon thread termination (join)
- Pointers to thread stack memory addresses are invalid
  - May appear as gibberish or lead to crash (seg fault)
- Not all threads join – ***What would be Examples ??***

What will this code do?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  struct myarg output;
  output.a = 1;
  output.b = 2;
  return (void *) &output;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_
  pthread_
  printf("
  return 0;
}
```

Data on thread stack

```
$ ./pthread_struct
a=10 b=20
Segmentation fault (core dumped)
```

How can this code be fixed?

How about this code?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  input->a = 1;
  input->b = 2;
  return (void *) &input;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_create(&p1, NULL, worker, &args);
  pthread_join(p1, (void *)&ret_args);
  printf("returned %d %d\n", ret_args->a, ret_args->b);
  return 0;
}
```

```
$ ./pthread_struct
a=10 b=20
returned 1 2
```


PASSING A SINGLE VALUE

Using this approach on your CentOS 7 VM
How large (in bytes) can the primitive data type be?

How large (in bytes) can the primitive data type be on a 32-bit operating system?

```
9       int rc, m;
10      pthread_create(&p, NULL, mythread, (void *) 100);
11      pthread_join(p, (void **) &m);
12      printf("returned %d\n", m);
13      return 0;
14  }
```


LOCKS

- pthread_mutex_t data type
- /usr/include/bits/pthread_types.h

```
// Global Address Space
static volatile int counter = 0;
pthread_mutex_t lock;

void *worker(void *arg)
{
  int i;
  for (i=0;i<10000000;i++)  {
    int rc = pthread_mutex_lock(&lock);
    assert(rc==0);
    counter = counter + 1;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}
```

LOCKS - 2

- Ensure critical sections are executed atomically
  - Provides implementation of "***Mutual Exclusion***"
- API

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

- Example w/o initialization & error checking

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

  - Blocks forever until lock can be obtained
  - Enters critical section once lock is obtained
  - Releases lock

LOCK INITIALIZATION

- Assigning the constant

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

- API call:

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

- Initializes mutex with attributes specified by 2nd argument
- If NULL, then default attributes are used
- Upon initialization, the mutex is initialized and unlocked

LOCKS - 3

- Error checking 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);
}
```

- What if lock can't be obtained?

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

- trylock – returns immediately (fails) if lock is unavailable
- timelock – tries to obtain a lock for a specified duration

CONDITIONS AND SIGNALS

- Condition variables support "signaling" between threads

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

- `pthread_cont_t` datatype
- pthread_cond_wait()
  - Waits (sleeps)
  - Listens for a "signal"
  - Releases the lock until signaled

CONDITIONS AND SIGNALS - 2

```
int pthread_cond_signal(pthread_cond_t * cond);
int pthread_cond_broadcast(pthread_cond_t * cond);
```

- `pthread_cond_signal()`
  - Called to send a "signal" to all listeners → to wake them up
  - The goal is to unblock (at least one) to respond to the signal
- `pthread_cond_broadcast()`
  - Unblocks all threads currently blocked on the specified condition
  - Used when all threads should respond to the signal
- Which thread is unblocked first?
  - Determined by OS scheduler (based on priority)
  - Thread(s) gain the lock individually (based on priority) as if they called `pthread_mutex_lock()`

CONDITIONS AND SIGNALS - 3

- Wait example

```
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);
```

- wait puts thread to sleep, releases lock
- when awoken, lock reacquired (and released by this code)
- Another thread signals the thread

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

Code performs required work before other thread(s) can continue

CONDITION AND SIGNALS - 4

```
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);
```

- Why do we wait inside a while loop?
- The while ensures upon awakening the condition is rechecked
  - A signal may have been raised, but the condition to proceed has not been satisfied.
  - Without checking the condition the thread may proceed to execute when it should not.

DO-IT-YOURSELF LOCK

- "initialized" -- global variable shared by multiple threads
- Wait (client thread):

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

- Signal (parent thread): *when ready…*

```
initialized = 1;
```

- How is this "wait" different that pthread_cond_wait() ?
  - Wastes CPU cycles → effectively pegs a core at 100%
  - Potential synchronization errors with changing the value of "initialized"
  - Thread API is provided to advance the DO-IT-YOURSELF approach

PTHREADS LIBRARY

- Compilation
  - gcc –pthread pthread.c –o pthread
  - Requires explicitly linking the library with compiler flag
- List of pthread manpages
  - man –k pthread

SAMPLE MAKEFILE

```
CC=gcc
CFLAGS=-pthread -I. -Wall

binaries=pthread pthread_int pthread_lock_cond pthread_struct

all: $(binaries)

pthread_mult: pthread.c pthread_int.c
    $(CC) $(CFLAGS) $^ -o $@

clean:
    $(RM) -f $(binaries) *.o
```

- Example builds multiple single file programs
  - All target
- pthread_mult
  - Example if multiple source files should produce a single executable
- clean target

QUESTIONS