Pthreads

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Traditional View

- Process = process context + address space

**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**

- Stack
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data

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Alternate View

- Process = thread context + kernel context + address space

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

Code and Data:
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data

Kernel context:
- VM structures
- Descriptor table
- Brk pointer
Logical View of Threads

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

- **How threads and processes are similar**
  - Each has its own logical control flow.
  - Each can run concurrently.
  - Each is context switched.

- **How threads and processes are different**
  - Threads share code and data, processes (typically) do not.
  - Threads are somewhat less expensive than processes.
    - Linux 2.4 Kernel, 512MB RAM, 2 CPUs
      - > 1,811 forks()/second
      - > 227,611 threads/second (125x faster)
Pthreads Interface

- POSIX Threads Interface
  - 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()
    - pthread_cond_init()
    - pthread_cond_[timed]wait()
    - pthread_cond_signal(), etc.
The Pthreads API

- Thread management
  - Work directly on threads – creating, terminating, joining, etc.
  - Include functions to set/query thread attributes.
- Mutexes
  - Provide for creating, destroying, locking and unlocking mutexes.
- Condition variables
  - Include functions to create, destroy, wait and signal based upon specified variable values.
Creating Threads (1)

- **int pthread_create (pthread_t *thread, pthread_attr_t *attr, void *(*start_routine)(void *), void *arg)**
  - **pthread_create()** returns the new thread ID via the `thread` argument.
    - The caller can use this thread ID to perform various operations on the thread.
  - The `attr` parameter is used to set thread attributes.
    - NULL for the default values.
  - The `start_routine` denotes the C routine that the thread will execute once it is created.
    - C routine that the thread will execute once it is created.
  - A single argument may be passed to `start_routine()` via `arg`. 
Creating Threads (2)

- **Notes:**
  - Initially, `main()` comprises a single, default thread.
  - All other threads should be explicitly created by the programmer.
  - Once created, threads are peers, and may create other threads.
  - The maximum number of threads that may be created by a process is implementation dependent.
Terminating Threads

- `void pthread_exit (void *retval)`
  - `pthread_exit()` terminates the execution of the calling thread.
    - Typically, this is called after a thread has completed its work and is no longer required to exist.
  - The `retval` argument is the return value of the thread.
    - It can be consulted from another thread using `pthread_join()`.
  - It does not close files; any files opened inside the thread will remain open after the thread is terminated.
Cancelling Threads

- **int pthread_cancel (pthread_t thread)**
  
  - *pthread_cancel()* sends a cancellation request to the thread denoted by the **thread** argument.
  
  - Depending on its settings, the target thread can then either ignore request, honor it immediately, or defer it till it reaches a cancellation point.
    
    - *pthread_setcancelstate()*:
      
      PTHREAD_CANCEL_(ENABLE|DISABLE)
    
    - *pthread_setcanceltype()*:
      
      PTHREAD_CANCEL_(DEFERRED|ASYNCHRONOUS)
  
  - Threads are always created by *pthread_create()* with cancellation enabled and deferred.
Joining Threads

- int pthread_join (pthread_t thread, void **retval)
  - pthread_join() suspends the execution of the calling thread until the thread identified by thread terminates, either by calling pthread_exit() or by being cancelled.
  - The return value of thread is stored in the location pointed by retval.
  - It returns PTHREAD_CANCELLED if thread was cancelled.
  - It is impossible to join a detached thread.
Detaching Threads

- `int pthread_detach (pthread_t thread)`
  - `pthread_detach()` puts the thread in the detached state.
    - This guarantees that the memory resources consumed by `thread` will be freed immediately when thread terminates.
    - However, this prevents other threads from synchronizing on the termination of thread using `pthread_join()`.
  - A thread can be detached when it is created:

```c
pthread_t tid;
pthread_attr_t attr;

pthread_attr_init (&attr);
pthread_attr_setdetachstate(&attr, PTHREAD_CREATE_DETACHED);
pthread_create(&tid, &attr, start_routine, NULL);
pthread_attr_destroy (&attr);
```
Thread Identifiers

- **pthread_t pthread_self (void)**
  - `pthread_self()` returns the unique, system assigned thread ID of the calling thread.

- **int pthread_equal (pthread_t t1, pthread_t t2)**
  - `pthread_equal()` returns a non-zero value if `t1` and `t2` refer to the same thread.
  - Because thread IDs are opaque objects, the C language equivalence operator `==` should not be used to compare two thread IDs against each other.
Example

```c
#include <pthread.h>
#include <stdio.h>
#define NTHREADS 10

void *PrintHello(void *threadid) {
    printf("%d: Hello World!\n", (int)threadid);
    pthread_exit(NULL);
}

int main () {
    pthread_t tid[NTHREADS];
    int t;
    for (t = 0; t < NTHREADS; t++)
        pthread_create(&tid[t], NULL, PrintHello, (void *)t);
    for (t = 0; t < NTHREADS; t++)
        pthread_join(tid[t], NULL);
}
Exercise: Mini Shell, Again

- To implement mini shell

- A shell program executing following commands
  - An application program that runs programs on behalf of the user
Exercise: Mini Shell

1. mini shell

- (1) mv
  - SYNOPSYS: mv file1 file2
  - DESCRIPTION:
    » 파일의 이름을 file1에서 file2로 바꾼다.

- (2) cp
  - SYNOPSYS: cp file1 file2
  - DESCRIPTION:
    » file1의 복사본 file2를 만든다.
    » File이 존재하지 않는 경우, 아래 에러 메시지를 출력한다.
    » swsh: No such file
    » (3) pwd (2) exit
Exercise: Mini Shell

1. Implement basic functions

- (1) mv
  - SYNOPSIS: mv file1 file2
  - DESCRIPTION:
    » 파일의 이름을 file1에서 file2로 바꾼다.
  - SEE ALSO: rename(2)

- (2) cp
  - SYNOPSIS: cp file1 file2
  - DESCRIPTION:
    » file1의 복사본 file2를 만든다.
    » File이 존재하지 않는 경우, 아래 에러 메시지를 출력한다.
    » swsh: No such file
1. Implement basic functions

- (1) `pwd`
  - SYNOPSYS: `pwd`
  - DESCRIPTION: 현재 working directory를 표준 출력으로 출력한다.
  - SEE ALSO: `getcwd(3)`

- (2) `exit`
  - SYNOPSYS: `exit [num]`
  - DESCRIPTION:
    » 표준 에러로 `exit`란 문자열을 출력한 뒤, swsh를 종료한다.
    » NUM이 존재할 경우 프로그램 종료 값을 NUM으로, 아닐 경우 0을 반환한다.
  - SEE ALSO: `exit(3)`
Threads Synchronization

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Mutex (1)

- Mutex is an abbrev. for “mutual exclusion”
  - Primary means of implementing thread synchronization.
    - Protects shared data when multiple writes occurs.
  - A mutex variable acts like a “lock” protecting access to a shared resource.
    - Only one thread can lock (or own) a mutex variable at any given time.
    - Even if several threads try to lock a mutex, only one thread will be successful. Other threads are blocked until the owner releases the lock.
  - Mutex is used to prevent “race” conditions.
    - race condition: anomalous behavior due to unexpected critical dependence on the relative timing of events.
Mutex (2)

```c
int deposit(int amount)
{
    int balance;
    balance = get_balance();
    balance += amount;
    put_balance(balance);
    return balance;
}

int withdraw(int amount)
{
    int balance;
    balance = get_balance();
    balance -= amount;
    put_balance(balance);
    return balance;
}
```

T1 executes `deposit(100)`
```
balance = get_balance();
balance += 100;
put_balance(balance);
```

T2 executes `withdraw(300)`
```
balance = get_balance();
balance -= 300;
put_balance(balance);
```
Creating/Destroying Mutexes

- **Static initialization**
  - `pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;`

- **Dynamic initialization**
  - `pthread_mutex_t m;`
  - `pthread_mutex_init (&m, (pthread_mutexattr_t *)NULL);`

- **Destroying a mutex**
  - `pthread_mutex_destroy (&m);`
  - Destroys a mutex object, freeing the resources it might hold.
Using Mutexes (1)

- **int pthread_mutex_lock (pthread_mutex_t *mutex)**
  - Acquire a lock on the specified `mutex` variable.
  - If the `mutex` is already locked by another thread, block the calling thread until the `mutex` is unlocked.

- **int pthread_mutex_unlock (pthread_mutex_t *mutex)**
  - Unlock a `mutex` if called by the owning thread.

- **int pthread_mutex_trylock (pthread_mutex_t *mutex)**
  - Attempt to lock a `mutex`.
  - If the `mutex` is already locked, return immediately with a “busy” error code.
Using Mutexes (2)

```c
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

int deposit(int amount)
{  
    int balance;
    
    pthread_mutex_lock(&m);
    balance = get_balance();
    balance += amount;
    put_balance(balance);
    
    pthread_mutex_unlock(&m);
    return balance;
}

int withdraw(int amount)
{
    int balance;
    
    pthread_mutex_lock(&m);
    balance = get_balance();
    balance -= amount;
    put_balance(balance);
    
    pthread_mutex_unlock(&m);
    return balance;
}
```
Condition Variables (1)

- Another way for thread synchronization
  - While mutexes implement synchronization by controlling thread access to data, condition variables allow threads to synchronize based upon the actual value of data.
  - Without condition variables, the programmer would need to have threads continually polling to check if the condition is met.
    - This can be very resource consuming since the thread would be continuously busy in this activity.
  - A condition variable is always used in conjunction with a mutex lock.
Condition Variables (2)

- How condition variables work
  - A thread locks a mutex associated with a condition variable.
  - The thread tests the condition to see if it can proceed.
  - If it can
    - Your thread does its work
    - Your thread unlocks the mutex
  - If it cannot
    - The thread sleeps. The mutex is automatically released.
    - Some other threads signals the condition variable.
    - Your thread wakes up from waiting with the mutex automatically locked, and it does its work.
    - Your thread releases the mutex when it’s done.
Creating/Destroying CV

- **Static initialization**
  - `typedef pthread_cond_t cond_t;
  `cond = PTHREAD_COND_INITIALIZER;

- **Dynamic initialization**
  - `cond_t cond;
    pthread_cond_init (&cond, (pthread_condattr_t*)NULL);

- **Destroying a condition variable**
  - `pthread_cond_destroy (&cond);
  `Destroys a condition variable, freeing the resources it might hold.
Using Condition Variables

- **int pthread_cond_wait (pthread_cond_t *cond, pthread_mutex_t *mutex)**
  - Blocks the calling thread until the specified condition is signalled.
  - This should be called while mutex is locked, and it will automatically release the mutex while it waits.

- **int pthread_cond_signal (pthread_cond_t *cond)**
  - Signals another thread which is waiting on the condition variable.
  - Calling thread should have a lock.

- **int pthread_cond_broadcast (pthread_cond_t *cond)**
  - Used if more than one thread is in a blocking wait state.
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

#define QSIZE 5
#define LOOP 30

typedef struct {
  int data[QSIZE];
  int index;
  int count;
  pthread_mutex_t lock;
  pthread_cond_t notfull;
  pthread_cond_t notempty;
} queue_t;

void *produce (void *args);
void *consume (void *args);
void put_data (queue_t *q, int d);
int get_data (queue_t *q);
Producer-Consumer (2)

```c
int main ()
{
    queue_t *q;
    pthread_t producer, consumer;

    q = qinit();

    pthread_create(&producer, NULL, produce, (void *)q);
    pthread_create(&consumer, NULL, consume, (void *)q);

    pthread_join (producer, NULL);
    pthread_join (consumer, NULL);

    qdelete();
}
```
queue_t *qinit()
{
    queue_t *q;

    q = (queue_t *) malloc(sizeof(queue_t));
    q->index = q->count = 0;
    pthread_mutex_init(&q->lock, NULL);
    pthread_cond_init(&q->notfull, NULL);
    pthread_cond_init(&q->notempty, NULL);

    return q;
}

void qdelete(queue_t *q)
{
    pthread_mutex_destroy(&q->lock);
    pthread_cond_destroy(&q->notfull);
    pthread_cond_destroy(&q->notempty);
    free(q);
}
void *produce(void *args)
{
    int i, d;
    queue_t *q = (queue_t *)args;
    for (i = 0; i < LOOP; i++) {
        d = random() % 10;
        put_data(q, d);
        printf("put data %d to queue\n", d);
    }
    pthread_exit(NULL);
}

void *consume(void *args)
{
    int i, d;
    queue_t *q = (queue_t *)args;
    for (i = 0; i < LOOP; i++) {
        d = get_data(q);
        printf("got data %d from queue\n", d);
    }
    pthread_exit(NULL);
}
Producer-Consumer (5)

```c
void put_data(queue_t *q, int d) {
    pthread_mutex_lock(&q->lock);
    while (q->count == QSIZE) pthread_cond_wait(&q->notfull, &q->lock);
    q->data[(q->index + q->count) % QSIZE] = d;
    q->count++;
    pthread_cond_signal(&q->notempty);
    pthread_mutex_unlock(&q->lock);
}

int get_data(queue_t *q) {
    int d;
    pthread_mutex_lock(&q->lock);
    while (q->count == 0) pthread_cond_wait(&q->notempty, &q->lock);
    d = q->data[q->index];
    q->index = (q->index + 1) % QSIZE;
    q->count--;
    pthread_cond_signal(&q->notfull);
    pthread_mutex_unlock(&q->lock);
    return d;
}
```
Thread Safety (1)

- **Thread-safe**
  - Functions called from a thread must be thread-safe.
  - We identify four (non-disjoint) classes of thread-unsafe functions:
    - Class 1: Failing to protect shared variables
    - Class 2: Relying on persistent state across invocations
    - Class 3: Returning a pointer to a static variable
    - Class 4: Calling thread-unsafe functions
Thread Safety (2)

- Class 1: Failing to protect shared variables.
  - Fix: Use mutex operations.
  - Issue: Synchronization operations will slow down code.

```c
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
int cnt = 0;

/* Thread routine */
void *count(void *arg) {
    int i;

    for (i=0; i<NITERS; i++) {
        pthread_mutex_lock (&lock);
        cnt++;
        pthread_mutex_unlock (&lock);
    }
    return NULL;
}
```
Class 2: Relying on persistent state across multiple function invocations.

- Random number generator relies on static state
- Fix: Rewrite function so that caller passes in all necessary state.

```
/* rand - return pseudo-random integer on 0..32767 */
int rand(void) {
    static unsigned int next = 1;
    next = next*1103515245 + 12345;
    return (unsigned int)(next/65536) % 32768;
}

/* srand - set seed for rand() */
void srand(unsigned int seed) {
    next = seed;
}
```
Thread Safety (4)

- **Class 3: Returning a ptr to a static variable.**

- **Fixes:**
  1. Rewrite code so caller passes pointer to **struct**.
     - Issue: Requires changes in caller and callee.
  2. **Lock-and-copy**
     - Issue: Requires only simple changes in caller (and none in callee)
       - However, caller must free memory.

```c
struct hostent
*gethostbyname(char *name){
    static struct hostent h;
    <contact DNS and fill in h>
    return &h;
}

hostp = malloc(...));
gethostbyname_r(name, hostp);

struct hostent
*gethostbyname_ts(char *name)
{
    struct hostent *unshared
        = malloc(...);
    pthread_mutex_lock(&lock); /* lock */
    shared = gethostbyname(name);
    *unshared = *shared; /* copy */
    pthread_mutex_unlock(&lock);
    return q;
}
```
Thread Safety (5)

- Class 4: Calling thread-unsafe functions.
  - Calling one thread-unsafe function makes an entire function thread-unsafe.
  - Fix: Modify the function so it calls only thread-safe functions
Reentrant Functions

- A function is *reentrant* iff it accesses NO shared variables when called from multiple threads.

  - Reentrant functions are a proper subset of the set of thread-safe functions.

  ![Diagram of function types]

  - NOTE: The fixes to Class 2 and 3 thread-unsafe functions require modifying the function to make it reentrant.
Thread-Safe Library

- All functions in the Standard C Library (at the back of your K&R text) are thread-safe.
  - Examples: `malloc`, `free`, `printf`, `scanf`

- Most Unix system calls are thread-safe, with a few exceptions:

<table>
<thead>
<tr>
<th>Thread-unsafe function</th>
<th>Class</th>
<th>Reentrant version</th>
</tr>
</thead>
<tbody>
<tr>
<td>asctime</td>
<td>3</td>
<td>asctime_r</td>
</tr>
<tr>
<td>ctime</td>
<td>3</td>
<td>ctime_r</td>
</tr>
<tr>
<td>gethostbyaddr</td>
<td>3</td>
<td>gethostbyaddr_r</td>
</tr>
<tr>
<td>gethostbyname</td>
<td>3</td>
<td>gethostbyname_r</td>
</tr>
<tr>
<td>inet_ntoa</td>
<td>3</td>
<td>(none)</td>
</tr>
<tr>
<td>localtime</td>
<td>3</td>
<td>localtime_r</td>
</tr>
<tr>
<td>rand</td>
<td>2</td>
<td>rand_r</td>
</tr>
</tbody>
</table>