PennState

CMPSC 311 - Introduction to Systems Programming

Introduction to Concurrency

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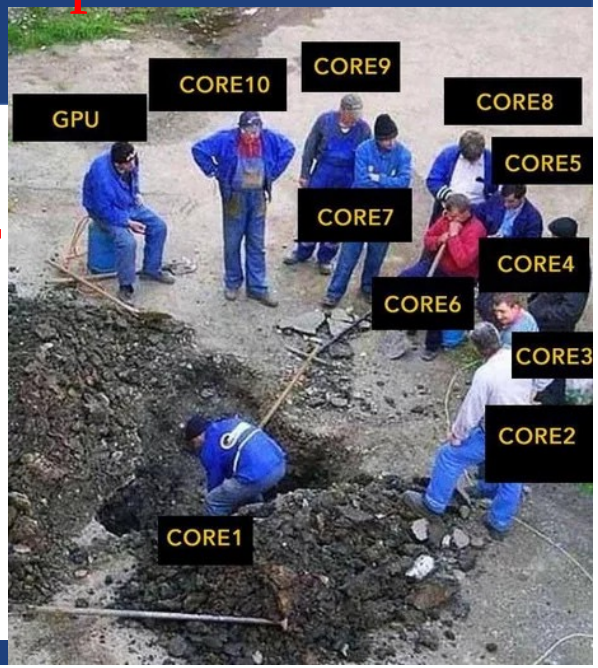
(Slides are mostly by Professors Patrick McDaniel and Abutalib Aghayev)



Sequential Programming

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- Processing a network connection as it arrives and fulfilling the exchange completely is sequential processing
  - i.e., connections are processed in sequence of arrival


```
listen_fd = Listen(port);
while(1) {
  client_fd = accept(listen_fd);
  buf = read(client_fd);
  write(client_fd, buf);
  close(client_fd);
}
```

Whither sequential?

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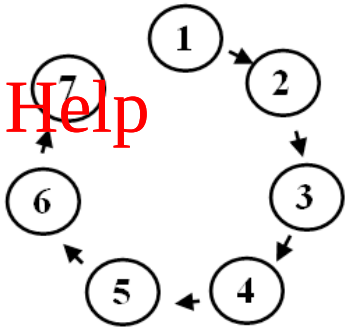
- Benefits
  - simple to implement
  - very little persistent state to maintain
  - few complex error conditions
- Disadvantages
  - Sometimes poor performance
    - one slow client causes all others to block
    - poor utilization of network, CPU



Think about it this way: if the class took the final exam sequentially, it would take 25 days to complete

An alternate design …

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- Why not process multiple requests at the same time, interleaving processing while waiting for other actions (e.g., read requests) to complete?
- This is known as concurrent processing …
  - Process multiple requests concurrently

- Approaches to concurrent server design
  - Asynchronous servers (`select()`)
  - Multiprocess servers (`fork()`)
  - Multithreaded servers (`pthreads`)

Concurrency with processes

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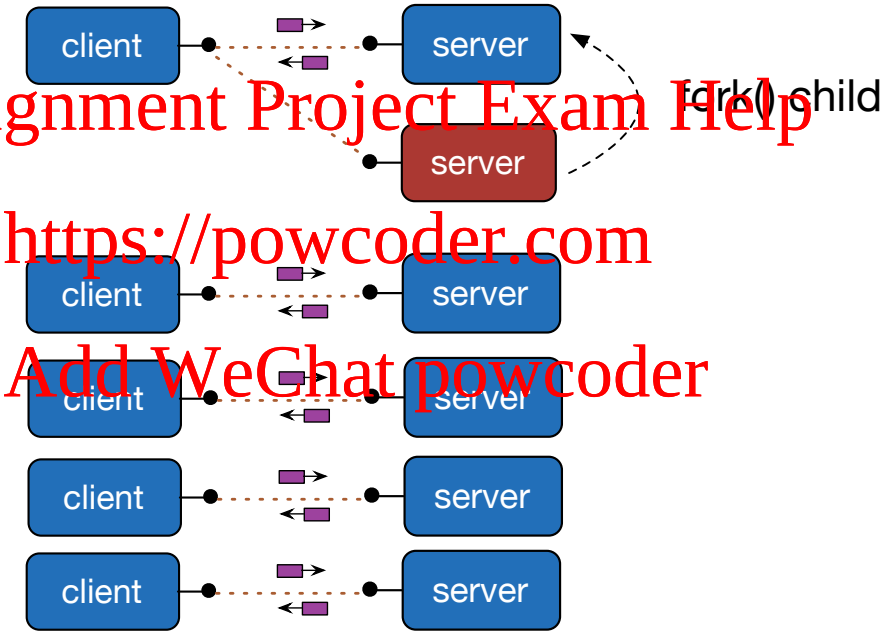
- The server process blocks on `accept()`, waiting for a new client to connect
  - when a new connection arrives, the parent calls `fork()` to create another process
  - the child process handles that new connection, and `exit()`'s when the connection terminates
- Children become "zombies" after death
  - `wait()` to "reap" children

Graphically



fork()

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- The fork function creates a new process by duplicating the calling process.

```
pid_t fork(void);
```


- The new child process is an exact duplicate of the calling parent process, except that it has its own process ID and pending signal queue
- The `fork()` function returns
  - 0 (zero) for the child process OR
  - The child's process ID in the parent code

Idea: think about duplicating the process state and running ....

Process control

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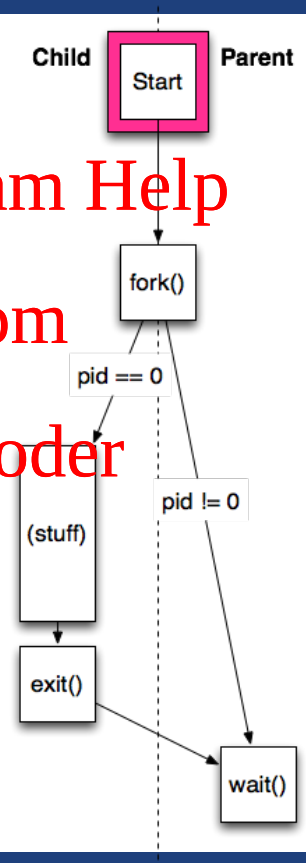
- Parent
  - fork (pid == child PID)
  - wait for child to complete (maybe)
- Child
  - begins at fork (pid == 0)
  - runs until done
  - calls exit



exit()

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- The `exit` causes normal process termination with a return value

```
void exit(int status);
```


- Where
  - status is sent to the to the parent

- Note: `exit` vs. `return` from a C program

  - `return` is a language keyword
    - returns (possibly a value) from a function
  - `exit` is a function, eventually calls `_exit` a system call
    - terminates process immediately, returns status to parent
- `exit` and `return` are similar in main function

wait()

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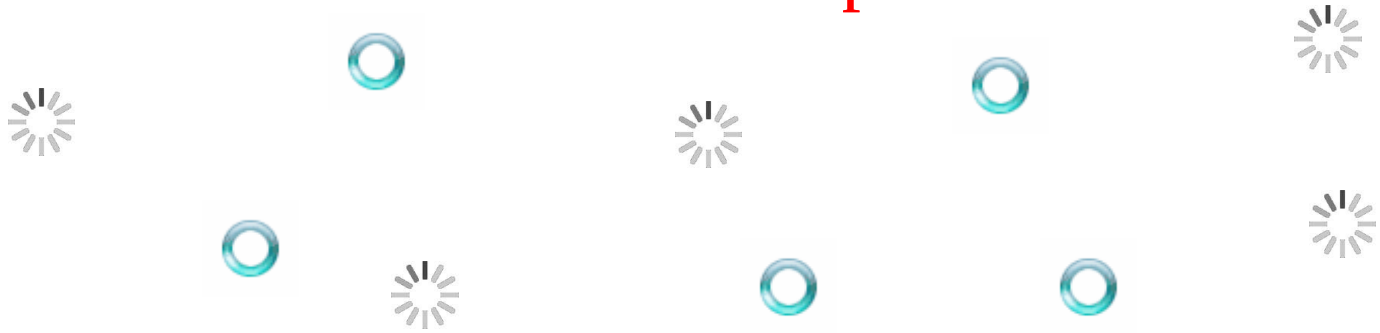
- The `wait` function is used to wait for state changes in a child of the calling process (e.g., to terminate)

```
pid_t wait(int *status);
```

- Where
  - returns the process ID of the child process
  - `status` is return value set by the child process



Putting it all together …

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```
int main(void)
{
    printf("starting parent process\n");
    pid_t pid = fork();

    if (pid < 0) {
        perror("fork failed");
        exit(EXIT_FAILURE);
    }
    if (pid == 0) {
        printf("child processing\n");
        sleep(50);
        exit(19);
    } else {
        printf("parent forked a child with pid = %d\n", pid);
        int status;
        wait(&status);
        printf("child exited with status = %d\n", WEXITSTATUS(status));
    }
    return 0;
}
```

Concurrency with processes

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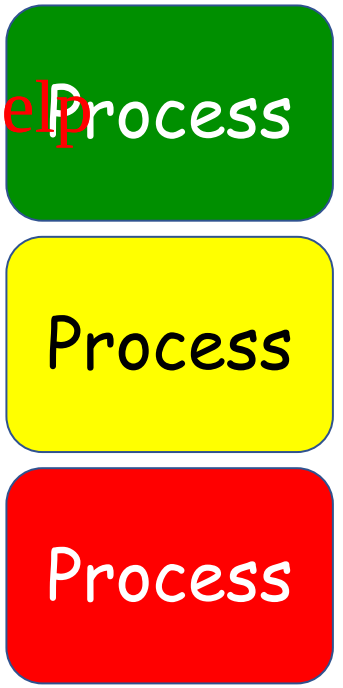
- Benefits
  - almost as simple as sequential
  - in fact, most of the code is identical!
  - parallel execution; good CPU, network utilization
  - often better security (isolation)
- Disadvantages
  - processes are heavyweight
  - relatively slow to fork
  - context switching latency is high
  - communication between processes is complicated



Concurrency with threads

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- A single process handles all of the connections
  - … but … a parent thread forks (dispatches) a new thread to handle each connection
  - the child thread:
    - handles the new connection
    - exits when the connection terminates

Note: you can create as many threads as you want (up to a system limit)

Threads

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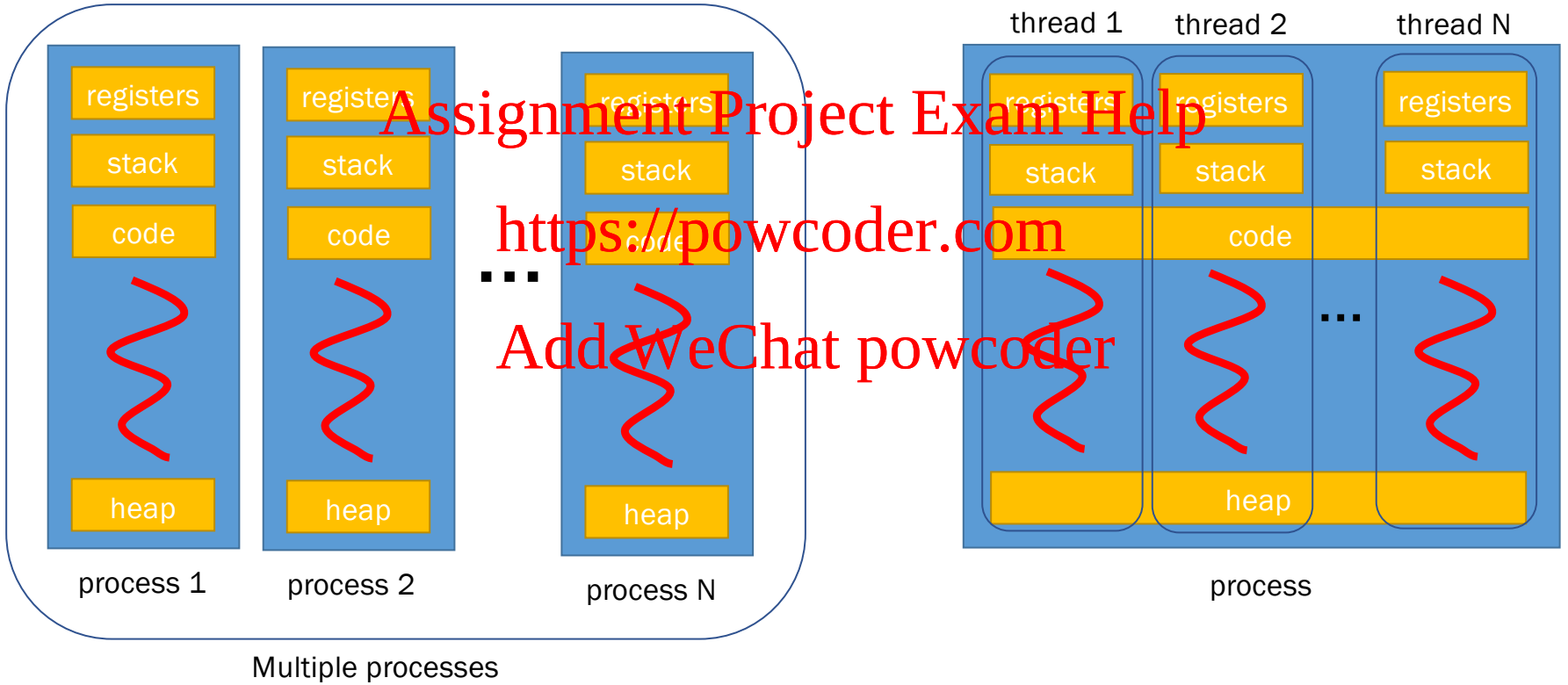
- A thread is defined as an independent stream of instructions that can be scheduled to run as such by the operating system.
  - To the software developer, the concept of a "procedure" that runs independently from its main program.
  - To go one step further, imagine a main program that contains a number of procedures. Now imagine all of these procedures being able to be scheduled to run simultaneously and/or independently by the operating system. That would describe a "*multi-threaded*" program.

Idea: "forking" multiple threads of execution in one process!

Multiple Processes vs Multiple Threads



Threads (cont.)

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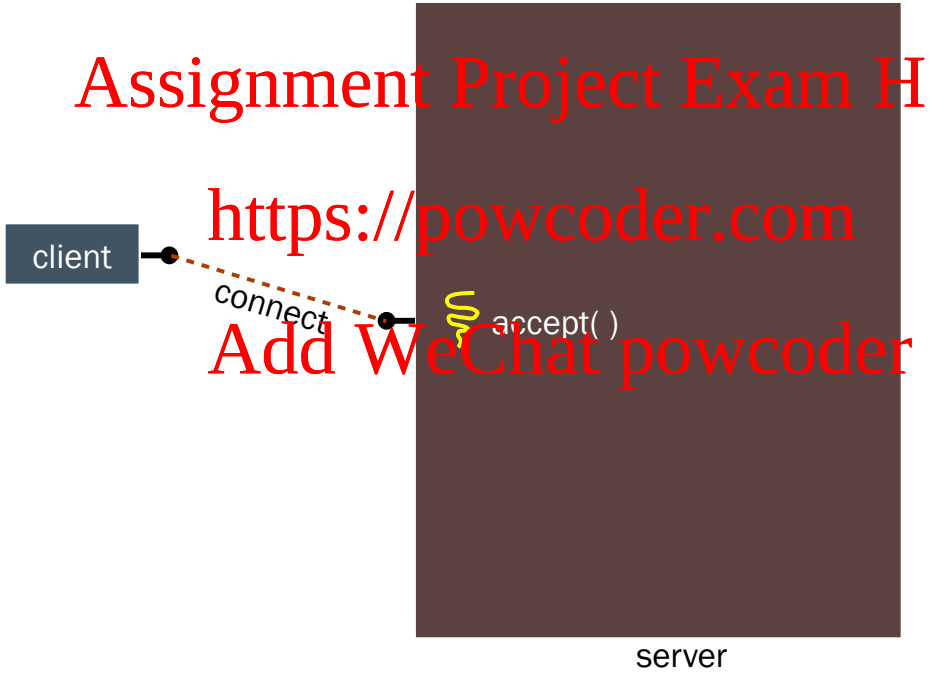
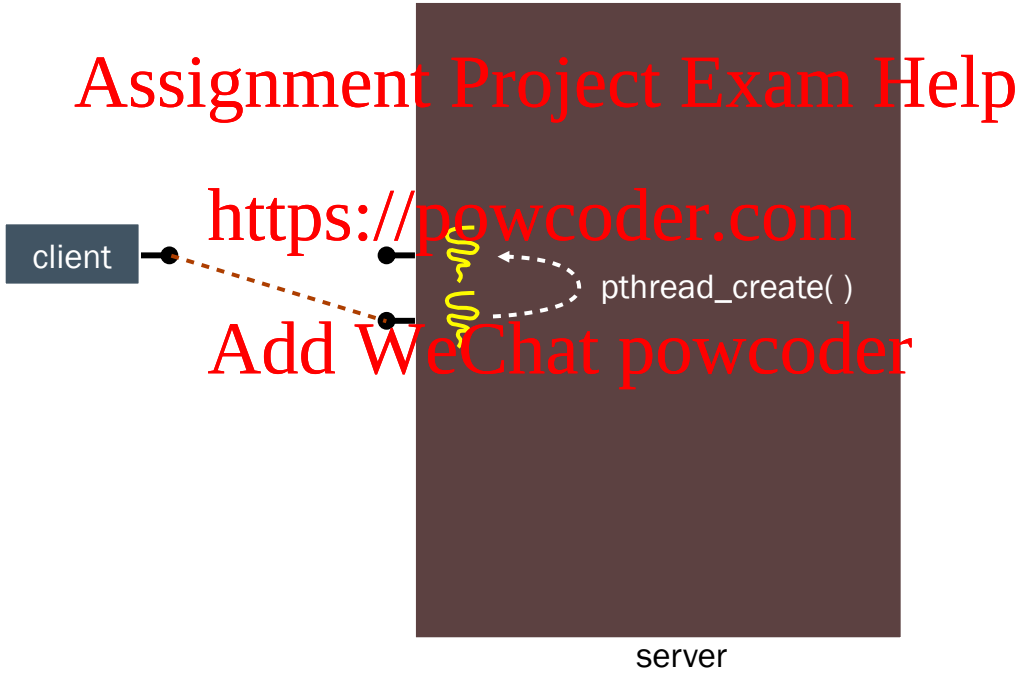
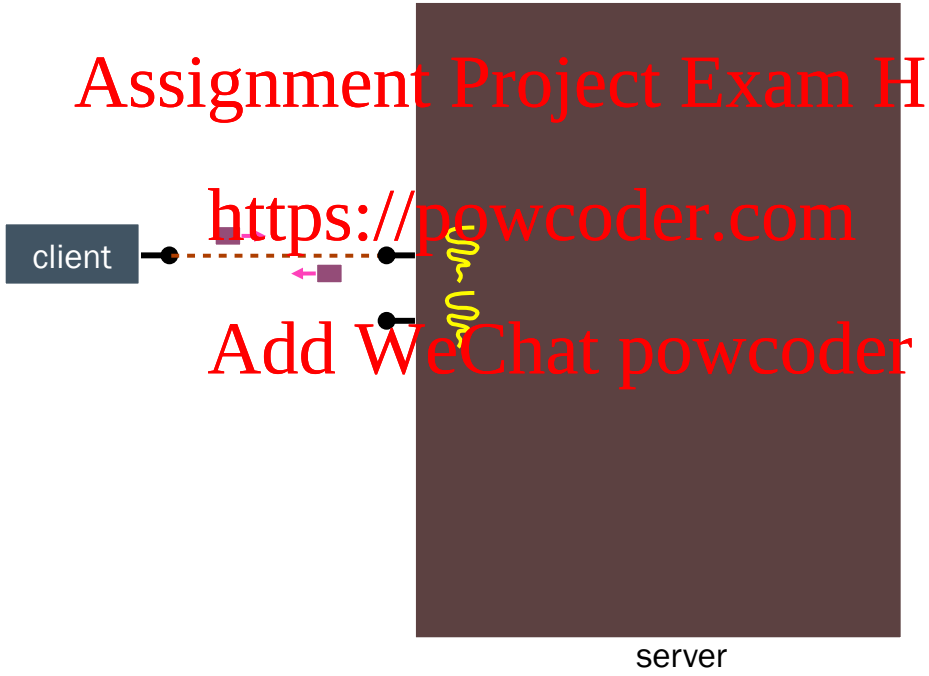


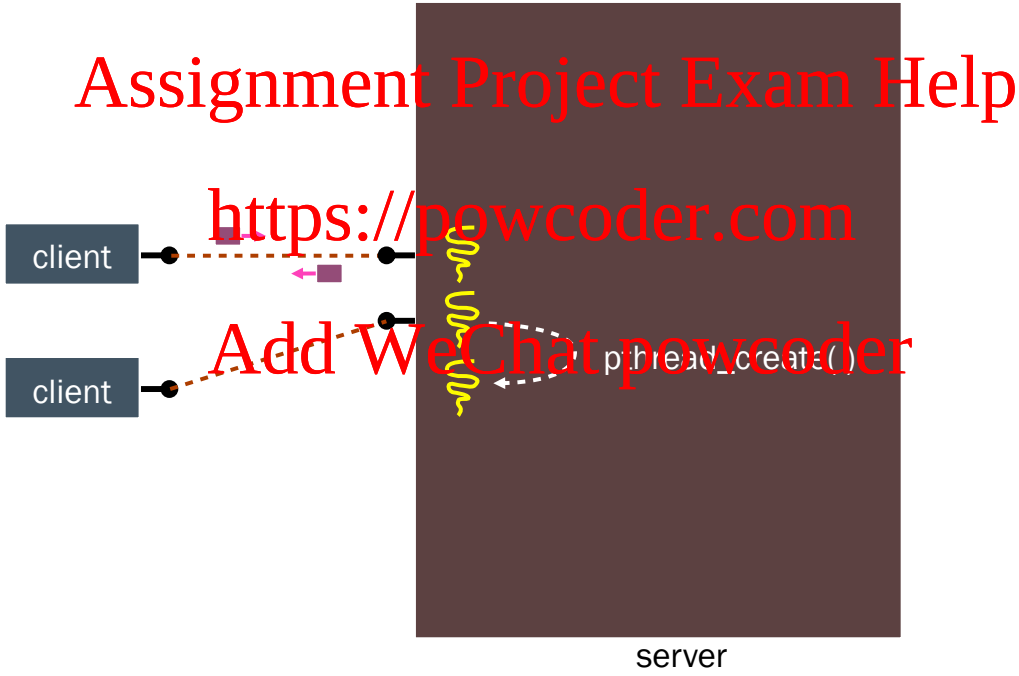
Threads (cont.)



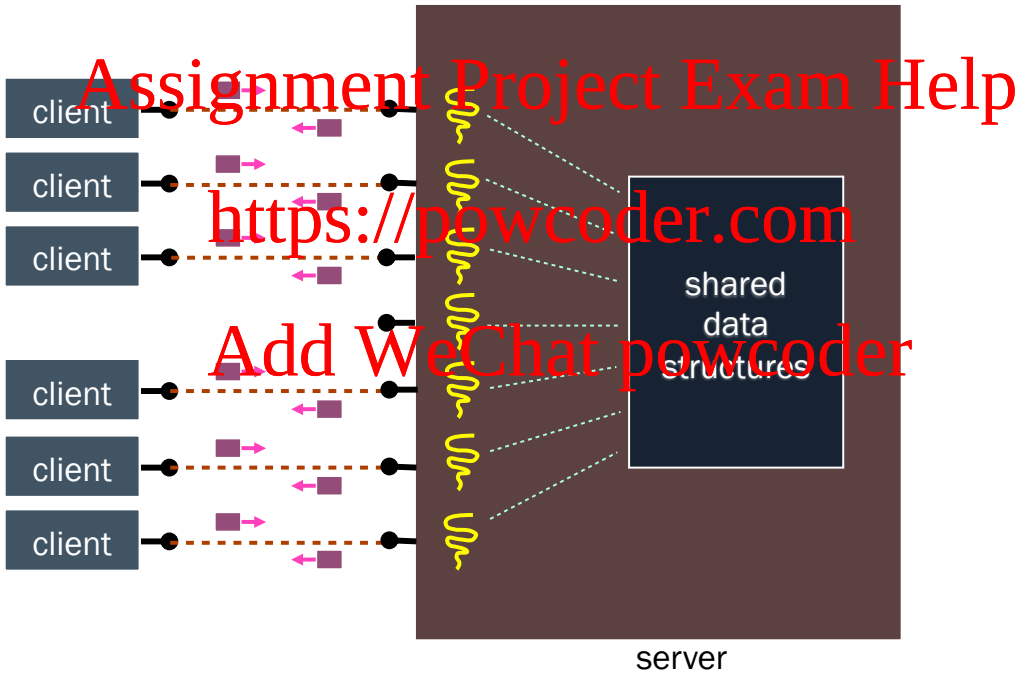
Threads (cont.)



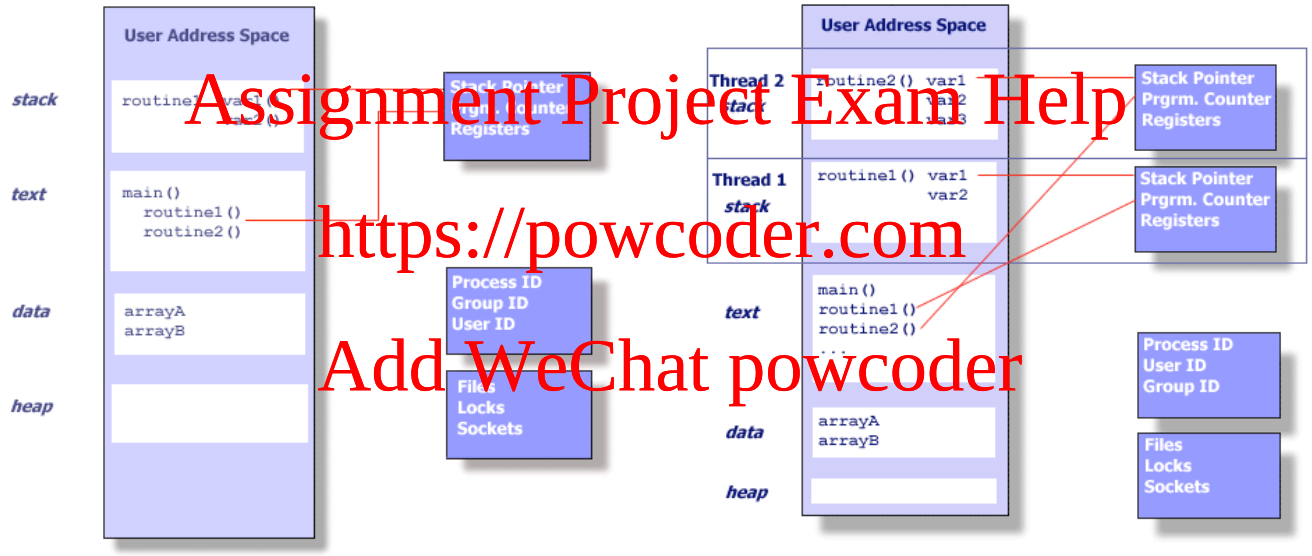
Threads (cont.)



Threads (cont.)



Threads (cont.)



UNIX Process

... and with threads

Threads (cont.)

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- This independent flow of control is accomplished because a thread maintains its own:
  - Stack pointer
  - Registers
  - Scheduling properties (such as policy or priority)
  - Set of pending and blocked signals
  - Thread specific data.

Thread Summary

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- Exists within a process and uses the process resources
- Has its own independent flow of control as long as its parent process exists and the OS supports it
- Duplicates only the essential resources it needs to be independently "schedulable"
- May share the process resources with other threads that act equally independently (and dependently)
- Dies if the parent process dies - or something similar
- Is "lightweight" because most of the overhead has already been accomplished through the creation of its process.

Caveats

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- Because threads within the same process share resources:
  - Changes made by one thread to shared system resources (such as closing a file) will be seen by all other threads.
  - Two pointers having the same value point to the same data.
  - Reading and writing to the same memory locations is possible, and therefore requires explicit synchronization by the programmer.

Warning: shared data between threads can cause conflicts, deadlocks, etc.

Thread control

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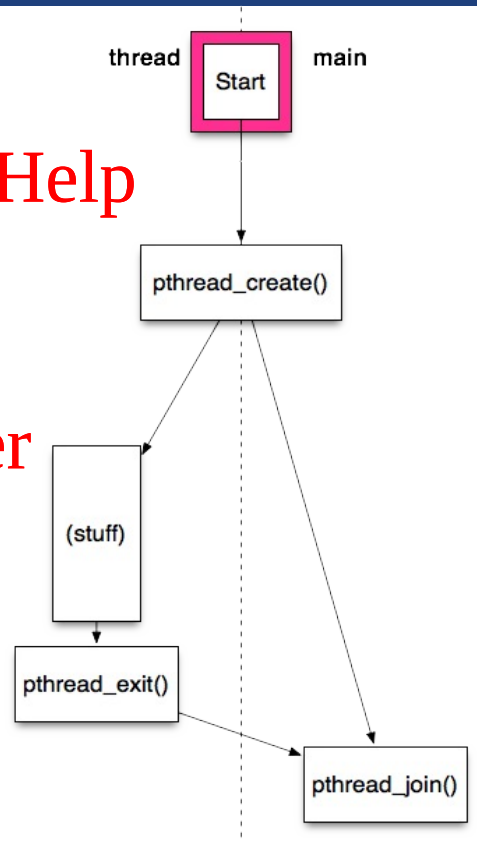
- main
  - `pthread_create()` (create thread)
  - wait for thread to finish via `pthread_join()` (maybe)
- thread
  - begins at function pointer
  - runs until the `return` or `pthread_exit()`
- Library support
  - #include <pthread.h>
  - Compile with option –lpthread to link with the pthread library



pthread_create()

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- The `pthread_create` function starts a new thread in the calling process.

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


- Where,
  - `thread` is a pthread library structure holding thread info
  - `attr` is a set of attributes to apply to the thread
  - `start_routine` is the thread function pointer
  - `arg` is an opaque data pointer to pass to thread

Thread with no arguments

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```c
void *func(void *arg) {
    printf("Hello from thread %lx\n", pthread_self());
    return NULL;
}

int main(void) {
    pthread_t t1, t2, t3;
    printf("main thread %lx starting a new thread\n", pthread_self());
    pthread_create(&t1, NULL, func, NULL);
    pthread_create(&t2, NULL, func, NULL);
    pthread_create(&t3, NULL, func, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    pthread_join(t3, NULL);
    return 0;
}
```

```
$ gcc -Wall t1.c -o t1 -lpthread
[0s euclid:~/tmp (master)]
$ ./t1
Hello from thread 7f475f9c7700
Hello from thread 7f475e6a5700
Hello from thread 7f475f036700
[0s euclid:~/tmp (master)]
$
```

```
$ ./t1
Hello from thread 7f2a426fb700
Hello from thread 7f2a4308c700
Hello from thread 7f2a41d6a700
[0s euclid:~/tmp (master)]
$
```


- Always check return values (omitted for brevity)
- Thread becomes alive in pthread_create – may even run before it returns

Thread with one argument

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```c
void *func(void *arg) {
    char *s = (char *) arg;
    printf("Hello from thread %s\n", s);
    return NULL;
}

int main(void) {
    pthread_t t1, t2, t3;
    pthread_create(&t1, NULL, func, "a");
    pthread_create(&t2, NULL, func, "b");
    pthread_create(&t3, NULL, func, "b");
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    pthread_join(t3, NULL);
    return 0;
}
```

```
$ ./t2
Hello from thread b
Hello from thread c
Hello from thread a
[0s euclid:~/tmp (master)]
$
```

```
$ ./t2
Hello from thread b
Hello from thread a
Hello from thread c
[0s euclid:~/tmp (master)]
$
```


- Run the above program in a loop to observe indeterminate scheduling

Thread with multiple arguments

```c
typedef struct {
    int num;
    const char *str;
} foo_t;

void *func(void *arg) {
    foo_t *val = arg;
    printf("thread %lx was passed values %d, %s\n", pthread_self(), val->num, val->str);
    return NULL;
}

int main(void) {
    foo_t v = {5678, "bar"};
    pthread_t t;
    printf("main thread %lx starting a new thread\n", pthread_self());
    pthread_create(&t, NULL, func, &v);
    pthread_join(t, NULL);
    return 0;
}
```

```
$ ./t3
main thread 7f46f18d0740 starting a new thread
thead 7f46f18cf700 was passed values 5678, bar
[05 euc:bin:~/tmp (master)]
$
```


- The above is effectively a procedure call – real programs are more complex

pthread_join()

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- The `pthread_join` function waits for the thread specified by thread to terminate.

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

- Where,
  - `thread` is a pthread library structure holding thread info
  - `retval` is a double pointer return value

Returning values from a thread

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```
typedef struct {
    int num;
    char *str;
} foo_t;

void *func(void *arg) {
    foo_t *a = arg;
    foo_t *b = malloc(sizeof(foo_t));
    b->num = a->num * 2;
    b->str = malloc(strlen(a->str) + 1);
    strcpy(b->str, a->str);
    for (char *p = b->str; *p; ++p)
        *p = toupper(*p);
    return b;
}

int main(void) {
    foo_t v = {5678, "bar"}, *p;
    pthread_t t;
    printf("main thread %lx starting a new thread\n", pthread_self());
    pthread_create(&t, NULL, func, &v);
    pthread_join(t, (void **) &p);
    printf("thread returned num = %d, str = %s\n", p->num, p->str);
    return 0;
}
```

```
$ ./t4
main thread 7ff9ecc10740 starting a new thread
thread returned num = 11356, str = BAR
[0s euclid:~/tmp (master)]
$
```

Returning values from a thread

```c
typedef struct {
    int num;
    const char *str;
} foo_t;

void *func(void *arg) {
    foo_t p;
    // fill p
    return &p;
}

int main(void) {
    foo_t v = {5678, "bar"}, *p;
    pthread_t t;
    printf("main thread %lx starting a new thread\n", pthread_self());
    pthread_create(&t, NULL, func, &v);
    pthread_join(t, (void **) &p);
    printf("thread returned num = %d, str = %s\n", p->num, p->str);
    return 0;
}
```


- The above will segfault! Do not return a pointer to a stack-allocated variable

pthread_exit()

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- The `pthread_exit` function terminates the calling thread and returns a value


```
void pthread_exit(void *retval);
```


- Where,
  - `retval` is a pointer to a return value

Threads accessing shared data

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```c
static int counter = 0;

void *func(void *arg) {
  for (int i = 0; i < 5000; ++i)
    ++counter;
  return NULL;
}

int main(void)
{
    pthread_t t1, t2;
    printf("counter = %d\n", counter);
    pthread_create(&t1, NULL, func, NULL);
    pthread_create(&t2, NULL, func, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("both threads completed, counter = %d\n", counter);
    return 0;
}
```

```
main: counter = 0
main: both threads completed, counter = 10000

main: counter = 0
main: both threads completed, counter = 7401

main: counter = 0
main: both threads completed, counter = 9552
```


- What will this program output?

What is happening? A race condition!

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- Race condition happens when the outcome of a program depends on the interleaving of the execution of multiple threads accessing critical section
- Critical section is a piece of code that accesses a shared variable and must not be concurrently executed by more than one thread


```
mov     0x2e50(%rip),%eax        # 4014 <counter>
add     $0x1,%eax
mov     %eax,0x2e47(%rip)        # 4014 <counter>
```

- Each instruction executed atomically
- Multiple threads executing the above instructions can result in different interleavings (and outcomes) due to uncontrollable OS scheduling

One Possible Interleaving

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OS	Thread 1	Thread 2	PC	eax (after instruction)	counter
	before critical section		100	0	50
	`mov 8049a1c,%eax`		105	**50**	50
	`add $0x1,%eax`		108	**51**	50
interrupt					
save T1					
restore T2			100	0	50
		`mov 8049a1c,%eax`	105	**50**	50
		`add $0x1,%eax`	108	**51**	50
		`mov %eax,8049a1c`	113	51	**51**
interrupt					
save T2					
restore T1			108	51	51
	`mov %eax,8049a1c`		113	51	**51**

Avoiding race conditions

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- To avoid race conditions we need to ensure that only a single thread can execute a critical section at any given time
- For simple cases we can use atomics (#include <stdatomic.h>)
  - modifying a variable results in a single CPU instruction
- In general, however, a critical section may contain complex logic
- We need primitives for mutual exclusion – a guarantee that only one thread is executing the critical section while others are prevented from doing so
- One way to achieve mutual exclusion is using locks:

```
lock_t mutex
lock(&mutex)
critical section
unlock(&mutex)
```

Threads accessing shared data

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- Fixing race condition using atomics

```
#include <stdatomic.h>

static atomic_int counter = 0;

void *func(void *arg) {
  for (int i = 0; i < 5000; ++i)
    ++counter;
  return NULL;
}

int main(void)
{
    pthread_t t1, t2;
    printf("counter = %d\n", counter);
    pthread_create(&t1, NULL, func, NULL);
    pthread_create(&t2, NULL, func, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("both threads completed, counter = %d\n", counter);
    return 0;
}
```

Threads accessing shared data – Fixed!

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- Fixing race condition using mutexes

```
static int counter = 0;
pthread_mutex_lock_t lock = PTHREAD_MUTEX_INITIALIZER;

void *func(void *arg) {
  for (int i = 0; i < 5000; ++i) {
    pthread_mutex_lock(&lock);
    ++counter;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}

int main(void)
{
    pthread_t t1, t2;
    printf("counter = %d\n", counter);
    pthread_create(&t1, NULL, func, NULL);
    pthread_create(&t2, NULL, func, NULL);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("both threads completed, counter = %d\n", counter);
    return 0;
}
```

Threads tradeoffs

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- Benefits
  - still the case that much of the code is identical!
  - parallel execution; good CPU, network utilization
  - lower overhead than processes
  - shared-memory communication is possible
- Disadvantages
  - synchronization is complicated
  - shared fate within a process; one rogue thread can hurt you
  - security (no isolation)

- We scratched the surface – more advanced usage will be taught in 473