Concurrency

CMSC 257: Computer Systems

Instructor:

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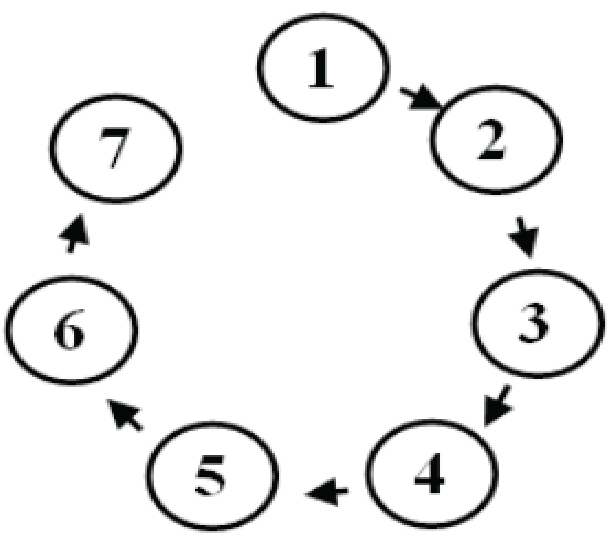
Sequential Programming

- 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);
}
```

Why Sequential

- Benefits
  - super simple to build
  - very little persistent state to maintain
- Disadvantages
  - incredibly poorly performing
    - one slow client causes *all others to block*
    - poor utilization of network, CPU
    - cannot interleave processing



An alternate design ...

- Why not process multiple requests at the same time, interleaving processing while waiting for other dependent actions (DB dips) to complete?
- This is known as *concurrent processing ...*
  - Process multiple requests concurrently

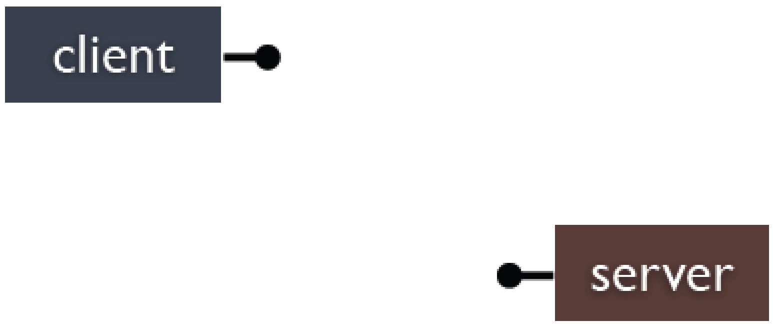
- We have/will explore three concurrency approaches
  1. Event programming using select() [will be covered later under network programming]
  2. Creating “child” processes using fork()
  3. Creating multithreaded programs using pthreads

Concurrency with processes

- 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

Graphically



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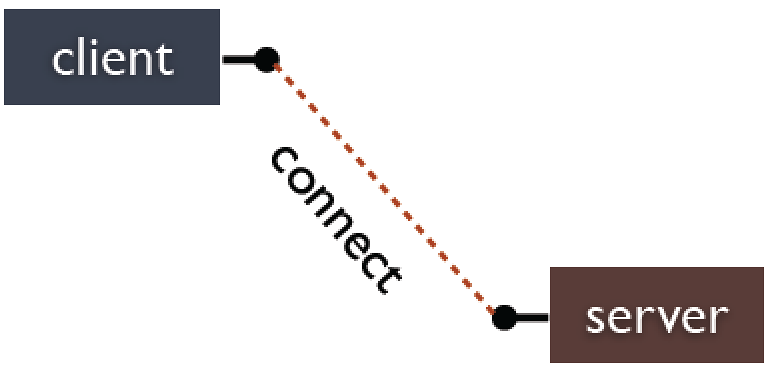

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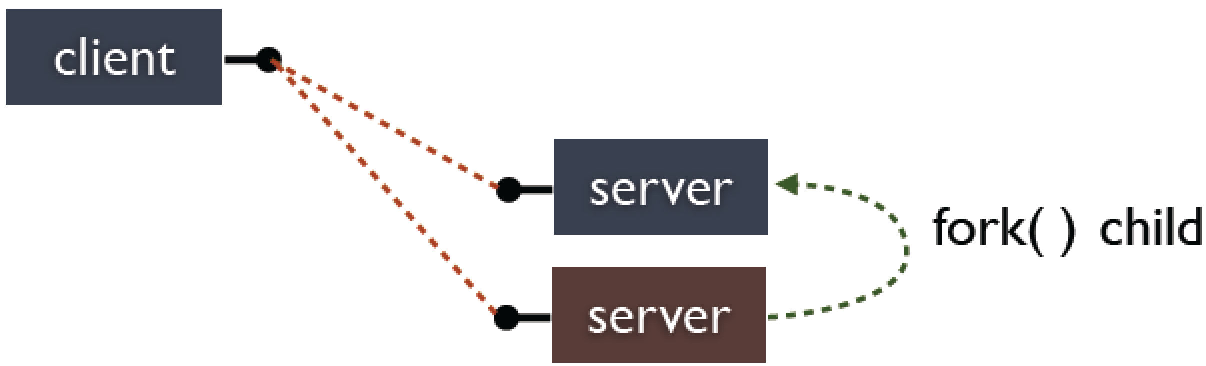

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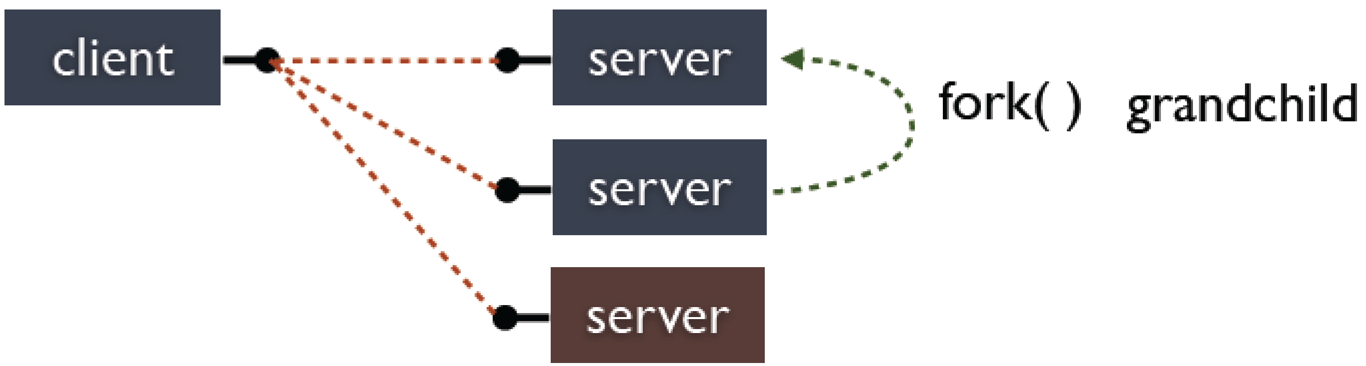

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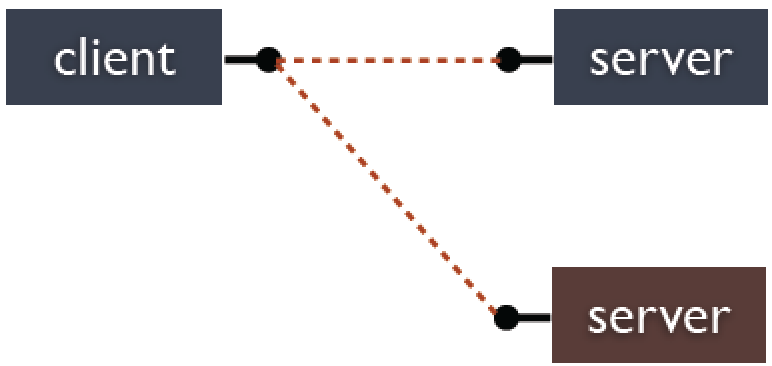
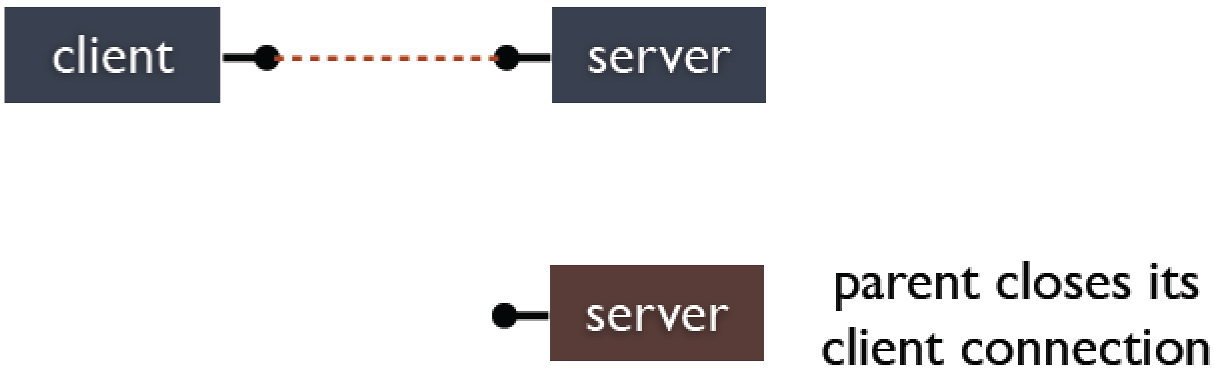


child exit( )'s / parent wait( )'s

Graphically



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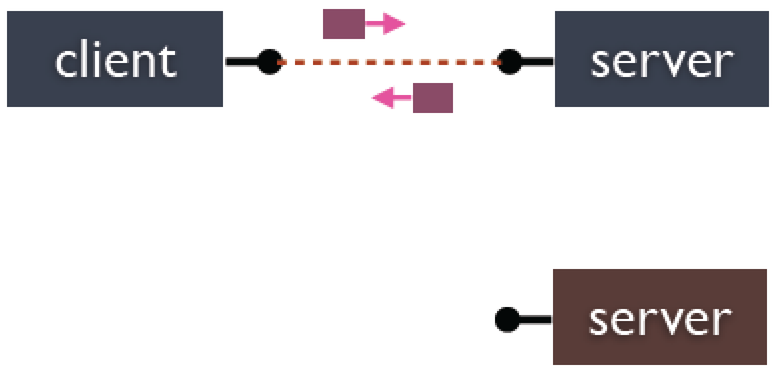

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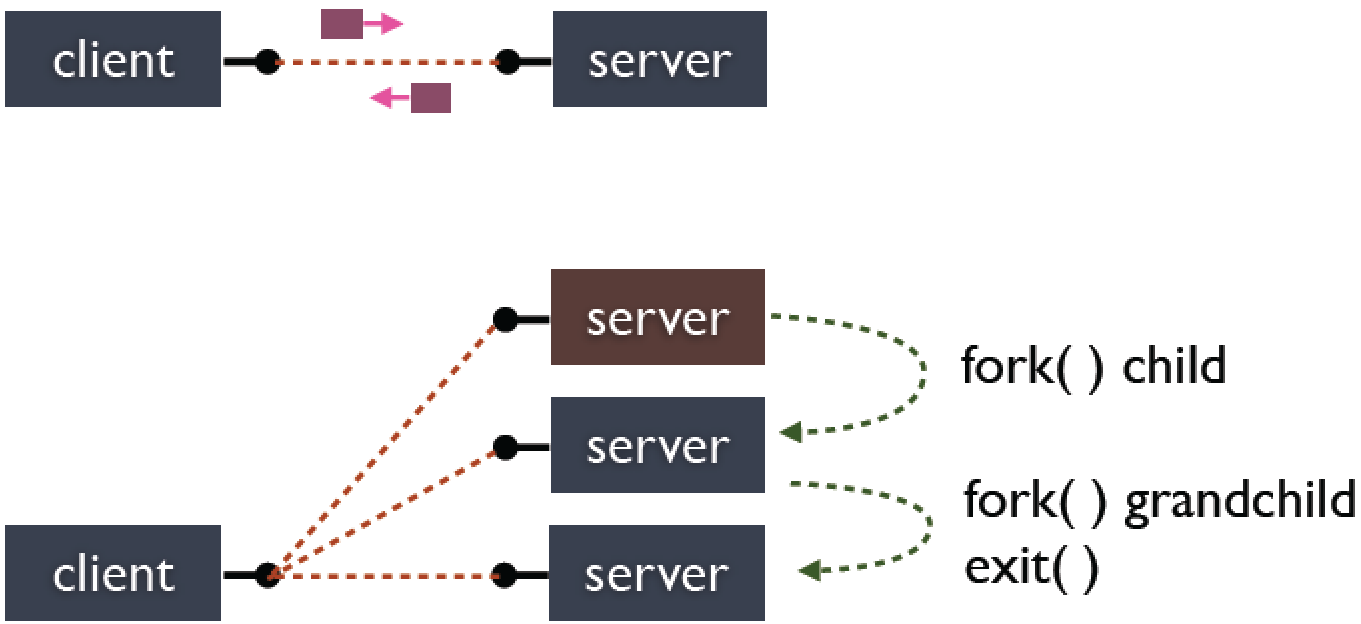

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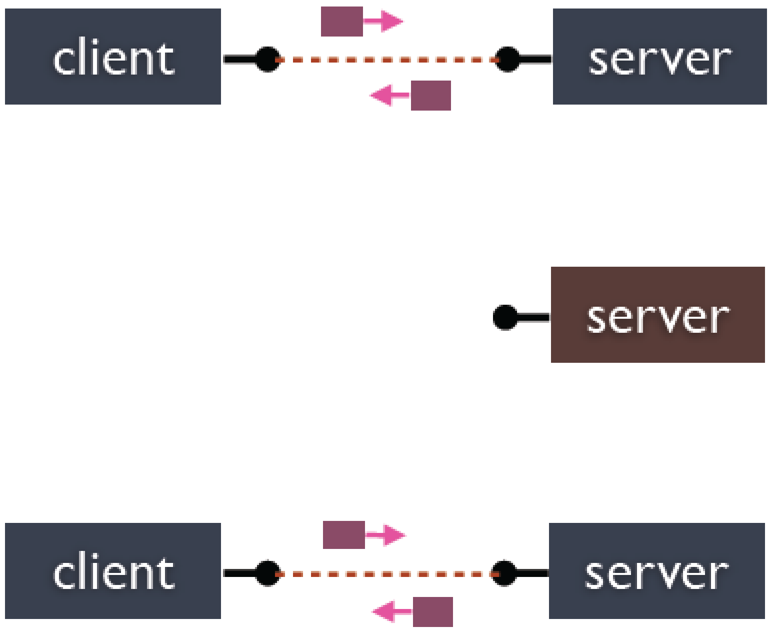

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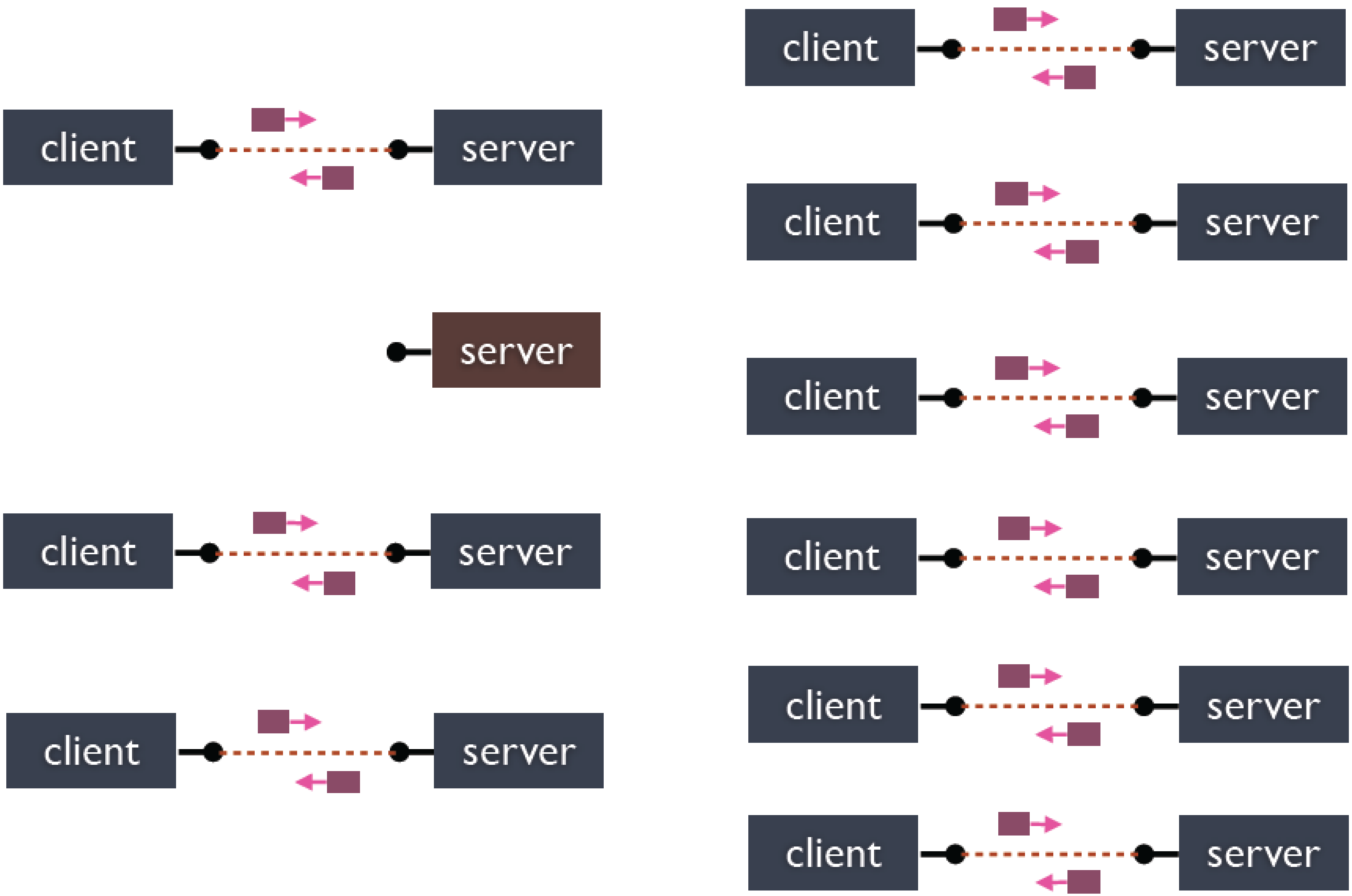


fork()

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

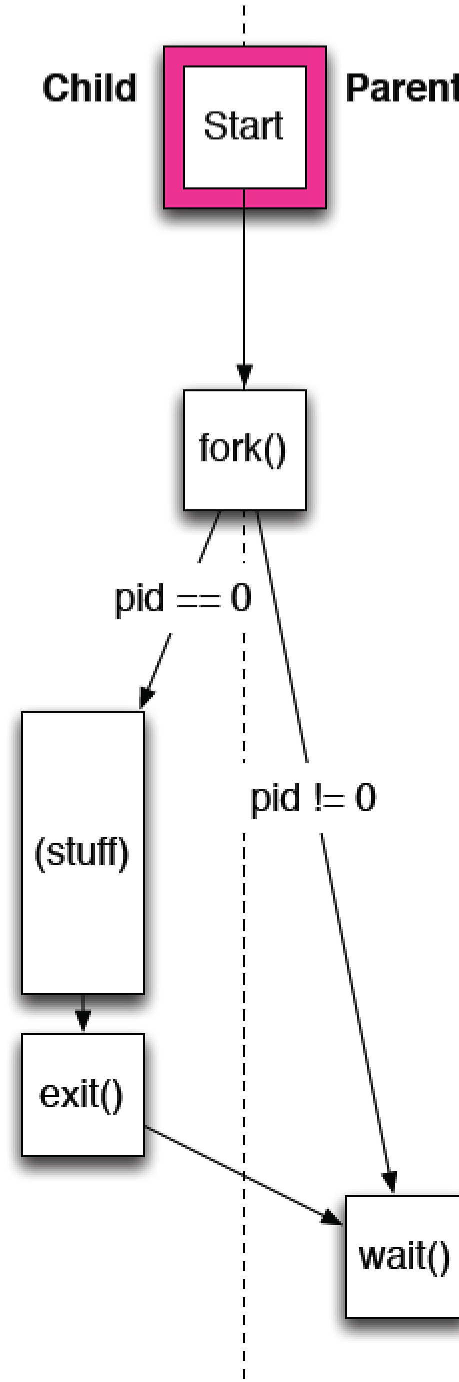
pid_t fork(void);

- 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

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



exit()

- The exit causes normal process termination with a return value

void exit(int status);

- Where
  - status is sent to the to the parent (&0377- in octal)

- Note: exit vs. return from a C program
  - return simply returns a normal execution
  - exit kills the process via system call
  - Consequence: return is often cleaner for certain things that run at exit (more of a C++ concern)

wait()

- 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

wait() and the watchdog

- Often you will want to safeguard a process by "watching" it execute. If the process terminates then you take some action (when wait() returns).
    - This is called a *watchdog process* *(or watchdog fork)*
    - Idea: you fork the process and simply wait for it to terminate
        - Take some action based on the idea that the termination should not have happened or that some recovery is needed.
            - e.g., restart a web server when it crashes

- Watchdogs are very often used for critical services.

Putting it all together ...

```
int main( void ) {

    pid_t childpid; // Child process ID
    int status;     // Childs exist status

    printf( "Stating our process control example ...\n" );
    childpid = fork(); // Fork the process

    if ( childpid >= 0 ) {
        if ( childpid == 0 ) { // In child process
            printf( "Child processing,\n" );
            sleep( 1 );
            exit( 19 );
        } else { // In parent process
            printf( "Parent processing (child=%d),\n", childpid );
            wait( &status );
            printf( "Child exited with status=%d.\n", WEXITSTATUS(status) );
        }
    }
    else {
        perror( "What the fork happened" );
        exit( -1 );
    }
    return( 0 );
}
```

Putting it all together ...

```c
int main( void ) {

    pid_t childpid; // Child process ID
    int status;     // Childs exist status

    printf( "Stating our process control example ...\n" );
    childpid = fork(); // Fork the process

    if ( childpid >= 0 ) {
        if ( childpid == 0 ) { // In child process
            printf( "Child processing,\n" );
            sleep( 1 );
            exit( 19 );
        } else { // In parent process
            printf( "Parent processing (child=%d),\n", childpid );
            wait( &status );
            printf( "Child exited with status=%d.\n", WEXITSTATUS(status) );
        }
    }
    else {
        perror( "What the fork h
        exit( -1 );
    }
    return( 0 );
}
```

```
$ ./forker
Stating our process control example ...
Parent processing (child=3530),
Child processing.
Child exited with status=19.
$
```

Process Control Tradeoffs

- Benefits
  - almost as simple as sequential
  - in fact, most of the code is identical!
  - parallel execution; good CPU, network utilization
  - often better security (isolation)

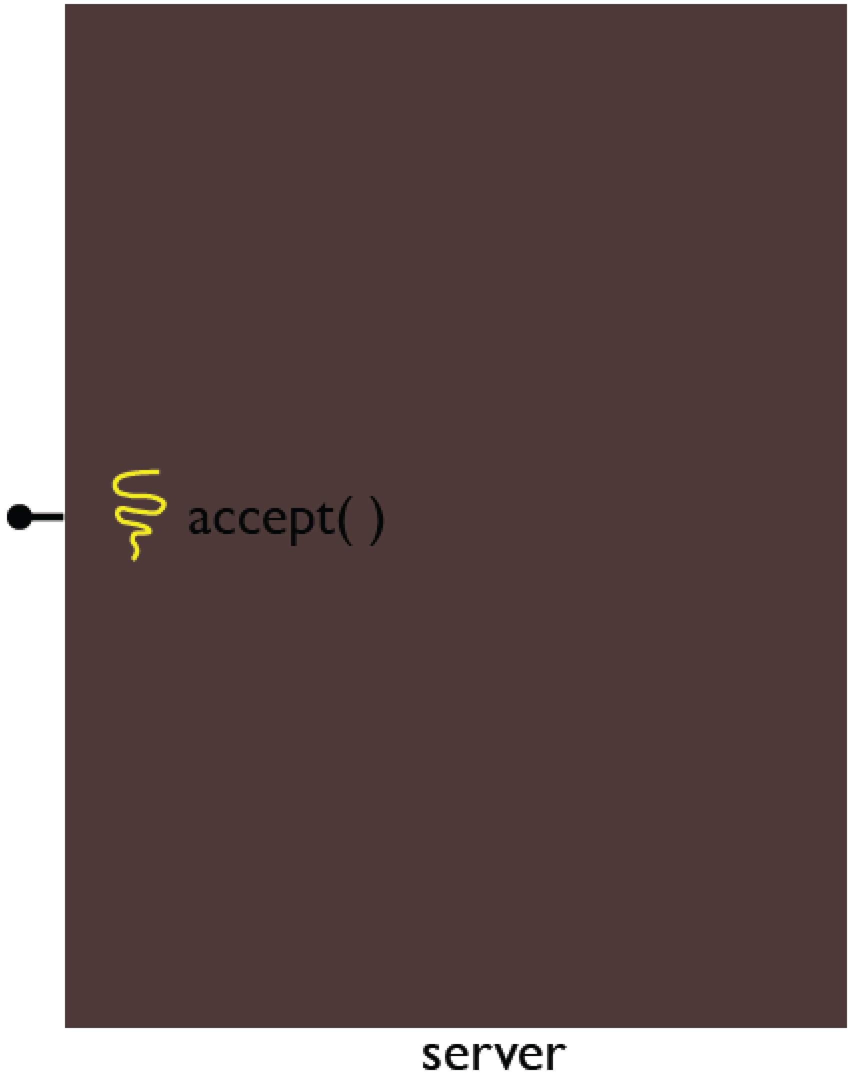
- Disadvantages
  - processes are heavyweight
  - relatively slow to fork
  - context switching latency is high
  - communication between processes is complicated

Concurrency with threads

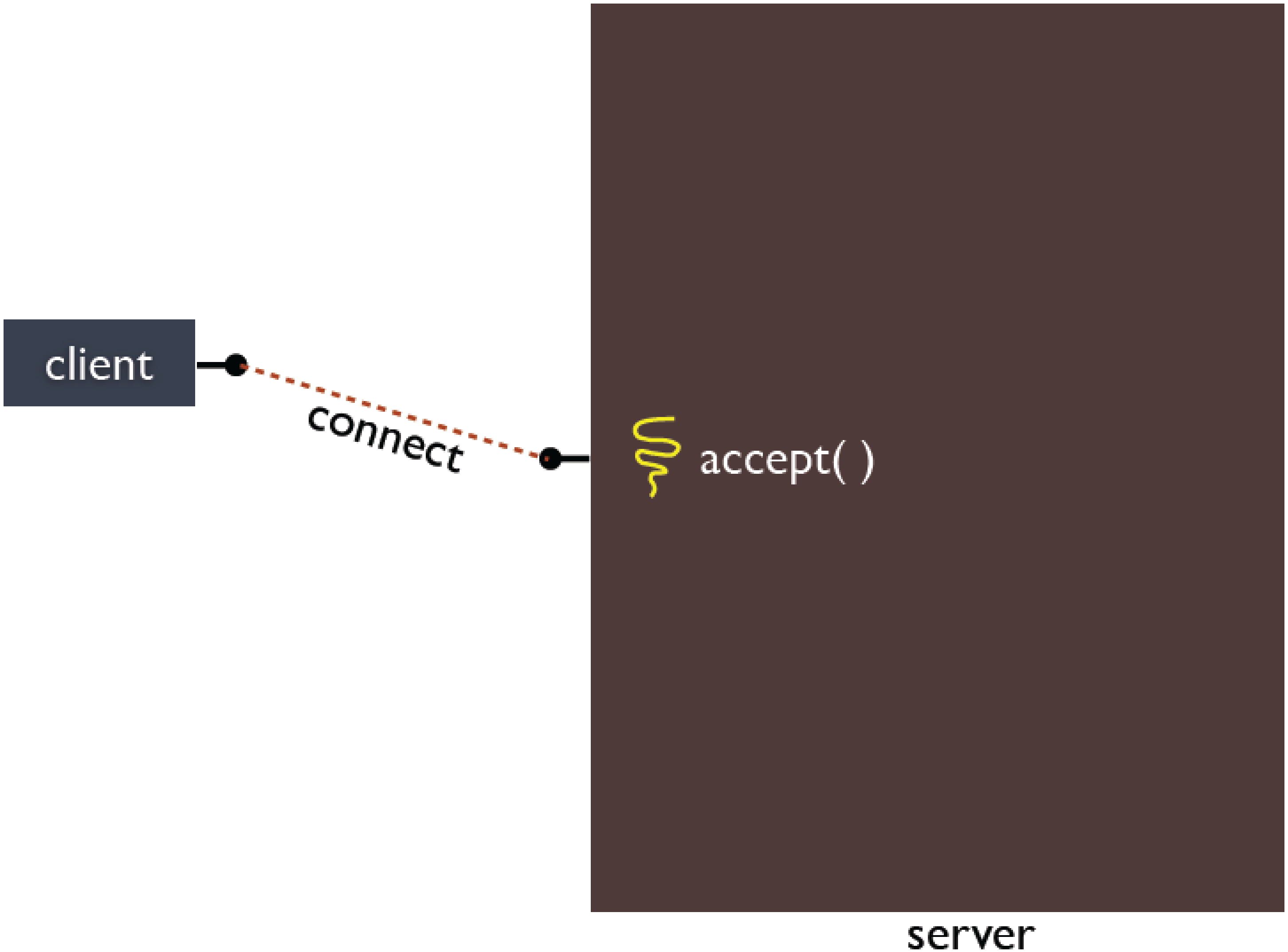
- A single process handles all of the connections
  - but, a *parent thread forks (or dispatches) a new thread to* handle each connection
  - the *child thread:*
    - handles the new connection
    - exits when the connection terminates

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

Threads (cont.)



Threads (cont.)



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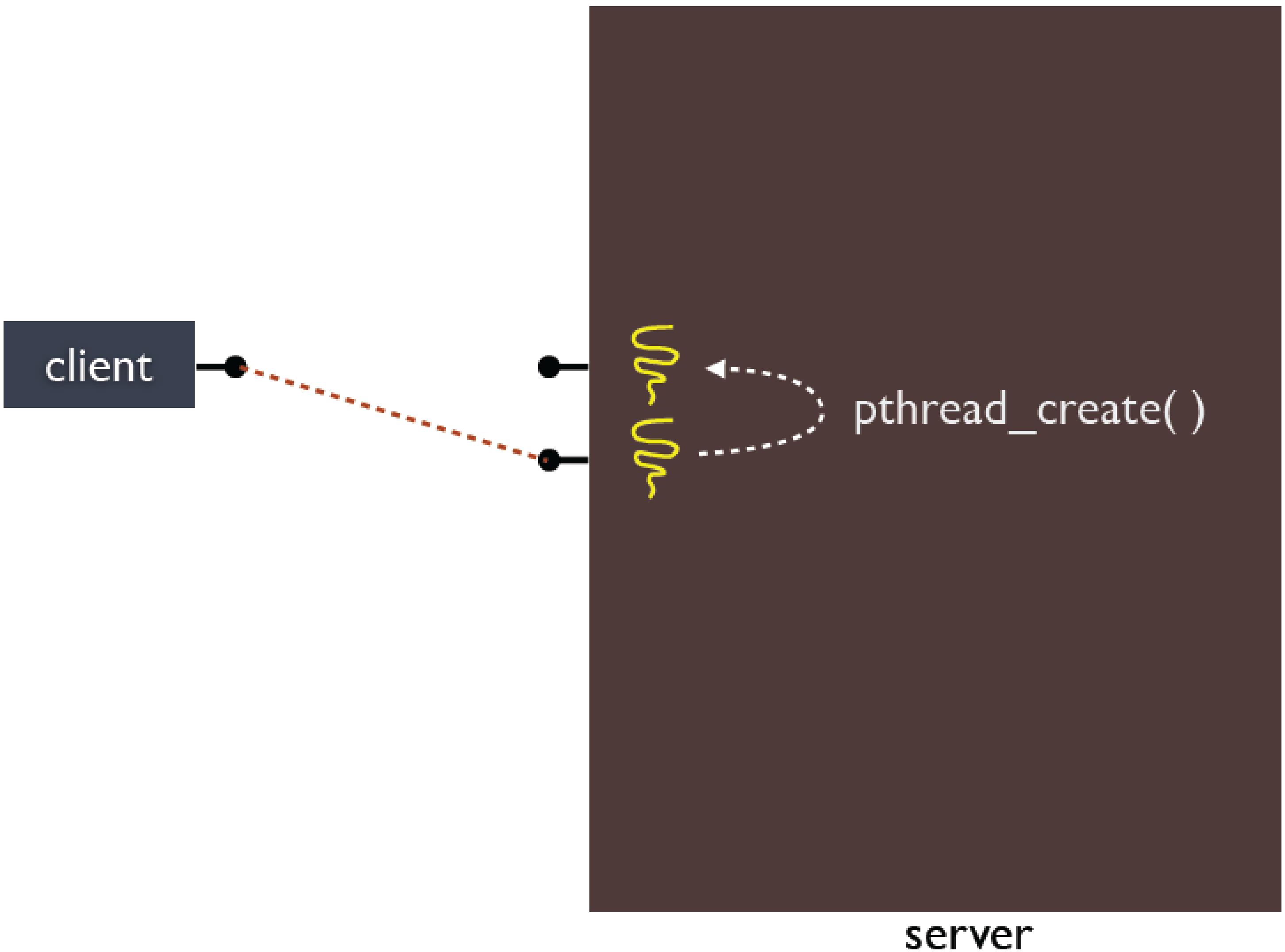
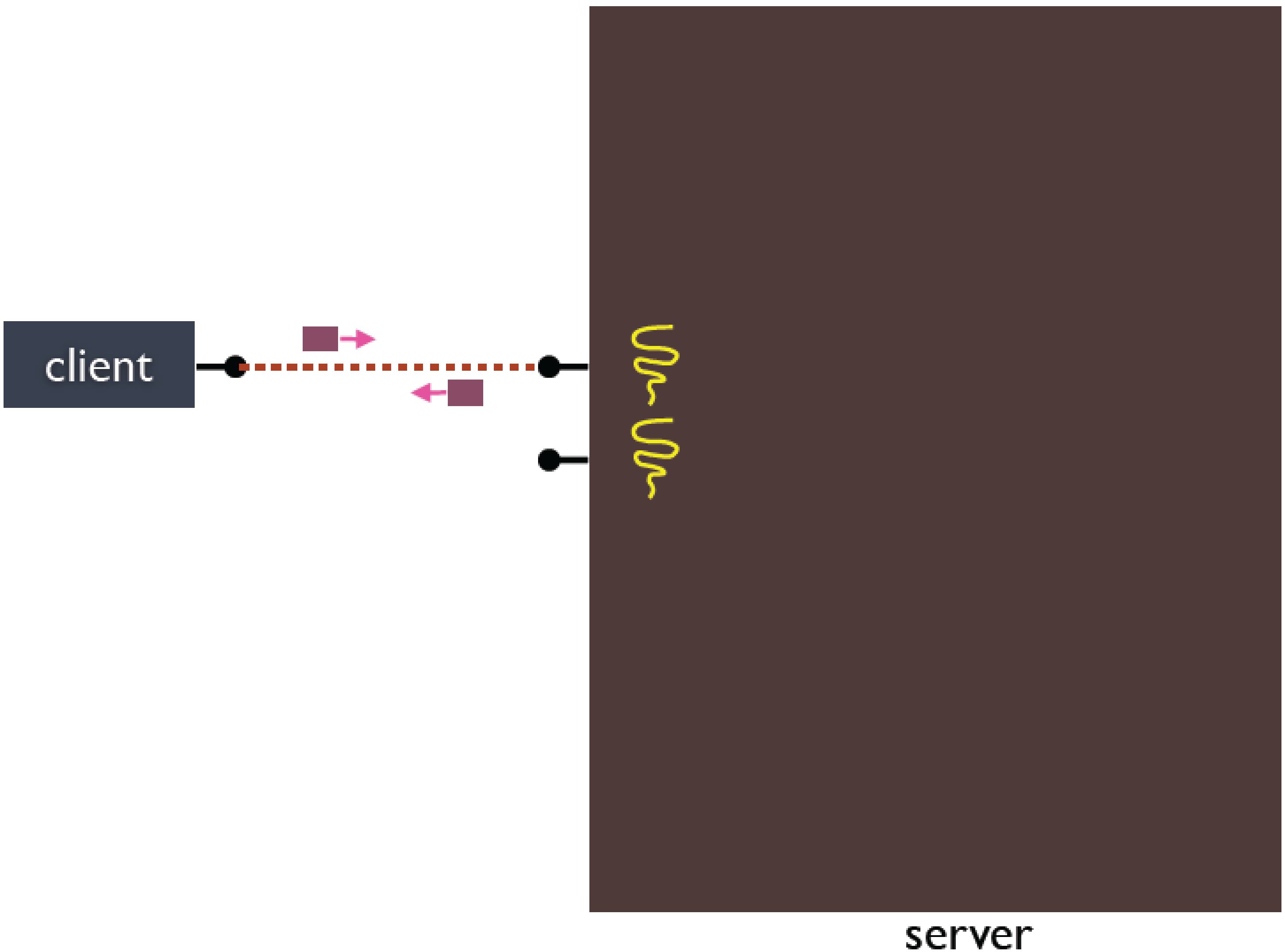
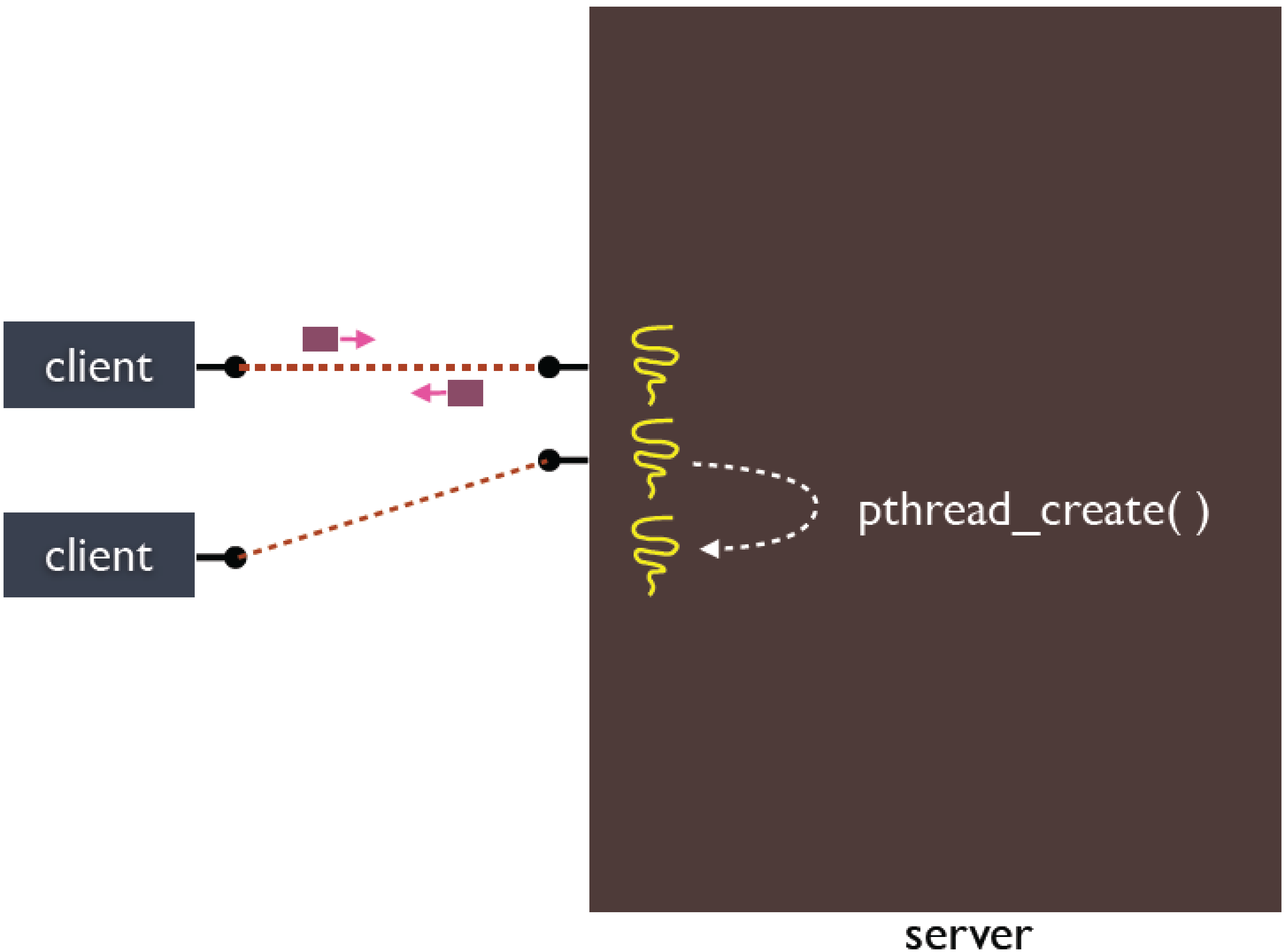


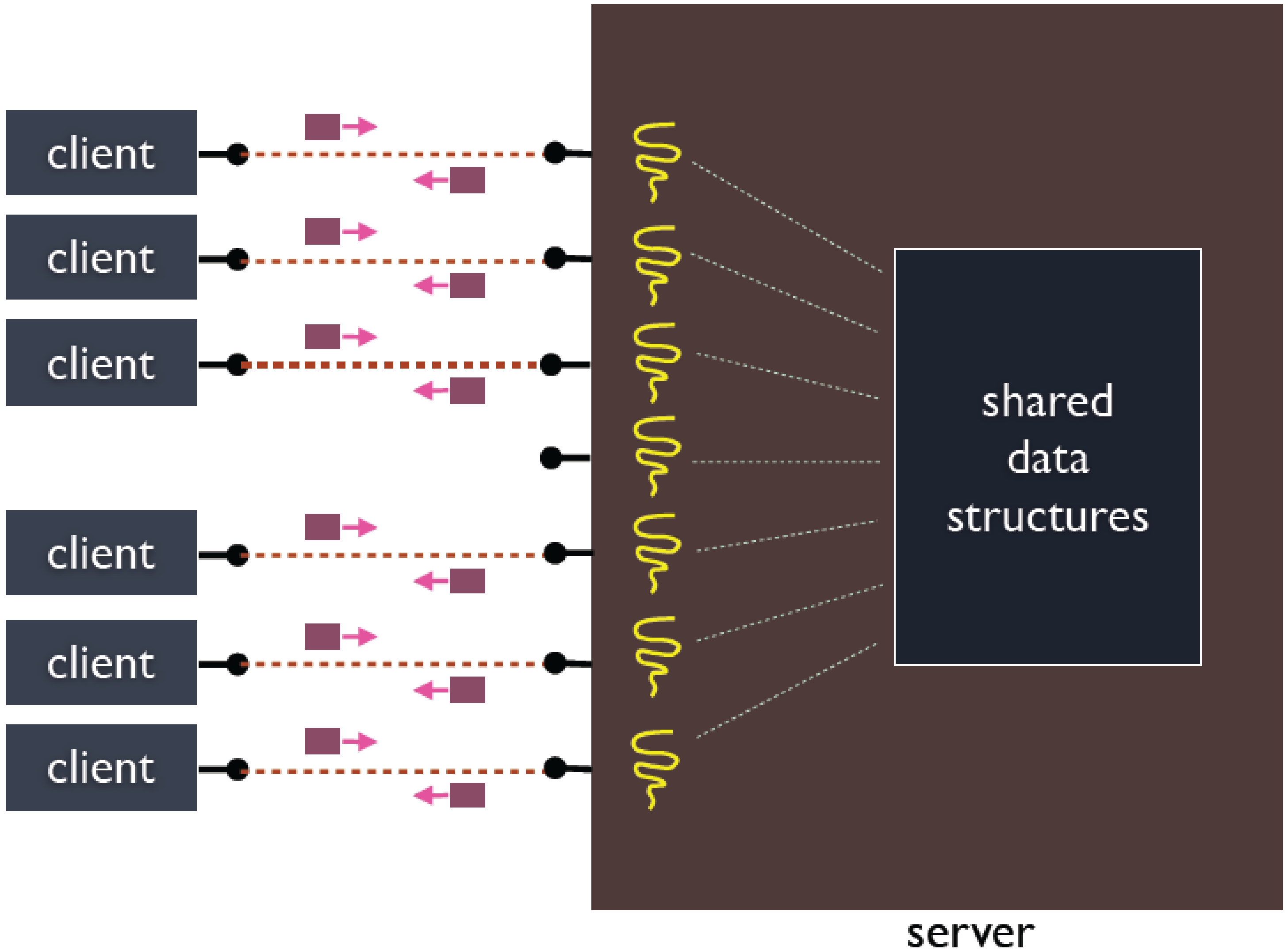
Threads (cont.)



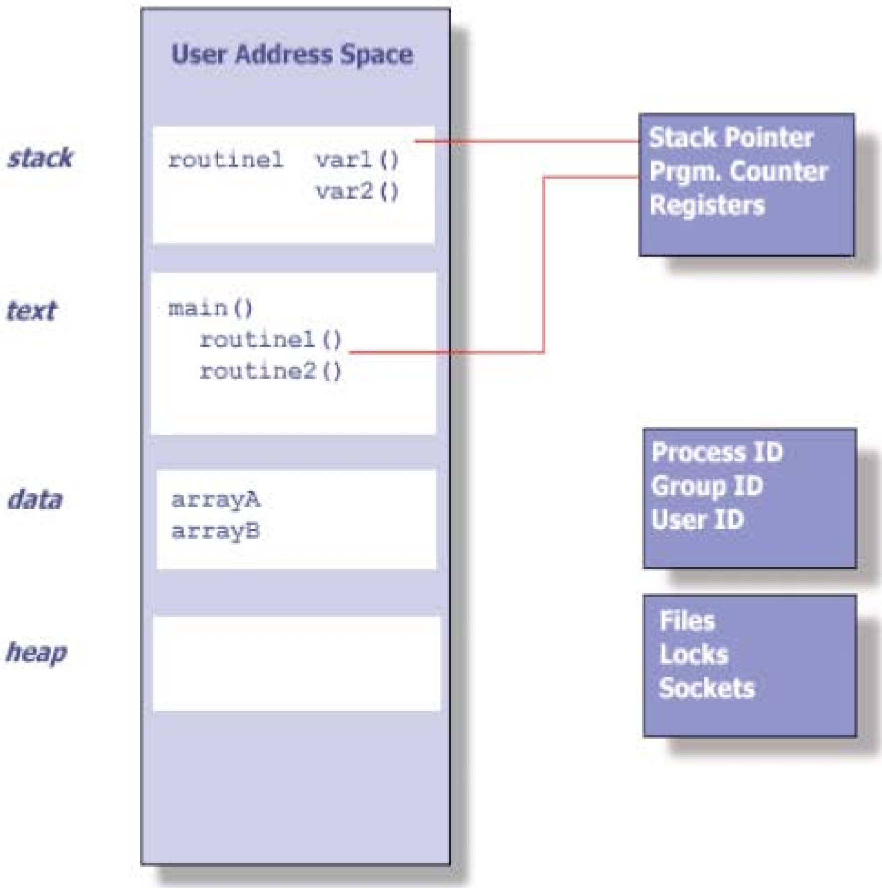
Threads (cont.)



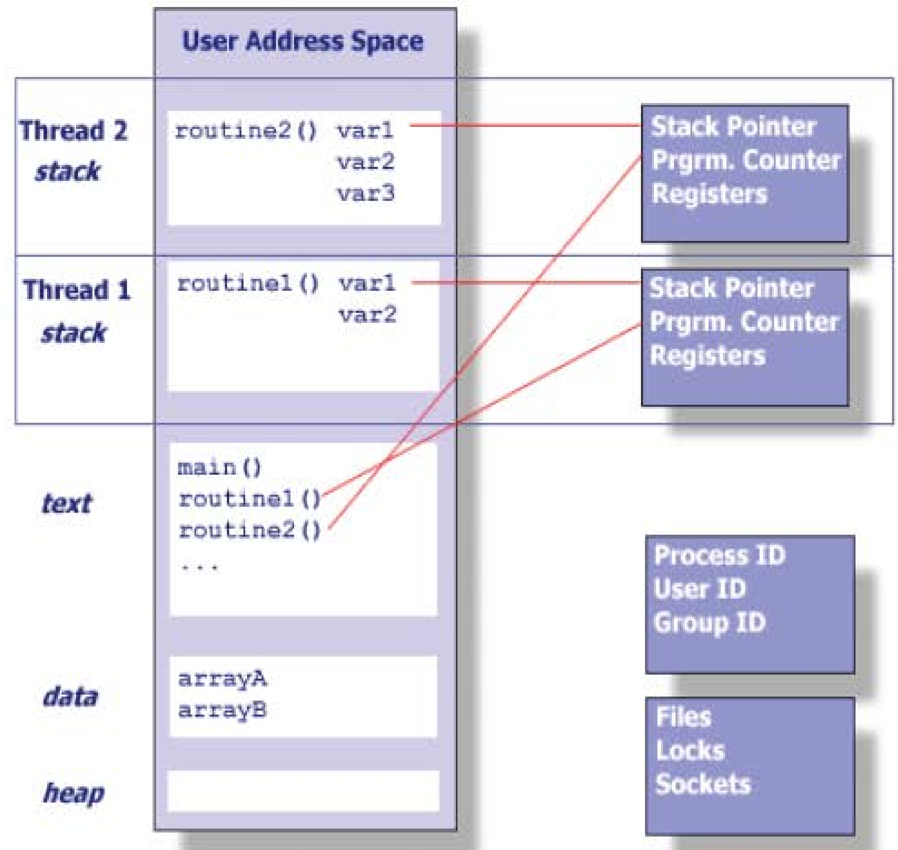
Threads (cont.)



Threads (cont.)



UNIX Process



...and with threads

Threads (cont.)

- 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

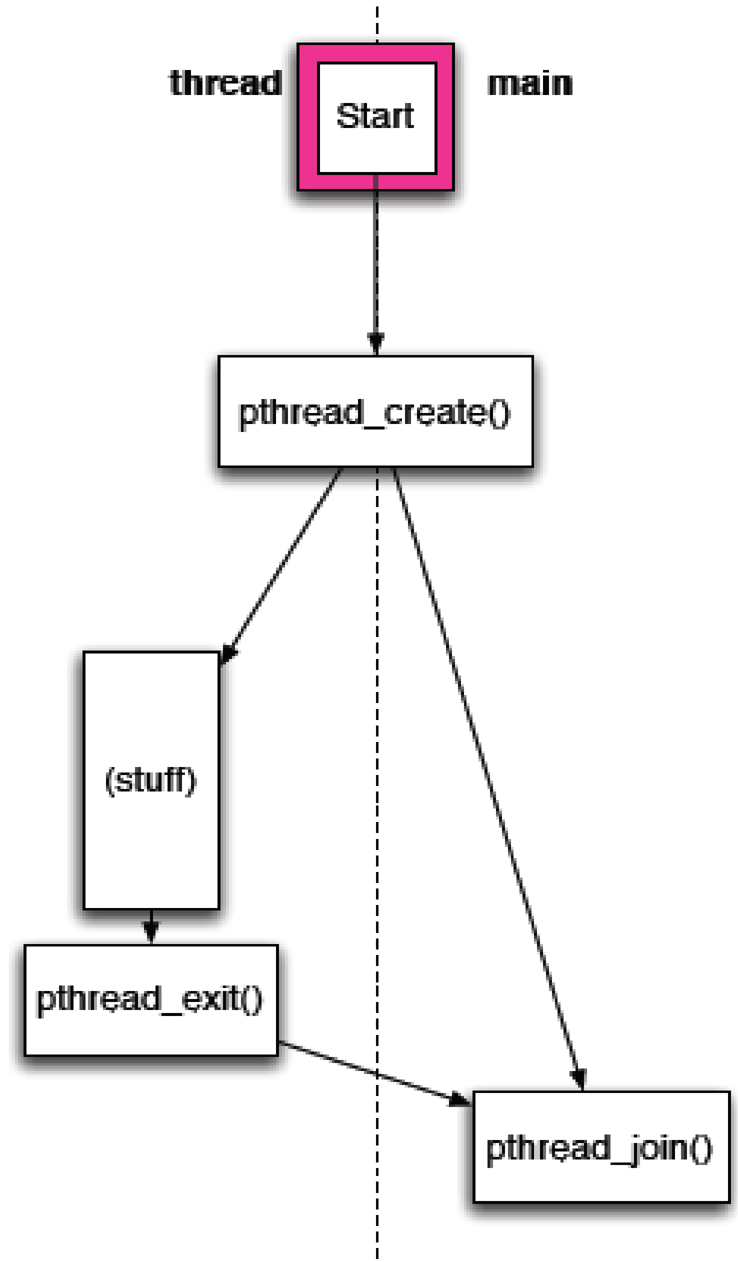
- Exists within a process and uses the process resources
- Has its own independent flow of control as long as its parent process exists and the OS supports it
- Duplicates only the essential resources it needs to be independently “schedulable“
- May share the process resources with other threads that 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

- 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.

Thread control

- main
  - pthread_create() (create thread)
  - wait for thread() to finish via pthread_join (maybe)
- thread
  - begins at function pointer
  - runs until pthread_exit()



pthread_create()

- 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

pthread_join()

- 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

pthread_exit()

- 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
        - Note: better be dynamically allocated because the thread stack will go away when the thread exits

Putting it all together ...

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

void * thread_function( void * arg ) {
    MY_STRUCT *val = (MY_STRUCT *)arg; // Cast to expected type
    printf( "Thread %lx has vaules %x,%s]\n", pthread_self(), val->num, val->str );
    pthread_exit( &val->num );
}

int main( void ) {
    MY_STRUCT v1 = { 0x12345, "Val 1" };
    MY_STRUCT v2 = { 0x54312, "Val 2" };
    pthread_t t1, t2;
    printf( "Starting threads\n" );
    pthread_create( &t1, NULL, thread_function, (void *)&v1 );
    pthread_create( &t2, NULL, thread_function, (void *)&v2 );
    pthread_join( t1, NULL );
    pthread_join( t2, NULL );
    printf( "All threads returned\n" );
    return( 0 );
}
```

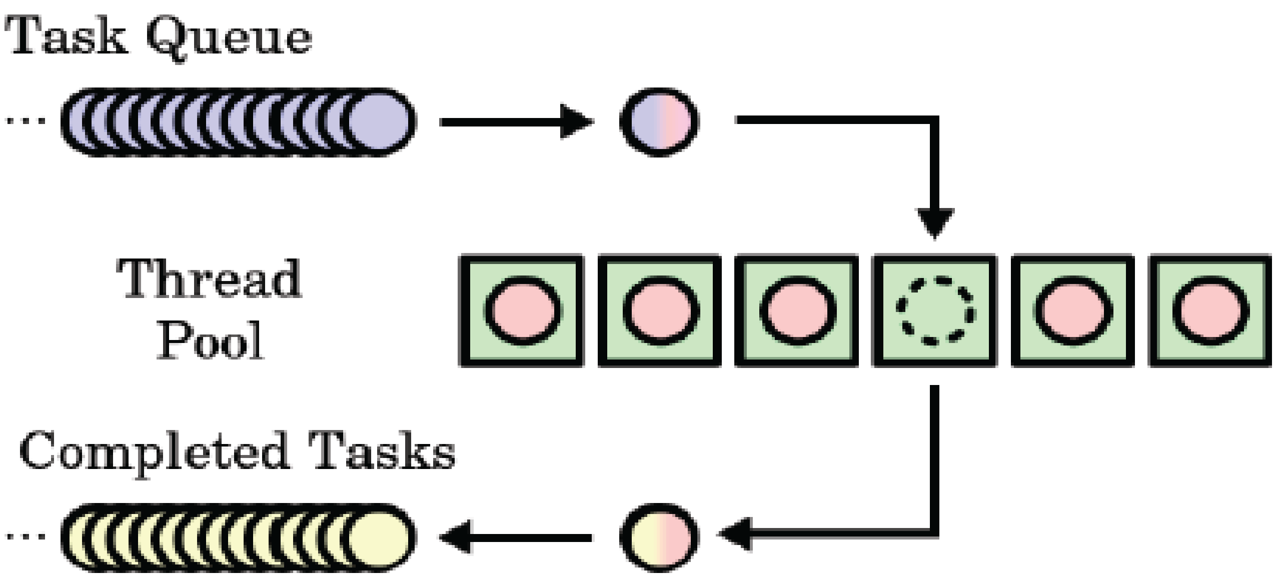
Putting it all together ...

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

void * thread_function( void * arg ) {
    MY_STRUCT *val = (MY_STRUCT *)arg; // Cast to expected type
    printf( "Thread %lx has vaules %x,%s]\n", pthread_self(), val->num, val->str );
    pthread_exit( &val->num );
}

int main( void ) {
    MY_STRUCT v1 = { 0x12345, "Val 1" };
    MY_STRUCT v2 = { 0x54312, "Val 2" };
    pthread_t t1, t2;
    printf( "Starting threads\n" );
    pthread_create( &t1, NULL, thread_function, (void *)&v1 );
    pthread_create( &t2, NULL, thread_function, (void *)&v2 );
    pthread_join( t1, NULL );
    pthread_join( t2, NULL );
    printf( "All threads returned\n" );
    return( 0 );
}
```

```
$ ./concurrency
Starting threads
Thread 7f51c3e05700 has vaules 54312,Val 2]
Thread 7f51c4606700 has vaules 12345,Val 1]
All threads returned
$
```

Thread pooling

- An operating system provides a number of threads that are pre-created and assigned to requests/tasks as needed
  - Once they are done processing, they go back on the queue



Idea: amortize the cost of thread creation over many requests

Challenge ...

- Consider the following function:

```
int accounts[5] = { 0, 0, 0, 0, 0 };
int addvalue( int account, int amount ) {
    int num = accounts[account];
    num = num+amount;
    accounts[account] = num;
    return( 0 );
}
```

- Now suppose thread “a” executes the following

```
addValue( 1, 100 );
```

- ... at the same time thread “b” executes

```
addValue( 1, 200 );
```

- What is the final value of accounts[1]?

Watch the execution!

Thread A	Thread B	num "A"	num "B"	accounts[1]
int num = accounts[account];		0		0
	int num = accounts[account];	0		0
	num = num+amount;		200	
	accounts[account] = num;		200	200
num = num+amount;		100		
accounts[account] = num;		100		100

- Q: What happened?
- A: The temporary value of shared held stomped on the other thread's data/computation.
  - This is a known as a race condition
- The OS course will teach you how to handle this using synchronization via MUTEXes (mutual exclusion)

Thread tradeoffs

- Benefits
  - straight-line code, lines are processed sequentially
  - 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)