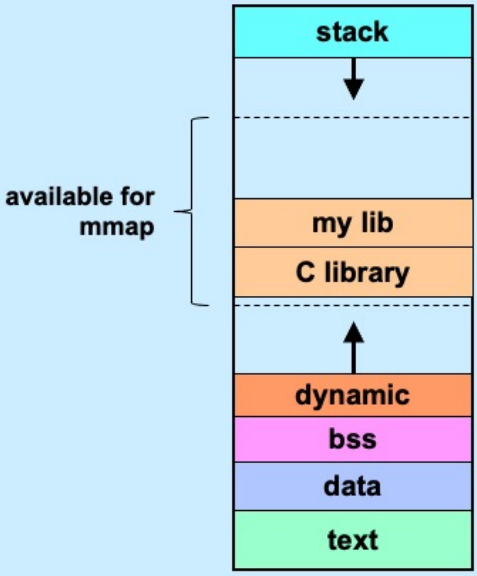
CS 33

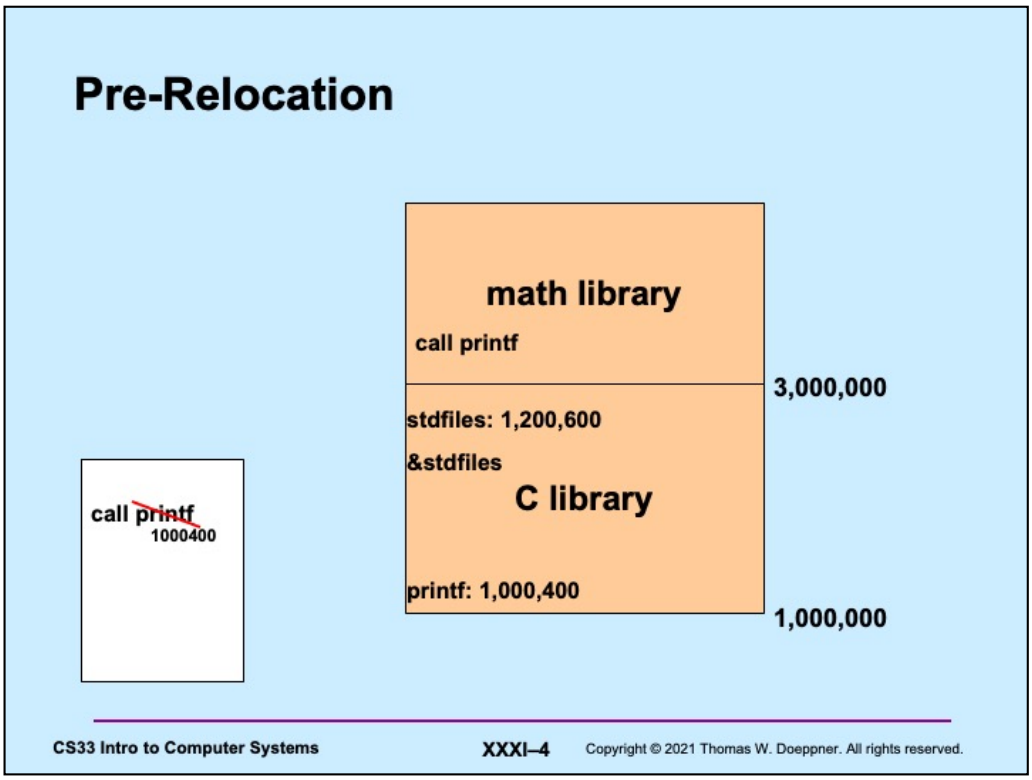
Linking and Libraries (2)

Mmapping Libraries

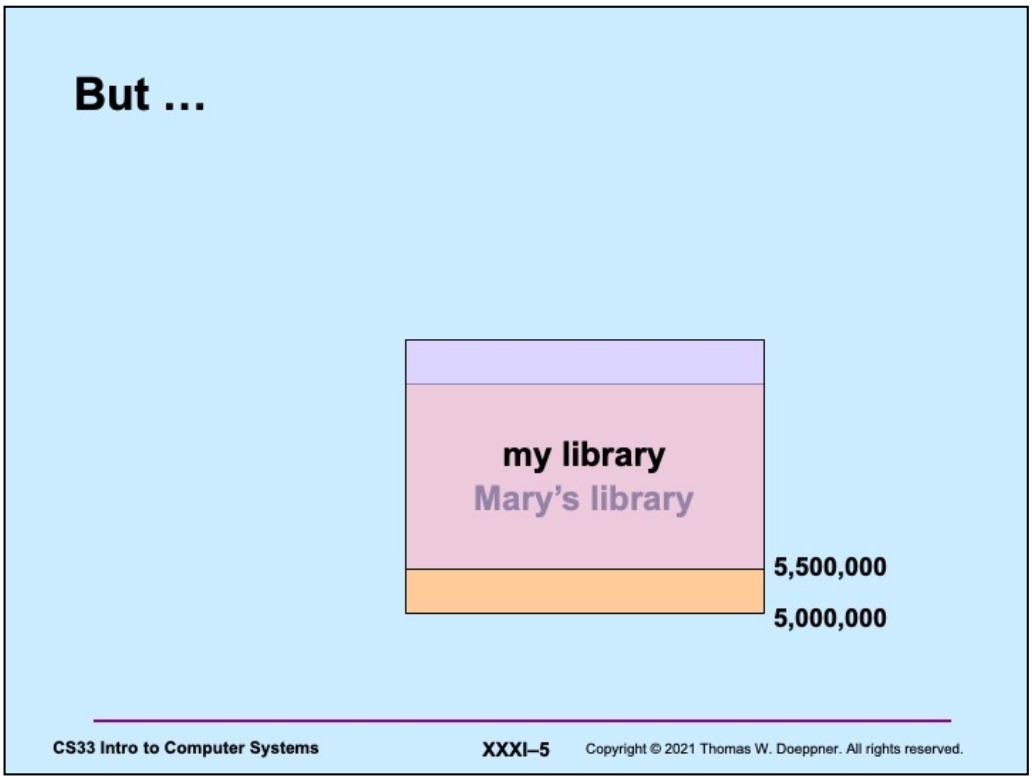


Problem

- How is relocation handled?

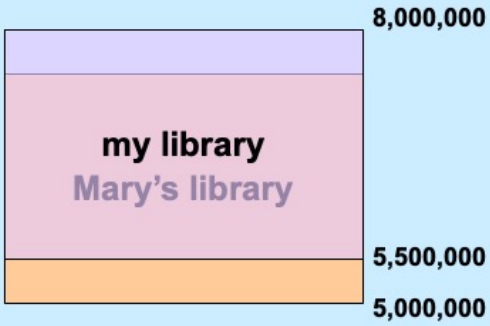


Assuming we're using pre-relocation, the C library and the math library would be assumed to be in virtual memory at their pre-assigned locations. In the slide, these would be starting at locations 1,000,000 and 3,000,000, respectively. Let's suppose printf, which is in the C library, is at location 1,000,400. Thus, calls to printf at static link time could be linked to that address. If the math library also contains calls to printf, these would be linked to that address as well. The C library might contain a global identifier, such as stdfiles. Its address would also be known.



Pre-relocation doesn't work if we have two libraries pre-assigned such that they overlap. If so, at least one of the two will have to be moved, necessitating relocation.

But …



Quiz 1

We need to relocate all references to Mary's library in my library. What option should we give to *mmap* when we map my library into our address space?

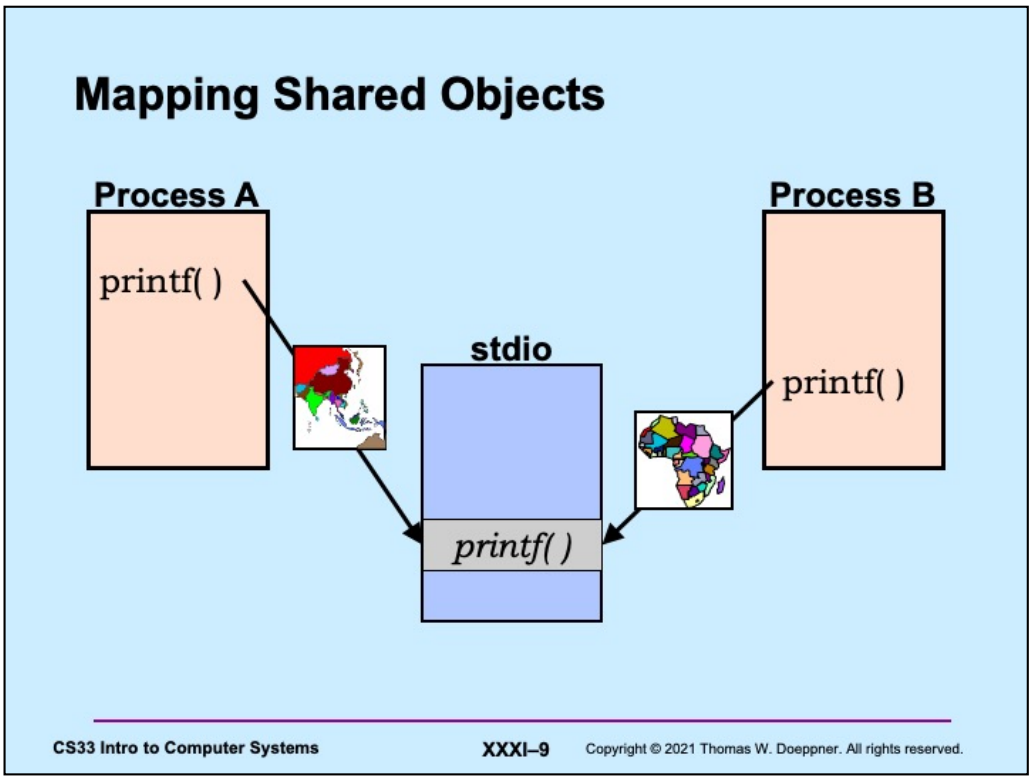
a) the MAP_PRIVATE option

b) the MAP_SHARED option

c) mmap can't be used in this situation

Relocation Revisited

- Modify shared code to effect relocation
  - result is no longer shared!
- Separate shared code from (unshared) addresses
  - position-independent code (PIC)
  - code can be placed anywhere
  - addresses in separate private section
    - » pointed to by a register



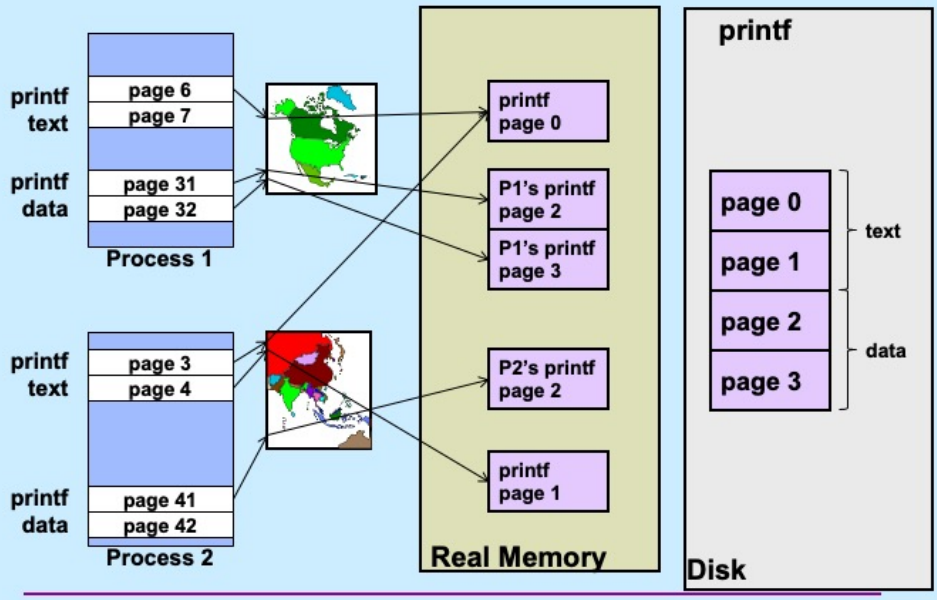
The C library (and other libraries) can be mapped into different locations in different processes' address spaces.

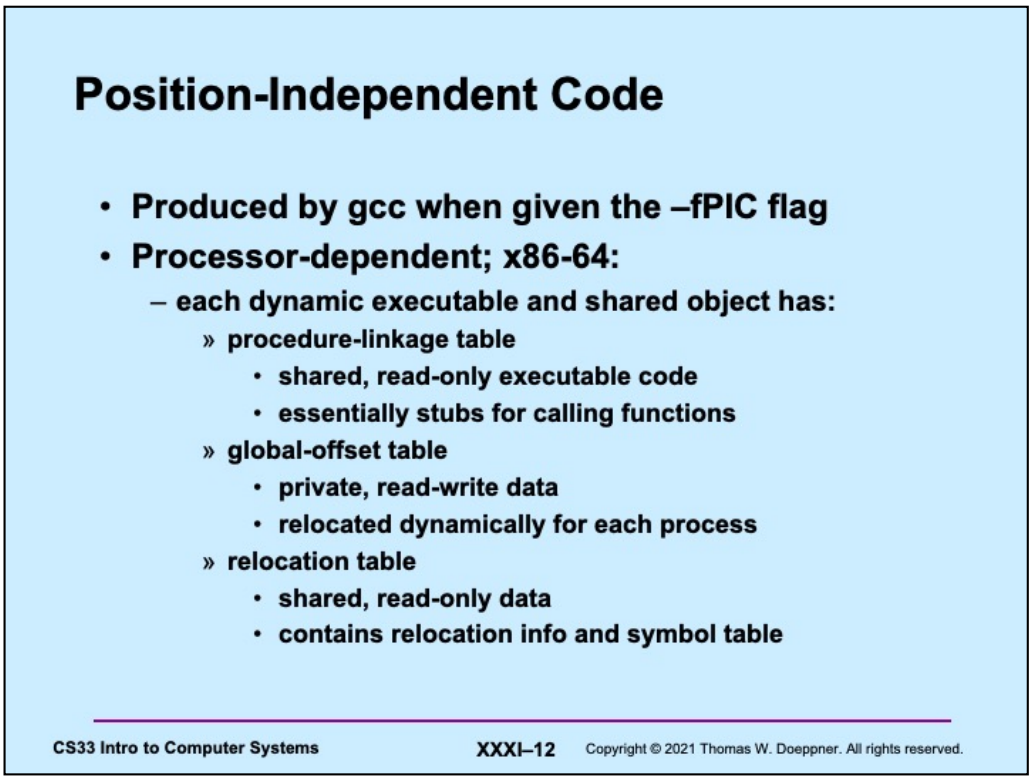
Mapping printf into the Address Space

- Printf's text
  - read-only
  - can it be shared?
    - » yes: use MAP_SHARED
- Printf's data
  - read-write
  - not shared with other processes
  - initial values come from file
  - can mmap be used?
    - » MAP_SHARED wouldn't work
      - changes made to data by one process would be seen by others
    - » MAP_PRIVATE does work!
      - mapped region is initialized from file
      - changes are private

For this slide, we assume relocation is dealt with through the use of **position-independent code** (PIC).

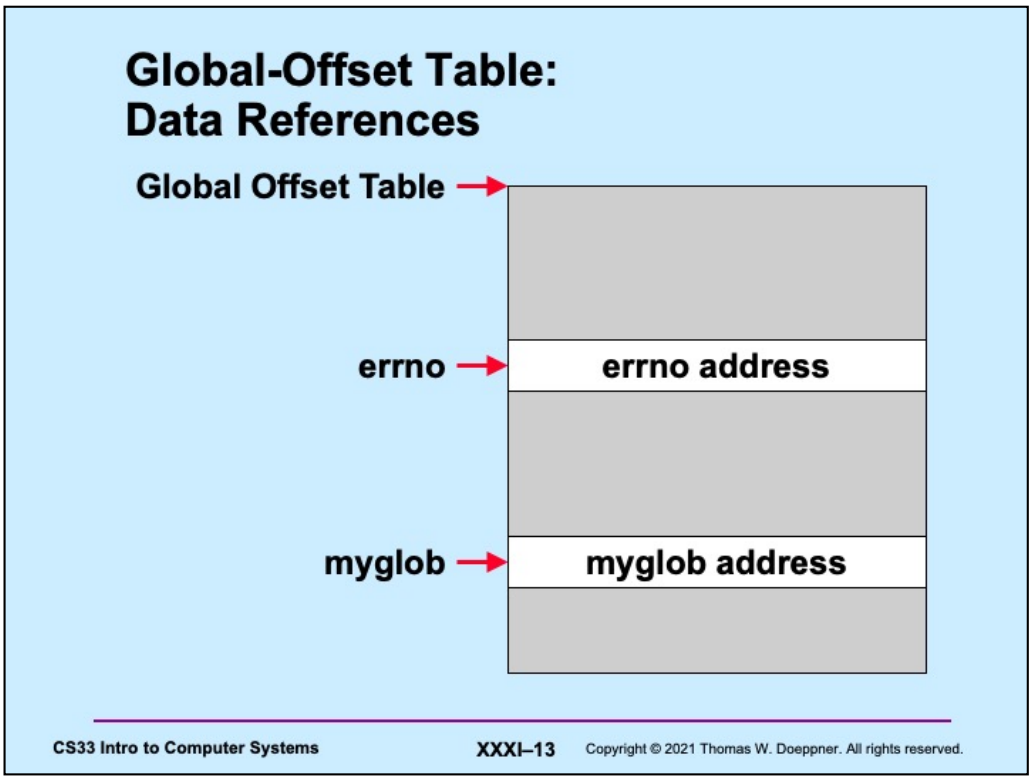
Mapping printf





To provide position-independent code on x86-64, ELF requires three data structures for each dynamic executable (i.e., the program binary loaded by *exec*) and shared object: the **procedure-linkage table**, the **global-offset table**, and the **relocation table**. To simplify discussion, we refer to dynamic executables and shared objects as **modules**. The procedure linkage table contains the code that's actually called when control is to be transferred to an externally defined routine. It is shared by all processes using the associated executable or object, and makes use of data in the global-object table to link the caller to the called program. Each process has its own private copy of each global-object table. It contains the relocated addresses of all externally defined symbols. Finally, the relocation table contains much information about each module. What is used for linking is relocation information and the symbol table, as we explain in the next few slides.

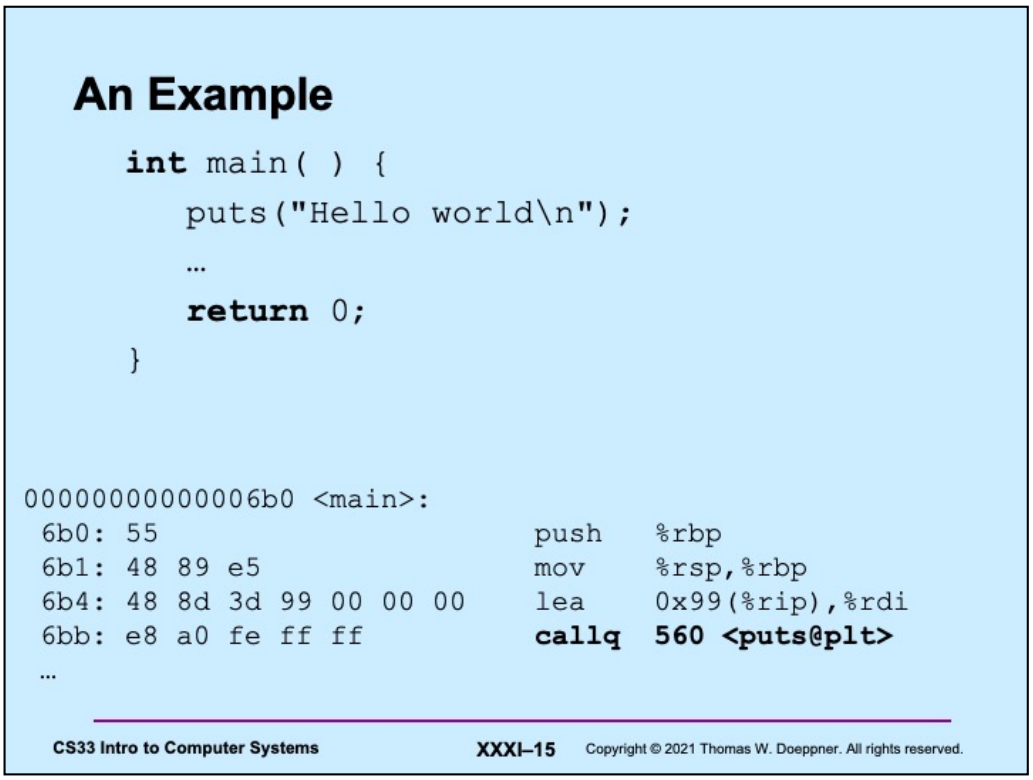
How things work is similar for other architectures, but definitely not the same.



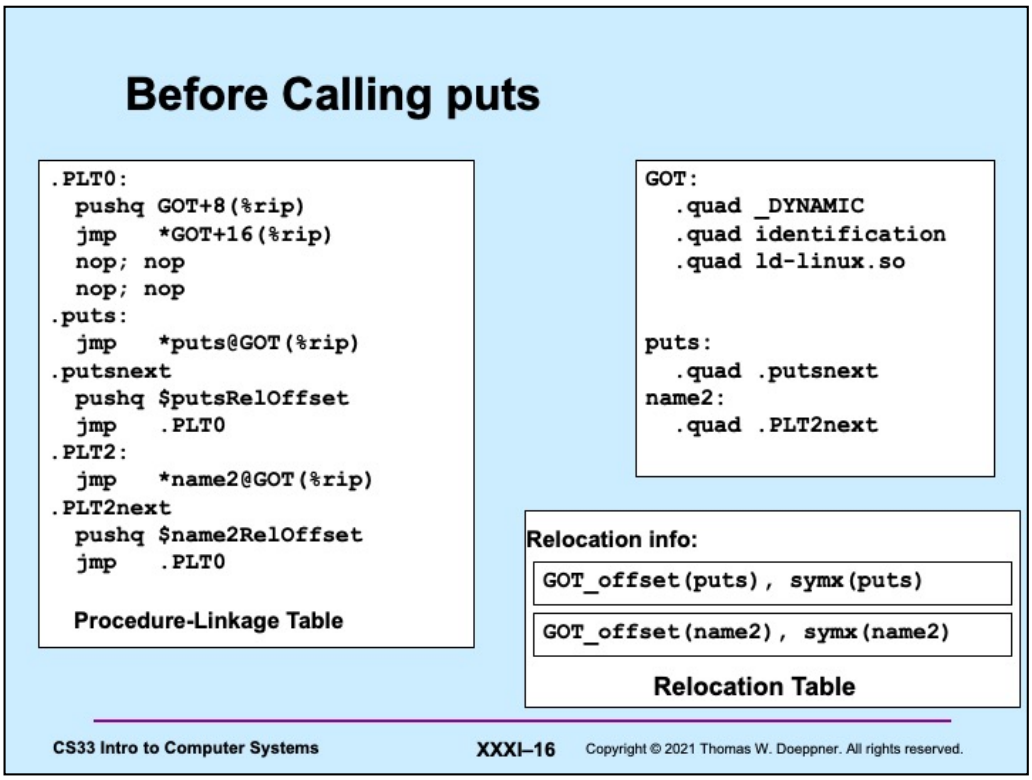
To establish position-independent references to global variables, the compiler produces, for each module, a **global-offset table**. Modules refer to global variables indirectly by looking up their addresses in the table, using PC-relative addressing. The item needed is at some fixed offset from the beginning of the table. When the module is loaded into memory, ld-linux.so is responsible for putting into it the actual addresses of all the needed global variables.

Functions in Shared Objects

- Lots of them
- Many are never used
- Fix up linkages on demand

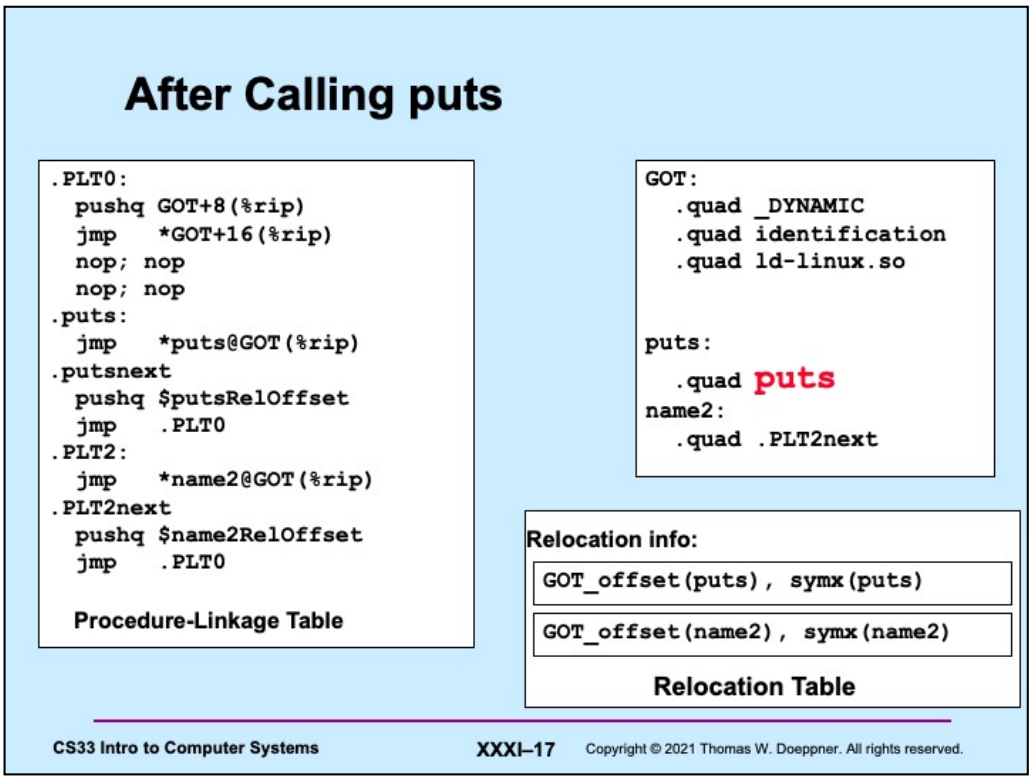


The top half of the slide contains an excerpt from a C program. For the bottom half, we've compiled the program and have printed what "objdump –d" produces for main. Note that the call to puts is actually a call to "puts@plt", which is a reference to the procedure linkage table.



Dealing with references to external procedures is considerably more complicated than dealing with references to external data. This slide shows the procedure linkage table, global offset table, and relocation information for a module that contains references to external procedures *puts* and *name2*. Let's follow a call to procedure *puts*. The general idea is before the first call to puts, the actual address of the puts procedure is not recorded in the global-offset table, Instead, the first call to puts actually invokes ld-linux.so, which is passed parameters indicating what is really wanted. It then finds puts and updates the global-offset table so that things are more direct on subsequent calls.

To make this happen, references from the module to **puts** are statically linked to entry .puts in the procedure-linkage table. This entry contains an unconditional jump (via PC-relative addressing) to the address contained in the **puts** offset of the global-offset table. Initially this address is of the instruction following the jump instruction, which contains code that pushes onto the stack the offset of the **puts** entry in the relocation table. The next instruction is an unconditional jump to the beginning of the procedure-linkage table, entry .PLT0. Here there's code that pushes onto the stack the second 64-bit word of the global-offset table, which contains a value identifying this module. The following instruction is an unconditional jump to the address in the third word of the global-offset table, which is conveniently the address of ld-linux.so. Thus, control finally passes to ld-linux.so, which looks back on the stack and determines which module has called it and what that module really wants to call. It figures this out based on the module-identification word and the relocation table entry, which contains the offset of the **puts** entry in the global-offset table (which is what must be updated) and the index of **puts** in the symbol table (so it knows the name of what it must locate).



Finally, ld-linux.so writes the actual address of the *puts* procedure into the puts entry of the global-offset table, and, after unwinding the stack a bit, passes control to **puts**. On subsequent calls by the module to puts, since the global-offset table now contains **puts**'s address, control goes to it more directly, without an invocation of ld-linux.so.

Not a Quiz!

On the second and subsequent calls to *puts*

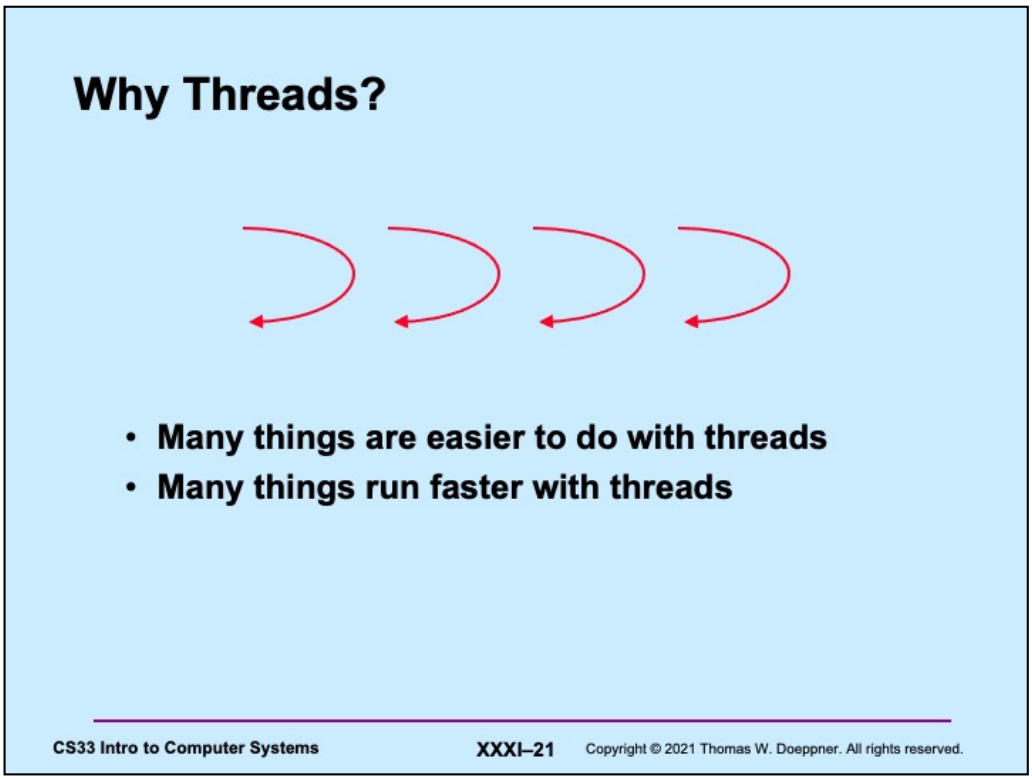
a) control goes directly to *puts*
b) control goes to an instruction that jumps to *puts*
c) control still goes to ld-linux.so, but it now transfers control directly to *puts*

CS 33

Multithreaded Programming (1)

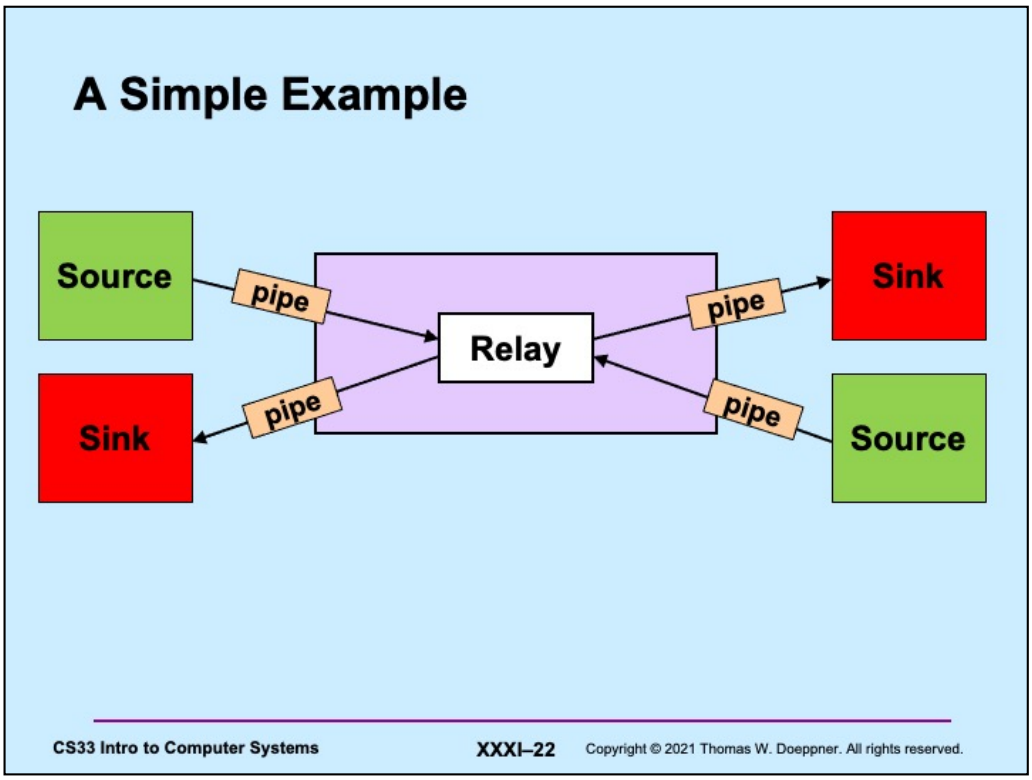
Multithreaded Programming

- A thread is a virtual processor
  - an independent agent executing instructions
- Multiple threads
  - multiple independent agents executing instructions



A *thread* is the abstraction of a processor — it is a *thread of control*. We are accustomed to writing single-threaded programs and to having multiple single-threaded programs running on our computers. Why does one want multiple threads running in the same program? Putting it only somewhat over-dramatically, programming with multiple threads is a powerful paradigm.

So, what is so special about this paradigm? Programming with threads is a natural means for dealing with *concurrency*. As we will see, concurrency comes up in numerous situations. A common misconception is that it is a useful concept only on multiprocessors. Threads do allow us to exploit the features of a multiprocessor, but they are equally useful on uniprocessors — in many instances a multithreaded solution to a problem is simpler to write, simpler to understand, and simpler to debug than a single-threaded solution to the same problem.



For a simple example of a problem that is more easily solved with threads than without, let's look at the stream relay example from the previous lecture.

Life Without Threads

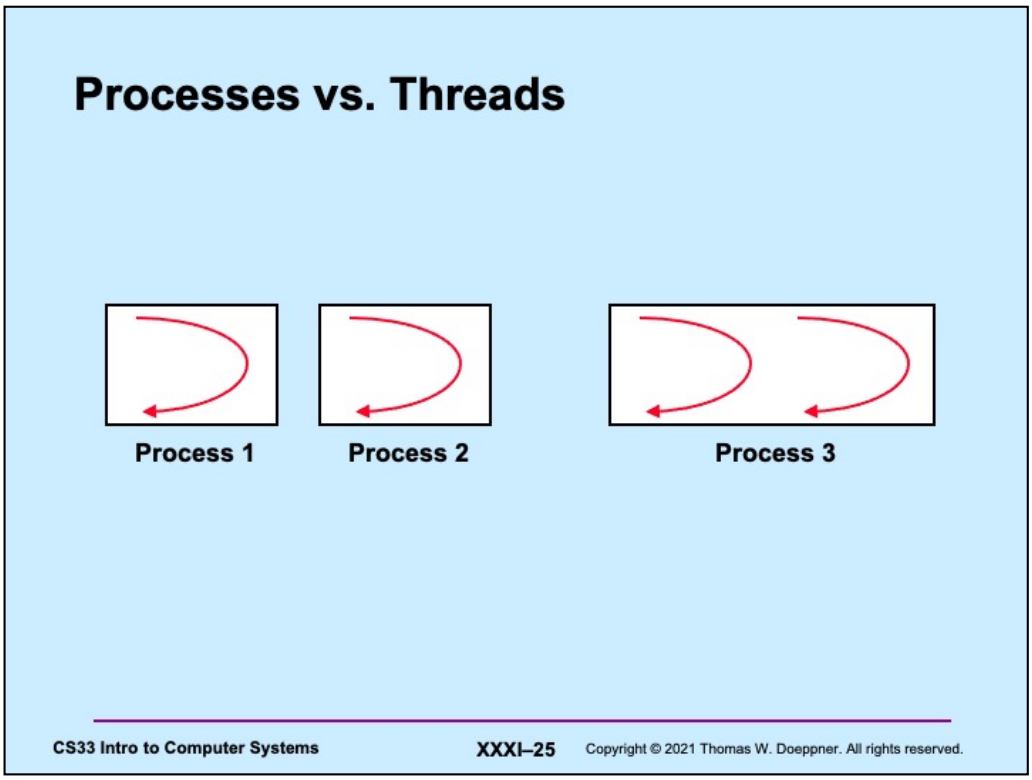
```
void relay(int left, int right) {
    fd_set rd, wr;
    int left_read = 1, right_write = 0;
    int right_read = 1, left_write = 0;
    int sizeLR, sizeRL, wret;
    char bufLR[BSIZE], bufRL[BSIZE];
    char *bufpR, *bufpL;
    int maxFD = max(left, right) + 1;

    fcntl(left, F_SETFL, O_NONBLOCK);
    fcntl(right, F_SETFL, O_NONBLOCK);

    while(1) {
     FD_ZERO(&rd);
     FD_ZERO(&wr);
     if (left_read)
      FD_SET(left, &rd);
     if (right_read)
      FD_SET(right, &rd);
     if (left_write)
      FD_SET(left, &wr);
     if (right_write)
      FD_SET(right, &wr);

     select(maxFD, &rd, &wr, 0, 0);

     if (FD_ISSET(left, &rd)) {
       sizeLR = read(left, bufLR, BSIZE);
       left_read = 0;
       right_write = 1;
       bufpR = bufLR;
     }
     if (FD_ISSET(right, &rd)) {
       sizeRL = read(right, bufRL, BSIZE);
       right_read = 0;
       left_write = 1;
       bufpL = bufRL;
     }
     if (FD_ISSET(right, &wr)) {
       if ((wret = write(right, bufpR, sizeLR)) == sizeLR) {
         left_read = 1; right_write = 0;
       } else {
         sizeLR -= wret; bufpR += wret;
       }
     }
     if (FD_ISSET(left, &wr)) {
       if ((wret = write(left, bufpL, sizeRL)) == sizeRL) {
         right_read = 1; left_write = 0;
       } else {
         sizeRL -= wret; bufpL += wret;
       }
     }
    }
    return 0;
}
```


Here's the event-oriented solution we devised earlier that uses *select* (and is rather complicated).

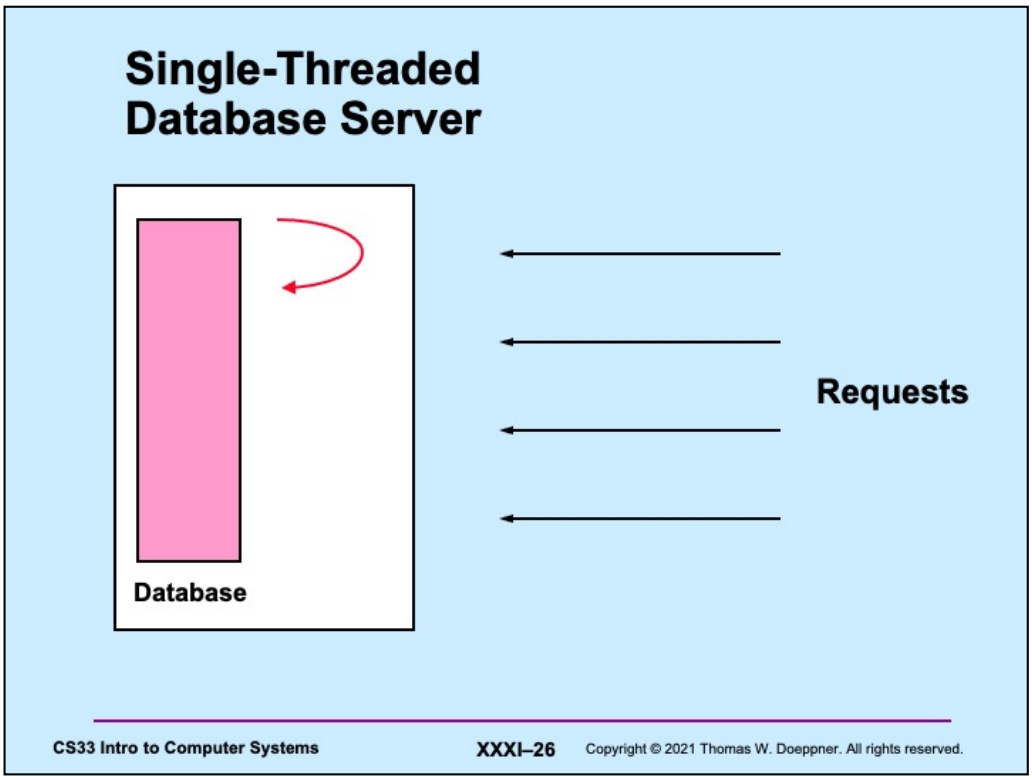
Life With Threads

```
void copy(int source, int destination) {
 struct args *targs = args;
 char buf[BSIZE];

 while(1) {
   int len = read(source, buf, BSIZE);
   write(destination, buf, len);
 }
}
```

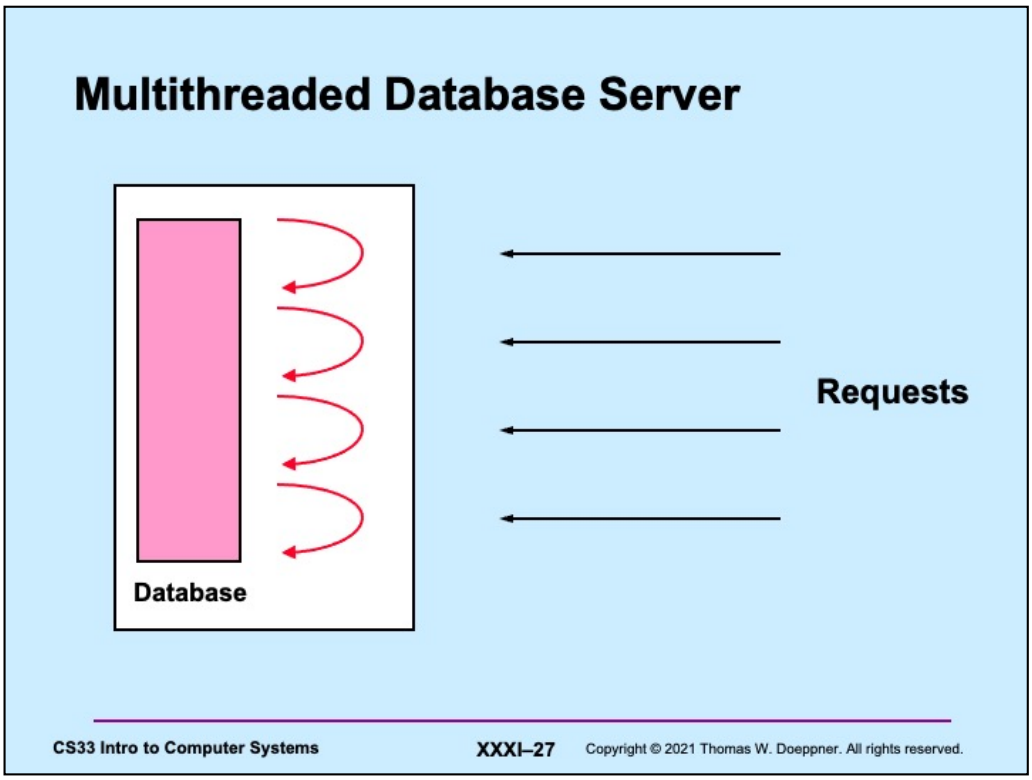

Here's an essentially equivalent solution that uses threads rather than select. We've left out the code that creates the threads (we'll see that pretty soon), but what's shown is executed by each of two threads. One has source set to the left side and destination to the right side, the other vice versa.



Threads provide concurrency, but so do processes. So, what is the difference between two single-threaded processes and one two-threaded process? First of all, if one process already exists, it is much cheaper to create another thread in the existing process than to create a new process. Switching between the contexts of two threads in the same process is also often cheaper than switching between the contexts of two threads in different processes. Finally, two threads in one process share everything — both address space and open files; the two can communicate without having to copy data. Though two different processes can share memory in modern Unix systems, the most common forms of interprocess communication are far more expensive.

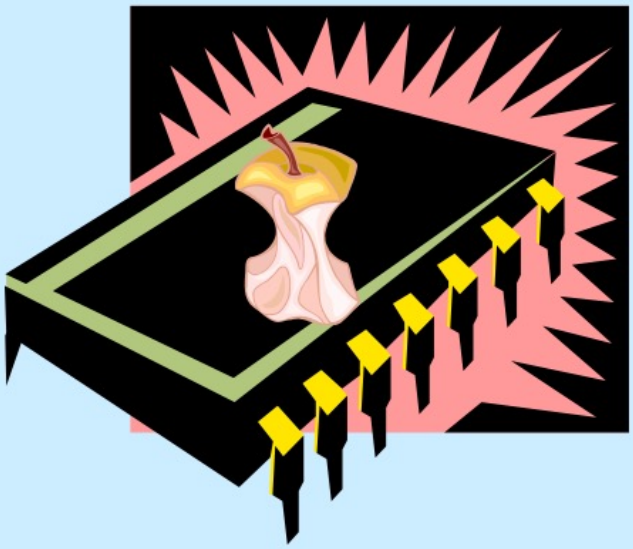


Here is another server example, a database server handling multiple clients. The single-threaded approach to dealing with these requests is to handle them sequentially or to multiplex them explicitly. The former approach would be unfair to quick requests occurring behind lengthy requests, and the latter would require fairly complex and error-prone code.

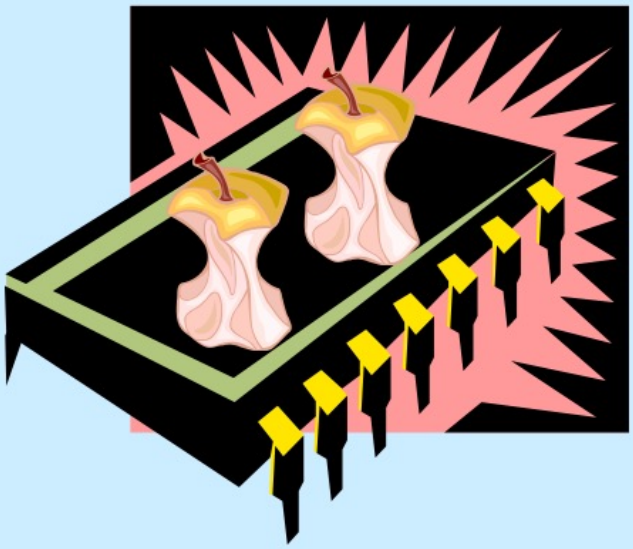


We now rearchitect our server to be multithreaded, assigning a separate thread to each request. The code is as simple as in the sequential approach and as fair as in the multiplexed approach. Some synchronization of access to the database is required, a topic we will discuss soon.

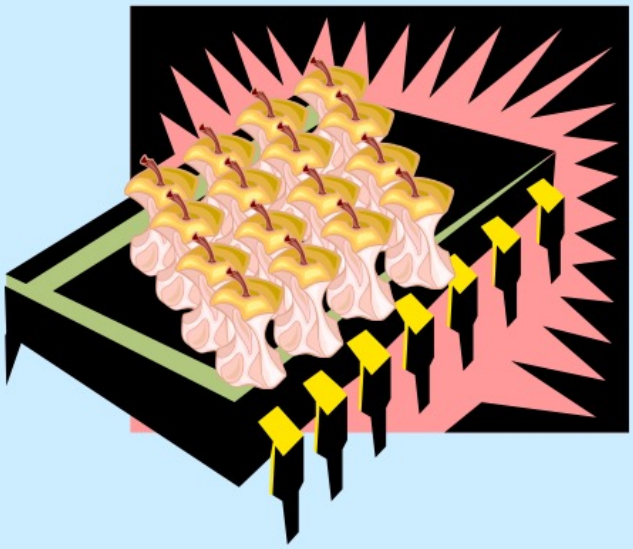
Single-Core Chips



Dual-Core Chips



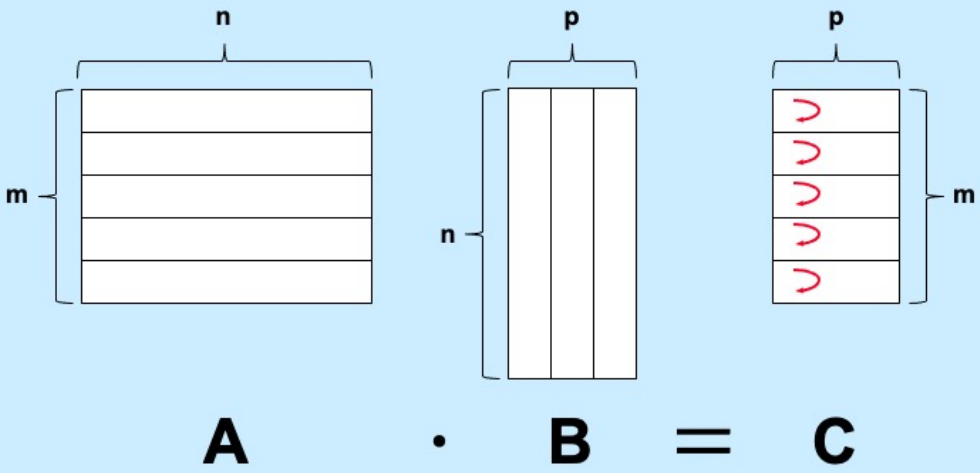
Multi-Core Chips

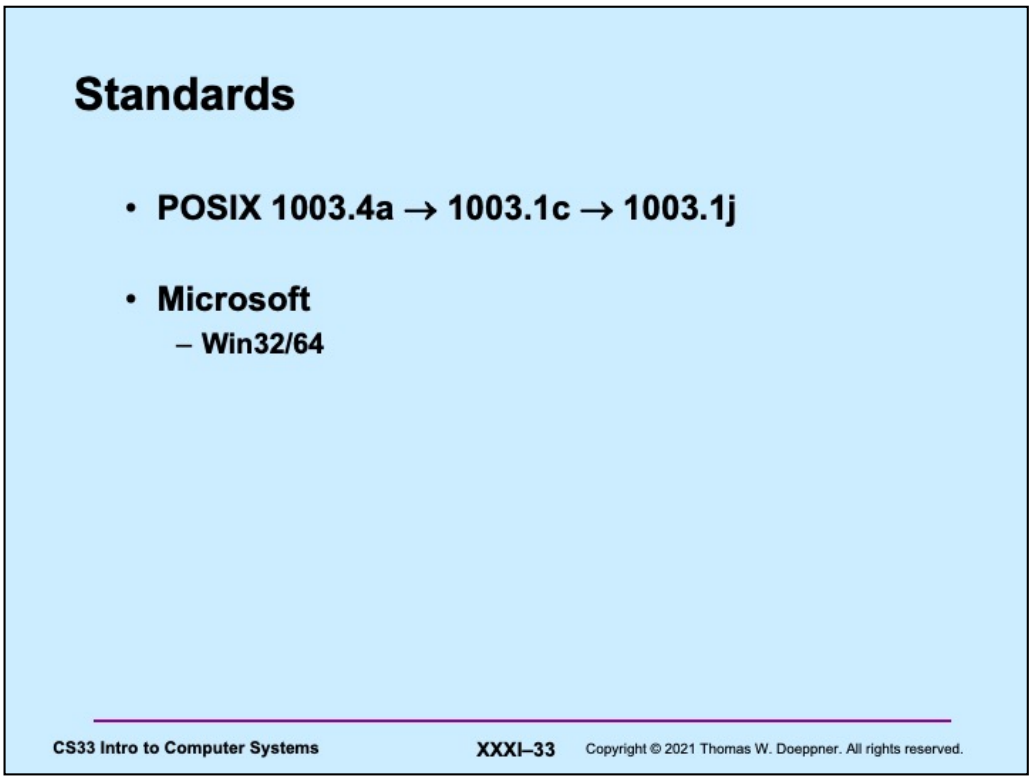


Good News/Bad News

- ☺ Good news
  - multi-threaded programs can take advantage of multi-core chips (single-threaded programs cannot)
- ☹ Bad news
  - it's not easy
    - » must have parallel algorithm
      - employing at least as many threads as processors
      - threads must keep processors busy
        - doing useful work

Matrix Multiplication Revisited





Despite the long-known advantages of programming with threads, only relatively recently have standard APIs for multithreaded programming been developed. The most important of these APIs, at least in the Unix world, is the one developed by the group known as POSIX 1003.4a. This effort took a number of years and in the summer of '95 resulted in an approved standard, which is now known by the number 1003.1c. In 2000, the POSIX advanced realtime standard, 1003.1j, was approved. It contains a number of additional features added to POSIX threads.

Microsoft, characteristically, has produced a threads package whose interface has little in common with those of the Unix world. Moreover, there are significant differences between the Microsoft and POSIX approaches — some of the constructs of one cannot be easily implemented in terms of the constructs of the other, and vice versa. Despite this, both approaches are equally useful for multithreaded programming.

Creating Threads

```
long A[M][N], B[N][P], C[M][P];
...
for (i=0; i<M; i++)    // create worker threads
 pthread_create(&thr[i], 0, matmult, i);

...


void *matmult(void *arg) {
  long i = (long)arg;
  // compute row i of the product C of A and B
  ...
}
```


To create a thread, one calls the **pthread_create** function. This skeleton code for a server application creates a number of threads, each to handle client requests. If **pthread_create** returns successfully (i.e., returns 0), then a new thread has been created that is now executing independently of the caller. This new thread has an ID that is returned via the first parameter. The second parameter is a pointer to an **attributes structure** that defines various properties of the thread. Usually, we can get by with the default properties, which we specify by supplying a null pointer (we discuss this in more detail later). The third parameter is the address of the function in which our new thread should start its execution. The last parameter is the argument that is actually passed to the first function of the thread.

If **pthread_create** fails, it returns a code indicating the cause of the failure.

This example in the slide is a sketch of a multi-threaded matrix multiplication program in which we have one thread per row of the product matrix.

When Is It Finished?

```
long A[M][N], B[N][P], C[M][P];
...
for (i=0; i<M; i++)    // create worker threads
 pthread_create(&thr[i], 0, matmult, i));

for (i=0; i<M; i++)    // wait for termination
  pthread_join(thr[i], 0);

printResult(C); // shouldn't do this until
                // workers have terminated
```


We'd like the first thread to be able to print the resulting produce matrix C, but it shouldn't attempt to do this until the worker threads have terminated. We have it call **pthread_join** for each of the worker threads, causing it to wait for each worker to terminate.

Example (1)

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

#define M   3
#define N   4
#define P   5

long A[M][N];
long B[N][P];
long C[M][P];

void *matmult(void *);
```

```
main( ) {
  long i;
  pthread_t thr[M];
  int error;

  // initialize the matrices
  ...
```


In this series of slide we show the complete matrix-multiplication program.

This slide shows the necessary includes, global declarations, and the beginning of the main routine.

Example (2)

```
  for (i=0; i<M; i++) {   // create worker threads
   if (error = pthread_create(
       &thr[i],
       0,
       matmult,
       (void *)i)) {
     fprintf(stderr, "pthread_create: %s", strerror(error));
     exit(1);
   }
  }
  for (i=0; i<M; i++) // wait for workers to finish their jobs
   pthread_join(thr[i], 0)
  /* print the results  ... */
}
```


Here we have the remainder of *main*. It creates a number of threads, one for each row of the result matrix, waits for all of them to terminate, then prints the results (this last step is not spelled out). Note that we check for errors when calling **pthread_create**. (It is important to check for errors after calls to almost all of the pthread functions, but we normally omit it in the slides for lack of space.) For reasons discussed later, the pthread calls, unlike Unix system calls, do not return -1 if there is an error, but return the error code itself (and return zero on success). However, the text associated with error codes is matched with error codes, just as for Unix-system-call error codes.

So that the first thread is certain that all the other threads have terminated, it must call **pthread_join** on each of them.

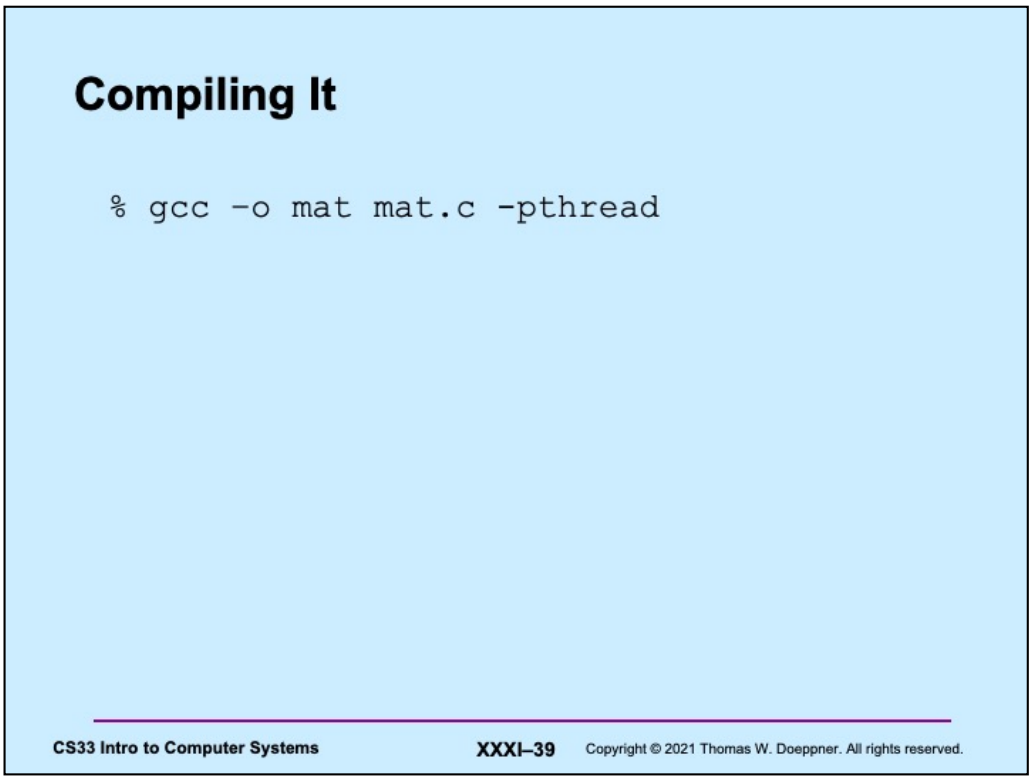
Example (3)

```
void *matmult(void *arg) {
  long row = (long)arg;
  long col;
  long i;
  long t;

  for (col=0; col < P; col++) {
   t = 0;
   for (i=0; i<N; i++)
     t += A[row][i] * B[i][col];
   C[row][col] = t;
  }
  return(0);
}
```


Here is the code executed by each of the threads. It's pretty straightforward: it merely computes a row of the result matrix.

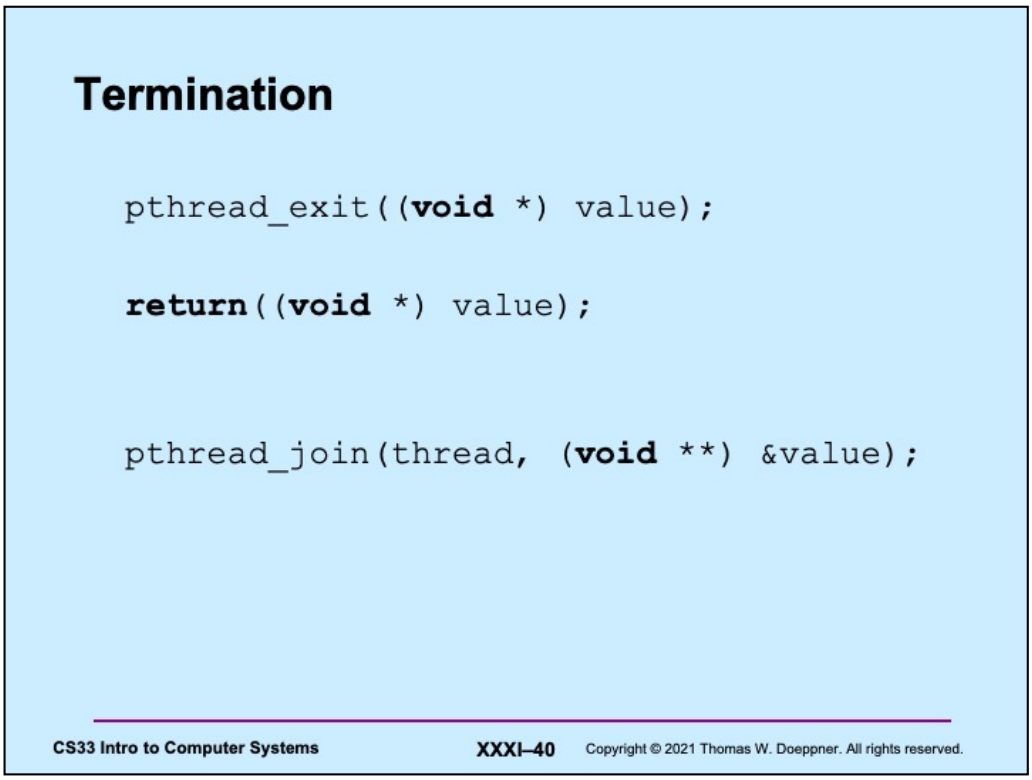
Note how the argument is explicitly converted from *void** to *long*.

This code does not make optimal use of the cache. How can it be restructured so it does?



Providing the –pthread flag to gcc is equivalent to providing all the following flags:

- -lpthread: include libpthread.so — the POSIX threads library
- -D_REENTRANT: defines certain things relevant to threads in stdio.h — we cover this later.
- -Dotherstuff, where "otherstuff" is a variety of flags required to get the correct versions of declarations for POSIX threads in a number of header (.h) files.



A thread terminates either by calling ***pthread_exit*** or by returning from its first function. In either case, it supplies a value that can be retrieved via a call (by some other thread) to **pthread_join**. The analogy to process termination and the **waitpid** system call in Unix is tempting and is correct to a certain extent — Unix's **waitpid**, like **pthread_join**, lets one caller synchronize with the termination of another. There is one important difference, however: Unix has the notion of parent/child relationships among processes. A process may wait only for its children to terminate. No such notion of parent/child relationship is maintained among POSIX threads: one thread may wait for the termination of any other thread in the process (though some threads cannot be "joined" by any thread — see the next page). It is, however, important that **pthread_join** be called for each joinable terminated thread — since threads that have terminated but have not yet been joined continue to use up some resources, resources that will be freed once the thread has been joined. The effect of multiple threads calling **pthread_join** on the same target thread is "undefined" — meaning that what happens can vary from one implementation to the next.

One should be careful to distinguish between terminating a thread and terminating a process. With the latter, all the threads in the process are forcibly terminated. So, if *any* thread in a process calls **exit**, the entire process is terminated, along with its threads. Similarly, if a thread returns from **main**, this also terminates the entire process, since returning from **main** is equivalent to calling **exit**. The only thread that can legally return from *main* is the one that called it in the first place. All other threads (those that did not call **main**) certainly do not terminate the entire process when they return from their first functions, they merely terminate themselves.

If no thread calls **exit** and no thread returns from main, then the process should terminate once all threads have terminated (i.e., have called **pthread_exit** or, for threads other than the first one, have returned from their first function). If the first thread calls **pthread_exit**, it self-destructs, but does not cause the process to terminate (unless no other threads are extant).

Detached Threads

```
start_servers( ) {
  pthread_t thread;
  int i;

  for (i=0; i<nr_of_server_threads; i++) {
    pthread_create(&thread, 0, server, 0);
    pthread_detach(thread);
  }
  ...
}

void *server(void * arg ) {
  ...
}
```


If there is no reason to synchronize with the termination of a thread, then it is rather a nuisance to have to call **pthread_join**. Instead, one can arrange for a thread to be **detached**. Such threads "vanish" when they terminate — not only do they not need to be joined, but they cannot be joined.

Complications

```
void relay(int left, int right) {
  pthread_t LRthread, RLthread;

  pthread_create(&LRthread,
      0,
      copy,
      left, right);         // Can't do this ...
  pthread_create(&RLthread,
      0,
      copy,
      right, left);         // Can't do this  ...
}
```


An obvious limitation of the **pthread_create** interface is that one can pass only a single argument to the first function of the new thread. In this example, we are trying to supply code for the **relay** example, but we run into a problem when we try to pass two parameters to each of the two threads.

Multiple Arguments

```
typedef struct args {
  int src;
  int dest;
} args_t;

void relay(int left, int right) {
  args_t LRargs, RLargs;
  pthread_t LRthread, RLthread;
  ...
  pthread_create(&LRthread, 0, copy, &LRargs);
  pthread_create(&RLthread, 0, copy, &RLargs);
}
```


To pass more than one argument to the first function of a thread, we must somehow encode multiple arguments as one. Here we pack two arguments into a structure, then pass the pointer to the structure.

Multiple Arguments

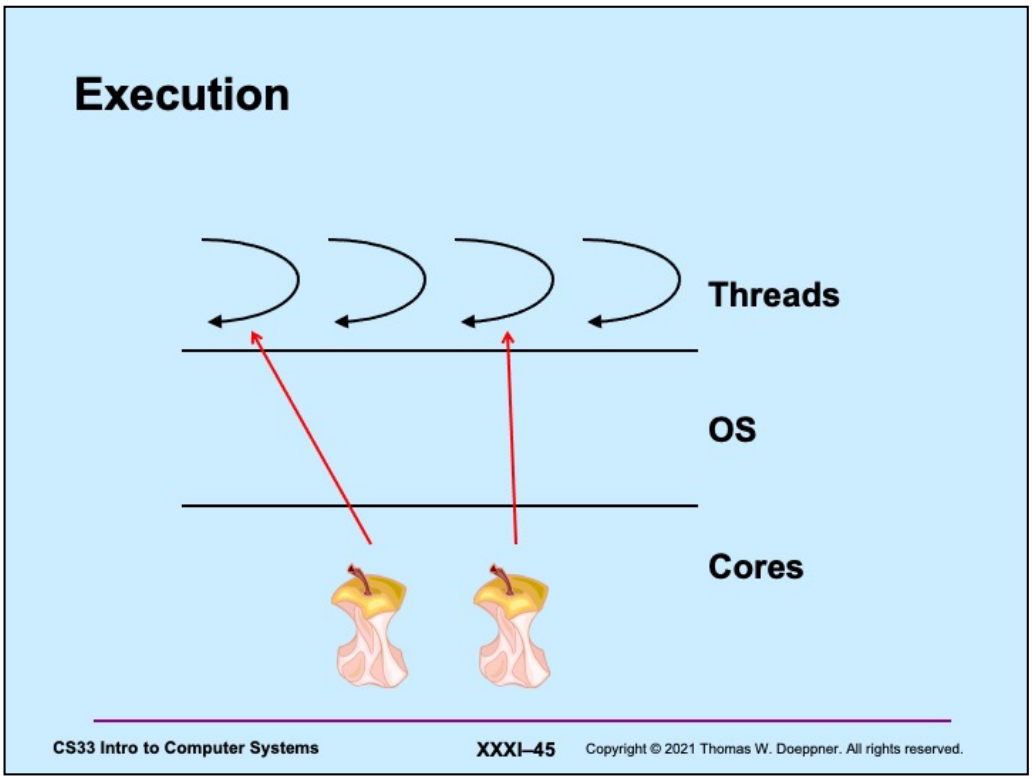
```
typedef struct args {
  int src;
  int dest;
} args_t;

void relay(int left, int right) {
  args_t LRargs, RLargs;
  pthread_t LRthread, RLthread;
  ...
  pthread_create(&LRthread, 0, copy, &LRargs);
  pthread_create(&RLthread, 0, copy, &RLargs);
}
```

Quiz 2

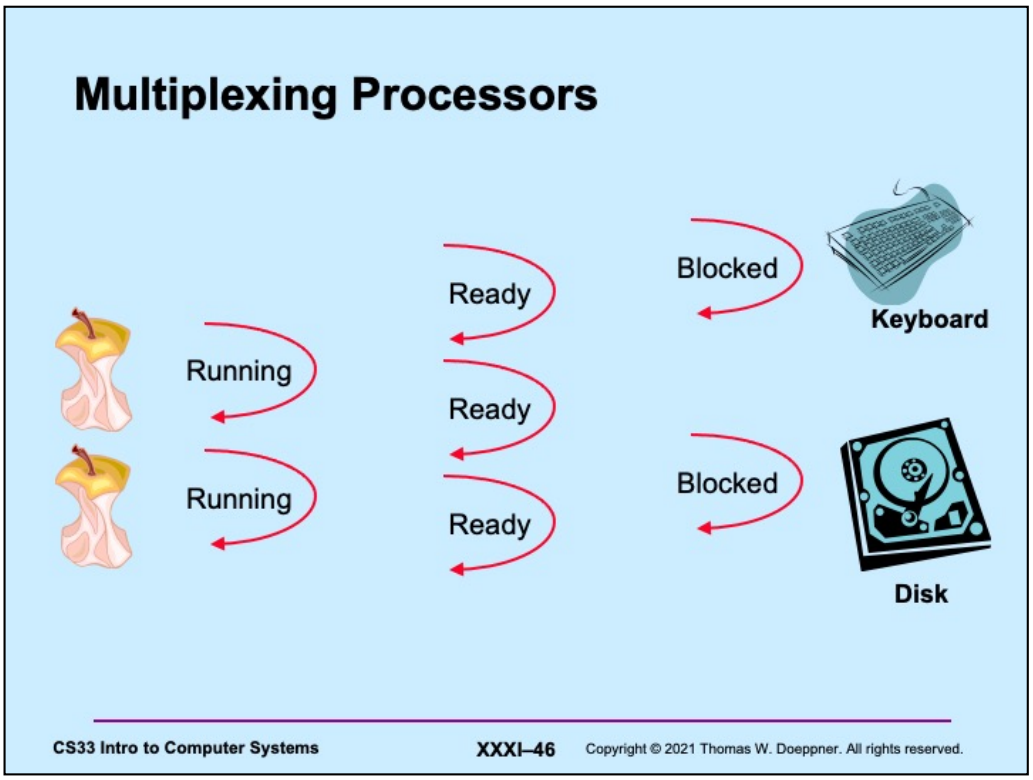
Does this work?

a) **yes**

b) **no**



The operating system is responsible for multiplexing the execution of threads on the available processors. The OS's **scheduler** is responsible for assigning threads to processor cores. Periodically, say every millisecond, each processor is core and calls upon the OS to determine if another thread should run. If so, the current thread on the core is preempted in favor of the next thread. Assuming all threads are treated equally, over a sufficient period of time each thread gets its fair share of available processor time. Thus, even though a system may have only one core, all threads make progress and give the appearance of running simultaneously.



To be a bit more precise about scheduling, let's define some more (standard) terms. Threads are in either a **blocked** state or a **ready** state: in the former they cannot be assigned a core, in the latter they can. The scheduler determines which ready threads should be assigned cores. Ready threads that have been assigned cores are called **running** threads.

Quiz 3

```
  pthread_create(&tid, 0, tproc, (void *)1);
  pthread_create(&tid, 0, tproc, (void *)2);

  printf("T0\n");

  ...

void *tproc(void *arg) {
  printf("T%dl\n", (long)arg);
  return 0;
}
```

In which order are things printed?

a) T0, T1, T2
b) T1, T2, T0
c) T2, T1, T0
d) indeterminate

Cost of Threads

```
int main(int argc, char *argv[]) {
   ...
   val = niters/nthreads;

   for (i=0; i<nthreads; i++)
      pthread_create(&thread, 0, work, (void *)val);
   pthread_exit(0);
   return 0;
}

void *work(void *arg) {
   long n = (long)arg; int i, j; volatile long x;

   for (i=0; i<n; i++) {
      x = 0;
      for (j=0; j<1000; j++)
         x = x*j;
   }
   return 0;
}
```


While it's not clear what the function work actually does, its purpose is simply to occupy a processor for a fair amount of time, time directly proportional to its argument N. The idea behind this code is that we compute how long it takes one thread to compute work(N). We then compute how long it takes for M threads to each compute work(N/M). The total amount of computation done by these M threads is the same is done by one thread calling work(N). If we run this on a one-core computer, then the ratio of the time for M threads each computing work(N/M) to the time of one thread computing work(N) is the the overhead of running M threads.

Similarly, if we run this on a P-core processor, the ratio of the time for PM threads each computing work(N/PM) to the time of P threads each computing work(N/P) is the overhead of running PM threads on a P-core processor.

Cost of Threads

```
int main(int argc, char *argv[]) {
   ...
   val = niters/nthreads;

   for (i=0; i<nthreads; i++)
      pthread_create(&thread, 0, work, (void *)val);
   pthread_exit(0);
   return 0;
}

void *work(void *arg) {
   long n = (long)arg; int i, j; volatile long x;

   for (i=0; i<n; i++) {
      x = 0;
      for (j=0; j<1000; j++)
         x = x*j;
   }
   return 0;
}
```

Quiz 4

This code runs in time *n* on a 4-core processor when *nthreads* is 8. It runs in time *p* on the same processor when *nthreads* is 400.

a) ***n* << *p* (slower)**
b) ***n* ≈ *p* (same speed)**
c) ***n* >> *p* (faster)**

Problem

```
  pthread_create(&thread, 0, start, 0);

  …


void *start(void *arg) {
  long BigArray[128*1024*1024];
  …
  return 0;
}
```


Here we are creating a thread that has a very large local variable that, of course, is allocated on the thread's stack. How can we be sure that the thread's stack is actually big enough? As it turns out, the default stack size for threads in Linux is two megabytes.

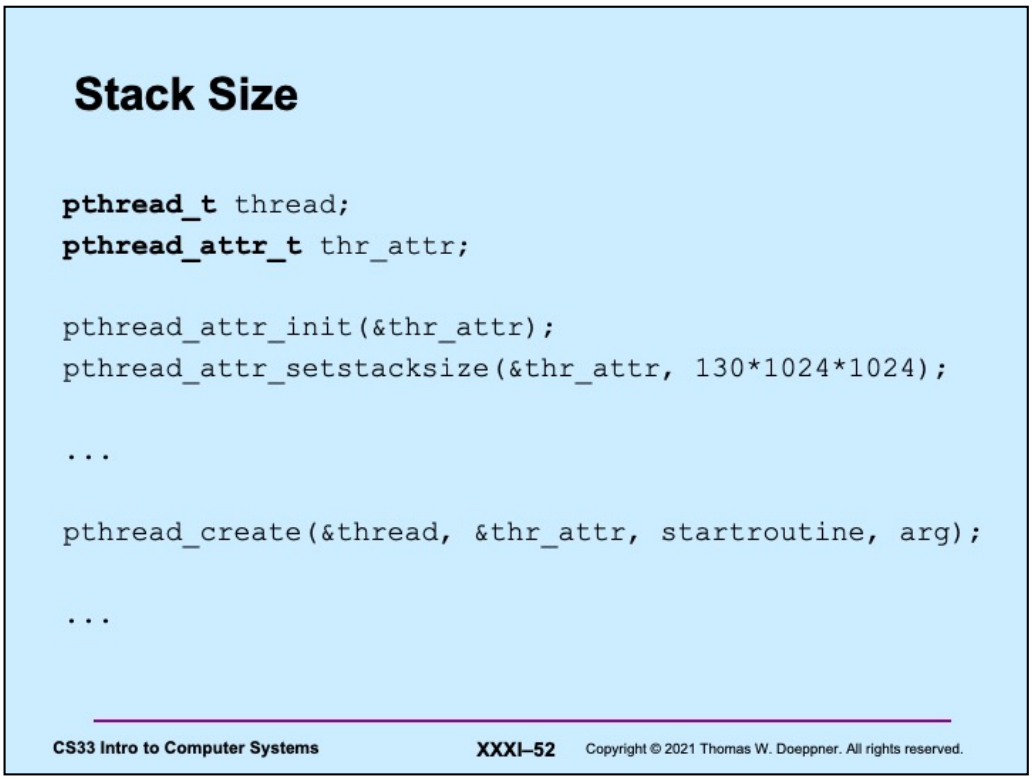
Thread Attributes

```
pthread_t thread;
pthread_attr_t thr_attr;

pthread_attr_init(&thr_attr);

...

/* establish some attributes */

...

pthread_create(&thread, &thr_attr, startroutine, arg);

...
```


A number of properties of a thread can be specified via the **attributes** argument when the thread is created. Some of these properties are specified as part of the POSIX specification, others are left up to the implementation. By burying them inside the attributes structure, we make it straightforward to add new types of properties to threads without having to complicate the parameter list of **pthread_create**. To set up an attributes structure, one must call **pthread_attr_init**. As seen in the next slide, one then specifies certain properties, or attributes, of threads. One can then use the attributes structure as an argument to the creation of any number of threads.

Note that the attributes structure only affects the thread when it is created. Modifying an attributes structure has no effect on already-created threads, but only on threads created subsequently with this structure as the attributes argument.

Storage may be allocated as a side effect of calling **pthread_attr_init**. To ensure that it is freed, call **pthread_attr_destroy** with the attributes structure as argument. Note that if the attributes structure goes out of scope, not all storage associated with it is necessarily released — to release this storage you must call **pthread_attr_destroy**.



Among the attributes that can be specified is a thread's **stack size**. The default attributes structure specifies a stack size that is probably good enough for "most" applications. How big is it? While the default stack size is not mandated by POSIX, in Linux it is two megabytes. To establish a different stack size, use the **pthread_attr_setstacksize** function, as shown in the slide.

How large a stack is necessary? The answer, of course, is that it depends. If the stack size is too small, there is the danger that a thread will attempt to overwrite the end of its stack. There is no problem with specifying too large a stack, except that, on a 32-bit machine, one should be careful about using up too much address space (one thousand threads, each with a one-megabyte stack, use a fair portion of the address space).

What happens if a thread uses more stack space than was allotted to it? It would probably clobber memory holding another thread's stack, which could lead to some rather difficult to debug problems. To guard against such happenings, The lowest-address page of a thread's stack (recall that stacks grow downwards) is made inaccessible, meaning that any reference to it will generate a fault. Thus, if the thread references just beyond its allotted stack, there will be a fault which, though not good, makes it clear that this thread has exceeded its stack space.