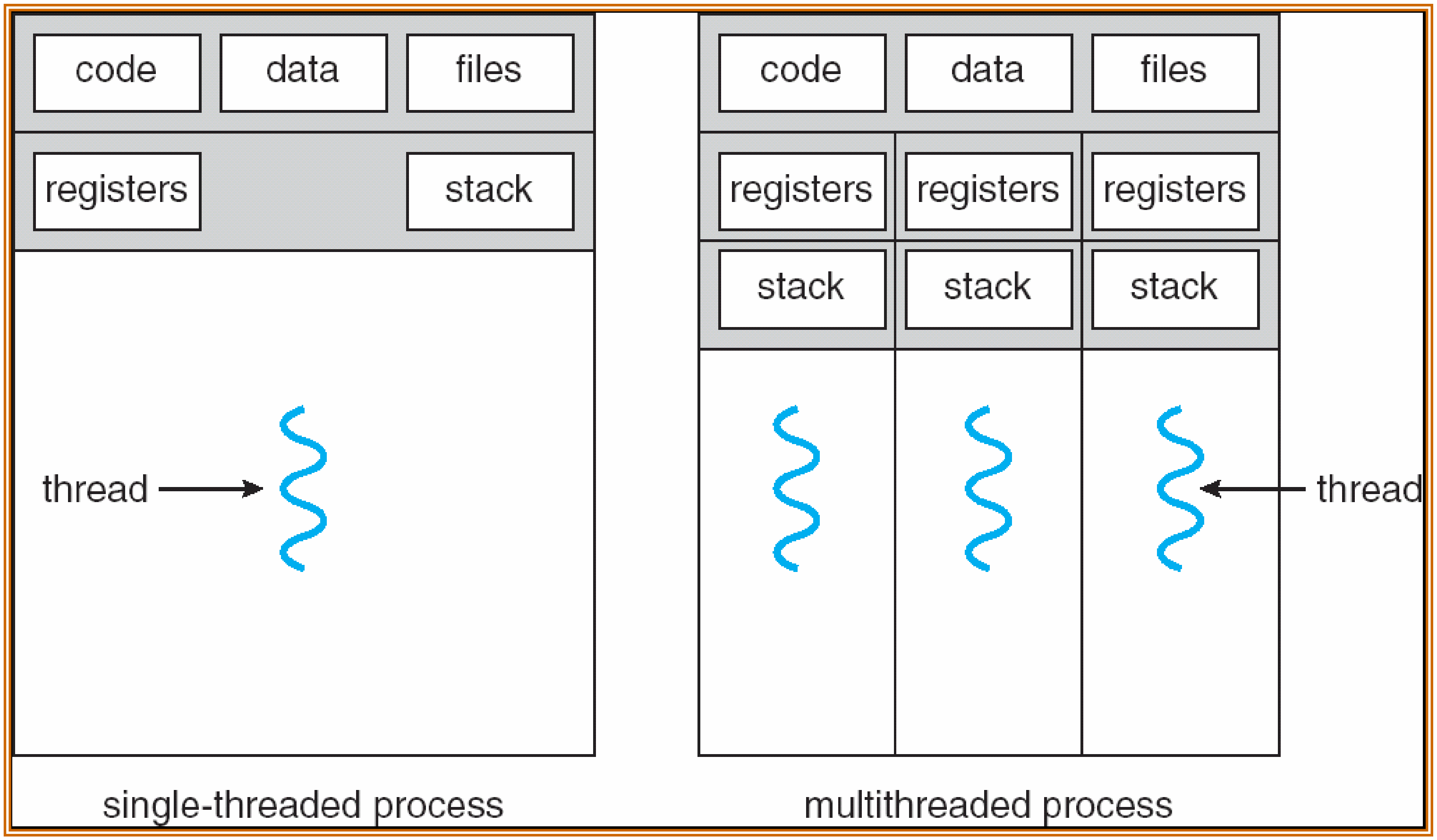
An Introduction to Programming with Threads

- Read the Birrell paper
  - excellent introductory paper
  - promotes understanding the material
  - abstract content with direct application
    - limited and rather outdated concrete technical content

Threads

- a thread is a single sequential flow of control
  - a process can have many threads and a single address space
  - threads share memory and, hence, need to cooperate to produce correct results
  - thread has thread specific data (registers, stack pointer, program counter…)


code
data
files
registers
stack
thread
single-threaded process
code
data
files
registers
registers
registers
stack
stack
stack
thread
multithreaded process

Why use threads

- Threads are useful because of real-world parallelism:
  - input/output devices (flesh or silicon) may be slow but are independent
  - distributed systems have many computing entities
  - multi-processors are becoming more common, and future platforms will all be multi-core
  - better resource sharing & utilization then processes

Thread Mechanisms

- Birrell identifies four mechanisms used in threading systems:
  - thread creation
  - mutual exclusion
  - waiting for events
  - interrupting a thread's wait
- In most mechanisms in current use, only the first three are covered

- primitives used abstract, not derived from actual threading system or programming language!

Example Thread Primitives

- Thread creation
  - `Thread` type
  - `Fork(proc, args)` returns thread
  - `Join(thread)` returns value

- Mutual Exclusion
  - `Mutex` type
  - `Lock(mutex)`, a block-structured language construct in this lecture

Example Thread Primitives

- Condition Variables
  - `Condition` type
  - `Wait(mutex, condition)`
  - `Signal(condition)`
  - `Broadcast(condition)`

- Fork, Wait, Signal, etc. are not to be confused with the UNIX "fork", "wait", "signal", etc. calls

Creation Example

```
Thread thread1;
thread1 = Fork(safe_insert, 4);
safe_insert(6);
Join(thread1); // Optional
```

Mutex Example

```
list<int> my_list;
Mutex m;

void safe_insert(int i) {
  Lock(m) {
     my_list.insert(i);
  }
}
```

Condition Variables

- Mutexes are used to control access to shared data
  - only one thread can execute inside a `Lock` clause
  - other threads who try to `Lock`, are blocked until the mutex is unlocked
- Condition variables are used to wait for specific events
  - free memory is getting low, wake up the garbage collector thread
  - 10,000 clock ticks have elapsed, update that window
  - new data arrived in the I/O port, process it
- Could we do the same with mutexes?
  - (think about it and we’ll get back to it)

Condition Variable Example

```
Mutex io_mutex;
Condition non_empty;
...
Consumer:
Lock (io_mutex) {
   while (port.empty())
     Wait(io_mutex, non_empty);
   process_data(port.first_in());
}
Producer:
Lock (io_mutex) {
   port.add_data();
   Signal(non_empty);
}
```

Condition Variables Semantics

- Each condition variable is associated with a single mutex
- Wait *atomically* unlocks the mutex and blocks the thread
- Signal awakes a blocked thread
  - the thread is awoken inside Wait
  - tries to lock the mutex
  - when it (finally) succeeds, it returns from the Wait
- Doesn’t this sound complex? Why do we do it?
  - the idea is that the “condition” of the condition variable depends on data protected by the mutex

Condition Variable Example

```
Mutex io_mutex;
Condition non_empty;
...
Consumer:
Lock (io_mutex) {
   while (port.empty())
     Wait(io_mutex, non_empty);
   process_data(port.first_in());
}
Producer:
Lock (io_mutex) {
   port.add_data();
   Signal(non_empty);
}
```

Couldn't We Do the Same with Plain Communication?

```
Mutex io_mutex;
...
Consumer:
Lock (io_mutex) {
   while (port.empty())
     go_to_sleep(non_empty);
   process_data(port.first_in());
}
Producer:
Lock (io_mutex) {
   port.add_data();
   wake_up(non_empty);
}
```

- What's wrong with this? What if we don't lock the mutex (or unlock it before going to sleep)?

Mutexes and Condition Variables

- Mutexes and condition variables serve different purposes
  - Mutex: exclusive access
  - Condition variable: long waits

- *Question*: Isn't it weird to have both mutexes and condition variables? Couldn't a single mechanism suffice?
- *Answer*:

Use of Mutexes and Condition Variables

- Protect shared mutable data:

```
void insert(int i) {
  Element *e = new Element(i);
  e->next = head;
  head = e;
}
```

- What happens if this code is run in two different threads with no mutual exclusion?

Using Condition Variables

```
Mutex io_mutex;
Condition non_empty;
...
Consumer:
Lock (io_mutex) {
   while (port.empty())
     Wait(io_mutex, non_empty);
   process_data(port.first_in());
}
Producer:
Lock (io_mutex) {
   port.add_data();
   Signal(non_empty);
}
```

Why use while instead of if? (think of many consumers, simplicity of coding producer)

Readers/Writers Locking

```
Mutex counter_mutex;
Condition read_phase,
          write_phase;
int readers = 0;
```

Reader:

```
Lock(counter_mutex) {
  while (readers == -1)
    Wait(counter_mutex,
         read_phase);
  readers++;
}
... //read data
Lock(counter_mutex) {
  readers--;
  if (readers == 0)
    Signal(write_phase);
}
```

Writer:

```
Lock(counter_mutex) {
 while (readers != 0)
  Wait(counter_mutex,
       write_phase);
 readers = -1;
}
... //write data
Lock(counter_mutex) {
  readers = 0;
  Broadcast(read_phase);
  Signal(write_phase);
}
```

Comments on Readers/Writers Example

- Invariant: readers >= -1
- Note the use of Broadcast
- The example could be simplified by using a single condition variable for phase changes
  - less efficient, easier to get wrong
- Note that a writer signals all potential readers and one potential writer. Not all can proceed, however
  - (*spurious wake-ups*)
- Unnecessary lock conflicts may arise (especially for multiprocessors):
  - both readers and writers signal condition variables while still holding the corresponding mutexes
  - Broadcast wakes up many readers that will contend for a mutex

Readers/Writers Example

Reader:

```
Lock(mutex) {
  while (writer)
    Wait(mutex, read_phase)
   readers++;
}

… // read data

Lock(mutex) {
  readers--;
  if (readers == 0)
    Signal(write_phase);
}
```

Writer:

```
Lock(mutex) {
  while (readers !=0 || writer)
      Wait(mutex, write_phase)
   writer = true;
}

… // write data

Lock(mutex) {
  writer = false;
  Broadcast(read_phase);
  Signal(write_phase);
}
```

Avoiding Unnecessary Wake-ups

```
Mutex counter_mutex;
Condition read_phase, write_phase;
int readers = 0, waiting_readers = 0;
```

Reader:

```
Lock(counter_mutex) {
  waiting_readers++;
  while (readers == -1)
    Wait(counter_mutex,
         read_phase);
  waiting_readers--;
  readers++;
}
... //read data
Lock(counter_mutex) {
  readers--;
  if (readers == 0)
    Signal(write_phase);
}
```

Writer:

```
Lock(counter_mutex) {
  while (readers != 0)
  Wait(counter_mutex,
       write_phase);
  readers = -1;
}
... //write data
Lock(counter_mutex) {
  readers = 0;
  if (waiting_readers > 0)
   Broadcast(read_phase);
  else
   Signal(write_phase);
}
```

Problems With This Solution

- Explicit scheduling: readers always have priority
  - may lead to starvation (if there are always readers)
  - fix: make the scheduling protocol more complicated than it is now

To Do:

- Think about avoiding the problem of waking up readers that will contend for a single mutex if executed on multiple processors

Deadlocks (brief)

- We’ll talk more later… for now beware of deadlocks
- Examples:
  - A locks M1, B locks M2, A blocks on M2, B blocks on M1
  - Similar examples with condition variables and mutexes
- Techniques for avoiding deadlocks:
  - Fine grained locking
  - Two-phase locking: acquire all the locks you’ll ever need up front, release all locks if you fail to acquire any one
    - very good technique for some applications, but generally too restrictive
  - Order locks and acquire them in order (e.g., all threads first acquire M1, then M2)

- The scope of multithreading

LWPs, kernel and user threads

- kernel-level threads – supported by the kernel
  - Solaris, Linux, Windows XP/2000
  - all scheduling, synchronization, thread structures maintained in kernel
  - could write apps using kernel threads, but would have to go to kernel for everything
- user-level threads – supported by a user-level library
  - Pthreads, Java threads, Win32…
  - sched. & synch can often be done fully in user space; kernel doesn't need to know there are many user threads
  - problem with blocking on a system call

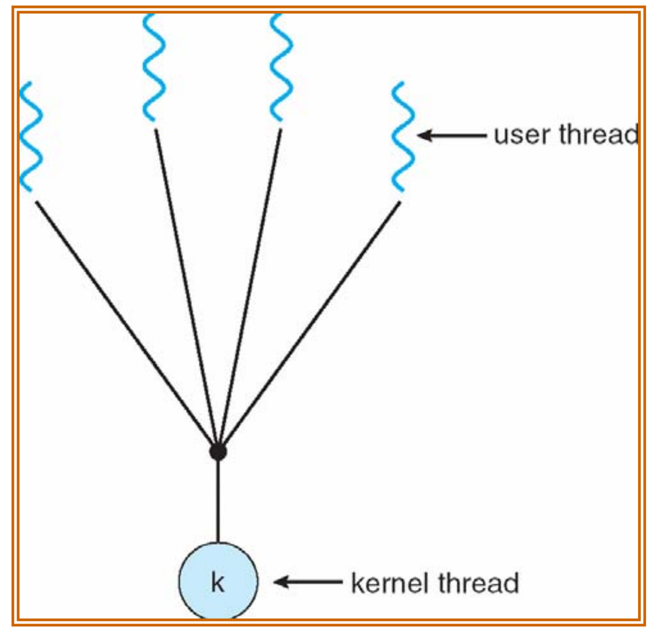
- LightWeight Processes - LWP
  - these are “virtual CPUs”, can be multiple per process
  - the scheduler of a threads library schedules user-level threads to these virtual CPUs
  - kernel threads implement LWPs => visible to the kernel, and can be scheduled
    - sometimes LWP & kernel threads used interchangeably, but there can be kernel threads without LWPs

Multithreading models

- There are three dominant models for thread libraries, each with its own trade-offs
  – many threads on one LWP (many-to-one)
  – one thread per LWP (one-to-one)
  – many threads on many LWPs (many-to-many)
- similar models can apply on scheduling kernel threads to real CPUs

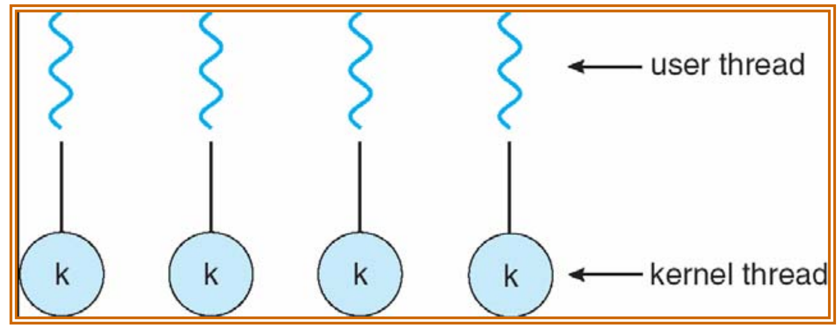
Many-to-one

- In this model, the library maps all threads to a single lightweight process
- Advantages:
  - totally portable
  - easy to do with few systems dependencies
- Disadvantages:
  - cannot take advantage of parallelism
  - may have to block for synchronous I/O
  - there is a clever technique for avoiding it
- Mainly used in language systems, portable libraries



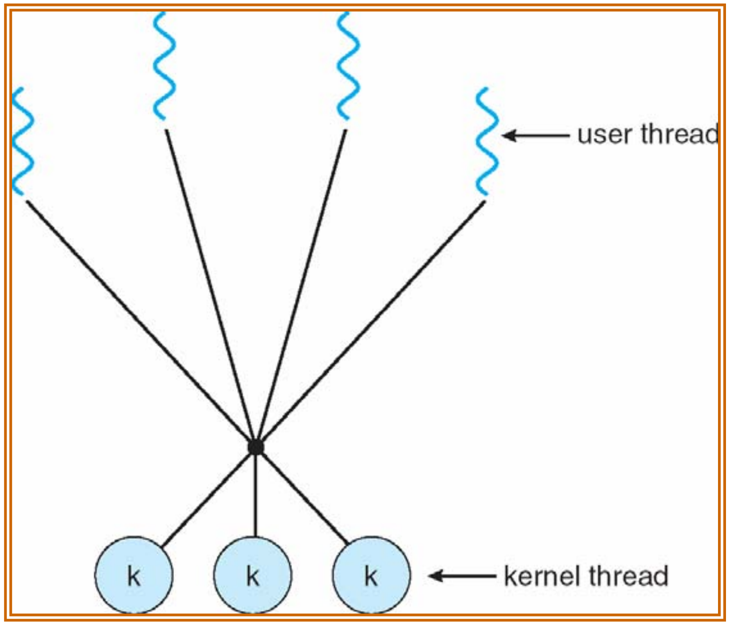
One-to-one

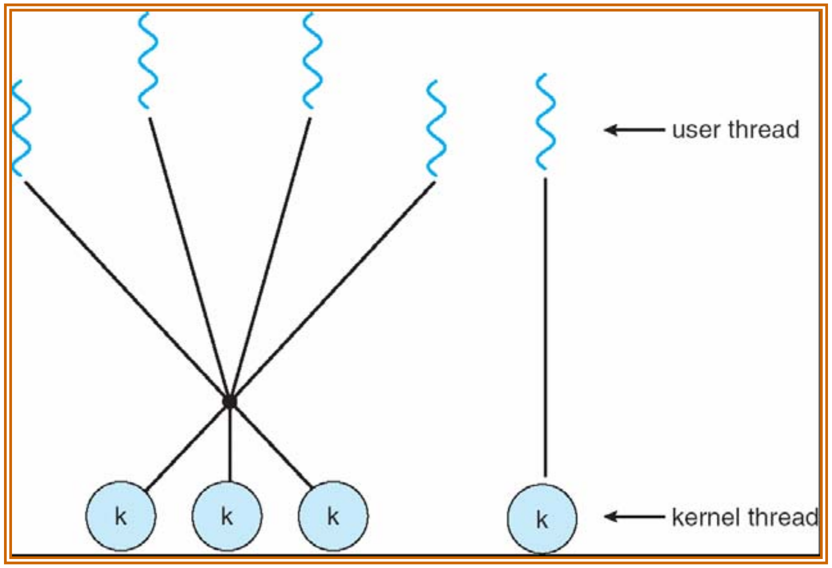
- In this model, the library maps each thread to a different lightweight process
- Advantages:
  - can exploit parallelism, blocking system calls
- Disadvantages:
  - thread creation involves LWP creation
  - each thread takes up kernel resources
  - limiting the number of total threads
- Used in LinuxThreads and other systems where LWP creation is not too expensive



Many-to-many

- In this model, the library has two kinds of threads: *bound* and *unbound*
  - bound threads are mapped each to a single lightweight process
  - unbound threads *may* be mapped to the same LWP
- Probably the best of both worlds
- Used in the Solaris implementation of Pthreads (and several other Unix implementations)





High-Level Program Structure Ideas

- Boss/workers model
- Pipeline model
- Up-calls
- Keeping shared information consistent using version stamps

Thread Design Patterns

Common ways of structuring programs using threads

- Boss/workers model
  - boss gets assignments, dispatches tasks to workers
  - variants (thread pool, single thread per connection…)
- Pipeline model
  - do some work, pass partial result to next thread
- Up-calls
  - fast control flow transfer for layered systems
- Version stamps
  - technique for keeping information consistent

Boss/Workers

Boss:

```
forever {
    get a request
    switch(request)
      case X: Fork (taskX)
    case Y: Fork (taskY)
    …
}
```

Worker:

```
taskX();
```

- Advantage: simplicity
- Disadvantage: bound on number of workers, overheard of threads creation, contention if requests have interdependencies
- Variants: fixed thread pool (aka *workpile*, *workqueue*), producer/consumer relationship, workers determine what needs to be performed…

Pipeline

- Each thread completes portion of a task, and passes results
- like an assembly line or a processor pipeline
- Advantages: trivial synchronization, simplicity
- Disadvantages: limits degree of parallelism, throughput driven by slowest stage, handtuning needed

Up-calls

- Layered applications, e.g. network protocol stacks have top-down and bottom-up flows
- Up-calls is a technique in which you structure layers so that they can expect calls from below
- Thread pool of specialized threads in each layer
  - essentially an up-call pipeline per connection
- Advantages: best when used with fast, synchronous control flow transfer mechanisms or program structuring tool
- Disadvantages: programming becomes more complicated, synchronization required for top-down

Version Stamps

- (not a programming structure idea but useful technique for any kind of distributed environment)
- maintain "version number" for shared data
  - keep local cached copy of data
  - check versions to determine if changed