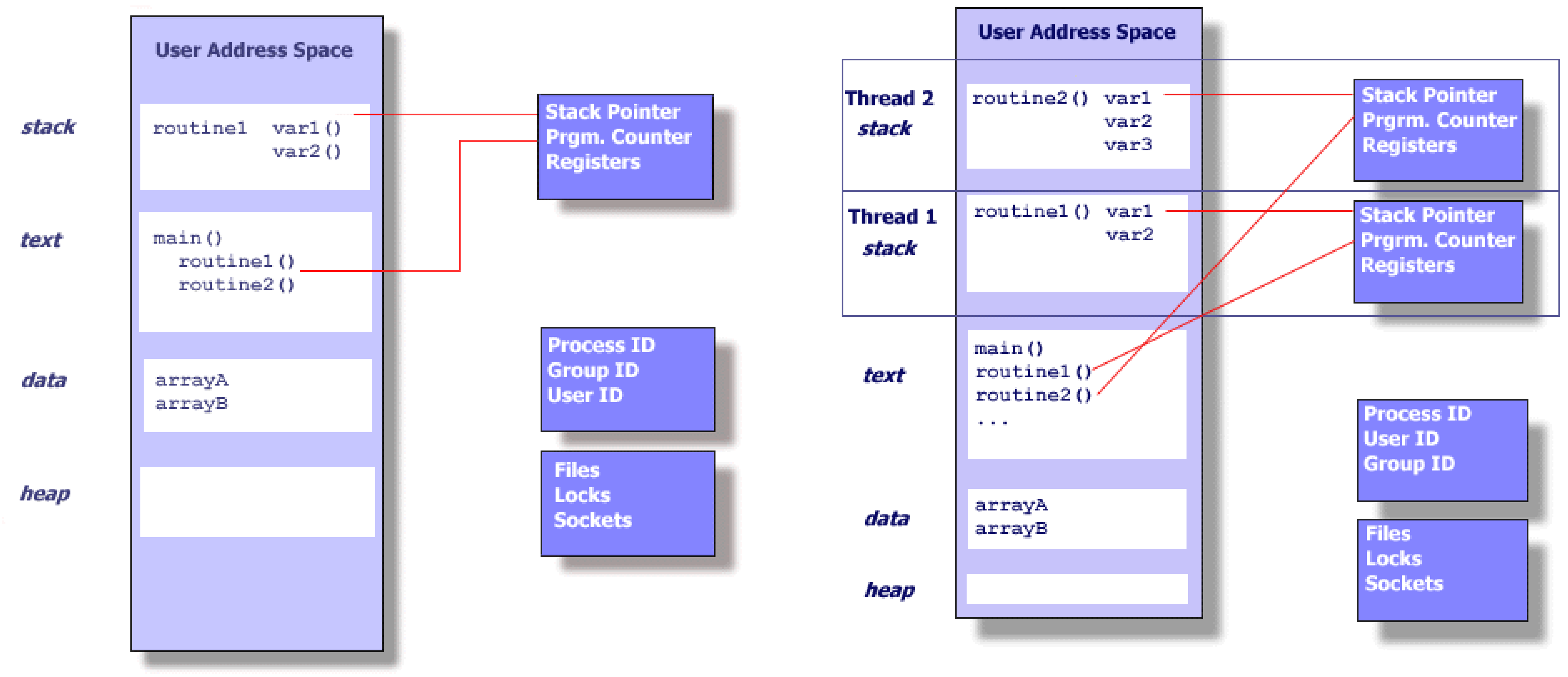
Programming Shared-memory Machines

Some slides adapted from Ananth Grama, Anshul Gupta, George Karypis, and Vipin Kumar ``Introduction to Parallel Computing'', Addison Wesley, 2003.

Overview

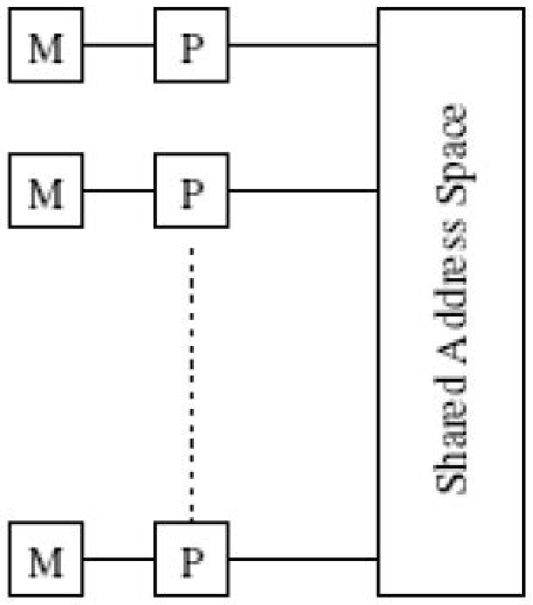
- Thread Basics
- The POSIX Thread API
- Synchronization primitives in Pthreads
  - locks
  - try-locks
- Deadlocks and how to avoid them
- Composite synchronization constructs
- Controlling Thread and Synchronization Attributes
- OpenMP: a Standard for Directive Based Parallel Programming

Process vs Threads



Thread Basics

- Each thread has its own stack, SP, PC, registers, etc.
- Threads share global variables and heap.
- Caveat: writing programs in which shared space is treated as a “flat” address space may give poor performance
  - Locality is just as important in shared-memory machines as it is in distributed-memory machines



The POSIX Thread API

- Commonly referred to as Pthreads, POSIX has emerged as the standard threads API, supported by most vendors.
- The concepts discussed here are largely independent of the API and can be used for programming with other thread APIs (NT threads, Solaris threads, Java threads, etc.) as well.

Thread Basics: Creation and Termination

- Creating Pthreads:

```
#include <pthread.h>
int pthread_create (
   pthread_t *thread_handle,
   const pthread_attr_t *attribute,
   void * (*thread_function)(void *),
   void *arg);
```

- Thread is created and it starts to execute thread_function with parameter arg
- Thread handle: opaque name for thread
- Type (void *) is C notation for “raw address” (that is, can point to anything)

Terminating threads

- Thread terminated when:
    - o it returns from its starting routine, or
    - o it makes a call to pthread_exit()
- Main thread
  - – exits with pthread_exit(): other threads will continue to execute
  - – Otherwise: other threads automatically terminated
- Cleanup:
  - – pthread_exit() routine does not close files
  - – any files opened inside the thread will remain open after the thread is terminated.

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#define NUM_THREADS 5

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

int main(int argc, char *argv[]) {
   pthread_t threads[NUM_THREADS];
   int rc, t;
   for(t=0;t<NUM_THREADS;t++){
          printf("Creating thread %d\n", t);
          rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
          if (rc){ printf("ERROR; return code from pthread_create() is %d\n", rc);
                    exit(-1);
                  }
   }
   pthread_exit(NULL);
}
```

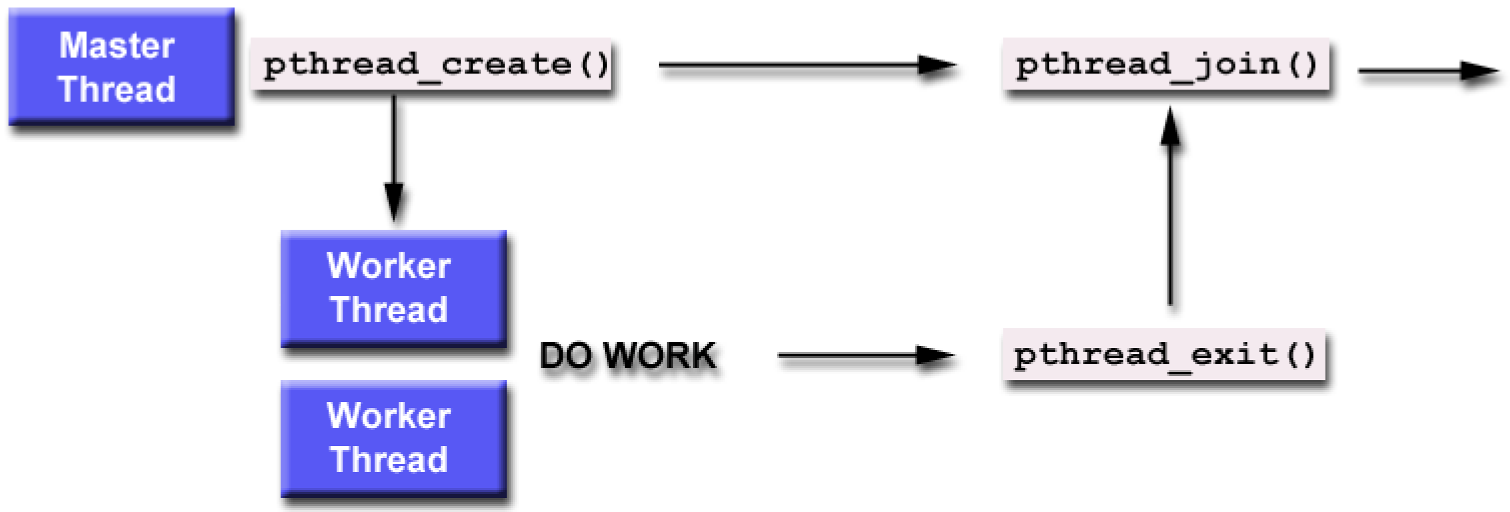
Output

```
Creating thread 0
Creating thread 1

0: Hello World!

1: Hello World!
Creating thread 2
Creating thread 3

2: Hello World!

3: Hello World!
Creating thread 4

4: Hello World!
```

Synchronizing threads

•"Joining" is one way to synchronize threads (not used very often)

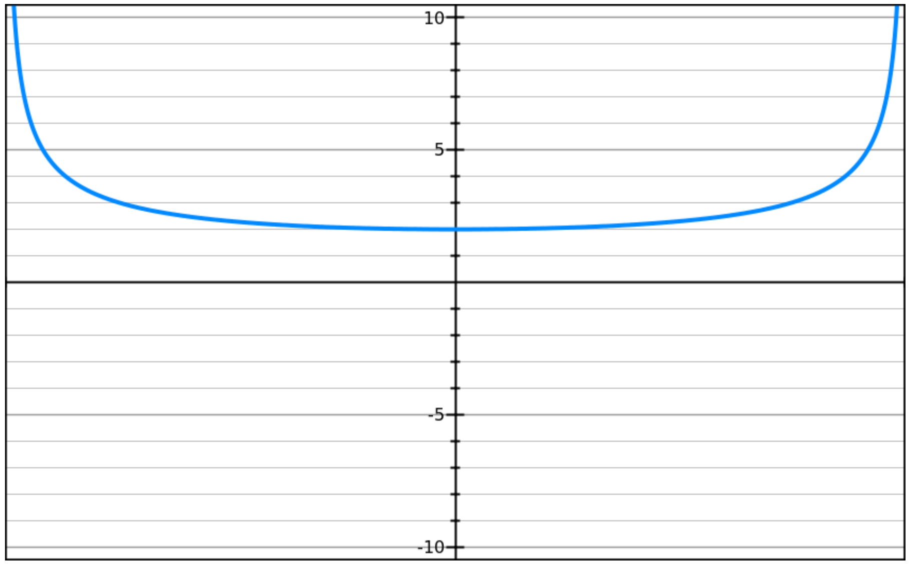
pthread_join (threadid,status)



•The pthread_join() function blocks the calling thread until the specified thread terminates.

•The programmer can obtain the target thread's termination return status if it was specified in the target thread's call to pthread_exit().

Threads: Example 2



$$f(x) = \frac{2}{\sqrt{1-x^2}}$$

- Estimate value of π using numerical integration

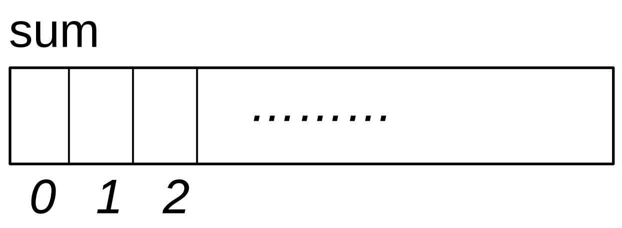
$$\int_0^1 f(x)dx = \pi$$

- Divide interval [0,1) into steps of equal size h and compute

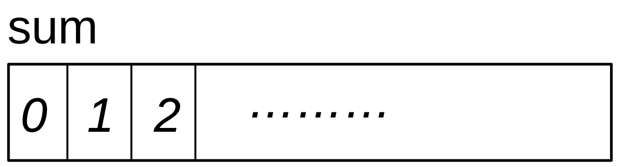
$$\sum_{i=0}^{\frac{1}{h}-1} f(i*h)*h$$

Code

```
#include <pthread.h>
#include <stdlib.h>
#include <math.h>
#include <stdio.h>

#define MAX_THREADS 512

void *compute_pi (void *);

int numPoints;
int numThreads;
double step;
double sum[MAXTHREADS];     //thread i will return its local sum in sum[i]

double f(double x) {
  return (2.0/sqrt(1-x*x));
}
```



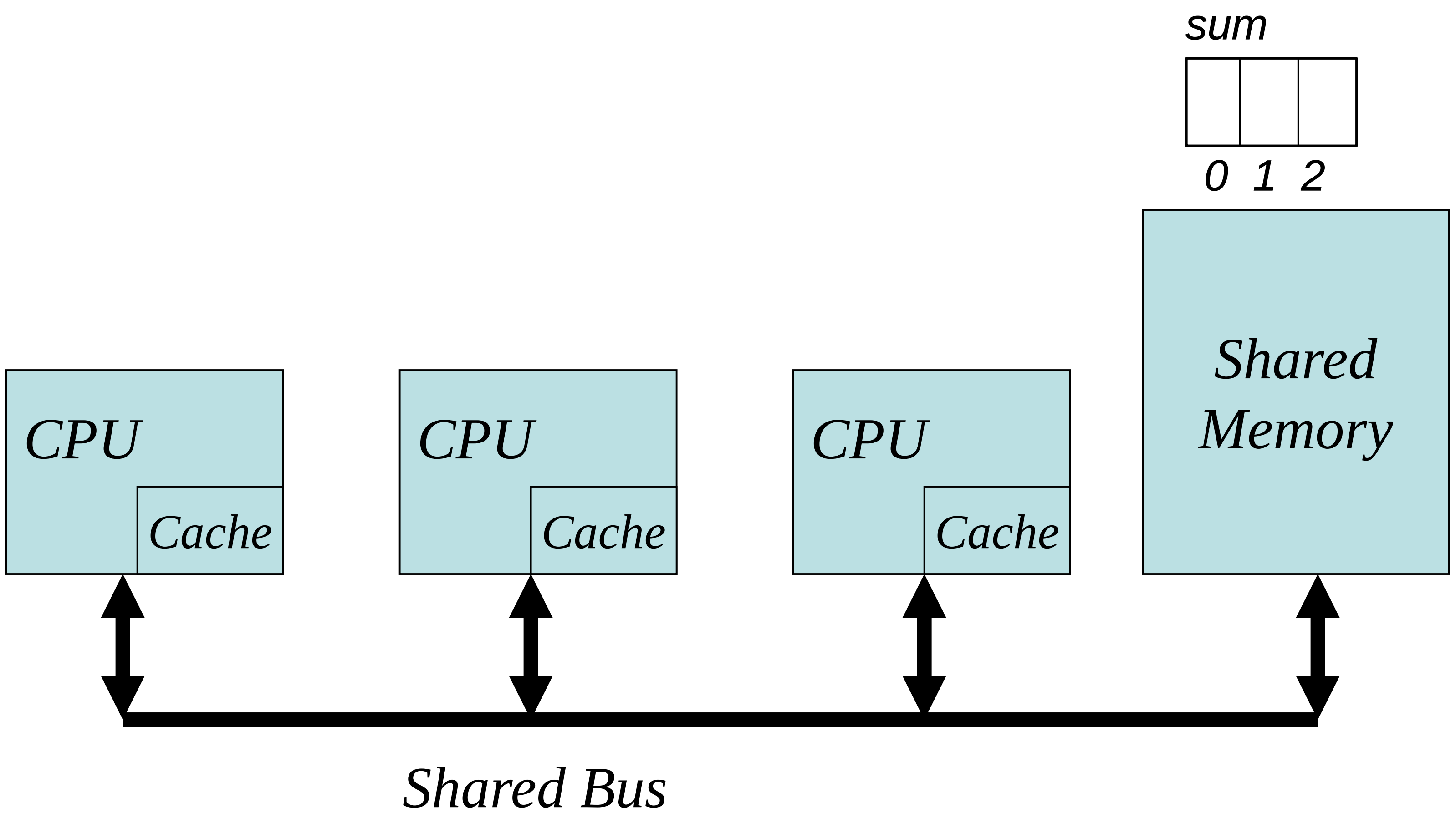
```
int main(int argc, char *argv[]) {
  pthread_t p_threads[MAX_THREADS];
  pthread_attr_t attr;
  pthread_attr_init (&attr);

  double pi = 0.0;

  numPoints = 100000000;
  numThreads = atoi(argv[1]);
  step = 1.0/numPoints;

  for (int i=0; i< numThreads; i++) {
    sum[i] = i;
    pthread_create(&p_threads[i],&attr,compute_pi,(void *) &sum[i]);
  }

  for (int i=0; i< numThreads; i++) {
    pthread_join(p_threads[i], NULL);
    pi += sum[i];
  }
  printf("%f\n", pi);
  return 0;
}
```



```
void *compute_pi (void *s) {
  int myId = *((double *) s);
  double mySum =0.0;
  double x;

  for (int i = myId; i < numPoints; i+=numThreads) {
    x = step * ((double) i);  // next x
    mySum = mySum + step*f(x);  // Add to local sum
  }
  sum[myId] = mySum;
}
```

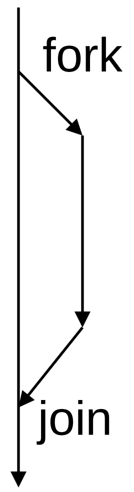
- Parameter to thread function compute_pi is address of sum[i]. Dereference this to get the id of thread.
- What happens if loop writes directly to sum[myId] instead of accumulating locally in mySum? See next slide.

False-sharing



Synchronizing threads

- Style of computing shown in Example 2 is sometimes called fork-join parallelism



- This style of parallel execution in which threads only synchronize at the end is quite rare
- Usually, threads need to synchronize during their execution

Need for synchronization

- Two common scenarios:
  - Mutual exclusion
    - Shared “resource” such as variable or device
    - Only one thread at a time can access resource
    - Critical section: portion of code that should be executed by only thread at a time
  - Producer-consumer
    - One thread (producer) generates a sequence of values
    - Another thread (consumer) reads these values
    - Values are communicated by writing them into a shared buffer
    - Producer must block if buffer is full
    - Consumer must block if buffer is empty

Need for Mutual Exclusion

- When multiple threads attempt to manipulate the same data item, the results can often be incorrect if proper care is not taken to synchronize them.
- Consider:

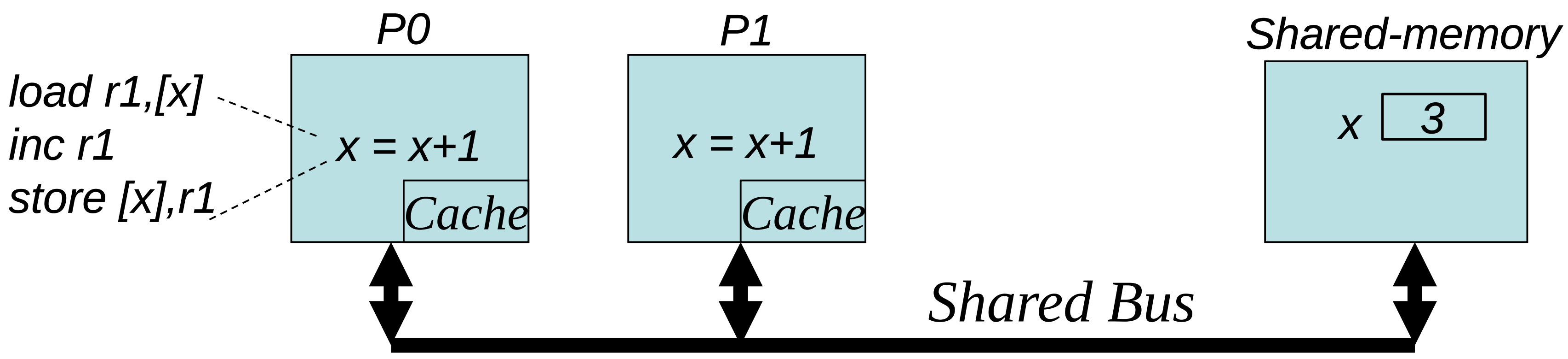
```
/* each thread tries to update variable best_cost as follows
   */
if (my_cost < best_cost)
    best_cost = my_cost;
```

- Assume that there are two threads, the initial value of `best_cost` is 100, and the values of `my_cost` are 50 and 75 at threads t1 and t2.
- Depending on the schedule of the threads, the value of `best_cost` could be 50 or 75!
  - Thread 1 reads best_cost (100)
  - Thread 2 reads best_cost (100)
  - Thread 1 writes best_cost (50)
  - Thread 2 writes best_cost (75)
- The value 75 does not “seem right” because it would not arise in a sequential execution of the same algorithm

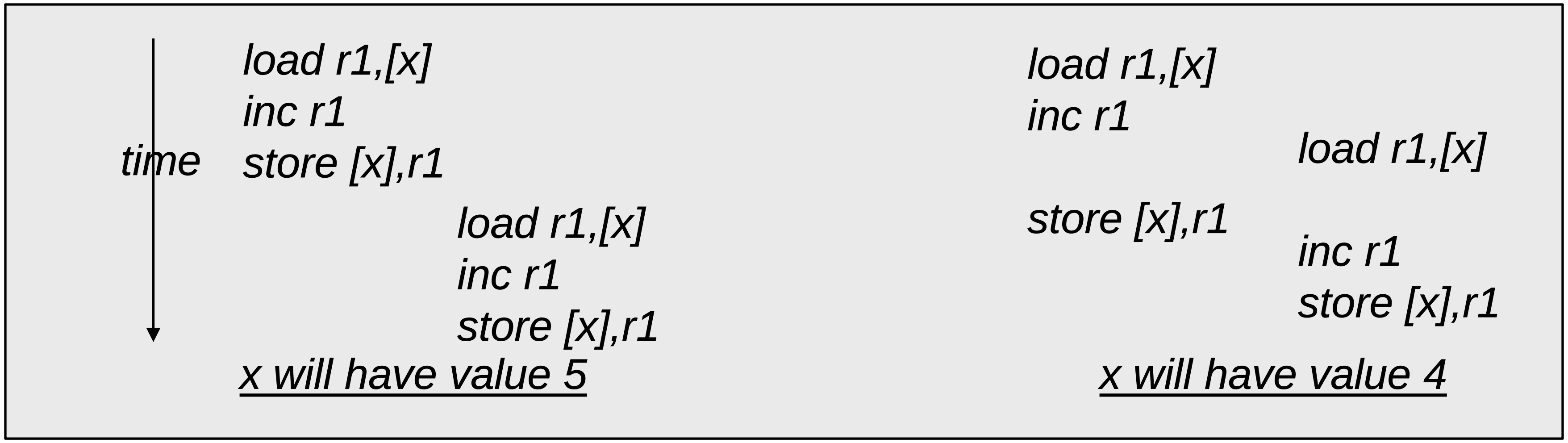
Mutual exclusion

- Basic problem: read/modify/write
  - Shared variable x
  - Two threads want to
    - *read* value of x
    - compute a *new value for x*
    - *write* new value to x
  - Unless you are careful, you get a *data-race*
    - final value can depend on
      - how code is compiled
      - scheduling of threads
      - may not be what you expect intuitively

Data-race problem



- Final value can be 4 or 5 depending on scheduling of instructions

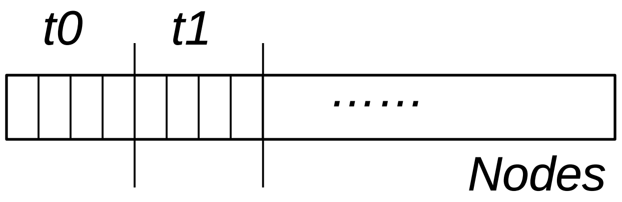


```
time   load r1,[x]                          load r1,[x]
       inc r1                               inc r1
       store [x],r1                                      load r1,[x]
                   load r1,[x]              store [x],r1
                   inc r1                                inc r1
                   store [x],r1                          store [x],r1
       x will have value 5                      x will have value 4
```

- Coherent caches do not change picture

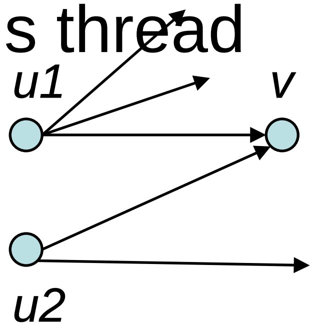
Counter-intuitive behavior

- Example: Bellman-Ford SSSP
  - assume 16 nodes and 4 threads
  - Work assignment
    - Thread 0 handles nodes 0..3
    - Thread 1 handles nodes 4..7
    - Thread 2 handles nodes 8..11
    - Thread 3 handles nodes 12..15



- Pseudo-code for thread function

```
//compute startNode and endNode for this thread
for node u = startNode to endNode
  for each edge (u,v)
      if (d(u)+length(u,v) < d(v))
        d(v) =  d(u)+length (u,v);
```



- What happens if two threads wants to update label of same node v?
  - data-race can cause incorrect results

Three solutions

- One solution: locks (mutex,spin-lock)
  - Threads compete for “acquiring” lock
  - Pthreads implementation guarantees that only one thread will succeed in acquiring lock
  - Successful thread performs read/modify/write
  - When this is done, lock is “released”
- Another solution: lock-free operations
  - Hardware provides a set of read/modify/write operations that are guaranteed to execute as if no other threads were executing concurrently (this is known as “atomic execution”)
    - These execute on ints, doubles, etc.
  - If these suffice, use them
    - This is how locks are implemented in Pthreads and other thread libraries
  - But what if you want to atomically update an entire structure or array?
    - write code that involves sequences of lock-free operations to achieve atomic execution
    - this can be quite tricky
- Most complex solution: synchronize using reads and writes
  - Decker’s algorithm for mutual exclusion of two threads
  - Brain-twister: very complex
  - Not portable: needs to be aware of memory consistency model of processor

Mutex in Pthreads

- The Pthreads API provides the following functions for handling mutex-locks:
  - Lock creation

```
int pthread_mutex_init (
   pthread_mutex_t *mutex_lock,
   const pthread_mutexattr_t *lock_attr);
```

  - Acquiring lock

```
int pthread_mutex_lock (
   pthread_mutex_t *mutex_lock);
```

  - Releasing lock

```
int pthread_mutex_unlock (
   pthread_mutex_t *mutex_lock);
```

Using locks

- Lock is implemented by
  - variable with two states: *available* or *not_available*
  - queue that can hold ids of threads waiting for the lock
- Lock acquire:
  - If state of lock is *available*, its state is changed to *not_available,* and control returns to application program
  - If state of lock is *not_available*, thread-id is queued up at the lock, and control returns to application program only when lock is acquired by that thread
  - Key invariant: once a thread tries to acquire lock, control returns to thread only after lock has been awarded to that thread
- Lock release:
  - next thread in queue is informed it has acquired lock, and it can proceed
- "Fairness": any thread that wants to acquire a lock can succeed ultimately even if other threads want to acquire the lock an unbounded number of times

Correct Mutual Exclusion

- We can now write our global min example as:

```
pthread_mutex_t minimum_value_lock;
...
main() {
    ....
    pthread_mutex_init(&minimum_value_lock, NULL);
    ....
}
void *find_min(void *list_ptr) {
    ....
    pthread_mutex_lock(&minimum_value_lock);
    if (my_min < minimum_value)
    minimum_value = my_min;
    /* and unlock the mutex */
    pthread_mutex_unlock(&minimum_value_lock);
}
```

critical section

Critical sections

- For performance, it is important to keep critical sections as small as possible
- While one thread is within critical section, all others threads that want to enter the critical section are blocked
- It is up to the programmer to ensure that locks are used correctly to protect variables in critical sections

```
Thread A        Thread B       Thread C
 lock(l)          lock(l)
   x:= ..x..        x:= ..x..      x: = …x
unlock(l)         unlock(l)
```

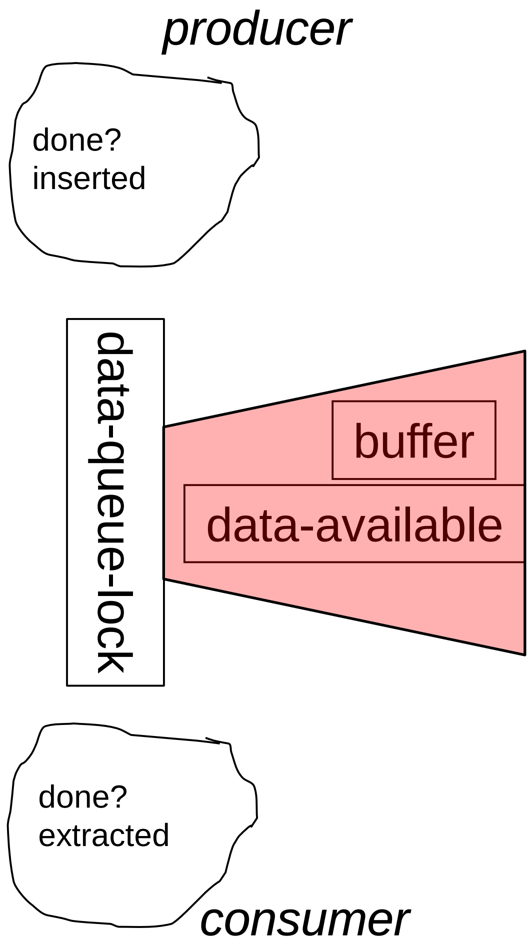
This program may fail to execute correctly because programmer forgot to use locks in Thread C

Producer-Consumer Using Locks

- Two threads
  - Producer: produces data
  - Consumer: consumes data
- Shared buffer is used to communicate data from producer to consumer
  - Buffer can contain one data value (in this example)
  - Flag is associated with buffer to indicate buffer has valid data
- Consumer must not read data from buffer unless there is valid data
- Producer must not overwrite data in buffer before it is read by consumer

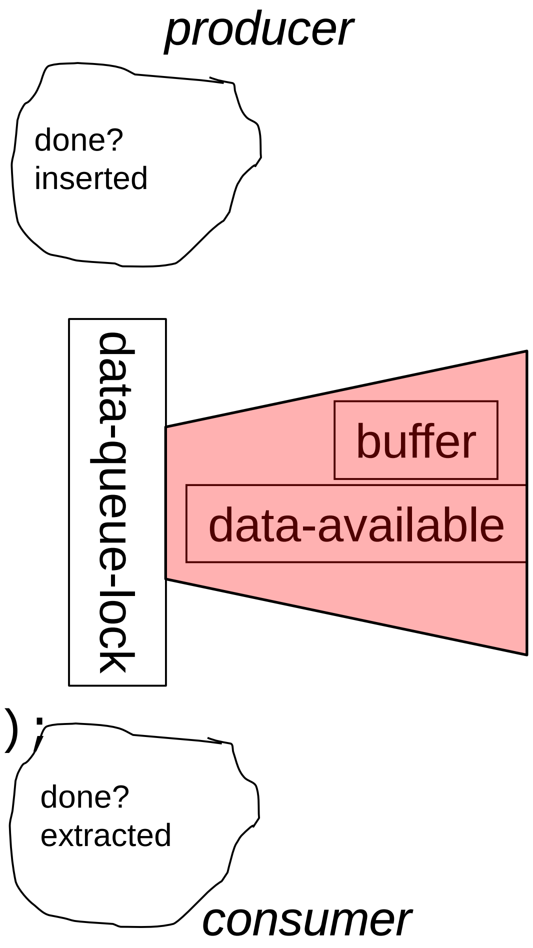
Producer-Consumer Using Locks

```
pthread_mutex_t data_queue_lock;
int data_available; //1 if buffer is full
...
main() {
    ....
    data_available = 0;
    pthread_mutex_init(&data_queue_lock, NULL);
    ....
}
void *producer(void *producer_thread_data) {
    ....
    while (!done()) {
        create_data(&my_data);
        inserted = 0;
        while (inserted == 0) {
            pthread_mutex_lock(&data_queue_lock);
            if (data_available == 0) {
                insert_data(my_data);
                data_available = 1;
                inserted = 1;
            }
            pthread_mutex_unlock(&data_queue_lock);
        }
    }
}
```



Producer-Consumer Using Locks

```
void *consumer(void *consumer_thread_data) {
    int extracted;
    struct data my_data;
    /* local data structure declarations */
    while (!done()) {
        extracted = 0;
        while (extracted == 0) {
            pthread_mutex_lock(&data_queue_lock);
            if (data_available == 1) {
                extract_data(&my_data);
                data_available = 0;
                extracted = 1;
            }
            pthread_mutex_unlock(&data_queue_lock);
        }
        process_data(my_data);
    }
}
```



Types of Mutexes

- Pthreads supports three types of mutexes - normal, recursive, and error-check.
- A normal mutex deadlocks if a thread that already has a lock tries a second lock on it.
- A recursive mutex allows a single thread to lock a mutex as many times as it wants. It simply increments a count on the number of locks. A lock is relinquished by a thread when the count becomes zero.
- An error check mutex reports an error when a thread with a lock tries to lock it again (as opposed to deadlocking in the first case, or granting the lock, as in the second case).
- The type of the mutex can be set in the attributes object before it is passed at time of initialization.

Spin locks/trylocks

- Another kind of lock: trylock.

```
int pthread_mutex_trylock (
        pthread_mutex_t *mutex_lock);
```

- If lock is available, acquire it; otherwise, return a "busy" error code (EBUSY)
- Faster than `pthread_mutex_lock` on typical systems since it does not have to deal with queues associated with locks for multiple threads waiting on the lock.

Using locks

```
/* Finding k matches in a list */
void *find_entries(void *start_pointer) {
    /* This is the thread function */
    struct database_record *next_record;
    int count;
    current_pointer = start_pointer;
    do {
        next_record = find_next_entry(current_pointer);
        count = output_record(next_record);
    } while (count < requested_number_of_records);
}
int output_record(struct database_record *record_ptr) {
    int count;
    pthread_mutex_lock(&output_count_lock);
    output_count ++;
    count = output_count;
    pthread_mutex_unlock(&output_count_lock);
    if (count <= requested_number_of_records)
        print_record(record_ptr);
    return (count);
}
```

Using spin-locks

```
/* rewritten output_record function */
int output_record(struct database_record
  *record_ptr) {
   int count;
   int lock_status;
   lock_status=pthread_mutex_trylock(&output_count_lock);
   if (lock_status == EBUSY) {
      insert_into_local_list(record_ptr);
      return(0);
   }
   else {
      count = output_count;
      output_count += number_on_local_list + 1;
      pthread_mutex_unlock(&output_count_lock);
      print_records(record_ptr, local_list,
         requested_number_of_records - count);
      return(count + number_on_local_list + 1);
   }
}
```

Problems with locks

- Locks are most dangerous when a thread needs to acquire multiple locks before releasing locks
- Two main problems:
  - deadlock
  - livelock
- Deadlock:
  - Threads A and B need locks L1 and l2
  - Thread A acquires L1 and wants L2
  - Thread B acquires L2 and wants L1
  - In general, there will be a cycle of threads in which each thread holds some locks and is waiting for locks held by other threads in the cycle
- Livelock:
  - may arise in some solutions to deadlock

Deadlock

- Code snippet shows example of possible deadlock
- Subtle point:
  - deadlock may happen in some executions and not in others!
- "Deadly embrace": Dijkstra
- How do we ensure deadlocks cannot occur?

```
Thread 1:          Thread 2:
…                  …
lock(L1);          lock(L2);
lock(L2);          lock(L1);
….                 …
```

$$\begin{tikzcd}
\text{Thread 1} \arrow[r, "\text{holds}"'] & \text{Lock L1} \arrow[d, "\text{needed by}"] \\
\text{Lock L2} \arrow[u, "\text{needed by}"'] & \text{Thread 2} \arrow[l, "\text{holds}"]
\end{tikzcd}$$

Deadlock: four conditions

- Mutual exclusion:
  - thread has exclusive control over resource it acquires
- Hold-and-wait:
  - thread does not release resource it holds if it is waiting for another resource
- No pre-emption:
  - No external agency forces a thread to release resources if thread is waiting for another resource
- Circular wait:
  - There is a cycle of threads such that each thread holds one or more resources needed by the next thread in the cycle

You prevent deadlocks by ensuring that one or more of these conditions cannot arise in your program.

Prevent circular wait

- Assign a logical total order to locks
  - (eg) name them L1,L2,L3,…
- Ensure that threads will never try to acquire a lower numbered lock while holding a higher numbered lock
  - (eg) if thread owns L3, it can try to acquire L4, L5, L6,… but it cannot try to acquire locks L1 or L2 (unless it already owns them and locks are re-entrant)
- Useful software engineering principle when you have control over the entire code base and you know what locks are required where
- However
  - easy to make mistakes
  - tension with encapsulation:
    - requires detailed knowledge of entire code base

Prevent hold-and-wait

- Try to acquire all locks atomically
- One implementation:
  - single global lock to get permission to acquire locks you need
- Problem:
  - not scalable
  - conflicts with modularity and encapsulation
- You might encounter a hidden version of this problem if thread has to enter the kernel to perform some function like storage allocation
  - kernel lock is like the global-lock in our example

```
…
lock(global-lock);
lock(l1);
lock(l2);
unlock(global-lock);
…
```

Self-preemption

- Coding discipline:
  - Use only try-locks
  - If a thread cannot acquire a lock while it is holding other locks, it releases all locks it holds and tries again
  - Variation: OS or some other agency steps in and preempts a thread
- Problems:
  - Encapsulation
  - Livelock: threads can keep on acquiring and releasing locks without making progress because no thread ever gets all the locks it needs
  - One solution to livelock: (Ethernet) backoff: thread does not retry until some randomly chosen amount of time has passed

```
loop:
  //start of lock acquires
  ….
  if (trylock(Lj) == EBUSY) {
    //unlock all locks you hold
    goto loop;
  }
  ….
endloop:

//compute with resources
//release locks
```

Lock-free synchronization

- Use hardware instructions that perform atomic computations on memory locations
  - enough for many applications but in general, they need to be composed and this can be tricky
- Many flavors of atomic instructions have been explored in the literature
  - test-and-set, test-and-test-and-set, atomic swap, atomic add, compare-and-swap,..
  - goal is to capture common patterns of atomicity in a single instruction

Example

- Atomic swap(addr,reg)
  - swap contents of address and register atomically
- Spin-lock using swap
  - location lock has 0/1 for unlocked/locked
  - lock code:

    load 1 into register rx;

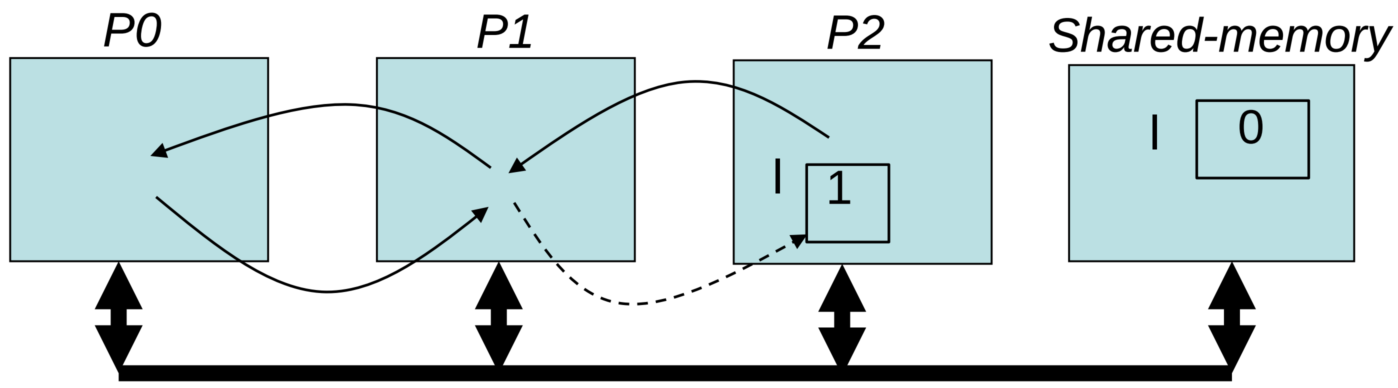
    swap(lock,rx);

    test rx:

      - if rx is 1, you don't have lock so try again
      - if rx is 0, you have lock and no one else can have it till you unlock
  - unlock
    - store 0 into lock;
- Problem:
  - swap must invalidate address in all caches even when lock acquire is not successful
  - if there are a lot of threads waiting for lock, busy-waiting will create a lot of bus traffic

Busy-waiting and bus traffic

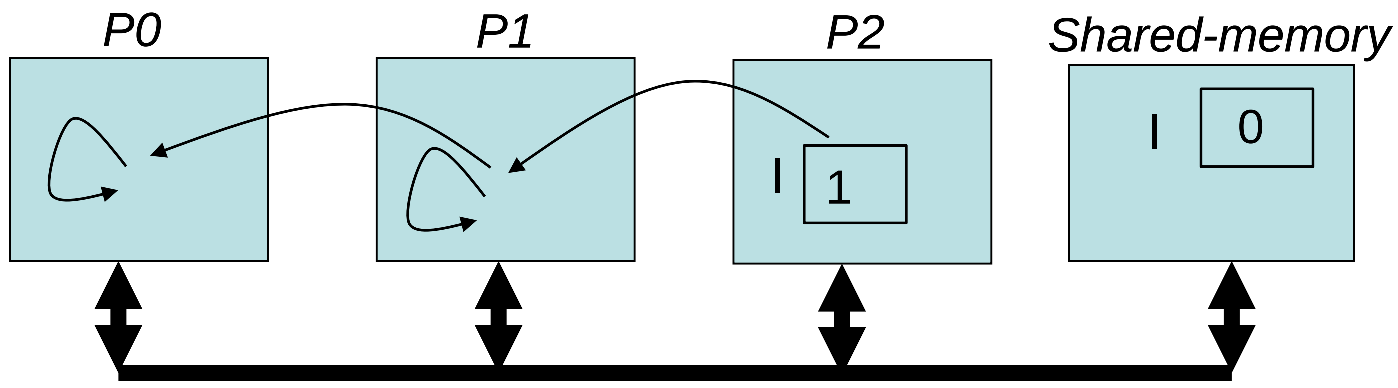
```
…..
        mov edx,1
acq: swap [l], edx
        test edx, edx
        jnz acq
…..
```



- Busy-waiting creates a lot of bus traffic
- Sequence of actions
  - all threads do exchg
  - P2 wins and gets lock
  - P0 and P1 keep doing swap operations, invalidating line in other caches
  - P2 releases lock by writing 0 to lock
  - ….
- Solution: test-and-test-and-set
  - keep doing ordinary reads until lock is 0
  - then go into acq loop and see if you can get lock
  - if you fail, jump back to read loop

Better busy-waiting

```
…..
        mov edx,1
 spin: mov eax, [l]
        test eax, eax
        jnz spin
        swap [l], edx
        test edx, edx
        jnz spin
…..
```



- Inner spin loop does not create bus traffic since all spinning threads spin on their local caches
- When P2 unlocks, line is invalidated from P0 and P1

Compare-and-swap (CAS)

- Consider Bellman-Ford
  - relaxation of edge (u,v)

```
tN = dist(u) + w(u,v);
acquire lock on v; //this uses swap
if (tN < dist(v)) dist(v) = tN;
release lock on v;
```

- New atomic instruction: compare-and-swap (cas)
  - cas addr, old-value, new-value
  - check if addr contains old-value
  - if so, update it to new-value and return SUCCESS; otherwise return FAIL.
- Bellman-Ford (II):
  - Relaxation of edge (u,v)

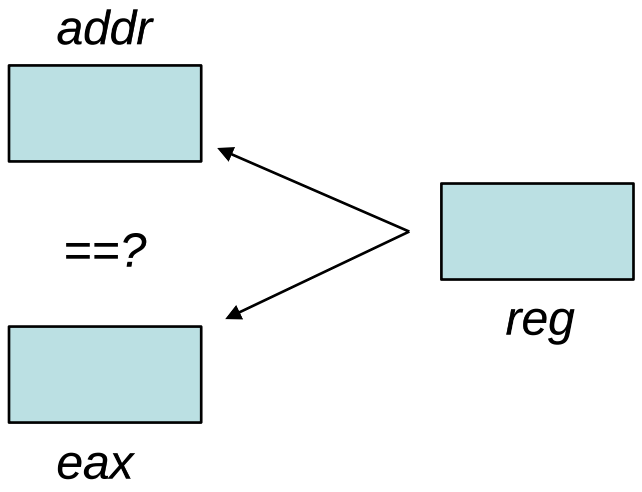
```
repeat {
  tO = dist(v); //read old value
  tN = dist(u)+w(u,v); //compute new value
  if (tN < tO)
     done = cas(dist(v),tO,tN); //write if dist(v) still contains tO
  else
     done = SUCCESS;
until (done==SUCCSS)}
```

- Advantages:
  - Separate locations for locks not needed
  - Smaller critical section
  - Fewer writes
- CAS operation was first introduced in IBM System 370

X86 instruction

- cmpxchg addr, reg; eax is implicit operand

```
if (contents(addr) == eax))
    {addr = reg;
     zero-flag = 1;
    }
   else
    {eax = reg;
     zero-flag = 0;
    }
```



- "lock cmpxchg addr,reg"
  - instruction is executed atomically

Spinlock example in x86

```
global main

extern printf
extern pthread_create
extern pthread_exit
extern pthread_join

section .data
        align 4
        sLock:                dd 0        ; The lock, values are:
                                          ; 0         unlocked
                                          ; 1         locked
        tID1:                 dd 0
        tID2:                 dd 0
        fmtStr1:    db "In thread %d with ID: %02x", 0x0A, 0
        fmtStr2:    db "Result %d", 0x0A, 0

section .bss
        align 4
        result:               resd 1
```

```
section .text
          main:                          ; Using main since we are using gcc to link

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

          push       dword 0             ; Arg Four: argument pointer
          push       thread1             ; Arg Three: Address of routine
          push       dword 0             ; Arg Two: Attributes
          push       tID1                ; Arg One: pointer to the thread ID
          call       pthread_create

          push       dword 0             ; Arg Four: argument pointer
          push       thread2             ; Arg Three: Address of routine
          push       dword 0             ; Arg Two: Attributes
          push       tID2                ; Arg One: pointer to the thread ID
          call       pthread_create

                                         ; Call int pthread_join(pthread_t thread, void **retval) ;
                                         ;
          push       dword 0             ; Arg Two: retval
          push       dword [tID1]  ; Arg One: Thread ID to wait on
          call       pthread_join
          push       dword 0             ; Arg Two: retval
          push       dword [tID2]  ; Arg One: Thread ID to wait on
          call       pthread_join

          push       dword [result]
          push       dword fmtStr2
          call       printf
          add        esp, 8              ; Pop stack 2 times 4 bytes

          call exit
```

```
thread1:
          pause
          push      dword [tID1]
          push      dword 1
          push      dword fmtStr1
          call      printf
          add       esp, 12               ; Pop stack 3 times 4 bytes

          call      spinLock

          mov       [result], dword 1
          call      spinUnlock

          push      dword 0               ; Arg one: retval
          call      pthread_exit

thread2:
          pause
          push      dword [tID2]
          push      dword 2
          push      dword fmtStr1
          call      printf
          add       esp, 12               ; Pop stack 3 times 4 bytes

          call      spinLock

          mov       [result], dword 2
          call      spinUnlock

          push      dword 0               ; Arg one: retval
          call      pthread_exit
```

```
spinLock:
            push        ebp
            mov         ebp, esp
            mov         edx, 1                      ; Value to set sLock to
spin:       mov         eax, [sLock]  ; Check sLock
            test        eax, eax      ; If it was zero, maybe we have the lock
            jnz         spin                        ; If not try again
            ;
            ; Attempt atomic compare and exchange:
            ; if (sLock == eax):
            ;           sLock         <- edx
            ;           zero flag     <- 1
            ; else:
            ;           eax           <- edx
            ;           zero flag     <- 0
            ;
            ; If sLock is still zero then it will have the same value as eax and
            ; sLock will be set to edx which is one and therefore we aquire the
            ; lock. If the lock was acquire between the first test and the
            ; cmpxchg then eax will not be zero and we will spin again.
            ;
            lock        cmpxchg [sLock], edx    ;eax is implicit operand
            test        eax, eax
            jnz         spin
            pop         ebp
            ret
spinUnlock:
            push        ebp
            mov         ebp, esp
            mov         eax, 0
            xchg        eax, [sLock]
            pop         ebp
            ret
```

```
exit:
                                                    ;
                                                    ; Call exit(3) syscall
                                                    ;void exit(int status)
                                                    ;
          mov         ebx, 0                        ; Arg one: the status
          mov         eax, 1                        ; Syscall number:
          int         0x80
```

Third solution to mutual exclusion

- Dekker’s solution
  - No atomic operations on memory locations
  - Uses ordinary reads and writes
- We won’t study it in this course.

Barriers

- Pthreads barrier type
  - pthread_barrier_t   varBarrier;
  - basically a struct
    - int total: initialized to # of threads to wait for
    - int count: tracks how many threads have reached barrier
    - mutex
- Initialize barrier
  - int pthread_barrier_init (&varBarrier,NULL,total);
- Waiting at barrier
  - int pthread_barrier_wait (&varBarrier);

Controlling Thread and Synchronization Attributes

- The Pthreads API allows a programmer to change the default attributes of entities using *attributes objects*.
- An attributes object is a data-structure that describes entity (thread, mutex, condition variable) properties.
- Once these properties are set, the attributes object can be passed to the method initializing the entity.
- Enhances modularity, readability, and ease of modification.

Attributes Objects for Threads

- Use `pthread_attr_init` to create an attributes object.
- Individual properties associated with the attributes object can be changed using the following functions:

  `pthread_attr_setdetachstate`,
  `pthread_attr_setguardsize_np`,
  `pthread_attr_setstacksize`,
  `pthread_attr_setinheritsched`,
  `pthread_attr_setschedpolicy`, and
  `pthread_attr_setschedparam`

Attributes Objects for Mutexes

- Initialize the attrributes object using function: `pthread_mutexattr_init`.
- The function `pthread_mutexattr_settype_np` can be used for setting the type of mutex specified by the mutex attributes object.

```
pthread_mutexattr_settype_np (
pthread_mutexattr_t *attr,
int type);
```

- Here, `type` specifies the type of the mutex and can take one of:
  - `PTHREAD_MUTEX_NORMAL_NP`
  - `PTHREAD_MUTEX_RECURSIVE_NP`
  - `PTHREAD_MUTEX_ERRORCHECK_NP`

Types of threads

- Thread implementations:
  - User-level threads:
    - Implemented by user-level runtime library
    - OS is unaware of threads
    - Portable, thread scheduling can be tuned to application requirements
    - Problem: cannot leverage multiprocessors, entire process blocks when one thread blocks
  - Kernel-level threads:
    - OS is aware of each thread and schedules them
    - Thread operations are performed by OS
    - Can leverage multiprocessors
    - Problem: higher overhead, usually not quite as portable
  - Hybrid-level threads: Solaris
    - OS provides some number of kernel level threads, and each of these can create multiple user-level threads
    - Problem: complexity

OpenMP: a Standard for Directive Based Parallel Programming

- OpenMP is a directive-based API that can be used with FORTRAN, C, and C++ for programming shared address space machines.
- OpenMP directives provide support for concurrency, synchronization, and data handling while obviating the need for explicitly setting up mutexes, condition variables, data scope, and initialization.

OpenMP Programming Model

- OpenMP directives in C and C++ are based on the `#pragma` compiler directives.
- A directive consists of a directive name followed by clauses.

```
#pragma omp directive [clause list]
```

- OpenMP programs execute serially until they encounter the `parallel` directive, which creates a group of threads.

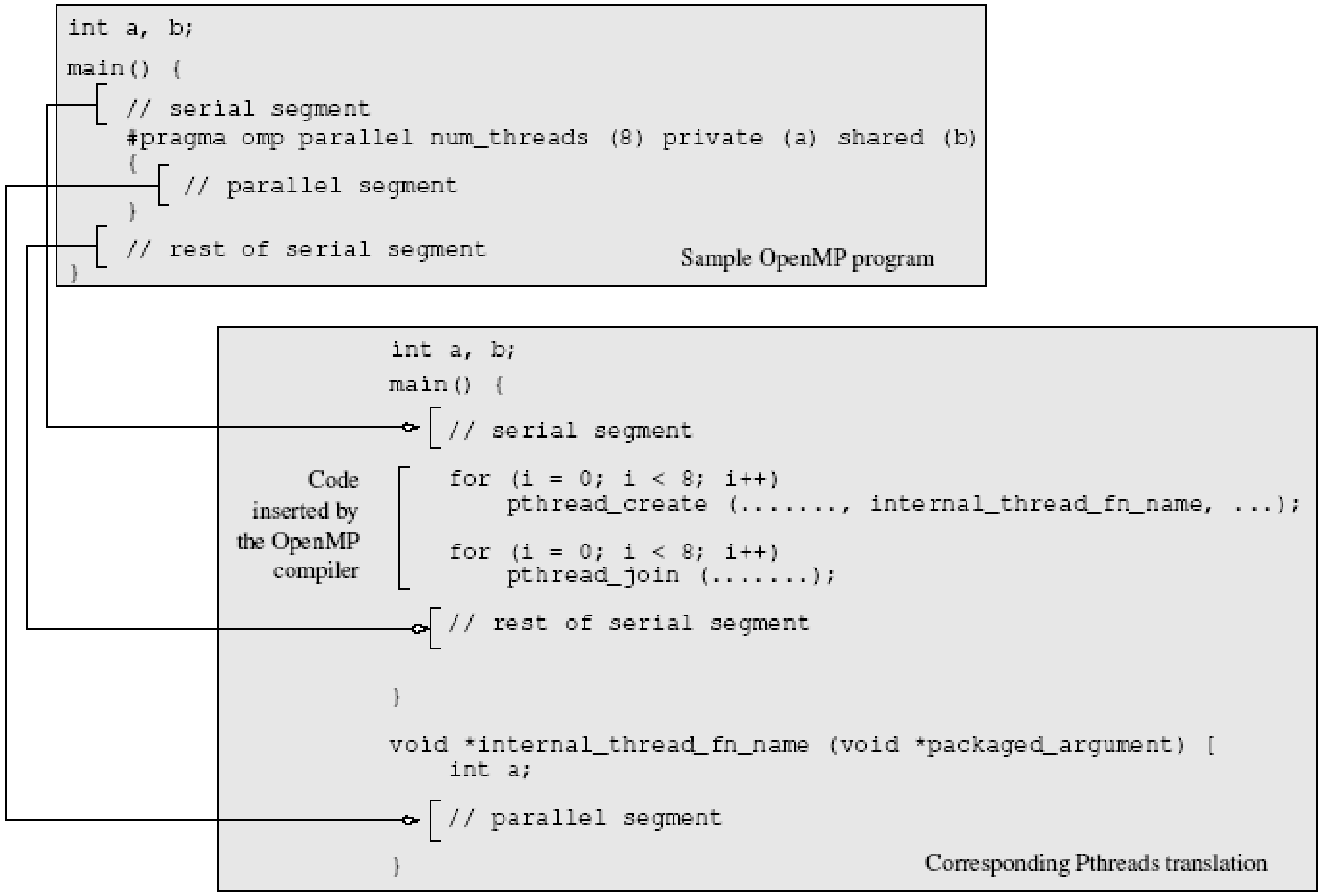
```
#pragma omp parallel [clause list]
/* structured block */
```

- The main thread that encounters the `parallel` directive becomes the *master* of this group of threads and is assigned the thread id 0 within the group.

OpenMP Programming Model

- The clause list is used to specify conditional parallelization, number of threads, and data handling.
  - **Conditional Parallelization:** The clause `if (scalar expression)` determines whether the parallel construct results in creation of threads.
  - **Degree of Concurrency:** The clause `num_threads(integer expression)` specifies the number of threads that are created.
  - **Data Handling:** The clause `private (variable list)` indicates variables local to each thread. The clause `firstprivate (variable list)` is similar to the `private`, except values of variables are initialized to corresponding values before the parallel directive. The clause `shared (variable list)` indicates that variables are shared across all the threads.

OpenMP Programming Model



```
int a, b;
main() {
    // serial segment
    #pragma omp parallel num_threads (8) private (a) shared (b)
    {
        // parallel segment
    }
    // rest of serial segment
}
```

Sample OpenMP program

```
int a, b;
main() {
    // serial segment
    for (i = 0; i < 8; i++)
        pthread_create (......., internal_thread_fn_name, ...);

    for (i = 0; i < 8; i++)
        pthread_join (.......);
    // rest of serial segment

}

void *internal_thread_fn_name (void *packaged_argument) [
    int a;
    // parallel segment
}
```

Code inserted by the OpenMP compiler

Corresponding Pthreads translation

- A sample OpenMP program along with its Pthreads translation that might be performed by an OpenMP compiler.

OpenMP Programming Model

```
#pragma omp parallel if (is_parallel== 1) num_threads(8) \
  private (a) shared (b) firstprivate(c) {
 /* structured block */
}
```

- If the value of the variable is_parallel equals one, eight threads are created.
- Each of these threads gets private copies of variables a and c, and shares a single value of variable b.
- The value of each copy of c is initialized to the value of c before the parallel directive.
- The default state of a variable is specified by the clause default (shared) or default (none).

Reduction Clause in OpenMP

- The `reduction` clause specifies how multiple local copies of a variable at different threads are combined into a single copy at the master when threads exit.
- The usage of the reduction clause is `reduction (operator: variable list)`.
- The variables in the list are implicitly specified as being private to threads.
- The `operator` can be one of `+, *, -, &, |, ^, &&,` and `||`.

```
#pragma omp parallel reduction(+: sum) num_threads(8) {
/* compute local sums here */
}
/*sum here contains sum of all local instances of sums */
```

OpenMP Programming: Example

```
/* *****************************************************
An OpenMP version of a threaded program to compute PI.
***************************************************** */
#pragma omp parallel default(private) shared (npoints) \
    reduction(+: sum) num_threads(8)
{
    num_threads = omp_get_num_threads();
    sample_points_per_thread = npoints / num_threads;
    sum = 0;
    for (i = 0; i < sample_points_per_thread; i++) {
        rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
        rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
        if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
            sum ++;
    }
}
```

Specifying Concurrent Tasks in OpenMP

- The `parallel` directive can be used in conjunction with other directives to specify concurrency across iterations and tasks.
- OpenMP provides two directives - `for` and `sections` - to specify concurrent iterations and tasks.
- The `for` directive is used to split parallel iteration spaces across threads. The general form of a for directive is as follows:

```
 #pragma omp for [clause list]
     /* for loop */
```

- The clauses that can be used in this context are: `private`, `firstprivate`, `lastprivate`, `reduction`, `schedule`, `nowait`, and `ordered`.

Specifying Concurrent Tasks in OpenMP: Example

```
#pragma omp parallel default(private) shared (npoints) \
    reduction(+: sum) num_threads(8)
{
    sum = 0;
    #pragma omp for
    for (i = 0; i < npoints; i++) {
        rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
        rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
        if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
            sum ++;
    }
}
```

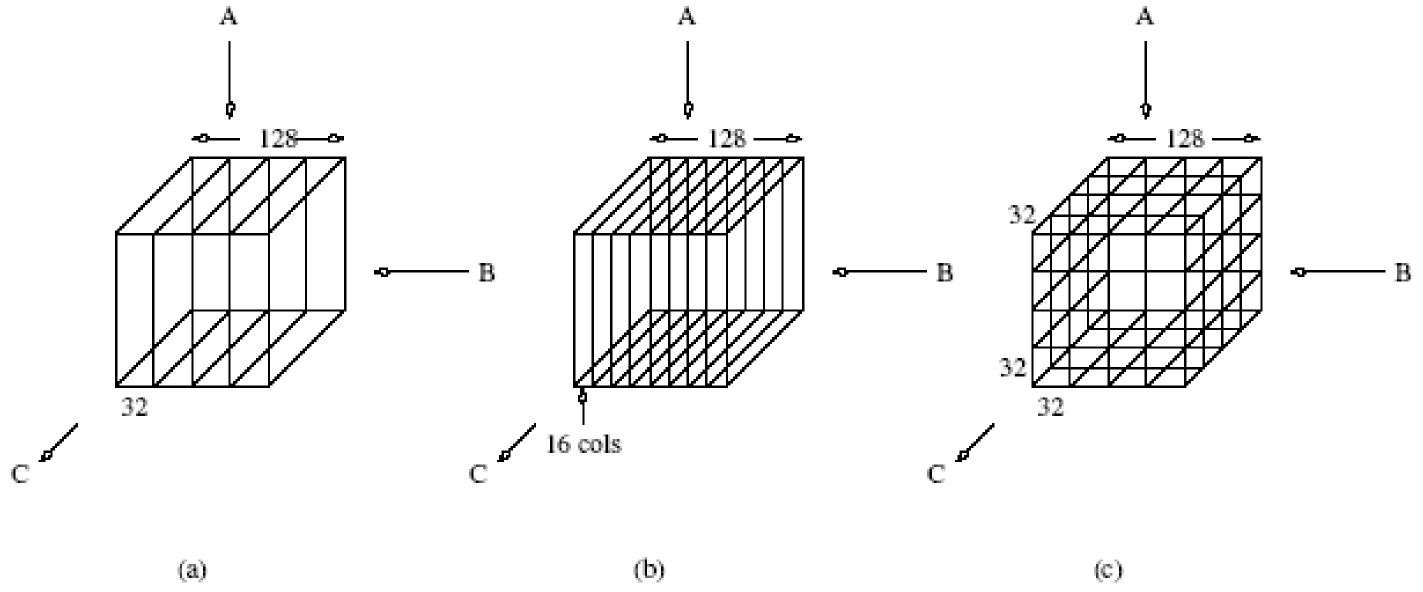
Assigning Iterations to Threads

- The `schedule` clause of the `for` directive deals with the assignment of iterations to threads.
- The general form of the `schedule` directive is `schedule(scheduling_class[, parameter])`.
- OpenMP supports four scheduling classes: `static`, `dynamic`, `guided`, and `runtime`.

Assigning Iterations to Threads: Example

```
/* static scheduling of matrix multiplication loops */
#pragma omp parallel default(private) shared (a, b, c, dim) \
    num_threads(4)
    #pragma omp for schedule(static)
    for (i = 0; i < dim; i++) {
        for (j = 0; j < dim; j++) {
            c(i,j) = 0;
            for (k = 0; k < dim; k++) {
                c(i,j) += a(i, k) * b(k, j);
            }
        }
    }
```

Assigning Iterations to Threads: Example



- Three different schedules using the static scheduling class of OpenMP.

Parallel For Loops

- Often, it is desirable to have a sequence of `for`-directives within a parallel construct that do not execute an implicit barrier at the end of each `for` directive.
- OpenMP provides a clause - `nowait`, which can be used with a for directive.

Parallel For Loops: Example

```
#pragma omp parallel
{
   #pragma omp for nowait
      for (i = 0; i < nmax; i++)
         if (isEqual(name, current_list[i])
            processCurrentName(name);
   #pragma omp for
      for (i = 0; i < mmax; i++)
         if (isEqual(name, past_list[i])
            processPastName(name);
}
```

The `sections` Directive

- OpenMP supports non-iterative parallel task assignment using the `sections` directive.
- The general form of the `sections` directive is as follows:

```
#pragma omp sections [clause list]
{
    [#pragma omp section
        /* structured block */
    ]
    [#pragma omp section
        /* structured block */
    ]
    ...
}
```

The sections Directive: Example

```
#pragma omp parallel
{
    #pragma omp sections
    {
        #pragma omp section
        {
            taskA();
        }
        #pragma omp section
        {
            taskB();
        }
        #pragma omp section
        {
            taskC();
        }
    }
}
```

Nesting `parallel` Directives

- Nested parallelism can be enabled using the `OMP_NESTED` environment variable.
- If the `OMP_NESTED` environment variable is set to `TRUE`, nested parallelism is enabled.
- In this case, each parallel directive creates a new team of threads.

Synchronization Constructs in OpenMP

- OpenMP provides a variety of synchronization constructs:

```
#pragma omp barrier
#pragma omp single [clause list]
   structured block
#pragma omp master
   structured block
#pragma omp critical [(name)]
   structured block
#pragma omp ordered
   structured block
```

OpenMP Library Functions

- In addition to directives, OpenMP also supports a number of functions that allow a programmer to control the execution of threaded programs.

```
/* thread and processor count */
void omp_set_num_threads (int
  num_threads);
int omp_get_num_threads ();
int omp_get_max_threads ();
int omp_get_thread_num ();
int omp_get_num_procs ();
int omp_in_parallel();
```

OpenMP Library Functions

```
/* controlling and monitoring thread creation */
void omp_set_dynamic (int dynamic_threads);
int omp_get_dynamic ();
void omp_set_nested (int nested);
int omp_get_nested ();
/* mutual exclusion */
void omp_init_lock (omp_lock_t *lock);
void omp_destroy_lock (omp_lock_t *lock);
void omp_set_lock (omp_lock_t *lock);
void omp_unset_lock (omp_lock_t *lock);
int omp_test_lock (omp_lock_t *lock);
```

- In addition, all lock routines also have a nested lock counterpart
- for recursive mutexes.

Environment Variables in OpenMP

- `OMP_NUM_THREADS`: This environment variable specifies the default number of threads created upon entering a parallel region.
- `OMP_SET_DYNAMIC`: Determines if the number of threads can be dynamically changed.
- `OMP_NESTED`: Turns on nested parallelism.
- `OMP_SCHEDULE`: Scheduling of for-loops if the clause specifies runtime

Explicit Threads versus Directive Based Programming

- Directives layered on top of threads facilitate a variety of thread-related tasks.
- A programmer is rid of the tasks of initializing attributes objects, setting up arguments to threads, partitioning iteration spaces, etc.
- There are some drawbacks to using directives as well.
- An artifact of explicit threading is that data exchange is more apparent. This helps in alleviating some of the overheads from data movement, false sharing, and contention.
- Explicit threading also provides a richer API in the form of condition waits, locks of different types, and increased flexibility for building composite synchronization operations.
- Finally, since explicit threading is used more widely than OpenMP, tools and support for Pthreads programs are easier to find.