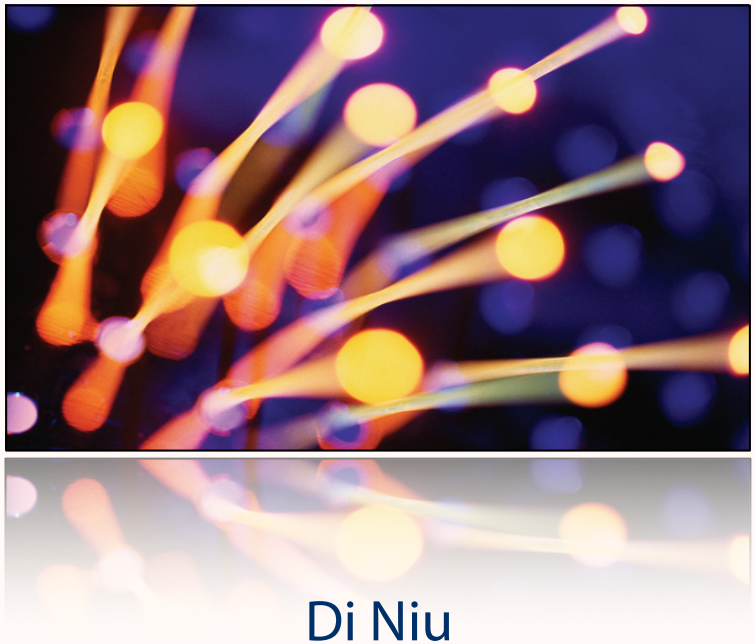
ECE 420 Parallel and Distributed Programming



Di Niu
Department of Electrical and Computer Engineering
University of Alberta

Prerequisites

Familiarity with C programming is necessary

Knowledge of the following is *required*

UNIX working environment: compiling, makefile, command line, VIM, Emacs

OS concepts: race conditions, critical sections, threads, memory hierarchy, concurrency

Version control and collaboration: git, svn.

Linear Algebra: matrix and vector operations

Algorithms: sorting, graph algorithms, trees, etc.

What is Parallel Computing?

Serial computation

A problem is broken into a discrete series of instructions

Instructions are executed sequentially one after another

Executed on a single processor

Only one instruction may execute at any moment in time

Parallel computation

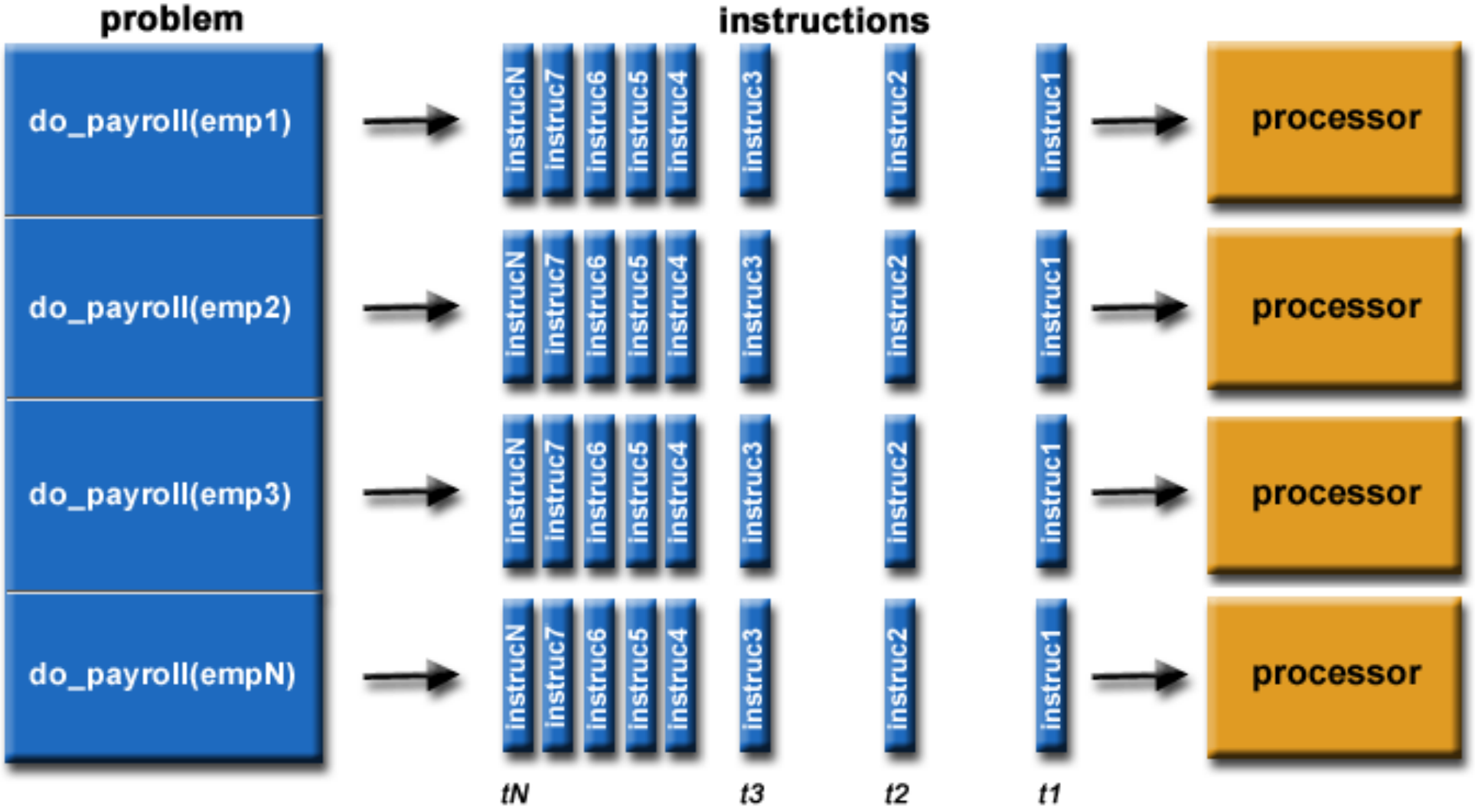
A problem is broken into discrete parts that can be solved concurrently

Each part is further broken down to a series of instructions

Instructions from each part execute simultaneously on different processors

An overall control/coordination mechanism is employed

Parallel Computing Example



Why Parallel Computing?

Need performance for problems that

require too much computation

use big data

In the natural world, many complex events are happening at the same time, yet within a temporal sequence

Galaxy Formation

Planetary Movments

Climate Change

Why Parallel Computing?

Need performance for problems that

require too much computation

use big data

In real-life, we have the pipelined model, which is essentially parallel computing

Auto Assembly

Jet Construction

Drive-thru Lunch

Why Parallel Computing?

Supercomputer compares modern and ancient DNA

With genetic tools, supercomputing simulations and modeling, they traced the origins of modern Europeans to three distinct populations.

Published in the journal *Nature*.

http://top500.org/blog/supercomputer-compares-modern-and-ancient-dna/

Oil and gas exploration

Finite-difference 3D modeling of seismic wave propagation through the subsurface.

Seismic (geophysical) imaging

Using multi-core CPU and NVIDIA GPU

http://www.acceleware.com

Why Should We Use Parallel Programming?

The need to save time or money

The need to solve large and complex problems

Sometimes, concurrency is a must

- Web servers, multi-threaded OS and applications, e.g., Skype

Take advantage of non-local resources

- Crowdsourcing: divides work between Internet users
- Crowdsensing: Google Map, Smart City Applications
- Cloud Computing: Amazon, Compute Canada

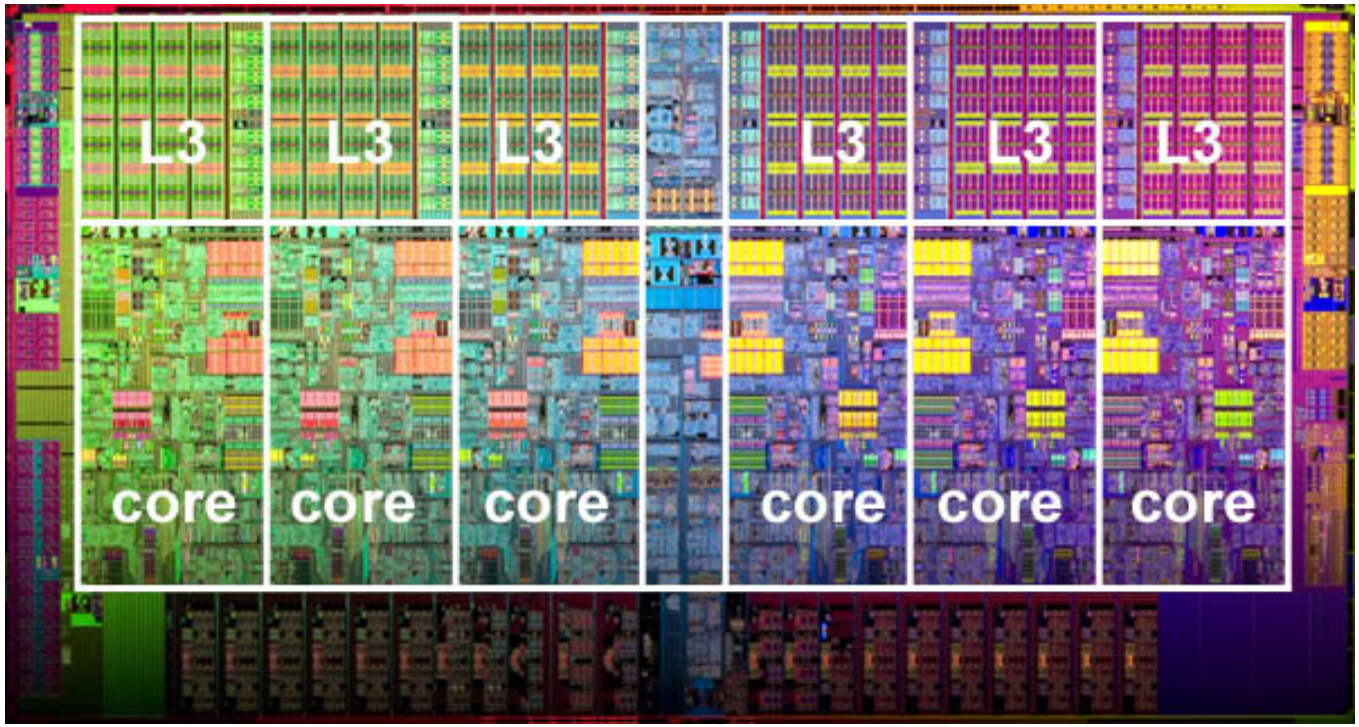
Why Should We Use Parallel Programming?

Make better use of commodity parallel hardware

Modern computers, even laptops, have multiple processors/cores.

In most cases, serial programs "waste" computing power.

GPUs (NVIDIA, ATI): supercomputer on a desktop.



Why Should We Use Parallel Programming?

Process a large amount of data

Big Data are generated or stored on different commodity computers .

But we need to operate on the entire dataset for, e.g.,

- Text Search
- Word Count
- Classification (e.g. Spam vs. non-Spam)

How Hard is Parallel Programming?

A well behaved single processor algorithm may behave poorly on a parallel computer, and may need to be reformulated

There is *no* magic compiler that can turn a serial program into an efficient parallel program *all the time* and on *all machines*

It's all about performance.

Concurrent, Parallel, Distributed

Concurrent computing: a program in which multiple tasks can be in progress at any instant. (even for one core)

A multitasking OS

Parallel computing: a program in which multiple tasks *cooperate* closely to solve a problem

Tightly coupled, running on the same machine

Distributed computing: a program cooperates with other programs to solve a problem

Loosely coupled, running on multiple machines

Parallel vs. Distributed

Parallel computing: shared memory

- multiprocessors (important trend)
- processes share logical address spaces
- processes share physical memory
- sometimes refers to the study of parallel algorithms

Distributed computing: distributed memory

- clusters and networks of workstations
- processes do not share address spaces
- processes do not share physical memory
- sometimes refers to the study of theoretical distributed algorithms

Parallel Hardware

Flynn's Classical Taxonomy (1966)

SISD: Single Instruction Stream Single Data Stream

Uniprocessor

SIMD: Single Instruction Stream Multiple Data Stream

Processors with local memory containing different data execute the same instruction in a synchronized fashion

Array processors, GPU

MISD: Multiple Instruction Stream Single Data Stream

Fault tolerance, but mostly nonsense

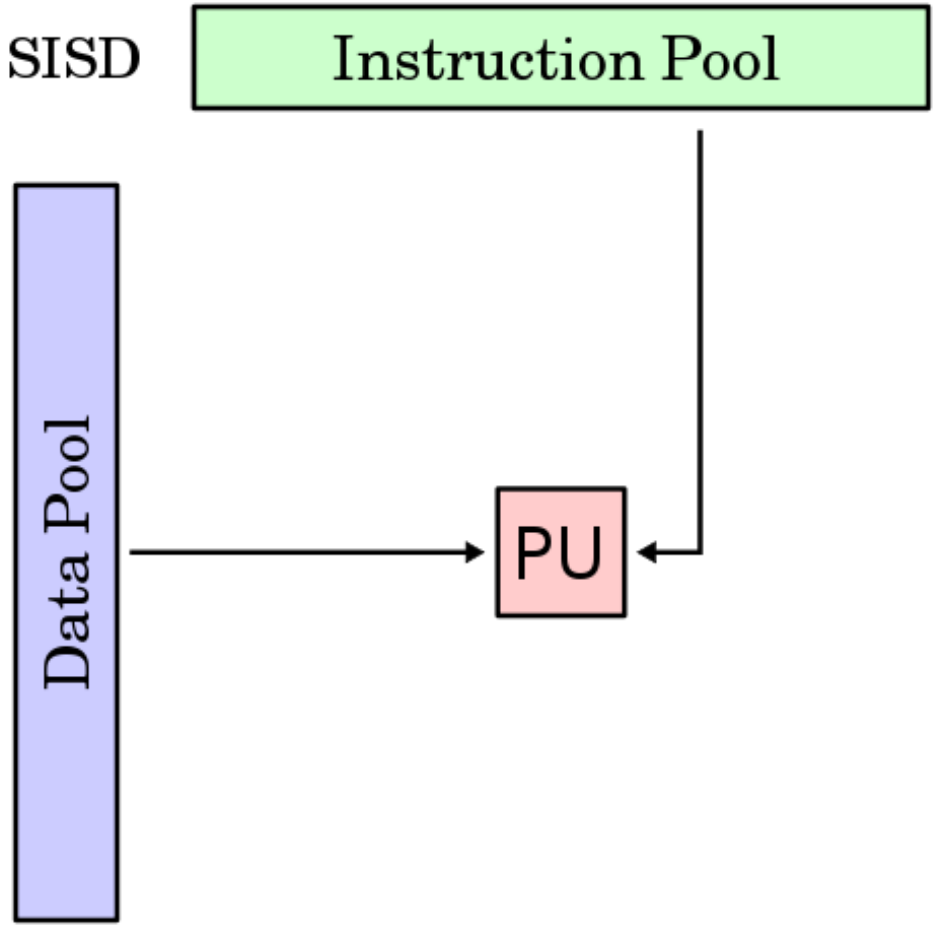
MIMD: Multiple Instruction Stream Multiple Data Stream

The MIMD architecture performs multiple actions simultaneously on numerous data pieces.

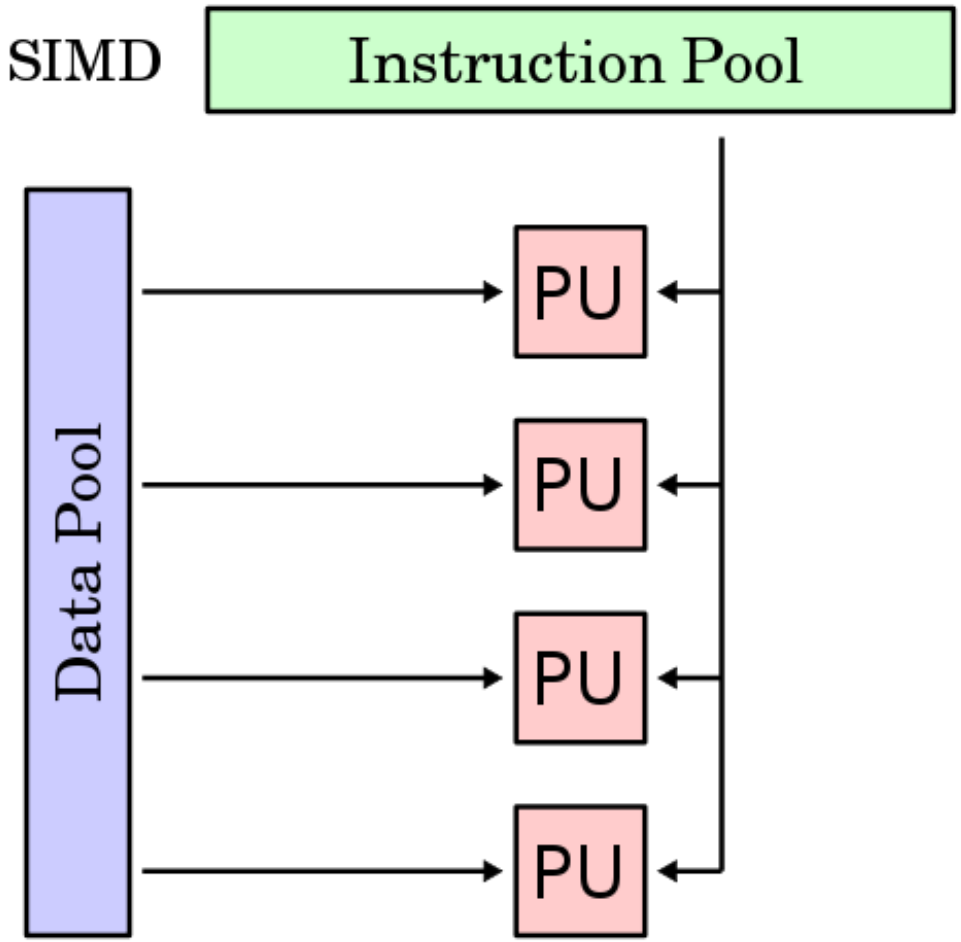
Multi-core processor (most modern PCs)

Computer Clusters, Network of workstations

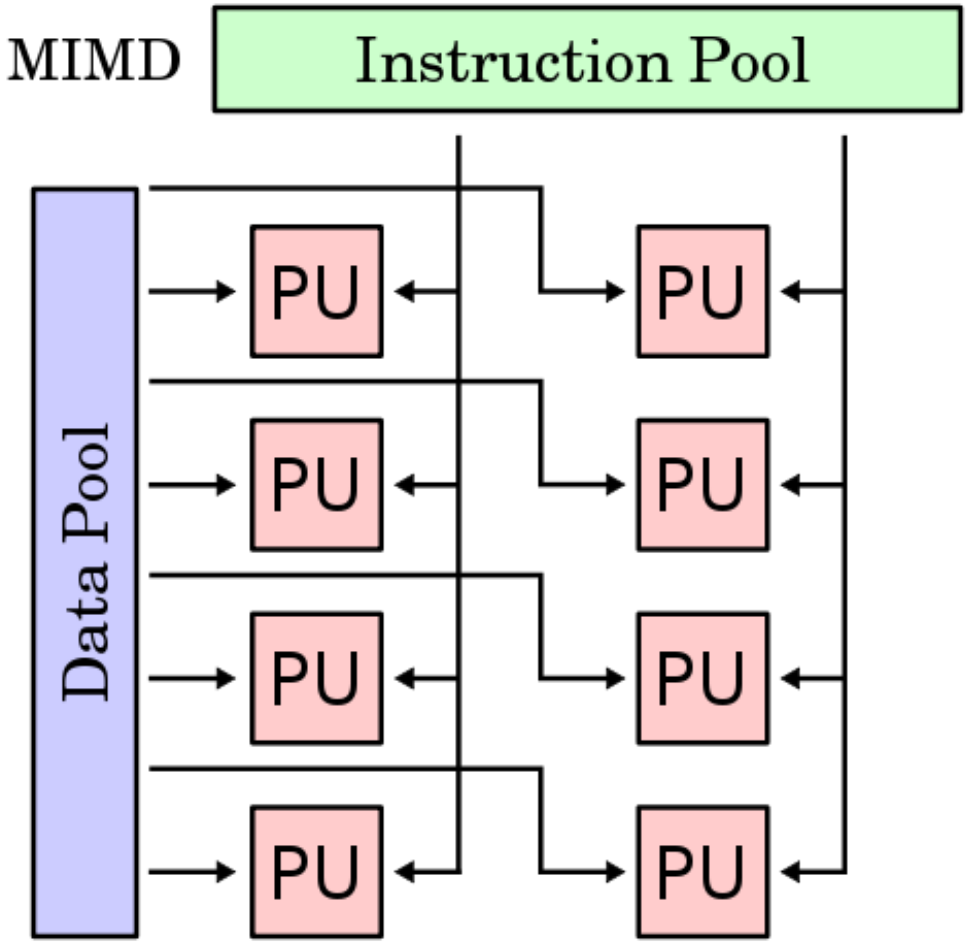
SISD



SIMD

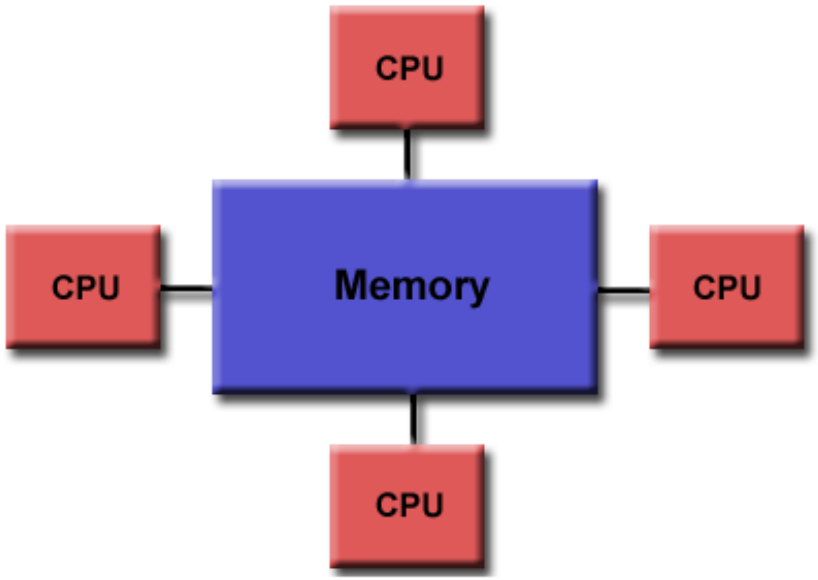


MIMD



MIMD includes both shared-memory and distributed-memory architectures

Shared Memory



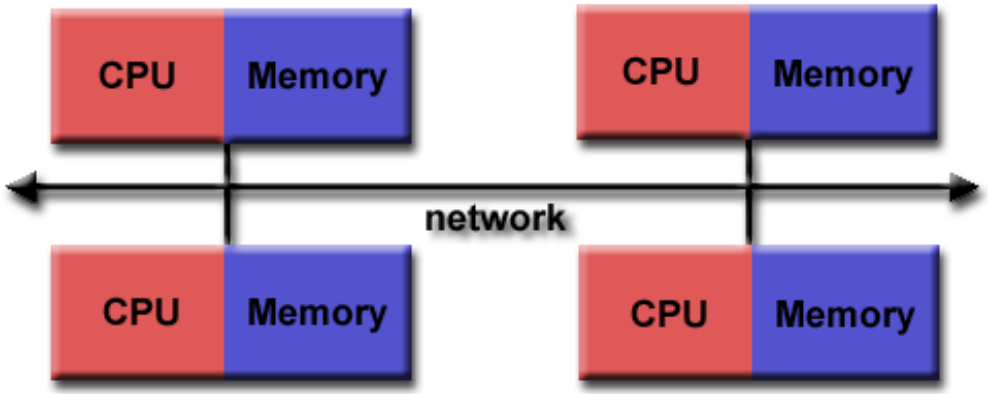
Pros: Provides a user-friendly programming perspective to memory

Data sharing between tasks is both fast and uniform

Cons: No scalability between memory and CPUs

Keys: correctly accessing shared resources, synchronization

Distributed Memory



Pros: Memory is scalable with the number of processors.

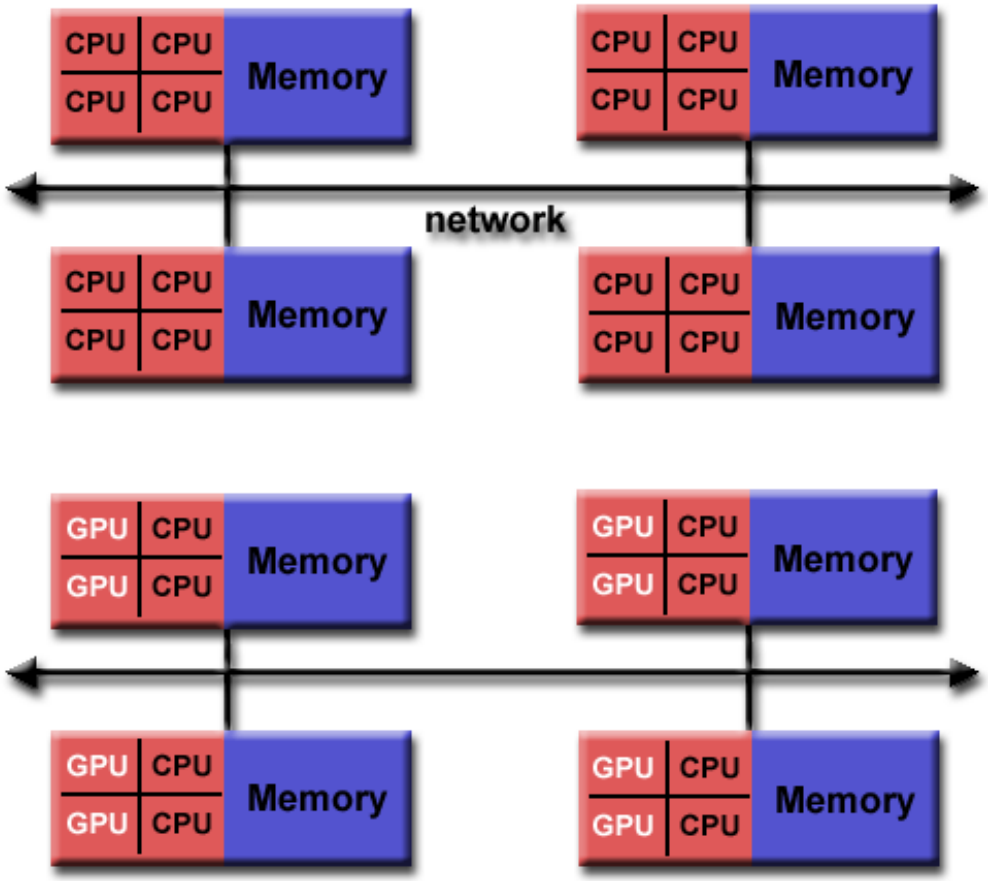
Cost effective, can use commodity, off-the-shelf processors.

Cons: Data communication between processors.

Difficult to map existing data structures to the memory organization.

Non-uniform memory access times: remote vs. local

Hybrid Distributed-Shared Memory



Parallel Software

Parallel Software

Multiple program multiple data (MPMD):

Mainly functional decomposition, e.g., client-server, etc.

Single program multiple data (SPMD):

In a single program, tasks are split up and run simultaneously on multiple processors with different input

Use Branch to implement data-parallelism

```
if (I'm thread/process 0)
  operate on the first half of the array;
else /* I'm thread/process 1 */
  operate on the second half of the array;
```

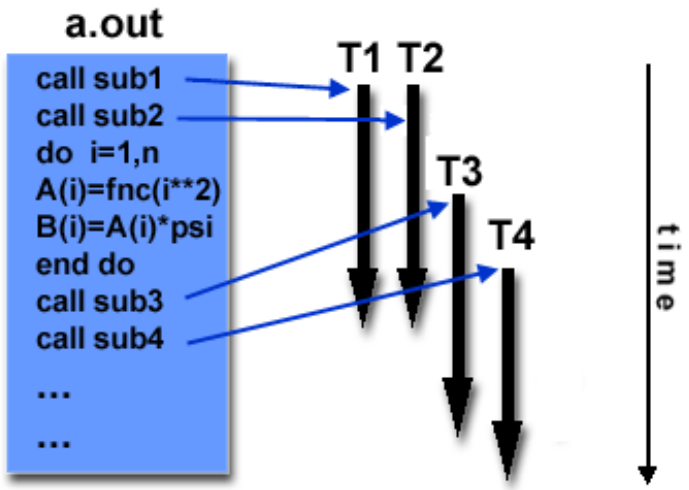
Parallel Software

Threads

Light-weight subroutines in a program

Threads communicate with each other through global memory (by writing and reading address locations) in a program

Example: POSIX Threads (Pthreads), OpenMP



Parallel Software

Message Passing Model

A set of tasks that use their own local memory during computation.

Tasks exchange data by sending and receiving messages.

Data transfer usually requires cooperative operations to be performed by each process.

For example, a *send* operation must have a matching *receive* operation.

Example: MPI

Message Passing Program Example

```
// Pseudo Code
char message[100]; ...
my rank = Get rank();
if (my rank == 1) {
    sprintf(message, "Greetings from process 1");
    Send(message, MSG CHAR, 100, 0);
} else if (my rank == 0) {
    Receive(message, MSG CHAR, 100, 1);
    printf("Process 0 > Received: %s\n", message);
}
```

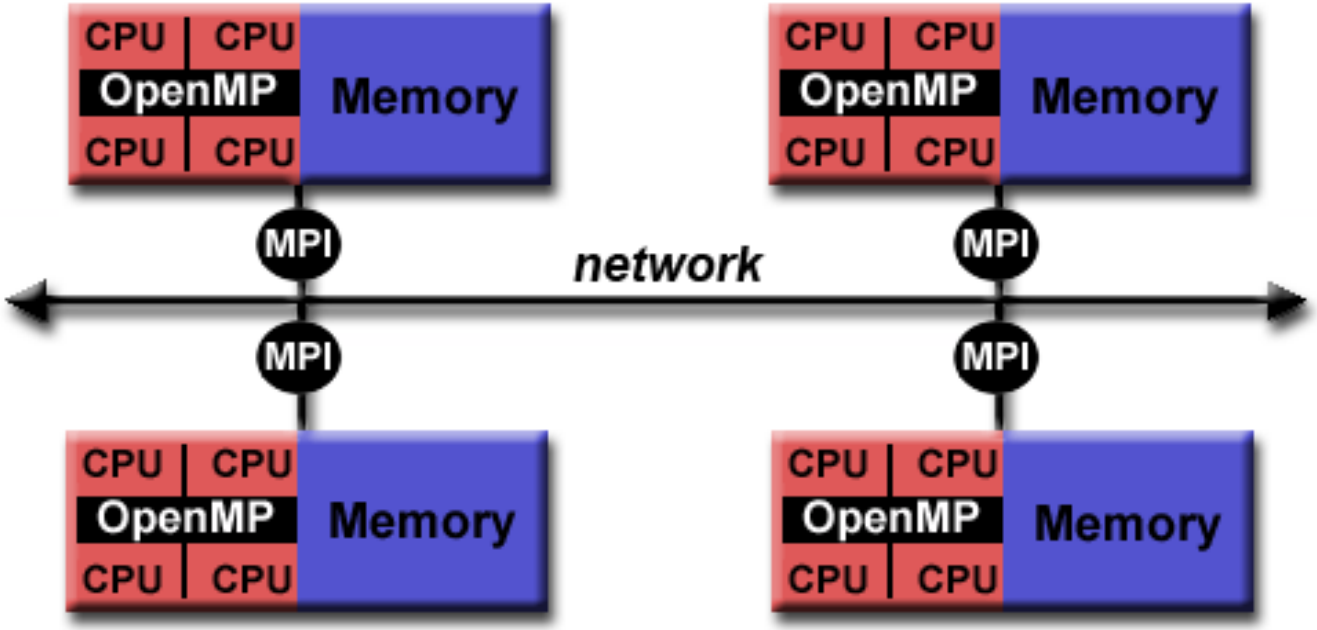
Parallel Software

Hybrid Programming Model

MPI + OpenMP

MPI + GPU

Used to achieve highest performance



Performance and Speedup

Speedup and Efficiency

Let T_1 be the time to solve the problem sequentially.

Let T_p be the time to solve the problem in parallel using p processors

Then, speedup $S(p)$ for problem size n is defined as:

$$S(p) = T_1/T_p$$

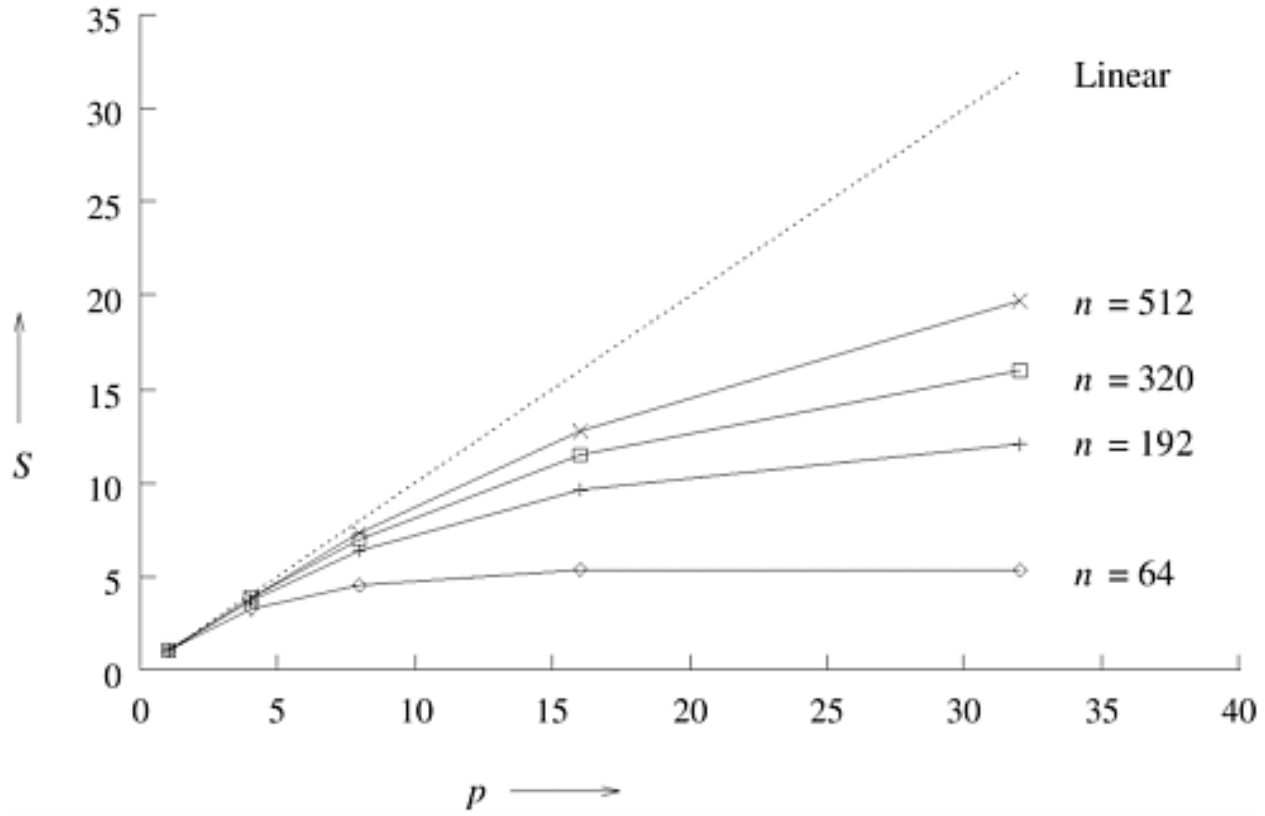
The overhead is defined by

$$T_p = T_1/p + T_{\text{overhead}}$$

T_1 represents the amount of work

Efficiency: $E(p) = S(p)/p$

A Typical Speedup Curve



Diminishing returns as p increases (efficiency goes down)

T_{overhead} grows slower than T_1 as problem size n increases

Speedup Calculation

$S(p) = p$: **linear speedup or ideal speedup**

***Embarrassingly parallel* with no communication overheads**

$S(p) < p$: **sublinear speedup. Common!**

$S(p+1) = S(p) + \delta$, **where** $\delta < 1$: **diminishing returns (efficiency drop)**

Idle time due to load unbalance
Overhead due to communication, etc.
Idle time due to synchronization
Extra computation in the algorithm of the parallel program
Many more reasons

$S(p+1) < S(p)$: **slowdown (may happen)**

Overheads are O(*p*) but work remains O(*n*)
Contention for a resource depends on p

$S(p) > p$: **Fallacy!**

Amdahl's Law

In 1960 Gene Amdahl argued

The speedup of a parallel program is inherently limited by its sequential portion (examples?)

If x fraction of a serial program can be parallelized and it takes time T_1 to run the serial program, then the speedup is at most

$$S(p) = \frac{T_1}{T_p} \leq \frac{T_1}{xT_1/p + (1-x)T_1}$$

And

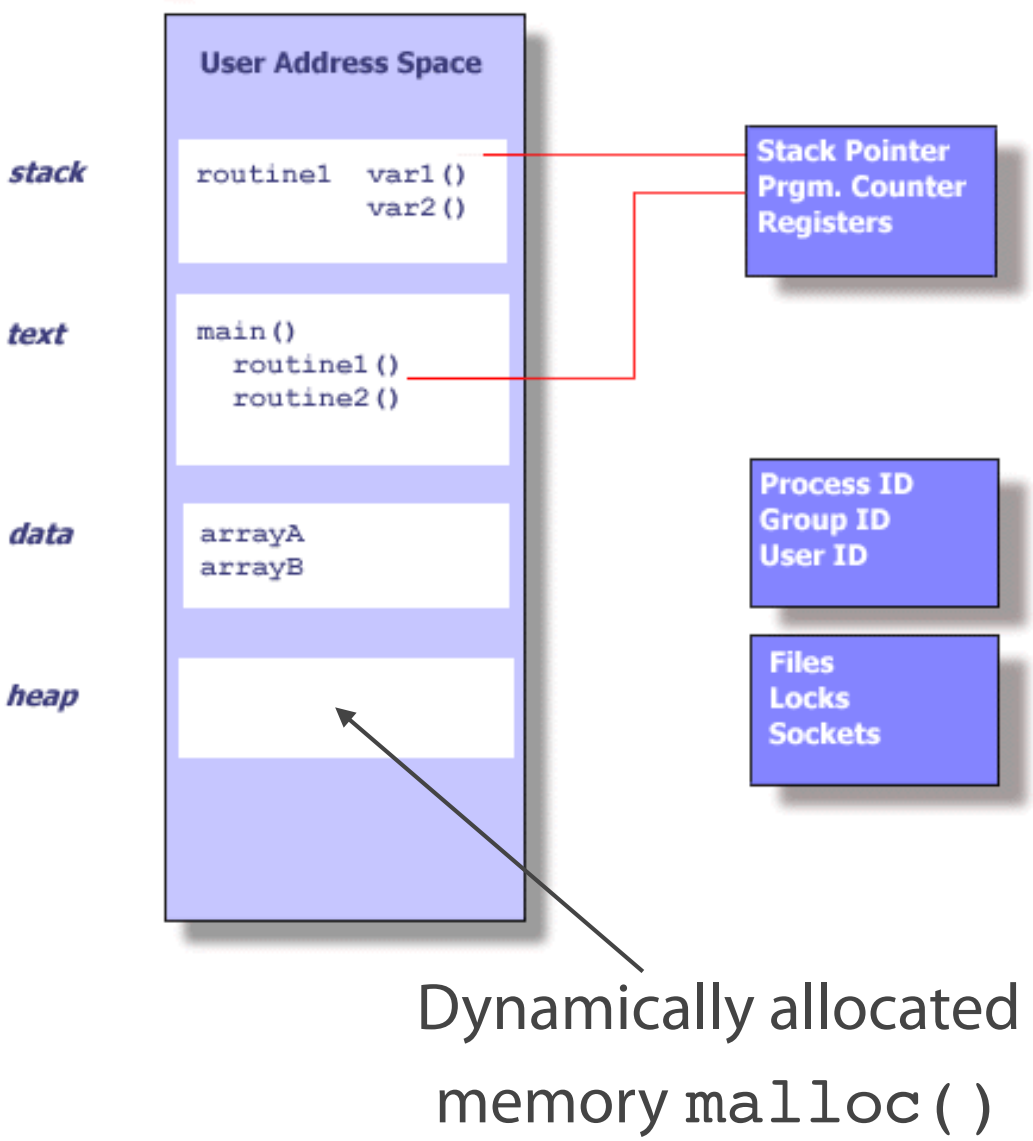
$$\lim_{p \to \infty} S(p) \leq \frac{1}{1-x}$$

Shared-Memory Programming with Pthreads

Process

Processes contain information about program resources and program execution state, including

Process ID, process group ID, user ID, and group ID, Environment, Working directory, Program instructions, Registers, Stack, Heap, File descriptors, Signal actions, Shared libraries, Inter-process communication tools.



Stack

Stack is a special region of your computer's memory that stores temporary variables created by each function (including the main() function).

The stack grows and shrinks as functions push and pop local variables

There is no need to manage the memory yourself, variables are allocated and freed automatically

The stack has size limits

Stack variables only exist while the function that created them, is running

Heap

The heap is a more free-floating region of memory (and is larger).

To allocate memory on the heap, you must use malloc() or calloc(), which are built-in C functions.

Use free() to deallocate that memory once you don't need it any more. If you fail to do this, your program will have memory leak.

Unlike the stack, the heap does not have size restrictions

Heap variables are essentially global in scope.

Unlike the stack, variables created on the heap are accessible by any function, anywhere in your program.

Stack vs. Heap

Stack

- very fast access
- don't have to explicitly de-allocate variables
- space is managed efficiently by CPU, memory will not become fragmented
- local variables only
- limit on stack size (OS-dependent)
- variables cannot be resized

Heap

- variables can be accessed globally
- no limit on memory size
- (relatively) slower access
- no guaranteed efficient use of space, memory may become fragmented over time as blocks of memory are allocated, then freed
- you must manage memory (you're in charge of allocating and freeing variables)
- variables can be resized using realloc()

Example: Creating variables on the Stack

```
#include <stdio.h>

double multiplyByTwo (double input) {
  double twice = input * 2.0;
  return twice;
}

int main (int argc, char *argv[])
{
  int age = 30;
  double salary = 12345.67;
  double myList[3] = {1.2, 2.3, 3.4};

  printf("double your salary is %.3f\n",
multiplyByTwo(salary));

  return 0;
}
```

Example: Creating variables on the Heap

```
double *multiplyByTwo (double *input) {
  double *twice = malloc(sizeof(double));
  *twice = *input * 2.0;
  return twice;
}

int main (int argc, char *argv[])
{
  int *age = malloc(sizeof(int));
  *age = 30;
  double *salary = malloc(sizeof(double));
  *salary = 12345.67;
  double *myList = malloc(3 * sizeof(double));
  myList[0] = 1.2;
  myList[1] = 2.3;
  myList[2] = 3.4;

  double *twiceSalary = multiplyByTwo(salary);
  printf("double your salary is %.3f\n", *twiceSalary);

  free(age);
  free(salary);
  free(myList);
  free(twiceSalary);
  return 0;
}
```

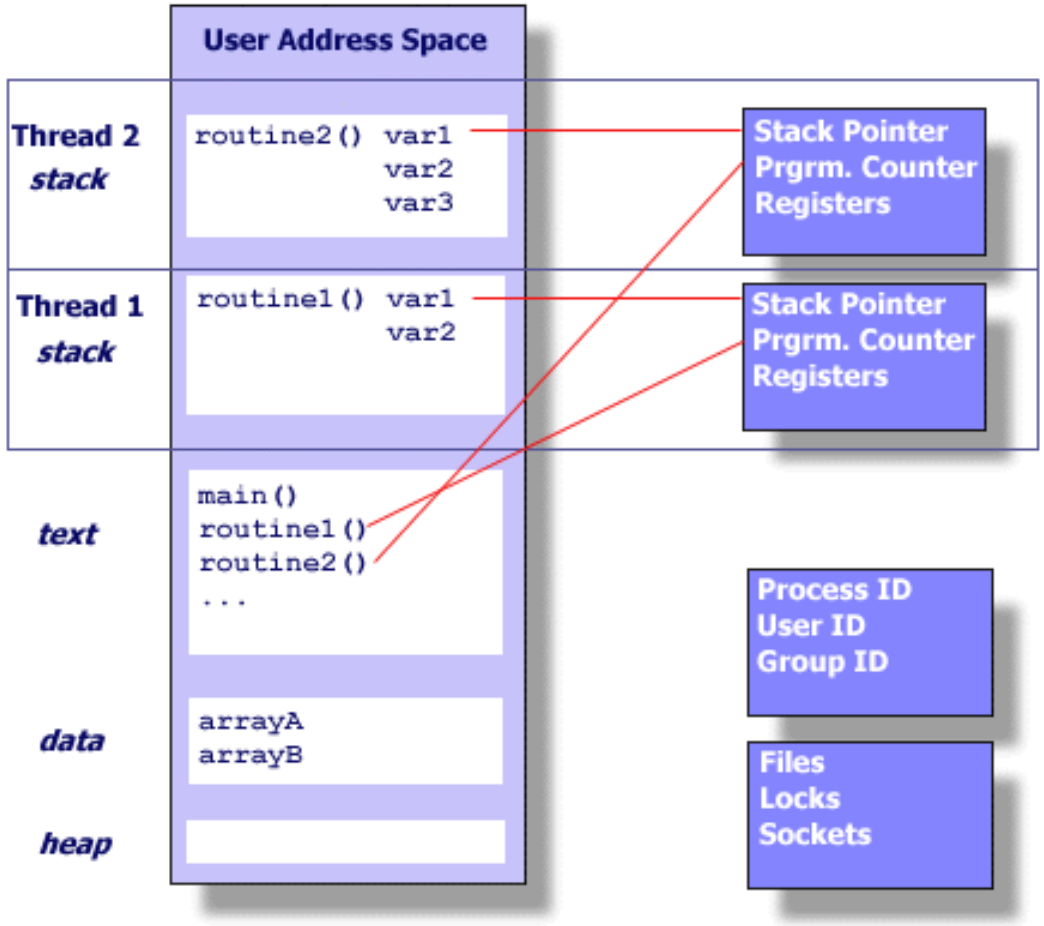
Thread

A "procedure" in a process that runs independently from its main program (can be scheduled by OS).

Threads only maintain essential resources to exist as executable code:

Stack pointer, Registers, Scheduling properties (such as policy or priority), Set of pending and blocked signals, Thread specific data.

Threads are light-weight



POSIX Threads (Pthreads)

For UNIX systems, a standard programming interface has been specified by the IEEE POSIX 1003.1c standard (1995).

Why Pthreads?

- Lightweight, faster startup: fork() vs. pthread_create()
- Efficient Communication
  - No need to copy data from process to process (like in fork())
  - No data transfer, because threads share the address space in a process
  - Pthreads communications are mostly memory-to-CPU which is faster
- Hides memory and I/O latency on a single core processor
- Priority/real-time scheduling
- Asynchronous event handling
  - Examples: a web server, video conferencing, an OS

Design Multi-threaded Programs

Working Modes

Manager/worker: a single thread, the manager assigns work to other threads, the workers. Static/dynamic worker pool.

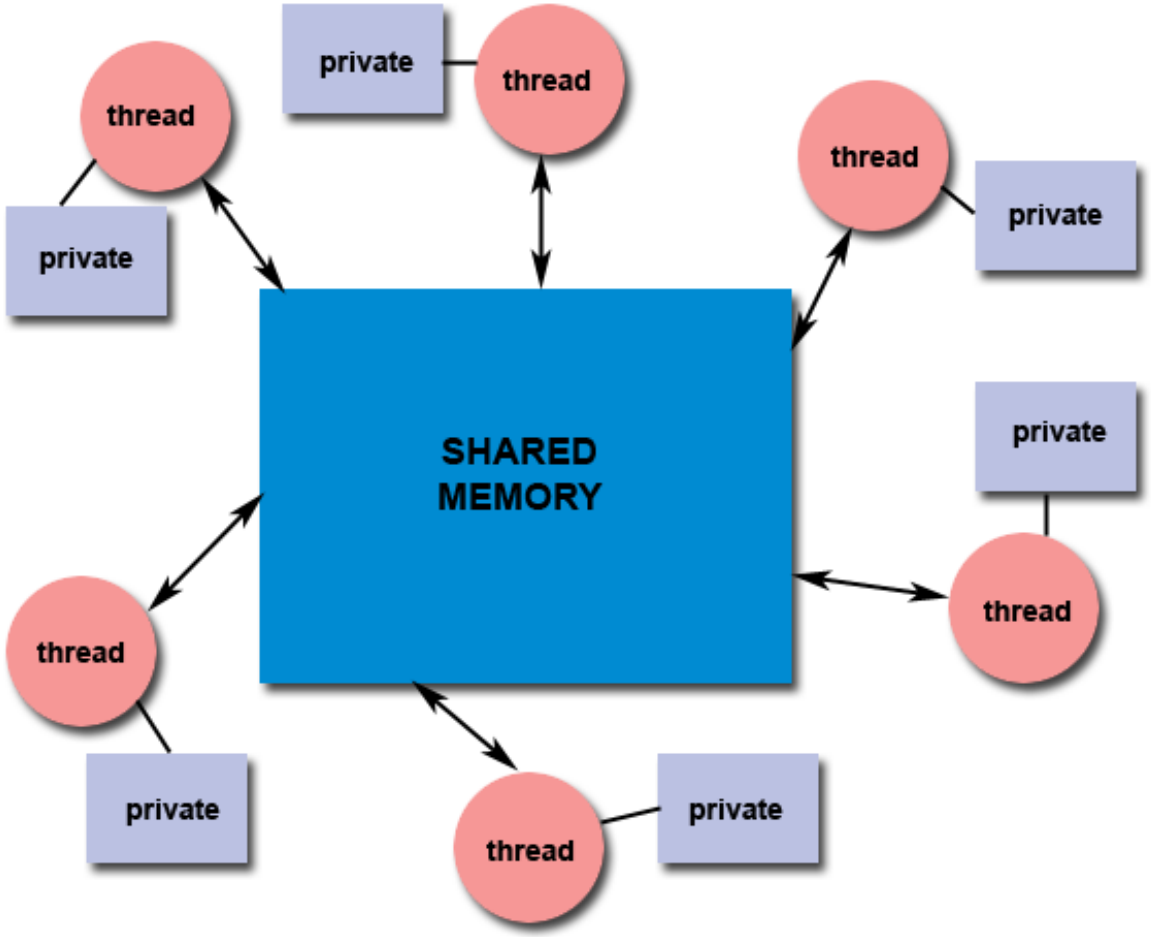
Peer: similar to the manager/worker model, but after the main thread creates other threads, it participates in the work.

Pipeline: a task is broken into a series of suboperations, each of which is handled in series, but concurrently, by a different thread. An automobile assembly line best describes this model.

Shared Memory Model

All threads have access to the same global, shared memory

Threads also have their own private data



Pthreads: Hello, World

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

const int MAX_THREADS = 64;

/* Global variable:  accessible to all threads */

int thread_count;

void *Hello(void* rank);  /* Thread function */

int main(int argc, char* argv[]) {
   long       thread;  /* Use long in case of a 64-bit system */
   pthread_t* thread_handles;

   /* Get number of threads from command line */
   thread_count = strtol(argv[1], NULL, 10);


   thread_handles = malloc (thread_count*sizeof(pthread_t));
```

Pthreads: Hello, World

```
...

for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL,
          Hello, (void*) thread);

   printf("Hello from the main thread\n");

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   free(thread_handles);
   return 0;
}  /* main */
```

Pthreads: Hello, World

```
void *Hello(void* rank) {
   long my_rank = (long) rank;  /* Use long in case of 64-bit system */
   printf("Hello from thread %ld of %d\n", my_rank, thread_count);
   return NULL;
}  /* Hello */
```

Create a Thread

```
int pthread_create(
    pthread_t*              thread_p                    /* out */
    const pthread_attr_t*   attr_p                      /* in */
    void*                   (*start_routine)(void*)     /* in */
    void*                   arg_p                       /* in */);
```

The function started by pthread_create should have a prototype like:

```
void* thread_function(void* args_p);
```

`void*` **can be cast to any pointer type in C, so** `args_p` **can point to a list containing one or more values needed by** `thread_function`

We have cast the loop variable `thread` **to have type** `void*`**.**

Then in the thread function, `hello`**, we have cast the argument back to a** `long`**.**

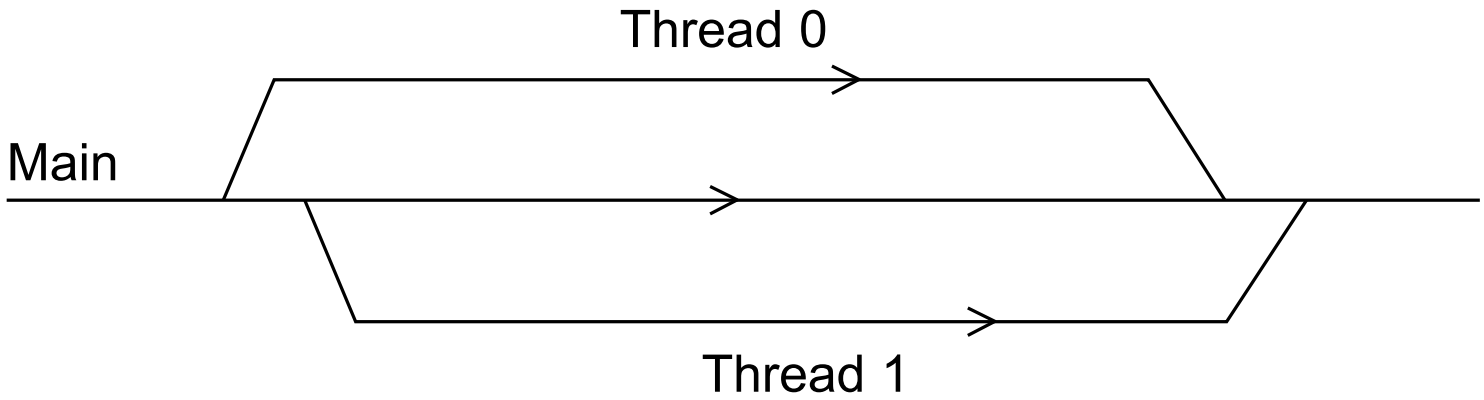
Stopping the Threads

```
int pthread_join(

    pthread_t           thread       /* in */
    void**              ret_val_ptr  /* out */);
```

A call to `pthread_join` will suspend the calling thread until the thread associated with the `pthread_t` object terminates.

The second argument can be used to receive any return value computed by the thread.

The scheduling of the threads is usually done by the OS.



Example: Matrix-Vector Multiplication

a_{00}	a_{01}	$\cdots$	$a_{0,n-1}$
a_{10}	a_{11}	$\cdots$	$a_{1,n-1}$
$\vdots$	$\vdots$		$\vdots$
a_{i0}	a_{i1}	$\cdots$	$a_{i,n-1}$
$\vdots$	$\vdots$		$\vdots$
$a_{m-1,0}$	$a_{m-1,1}$	$\cdots$	$a_{m-1,n-1}$

x_0
x_1
$\vdots$
x_{n-1}

$=$

y_0
y_1
$\vdots$
$y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1}$
$\vdots$
y_{m-1}

$$y_i = \sum_{j=0}^{n-1} a_{ij}x_j.$$

```
/* For each row of A */
for (i = 0; i < m; i++) {
    y[i] = 0.0;
    /* For each element of the row and each element of x */
    for (j = 0; j < n; j++)
        y[i] += A[i][j]* x[j];
}
```

Example: Matrix Vector Multiplication

Let each thread compute multiple y[i]

To compute y[i], the thread that takes care of it needs to run the code

```
y[i] = 0.0;
for (j = 0; j < n; j++)
   y[i] += A[i][j]*x[j];
```

Just need to decide which rows to be assigned to which thread

Assume m (# rows) and n (# columns) are divisable by t (# threads).

Each thread handles m/t rows.

Thread q handles the rows with indices $q \times m/t$ — $(q+1) \times m/t$ - 1

Matrix-Vector Multiplication

```
/*--------------------------------------------------------------------
 * Function:       Pth_mat_vect
 * Purpose:        Multiply an mxn matrix by an nx1 column vector
 * In arg:         rank
 * Global in vars: A, x, m, n, thread_count
 * Global out var: y
 */
void *Pth_mat_vect(void* rank) {
   long my_rank = (long) rank;
   int i, j;
   int local_m = m/thread_count;
   int my_first_row = my_rank*local_m;
   int my_last_row = (my_rank+1)*local_m - 1;

   for (i = my_first_row; i <= my_last_row; i++) {
      y[i] = 0.0;
      for (j = 0; j < n; j++)
          y[i] += A[i*n+j]*x[j];
   }

   return NULL;
}  /* Pth_mat_vect */
```

Passing Arguments to the Thread Function

```
long t;

for(t=0; t<NUM_THREADS; t++)
{
   printf("Creating thread %ld\n", t);
   rc = pthread_create(&threads[t], NULL, PrintHello, (void *) t);
   ...
}
```

Correct!

```
int rc;
long t;

for(t=0; t<NUM_THREADS; t++)
{
   printf("Creating thread %ld\n", t);
   rc = pthread_create(&threads[t], NULL, PrintHello, (void *) &t);
   ...
}
```

(not recommended in pthreads, need to watch out for the lifetime of t).

Stack vs. Heap

Stack

- very fast access
- don't have to explicitly de-allocate variables
- space is managed efficiently and automatically by CPU
- local variables only
- limit on stack size (OS-dependent)
- variables cannot be resized

Heap

- variables can be accessed globally
- no limit on memory size
- (relatively) slower access
- memory may become fragmented over time
- you must manage memory (you're in charge of allocating and freeing variables)
- variables can be resized using realloc()

Global vs. Local Variables

Global

Global variables (declared outside any function)

Dynamically allocated variables on the heap

Local

Variables on stack (declared in each function)

Watch out for the pointer and dereferencing!

Where are variables stored?

Global variables -------> data

Static variables -------> data

Constant data types -----> code and/or data.

Consider string literals for a situation when a constant itself would be stored in the data segment, and references to it would be embedded in the code

Local variables(declared and defined in functions) --------> stack

Variables declared and defined in main function -----> also stack

Pointers (ex: char *arr, int *arr) -------> data or stack

depending on the context. C lets you declare a global or a static pointer, in which case the pointer itself would end up in the data segment.

Dynamically allocated space(using malloc, calloc, realloc) --------> heap

https://stackoverflow.com/questions/14588767/where-in-memory-are-my-variables-stored-in-c

Passing Multiple Arguments (via struct)

```
struct thread_data{
   int  thread_id;
   int  sum;
   char *message;
};

struct thread_data thread_data_array[NUM_THREADS];

void *PrintHello(void *threadarg)
{
   struct thread_data *my_data;
   ...
   my_data = (struct thread_data *) threadarg;
   taskid = my_data->thread_id;
   sum = my_data->sum;
   hello_msg = my_data->message;
   ...
}

int main (int argc, char *argv[])
{
   ...
   thread_data_array[t].thread_id = t;
   thread_data_array[t].sum = sum;
   thread_data_array[t].message = messages[t];
   rc = pthread_create(&threads[t], NULL, PrintHello,
        (void *) &thread_data_array[t]);
   ...
}
```

Terminating Threads

Several ways in which a thread may be terminated:

- The thread returns normally from its starting routine.
- The thread makes a call to the `pthread_exit(status)`
- The entire process is terminated due to making a call to either the `return` or `exit()`
- If `main()` finishes first, without calling `pthread_exit()` explicitly itself (but `return` is called implicitly to terminate the process).

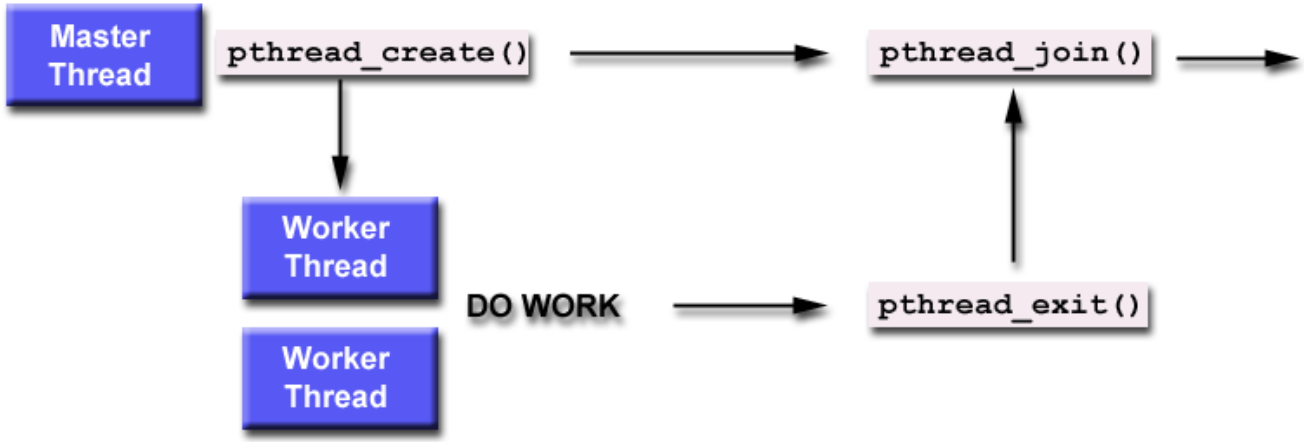
In subroutines that execute to completion normally, you can often omit calling `pthread_exit()`

By having `main()` explicitly call `pthread_exit()` as the last thing it does, the process will be kept alive to support the threads it created until they are all done.

Terminating Threads

```
void *PrintHello(void *threadid)
{
   long tid;
   tid = (long)threadid;
   printf("Hello World! It's me, thread #%ld!\n", tid);
   pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
   pthread_t threads[NUM_THREADS];
   int rc;
   long t;
   for(t=0; t<NUM_THREADS; t++){
      printf("In main: creating thread %ld\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);
      }
   }

   /* Last thing that main() should do */
   pthread_exit(NULL);
}
```

Joining - A way of synchronization



The `pthread_join()` subroutine blocks the calling thread until the specified `threadid` thread terminates.

```
int pthread_join(pthread_t thread, void **value_ptr);
void pthread_exit(void *value_ptr);
```

`value_ptr` in `pthread_join()` will obtain value from the argument passed to `pthread_exit()`

Joining - A way of synchronization

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#define NUM_THREADS4

void *BusyWork(void *t)
{
   int i;
   long tid;
   double result=0.0;
   tid = (long)t;
   printf("Thread %ld starting...\n",tid);
   for (i=0; i<1000000; i++)
   {
      result = result + sin(i) * tan(i);
   }
   printf("Thread %ld done. Result = %e\n",tid, result);
   pthread_exit((void*) t);
}
```

Joining - A way of synchronization

```
int main (int argc, char *argv[])
{
   pthread_t thread[NUM_THREADS];
   pthread_attr_t attr;
   int rc;
   long t;
   void *status;

   /* Initialize and set thread detached attribute */
   pthread_attr_init(&attr);
   pthread_attr_setdetachstate(&attr, PTHREAD_CREATE_JOINABLE);

   for(t=0; t<NUM_THREADS; t++) {
      printf("Main: creating thread %ld\n", t);
      rc = pthread_create(&thread[t], &attr, BusyWork, (void *)t);
      if (rc) {
         printf("ERROR; return code from pthread_create()
                is %d\n", rc);
         exit(-1);
      }
   }
```

Joining - A way of synchronization

```
/* Free attribute and wait for the other threads */
   pthread_attr_destroy(&attr);
   for(t=0; t<NUM_THREADS; t++) {
      rc = pthread_join(thread[t], &status);
      if (rc) {
         printf("ERROR; return code from pthread_join()
                is %d\n", rc);
         exit(-1);
         }
      printf("Main: completed join with thread %ld having a status
            of %ld\n",t,(long)status);
      }

printf("Main: program completed. Exiting.\n");
pthread_exit(NULL);
}
```

Critical Section and Race Condition

Example of Race Condition

Two threads both want to execute: Balance = Balance + 20.

A possible sequence of instructions

Thread 1 reads Balance of 1000

Thread 2 reads Balance of 1000

Thread 1 adds 20 to Balance and gets a new Balance of 1020

Thread 2 adds 20 to Balance and gets a new Balance of 1020 (Wrong!)

The code "Balance = Balance + 20" is a critical section

When multiple threads access a shared resource such as a shared variable or a file, at least one of the accesses is a *write*, and the accesses can result in an error, we have a *race condition*.

Mutex (Mutual Exclusion)

Guarantee that one thread "excludes" all other threads while it executes the critical section.

Mutex: a variable of type

```
pthread_mutex_t
```

Initialize a mutex variable

```
int pthread_mutex_init(
  pthread_mutex_t*              mutex_p /* out */,
  const pthread_mutexattr_t*    attr_p  /* in */);
```

Destroy a mutex variable

```
int pthread_mutex_destroy(pthread_mutex_t* mutex_p);
```

Mutex (Mutual Exclusion)

Before entering a critical section, a thread should call

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

Done with the code in a critical section, a thread should call

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

Sequence of actions

Several threads attempt to lock the mutex

Only one succeeds and owns the mutex

(When several threads try to "lock", the losers block at that call)

The owner thread performs some set of actions

The owner unlocks the mutex

Another thread acquires the mutex and repeats the process

Finally the mutex is destroyed

Mutex Example: Calculating Pi

$$\pi = 4\left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots + (-1)^n \frac{1}{2n+1} + \cdots\right).$$

Serial Code

```
double factor = 1.0;
double sum = 0.0;
for (i = 0; i < n; i++, factor = -factor)
{
   sum += factor/(2*i+1);
}
pi = 4.0*sum;
```

Mutex Example: Calculating Pi

Pthreads code

```
/*--------------------------------------------------------------------*/
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;
   double my_sum = 0.0;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;

   for (i = my_first_i; i < my_last_i; i++, factor = -factor) {
      my_sum += factor/(2*i+1);
   }
   pthread_mutex_lock(&mutex);
   sum += my_sum;
   pthread_mutex_unlock(&mutex);

   return NULL;
}  /* Thread_sum */
```

Semaphores

Used for Producer-Consumer Synchronization

Suppose we have *t* threads and we want thread 0 to send a message to thread 1, thread 1 to send a message to thread 2, ..., thread *t*-1 to send a message to thread 0.

After a thread has received the message, it prints the message.

Implementation

Allocate a global array of char *

Each thread initializes the message locally and set a pointer in the global to refer to it.

Need to make sure that each thread prints its message **after** it has received it (not before).

Busy-waiting is a solution, but consumes CPU cycle.

Semaphore Usage

Semaphores can be deemed as a special type of `unsigned int`

```
#include <semaphore.h>
```

Initialize

```
int sem_init(sem_t* semaphore_p, int shared, unsigned init_val);

//shared==0: shared between threads, init_val: the initial value
```

Destroy

```
int sem_destroy(sem_t* semaphore_p);
```

Wait

```
int sem_wait(sem_t* semaphore_p);

//Block if the semaphore is 0; otherwise, decrement the semaphore and proceed
```

Unlock

```
int sem_post(sem_t* semaphore_p);

//Just increment the semaphore
```

Semaphore Examples

Solving the message sending task (synchronization) using

- Busy Waiting
- Semaphores

See the 2 sample programs on eClass

- Pthreads: Sending messages (via busy waiting)
- Pthreads: Sending messages (via semaphores)

Mutex vs. Semaphores

Mutex

A binary mutual exclusion semaphore (with a count of one)

Can only be released by the same thread that locked it

Usually used to avoid race conditions

Semaphores

Has a count, which could be more than one

Can be locked by *count* number of threads concurrently

You have a number of resource instances to lock (e.g., 3 drives)

Can be unlocked by any thread (doesn't have to be the thread that locked it).

Usually used for producer-consumer synchronization

Condition Variables

A condition variable is a data object that allows a thread to suspend execution (block-waiting) until a certain event or condition occurs.

When the event or condition occurs, another thread can signal the thread to "wake up."

A condition variable is always used with a mutex to protect the "condition".

Initialization and Destroy

```
int pthread_cond_init(pthread_cond_t *cond,
                      const pthread_condattr_t *attr);

int pthread_cond_destroy(pthread_cond_t *cond);
```

Condition Variables

Wait: blocks the calling thread until condition is signalled

Shall be called with mutex locked by the calling thread

```
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
```

Upon successful completion, a value of zero shall be returned

Signal: unblock *one* of the threads blocked on the condition variable

Shall be called with mutex locked by the calling thread

```
int pthread_cond_signal(pthread_cond_t *cond);
```

Broadcast: unblock all threads blocked on the condition variable

Shall be called with mutex locked by the calling thread

```
int pthread_cond_broadcast(pthread_cond_t *cond);
```

Condition Variables Standard Usage

The blocking thread typically looks like

```
// safely examine the condition, prevent other threads from altering it
pthread_mutex_lock (&lock);
while ( SOME-CONDITION is false) // to avoid spurious wakeup
    pthread_cond_wait (&cond, &lock);

// Do whatever you need to do when condition becomes true
do_stuff();
pthread_mutex_unlock (&lock);
```

A thread, notifying the condition variable, typically looks like

```
// ensure we have exclusive access to whatever comprises the condition
pthread_mutex_lock (&lock);

ALTER-CONDITION

// Wakeup any threads that may be waiting on the condition
pthread_cond_signal (&cond);

// allow others to proceed
pthread_mutex_unlock (&lock)
```

Condition Variables

Wait: blocks the calling thread until condition is signalled

Shall be called with mutex locked by the calling thread

```
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
```

Actually this "wait" automatically does the following:

```
pthread_mutex_unlock(&mutex);
block waiting on the signal (&cond);
pthread_mutex_lock(&mutex);
```

See the sample code on eClass

"Pthreads: A condition variable example"

Barriers

Sometimes, threads need to "meet up" (make sure they are all at the same point.)

- Multiplication of multiple matrices
- Time measurement for a certain phase of code

We'll look at barrier implementation through

- Barriers (pthread_barrier_t)
- Busy waiting and a mutex
- Semaphores
- Condition Variables (*the best way*)

Barrier through pthread_barrier_t

```
double initial_matrix[ROWS][COLS];
double final_matrix[ROWS][COLS];
pthread_barrier_t barr; // Barrier variable

extern void DotProduct(int row, int col,
                       double source[ROWS][COLS],
                       double destination[ROWS][COLS]);
extern double determinant(double matrix[ROWS][COLS]);

void * entry_point(void *arg)
{
    int rank = (int)arg;
    for(int row = rank * ROWS / THREADS; row < (rank + 1) * THREADS; ++row)
        for(int col = 0; col < COLS; ++col)
            DotProduct(row, col, initial_matrix, final_matrix);

    // Synchronization point
    int rc = pthread_barrier_wait(&barr);

    if(rc != 0 && rc != PTHREAD_BARRIER_SERIAL_THREAD)
    {
        printf("Could not wait on barrier\n");
        exit(-1);
    }
    for(int row = rank * ROWS / THREADS; row < (rank + 1) * THREADS; ++row)
        for(int col = 0; col < COLS; ++col)
            DotProduct(row, col, final_matrix, initial_matrix);
}
```

Barrier through `pthread_barrier_t`

```
int main(int argc, char **argv)
{
    pthread_t thr[THREADS];

    // Barrier initialization
    if(pthread_barrier_init(&barr, NULL, THREADS)) // THREADS is the number of threads to be synched on barrier
    {
        printf("Could not create a barrier\n");
        return -1;
    }

    for(int i = 0; i < THREADS; ++i)
    {
        if(pthread_create(&thr[i], NULL, &entry_point, (void*)i))
        {
            printf("Could not create thread %d\n", i);
            return -1;
        }
    }

    for(int i = 0; i < THREADS; ++i)
    {
        if(pthread_join(thr[i], NULL))
        {
            printf("Could not join thread %d\n", i);
            return -1;
        }
    }


    double det = Determinant(initial_matrix);
    printf("The determinant of M^4 = %f\n", det);

    return 0;
}
```

Barriers via Busy Waiting and a Mutex

```
/* Shared and initialized by the main thread */
int count;    // Initialize to 0
int thread_count;
pthread_mutex_t barrier_mutex;
...
void* Thread_func(void* ...){
    ...
    /* Barrier */
    pthread_mutex_lock(&barrier_mutex);
    count++;
    pthread_mutex_unlock(&barrier_mutex);
    while (count<thread_count);    // Busy waiting
    ...
}
```

Not efficient and hard to reuse the same `count` for a 2nd barrier

Barrier through Semaphores

```
/* Shared variables */
int counter;    // Initialize to 0
sem_t count_sem;    // Initialize to 1
sem_t barrier_sem;    // Initialize to 0
...

void* Thread_func(void* ...){
    ...

    /*Barrier*/
    sem_wait(&count_sem);
    if (counter == thread_count-1){
        counter = 0;
        sem_post(&count_sem);
        for (j = 0; j < thread_count-1; j++)
            sem_post(&barrier_sem);
    } else {
        counter++;
        sem_post(&count_sem);
        sem_wait(&barrier_sem);

    }
```

Hard to reuse the same variables for a 2nd barrier

Barrier via a Condition Variable

```
/* Shared */
int counter = 0;
pthread_mutex_t mutex;
pthread_cond_t cond_var;

...
void* Thread_func(void* arg){
    ...
    /* Barrier */
    pthread_mutex_lock(&mutex);
    counter++;
    if (counter == thread_count){
        counter = 0;
        pthread_cond_broadcast(&cond_var);
    } else {
        while (pthread_cond_wait(&cond_var, &mutex)!= 0);
    }
    pthread_mutex_unlock(&mutex);
    ...
}
```

Composite Synchronization Constructs

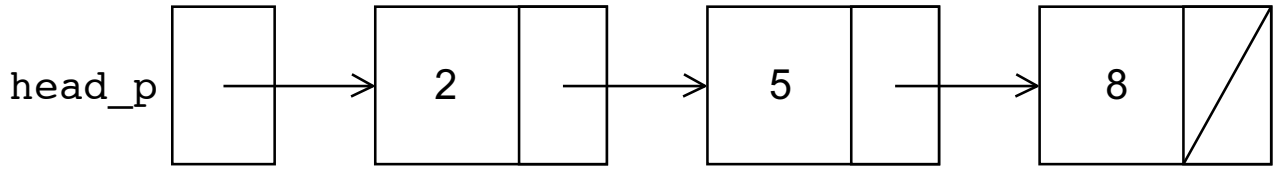
Barrier as a Composite Construct

```
typedef struct {
  pthread_mutex_t count_lock;
  pthread_cond_t ok_to_proceed;
  int count;
} mylib_barrier_t;

void mylib_init_barrier(mylib_barrier_t *b) {
  b -> count = 0;
  pthread_mutex_init(&(b -> count_lock), NULL);
  pthread_cond_init(&(b -> ok_to_proceed), NULL);
}

void mylib_barrier (mylib_barrier_t *b, int num_threads) {
  pthread_mutex_lock(&(b -> count_lock));
  b -> count ++;
  if (b -> count == num_threads) {
    b -> count = 0;
    pthread_cond_broadcast(&(b -> ok_to_proceed));
  }
  else
    while (pthread_cond_wait(&(b -> ok_to_proceed),
      &(b -> count_lock)) != 0);
  pthread_mutex_unlock(&(b -> count_lock));
}
```

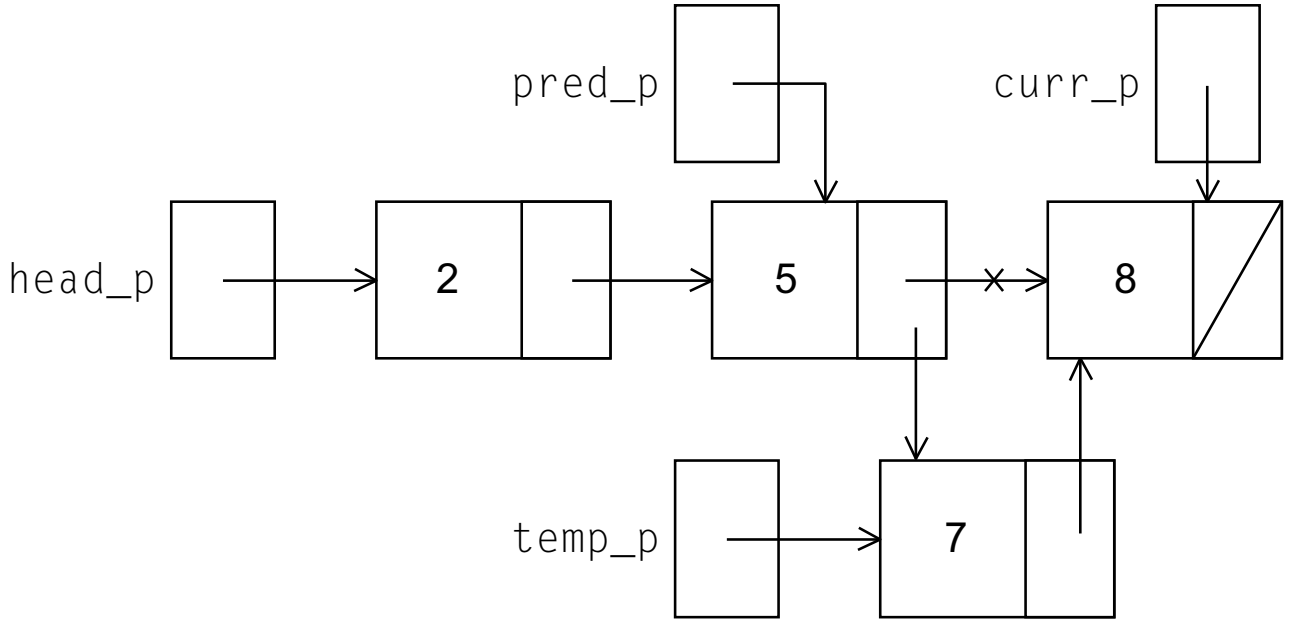
Read-Write Locks

In many applications, a data structure is read frequently but written infrequently. For such applications, we should use read-write locks.

A Linked List

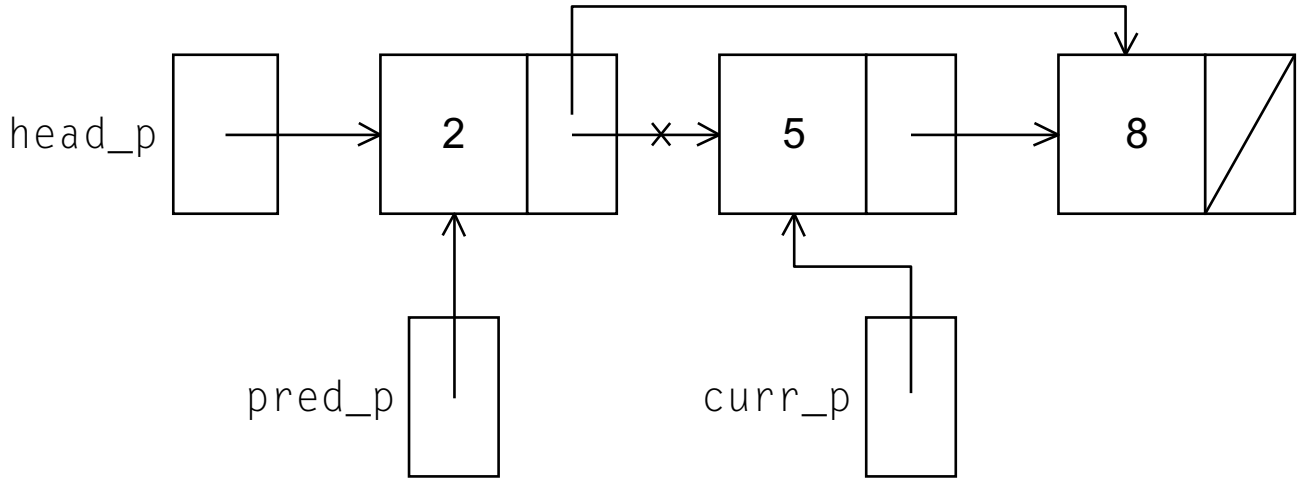


Insert

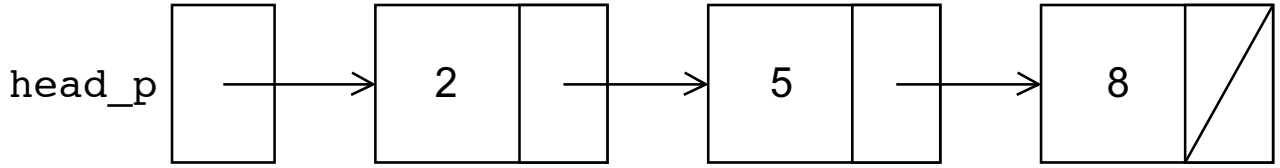


Read-Write Locks

Delete



Member



Read-Write Locks

Implementation Requirements

1. A read lock can be granted when there are other threads that already have read locks.

2. If there is a write lock on the data (or if there are queued write locks), the thread performs a condition wait (no matter whether it's a read or write).

3. If there are multiple threads requesting a write lock, they must perform a condition wait.

With this description, we can design functions for read locks `mylib_rwlock_rlock`, write locks `mylib_rwlock_wlock`, and unlocking `mylib_rwlock_unlock`.

Read-Write Locks vs. Mutex Locks

Run times Comparison

Table 4.3 Linked List Times: 1000 Initial Keys, 100,000 ops, 99.9% `Member`, 0.05% `Insert`, 0.05% `Delete`

Implementation	Number of Threads			
	1	2	4	8
Read-Write Locks	0.213	0.123	0.098	0.115
One Mutex for Entire List	0.211	0.450	0.385	0.457
One Mutex per Node	1.680	5.700	3.450	2.700

Table 4.4 Linked List Times: 1000 Initial Keys, 100,000 ops, 80% `Member`, 10% `Insert`, 10% `Delete`

Implementation	Number of Threads			
	1	2	4	8
Read-Write Locks	2.48	4.97	4.69	4.71
One Mutex for Entire List	2.50	5.13	5.04	5.11
One Mutex per Node	12.00	29.60	17.00	12.00

Read-Write Locks

Application: computing the minimum of a list of numbers

```
void *find_min_rw(void *list_ptr) {
   int *partial_list_pointer, my_min, i;
   my_min = MIN_INT;
   partial_list_pointer = (int *) list_ptr;
   for (i = 0; i < partial_list_size; i++)
      if (partial_list_pointer[i] < my_min)
         my_min = partial_list_pointer[i];
   /* lock the mutex associated with minimum_value and update the
variable as required */
   mylib_rwlock_rlock(&read_write_lock);
   if (my_min < minimum_value) {
      mylib_rwlock_unlock(&read_write_lock);
      mylib_rwlock_wlock(&read_write_lock);
      if (my_min < minimum_value)
           minimum_value = my_min;
   }
   /* and unlock the mutex */
   mylib_rwlock_unlock(&read_write_lock);
   pthread_exit(0);
```

Read-Write Locks

The lock data type `mylib_rwlock_t` holds the following:

a count of the number of readers,

the `writer` (a 0/1 integer specifying whether a writer is present)

a condition variable `readers_proceed` that is signaled when readers can proceed,

a condition variable `writer_proceed` that is signaled when ***one of the writers*** can proceed,

a count `pending_writers` of pending writers, and

a mutex `read_write_lock` associated with the shared data structure.

Read-Write Locks

```
typedef struct {
  int readers;
  int writer;
  pthread_cond_t readers_proceed;
  pthread_cond_t writer_proceed;
  int pending_writers;
  pthread_mutex_t read_write_lock;
} mylib_rwlock_t;

void mylib_rwlock_init (mylib_rwlock_t *l) {
  l -> readers = l -> writer = l -> pending_writers = 0;
  pthread_mutex_init(&(l -> read_write_lock), NULL);
  pthread_cond_init(&(l -> readers_proceed), NULL);
  pthread_cond_init(&(l -> writer_proceed), NULL);
}
```

Read-Write Locks

```
void mylib_rwlock_rlock(mylib_rwlock_t *l) {
  /* if there is a write lock or pending writers, perform
condition wait, else increment count of readers and grant
read lock */

  pthread_mutex_lock(&(l -> read_write_lock));
  while ((l -> pending_writers > 0) || (l -> writer > 0))
    pthread_cond_wait(&(l -> readers_proceed),
      &(l -> read_write_lock));
  l -> readers ++;
  pthread_mutex_unlock(&(l -> read_write_lock));
}
```

Read-Write Locks

```
void mylib_rwlock_wlock(mylib_rwlock_t *l) {
  /* if there are readers or writers, increment pending
writers count and wait. On being woken, decrement pending
writers count and increment writer count */

  pthread_mutex_lock(&(l -> read_write_lock));
  while ((l -> writer > 0) || (l -> readers > 0)) {
    l -> pending_writers ++;
    pthread_cond_wait(&(l -> writer_proceed),
      &(l -> read_write_lock));
    l -> pending_writers --;
  }
  l -> writer ++;
  pthread_mutex_unlock(&(l -> read_write_lock));
}
```

Read-Write Locks

```
void mylib_rwlock_unlock(mylib_rwlock_t *l) {
  /* if there is a write lock then unlock, else if there are
read locks, decrement count of read locks. If the count is 0
and there is a pending writer, let it through, else if there
are pending readers, let them all go through */

  pthread_mutex_lock(&(l -> read_write_lock));
  if (l -> writer > 0)
    l -> writer = 0;
  else if (l -> readers > 0)
    l -> readers --;
  if (l -> readers > 0)
    pthread_cond_broadcast(&(l -> readers_proceed));
  else if ((l -> readers == 0) && (l -> pending_writers > 0))
    pthread_cond_signal(&(l -> writer_proceed));
  else if ((l -> readers == 0) && (l -> pending_writers==0))
    pthread_cond_broadcast(&(l -> readers_proceed));
  pthread_mutex_unlock(&(l -> read_write_lock));
}
```

How Caches Affect Shared-Memory Programming?

Memory Hierarchy Review

Block (aka cache line): unit of copying

May be multiple words
(a word = 64 bits or 32 bits)

If accessed data is present in upper level

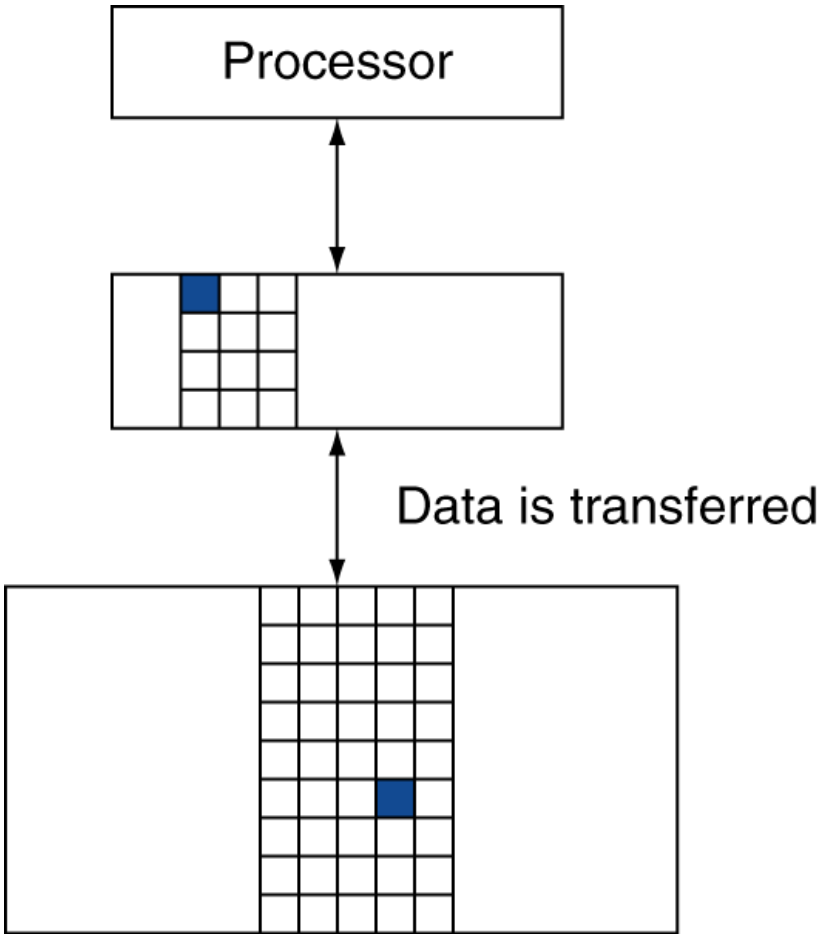
Hit: access satisfied by upper level

Hit ratio: hits/accesses

If accessed data is absent

Miss: block copied from lower level

Then accessed data supplied from upper level

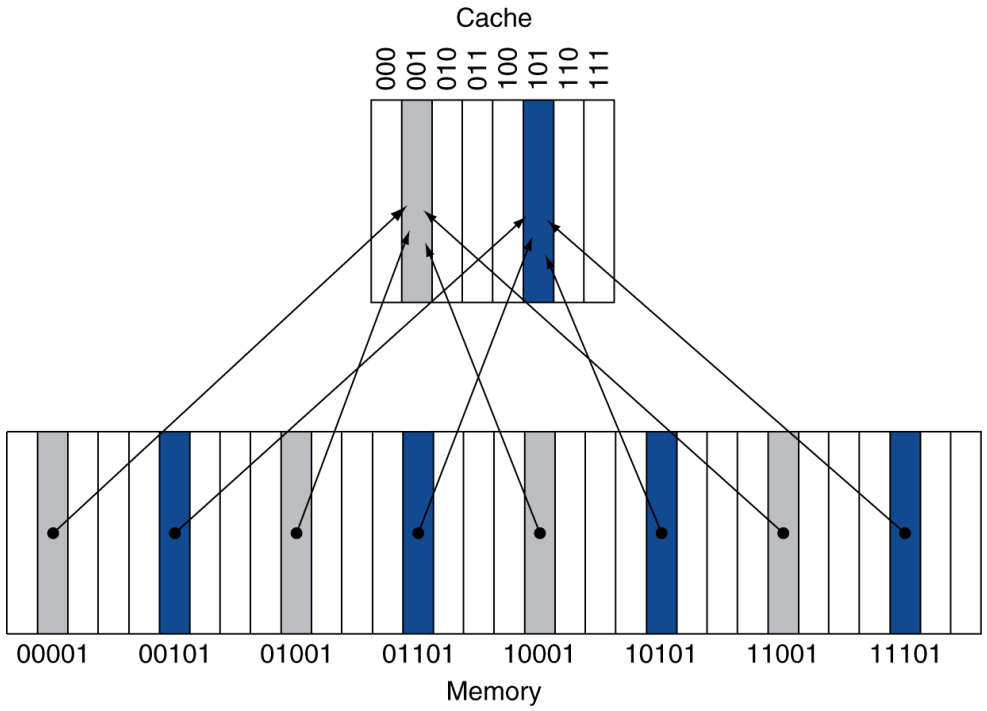


Memory Hierarchy Review

Cache position determined by address

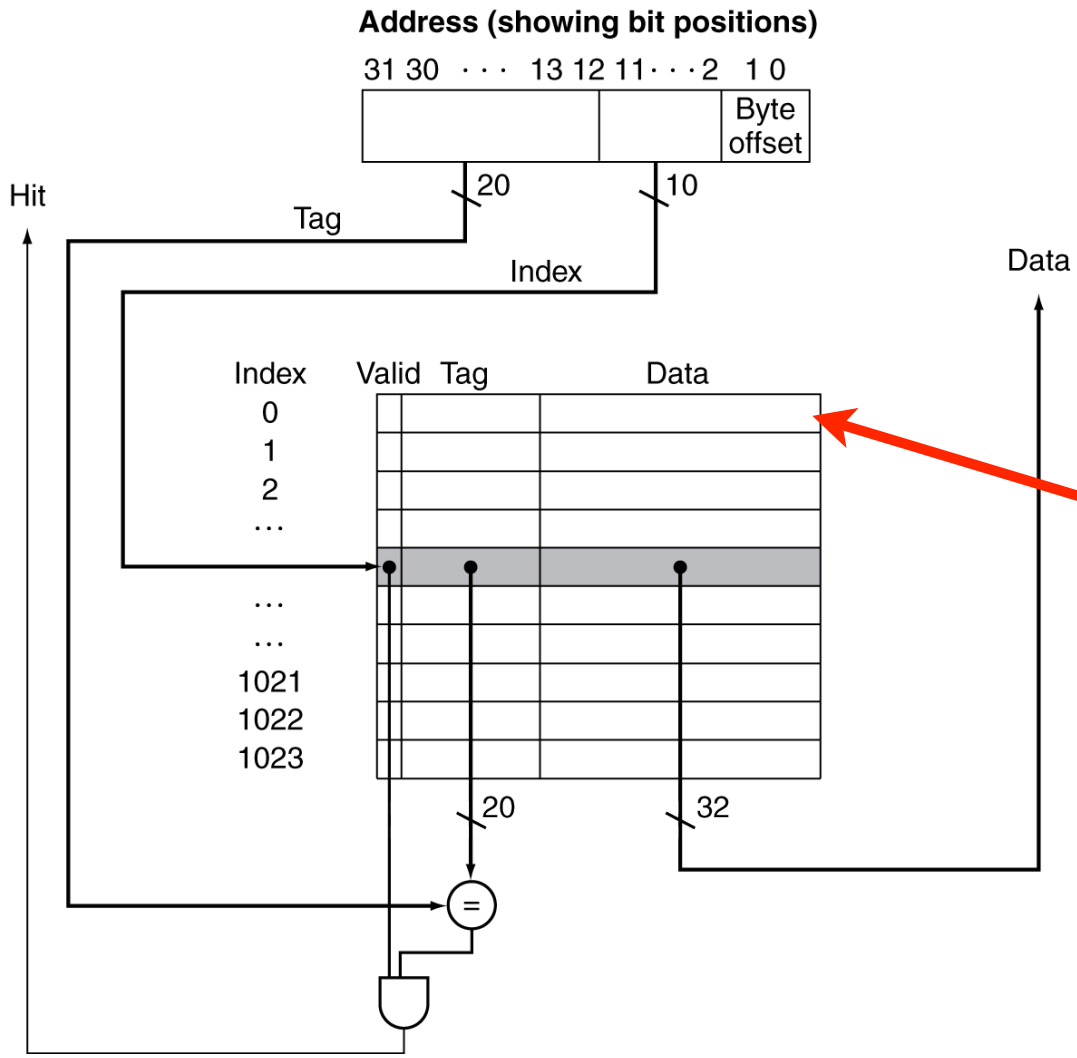
Direct mapped: multiple memory cells share a certain cache line

Cache line position = (Block address) modulo (#Blocks in cache)



Memory Hierarchy Review

Cache Example



A block or cache line (4 Bytes in this case)

Cache Coherence

Cache Coherence in Shared Memory Systems

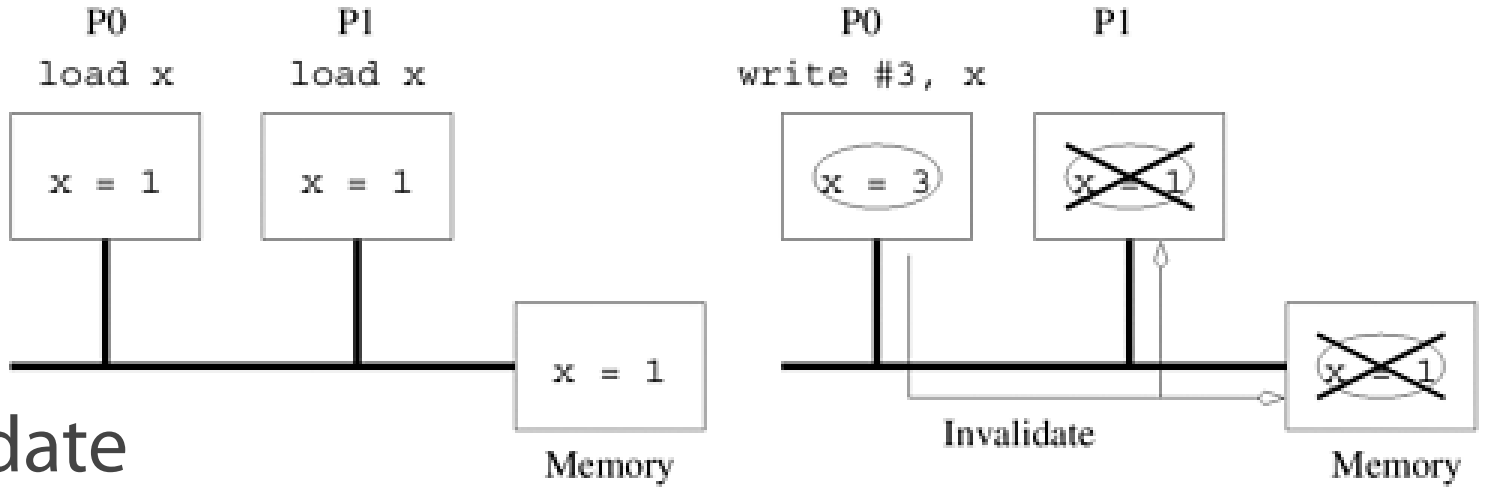
- A certain level of consistency must be maintained for multiple copies of the same data
- Required to ensure proper semantics and correct program execution
- Serializability: there exists some serial order of instruction execution that corresponds to the parallel schedule
- Cache coherence is enforced at the "cache-line level"

Two general protocols for dealing with it

- Invalidate vs. Update
- Classical trade-off between communication overhead (updates) and idling (stalling in invalidates)
- Most existing schemes are based on the **invalidate protocol**

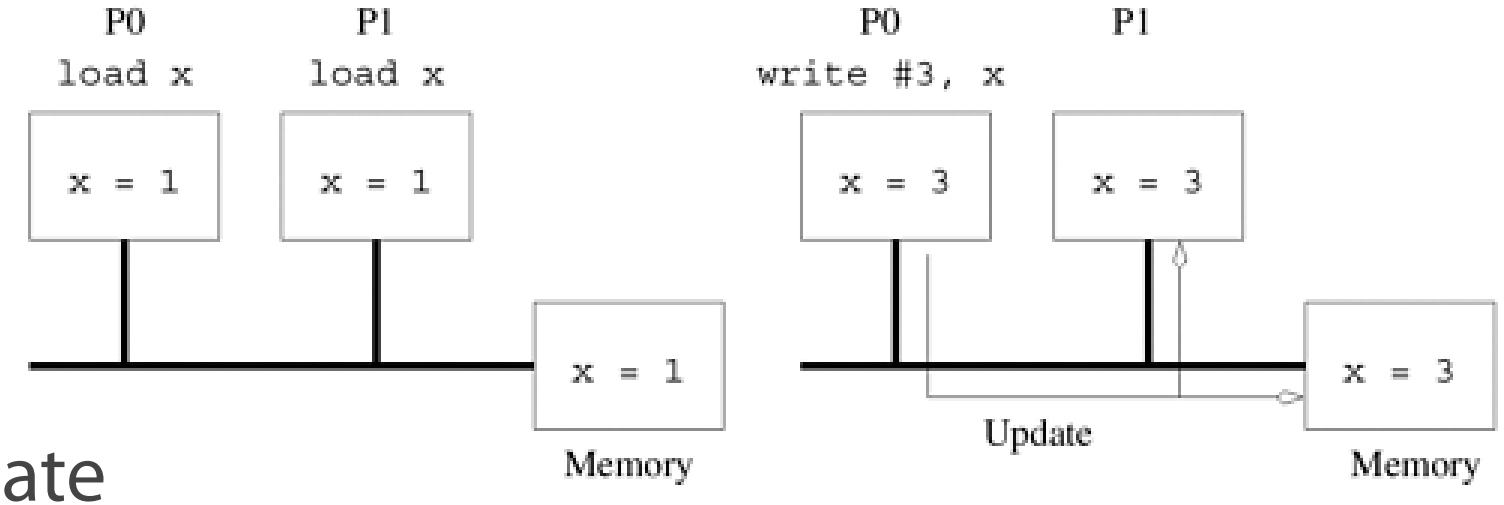
Cache Coherence Mechanisms

Invalidate



(a)

Update



(b)

Cache Invalidating Protocol

Steps:

Cache gets exclusive access to a block when it is to be written

Broadcasts an invalidate message on the bus

Subsequent read for the block from another cache misses

Owning cache supplies updated value

CPU activity	Bus activity	CPU A's cache	CPU B's cache	Memory
				0
CPU A reads X	Cache miss for X	0		0
CPU B reads X	Cache miss for X	0	0	0
CPU A writes 1 to X	Invalidate for X	1		0
CPU B read X	Cache miss for X	1	1	1

False Sharing

Suppose multiple threads with separate caches access different variables that belong to the same cache line.

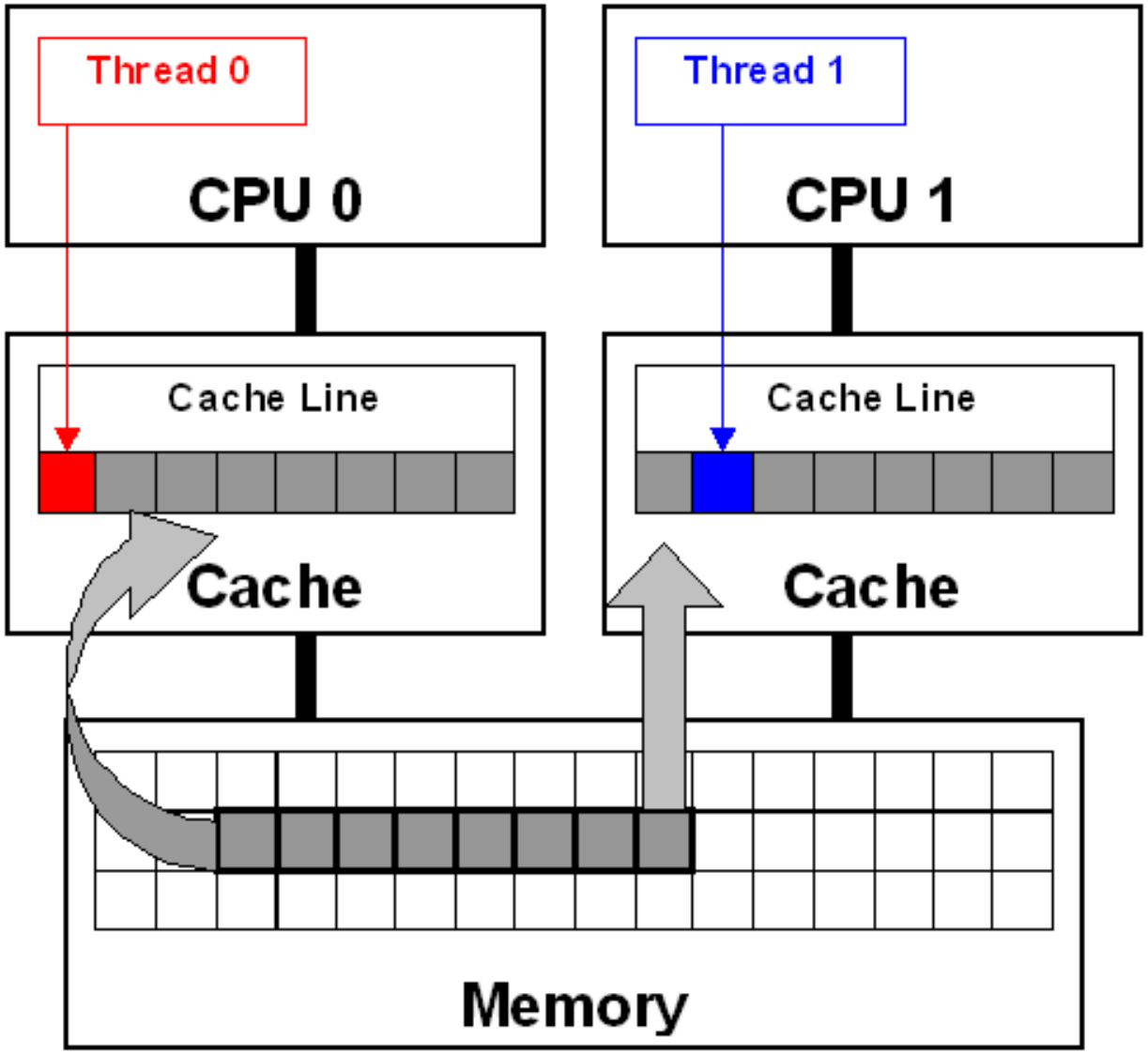
At least one of the threads updates its variable.

Even though neither thread has written to a variable that the other thread is accessing, the cache controller invalidates the ***entire cache line*** and forces the threads to get the values of the variables from main memory.

The behavior of the threads with respect to memory access is the same as if they were sharing a variable, hence the name *false sharing*.

False Sharing

Write Invalidates the entire cache line



Read has to fetch from main memory

False Sharing: Matrix-Vector Multiplication

```
1  void *Pth_mat_vect(void* rank) {
2     long my_rank = (long) rank;
3     int i, j;
4     int local_m = m/thread_count;
5     int my_first_row = my_rank*local_m;
6     int my_last_row = (my_rank+1)*local_m - 1;
7
8     for (i = my_first_row; i <= my_last_row; i++) {
9        y[i] = 0.0;
10       for (j = 0; j < n; j++)
11           y[i] += A[i][j]*x[j];
12    }
13
14    return NULL;
15 }  /* Pth_mat_vect */
```

Table 4.5 Run-Times and Efficiencies of Matrix-Vector Multiplication (times are in seconds)

	Matrix Dimension					
	$8,000,000 \times 8$		8000×8000		$8 \times 8,000,000$	
Threads	Time	Eff.	Time	Eff.	Time	Eff.
1	0.393	1.000	0.345	1.000	0.441	1.000
2	0.217	0.906	0.188	0.918	0.300	0.735
4	0.139	0.707	0.115	0.750	0.388	0.290

False Sharing: Matrix-Vector Multiplication

Write-miss for y: Line 9

Read-miss in x, A: Line 11

Table 4.5 Run-Times and Efficiencies of Matrix-Vector Multiplication (times are in seconds)

	Matrix Dimension					
	$8,000,000 \times 8$		8000×8000		$8 \times 8,000,000$	
Threads	Time	Eff.	Time	Eff.	Time	Eff.
1	0.393	1.000	0.345	1.000	0.441	1.000
2	0.217	0.906	0.188	0.918	0.300	0.735
4	0.139	0.707	0.115	0.750	0.388	0.290

Unlikely to have false sharing. Why?

False Sharing when updating y[i]: Line 11

Tips to Avoid False Sharing

1. Pad the y vector with dummy elements in order to ensure that any update by one thread won't affect another thread's cache line.

2. Avoid frequent writing to global data that is accessed from multiple threads!

   Have each thread use its own private storage during the multiplication loop, and then update the shared storage when they're done.

3. False sharing may be less visible when dealing with larger problem sizes, as there might be less sharing.

4. Other methods: align shared global data to cache line boundaries using compiler directives

   When parallelizing an algorithm, partition data sets along cache lines, not across cache lines.

Tips to Avoid False Sharing

Padding a data structure to a cache line boundary and ensuring the array is also aligned using the compiler __declspec (align(n)) statement (not required in this course), where n equals 64 (64 byte boundary).

```
struct ThreadParams
{
  // For the following 4 variables: 4*4 = 16 bytes
  unsigned long thread_id;
  unsigned long v; // Frequent read/write access variable
  unsigned long start;
  unsigned long end;

  // expand to 64 bytes to avoid false-sharing
  // (4 unsigned long variables + 12 padding)*4 = 64
  int padding[12];
};

__declspec (align(64)) struct ThreadParams Array[10];
```

Tips to Avoid False Sharing

Using local copies to avoid the frequency of writing and thus alleviate the impact of false sharing

```
struct ThreadParams
{
   // For the following 4 variables: 4*4 = 16 bytes
   unsigned long thread_id;
   unsigned long v; //Frequent read/write access variable
   unsigned long start;
   unsigned long end;
};

void threadFunc(void *parameter)
{
   ThreadParams *p = (ThreadParams*) parameter;
   // local copy for read/write access variable
   unsigned long local_v = p->v;

   for(int i = p->start; i < p->end; i++)
   {
      // update local_v multiple times
   }

   p->v = local_v; // Update shared data structure only once
}
```

Thread Safety

Some C functions cache data between calls by declaring variables to be static, e.g., strtok()

This can cause errors when multiple threads call the function;

Since static storage is shared among the threads, one thread can overwrite another thread's data. Such a function is not thread-safe,

There are serval such functions in the C library. Sometimes, however, there is a thread-safe variant.

rand() is not thread-safe, use rand_r (or drand48_r on Linux)

strtok() is not thread-safe, use strtok_r()

Thread Safety

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

int main()
{
   const char str[80] = "This is - ECE - 420";
   const char s[2] = "-";
   char *token;

   /* get the first token */
   token = strtok(str, s);

   /* walk through other tokens */
   while( token != NULL )
   {
      printf( " %s\n", token );

      token = strtok(NULL, s);
   }

   return(0);
}
```

```
================================================
Output:

This is
ECE
420
```

Thread-Safety

See the multi-threaded thread-safety examples:

Pthreads: Tokenize

Pthreads: Tokenize (thread-safe)

Wrong programs may produce right results!