Agenda – Day 1

Time	Title	Presenter
9:00-9:10	Welcome	Frank McKenna
9:10-10:30	Debugging	Wael Elhaddad
10:30-11:00	PI	
11:00-11:15	Parallel Machines	Frank McKenna
11.15-12:00	Parallel Programming With MPI	Frank McKenna
12:00-1:00	LUNCH	
1:00-2:30	EXERCISE	YOU
2:30-3:00	Parallel Programming with OpenMP	Frank McKenna
3:00-4:30	EXERCISE	YOU
4:30-5:00	Load Balancing	Frank McKenna
Day 3	Abstraction, More C & Introducing C++	
Day 4	User Interface Design & Qt	
Day 5	SimCenter & Cloud Computing	

SimCenter NHERI
Center for Computational Modeling and Simulation

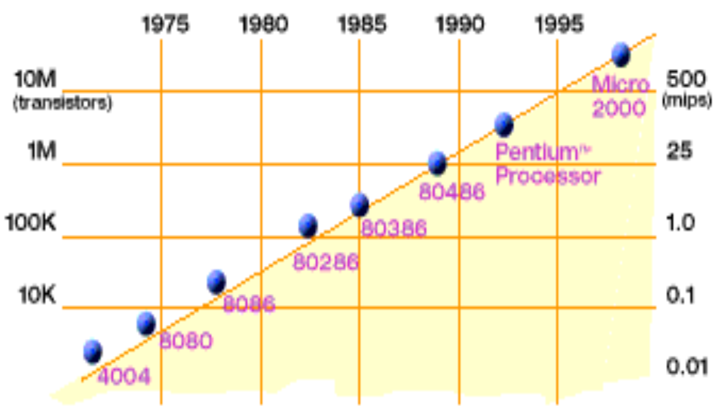
Parallel Programming
Frank McKenna

Outline

- Parallel Machines & Parallel Machine Models
- Parallel Programming
  - Message Passing With MPI
  - Shared Memory Programming with OpenMP

Ignoring co-processors and GPUs

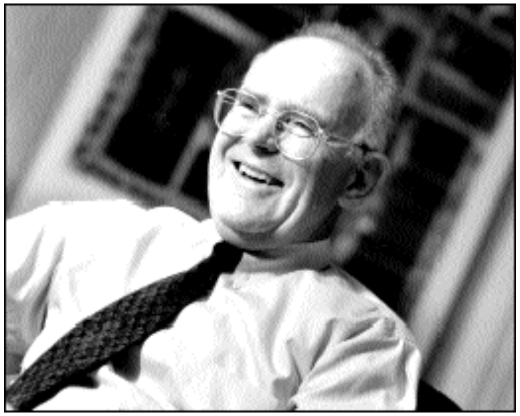
Why is Parallel Programming Important



2X transistors/Chip Every 1.5 years

Called "[Moore' s Law]"

Microprocessors have become smaller, denser, and more powerful.

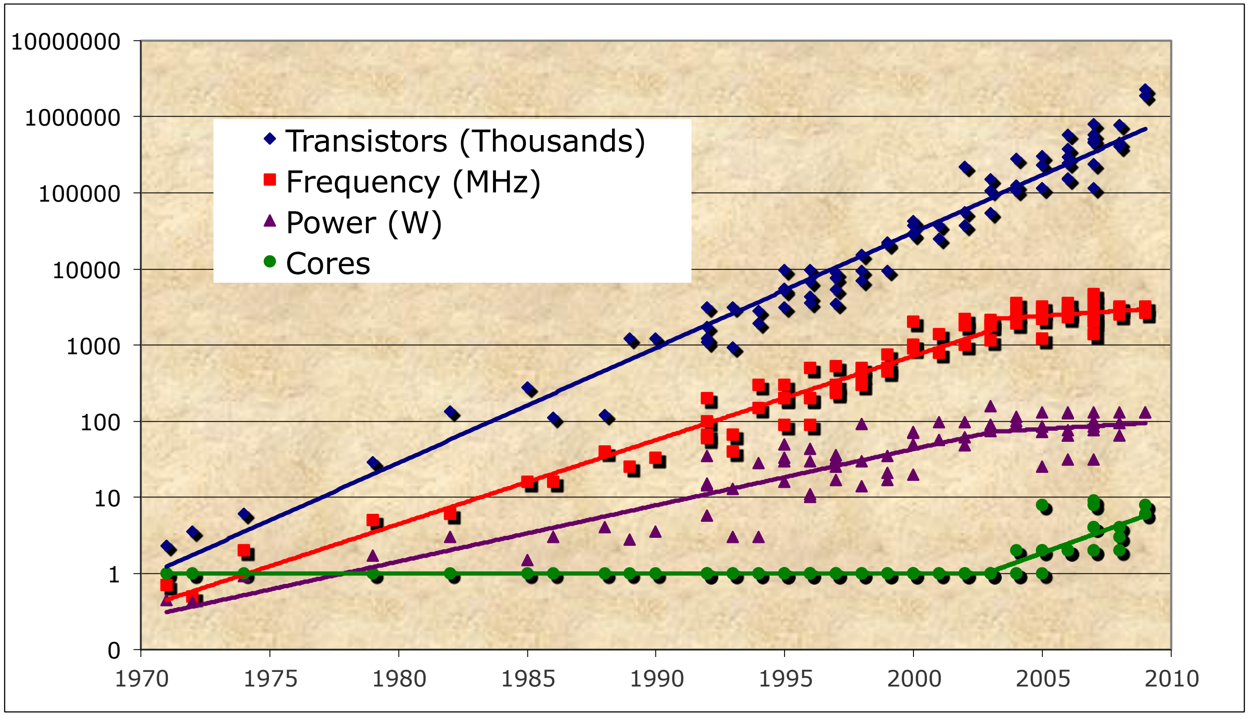


Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 18 months.

Slide source: Jack Dongarra

source: CS267, Jim Demmell

Revolution in Processors



- Chip density is continuing increase ~2x every 2 years
- Clock speed is not
- Number of processor cores may double instead
- Power is under control, no longer growing

source: CS267, Jim Demmell

Multiple Cores!

What does it mean for Programmers

“The Free Lunch is Over” Herb Sutter

- Up until 2003 programmers had been relying on Hardware to make their programs go faster. No longer. They had to start programming again!
- **Performance now comes from Software**
- **To be fast and utilize the resources, Software must run in parallel, that is it must run on multiple cores at same time.**

How many cores?

1,736 Intel Xeon Skylake nodes, each with 48 cores + 192GB of RAM
4,200 Intel Knights Landing nodes, each with 68 cores + 96GB of DDR RAM

TACC DESIGNSAFE-CI

1 Intel i7 node, 6 cores + 16GB RAM

Apple A11, 6 cores + 64GB RAM

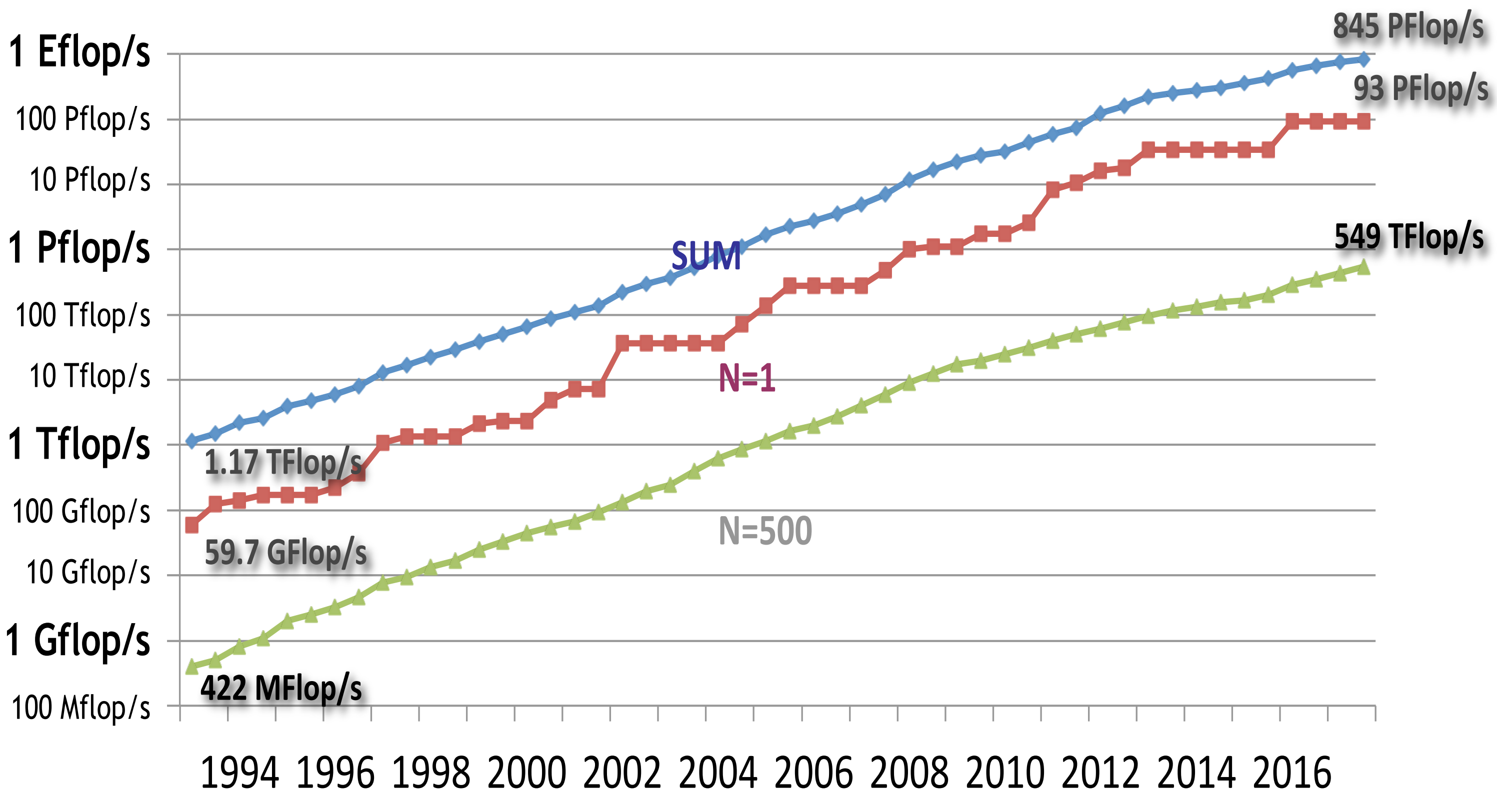
How Big & Fast!

TOP500 SUPERCOMPUTER SITES

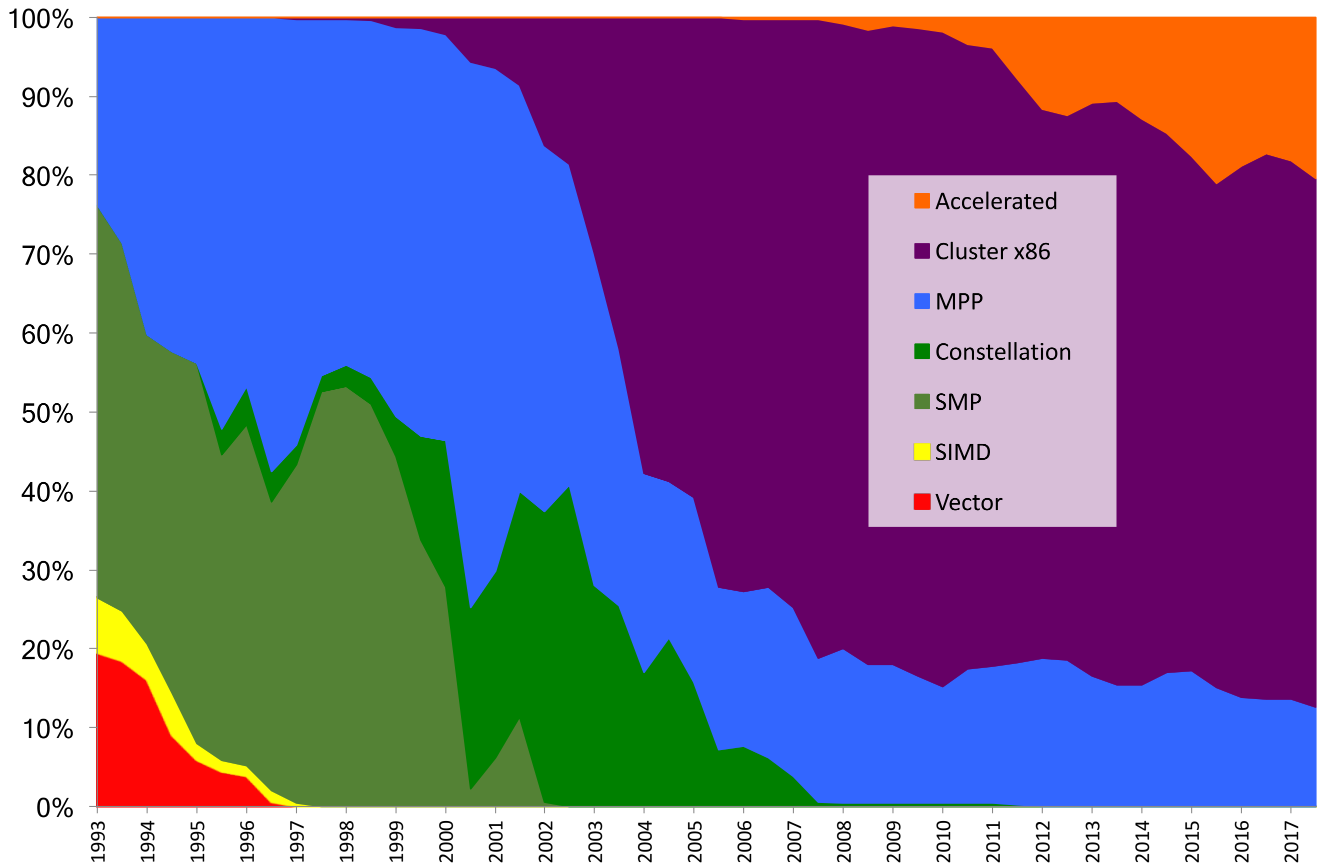
Rmax of Linpack
Solve Ax = b

Rank	Site	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	DOE/SC/Oak Ridge National Laboratory United States	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband IBM	2,282,544	122,300.0	187,659.3	8,806
2	National Supercomputing Center in Wuxi China	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway NRCPC	10,649,600	93,014.6	125,435.9	15,371
3	DOE/NNSA/LLNL United States	**Sierra** - IBM Power System S922LC, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband IBM	1,572,480	71,610.0	119,193.6	
4	National Super Computer Center in Guangzhou China	**Tianhe-2A** - TH-IVB-FEP Cluster, Intel Xeon E5-2692v2 12C 2.2GHz, TH Express-2, Matrix-2000 NUDT	4,981,760	61,444.5	100,678.7	18,482
5	National Institute of Advanced Industrial Science and Technology (AIST) Japan	**AI Bridging Cloud Infrastructure (ABCI)** - PRIMERGY CX2550 M4, Xeon Gold 6148 20C 2.4GHz, NVIDIA Tesla V100 SXM2, Infiniband EDR Fujitsu	391,680	19,880.0	32,576.6	1,649
15	Texas Advanced Computing Center/Univ. of Texas United States	**Stampede2** - PowerEdge C6320P/C6420, Intel Xeon Phi 7250 68C 1.4GHz/Platinum 8160, Intel Omni-Path Dell EMC	367,024	10,680.7	18,309.2	

Performance Development (2018)



From Vector Supercomputers to Massively Parallel Accelerator Systems



Moore's Law reinterpreted

- Number of cores per chip can double every two years
- Clock speed will not increase (possibly decrease)
- Need to deal with systems with millions of concurrent threads
- Need to deal with inter-chip parallelism as well as intra-chip parallelism

source: CS267, Jim Demmell

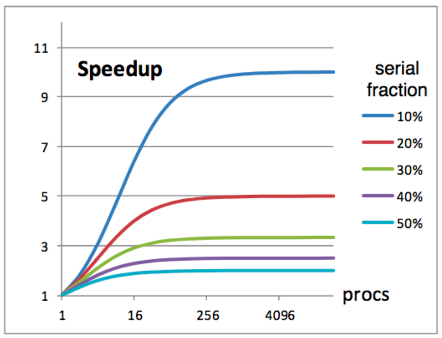
Can All Programs Be Made to Run Faster?

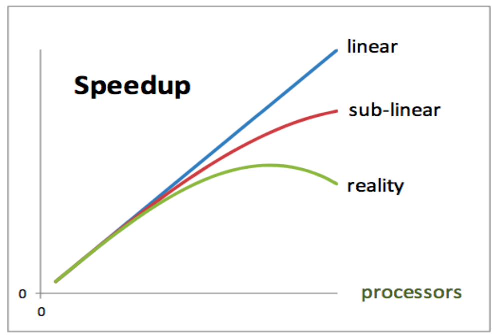
- Suppose only part of an application can run in parallel
- Amdahl's law
  - let s be the fraction of work done sequentially, so (1-s) is fraction parallelizable
  - P = number of processors

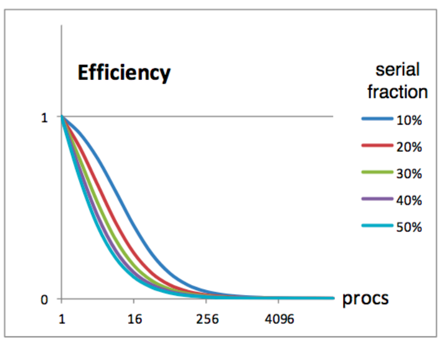
$$\text{Speedup}(P) = \text{Time}(1)/\text{Time}(P)$$
$$\leq 1/(s + (1-s)/P)$$
$$\leq 1/s$$

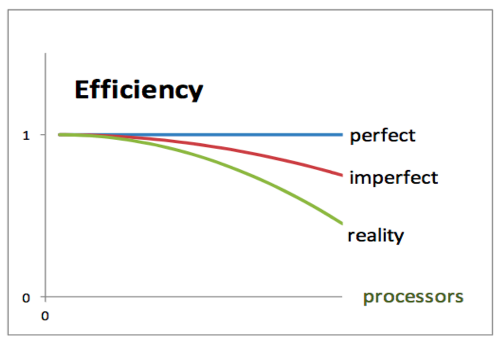
QUIZ: if 10% of program is sequential, What is the maximum speedup I Can obtain?

- **Even if the parallel part speeds up perfectly performance is limited by the sequential part**
- Top500 list: currently fastest machine has P~2.2M; Stampede2 has 367,000









Source: Doug James, TACC

This Does not Take into Account Overhead of Parallelism

- Parallelism overheads include:
  - cost of starting a thread or process
  - cost of communicating shared data
  - cost of synchronizing
  - extra (redundant) computation
- Each of these can be in the range of milliseconds (=millions of flops) on some systems
- Tradeoff: Algorithm needs sufficiently large units of work to run fast in parallel (i.e. large granularity), but not so large that there is not enough parallel work

source: CS267, Jim Demmell

Load Imbalance

- Load imbalance is the time that some processors in the system are idle due to
  - insufficient parallelism (during that phase)
  - unequal size tasks
- Examples of the latter
  - adapting to "interesting parts of a domain"
  - tree-structured computations
  - fundamentally unstructured problems
- Algorithm needs to balance load
  - Sometimes can determine work load, divide up evenly, before starting
    - "Static Load Balancing"
  - Sometimes work load changes dynamically, need to rebalance dynamically
    - "Dynamic Load Balancing," eg work-stealing

Improving Real Performance

Peak Performance grows exponentially, a la Moore's Law

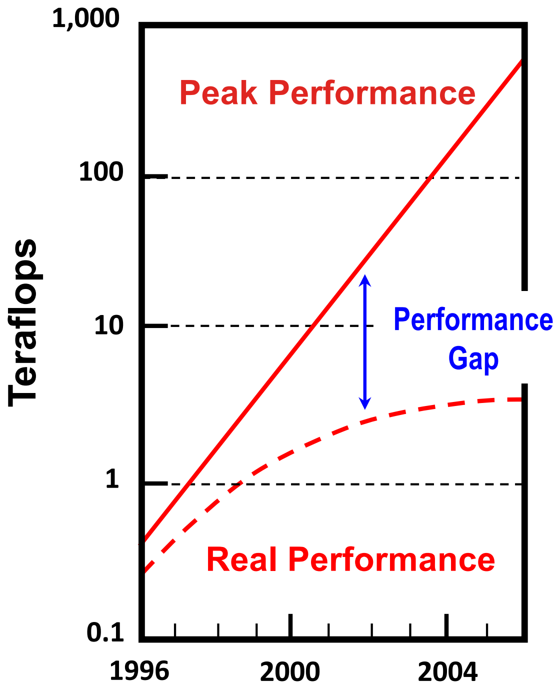
- In 1990's, peak performance increased 100x; in 2000's, it will increase 1000x

But efficiency (the performance relative to the hardware peak) has declined

- was 40-50% on the vector supercomputers of 1990s
- now as little as 5-10% on parallel supercomputers of today

Close the gap through ...

- Mathematical methods and algorithms that achieve high performance on a single processor and scale to thousands of processors
- More efficient programming models and tools for massively parallel supercomputers



Art of Programming - II

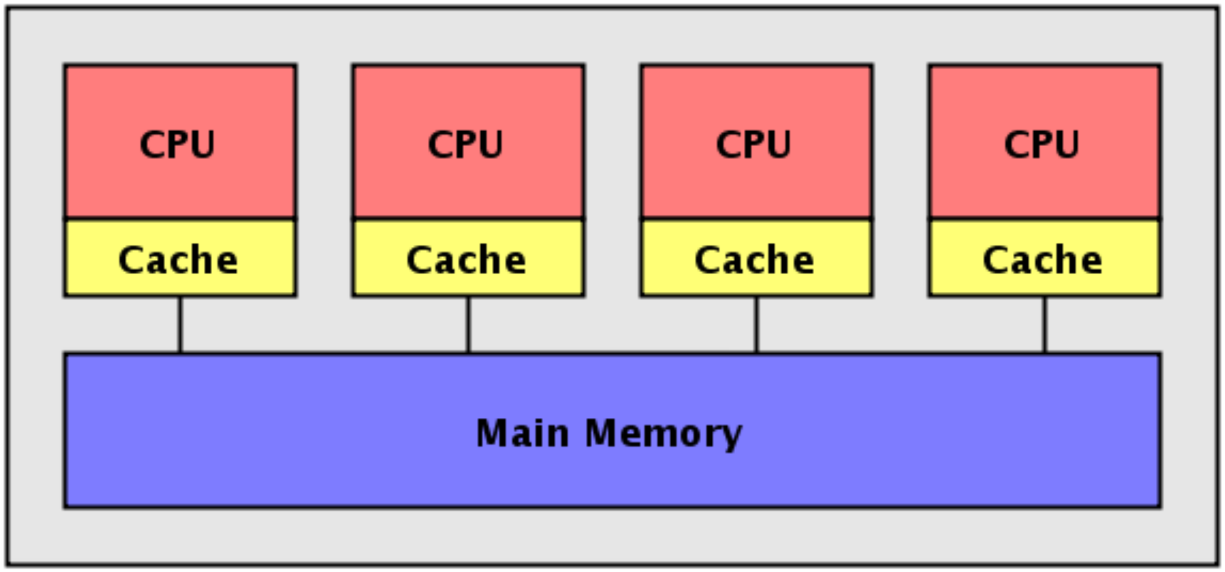
- To take a problem, and continually break it down into a series of smaller ideally concurrent tasks until ultimately these tasks become a series of small specific individual instructions.
- Mindful of the architecture on which the program will run, identify those tasks which can be run concurrently and map those tasks onto the processing units of the target architecture.

Considerations for Parallel Programming:

- Finding enough parallelism (Amdahl's Law)
- Granularity – how big should each parallel task be
- Locality – moving data costs more than arithmetic
- Load balance – don't want 1K processors to wait for one slow one
- Coordination and synchronization – sharing data safely
- Performance modeling/debugging/tuning

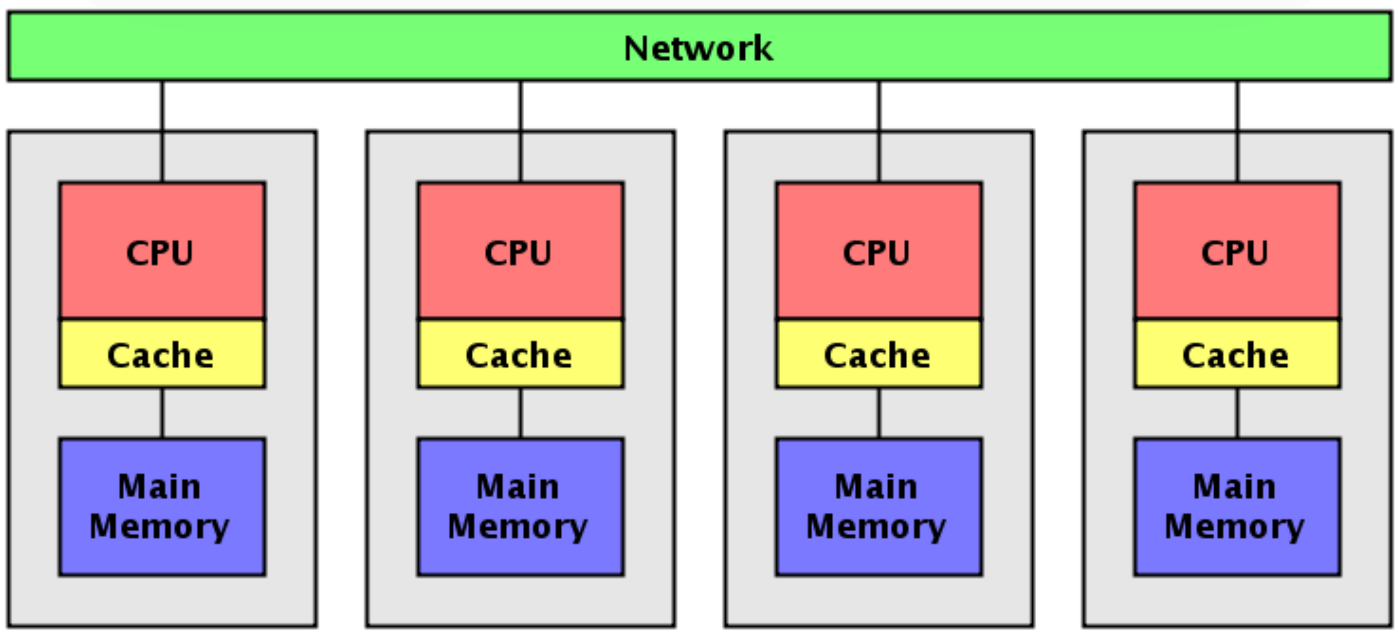
⇨ All of these things makes parallel programming even harder than sequential programming.

Simplified Parallel Machine Models



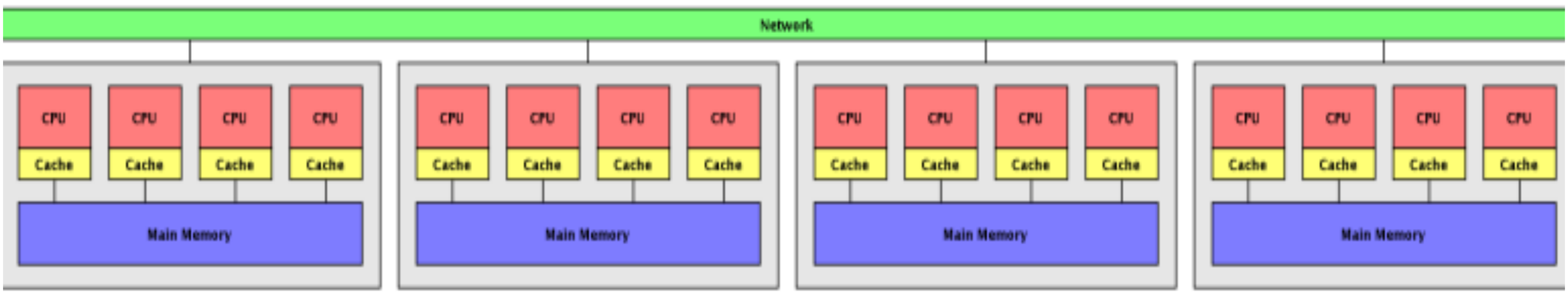
Shared Memory Model

Simplified Parallel Machine Models



Distributed Memory Model

Simplified Parallel Machine Models



Hybrid Model

Writing Programs to Run on Parallel Machines

- C Programming Libraries Exist that make it possible to write programs that run on these machines.
- They provide a **Programming Model** that is portable across architectures, i.e. can provide a message passing model that runs on a shared memory machine.
- We will look at 2 of these Programming Models and Libraries that support the model:
  - Message Passing Programming using MPI
  - Thread Programming using OpenMP
- As will all libraries they can incur an overhead.

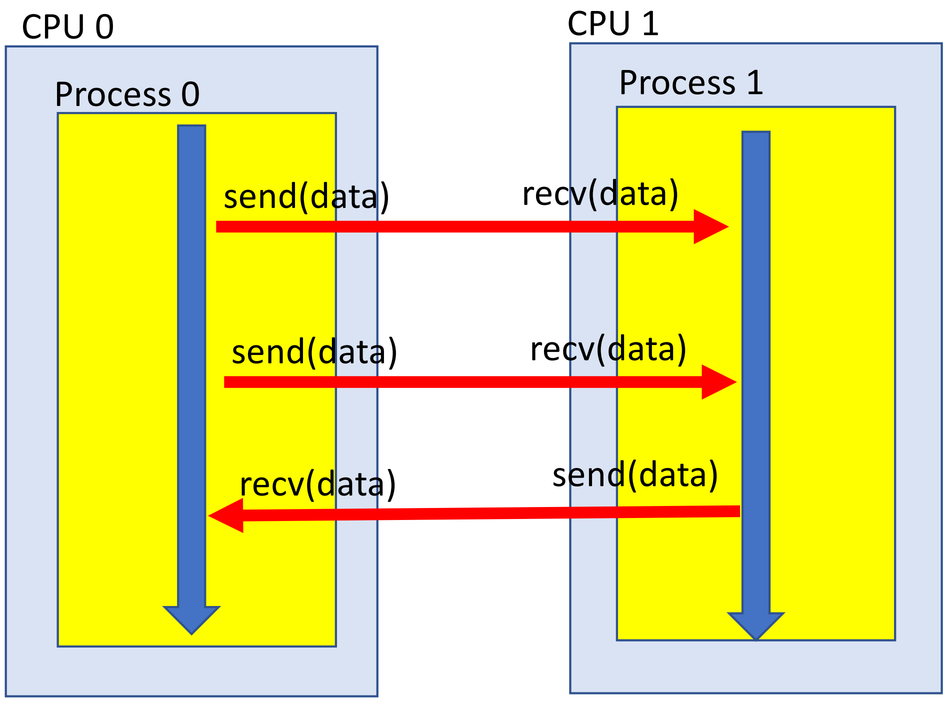
Outline

- Parallel Machines & Parallel Machine Models
- Parallel Programming
  - Message Passing With MPI
  - Shared Memory Programming with OpenMP

Ignoring co-processors and GPUs

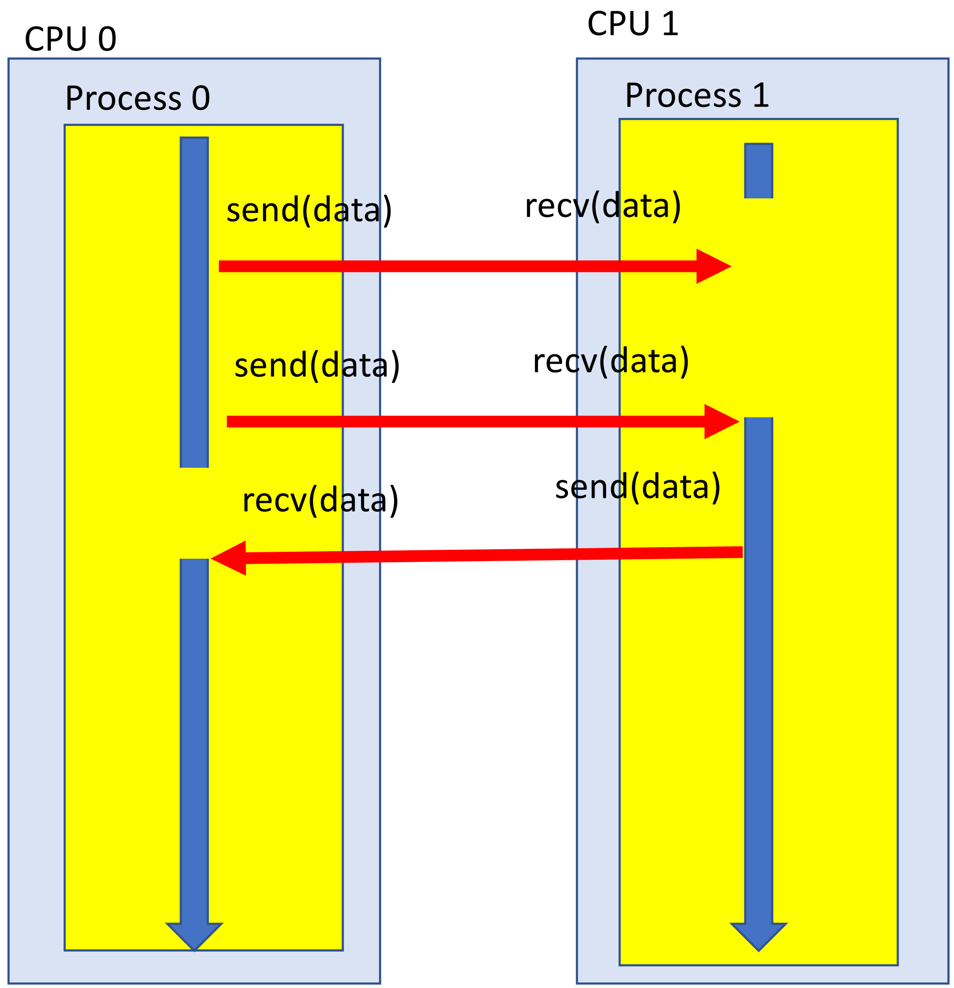
Message Passing Model

- Processes run independently in their own memory space and processes communicate with each other when data needs to be shared

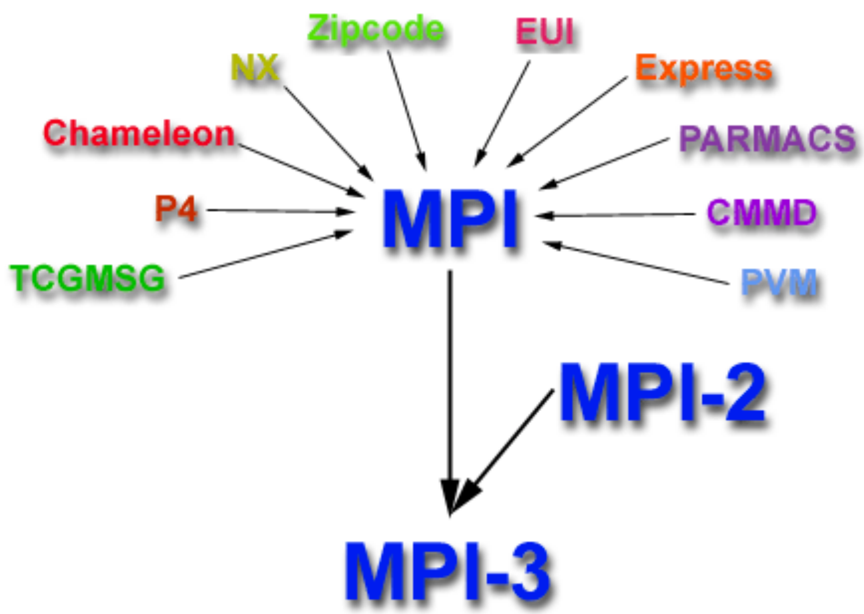


- Basically you write sequential applications with additional function calls to send and recv data.

Only get Speedup if processes can be kept busy



Programming Libraries



- Coalasced around a single standard MPI
- Allows for portable code

MPI

Provides a number of functions:

1. Enquiries
   - How many processes?
   - Which one am I?
   - Any messages Waiting?
2. Communication
   - Pair-wise point to point send and receive
   - Collective/Group: Broadcast, Scatter/Gather
   - Compute and Move: sum, product, max …
3. Synchronization
   - Barrier

REMEMBER:

What I am about to show is just C code with some functions you have not yet seen.

Hello World

Code/Parallel/mpi/hello1.c

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

int main( int argc, char **argv)
{
    int procID, numP;

    MPI_Init( &argc, &argv );
    MPI_Comm_size( MPI_COMM_WORLD, &numP );
    MPI_Comm_rank( MPI_COMM_WORLD, &procID );

    printf( "Hello World, I am %d of %d\n", procID, numP );
    MPI_Finalize();
    return 0;
}
```

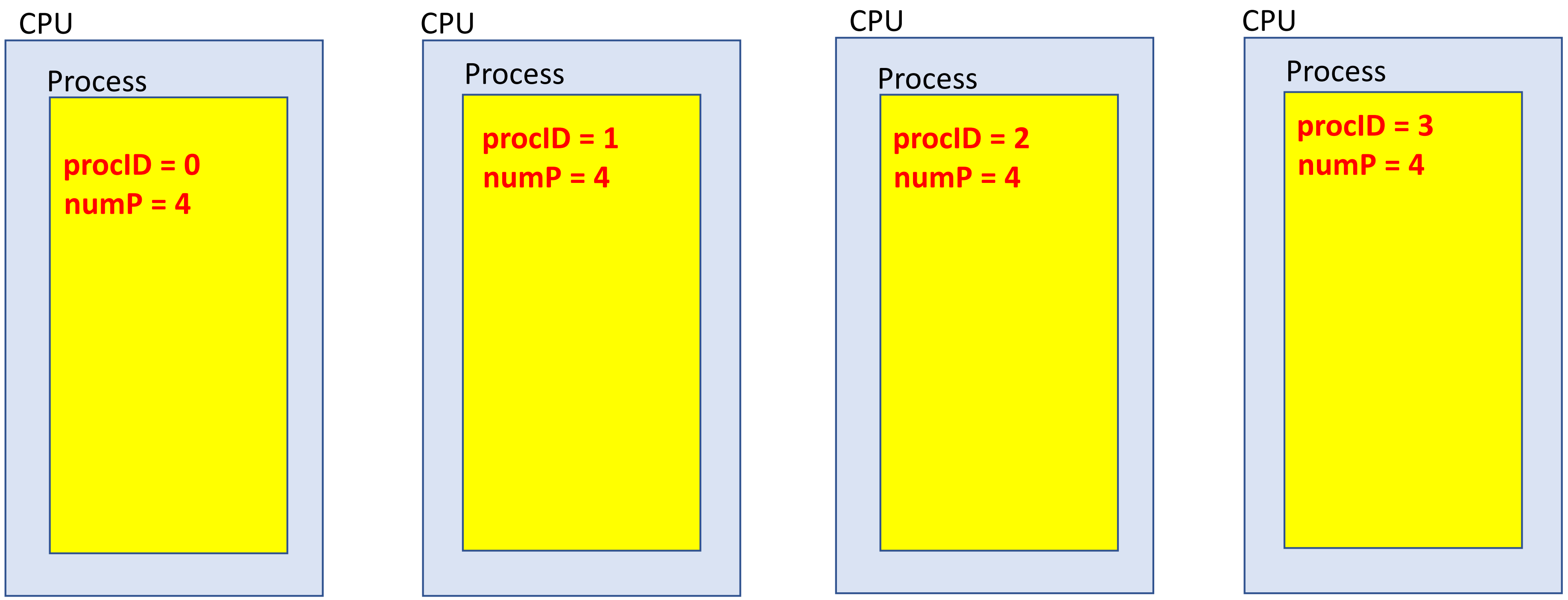
MPI functions (and MPI_COMM_WORLD) are defined in mpi.h

MPI_Init() and MPI_finalize() must be first and last functions called

MPI_COMM_WORLD is a default group contaning all processes

MPI_Comm_size returns # of processes in the group

MPI_Comm_rank returns processes unique ID the group, 0 through (numP-1)


CPU
Process
procID = 0
numP = 4
CPU
Process
procID = 1
numP = 4
CPU
Process
procID = 2
numP = 4
CPU
Process
procID = 3
numP = 4

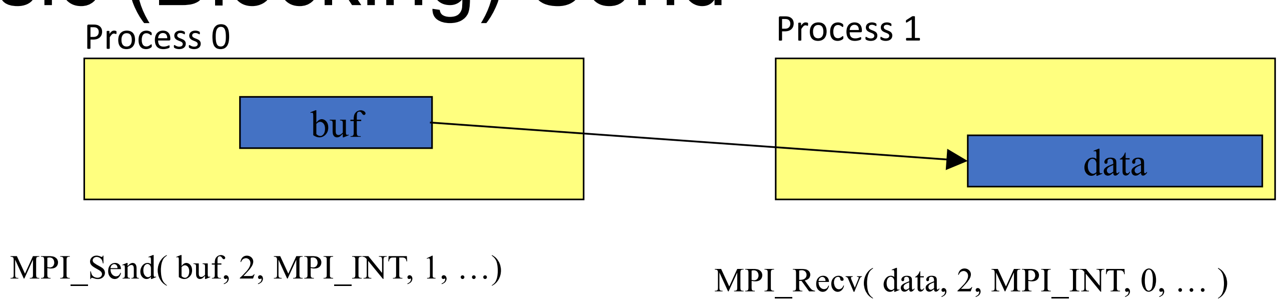
Send/Recv blocking

Code/Parallel/mpi/send1.c

```
#include <mpi.h>
#include <stdio.h>
int main( int argc, char **argv) {
  int procID;
  MPI_Status status;
  MPI_Init(&argv, &argc);
  MPI_Comm_rank( MPI_COMM_WORLD, &procID );

  if (procID == 0) { // process 0 sends
    int buf[2] = {12345, 67890};
    MPI_Send( &buf, 2, MPI_INT, 1, 0, MPI_COMM_WORLD);
  }
  else if (procID == 1) { // process 1 receives

    int data[2];
    MPI_Recv( &data, 2, MPI_INT, 0, 0, MPI_COMM_WORLD, &status );
    printf( "Received %d %d\n", data[0], data[1] );
  }

  MPI_Finalize();
  return 0;
}
```

NOTE the PAIR of Send/Recv

MPI Basic (Blocking) Send

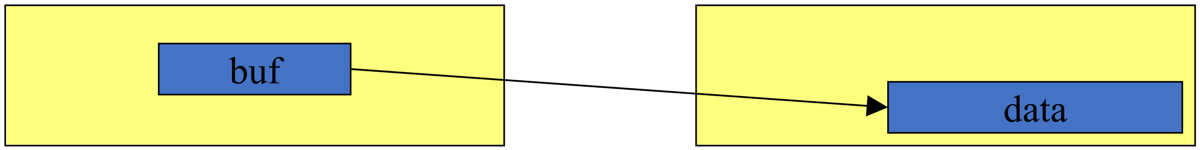


`MPI_SEND(start, count, datatype, dest, tag, comm)`

- The message buffer is described by (**`start, count, datatype`**).
- The target process is specified by **`dest`**, which is the rank of the target process in the communicator specified by **`comm`**. The message has an identifier **tag.**
- When this function returns, the data has been delivered to the system and the buffer can be reused. The message may not have been received by the target process.

MPI_CHAR	char
MPI_WCHAR	wchar_t - wide character
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_LONG_LONG_INT **MPI_LONG_LONG**	signed long long int
MPI_SIGNED_CHAR	signed char
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_UNSIGNED_LONG_LONG	unsigned long long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_C_COMPLEX **MPI_C_FLOAT_COMPLEX**	float _Complex
MPI_C_DOUBLE_COMPLEX	double _Complex
MPI_C_LONG_DOUBLE_COMPLEX	long double _Complex
MPI_C_BOOL	_Bool
MPI_INT8_T **MPI_INT16_T** **MPI_INT32_T** **MPI_INT64_T**	int8_t int16_t int32_t int64_t
MPI_UINT8_T **MPI_UINT16_T** **MPI_UINT32_T** **MPI_UINT64_T**	uint8_t uint16_t uint32_t uint64_t
MPI_BYTE	8 binary digits
MPI_PACKED	data packed or unpacked with MPI_Pack()/ MPI_Unpack

MPI Basic (Blocking) Receive



MPI_Send(buf, 2, MPI_INT, 1, …)

MPI_Recv(data, 2, MPI_INT, 0, …)

`MPI_RECV(start, count, datatype, source, tag, comm, status)`

- Waits until a matching (both **`source`** and **`tag`**) message is received from the system, and the buffer can be used
- **`source`** is rank in communicator specified by **`comm`**, or **`MPI_ANY_SOURCE`**
- **`tag`** is a tag to be matched or **`MPI_ANY_TAG`**
- receiving fewer than **`count`** occurrences of **`datatype`** is OK, but receiving more is an error
- **`status`** contains further information (e.g. size of message)

Retrieving Further Information

- **`Status`** is a data structure allocated in the user's program.
- In C:

```
int recvd_tag, recvd_from, recvd_count;
MPI_Status status;
MPI_Recv(..., MPI_ANY_SOURCE, MPI_ANY_TAG, ..., &status )
recvd_tag  = status.MPI_TAG;
recvd_from = status.MPI_SOURCE;
MPI_Get_count( &status, datatype, &recvd_count );
```

Not Quite So Simple as ensuring PAIRS of send/recv

Code/Parallel/mpi/send2.c

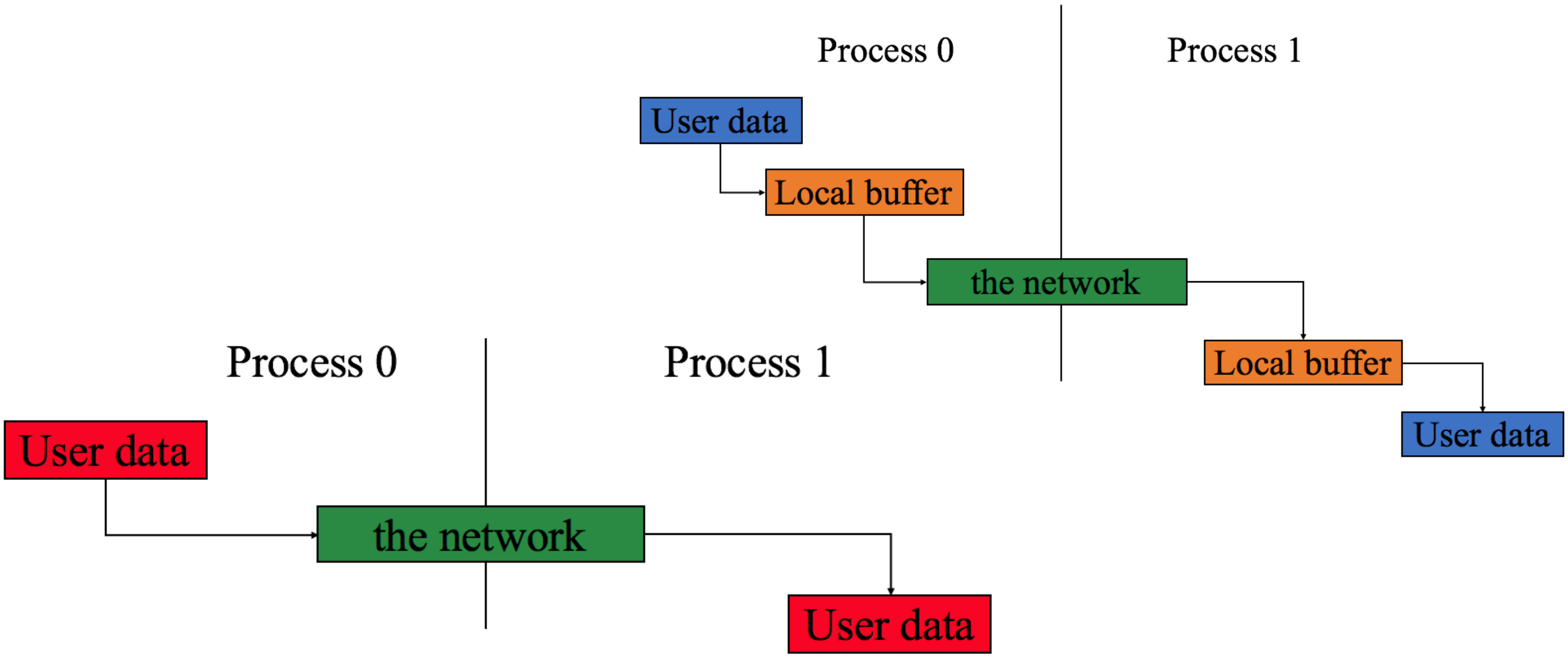
```
#include <mpi.h>
#include <stdio.h>
#define DATA_SIZE 1000
int main(int argc, char **argv) {
   int procID, numP;
   MPI_Status status;
   int buf[DATA_SIZE];

   MPI_Init( &argc, &argv );
   MPI_Comm_size( MPI_COMM_WORLD, &numP );
   MPI_Comm_rank( MPI_COMM_WORLD, &procID );

   If (procID == 0) {
      for (int i=0; i<DATA_SIZE; i++) buf[i]=1+i;
      MPI_Send(&buf, DATA_SIZE, MPI_INT, 1, 0, MPI_COMM_WORLD);
      MPI_Recv(&buf, DATA_SIZE, MPI_INT, 1, 0, MPI_COMM_WORLD, &status);
      printf("%d Received %d %d\n", procID, buf[0], buf[DATA_SIZE-1]);
   } else if (procID == 1) {
      for (int i=0; i<DATA_SIZE; i++) buf[i]=DATA_SIZE-i;
      MPI_Send(&buf, DATA_SIZE, MPI_INT, 0, 0, MPI_COMM_WORLD);
      MPI_Recv(&buf, DATA_SIZE, MPI_INT, 0, 0, MPI_COMM_WORLD, &status);
     printf("%d Received %d %d\n", procID, buf[0], buf[DATA_SIZE-1]);
   }
   MPI_Finalize();
   return 0;
}
```

```
mpi >mpicc send2.c; mpirun -n 2 ./a.out
Buffer Size: 1000
0 Received 1000 1
1 Received 1 1000
```

```
mpi >mpicc send2.c; mpirun -n 2 ./a.out
Buffer Size: 10000
^Cmpi >
mpi >
```

DEADLOCK .. PROGRAM HANGS .. WHY?

Why Deadlock? .. Where Does the Data Go



If large message & insufficient data, the send() must wait for buffer to clear through a recv()

source: CS267, Jim Demmell

Current Problem:

Process 0	Process 1
`Send(1)`	`Send(0)`
`Recv(1)`	`Recv(0)`

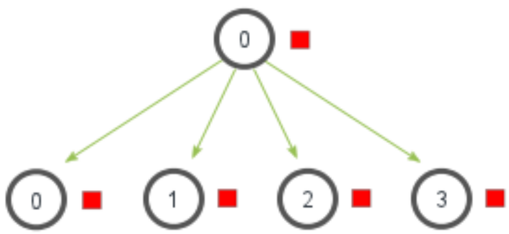
Could revise order
  this requires some code rewrite:

Process 0	Process 1
`Send(1)`	`Recv(0)`
`Recv(1)`	`Send(0)`

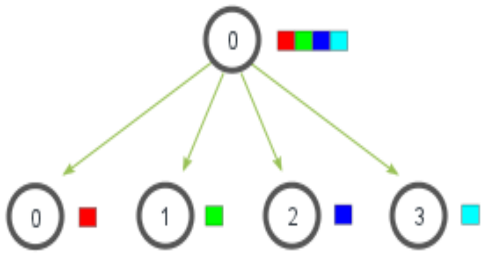
Alternatives use non-blocking sends.

Some Collective Functions

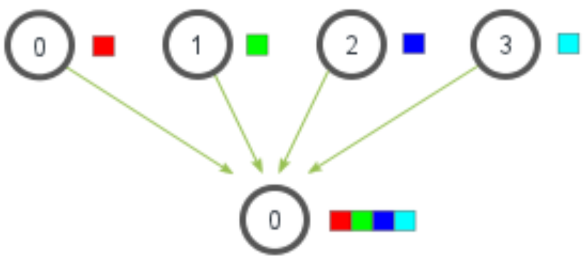
MPI_Bcast



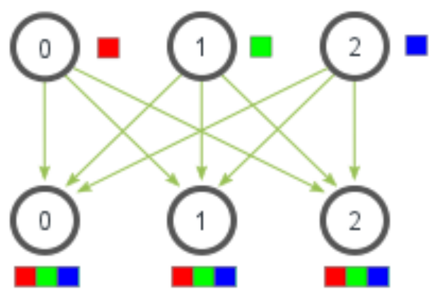
MPI_Scatter



MPI_Gather



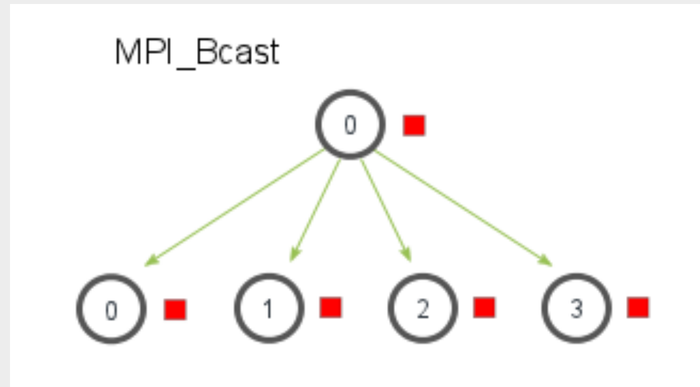
MPI_Allgather



Broadcast

Code/Parallel/mpi/bcast1.c

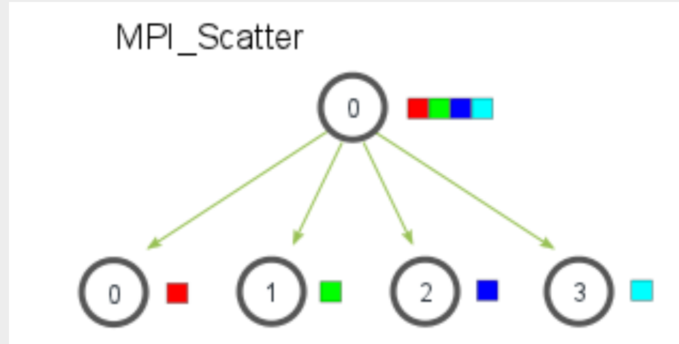
```
#include <mpi.h>
#include <stdio.h>

int main( int argc, char **argv) {
   int procID; buf[2];

    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &procID );

    if (procID == 0) {
       buf[0] = 12345;
       buf[1] = 67890;
    }

    MPI_Bcast(&buf, 2, MPI_INT, 0, MPI_COMM_WORLD);

    printf("Process %d data %d %d\n", procID, buf[0], buf[1]);

    MPI_Finalize();
    return 0;
}
```



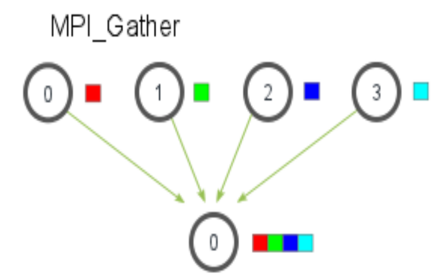
Scatter

Code/Parallel/mpi/scatter1.c

```
#include <mpi.h>
#include <stdio.h>
#include <stdlib.h>
#define LUMP 5
int main(int argc, char **argv) {
  int numP, procID;
  MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &numP);
  MPI_Comm_rank(MPI_COMM_WORLD, &procID);

 int *globalData=NULL;
 int localData[LUMP];

 if (procID == 0) { // malloc and fill in with data
  globalData = malloc(LUMP * numP * sizeof(int) );
  for (int i=0; i<LUMP*numP; i++)
   globalData[i] = i;
 }
 MPI_Scatter(globalData, LUMP, MPI_INT, &localData, LUMP, MPI_INT, 0, MPI_COMM_WORLD);
 printf("Processor %d has first: %d last %d\n", procID, localData[0], localData[LUMP-1]);

 if (procID == 0)  free(globalData);

 MPI_Finalize();
}
```



```
#include “mpi.h”
#include <stdio.h>
#define LUMP 5
int main(int argc, const charr **argv) {
     int procID, numP, ierr;
     MPI_Init(&argc, &argv);
     MPI_Comm_size(MPI_COMM_WORLD, &numP);
     MPI_Comm_rank(MPI_COMM_WORLD, &procID);

     int *globalData=NULL;
     int localData[LUMP];
     if (procID == 0) { // malloc global data array only on P0
        globalData = malloc(LUMP * numP * sizeof(int) );
     }
     for (int i=0; i<LUMP; i++)
          localData[i] = procID*10+i;

     MPI_Gather(localData, LUMP, MPI_INT, globalData, LUMP, MPI_INT, 0, MPI_COMM_WORLD);

     if (procID == 0) {
         for (int i=0; i<numP*LUMP; i++)
                printf("%d ", globalData[i]);
         printf("\n");
     }
     if (procID == 0) free(globalData);
     MPI_Finalize();
```



MPI can be simple

- Claim: most MPI applications can be written with only 6 functions (although which 6 may differ)

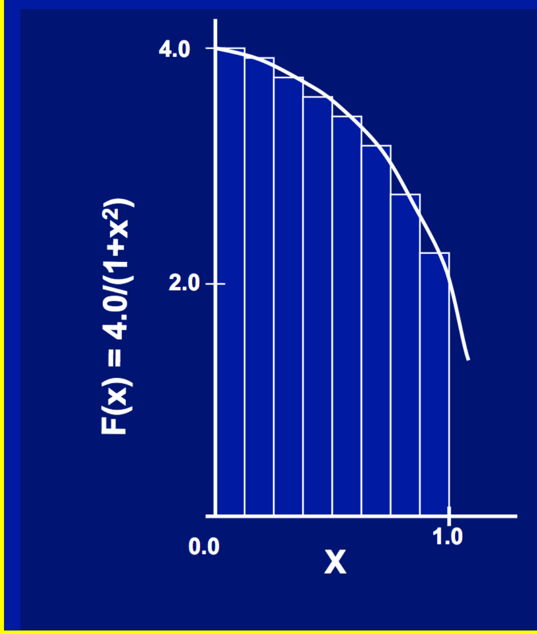
- Using point-to-point:
  - **MPI_INIT**
  - **MPI_FINALIZE**
  - **MPI_COMM_SIZE**
  - **MPI_COMM_RANK**
  - **MPI_SEND**
  - **MPI_RECEIVE**

- Using collectives:
  - **MPI_INIT**
  - **MPI_FINALIZE**
  - **MPI_COMM_SIZE**
  - **MPI_COMM_RANK**
  - **MPI_BCAST/MPI_SCATTER**
  - **MPI_GATHER/MPI_ALLGATHER**

- You may use more for convenience or performance

Exercise: Parallelize Compute PI using MPI

Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)} dx = \pi$$

We can approximate the integral as a sum of rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

```
#include <stdio>
static int long numSteps = 100000;
int main() {
  double pi = 0; double time=0;
  // your code
  for (int i=0; i<numSteps; i++) {
     // your code
  }
   // your code
  printf("PI = %f, duration: %f ms\n",pi, time);
  return 0;
}
```

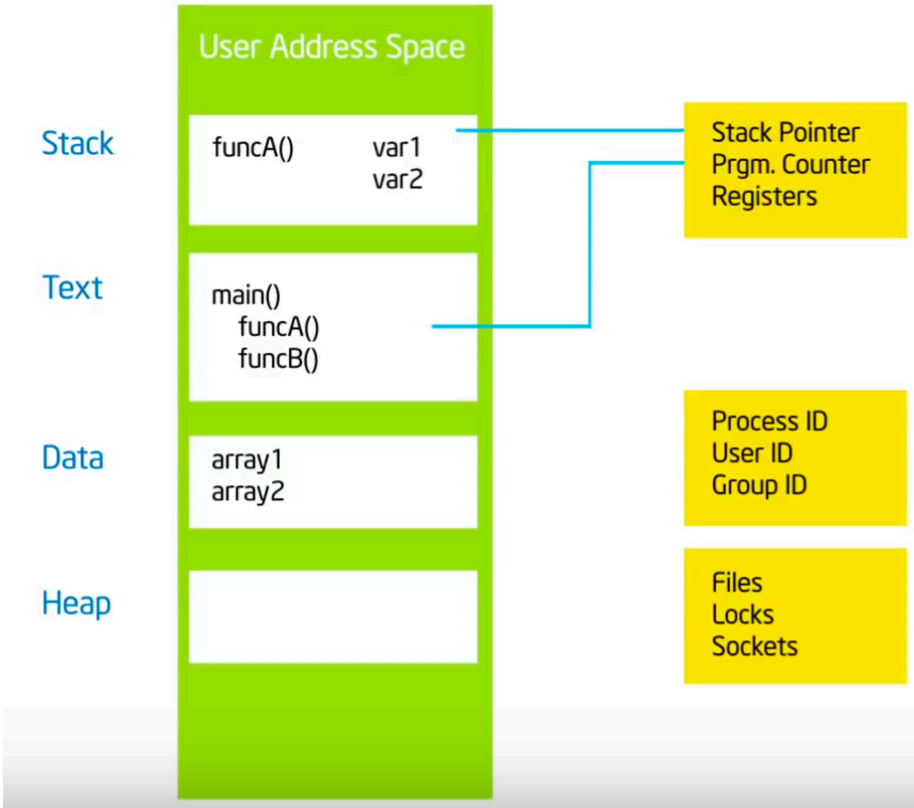
Source: UC Berkeley, Tim Mattson (Intel Corp), CS267 & elsewhere

Outline

- Parallel Machines & Parallel Machine Models
- Parallel Programming
  - Message Passing With MPI
  - Shared Memory Programming with OpenMP

Ignoring co-processors and GPUs

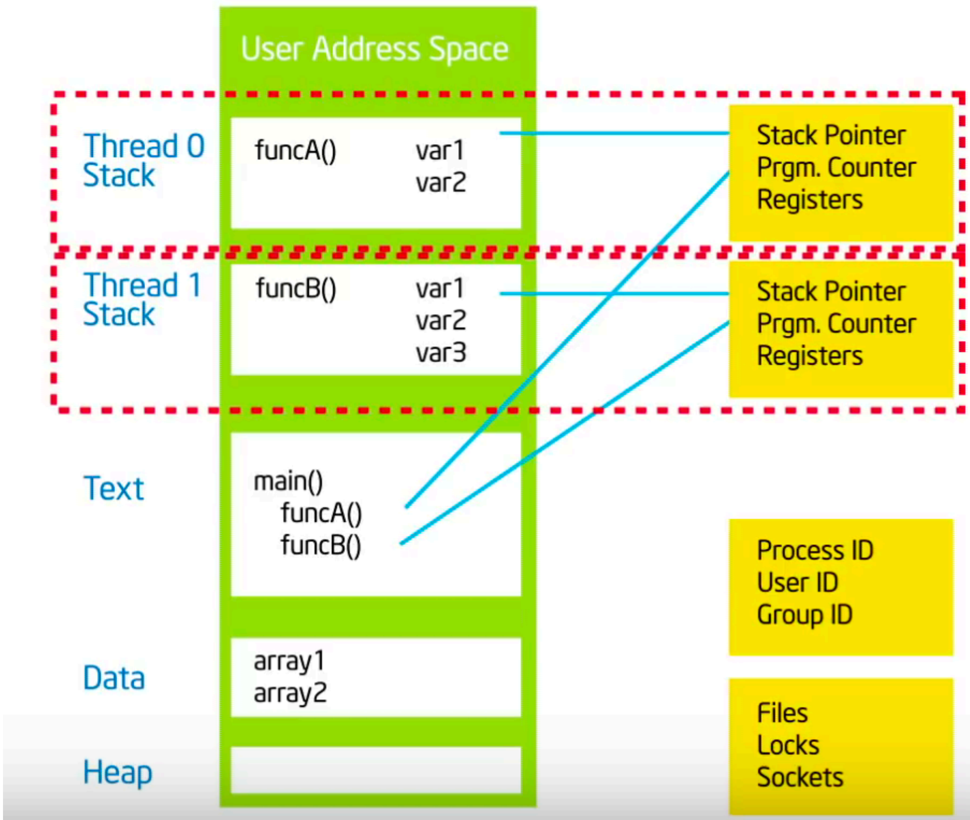
Process



Process:

* An instance of a program execution.
* The execution context of a running program... i.e. the resources associated with a program's execution.

Threads

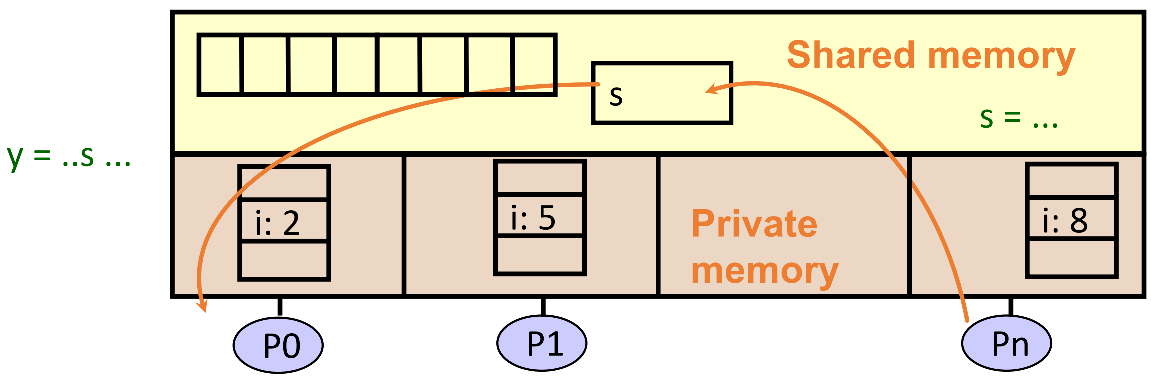


Threads:

* Threads are "light weight processes"
* Threads share Process state among multiple threads. This greatly reduces the cost of switching context.

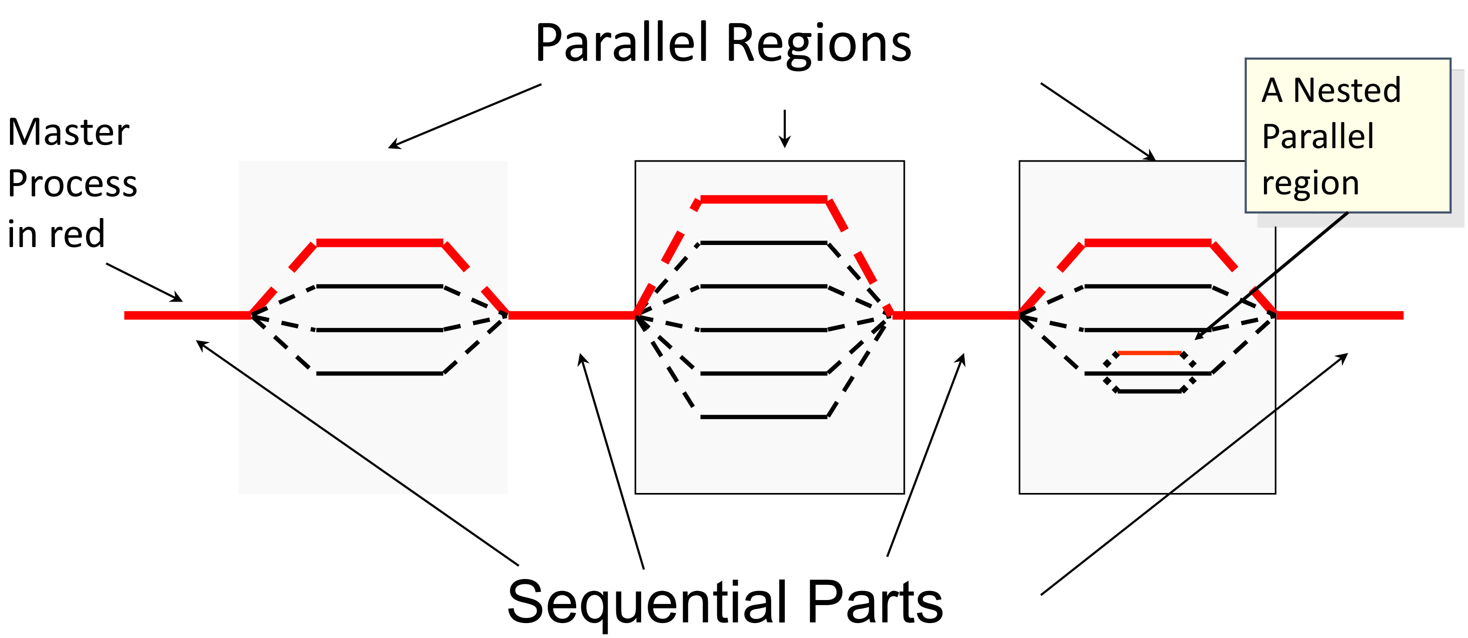
Threads

- Can be created dynamically, mid-execution, in some languages
- Each thread has a set of private variables, e.g., local stack variables
- Also a set of shared variables, e.g., static variables, shared common blocks, or global heap.
  - Threads communicate implicitly by writing and reading shared variables.
  - Threads coordinate by synchronizing on shared variables



Programming Model for Threads

- Master Process spawns a team of threads as needed.
- Parallelism added incrementally until performance goals are met, i.e., the sequential program evolves into a parallel program.



- OpenMP provides multi-threaded capabilities to C, C++ and Fortran Programs
- In a threaded environment, threads communicate by sharing data
- Unintended sharing of data causes **race conditions**
- **Race Condition**: program output is different every time you run the program, a consequence of the threads being scheduled differently
- OpenMP provides constructs to control what blocks of code are run in parallel and also constructs for providing access to shared data using synchronization
- Synchronization has overhead consequences, you have to minimize them to get good speedup.

- Mostly Set of Compiler directives (#pragma) applying to structured block

```
#pragma omp parallel
```

- Some runtime library calls

```
omp_num_threads(4);
```

- Being compiler directives, they are built into most compilers .
- Just have to activate it when compiling

```
gcc hello.c -fopenmp
```

```
icc hello.c /Qopenmp
```

Hello World

Code/Parallel/openmp/hello1.c

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

int main( int argc, char *argv[] )
{
  #pragma omp parallel
  {
     int id = omp_get_thread_num();
     int numP = omp_get_num_threads();
     printf("Hello World, I am  %d of %d\n",id,numP);
  }
  return 0;
}
```

```
openmp >gcc-7.2 hello1.c -fopenmp; ./a.out
Hello World, I am  0 of 4
Hello World, I am  3 of 4
Hello World, I am  1 of 4
Hello World, I am  2 of 4
openmp >
```

```
openmp >export env OMP_NUM_THREADS=2
openmp >./a.out
Hello World, I am  0 of 2
Hello World, I am  1 of 2
openmp >
```

Hello World – changing num threads

Code/Parallel/openmp/hello2.c

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

int main( int argc, char *argv[] )
{
  omp_set_num_threads(2);
  #pragma omp parallel
   {
      int id = omp_get_thread_num();
      int numP = omp_get_num_threads();
      printf("Hello World, I am  %d of
   }
  return 0;
}
```

Runtime function to request a certain number of threads

Runtime function to return actual number of threads in the team

Code/Parallel/openmp/hello3.c

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

int main( int argc, char *argv[] )
{
#pragma omp parallel num_threads(2)
   {
         int id = omp_get_thread_num();
         int numP = omp_get_num_threads();
         printf("Hello World, I am  %d of %d\n",id,numP);
   }
  return 0;
}
```

Different # threads in different blocks

Code/Parallel/openmp/hello4.c

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

int main(int argc, const char **argv) {

#pragma omp parallel num_threads(2)
  {
    int id = omp_get_thread_num();
    int numP = omp_get_num_threads();
    printf("Hello World, I am  %d of %d\n",id,numP);
  }
#pragma omp parallel num_threads(4)
  {
    int id = omp_get_thread_num();
    int numP = omp_get_num_threads();
    printf("Hello World Again, I am  %d of %d\n",id,numP);
  }
  return(0);
}
```

```
openmp >gcc-7.2 hello4.c -fopenmp; ./a.out
Hello World, I am  0 of 2
Hello World, I am  1 of 2
Hello World Again, I am  1 of 4
Hello World Again, I am  2 of 4
Hello World Again, I am  3 of 4
Hello World Again, I am  0 of 4
openmp >
```

Hello World – shared variables & RACE CONDITIONS

Code/Parallel/openmp/hello5.c

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

int main(int argc, const char **argv) {

 int id, numP;

#pragma omp parallel num_threads(4)
  {
    id = omp_get_thread_num();
    numP = omp_get_num_threads();
    printf("Hello World from %d of %d th
  }

  return(0);
}
```

```
openmp >gcc-7.2 hello5.c -fopenmp; ./a.out
Hello World from 1 of 4 threads
Hello World from 2 of 4 threads
Hello World from 3 of 4 threads
Hello World from 0 of 4 threads
openmp >gcc-7.2 hello5.c -fopenmp; ./a.out
Hello World from 0 of 4 threads
Hello World from 3 of 4 threads
Hello World from 2 of 4 threads
Hello World from 1 of 4 threads
openmp >gcc-7.2 hello5.c -fopenmp; ./a.out
Hello World from 0 of 4 threads
Hello World from 0 of 4 threads
Hello World from 2 of 4 threads
Hello World from 3 of 4 threads
```

What We Want Threads To DO

- Work Independently With Controlled Access at times to Shared Data
  - Parallel Tasks Constructs
    - omp parallel
    - Opr for
  - Shared Data

Simple Vector Sum

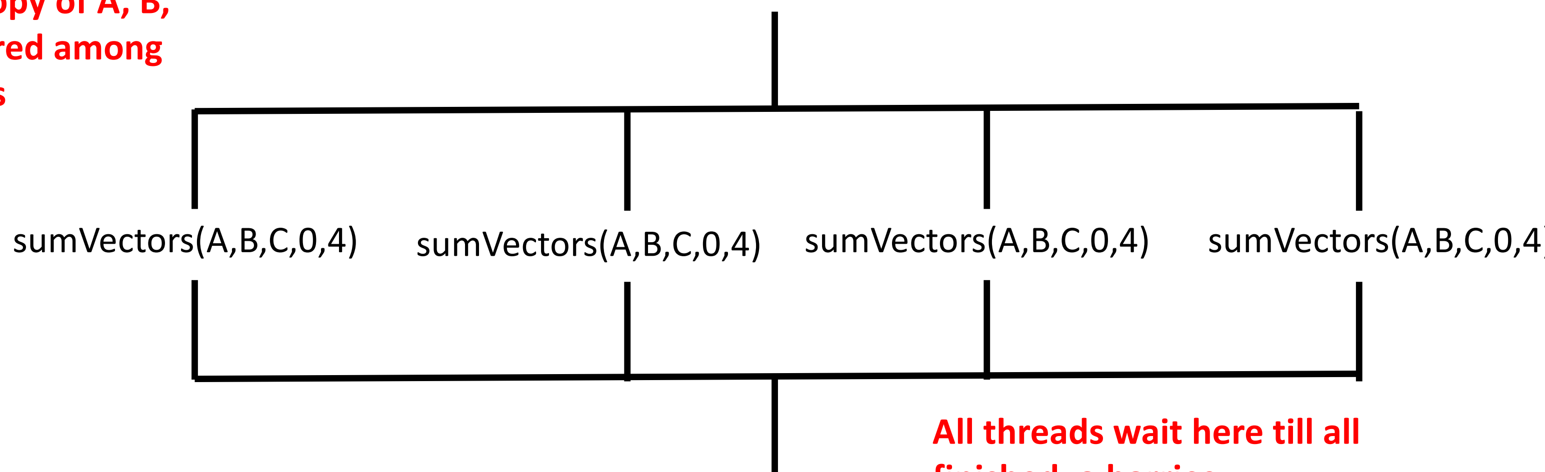
Code/Parallel/openmp/sum1.c

```c
#include <omp.h>
#include <stdio.h>
#define DATA_SIZE 10000

void sumVectors(int N, double *A, double *B, double *C, int tid, int numT);
I
nt main(int argc, const char **argv) {
  double a[DATA_SIZE], b[DATA_SIZE], c[DATA_SIZE];
  int num;
  for (int i=0; i<DATA_SIZE; i++) { a[i] = i+1; b[i] = i+1; }
  double tdata = omp_get_wtime();
#pragma omp parallel
  {
    int tid = omp_get_thread_num();
    int numT = omp_get_num_threads();
    num = numT;
    sumVectors(DATA_SIZE, a, b, c, tid, numT);
  }
  tdata = omp_get_wtime() - tdata;
  printf("first %f last %f in time %f using %d threads\n
  return 0;
}
```

```c
void sumVectors(int N, double *A, double *B, double *C, int tid, int numT)
  // determine start & end for each thread
  int start =   tid * N / numT;
  int end = (tid+1) * N / numT;
  if (tid == numT-1)
    end = N;


  // do the vector sum for threads bounds
  for(int i=start; i<end; i++) {
    C[i] = A[i]+B[i];
  }
}
```

Implicit Barrier in Code

A single copy of A, B, and C shared among all threads



All threads wait here till all finished, a barries.

```
openmp >export env OMP_NUM_THREADS=1; ./a.out
first 2.000000 last 200000.000000 in time 0.000902 using 1 threads
openmp >export env OMP_NUM_THREADS=2; ./a.out
first 2.000000 last 200000.000000 in time 0.000678 using 2 threads
openmp >export env OMP_NUM_THREADS=4; ./a.out
first 2.000000 last 200000.000000 in time 0.000652 using 4 threads
openmp >export env OMP_NUM_THREADS=8; ./a.out
first 2.000000 last 200000.000000 in time 0.000693 using 8 threads
```

The for is such an obvious candidate for threads:

Code/Parallel/openmp/sum2.c

```
#include <omp.h>
#include <stdio.h>
#include <math.h>
#define DATA_SIZE 10000

int main(int argc, const char **argv) {
   double a[DATA_SIZE], b[DATA_SIZE], c[DATA_SIZE];
   for (int i=0; i<DATA_SIZE; i++) { a[i] = i+1; b[i] = i+1; }
   double tdata = omp_get_wtime();
#pragma omp parallel
   {
    #pragma omp for
    for (int i=0; i<DATA_SIZE; i++)
        c[i] = a[i]+b[i];
  }
  tdata = omp_get_wtime() - tdata;
  printf("first %f last %f in time %f \n",c[0], c[DATA_SIZE-1], tdata);
  return 0;
}
```

Code/Parallel/openmp/sum3.c

```
#pragma omp parallel for
     for (int i=0; i<DATA_SIZE; i++)
      c[i] = a[i]+b[i];
```

How About Dot Product?

Code/Parallel/openmp/dot1.c

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#define DATA_SIZE 10000

int main(int argc, const char **argv) {
  int nThreads = 0;
  double dot = 0, a[DATA_SIZE], sum[64];
  for (int i=0; i<DATA_SIZE; i++) a[i] = i+1;
  for (int i=0; i<64; i++) sum[i] = 0;

#pragma omp parallel
  {
    int tid = omp_get_thread_num();
    int numT = omp_get_num_threads();
    if (tid == 0)  nThreads = numT;
    for (int i=tid; i<DATA_SIZE; i+= numT)
      sum[tid] += a[i]*a[i];
  }
  for (int i=0; i<nThreads; i++)
      dot += sum[i];
  dot = sqrt(dot);
  printf("dot %f\n", dot);
  return 0;
}
```

Code/Parallel/openmp/dot2.c

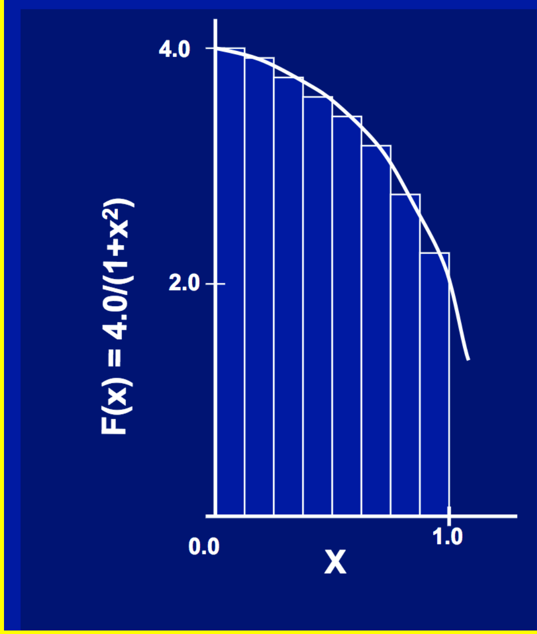
```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#define DATA_SIZE 10000
#define PAD 64

int main(int argc, const char **argv) {
 int nThreads = 0;
 double dot = 0, a[DATA_SIZE], sum[64][PAD];
 for (int i=0; i<DATA_SIZE; i++) a[i] = i+1;
 for (int i=0; i<64; i++) sum[i][0]= 0;

#pragma omp parallel
 {
  int tid = omp_get_thread_num();
  int numT = omp_get_num_threads();
  if (tid == 0)  nThreads = numT;
  for (int i=tid; i<DATA_SIZE; i+= numT)
   sum[tid][0]+= a[i]*a[i];
 }
 for (int i=0; i<nThreads; i++)
     dot += sum[i][0];
 dot = sqrt(dot);
 printf("dot %f \n", dot);
 return 0;
```

Code/Parallel/openmp/dot3.c

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#define DATA_SIZE 10000

int main(int argc, const char **argv) {
  double dot = 0;
  double a[DATA_SIZE];
  for (int i=0; i<DATA_SIZE; i++) a[i] = i+1;

#pragma omp parallel
  {
    int tid = omp_get_thread_num();
    int numT = omp_get_num_threads();
    double sum = 0.;
    for (int i=tid; i<DATA_SIZE; i+= numT)
      sum += a[i]*a[i];
#pragma omp_critical
    dot += sum;
  }
  dot = sqrt(dot);
    printf("dot %f  \n", dot);
  return 0;
}
```

Exercise: Parallelize Compute PI using OpenMP

Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx = \pi$$

We can approximate the integral as a sum of rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

```
#include <stdio>
static int long numSteps = 100000;
int main() {
  double pi = 0; double time=0;
  // your code
  for (int i=0; i<numSteps; i++) {
     // your code
  }
   // your code
  printf(“PI = %f, duration: %f ms\n”,pi, time);
  return 0;
}
```

Source: UC Berkeley, Tim Mattson (Intel Corp), CS267 & elsewhere