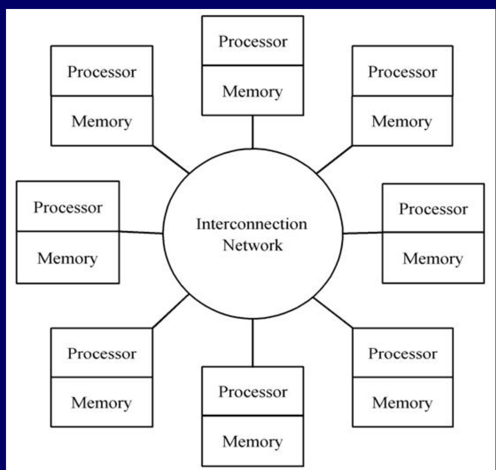
Chapter 4

Message-Passing Programming

Message-passing Model



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Characteristics of Processes

- Number is specified at start-up time
- Remains constant throughout the execution of program
- All execute same program
- Each has unique ID number
- Alternately performs computations and communicates
- Passes messages both to communicate and to synchronize with each other.

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Features of Message-passing Model

- Runs well on a variety of MIMD architectures.
  - Natural fit for multicomputers
- Execute on multiprocessors by using shared variables as message buffers
  - Model's distinction between faster, directly accessible local memory and slower, indirectly accessible remote memory encourages designing algorithms that maximize local computation and minimize communications
- Simplifies debugging
  - Easier than debugging shared-variable programs

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Message Passing Interface History

- Late 1980s: vendors had unique libraries
  – Usually FORTRAN or C augmented with functions calls that supported message-passing
- 1989: Parallel Virtual Machine (PVM) developed at Oak Ridge National Lab
  – Supported execution of parallel programs across a heterogeneous group of parallel and serial computers
- 1992: Work on MPI standard began
  – Chose best features of earlier message passing languages
  – Not for heterogeneous setting – i.e., homogeneous
- Today: MPI is dominant message passing library standard

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What We Will Assume

- The programming paradigm typically used with MPI is called a SPMD paradigm (single program multiple data)
- Consequently, the same program runs on each processor
- The effect of running different programs is achieved by branches within the source code where different processors execute different branches

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Circuit Satisfiability Problem

Given a circuit containing AND, OR, and NOT gates, find if there are any combinations of input 0/1 values for which the circuit output is the value 1

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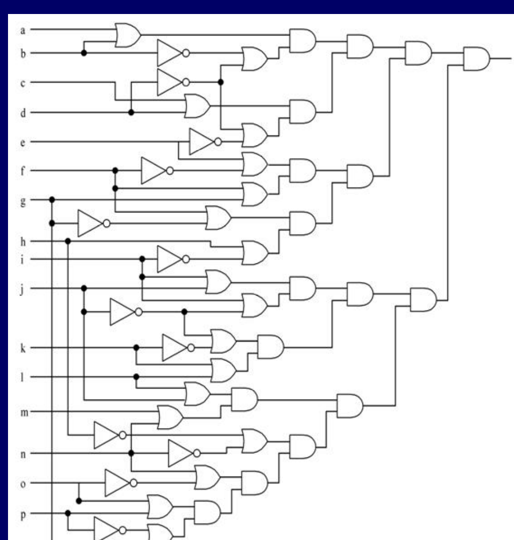
Circuit Satisfiability



Note: The input consists of variables a, b, ..., p

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Solution Method

- Circuit satisfiability is NP-complete
  - What combinations of input values will the circuit output the value 1
- We seek all solutions
  - Not a “Yes/No” answer about solution existing
- We find solutions using exhaustive search
  - 16 inputs $\Rightarrow 2^{16} = 65{,}536$ combinations to test
- Functional decomposition natural here

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Embarrassingly Parallel

- The problem solution falls easily into the definition of tasks that do now need to interact with each other, then the problem is said to be embarrassingly parallel
- H.J. Siegel calls this situation instead pleasingly parallel and many professionals use this term

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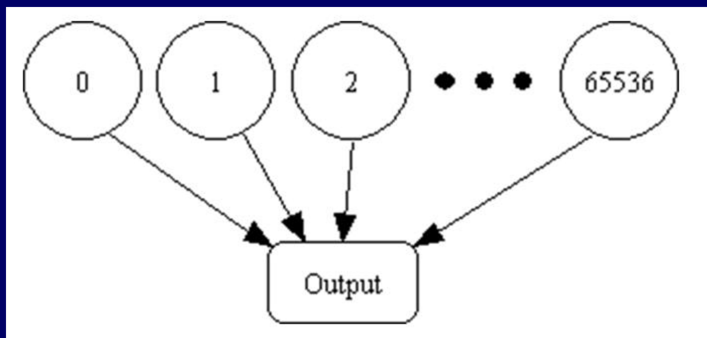
Partitioning: Functional Decomposition



- Embarrassingly (or pleasingly) parallel

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Agglomeration and Mapping

- Properties of parallel algorithm
  - Fixed number of tasks
  - No communications between tasks
  - Time needed per task is variable
    - Bit sequences for most tasks do not satisfy circuit
    - Some bit sequences are quickly seen unsatisfiable
    - Other bit sequences may take more time
- Consult mapping strategy decision tree
  - Map tasks to processors in a cyclic fashion

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Cyclic (interleaved) Allocation

- Assume *p* processes
- Each process gets every p^{th} piece of work
  - i.e., each piece of work, I, is assigned to process k where k = i mod 5

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Questions to Consider

- Assume *n* pieces of work, *p* processes, and cyclic allocation
- What is the maximum pieces of work any process has?
- What is the minimum pieces of work any process has?
- How many processes have the most pieces of work?

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Summary of Program Design

- Program considers all 65,536 combinations of 16 boolean inputs
- Combinations allocated in cyclic fashion to processes
- Each process examines each of its combinations
- If it finds a satisfiable combination, it prints this combination

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MPI Program for Circuit Satisfiability

- Each active MPI process executes its own copy of the program
- Each process has its own copy of all the variables declared in the program, including:
  - External variables declared outside of any function
  - Automatic variables declared inside a function

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C Code Include Files

```
#include <mpi.h> /* MPI header file */
#include <stdio.h> /* Standard C I/O
            header file */
```

- These appear at the beginning of the program file.
- The file name will have a .c as these are C programs, augmented with the MPI library.

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Header for C Function Main (Local Variables)

```
int main (int argc, char *argv[]) {
  int i;  /* loop index */
  int id; /* Process ID number */
  int p;  /* Number of processes */
  void check_circuit (int, int);
```

- Include argc and argv: they are needed to initialize MPI
- The i, id, and p are local (or automatic) variables.
- One copy of every variable is needed for each process running this program
- If there are p processes, then the ID numbers start at 0 and end at p -1.

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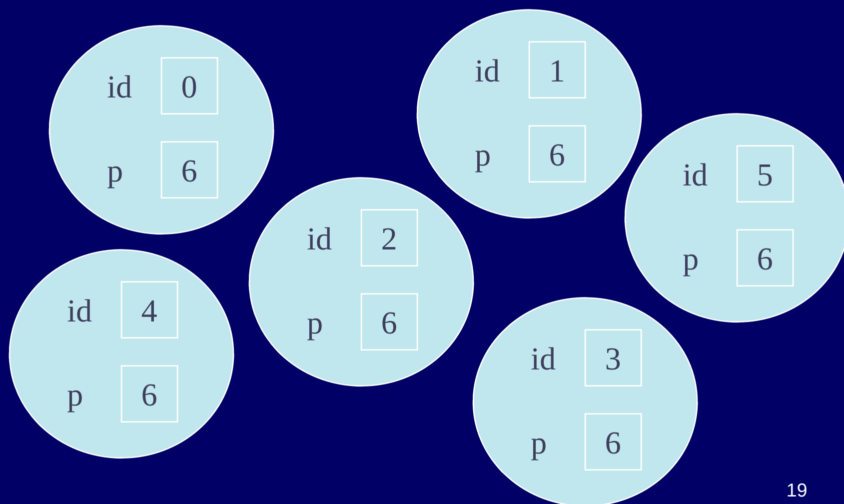
Replication of Automatic Variables (Shown for id and p only)



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Initialize MPI

MPI_Init (&argc, &argv);

- First MPI function called by each process
- Not necessarily first executable statement
- In fact, call need not be located in main
- But, it must be called before any other MPI function is invoked
- Allows system to do any necessary setup to handle calls to MPI library

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MPI Identifiers

- All MPI identifiers (including function identifiers) begin with the prefix “MPI_”
- The next character is a capital letter followed by a series of lowercase letters and underscores.
- Example: MPI_Init
- All MPI constants are strings of capital letters and underscores beginning with MPI_
- Recall C is case-sensitive as it was developed in a UNIX environment.

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Communicators

- When MPI is initialized, every active process becomes a member of a communicator called MPI_COMM_WORLD.
- Communicator: Opaque object that provides the message-passing environment for processes
- MPI_COMM_WORLD
  - This is the default communicator
  - It includes all processes automatically
  - For most programs, this is sufficient
- It is possible to create new communicators
  - These are needed if you need to partition the processes into independent communicating groups

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Communicators (cont.)

- Processes within a communicator are ordered
- The rank of a process is its position in the overall order
- In a communicator with p processes, each process has a unique rank, which we often think of as an ID number, between 0 and p-1
- A process may use its rank to determine the portion of a computation or portion of a dataset that it is responsible for

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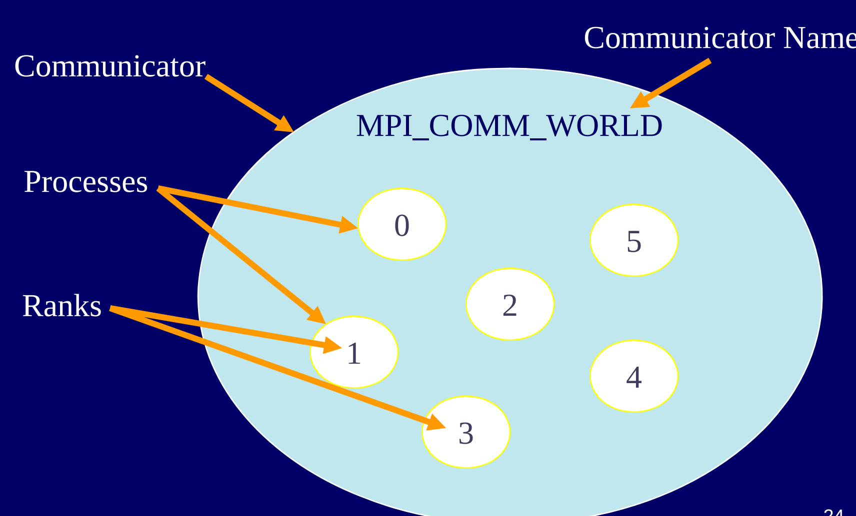
Communicator



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Determine Process Rank

MPI_Comm_rank (MPI_COMM_WORLD, &id);

- A process can call this function to determine its rank with a communicator
- The first argument is the communicator name
- The process rank (in range 0, 1, …, *p*-1) is returned through second argument

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Determine Number of Processes

MPI_Comm_size (MPI_COMM_WORLD, &p);

- A process can call this MPI function
- First argument is the communicator name
- This call determines the number of processes
- The number of processes is returned through the second argument

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What about External Variables or Global Variables?

```
int total;

int main (int argc, char *argv[]) {
   int i;
   int id;
   int p;
   …
```

- Try to avoid them
  - They can cause major debugging problems. However, sometimes they are needed

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Cyclic Allocation of Work

```
for (i = id; i < 65536; i += p)
   check_circuit (id, i);
```

- Now that the MPI process knows its rank and the total number of processes, it may check its share of the 65,536 possible inputs to the circuit
- For example, if there are 5 processes, process id = 3 checks i = id = 3

  i += 5 = 8

  i += 5 = 13 etc.
- Parallelism is in the outside function check_circuit
- It can be an ordinary, sequential function

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After the Loop Completes

```
printf ("Process %d is done\n", id);
fflush (stdout);
```

- After the process completes the loop, its work is finished and it prints a message that it is done
- It then flushes the output buffer to ensure the eventual appearance of the message on standard output even if the parallel program crashes
- Put an fflush command after each printf command
- The printf is the standard output command for C. The %d says integer data is to be output and the data appears after the comma – i.e. insert the id number in its place in the text

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Shutting Down MPI

```
MPI_Finalize();
return 0;
```

- Call after all other MPI library calls
- Allows system to free up MPI resources
- Return code:
  - 0 means the code ran to completion
  - 1 is used to signal an error has occurred

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MPI Program for Circuit Satisfiability (Main, version 1)

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

int main (int argc, char *argv[])
{  int i;
   int id;
   int p;
   void check_circuit (int, int);
   MPI_Init (&argc, &argv);
   MPI_Comm_rank (MPI_COMM_WORLD, &id);
   MPI_Comm_size (MPI_COMM_WORLD, &p);
   for (i = id; i < 65536; i += p)
      check_circuit (id, i);
   printf ("Process %d is done\n", id);
   fflush (stdout);
   MPI_Finalize();
   return 0;
}
```

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Enhancing the Program

- We want to find the total number of solutions
- A single process can maintain an integer variable that holds the number of solutions it finds, but we want the processors to cooperate to compute the global sum of the values
- Said another way, we want to incorporate a sum-reduction into program. This will require message passing
- Reduction is a collective communication –
  - i.e. a communication operation in which a group of processes works together to distribute or gather together a set of one or more values

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Modifications

- Modify function check_circuit
  - Return 1 if the circuit is satisfiable with the input combination
  - Return 0 otherwise
- Each process keeps local count of satisfiable circuits it has found
- We perform reduction after the 'for' loop

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Modifications

- In function main we need to add two variables:
  - An integer solutions – This keeps track of solutions for this process
  - An integer global_solutions – This is used only by process 0 to store the grand total of the count values from the other processes
  - Process 0 is also responsible for printing the total count at the end
  - Remember that each process runs the same program, but if statements and various assignment statements dictate which code a process executes

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New Declarations and Code

```
int solutions;        /* Local sum */
int global_solutions; /* Global sum */
int check_circuit (int, int);

solutions = 0;
for (i = id; i < 65536; i += p)
   solutions += check_circuit (id, i);
```

This loop calculates the total number of solutions for each individual process. We now have to collect the individual values with a reduction operation,

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The Reduction

- After a process completes its work, it is ready to participate in the reduction operation.
- MPI provides a function, MPI_Reduce, to perform one or more reduction operation on values submitted by all the processes in a communicator.
- The next slide shows the header for this function and the parameters we will use.
- Most of the parameters are self-explanatory.

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Header for **MPI_Reduce()**

```
int MPI_Reduce (
  void *operand, /* addr of 1st reduction element */
  void *result,  /* addr of 1st reduction result */
  int  count,    /* reductions to perform */
  MPI_Datatype type, /* type of elements */
  MPI_Op operator,  /* reduction operator */
  int root,  /* process getting result(s) */
  MPI_Comm comm /* communicator */
)
```

Our call will be:

```
MPI_Reduce (&solutions, &global_solutions, 1,
        MPI_INT, MPI_SUM, 0,MPI_COMM_WORLD);
```

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MPI_Datatype Options

- MPI_CHAR
- MPI_DOUBLE
- MPI_FLOAT
- MPI_INT
- MPI_LONG
- MPI_LONG_DOUBLE
- MPI_SHORT
- MPI_UNSIGNED_CHAR
- MPI_UNSIGNED
- MPI_UNSIGNED_LONG
- MPI_UNSIGNED_SHORT

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MPI_Op Options for Reduce

- MPI_BAND B = bitwise
- MPI_BOR
- MPI_BXOR
- MPI_LAND L = logical
- MPI_LOR
- MPI_LXOR
- MPI_MAX
- MPI_MAXLOC Max and location of max
- MPI_MIN
- MPI_MINLOC
- MPI_PROD
- MPI_SUM

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Our Call to **MPI_Reduce()**

```
MPI_Reduce (&solutions,
            &global_solutions,
            1,
            MPI_INT,
            MPI_SUM,
            0,
            MPI_COMM_WORLD);
```

If count > 1, list elements for reduction are found in contiguous memory.

Only process 0 will get the result

After this call, process 0 has in **global_solutions** the sum of all of the other processes **solution**s. We then conditionally execute the print statement:

if (id==0) printf ("There are %d different solutions\n", global_solutions);

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Version 2 of Circuit Satisfiability

- The code for main is on page 105 and incorporates all the changes we made plus we make trivial changes for check_circuit to return the values of 1 or 0.
- First, in main, the declaration must show an integer being returned instead of a void function:

    int check_circuit(int, int);

and in the function we need to return a 1 if a solution is found and a 0 otherwise.

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Main Program, Circuit Satisfiability, Version 2

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

int main (int argc, char *argv[]) {
  int count;          /* Solutions found by this proc */
  int global_count;   /* Total number of solutions */
  int i;
  int id;             /* Process rank */
  int p;              /* Number of processes */
  int check_circuit (int, int);

  MPI_Init (&argc, &argv);
  MPI_Comm_rank (MPI_COMM_WORLD, &id);
  MPI_Comm_size (MPI_COMM_WORLD, &p);

  count = 0;
  for (i = id; i < 65536; i += p)
    count += check_circuit (id, i);

  MPI_Reduce (&count, &global_count, 1, MPI_INT, MPI_SUM, 0,
    MPI_COMM_WORLD);
  printf ("Process %d is done\n", id);
  fflush (stdout);
  MPI_Finalize();
  if (!id) printf ("There are %d different solutions\n",  global_count);
  return 0;}
```

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Some Cautions About Thinking "Right" About MPI Programming

- The printf statement must be a conditional because only process 0 has the total sum at the end.
- That variable is undefined for the other processes.
- In fact, even if all of them had a valid value, you don't want all of them printing the same message over and over for 9 times!

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Some Cautions About Thinking "Right" about MPI Programming

- Every process in the communicator must execute the MPI_Reduce.
- Processes enter the reduction by volunteering the value – they cannot be called by process 0.
- If you fail to have all process in a communicator call the MPI_Reduce, the program will hang at the point the function is executed,

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Execution of Second Program with 3 Processes

0) 0110111110011001
0) 1110111111011001
1) 1110111110011001
1) 1010111111011001
2) 1010111110011001
2) 0110111111011001
2) 1110111110111001
1) 0110111110111001
0) 1010111110111001
Process 1 is done
Process 2 is done
Process 0 is done
There are 9 different solutions

Compare this with slide 42.

The same solutions are found, but output order is different,

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Benchmarking

Measuring the Benefit for Parallel Execution

Benchmarking – What is It?

- Benchmarking: Uses a collection of runs to test how efficient various programs (or machines) are.
- Usually some kind of counting function is used to count various operations.
- Complexity analysis provides a means of evaluating how good an algorithm is
  - Focuses on the asymptotic behavior of algorithm as size of date increases.
  - Does not require you to examine a specific implementation.
- Once you decide to use benchmarking, you must first have a program as well as a machine on which you can run.
- There are advantages and disadvantages to both types of analysis.

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Benchmarking

- Determining the complexity analysis for ASC algorithms is done as with sequential algorithms since all PEs are working in lockstep.
- Thus, as with sequential algorithms, you basically have to look at your loops to judge complexity.
- Recall that ASC has a performance monitor that counts the number of scalar operations performed and the number of parallel operations performed.
- Then, given data about a specific machine, run times can be estimated.

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Benchmarking with MPI

- When running on a parallel machine that is not synchronized as a SIMD is, we have more difficulties in seeing the effect of parallelism by looking at the code.
- Of course, we can always, in that situation, use the wall clock provided the machine is not being shared with anyone else – background jobs can completely louse up your perceptions.
- As with the ASC, we want to exclude some things from our timings:

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Benchmarking a Program

- We will use several MPI-supplied functions:
- double MPI_Wtime (void)
  - current time
  - By placing a pair of calls to this function, one before code we wish to time and one after that code, the difference will give us the execution time.
- double MPI_Wtick (void)
  - timer resolution
  - Provides the precision of the result returned by MPI_Wtime.
- int MPI_Barrier (MPI_Comm comm)
  - barrier synchronization

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Barrier Synchronization

- Usually encounter this term first in operating systems classes.
- A barrier is a point where no process can proceed beyond it until all processes have reached it.
- A barrier ensures that all processes are going into the covered section of code at more or less the same time.
- MPI processes theoretically start executing at the same time, but in reality they don't.
- That can throw off timings significantly.
- In the second version, the call to reduce requires all processes to participate.
- Processes that execute early may wait around a lot before stragglers catch up. These processes would report significantly higher computation times than the latecomers.

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Barrier Synchronization

- In operating systems you learn how barriers can be implemented in either hardware or software.
- In MPI, a function is provided that implements a barrier.
- All processes in the specified communicator wait at the barrier point.

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Benchmarking Code

```
double elapsed_time; /* local in main */
…
MPI_Init (&argc, &argv);
MPI_Barrier (MPI_COMM_WORLD); /* wait */
elapsed_time = - MPI_Wtime();
…             /* timing all in here */

MPI_Reduce (…);  /* Call to Reduce */
elapsed_time += MPI_Wtime();/* stop timer */
```

As we don't want to count I/O, comment out the printf and fflush

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