Parallel Programming
in C with MPI and OpenMP

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Chapter 4

Message-Passing Programming

Learning Objectives

- Understanding how MPI programs execute
- Familiarity with fundamental MPI functions

Outline

- Message-passing model
- Message Passing Interface (MPI)
- Coding MPI programs
- Compiling MPI programs
- Running MPI programs
- Benchmarking MPI programs

Task/Channel vs. Message-passing

Task/Channel	**Message-passing**
Task	Process
Explicit channels	Any-to-any communication

Processes

- Number is specified at start-up time
- Remains constant throughout execution of program
- All execute same program
- Each has unique ID number
- Alternately performs computations and communicates

Advantages of Message-passing Model

- Gives programmer ability to manage the memory hierarchy
- Portability to many architectures
- Easier to create a deterministic program
- Simplifies debugging

The Message Passing Interface

- Late 1980s: vendors had unique libraries
- 1989: Parallel Virtual Machine (PVM) developed at Oak Ridge National Lab
- 1992: Work on MPI standard begun
- 1994: Version 1.0 of MPI standard
- 1997: Version 2.0 of MPI standard
- Today: MPI is dominant message passing library standard

Solution Method

- Circuit satisfiability is NP-complete
- No known algorithms to solve in polynomial time
- We seek all solutions
- We find through exhaustive search
- 16 inputs $\Rightarrow$ 65,536 combinations to test

Agglomeration and Mapping

- Properties of parallel algorithm
  - Fixed number of tasks
  - No communications between tasks
  - Time needed per task is variable
- Consult mapping strategy decision tree
  - Map tasks to processors in a cyclic fashion

Cyclic (interleaved) Allocation

- Assume *p* processes
- Each process gets every *p*th piece of work
- Example: 5 processes and 12 pieces of work
  - P_0: 0, 5, 10
  - P_1: 1, 6, 11
  - P_2: 2, 7
  - P_3: 3, 8
  - P_4: 4, 9

Pop Quiz

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

Summary of Program Design

- Program will consider 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 will print it

Include Files

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

- MPI header file

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

- Standard I/O header file

Local Variables

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

- Include **argc** and **argv**: they are needed to initialize MPI
- One copy of every variable for each process running this program

Initialize MPI

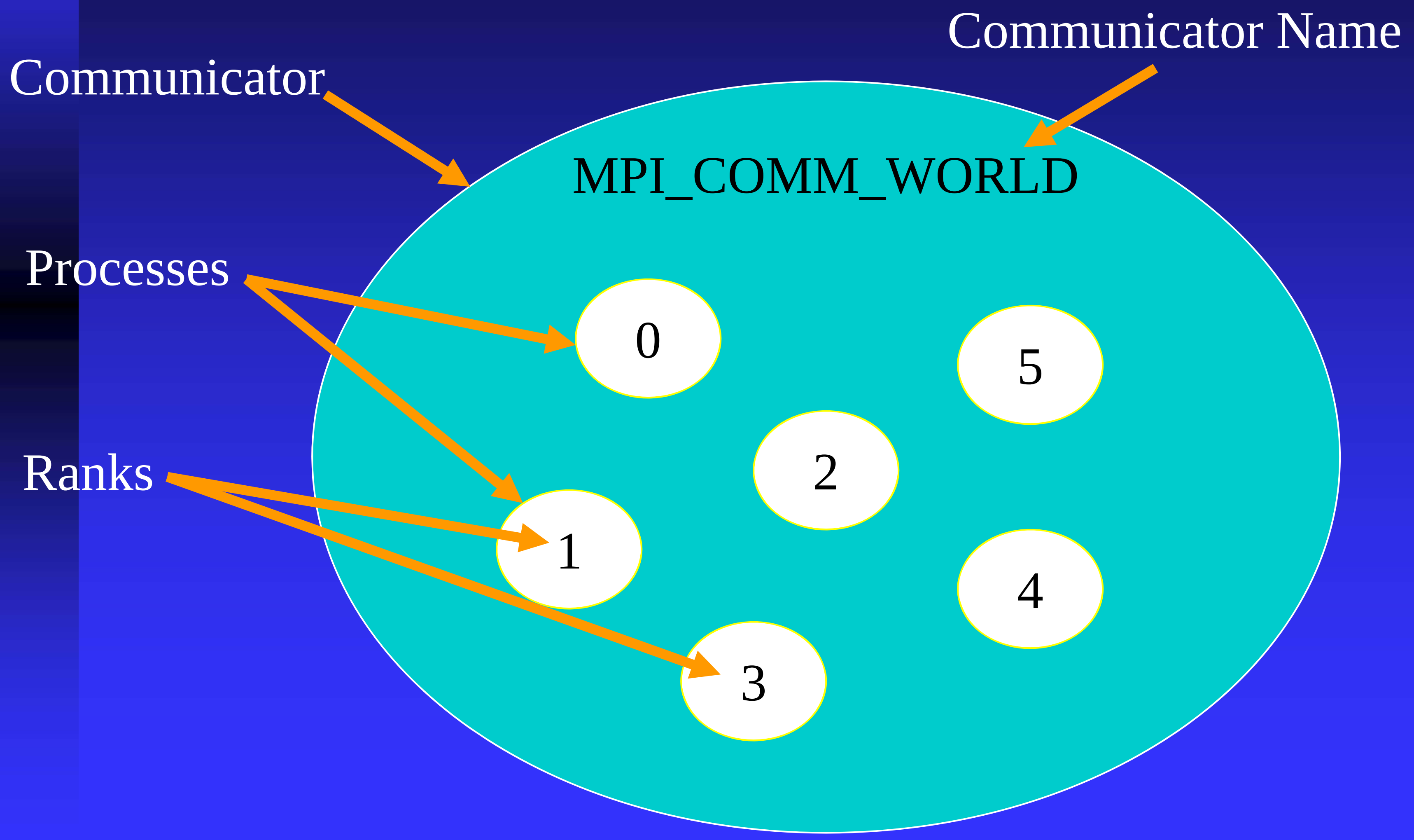
```
MPI_Init (&argc, &argv);
```

- First MPI function called by each process
- Not necessarily first executable statement
- Allows system to do any necessary setup

Communicators

- Communicator: opaque object that provides message-passing environment for processes
- MPI_COMM_WORLD
  - Default communicator
  - Includes all processes
- Possible to create new communicators
  - Will do this in Chapters 8 and 9

Communicator



Determine Number of Processes

```
MPI_Comm_size (MPI_COMM_WORLD, &p);
```

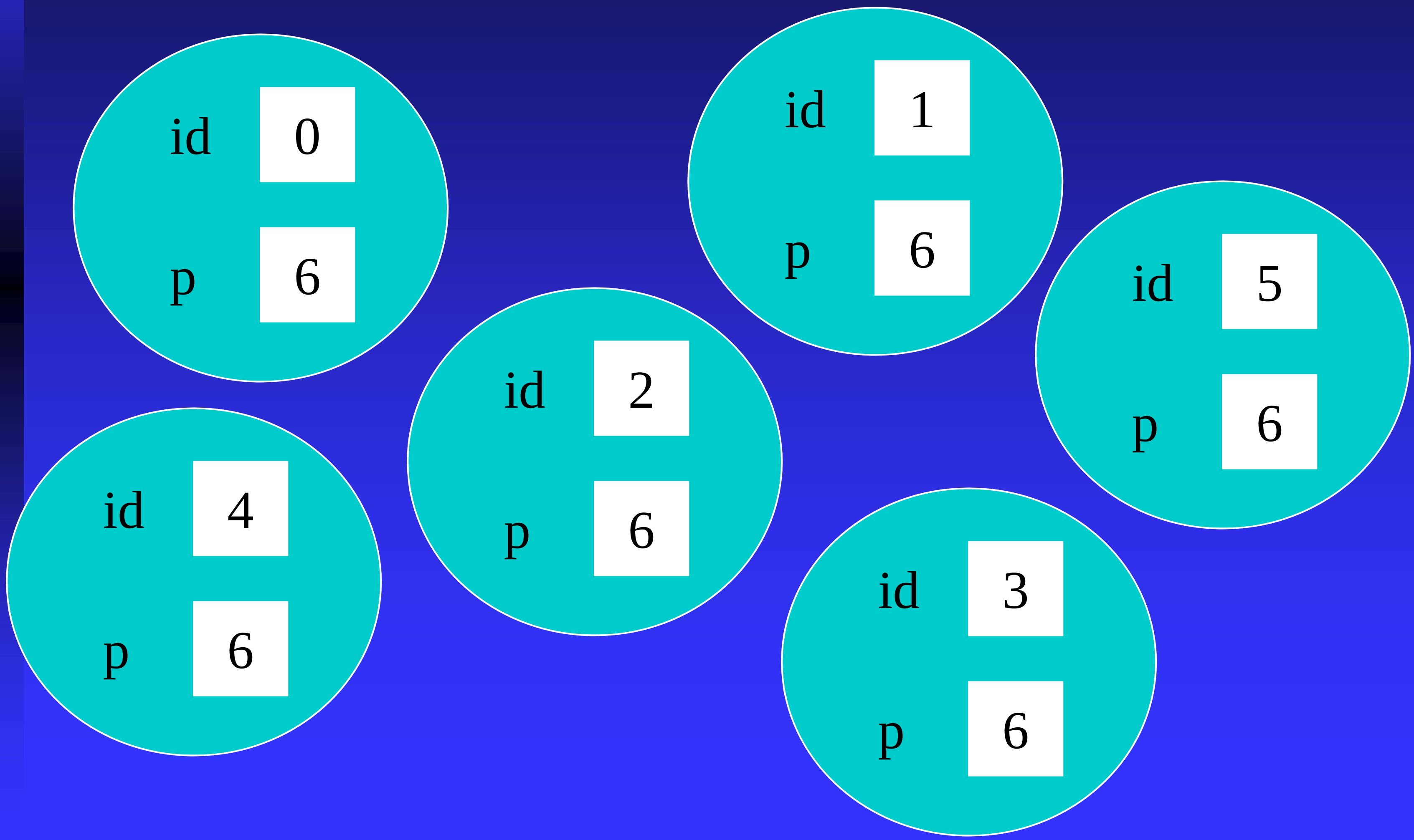
- First argument is communicator
- Number of processes returned through second argument

Determine Process Rank

```
MPI_Comm_rank (MPI_COMM_WORLD, &id);
```

- First argument is communicator
- Process rank (in range 0, 1, …, p-1) returned through second argument

Replication of Automatic Variables



What about External Variables?

```
int total;

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

- Where is variable **`total`** stored?

Cyclic Allocation of Work

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

- Parallelism is outside function **check_circuit**
- It can be an ordinary, sequential function

Shutting Down MPI

```
MPI_Finalize();
```

- Call after all other MPI library calls
- Allows system to free up MPI resources

```
#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;
}
```

Put `fflush()` after every `printf()`

```
/* Return 1 if 'i'th bit of 'n' is 1; 0 otherwise */
#define EXTRACT_BIT(n,i) ((n&(1<<i))?1:0)

void check_circuit (int id, int z) {
   int v[16];        /* Each element is a bit of z */
   int i;

   for (i = 0; i < 16; i++) v[i] = EXTRACT_BIT(z,i);

   if ((v[0] || v[1]) && (!v[1] || !v[3]) && (v[2] || v[3])
      && (!v[3] || !v[4]) && (v[4] || !v[5])
      && (v[5] || !v[6]) && (v[5] || v[6])
      && (v[6] || !v[15]) && (v[7] || !v[8])
      && (!v[7] || !v[13]) && (v[8] || v[9])
      && (v[8] || !v[9]) && (!v[9] || !v[10])
      && (v[9] || v[11]) && (v[10] || v[11])
      && (v[12] || v[13]) && (v[13] || !v[14])
      && (v[14] || v[15])) {
      printf ("%d) %d%d%d%d%d%d%d%d%d%d%d%d%d%d%d%d\n", id,
         v[0],v[1],v[2],v[3],v[4],v[5],v[6],v[7],v[8],v[9],
         v[10],v[11],v[12],v[13],v[14],v[15]);
      fflush (stdout);
   }
}
```

Compiling MPI Programs

```
mpicc -O -o foo foo.c
```

- **mpicc**: script to compile and link C+MPI programs
- Flags: same meaning as C compiler
  - **`-O`** — optimize
  - **`-o <file>`** — where to put executable

Running MPI Programs

- `mpirun -np <p> <exec> <arg1> …`
  - `-np <p>` — number of processes
  - `<exec>` — executable
  - `<arg1> …` — command-line arguments

Execution on 1 CPU

```
% mpirun -np 1 sat
0) 1010111110011001
0) 0110111110011001
0) 1110111110011001
0) 1010111111011001
0) 0110111111011001
0) 1110111111011001
0) 1010111110111001
0) 0110111110111001
0) 1110111110111001
Process 0 is done
```

Execution on 2 CPUs

```
% mpirun -np 2 sat
0) 0110111110011001
0) 0110111111011001
0) 0110111110111001
1) 1010111110011001
1) 1110111110011001
1) 1010111111011001
1) 1110111111011001
1) 1010111110111001
1) 1110111110111001
Process 0 is done
Process 1 is done
```

Execution on 3 CPUs

```
% mpirun -np 3 sat
0) 0110111110011001
0) 1110111111011001
2) 1010111110011001
1) 1110111110011001
1) 1010111111011001
1) 0110111110111001
0) 1010111110111001
2) 0110111111011001
2) 1110111110111001
Process 1 is done
Process 2 is done
Process 0 is done
```

Deciphering Output

- Output order only partially reflects order of output events inside parallel computer
- If process A prints two messages, first message will appear before second
- If process A calls **`printf`** before process B, there is no guarantee process A's message will appear before process B's message

Enhancing the Program

- We want to find total number of solutions
- Incorporate sum-reduction into program
- Reduction is a collective communication

Modifications

- Modify function **`check_circuit`**
  - Return 1 if circuit satisfiable with input combination
  - Return 0 otherwise
- Each process keeps local count of satisfiable circuits it has found
- Perform reduction after **`for`** loop

New Declarations and Code

```
int count;  /* Local sum */
int global_count; /* Global sum */
int check_circuit (int, int);

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

Prototype of 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 */
)
```

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

MPI_Op Options

- MPI_BAND
- MPI_BOR
- MPI_BXOR
- MPI_LAND
- MPI_LOR
- MPI_LXOR
- MPI_MAX
- MPI_MAXLOC
- MPI_MIN
- MPI_MINLOC
- MPI_PROD
- MPI_SUM

Our Call to MPI_Reduce()

```
MPI_Reduce (&count,
            &global_count,
            1,
            MPI_INT,
            MPI_SUM,
            0,
            MPI_COMM_WORLD);
```

Only process 0 will get the result

```
if (!id) printf ("There are %d different solutions\n",
   global_count);
```

Execution of Second Program

```
% mpirun -np 3 seq2
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
```

Benchmarking the Program

- **`MPI_Barrier`** — barrier synchronization
- **`MPI_Wtick`** — timer resolution
- **`MPI_Wtime`** — current time

Benchmarking Code

```
double elapsed_time;
…
MPI_Init (&argc, &argv);
MPI_Barrier (MPI_COMM_WORLD);
elapsed_time = - MPI_Wtime();
…
MPI_Reduce (…);
elapsed_time += MPI_Wtime();
```

Benchmarking Results

Processors	Time (sec)
1	15.93
2	8.38
3	5.86
4	4.60
5	3.77

Summary (1/2)

- Message-passing programming follows naturally from task/channel model
- Portability of message-passing programs
- MPI most widely adopted standard

Summary (2/2)

- MPI functions introduced
  - `MPI_Init`
  - `MPI_Comm_rank`
  - `MPI_Comm_size`
  - `MPI_Reduce`
  - `MPI_Finalize`
  - `MPI_Barrier`
  - `MPI_Wtime`
  - `MPI_Wtick`