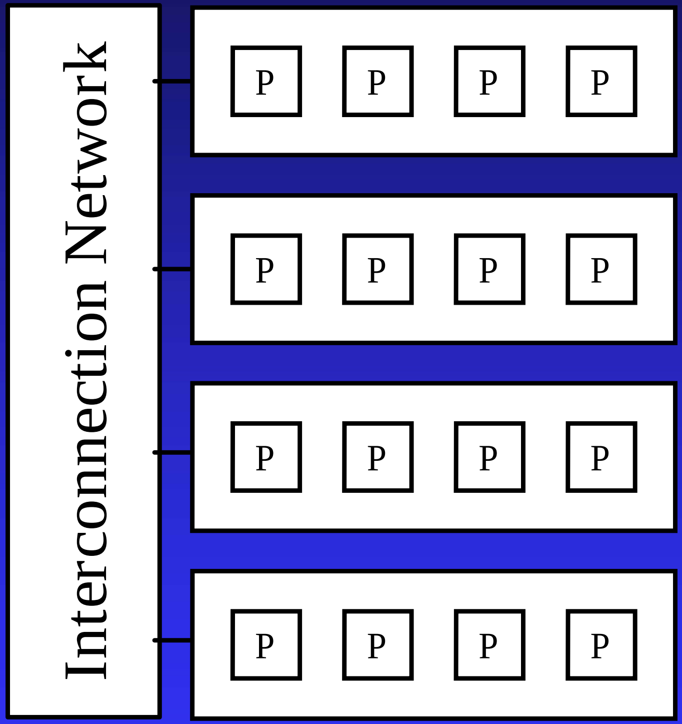
Chapter 18

Combining MPI and OpenMP

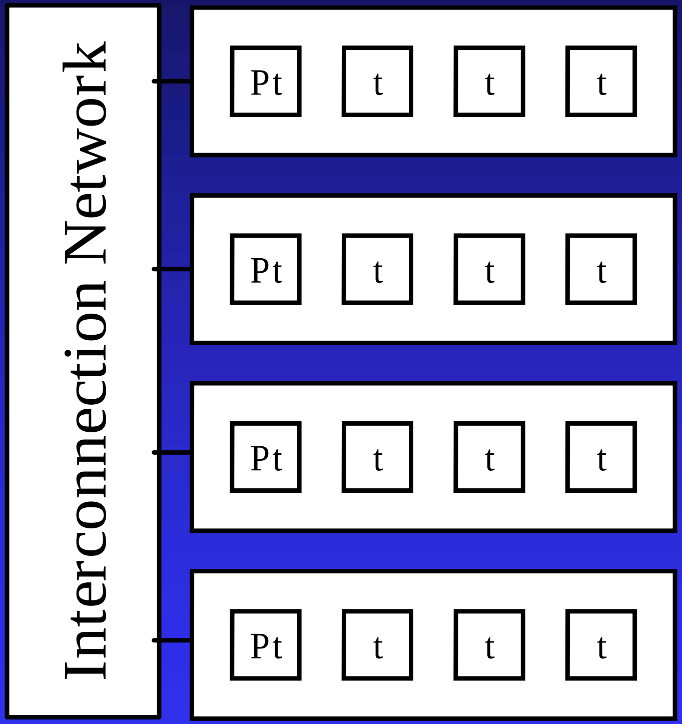
Outline

- Advantages of using both MPI and OpenMP
- Case Study: Conjugate gradient method
- Case Study: Jacobi method

C+MPI vs. C+MPI+OpenMP



C + MPI



C + MPI + OpenMP

Why C + MPI + OpenMP Can Execute Faster

- Lower communication overhead
- More portions of program may be practical to parallelize
- May allow more overlap of communications with computations

Case Study: Conjugate Gradient

- Conjugate gradient method solves $Ax = b$
- In our program we assume A is dense
- Methodology
  - Start with MPI program
  - Profile functions to determine where most execution time spent
  - Tackle most time-intensive function first

Result of Profiling MPI Program

Function	*1 CPU*	*8 CPUs*
matrix_vector_product	99.55%	97.49%
dot_product	0.19%	1.06%
cg	0.25%	1.44%

Clearly our focus needs to be on function **`matrix_vector_product`**

Code for matrix_vector_product

```
void matrix_vector_product (int id, int p,
   int n, double **a, double *b, double *c)
{
   int    i, j;
   double tmp;       /* Accumulates sum */
   for (i=0; i<BLOCK_SIZE(id,p,n); i++) {
      tmp = 0.0;
      for (j = 0; j < n; j++)
         tmp += a[i][j] * b[j];
      piece[i] = tmp;
   }
   new_replicate_block_vector (id, p,
      piece, n, (void *) c, MPI_DOUBLE);
}
```

Adding OpenMP directives

- Want to minimize fork/join overhead by making parallel the outermost possible loop
- Outer loop may be executed in parallel if each thread has a private copy of tmp and j

```
#pragma omp parallel for private(j,tmp)
   for (i=0; i<BLOCK_SIZE(id,p,n); i++) {
```

User Control of Threads

- Want to give user opportunity to specify number of active threads per process
- Add a call to omp_set_num_threads to function main
- Argument comes from command line

```
omp_set_num_threads (atoi(argv[3]));
```

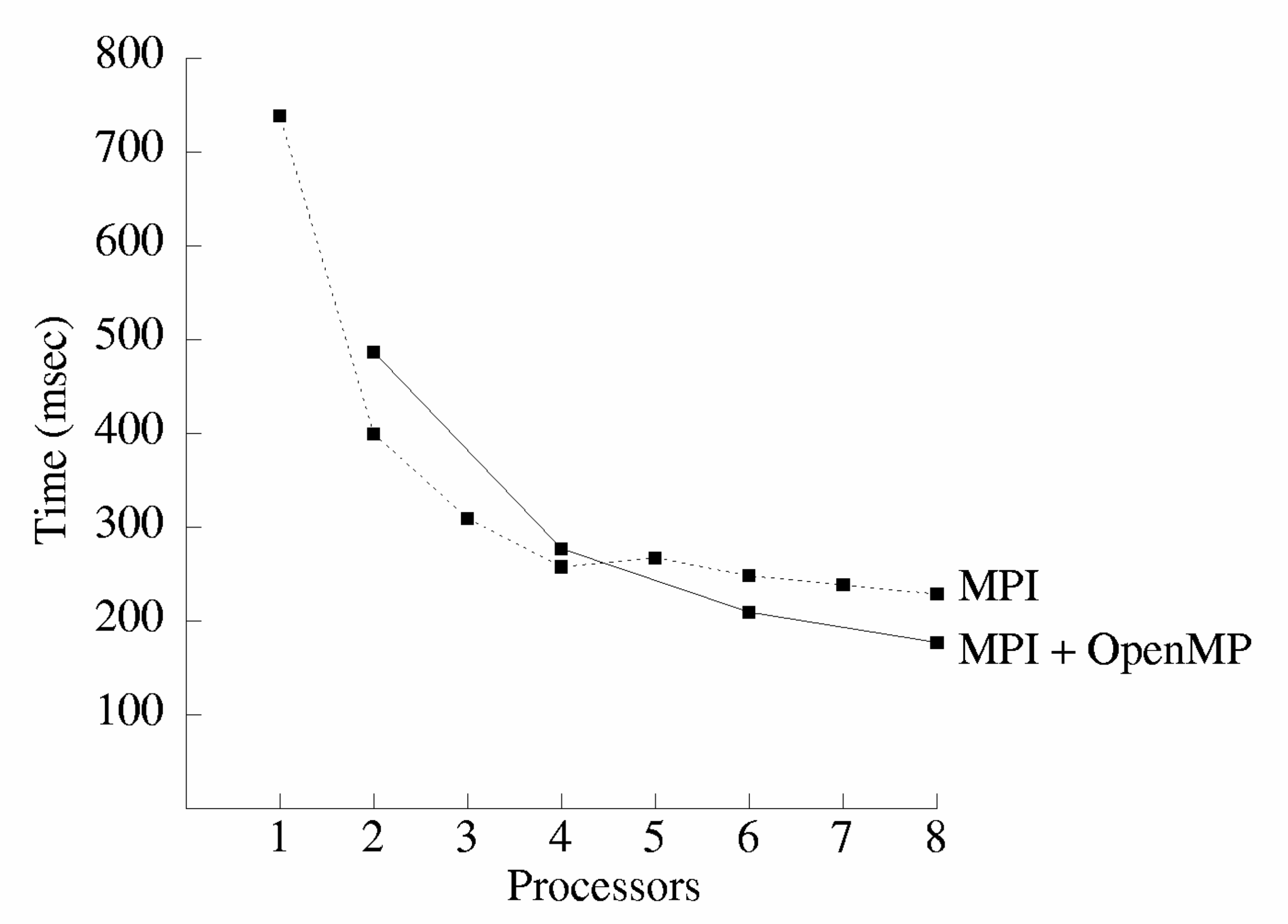
What Happened?

- We transformed a C+MPI program to a C+MPI+OpenMP program by adding only two lines to our program!

Benchmarking

- Target system: a commodity cluster with four dual-processor nodes
- C+MPI program executes on 1, 2, ..., 8 CPUs
- On 1, 2, 3, 4 CPUs, each process on different node, maximizing memory bandwidth per CPU
- C+MPI+OpenMP program executes on 1, 2, 3, 4 processes
- Each process has two threads
- C+MPI+OpenMP program executes on 2, 4, 6, 8 threads

Results of Benchmarking



Analysis of Results

- C+MPI+OpenMP program slower on 2, 4 CPUs because C+MPI+OpenMP threads are sharing memory bandwidth, while C+MPI processes are not
- C+MPI+OpenMP programs faster on 6, 8 CPUs because they have lower communication cost

Case Study: Jacobi Method

- Begin with C+MPI program that uses Jacobi method to solve steady state heat distribution problem of Chapter 13
- Program based on rowwise block striped decomposition of two-dimensional matrix containing finite difference mesh

Methodology

- Profile execution of C+MPI program
- Focus on adding OpenMP directives to most compute-intensive function

Result of Profiling

Function	*1 CPU*	*8 CPUs*
initialize_mesh	0.01%	0.03%
find_steady_state	98.48%	93.49%
print_solution	1.51%	6.48%

Function find_steady_state (1/2)

```
its = 0;
for (;;) {
   if (id > 0)
      MPI_Send (u[1], N, MPI_DOUBLE, id-1, 0,
         MPI_COMM_WORLD);
   if (id < p-1) {
      MPI_Send (u[my_rows-2], N, MPI_DOUBLE, id+1,
         0, MPI_COMM_WORLD);
      MPI_Recv (u[my_rows-1], N, MPI_DOUBLE, id+1,
         0, MPI_COMM_WORLD, &status);
   }
   if (id > 0)
      MPI_Recv (u[0], N, MPI_DOUBLE, id-1, 0,
         MPI_COMM_WORLD, &status);
```

Function find_steady_state (2/2)

```
diff = 0.0;
for (i = 1; i < my_rows-1; i++)
   for (j = 1; j < N-1; j++) {
      w[i][j] = (u[i-1][j] + u[i+1][j] +
                 u[i][j-1] + u[i][j+1])/4.0;
      if (fabs(w[i][j] - u[i][j]) > diff)
         diff = fabs(w[i][j] - u[i][j]);
   }
for (i = 1; i < my_rows-1; i++)
   for (j = 1; j < N-1; j++)
      u[i][j] = w[i][j];
MPI_Allreduce (&diff, &global_diff, 1,
   MPI_DOUBLE, MPI_MAX, MPI_COMM_WORLD);
if (global_diff <= EPSILON) break;
its++;
```

Making Function Parallel (1/2)

- Except for two initializations and a return statement, function is a big **`for`** loop
- Cannot execute **`for`** loop in parallel
  - Not in canonical form
  - Contains a **`break`** statement
  - Contains calls to MPI functions
  - Data dependences between iterations

Making Function Parallel (2/2)

- Focus on first `for` loop indexed by `i`
- How to handle multiple threads testing/updating `diff`?
- Putting `if` statement in a critical section would increase overhead and lower speedup
- Instead, create private variable `tdiff`
- Thread tests `tdiff` against `diff` before call to `MPI_Allreduce`

Modified Function

```
      diff = 0.0;
#pragma omp parallel private (i, j, tdiff)
{
      tdiff = 0.0;
#pragma omp for
      for (i = 1; i < my_rows-1; i++)
         ...
#pragma omp for nowait
      for (i = 1; i < my_rows-1; i++)
#pragma omp critical
      if (tdiff > diff) diff = tdiff;
}
      MPI_Allreduce (&diff, &global_diff, 1,
         MPI_DOUBLE, MPI_MAX, MPI_COMM_WORLD);
```

Making Function Parallel (3/3)

- Focus on second `for` loop indexed by `i`
- Copies elements of `w` to corresponding elements of `u`: no problem with executing in parallel

Benchmarking

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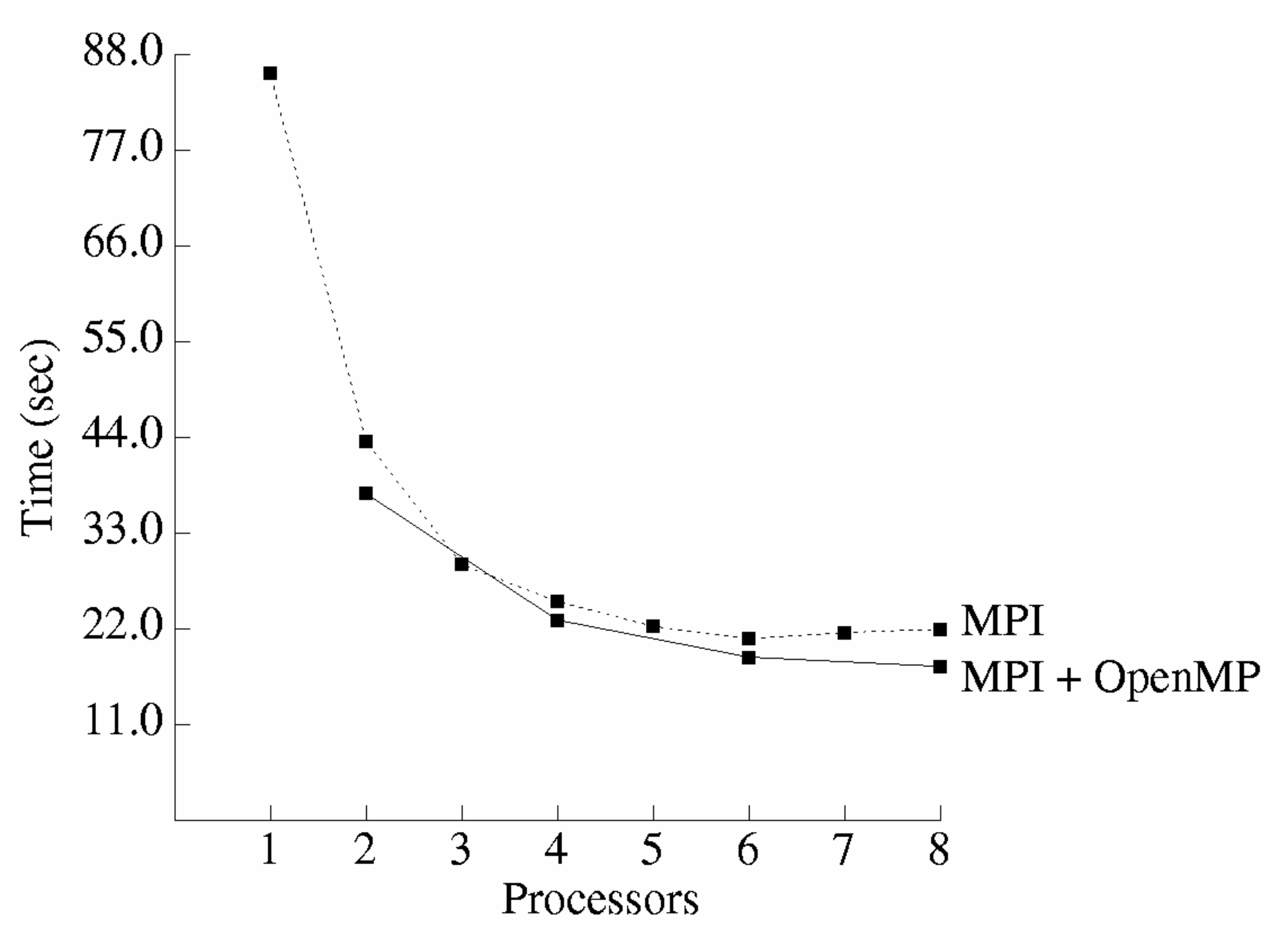
Benchmarking Results



Analysis of Results

- Hybrid C+MPI+OpenMP program uniformly faster than C+MPI program
- Computation/communication ratio of hybrid program is superior
- Number of mesh points per element communicated is twice as high per node for the hybrid program
- Lower communication overhead leads to 19% better speedup on 8 CPUs

Summary

- Many contemporary parallel computers consists of a collection of multiprocessors
- On these systems, performance of C+MPI+OpenMP programs can exceed performance of C+MPI programs
- OpenMP enables us to take advantage of shared memory to reduce communication overhead
- Often, conversion requires addition of relatively few pragmas