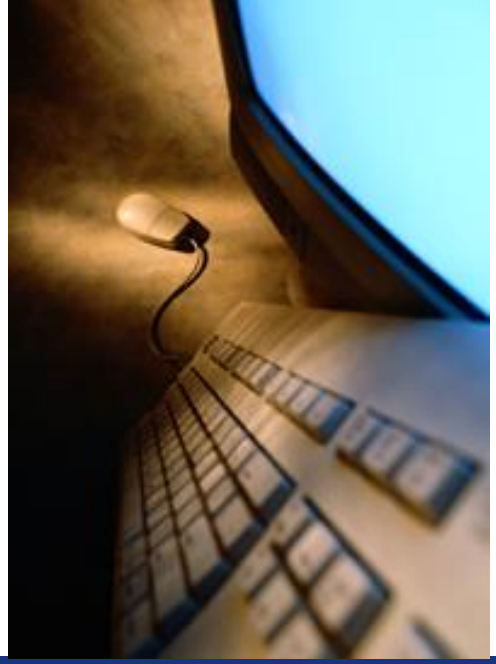
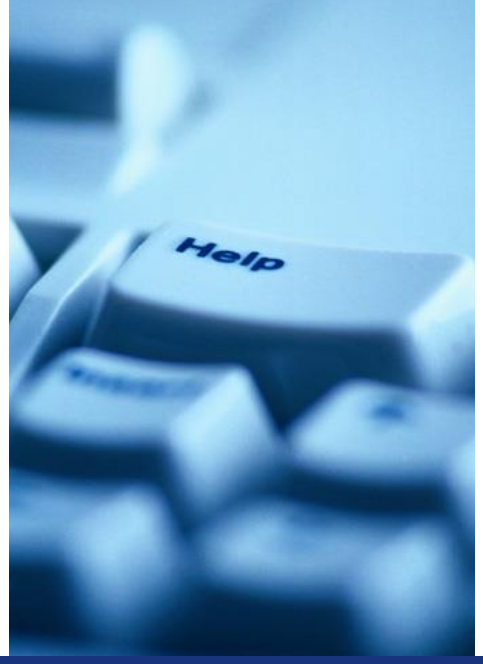

并行与分布式计算

Parallel & Distributed Computing

陈鹏飞
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2018-05-16
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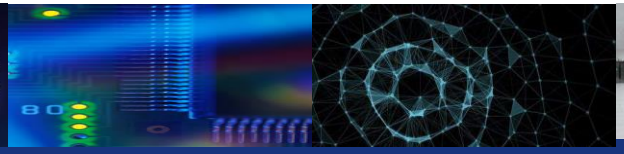

Lecture 9 — Programming with MPI

- Matrix-Vector Multiplication and MPI + OpenMP

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May 16, 2018

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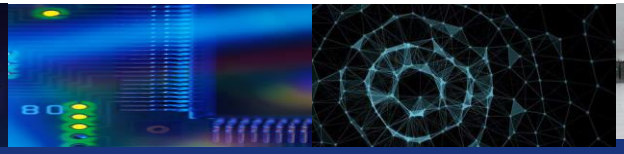


Outline:

- **Example: matrix-vector multiplication**
  - **Sequential algorithm;**
  - **Design, analysis, and implementation of three parallel programs;**
    - **Rowwise block striped**
    - **Columnwise block striped**
    - **Checkerboard block**
- **MPI + OpenMP**

Sequential Algorithm

2	1	0	4
3	2	1	1
4	3	1	2
3	0	2	0

$\times$

1
3
4
1

$=$

9
14
19
11

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

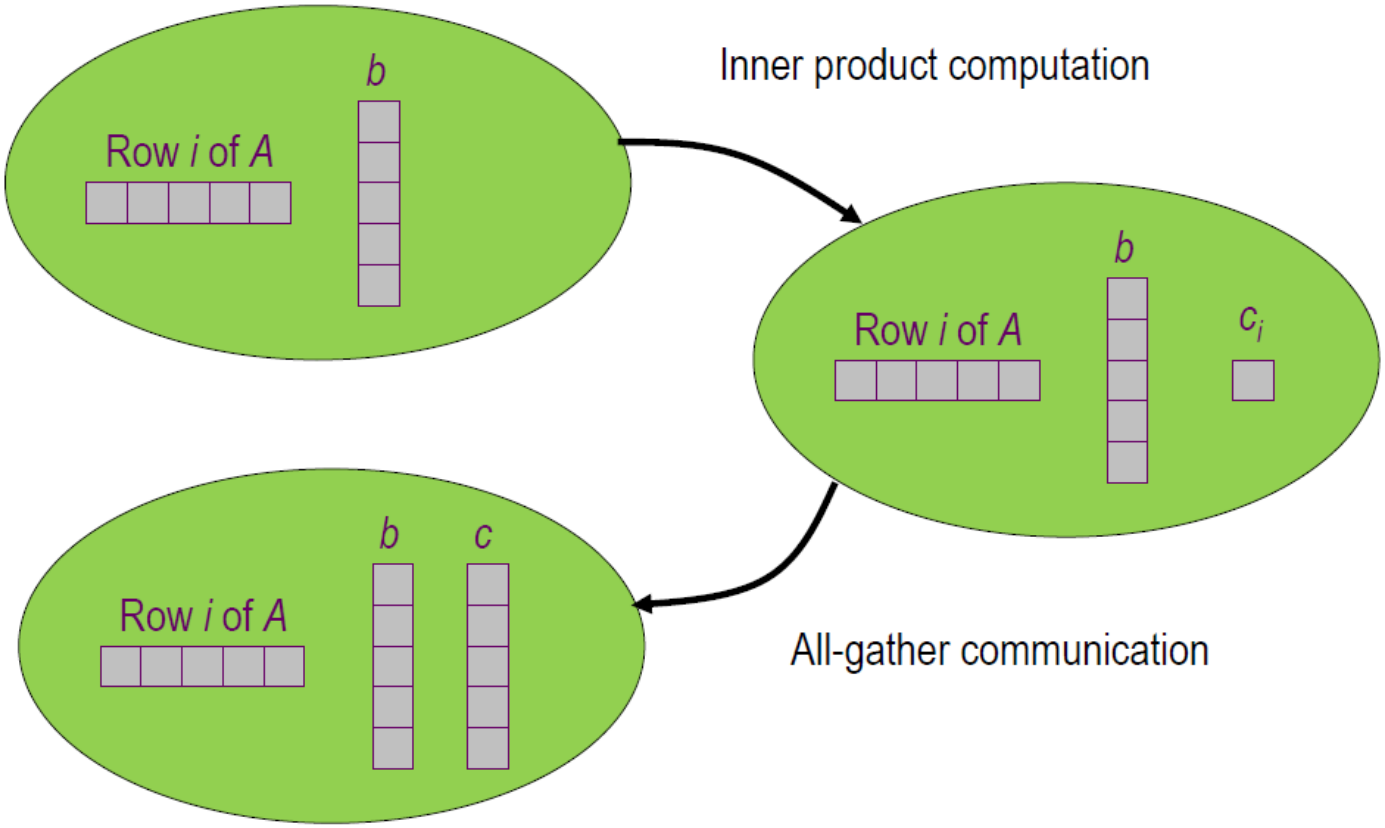


Rowwise Block Striped Matrix

- **Partitioning through domain decomposition**
- **Primitive task associated with**
  - **Row of matrix**
  - **Entire vector**

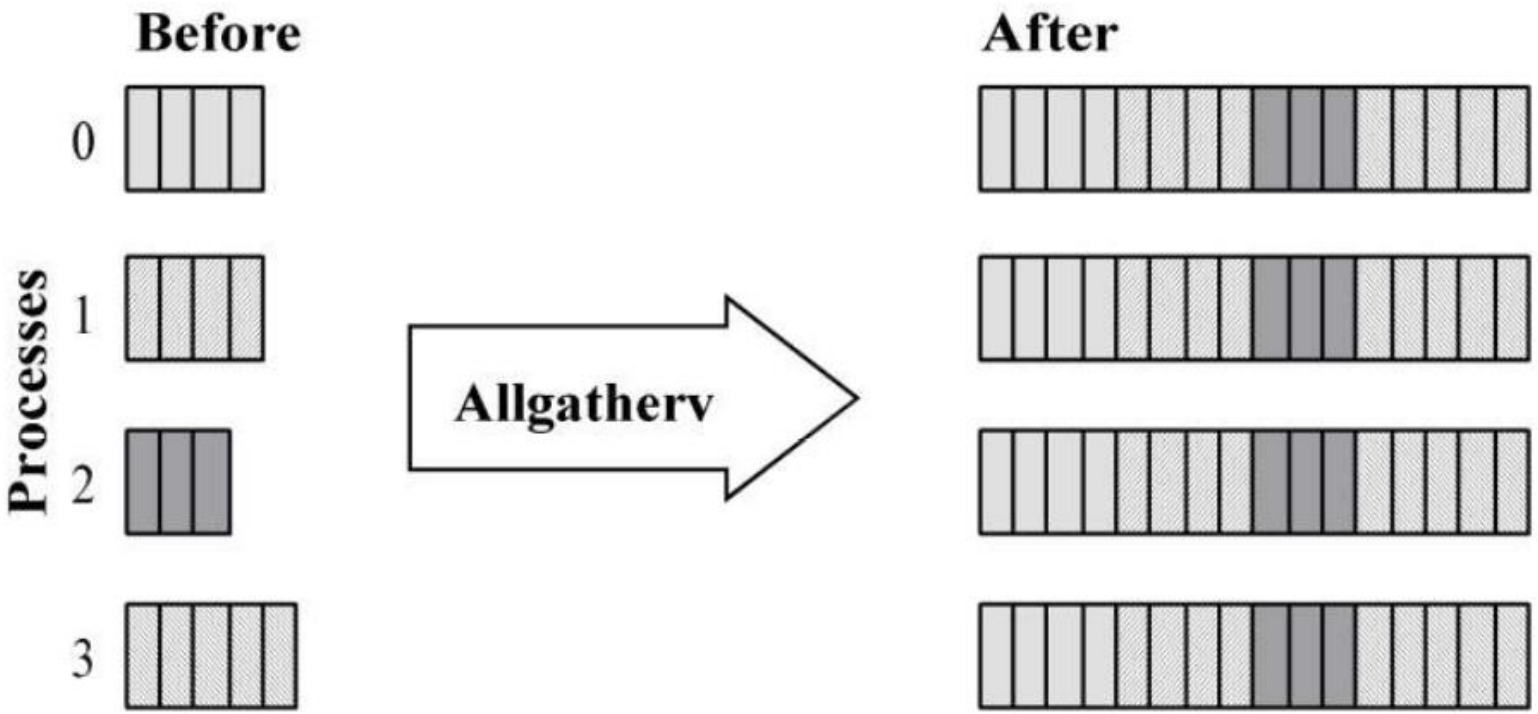
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Phases of Parallel Algorithm



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI_Allgatherv



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI_Allgatherv

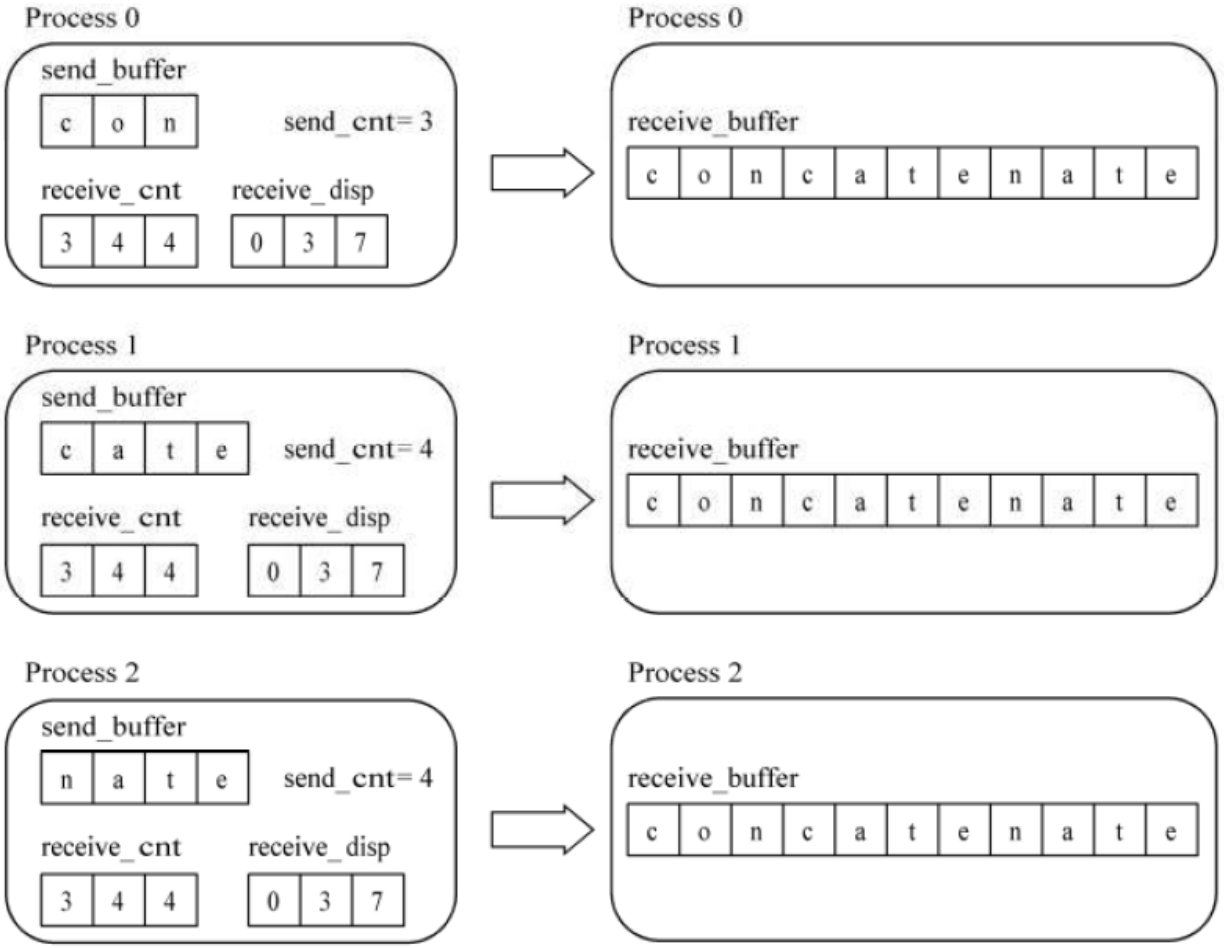
```
int MPI_Allgatherv (
void *send_buffer,
int send_cnt,
MPI_Datatype send_type,
void *receive_buffer,
int *receive_cnt,
int *receive_disp,
MPI_Datatype receive_type,
MPI_Comm communicator)
```

Use a simpler function *MPI_Allgather(…)*

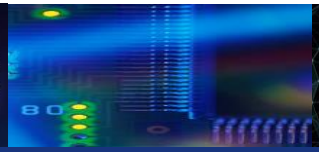
when the number of elements per processor is a constant

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI_Allgatherv in Action



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



Agglomeration and Mapping

- **Static number of tasks**
- **Regular communication pattern (all-gather)**
- **Computation time per task is constant**
- **Strategy:**
  - **Agglomerate groups of rows**
  - **Create one task per MPI process**

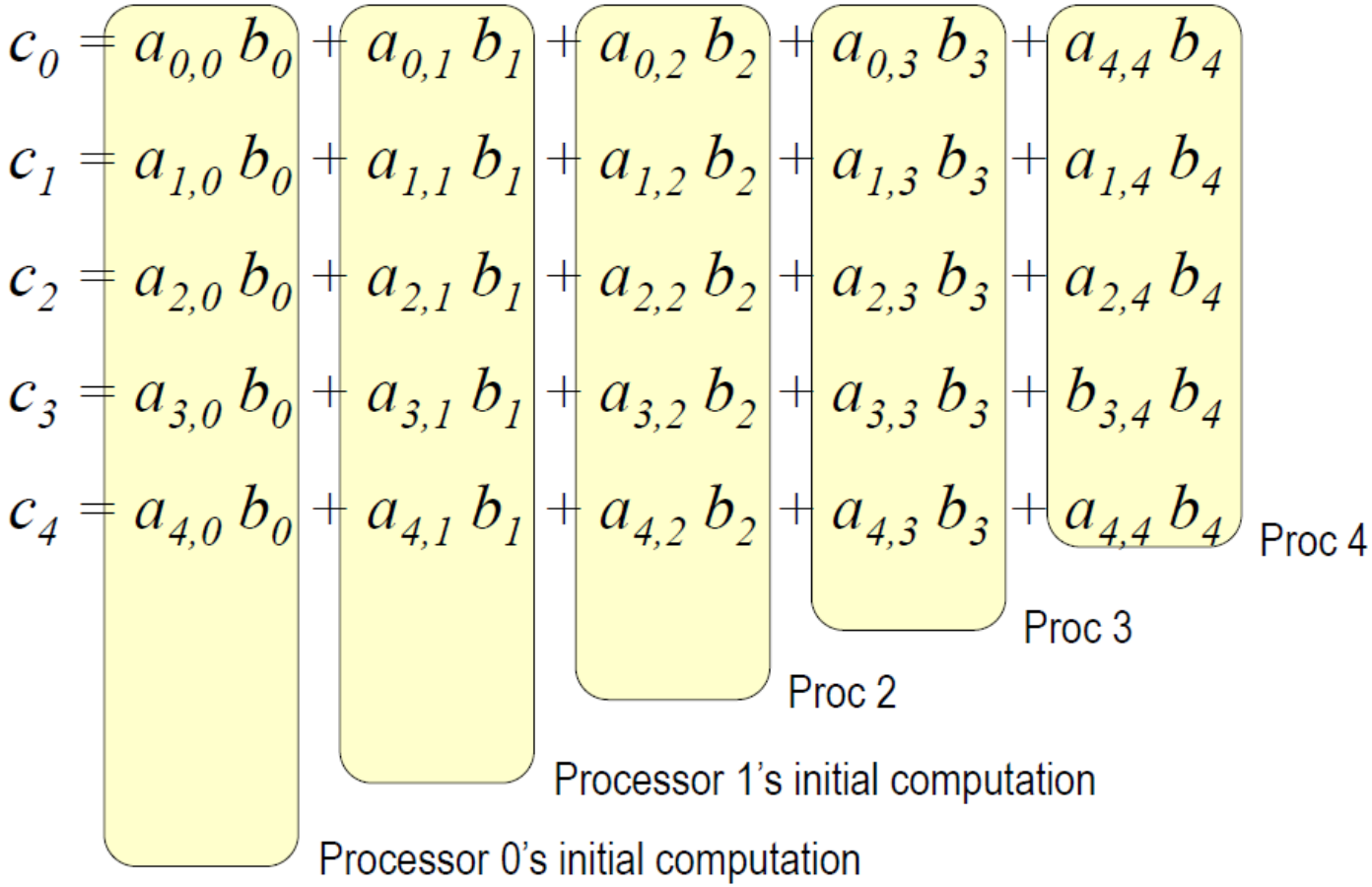
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Columnwise Block Striped Matrix

- Partitioning through domain decomposition
- Task associated with
  - Column of matrix
  - Vector element

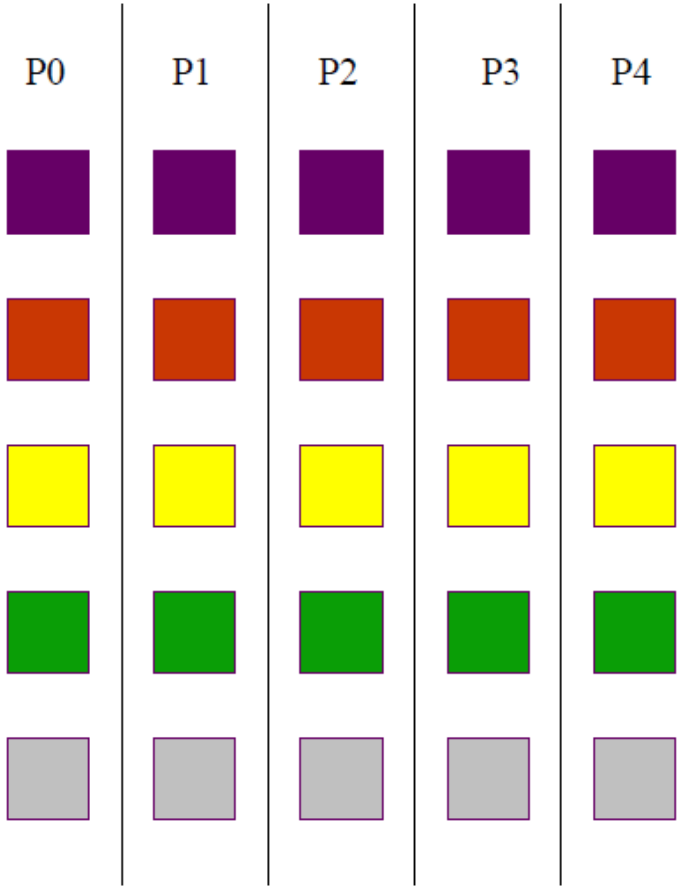
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Matrix-Vector Multiplication



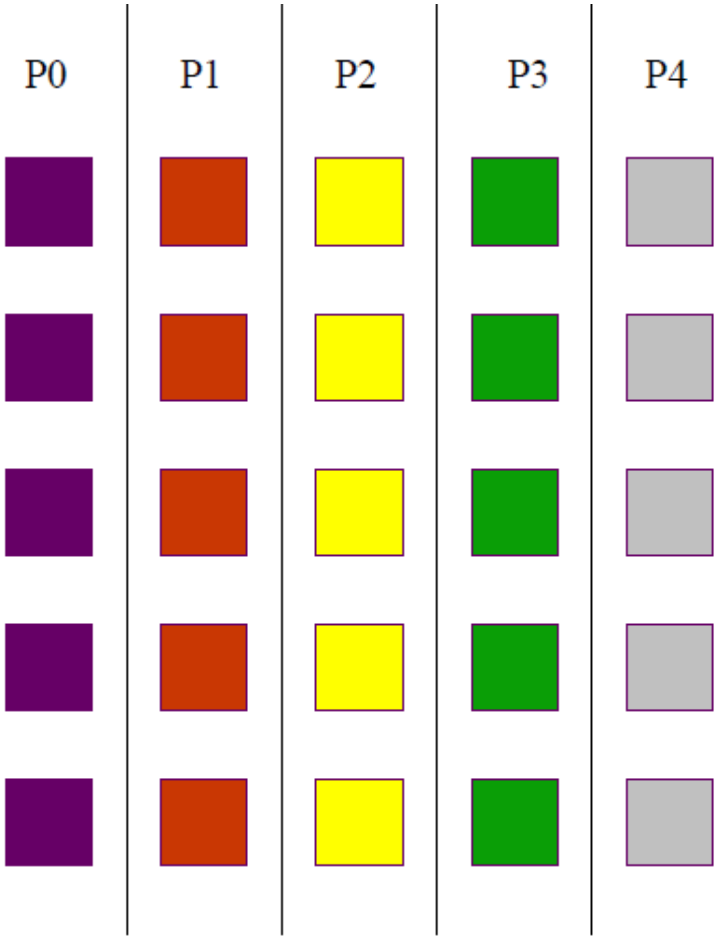
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

All-to-all Exchange (Before)



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

All-to-all Exchange (After)



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

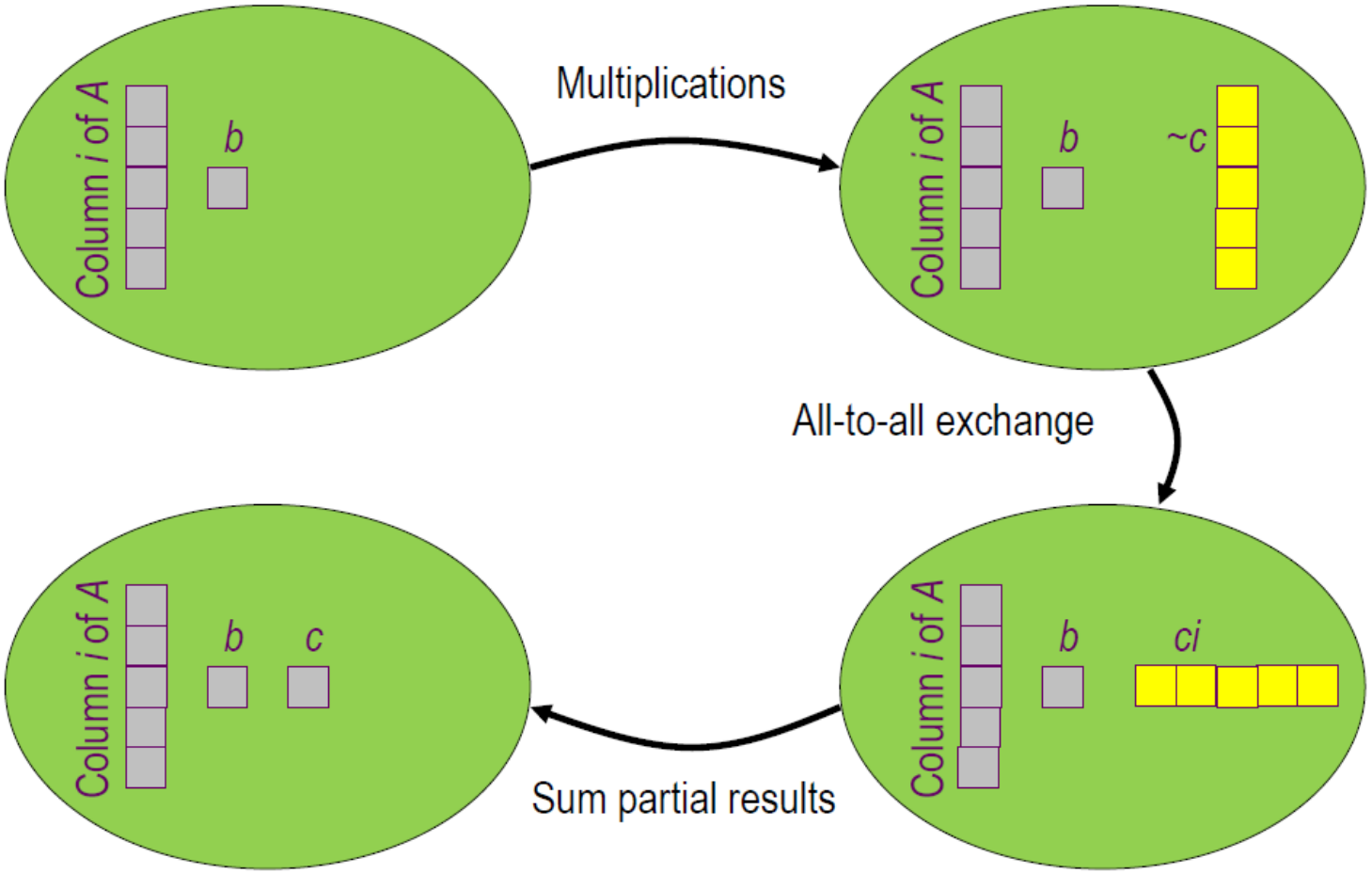
All-to-All Exchange (All-to-All Personalized Communication)

A. Grama et al., “Introduction to Parallel Computing,” Addison Wesley, 2003

All-to-All Exchange (All-to-All Personalized Communication)

A. Grama et al., “Introduction to Parallel Computing,” Addison Wesley, 2003

Phases of Parallel Algorithm



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Agglomeration and Mapping

- **Static number of tasks**
- **Regular communication pattern (all-to-all)**
- **Computation time per task is constant**
- **Strategy:**
  - **Agglomerate groups of columns**
  - **Create one task per MPI process**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Agglomeration and Mapping

- **Static number of tasks**
- **Regular communication pattern (all-to-all)**
- **Computation time per task is constant**
- **Strategy:**
  - **Agglomerate groups of columns**
  - **Create one task per MPI process**

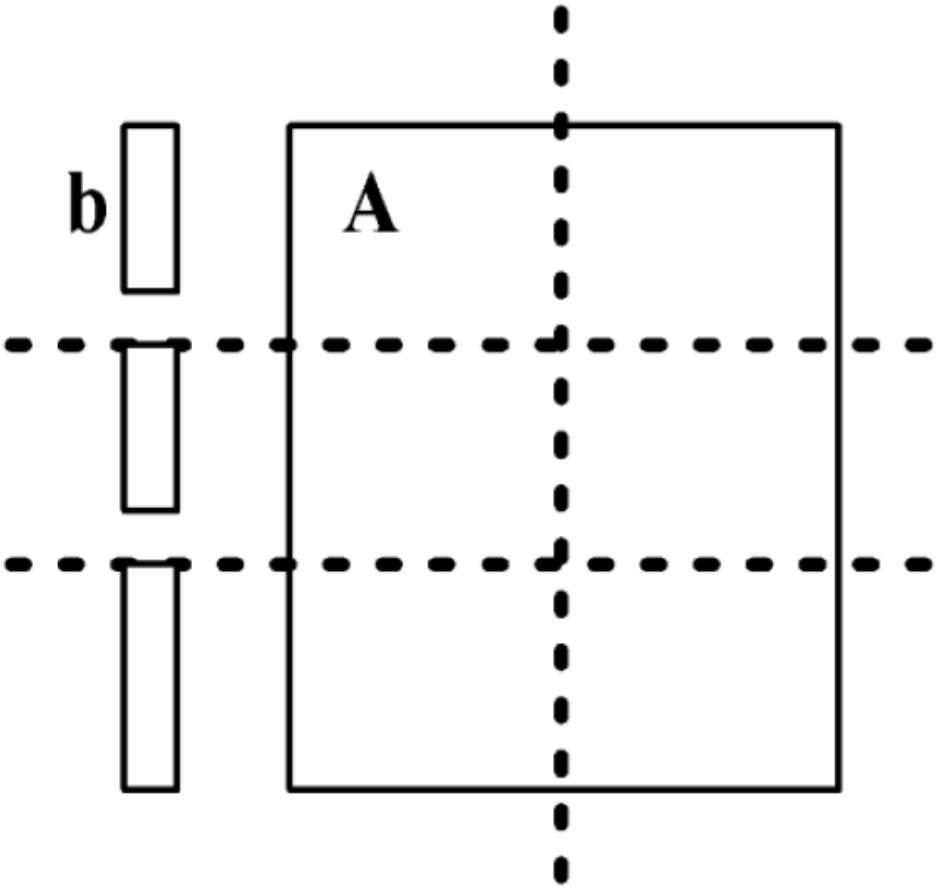
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Checkerboard Block Decomposition

- **Associate primitive task with each element of the matrix** A
- **Each primitive task performs one multiply**
- **Agglomerate primitive tasks into rectangular blocks**
- **Processes form a 2-D grid**
- **Vector** b **distributed by blocks among processes in first column of grid**

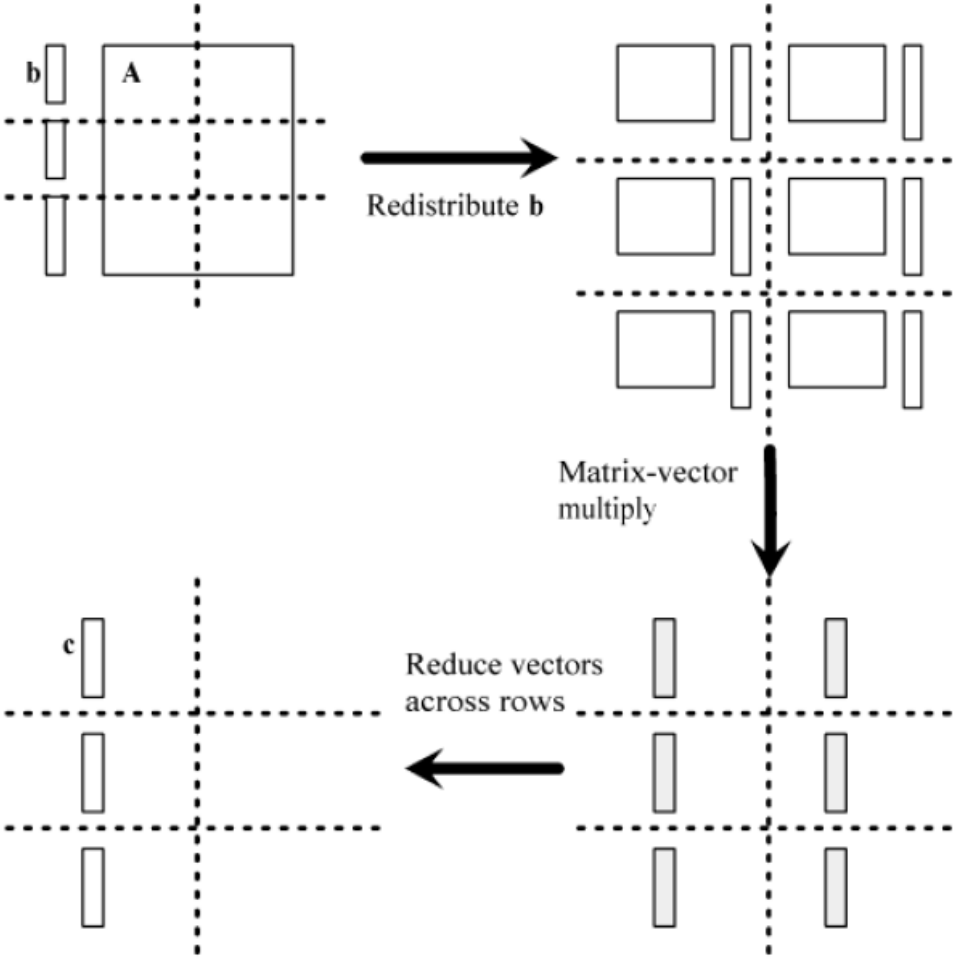
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Tasks after Agglomeration



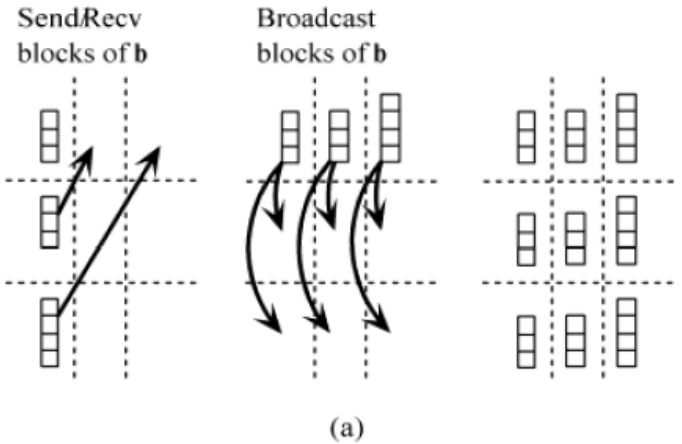
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

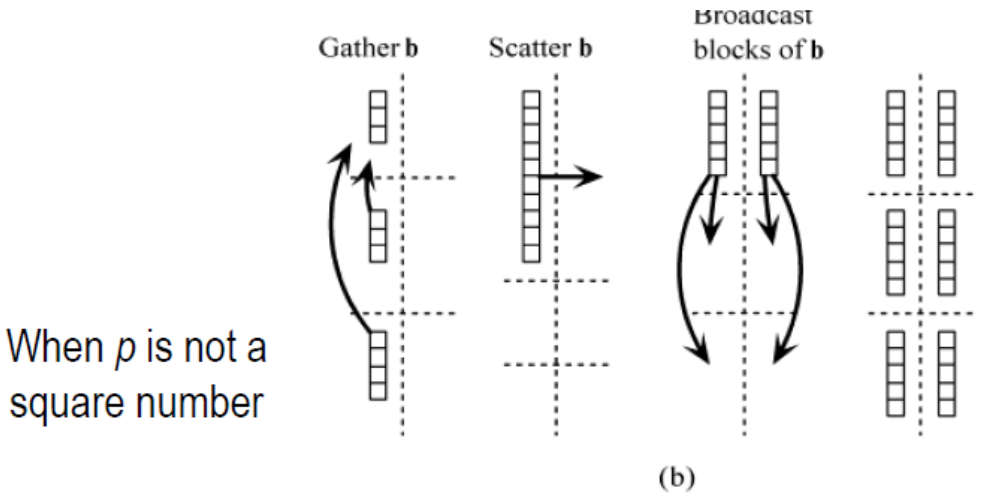
Algorithm's Phases



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

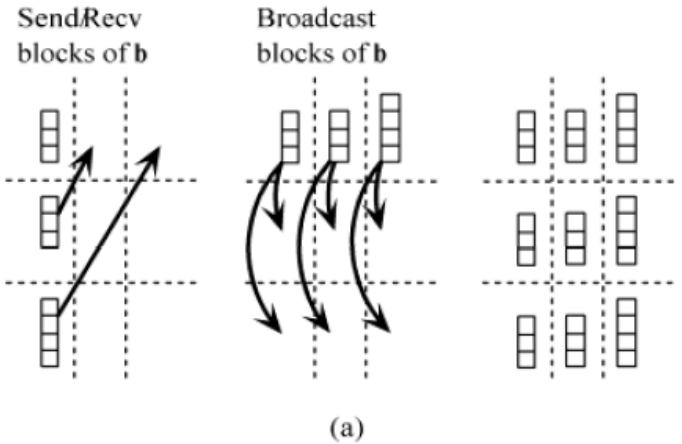
Algorithm's Phases





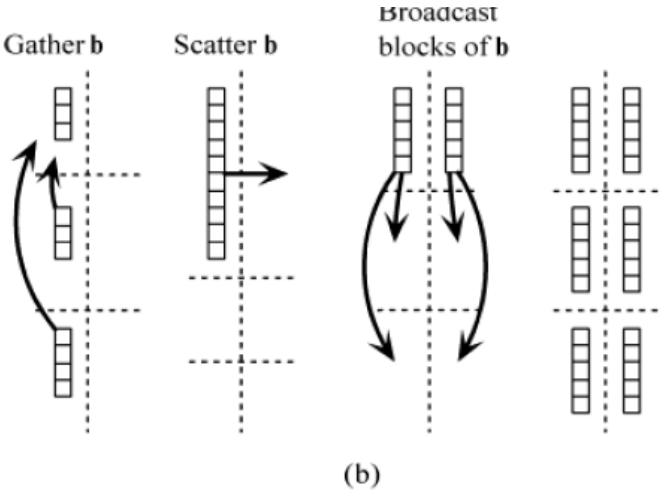
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Algorithm's Phases



When p is a square number

(a)



When p is not a square number

(b)

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Redistributing Vector *b*

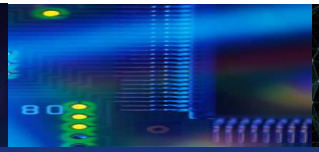
- **Step 1: Move *b* from processes in first row to processes in first column**
  - **If *p* square**
    - **First column/first row processes send/receive portions of *b***
  - **If *p* not square**
    - **Gather *b* on process 0, 0**
    - **Process 0, 0 broadcasts to first row procs**
- **Step 2: First row processes scatter *b* within columns**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Creating Communicators

- **Want processes in a virtual 2-D grid**
- **Create a custom communicator to do this**
- **Collective communications involve all processes in a communicator**
- **We need to do broadcasts, reductions among subsets of processes**
- **We will create communicators for processes in same row or same column**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



What's in a Communicator?

- **Process group**
- **Context**
- **Attributes**
  - **Topology (lets us address processes another way)**
  - **Others we won't consider**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Creating 2-D Virtual Grid of Processes

- *MPI_Dims_create*
  - **Input parameters**
    - **Total number of processes in desired grid**
    - **Number of grid dimensions**
  - **Returns number of processes in each dim**
- *MPI_Cart_create*
  - **Creates communicator with Cartesian topology (笛卡尔拓扑结构)**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI_Dims_create

```
int MPI_Dims_create (
    int nodes,
        /* Input - Procs in grid */
    int dims,
        /* Input - Number of dims */
    int *size)
        /* Input/Output - Size of
           each grid dimension */
```

dims before call	function call	dims on return
(0,0)	MPI_DIMS_CREATE(6, 2, dims)	(3,2)
(0,0)	MPI_DIMS_CREATE(7, 2, dims)	(7,1)
(0,3,0)	MPI_DIMS_CREATE(6, 3, dims)	(2,3,1)
(0,3,0)	MPI_DIMS_CREATE(7, 3, dims)	erroneous call

source: DeinoMPI

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI_Cart_create （创建笛卡尔拓扑）

```
int MPI_Cart_create (
   MPI_Comm old_comm, /* Input - old communicator */

   int dims, /* Input - grid dimensions */

   int *size, /* Input - # procs in each dim */

   int *periodic,
       /* Input - periodic[j] is 1 if dimension j
          wraps around; 0 otherwise */

   int reorder,
       /* 1 if process ranks can be reordered */

   MPI_Comm *cart_comm)
       /* Output - new communicator */
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Using MPI_Dims_create and MPI_Cart_create

```
MPI_Comm cart_comm;
int p;
int periodic[2];
int size[2];
...
size[0] = size[1] = 0;
MPI_Dims_create (p, 2, size);
periodic[0] = periodic[1] = 0;
MPI_Cart_create (MPI_COMM_WORLD, 2, size,
1, &cart_comm);
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Using MPI_Dims_create and MPI_Cart_create

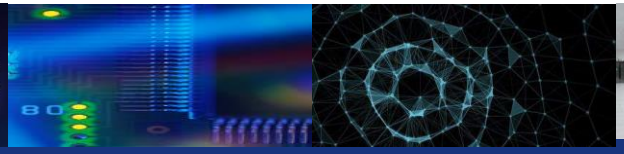
```
MPI_Comm cart_comm;
int p;
int periodic[2];
int size[2];
...
size[0] = size[1] = 0;
MPI_Dims_create (p, 2, size);
periodic[0] = periodic[1] = 0;
MPI_Cart_create (MPI_COMM_WORLD, 2, size,
1, &cart_comm);
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Useful Grid-related Functions

- *MPI_Cart_rank*
  - **Given coordinates of process in Cartesian communicator, returns process rank**
- *MPI_Cart_cords*
  - **Given rank of process in Cartesian communicator , returns process' coordinates**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



Header for *MPI_Cart_rank*

```
int MPI_Cart_rank (
    MPI_Comm comm,
        /* In - Communicator */
    int *coords,
        /* In - Array containing process'
                grid location */
    int *rank)
        /* Out - Rank of process at
           specified coords */
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Header for *MPI_Cart_coords*

```
int MPI_Cart_coords (
    MPI_Comm comm,
        /* In - Communicator */
    int rank,
        /* In - Rank of process */
    int dims,
        /* In - Dimensions in virtual grid
*/
    int *coords)
        /* Out - Coordinates of specified
           process in virtual grid */
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Collective Communications

	Ring	2-D Mesh	Hypercube
One-to-All Broadcast			
All-to-One Reduction			
All-to-All Broadcast			
All-to-All Reduction			
Scatter			
Gather			
All-to-All Personalized Communication			

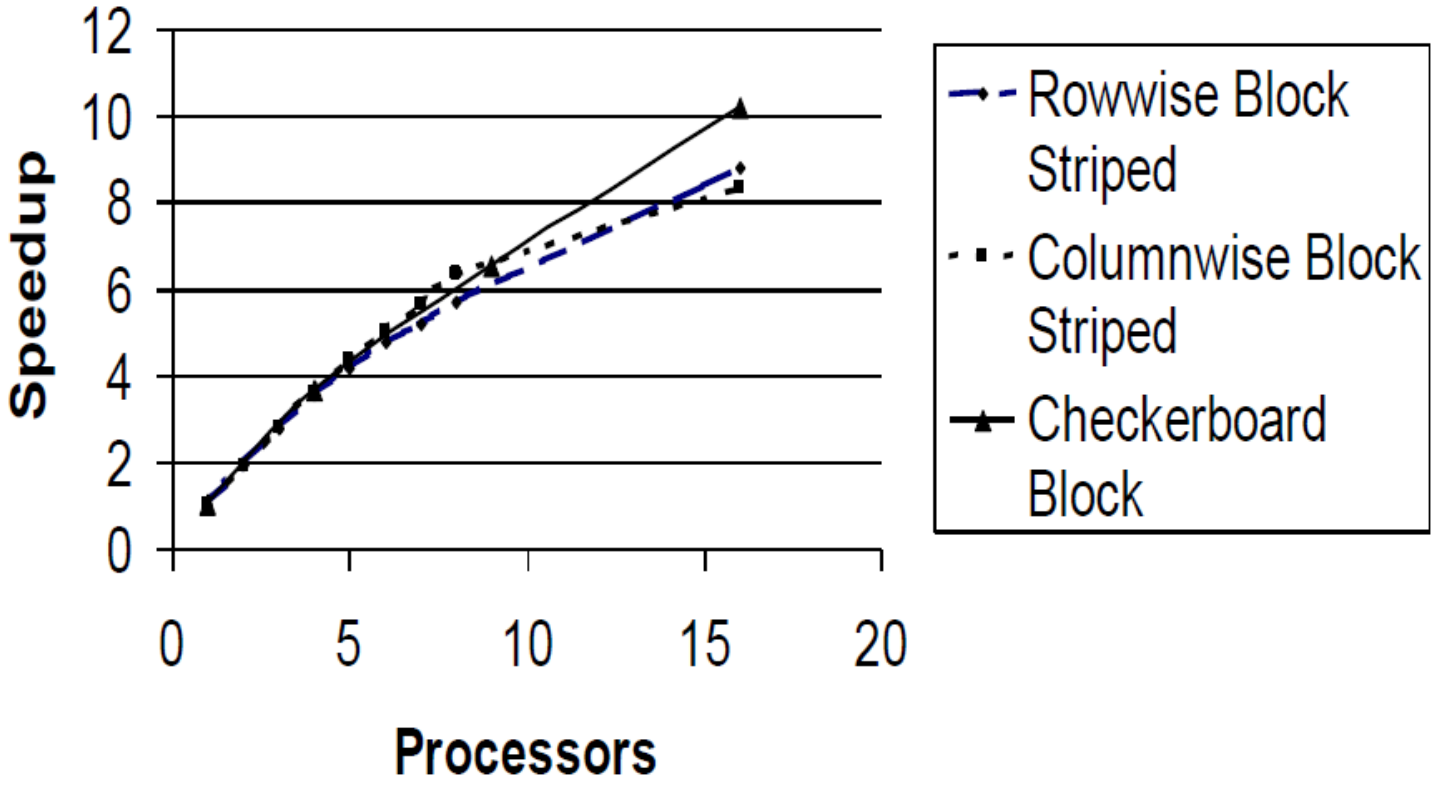
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

MPI Names of the Various Operations

Operation	MPI Name
One-to-all broadcast	MPI_Bcast
All-to-one reduction	MPI_Reduce
All-to-all broadcast	MPI_Allgather
All-to-all reduction	MPI_Reduce_scatter
All-reduce	MPI_Allreduce
Gather	MPI_Gather
Scatter	MPI_Scatter
All-to-all personalized	MPI_Alltoall

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Comparison of Three Algorithms



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



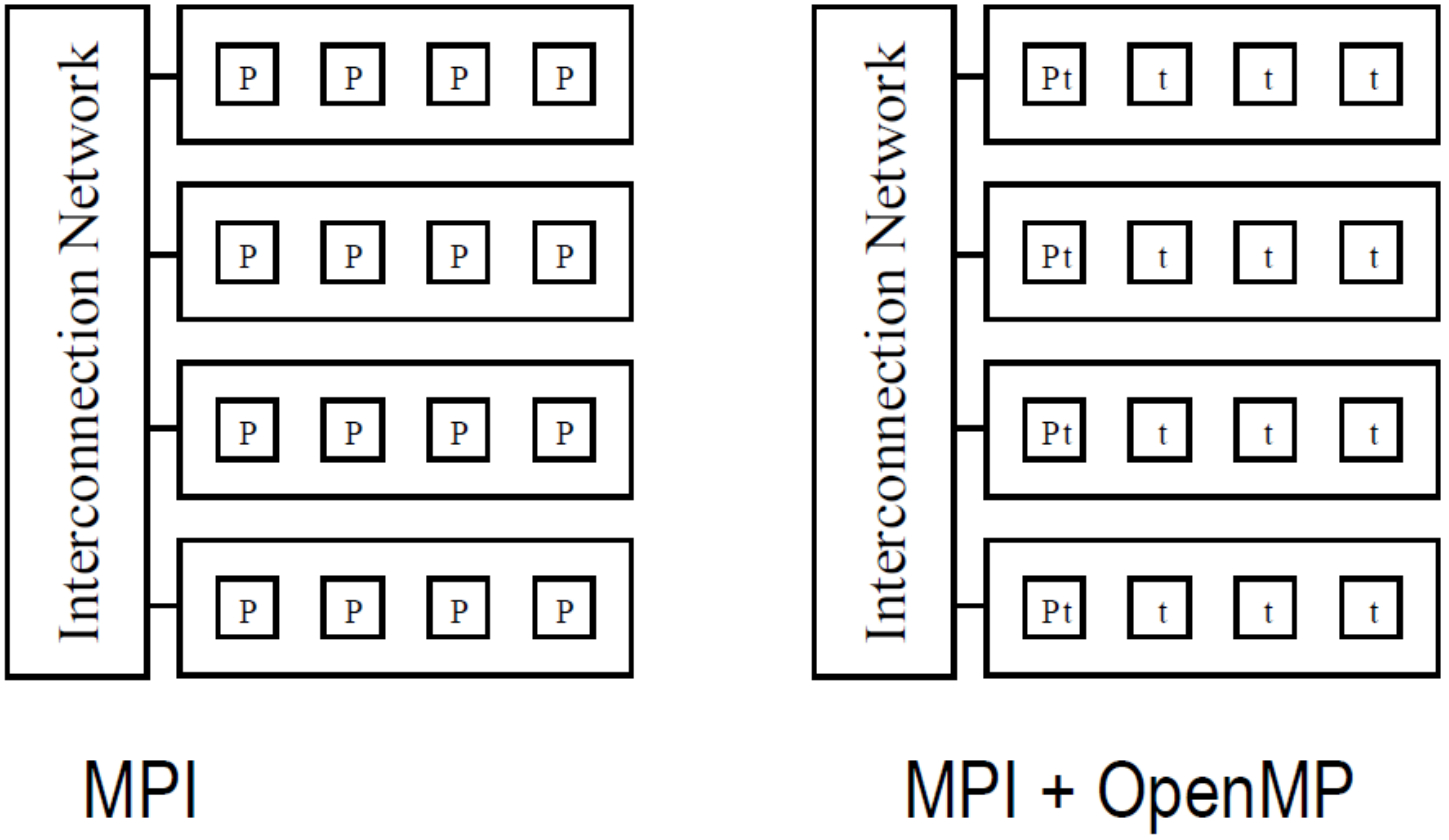
Programming with MPI

MPI + OpenMP

MPI + OpenMP

- **Advantages of using both MPI and OpenMP**
  - **Case Study: Jacobi method**
    - **An iterative methods to solve linear systems**

MPI vs. MPI + OpenMP



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Why MPI + OpenMP Can Execute Faster?

- Lower communication overhead
  - Message passing with *mk* processes, versus
  - Message passing with *m* processes with *k* threads each
- More portions of program may be practical to parallelize
- May allow more overlap of communications with computations
  - For example, if 3 MPI processes are waiting for messages, and 1 MPI process is active, it is worthwhile to fork some threads to speedup the 4th process

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Hybrid Light-Weight Threads & Heavier-Weight Processes

- For example, a serial program runs in 100s
  - S: 5s is inherent sequential
  - P_1: 5s are parallelizable but not worth message passing
  - P_2: 90s are perfectly parallelizable
- MPI-only with 16 processes
  - Replicate the P_1 part of program on all processes
  - Speedup = 1 / (0.10 + 0.90/16) = 6.4
- Hybrid MPI & threads
  - Execute the replicated P_1 with 2 threads
  - Speedup = 1 / (0.05 + 0.05/2 + 0.90/16) = 7.6
  - 19% faster than MPI-only

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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);
}
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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++) {
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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]));
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



What Happened?

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

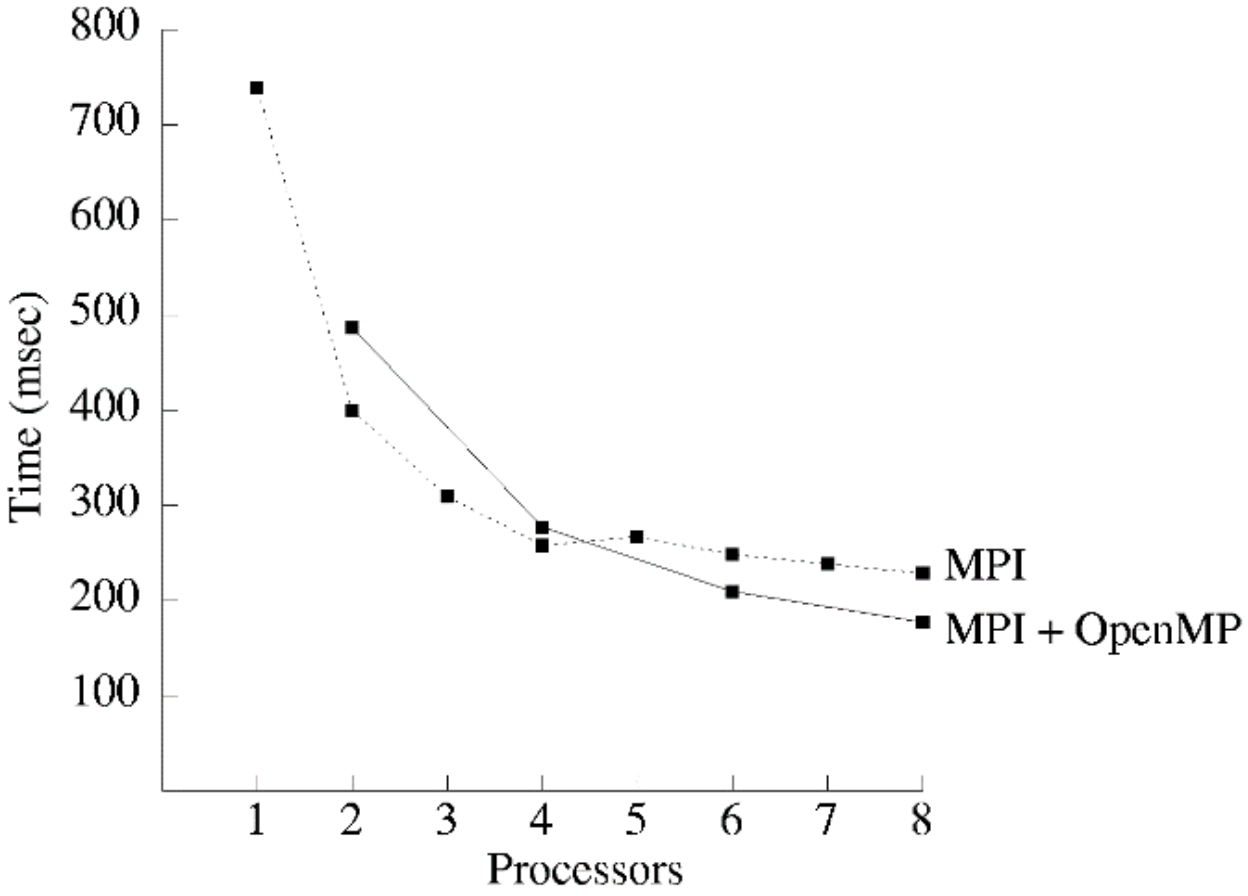
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Benchmarking

- **Target system: a commodity cluster with four dualprocessor nodes**
- **MPI program executes on 1, 2, ..., 8 CPUs**
  - **On 1, 2, 3, 4 CPUs, each process on different node, maximizing memory bandwidth per CPU**
- **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**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Results of Benchmarking



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Analysis of Results

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

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Case Study: Jacobi Method

- **Begin with MPI program that uses Jacobi method to solve steady state heat distribution problem**
- **Program based on rowwise block striped decomposition of two-dimensional matrix containing finite difference mesh (有限差分网格，FDM)**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Gaussian Elimination (高斯消元)

- **Used to solve** $Ax = b$ **when** A **is dense**
- **Reduces** $Ax = b$ **to upper triangular system** $Tx = c$
- **Back substitution can then solve** $Tx = c$ **for** x

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Gaussian Elimination Example (1/4)

$$
\begin{aligned}
4x_0 + 6x_1 + 2x_2 - 2x_3 &= 8 \\
2x_0 + 5x_2 - 2x_3 &= 4 \\
-4x_0 - 3x_1 - 5x_2 + 4x_3 &= 1 \\
8x_0 + 18x_1 - 2x_2 + 3x_3 &= 40
\end{aligned}
$$

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Gaussian Elimination Example (2/4)

$$
\begin{aligned}
4x_0 + 6x_1 + 2x_2 - 2x_3 &= 8 \\
-3x_1 + 4x_2 - 1x_3 &= 0 \\
+3x_1 - 3x_2 + 2x_3 &= 9 \\
+6x_1 - 6x_2 + 7x_3 &= 24
\end{aligned}
$$

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Gaussian Elimination Example (3/4)

$$
\begin{aligned}
4x_0 + 6x_1 + 2x_2 - 2x_3 &= 8 \\
-3x_1 + 4x_2 - 1x_3 &= 0 \\
1x_2 + 1x_3 &= 9 \\
2x_2 + 5x_3 &= 24
\end{aligned}
$$

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Gaussian Elimination Example (4/4)

$$
\begin{aligned}
4x_0 + 6x_1 + 2x_2 - 2x_3 &= 8 \\
-3x_1 + 4x_2 - 1x_3 &= 0 \\
1x_2 + 1x_3 &= 9 \\
3x_3 &= 6
\end{aligned}
$$

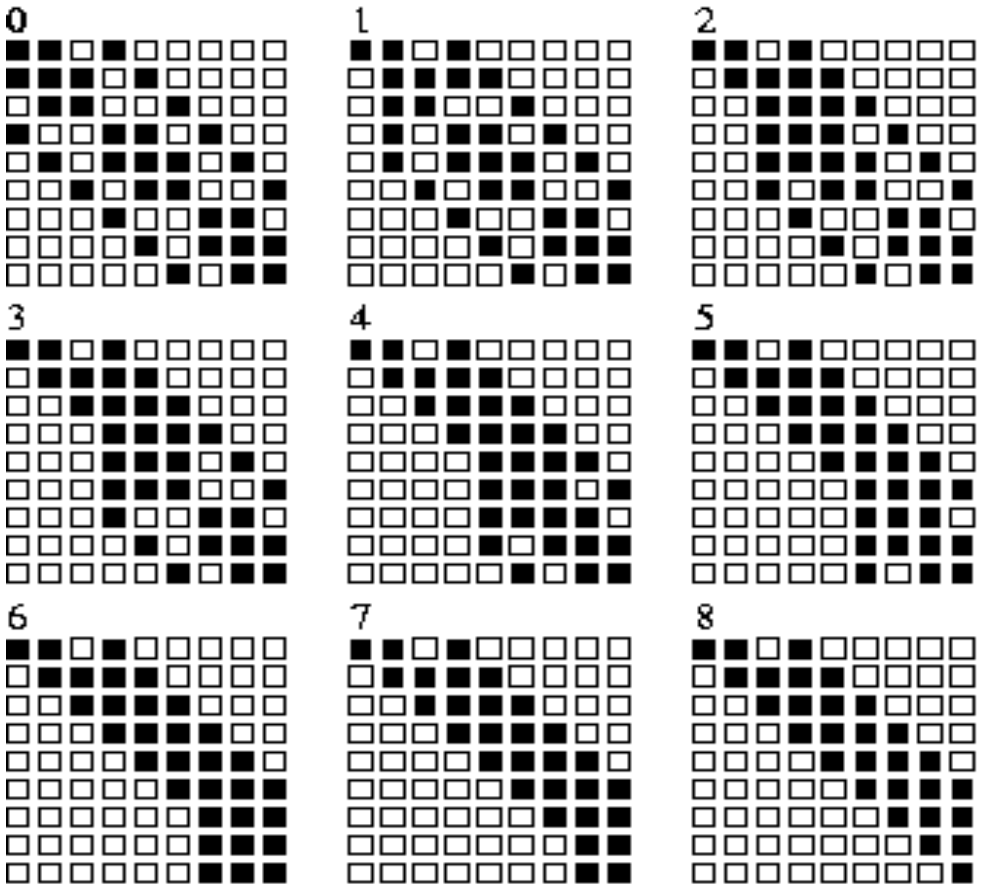
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Sparse Systems

- **Gaussian elimination not well-suited for sparse systems**
- **Coefficient matrix gradually fills with nonzero elements**
  - **Increases storage requirements**
  - **Increases total operation count**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Example of "Fill" in Gaussian Elimination



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



Iterative Methods

- **Iterative method: algorithm that generates a series of approximations to solution's value**
- **Require less storage than direct methods**
- **Since they avoid computations on zero elements, they can save a lot of computations**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Jacobi Method

Let

$$A\mathbf{x} = \mathbf{b}$$

be a square system of n linear equations, where:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}.$$

Then A can be decomposed into a diagonal component D, and the remainder R:

$$A = D + R \quad \text{where} \quad D = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ 0 & a_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{nn} \end{bmatrix} \text{ and } R = \begin{bmatrix} 0 & a_{12} & \cdots & a_{1n} \\ a_{21} & 0 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 0 \end{bmatrix}.$$

The solution is then obtained iteratively via

$$\mathbf{x}^{(k+1)} = D^{-1}(\mathbf{b} - R\mathbf{x}^{(k)}),$$

where $\mathbf{x}^{(k)}$ is the kth approximation or iteration of $\mathbf{x}$ and $\mathbf{x}^{(k+1)}$ is the next or $k + 1$ iteration of $\mathbf{x}$. The element-based formula is thus:

$$x_i^{(k+1)} = \frac{1}{a_{ii}} \left(b_i - \sum_{j \neq i} a_{ij} x_j^{(k)} \right), \quad i = 1, 2, \ldots, n.$$

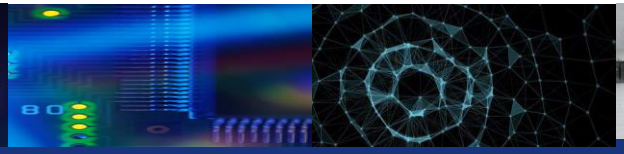
Values of elements of vector x at iteration k+1 depend upon values of vector x at iteration k

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Rate of Convergence

- **Even when Jacobi method, rate of convergence often too slow to make them practical**
- **We will move on to an iterative method with much faster convergence**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.



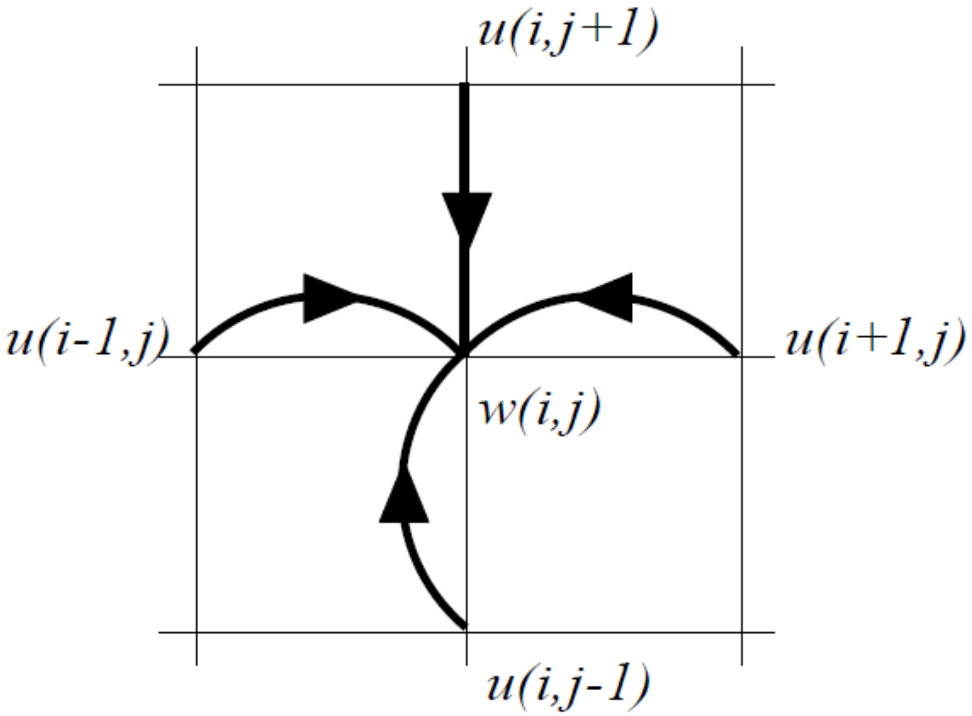
Methodology

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

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Heart of Sequential C Program

```
w[i][j] = (u[i-1][j] + u[i+1][j] +
u[i][j-1] + u[i][j+1]) / 4.0;
```



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Heart of Sequential C Program

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

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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);
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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++;
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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`

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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);
```

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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**

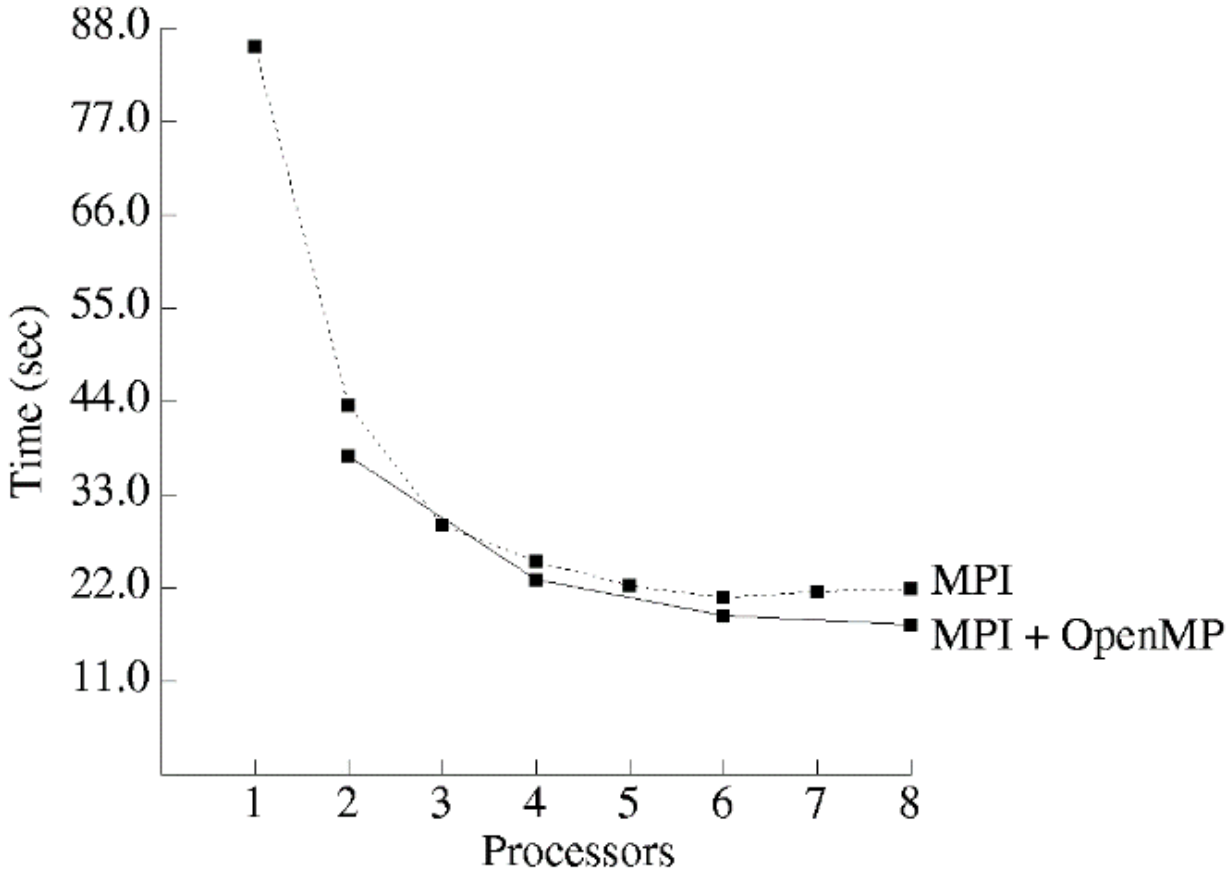
Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Benchmarking

- **Target system: a commodity cluster with four dual-processor nodes**
- **C+MPI program executes on 1, 2, ..., 8 processes**
  - **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**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Benchmarking Results



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

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**

Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Summary

- **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**
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Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

Thank You !