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Chapter 3 Distributed Memory Programming with MPI

软件学院　邵兵

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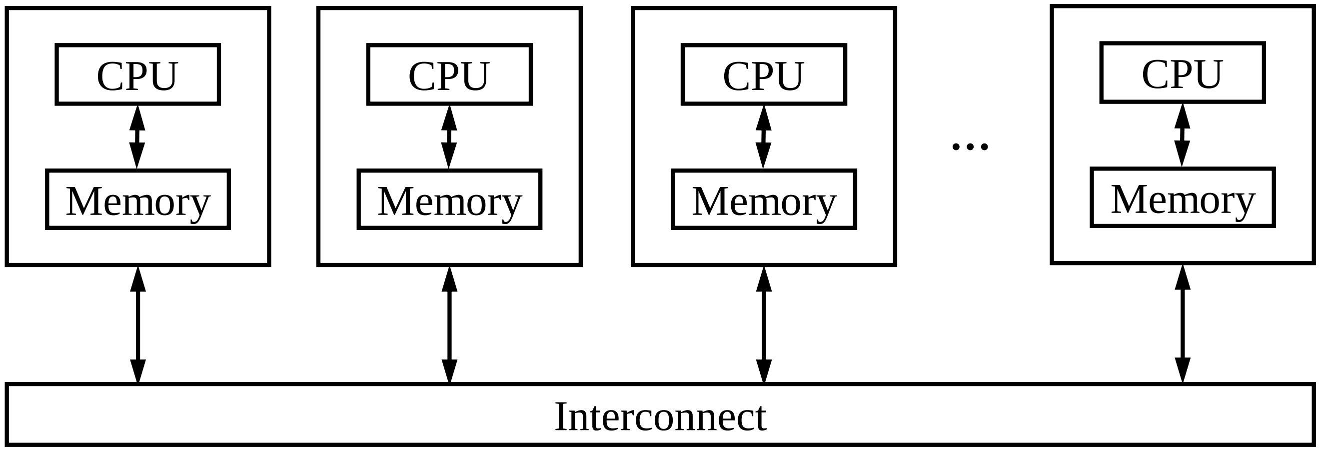
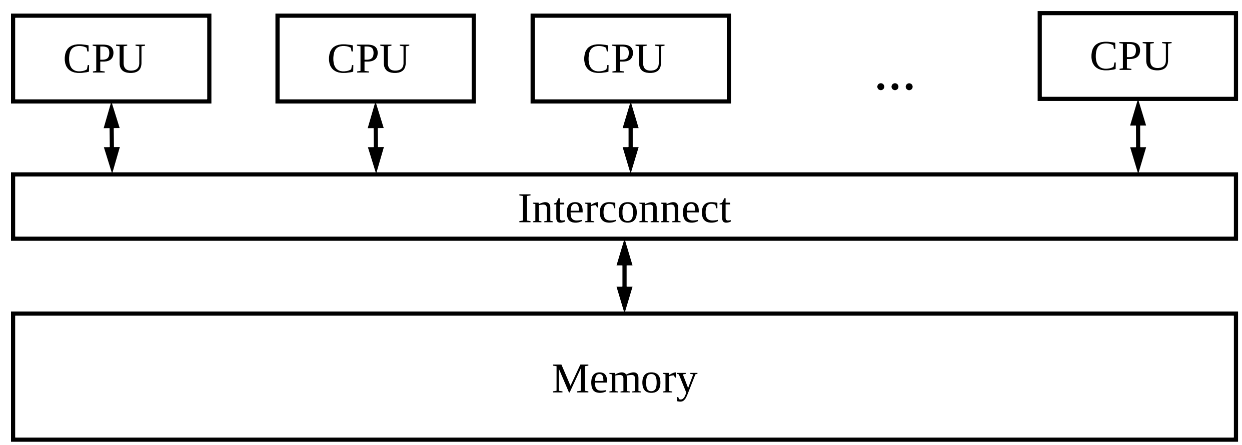
A distributed memory system





A shared memory system

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1. WRITING OUR FIRST MPI PROGRAM

```c
#include <stdio.h>
int main(void) {
    printf("hello, world\n");

    return 0;
}
```

(a classic)

Identifying MPI processes

- **Common practice to identify processes by nonnegative integer ranks.**

- ***p* processes are numbered *0, 1, 2, .. p-1***

Our first MPI program

```c
#include <stdio.h>
#include <string.h>    /* For strlen             */
#include <mpi.h>       /* For MPI functions, etc */

const int MAX_STRING = 100;

int main(void) {
   char    greeting[MAX_STRING];
   int     comm_sz;     /* 处理器个数 */
   int     my_rank;     /* 当前进程（My process）序号 */

   MPI_Init(NULL, NULL);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);

   if (my_rank != 0) {
      sprintf(greeting, "Greetings from process %d of %d!",
            my_rank, comm_sz);
      MPI_Send(greeting, strlen(greeting)+1, MPI_CHAR, 0, 0,
            MPI_COMM_WORLD);
   } else {
      printf("Greetings from process %d of %d!\n", my_rank, comm_sz);
      for (int q = 1; q < comm_sz; q++) {
         MPI_Recv(greeting, MAX_STRING, MPI_CHAR, q,
            0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
         printf("%s\n", greeting);
      }
   }

   MPI_Finalize();
   return 0;
} /* main */
```

mpi_hello.c

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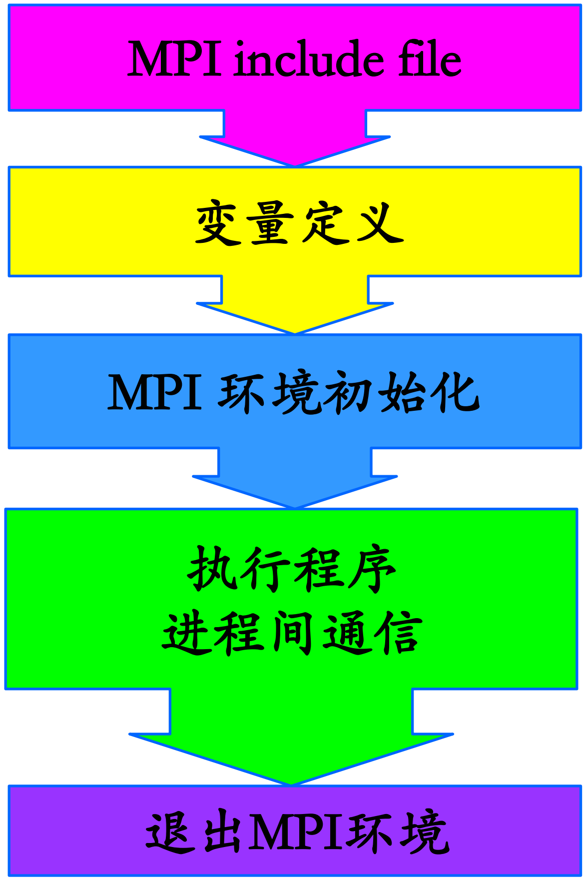
MPI程序基本结构

```c
#include <mpi.h>
void main(int argc, char *argv[]) {
   int comm_sz, my_rank, ierr;
   ierr = MPI_Init(&argc, &argv);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);
   /* Do some works  */
   ierr = MPI_Finalize();
}
```



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Compilation

wrapper script to compile

source file

```
mpicc -g -Wall -o mpi_hello mpi_hello.c
```

produce debugging information

create this executable file name (as opposed to default a.out)

turns on all warnings

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Execution

```
mpiexec -n <number of processes> <executable>
```

```
mpiexec -n 1 ./mpi_hello
```

run with 1 process

```
mpiexec -n 4 ./mpi_hello
```

run with 4 processes

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Execution

```
mpiexec -n 1 ./mpi_hello
```

```
Greetings from process 0 of 1 !
```

```
mpiexec -n 4 ./mpi_hello
```

```
Greetings from process 0 of 4 !
Greetings from process 1 of 4 !
Greetings from process 2 of 4 !
Greetings from process 3 of 4 !
```

MPI Programs

- Written in C.
  - Has main.
  - Uses stdio.h, string.h, etc.
- Need to add mpi.h header file.
- Identifiers defined by MPI start with "MPI_".
- First letter following underscore is uppercase.
  - For function names and MPI-defined types.
  - Helps to avoid confusion.

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MPI Components

- **MPI_Init**
  - **Tells MPI to do all the necessary setup.**

```
int MPI_Init(
    int*       argc_p     /* in/out */,
    char***    argv_p     /* in/out */);
```

- **MPI_Finalize**
  - **Tells MPI we're done, so clean up anything allocated for this program.**

```
int MPI_Finalize(void);
```

Basic Outline

```
...
#include <mpi.h>
...
int main(int argc, char* argv[]) {
    ...
    /* No MPI calls before this */
    MPI_Init(&argc, &argv);
    ...
    MPI_Finalize();
    /* No MPI calls after this */
    ...
    return 0;
}
```

Communicators

- **A collection of processes that can send messages to each other.**
- **MPI_Init defines a communicator that consists of all the processes created when the program is started.**
- **Called MPI_COMM_WORLD.**

Communicators

```
int MPI_Comm_size(
    MPI_Comm    comm        /* in  */,
    int*        comm_sz_p   /* out */);
```

number of processes in the communicator

```
int MPI_Comm_rank(
    MPI_Comm    comm        /* in  */,
    int*        my_rank_p   /* out */);
```

my rank
(the process making this call)

SPMD

- **Single-Program Multiple-Data**
- **We compile <u>one</u> program.**
- **Process 0 does something different.**
  - **Receives messages and prints them while the other processes do the work.**

- **The if-else construct makes our program SPMD.**

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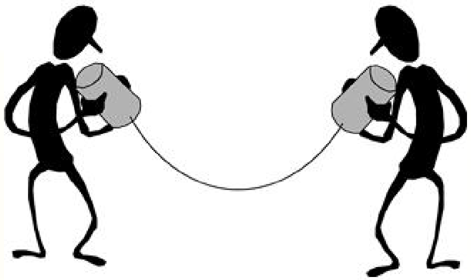
Communication

```
int MPI_Send(
    void*          msg_buf_p      /* in */,
    int            msg_size       /* in */,
    MPI_Datatype   msg_type       /* in */,
    int            dest           /* in */,
    int            tag            /* in */,
    MPI_Comm       communicator   /* in */);
```

消息缓冲

消息信封



Message

子程序名　　消息长度　　接收进程标识号　　通信子

MPI_Send (buffer, count, datatype, destination, tag, communicator)

消息地址　　消息数据类型　　消息标签

快递详情单

025800001

寄件人姓名 始发地
单位名称
寄件人详细地址
联系电话（非常重要） 手机
文件 物品 如系物品，请据实填写内件名称及数量。如需保价，请据实申报保价金额并交纳保价费。
重量 千克 体积 长 ×宽 ×高 = 厘米
内件品名及数量 特别注意：请阅读背面快递服务协议，贵重物品请保价，未保价物品的理赔限额为资费的5倍。
寄件人签名： 收寄人员签章：
证件号 年 月 日 时

收件人姓名 目的地
单位名称
收件人详细地址
联系电话（非常重要） 手机
付款方式 现金 到付 协议结算
保价 保价金额 万 仟 佰 拾 元（大写）
代收货款¥ 万 仟 佰 拾 元（大写）
运费¥ 加急费¥ 包装费¥ 保价费¥ 总计¥
收件人签名： 证件号 年 月 日 时
我们不是无所不能，但一定竭尽所能！
备注：

025800001 填写本详单前，请务必阅读背面快递服务协议！使用本单表示您理解并接受协议内容。

第二联 财务联

Data types

MPI datatype	C datatype
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_LONG_LONG	signed long long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	
MPI_PACKED	

为什么要使用消息标签(Tag)?

为了说明为什么要用标签，我们先来看右面一段没有使用标签的代码。

这段代码打算传送A的前32个字节进入X，传送B的前16个字节进入Y。但是， 如果消息B尽管后发送但先到达进程Q，就会被第一个recv()接收在X中。

使用标签可以避免这个错误。

未使用标签

Process P:	Process Q:
send(A, 32, Q) send(B, 16, Q)	recv(X, 32, P) recv(Y, 16, P)

使用了标签

Process P:	Process Q:
send(A, 32, Q, tag1) send(B, 16, Q, tag2)	recv (X, 32, P, tag1) recv (Y, 16, P, tag2)

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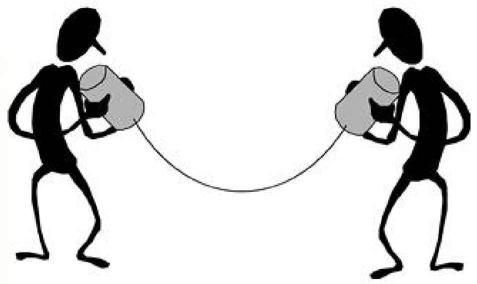
Communication

```
int MPI_Recv(
    void*           msg_buf_p      /* out */,
    int             buf_size       /* in  */,
    MPI_Datatype    buf_type       /* in  */,
    int             source         /* in  */,
    int             tag            /* in  */,
    MPI_Comm        communicator   /* in  */,
    MPI_Status*     Status_p       /* out */);
```



Message matching

```
MPI_Send(send_buf_p, send_buf_sz, send_type, dest, send_tag,
         send_comm);
```

r

MPI_Send

src = q

MPI_Recv

dest = r

```
MPI_Recv(recv_buf_p, recv_buf_sz, recv_type, src, recv_tag,
         recv_comm, &status);
```

q

Message matching "wildcard" arguments

- It's possible that the receiving process doesn't know the order in which the messages will be sent, and one process can receive multiple messages with different tags from another process.

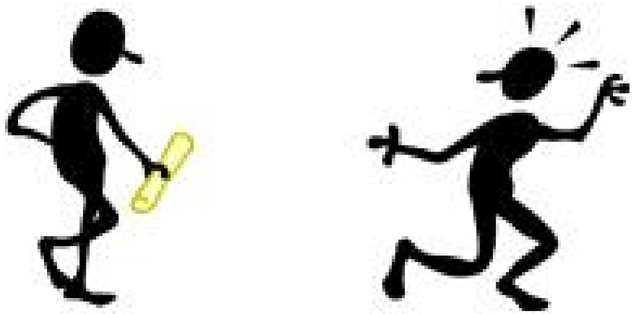
q

```
for (i = 1; i < comm_sz; i++) {
   MPI_Recv(result, result_sz, result_type, MPI_ANY_SOURCE,
         MPI_ANY_TAG, comm, MPI_STATUS_IGNORE);
   Process_result(result);
}
```

recv_tag

Receiving messages

- **A receiver can get a message without knowing:**
  - **the amount of data in the message,**
  - **the sender of the message,**
  - **or the tag of the message.**



status_p argument

```
MPI_Recv(recv_buf_p, recv_buf_sz, recv_type, src, recv_tag,
         recv_comm, &status);
```

MPI_Status*

MPI_SOURCE

MPI_TAG

MPI_ERROR

```
MPI_Status* status;

status.MPI_SOURCE
status.MPI_TAG
status.MPI_ERROR
```

How much data am I receiving?

```
int MPI_Get_count(
      MPI_Status*   Status_p    /* in  */,
      MPI_Datatype  type        /* in  */,
      int*          count_p     /* out */);
```

Issues with send and receive

- **Exact behavior is determined by the MPI implementation.**
- **MPI_Send may behave differently with regard to buffer size, cutoffs and blocking.**
- **MPI_Recv always blocks until a matching message is received.**
- **Know your implementation;**
  don't make assumptions!

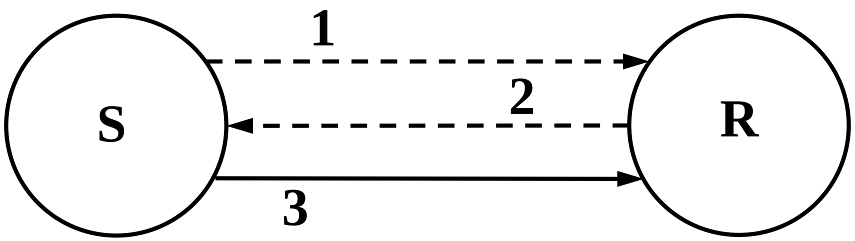
MPI中的四种通信模式 (communication mode)

① 同步的(synchronous)

发送进程直到相应的接收过程已经启动才返回，因此接收端要有存放到达消息的应用缓冲。

注意：在MPI中可以有非阻塞的同步发送，它的返回不意味着消息已经被发出！它的实现不需要在接收端有附加的缓冲，但需要在发送端有一个系统缓冲。为了消除额外的消息拷贝，应使用阻塞的同步发送。

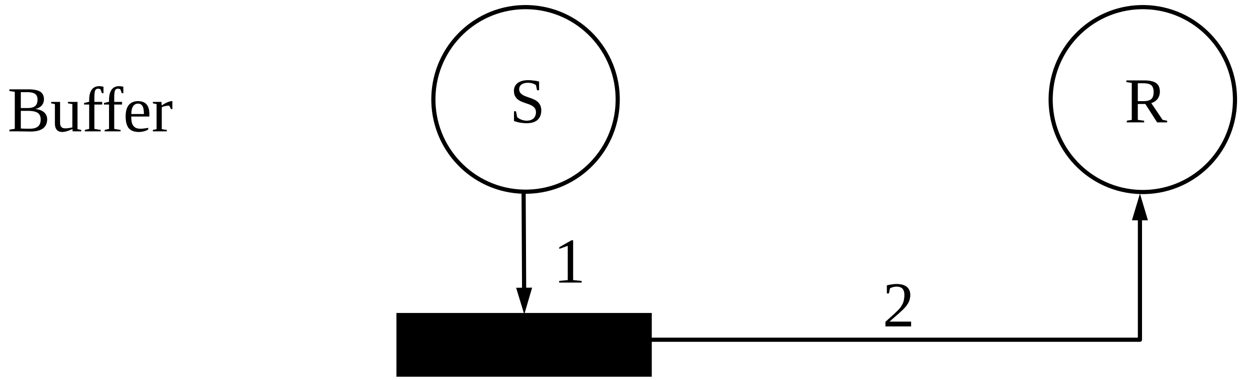
Synchronous



MPI中的四种通信模式

② 缓冲的(buffered)

缓冲的发送假定能得到一定大小的缓冲空间，它必须事先由用户程序通过调用子例程**MPI_Buffer_attch(buffer, size)**来定义，由它来分配大小为**size**的用户缓冲。这个缓冲可以用**MPI_Buffer_detach(*buffer, *size)**来实现。

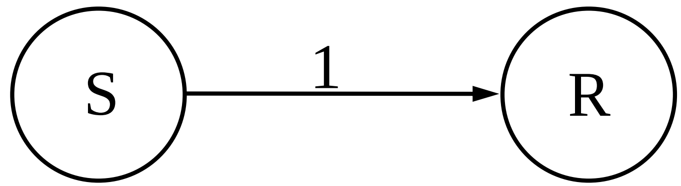


MPI中的四种通信模式

③ 标准的(standard)

发送可以是同步的或缓冲的，取决于实现。

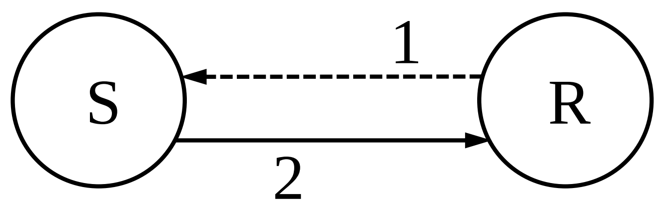
Standard



④ 就绪的(ready)

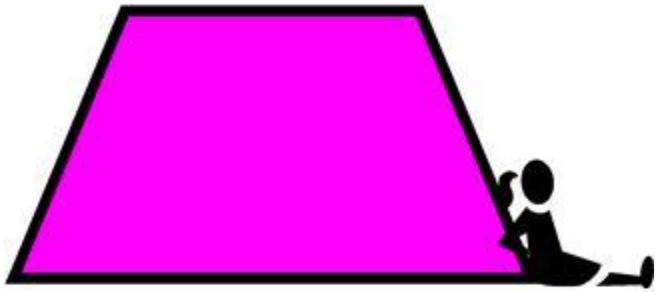
在肯定相应的接收已经开始才进行发送。它不像在同步模式中那样需要等待。这就允许在相同的情况下实际使用一个更有效的通信协议。

Ready



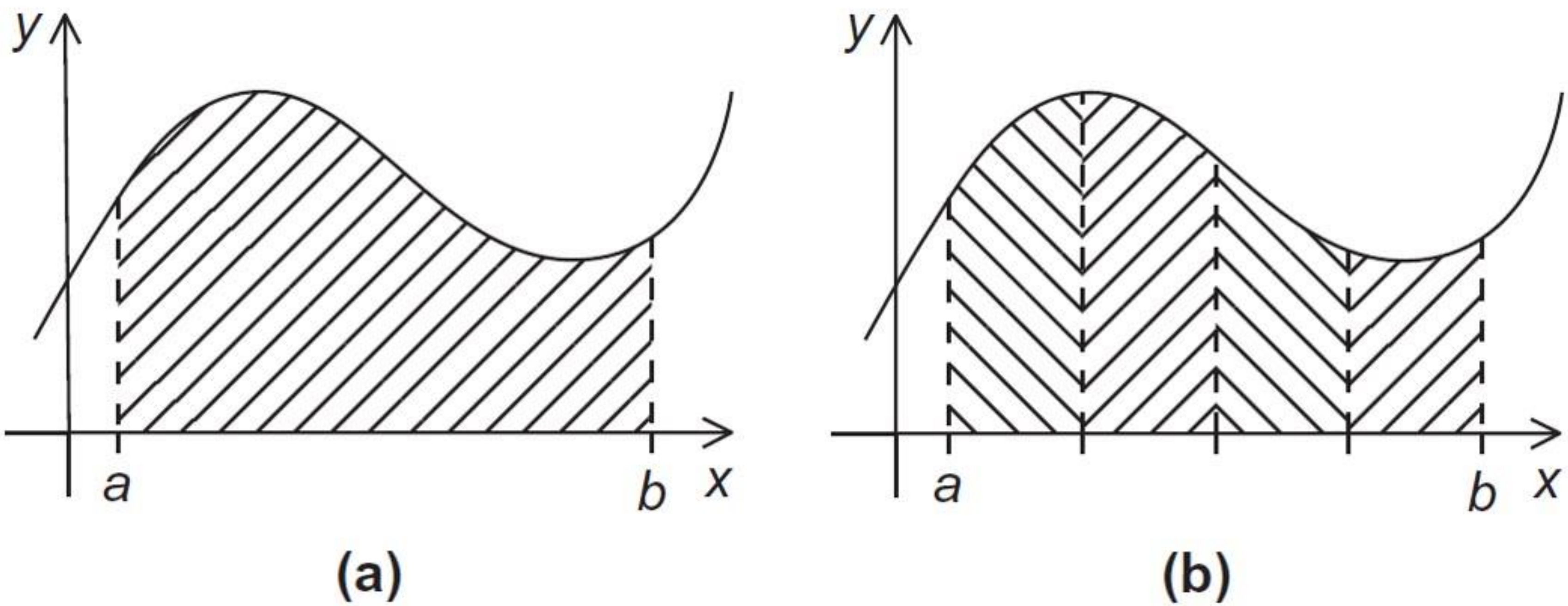
MPI点对点通信中不同的发送和接收操作

通信模式	MPI Primitive	Blocking	Non-Blocking
标准通信	Standard Send	MPI_Send	MPI_Isend
同步通信	Synchronous Send	MPI_ Ssend	MPI_ Issend
缓冲通信	Buffered Send	MPI_ Bsend	MPI_ Ibsend
就绪通信	Ready Send	MPI_ Rsend	MPI_ Irsend
	Receive	MPI_Recv	MPI_Irecv
	Completion Check	MPI_Wait	MPI_Test

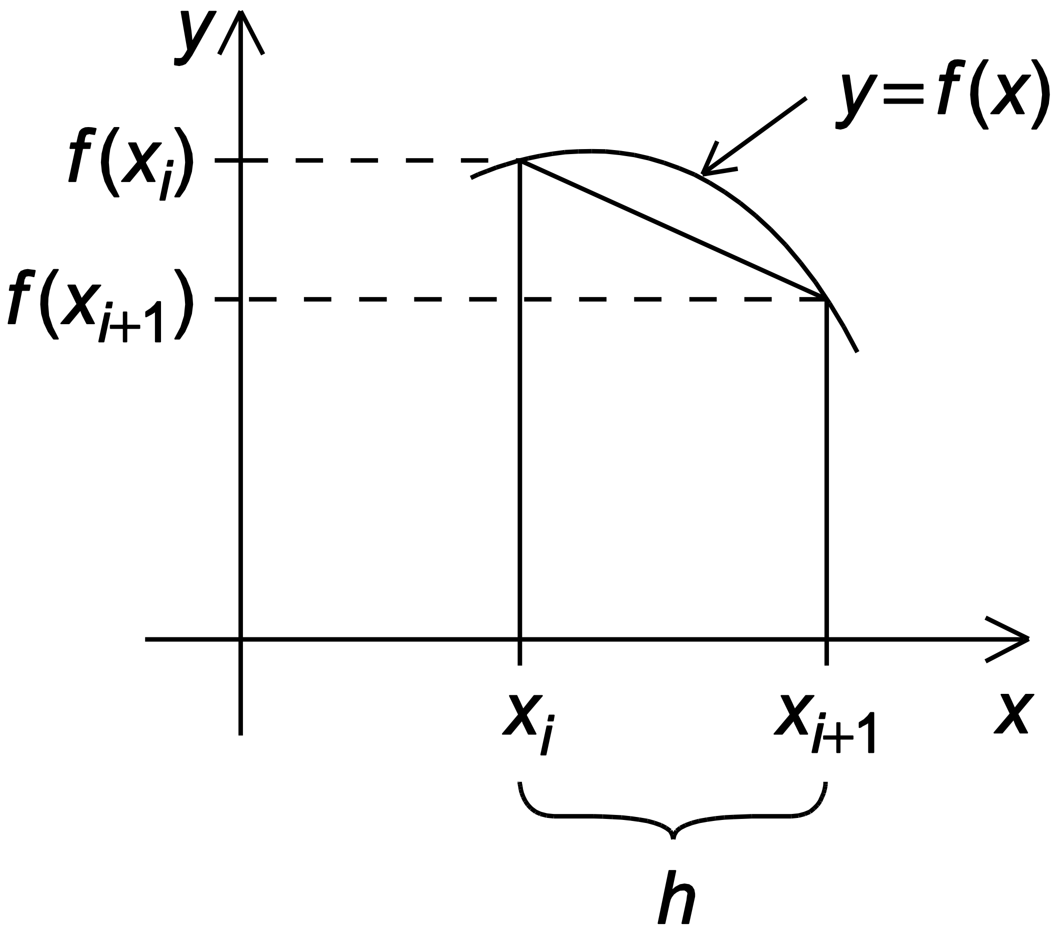


2. TRAPEZOIDAL RULE IN MPI

The Trapezoidal Rule



One trapezoid



The Trapezoidal Rule

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$

$$h = \frac{b-a}{n}$$

$$x_0 = a,\ x_1 = a + h,\ \ x_2 = a + 2h, \ldots,\ \ x_{n-1} = a + (n-1)h,\ \ x_n = b$$

$$\text{Sum of trapezoid areas} = h[f(x_0)/2 + f(x_1) + f(x_2) + \cdots + f(x_{n-1}) + f(x_n)/2]$$

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Pseudo-code for a serial program

```
/* Input: a, b, n */
h = (b - a) / n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n - 1; i++) {
   x_i = a + i * h;
   approx += f(x_i);
}
approx = h * approx;
```

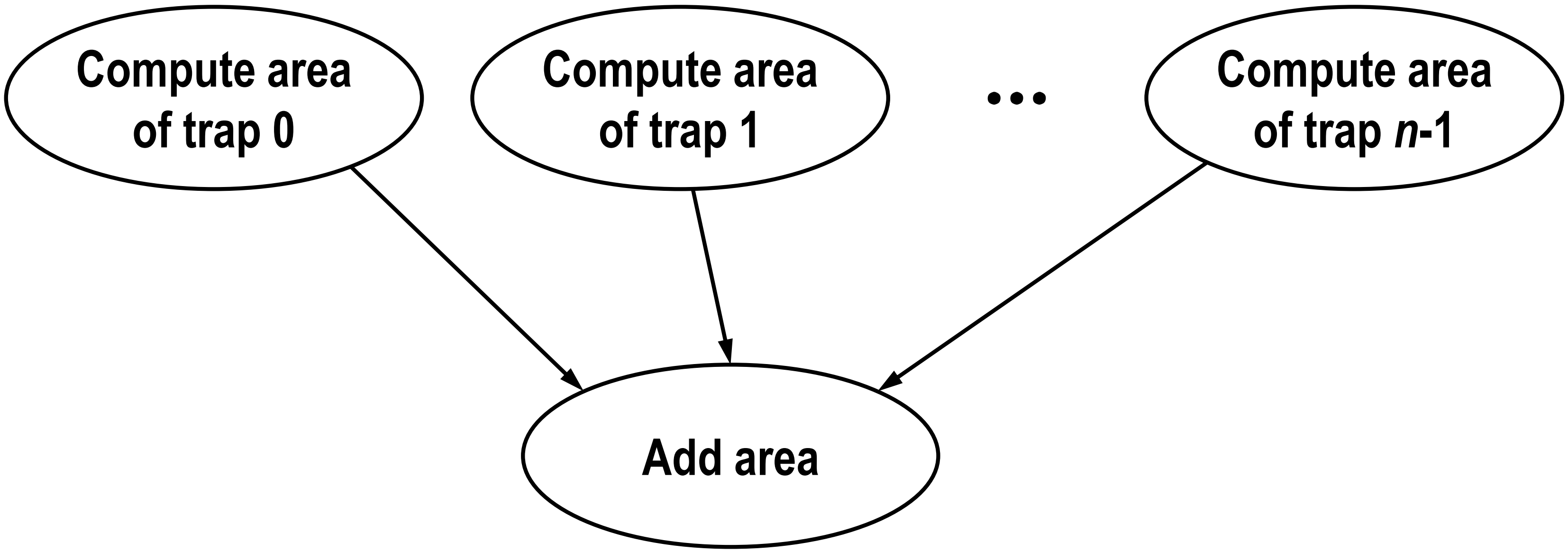
Parallelizing the Trapezoidal Rule

1. Partition problem solution into tasks.
2. Identify communication channels between tasks.
3. Aggregate tasks into composite tasks.
4. Map composite tasks to cores.

Parallel pseudo-code

```
Get a, b, n;
h = (b - a) / n;
local_n = n / comm_sz;
local_a = a + my_rank * local_n * h;
local_b = local_a + local_n * h;
local_integral = Trap(local_a, local_b, local_n, h);
if (my_rank != 0)
   Send local_integral to process 0;
else /* my_rank == 0 */
   total_integral = local_integral;
   for (proc = 1; proc < comm_sz; proc++) {
      Receive local_integral from proc;
      total_integral += local_integral;
   }
}
if (my_rank == 0)
   print result;
```

Tasks and communications for Trapezoidal Rule



First version (1)

```
int main(void) {
   int my_rank, comm_sz, n = 1024, local_n;
   double a = 0.0, b = 3.0, h, local_a, local_b;
   double local_int, total_int;
   int source;

   MPI_Init(NULL, NULL);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);

   h = (b - a)/n;          /* h is the same for all processes */
   local_n = n/comm_sz; /* So is the number of trapezoids  */

   local_a = a + my_rank * local_n * h;
   local_b = local_a + local_n * h;
   local_int = Trap(local_a, local_b, local_n, h);

   if (my_rank != 0) {
      MPI_Send(&local_int, 1, MPI_DOUBLE, 0, 0,
            MPI_COMM_WORLD);
```

First version (2)

```
} else {
      total_int = local_int;
      for (source = 1; source < comm_sz; source++) {
         MPI_Recv(&local_int, 1, MPI_DOUBLE, source, 0,
                MPI_COMM_WORLD, MPI_STATUS_IGNORE);
         total_int += local_int;
      }
   }

   if (my_rank == 0) {
      printf("With n = %d trapezoids, our estimate\n", n);
      printf("of the integral from %f to %f = %.15e\n",
          a, b, total_int);
   }
   MPI_Finalize();
   return 0;
}  /* main */
```

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First version (3)

```c
double Trap(
        double left_endpt  /* in */,
        double right_endpt /* in */,
        int    trap_count  /* in */,
        double base_len    /* in */) {
    double estimate, x;
    int i;

    estimate = (f(left_endpt) + f(right_endpt))/2.0;
    for (i = 1; i <= trap_count - 1; i++) {
        x = left_endpt + i*base_len;
        estimate += f(x);
    }
    estimate = estimate*base_len;

    return estimate;
} /* Trap */
```

Dealing with I/O

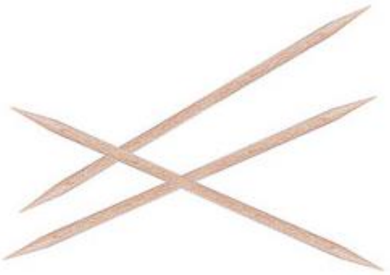
```
#include <stdio.h>
#include <mpi.h>

int main(void) {
   int my_rank, comm_sz;

   MPI_Init(NULL, NULL);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);

   printf("Proc %d of %d > Does anyone have a toothpick?\n",
         My_rank, comm_sz);

   MPI_Finalize();
   return 0;
} /* main */
```

Each process just prints a message.

Running with 6 processes

```
Proc 0 of 6 > Does anyone have a toothpick?
Proc 1 of 6 > Does anyone have a toothpick?
Proc 2 of 6 > Does anyone have a toothpick?
Proc 4 of 6 > Does anyone have a toothpick?
Proc 3 of 6 > Does anyone have a toothpick?
Proc 5 of 6 > Does anyone have a toothpick?
```

unpredictable output



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Input

- **Most MPI implementations only allow process 0 in MPI_COMM_WORLD access to stdin.**
- **Process 0 must read the data (scanf) and send to the other processes.**

教材有误

```
...
MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);

Get_input(my_rank, comm_sz, &a, &b, &n);

H = (b - a)/n
...
```

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Function for reading user input

```
void Get_input(
      int      my_rank   /* in  */,
      int      comm_sz   /* in  */,
      double*  a_p       /* out */,
      double*  b_p       /* out */,
      int*     n_p       /* out */) {
   int dest;

   if (my_rank == 0) {
      printf("Enter a, b, and n\n");
      scanf("%lf %lf %d", a_p, b_p, n_p);
      for (dest = 1; dest < comm_sz; dest++) {
         MPI_Send(a_p, 1, MPI_DOUBLE, dest, 0, MPI_COMM_WORLD);
         MPI_Send(b_p, 1, MPI_DOUBLE, dest, 0, MPI_COMM_WORLD);
         MPI_Send(n_p, 1, MPI_INT, dest, 0, MPI_COMM_WORLD);
      }
   } else { /* my_rank != 0 */
      MPI_Recv(a_p, 1, MPI_DOUBLE, 0, 0, MPI_COMM_WORLD,
            MPI_STATUS_IGNORE);
      MPI_Recv(b_p, 1, MPI_DOUBLE, 0, 0, MPI_COMM_WORLD,
            MPI_STATUS_IGNORE);
      MPI_Recv(n_p, 1, MPI_INT, 0, 0, MPI_COMM_WORLD,
            MPI_STATUS_IGNORE);
   }
}  /* Get_input */
```

3. COLLECTIVE COMMUNICATION

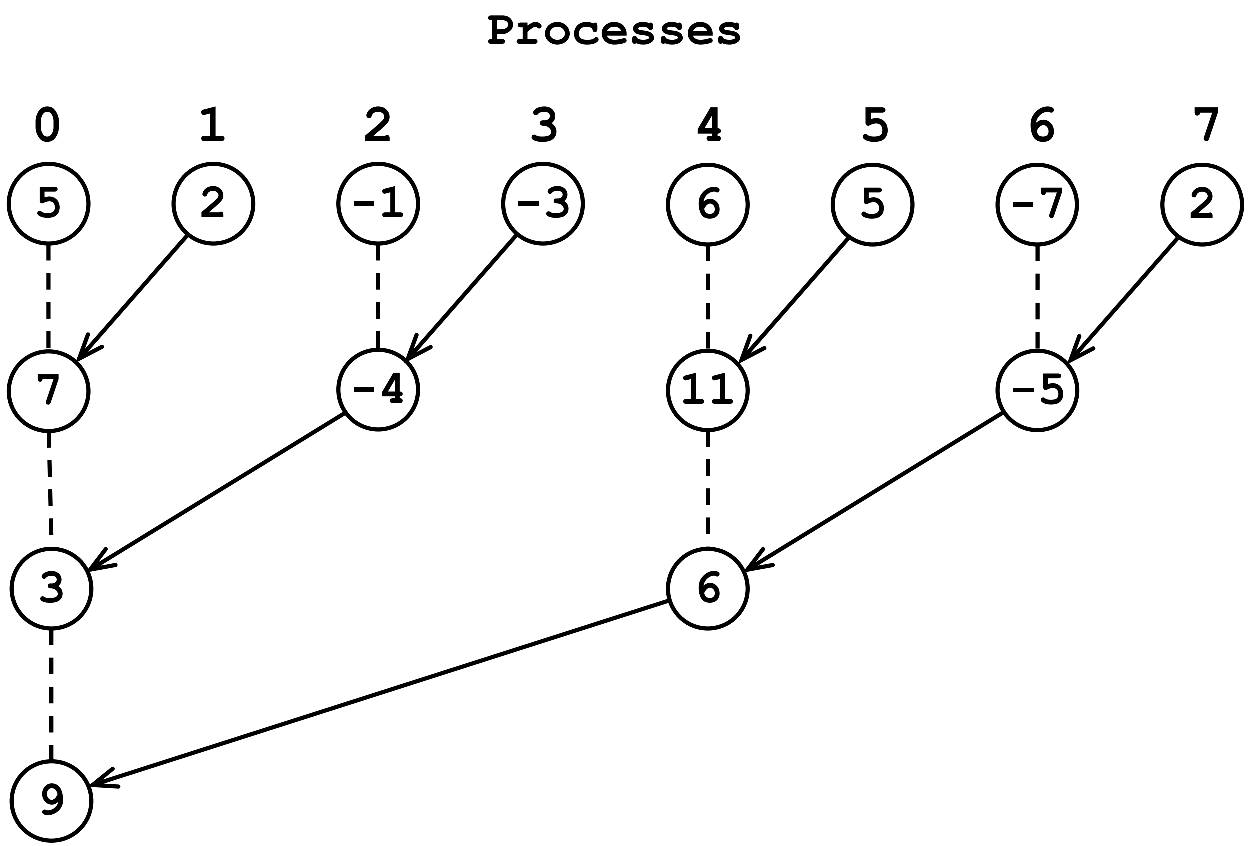
Optimize the trapezoidal rule program

The "global sum" after each process has computed its part of the integral.

```
if (my_rank != 0) {
   MPI_Send(&local_int, 1, MPI_DOUBLE, 0, 0,
         MPI_COMM_WORLD);
} else {
   total_int = local_int;
   for (source = 1; source < comm_sz; source++) {
      MPI_Recv(&local_int, 1, MPI_DOUBLE, source, 0,

            MPI_COMM_WORLD, MPI_STATUS_IGNORE);
      total_int += local_int;
   }
}
```

A tree-structured global sum



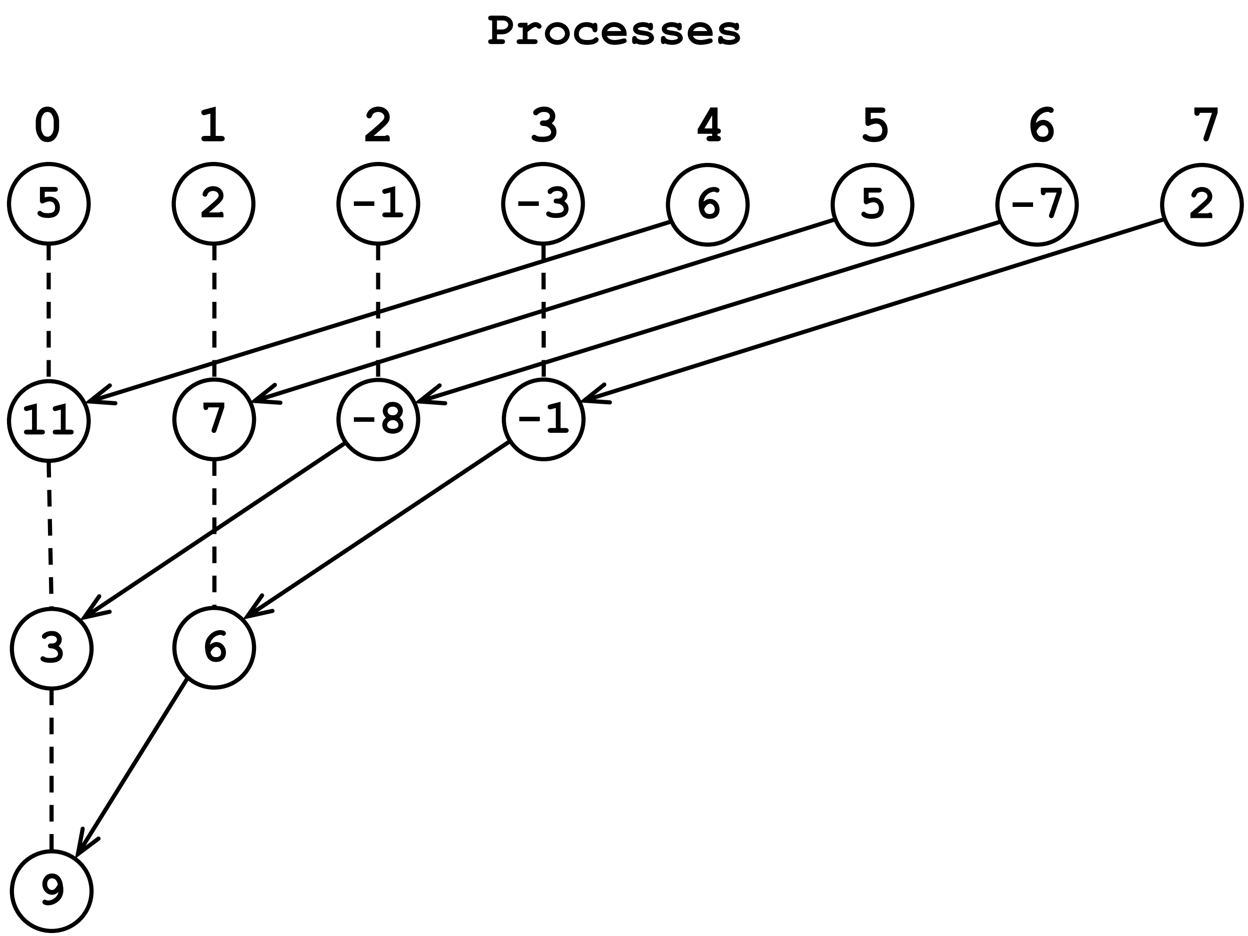
Tree-structured communication

1. (a) Process 1 sends to 0, 3 sends to 2, 5 sends to 4, and 7 sends to 6.
   (b) Processes 0, 2, 4, and 6 add in the received values.

2. (a) Processes 2 and 6 send their new values to processes 0 and 4, respectively.
   (b) Processes 0 and 4 add the received values into their new values.

3. (a) Process 4 sends its newest value to process 0.
   (b) Process 0 adds the received value to its newest value.

An alternative tree-structured global sum



(1) MPI_Reduce

```
int MPI_Reduce(
    void*           input_data_p     /* in  */,
    void*           output_data_p    /* out */,
    int             count            /* in  */,
    MPI_Datatype    datatype         /* in  */,
    MPI_Op          operator         /* in  */,
    int             dest_process     /* in  */,
    MPI_Comm        comm             /* in  */);
```

```
MPI_Reduce(&local_int, &total_int, 1, MPI_DOUBLE, MPI_SUM,
      0, MPI_COMM_WORLD);
```

```
double local_x[N], sum[N];
...
MPI_Reduce(local_x, sum, N, MPI_DOUBLE, MPI_SUM, 0,
      MPI_COMM_WORLD);
```

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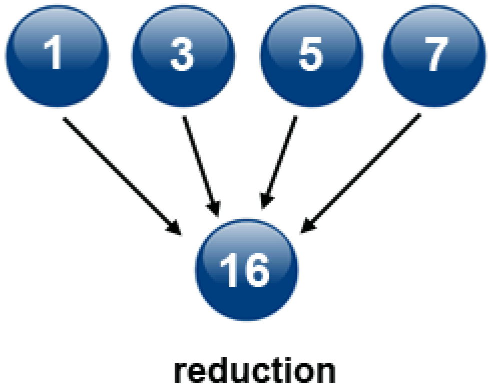
Predefined reduction operators in MPI

Operation Value	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical and
MPI_BAND	Bitwise and
MPI_LOR	Logical or
MPI_BOR	Bitwise or
MPI_LXOR	Logical exclusive or
MPI_BXOR	Bitwise exclusive or
MPI_MAXLOC	Maximum and location of maximum
MPI_MINLOC	Minimum and location of minimum



Collective vs. Point-to-Point Communications

- All the processes in the communicator must call the same collective function.

- For example, a program that attempts to match a call to MPI_Reduce on one process with a call to MPI_Recv on another process is erroneous, and, in all likelihood, the program will hang or crash.

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Collective vs. Point-to-Point Communications

- **The arguments passed by each process to an MPI collective communication must be "compatible."**

- **For example, if one process passes in 0 as the dest_process and another passes in 1, then the outcome of a call to MPI_Reduce is erroneous, and, once again, the program is likely to hang or crash.**

Collective vs. Point-to-Point Communications

- **The output_data_p argument is only used on dest_process.**

- **However, all of the processes still need to pass in an actual argument corresponding to output_data_p, even if it's just NULL.**

Collective vs. Point-to-Point Communications

- **Point-to-point communications are matched on the basis of tags and communicators.**
- **Collective communications don't use tags. They're matched solely on the basis of the communicator and the order in which they're called.**

Example (1)

Time	Process 0	Process 1	Process 2
0	`a = 1; c = 2`	`a = 1; c = 2`	`a = 1; c = 2`
1	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`
2	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`

Multiple calls to MPI_Reduce

Example (2)

- **Suppose that each process calls MPI_Reduce with operator MPI_SUM, and destination process 0.**

- **At first glance, it might seem that after the two calls to MPI_Reduce, the value of b will be 3, and the value of d will be 6.**

Example (3)

- **However, the names of the memory locations are irrelevant to the matching of the calls to MPI_Reduce.**

- **The order of the calls will determine the matching so the value stored in b will be 1+2+1 = 4, and the value stored in d will be 2+1+2 = 5.**

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Anther question

```
MPI_Reduce(&x, &x, 1, MPI_DOUBLE, MPI_SUM, 0, comm);
```

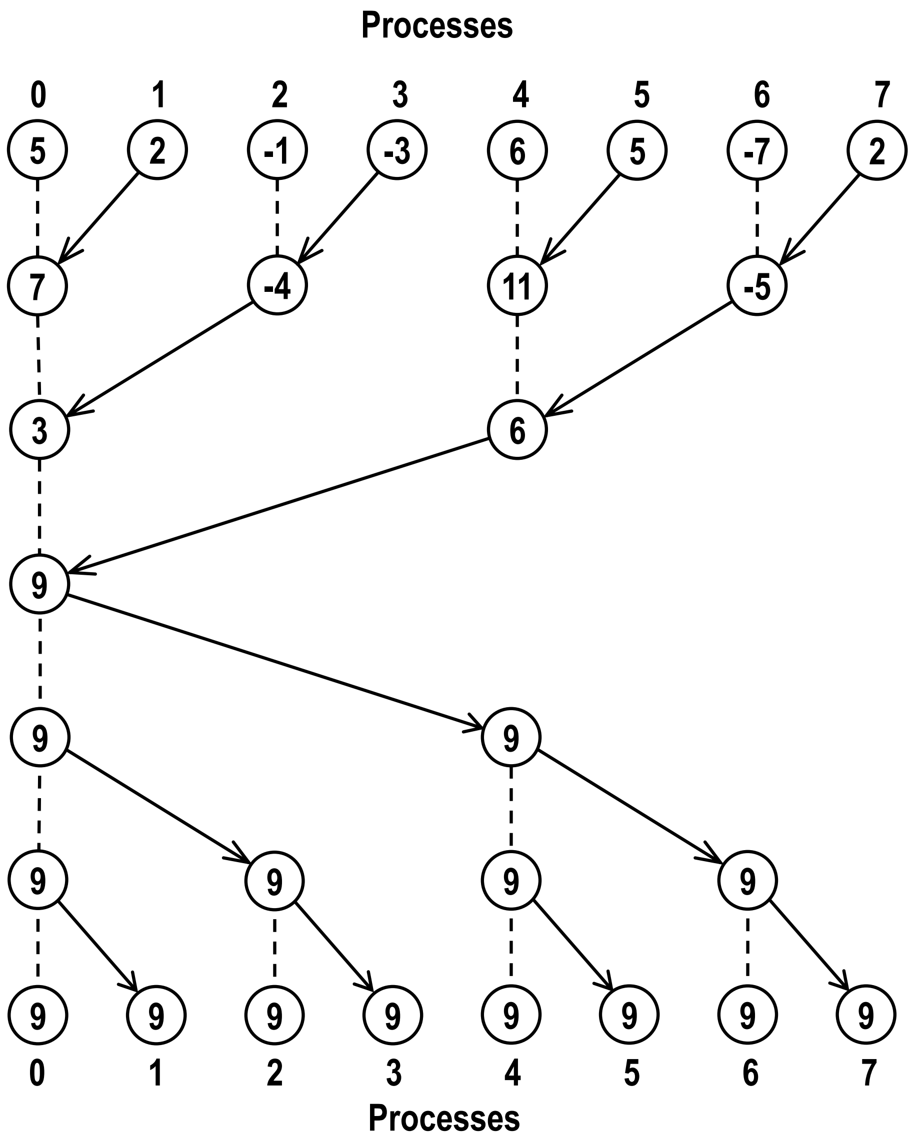
- **How about using the same buffer as input and output?**

—The result is unpredictable.

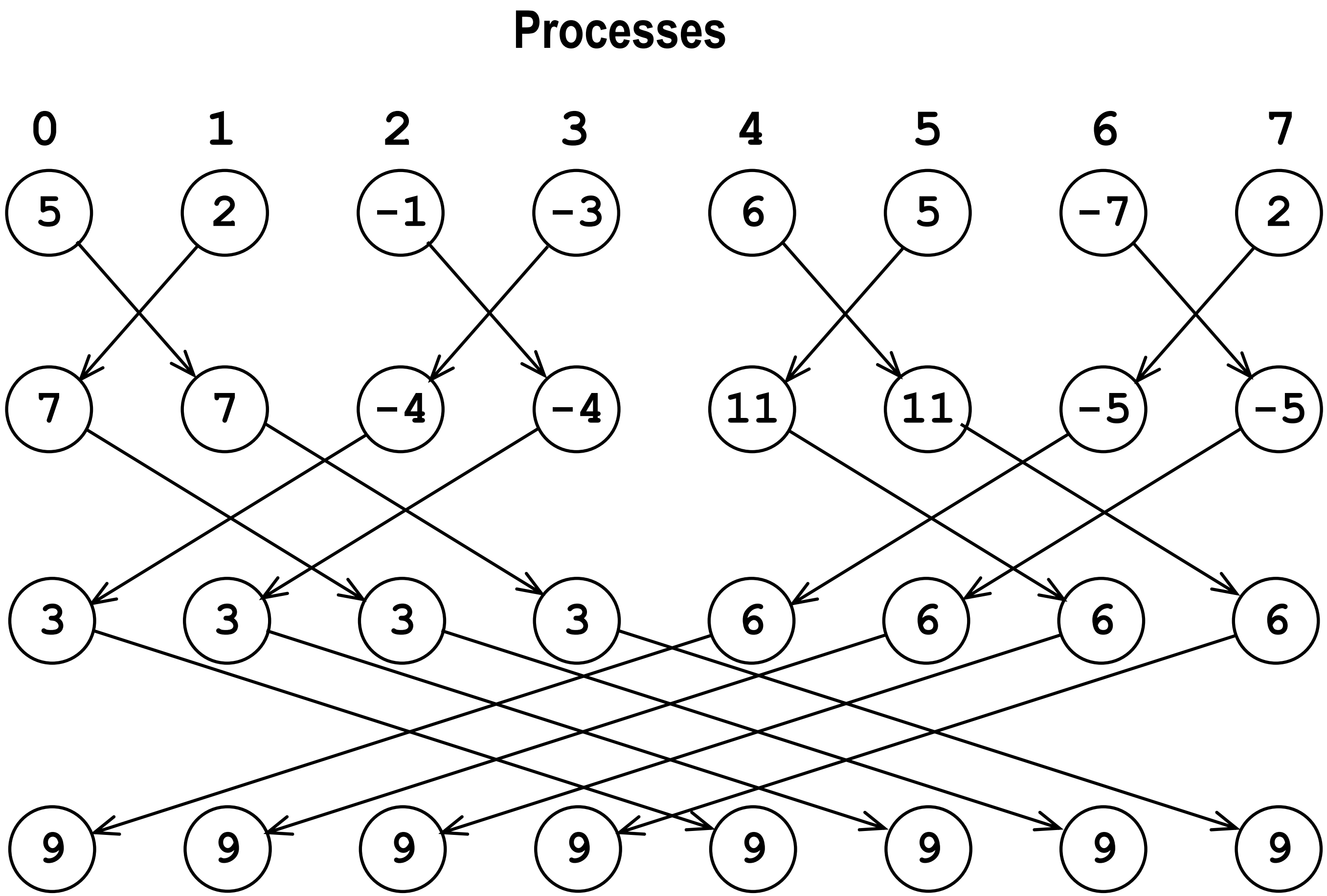
(2) MPI_Allreduce

- **Useful in a situation in which all of the processes need the result of a global sum in order to complete some larger computation.**

```
int MPI_Allreduce(
      void*          input_data_p     /* in  */,
      void*          output_data_p    /* out */,
      int            count            /* in  */,
      MPI_Datatype   datatype         /* in  */,
      MPI_Op         operator         /* in  */,
      MPI_Comm       comm             /* in  */);
```



A global sum followed by distribution of the result.



A butterfly-structured global sum.

(3) Broadcast

- **Data belonging to a single process is sent to all of the processes in the communicator.**

```
int MPI_Bcast(
      void*          data_p         /* in/out */,
      int            count          /* in     */,
      MPI_Datatype   datatype       /* in     */,
      int            source_proc    /* in     */,
      MPI_Comm       comm           /* in     */);
```

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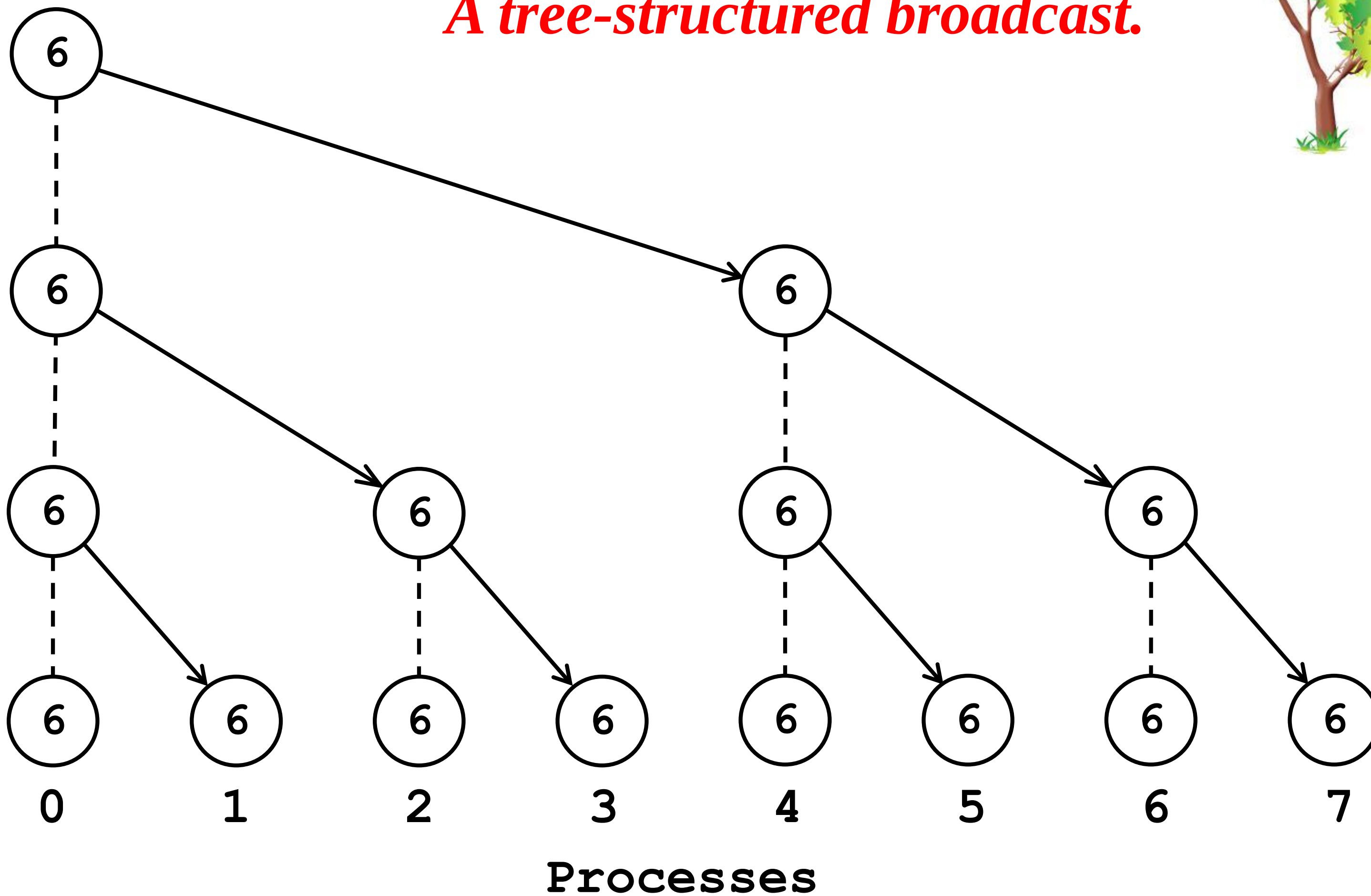
A tree-structured broadcast.



A version of Get_input that uses MPI_Bcast

```c
void Get_input(
      int        my_rank   /* in   */,
      int        comm_sz   /* in   */,
      double*    a_p       /* out  */,
      double*    b_p       /* out  */,
      int*       n_p       /* out  */) {

   if (my_rank == 0) {
      printf("Enter a, b, and n\n");
      scanf("%lf %lf %d", a_p, b_p, n_p);
   }
   MPI_Bcast(a_p, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
   MPI_Bcast(b_p, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
   MPI_Bcast(n_p, 1, MPI_INT, 0, MPI_COMM_WORLD);
}  /* Get_input */
```

Data distributions

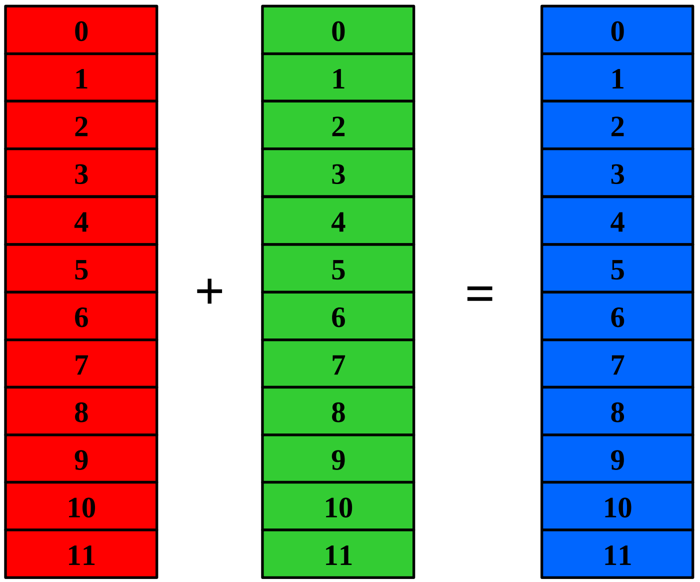
$$
\begin{aligned}
x + y &= (x_0, x_1, \dots, x_{n-1}) + (y_0, y_1, \dots, y_{n-1}) \\
&= (x_0 + y_0, x_1 + y_1, \dots, x_{n-1} + y_{n-1}) \\
&= (\mathrm{z}_0, z_1, \dots, \mathrm{z}_{n-1}) \\
&= \mathrm{z}
\end{aligned}
$$

Compute a vector sum.

Serial implementation of vector addition

```
void Vector_sum(double x[], double y[], double z[], int n) {
   int i;

   for (i = 0; i < n; i++)
      z[i] = x[i] + y[i];
} /* Vector_sum */
```



Different partitions of a 12-component vector among 3 processes

Process	Components											
	Block				Cyclic				Block-cyclic Blocksize = 2			
0	0	1	2	3	0	3	6	9	0	1	6	7
1	4	5	6	7	1	4	7	10	2	3	8	9
2	8	9	10	11	2	5	8	11	4	5	10	11

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Partitioning options

- **Block partitioning**
  - **Assign blocks of consecutive components to each process.**
- **Cyclic partitioning**
  - **Assign components in a round robin fashion.**
- **Block-cyclic partitioning**
  - **Use a cyclic distribution of blocks of components.**

Parallel implementation of vector addition

```
void Parallel_vector_sum(
      double  local_x[]    /* in  */,
      double  local_y[]    /* in  */,
      double  local_z[]    /* out */,
      int     local_n      /* in  */) {
   int local_i;

   for (local_i = 0; local_i < local_n; local_i++)
      local_z[local_i] = local_x[local_i] + local_y[local_i];
} /* Parallel_vector_sum */
```

(4) Scatter

- **MPI_Scatter can be used in a function that reads in an entire vector on process 0 but only sends the needed components to each of the other processes.**

```
int MPI_Scatter(
        void*         send_buf_p   /* in  */,
        int           send_count   /* in  */,
        MPI_Datatype  send_type    /* in  */,
        void*         recv_buf_p   /* out */,
        int           recv_count   /* in  */,
        MPI_Datatype  recv_type    /* in  */,
        int           src_proc     /* in  */,
        MPI_Comm      comm         /* in  */);
```

Reading and distributing a vector

```
void Read_vector(
      double      local_a[]   /* out */,
      int         local_n     /* in  */,
      int         n           /* in  */,
      char        vec_name[]  /* in  */,
      int         my_rank     /* in  */,
      MPI_Comm    comm        /* in  */) {
   double* a = NULL;
   int i;

   if (my_rank == 0) {
      a = malloc(n*sizeof(double));
      printf("Enter the vector %s\n", vec_name);
      for (i = 0; i < n; i++)
         scanf("%lf", &a[i]);
      MPI_Scatter(a, local_n, MPI_DOUBLE, local_a, local_n, MPI_DOUBLE,
            0, comm);
      free(a);
   } else {
      MPI_Scatter(a, local_n, MPI_DOUBLE, local_a, local_n, MPI_DOUBLE,
            0, comm);
   }
} /* Read_vector */
```

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(5) Gather

- **Collect all of the components of the vector onto process 0, and then process 0 can process all of the components.**

```
int MPI_Gather(
      void*          send_buf_p     /* in  */,
      int            send_count     /* in  */,
      MPI_Datatype   send_type      /* in  */,
      void*          recv_buf_p     /* out */,
      int            recv_count     /* in  */,
      MPI_Datatype   recv_type      /* in  */,
      int            dest_proc      /* in  */,
      MPI_Comm       comm           /* in  */);
```

Print a distributed vector (1)

```
int Print_vector(
      double          local_b[]      /* in  */,
      int             local_n        /* in  */,
      int             n              /* in  */,
      char            title[]        /* in  */,
      int             my_rank        /* in  */,
      MPI_Comm        comm           /* in  */) {

   double* b = NULL;
   int i;
```

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Print a distributed vector (2)

```
if (my_rank == 0) {
   b = malloc(n*sizeof(double));
   MPI_Gather(local_b, local_n, MPI_DOUBLE, b, local_n,
         MPI_DOUBLE, 0, comm);
   printf("%s\n", title);
   for (i = 0; i < n; i++)
      printf("%f ", b[i]);
   printf("\n");
   free(b);
} else {
   MPI_Gather(local_b, local_n, MPI_DOUBLE, b, local_n,
         MPI_DOUBLE, 0, comm);
   }
} /* Print_vector */
```


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(6) Allgather

- **Concatenates the contents of each process' send_buf_p and stores this in each process' recv_buf_p.**
- **As usual, recv_count is the amount of data being received from each process.**

```
int MPI_Allgather(
      void*          send_buf_p     /* in  */,
      int            send_count     /* in  */,
      MPI_Datatype   send_type      /* in  */,
      void*          recv_buf_p     /* out */,
      int            recv_count     /* in  */,
      MPI_Datatype   recv_type      /* in  */,
      MPI_Comm       comm           /* in  */);
```

Matrix-vector multiplication

A=(a_{ij}) *is an* $m \times n$ *matrix*

x is a vector with n components

y = Ax is a vector with *m* components

$$y_i = a_{i,0}x_0 + a_{i,1}x_1 + a_{i,2}x_2 + \cdots + a_{i,n-1}x_{n-1}$$

i-th component of y

Dot product of the ith row of A with x.

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Matrix-vector multiplication

$$\begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,n-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,n-1} \\ \vdots & \vdots & & \vdots \\ a_{i,0} & a_{i,1} & \cdots & a_{i,n-1} \\ \vdots & \vdots & & \vdots \\ a_{m-1,0} & a_{m-1,1} & \cdots & a_{m-1,n-1} \end{bmatrix} \bullet \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{n-1} \end{bmatrix} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_i = a_{i,0}x_0 + a_{i,1}x_1 + \cdots + a_{i,n-1}x_{n-1} \\ \vdots \\ y_{m-1} \end{bmatrix}$$

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Multiply a matrix by a vector

```
/* For each row of A */
for (i = 0; i < m; i++) {
   /* Form dot product of ith row with x */
   y[i] = 0.0;
   for (j = 0; j < n; j++)
       y[i] += A[i][j] * x[j];
}
```

Serial pseudo-code

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C style arrays

$$\begin{pmatrix} 0 & 1 & 2 & 3 \\ 4 & 5 & 6 & 7 \\ 8 & 9 & 10 & 11 \end{pmatrix}$$

stored as

0 1 2 3 4 5 6 7 8 9 10 11

Serial matrix-vector multiplication

```
void Mat_vec_mult(
      double  A[]   /* in  */,
      double  x[]   /* in  */,
      double  y[]   /* out */,
      int     m     /* in  */,
      int     n     /* in  */) {
   int i, j;

   for (i = 0; i < m; i++) {
      y[i] = 0.0;
      for (j = 0; j < n; j++)
         y[i] += A[i*n+j] * x[j];
   }
} /* Mat_vec_mult */
```

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An MPI matrix-vector multiplication function (1)

```
void Mat_vec_mult(
      double      local_A[]   /* in  */,
      double      local_x[]   /* in  */,
      double      local_y[]   /* out */,
      int         local_m     /* in  */,
      int         n           /* in  */,
      int         local_n     /* in  */,
      MPI_Comm    comm        /* in  */) {
   double* x;
   int local_i, j;
   int local_ok = 1;
```

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An MPI matrix-vector multiplication function (2)

```
   x = malloc(n*sizeof(double));
   MPI_Allgather(local_x, local_n, MPI_DOUBLE,
         x, local_n, MPI_DOUBLE, comm);

   for (local_i = 0; local_i < local_m; local_i++) {
      local_y[local_i] = 0.0;
      for (j = 0; j < n; j++)
         local_y[local_i] += local_A[local_i*n+j] * x[j];
   }
   free(x);
} /* Mat_vec_mult */
```

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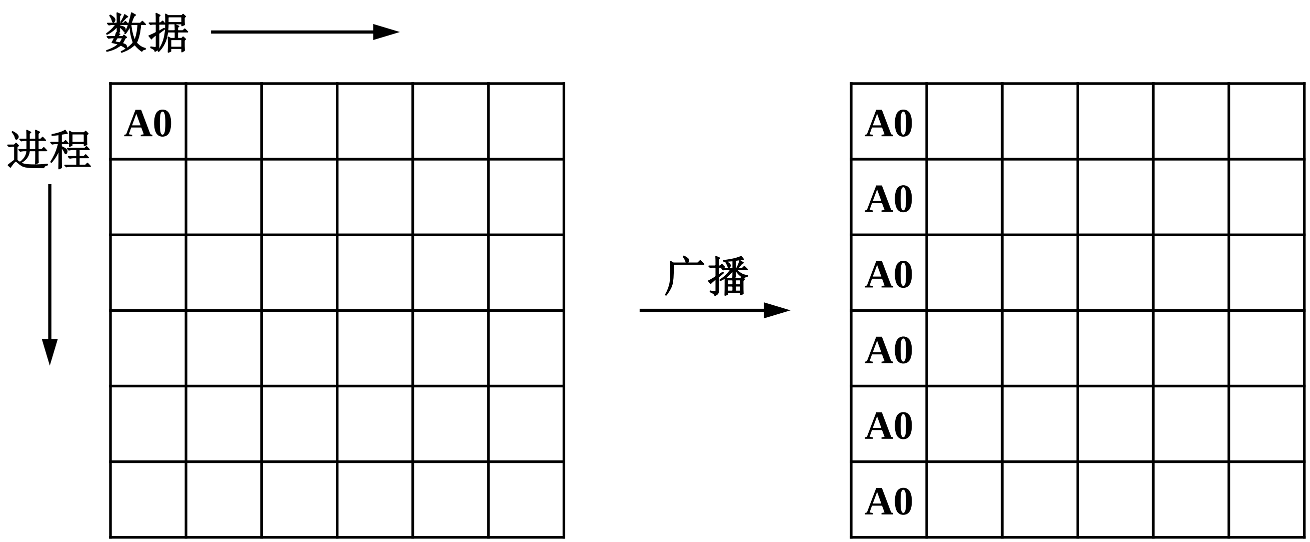
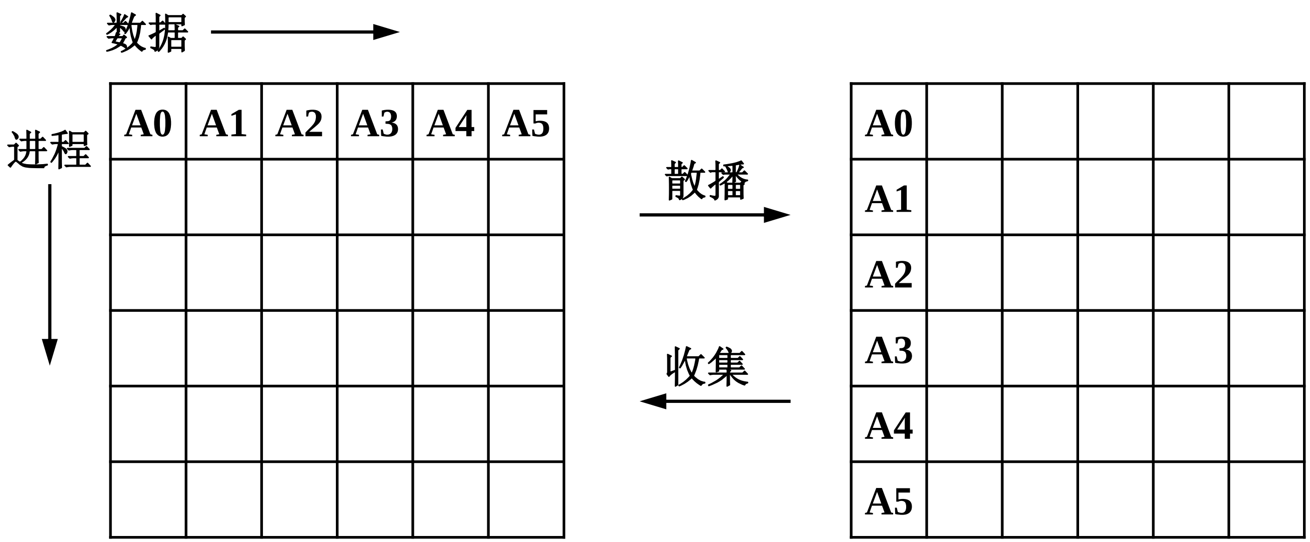
广播 (MPI_Bcast)



收集和散播 (MPI_Gather & MPI_Scatter)



全局收集 (MPI_Allgather)

数据 →

进程 ↓

A0	B0	C0	D0	E0	F0
A0	B0	C0	D0	E0	F0
A0	B0	C0	D0	E0	F0
A0	B0	C0	D0	E0	F0
A0	B0	C0	D0	E0	F0
A0	B0	C0	D0	E0	F0

← 全局收集

A0					
B0					
C0					
D0					
E0					
F0					

全局交换 (MPI_Alltoall)

数据 →

进程 ↓

A0	A1	A2	A3	A4	A5
B0	B1	B2	B3	B4	B5
C0	C1	C2	C3	C4	C5
D0	D1	D2	D3	D4	D5
E0	E1	E2	E3	E4	E5
F0	F1	F2	F3	F4	F5

全局交换 →

A0	B0	C0	D0	E0	F0
A1	B1	C1	D1	E1	F1
A2	B2	C2	D2	E2	F2
A3	B3	C3	D3	E3	F3
A4	B4	C4	D4	E4	F4
A5	B5	C5	D5	E5	F5

4. MPI DERIVED DATATYPES

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Derived datatypes

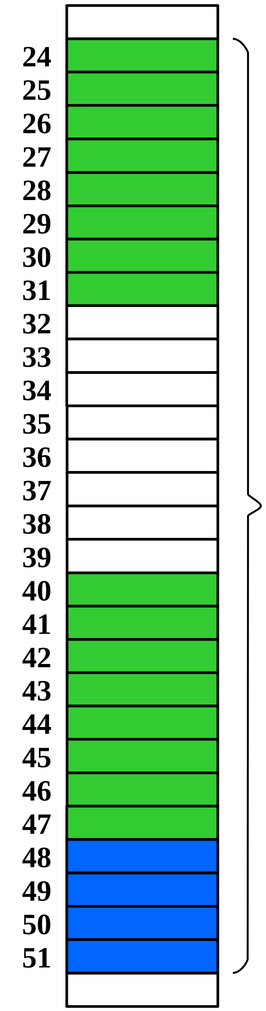
- **Used to represent any collection of data items in memory by storing both the types of the items and their relative locations in memory.**
- **The idea is that if a function that sends data knows this information about a collection of data items, it can collect the items from memory before they are sent.**
- **Similarly, a function that receives data can distribute the items into their correct destinations in memory when they're received.**

Derived datatypes

- **Formally, consists of a sequence of basic MPI data types together with a displacement for each of the data types.**
- **Trapezoidal Rule example:**

Variable	Address
a	24
b	40
n	48

{(MPI_DOUBLE, 0), (MPI_DOUBLE, 16), (MPI_INT, 24)}

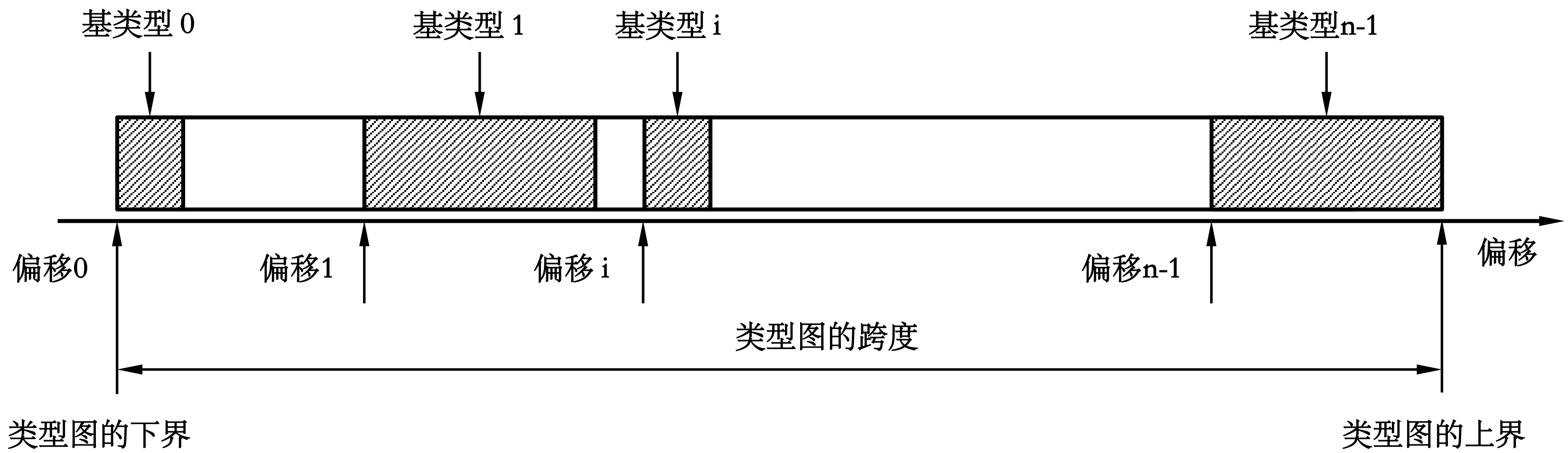


MPI_Type_create_struct

- **Builds a derived datatype that consists of individual elements that have different basic types.**

```
int MPI_Type_create_struct (
      int             count                    /* in  */,
      int             array_of_blocklengths[]  /* in  */,
      MPI_Aint        array_of_displacements[] /* in  */,
      MPI_Datatype    array_of_types[]         /* in  */,
      MPI_Datatype*   new_type_p               /* out */);
```

派生数据类型的类型图示意结构



MPI_Get_address

- **Returns the address of the memory location referenced by location_p.**
- **The special type MPI_Aint is an integer type that is big enough to store an address on the system.**

```
int MPI_Get_address(
      void*        location_p    /* in  */,
      MPI_Aint*    address_p     /* out */);
```

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MPI_Type_commit

- **Allows the MPI implementation to optimize its internal representation of the datatype for use in communication functions.**

```
int MPI_Type_commit(MPI_Datatype* new_mpi_t_p  /* in/out */);
```

MPI_Type_free

- **When we're finished with our new type, this frees any additional storage used.**

```
int MPI_Type_free(MPI_Datatype* old_mpi_t_p  /* in/out */);
```

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Get_input function with a derived datatype (1)

```
void Build_mpi_type(
      double*         a_p            /* in  */,
      double*         b_p            /* in  */,
      int*            n_p            /* in  */,
      MPI_Datatype*   input_mpi_t_p  /* out */) {

   int array_of_blocklengths[3] = {1, 1, 1};
   MPI_Datatype array_of_types[3] = {MPI_DOUBLE,
         MPI_DOUBLE, MPI_INT};
   MPI_Aint a_addr, b_addr, n_addr;
   MPI_Aint array_of_displacements[3] = {0};
```

Get_input function with a derived datatype (2)

```
    MPI_Get_address(a_p, &a_addr);
    MPI_Get_address(b_p, &b_addr);
    MPI_Get_address(n_p, &n_addr);
    array_of_displacements[1] = b_addr - a_addr;
    array_of_displacements[2] = n_addr - a_addr;
    MPI_Type_create_struct(3, array_of_blocklengths,
          array_of_displacements, array_of_types,
          input_mpi_t_p);
    MPI_Type_commit(input_mpi_t_p);  /*派生出的新数据类型，必须
                                      先要经过MPI系统的确认后才能使用。*/
} /* Build_mpi_type */
```

Get_input function with a derived datatype (3)

```
void Get_input(int my_rank, int comm_sz, double* a_p,
      double* b_p, int* n_p) {
   MPI_Datatype input_mpi_t;

   Build_mpi_type(a_p, b_p, n_p, &input_mpi_t);

   if (my_rank == 0) {
      printf("Enter a, b, and n\n");
      scanf("%lf %lf %d", a_p, b_p, n_p);
   }
   MPI_Bcast(a_p, 1, input_mpi_t, 0, MPI_COMM_WORLD);

   MPI_Type_free(&input_mpi_t);
} /* Get_input */
```

5. PERFORMANCE EVALUATION

Elapsed parallel time

- **Returns the number of seconds that have elapsed since some time in the past.**

```
double MPI_Wtime(void);
```

```
double start, finish;
. . .
start = MPI_Wtime();
/* Code to timed */
. . .
finish = MPI_Wtime();
printf("Proc %d > Elapsed time = %e seconds\n"
      my_rank, finish-start);
```

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Elapsed serial time

- **In this case, you don't need to link in the MPI libraries.**
- **Returns time in microseconds elapsed from some point in the past.**

```
#include "timer.h"
. . .
double now;
. . .
GET_TIME(now);
```

Elapsed serial time

```
#include "timer.h"
. . .
double start, finish;
. . .
GET_TIME(start);
/* Code to be timed */
. . .
GET_TIME(finish);
printf("Elapsed time = %e seconds\n", finish - start);
```

MPI_Barrier

- **Ensures that no process will return from calling it until every process in the communicator has started calling it.**

```
int MPI_Barrier(MPI_Comm  comm   /* in */);
```

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MPI_Barrier

```
double local_start, local_finish, local_elapsed, elapsed;
. . .
MPI_Barrier(comm);
local_start = MPI_Wtime();
/* Code to be timed */
. . .

local_finish = MPI_Wtime();
local_elapsed = local_finish - local_start;
MPI_Reduce(&local_elapsed, &elapsed, 1, MPI_DOUBLE,
      MPI_MAX, 0, comm);

if (my_rank == 0)
   printf("Elapsed time = %e seconds\n", elapsed);
```

Run-times of serial and parallel matrix-vector multiplication

comm_sz	Order of Matrix				
	1024	2048	4096	8192	16,384
1	4.1	16.0	64.0	270	1100
2	2.3	8.5	33.0	140	560
4	2.0	5.1	18.0	70	280
8	1.7	3.3	9.8	36	140
16	1.7	2.6	5.9	19	71

(milliseconds)

Speedup

$$S(n, p) = \frac{T_{\text{serial}}(n)}{T_{\text{parallel}}(n, p)}$$

Efficiency

$$E(n, p) = \frac{S(n, p)}{p} = \frac{T_{\text{serial}}(n)}{p \times T_{\text{parallel}}(n, p)}$$

Speedups of Parallel Matrix-Vector Multiplication

comm_sz	Order of Matrix				
	1024	2048	4096	8192	16,384
1	1.0	1.0	1.0	1.0	1.0
2	1.8	1.9	1.9	1.9	2.0
4	2.1	3.1	3.6	3.9	3.9
8	2.4	4.8	6.5	7.5	7.9
16	2.4	6.2	10.8	14.2	15.5

Efficiencies of Parallel Matrix-Vector Multiplication

comm_sz	Order of Matrix				
	1024	2048	4096	8192	16,384
1	1.00	1.00	1.00	1.00	1.00
2	0.89	0.94	0.97	0.96	0.98
4	0.51	0.78	0.89	0.96	0.98
8	0.30	0.61	0.82	0.94	0.98
16	0.15	0.39	0.68	0.89	0.97

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Scalability

- **A program is scalable if the problem size can be increased at a rate so that the efficiency doesn’t decrease as the number of processes increase.**

Scalability

- **Programs that can maintain a constant efficiency without increasing the problem size are sometimes said to be strongly scalable.**

- **Programs that can maintain a constant efficiency if the problem size increases at the same rate as the number of processes are sometimes said to be weakly scalable.**

6. A PARALLEL SORTING ALGORITHM

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Sorting

- **n keys and p = comm_sz processes.**
- **n/p keys assigned to each process.**
- **No restrictions on which keys are assigned to which processes.**
- **When the algorithm terminates:**
  - **The keys assigned to each process should be sorted in (say) increasing order.**
  - **If $0 \le q < r < p$, then each key assigned to process q should be less than or equal to every key assigned to process r.**

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Serial bubble sort

```
void Bubble_sort(
      int  a[]     /* in/out */,
      int  n       /* in     */) {
   int list_length, i, temp;

   for (list_length = n; list_length >= 2; list_length--)
      for (i = 0; i < list_length-1; i++)
         if (a[i] > a[i+1]) {
            temp = a[i];
            a[i] = a[i+1];
            a[i+1] = temp;
         }
} /* Bubble sort */
```

Odd-even transposition sort

- **A sequence of phases.**
- **Even phases, compare swaps:**

$$(a[0], a[1]), (a[2], a[3]),\ (a[4], a[5]), \cdots$$

- **Odd phases, compare swaps:**

$$(a[1], a[2]), (a[3], a[4]),\ (a[5], a[6]), \cdots$$

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Example

Start: 5, 9, 4, 3

Even phase: compare-swap (5,9) and (4,3)
getting the list 5, 9, 3, 4

Odd phase: compare-swap (9,3)
getting the list 5, 3, 9, 4

Even phase: compare-swap (5,3) and (9,4)
getting the list 3, 5, 4, 9

Odd phase: compare-swap (5,4)
getting the list 3, 4, 5, 9

Serial odd-even transposition sort

```
void Odd_even_sort(
      int    a[]     /* in/out */,
      int    n       /* in     */) {
   int phase, i, temp;

   for (phase = 0; phase < n; phase++)
      if (phase % 2 == 0) {    /* Even phase */
         for (i = 1; i < n; i += 2)
            if (a[i-1] > a[i]) {
               temp = a[i];  a[i] = a[i-1];  a[i-1] = temp;
            }
      } else {                 /* Odd phase */
         for (i = 1; i < n-1; i += 2)
            if (a[i] > a[i+1]) {
               temp = a[i];  a[i] = a[i+1];  a[i+1] = temp;
            }
      }
} /* Odd_even_sort */
```

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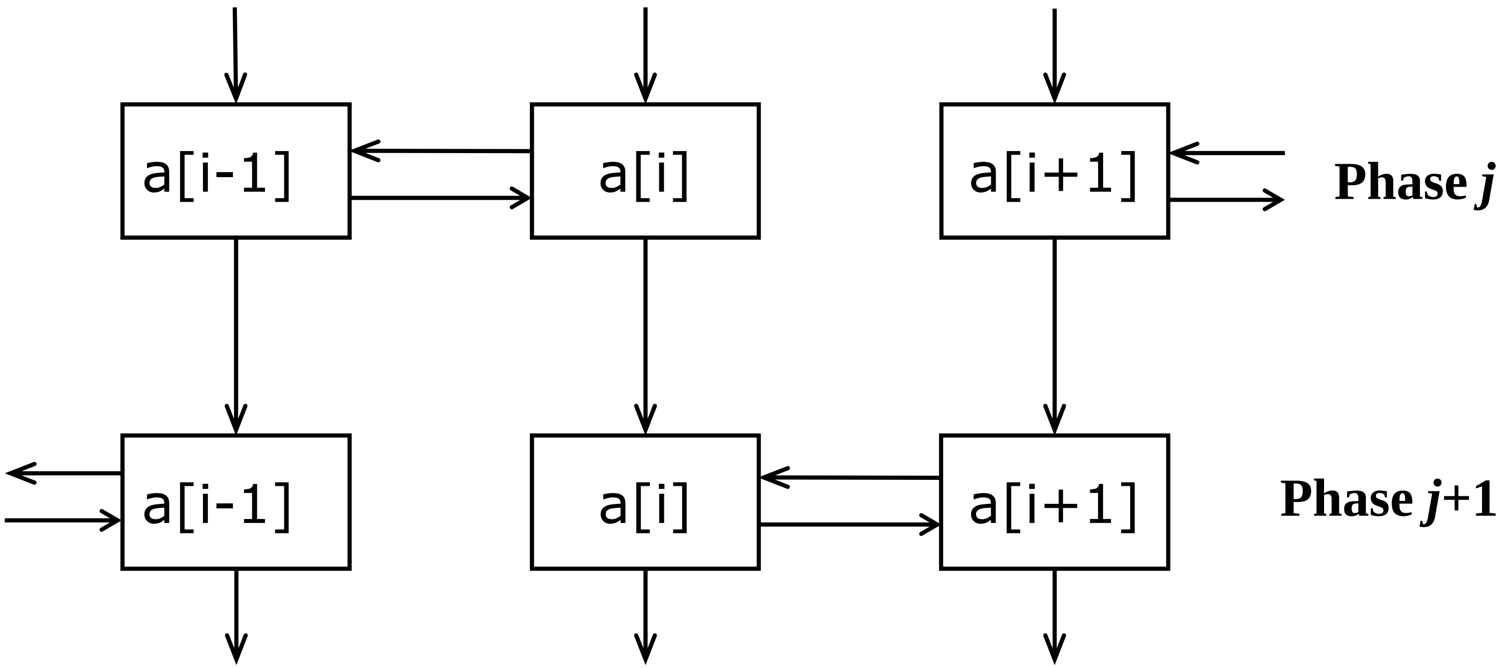
Communications among tasks in odd-even sort



Tasks determining a[i] are labeled with a[i].

Parallel odd-even transposition sort

15, 11, 9, 16 , 3, 14, 8, 7, 4, 6, 12, 10, 5, 2, 13, 1

Time	Process			
	0	1	2	3
Start	15, 11, 9, 16	3, 14, 8, 7	4, 6, 12, 10	5, 2, 13, 1
After Local Sort	9, 11, 15, 16	3, 7, 8, 14	4, 6, 10, 12	1, 2, 5, 13
After Phase 0	3, 7, 8, 9	11, 14, 15, 16	1, 2, 4, 5	6, 10, 12, 13
After Phase 1	3, 7, 8, 9	1, 2, 4, 5	11, 14, 15, 16	6, 10, 12, 13
After Phase 2	1, 2, 3, 4	5, 7, 8, 9	6, 10, 11, 12	13, 14, 15, 16
After Phase 3	1, 2, 3, 4	5, 6, 7, 8	9, 10, 11, 12	13, 14, 15, 16

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Pseudo-code

```
Sort local keys;
for (phase = 0; phase < comm_sz; phase++) {
   partner = Compute_partner(phase, my_rank);
   if (I'm not idle) {
      Send my keys to partner;
      Receive keys from partner;
      if (my_rank < partner)
         Keep smaller keys;
      else
         Keep larger keys;
   }
}
```

Compute_partner

```
if (phase % 2 == 0)              /* Even phase */
   if (my_rank % 2 != 0)         /* Odd rank */
      partner = my_rank - 1;
   else                          /* Even rank */
      partner = my_rank + 1;
else                             /* Odd phase */
   if (my_rank % 2 != 0)         /* Odd rank */
      partner = my_rank + 1;
   else                          /* Even rank */
      partner = my_rank - 1;
if (partner == -1 || partner == comm_sz)
   partner = MPI_PROC_NULL;
```

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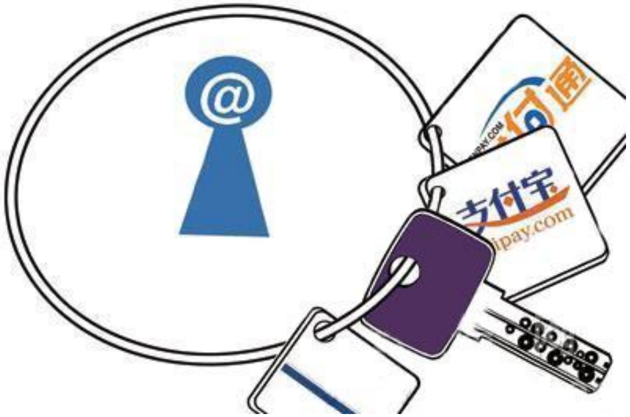
SAFETY IN MPI PROGRAMS



Safety in MPI programs

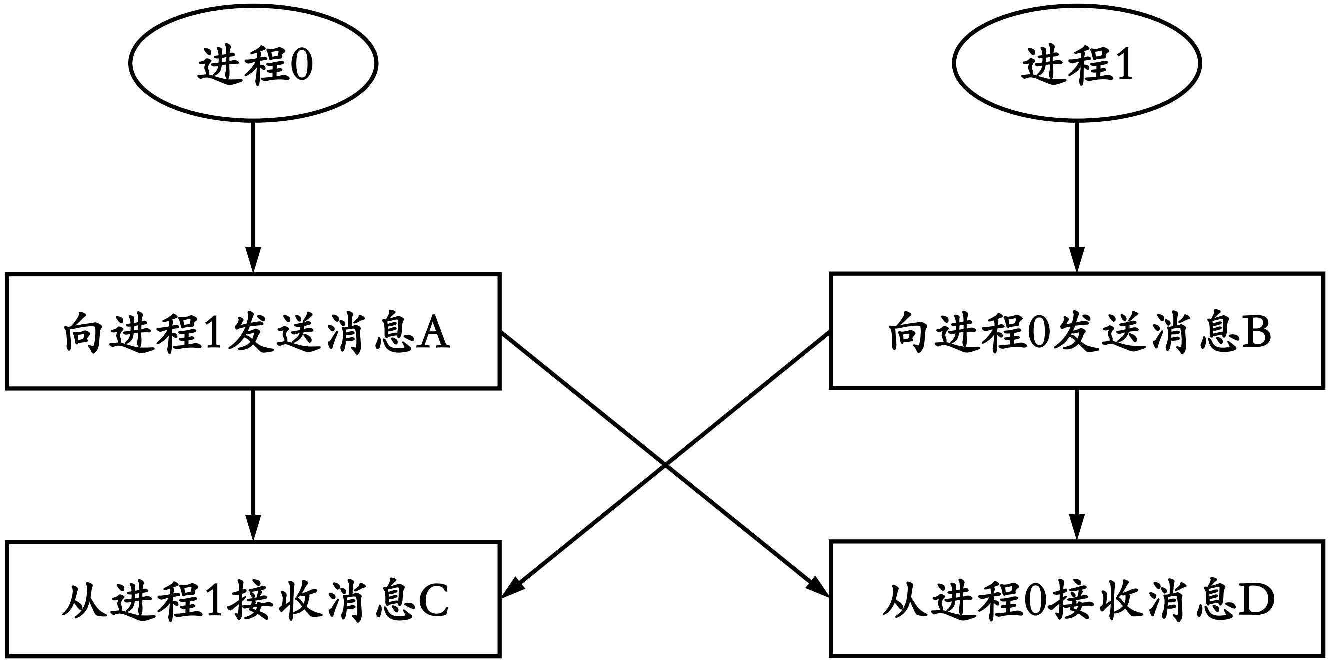
- **The MPI standard allows MPI_Send to behave in two different ways:**
  - **it can simply copy the message into an MPI managed buffer and return,**
  - **or it can block until the matching call to MPI_Recv starts.**

Safety in MPI programs

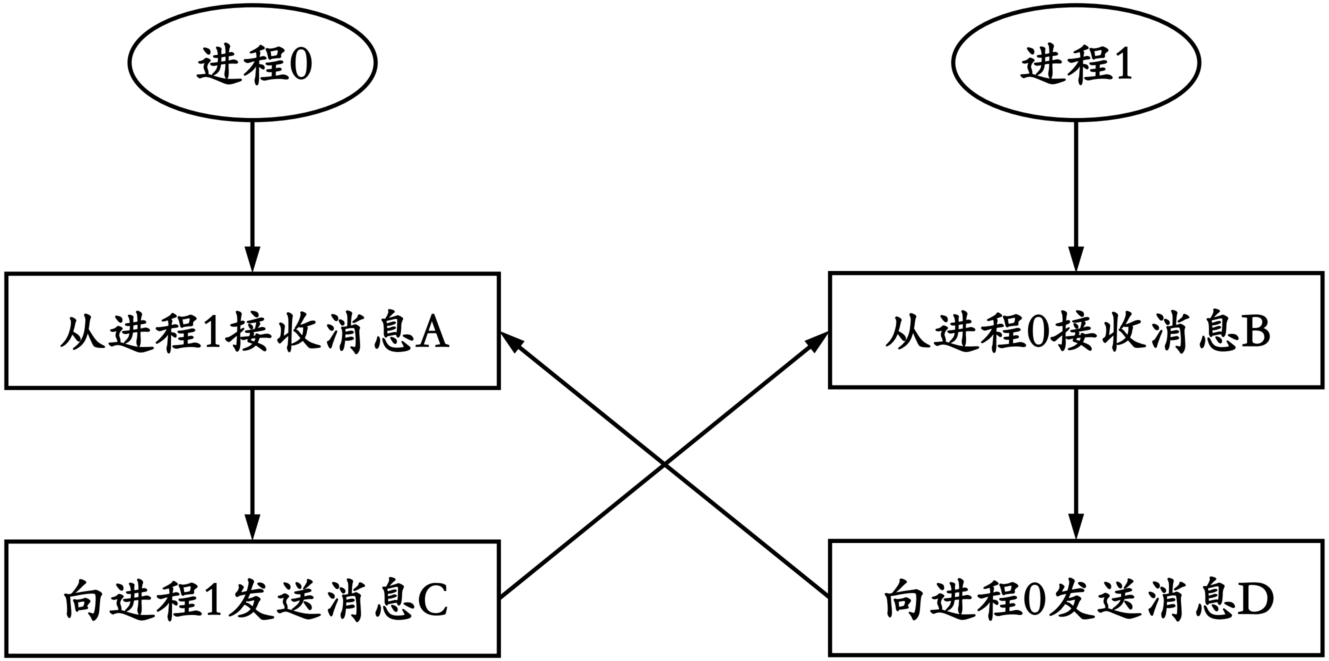
- **Many implementations of MPI set a threshold at which the system switches from buffering to blocking.**
- **Relatively small messages will be buffered by MPI_Send.**
- **Larger messages, will cause it to block.**

避免死锁deadlock

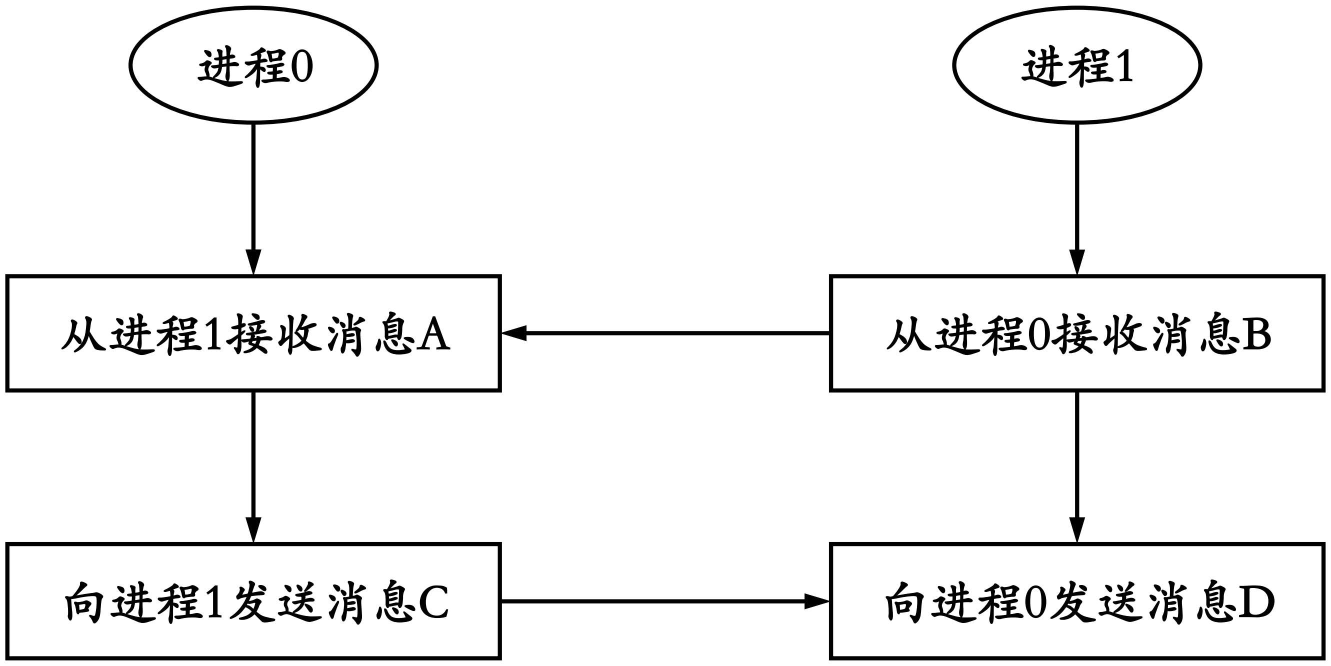
- 发送和接收是成对出现的，忽略这个原则 很可能会产生死锁



不安全的通信调用次序

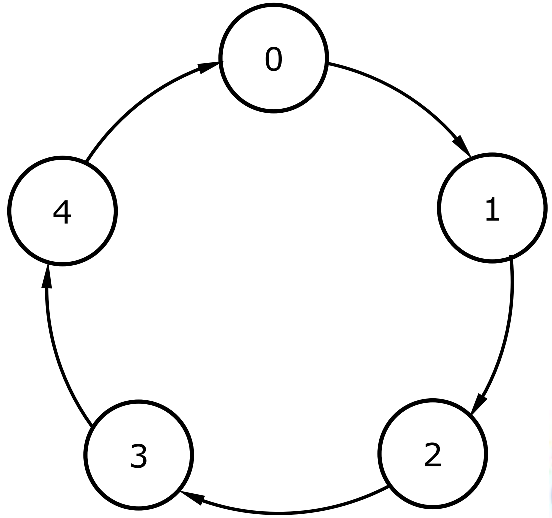


安全的通信调用次序



Safety in MPI programs

- If the MPI_Send executed by each process blocks, no process will be able to start executing a call to MPI_Recv, and the program will hang or **deadlock**.
- Each process is blocked waiting for an event that will never happen.



Safety in MPI programs

- **A program that relies on MPI provided buffering is said to be unsafe.**

- **Such a program may run without problems for various sets of input, but it may hang or crash with other sets.**

MPI_Ssend

- **An alternative to MPI_Send defined by the MPI standard.**
- **The extra "s" stands for synchronous and MPI_Ssend is guaranteed to block until the matching receive starts.**

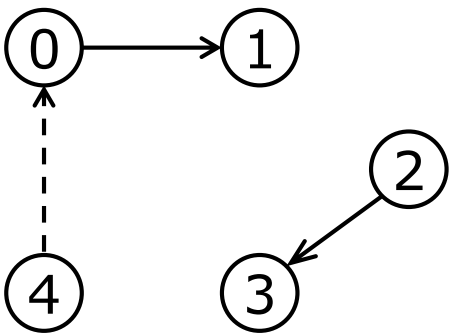
```
int MPI_Ssend(
      void*          msg_buf_p      /* in */,
      int            msg_size       /* in */,
      MPI_Datatype   msg_type       /* in */,
      int            dest           /* in */,
      int            tag            /* in */,
      MPI_Comm       communicator   /* in */);
```

Restructuring communication

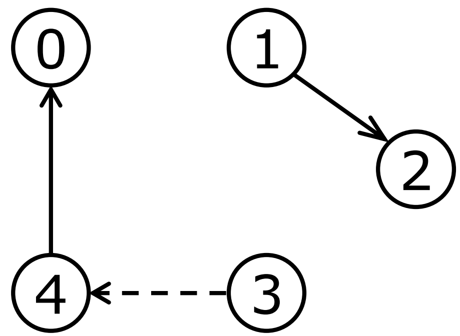
```
MPI_Send(msg, size, MPI_INT, (my_rank+1)%comm_sz, 0, comm);
MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz-1)%comm_sz,
      0, comm, MPI_STATUS_IGNORE).
```

```
if (my_rank % 2 == 0) {
   MPI_Send(msg, size, MPI_INT, (my_rank+1)%comm_sz, 0, comm);
   MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz-1)%comm_sz,
         0, comm, MPI_STATUS_IGNORE).
} else {
   MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz-1)%comm_sz,
         0, comm, MPI_STATUS_IGNORE).
   MPI_Send(msg, size, MPI_INT, (my_rank+1)%comm_sz, 0, comm);
}
```

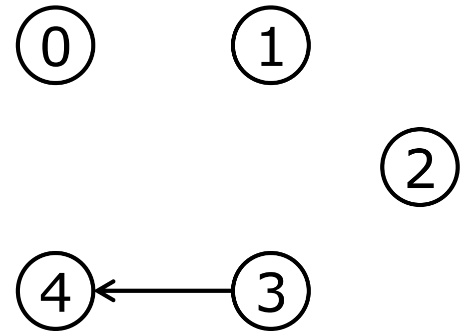
Safe communication with five processes



Time 0
偶发奇收



Time 1
奇发偶收



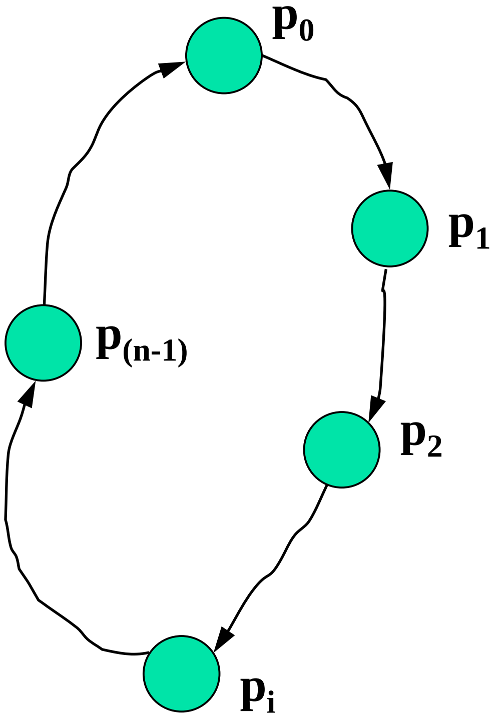
Time 2
偶发奇收

MPI_Sendrecv

- **An alternative to scheduling the communications ourselves.**
- **Carries out a blocking send and a receive in a single call.**
- **The dest and the source can be the same or different.**
- **Especially useful because MPI schedules the communications so that the program won't hang or crash.**

MPI_Sendrecv

```
int MPI_Sendrecv(
      void*          send_buf_p      /* in  */,
      int            send_buf_size   /* in  */,
      MPI_Datatype   send_buf_type   /* in  */,
      int            dest            /* in  */,
      int            send_tag        /* in  */,
      void*          recv_buf_p      /* out */,
      int            recv_buf_size   /* in  */,
      MPI_Datatype   recv_buf_type   /* in  */,
      int            source          /* in  */,
      int            recv_tag        /* in  */,
      MPI_Comm       communicator    /* in  */,
      MPI_Status*    status_p        /* in  */);
```



MPI_Sendrecv用法示意

```
…
int a, b;
…
MPI_Status status;
int dest = (rank + 1)%p;
int source = (rank + p -1)%p;    /* p为进程个数 */
MPI_Sendrecv( &a, 1, MPI_INT, dest, 99, &b, 1, MPI_INT,
   source, 99, MPI_COMM_WORLD, &status);
```

该函数被每一进程执行一次.

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Parallel odd-even transposition sort

```
void Merge_low(
        int my_keys[],      /* in/out     */
        int recv_keys[],    /* in         */
        int temp_keys[],    /* scratch    */
        int local_n         /* = n/p, in */){
    int m_i, r_i, t_i;

    m_i = r_i = t_i = 0;
    while (t_i < local_n) {
        if (my_keys[m_i] <= recv_keys[r_i]){
            temp_keys[t_i] = my_keys[m_i];
            t_i++; m_i++;
        } else {
            temp_keys[t_i] = recv_keys[r_i];
            t_i++; r_i++;
        }
    }
    for (m_i = 0; m_i < local_n; m_i++)
        my_keys[m_i] = temp_keys[m_i];
} /* Merge_low */
```

My_keys[ ]和recv_keys[ ]都是已排序的列表!

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Run-times of parallel odd-even sort

Processes	Number of Keys (in thousands)				
	200	400	800	1600	3200
1	88	190	390	830	1800
2	43	91	190	410	860
4	22	46	96	200	430
8	12	24	51	110	220
16	7.5	14	29	60	130

(times are in milliseconds)

Concluding Remarks (1)

- MPI or the Message-Passing Interface is a library of functions that can be called from C, C++, or Fortran programs.
- A communicator is a collection of processes that can send messages to each other.
- Many parallel programs use the single-program multiple data or SPMD approach.

Concluding Remarks (2)

- **Most serial programs are deterministic: if we run the same program with the same input we'll get the same output.**
- **Parallel programs often don't possess this property.**
- **Collective communications involve all the processes in a communicator.**

Concluding Remarks (3)

- **When we time parallel programs, we're usually interested in elapsed time or "wall clock time".**
- **Speedup is the ratio of the serial run-time to the parallel run-time.**
- **Efficiency is the speedup divided by the number of parallel processes.**

Concluding Remarks (4)

- **If it’s possible to increase the problem size (n) so that the efficiency doesn’t decrease as p is increased, a parallel program is said to be scalable.**
- **An MPI program is unsafe if its correct behavior depends on the fact that MPI_Send is buffering its input.**

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MPI常用例程一览表

1	MPI_Init	
2	MPI_Finalize	
3	MPI_Comm_rank	
4	MPI_Comm_size	
5	MPI_Wtime	
6	MPI_Send	MPI_Ssend, MPI_Isend
7	MPI_Recv	MPI_Irecv
8	MPI_Sendrecv	MPI_Sendrecv_replace
9	MPI_Status	
10	MPI_Barrier	
11	MPI_Bcast	
12	MPI_Gather	MPI_Allgather
13	MPI_Scatter	
14	MPI_Reduce	MPI_Allreduce