合肥學院
HEFEI UNIVERSITY

Distributed Computing
Lesson 22: MPI

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经济技术开发区 锦绣大道99号

Outline

website

Overview

- Discuss the requirements of scientific and engineering computing
- Consider the algorithm and the hardware perspective
- Get to know MPI as an example framework for using cluster computing
- Learn about the basic components and data structures in MPI
- Apply it by yourself in a homework

Introduction

- Research and Engineering often require enormous amonts of computing power

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  - Data mining [3, 4], and
  - solving optimization prolems [5–8]

Segments System Share (November 2011)

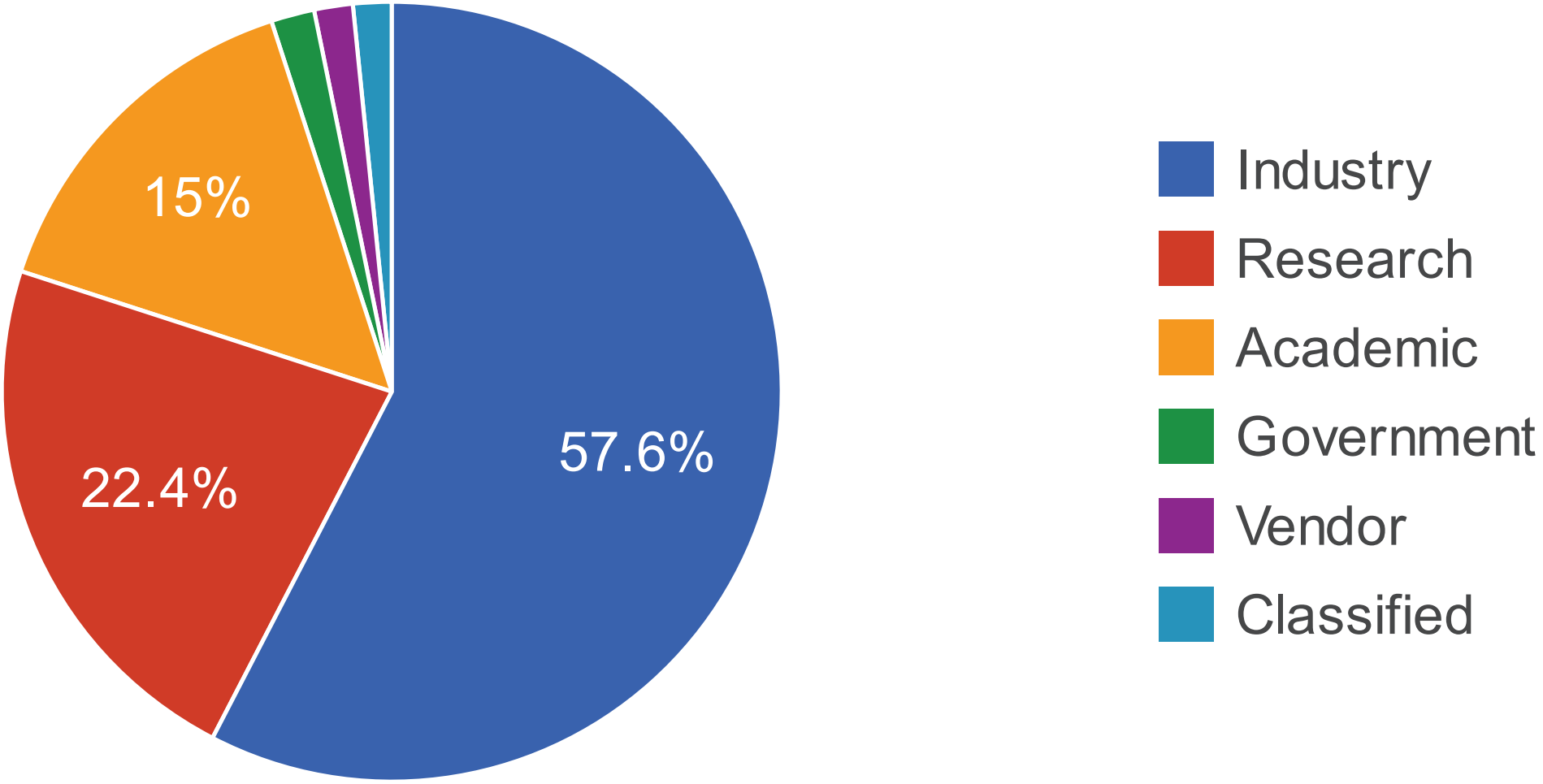
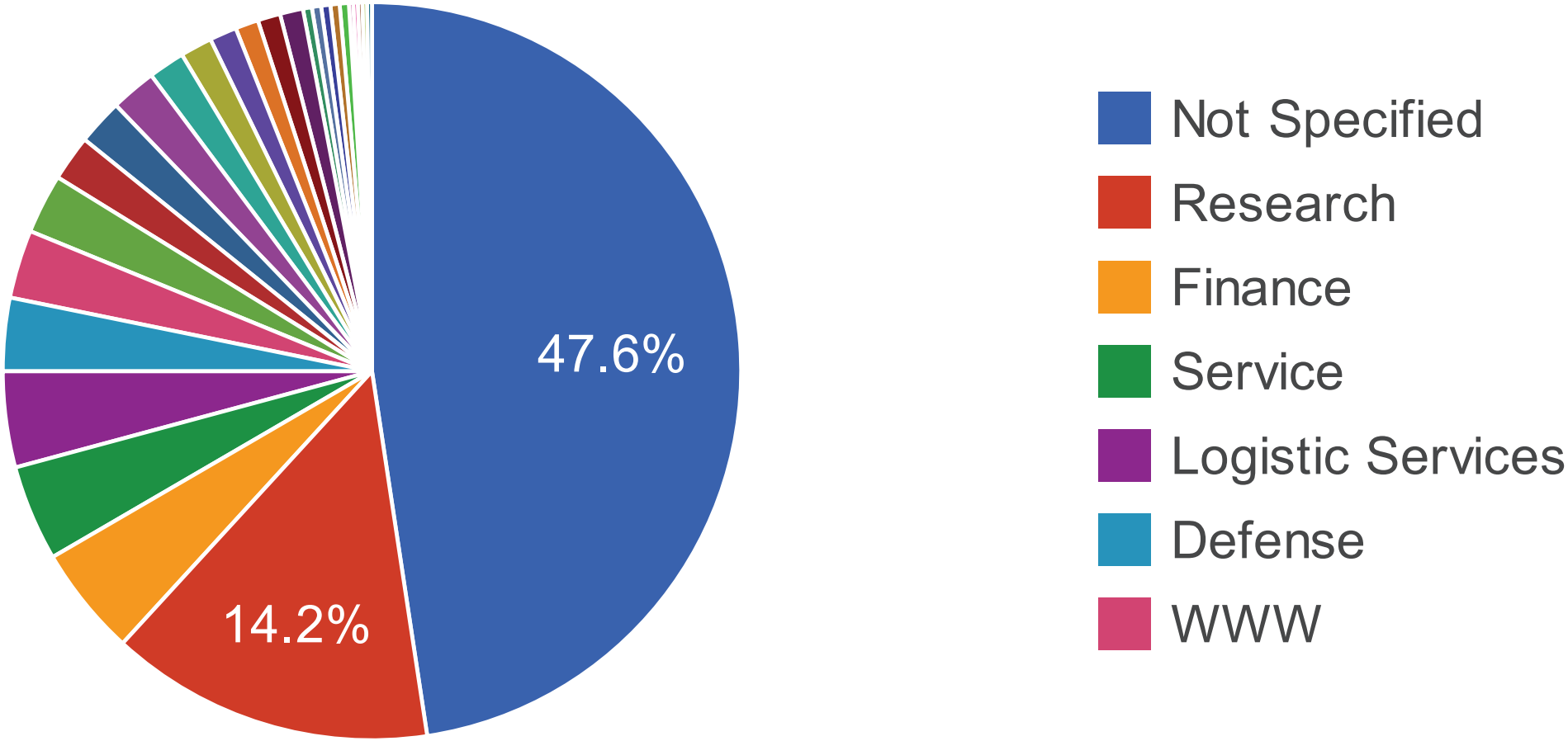


image source: [9]

Application Area System Share (November 2011)



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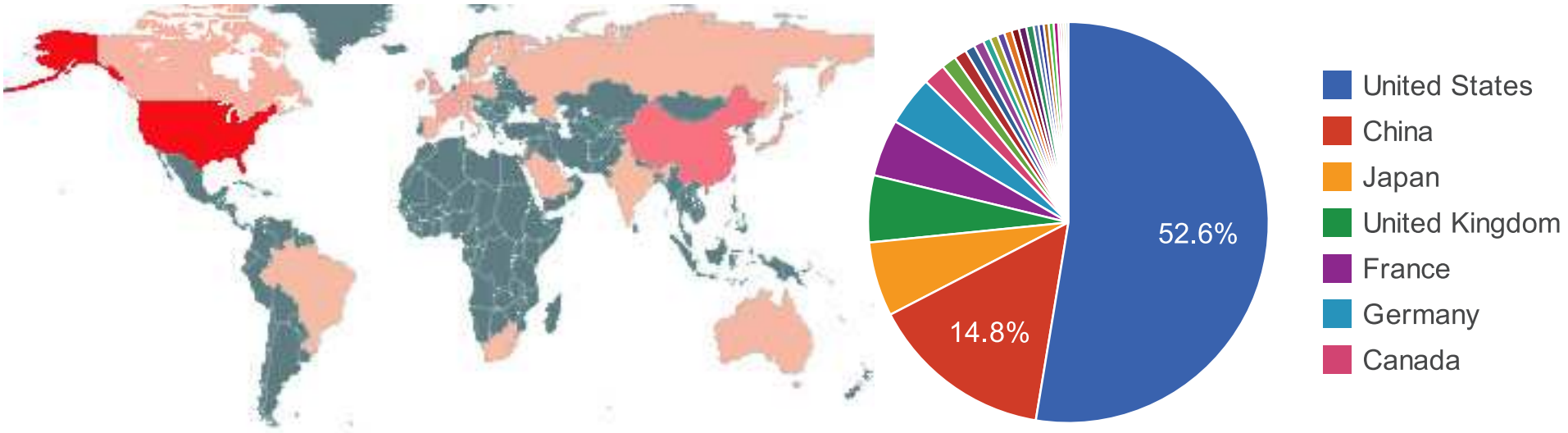
TOP 500 Super Computers



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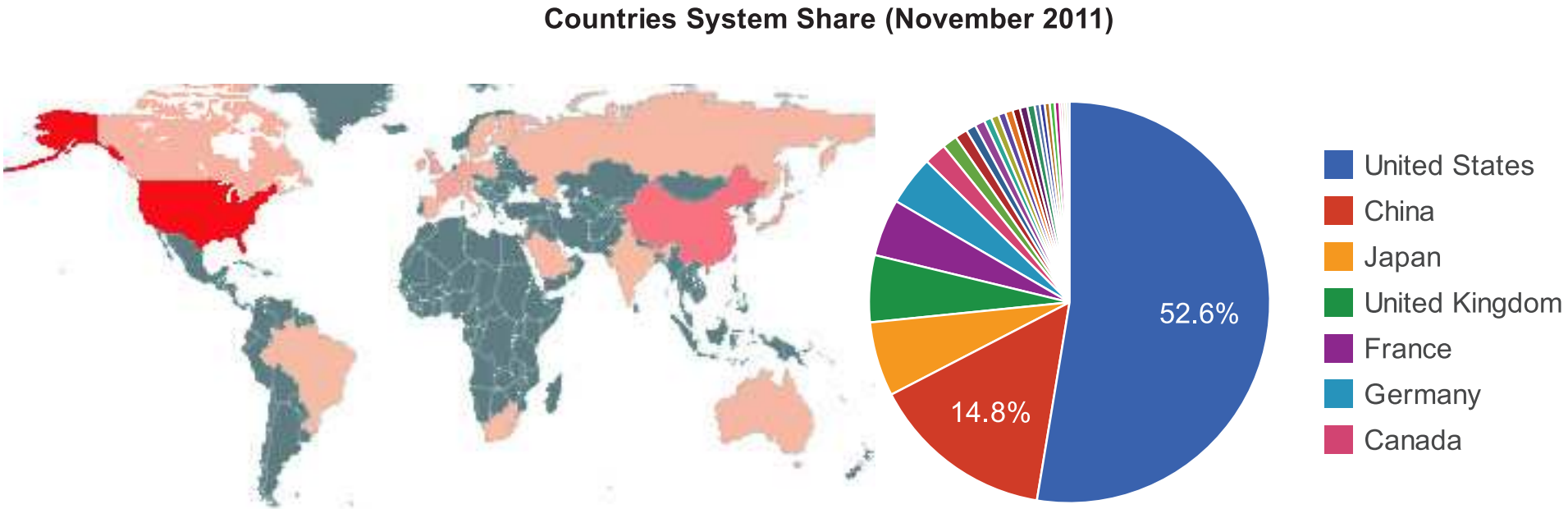

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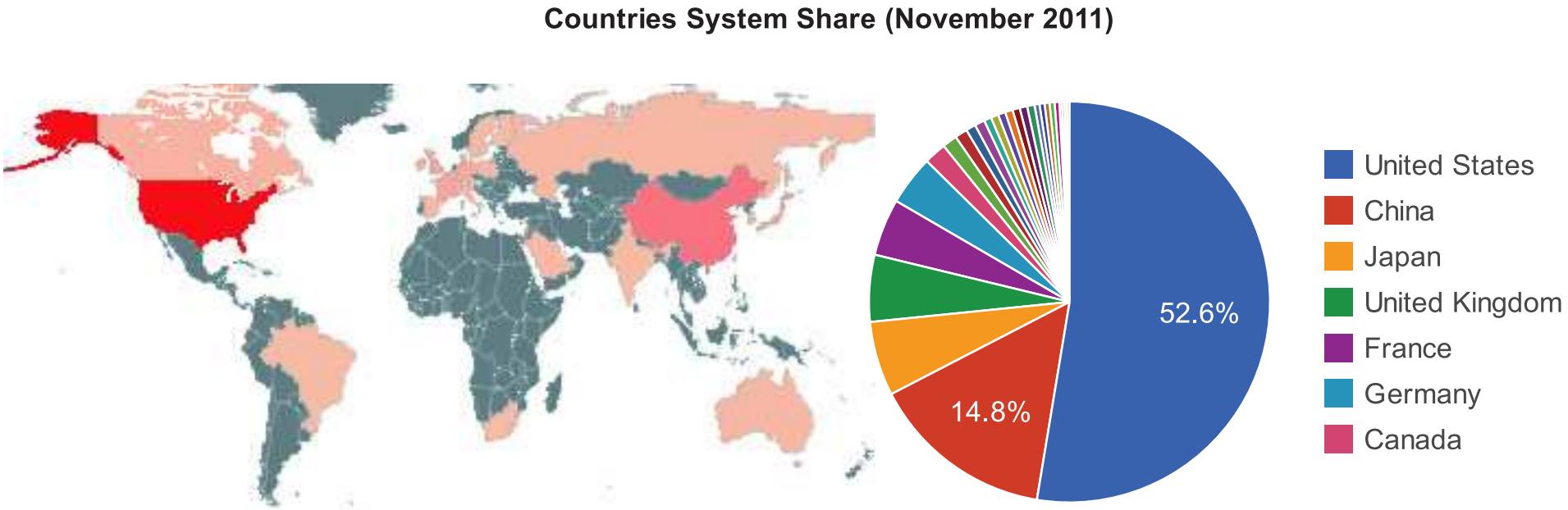
TOP 500 Super Computers



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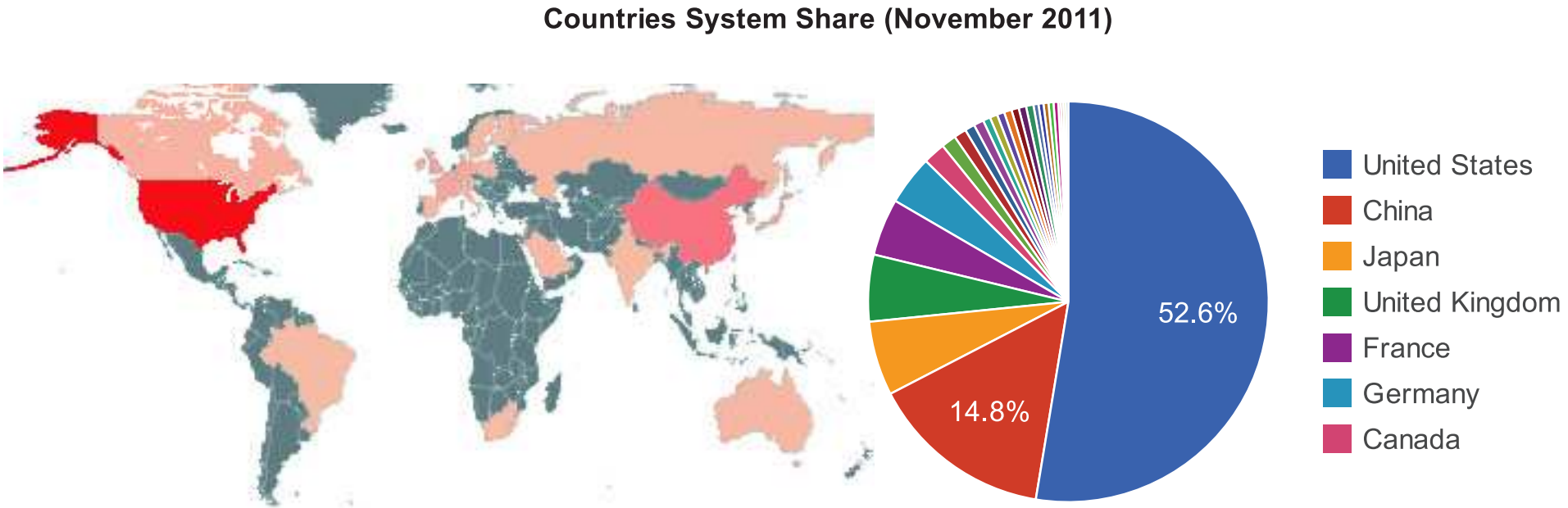

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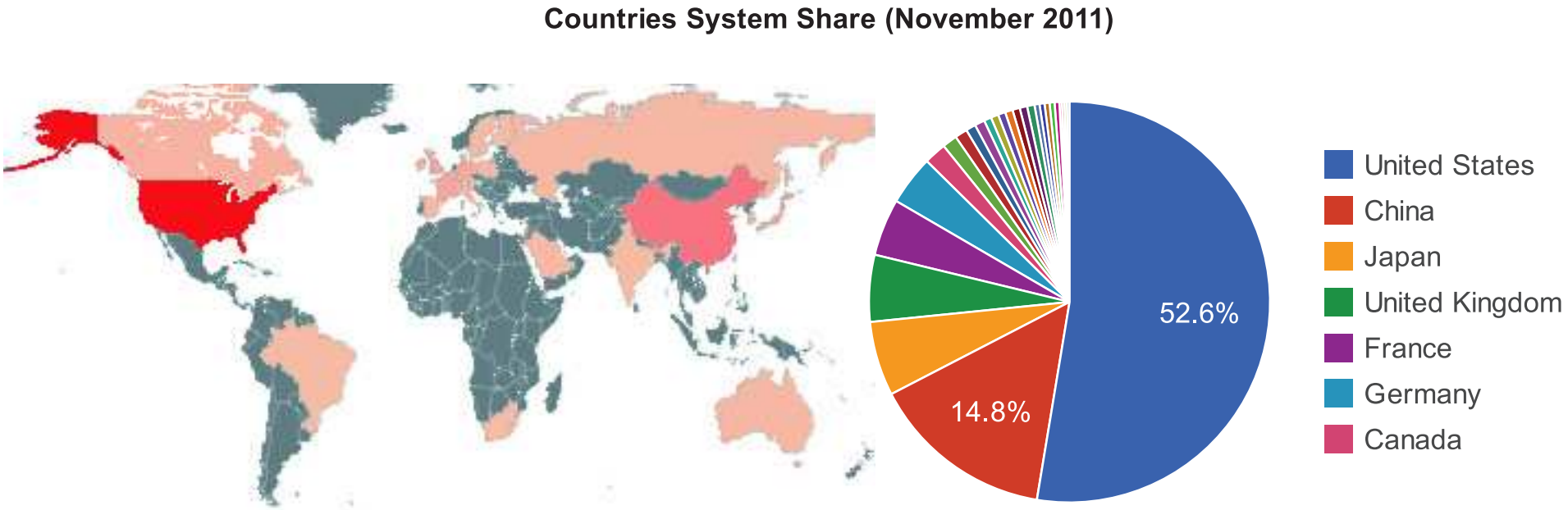

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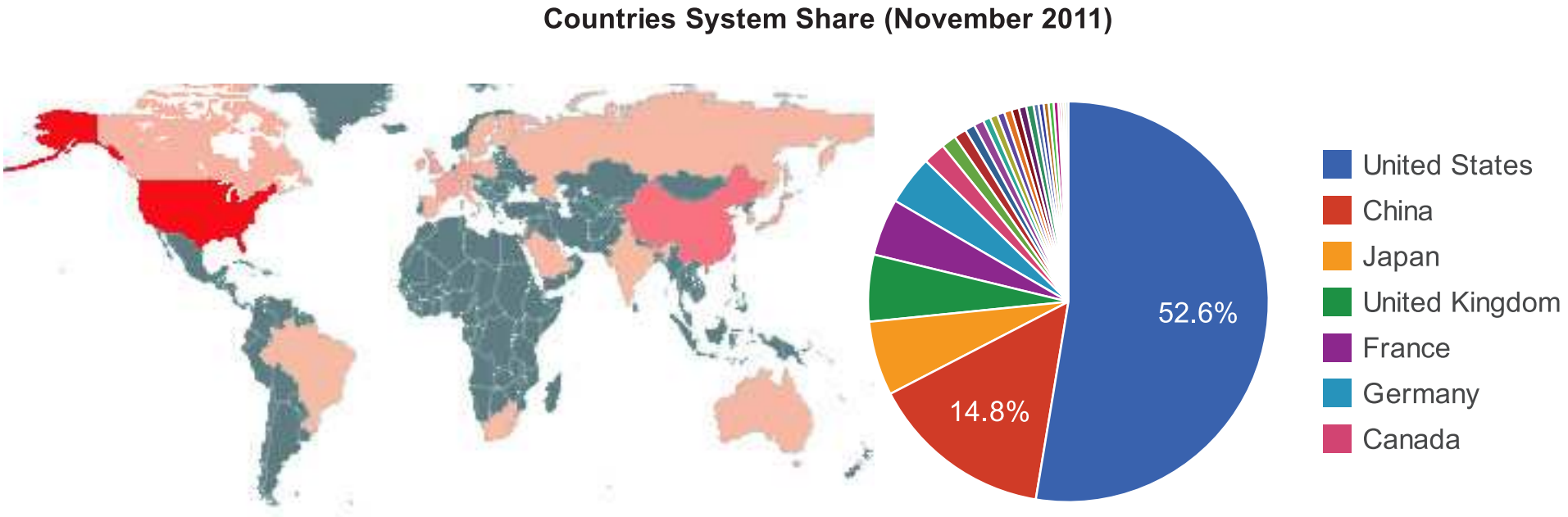

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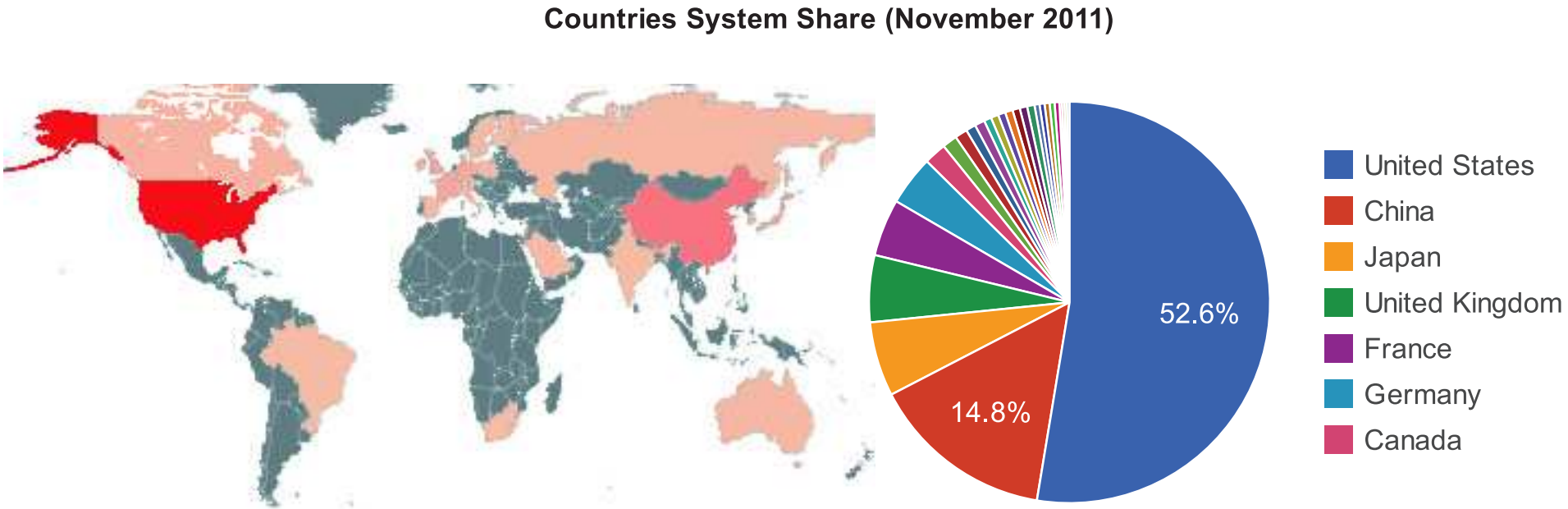

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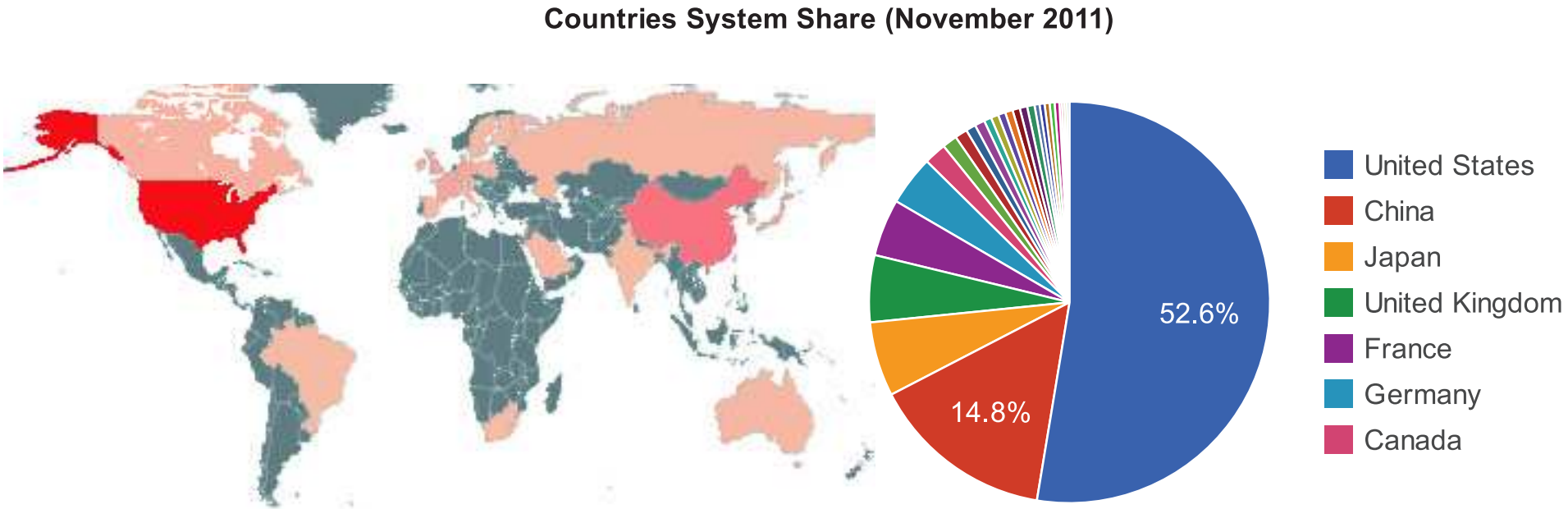

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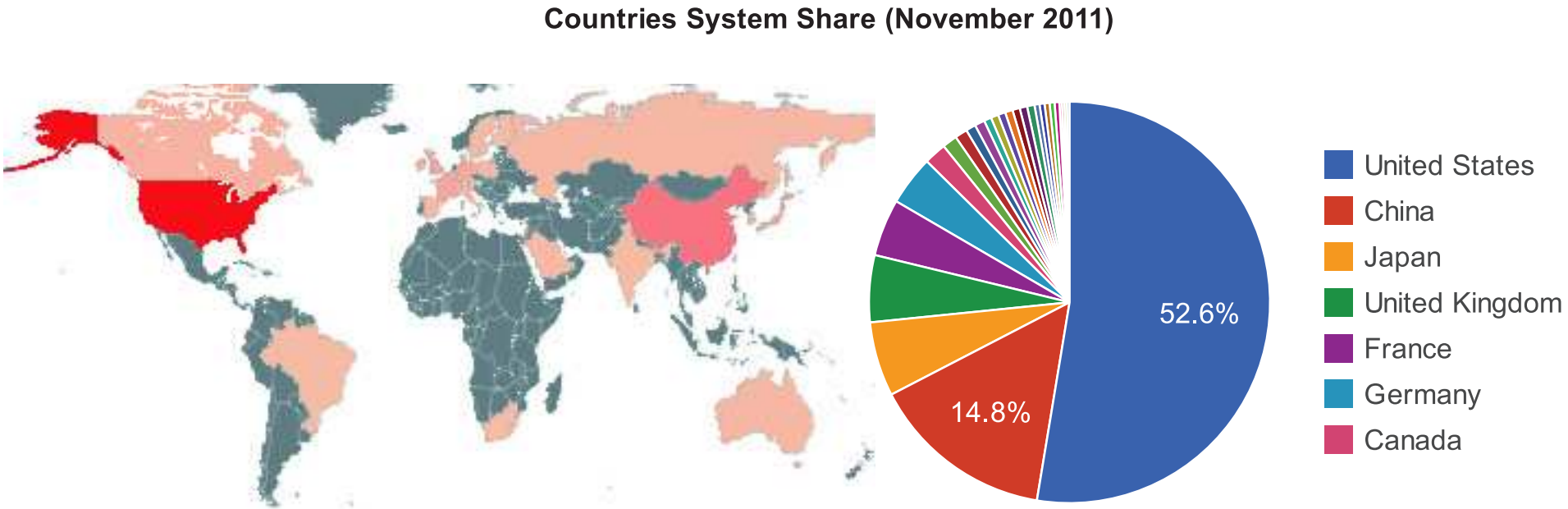

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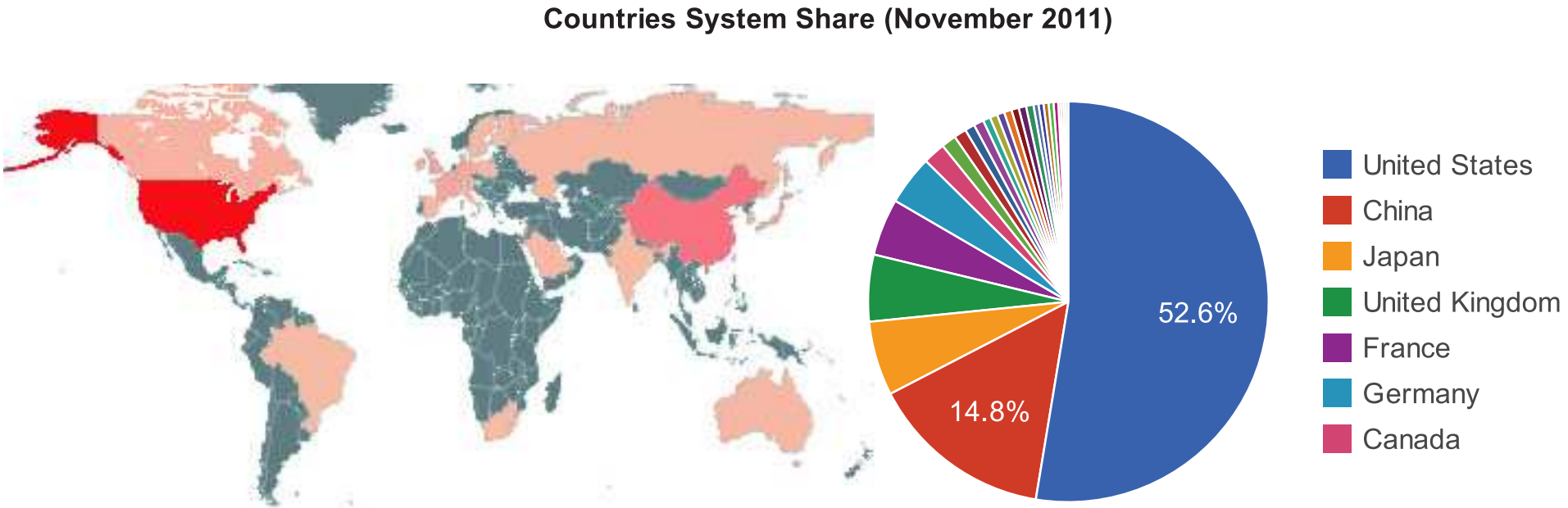

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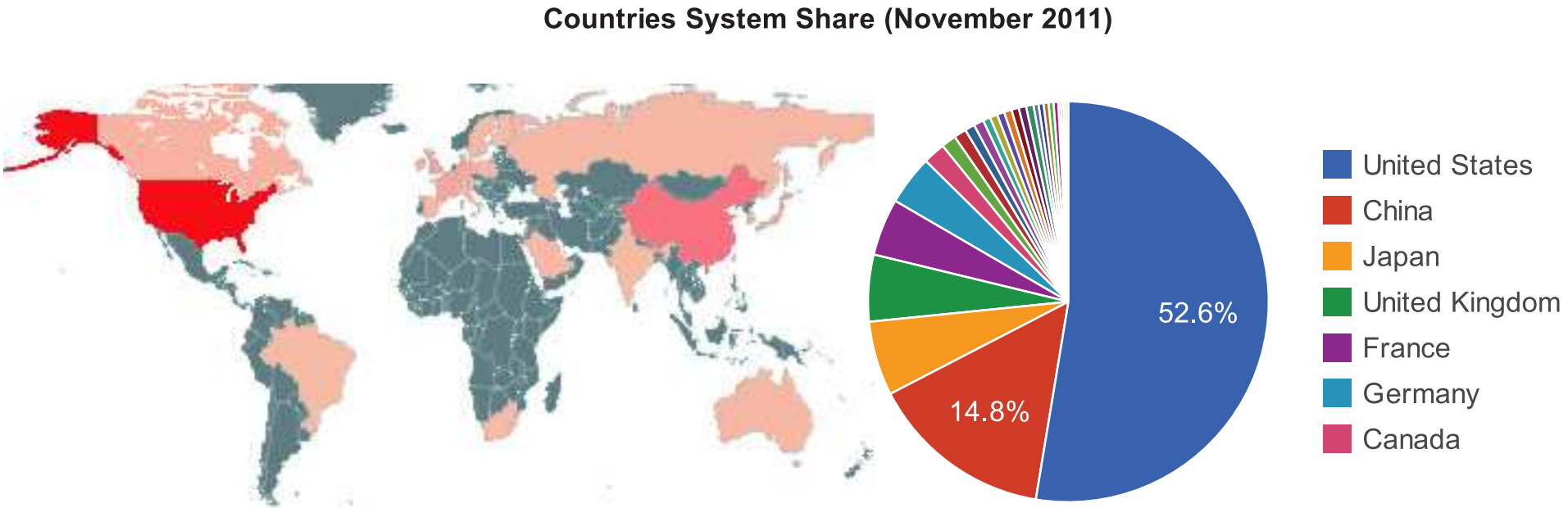

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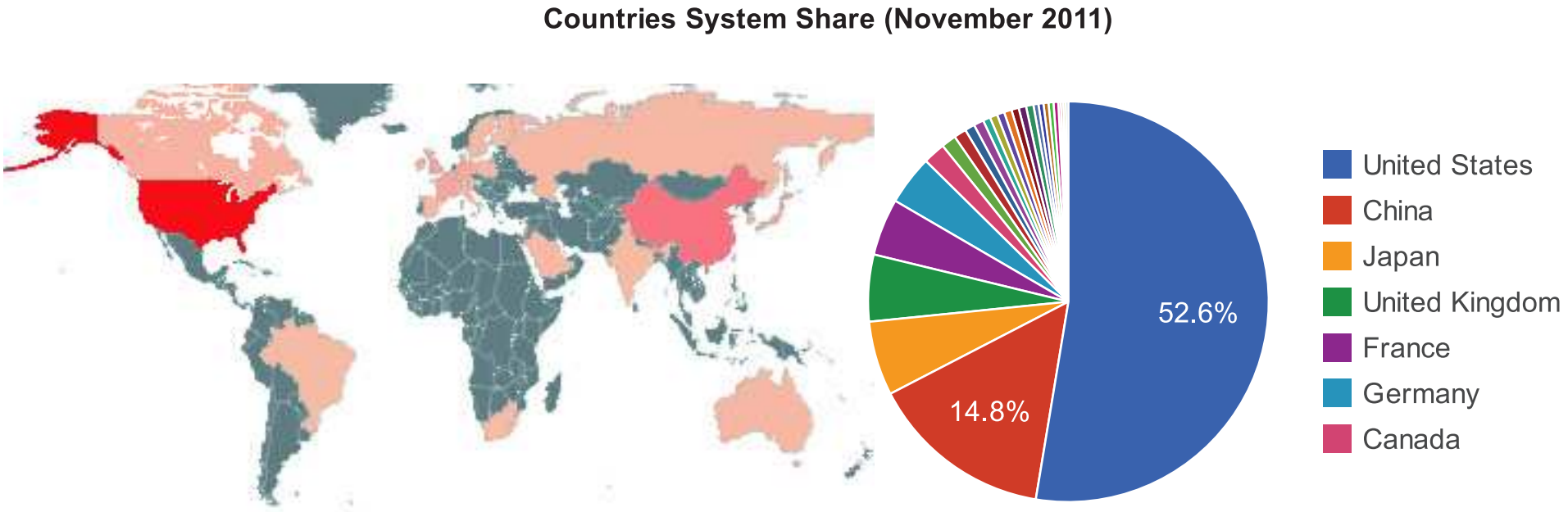

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- Tianhe-2: fastest super computer in 2015, fully Intel-based USA moved super computing center + NUDT + Tianhe center on 'Denial List'[10] . . . . . now wants to build faster super computer using Intel tech[11]

Divide & Conquer

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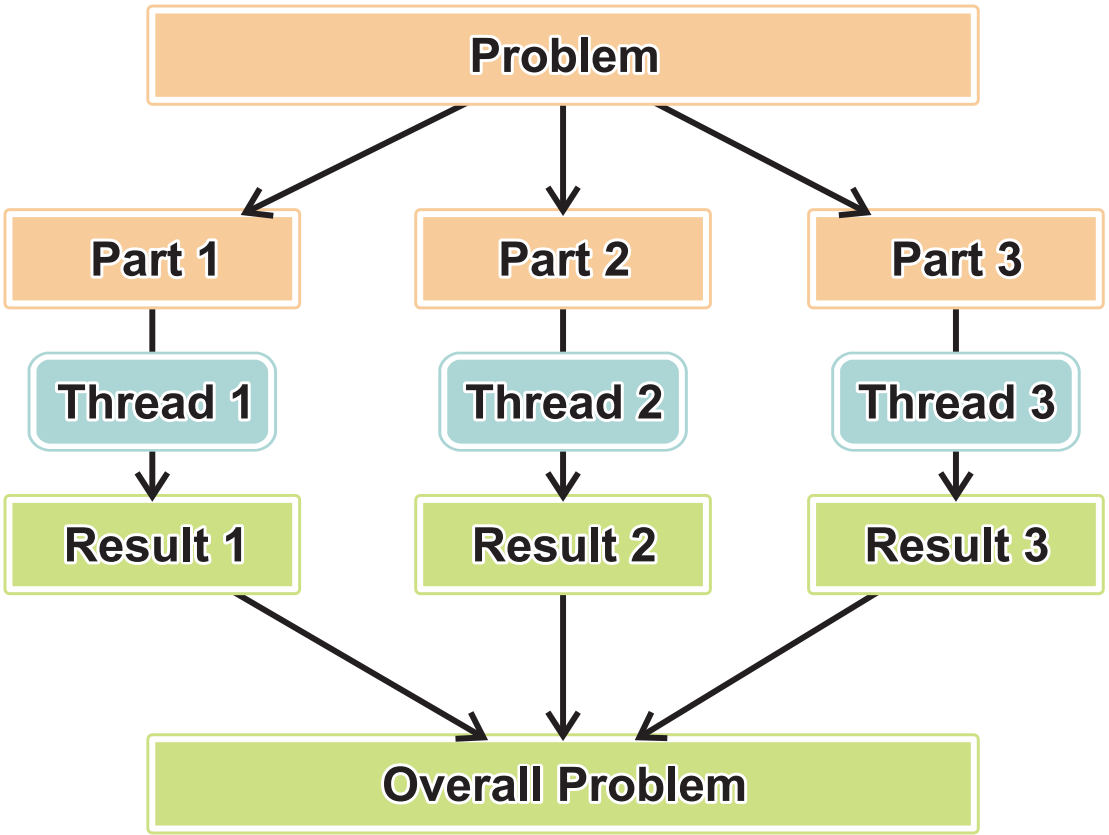

image source: [12]

Partition = Divide

Conquer

Combine

Scalability

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- Let's say we have a large-scale simulation of the air over China for predicting the weather.
- Let's make it faster!
- But how fast can we get at most?
- Does using p computers mean we can solve a task in $\frac{1}{p}$ of the time on a single computer?

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- Thus, even with $p \to \infty$ processors, we cannot finish a task in 0 time...
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- But how much faster can we go, if we include the time needed for communication into our considerations?

Limits of Scalability

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$$S \tag{1}$$

S . . . the speed-up

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S ... the speed-up
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$$S = \frac{T_{seq}}{T_{par}} = \frac{T_{seq}}{T_{seq}\left[\alpha + c_p * \beta + \frac{1-\alpha-\beta}{p}\right]} \tag{1}$$

S ... the speed-up
T_{seq} ... runtime when sequential
α ... fraction of sequential instructions, e.g., for start-up
c_p ... value depending on communication model
T_{par} ... runtime when parallelized
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part of the program that performs the communication: tell all nodes what to do; receive the results from the nodes

the rest: stuff that can be parallelized

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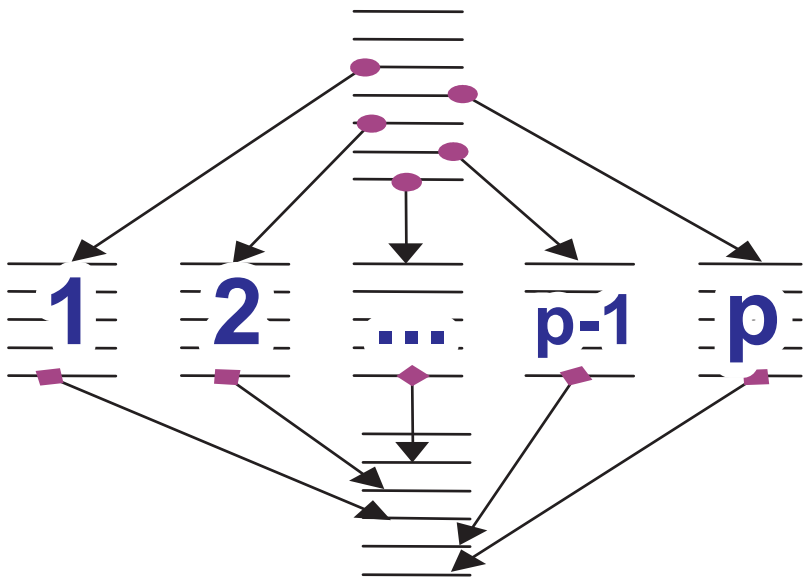

unicast: $c_p = 2p$

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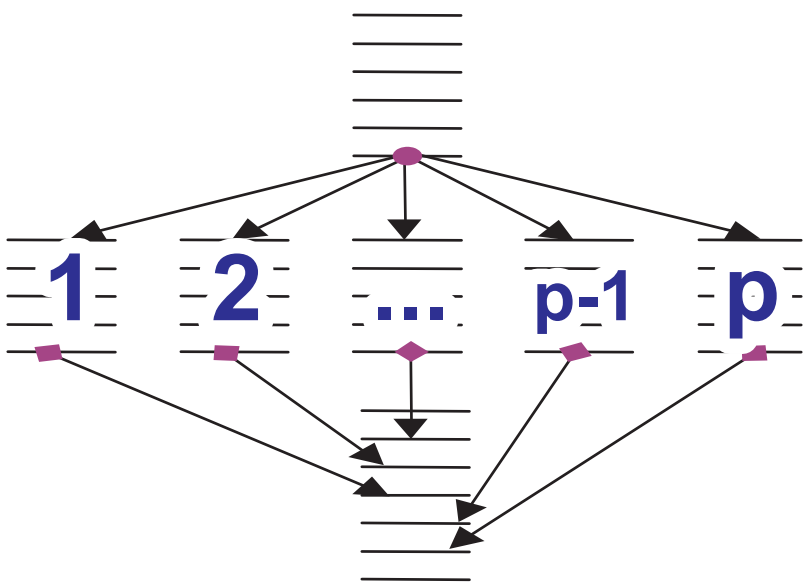

multicast: $c_p = 1 + p$

Amdahl's Law

$$S = \frac{1}{\alpha + c_p * \beta + \frac{1-\alpha-\beta}{p}} \tag{2}$$

(5)

α... fraction of sequential instructions
β... fraction of instructions needed for communication
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$$S = \frac{1}{\alpha + c_p * \beta + \frac{1-\alpha-\beta}{p}} \tag{2}$$

$$\lim_{\beta \to 0} S = \frac{1}{\alpha + \frac{1-\alpha}{p}} \quad \text{(classical Amdahl's Law [14])} \quad \text{ignore communication, } \beta \to 0 \tag{3}$$

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$$\beta \neq 0 \Rightarrow \lim_{p \to \infty} S = 0 \quad \text{communication} \wedge \infty \text{ processors} \tag{5}$$

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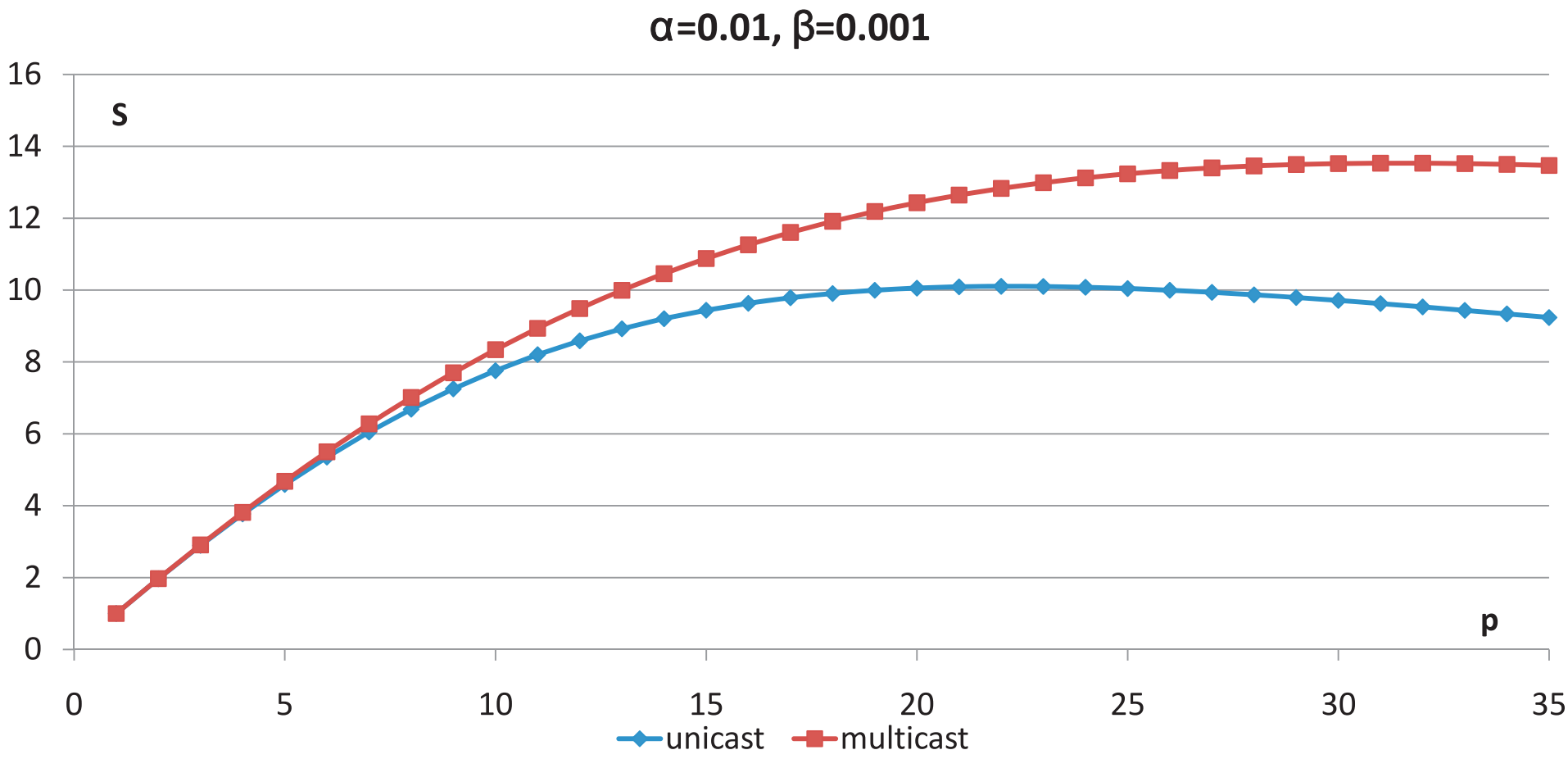
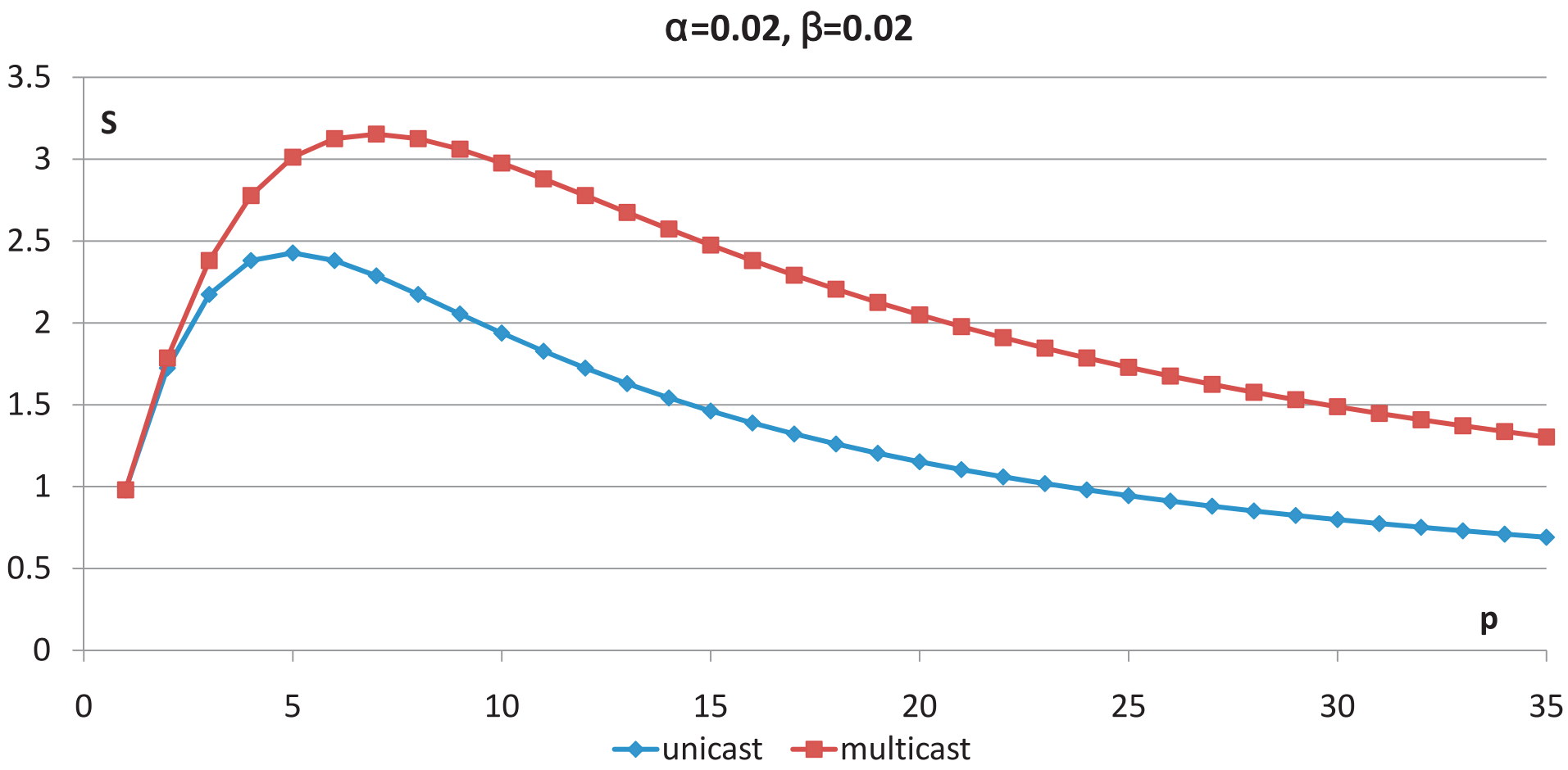

α=0.01, β=0.001
S
p
0
2
4
6
8
10
12
14
16
0
5
10
15
20
25
30
35
unicast
multicast

Amdahl's Law


α=0.02, β=0.02
S
p
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
unicast
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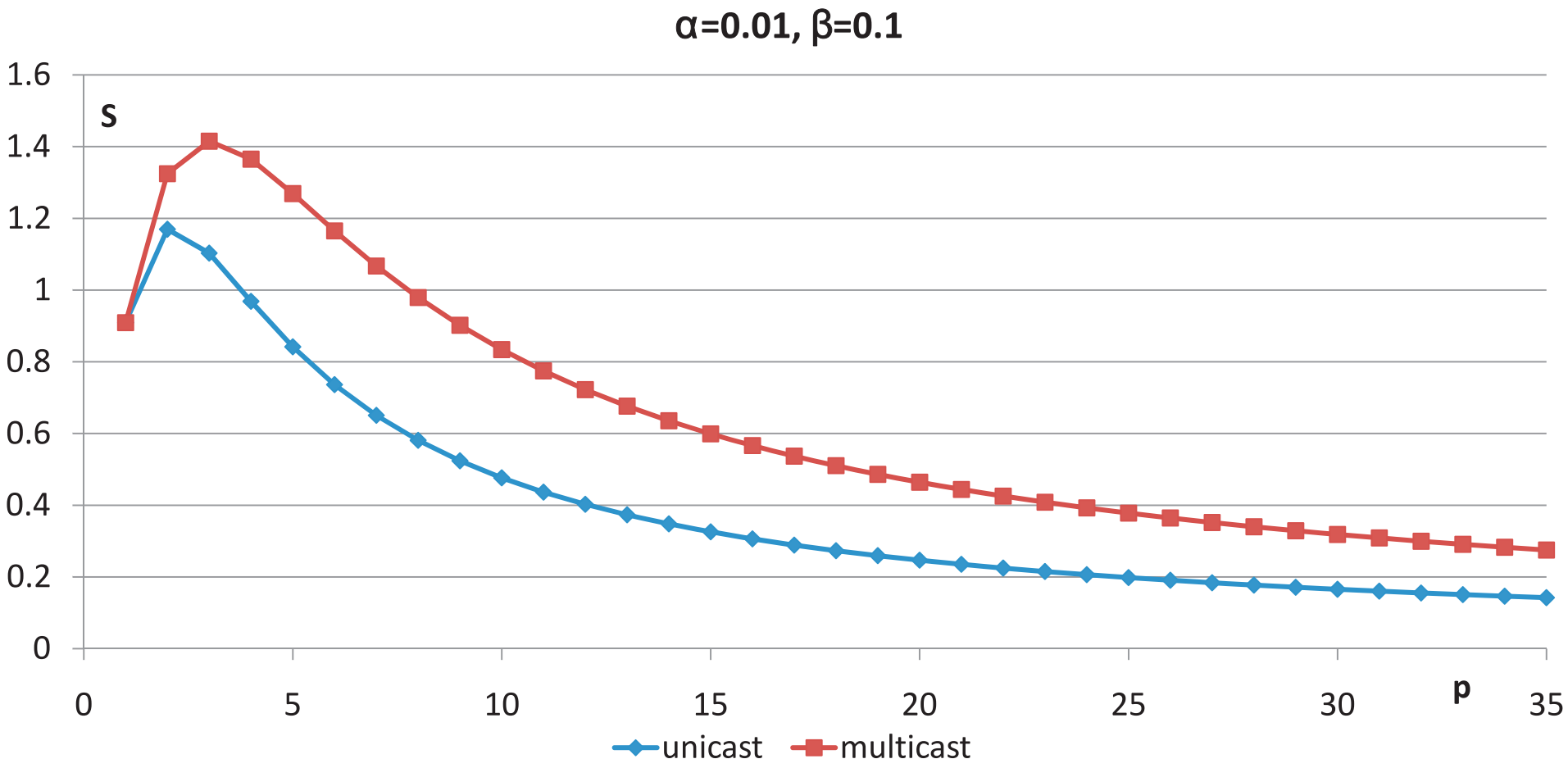
Amdahl's Law


α=0.01, β=0.1
S
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
p
unicast
multicast

Amdahl's Law: Consequences

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- Two lessons valid for every parallel or distributed application

Amdahl's Law: Consequences

- Speedup can be high but is always limited
- Two lessons valid for every parallel or distributed application:
  - Try to communicate as little as possible

Amdahl's Law: Consequences

- Speedup can be high but is always limited
- Two lessons valid for every parallel or distributed application:
  - Try to communicate as little as possible
  - Try to minimize the fraction of sequential code and increase fraction of the code that can run in parallel

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     Example: Evolutionary Algorithm with a population distributed over several threads/processors/computers [6, 16, 17]

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  1. Parallel Problems
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  4. Any combination of the above: division into parts of the above types

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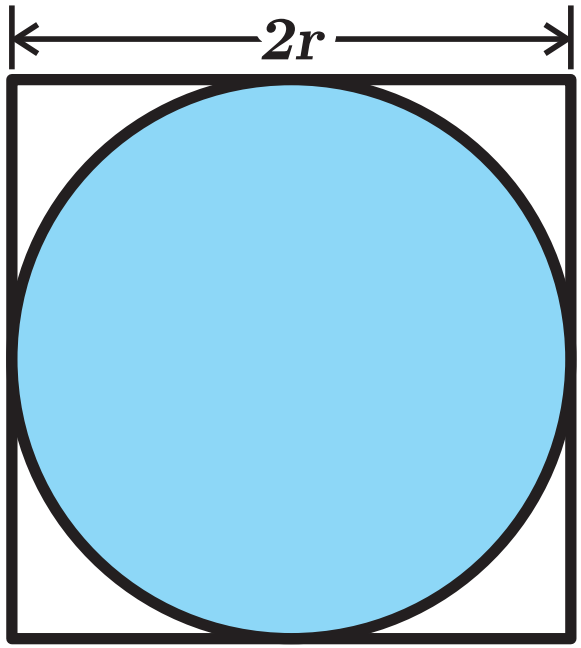
- *Examples:* simple matrix-vector products, rendering of fractals ($\rightarrow$ see your homework)

Estimation of π

- Simple way to estimate the value of π [18, 19]



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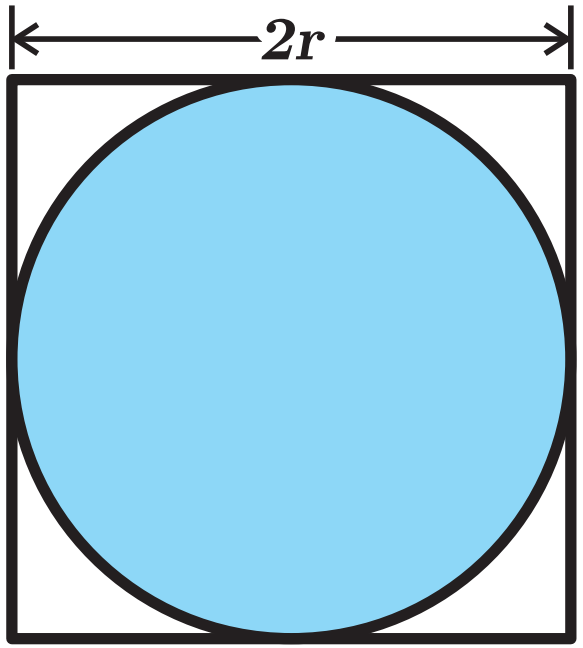

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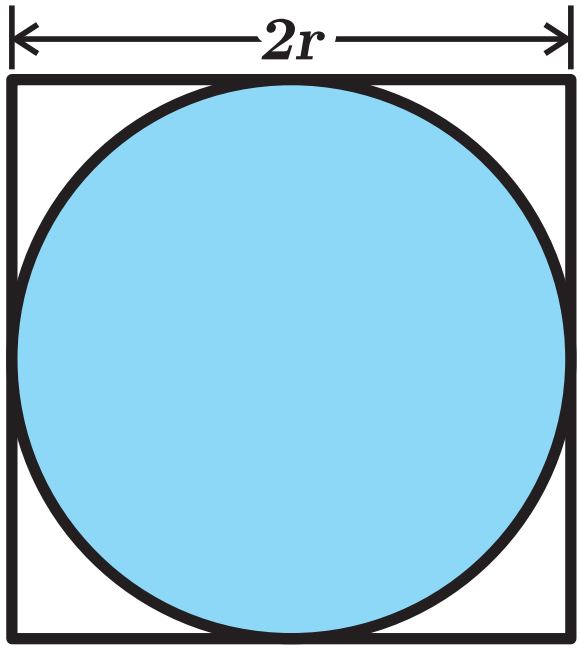

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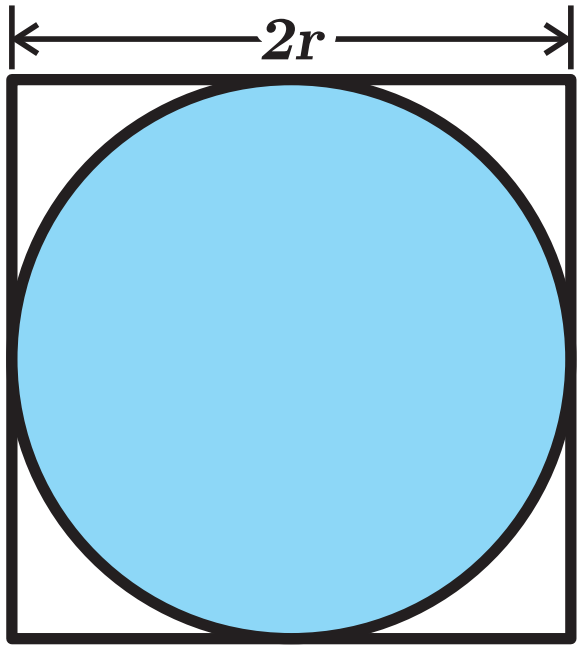

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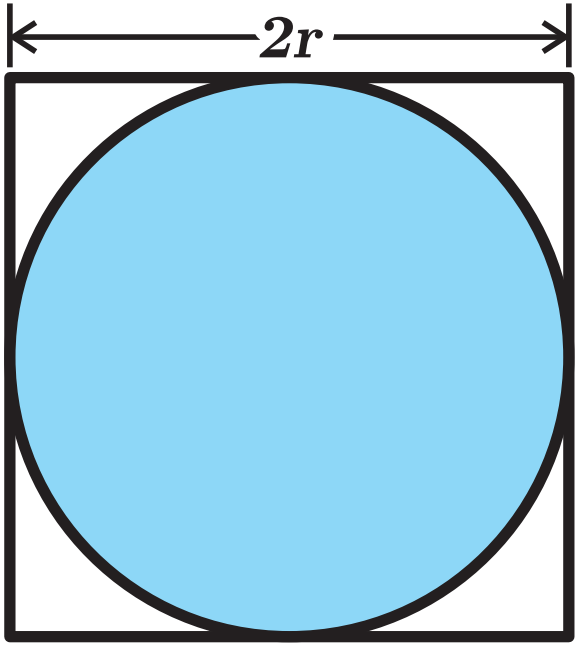

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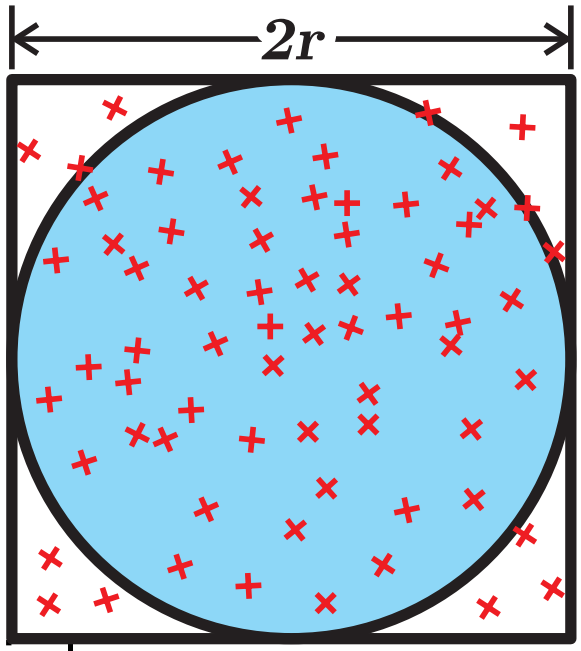

- Randomly generate n points in a square
- Count the number c of points falling into the circle

$$\pi \approx \frac{4c}{n} \quad (9)$$

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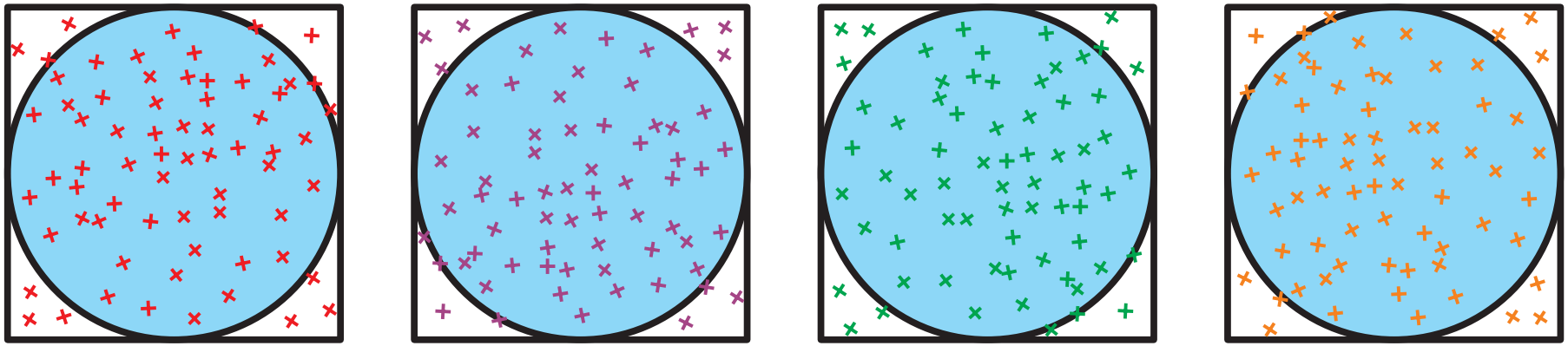

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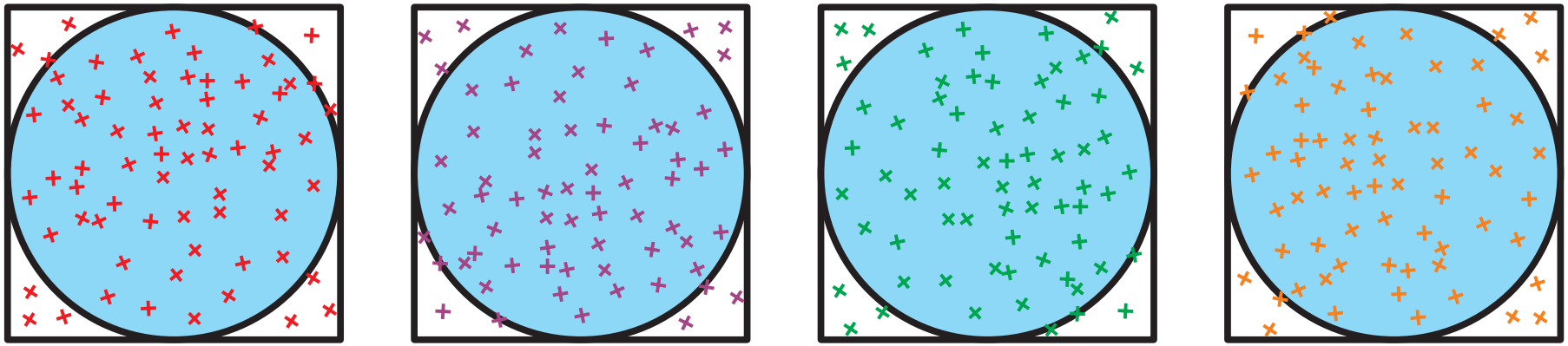
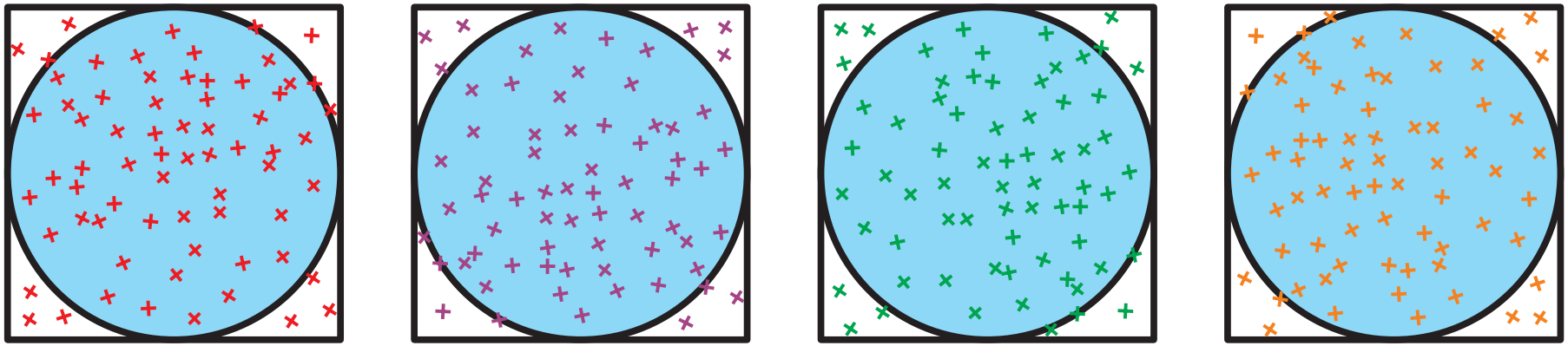


Parallel Estimation of π

- Ideal for parallelization and distribution [18, 19]:
  - Let p threads each create $\frac{n}{p}$ random points...
  - ...and combine the results.
- No communication between workers necessary!



Listing: Server program estimating π (PiServer.java).

```
import java.io.ByteArrayInputStream;    import java.io.ByteArrayOutputStream;   import
    java.io.DataInputStream;
import java.io.DataOutputStream;        import java.io.OutputStream;            import
    java.net.DatagramPacket;
import java.net.DatagramSocket;         import java.net.InetAddress;

public class PiServer {
  public static final void main(final String[] args) {
    DatagramSocket        server;   DatagramPacket    p, answer;
    ByteArrayInputStream  bis;      DataInputStream   dis;
    byte[]                data;     String            s;
    long                  n, c;     double            d;

    n=0;c=0;//try to approximate PI
    try {
      server = new DatagramSocket(9992);//create server socket
      data   = new byte[16];//create package: 2* 8 byte long ints must fit

      for (;;) {//forever
        p = new DatagramPacket(data, data.length);//create new package
        server.receive(p); //wait for and receive incoming data

        bis = new ByteArrayInputStream(data, 0, p.getLength());//wrap data into stream
        dis = new DataInputStream(bis);//unmarshall data

        n += dis.readLong(); //update total number of random points sampled from unit square
        c += dis.readLong(); //update number of these points that fell into the unit circle
        d  = ((4.0 * c) / n);//approximate PI
        System.out.println(d + "␣" + (d - Math.PI)); //print approximation and error
      }
    } catch (Throwable t) {
      t.printStackTrace();
    }
  }
}
```

Listing: Client/Slave program for doing the work when computing π (PiClient.java).

```
import java.io.ByteArrayInputStream;   import java.io.ByteArrayOutputStream;   import
    java.io.DataInputStream;   import java.io.DataOutputStream;
import java.net.DatagramPacket;        import java.net.DatagramSocket;         import
    java.net.InetAddress;

public class PiClient { //the worker part of the example for approximating the number of pi
  public static final void main(final String[] args) {
    DatagramSocket  client;         InetAddress           ia;
    ByteArrayOutputStream bos;      DataOutputStream      dos;
    DatagramPacket        p;        byte[]                data;
    long                  c, n;     double                x, y;

    c = 0;//work: approximate fraction of points in unit square which are in unit circle
    for(n = 1; n <= 100000000; n++) {//create a lot of random points in [0, 1)
      x = Math.random(); //x-coordinate of point
      y = Math.random(); //y-coordinate of point
      if(Math.sqrt((x*x) + (y*y)) <= 1d){ //is the point inside the unit circle?
        c++; //count
        }
      }

    try {
      ia = InetAddress.getByName("localhost");//get local host address
      client = new DatagramSocket(); //create UDP/datagram socket

      bos = new ByteArrayOutputStream();//create buffered output stream
      dos = new DataOutputStream(bos);//marshall computed data
      dos.writeLong(n);//store the number of generated points in unit square
      dos.writeLong(c);//store the number of points in unit circle
      dos.close();//close and flush
      data = bos.toByteArray();//get data

      p = new DatagramPacket(data, data.length, ia, 9992);//create data package
      client.send(p);//send the package to the server

      client.close();//close connection
    } catch (Throwable t) {
      t.printStackTrace();
    }
  }
}
```

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$$\vec{M} \times \vec{v} = \vec{r} \tag{11}$$

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- *Examples:* Parallel Evolutionary Algorithms, Finding low-energy molecule states in chemistry, Cellular Automata-based simulations, discrete time simulation of ion movements, multi-player games with large worlds

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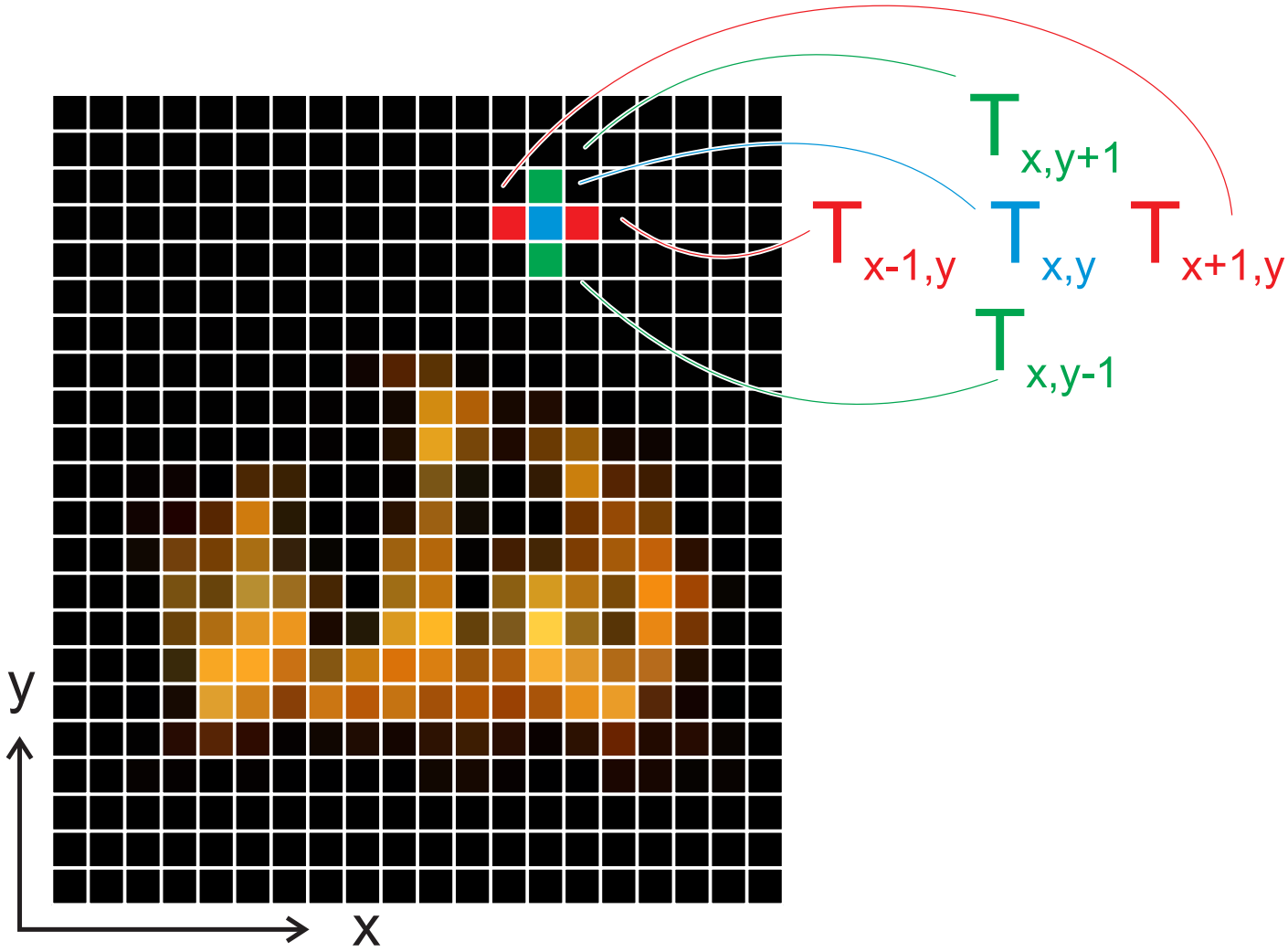

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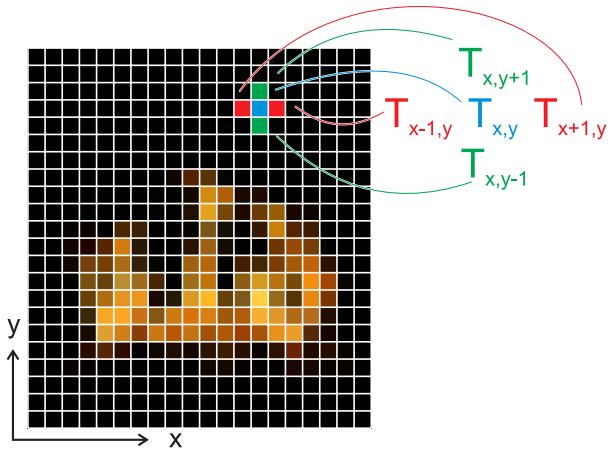

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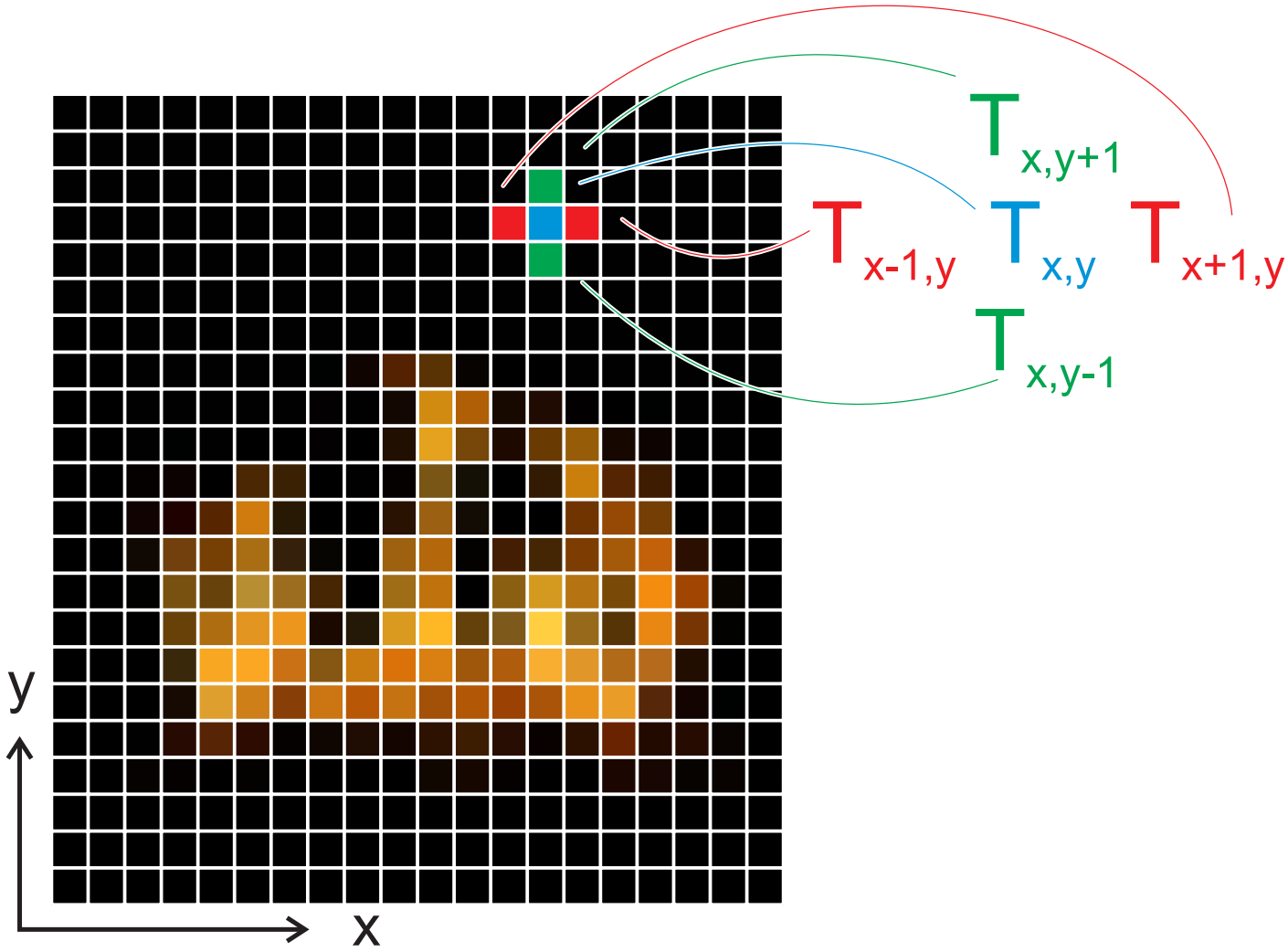
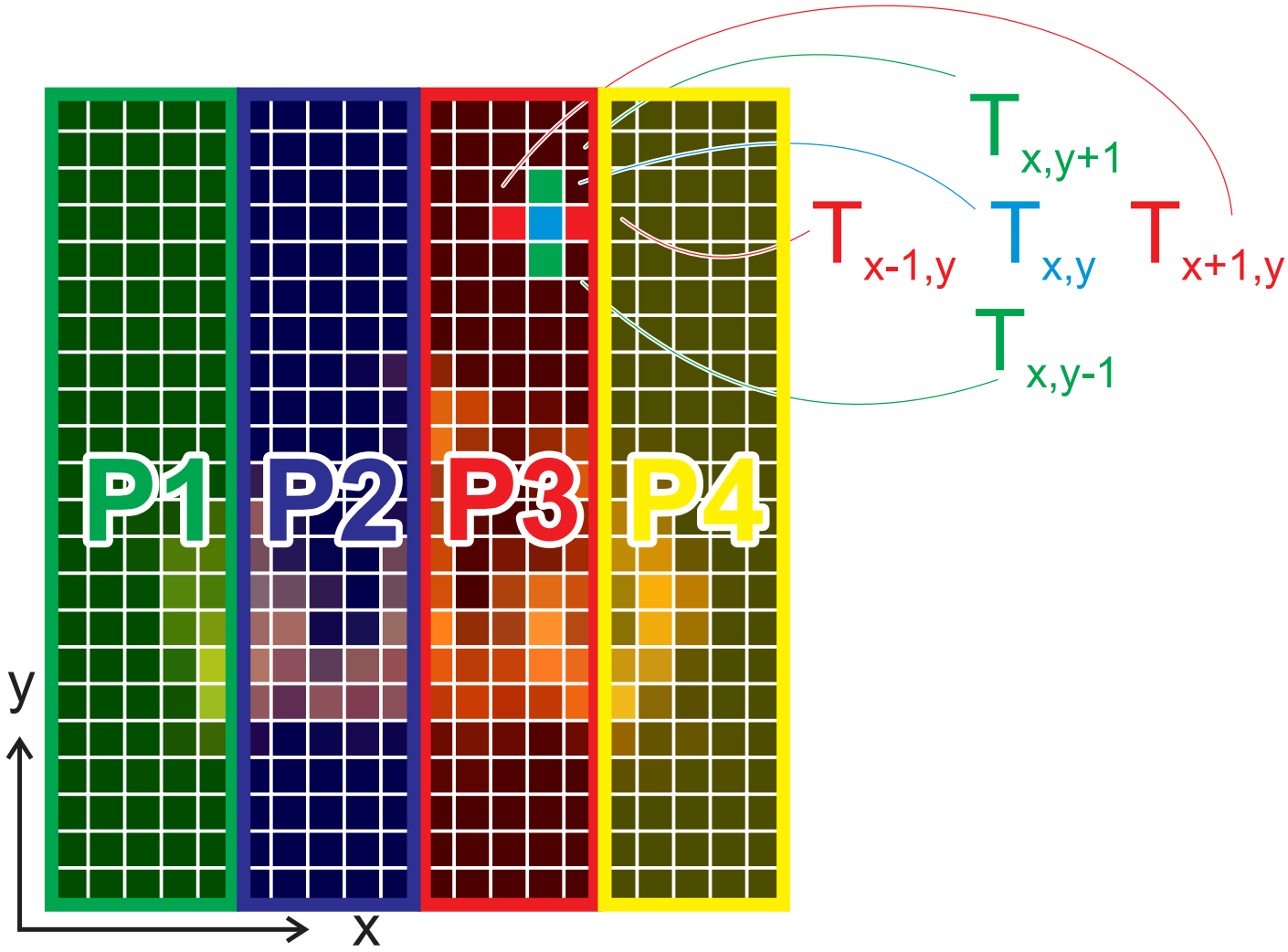
- Finite differencing approximation, numerical, based on a rectangular grid

$$T_{x,y}(t+1) = T_{x,y}(t) + c_x\left(T_{x-1,y}(t) + T_{x+1,y}(t) - 2T_{x,y}(t)\right) + c_y\left(T_{x,y-1}(t) + T_{x,y+1}(t) - 2T_{x,y}(t)\right) \quad (12)$$

Distributed Heat Dissemination Simulation




P1
P2
P3
P4
y
x
T x,y+1
T x-1,y
T x,y
T x+1,y
T x,y-1

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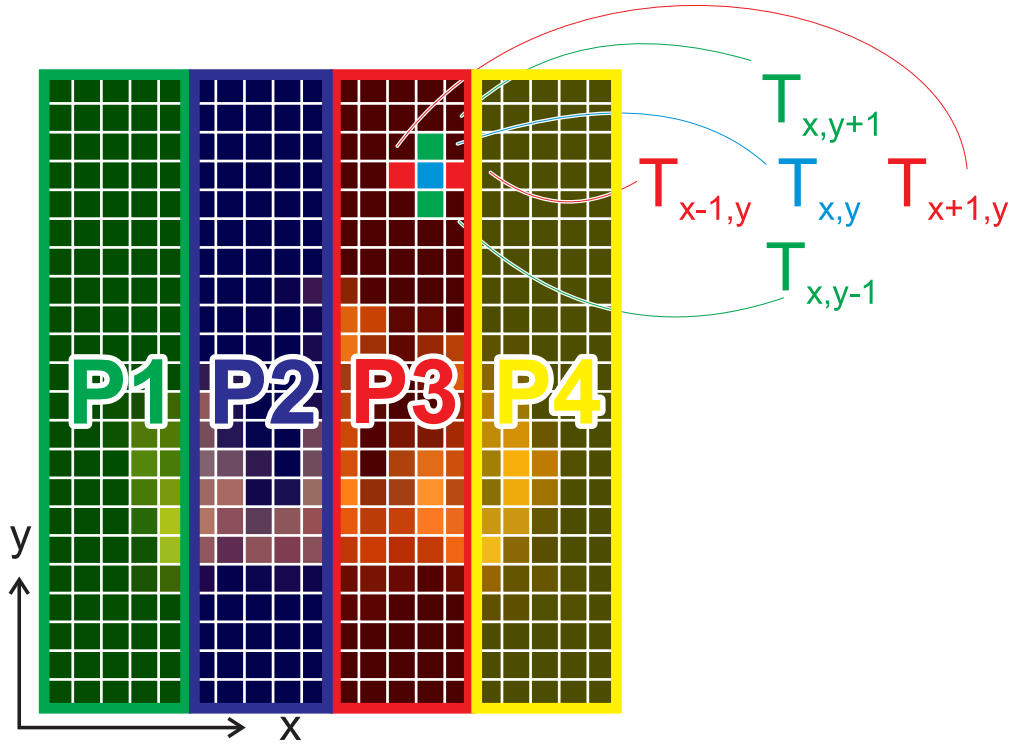

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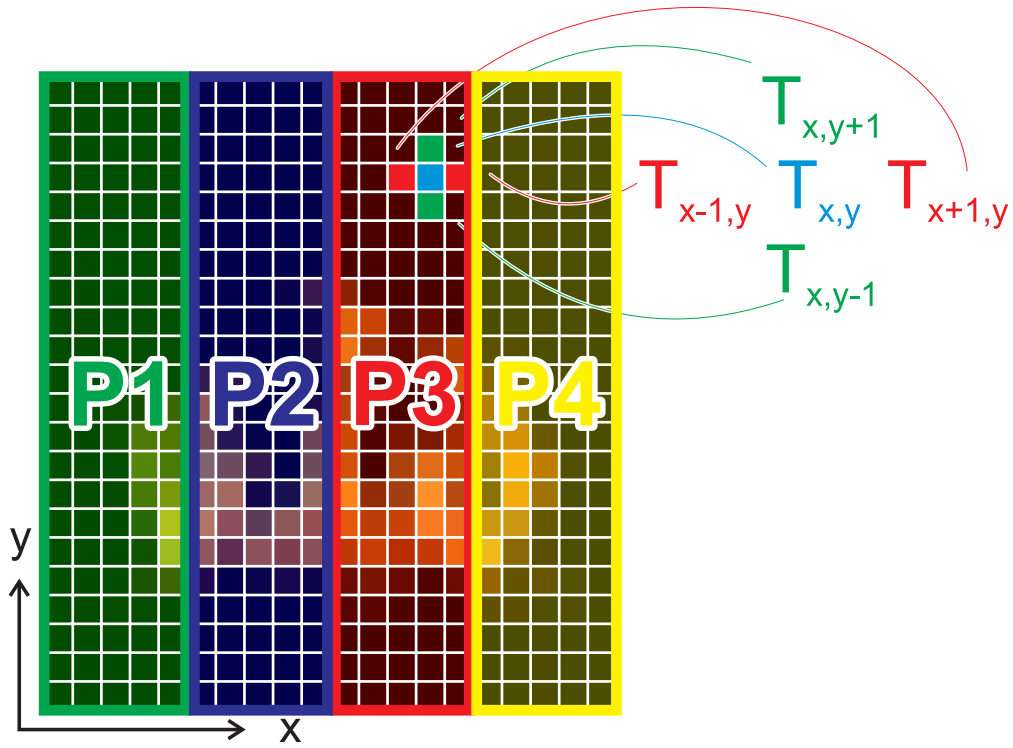
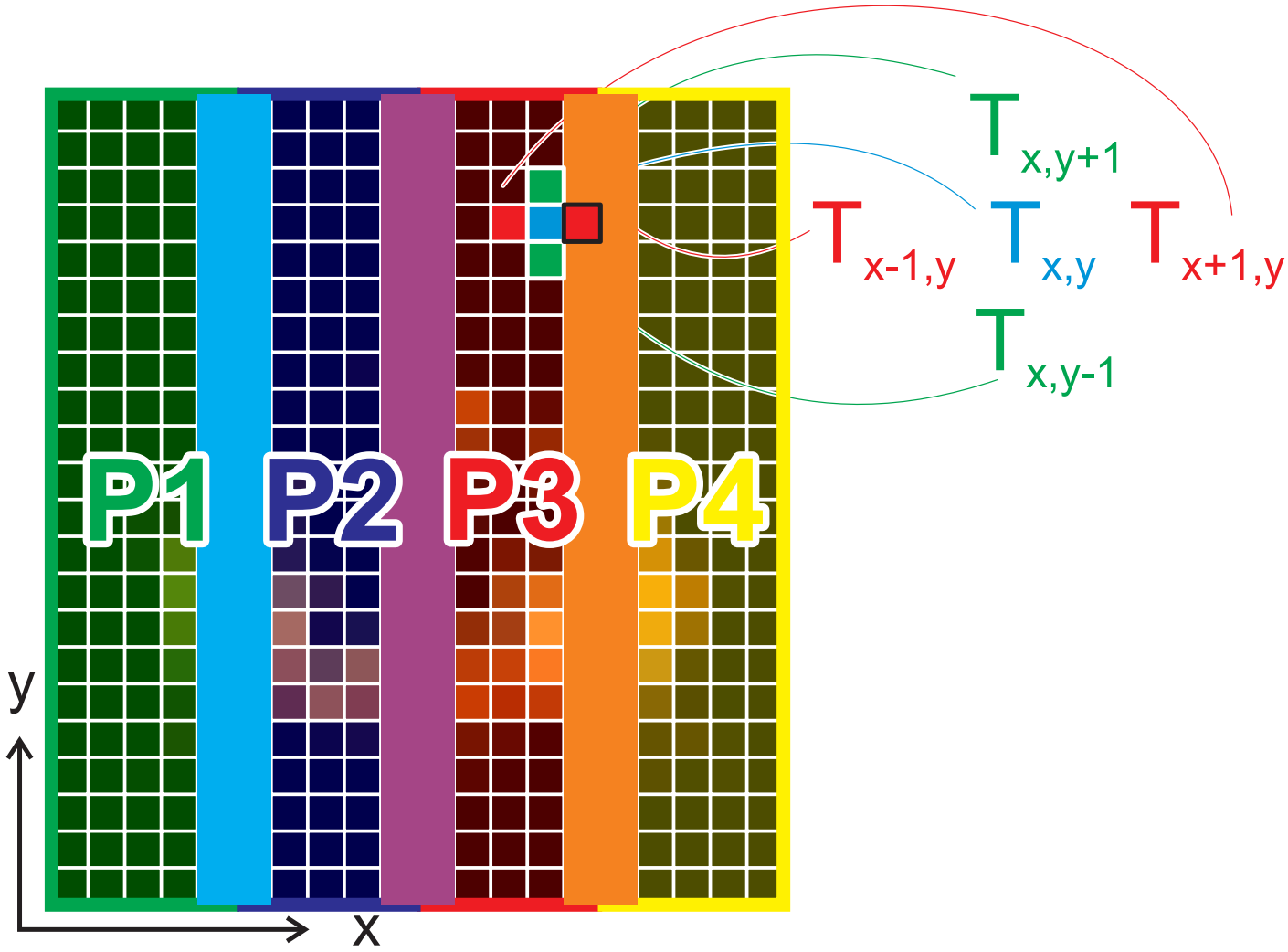


- Divide data into several pieces and simulate in parallel [19]
- But: After *each* time step, exchange data on boundary between "neighboring" threads

Distributed Heat Dissemination Simulation



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Irregular Problems

- Irregular algorithm which cannot be parallelized/distributed efficiently except with high communication overhead
- Communication often asynchronous, complex, may require load balancing
- Often dynamic repartitioning of data between processors is required
- *Examples:* calculate Fibonacci Numbers [20] by using $F(n) = F(n-1) + F(n-2)$, multi-player games or simulations with strong interaction, such as car racing

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- We want a uniform programming interface and implementations which provide the services we need.

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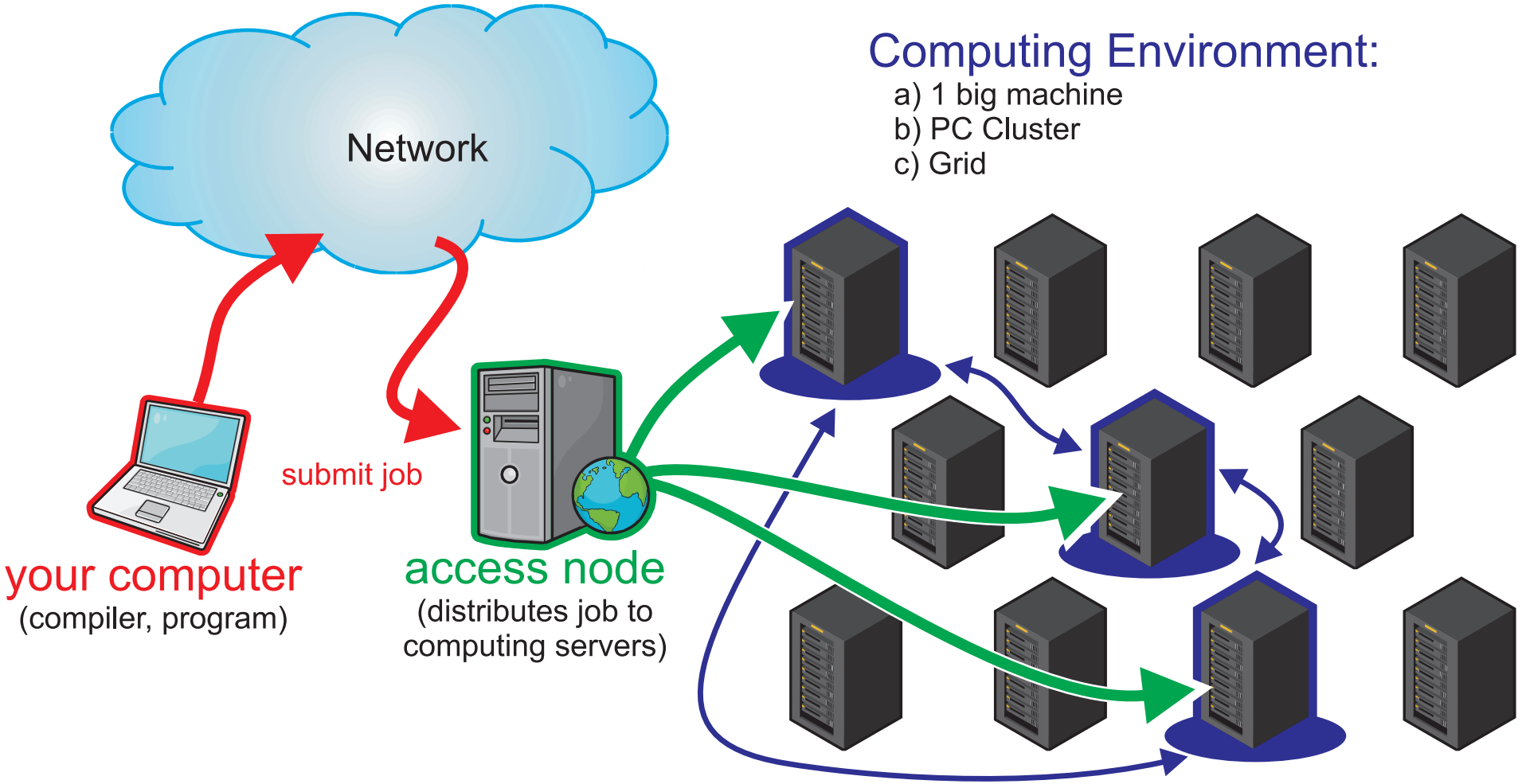
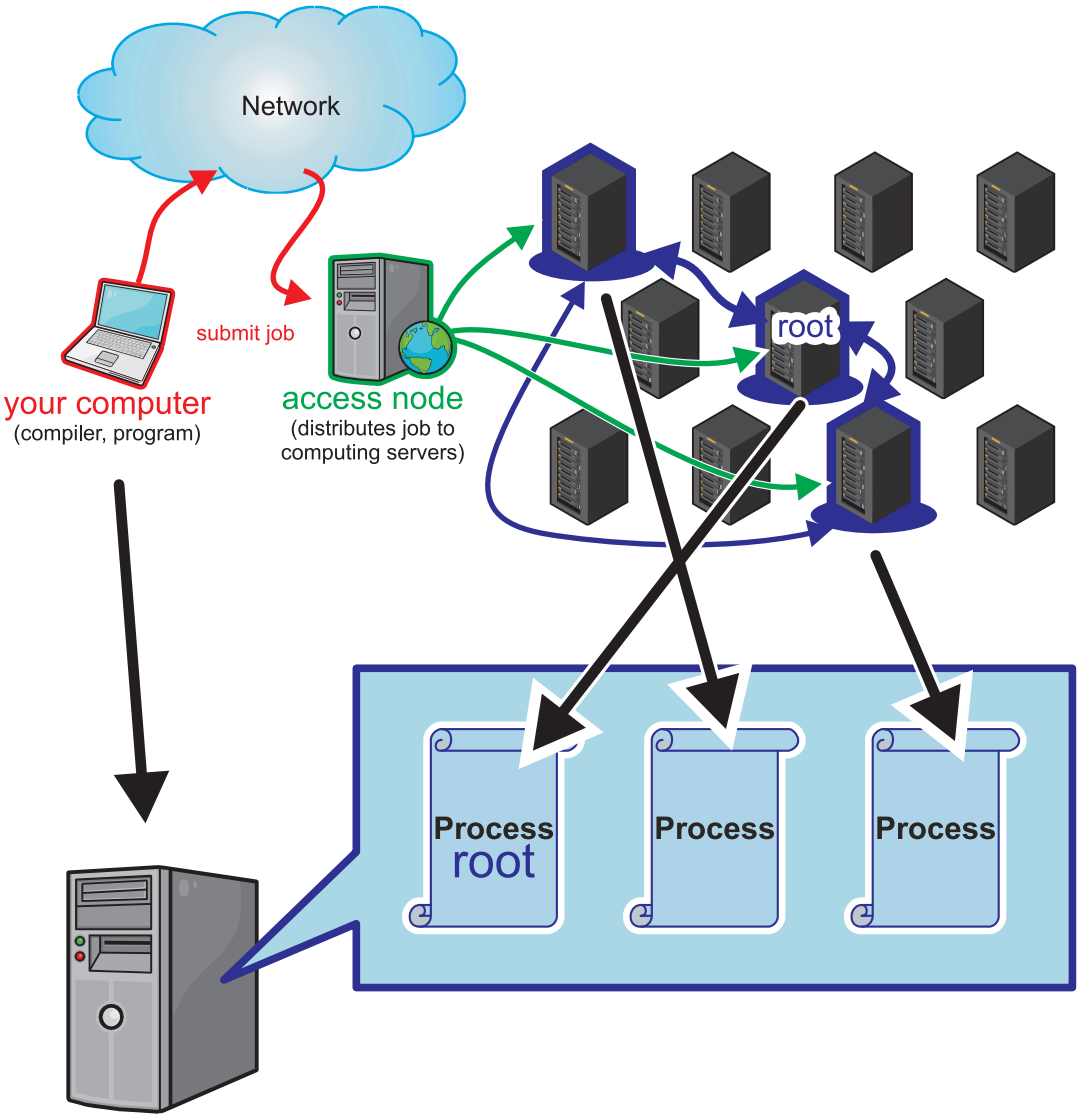


. . . but in our experiments. . .



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Listing: Care bones of MPI program (bareBones.c).

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- `MPI_Init` starts the MPI subsystem
- `MPI_Finalize` shuts down the MPI subsystem
- Similar to `WSAStartup` and `WSACleanup` in the sockets lecture

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- All MPI routines return an `int` with the result status, `MPI_SUCCESS` means everything went OK

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  - `rank` $\in \{0 \ldots \texttt{size} - 1\}$

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- For now, we just use `MPI_COMM_WORLD`
- which contains all MPI processes, i.e., does broadcast

Listing: Extended MPI Program (basicInfo.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h> // import for printf

int main(int argc, char **argv) {
  int size, rank;

  MPI_Init(&argc, &argv); // initialize MPI

  MPI_Comm_size(MPI_COMM_WORLD, &size); // get number of program instances
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own ID/address

  // often, an MPI application has a master and some slaves
  // master distributes tasks and combine partial results to final results
  // slaves receive partial task, compute partial result, and send to master
  if(rank == 0) { // the instance with rank=0 is often chosen as master
    printf("Hi␣from␣Master\n");
  } else {        // the others are often slaves
    printf("Just␣Slave␣%d␣out␣of␣%d\n", rank, size);
  }

  MPI_Finalize(); // finalize = shut down MPI
  return 0;
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Blocking Send: MPI_Send

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  - Buffer can be overwritten after function returns
- Input Parameters
  - `buf` ... initial address of send buffer
  - `count` ... number of elements in send buffer
  - `datatype` ... datatype of each send buffer element
  - `dest` ... rank/id of destination process
  - `tag` ... message tag: which send belongs to which receive
  - `comm` dotsthe communicator to use

Blocking Receive: MPI_Recv

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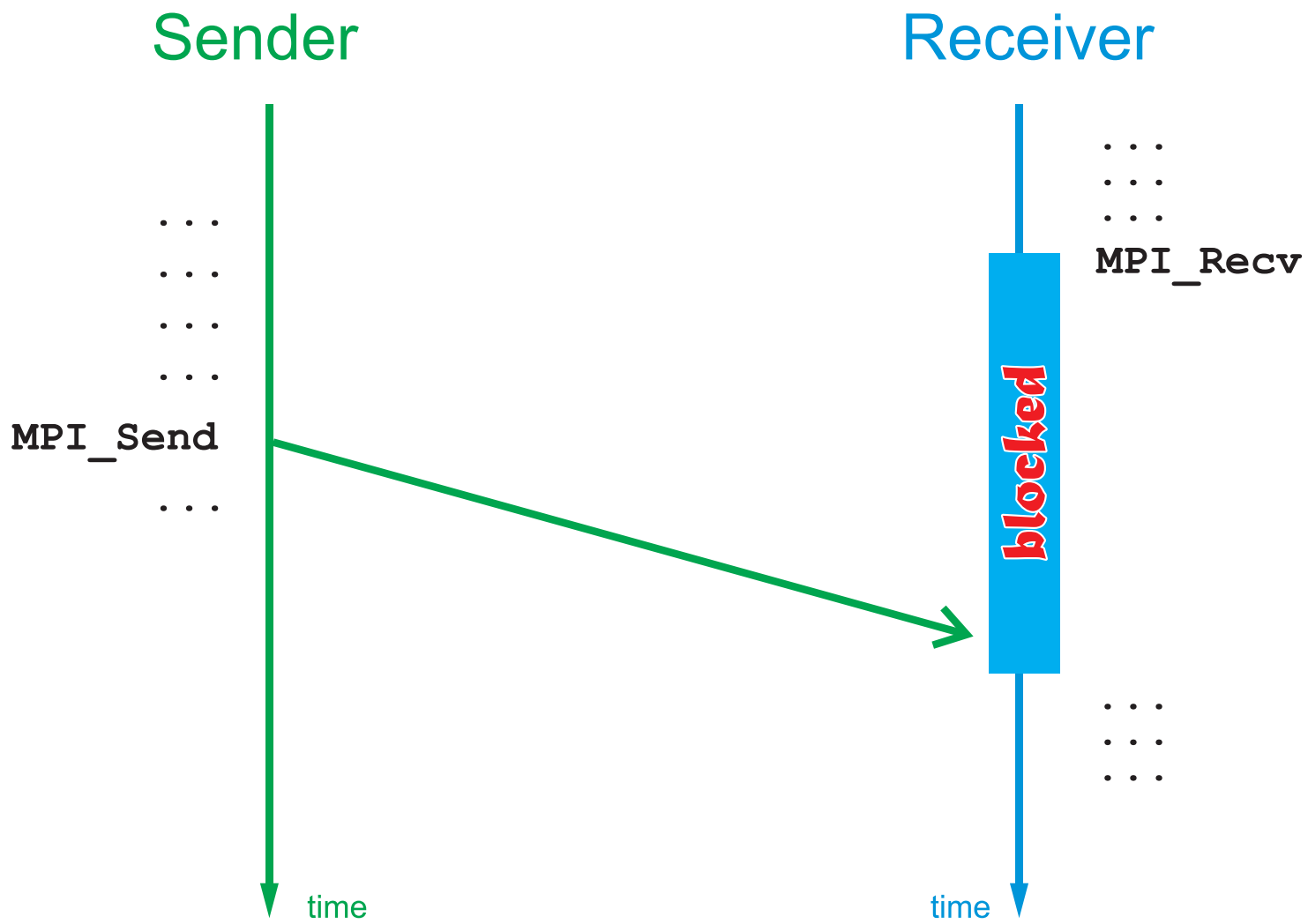
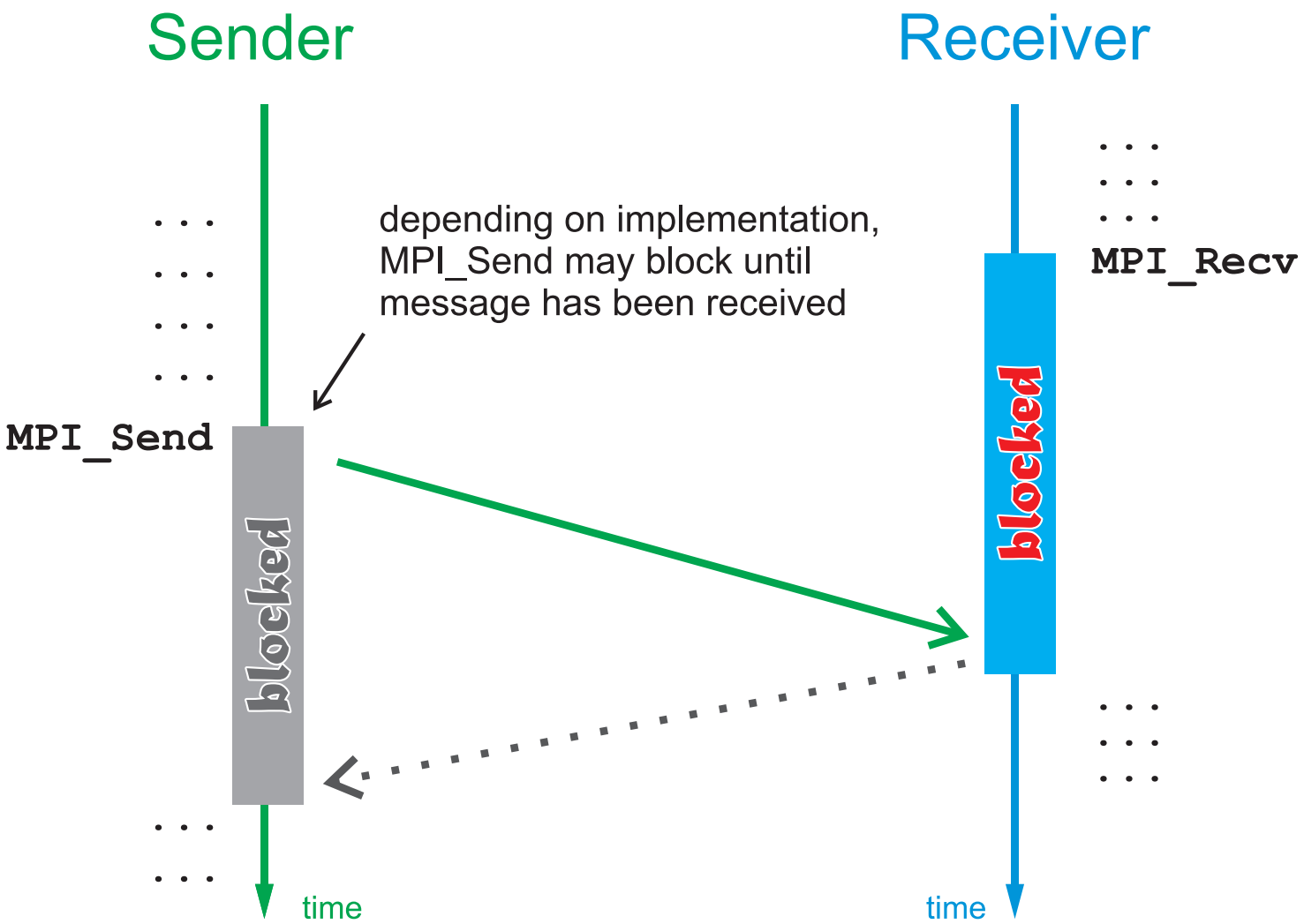


MPI_Send and MPI_Recv



Synchronized Send: MPI_Ssend

```
int MPI_Ssend(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)
```

- Performs a blocking and synchronized send

Synchronized Send: MPI_Ssend

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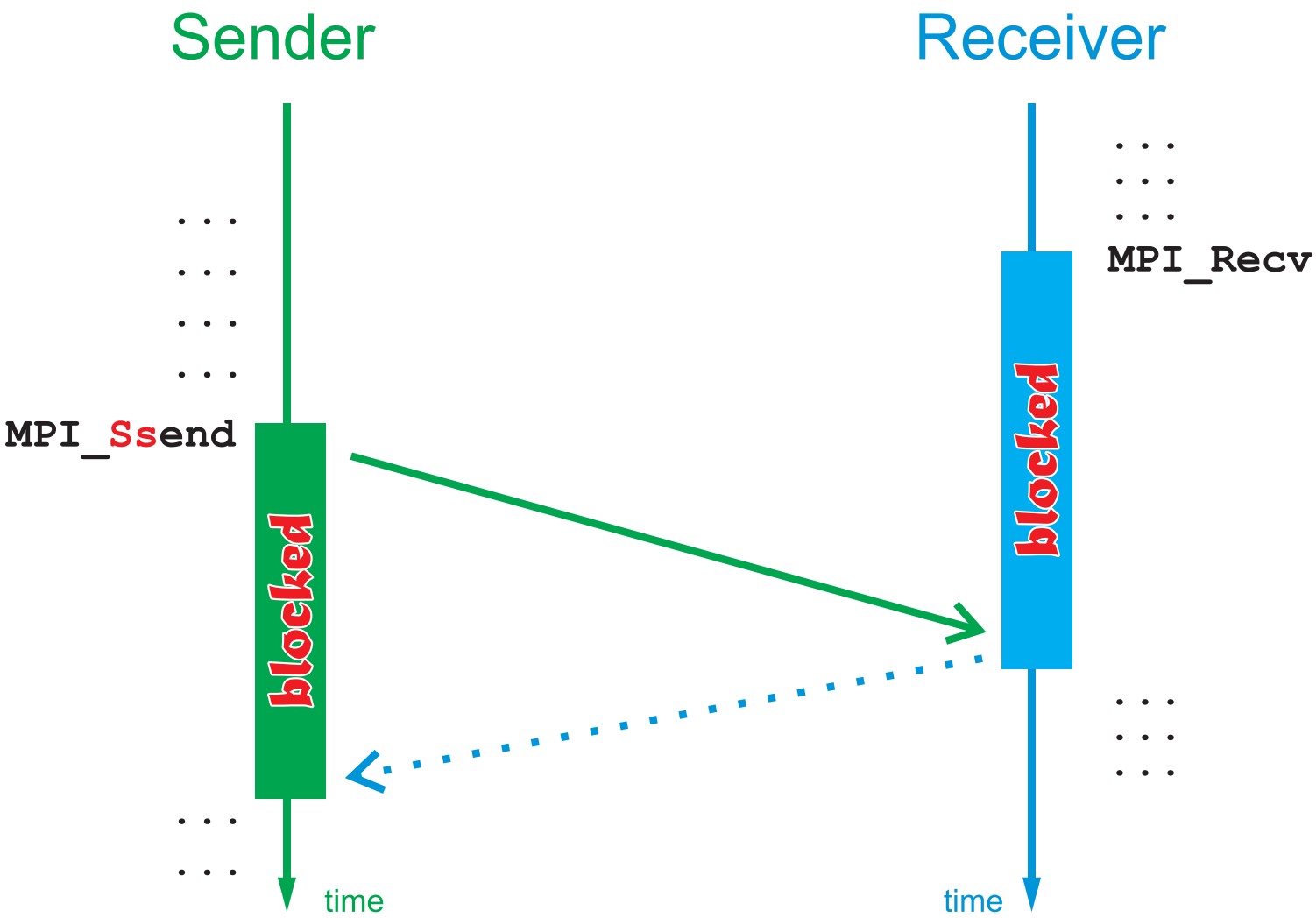
- Performs a blocking and synchronized send:
  - Will block until message has been copied to OS/network stack buffers

Synchronized Send: MPI_Ssend

```
int MPI_Ssend(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)
```

- Performs a blocking and synchronized send:
  - Will block until message has been copied to OS/network stack buffers
  - Will block until message has received at destination process

MPI_Ssend and MPI_Recv



Listing: A Point-to-Point communication example (simplePointToPoint1.c)

```c
#include <mpi.h>   // import MPI header
#include <stdio.h> // needed for printf

int main(int argc, char **argv) {
  int size, rank, s_msg, r_msg, next, prev;
  MPI_Status status;

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get number of program instances
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own ID/address

  next  = ((rank + 1) % size);  // next higher id, wrap from size-1 to 0
  prev  = ((rank + size - 1) % size); // next lower id, wrap from 0 to size-1
  s_msg = ((size * rank) + next); // the example message, just some number

  if((rank % 2) == 0) { // even rank: message to next, receive from prev
    MPI_Send(&s_msg, 1, MPI_INT, next, 42, MPI_COMM_WORLD);
    MPI_Recv(&r_msg, 1, MPI_INT, prev, 42, MPI_COMM_WORLD, &status);
  } else { // otherwise: receive from rev, send to next
    MPI_Recv(&r_msg, 1, MPI_INT, prev, 42, MPI_COMM_WORLD, &status);
    MPI_Send(&s_msg, 1, MPI_INT, next, 42, MPI_COMM_WORLD);
  }

  printf("id: %d, next: %d, prev: %d, send: %d, recv: %d\n", rank, next, prev, s_msg,
      r_msg);

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

Listing: A Point-to-Point communication example (simplePointToPoint2.c)

```c
#include <mpi.h>     // import MPI header
#include <stdio.h>   // needed for printf
#include <string.h> // needed for strlen

int main(int argc, char *argv[]) {
  char message[20];  // char array big enough to hold message
  int rank;          // own rank
  MPI_Status status; // status variable

  MPI_Init(&argc, &argv); // initialize mpi
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank

  if (rank == 0) { // if we have rank 0...
    strcpy(message, "Hello, there"); /// ...create and send message to rank 1
    MPI_Send(message, strlen(message)+1, MPI_CHAR, 1, 42, MPI_COMM_WORLD);
    printf("sent: \"%s\"\n", message); // print the message that was sent
  } else { // if we are rank 1, receive message coming from rank 0
    MPI_Recv(message, 20, MPI_CHAR, 0, 42, MPI_COMM_WORLD, &status);
    printf("received: \"%s\"\n", message); // print message
  }

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

Listing: Computing Pi with Point-to-Point communication example (piPointToPoint.c)

```c
#include <mpi.h>
#include <stdlib.h>
#include <stdio.h>
#include <time.h>

int main(int argc, char **argv) {
  int           i, size, rank;            double     x, y;
  long long int root[2], worker[2];       MPI_Status status;

  MPI_Init(&argc, &argv);                                 //initialize MPI
  MPI_Comm_size(MPI_COMM_WORLD, &size);                   //get the number of processes in the global communicator
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);                   //get the rank of this process within the global communicator
  root[0] = root[1] = worker[0] = worker[1] = 0LL;        //clear the data buffer

  if(rank == 0) {                                         //check if we are root
    for(i = size; (--i) > 0; ) {                          //receive data from the workers
      MPI_Recv(&worker[0], 2, MPI_LONG_LONG_INT, i, 42, MPI_COMM_WORLD, &status); //do receive
      root[0] += worker[0];                               //get the received sample size (number of points)
      root[1] += worker[1];                               //get the number of samples (points) inside the unit circle
      printf("worker␣%d␣sends␣estimate␣%G␣(based␣on␣%lld␣samples),␣total␣estimate␣now␣is␣%G␣(based␣on␣%lld␣samples).\n", i,
                  ((4.0 * worker[1]) / worker[0]), worker[0], ((4.0 * root[1]) / root[0]), root[0]);
      fflush(stdout);                                     //flush the standard out
    }
  } else {                                                //ok, we are a worker
    srand(time(NULL));
    for(worker[0] = 1; worker[0] < (rank * 100000000LL); worker[0]++) { //make 100 000 000 samples
      x = (rand() / ((double)RAND_MAX));                  //random x-coordinate in [0,1]
      y = (rand() / ((double)RAND_MAX));                  //random y-coordinate in [0,1]
      if( ((x*x) + (y*y)) <= 1.0 ) {                      //did it fall into the inner circle?
        worker[1]++;                                      //yes, it did - increase counter
      }
    }
    MPI_Send(&worker[0], 2, MPI_LONG_LONG_INT, 0, 42, MPI_COMM_WORLD); //send worker result synchronously
  }

  MPI_Finalize();                                         //finish the MPI stuff
  return 0;
}
```

Listing: Point-to-Point with error (deadlock.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf
#include <string.h> // needed for strlen

int main(int argc, char **argv) {
  int         rank, size, prev, next;
  MPI_Status  status;
  char        messageIn[20], messageOut[20];

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank/ID
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get total number of processes

  prev = ((size + rank - 1) % size); // get rank of process to receive from, wrap at 0
  MPI_Recv(messageIn, 20, MPI_CHAR, prev, 0, MPI_COMM_WORLD, &status); // receive msg
  printf("Process␣%d␣received␣message␣%s␣from␣process␣%d.\n", rank, messageIn, prev);

  next = ((rank + 1) % size); // get rank of process to send message to
  strcpy(messageOut, "Important␣message!"); // construct message
  printf("Process␣%d␣is␣sending␣message␣%s␣to␣process␣%d.\n", rank, messageOut, next);
  MPI_Send(messageOut, 20, MPI_CHAR, next, 0, MPI_COMM_WORLD); // send message

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

Non-blocking Operations

- Sometimes, we want to keep calculating while sending/receiving is going on: non-blocking operations

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- Sometimes, we want to keep calculating while sending/receiving is going on: non-blocking operations

```
int MPI_Isend(void* buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm
m, MPI_Request* request)
```

```
int MPI_Irecv(void* buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm
m, MPI_Request* request)
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Non-blocking Operations

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m, MPI_Request* request)
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```
int MPI_Irecv(void* buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm
m, MPI_Request* request)
```

- Return immediately, i.e., do not wait until data is copied (will be done in background)
- `request` . . . address of a data structure for information about the operation

Non-blocking Operations

- Sometimes, we want to keep calculating while sending/receiving is going on: non-blocking operations

```
int MPI_Isend(...MPI_Request* request)
```

```
int MPI_Irecv(...MPI_Request* request)
```

- Return immediately, i.e., do not wait until data is copied (will be done in background)
- `request` ... address of a data structure for information about the operation

Non-blocking Operations

- If we start an *asynchronous* operation, like sending or receiving...

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- If we start an *asynchronous* operation, like sending or receiving...
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```
int MPI_Test(MPI_Request* request, int* flag, MPI_Status* status)
```

Non-blocking Operations

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- ...how do we know when we can change the data (being sent) or use the data (being received) if the operation returns immediately?

```
int MPI_Test(MPI_Request* request, int* flag, ...)
```

- check operation status
- stores `flag=1` if operation is finished, `flag=0` if it is ongoing

Non-blocking Operations

- If we start an *asynchronous* operation, like sending or receiving...
- ...how do we know when we can change the data (being sent) or use the data (being received) if the operation returns immediately?

```
int MPI_Test(MPI_Request* request, int* flag, ...)
```

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- stores `flag=1` if operation is finished, `flag=0` if it is ongoing

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int MPI_Wait(MPI_Request* request, MPI_Status* status)
```

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```
int MPI_Wait(MPI_Request* request, MPI_Status* status)
```

- blocks until operation has finished

Non-blocking Operations

- If we start an *asynchronous* operation, like sending or receiving...
- ...how do we know when we can change the data (being sent) or use the data (being received) if the operation returns immediately?

```
int MPI_Test(MPI_Request* request, int* flag, ...)
```

- check operation status
- stores `flag=1` if operation is finished, `flag=0` if it is ongoing

```
int MPI_Wait(MPI_Request* request, MPI_Status* status)
```

- blocks until operation has finished

```
int MPI_Waitany(int count, MPI_Request array_of_requests[], int *index, MPI_Status *status)
```

Non-blocking Operations

- If we start an *asynchronous* operation, like sending or receiving...
- ...how do we know when we can change the data (being sent) or use the data (being received) if the operation returns immediately?

```
int MPI_Test(MPI_Request* request, int* flag, ...)
```

- check operation status
- stores `flag=1` if operation is finished, `flag=0` if it is ongoing

```
int MPI_Wait(MPI_Request* request, MPI_Status* status)
```

- blocks until operation has finished

```
int MPI_Waitany(int count, ..., int *index, ...)
```

- blocks until *one* of the `count` operations in `array_of_requests` has finished

Non-blocking Operations

- If we start an *asynchronous* operation, like sending or receiving...
- ...how do we know when we can change the data (being sent) or use the data (being received) if the operation returns immediately?

```
int MPI_Test(MPI_Request* request, int* flag, ...)
```

- check operation status
- stores `flag=1` if operation is finished, `flag=0` if it is ongoing

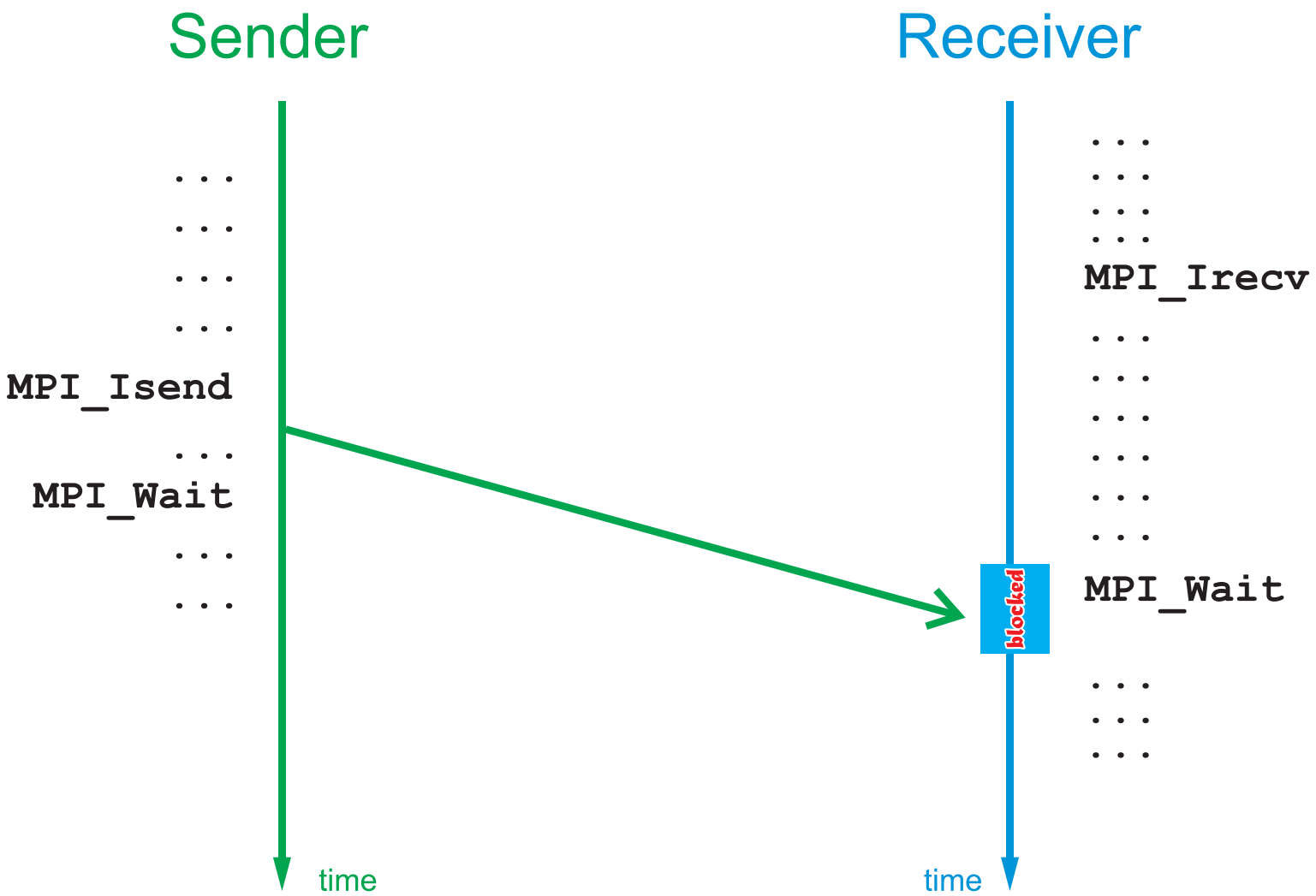
```
int MPI_Wait(MPI_Request* request, MPI_Status* status)
```

- blocks until operation has finished

```
int MPI_Waitany(int count, ..., int *index, ...)
```

- blocks until *one* of the `count` operations in `array_of_requests` has finished
- returns index of finished operation in `index`

MPI_Isend and MPI_Irecv



Listing: Non-blocking Point-to-Point communication [33] (nonBlockingPointToPoint.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf

int main(int argc, char *argv[]) {
  int            rank, size, prev, next;
  char           receiveBuffer[30], sendBuffer[30];
  MPI_Request    receiveRequest, sendRequest;
  MPI_Status     status;

  MPI_Init(&argc,&argv); // initialize MPI
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get own rank / ID
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get total number of processes

  next = ((rank + 1) % size); // get rank of process to receive from
  // _initiate_ receive operation, but do not wait for its completion
  MPI_Irecv(receiveBuffer, 30, MPI_CHAR, prev, 42, MPI_COMM_WORLD, &receiveRequest);

  prev = ((rank + size - 1) % size); // get rank of process to send to
  sprintf(sendBuffer, "Non-blocking from %d!", rank);
  // _initiate_ send operation, but do not wait for its completion
  MPI_Isend(sendBuffer, 30, MPI_CHAR, next, 42, MPI_COMM_WORLD, &sendRequest);

  MPI_Wait(&receiveRequest, &status); // wait for receive to complete
  printf("%d received \"%s\"\n", rank, receiveBuffer); // print received msg

  MPI_Wait(&sendRequest, &status); // wait for send to complete

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

Listing: An asynchronous Pi computation (piNonBlockingPointToPoint.c)

```c
#include <mpi.h>
#include <stdlib.h>
#include <string.h>
#include <time.h>
#include <stdio.h>

int main(int argc, char **argv) {
  int           i, j, size, rank;  double     x, y;
  long long int *data;             MPI_Status status;
  MPI_Request   *req;

  MPI_Init(&argc, &argv);                              //initialize MPI
  MPI_Comm_size(MPI_COMM_WORLD, &size);                //get the number of processes in the global communicator
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);                //get the rank of this process within the global communicator

  data = (long long int*)malloc(sizeof(long long int) * size * 2);//allocate data (ok, waste some memory in the workers)
  memset(data, 0, (sizeof(sizeof(long long int)) * 2 * size));    //clear the data buffer

  if(rank == 0) {                                      //check if we are root
    req = (MPI_Request*)malloc(sizeof(MPI_Request) * size); //allocate request list
    for(i = size; (--i) > 0; ) {                       //initiate receives from the workers
      MPI_Irecv(&data[2*i], 2, MPI_LONG_LONG_INT, i, 42, MPI_COMM_WORLD, &req[i]);
    }

    for(i = size-2; i >= 0; i--) {                     //for each unfulfilled receive request
      MPI_Waitany(size-1, &req[1], &j, &status);       //now wait until something has been received from any worker
      j++;
      data[0] += data[2*j];                            //get the received sample size (number of points)
      data[1] += data[2*j + 1];                        //get the number of samples (points) inside the unit circle
      printf("worker %d sends estimate %G (based on %lld samples), total estimate now is %G (based on %lld samples).\n", j,
                  ((4.0 * data[2*j + 1]) / data[2*j]), data[2*j], ((4.0 * data[1]) / data[0]), data[0]);
      fflush(stdout);                                  //flush the standard out
    }
  } else {                                             //ok, we are a worker
    srand(time(NULL));
    for(data[0] = 1; data[0] < (rank * 100000000LL); data[0]++) { //make 100 000 000 samples
      x = (rand() / ((double)RAND_MAX));               //random x-coordinate in [0,1]
      y = (rand() / ((double)RAND_MAX));               //random y-coordinate in [0,1]
      if( ((x*x) + (y*y)) <= 1.0 ) {                   //did it fall into the inner circle?
        data[1]++;                                     //yes, it did - increase counter
      }
    }
    MPI_Send(&data[0], 2, MPI_LONG_LONG_INT, 0, 42, MPI_COMM_WORLD); //send worker result synchronously
  }

  MPI_Finalize();                                      //finish the MPI stuff
  return 0;
}
```

So far...

- So far: data transfer using "classical point-to-point communication"

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- `MPI_Send`, `MPI_Ssend`, `MPI_Isend`, ... `MPI_Recv`, `MPI_Irecv`, ...

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- Addressing using the "`rank`"

So far...

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- `MPI_Send`, `MPI_Ssend`, `MPI_Isend`, ... `MPI_Recv`, `MPI_Irecv`, ...
- Addressing using the "`rank`"
- blocking/non-blocking

So far...

- So far: data transfer using "classical point-to-point communication"
- `MPI_Send`, `MPI_Ssend`, `MPI_Isend`, ... `MPI_Recv`, `MPI_Irecv`, ...
- Addressing using the "`rank`"
- blocking/non-blocking
- synchronized/non-synchronized

Process Groups

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  - Processes can be members of arbirary groups

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- MPI supports process groups
  - Processes can be members of arbirary groups
  - For each group it is member of, a process has a specific rank (relative to that group)
- So far, we only used the pre-defined group (communicator) `MPI_COMM_WORLD` of all processes

Communicators and Process Groups

- Communicators and process groups are closely related

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- But: MPI-communicators and MPI-groups are different constructs!
- A communicator always belongs to exactly one group
- But: A group can associated with multiple communicators

Predefined Groups/Communicators

- At startup, there are two communicators

Predefined Groups/Communicators

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  1. `MPI_COMM_WORLD` . . . corresponds to all processes

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Predefined Groups/Communicators

- At startup, there are two communicators:
  1. `MPI_COMM_WORLD` ... corresponds to all processes
  2. `MPI_COMM_SELF` ... corresponds to the calling process itself
- New process groups and communicators can be created at runtime with methods such as `MPI_Group_union`, `MPI_Group_intersection`, `MPI_Group_difference`, ...

Collective Communication

- All processes within a communicator can exchange information at the same time

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Collective Communication

- All processes within a communicator can exchange information at the same time
  - There are different semantics for the information exchange
  - Either all processes or pair-wise
- Synchronization usually implicitly contained
- Every collective operation can also be expressed with `MPI_Send` / `MPI_Recv`

Broadcast

```
int MPI_Bcast(void *buffer, int count, MPI_Datatype datatype, int root, MPI_Comm comm)
```

- Simplest way to do collective communication is broadcast

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- Broadcast a message from the process with rank `root` to all other processes of the communicator

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- Simplest way to do collective communication is broadcast
- Broadcast a message from the process with rank `root` to all other processes of the communicator
- Input/Output Parameter
  - `buffer` . . . starting address of the buffer used for input (at `root`) or output (other processes)

Broadcast

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int MPI_Bcast(void *buffer, int count, MPI_Datatype datatype, int root, MPI_Comm comm)
```

- Simplest way to do collective communication is broadcast
- Broadcast a message from the process with rank `root` to all other processes of the communicator
- Input/Output Parameter
  - `buffer` ... starting address of the buffer used for input (at `root`) or output (other processes)
- Input Parameters
  - `count` ... number of entries in buffer
  - `datatype` ... data type of buffer
  - `root` ... rank of broadcast root (must be the same for all processes calling this function)
  - `comm` ... the communicator

Broadcast

Listing: Broadcast (broadcast.c)

```
#include <mpi.h>   // import MPI header
#include <stdio.h> // import for printf

int main(int argc, char *argv[]) {
  char message[60]; // space allocated for the message
  int rank;         // variable for process id

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank

  if (rank == 0) { // create message if process is "root" (rank = 0)
    sprintf(message, "Message from root (rank %d).", rank);
  }

  // broadcast: send message to all if rank==0, otherwise receive
  MPI_Bcast(message, 60, MPI_CHAR, 0, MPI_COMM_WORLD);
  printf("The message sent/received at node %d is \"%s\"\n", rank, message);

  MPI_Finalize(); // shutdown MPI
  return 0;
}
```

Scatter

```
int MPI_Scatter(void *sendbuf, int sendcnt, MPI_Datatype sendtype, void *recvbuf, int recvcnt,
atatype recvtype, int root, MPI_Comm comm)
```

- Divides an array of `sendcnt` elements into n pieces, where n is the number of processes in a communicator

Scatter

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- Divides an array of `sendcnt` elements into n pieces, where n is the number of processes in a communicator
- If root: sends the pieces to each of the n processes (including itself)

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int MPI_Scatter(void *sendbuf, int sendcnt, MPI_Datatype sendtype, void *recvbuf, int recvcnt,
atatype recvtype, int root, MPI_Comm comm)
```

- Divides an array of `sendcnt` elements into n pieces, where n is the number of processes in a communicator
- If root: sends the pieces to each of the n processes (including itself)
- If not root: receive a data piece

Scatter

```
int MPI_Scatter(...
```

- Divides an array of `sendcnt` elements into n pieces, where n is the number of processes in a communicator
- If root: sends the pieces to each of the n processes (including itself)
- If not root: receive a data piece
- Input Parameters
  - `sendbuf` ... address of send buffer (only relevant at `root`)
  - `sendcount` ... number of elements sent to each process (only relevant at `root`)
  - `sendtype` ... data type of send buffer elements (only relevant at `root`)
  - `recvcount` ... number of elements in receive buffer
  - `recvtype` ... data type of receive buffer elements
  - `root` ... rank of sending process
  - `comm` ... the communicator to use

Scatter

```
int MPI_Scatter(...
```

- Divides an array of `sendcnt` elements into n pieces, where n is the number of processes in a communicator
- If root: sends the pieces to each of the n processes (including itself)
- If not root: receive a data piece
- Input Parameters
  - `sendbuf` ... address of send buffer (only relevant at `root`)
  - `sendcount` ... number of elements sent to each process (only relevant at `root`)
  - `sendtype` ... data type of send buffer elements (only relevant at `root`)
  - `recvcount` ... number of elements in receive buffer
  - `recvtype` ... data type of receive buffer elements
  - `root` ... rank of sending process
  - `comm` ... the communicator to use
- Output Parameter
  - `recvbuf` ... address of receive buffer

Gather

```
int MPI_Gather(void *sendbuf, int sendcnt, MPI_Datatype sendtype, void *recvbuf, int recvcnt, MPI_Datatype
ype, int root, MPI_Comm comm)
```

- Complement to `MPI_Scatter`

Gather

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- Receives data in small arrays from all processes in a communicator

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- If root: combines all the data into one array (order like in `MPI_Gather`)

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- Receives data in small arrays from all processes in a communicator
- If root: combines all the data into one array (order like in `MPI_Gather`)
- Input Parameters
  - `sendbuf` ... address of send buffer
  - `sendcount` ... number of elements in the send buffer
  - `sendtype` ... data type of send buffer elements
  - `recvcount` ... number of elements in receive buffer (only relevant at `root`)
  - `recvtype` ... data type of receive buffer elements (only relevant at `root`)
  - `root` ... rank of receiving process
  - `comm` ... the communicator to use

Gather

`int MPI_Gather(...`

- Complement to `MPI_Scatter`
- Receives data in small arrays from all processes in a communicator
- If root: combines all the data into one array (order like in `MPI_Gather`)
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- Output Parameter
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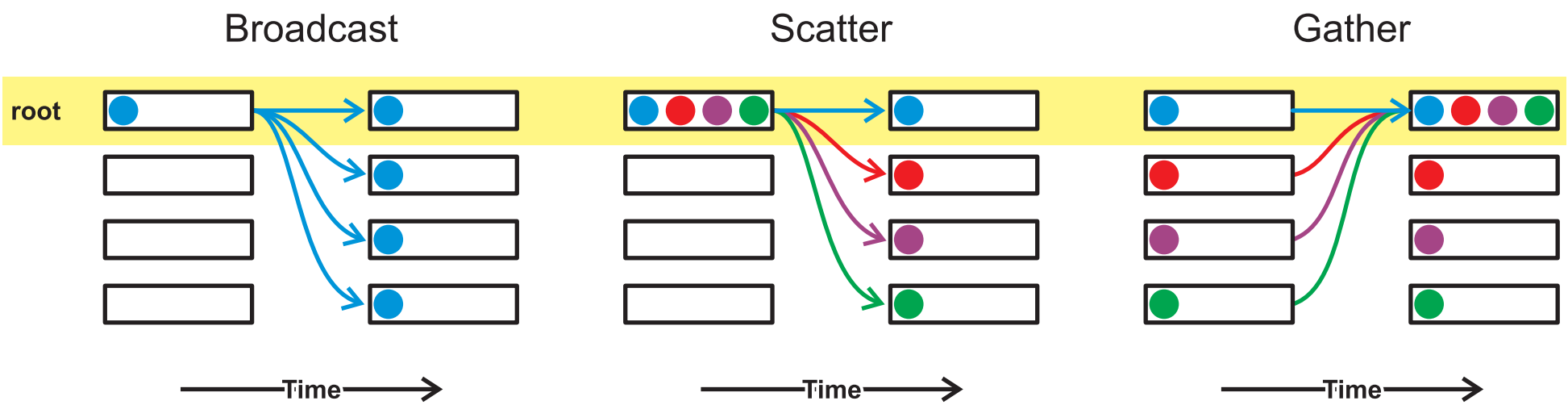
Broadcast, Scatter, & Gather



Listing: Gather/Scatter: bare bones (gatherScatterBareBones.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf

#define DATA_SIZE 1024 // the data size

int main(int argc, char *argv[]) {
  int send[DATA_SIZE], recv[DATA_SIZE];
  int rank, size, count, root, res;
  MPI_Status status;

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank/ID
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get total number of processes

  if(rank == 0) { //If root: Generate data to be distributed.
  }

  //Send data to all nodes. here: an integer array of length "count".
  count = (DATA_SIZE / size); // each receive gets chunk of same size
  // scatter: if rank=0, send data (and get own share); otherwise: receive data
  MPI_Scatter(send, count, MPI_INT, recv, count, MPI_INT, 0, MPI_COMM_WORLD);

  // Each node processes its share of data and sends the result (here: int "res") to
      root.
  MPI_Gather(&res, 1, MPI_INT, recv, 1, MPI_INT, 0, MPI_COMM_WORLD);

  if(rank == 0) { //If root: process the received data.
  }

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

Listing: Gather/Scatter: Count Primes (gatherScatterPrimes.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf
#include <math.h>   // needed for sqrt

#define DATA_SIZE 1024 // let's count the primes among the first 1024 numbers

int main(int argc, char *argv[]) {
  int send[DATA_SIZE], recv[DATA_SIZE];
  int rank, size, count, root, res, i, j;
  MPI_Status status;

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank/ID
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get total number of processes

  if(rank == 0) { //generate data (i.e., the first DATA_SIZE natural numbers) if root
    for(i = DATA_SIZE; (--i)>=0; ) { send[i] = (i + 1); }
  }

  count = (DATA_SIZE / size); // divide the data among _all_ processes
  // scatter: if rank=0, send data (and get own share); otherwise: receive data
  MPI_Scatter(send, count, MPI_INT, recv, count, MPI_INT, 0, MPI_COMM_WORLD);

  // each node now processes its share of the numbers
  res = count; //here: count how many prime numbers are contained in the array
  for(i = count; (--i) >= 0; ) { //j: test all odd numbers 1<j<sqrt(j)|1
    for(j = ((int)(sqrt(recv[i]))|1); j>1; j -= 2) {
      if((recv[i] % j) == 0) { // if a number can be divided by j
        res--; // it cannot be a prime number, reduce number of primes
        break; } // break inner loop to test next number
    }
  }
  printf("Process␣%d␣discovered␣%d␣primes␣in␣the␣numbers␣from␣%d␣to␣%d.\n", rank, res, recv[0], recv[count-1]);

  // gather: all processes send data to root, only root receives data
  MPI_Gather(&res, 1, MPI_INT, recv, 1, MPI_INT, 0, MPI_COMM_WORLD);

  if(rank == 0) { //if root, process the received data
    res = 0;
    for(i = size; (--i) >= 0; ) { //add up the prime number counts
      res += recv[i];
    }
    printf("The␣total␣number␣of␣primes␣in␣the␣first␣%d␣natural␣numbers␣is␣%d.\n", (count*size), res);
  }

  MPI_Finalize();
  return 0;
}
```

Listing: Gather/Scatter: Pi (piGatherScatter.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf
#include <stdlib.h> // for rand and RAND_MAX
#include <string.h> // for memset
#include <time.h>   // for srand(time(NULL));

int main(int argc, char **argv) {
  int           i, size, rank;     double     x, y;
  long long int *data, worker[2];  MPI_Status status;

  MPI_Init(&argc, &argv);                              //initialize MPI
  MPI_Comm_size(MPI_COMM_WORLD, &size);                //get the number of processes in the global communicator
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);                //get the rank of this process within the global communicator

  if(rank != 0) {
    worker[0] = worker[1] = 0LL;                       //the local worker array
    srand(time(NULL));
    for(worker[0] = 1; worker[0] < (rank * 100000000LL); worker[0]++) { //make 100 000 000 samples
      x = (rand() / ((double)RAND_MAX));               //random x-coordinate in [0,1]
      y = (rand() / ((double)RAND_MAX));               //random y-coordinate in [0,1]
      if( ((x*x) + (y*y)) <= 1.0 ) {                   //did it fall into the inner circle?
        worker[1]++;                                   //yes, it did - increase counter
      }
    }
  }

  data = (long long int*)malloc(sizeof(long long int) * size * 2); //allocate data (ok, waste some memory in the workers)
  memset(data, 0, (sizeof(data[0]) * 2 * size));       //clear the data buffer
  MPI_Gather(worker, 2, MPI_LONG_LONG_INT, data, 2, MPI_LONG_LONG_INT, 0, MPI_COMM_WORLD);  //gather results

  if(rank == 0) {                                      //root now evaluates results
    for(i = size; (--i) > 0; ) {                       //receive data from the workers
      data[0] += data[2*i];                            //get the received sample size (number of points)
      data[1] += data[2*i+1];                          //get the number of samples (points) inside the unit circle
      printf("worker %d sends estimate %G (based on %lld samples), total estimate now is %G (based on %lld samples).\n", i,
            ((4.0 * data[2*i + 1]) / data[2*i]), data[2*i], ((4.0 * data[1]) / data[0]), data[0]);
    }
  }
  MPI_Finalize();                                      //finish the MPI stuff
  return 0;
}
```

Reduce

```
int MPI_Reduce (void *sendbuf, void *recvbuf, int count, MPI_Datatype type, MPI_Op op, int root,
I_Comm comm)
```

- Similar to `MPI_Gather`

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```

- Similar to `MPI_Gather`, but
- Data is aggregated by applying a specific reduction operation `op`
- Therefore, volume of data transmission is reduced (not all needs to be sent)
- Values for `op`
  - `MPI_LAND` / `MPI_BAND` ... logical/bitwise *and*
  - `MPI_LOR` / `MPI_BOR` ... logical/bitwise *or*
  - `MPI_LXOR` / `MPI_BXOR` ... logical/bitwise *xor*
  - `MPI_MAX` ... compute the maximum
  - `MPI_MIN` ... compute the minimum
  - `MPI_SUM` ... compute the sum
  - `MPI_PROD` ... compute the product

Listing: Scatter/Reduce: Count Primes (reducePrimes.c)

```c
#include <mpi.h>    // import MPI header
#include <stdio.h>  // needed for printf
#include <math.h>   // needed for sqrt

#define DATA_SIZE 1024 // let's count the primes among the first 1024 numbers

int main(int argc, char *argv[]) {
  int send[DATA_SIZE], recv[DATA_SIZE];
  int rank, size, count, root, res, i, j;
  MPI_Status status;

  MPI_Init(&argc, &argv); // initialize MPI
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // get own rank/ID
  MPI_Comm_size(MPI_COMM_WORLD, &size); // get total number of processes

  if(rank == 0) { //generate data (i.e., the first DATA_SIZE natural numbers) if root
    for(i = DATA_SIZE; (--i)>=0; ) { send[i] = (i + 1); }
  }

  count = (DATA_SIZE / size); // divide the data among _all_ processes
  // scatter: if rank=0, send data (and get own share); otherwise: receive data
  MPI_Scatter(send, count, MPI_INT, recv, count, MPI_INT, 0, MPI_COMM_WORLD);

  // each node now processes its share of the numbers
  res = count; //here: count how many prime numbers are contained in the array
  for(i = count; (--i) >= 0; ) { //j: test all odd numbers 1<j<sqrt(j)|1
    for(j = ((int)(sqrt(recv[i]))|1); j>1; j -= 2) {
      if((recv[i] % j) == 0) { // if a number can be divided by j
        res--; // it cannot be a prime number, reduce number of primes
        break; } // break inner loop to test next number
    }
  }
  printf("Process %d discovered %d primes in the numbers from %d to %d.\n", rank, res, recv[0], recv[count-1]);

  // reduce: each node takes results, applies operator MPI_SUM locally, sends result to root, where MPI_SUM is
  // applied again. (here: locally summing up does not matter, as only 1 number). The final result is returned.
  MPI_Reduce(&res, recv, 1, MPI_INT, MPI_SUM, 0, MPI_COMM_WORLD);
  if(rank == 0) { //if root, print
    printf("The total number of primes in the first %d natural numbers is %d.\n", (count*size), recv[0]);
  }

  MPI_Finalize(); // shut down MPI
  return 0;
}
```

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3. Two basic parallelization schemes
   1. data-based parallelization
   2. function-based parallelization

Data-based Partition

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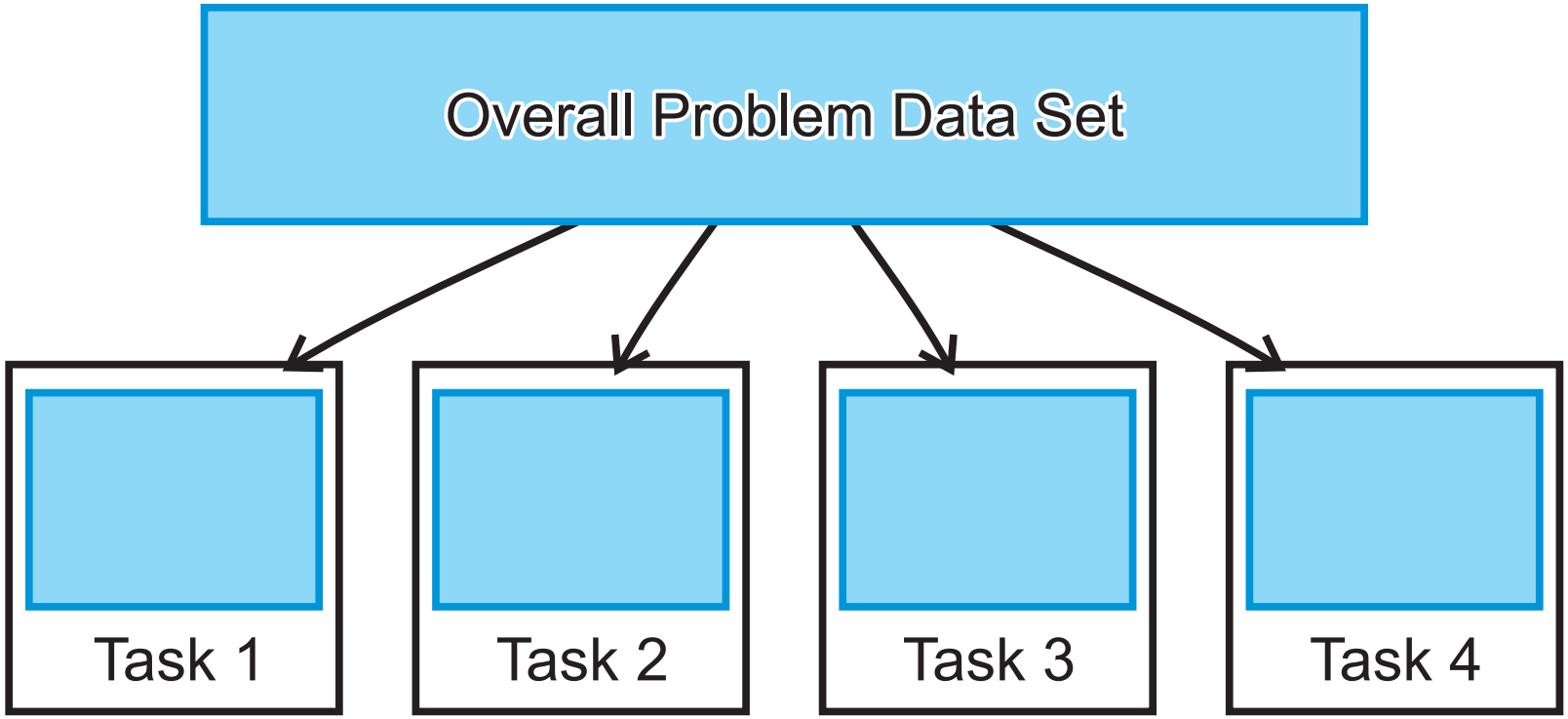

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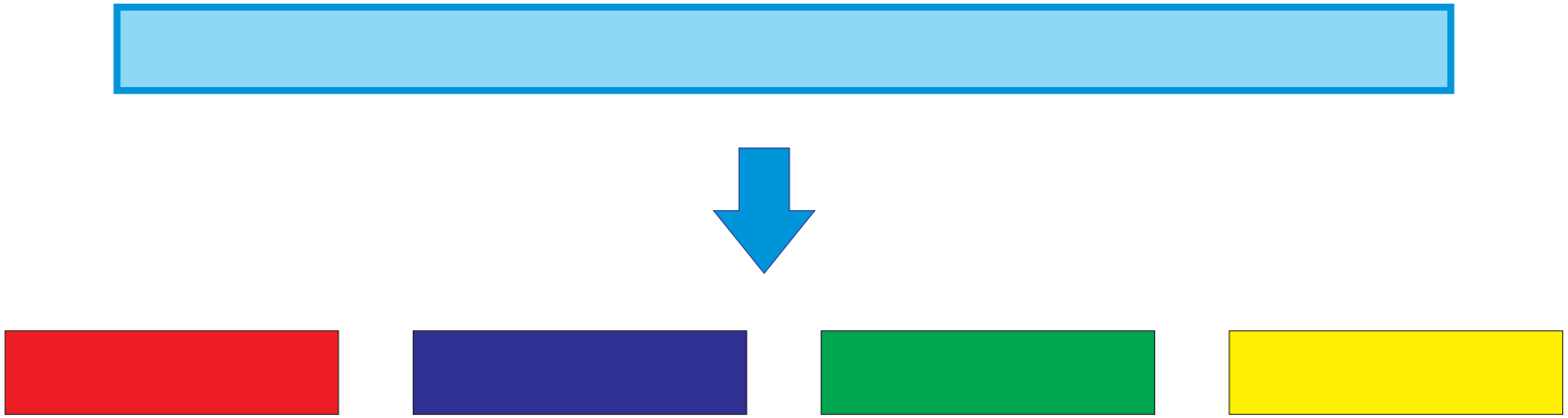

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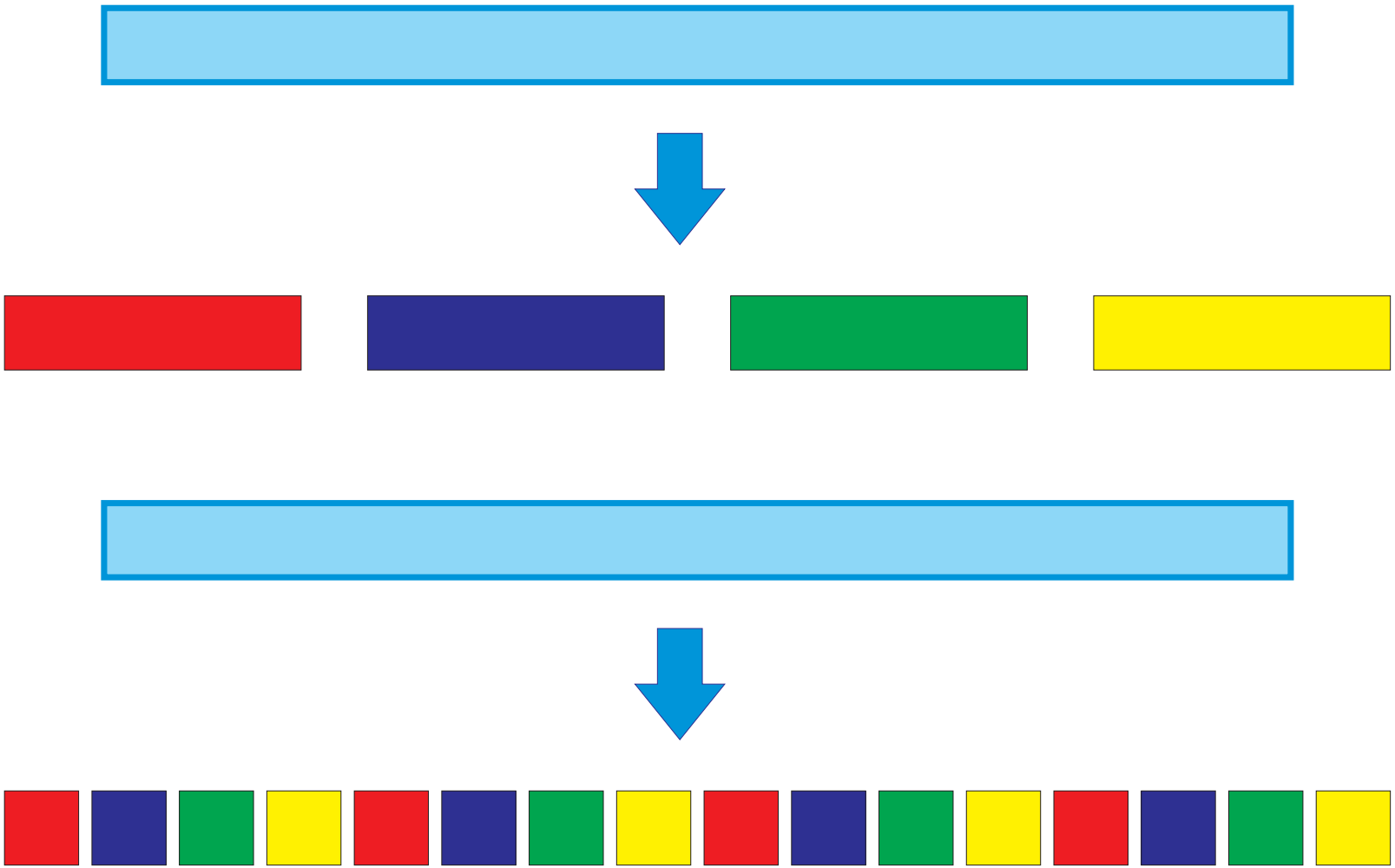

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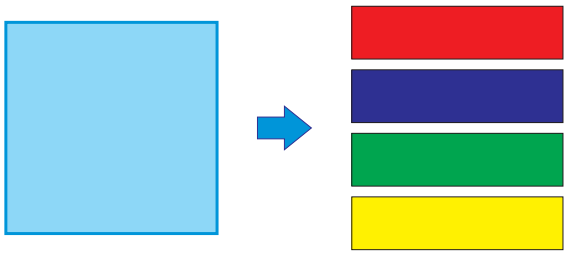

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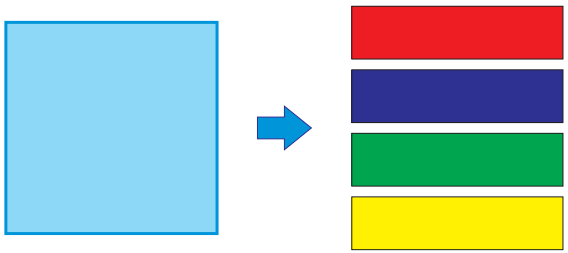

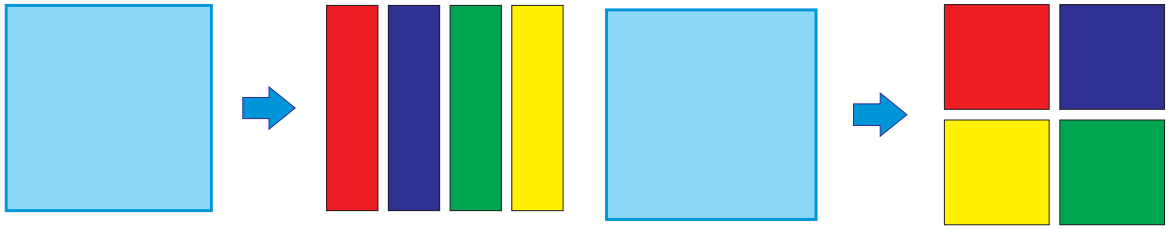

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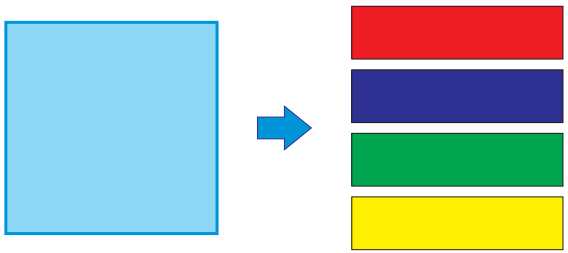

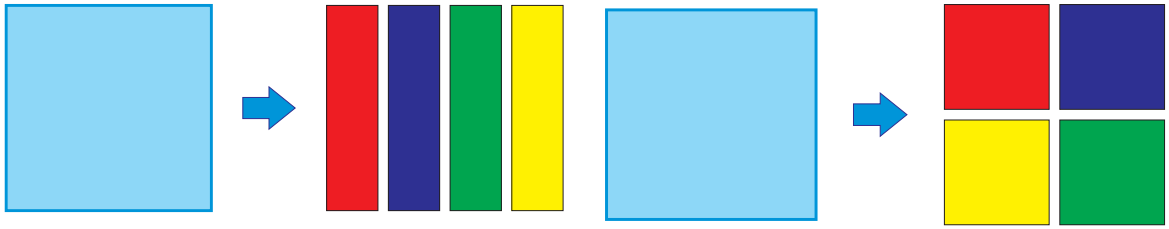

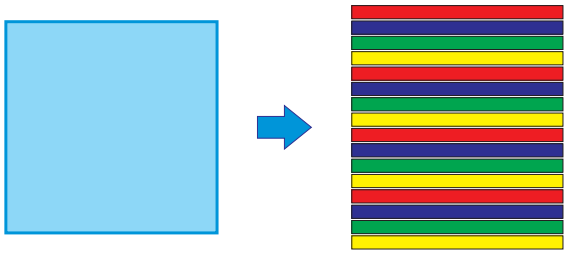

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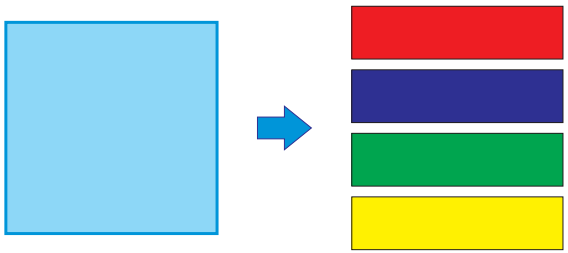

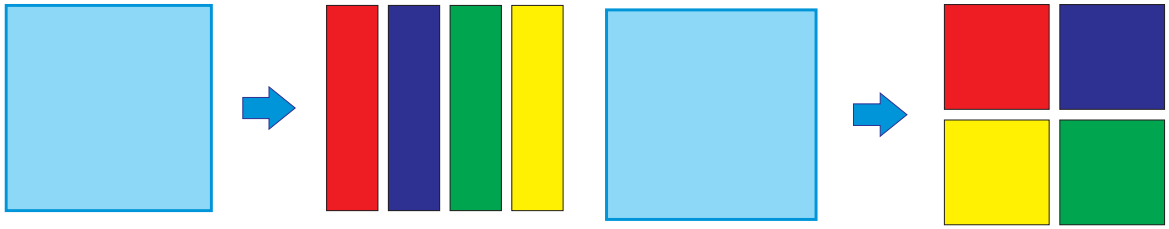

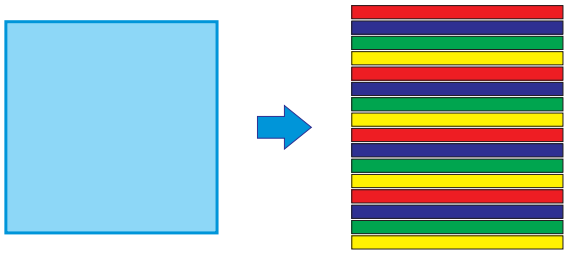

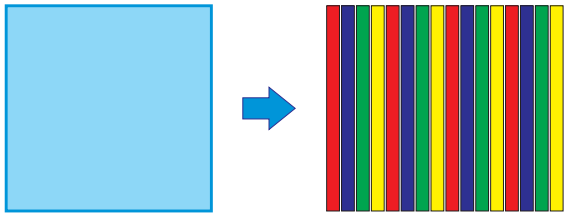

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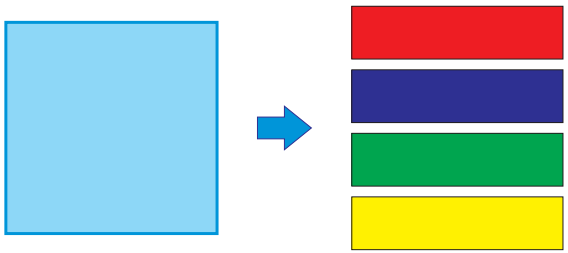

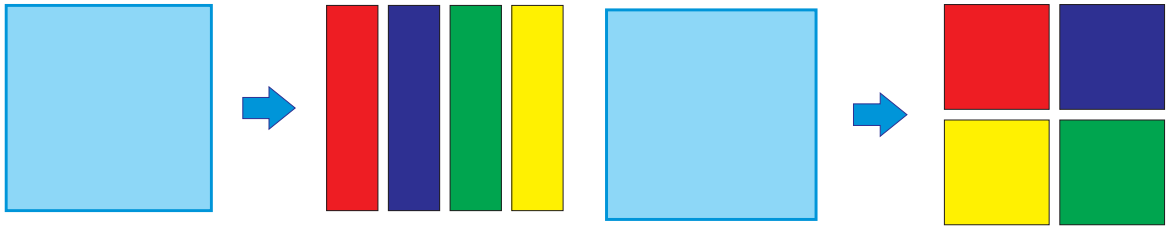

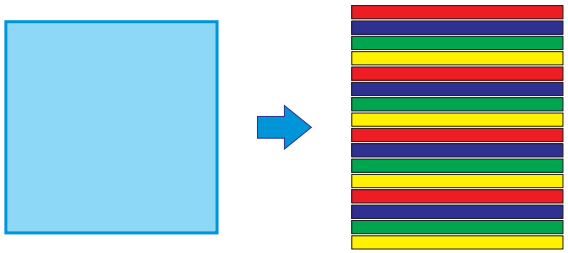

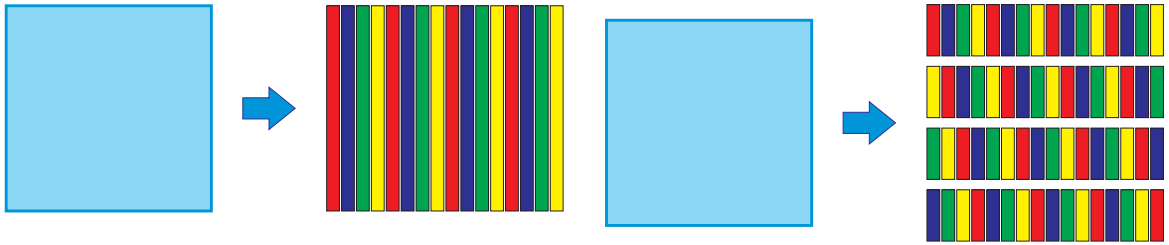

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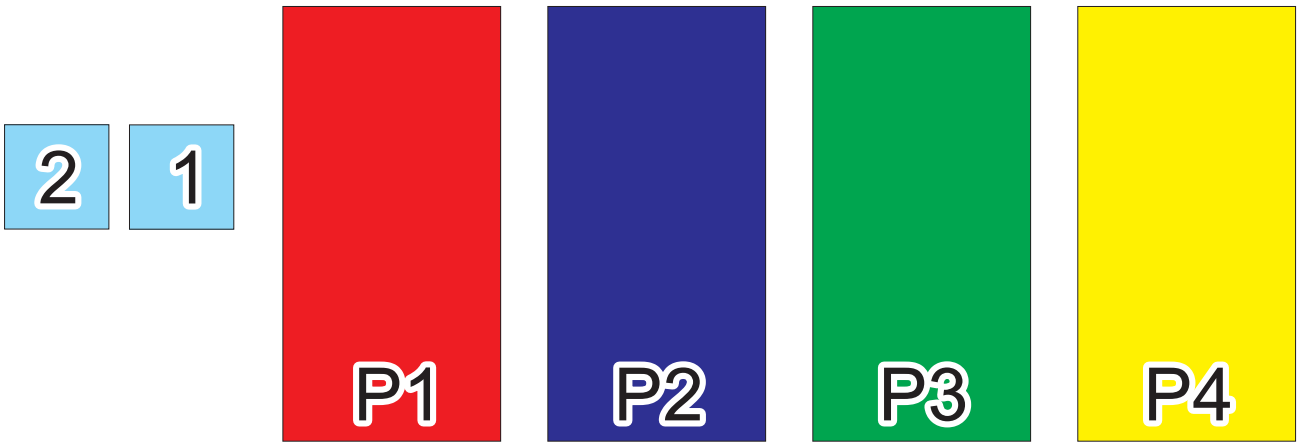

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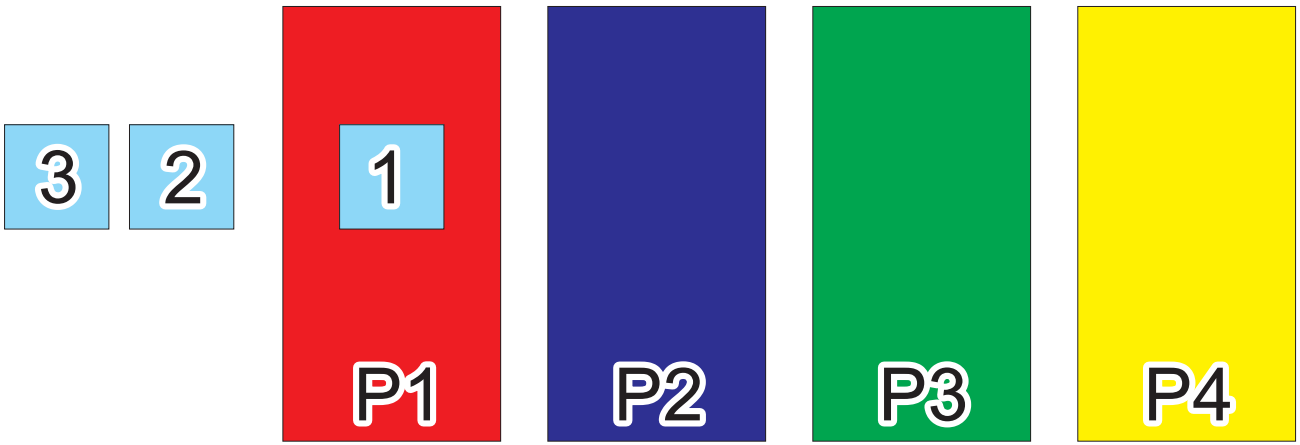

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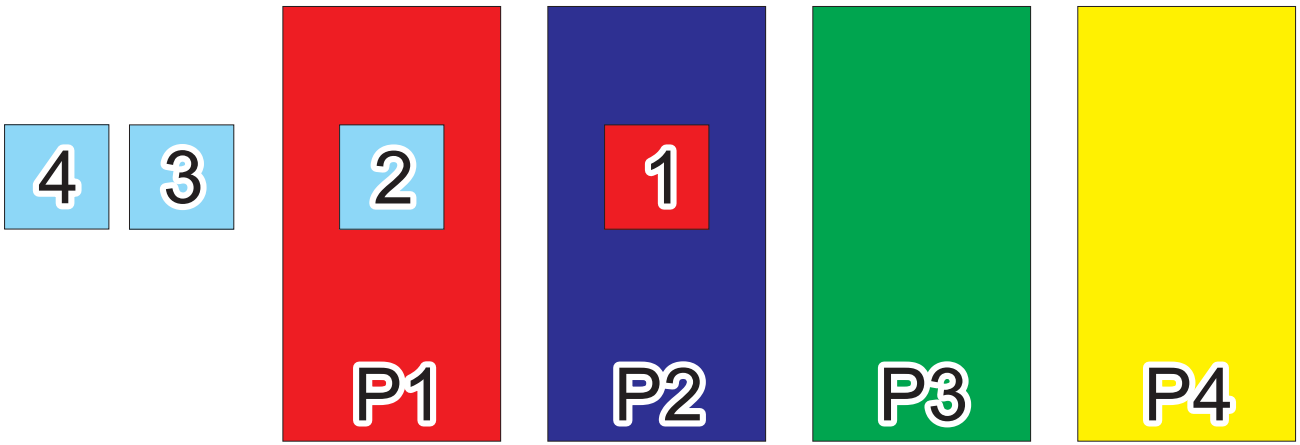

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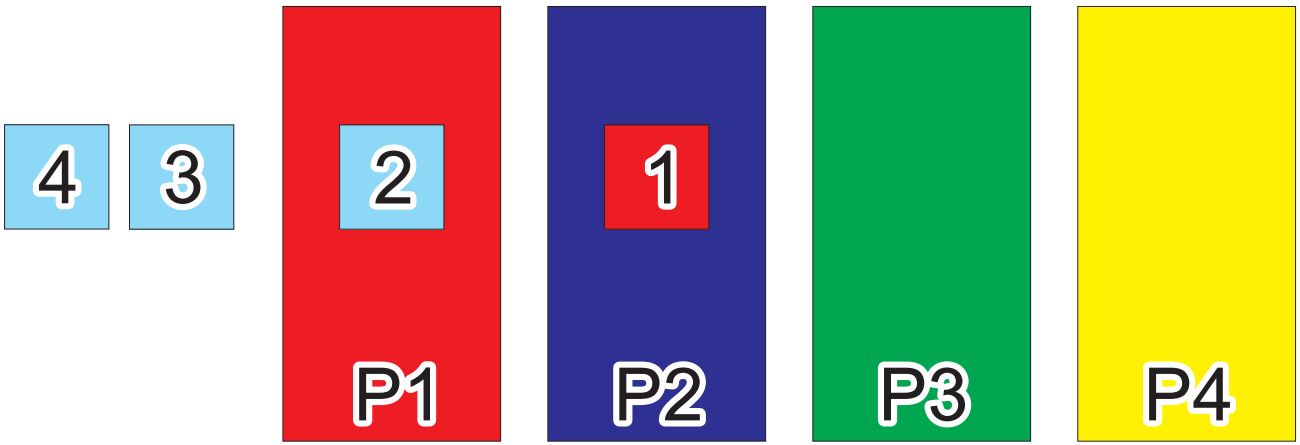

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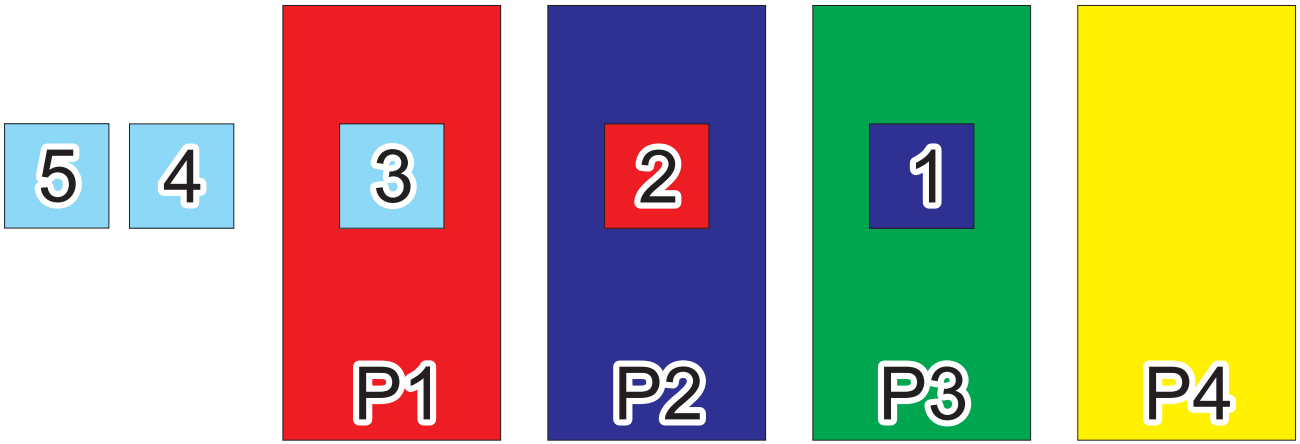

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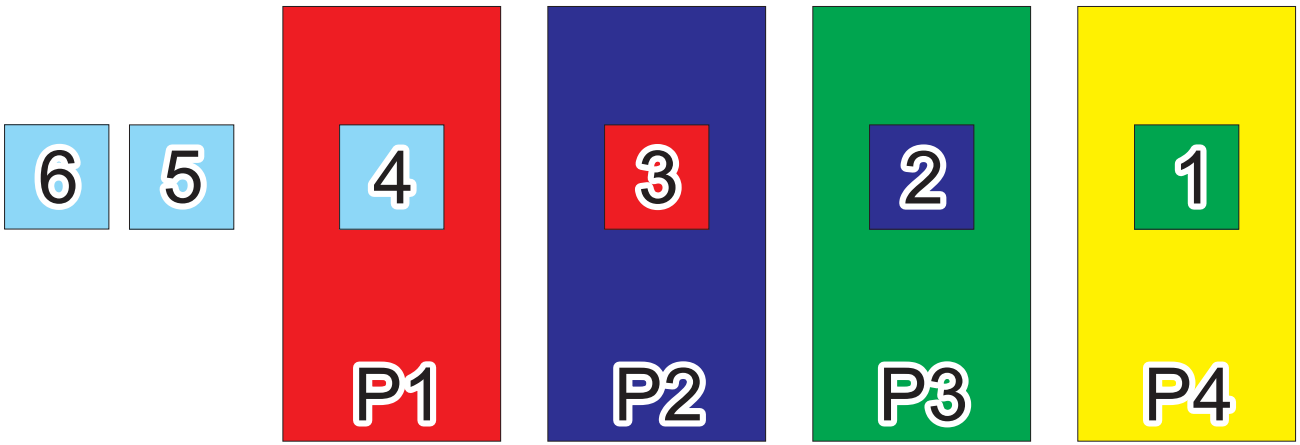

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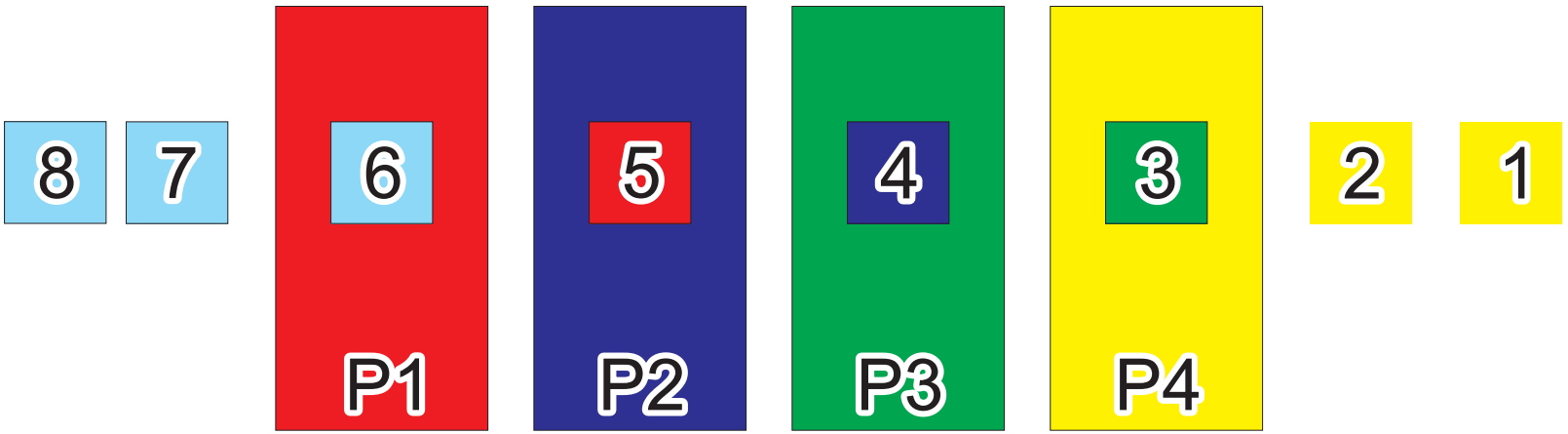

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- `sudo apt-get install mpich libmpich-dev`

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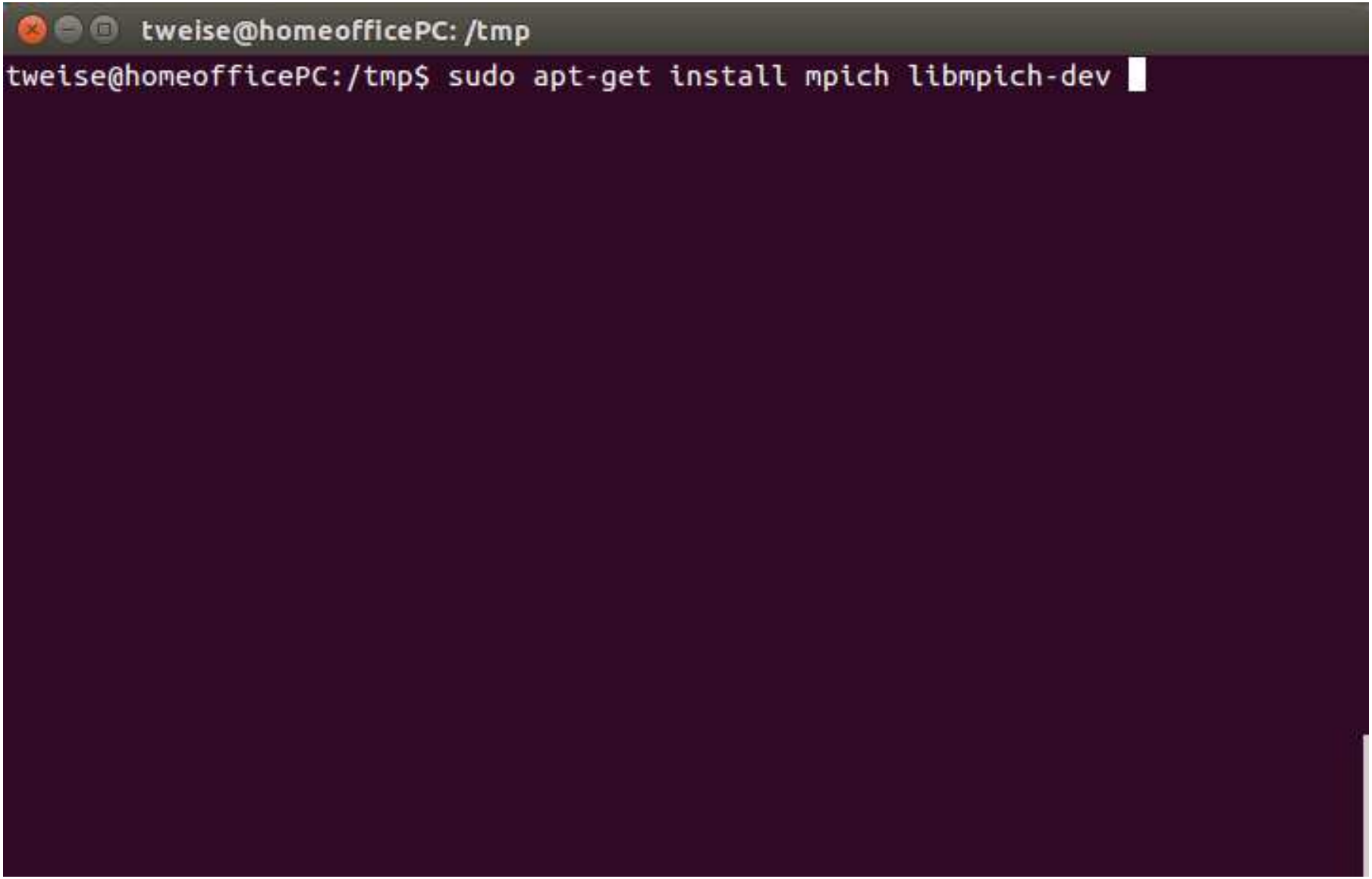

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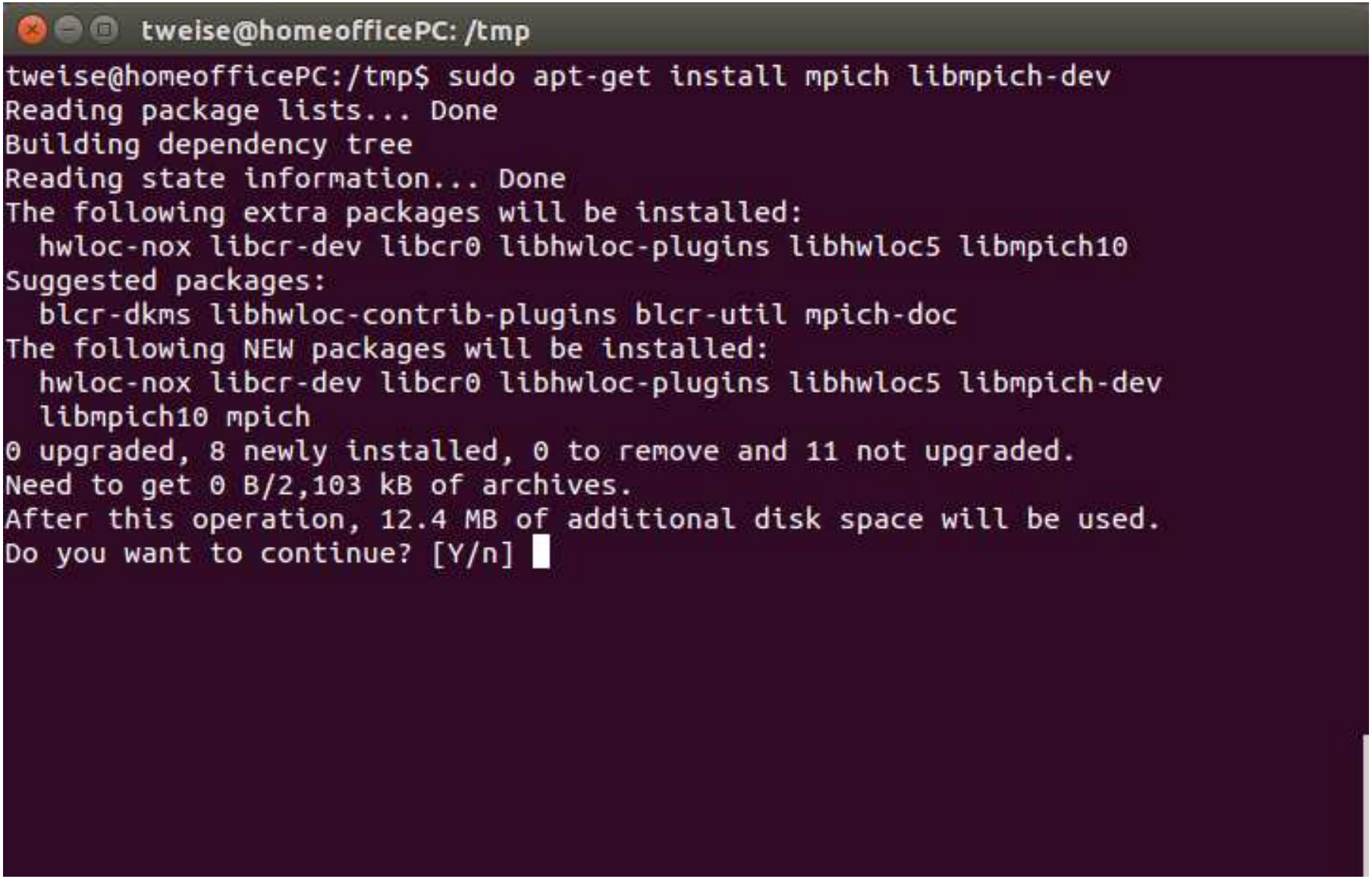

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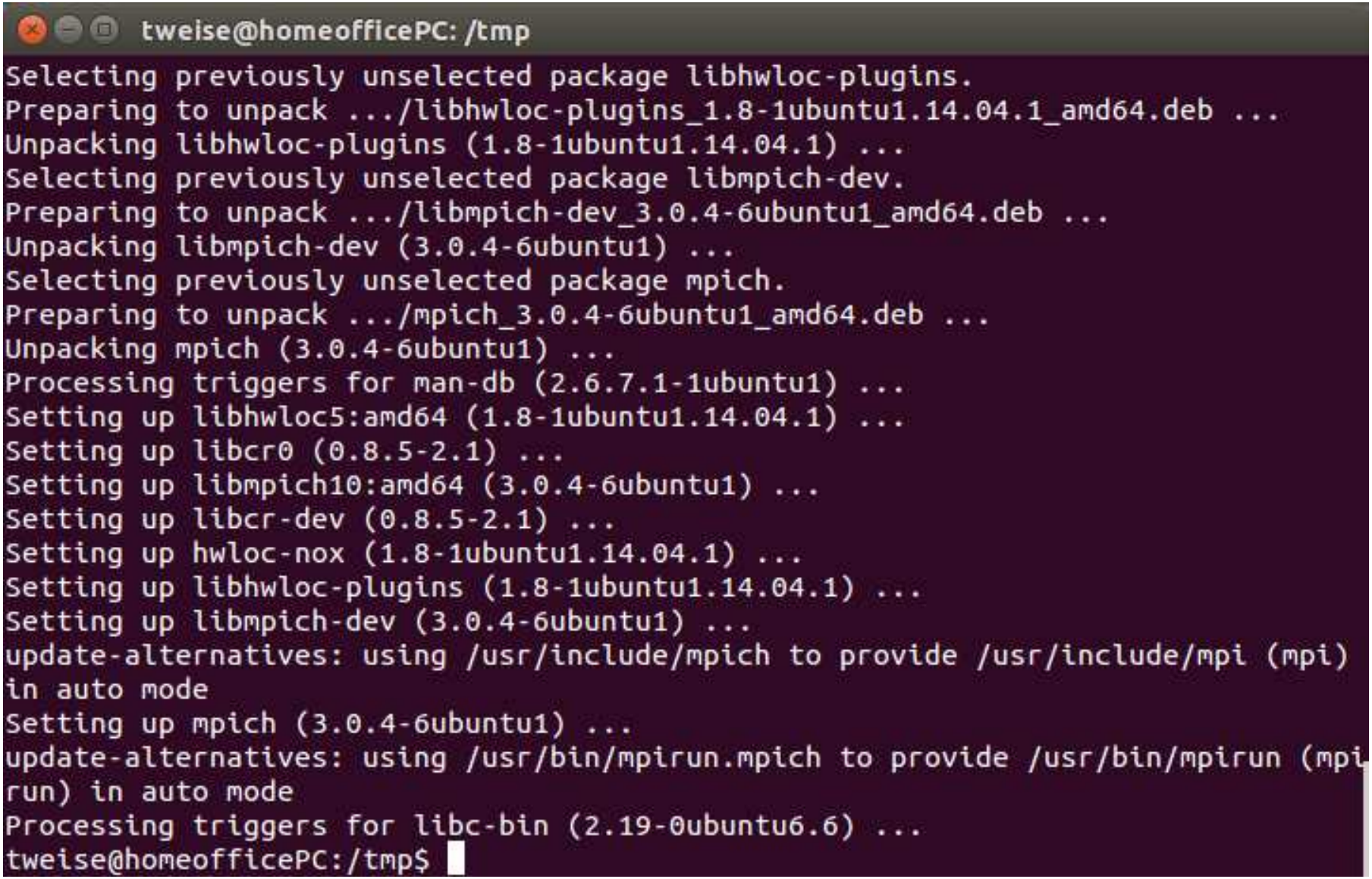

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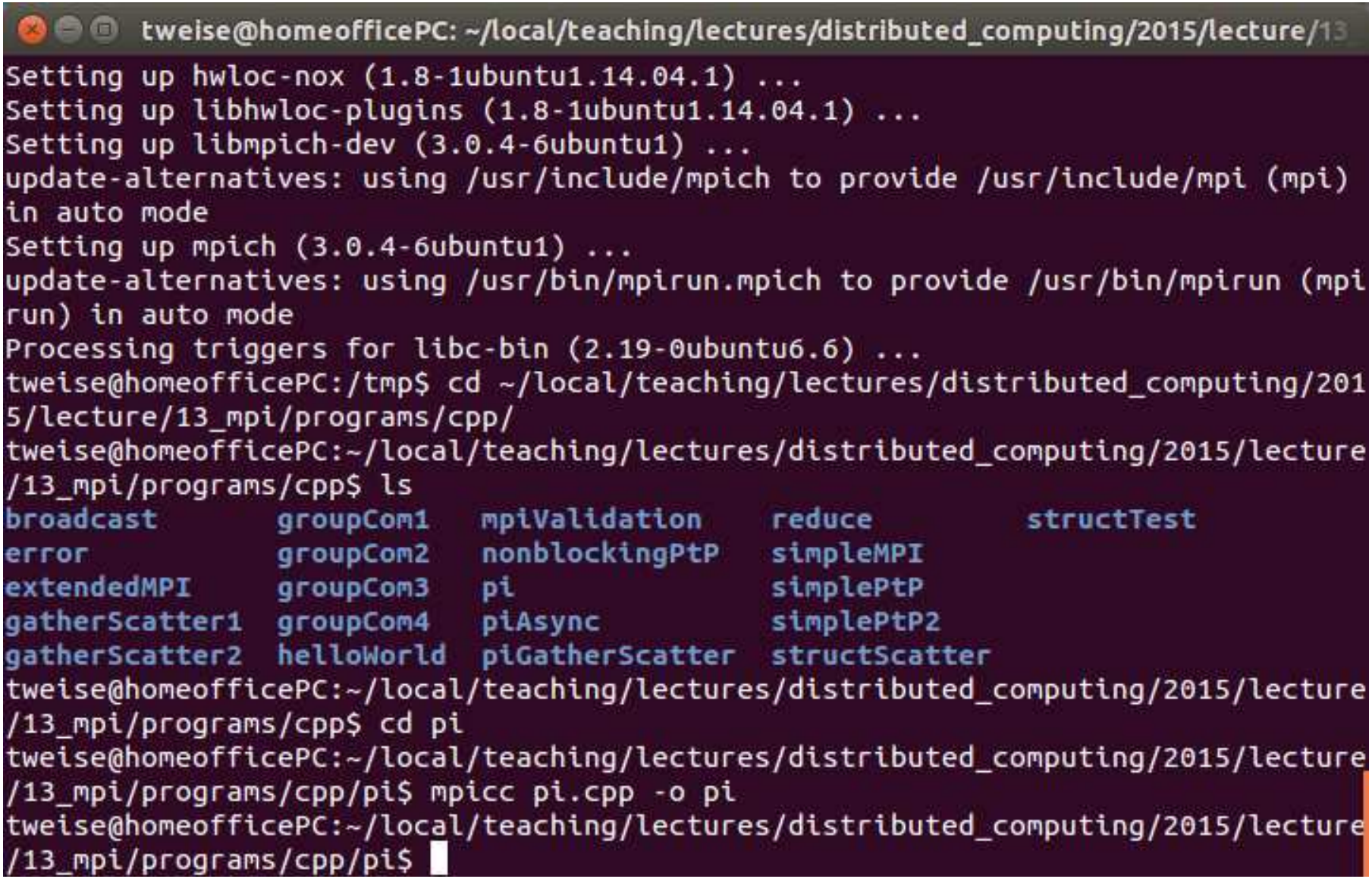

Installation: Linux

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- `mpicc myprogram.cpp -o myprogram`
- `mpirun -np 4 ./myprogram`

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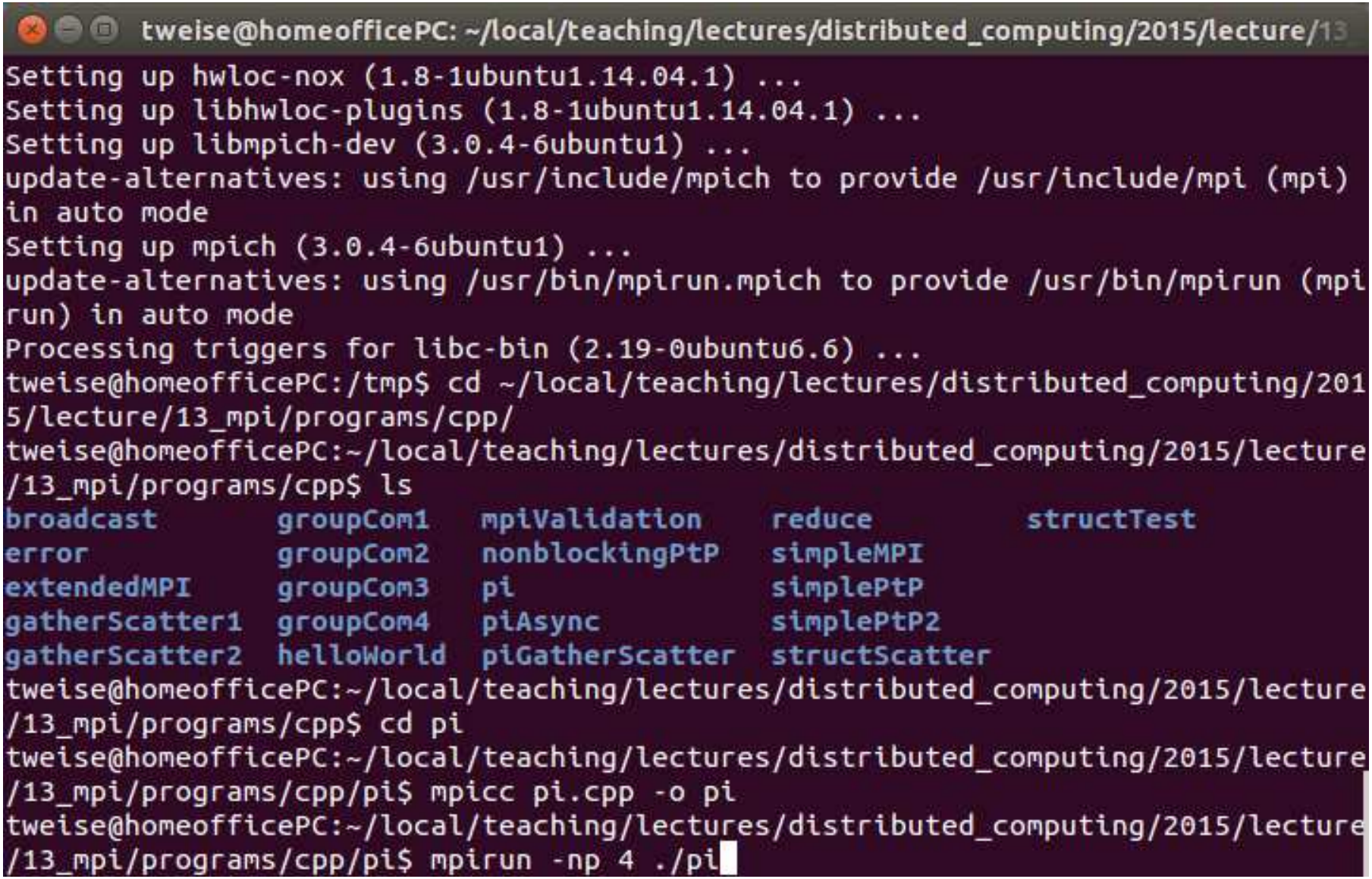

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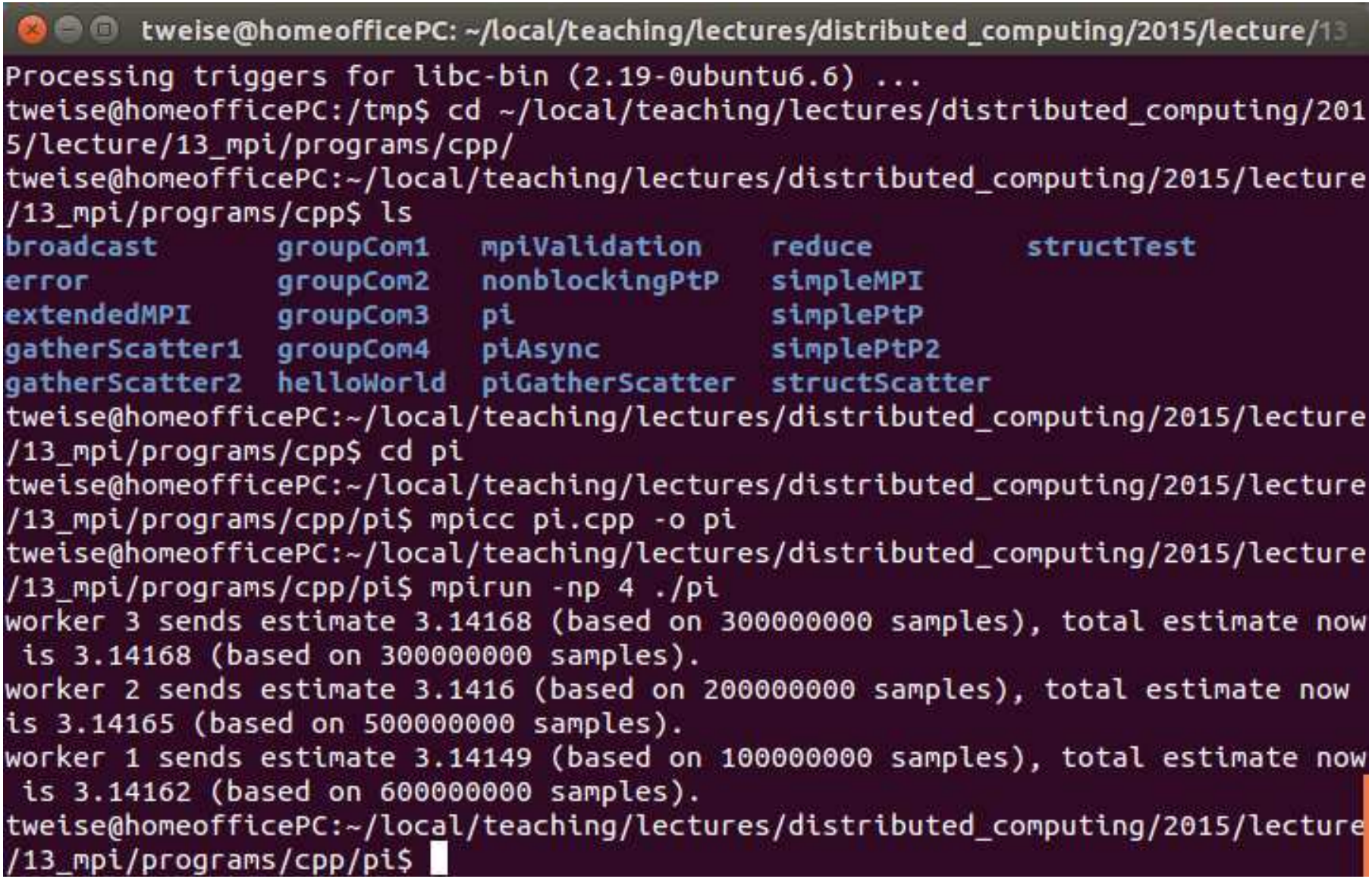

谢谢

Thank you

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