A First Look at the CPU Parallel Programming Framework

OpenMP & MPI

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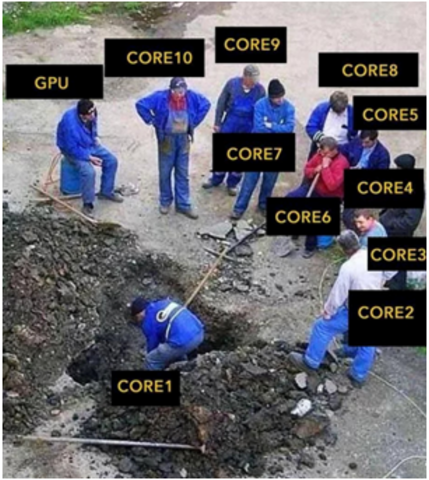
Outline

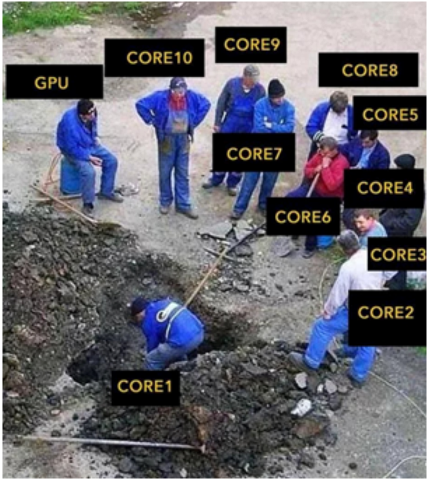
1. Introduction
2. OpenMP
3. MPI

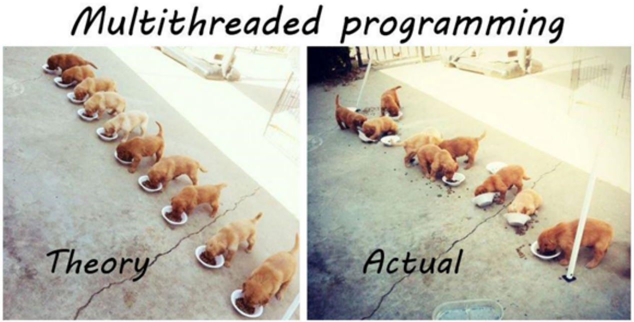
Introduction

🤔 Parallel Programming



🤔 Parallel Programming

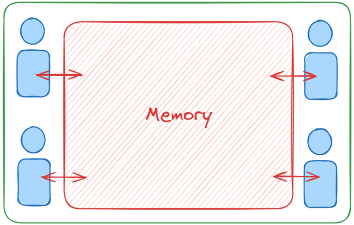




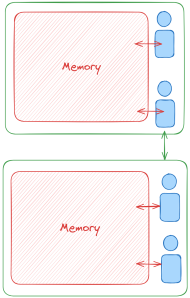
Shared Memory Parallel Model

NUMA

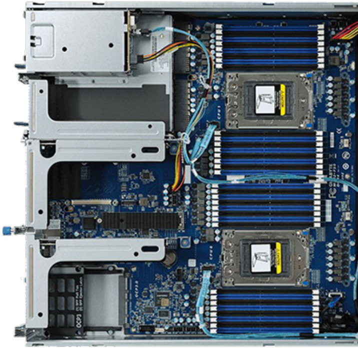
UMA



Uniform memory access



Non-uniform memory access



In real world

OpenMP

OpenMP (Open Multi-Processing) is an API that supports multi-platform shared-memory multiprocessing programming in **C, C++, and Fortran**.

It provides a set of compiler directives, library routines, and environment variables that allow developers to specify parallel regions, tasks, and other parallelism constructs.

💡 **OpenMP provides us an easy way to transform serial programs into parallel.**

Example 1: Hello OpenMP

```c
#include <stdio.h>
#include <omp.h>
int main() {
  printf("Welcome to OpenMP!\n");
  #pragma omp parallel
  {
    int ID = omp_get_thread_num();
    printf("hello(%d)", ID);
    printf("world(%d)\n", ID);
  }
  printf("Bye!");
  return 0;
}
```

Output:

```
lcx@M602:~/openmp-examples$ ./1_hello_openmp
Welcome to OpenMP program!
hello (2)hello (1)hello (3)world (2)
world (3)
world (1)
hello (0)world (0)
Bye!
lcx@M602:~/openmp-examples$ ./1_hello_openmp
Welcome to OpenMP program!
hello (0)world (0)
hello (2)world (2)
hello (3)world (3)
hello (1)world (1)
Bye!
```

```
$ gcc -o hello_omp hello_omp.c -fopenmp # <-- Compiler Option
```

Example 1: Hello OpenMP

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int main() {
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```

Differences:

- **Import OpenMP Header**
- Preprocessing directive
- Parallel Region

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  return 0;
}
```

Differences:

- Import OpenMP Header
- **Preprocessing directive**
  - **Will cover commonly used directives**
- Parallel Region

Example 1: Hello OpenMP

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  }
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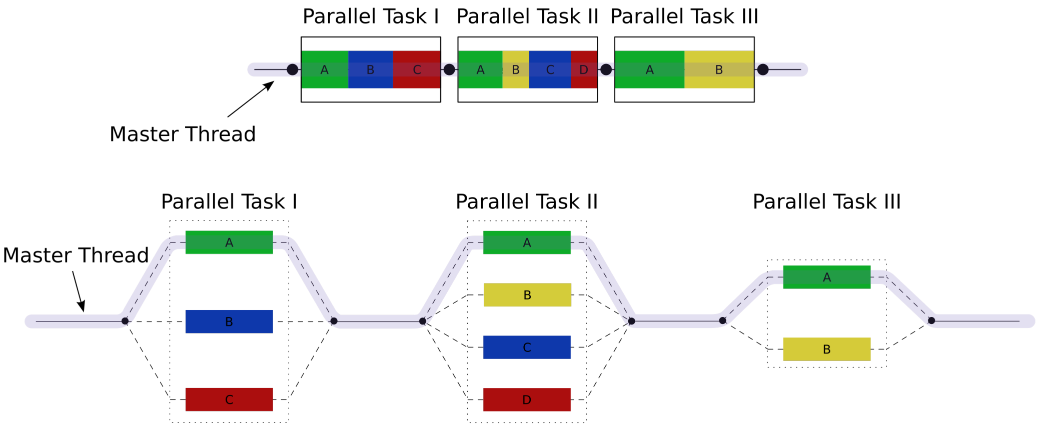
  return 0;
}
```

Differences:

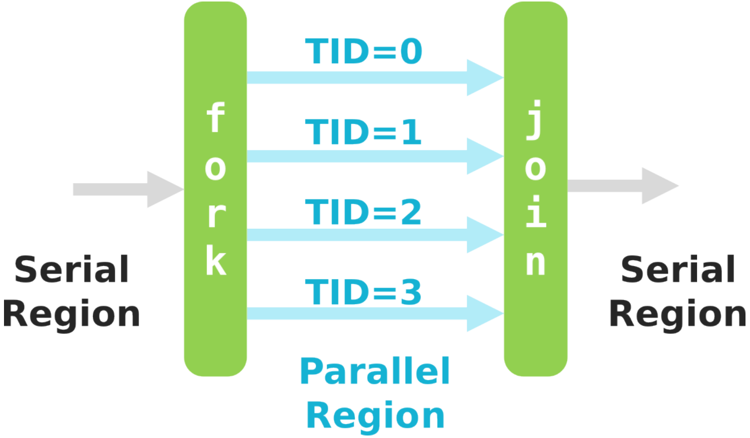
- Import OpenMP Header
- Preprocessing directive
  - Will cover commonly used directives
- **Parallel Region**
  - Relates to the **fork-join** model

Fork - Join Model



Fork-Join Model

Thread ID: `omp_get_thread_num()`



OpenMP

OpenMP directives and constructs

OpenMP Directives

A legal OpenMP Directive must has the following format (C/C++):

Pragma	Directive	[clause[[,]clause] …]
#pragma omp	parallel, atomic, critical, …	0 to many

- 🌰 **For example:**

```
#pragma omp parallel for collapse(2) private(tmp_v, d, v)
```

- Case sensitive
- Affects the block (single statement or wrapped by {}) after this directive
- 🤪 Here's an official **Cheet Sheet**

Constructs

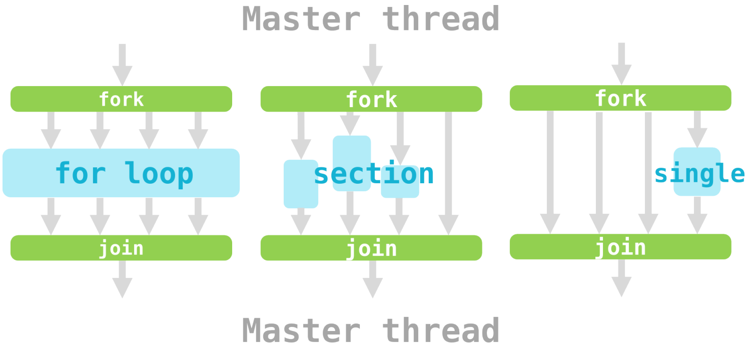
🤔 What is the difference between **construct** and **directive**?

🤓 An OpenMP construct is a formation for which the directive is executable.[1]

```
#pragma omp parallel    // <--\--- Directive
{                       //    |
    printf("Do sth.");  //    | Construct
}                       // ---/
```

[1] https://www.openmp.org/spec-html/5.2/openmpse14.html

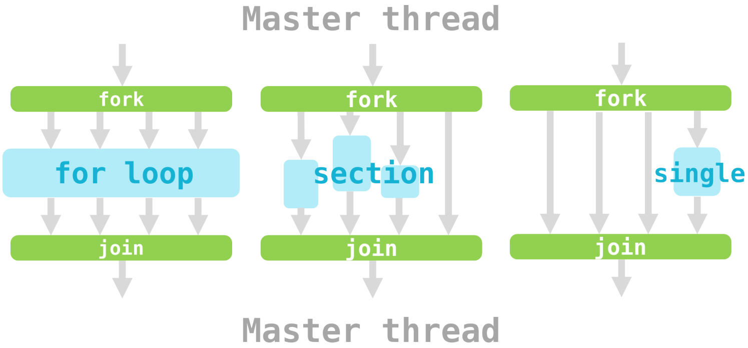
Work-distribution constructs



Work-distribution constructs:

- **single**
- section
- for

Work-distribution constructs



Work-distribution constructs:

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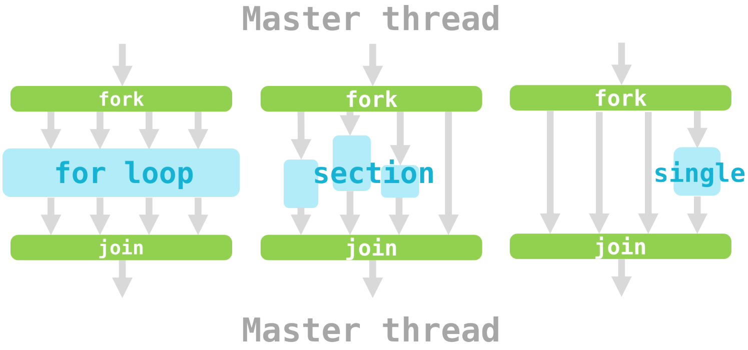
Work-distribution constructs



Work-distribution constructs:

- single
- section
- **for**

parallel Directive

```c
#include <stdio.h>
#include <omp.h>
int main() {
  printf("Welcome to OpenMP!\n");
  #pragma omp parallel
  {
    int ID = omp_get_thread_num();
    printf("hello(%d)", ID);
    printf("world(%d)\n", ID);
  }
  printf("Bye!");
  return 0;
}
```

Example 2: *parallel for* Directive

```c
// Addition of two vectors
for (int i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```

```c
// Addition of two vectors
#pragma omp parallel for
for (int i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```

```
lcx@M602:~/openmp-examples$ echo $OMP_NUM_THREADS
4
lcx@M602:~/openmp-examples$ ./2_vector_addition
Serial: 1290.71 us
Parallel: 419.164 us
Speed Up: 3.07926x
```

Example 2: *parallel for* Directive

```c
// Addition of two vectors
for (int i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```

```c
// Addition of two vectors
#pragma omp parallel for
for (int i = 0; i < N; i++) {
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}
```

```
lcx@M602:~/openmp-examples$ echo $OMP_NUM_THREADS
4
lcx@M602:~/openmp-examples$ ./2_vector_addition
Serial: 1290.71 us
Parallel: 419.164 us
Speed Up: 3.07926x
```

🤯 Not 4x speed up

Example 2: *parallel for* Directive

```c
// Addition of two vectors
for (int i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```

```c
// Addition of two vectors
#pragma omp parallel for
for (int i = 0; i < N; i++) {
    c[i] = a[i] + b[i];
}
```

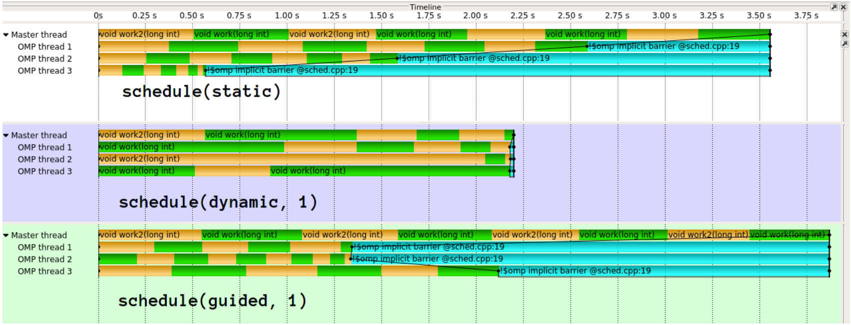
🤗 **Overhead**: any combination of excess or indirect computation time, memory, bandwidth, or other resources that are required to perform a specific task.

Loop Schedule

```c
#pragma omp parallel for
for (int i = 0; i < N; i++) {
    c[i] = f(i); // What if f is not O(1)
}
```

Workload is unbalanced!

Loop Schedule



Static, Dynamic, Guided, Runtime, Auto

Loop Schedule - Static

```c
#pragma omp parallel for schedule(static)
for (int i = 0; i < N; i++) {
    c[i] = f(i);
}
```

Static, Dynamic, Guided, Auto

Loop Schedule - Dynamic

```c
#pragma omp parallel for schedule(dynamic, 2)
for (int i = 0; i < N; i++) {
    c[i] = f(i); // What is f is O(N^2)
}
```

- 👍 Pros: More flexible scheduling
- 👎 Cons: More overhead in scheduling

Nested *for* Loop

```c
// Matrix Element-wise Addition
#pragma omp parallel for
for (int i = 0; i < n; i++) {
    for (int j = 0; j < n; j++) {
        c[i][j] = a[i][j] + b[i][j];
    }
}
```

```c
#pragma omp parallel for collapse(2)
for (int i = 0; i < n; i++) {
    for (int j = 0; j < n; j++) {
        c[i][j] = a[i][j] + b[i][j];
    }
}
```

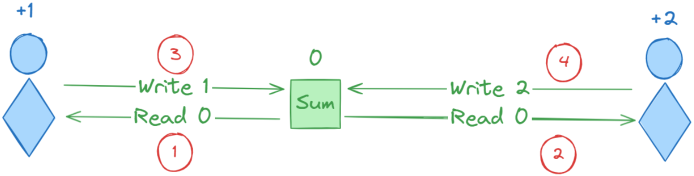
OpenMP

Shared Data and Data Hazards

Example: Data Hazards in Summation

```c
#include <stdio.h>
#include "omp.h"
int main() {
    int a[100];
    int sum = 0;
    // initialize
    for (int i = 0; i < 100; i++) a[i] = i + 1;
    // Sum up from 1 to 100
#pragma omp parallel for
    for (int i = 0; i < 100; i++) {
        sum += a[i];
    }
    printf("Sum = %d\n", sum);
}
```

How Data Hazards Happen?



Thread 1	Thread 2
Read sum	
	Read sum
Write sum	
	Write sum

Scope and Data Hazard

- Shared & private data in default
- Explicit scopes definition
  - *private*
  - *shared*
  - *firstprivate*
  - *lastprivate*
- Data hazards happen when operating shared data

```c
    int sum = 0;
    // Sum up from 1 to 100
#pragma omp parallel for
    for (int i = 0; i <= 99; i++) {
        sum += a[i];
    }
```

Resolve Data Hazard

- Critical Section
- Atomic Operations
- Reduction

Example: Solution with Critical Section

- Only one thread can enter critical section at the same time.
- A critical section can contain multiple statements.

```c
#pragma omp parallel for
    for (int i = 0; i < 100; i++) {
#pragma omp critical
        { sum += a[i]; }
    }
    printf("Sum = %d\n", sum);
```

Example: Solution with Atomic Operation

- Atomic operation cannot be separated.
- Only can be applied to one operation
- Limited set of operators supported

```c
#pragma omp parallel for
    for (int i = 0; i < 100; i++) {
#pragma omp atomic
        sum += a[i];
    }
    printf("Sum = %d\n", sum);
```

Example: Solution with Reduction

- Create temporary private variables for each thread
- Reduce these private variables in the end
- Limited set of operators supported

```c
#pragma omp parallel for reduction(+:sum)
    for (int i = 0; i < 100; i++) {
        sum += a[i];
    }
    printf("Sum = %d\n", sum);
```

Comparison

- Critical Region: Based on locking
- Atomic Operation: Based on hardware atomic operations
- Reduction: only synchronize in the end

Another Example: GEMM

```c
// General Matrix Multiplication (GEMM)
for (int i = 0; i < N; i++) {
    for (int j = 0; j < N; j++) {
        c[i][j] = 0;
        for (int k = 0; k < N; k++) {
            c[i][j] += a[i][k] * b[k][j];
        }
    }
}
```

Another Example: GEMM

```c
#pragma omp parallel for collapse(3) reduction(+ : c)
    for (int i = 0; i < N; i++) {
        for (int j = 0; j < N; j++) {
            c[i][j] = 0;
            for (int k = 0; k < N; k++) {
                c[i][j] += a[i][k] * b[k][j];
            }
        }
    }
```

OpenMP

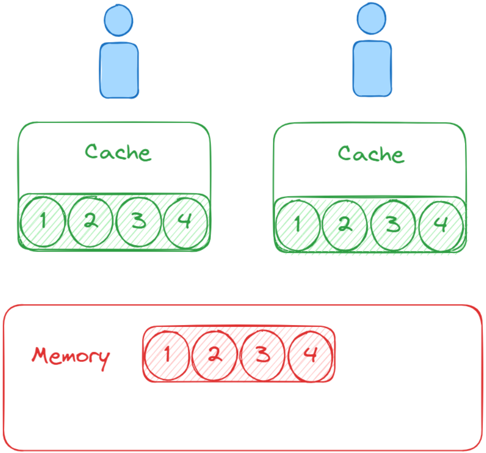
Pitfalls & Fallacies

Nested Parallel Region

- Disabled in default.
- Use *omp_set_nested* to enable.

```c
#pragma omp parallel for
for (int i = 0; i < n; i++) {
#pragma omp parallel for
    for (int j = 0; j < n; j++) {
        c[i][j] = a[i][j] + b[i][j];
    }
}
```

False Sharing



Takeaway: How to Optimize a program with OpenMP

1. **Where**: Profiling
2. **Why**: Analyze data dependency
3. **How**: Analysis and Skills
    - Sub-task Distribution
    - Scheduling Strategy
    - Cache and Locality
    - Hardware Environment
4. Get Down to Work: Testing

Takeaway: Tips

1. Ensure correctness while parallelizing
2. Be aware of overhead
3. Check more details in official documents

MPI

History

- **Before 1990's**: Many libraries.
  Writing code was a **difficult** task.

Models commonly adopted:
Message Passing Model
An application **passes messages** among processes in order to perform a task.
e.g. Job assignment, Results of sub-problems...

- Supercomputing '92
  Defined a **standard interface**
- 1994
  MPI-1
- 2025.6.5
  MPI-5.0 Standard Release

What is MPI

MPI, a **M**essage **P**assaing **I**nterface.

There exists many implementations:

- OpenMPI
- Intel-MPI
- MPICH
- HMPI (Hyper-MPI)
- ……

Kindly Reminder: Please do not mess up MPI implementations with MPI standard.

Installation

- OpenMPI
  Lab0
- Intel-MPI: Included in Intel- neAPI
  Can be installed using spack
- HMPI: Huawei

Hello MPI World!

```c
#include <mpi.h>
#include <stdio.h>
int main(int argc, char** argv) {
    MPI_Init(&argc, &argv);
    int world_size;
    MPI_Comm_size(MPI_COMM_WORLD, &world_size);
    int world_rank;
    MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);
    printf("Hello world from processor %s, rank %d out of %d processors\n",
    processor_name, world_rank, world_size);
    MPI_Finalize();
    return 0;
}
```

MPI

Basic Concepts

Communicator

Definition

A communicator defines a group of processes that have the ability to communicate with one another.

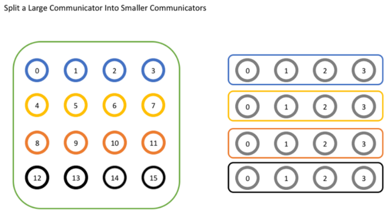
Each process has a **unique rank**.

Communicator (cont.)

- MPI_COMM_WORLD

Communicator (cont.)

- MPI_COMM_SPLIT
  - comm: The communicator that will be used as the basis for the new communicators.
  - color: Which new communicator each processes will belong.
  - key: The ordering (rank) within each new communicator.
  - new_comm: [OUT]



Blocking vs Non-blocking

Blocking

It does not return until the message data and envelope have been **safely stored away** so that the sender is free to modify the send buffer.

The message might be copied directly into the **matching receive buffer**, or it might be copied into a **temporary system buffer**.

Non-blocking

A nonblocking call initiates the operation, but does not complete it. They will return **almost immediately**.

Messages are non-overtaking

Order is preserved.(Only under single thread)

If a sender sends two messages in succession to the same destination, and both match the same receive, then this operation cannot receive the second message if the first one is still pending.

If a receiver posts two receives in succession, and both match the same message, then the second receive operation cannot be satisfied by this message, if the first one is still pending.

Fairness

MPI makes **no guarantee** of fairness in the handling of communication.

There may be starvation.

Example

Rank1 $\rightarrow^{send}$ Rank0

Rank2 $\rightarrow^{send}$ Rank0

Rank0 $\leftarrow^{receive}$ from any source.

MPI

Point-to-Point Communication

Blocking Send and Receive

```c
int MPI_Send(
    const void* buffer,
    int count,
    MPI_Datatype datatype,
    int recipient,
    int tag,
    MPI_Comm communicator);
```

Parameters:

- **buffer** The buffer to send.
- **count** The number of elements to send.
- **datatype** The type of one buffer element.
- **recipient** The rank of the recipient MPI process.
- **tag** The tag to assign to the message.
- **communicator** The communicator in which the standard send takes place.

Blocking Send and Receive

```
int MPI_Recv(
    void* buffer,
    int count,
    MPI_Datatype datatype,
    int sender,
    int tag,
    MPI_Comm communicator,
    MPI_Status* status);
```

Parameters:

- **buffer** The buffer to receive.
- **count** The number of elements to receive.
- **datatype** The type of one buffer element.
- **sender** The rank of the sender MPI process.
- **tag** The tag to assign to the message.
- **communicator** The communicator in which the standard receive takes place.
- **status** The variable in which store the status of the receive operation. Pass MPI_STATUS_IGNORE if unused.

MPI_Status

MPI_Status represents the status of a reception operation.

At least 3 attributes:

- MPI_SOURCE
- MPI_TAG
- MPI_ERROR

There may be additional attributes that are implementation-specific.

Message Envelope

In addition to the data part, messages carry information that can be used to distinguish messages and selectively receive them.

- source
- destination
- tag
- communicator

Communication Mode

- **Buffer Mode**
  Can be started whether or not a matching receive was posted.
  Completion does not depend on the occurrence of a matching receive.
- **Synchronous Mode**
  Can be started whether or not a matching receive was posted.
  The send will be completed successfully only if a matching receive is posted.
- **Ready Mode**
  May be started only if the matching receive is already posted.
- **Standard Mode**
  Depends.

Communication Mode

Communication mode	Start time	Completion time
Buffer mode	Immediately	Message has gone to buffer
Synchronous mode	Immediately	Matching receive has posted
Ready mode	Matching receive has posted	When the send buffer can be reused
Standard mode	Depends	Depends

Communication mode: A common mistake

Note: MPI_Ssend will **always wait until the receive has been posted** on the receiving end.

```
// n = 2
MPI_Comm_rank(comm, &my_rank);
MPI_Ssend(sendbuf, count, MPI_INT, my_rank ^ 1, tag, comm);
MPI_Recv(recvbuf, count, MPI_INT, my_rank ^ 1, tag, comm, &status);
```

🤔 What will happen?

Communication mode: A common mistake

Note: MPI_Ssend will **always wait until the receive has been posted** on the receiving end.

```c
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MPI_Recv(recvbuf, count, MPI_INT, my_rank ^ 1, tag, comm, &status);
```

🤔 What will happen?

🤯 Deadlock! Any solutions?

Communication mode: Solution

```c
// n = 2
MPI_Comm_rank(comm, &my_rank);
if (my_rank == 0) {
    MPI_Ssend(sendbuf, count, MPI_INT, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_INT, 1, tag, comm, &status);
} else if (my_rank == 1) {
    MPI_Recv(recvbuf, count, MPI_INT, 0, tag, comm, &status);
    MPI_Ssend(sendbuf, count, MPI_INT, 0, tag, comm);
}
```

Communication mode: Solution

```c
// n = 2
MPI_Comm_rank(comm, &my_rank);
if (my_rank == 0) {
    MPI_Ssend(sendbuf, count, MPI_INT, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_INT, 1, tag, comm, &status);
} else if (my_rank == 1) {
    MPI_Recv(recvbuf, count, MPI_INT, 0, tag, comm, &status);
    MPI_Ssend(sendbuf, count, MPI_INT, 0, tag, comm);
}
```

🤔 Any other solutions?

Blocking Send and Receive

```c
int MPI_Sendrecv(
    const void* buffer_send,
    int count_send,
    MPI_Datatype datatype_send,
    int recipient,
    int tag_send,
    void* buffer_recv,
    int count_recv,
    MPI_Datatype datatype_recv,
    int sender,
    int tag_recv,
    MPI_Comm communicator,
    MPI_Status* status);
```

Notice

The buffers used for send and receive must be different.

Blocking Send and Receive

```c
int MPI_Sendrecv(
    const void* buffer_send,
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    int tag_send,
    void* buffer_recv,
    int count_recv,
    MPI_Datatype datatype_recv,
    int sender,
    int tag_recv,
    MPI_Comm communicator,
    MPI_Status* status);
```

Notice

The buffers used for send and receive must be different.

🤔 Any other solutions?

Non-Blocking Send and Receive

Recall

A nonblocking call initiates the operation, but does not complete it.

They will return almost immediately.

```c
int MPI_Isend(const void* buffer,
              int count,
              MPI_Datatype datatype,
              int recipient,
              int tag,
              MPI_Comm communicator,
              MPI_Request* request);
```

Synchronization

- **MPI_Test**
  MPI_TEST(request, flag, status)
  - Checks if a non-blocking operation is complete at a given time.
  - flag=true if completes.

- **MPI_Wait**
  MPI_WAIT(request, status)
  - Waits for a non-blocking operation to complete.
  - That is, unlike MPI_Test, MPI_Wait will block until the underlying non-blocking operation completes.

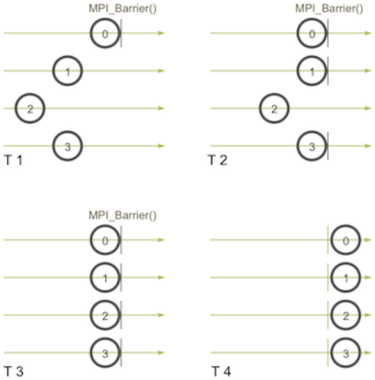
Non-Blocking Send and Receive(Deadlock revisit)

```
MPI_Request req;
MPI_Isend(sendbuf, 0x100, MPI_INT, my_rank^1, 0, MPI_COMM_WORLD,
 ↪  &req);
MPI_Recv(recvbuf, 0x100, MPI_INT, my_rank^1, 0, MPI_COMM_WORLD,
 ↪  MPI_STATUS_IGNORE);
```

MPI

Collective Communication

- **MPI_Barrier**
  MPI_Barrier(COMM)
  Blocks all MPI processes in the given communicator until they all call this routine.

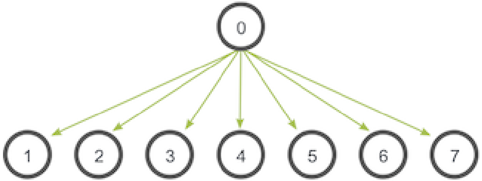


MPI_Barrier

Broadcast: One to All

```c
int MPI_Bcast(
    void* buffer,
    int count,
    MPI_Datatype datatype,
    int emitter_rank,
    MPI_Comm
    ↪  communicator);
```

- **emitter_rank** The rank of the MPI process that broadcasts the data, all other processes receive the data broadcasted.

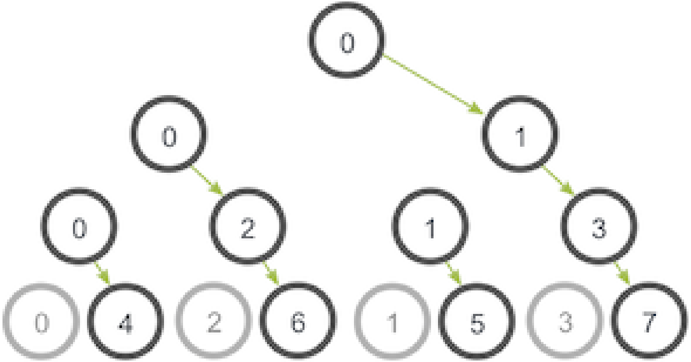


Bcast

Why not Send and Receive?

```c
double start = MPI_Wtime();

if(my_rank == 0){
    for(int i=1; i<=31; i++)
        MPI_Send(sendbuf, 0x10000, MPI_INT, i, 0, MPI_COMM_WORLD);
}else{
    MPI_Recv(recvbuf, 0x10000, MPI_INT, 0, 0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}

double end = MPI_Wtime();

if(my_rank == 0) printf("[Send Recv] Finished in %f seconds\n", my_rank, end-start);

start = MPI_Wtime();
MPI_Bcast(&sendbuf, 0x10000, MPI_INT, 0, MPI_COMM_WORLD);
end = MPI_Wtime();

if(my_rank == 0) printf("[Bcast] Finished in %f seconds\n", my_rank, end-start);
```

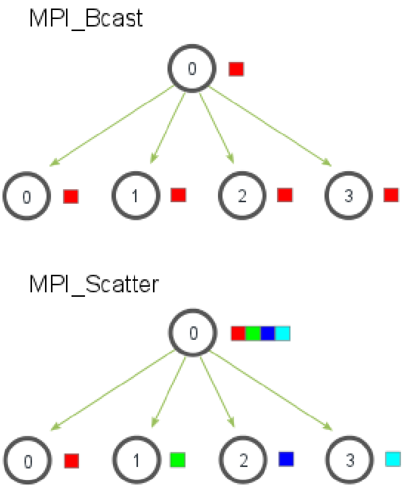
Broadcast: Tree based algorithm



Scatter(One to All)

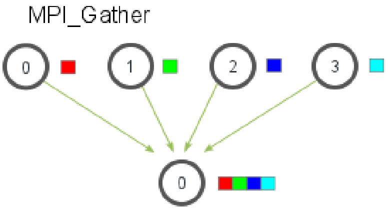
```c
int MPI_Scatter(
    const void* buffer_send,
    int count_send,
    MPI_Datatype datatype_send,
    void* buffer_recv,
    int count_recv,
    MPI_Datatype datatype_recv,
    int root,
    MPI_Comm communicator);
```

- **count_send** The number of elements to send to each process.
- **count_receive** The number of elements in the receive buffer



Gather: All to One

```c
int MPI_Gather(
    const void* buffer_send,
    int count_send,
    MPI_Datatype datatype_send,
    void* buffer_recv,
    int count_recv,
    MPI_Datatype datatype_recv,
    int root,
    MPI_Comm communicator);
```



MPI_Gather

Scatter and Gather

Example

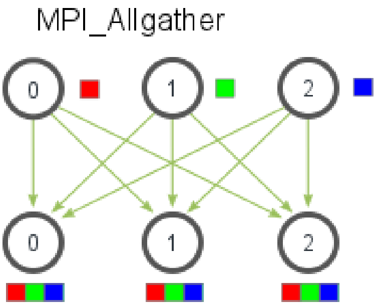
Compute average

```
MPI_Scatter(buffer, 0x1000000/4, MPI_DOUBLE, local_buffer, 0x1000000/4,
↪  MPI_DOUBLE, 0, MPI_COMM_WORLD);
double local_avg = 0;
for(int i=0; i<0x1000000/4; i++){
    local_avg += local_buffer[i];
}
local_avg /= 0x1000000/4;
double avgs[4];
MPI_Gather(&local_avg, 1, MPI_DOUBLE, avgs, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
```

Allgather(All to All)

```
int MPI_Allgather(
    const void* buffer_send,
    int count_send,
    MPI_Datatype datatype_send,
    void* buffer_recv,
    int count_recv,
    MPI_Datatype datatype_recv,
    MPI_Comm communicator);
```

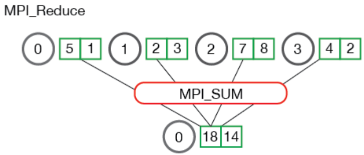
Actually MPI_Gather + MPI_Bcast.



MPI_Allgather

Reduce

```c
int MPI_Reduce(
    const void* send_buffer,
    void* receive_buffer,
    int count,
    MPI_Datatype datatype,
    MPI_Op operation,
    int root,
    MPI_Comm communicator);
```



Reduce

Reduce

Example

Compute average revisit

```
MPI_Scatter(buffer, 0x1000000/4, MPI_DOUBLE, local_buffer, 0x1000000/4,
↪  MPI_DOUBLE, 0, MPI_COMM_WORLD);
double local_avg = 0;
for(int i=0; i<0x1000000/4; i++){
    local_avg += local_buffer[i];
}
local_avg /= 0x1000000/4;
double global_avg;
MPI_Reduce(&local_avg, &global_avg, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
```

MPI

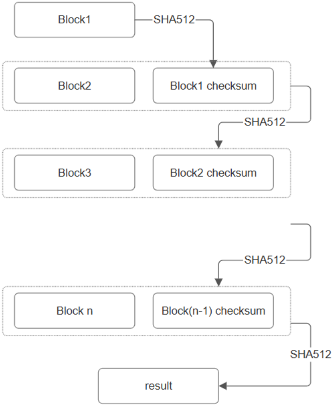
Example

Task

Implement a data validation algorithm using SHA512.
Algorithm procedure:

1. Tile the input file into blocks of 1MB. (If the last block is smaller than 1MB, pad it with zeros.)
2. For the i^{th} block, concatenate it with the validation sum SHA512 of $(i-1)^{th}$ block and calculate validation sum of SHA512.
3. The validation sum of the last block is considered as the validation sum of the entire file.

Source: HPC Game 2024



Baseline Code

```
int num_block = (len + BLOCK_SIZE - 1) /
↪  BLOCK_SIZE;
uint8_t prev_md[SHA512_DIGEST_LENGTH];

EVP_MD_CTX *ctx = EVP_MD_CTX_new();
EVP_MD *sha512 = EVP_MD_fetch(nullptr, "SHA512",
↪  nullptr);

SHA512(nullptr, 0, prev_md);
```

```
for (int i = 0; i < num_block; i++) {
    uint8_t buffer[BLOCK_SIZE]{};
    EVP_DigestInit_ex(ctx, sha512, nullptr);
    std::memcpy(buffer, data + i * BLOCK_SIZE,
                std::min(BLOCK_SIZE, len - i *
                ↪  BLOCK_SIZE));
    EVP_DigestUpdate(ctx, buffer, BLOCK_SIZE);
    EVP_DigestUpdate(ctx, prev_md,
    ↪  SHA512_DIGEST_LENGTH);

    unsigned int len = 0;
    EVP_DigestFinal_ex(ctx, prev_md, &len);
}
```

Notice

EVP_DigestUpdate(a); EVP_DigestUpdate(b);

Equivalent to EVP_DigestUpdate(concate(a,b)) !

Analysis

Computation is dependent on the result of the previous one.

How to exploit MPI?

Analysis

Computation is dependent on the result of the previous one.

How to exploit MPI?

Answer:

File **I/O** accounts! We can **overlap** I/O operations with computation.

MPI Code

Non-Blocking receives the previous block's checksum.

```
if(i != 0) {
  MPI_Irecv((void *)prev_md,
           SHA512_DIGEST_LENGTH,
           MPI_UINT8_T,
           sender,
           0,
           MPI_COMM_WORLD,
           &request);
}
```

Meanwhile... File I/O and Digest

```
istrm.seekg(i * BLOCK_SIZE);
istrm.read(reinterpret_cast<char *>(data + i *
↪  BLOCK_SIZE), std::min(BLOCK_SIZE*local_size,
↪  file_size - i * BLOCK_SIZE));

for(int j=i; j<upper_bound; j++){
    uint8_t buffer2[BLOCK_SIZE]{};
    EVP_DigestInit_ex(ctx[j-i], sha512, nullptr);
    std::memcpy(buffer2, data + j * BLOCK_SIZE,
                std::min(BLOCK_SIZE, len - j *
                ↪  BLOCK_SIZE));
    EVP_DigestUpdate(ctx[j-i], buffer2,
    ↪  BLOCK_SIZE);
}

if(i != 0){
    MPI_Wait(&request, MPI_STATUS_IGNORE);
}
```

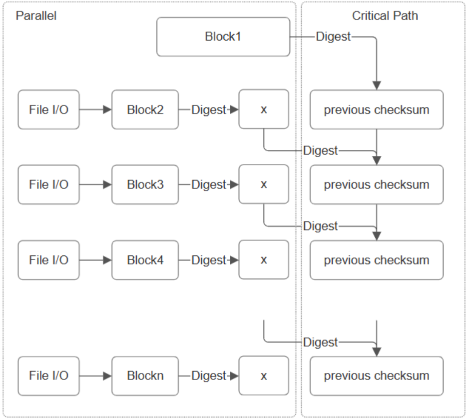
MPI Code (cont.)

Non-blocking send my checksum

```c
unsigned int len = 0;
for(int j=i; j<upper_bound; j++){
    EVP_DigestUpdate(ctx[j-i], prev_md,
    ↪ SHA512_DIGEST_LENGTH);
    EVP_DigestFinal_ex(ctx[j-i], prev_md,
    ↪ &len);
}
if(upper_bound != num_block) {
    MPI_Isend(prev_md,
        SHA512_DIGEST_LENGTH,
        MPI_UINT8_T,
        recepient,
        0,
        MPI_COMM_WORLD,
        &request);
}
```

```
(hpc101) jrguo@M600:~/hpc101/sha512$ mpirun -n 1 baseline 2G1.bin baseline.out
"2G1.bin" size: 2147483648
checksum: 7224ec372ae2480f6609c35fe3ed6e1c7ea37f87a9d5e3e79b90038647eab9299db7d810a21acb7fb53884993869d5e160604e69ae5e459e5fbb3bf12c8
0b270
checksum time cost: 4230ms
total time cost: 22535ms
(hpc101) jrguo@M600:~/hpc101/sha512$ cp 2G.bin 2G2.bin
(hpc101) jrguo@M600:~/hpc101/sha512$ mpirun -n 8 mycode 2G2.bin mycode.out
"2G2.bin" size: 2147483648
checksum: 7224ec372ae2480f6609c35fe3ed6e1c7ea37f87a9d5e3e79b90038647eab9299db7d810a21acb7fb53884993869d5e160604e69ae5e459e5fbb3bf12c8
0b270
checksum time cost: 18401ms
total time cost: 18403ms
```

Wrap up



Parallel
Critical Path
Block1
Digest
File I/O
Block2
Digest
x
previous checksum
Digest
File I/O
Block3
Digest
x
previous checksum
Digest
File I/O
Block4
Digest
x
previous checksum
Digest
File I/O
Blockn
Digest
x
previous checksum

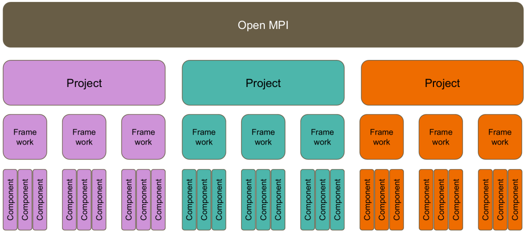
MPI

Miscellaneous

OpenMPI

Modular Component Architecture(MCA)

- MCA framework
- MCA component
- MCA module



OpenMPI Overall Architecture Terminology

OpenMPI

3 Types of OpenMPI Framework

- In the MPI layer (OMPI)
- In the run-time layer (ORTE)
- In the operating system/platform layer (OPAL)

You might think of these frameworks as ways to group MCA parameters by function. (e.g. btl in OMPI)

```
~$ ompi_info --param btl all
         MCA btl: vader (MCA v2.1.0, API v3.1.0, Component v4.1.6)
         MCA btl: self (MCA v2.1.0, API v3.1.0, Component v4.1.6)
         MCA btl: tcp (MCA v2.1.0, API v3.1.0, Component v4.1.6)
     MCA btl tcp: ---------------------------------------------------
     MCA btl tcp: parameter "btl_tcp_if_include" (current value: "",
                  data source: default, level: 1 user/basic, type:
                  string)
                  Comma-delimited list of devices and/or CIDR
                  notation of networks to use for MPI communication
                  (e.g., "eth0,192.168.0.0/16").  Mutually exclusive
                  with btl_tcp_if_exclude.
     MCA btl tcp: parameter "btl_tcp_if_exclude" (current value:
                  "127.0.0.1/8,sppp", data source: default, level: 1
                  user/basic, type: string)
                  Comma-delimited list of devices and/or CIDR
                  notation of networks to NOT use for MPI
                  communication -- all devices not matching these
                  specifications will be used (e.g.,
                  "eth0,192.168.0.0/16").  If set to a non-default
                  value, it is mutually exclusive with
                  btl_tcp_if_include.
     MCA btl tcp: parameter "btl_tcp_progress_thread" (current value:
                  "0", data source: default, level: 1 user/basic,
                  type: int)
```

ompi_info

OpenMPI(Installation) cont.

Specify Compilers

./configure CC=/path/to/clang

CXX=/path/to/clang++ FC=/path/to/gfortran ...

Static or Shared ?

- –enable-static / –disable-static (default)
  libmpi.a
- –enable-shared / –disable-shared
  libmpi.so

Communication Library

UCX (Unified Communication X)

–with-ucx[=UCX_INSTALL_DIR]

With CUDA support

./configure –with-cuda[=/path/to/cuda]

OpenMPI (mpirun)

- -x [env]
  Passes environment variables to remote nodes.
- –bind-to core
- -hostfile [hostfile]
- ...

Thank You

Any Questions?