Parallel Computing

MPI – Last Touch

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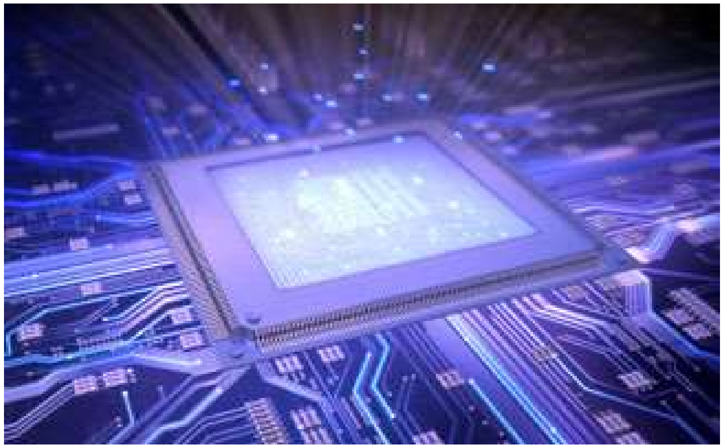
Many slides of this lecture are adopted and slightly modified from:
• Gerassimos Barlas
• Peter S. Pacheco



A PARALLEL SORTING ALGORITHM

Sorting

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

Serial bubble sort

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

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

}  /* Bubble_sort */
```

$O(n^2)$

How can we parallelize this?

The problem with bubble-sort

- We cannot execute the compare-swap out-of-order!
- Can we decouple that?

Odd-even transposition sort

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

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

- Odd phases, compare swaps:

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

Example

Start: 5, 9, 4, 3

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

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

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

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

Serial odd-even transposition sort

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

   for (phase = 0; phase < n; phase++)
```

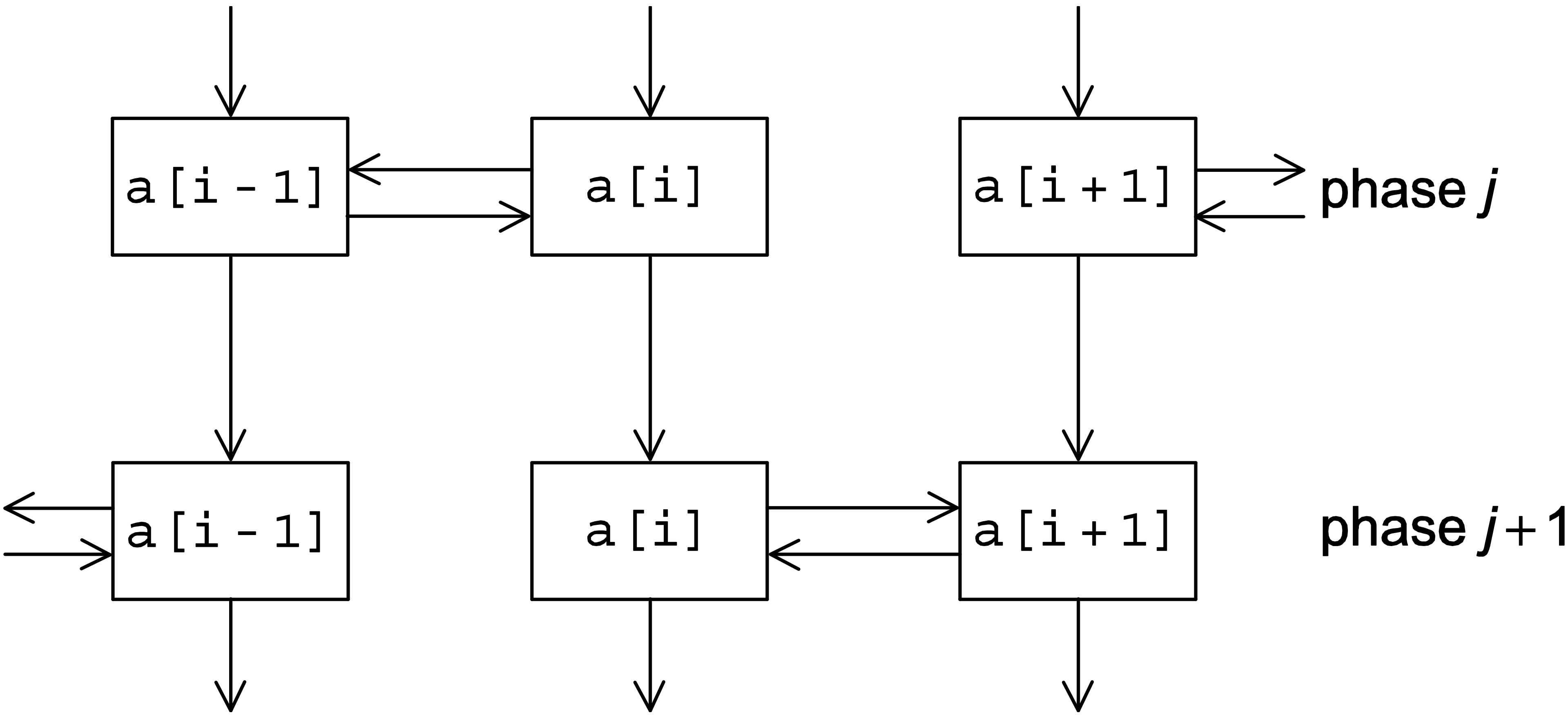
Even phase

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

Odd phase

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

Communications among tasks in odd-even sort



Parallel odd-even transposition sort

Assume P processors (=4) and list n (=16) numbers

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

phase 0 and phase 2

- Processes (0,1) exchange their elements
- Processes (2, 3) exchange their elements
- Processes 0 and 2 keep the smallest 4
- Processes 1 and 3 keep the largest 4

phase 1 and phase 3

- Processes (1, 2) exchange their elements
- Process 1 keeps smallest 4 and process 2 keeps largest 4

Pseudo-code

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

Compute_partner

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

- Constant defined by MPI
- When used as source/destination in point-to-point comm, no comm will take place.

Safety in MPI programs

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

Safety in MPI programs

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

Safety in MPI programs

- If the MPI_Send executed by each process blocks, no process will be able to start executing a call to MPI_Recv, and the program will hang or deadlock.

- Each process is blocked waiting for an event that will never happen.

Safety in MPI programs

- A program that relies on MPI provided buffering is said to be unsafe.
- Such a program may run without problems for various sets of input, but it may hang or crash with other sets.

So … What can we do?

MPI_Ssend

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

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

How does MPI_Ssend help?

- Replace all MPI_Send calls in your code with MPI_Ssend
- If your program does not hang or crash → the original program is safe
- What do we do if we find out that our program is not safe?
- The problem occurs because all processes send then all of them receive… Let's change that!

Restructuring communication

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

original

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

Updated version

Note: The above two versions show a ring communication
(i.e. processor comm_sz-1 sends to process 0.)

MPI_Sendrecv

- An alternative to scheduling the communications ourselves.
- Carries out a blocking send and a receive in a single call.
- Especially useful because MPI schedules the communications so that the program won't hang or crash.
- Replaces a pair of consecutive send and receive calls.

MPI_Sendrecv

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

MPI_Sendrecv_replace

```
int MPI_Sendrecv_replace{
        void *              buf_p,
        int                 buf_size,
        MPI_Datatype        buf_type,
        int                 dest,
        int                 send_tag,
        int                 recv_tag,
        MPI_Comm            communicator,
        MPI_Status *        status_p };
```

In this case, what is in buf_p will be sent and replaced by what is received.

Back to our pseudo-code

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

How will you implement this?

Parallel odd-even transposition sort

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

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

    for (m_i = 0; m_i < local_n; m_i++)
        my_keys[m_i] = temp_keys[m_i];
}  /* Merge_low */
```

At the end, my_keys[] will have the smallest n/p keys of local and received keys

Run-times of parallel odd-even sort

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

(times are in milliseconds)

Run-times of parallel odd-even sort (Larger problem size)

comm_sz	Run-Times (in seconds)				
	Number of Elements				
	1M	2M	4M	8M	16M
1	4.10E-02	8.73E-02	2.22E+00	4.65E+00	9.69E+00
2	2.04E-02	4.32E-02	1.10E+00	2.31E+00	4.81E+00
4	1.10E-02	2.24E-02	5.65E-01	1.18E+00	2.46E+00
8	6.73E-03	1.25E-02	2.98E-01	6.22E-01	1.29E+00
16	5.19E-03	8.45E-03	1.70E-01	3.53E-01	7.31E-01

Run-times of parallel odd-even sort (Larger problem size)

comm_sz	Speedups				
	Number of Elements				
	1M	2M	4M	8M	16M
1	1.00	1.00	1.00	1.00	1.00
2	2.01	2.02	2.02	2.02	2.02
4	3.73	3.90	3.93	3.94	3.93
8	6.09	6.98	7.46	7.48	7.50
16	7.89	10.34	13.11	13.19	13.26

comm_sz	Efficiencies				
	Number of Elements				
	1M	2M	4M	8M	16M
1	1.00	1.00	1.00	1.00	1.00
2	1.00	1.01	1.01	1.01	1.01
4	0.93	0.97	0.98	0.98	0.98
8	0.76	0.87	0.93	0.93	0.94
16	0.49	0.65	0.82	0.82	0.83

Questions

Suppose we have p processes, and we need to compute a vector sum. If we ignore the I/O time, can we get more than p speedup over sequential version?

Questions

Assume we have p processes and we need to implement a binary tree search. Can we get more than p speedup, also ignoring I/O delay?

The Communicators

The Communicator(s)

- We are familiar with the communicator MPI_COMM_WORLD
- A communicator can be thought of as a handle to a group of an ordered set of processes
- For many applications maintaining different groups is appropriate.
- Groups allow collective operations to work on a subset of processes

MPI_Comm_split

```
int MPI_Comm_split(
    MPI_Comm comm,
    int            color,
    int            key,
    MPI_Comm * newcomm);
```

Called by all processes in comm

Must be non-negative

Rank of the process in newcomm

The original communicator does not go away!

MPI_Comm_split

- Partitions the group associated with comm into disjoint subgroups
- Processes with the same color will be in the same group
- Within each subgroup, the processes are ranked in the order defined by the value of the "key"
  - with ties broken according to their rank in the old group

MPI_Comm_split

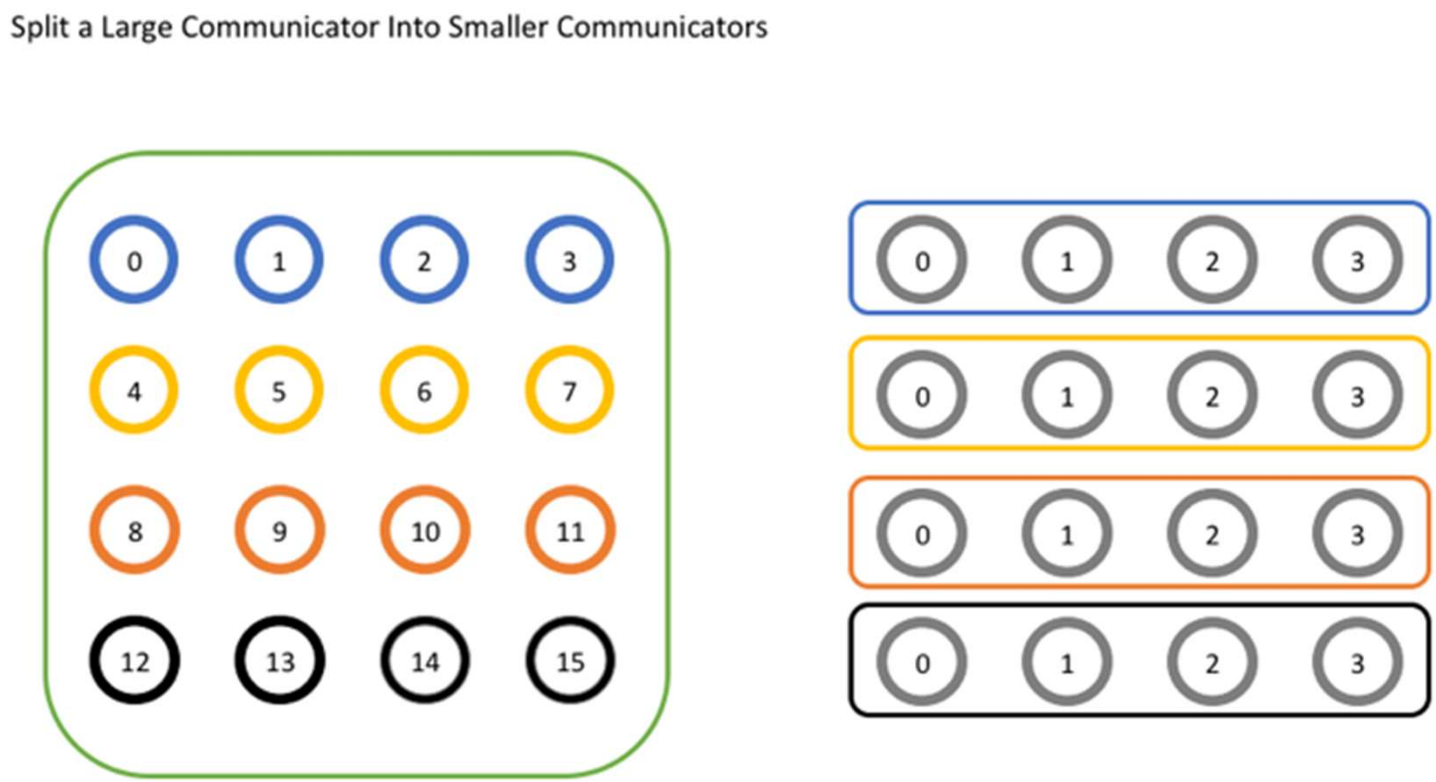
- If a process uses the color MPI_UNDEFINED it won't be included in the new communicator.

MPI_Comm_free

```
int MPI_Comm_free(
  MPI_Comm * newcomm);
```

- Deallocation of created communicator
- Better do it if you are not using the comm again.

Example



Source: http://mpitutorial.com/tutorials/introduction-to-groups-and-communicators/

Example

```
// Get the rank and size in the original communicator
int world_rank, world_size;
MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);
MPI_Comm_size(MPI_COMM_WORLD, &world_size);
int color = world_rank / 4;

// Determine color based on row
// Split the communicator based on the color and use the
// original rank for ordering
MPI_Comm row_comm;
MPI_Comm_split(MPI_COMM_WORLD, color, world_rank, &row_comm);

int row_rank, row_size;
MPI_Comm_rank(row_comm, &row_rank);
MPI_Comm_size(row_comm, &row_size);
printf("WORLD RANK/SIZE: %d/%d \t ROW RANK/SIZE: %d/%d\n",
    world_rank, world_size, row_rank, row_size);

MPI_Comm_free(&row_comm);
```

Source: http://mpitutorial.com/tutorials/introduction-to-groups-and-communicators/

Example

Output:

```
WORLD RANK/SIZE: 0/16     ROW RANK/SIZE: 0/4
WORLD RANK/SIZE: 1/16     ROW RANK/SIZE: 1/4
WORLD RANK/SIZE: 2/16     ROW RANK/SIZE: 2/4
WORLD RANK/SIZE: 3/16     ROW RANK/SIZE: 3/4
WORLD RANK/SIZE: 4/16     ROW RANK/SIZE: 0/4
WORLD RANK/SIZE: 5/16     ROW RANK/SIZE: 1/4
WORLD RANK/SIZE: 6/16     ROW RANK/SIZE: 2/4
WORLD RANK/SIZE: 7/16     ROW RANK/SIZE: 3/4
WORLD RANK/SIZE: 8/16     ROW RANK/SIZE: 0/4
WORLD RANK/SIZE: 9/16     ROW RANK/SIZE: 1/4
WORLD RANK/SIZE: 10/16    ROW RANK/SIZE: 2/4
WORLD RANK/SIZE: 11/16    ROW RANK/SIZE: 3/4
WORLD RANK/SIZE: 12/16    ROW RANK/SIZE: 0/4
WORLD RANK/SIZE: 13/16    ROW RANK/SIZE: 1/4
WORLD RANK/SIZE: 14/16    ROW RANK/SIZE: 2/4
WORLD RANK/SIZE: 15/16    ROW RANK/SIZE: 3/4
```

Source: http://mpitutorial.com/tutorials/introduction-to-groups-and-communicators/

Words of Wisdom!

Don't Forget!

- MPI is a library
  - → Any MPI operation requires one or more function calls.
  - → Not very efficient for very short data transfers.
  - → Communication should be aggregated as much as possible.
- Avoid unnecessary synchronizations.

When to use MPI

- Portability and Performance
- Building Tools for Others
  - Libraries
- Need to Manage memory on a per process basis

When *not* to use MPI

- Programs that have irregular communication patterns are often difficult to express in MPI's message-passing model.
- Domain-specific applications with an API tailored to that application
- Require Fault Tolerance

Strengths of MPI

- **Small**
  - Many programs can be written with only 6 basic functions
- **Large**
  - MPI's extensive functionality (MPI-1 contains about 125 API, let alone MPI-2 and MPI-3)
- **Scalable**
  - Point-to-point communication
- **Flexible**
  - Don't need to rewrite parallel programs across platforms

Conclusions

- You now know enough to use MPI in many problem solving
- We have not studied all APIs though.
- It is easy to understand the rest of APIs.
- The main rules:
  - Reduce communication
  - Ensure load-balancing
  - Increase concurrency