PARALLEL PROGRAMMING USING MPI – SPEEDUP AND MEMORY

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BEFORE WE BEGIN

- **A FEW THINGS …**
  - *This is more of an introductory workshop on MPI*
  - *No prior background on MPI is needed*
  - *Some basic background on sequential programming would be assumed.*
  - *Examples will be shown in FORTRAN. The concepts are equally valid for C.*
  - *The codes for the examples are written by the speaker himself. Please be ‘aggressive’ to point out any ‘shabby’ coding habits that you come across.*
  - *The remarks and conclusions made hereafter are solely the speaker’s personal opinions. The speaker does not represent any of the official implementers of MPI.*

OUTLINE

- PARALLEL PROGRAMMING
- GETTING STARTED WITH MPI
- SPEEDUP
- MPI SHARED MEMORY
- SUMMARY

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WHY PARALLEL PROGRAMMING?

❑ <u>**THE BIG PICTURE**</u>

Growth of processor clock-rate is slowing down – the main reasons being :

- size limits of the processor components
- higher power consumption at higher clock rates.

What does that mean to us?

- **Slow execution of codes and more time to reach solution**
- **Limit on available memory**

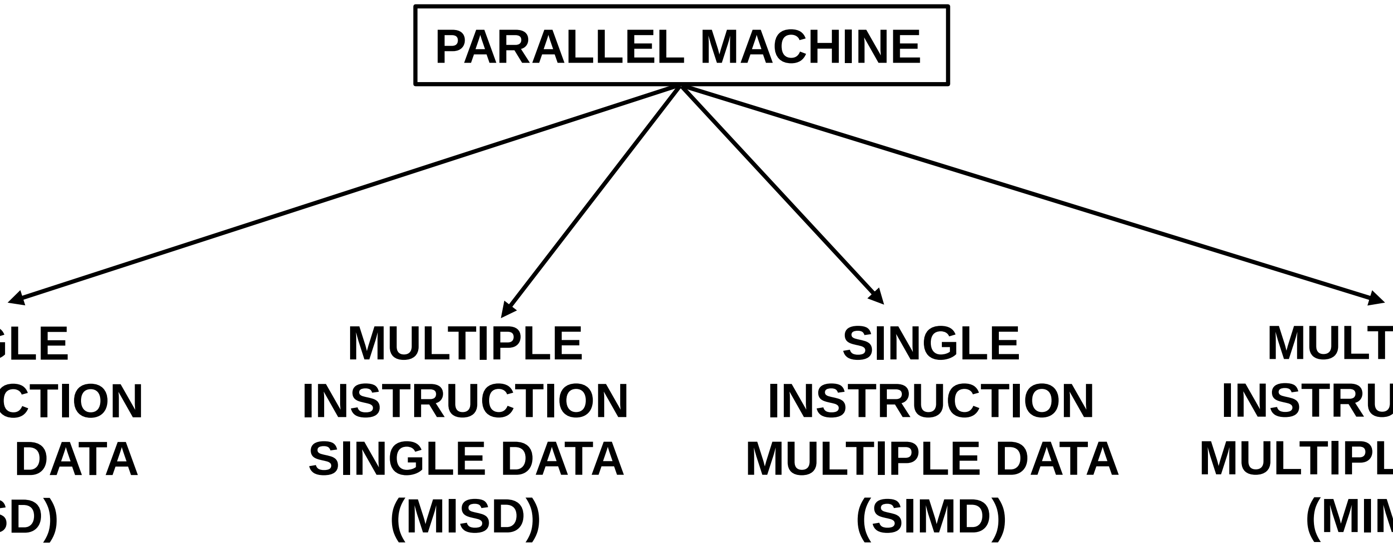
But that's limited by processor manufacturing. What do we programmers do?

- **Simple, use multiple processors**

PARALLEL COMPUTER ARCHITECTURE

T. Rauber and G. Runger, Parallel Programming, Springer 2013

- **FLYNN'S TAXONOMY**


PARALLEL MACHINE
SINGLE INSTRUCTION SINGLE DATA (SISD)
MULTIPLE INSTRUCTION SINGLE DATA (MISD)
SINGLE INSTRUCTION MULTIPLE DATA (SIMD)
MULTIPLE INSTRUCTION MULTIPLE DATA (MIMD)

Single processing element, single data memory.
Ex: a sequential computer

Multiple processing element ,single data memory.
Ex: No such commercial machine exists

Multiple processing elements - single instruction set (one program memory) and private data memories
Ex: single core computers

Multiple processing elements - private instruction sets and private data memories.
Ex: modern clusters.

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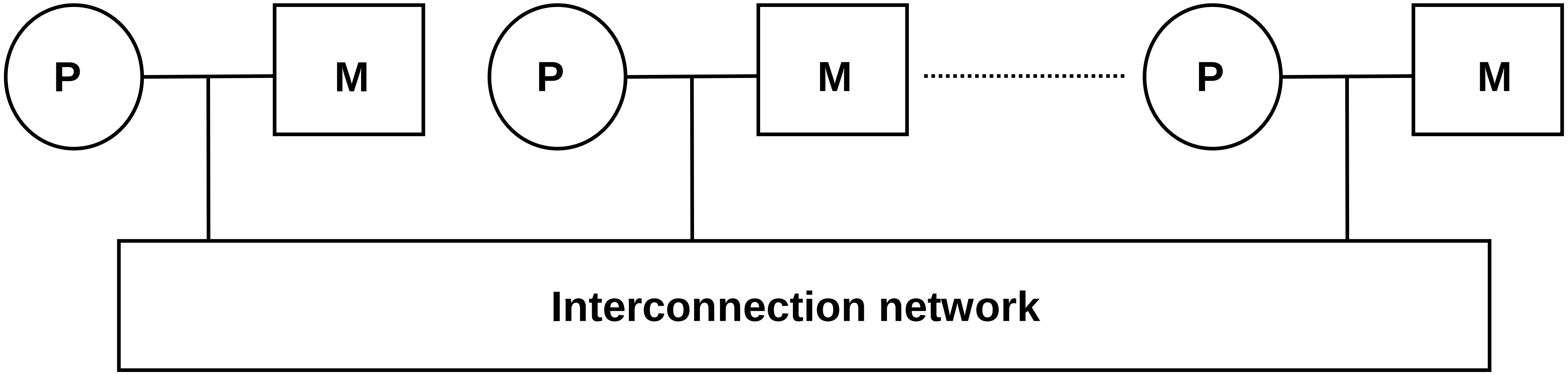
WHAT IS MPI?

W.P. Petersen and P. Arbenz, Introduction to Parallel Programming
Oxford University Press, 2004

- **<u>An MIMD system</u>**



- Message Passing Interface (MPI) establishes data access between nodes
- MPI is a standard message passing system on both shared and distributed systems
- A communicator group of processes perform a certain task
- Arbitrary master-slave relation

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GETTING ACCESS TO MPI

❑ **MPI IMPLEMENTATIONS**

MPICH (http://www.mpich.org/), Argonne National Laboratory

MVAPICH (http://mvapich.cse.ohio-state.edu/), Ohio State University

OpenMPI (https://www.open-mpi.org/), U of Tennessee, Los Alamos National Laboratory, Indiana University, and U of Stuttgart

INTEL MPI (https://software.intel.com/en-us/intel-mpi-library), Intel

❑ **MPI ON CCR AT UB**

```
module avail intel-mpi
module avail mvapich2
module avail openmpi
```

} Different modules available under each of these. Try to use the latest ones to get new features.

➢ Some implementations might have hardware interconnect specific modules. Load the one appropriate for you.

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FIRST PROGRAM

❑ HELLO WORLD WITH MPI

We want each proc to print its id

```
!-------------------------------------------
PROGRAM hello_world
!-------------------------------------------
USE mpi
!
IMPLICIT NONE
!
INTEGER       :: id, ierr, p
!
CALL mpi_init(ierr)
CALL mpi_comm_rank (MPI_COMM_WORLD, id, ierr)
CALL mpi_comm_size (MPI_COMM_WORLD, p, ierr)
!
PRINT '(" Total number of procs", i3, "  and my id is ", i3)',p, id
!
CALL mpi_finalize(ierr)
!
!
END PROGRAM hello_world
```

Initializes the MPI environment, ierr is almost ubiquitous in MPI FORTRAN, denotes the error code incase of an error

Gives id of a proc

Gives number of procs

Global Communicator, a predefined constant

Kills MPI

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BUILDING YOUR CODE WITH MPI

BUILD ➡

```
#!/bin/bash

module load intel/15.0
module load intel-mpi/5.0.2
which mpiifort
export MPIF90=mpiifort
$MPIF90 -traceback -g hello_world.f90 -o hello.x
```

LAUNCH ➡

```
# count the number of processors
np=`srun hostname -s | wc -l`
export I_MPI_PMI_LIBRARY=/usr/lib64/libpmi.so
srun -n $np hello.x
```

Integrates Intel-MPI to SLURM

OUTPUT ➡

```
Total number of procs  8  and my id is  0
Total number of procs  8  and my id is  1
Total number of procs  8  and my id is  2
Total number of procs  8  and my id is  3
Total number of procs  8  and my id is  4
Total number of procs  8  and my id is  5
Total number of procs  8  and my id is  6
Total number of procs  8  and my id is  7
```

BASIC MPI COMMANDS

We will only discuss a partial list of commands that are commonly used.

❑ **ENVIRONMENT MANAGEMENT**

4 such routines are used and explained in the hello_world program (slide 10)

❑ **POINT-TO-POINT COMMUNICATIONS**

MPI_SEND (buf, count, datatype, dest, tag, comm, ierr)

MPI_RECV (buf, count, datatype, source, tag, comm, status, ierr)

- **buf** is the data sent (received).
- **count** is the length of the data (like number of elements in an array)
- **dest** (**source**) is which proc id the data is going to (coming from)
- **tag** is an unique identification to a message. send tag = receive tag

  (wild card MPI_ANY_TAG will receive any message)

Petersen and Arbenz, IPP, Oxford University Press, 2004

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BASIC MPI COMMANDS

❑ EXAMPLE – *send and receive*

We want to send the proc ids of each proc to all other procs by point-to-point communication

```
DO iproc = 1, np
  !
  src = iproc - 1
  !
  DO jproc = 1, np
    !
    dest = jproc - 1
    !
    IF (p_id .EQ. src .AND. .NOT. (dest.EQ.src)  )  &
      CALL MPI_SEND (p_id, 1, MPI_INTEGER, dest , 10, MPI_COMM_WORLD, ierr)
    !
    IF (p_id .EQ. dest .AND. .NOT. (dest.EQ.src)  ) THEN
       CALL MPI_RECV (p_id_, 1, MPI_INTEGER,  src , 10, MPI_COMM_WORLD, MPI_STATUS_IGNORE, ierr)
       PRINT '(" I am proc", i3, " and my buddy is proc", i3 )',p_id, p_id_
    ENDIF
    !
    CALL MPI_BARRIER(MPI_COMM_WORLD, ierr)
    !
  ENDDO
  !
ENDDO
```

src sends its p_id to dest

p_id is the id of the current proc

dest receives it

note both tags are equal

p_id_ is the id of the sending proc

Will come to this in next slide

OUTPUT ➡

```
Total number of procs is   2

I am proc  0 and my buddy is proc  1
I am proc  1 and my buddy is proc  0
```

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BASIC MPI COMMANDS

❑ <u>**COLLECTIVE COMMUNICATIONS – *broadcast, barrier, and reduction***</u>

MPI_BARRIER (comm, ierr)

Petersen and Arbenz, IPP, Oxford University Press, 2004

➢ Each proc in **comm** waits until all of them reach at this step

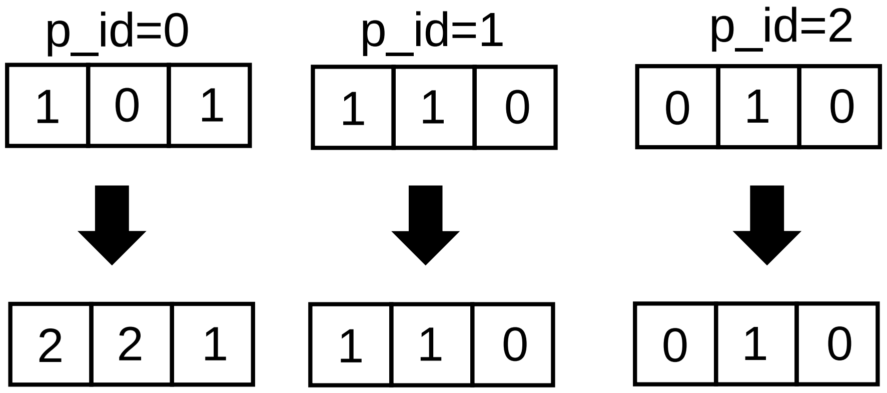
MPI_BCAST (data, count, datatype, root, comm, ierr)

➢ Proc **root** spreads **data** of length **count** to all other procs in **comm**.

MPI_REDUCE (segment, result, count, datatype, operator, root, comm, ierr)

➢ Proc dependent **segments** are merged as **result** in **root**. The merging is defined by **operator.**

MPI_REDUCE
(with operator = MPI_SUM and root=0)



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BASIC MPI COMMANDS

- **EXAMPLE – *broadcast and barrier***

We want one proc to read input and broadcast among others

```
! ---------------- Read input arguments --------------------
! --- Only one proc reads and then bcasts to others --------
!
IF (p_id.EQ.master) THEN
  !
  DO iiarg = 1, iargc()
    !
    CALL getarg( iiarg, inp_string(iiarg) )
    !
  ENDDO
  !
  READ ( inp_string(1), *) flag
  READ ( inp_string(2), *) m
  READ ( inp_string(3), *) n
  !
ENDIF
!
CALL mpi_barrier (MPI_COMM_WORLD, ierr)
CALL mpi_bcast(m,1,MPI_INTEGER,master,MPI_COMM_WORLD,ierr)
CALL mpi_bcast(n,1,MPI_INTEGER,master,MPI_COMM_WORLD,ierr)
CALL mpi_bcast(flag,10,MPI_CHARACTER,master,MPI_COMM_WORLD,ierr)
```

Only p_id = master does the i/o job

Other procs wait until master is done

Input data is broadcasted to other procs

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BASIC MPI COMMANDS

- **EXAMPLE – *reduction***

We want to compute $\{c\}_{n\times1} = [A]_{n\times m}\{b\}_{m\times1}$

```
! ----------- Split sample among procs --------------
!
n_per_proc = n / np
rest = MOD ( n , np)
IF (p_id .LE. (rest - 1)) n_per_proc = n_per_proc + 1
!
lower_bound = n_per_proc * p_id + 1
IF (p_id .GE. rest ) lower_bound = (n_per_proc + 1) * rest + n_per_proc * (p_id - rest) + 1
upper_bound = lower_bound + n_per_proc - 1
 ............
  ............

! ----------- Compute the proc wise split parts and then reduce to a single proc ---------
!
DO i = lower_bound, upper_bound
  !
  DO j = 1, m
     !
     c(i) = c(i) + A(i,j)*b(j)
     !
  ENDDO
  !
ENDDO
!
CALL mpi_barrier (MPI_COMM_WORLD, ierr)
CALL mpi_reduce (c,c_tot,n,MPI_FLOAT,MPI_SUM,master,MPI_COMM_WORLD,ierr)
```

n is split among np. Each proc gets n_per_proc

when mod (n, np) ≠ 0

index bounds on each proc

Each proc computes its own share

Total $\{c\}_{n\times1}$ reduced to master

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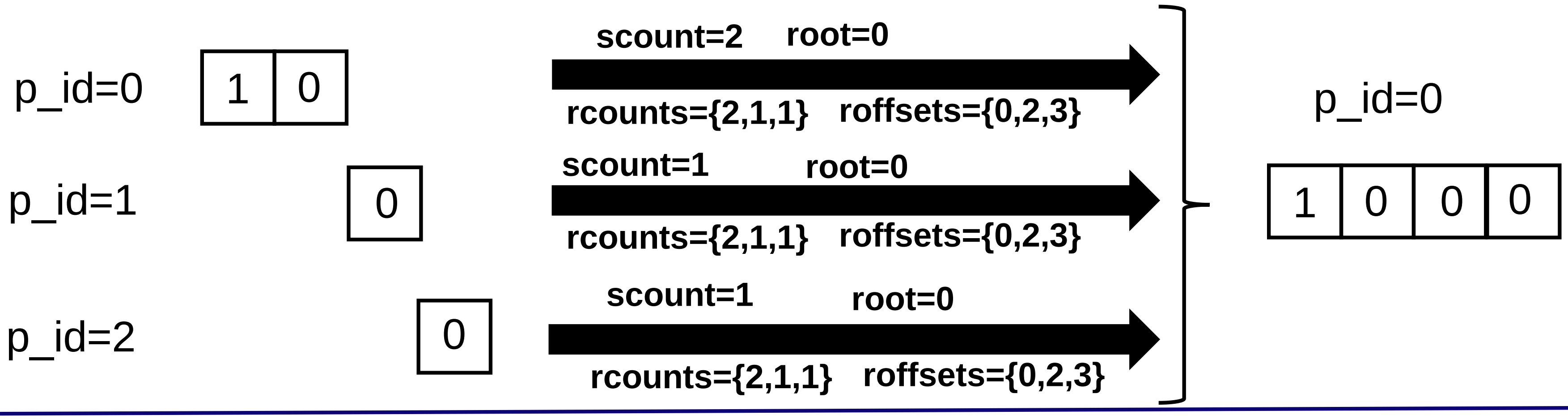
BASIC MPI COMMANDS

❑ <u>COLLECTIVE COMMUNICATIONS – *scatter(v) and gather(v)*</u>

- **MPI_SCATTER (MPI_GATHER)** – distribute (assemble) data segments
- **MPI_SCATTERV (MPI_GATHERV)** – additional features to non-uniformly distribute (assemble) data segments.
- We discuss the latter ones as that would clarify the former ones too.

Petersen and Arbenz, IPP, Oxford University Press, 2004

MPI_GATHERV (segment, scount, stype, result, rcounts, roffsets, rtype, root, comm, ierr)


p_id=0
1 0
scount=2 root=0
rcounts={2,1,1} roffsets={0,2,3}
p_id=1
0
scount=1 root=0
rcounts={2,1,1} roffsets={0,2,3}
p_id=2
0
scount=1 root=0
rcounts={2,1,1} roffsets={0,2,3}
p_id=0
1 0 0 0

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BASIC MPI COMMANDS

❑ **EXAMPLE – *gatherv***

Again we want to compute $\{c\}_{n\times 1} = [A]_{n\times m}\{b\}_{m\times 1}$

```
DO i = 1, n_per_proc
  !
  DO j = 1, m
     !
     c(i) = c(i) + A(i,j)*b(j)
     !
  ENDDO
  !
ENDDO
..............
counts(:) = 0
offsets(:) = 0
counts(p_id+1) = n_per_proc
offsets(p_id+1) = lower_bnd - 1
..............

CALL mpi_barrier(MPI_COMM_WORLD, ierr)
CALL mpi_allreduce (counts, all_counts, np, MPI_INTEGER, MPI_SUM, MPI_COMM_WORLD, ierr)
CALL mpi_allreduce (offsets, all_offsets, np, MPI_INTEGER, MPI_SUM, MPI_COMM_WORLD, ierr)
!
CALL mpi_gatherv(c,n_per_proc,MPI_FLOAT,c_tot,all_counts,all_offsets,MPI_FLOAT,master,&
                                                                    MPI_COMM_WORLD,ierr)
```

Each proc computes its share.

However, note that the size of the vector c in each proc is n_per_proc unlike the reduction case where it was n. Similar argument is valid for the matrix A

Each proc gets its own send counts and offsets

counts and offsets are merged in arrays using allreduce (all procs get the merged result)

Segments of c are gathered in c_tot

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MPI DATATYPES

❑ **COMMONLY USED ELEMENTARY MPI FORTRAN DATATYPES**

MPI TYPE	FORTRAN TYPE
MPI_INTEGER	INTEGER(KIND=4)
MPI_INTEGER8	INTEGER(KIND=8)
MPI_FLOAT	REAL (KIND=4)
MPI_DOUBLE	REAL (KIND=8)
MPI_COMPLEX	COMPLEX
MPI_LOGICAL	LOGICAL
MPI_CHARACTER	CHARACTER(LEN=1)

MPI 3.0 Standard http://mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf

OUTLINE

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RULE OF THE GAME

T. Rauber and G. Runger, Parallel Programming, Springer 2013

- **AMDAHL'S LAW**

$$\boxed{S_p(n) = \frac{1}{f + \frac{1-f}{p}}}$$

- $S_p(n)$ is the limit in actual speedup of the entire code of a given size n
- p is the speed up of the code that benefits from the increase in resources.
- f is the fraction of the total execution time taken by the sequential part of the code

Take home message – *Overall speedup is limited by the percentage of the sequential part of the code*

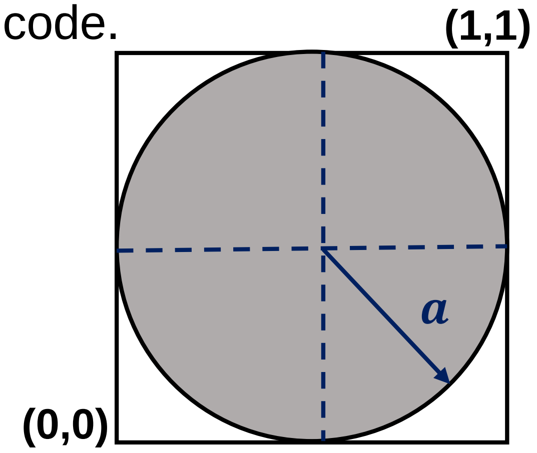
SPEEDUP – EXAMPLE

- **Goal** – Improve scalability/speedup through optimizing code.

- **Task** – Compute the value of π stochastically.

- **Method –**

  - Generate random points (x, y) inside an unit square.
  - Count the fraction of them falling inside an unit circle.
  - $\pi = 4 \times \frac{Points\ inside\ unit\ circle}{Total\ number\ of\ points}$
  - This is referred to as the dartboard algorithm **[Message Passing Interface, B. Barney, LLNL]**



Square area = $4a^2$

Circle area = πa^2

✓ ***We would compute this in parallel using MPI in different ways and compare the speedup and accuracy of the calculation.***

SPEEDUP – EXAMPLE

❑ SEQUENTIAL VERSION

```
c_ser = 0
DO i = 1,n
   !
   CALL RANDOM_NUMBER(r1)
   CALL RANDOM_NUMBER(r2)
   !
   a = (r1*r1 + r2*r2)
   IF(a.LT.(1.0)) c_ser = c_ser + 1
   !
END DO
!
PRINT'("Serially calculated Pi  = ",f16.10)',4.0D0*float(c_ser)/float(n)
```

In-built pseudo random number generator (RNG) with a period of $2^{1024} – 1$ (https://gcc.gnu.org/) Based on XORshift logic.

Output 3.1400

✓ A higher value of the sample size (n) will produce more accurate result

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SPEEDUP – EXAMPLE

❑ **PARALLEL VERSION 1**

Same program run on split samples and reduced at the end

```
DO i = 1, n_per_proc
  !
  CALL RANDOM_NUMBER(r1)
  CALL RANDOM_NUMBER(r2)
  !
  a = r1*r1 + r2*r2
  IF(a.LT.(1.0)) c_par = c_par + 1
  !
END DO
!
CALL mpi_barrier (MPI_COMM_WORLD, ierr)
CALL mpi_allreduce (c_par,c_par_tot,1,MPI_INTEGER,MPI_SUM,MPI_COMM_WORLD,ierr)
```

Each proc gets n_per_proc number of samples

all_reduce merges the results

Output **NOT ACCURATE** and
ACCURACY DROPS WITH INCREASING NUMBER OF PROCS !

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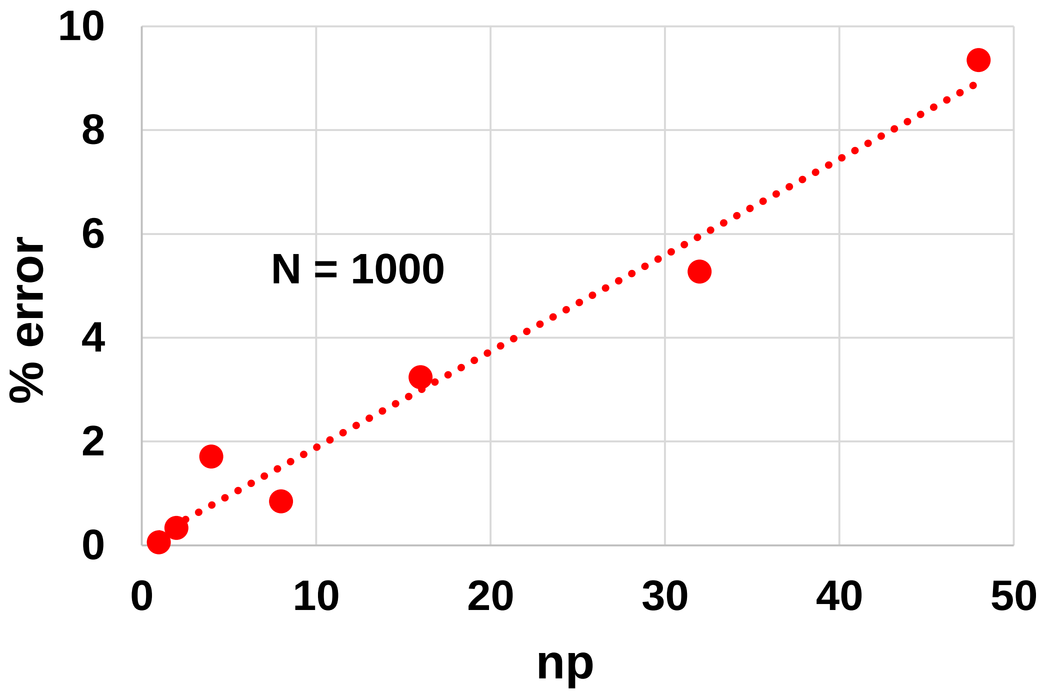
SPEEDUP – EXAMPLE

❑ **PARALLEL VERSION 1**

- ➢ Aliasing among the RNGs in different procs.
- ➢ Effective sample size drops
- ➢ Poor statistics.
- ➢ For very large number of procs result becomes unreliable.



- ➢ For this particular problem you can get away with any significant error simply choosing a very high N
- ➢ But think about large problem sizes where you cannot afford to have a high N.

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SPEEDUP – EXAMPLE

❑ PARALLEL VERSION 2

```
IF (ip.EQ.master) THEN
...........
  DO i = 1, n
     !
     CALL RANDOM_NUMBER(x)
     r1_all(i) = x
     CALL RANDOM_NUMBER(x)
     r2_all(i) = x
     !
  ENDDO
  !
ENDIF
!
CALL mpi_barrier (MPI_COMM_WORLD, ierr)
...........
```

RNG is called by only one proc to generate all the random numbers to avoid aliasing.

Random numbers are scattered across procs

```
CALL mpi_scatterv ( r1_all, all_counts, all_offsets, MPI_DOUBLE, &
                   r1, n_per_proc, MPI_DOUBLE, master, MPI_COMM_WORLD, ierr)
...........
 DO i = 1, n_per_proc
   !
   a = (r1(i)*r1(i) + r2(i)*r2(i))
   IF(a.LT.(1.0)) c_par = c_par + 1
   !
 END DO
 !
 CALL mpi_barrier (MPI_COMM_WORLD, ierr)
 CALL mpi_allreduce (c_par,c_par_tot,1,MPI_INTEGER,MPI_SUM,MPI_COMM_WORLD,ierr)
```

‘area’ calculation in parallel

Output

Good accuracy ☺
Poor (no) speedup ☹

Amdahl’s law in action !

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SPEEDUP – EXAMPLE

❑ **PARALLEL VERSION 3**

```
CALL RANDOM_SEED(PUT=arr)
!
DO i = 1, n_per_proc
  !
  CALL RANDOM_NUMBER(r1)
  CALL RANDOM_NUMBER(r2)
  !
  a = r1*r1 + r2*r2
  IF(a.LT.(1.0)) c_par = c_par + 1
  !
END DO
!
CALL mpi_barrier (MPI_COMM_WORLD, ierr)
CALL mpi_allreduce (c_par,c_par_tot,1,MPI_INTEGER,MPI_SUM,MPI_COMM_WORLD,ierr)
```

arr is dependent on the proc_id

Each proc gets its distinct own seed to start the RNG.

This ensures each proc gets a distinct number stream although they run in parallel

Avoids aliasing. Choose the initial seed carefully to minimize correlation among streams

Output

Good accuracy ☺
Good speedup ☺

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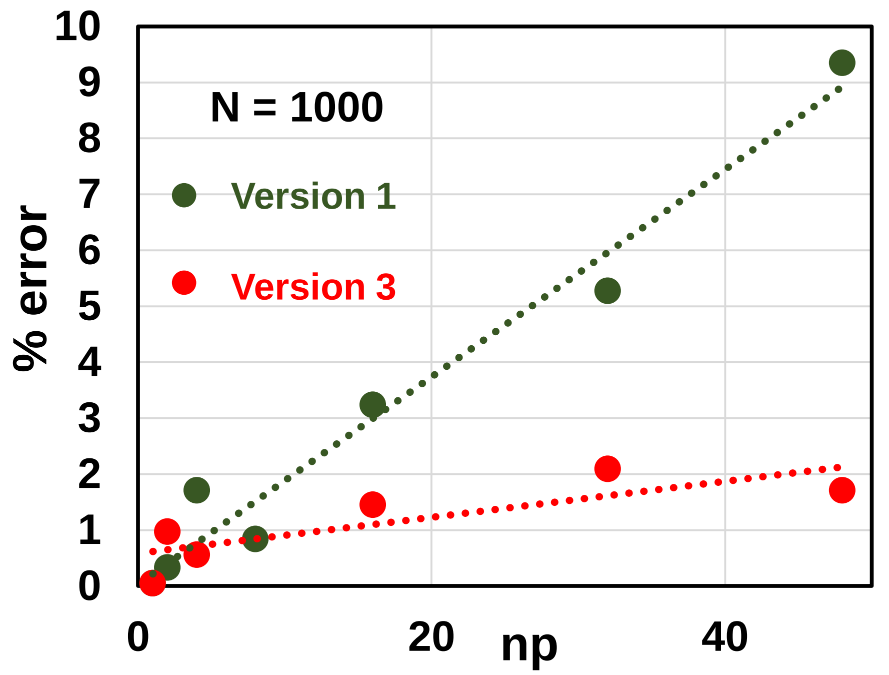
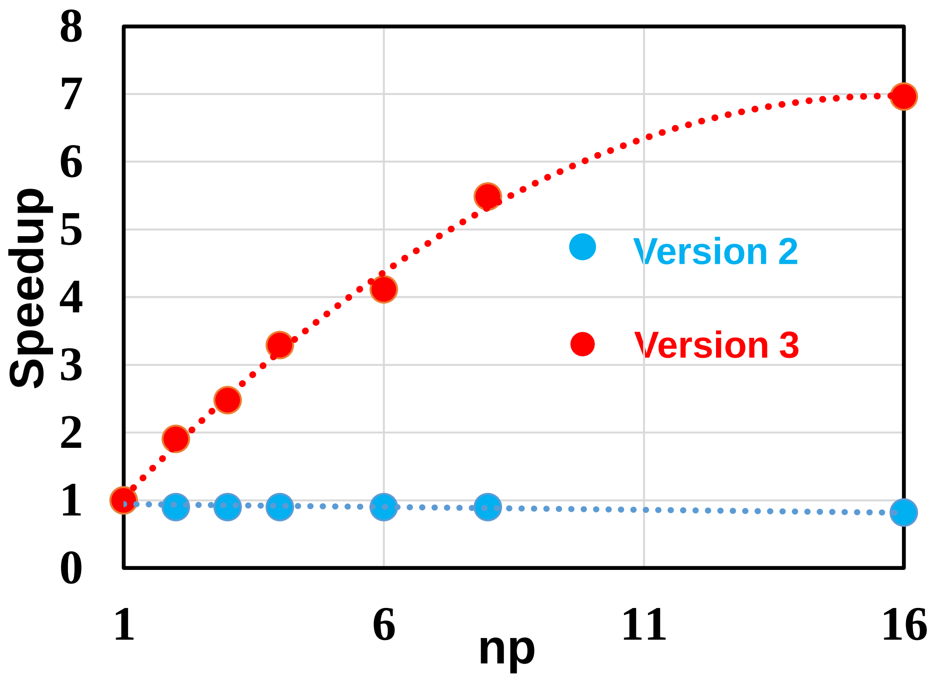
SPEEDUP – EXAMPLE

❑ PERFORMANCE COMPARISON





- The sample size, N, for speedup comparison is taken to be much higher so that the problem size becomes reasonable to compare the speedup.

- I use INTEL MKL (https://software.intel.com/en-us/intel-mkl) RNGs where separate generators can be used for each proc.

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OUTLINE

WHY SHARED MEMORY (SHM)?

- **PROBLEM WITH DISTRIBUTED MEMORY (PURE MPI)**
  - Each proc has its own copy of all the variables.
  - This becomes a problem as array sizes grow and is redundant for SHM procs
  - Total memory requirement exceeds the given node’s memory capacity.
  - Plus, unnecessary MPI calls among the SHM procs.
- **SHARING THE MEMORY AMONG PROCS (HYBRID)**
  - Allocate a shared memory window in each proc that is accessible to all procs
  - Split the variable among procs, one proc can access other’s share.
  - This hybrid approach drastically cuts down the memory requirement
  - Different ways – MPI+OpenMP, MPI+MPI-3, etc.

Let’s see how this can be done using MPI. You need to use MPI-3 for SHM

SHM ALLOCATION

MPI_WIN_ALLOCATE_SHARED (size, disp_unit, info, comm, baseptr, win, ierr)

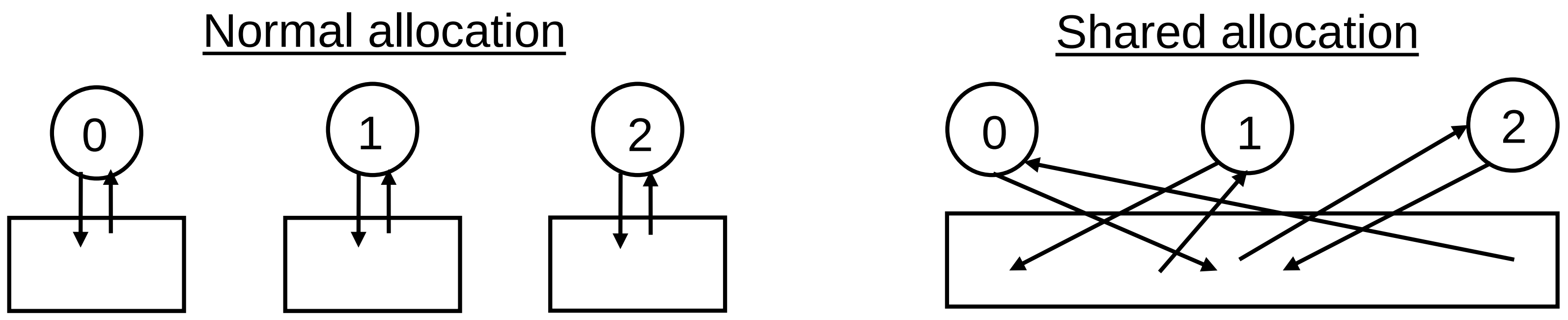
locally allocated size in bytes

local unit size displacement

how memory should be allocated

pointer to locally allocated segment

window object for future reference



- Programmer's responsibility to make sure that all procs under comm can have a shared memory segment. Will see how.
- info = MPI_INFO_NULL allocates contiguous memory; segments are next to each other. Use ALLOC_SHARED_NONCONTIG for non-contiguous memory.

MPI 3.0 Standard http://mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf

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SHM ACCESS

$$\textbf{MPI\_WIN\_SHARED\_QUERY (}\underbrace{\textbf{win, rank,}}_{\text{i/p}}\ \underbrace{\textbf{size, disp\_unit, baseptr}}_{\text{o/p}}\textbf{)}$$

- Rank should be the local rank of the target proc
- baseptr points to the local segment in the target proc
- Often the storing and loading of data from remote target procs are referred to as *Remote Memory Access (RMA)*
- <u>FORTRAN only</u>

USE, INTRINSIC :: ISO_C_BINDING

CALL C_F_POINTER(baseptr, a, shape)

C pointer
type (c_ptr)

Fortran pointer

Shape of a

Or use Cray pointers. Some compliers may need separate option for Cray pointers during compilation.

MPI 3.0 Standard **http://mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf**

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SPLITING THE COMMUNICATOR

❑ **MAKING SURE PROCS HAVE A SHM SEGMENT**

➢ First job in any SHM program is to split the communicator group into SHM communicator groups (shmcomm)

➢ This ensures all procs under shmcomm can have a shared memory segment.

➢ If we work on a single node (unusual for big codes), MPI_COMM_WORLD and shmcomm are same.

❑ **EXAMPLE**

```
!
! *********** Split global comm into SMP comms; the third argument 0 says that SMP ranks ********
! ****************************** should be consistent with global ranks **************************
!
CALL MPI_COMM_SPLIT_TYPE (MPI_COMM_WORLD, MPI_COMM_TYPE_SHARED, 0, MPI_INFO_NULL, shmcomm, ierr)
CALL mpi_comm_rank (shmcomm, my_rank, ierr)
CALL mpi_comm_size (shmcomm, my_size, ierr)
!
```

Rank within shmcomm
Size of shmcomm

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SHM – EXAMPLE

- **ALLOCATE SHARED MEMORY**

We want to store a 2D array $A_{mk \times nk}$ inside a shared window

```
! ********* Allocate shared memory. Change MPI_INFO_NULL to ALLOC_SHARED_NONCONTIG if you *******
! ****************************** want noncontiguous memory segments. *****************************
!
shape1 = (/loc_size, nk/)
size1 = DP_size * shape1(1) * shape1(2)
!
IF (p_id.LT.my_size) PRINT '( " My rank is ", i3, " and local size is ", i3)' , my_rank, loc_size
!
CALL MPI_WIN_ALLOCATE_SHARED (size1, 1 , MPI_INFO_NULL, shmcomm, p, smwin, ierr)
!
CALL C_F_POINTER(p, a, shape1)  ! to assign C pointer target to FORTRAN pointer
!
 ............
 ............
 CALL DD(a)
 CALL MPI_Win_fence (0, smwin, ierr)
 CALL DD(a)
 !
 DO i = 1, loc_size
   !
   DO j = 1, nk
      !
      a(i, j) = FLOAT ( ( p_id + my_rank + 2) * ( i + j ) )
      !
   ENDDO
   !
 ENDDO
 !
 CALL DD(a)
 CALL MPI_Win_fence (0, smwin, ierr)
 CALL DD(a)
```

loc_size is mk split over np
size1 is the actual size in bytes

fence. Different from MPI_BARRIER. Ensures no wrong loading of data during the RMA operation.

Fortran only, DD is just an user defined empty routine to make sure register copies of *a* are written back to memory. See MPI 3.0 Standard (page 638) for more details

SHM – EXAMPLE

❑ **SHARED QUERY**

Next we want to remote access some elements of the array

```
DO iproc = 1, my_size - 1
   !
   IF ( imk.GT.all_offsets(iproc) .AND. imk.LE.all_offsets(iproc+1) ) THEN
      !
      ipool = iproc - 1
      ipos  = imk - all_offsets(iproc)
      PRINT '( (/1x), "proc address and local positions are ", 2i3, (/1x) )', ipool, ipos
      EXIT
      !
   ELSEIF ( imk.GT.all_offsets(my_size)) THEN
      !
      ipool = my_size - 1
      ipos  = imk - all_offsets(ipool)
      PRINT '( (/1x), "proc address and local positions are ", 2i3, (/1x))', ipool, ipos
      EXIT
      !
   ENDIF
   !
ENDDO
!
! ************ Ask for remote proc attributes *****
!
CALL MPI_WIN_SHARED_QUERY (smwin, ipool, size1, disp1, p1, ierr)
rm_shape (2) = shape1(2)
rm_shape (1) = size1 / ( DP_size * rm_shape(2) )
!
CALL C_F_POINTER(p1, a1, rm_shape)
```

First find out which proc the asked element belongs to and what is its position inside that proc

Next access that element through shared query

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SHM – EXAMPLE

❑ **OUTPUT**

```
My rank is   0 and local size is  14
My rank is   1 and local size is  13
My rank is   2 and local size is  13
```

Let's take mk=40, nk=40 with mk being split among 3 procs

Suppose one of the proc (say p_id=0) wants to access A (21, :)

```
  32.0
  36.0
  40.0
  44.0
  48.0
  .........
  .........
  176.0
  180.0
  184.0
  188.0
```

Here we double-check the functionality of the code –

Definition of A : $A(i,j) = (p\_id + my\_rank + 2) * (i + j)$

Now imk=21 belongs to p_id=1 and my_rank=1

Local position of imk=21 in p_id=3 should be ipos=(21-14) = 7

Hence the array should be $A(21,j) = 4 * (7 + j)\ \forall\ j \in [1,40]$

This is what we see at the output.

OUTLINE

SUMMARY AND ACKNOWLEDGEMENT

❑ <u>SUMMARY</u>

- Parallel programming becomes more important and powerful in scientific computing every passing year.
- MPI is an extremely useful and efficient standard to build parallel codes.
- Speedup in parallel codes is limited by the sequential percentage of the code.
- MPI shared memory provides excellent features to deal with large memory.

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THANK YOU ALL!

HAPPY PARALLEL PROGRAMMING!

… Enjoy responsibly ☺

Cheers,
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