Introduction to parallel Computing

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What is high performance computing?

- Large volume numerical calculations: Set up facilities to run large number of codes in an efficient manner.
- Fast and efficient algorithms: Increase the speed of computing by optimizing the algorithm for a particular architecture.
- Highly scalable algorithms: Develop parallel codes that can scale linearly with number of processors.
- Modification of the computing model to allow for the use of recent advances in hardware: Cuda programming for GPU.
- Codes for complex problems: climate modeling, turbulence, protein folding, pattern and speech recognition, structural predictions.
Sequential vs Parallel

• We are used to sequential programming – C, Java, C++, etc. E.g., Bubble Sort, Binary Search, Multiplication, FFT, BLAST, …

• Main idea – Specify the steps in perfect order

• Reality – We are used to parallelism a lot more than we think – as a concept; not for programming

• Methodology – Launch a set of tasks; communicate to make progress. E.g., Sorting 500 answer papers by – making 5 equal piles, have them sorted by 5 people, merge them together.
Main Paradigms: Shared vs Distributed Memory Programming

- Shared Memory – All tasks access the same memory, the same data. *pthreads*

- Distributed Memory – All memory is local. Data sharing is by explicitly transporting data from one task to another (*send-receive* pairs in MPI, e.g.)

- Tasks vs CPUs;
- SMPs vs Clusters
Simple Parallel Program – sorting numbers in a large array A

- Notionally divide A into 5 pieces [0..99; 100..199; 200..299; 300..399; 400..499].
- Each part is sorted by an independent sequential algorithm and left within its region.

- The resultant parts are merged by simply reordering among adjacent parts.
Work Break-down

- Parallel algorithm
- Prefer simple intuitive breakdowns
- Usually highly optimized sequential algorithms are not easily parallelizable
- Breaking work often involves some pre- or post-processing (much like divide and conquer)
- Fine vs large grain parallelism and relationship to communication
Sample OpenMP code

```c
!$omp PARALLEL
!$OMP do
    do I=1,n
        y(I)=f(x(I))
    Enddo
!$OMP end do
!$omp end PARALLEL
```

```c
#pragma omp PARALLEL for
for { I==1;I<=m;I++
    y(I)=f(x(I))
}
```

- ifort -openmp test.f
- export omp_NUM_THREADS=8
- ./a.out

- icc -openmp test.f
- export omp_NUM_THREADS=8
- ./a.out
MPI: What do we need to think about…

- How many people are doing the work. (Degree of Parallelism)
- What is needed to begin the work. (Initialization)
- Who does what. (Work distribution)
- Access to work part. (Data/IO access)
- Whether they need info from each other to finish their own job. (Communication)
- When are they all done. (Synchronization)
- What needs to be done to collate the result.
MPI program structure

- All MPI programs must follow the same general structure. This structure is outlined as follows:
  - include MPI header file
  - variable declarations
  - initialize the MPI environment
  - ...do computation and MPI communication calls...
  - close MPI communications
Hello world !!!
#include <stdio.h>
#include <mpi.h>

void main (int argc, char *argv[]) {
    int myrank, size;
    MPI_Init(&argc, &argv);    /* Initialize MPI    */
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank); /* Get my rank */
    MPI_Comm_size(MPI_COMM_WORLD, &size);   /* Get the total number of processors */
    printf("Processor %d of %d: Hello World!\n", myrank, size);
    MPI_Finalize();               /* Terminate MPI     */
}

• Out put if run with "mpirun -np 4 ./a.out"
• Processor 2 of 4: Hello World!
• Processor 1 of 4: Hello World!
• Processor 3 of 4: Hello World!
• Processor 0 of 4: Hello World!

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This program evaluates the trapezoidal rule estimate for an integral of \( F(x) \). In this case, \( F(x) = \exp(x) \) evaluated for the interval of 0 to 1.

* This program requires the following call(s)
  * MPI_Init, MPI_Comm_rank, MPI_Comm_size, MPI_Abort, MPI_Finalize

```c
main (int argc, char **argv)
{
  double A = 0.0, B = 1.0;
  MPI_Init(&argc, &argv); /* Initialize MPI */
  MPI_Comm_rank(MPI_COMM_WORLD, &whoami); /* Find out this processor number */
  MPI_Comm_size(MPI_COMM_WORLD, &nworkers); /* Find out the number of processors */
  DH=(B-A)/nworkers;
  if (whoami > NP)  MPI_Abort(MPI_COMM_WORLD, errcode);

  T1=A+whoami*DH; T2=A+(whoami+1)*DH; H=(T2-T1)/50.0;

  SUM = 0.0;
  for (i = 0; i <=49; i++)   SUM = SUM+F(T1+H*i)+F(T1+H*(i+1));
  TN = SUM*H;

  MPI_Reduce (&TN, &res,1,MPI_DOUBLE, MPI_SUM, 1, MPI_COMM_WORLD);
  if(whoami==2)printf("Integral = %10.6f\n",res);

  MPI_Finalize(); }
```
An MPI program to simulate the Ising model in two dimensions.

This program demonstrate the usage of mpi grid topology and communication between grid elements.

Help from Ms. Prathyusha in the preparation of this code is acknowledged.
```c
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <mpi.h>
#include <string.h>

#define LENGTH 6        /* system+boundary layer size is LENGTH*LENGTH */
#define BUFSIZE (LENGTH-2)*(LENGTH-2)        /* system size*/
#define TEMP 1.0         /* TEMP in units of interaction and k_B */
#define WARM 1000
#define MCS 1250

int    total_energy( int [[LENGTH], int [] , int []]);
int    total_mag( int [[LENGTH]]); int coordinates[2];

double ran3( long int *); float fpow (float , float); float mag_analytic(float);
/* total number of processes "nworkers", identity of each process "rank" */
int nworkers, rank, NP;
int spin[LENGTH][LENGTH]; int nbr1[LENGTH]; int nbr2[LENGTH];

/* structure defining the variables of the grid topology */
typedef struct GRID_INFO_TYPE{
    int p;
    MPI_Comm comm;   MPI_Comm row_comm;  MPI_Comm col_comm;
    int q;  int my_row;  int my_col;  int my_rank;
}GRID_INFO_TYPE;
```
void    print_config (GRID_INFO_TYPE* grid, int [][]LENGTH, int );
/* set up the grid-topology */
void Setup_grid(GRID_INFO_TYPE* grid);

void initialize(GRID_INFO_TYPE* grid, int [][]LENGTH, int [] , int []);

void mcmmove(GRID_INFO_TYPE* grid, int[][]LENGTH , int [] , int [] );
/* communicate the state of the spins at the boundaries to neighbors */
void boundary(GRID_INFO_TYPE* grid, int[][]LENGTH , int [] , int [] );
main (int argc, char **argv)
{
    /* Allocate memory for the structure grid */
    GRID_INFO_TYPE *grid = (GRID_INFO_TYPE *)malloc(sizeof(GRID_INFO_TYPE));
    /* Initialize MPI */
    MPI_Init(&argc, &argv);
    /* Find out this process number */
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    /* Find out the number of processes */
    MPI_Comm_size(MPI_COMM_WORLD, &nworkers);

    Setup_grid(grid);

    int itime;
    int i;
    int big_energy,E;
    int big_mag,M;
    double E_per_spin;
    double M_per_spin;
    NP=sqrt(nworkers);
    iseed=iseed*(rank+1);
    itime = 0;
    big_energy = 0;
    big_mag = 0;
/* get started */
  initialize(grid, spin, nbr1, nbr2);
  boundary(grid, spin, nbr1, nbr2);
/* warm up system */
  for (i = 1 ; i <= WARM; i++)
  {   itime = i;
      mcmov(e(grid, spin, nbr1, nbr2);
      boundary(grid, spin, nbr1, nbr2);  }
/* do Monte Carlo steps and collect stuff for averaging */
  for (i = (WARM + 1) ; i <= MCS; i++)
  {   itime = i;
      mcmov(e(grid, spin, nbr1, nbr2);
      if(i!=MCS)boundary(grid, spin, nbr1, nbr2);
      big_mag = big_mag + total_mag(spin);
      big_energy = big_energy + total_energy(spin,nbr1,nbr2); }
  printf("Mag  %f rank %d time %d\n", 1.0*big_mag/(MCS-WARM), rank, MCS-WARM);
  MPI_Reduce (&big_mag, &M,1,MPI_INT, MPI_SUM, 0, MPI_COMM_WORLD);
  MPI_Reduce (&big_energy, &E,1,MPI_INT, MPI_SUM, 0, MPI_COMM_WORLD);
  if(rank==0)
  { M_per_spin = (float)M/((MCS - WARM)*(nworkers*(LENGTH-2)*(LENGTH-2)));
    E_per_spin = (float)E/((MCS - WARM)*nworkers*((LENGTH-2)*(LENGTH-2)));
    print_config(grid, spin, itime );
    MPI_Finalize(); /* exit all MPI functions */  }
void Setup_grid(GRID_INFO_TYPE* grid){
    int dimensions[2];
    int periods[2];
    int varying_coords[2];
    MPI_Comm   localname;

    MPI_Comm_size(MPI_COMM_WORLD, (&grid->p)); /* get the total number of processes */
    grid->q=(int)sqrt((double) grid->p); /* square grid */
    dimensions[0]=dimensions[1]=grid->q; /* dimension of the grid */
    periods[0]=periods[1]=1; /* periodic if 1 and non-periodic if 0 */

    MPI_Cart_create(MPI_COMM_WORLD, 2, dimensions, periods, 1, &(grid->comm)); /* create a grid communicator from the "Comm_world" , having dimension 2, reorder process to processor mapping */

    MPI_Comm_rank(grid->comm, &(grid->my_rank));
    MPI_Cart_coords(grid->comm, grid->my_rank,2,coordinates);
    grid->my_row=coordinates[0];
    grid->my_col=coordinates[1];
    varying_coords[0]=0;varying_coords[1]=1;
    MPI_Cart_sub(grid->comm,varying_coords,&(grid->row_comm));
    varying_coords[0]=1;varying_coords[1]=0;
    MPI_Cart_sub(grid->comm,varying_coords,&(grid->col_comm));
}
void initialize(GRID_INFO_TYPE* grid, int spin[][LENGTH], int nbr1[], int nbr2[]) {
    int i, ix, iy, m, n, mt, nt, tag = 50; float sd;

    char message[100];

    for (iy = 0; iy < LENGTH; iy++) /* start with random spins */
        for (ix = 0; ix < LENGTH; ix++)
        {
            sd = ran3(&iseed);
            if (sd > 0.5) spin[ix][iy] = 1;
            if (sd <= 0.5) spin[ix][iy] = -1;
        }

    for (i = 1; i < LENGTH - 1; i++) /* set up neighbor list */
    {
        nbr1[i] = i - 1;
        nbr2[i] = i + 1;
    }
}
void print_config(GRID_INFO_TYPE *grid, int spin[][LENGTH], int itime)
{
    int ix, iy, i, buf[(LENGTH-2)], buf1[LENGTH-2], tag=147, n, mp, np;
    char fname[30], message[50];
    float cx[1];
    FILE* fpr;
    MPI_Status status;
    if (grid->my_rank!=0) /* if rank is not zero pack all spins into a 1-d array */
    {
        i = 0;
        for (iy = 1; iy < LENGTH-1; iy++)
        {
            for (ix = 1; ix < LENGTH-1; ix++)
            {
                buf[i] = spin[iy][ix];
                i++;
            }
        }
        MPI_Send(buf, BUFSIZE, MPI_INT, 0, tag, MPI_COMM_WORLD); /* send it to process 0 */
    }
    else /* if the rank is zero */
    {
        fpr = fopen("config", "w"); /* open the file */
        for (iy = 1; iy < LENGTH-1; iy++) /* print the own configuration */
        {
            for (ix = 1; ix < LENGTH-1; ix++)
            {
                fprintf(fpr, "%d \t", spin[iy][ix]);
            }
        }
        for (n = 1; n < nworkers; n++)
        {
            MPI_Recv(buf1, BUFSIZE, MPI_INT, n, tag, MPI_COMM_WORLD, MPI_STATUS_IGNORE); /* receive from all other processes */
            for (i = 0; i < (LENGTH-2); i++)
            {
                for (ix = i*(LENGTH-2); ix < (i+1)*(LENGTH-2); ix++)
                {
                    fprintf(fpr, "%d \t", buf1[ix]);
                }
            }
        }
    }
}
void mcmove(GRID_INFO_TYPE* grid, int spin[][LENGTH], int nbr1[], int nbr2[])
{
    int *U1,*D1,*R1,*L1;
    /* arrays to receive the spin configuration from neighbors */
    U1=(int *)malloc(LENGTH*sizeof(int));
    D1=(int *)malloc(LENGTH*sizeof(int));
    R1=(int *)malloc(LENGTH*sizeof(int));
    L1=(int *)malloc(LENGTH*sizeof(int));
    MPI_Status status;
    MPI_Cart_shift(grid->comm,0,-1,&m,&n);
    MPI_Recv(U1,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD,&status); /* receive U1
    buffer with dimension LENGTH of type MPI_INT from process "n" with "tag" */
    MPI_Cart_shift(grid->comm,0,1,&m,&n);
    MPI_Recv(D1,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD,&status);
    MPI_Cart_shift(grid->comm,1,-1,&m,&n);
    MPI_Recv(L1,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD,&status);
    MPI_Cart_shift(grid->comm,1,1,&m,&n);
    MPI_Recv(R1,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD,&status);
    prob1 = exp(-8.0/TEMP);
    prob2 = exp(-4.0/TEMP);
    for (i = 1 ; i < LENGTH-1; i++)
    {
        spin[i][0]=U1[i]; spin[i][LENGTH-1]=D1[i]; spin[0][i]=R1[i]; spin[LENGTH-1][i]=L1[i];
    }
    free(U1); free(D1); free(L1); free(R1);
    DO THE MC SPIN FLIP MOVES
void boundary(GRID_INFO_TYPE* grid, int spin[][LENGTH], int nbr1[], int nbr2[])
{
    U2=(int *)malloc(LENGTH*sizeof(int));  D2=(int *)malloc(LENGTH*sizeof(int));
    R2=(int *)malloc(LENGTH*sizeof(int));  L2=(int *)malloc(LENGTH*sizeof(int));
    /* put the spins at the left, right, up and down boundaries into separate arrays */
    for (i = 1 ; i < LENGTH-1 ; i++)
    {
        U2[i]=spin[i][1];  D2[i]=spin[i][LENGTH-2];  L2[i]=spin[1][i];  R2[i]=spin[LENGTH-2][i];
    }

    /*send the boundary arrays to appropriate neighbor process
    Remember 0 is up and down and  1 is left and right. */
    MPI_Cart_shift(grid->comm,0,-1,&m,&n); /* find the neighbor process down the current one */
    MPI_Send(U2,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD); /* send U2 buffer with dimension LENGTH of type MPI_INT to process "n" with "tag" */
    MPI_Cart_shift(grid->comm,0,1,&m,&n);
    MPI_Send(D2,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD);
    MPI_Cart_shift(grid->comm,1,1,&m,&n);
    MPI_Send(R2,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD);
    MPI_Cart_shift(grid->comm,1,-1,&m,&n);
    MPI_Send(L2,LENGTH, MPI_INT,n,tag,MPI_COMM_WORLD);
    free(U2);  free(D2);       free(L2);   free(R2);
}
Introduction to Parallel Computing. Michael Skuhersky vex@mit.edu. What is Parallel Computing? — Wikipedia says: “Parallel computing is a form of computation in which many calculations are carried out simultaneously.” — Speed measured in FLOPS. What is Parallel Computing? (cont.) How can this be useful? — Main Granularity Paradigms. — Granularity: the ratio of computation to communication. — 3 approaches to parallelism, depending on what kind of problem you need to solve. Embarrassingly Parallel. — No effort required to separate tasks — Tasks do not depend on, or communicate, with each other. — Examples: Mandelbrot, Folding@home, Password brute-forcing, Bitcoin Mining!
