CS140 HW #2

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Parallelization of Matrix-Vector Multiplication and the Power Method

This report describes the code and result of designing and implementing an algorithm for finding the highest eigenvalue of a matrix, called the Power Method. The algorithm is designed to run in parallel on N processors to enhance the performance. The Power Method can easily be described by the following Matlab code

Listing 1: Power Method algorithm implemented in Matlab (by John R. Gilbert)

```
funciton lambda =Powermethod(A)
    [n,n] = size(A);          % number of rows and columns in A
    x = ones(n,1);            % creates a starting n vector of all ones
    for i = 1:1000
        x = x / norm2(x);     % norm2(x) is sqrt(x(1)^2 + x(2)^2 + ... + x(n)^2)
        x = A * x;            % use your parallel matrix * vector routine here
    end;
    lambda = norm2(x);
```

Implementation in the C language

The code was implemented in C using the MPI library for parallelization. The design of the code was based on first partitioning the matrix operation between the N processors. First a matrix where generated in the function $generatematrix()$. This function generated $\frac{N}{nprocs}$ where nprocs is the number of processors. Further in the code each processors did operations on the same amount of rows. Further, following the algorithm in Listing 1, each processor generated a row column vector of dimension N with 1's in all the entries. Each processor executed the $norm2()$ function on the vector. The parallelization used that helped the performance the most where implemented in the matrix-vector multiplication, in the funciton matVec(). Each processor performed a multiplication with each of the rows and the column vector, producing a column vector of dimension $\frac{N}{nprocs}$. The column vectors from all the processors where gathered in processor 0 using the MPI_gather library function to form the total matrix-vector product Ax. To make the total vector accessible to the other processors, MPI_Bcast where used. For more details the reader should look at the c-code implementations in functions.c.

Performance and timing

The c-code where tested on matrices of dimension N where N allways where the quotient $\frac{N}{nprocs}$ always was an integer. The algorithm proved successful and returned the same values as the matlab code, both using the matrix provided in the assignment text, and on an arbitrary matrix. For the

nprocs	Execution Time (Seconds)
1	25.67
2	12.95
4	6.47
8	3.41
16	1.97

timing of the code the dimension matrix dimension $N = 2400$ where used, yielding 25.67 seconds of execution time running the code on one processor. The rest of the execution times can be found in Fig. 1 and Table 1.
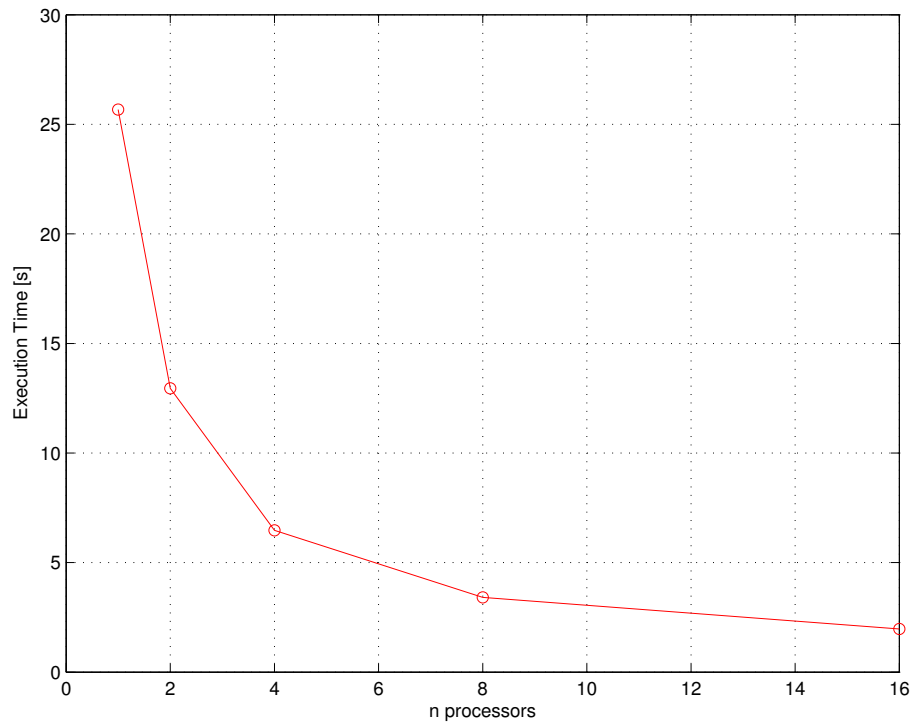
Figure 1: Plot of the execution times for the code running on 1 to 16 processors

As we can from Fig. 1 and Fig. 2 the parallelization of the code worked very well. On matrices with high dimensions the execution time where almost halved when the number of processors where doubled, for a small number of processors.

Tau Profiling Tool

The Tau Profiling tool where used to analyze the performance of the code both with a text based interface and with the graphical interface *paraprof*.
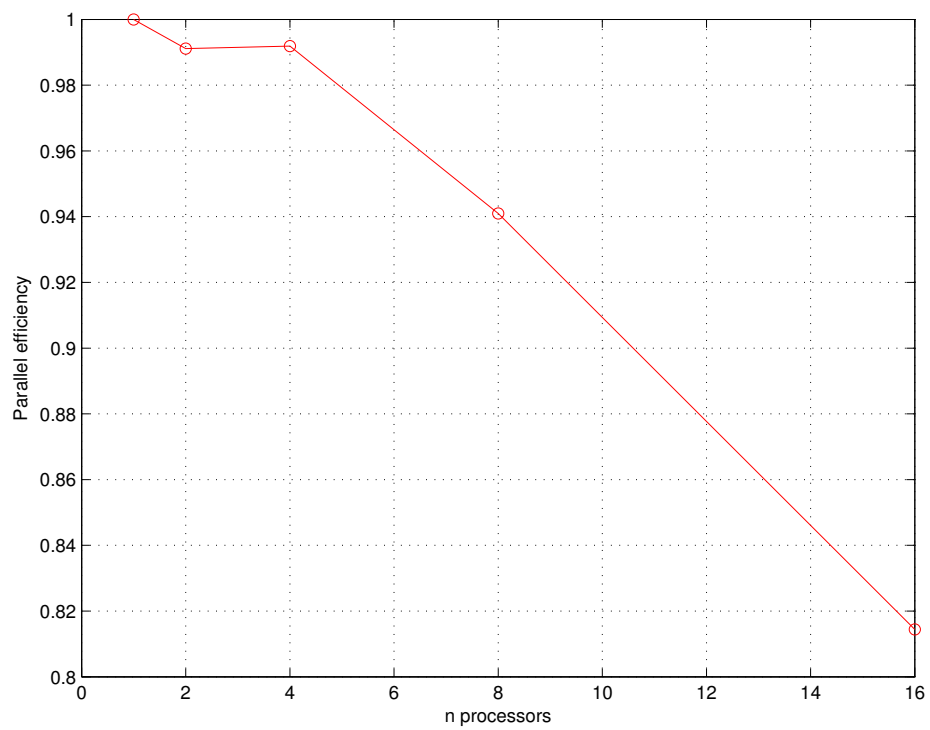
Figure 2: Plot of the parallel efficiency for the different numbers of processors

■ MPI_Bcast()
■ MPI_Comm_rank()
■ MPI_Comm_size()
■ MPI_Finalize()
■ MPI_Gather()
■ MPI_Init()
■ double norm2(double *, int) C [{functions.c} {15,1}–{22,1}]
■ double powerMethod(double *, double *, int, int) C [{functions.c} {81,1}–{101,1}]
■ int main(int, char **) C [{powermethod.c} {13,1}–{76,1}]
■ void generatematrix(double *, int) C [{functions.c} {51,1}–{68,1}]
■ void generatevec(double *, int) C [{functions.c} {72,1}–{78,1}]
■ void matVec(double *, double *, double *, int) C [{functions.c} {25,1}–{48,1}]

(a)
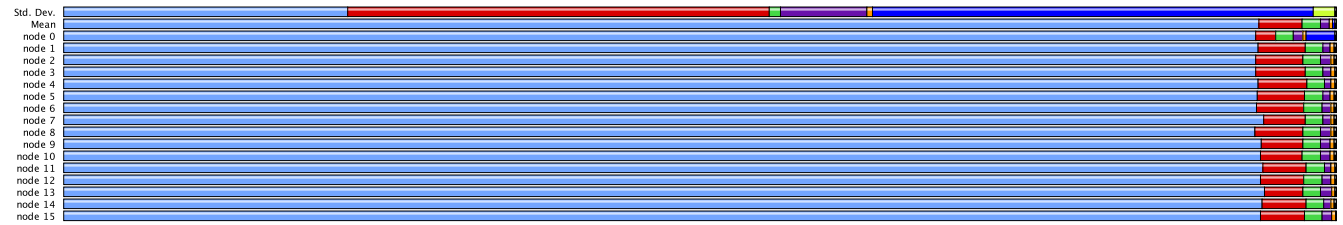
(b)

Figure 3: The figure shows the execution time for the different MPI functions running on the different processors

(a)

(b)

Figure 4: The figure shows the execution time for all the functions on the different processors

A.1 pprof output

4 Processors

```
Reading Profile files in profile.*

NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            2        1,115           1           7   1115667 int main(int, char **) C
 92.1        1,027        1,027           1           0   1027312 MPI_Init()
  6.4        0.249           71           1          23     71167 double powerMethod(double *, double *, int, int) C
  6.4           68           70          10          40      7088 void matVec(double *, double *, double *, int) C
  1.1           12           12           1           2     12621 void generatematrix(double *, int) C
  0.2            2            2           1           0      2505 MPI_Finalize()
  0.1            1            1          10           0       145 MPI_Gather()
  0.1         0.61         0.61          10           0        61 MPI_Bcast()
  0.0        0.041        0.041          11           0         4 double norm2(double *, int) C
  0.0        0.009        0.009          13           0         1 MPI_Comm_size()
  0.0        0.004        0.004          13           0         0 MPI_Comm_rank()
  0.0        0.004        0.004           1           0         4 void generatevec(double *, int) C
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 0, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
        10       5000       5000       5000          0  Message size for gather
---------------------------------------------------------------------------------

NODE 1;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            1        1,115           1           7   1115490 int main(int, char **) C
 92.1        1,027        1,027           1           0   1027362 MPI_Init()
  6.3         0.25           70           1          23     70733 double powerMethod(double *, double *, int, int) C
  6.3           68           70          10          40      7045 void matVec(double *, double *, double *, int) C
  1.2           13           13           1           2     13063 void generatematrix(double *, int) C
  0.2            2            2           1           0      2332 MPI_Finalize()
  0.1            1            1          10           0       128 MPI_Bcast()
  0.0        0.408        0.408          10           0        41 MPI_Gather()
  0.0        0.036        0.036          11           0         3 double norm2(double *, int) C
  0.0        0.008        0.008          13           0         1 MPI_Comm_size()
  0.0        0.004        0.004           1           0         4 void generatevec(double *, int) C
  0.0            0            0          13           0         0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 1, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 2;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            1        1,115           1           7   1115586 int main(int, char **) C
 92.1        1,027        1,027           1           0   1027346 MPI_Init()
  6.3         0.25           70           1          23     70504 double powerMethod(double *, double *, int, int) C
  6.3           69           70          10          40      7022 void matVec(double *, double *, double *, int) C
  1.2           13           13           1           2     13232 void generatematrix(double *, int) C
  0.2            2            2           1           0      2688 MPI_Finalize()
  0.1        0.868        0.868          10           0        87 MPI_Bcast()
  0.0        0.309        0.309          10           0        31 MPI_Gather()
  0.0        0.037        0.037          11           0         3 double norm2(double *, int) C
  0.0        0.007        0.007          13           0         1 MPI_Comm_size()
  0.0        0.004        0.004           1           0         4 void generatevec(double *, int) C
  0.0        0.001        0.001          13           0         0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 2, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------
```
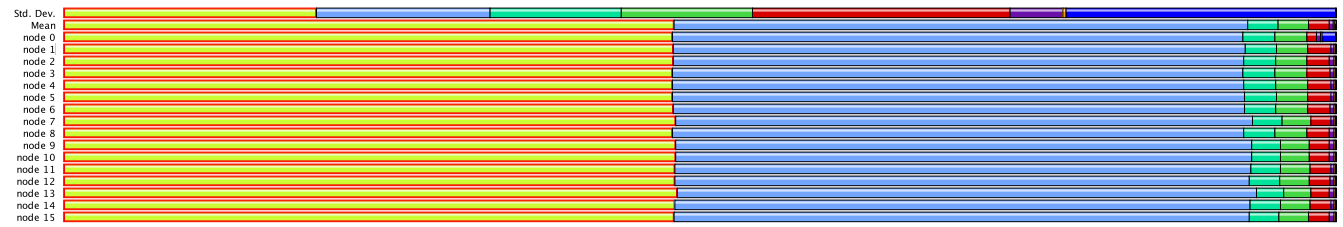
```
NODE 3;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive     #Call    #Subrs  Inclusive Name
             msec    total msec                      usec/call
---------------------------------------------------------------------------------
100.0           1        1,115          1         7  1115479 int main(int, char **) C
 92.1       1,027        1,027          1         0  1027346 MPI_Init()
  6.3       0.245           70          1        23    70319 double powerMethod(double *, double *, int, int) C
  6.3          69           70         10        40     7003 void matVec(double *, double *, double *, int) C
  1.2          13           13          1         2    13481 void generatematrix(double *, int) C
  0.2           2            2          1         0     2545 MPI_Finalize()
  0.1       0.648        0.648         10         0       65 MPI_Bcast()
  0.0       0.337        0.337         10         0       34 MPI_Gather()
  0.0       0.041        0.041         11         0        4 double norm2(double *, int) C
  0.0       0.008        0.008         13         0        1 MPI_Comm_size()
  0.0       0.005        0.005          1         0        5 void generatevec(double *, int) C
  0.0       0.003        0.003         13         0        0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 3, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

FUNCTION SUMMARY (total):
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive     #Call    #Subrs  Inclusive Name
             msec    total msec                      usec/call
---------------------------------------------------------------------------------
100.0           7        4,462          4        28  1115556 int main(int, char **) C
 92.1       4,109        4,109          4         0  1027342 MPI_Init()
  6.3       0.994          282          4        92    70681 double powerMethod(double *, double *, int, int) C
  6.3         275          281         40       160     7039 void matVec(double *, double *, double *, int) C
  1.2          52           52          4         8    13099 void generatematrix(double *, int) C
  0.2          10           10          4         0     2518 MPI_Finalize()
  0.1           3            3         40         0       85 MPI_Bcast()
  0.1           2            2         40         0       63 MPI_Gather()
  0.0       0.155        0.155         44         0        4 double norm2(double *, int) C
  0.0       0.032        0.032         52         0        1 MPI_Comm_size()
  0.0       0.017        0.017          4         0        4 void generatevec(double *, int) C
  0.0       0.008        0.008         52         0        0 MPI_Comm_rank()

FUNCTION SUMMARY (mean):
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive     #Call    #Subrs  Inclusive Name
             msec    total msec                      usec/call
---------------------------------------------------------------------------------
100.0           1        1,115          1         7  1115556 int main(int, char **) C
 92.1       1,027        1,027          1         0  1027342 MPI_Init()
  6.3       0.248           70          1        23    70681 double powerMethod(double *, double *, int, int) C
  6.3          68           70         10        40     7039 void matVec(double *, double *, double *, int) C
  1.2          13           13          1         2    13099 void generatematrix(double *, int) C
  0.2           2            2          1         0     2518 MPI_Finalize()
  0.1       0.853        0.853         10         0       85 MPI_Bcast()
  0.1       0.626        0.626         10         0       63 MPI_Gather()
  0.0      0.0387       0.0387         11         0        4 double norm2(double *, int) C
  0.0       0.008        0.008         13         0        1 MPI_Comm_size()
  0.0     0.00425      0.00425          1         0        4 void generatevec(double *, int) C
  0.0       0.002        0.002         13         0        0 MPI_Comm_rank()
```

16 Processors

```
Reading Profile files in profile.*

NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                           usec/call
---------------------------------------------------------------------------------------
100.0            1        1,109           1           7    1109381 int main(int, char **) C
 96.7        1,073        1,073           1           0    1073154 MPI_Init()
  2.1        0.257           23           1          23      23181 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40       2288 void matVec(double *, double *, double *, int) C
  0.7            8            8           1           0       8135 MPI_Finalize()
  0.3            3            3           1           2       3441 void generatematrix(double *, int) C
  0.2            2            2          10           0        261 MPI_Gather()
  0.2            2            2          10           0        243 MPI_Bcast()
  0.0        0.039        0.039          11           0          4 double norm2(double *, int) C
  0.0        0.012        0.012           1           0         12 void generatevec(double *, int) C
  0.0        0.005        0.005          13           0          0 MPI_Comm_size()
  0.0        0.003        0.003          13           0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------------

USER EVENTS Profile :NODE 0, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
        10       1248       1248       1248          0  Message size for gather
---------------------------------------------------------------------------------------

NODE 1;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                           usec/call
---------------------------------------------------------------------------------------
100.0            1        1,104           1           7    1104604 int main(int, char **) C
 97.1        1,072        1,072           1           0    1072019 MPI_Init()
  2.1        0.256           23           1          23      23029 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40       2273 void matVec(double *, double *, double *, int) C
  0.5            5            5          10           0        514 MPI_Bcast()
  0.4            4            4           1           0       4548 MPI_Finalize()
  0.3            3            3           1           2       3424 void generatematrix(double *, int) C
  0.0        0.161        0.161          10           0         16 MPI_Gather()
  0.0        0.039        0.039          11           0          4 double norm2(double *, int) C
  0.0        0.015        0.015           1           0         15 void generatevec(double *, int) C
  0.0        0.008        0.008          13           0          1 MPI_Comm_size()
  0.0        0.003        0.003          13           0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------------

USER EVENTS Profile :NODE 1, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------------

NODE 2;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                           usec/call
---------------------------------------------------------------------------------------
100.0            1        1,103           1           7    1103953 int main(int, char **) C
 97.0        1,071        1,071           1           0    1071366 MPI_Init()
  2.1        0.257           23           1          23      23030 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40       2273 void matVec(double *, double *, double *, int) C
  0.5            5            5          10           0        511 MPI_Bcast()
  0.4            4            4           1           0       4669 MPI_Finalize()
  0.3            3            3           1           2       3428 void generatematrix(double *, int) C
  0.0        0.146        0.146          10           0         15 MPI_Gather()
  0.0         0.04         0.04          11           0          4 double norm2(double *, int) C
  0.0        0.016        0.016           1           0         16 void generatevec(double *, int) C
  0.0        0.012        0.012          13           0          1 MPI_Comm_rank()
  0.0        0.006        0.006          13           0          0 MPI_Comm_size()
---------------------------------------------------------------------------------------

USER EVENTS Profile :NODE 2, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------------
```

```
NODE 3;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive    #Call    #Subrs  Inclusive Name
          msec      total msec                      usec/call
---------------------------------------------------------------------------------
100.0         1        1,103          1         7    1103833 int main(int, char **) C
 97.1     1,071        1,071          1         0    1071370 MPI_Init()
  2.1     0.259           23          1        23      23032 double powerMethod(double *, double *, int, int) C
  2.1        17           22         10        40       2273 void matVec(double *, double *, double *, int) C
  0.5         5            5         10         0        504 MPI_Bcast()
  0.4         4            4          1         0       4730 MPI_Finalize()
  0.3         3            3          1         2       3414 void generatematrix(double *, int) C
  0.0     0.118        0.118         10         0         12 MPI_Gather()
  0.0     0.038        0.038         11         0          3 double norm2(double *, int) C
  0.0     0.014        0.014          1         0         14 void generatevec(double *, int) C
  0.0     0.006        0.006         13         0          0 MPI_Comm_size()
  0.0     0.002        0.002         13         0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 3, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 4;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive    #Call    #Subrs  Inclusive Name
          msec      total msec                      usec/call
---------------------------------------------------------------------------------
100.0         1        1,103          1         7    1103954 int main(int, char **) C
 97.0     1,071        1,071          1         0    1071374 MPI_Init()
  2.1     0.247           23          1        23      23014 double powerMethod(double *, double *, int, int) C
  2.1        17           22         10        40       2273 void matVec(double *, double *, double *, int) C
  0.5         5            5         10         0        516 MPI_Bcast()
  0.4         4            4          1         0       4605 MPI_Finalize()
  0.3         3            3          1         2       3467 void generatematrix(double *, int) C
  0.0      0.11         0.11         10         0         11 MPI_Gather()
  0.0     0.038        0.038         11         0          3 double norm2(double *, int) C
  0.0     0.012        0.012          1         0         12 void generatevec(double *, int) C
  0.0     0.006        0.006         13         0          0 MPI_Comm_size()
  0.0     0.002        0.002         13         0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 4, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 5;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive    #Call    #Subrs  Inclusive Name
          msec      total msec                      usec/call
---------------------------------------------------------------------------------
100.0         1        1,103          1         7    1103057 int main(int, char **) C
 97.0     1,070        1,070          1         0    1070183 MPI_Init()
  2.1     0.253           22          1        23      22907 double powerMethod(double *, double *, int, int) C
  2.1        17           22         10        40       2262 void matVec(double *, double *, double *, int) C
  0.5         5            5          1         0       5036 MPI_Finalize()
  0.4         4            4         10         0        492 MPI_Bcast()
  0.3         3            3          1         2       3473 void generatematrix(double *, int) C
  0.0      0.11         0.11         10         0         11 MPI_Gather()
  0.0     0.038        0.038         11         0          3 double norm2(double *, int) C
  0.0     0.014        0.014          1         0         14 void generatevec(double *, int) C
  0.0     0.007        0.007         13         0          1 MPI_Comm_size()
  0.0     0.005        0.005         13         0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 5, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 6;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
```

```
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            1        1,101           1           7   1101804 int main(int, char **) C
 97.1        1,069        1,069           1           0   1069359 MPI_Init()
  2.1        0.247           22           1          23     22967 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40      2268 void matVec(double *, double *, double *, int) C
  0.5            4            4          10           0       500 MPI_Bcast()
  0.4            4            4           1           0      4449 MPI_Finalize()
  0.3            3            3           1           2      3501 void generatematrix(double *, int) C
  0.0        0.117        0.117          10           0        12 MPI_Gather()
  0.0         0.04         0.04          11           0         4 double norm2(double *, int) C
  0.0         0.02         0.02           1           0        20 void generatevec(double *, int) C
  0.0        0.006        0.006          13           0         0 MPI_Comm_size()
  0.0        0.005        0.005          13           0         0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 6, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 7;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            1        1,108           1           7   1108454 int main(int, char **) C
 96.5        1,069        1,069           1           0   1069599 MPI_Init()
  2.1         0.25           23           1          23     23130 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40      2284 void matVec(double *, double *, double *, int) C
  1.0           10           10           1           0     10871 MPI_Finalize()
  0.5            5            5          10           0       532 MPI_Bcast()
  0.3            3            3           1           2      3505 void generatematrix(double *, int) C
  0.0        0.086        0.086          10           0         9 MPI_Gather()
  0.0        0.035        0.035          11           0         3 double norm2(double *, int) C
  0.0        0.014        0.014           1           0        14 void generatevec(double *, int) C
  0.0        0.005        0.005          13           0         0 MPI_Comm_size()
  0.0        0.003        0.003          13           0         0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 7, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 8;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0            1        1,090           1           7   1090861 int main(int, char **) C
 97.0        1,057        1,057           1           0   1057941 MPI_Init()
  2.1        0.267           22           1          23     22966 double powerMethod(double *, double *, int, int) C
  2.1           17           22          10          40      2266 void matVec(double *, double *, double *, int) C
  0.5            4            4           1           0      4989 MPI_Finalize()
  0.4            4            4          10           0       459 MPI_Bcast()
  0.3            3            3           1           2      3524 void generatematrix(double *, int) C
  0.0        0.206        0.206          10           0        21 MPI_Gather()
  0.0        0.037        0.037          11           0         3 double norm2(double *, int) C
  0.0        0.014        0.014           1           0        14 void generatevec(double *, int) C
  0.0        0.005        0.005          13           0         0 MPI_Comm_size()
  0.0        0.003        0.003          13           0         0 MPI_Comm_rank()
---------------------------------------------------------------------------------

USER EVENTS Profile :NODE 8, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 9;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
```

```
--------------------------------------------------------------------------------
100.0            1        1,090            1            7    1090874 int main(int, char **) C
 97.0        1,057        1,057            1            0    1057936 MPI_Init()
  2.1        0.249           22            1           23      22947 double powerMethod(double *, double *, int, int) C
  2.1           17           22           10           40       2266 void matVec(double *, double *, double *, int) C
  0.5            4            4            1            0       4969 MPI_Finalize()
  0.5            4            4           10            0        491 MPI_Bcast()
  0.3            3            3            1            2       3513 void generatematrix(double *, int) C
  0.0        0.322        0.322           10            0         32 MPI_Gather()
  0.0        0.037        0.037           11            0          3 double norm2(double *, int) C
  0.0        0.013        0.013            1            0         13 void generatevec(double *, int) C
  0.0        0.004        0.004           13            0          0 MPI_Comm_rank()
  0.0        0.003        0.003           13            0          0 MPI_Comm_size()
--------------------------------------------------------------------------------

USER EVENTS Profile :NODE 9, CONTEXT 0, THREAD 0
--------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
--------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
--------------------------------------------------------------------------------

NODE 10;CONTEXT 0;THREAD 0:
--------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
--------------------------------------------------------------------------------
100.0            1        1,090            1            7    1090315 int main(int, char **) C
 97.0        1,057        1,057            1            0    1057399 MPI_Init()
  2.1        0.247           22            1           23      22901 double powerMethod(double *, double *, int, int) C
  2.1           17           22           10           40       2261 void matVec(double *, double *, double *, int) C
  0.5            5            5            1            0       5052 MPI_Finalize()
  0.5            4            4           10            0        491 MPI_Bcast()
  0.3            3            3            1            2       3573 void generatematrix(double *, int) C
  0.0        0.255        0.255           10            0         26 MPI_Gather()
  0.0        0.039        0.039           11            0          4 double norm2(double *, int) C
  0.0        0.009        0.009            1            0          9 void generatevec(double *, int) C
  0.0        0.005        0.005           13            0          0 MPI_Comm_size()
  0.0        0.004        0.004           13            0          0 MPI_Comm_rank()
--------------------------------------------------------------------------------

USER EVENTS Profile :NODE 10, CONTEXT 0, THREAD 0
--------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
--------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
--------------------------------------------------------------------------------

NODE 11;CONTEXT 0;THREAD 0:
--------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
--------------------------------------------------------------------------------
100.0            1        1,096            1            7    1096643 int main(int, char **) C
 96.4        1,057        1,057            1            0    1057706 MPI_Init()
  2.1        0.255           22            1           23      22931 double powerMethod(double *, double *, int, int) C
  2.1           17           22           10           40       2264 void matVec(double *, double *, double *, int) C
  1.0           11           11            1            0      11130 MPI_Finalize()
  0.4            4            4           10            0        482 MPI_Bcast()
  0.3            3            3            1            2       3528 void generatematrix(double *, int) C
  0.0        0.244        0.244           10            0         24 MPI_Gather()
  0.0        0.037        0.037           11            0          3 double norm2(double *, int) C
  0.0        0.012        0.012            1            0         12 void generatevec(double *, int) C
  0.0        0.004        0.004           13            0          0 MPI_Comm_size()
  0.0        0.001        0.001           13            0          0 MPI_Comm_rank()
--------------------------------------------------------------------------------

USER EVENTS Profile :NODE 11, CONTEXT 0, THREAD 0
--------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
--------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
--------------------------------------------------------------------------------

NODE 12;CONTEXT 0;THREAD 0:
--------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
--------------------------------------------------------------------------------
100.0            1        1,090            1            7    1090713 int main(int, char **) C
```

```
 97.0         1,057          1,057          1            0     1057745 MPI_Init()
  2.1         0.251             22          1           23       22882 double powerMethod(double *, double *, int, int) C
  2.1            17             22         10           40        2259 void matVec(double *, double *, double *, int) C
  0.5             4              4          1            0        4909 MPI_Finalize()
  0.4             4              4         10            0         481 MPI_Bcast()
  0.3             3              3          1            2        3567 void generatematrix(double *, int) C
  0.0         0.236          0.236         10            0          24 MPI_Gather()
  0.0         0.036          0.036         11            0           3 double norm2(double *, int) C
  0.0         0.014          0.014          1            0          14 void generatevec(double *, int) C
  0.0         0.006          0.006         13            0           0 MPI_Comm_size()
  0.0         0.003          0.003         13            0           0 MPI_Comm_rank()
---------------------------------------------------------------------------------
USER EVENTS Profile :NODE 12, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 13;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
            msec    total msec                             usec/call
---------------------------------------------------------------------------------
100.0             1          1,089          1            7     1089178 int main(int, char **) C
 97.0         1,056          1,056          1            0     1056270 MPI_Init()
  2.1         0.247             22          1           23       22860 double powerMethod(double *, double *, int, int) C
  2.1            17             22         10           40        2257 void matVec(double *, double *, double *, int) C
  0.5             5              5          1            0        5299 MPI_Finalize()
  0.4             4              4         10            0         481 MPI_Bcast()
  0.3             3              3          1            2        3613 void generatematrix(double *, int) C
  0.0         0.181          0.181         10            0          18 MPI_Gather()
  0.0          0.04           0.04         11            0           4 double norm2(double *, int) C
  0.0         0.012          0.012          1            0          12 void generatevec(double *, int) C
  0.0         0.007          0.007         13            0           1 MPI_Comm_rank()
  0.0         0.003          0.003         13            0           0 MPI_Comm_size()
---------------------------------------------------------------------------------
USER EVENTS Profile :NODE 13, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 14;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
            msec    total msec                             usec/call
---------------------------------------------------------------------------------
100.0             1          1,089          1            7     1089593 int main(int, char **) C
 97.1         1,058          1,058          1            0     1058327 MPI_Init()
  1.9         0.253             21          1           23       21060 double powerMethod(double *, double *, int, int) C
  1.9            17             20         10           40        2077 void matVec(double *, double *, double *, int) C
  0.5             4              4          1            0        4975 MPI_Finalize()
  0.3             3              3          1            2        3768 void generatematrix(double *, int) C
  0.3             3              3         10            0         327 MPI_Bcast()
  0.0         0.212          0.212         10            0          21 MPI_Gather()
  0.0         0.036          0.036         11            0           3 double norm2(double *, int) C
  0.0         0.017          0.017          1            0          17 void generatevec(double *, int) C
  0.0         0.004          0.004         13            0           0 MPI_Comm_size()
  0.0         0.003          0.003         13            0           0 MPI_Comm_rank()
---------------------------------------------------------------------------------
USER EVENTS Profile :NODE 14, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------

NODE 15;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
            msec    total msec                             usec/call
---------------------------------------------------------------------------------
100.0             1          1,097          1            7     1097394 int main(int, char **) C
 96.4         1,057          1,057          1            0     1057727 MPI_Init()
  2.1         0.249             22          1           23       22822 double powerMethod(double *, double *, int, int) C
```

```
    2.1          17         22         10        40     2253 void matVec(double *, double *, double *, int) C
    1.1          11         11          1         0    11736 MPI_Finalize()
    0.4           4          4         10         0      493 MPI_Bcast()
    0.3           3          3          1         2     3662 void generatematrix(double *, int) C
    0.0       0.181      0.181         10         0       18 MPI_Gather()
    0.0       0.037      0.037         11         0        3 double norm2(double *, int) C
    0.0       0.019      0.019          1         0       19 void generatevec(double *, int) C
    0.0       0.006      0.006         13         0        0 MPI_Comm_rank()
    0.0       0.005      0.005         13         0        0 MPI_Comm_size()
---------------------------------------------------------------------------------
```

USER EVENTS Profile :NODE 15, CONTEXT 0, THREAD 0
```
---------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------
        10      2E+04      2E+04      2E+04          0  Message size for broadcast
         0          0          0          0          0  Message size for gather
---------------------------------------------------------------------------------
```

FUNCTION SUMMARY (total):
```
---------------------------------------------------------------------------------
%Time   Exclusive   Inclusive       #Call      #Subrs  Inclusive Name
            msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0          22      17,574          16         112    1098413 int main(int, char **) C
 96.9      17,029      17,029          16           0    1064342 MPI_Init()
  2.1           4         365          16         368      22854 double powerMethod(double *, double *, int, int) C
  2.1         280         360         160         640       2256 void matVec(double *, double *, double *, int) C
  0.6         100         100          16           0       6256 MPI_Finalize()
  0.4          75          75         160           0        470 MPI_Bcast()
  0.3          56          56          16          32       3525 void generatematrix(double *, int) C
  0.0           5           5         160           0         33 MPI_Gather()
  0.0       0.606       0.606         176           0          3 double norm2(double *, int) C
  0.0       0.227       0.227          16           0         14 void generatevec(double *, int) C
  0.0       0.084       0.084         208           0          0 MPI_Comm_size()
  0.0       0.066       0.066         208           0          0 MPI_Comm_rank()
```

FUNCTION SUMMARY (mean):
```
---------------------------------------------------------------------------------
%Time   Exclusive   Inclusive       #Call      #Subrs  Inclusive Name
            msec   total msec                          usec/call
---------------------------------------------------------------------------------
100.0           1       1,098           1           7    1098413 int main(int, char **) C
 96.9       1,064       1,064           1           0    1064342 MPI_Init()
  2.1       0.253          22           1          23      22854 double powerMethod(double *, double *, int, int) C
  2.1          17          22          10          40       2256 void matVec(double *, double *, double *, int) C
  0.6           6           6           1           0       6256 MPI_Finalize()
  0.4           4           4          10           0        470 MPI_Bcast()
  0.3           3           3           1           2       3525 void generatematrix(double *, int) C
  0.0       0.331       0.331          10           0         33 MPI_Gather()
  0.0      0.0379      0.0379          11           0          3 double norm2(double *, int) C
  0.0      0.0142      0.0142           1           0         14 void generatevec(double *, int) C
  0.0     0.00525     0.00525          13           0          0 MPI_Comm_size()
  0.0     0.00413     0.00413          13           0          0 MPI_Comm_rank()
```