Parallel MATLAB: Single Program Multiple Data

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.... NLI ....
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- **SPMD: Single Program, Multiple Data**
- QUAD Example
- Distributed Arrays
- LBVP & FEM_2D_HEAT Examples
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- Batch Computing
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SPMD: is not PARFOR

Lecture #2: PARFOR - 21 October

The **parfor** command, described in a last month's lecture, is easy to use, but it only lets us do parallelism in terms of loops. The only choice we make is whether a loop is to run in parallel.

- We can't determine how the loop iterations are divided up;
- we can't be sure which worker runs which iteration;
- workers cannot exchange data.

Using **parfor**, the individual workers are *anonymous*, and all the data are shared (or copied and returned).

SPMD: is Single Program, Multiple Data

Lecture #3: SPMD - today

The **SPMD** construct (today's lecture) is like a very simplified version of **MPI**. There is one client process, supervising workers who cooperate on a single program. Each worker (sometimes also called a "lab") has an identifier, knows how many total workers there are, and can determine its behavior based on that identifier.

- each worker runs on a separate core (ideally);
- each worker uses a separate workspace;
- a common program is used;
- workers meet at synchronization points;
- the client program can examine or modify data on any worker;
- any two workers can communicate directly via messages.

SPMD: Getting Workers

An **spmd** program needs workers to cooperate on the program.

So on a desktop, we issue an interactive **matlabpool** or **parpool** request:

```
pool_obj = parpool('local', 4 );
results = myfunc ( args );
```

or use **batch** to run in the background on your desktop:

```
job = batch ( 'myscript', 'Profile', 'local', ...
  'pool', 4 )
```

or send the **batch** command to the Ithaca cluster:

```
job = batch ( 'myscript', 'Profile', ...
  'ithaca_R2015a', 'pool', 7 )
```

SPMD: The SPMD Environment

MATLAB sets up one special agent called the client.

MATLAB sets up the requested number of workers, each with a copy of the program. Each worker "knows" it's a worker, and has access to two special functions:

- **numlabs()**, the number of workers;
- **labindex()**, a unique identifier between 1 and **numlabs()**.

The empty parentheses are usually dropped, but remember, these are functions, not variables!

If the client calls these functions, they both return the value 1! That's because when the client is running, the workers are not. The client could determine the number of workers available by

```
n = matlabpool ( 'size' )  or n = pool_obj.NumWorkers
```

SPMD: The SPMD Command

The client and the workers share a single program in which some commands are delimited within blocks opening with **spmd** and closing with **end**.

The client executes commands up to the first **spmd** block, when it pauses. The workers execute the code in the block. Once they finish, the client resumes execution.

The client and each worker have separate workspaces, but it is possible for them to communicate and trade information.

The value of variables defined in the “client program” can be referenced by the workers, but not changed.

Variables defined by the workers can be referenced or changed by the client, but a special syntax is used to do this.

SPMD: How SPMD Workspaces Are Handled

```
                  Client        Worker 1     Worker 2
                  a  b  e   |   c  d  f  |   c  d  f
                  ---------------------------------
a = 3;            3  -  -   |   -  -  -  |   -  -  -
b = 4;            3  4  -   |   -  -  -  |   -  -  -
spmd                        |            |
  c = labindex(); 3  4  -   |   1  -  -  |   2  -  -
  d = c + a;      3  4  -   |   1  4  -  |   2  5  -
end                         |            |
e = a + d{1};     3  4  7   |   1  4  -  |   2  5  -
c{2} = 5;         3  4  7   |   1  4  -  |   5  6  -
spmd                        |            |
  f = c * b;      3  4  7   |   1  4  4  |   5  6 20
end
```

SPMD: When is Workspace Preserved?

A program can contain several **spmd** blocks. When execution of one block is completed, the workers pause, but they do not disappear and their workspace remains intact. A variable set in one **spmd** block will still have that value if another **spmd** block is encountered. Unless the *client* has changed it, as in our example. You can imagine the client and workers simply alternate execution. In MATLAB, variables defined in a function 'disappear' once the function is exited. The same thing is true, in the same way, for a MATLAB program that calls a function containing **spmd** blocks. While inside the function, worker data is preserved from one block to another, but when the function is completed, the worker data defined there disappears, just as the regular MATLAB data does. It's not legal to nest an **smpd** block within another **spmd** block or within a **parfor** loop. Some additional limitations are discussed at

http://www.mathworks.com/help/distcomp/programming-tips_brukbnp-9.html?searchHighlight=nested+spmd

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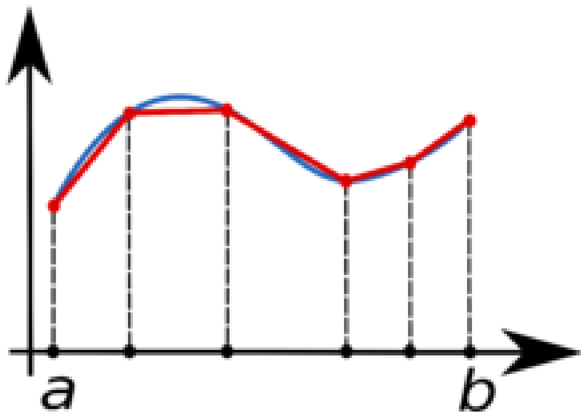
QUAD: The Trapezoid Rule



Area of one trapezoid = average height * base.

QUAD: The Trapezoid Rule

To estimate the area under a curve using one trapezoid, we write

$$\int_a^b f(x)\,dx \approx (\frac{1}{2}f(a) + \frac{1}{2}f(b)) * (b - a)$$

We can improve this estimate by using $n - 1$ trapezoids defined by equally spaced points x_1 through x_n:

$$\int_a^b f(x)\,dx \approx (\frac{1}{2}f(x_1) + f(x_2) + ... + f(x_{n-1}) + \frac{1}{2}f(x_n)) * \frac{b - a}{n - 1}$$

If we have several workers available, then each one can get a part of the interval to work on, and compute a trapezoid estimate there. By adding the estimates, we get an approximation to the integral of the function over the whole interval.

QUAD: Use the ID to assign work

To simplify things, we'll assume our original interval is [0,1], and we'll let each worker define a and b to mean the ends of its subinterval. If we have 4 workers, then worker number 3 will be assigned $[\frac{1}{2}, \frac{3}{4}]$.

To start our program, each worker figures out its interval:

```
fprintf ( 1, '  Set up the integration limits:\n' );

spmd
  a = ( labindex() - 1 ) / numlabs();
  b =   labindex()       / numlabs();
end
```

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QUAD: One Name Must Reference Several Values

Each worker has its own workspace. It can "see" the variables on the client, but it usually doesn't know or care what is going on on the other workers.

Each worker defines **a** and **b** but stores *different values* there.

The client can "see" the workspace of all the workers. Since there are multiple values using the same name, the client must specify the index of the worker whose value it is interested in. Thus **a**{**1**} is how the client refers to the variable **a** on worker 1. The client can read or write this value.

MATLAB's name for this kind of variable, indexed using curly brackets, is a composite variable. The syntax is similar to a cell array.

Each worker can "see" the client's variables and inherits a copy of their values, but cannot change the client's data.

QUAD: Dealing with Composite Variables

So in QUAD, each worker could print **a** and **b**:

```
spmd
  a = ( labindex() - 1 ) / numlabs();
  b =   labindex()       / numlabs();
  fprintf ( 1, '  A = %f, B = %f\n', a, b );
end
```

—————— or the client could print them all ——————

```
spmd
  a = ( labindex() - 1 ) / numlabs();
  b =   labindex()        / numlabs();
end
for i = 1 : 4   <-- "numlabs" wouldn't work here!
  fprintf ( 1, '  A = %f, B = %f\n', a{i}, b{i} );
end
```

QUAD: The Solution in 4 Parts

Each worker can now carry out its trapezoid computation:

```
spmd
  x = linspace ( a, b, n );
  fx = f ( x );     (Assume f can handle vector input.)
  quad_part = ( b - a ) / ( n - 1 ) *
    * ( 0.5 * fx(1) + sum(fx(2:n-1)) + 0.5 * fx(n) );
  fprintf ( 1, '  Partial approx %f\n', quad_part );
end
```

with result:

```
2    Partial approx 0.874676
4    Partial approx 0.567588
1    Partial approx 0.979915
3    Partial approx 0.719414
```

QUAD: Combining Partial Results

We really want one answer, the sum of all these approximations.

One way to do this is to gather the answers back on the client, and sum them:

```
quad = sum ( quad_part{1:4} );
fprintf ( 1, '  Approximation %f\n', quad );
```

with result:

```
Approximation 3.14159265
```

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QUAD: Source Code for QUAD_FUN

```
function value = quad_fun ( n )

%*****************************************************************************80
%
%% QUAD_FUN demonstrates MATLAB's SPMD command for parallel programming.
%
%  Discussion:
%
%    A block of statements that begin with the SPMD command are carried
%    out in parallel over all the LAB's.  Each LAB has a unique value
%    of LABINDEX, between 1 and NUMLABS.
%
%    Values computed by each LAB are stored in a composite variable.
%    The client copy of MATLAB can access these values by using an index.
%
%  Licensing:
%
%    This code is distributed under the GNU LGPL license.
%
%  Modified:
%
%    18 August 2009
%
%  Author:
%
%    John Burkardt
%
%  Parameters:
%
%    Input, integer N, the number of points to use in each subinterval.
%
%    Output, real VALUE, the estimate for the integral.
%
```

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QUAD: Source Code for QUAD_FUN (cont'd)

```
  fprintf ( 1, '\n' );
  fprintf ( 1, 'QUAD_FUN\n' );
  fprintf ( 1, '  Demonstrate the use of MATLAB''s SPMD command\n' );
  fprintf ( 1, '  to carry out a parallel computation.\n' );
%
%  The entire integral goes from 0 to 1.
%  Each LAB, from 1 to NUMLABS, computes its subinterval [A,B].
%
  fprintf ( 1, '\n' );

  spmd
    a = ( labindex - 1 ) / numlabs;
    b =   labindex       / numlabs;
    fprintf ( 1, '  Lab %d works on [%f,%f].\n', labindex, a, b );
  end
%
%  Each LAB now estimates the integral, using N points.
%
  fprintf ( 1, '\n' );

  spmd
    if ( n == 1 )
      quad_local = ( b - a ) * f ( ( a + b ) / 2 );
    else
      x = linspace ( a, b, n );
      fx = f ( x );
      quad_local = ( b - a ) * ( fx(1) + 2 * sum ( fx(2:n-1) ) + fx(n) ) ...
        / (2.0 * ( n - 1 ));
    end
    fprintf ( 1, '  Lab %d computed approximation %f\n', labindex, quad_local );
  end
```

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QUAD: Source Code for QUAD_FUN (cont'd)

```
%
%  The variable quad_local has been computed by each LAB.
%  Variables computed inside an SPMD statement are stored as "composite"
%  variables, similar to MATLAB's cell arrays.  Outside of an SPMD
%  statement, composite variable values are accessible to the
%  client copy of MATLAB by index.
%
%  The GPLUS function adds the individual values, returning
%  the sum to each LAB - so QUAD is also a composite value,
%  but all its values are equal.
%
  spmd
    quad = gplus ( quad_local ); % Note use of a gop
  end
%
%  Outside of an SPMD statement, the client copy of MATLAB can
%  access any entry in a composite variable by indexing it.
%
  value = quad{1};

  fprintf ( 1, '\n' );
  fprintf ( 1, '  Result of quadrature calculation:\n' );
  fprintf ( 1, '  Estimate QUAD = %24.16f\n', value );
  fprintf ( 1, '  Exact value   = %24.16f\n', pi );
  fprintf ( 1, '  Error          = %e\n', abs ( value - pi ) );
  fprintf ( 1, '\n' );
  fprintf ( 1, 'QUAD_FUN\n' );
  fprintf ( 1, '  Normal end of execution.\n' );

  return
end
```

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DISTRIBUTED: The Client Can Distribute

If the client process has a 300x400 array called **a**, and there are 4 SPMD workers, then the simple command

```
ad = distributed ( a );
```

distributes the elements of **a** by columns:

```
      Worker 1   Worker 2   Worker 3   Worker 4
Col:     1:100 | 101:200 | 201:300 | 301:400 ]
Row
  1 [ a b c d | e f g h | i j k l | m n o p ]
  2 [ A B C D | E F G H | I J K L | M N O P ]
... [ * * * * | * * * * | * * * * | * * * * ]
300 [ 1 2 3 4 | 5 6 7 8 | 9 0 1 2 | 3 4 5 6 ]
```

By default, the last dimension is used for distribution.

DISTRIBUTED: Workers Can Get Their Part

Once the client has distributed the matrix by the command

```
ad = distributed ( a );
```

then each worker can make a local variable containing its part:

```
spmd
  al = getLocalPart ( ad );
  [ ml, nl ] = size ( al );
end
```

On worker 3, [ml, nl] = (300, 100), and **al** is

```
[ i j k l ]
[ I J K L ]
[ * * * * ]
[ 9 0 1 2 ]
```

Notice that local and global column indices will differ!

DISTRIBUTED: The Client Can Collect Results

The client can access any worker's local part by using curly brackets. Thus it could copy what's on worker 3 by

```
worker3_array = al{3};
```

However, it's likely that the client simply wants to collect all the parts and put them back into one normal MATLAB array. If the local arrays are simply column-sections of a 2D array:

```
a2 = [ al{:} ]
```

Suppose we had a 3D array whose third dimension was 3, and we had distributed it as 3 2D arrays. To collect it back:

```
a2 = al{1};
a2(:,:,2) = al{2};
a2(:,:,3) = al{3};
```

DISTRIBUTED: Methods to Gather Data

Instead of having an array created on the client and distributed to the workers, it is possible to have a distributed array constructed by having each worker build its piece. The result is still a distributed array, but when building it, we say we are building a **codistributed** array.

Codistributing the creation of an array has several advantages:

1. The array might be too large to build entirely on one core (or processor);
2. The array is built faster in parallel;
3. You avoid the communication cost of distributing it.

DISTRIBUTED: Accessing Distributed Arrays

The command **al = getLocalPart (ad)** makes a local copy of the part of the distributed array residing on each worker. Although the workers could reference the distributed array directly, the local part has some uses:

- references to a local array are faster;
- the worker may only need to operate on the local part; then it's easier to write **al** than to specify **ad** indexed by the appropriate subranges.

The client can copy a distributed array into a "normal" array stored entirely in its memory space by the command

```
a = gather ( ad );
```

or the client can access and concatenate local parts.

DISTRIBUTED: Conjugate Gradient Setup

Because many MATLAB operators and functions can automatically detect and deal with distributed data, it is possible to write programs that carry out sophisticated algorithms in which the computation never explicitly worries about where the data is!

The only tricky part is distributing the data initially, or gathering the results at the end.

Let us look at a conjugate gradient code which has been modified to deal with distributed data.

Before this code is executed, we assume the user has requested some number of workers, using the interactive **matlabpool** or indirect **batch** command.

DISTRIBUTED: Conjugate Gradient Setup

```
% Script to invoke conjugate gradient solution
% for sparse distributed (or not) array
%

    N       = 1000;
    nnz     = 5000;
    rc      = 1/10;    % reciprocal condition number

    A = sprandsym(N, nnz/N^2, rc, 1); % symmetric, positive definite
    A = distributed(A);%A = distributed.sprandsym() is not available

    b = sum(A, 2);
%   fprintf( 1, '\n isdistributed(b): %2i  \n', isdistributed(b) );

    [x, e_norm ] = cg_emc( A, b);

    fprintf( 1, 'Error residual :    %8.4e \n', e_norm{1});

    np = 10;
    fprintf( 1, 'First few x values: \n');
    fprintf( 1, ' x( %02i )  = %8.4e \n', [ 1:np ; gather(x(1:np))']);
```

`sprandsym` sets up a sparse random symmetric array **A**.

`distributed` 'casts' **A** to a distributed array on the workers.

Why do we write `e_norm{1}` & `gather(x)` ?

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DISTRIBUTED: Conjugate Gradient Iteration

```
function [x, resnrm ] = cg_emc( A, b, x0, tol, itmax)
% Conjugate gradient iteration for A x = b,
% (from Gill, Murray and Wright, p 147)

% Possibly supply missing input parameters (omitted)
  spmd
% initialization
     p     = codistributed.zeros(size(x0));
     beta  = 0;
     r     = A*x0 - b;
     rknrm= r'*r;
     x     = x0;
     iter  = 0;
%   CG loop
     while 1
         p      = beta*p - r;
         tmp    = A*p;
         alpha  = rknrm/(p'*tmp);
         x      = x + alpha*p;
         r      = r + alpha*tmp;
         rkpnrm= r'*r;
         beta   = rkpnrm/rknrm;
         rknrm  = rkpnrm;
         iter   = iter + 1;
         resnrm= norm(A*x - b);
         if iter >= itmax || resnrm <= tol
             break
         end
     end % while 1
  end % spmd

end % function
```

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DISTRIBUTED: Comment

In `cg_emc.m`, we can remove the `spmd` block and simply invoke **distributed()**; the operational commands don't change.

There are several comments worth making:

- The communication overhead can be severely increased
- Not all MATLAB operators have been extended to work with distributed memory. In particular, (the last time we asked), the backslash or "linear solve" operator **x=A\b** can't be used yet for sparse distributed arrays.
- Getting "real" data (as opposed to matrices full of random numbers) properly distributed across multiple processors involves more choices and more thought than is suggested by the `conjugate gradient` example !

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DISTRIBUTED: Linear Boundary Value Problem

In the next example, we demonstrate a mixed approach wherein the `stiffness matrix` (**K**) is initially constructed as a **codistributed** array on the workers. Each worker then modifies its `localPart`, and also assembles the local contribution to the forcing term (**F**). The *local* forcing arrays are then used to build a **codistributed** array.

DISTRIBUTED: FD_LBVP_script

```
%% FD_LBVP_SCRIPT invokes the function fd_lbvp_fun
%
%  Licensing:
%
%    This code is distributed under the GNU LGPL license.
%
%  Author:
%
%%     Gene Cliff

       n = 100;                % grid parameter

% Define coefficient functions and boundary data for LBVP
       hndl_p = @(x)  0;
       c_q    = 4;             % positive for exact solution match
       hndl_q = @(x)  c_q;
       c_r    = -4;
       hndl_r = @(x) c_r*x; % linear for exact solution match

       alpha = 0;
       beta  = 2;

%  Invoke solver
       fprintf( 1, '\n Invoke fd_lbvp_fun \n');
       T  = fd_lbvp_fun(n, hndl_p, hndl_q, hndl_r, alpha, beta);

% gather the distributed solution on the client process

       Tg = gather(T); % When 'batch' finishes the 'pool' is closed
                       % and distributed data is lost
```

DISTRIBUTED: FD_LBVP code

```
function T =  fd_lbvp_fun(n, hndl_p, hndl_q, hndl_r, alpha, beta)
% Finite-difference approximation to the BVP
%  T''(x) =  p(x) T'(x) + q(x) T(x) + r(x),      0 \le x \le 1
%  with   T(0) = alpha,  T(1) = beta

%  Modified:
%
%    2 March 2012
%
%  Author:
%
%    Gene Cliff

% We use a uniform grid with n interior grid points
% From Numerical Analysis, Burden & Faires, 2001, \S~11.3

  h = 1/(n+1); ho2 = h/2; h2 = h*h;
  spmd
     A    = codistributed.zeros(n,n);
     locP = getLocalPart(codistributed.colon(1, n)); %index vals on lab
     locP = locP(:);% make it a column array

% Loop over columns entering unity above/below the diagonal entry
% along with 2 plus the appropriate q function values
% Note that columns 1 and n are exceptions
     for jj=locP(1):locP(end)
         % on the diagonal
         A(jj, jj) =    2 + h2*feval(hndl_q, jj*h);
         % above the diagonal
        if jj ~= 1;  A(jj-1, jj) = -1+ho2*feval(hndl_p, (jj-1)*h); end
        % below the diagonal
        if jj ~= n;  A(jj+1, jj) = -1+ho2*feval(hndl_p,   jj  *h); end
     end
```

DISTRIBUTED: FD_LBVP code (cont'd)

```
    locF   = -h2*feval(hndl_r, locP*h); % hndl_r okay for vector input

    if labindex() == 1
        locF( 1 ) = locF( 1 ) + alpha*(1+ho2*feval(hndl_p,  h ));
    end
    if labindex() == numlabs();
        locF(end) = locF(end) +  beta*(1-ho2*feval(hndl_p, 1-h));
    end

%   codist = codistributor1d(dim,        partition,          global_size);
    codist = codistributor1d(1,  codistributor1d.unsetPartition, [n, 1]);
    F      = codistributed.build(locF, codist); % distribute the array(s)
  end % spmd block

   T = A\F;   % mldivide is defined for codistributed arrays
```

DISTRIBUTED: 2D Finite Element Heat Model

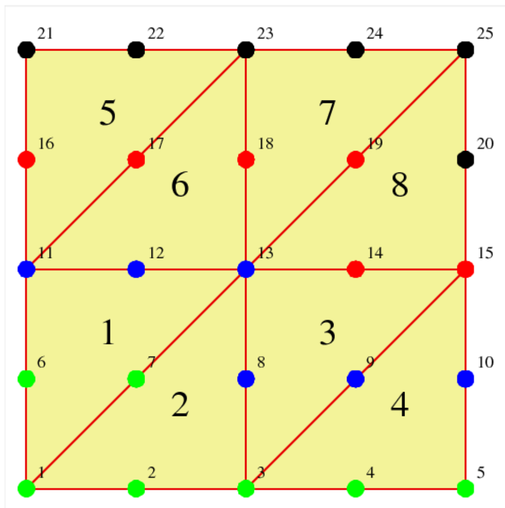
Next, we consider an example that combines SPMD and distributed data to solve a steady state heat equations in 2D, using the finite element method. Here we demonstrate a different strategy for assembling the required arrays.

Each worker is assigned a subset of the finite element nodes. That worker is then responsible for constructing the columns of the (sparse) finite element matrix associated with those nodes.

Although the matrix is assembled in a distributed fashion, it has to be gathered back into a standard array before the linear system can be solved, because sparse linear systems can't be solved as a distributed array (yet).

This example is available as in the **fem_2D_heat** folder.

DISTRIBUTED: The Grid & Node Coloring for 4 labs



DISTRIBUTED: Finite Element System matrix

The discretized heat equation results in a linear system of the form

$$K\,z = F + b$$

where **K** is the stiffness matrix, **z** is the unknown finite element coefficients, **F** contains source terms and **b** accounts for boundary conditions.

In the parallel implementation, the system matrix **K** and the vectors **F** and **b** are distributed arrays. The default distribution of **K** by columns essentially associates each SPMD worker with a group of finite element nodes.

DISTRIBUTED: Finite Element System Matrix

To assemble the matrix, each worker loops over all elements. If element E contains *any* node associated with the worker, the worker computes the entire local stiffness matrix K. Columns of K associated with worker nodes are added to the local part of $\mathbf{K}$. The rest are discarded (which is OK, because they will also be computed and saved by the worker responsible for those nodes).

When element 5 is handled, the "blue", "red" and "black" processors each compute K. But blue only updates column 11 of $\mathbf{K}$, red columns 16 and 17, and black columns 21, 22, and 23.

At the cost of some redundant computation, we avoid a lot of communication.

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Assemble Codistributed Arrays - code fragment

```
spmd
%
%  Set up codistributed structure
%
%  Column pointers and such for codistributed arrays.
%
    Vc   = codistributed.colon(1, n_equations);
    lP   = getLocalPart(Vc);
    lP_1= lP(1); lP_end = lP(end); %first and last columns of K on this lab
    co_dist_Vc = getCodistributor(Vc); dPM = co_dist_Vc.Partition;
  ...
% sparse arrays on each lab
%
    K_lab = sparse(n_equations, dPM(labindex));
  ...
%  Build the finite element matrices - Begin loop over elements
%
    for n_el=1:n_elements
      nodes_local     = e_conn(n_el,:);% which nodes are in this element
    % subset of nodes/columns on this lab
      lab_nodes_local = extract( nodes_local, lP_1, lP_end);
  ... if empty do nothing, else accumulate K_lab, etc end
    end  % n_el
%
% Assemble the 'lab' parts in a codistributed format.
%  syntax for version R2009b
    codist_matrix = codistributor1d( 2, dPM, [n_equations, n_equations]);
    K = codistributed.build(K_lab, codist_matrix );

end % spmd
```

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DISTRIBUTED: 2D Heat Equation - The Results

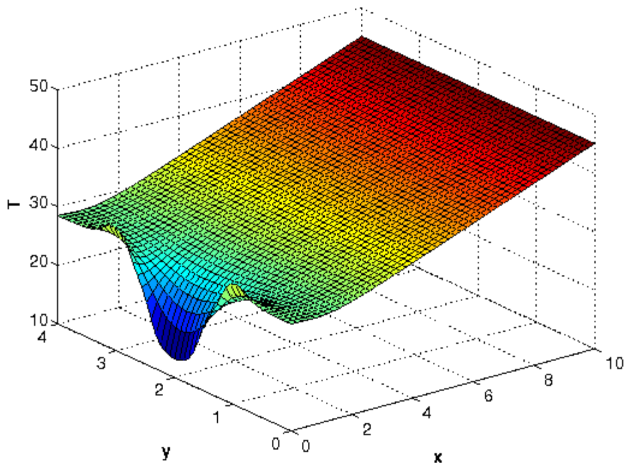

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IMAGE: Image Processing in Parallel

Here is a mysterious SPMD program to be run with 3 workers:

```
x = imread ('balloons.tif');

y = imnoise ( x, 'salt & pepper', 0.30 );

yd = distributed ( y );

spmd
  yl = getLocalPart ( yd );
  yl = medfilt2 ( yl, [ 3, 3 ] );
end

z(1:480,1:640,1) = yl{1};
z(1:480,1:640,2) = yl{2};
z(1:480,1:640,3) = yl{3};

figure;
subplot ( 1, 3, 1 );imshow ( x );title ( 'X' );
subplot ( 1, 3, 2 );imshow ( y );title ( 'Y' );
subplot ( 1, 3, 3 );imshow ( z );title ( 'Z' );
```

Without comments, what can you guess about this program?

IMAGE: Image → Noisy Image → Filtered Image

Original image

Noisy Image

Median Filtered Image

This filtering operation uses a 3x3 pixel neighborhood.
We could blend *all* the noise away with a larger neighborhood.

IMAGE: Image → Noisy Image → Filtered Image

```
%  Read a color image, stored as 480x640x3 array.
%
  x = imread ('balloons.tif');
%
%  Create an image Y by adding "salt and pepper" noise to X.
%
  y = imnoise ( x, 'salt & pepper', 0.30 );
%
%  Make YD, a distributed version of Y.
%
  yd = distributed ( y );
%
%  Each worker works on its "local part", YL.
%
  spmd
    yl = getLocalPart ( yd );
    yl = medfilt2 ( yl, [ 3, 3 ] );
  end
%
%  The client retrieves the data from each worker.
%
  z(1:480,1:640,1) = yl{1};
  z(1:480,1:640,2) = yl{2};
  z(1:480,1:640,3) = yl{3};
%
%  Display the original, noisy, and filtered versions.
%
  figure;
  subplot ( 1, 3, 1 ); imshow ( x ); title ( 'Original image' );
  subplot ( 1, 3, 2 ); imshow ( y ); title ( 'Noisy Image' );
  subplot ( 1, 3, 3 ); imshow ( z ); title ( 'Median Filtered Image' );
```

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CONTRAST: Image → Contrast Enhancement → Image2

```
%
% Get 4 SPMD workers
%
  matlabpool open 4
%
% Read an image
%
  x = imageread( 'surfsup.tif' );
%
% Since the image is black and white, it will be distributed by columns
%
  xd = distributed(x);
%
%  Each worker enhances the contrast on its portion of the picture
%
  spmd
      xl = getLocalPart(xd);
      xl = nlfilter( xl, [3, 3], @contrast_enhance);
      xl = uint8(xl);
  end
%
% Concatenate the submatrices to assemble the whole image
%
  xf_spmd = [ xl{:} ];

  matlabpool close
```

CONTRAST: Image → Contrast Enhancement → Image2

When a filtering operation is done on the client, we get picture 2. The same operation, divided among 4 workers, gives us picture 3. What went wrong?

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CONTRAST: Image → Contrast Enhancement → Image2

Each pixel has had its contrast enhanced. That is, we compute the average over a 3x3 neighborhood, and then increase the difference between the center pixel and this average. Doing this for each pixel sharpens the contrast.

```
+-----+-----+-----+
| P11 | P12 | P13 |
+-----+-----+-----+
| P21 | P22 | P23 |
+-----+-----+-----+
| P31 | P32 | P33 |
+-----+-----+-----+

P22 <- C * P22 + ( 1 - C ) * Average
with   C > 1 (specified)
```

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CONTRAST: Image → Contrast Enhancement → Image2

When the image is divided by columns among the workers, artificial internal boundaries are created. The **nlfilter** algorithm turns any pixel lying along the boundary to white. (The same thing happened on the client, but we didn't notice!)

```
       Worker 1                 Worker 2

  +-----+-----+-----+     +-----+-----+-----+     +----
  | P11 | P12 | P13 |     | P14 | P15 | P16 |     | P17
  +-----+-----+-----+     +-----+-----+-----+     +----
  | P21 | P22 | P23 |     | P24 | P25 | P26 |     | P27
  +-----+-----+-----+     +-----+-----+-----+     +----
  | P31 | P32 | P33 |     | P34 | P35 | P36 |     | P37
  +-----+-----+-----+     +-----+-----+-----+     +----
  | P41 | P42 | P43 |     | P44 | P45 | P46 |     | P47
  +-----+-----+-----+     +-----+-----+-----+     +----
```

Dividing up the data has created undesirable artifacts!

CONTRAST: Image → Contrast Enhancement → Image2

The result is spurious lines on the processed image.

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CONTRAST2: Workers Need to Communicate

The spurious lines would disappear if each worker could just be allowed to peek at the last column of data from the previous worker, and the first column of data from the next worker.

Just as in MPI, MATLAB includes commands that allow workers to exchange data.

The command we would like to use is **labSendReceive()** which controls the simultaneous transmission of data from all the workers.

```
data_received = labSendReceive ( to, from, data_sent );
```

CONTRAST2: Whom Do I Want to Communicate With?

```
spmd

  xl = getLocalPart ( xd );

  if ( labindex() ~= 1 )
    previous = labindex() - 1;
  else
    previous = numlabs();
  end

  if ( labindex() ~= numlabs())
    next = labindex() + 1;
  else
    next = 1;
  end
```

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CONTRAST2: First Column Left, Last Column Right

```
column = labSendReceive ( previous, next, xl(:,1) );

if ( labindex() < numlabs() )
  xl = [ xl, column ];
end

column = labSendReceive ( next, previous, xl(:,end) );

if ( 1 < labindex() )
  xl = [ column, xl ];
end
```

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CONTRAST2: Filter, then Discard Extra Columns

```
  xl = nlfilter ( xl, [3,3], @enhance_contrast );

  if ( labindex() < numlabs() )
    xl = xl(:,1:end-1);
  end

  if ( 1 < labindex() )
    xl = xl(:,2:end);
  end

  xl = uint8 ( xl );

end
```

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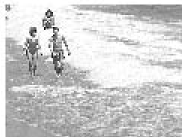
CONTRAST2: Image $\rightarrow$ Enhancement $\rightarrow$ Image2

Original image

Filtered on Client



Filtered on 4 SPMD Workers

Four SPMD workers operated on columns of this image. Communication was allowed using **labSendReceive**.

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BATCH: Indirect Execution

We can run quick, local interactive jobs using the **matlabpool** or **parpool** command to get parallel workers.

The **batch** command is an alternative which allows you to execute a MATLAB script (using either **parfor** or **spmd** statements) in the background on your desktop...or on a remote machine.

The **batch** command includes a **matlabpool** or **pool** argument that allows you to request a given number of workers.

For remote jobs, the number of cores or processors you are asking for is the matlabpool **plus one**, because of the client.

Since Ithaca allocates cores in groups of 8, it makes sense to ask for 7, or 15, or 23 or 31 workers, for instance.

BATCH: Contrast2

Running contrast2 on Ithaca and locally:

```
% Run on Ithaca
job = batch ( 'contrast2_script', ...
  'Profile', 'ithaca_R2013b', ...
  'CaptureDiary', true, ...
  'AttachedFiles', { 'contrast2_fun', 'contrast_enhance', 'surfsup.tif' }, ...
  'CurrentDirectory', '.', ...
  'pool', n );

% Run locally
x = imread ( 'surfsup.tif' );
xf = nlfilter ( x, [3,3], @contrast_enhance );
xf = uint8 ( xf );

% Wait for Ithaca job to complete
wait ( job );
% Load results from Ithaca job
load ( job );
```

BATCH: Contrast2

Notes:

- We need to include both scripts and the input file `surfsup.tif` in the `AttachedFiles` flag
- We can do some work before issuing `wait()`
- We leverage two kinds of parallelism:
  - Parallel (using spmd) on Ithaca
  - Run locally while job is running on Ithaca

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CONCLUSION: Summary of Examples

The QUAD example showed a simple problem that could be done as easily with SPMD as with PARFOR. We just needed to learn about composite variables!

The CONJUGATE GRADIENT example showed that many MATLAB operations work for distributed arrays, a kind of array storage scheme associated with SPMD.

The LBVP & FEM_2D_HEAT examples show how to construct local arrays and assemble these to **codistributed** arrays. This enables treatment of very large problems.

The IMAGE and CONTRAST examples showed us problems which can be broken up into subproblems to be dealt with by SPMD workers. We also saw that sometimes it is necessary for these workers to communicate, using a simple message-passing system.

CONCLUSION: VT MATLAB LISTSERV

There is a local LISTSERV for people interested in MATLAB on the Virginia Tech campus. We try **not** to post messages here unless we really consider them of importance!

Important messages include information about workshops, special MATLAB events, and other issues affecting MATLAB users.

To subscribe to this email list, send a blank email to

`mathworks-g+subscribe@vt.edu`

The subject and body of the message should both be empty.

CONCLUSION: Where is it?

- MATLAB Parallel Computing Toolbox Product Documentation
  http://www.mathworks.com/help/toolbox/distcomp/
- Gaurav Sharma, Jos Martin,
  MATLAB: A Language for Parallel Computing, International Journal of Parallel Programming,
  Volume 37, Number 1, pages 3-36, February 2009.
- An ADOBE PDF with these notes, along with a zipped-folder containing the MATLAB codes can be downloaded from the ARC website at

  `http://www.arc.vt.edu/matlab#resources`

AFTERWORD: PMODE

PMODE allows interactive parallel execution of MATLAB commands. PMODE achieves this by defining and submitting a parallel job, and it opens a Parallel Command Window connected to the labs running the job. The labs receive commands entered in the Parallel Command Window, process them, and send the command output back to the Parallel Command Window.

`pmode start 'local' 2` will initiate **pmode**; `pmode exit` will delete the parallel job and end the **pmode** session

This may be a useful way to experiment with computations on the **labs**.

THE END

Please complete the evaluation form

Thanks

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