MATLAB Parallel Computing

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**ICAM**: Interdisciplinary Center for Applied Mathematics

...........

FDI Fall Short Course:
Introduction to Parallel MATLAB at Virginia Tech
http://people.sc.fsu.edu/~jburkardt/presentations/...
matlab_parallel_2009_vt2.pdf

09 September 2009
MATLAB Parallel Computing: Some Announcements

While we have your attention...
**ITHACA** is an IBM iDataPlex cluster recently installed by Virginia Tech’s Advanced Research Computing facility.

It is intended to gradually take over the high performance computing load from System X.

**ITHACA** supports OpenMP, MPI and Parallel MATLAB programming.

- **Right Now**: Friendly users accepted for Ithaca *(talk to John Burkardt if you are interested,*);
- **Mid October**: Ithaca opened to general users *(accounts given out through online application,*).
MATLAB Training is available this fall.

These classes will be presented by the MathWorks. Some of these classes are tentative. Check the FDI website for details.

- **2 October**: Simulink (daylong);
- **3 October**: SimMechanics (daylong);
- **8 October**: MATLAB Programming Techniques.
- **8 October**: Parallel Computing with MATLAB.
- **29 October**: Parallel Computing with MATLAB (daylong).
- **19 November**: Real-time Data Acquisition and Control.
- **19 November**: Statistical Methods in MATLAB.
“Why There Isn’t Parallel MATLAB”

“*There actually have been a few experimental versions of MATLAB for parallel computers... We have learned enough from these experiences to make us skeptical about the viability of a fully functional MATLAB running on today’s parallel machines.*”

(Let There Be) “Parallel MATLAB”

"We now have parallel MATLAB."

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MATLAB is a computing environment that is halfway between a programming language (where a user must do everything) and a menu-driven application (where the user only makes high level decisions).

Users always have the ability to lay out the precise details of an algorithm themselves.

They rely on MATLAB commands to access intelligent, flexible, and optimized versions of standard algorithms.
The MathWorks has recognized that parallel computing is necessary for scientific computation.

The underlying MATLAB core and algorithms are being extended to work with parallelism.

An explicit set of commands has been added to allow the user to request parallel execution or to control distributed memory.

New protocols and servers allow multiple copies of MATLAB to carry out the user’s requests, to transfer data and to communicate.

MATLAB’s parallelism can be enjoyed by novices and exploited by experts.
MATLAB has developed a *Parallel Computing Toolbox* which is required for all parallel applications.

The Toolbox allows a user to run a job in parallel on a desktop machine, using up to 8 "workers" (additional copies of MATLAB) to assist the main copy.

If the desktop machine has multiple processors, the workers will activate them, and the computation should run more quickly.

This use of MATLAB is very similar to the shared memory parallel computing enabled by OpenMP; however, MATLAB requires much less guidance from the user.
MATLAB has developed a *Distributed Computing Server* or **DCS**. Assuming the user’s code runs properly under the local parallel model, then it will also run under **DCS** with no further changes.

With the **DCS**, the user can start a job on the desktop that gets assistance from workers on a remote cluster.
Introduction: Local and Remote MATLAB Workers

**Desktop System**
- Parallel Computing Toolbox
  - Local Workers
  - Simulink, Blocksets, and Other Toolboxes
  - MATLAB

**Computer Cluster**
- MATLAB Distributed Computing Server
  - Workers
  - Scheduler
If a cluster is available, the shared memory model makes less sense than a distributed memory model.

In such a computation, very large arrays can be defined and manipulated. Each computer does not have a copy of the same array, but instead a distinct portion of the array. In this way, the user has access to a memory space equal to the sum of the memories of all the participating computers.

MATLAB provides the `spmd` command to allow a user to declare such distributed arrays, and provides a range of operators that are appropriate for carrying out computations on such arrays.
MATLAB also includes a **batch** command that allows you to write a script to run a job (parallel or not, remote or local) as a separate process.

This means you can use your laptop or desktop copy of MATLAB to set up and submit a script for running a remote job. You can exit the local copy of MATLAB, turn off your laptop or do other work, and later check on the remote job status and retrieve your results.

Many computer clusters that have parallel MATLAB installed require users to submit their jobs in batch mode.
Introduction: PMODE: Interactive Parallel Mode

A typical parallel MATLAB user working interactively still sees the familiar MATLAB command window, which we may think of as being associated with the “master” copy of MATLAB.

However, MATLAB also allows a user to open a parallel command window. This is known as pmode.

Commands given in pmode are executed simultaneously on all the workers. Within pmode, the user has access to distributed arrays, parallel functions, and message-passing functions that are not visible or accessible in the normal command window.
Parallel MATLAB uses a version of MPI (MPICH2).

In most cases, a user is happy not to see the underlying MPI activity that goes on.

However, MATLAB includes a rich set of calls that allow the user to employ the typical MPI activities of sending and receiving messages, broadcasting data, defining synchronization barriers and so on.
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If your desktop or laptop computer is fairly recent, it may have more than one processor; the processors may have multiple cores.

Executing MATLAB in the regular way only engages one core, leaving the others idle. (However, some MATLAB linear algebra routines will notice these idle cores and engage them for subtasks).

The Parallel Computing Toolbox runs up to 8 cooperating copies of MATLAB, taking direct advantage of the extra power.

You’ll need:

- the right version of MATLAB;
- the Parallel Computing Toolbox;
- a MATLAB M-file that uses new parallel keywords.
Local Parallel Computing: What Do You Need?

Your machine must have multiple cores.

Your MATLAB must be version 2008a or later.

***To check MATLAB’s version, go to the HELP menu, and choose About Matlab.

Your MATLAB must include the Parallel Computing Toolbox.

***To list all your toolboxes, type the MATLAB command ver.
Suppose you have a MATLAB M-file modified to compute in parallel (we’ll explain that later!).

To do local parallel programming, start MATLAB the regular way.

This copy of MATLAB will be called the client copy; the extra copies created later are known as workers or sometimes as labs.

Running in parallel requires three steps:

1. request a number of (local) workers;
2. issue the normal command to run the program. The client MATLAB will call on the workers for help as needed;
3. release the workers.
Suppose you have an M file named `samson.m`.

To run `samson.m` in parallel, type:

```matlab
matlabpool open local 4

samson

matlabpool close
```

When we want to run on a cluster, we’ll only have to replace the word `local` by another suitable word, which defines the “configuration” (how MATLAB rounds up the workers.)
If all is well, the program runs the same as before... but faster.

Output will still appear in the command window in the same way, and the data will all be available to you.

What has happened is simply that some of the computations were carried out by other cores in a way that was hidden from you.

The program may seem like it ran faster, but it’s important to measure the time exactly.
To time a program, you can use **tic** and **toc**:

```matlab
matlabpool open local 4

tic
samson
toc

matlabpool close
```

**tic** starts the clock, **toc** stops the clock and prints the time.
To measure the speedup of a program, you can try different numbers of workers:

```matlab
for labs = 0 : 4
    if (0 < labs)
        matlabpool ('open', 'local', labs)
    end
    tic
    samson
    toc
    if (0 < labs)
        matlabpool ('close')
    end
end
```

Because labs is a variable, we use the “function” form of matlabpool.
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The simplest way of parallelizing a MATLAB program focuses on the `for` loops in the program.

If a `for` loop is suitable for parallel execution, replace the word `for` by the word `parfor` (meaning “parallel for”).

When the MATLAB program is run in parallel, the work in each `parfor` loop will be distributed among the workers.
What determines whether a `for` loop is suitable for parallelization?

The crucial question that must be answered satisfactorily is this:

*Can the iterations of the loop be performed in any order without affecting the results?*

If the answer is "yes", then generally the loop can be parallelized.
We’re going to look at some examples of the use of the `parfor` keyword to make loops execute in parallel.

These are not realistic examples; the loops are short, and the operations are simple, and it would be easier to use MATLAB’s built-in operations to replace the entire loop by a simple command.

But these examples are for illustration, only. They give you an idea of how `parfor` can be used.
As a simple example of a loop that can be parallelized, think about the task of normalizing each column of a matrix. We find the largest entry in a column and divide the column by that value. What happens in each column is independent.
for j = 1 : n
    c = 0.0
    for i = 1 : m
        c = max ( c, a(i,j) );
    end
    if ( c ~= 0 )
        for i = 1 : m
            a(i,j) = a(i,j) / c;
        end
    end
end
As an example of when the `parfor` command cannot be used, consider the following difference equation:

\[
\begin{align*}
u(1:m) &= \text{rand}(1, m) \\
\text{for } j = 1 : n \\
\quad &\text{for } i = 2 : m - 1 \\
\quad &\quad v(i) = u(i-1) - 2 * u(i) + u(i+1) \\
\quad &\text{end} \\
\quad &u(2:m-1) = v(2:m-1) \\
\text{end}
\end{align*}
\]

The iterations (on \( j \)) are not independent. Each iteration needs results from the previous one. (We could, however, use a `parfor` on the \( i \) loop.)
Using `parfor` for parallel computing is very similar to the OpenMP shared memory model.

The MATLAB workers correspond to separate threads of execution.

In general, we think of all the data as being “shared” - that is, every worker can see or change any variable.

Variables that cannot be shared so simply include `private` variables and `reduction` variables.

OpenMP requires you to identify such variables; MATLAB tries to determine what do do implicitly, based on how the variables are used in the loop.
A loop containing `break` or `return` cannot run in parallel; the sequential code breaks at the first occurrence of the test. The parallel code can't do the same.

```matlab
function value = prime ( i )
    value = 1;
    for j = 2 : i - 1;
        if ( mod ( i, j ) == 0 )
            value = 0;
            break
        end
    end
end
return
end
```

You cannot replace `for` by `parfor` here!
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For our first example, we want a simple computation involving a loop which we can set up to run for a long time.

We’ll choose a program that determines how many prime numbers there are between 1 and $N$.

If we want the program to run longer, we increase the variable $N$. Doubling $N$ makes the run time increase by a factor of 4.

Notice that this program includes a loop that has a break statement. That’s OK, because we do not parallelize that loop!
function total = prime_number ( n )

%% PRIME_NUMBER returns the number of primes between 1 and N.

total = 0;
for i = 2 : n
    prime = 1;
    for j = 2 : i - 1
        if ( mod ( i, j ) == 0 )
            prime = 0;
            break
        end
    end
    total = total + prime;
end
return
We can parallelize the loop whose index is $i$, replacing `for` by `parfor`. The computations for different values of $i$ are independent.

*But there’s a break inside this loop! Why is that not a problem?*

There is one variable that is not independent of the loops, namely `total`. This is simply computing a running sum (a `reduction variable`), and we only care about the final result. MATLAB is smart enough to be able to handle this computation in parallel.

To make the program parallel, we replace `for` by `parfor`. That’s all!
lab_num_array = [ 0, 1, 2, 4 ];
for lab_num = lab_num_array(1:4)
    fprintf ( 1, '\n' );

    if ( 0 < lab_num )
        matlabpool ( 'open', 'local', lab_num )
    end

    n = 50;

    while ( n <= 500000 )
        tic;
        primes = prime_number_parallel ( n );
        wtime = toc;
        fprintf ( 1, '%8d%8d%8d%14f\n', lab_num, n, primes, wtime );
        n = n * 10;
    end

    if ( 0 < lab_num )
        matlabpool ( 'close' )
    end
end
**The PRIME NUMBER Example: Timing**

PRIME_NUMBER_PARALLEL_RUN

Run PRIME_NUMBER_PARALLEL with 0, 1, 2, and 4 labs.

<table>
<thead>
<tr>
<th>N</th>
<th>1+0</th>
<th>1+1</th>
<th>1+2</th>
<th>1+4</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.067</td>
<td>0.179</td>
<td>0.176</td>
<td>0.278</td>
</tr>
<tr>
<td>500</td>
<td>0.008</td>
<td>0.023</td>
<td>0.027</td>
<td>0.032</td>
</tr>
<tr>
<td>5000</td>
<td>0.100</td>
<td>0.142</td>
<td>0.097</td>
<td>0.061</td>
</tr>
<tr>
<td>50000</td>
<td>7.694</td>
<td>9.811</td>
<td>5.351</td>
<td>2.719</td>
</tr>
<tr>
<td>500000</td>
<td>609.764</td>
<td>826.534</td>
<td>432.233</td>
<td>222.284</td>
</tr>
</tbody>
</table>
There are many thoughts that come to mind from these results!

Why does 500 take less time than 50? (It doesn’t, really).

How can ”1+1” take longer than ”1+0”? (It does, but it’s probably not as bad as it looks!)

This data suggests two conclusions:

*Parallelism doesn’t pay until your problem is big enough;*

*AND*

*Parallelism doesn’t pay until you have a decent number of workers.*
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Behind the Magic:

What is behind the curtain of MATLAB’s Magic?
In other parallel languages, the user declares how variables are to be handled. This means more work, but also indicates that some ambiguous situations are safe to parallelize.

MATLAB figures out how to parallelize the user’s code implicitly; that is, it looks at the code, and figures out by itself how the variables are used, and which ones must be treated in special ways. This is easy for the user, but it also means that some parallelizable operations will not be parallelized by MATLAB!

In particular, if an array is involved, MATLAB will only parallelize the loop if the array can be “sliced”, that is, if each iteration of the loop only refers to a distinct, separate portion of the array.

Let us look at how MATLAB’s classification of your variables determines whether you can run in parallel.
a = 0;
c = pi;
z = 0;
r = rand ( 1, 10 );

parfor i = 1 : 10  
    a = i;  <-- a is a "temporary"
    z = z + i;  <-- z is a "reduction"
    b(i) = r(i);  <-- b and r are "sliced"
    if ( i <= c )  <-- c is "broadcast"
        d = 2 * a;  <-- d is "trouble"
    end
end
When MATLAB encounters a `parfor` loop, it must classify all the variables used in the loop, in order to determine how to carry out the operations in parallel.

MATLAB’s variable classes are:

- **loop index**, the `parfor` index;
- **sliced**, any array uniquely indexed by the loop index;
- **broadcast**, defined before the loop, not set inside the loop;
- **reduction**, accumulates a result in a standard way;
- **temporary**, assigned, then used, in each iteration.
The **loop index** is the index of the loop to which the `parfor` has been applied. The range of this index is divided up (in an unpredictable way) among the workers.

The loop index is also used to determine which arrays used in the loop must be divided among the workers.

Of course, the `parfor` loop may occur inside a loop, and may contain loops. The indices of those loops are treated as regular variables (broadcast or temporary).

MATLAB requires that the range of a `parfor` loop index be **consecutive integers**.
**Sliced variables** are vectors or arrays whose entries can be uniquely associated with a particular loop iteration.

Assume the parfor loop index is $i$. Then the following are examples of sliced vectors:

```plaintext
parfor i = 1 : n
    a(i) = b(i) + c(i+1) + d(i-2) + e(n+1-i);
end
```
Unfortunately, in many calculations, the way we use arrays does not correspond to what MATLAB wants. In particular, if loop iteration $i$ works with vector entries $i$ and $i+1$, then MATLAB cannot slice the variable the way it wants.

For example, entry $x(45)$ is needed by two distinct loop iterations, with $i=44$ and 45:

```matlab
for i = 1 : n - 1
    dudx(i) = ( u(i+1) - u(i) ) / dx;
end
```
Here are two ways to get around the problem:

```matlab
up1(1:n-1) = u(2:n);
parfor i = 1 : n - 1
    dudx(i) = ( up1(i) - u(i) ) / dx;
end

or

parfor i = 1 : n - 1
    dudx(i) = u(i+1);
end
parfor i = 1 : n - 1
    dudx(i) = ( dudx(i) - u(i) ) / dx;
end
```
Broadcast variables are defined by what they are not:

1. *not* the loop index;
2. *not* sliced variables;
3. *not* assigned a value inside the loop.

Broadcast variables are only used on the right hand side of assignment statements, and don’t change during the loop.

So their initial values can be broadcast to all workers before the iterations begin, and there’s nothing more to worry about.
In this loop, \( x, \ dx, \ dy, \ j \) and \( c(j) \) are broadcast variables.

(Meanwhile, \( i \) is the (parfor) loop index, \( u(i) \) and \( d(i) \) are sliced variables, and \( y \) is a temporary.)

```plaintext
dx = 0.25;
for j = 1 : n
    x = j * dx;
    dy = j * 0.01;
    parfor i = 1 : n
        y = i * dy;
        u(i) = c(j) * d(i) * f(x, y) / dx / dy;
    end
end
```
Reduction variables occur when certain functions such as max, min, sum or prod are used iteratively.

These operations are “semi-parallel”, that is, each worker can compute part of the result, as long as the partial results are put together in the end in the correct way.

During parallel execution of the loop, a reduction variable does not have a definable value - it is really just a set of partial results.

MATLAB recognizes and automatically parallelizes many reductions.
In this loop, `total`, `big` and `fact` are reduction variables.

MATLAB is able to handle this calculation in parallel. The user simply replaces `for` by `parfor`:

```matlab
total = 0.0;
big = - Inf;
fact = 1;

for i = 1 : n
    total = total + x(i);
    big = max ( big, x(i) );
    fact = fact * x(i);
end
```
Behind the Magic: Reduction Variables

Because they are shared over many workers, reduction variables do not have a definable value inside a parallel loop.

If your loop tries to test, use or print a reduction variable while it is being formed, MATLAB can’t parallelize the loop.

```matlab
total = 0.0;
for i = 1 : n
    total = total + x(i);
    if ( 1.0 < total )
        large_enough = 1;
    end
    cum(i) = total;
    fprintf ( 1, ’ Current total is %f\n’, total );
end
```

You cannot replace `for` by `parfor` here!
Temporary variables are often shorthand for a long expression. Such a variable is redefined and then used within each iteration of a loop.

If MATLAB can’t classify a variable otherwise, it assumes it is temporary. It then checks to ensure that, on every iteration, the variable is assigned and then used. If not, it generates an error.

So if you have mishandled a sliced or reduction variable, MATLAB will try to classify it as a temporary. You may get a confusing message about an uninitialized temporary variable.
In this loop, `angle`, `nm1`, `c`, `s`, and `ui` are temporary variables.

MATLAB can parallelize this as soon as `for` is replaced by `parfor`:

```matlab
u = rand ( 1, n );
v = rand ( 1, n );
for i = 1 : n
    nm1 = n - 1;
    angle = ( i - 1 ) * pi / nm1;
    c = cos ( angle );
    s = sin ( angle );
    ui = u(i);
    u(i) = c * u(i) + s * v(i);
    v(i) = - s * ui + c * v(i);
end
```
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Bumps in the Road: And How to Avoid Some of Them

Are there hazards awaiting the new user?
A big concern when using parallel programming is that the parallelized code can actually run more slowly than the original. (This is a *semantic* question, about programming performance.)

But right now we ask a more basic question - What programming causes MATLAB to refuse to parallelize your `parfor` loop. (This is a *syntactic* question, about programming language.)

If you enable `mlint` in MATLAB’s editor, you will get warnings right there, with the offending loop highlighted, and an error message.

Otherwise, you will get error messages at run time, which are sometimes less specific.
A common programming practice that will make parallelization impossible occurs when the data used in one iteration of the loop is not available until a previous iteration has been computed.

Parallel MATLAB can’t handle such a calculation properly, since the iteration where the variable is set may happen on a different processor than the iteration where the variable is needed.

Moreover, the iteration that needs the value might be computed before the iteration that sets the value.

Sometimes the loop can be rewritten; other times, the problem cannot be fixed because the computation is inherently recursive.
Suppose you compute the X locations of a set of nodes this way:

```matlab
dx = 0.25;
x = zeros (1,n);
for i = 2 : n
    x(i) = x(i-1) + dx;
end
```

Parallel MATLAB’s cannot be applied to this loop as it is written. This loop assumes the iterations will be done in exactly the usual order.

Luckily, this calculation can be rewritten to parallelize.
Another example of temporary variable use involves counting how many times some condition has occurred, perhaps using this value as an index to store the corresponding value.

In this loop, we are looking for nonzero entries of the matrix $A$, and storing them in a compressed vector. The variable $k$, which counts how many such entries we have seen so far, is a "wraparound" temporary, whose value, set in one loop iteration, is needed in a later loop iteration.

It is not possible to ask MATLAB to carry out this operation in parallel simply by replacing the `for` loop by a `parfor`. A better choice might be to explore the `find` command!
k = 0;
for i = 1 : m
    for j = 1 : n
        if ( a(i,j) ~= 0.0 )
            k = k + 1
            a2(k) = a(i,j);
            i2(k) = i;
            j2(k) = j;
        end
    end
end
end
Suppose we approximate the solution of a differential equation:

\[
\begin{align*}
\text{dt} & = 0.25; \\
u & = \text{zeros (1,n);} \\
\text{for } i = 2 : n \\
& \quad u(i) = u(i-1) + \text{dt} * f( t, u(i-1) ); \\
\text{end}
\end{align*}
\]

There is no way to parallelize this loop. The value of \( u(i) \) cannot be computed until the value of \( u(i-1) \) is known, and that means the loop iterations cannot be executed in arbitrary order.

Similar issues arise when a Newton iteration is being carried out.
PARFOR is easy because MATLAB does a lot of work for you.

MATLAB is usually intelligent enough to determine how to classify and handle the variables in a loop.

But if it gets confused, there is no easy mechanism to help MATLAB or to argue with it!
n = 100;
Q = zeros(n,n);

parfor i = 1 : n
    for j = i : n
        if ( j == i )
            Q(i,j) = 1;
        else
            Q(i,j) = sqrt(i/j);
        end
    end
end

Q
MATLAB 2008b refuses to allow this program to run in parallel, complaining that it cannot determine the status of the variable Q. Q should “obviously” be a sliced variable. It’s an indexed variable whose entries can be divided up among different processors in a simple way.

However, MATLAB’s decisions are “final”, so if we really want the code to run in parallel, we have to reword it so that MATLAB is happy with it. One way is to use a vector in the loop, and copy its entries into Q.
n = 100;
Q = zeros(n,n);

parfor i = 1 : n

    z = zeros(1,n);

    for j = i : n

        if ( j == i )
            z(j) = 1;
        else
            z(j) = sqrt ( i / j );
        end

    end

    Q(i,:) = z;

end

Q
Here is another example of a calculation that is completely parallel, in X, in Y, (and even in time T). Again, MATLAB refuses to parallelize the loop over X and Y.

Q should “obviously” be a sliced variable. It’s an indexed variable whose entries can be divided up among different processors in a simple way.

However, MATLAB’s decisions are “final”, so if we really want the code to run in parallel, we have to reword it so that MATLAB is happy with it. One way is to use a vector in the loop, and copy its entries into Q.
for t=1:Nt
    tm=dt*(t-1);
    a=eps*sin(w*tm);
    b=1-2*eps*sin(w*tm);
    for i=1:Nx+1
        for j=1:Ny+1
            f=a*x(i,j)*x(i,j)+b*x(i,j);
            dfx=2*a*x(i,j)+b;
            u(i,j,t)=-pi*A*sin(pi*f)*cos(pi*y(i,j));
            v(i,j,t)= pi*A*cos(pi*f)*sin(pi*y(i,j))*dfx;
        end
    end
end
If we turn the doubly-dimensioned array into a vector, MATLAB allows us to parallelize over the vector index $K$.

We have to use the relationships

$$k = i + (j - 1) \times (Nx + 1);$$
$$i = \text{mod}(k, Nx + 1);$$
$$j = \text{floor}(k/(Nx + 1)) + 1;$$

or we could use the builtin MATLAB commands \texttt{ind2sub} and \texttt{sub2ind}.
for t=1:Nt
    tm=dt*(t-1);
    a=eps*sin(w*tm);
    b=1-2*eps*sin(w*tm);
    parfor k = 1 : kmax
        % i = mod ( k - 1, Nx + 1 ) + 1;
        % j = floor ( k / ( Nx + 1 ) ) + 1;
        f=a*x(k)*x(k)+b*x(k);
        dfx=2*a*x(k)+b;
        u(k,t)=-pi*A*sin(pi*f)*cos(pi*y(k));
        v(k,t)= pi*A*cos(pi*f)*sin(pi*y(k))*dfx;
    end
end
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The MD program runs a simple molecular dynamics simulation.

The problem size $N$ counts the number of molecules being simulated.

The program takes a long time to run, and it would be very useful to speed it up.

There are many for loops in the program, but it is a mistake to try to parallelize everything!

MATLAB has a `profile` command that can report where the CPU time was spent - which is where we should try to parallelize.
### The MD Example: Run MATLAB’s Profiler

```matlab
profile on
md
profile viewer
```

<table>
<thead>
<tr>
<th>Step</th>
<th>Potential Energy</th>
<th>Kinetic Energy</th>
<th>((P+K-E_0)/E_0) Energy Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>498108.113974</td>
<td>0.000000</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>2</td>
<td>498108.113974</td>
<td>0.000009</td>
<td>1.794265e-11</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9</td>
<td>498108.111972</td>
<td>0.002011</td>
<td>1.794078e-11</td>
</tr>
<tr>
<td>10</td>
<td>498108.111400</td>
<td>0.002583</td>
<td>1.793996e-11</td>
</tr>
</tbody>
</table>

CPU time = 415.740000 seconds.
Wall time = 378.828021 seconds.
### The MD Example

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Calls</th>
<th>Total Time</th>
<th>Self Time*</th>
<th>Total Time Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>md</td>
<td>1</td>
<td>415.847 s</td>
<td>0.096 s</td>
<td></td>
</tr>
<tr>
<td>compute</td>
<td>11</td>
<td>415.459 s</td>
<td>410.703 s</td>
<td></td>
</tr>
<tr>
<td>repmat</td>
<td>11000</td>
<td>4.755 s</td>
<td>4.755 s</td>
<td></td>
</tr>
<tr>
<td>timestamp</td>
<td>2</td>
<td>0.267 s</td>
<td>0.108 s</td>
<td></td>
</tr>
<tr>
<td>datestr</td>
<td>2</td>
<td>0.130 s</td>
<td>0.040 s</td>
<td></td>
</tr>
<tr>
<td>timefun/private/formatdate</td>
<td>2</td>
<td>0.084 s</td>
<td>0.084 s</td>
<td></td>
</tr>
<tr>
<td>update</td>
<td>10</td>
<td>0.019 s</td>
<td>0.019 s</td>
<td></td>
</tr>
<tr>
<td>datevec</td>
<td>2</td>
<td>0.017 s</td>
<td>0.017 s</td>
<td></td>
</tr>
<tr>
<td>now</td>
<td>2</td>
<td>0.013 s</td>
<td>0.001 s</td>
<td></td>
</tr>
<tr>
<td>datenum</td>
<td>4</td>
<td>0.012 s</td>
<td>0.012 s</td>
<td></td>
</tr>
<tr>
<td>datestr&gt;getdateform</td>
<td>2</td>
<td>0.005 s</td>
<td>0.005 s</td>
<td></td>
</tr>
<tr>
<td>initialize</td>
<td>1</td>
<td>0.005 s</td>
<td>0.005 s</td>
<td></td>
</tr>
<tr>
<td>etime</td>
<td>2</td>
<td>0.002 s</td>
<td>0.002 s</td>
<td></td>
</tr>
</tbody>
</table>

**Self time** is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling.
function [ f, pot, kin ] = compute ( np, nd, pos, vel, mass )

f = zeros ( nd, np );
pot = 0.0;
pi2 = pi / 2.0;

for i = 1 : np
    Ri = pos - repmat ( pos(:,i), 1, np ); % array of vectors to 'i'
    D = sqrt ( sum ( Ri.^2 ) ); % array of distances
    Ri = Ri(:, (D > 0.0)); % save only pos values
    D2 = D .* ( D <= pi2 ) + pi2 .* ( D > pi2 ); % truncate the potential.
    pot = pot + 0.5 * sum ( sin ( D2 ).^2 ); % accumulate pot. energy
    f(:,i) = Ri * ( sin( 2*D2 ) ./ D ); % force on particle 'i'
end

kin = 0.5 * mass * sum ( diag ( vel' * vel ) ); % kinetic energy

return
end
The MD Example: Speedup

By inserting a PARFOR in COMPUTE, here is our speedup:

![Graph showing speedup vs. number of workers]
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**SPMD**: for **Single Program, Multiple Data**:

The `parfor` command 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 lab runs which iteration, we can’t examine the work of any individual lab.

The **SPMD** command allows a programmer more control over how parallelism is done. Using **SPMD** is like working with a very simplified version of **MPI**.
Let’s assume we’ve issued a `matlabpool` command, and have a *client* (that is, the “main” copy of MATLAB) and a number of workers or labs.

The first thing to notice about a program using **SPMD** is that certain blocks of code are delimited:

```matlab
fprintf ( 1, ’ Set up the integration limits:
’ );
spmd
    a = ( labindex - 1 ) / numlabs;
    b = labindex / numlabs;
end
```
The `spmd` delimiter marks a section of code which is to be carried out by each lab, and *not* by the client.

The fact that the MATLAB program can be marked up into instructions for the client and instructions for the workers explains the **single program** part of **SPMD**.

But how do multiple workers do different things if they see the same instructions? Luckily, each worker is assigned a unique identifier, the value of the variable `labindex`.

The worker also gets the value of `numlabs`, the total number of workers. This information is enough to ensure that each worker can be assigned different tasks. This explains the **multiple data** part of **SPMD**!
Now let’s go back to our program fragment. But first we must explain that we are trying to approximate an integral over the interval [0,1]. Using **SPMD**, we are going to have each lab pick a portion of that interval to work on, and we’ll sum the result at the end. Now let’s look more closely at the statements:

```plaintext
fprintf ( 1, ’ Set up the integration limits:
’ );
spmd
    a = ( labindex - 1 ) / numlabs;
    b =  labindex      / numlabs;
end
```
Each worker will compute different values of \texttt{a} and \texttt{b}. These values are stored locally on that worker’s memory.

The client can access the values of these variables, but it must specify the particular lab from whom it wants to check the value, using “curly brackets”: \texttt{a\{i\}}.

The variables stored on the workers are called \textit{composite variables}; they are somewhat similar to MATLAB’s cell arrays.

It’s important to respect the rules for composite variable names. In particular, if \texttt{a} is used on the workers, then the name \texttt{a} is also “reserved” on the client program (although there it’s an indexed variable). The client should not try to use the name \texttt{a} for other variables!
The SPMD Command

So we could print all the values of `a` and `b` in two ways:

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

or

spmd
    a = ( labindex - 1 ) / numlabs;
    b = labindex / numlabs;
end
for i = 1 : numlabs
    fprintf ( 1, ' A = %f, B = %f\n', a{i}, b{i} );
end
```
The SPMD Command

Assuming we’ve defined our limits of integration, we now want to carry out the trapezoid rule for integration:

```matlab
spmd
    x = linspace ( a, b, n );
    fx = f ( x );
    quad_part = ( fx(1) + 2 * sum(fx(2:n-1)) + fx(n) ) /2 / (n-1);
    fprintf ( 1, ’ Partial approx %f\n’, quad_part );
end
```

with result:

<table>
<thead>
<tr>
<th></th>
<th>Partial approx</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.874676</td>
</tr>
<tr>
<td>4</td>
<td>0.567588</td>
</tr>
<tr>
<td>1</td>
<td>0.979915</td>
</tr>
<tr>
<td>3</td>
<td>0.719414</td>
</tr>
</tbody>
</table>
The SPMD Command

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:

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

with result:

```
Approximation 3.14159265
```

```c
```
function value = quad_spmd ( n )

fprintf ( 1, 'Compute limits\n' );
spmmd
    a = ( labindex - 1 ) / numlabs;
    b = labindex / numlabs;
    fprintf ( 1, '\nLab\n%d\nworks on [\%f,\%f].\n', labindex, a, b );
end

fprintf ( 1, 'Each lab estimates part of the integral.\n' );
spmmd
    if ( n == 1 )
        quad_part = ( b - a ) * f ( ( a + b ) / 2 );
    else
        x = linspace ( a, b, n );
        fx = f ( x );
        quad_part = ( b - a ) * ( fx(1) + 2 * sum ( fx(2:n-1) ) + fx(n) ) ... / 2.0 / ( n - 1 );
    end
    fprintf ( 1, '\nApprox\n%f\n', quad_part );
end

fprintf ( 1, 'Use GPLUS to sum the parts.\n' );
spmmd
    quad = gplus ( quad_part );
    if ( labindex == 1 )
        fprintf ( 1, '\nApproximation =\n%f\n', quad )
    end
end

return
end
MATLAB also provides commands to combine values directly on the labs. The command we need is called `gplus()`; it computes the sum across all the labs of the given variable, and returns the value of that sum to each lab:

```matlab
spmd
    x = linspace ( a, b, n );
    fx = f ( x );
    quad_part = ( fx(1) + 2 * sum(fx(2:n-1)) + fx(n) )
                /2 /(n-1);
    quad = gplus(quad_part);
    if ( labindex == 1 )
        fprintf ( 1, ' Approximation %f
', quad );
    end
end
```
The SPMD Command: Reduction Operators

\texttt{gplus()} is implemented by the \texttt{gop()} command, which carries out an operation across all the labs. \texttt{gplus(a)} is really shorthand for \texttt{gop (@plus, a )}, where \texttt{plus} is the name of MATLAB’s function that actually adds numbers. Other reduction operations include:

- \texttt{gop(@max,a)}, maximum of \texttt{a};
- \texttt{gop(@min,a)}, minimum of \texttt{a};
- \texttt{gop(@and,a)}, AND of \texttt{a};
- \texttt{gop(@or,a)}, OR of \texttt{a};
- \texttt{gop(@xor,a)}, XOR of \texttt{a};
- \texttt{gop(@bitand,a)}, bitwise AND of \texttt{a};
- \texttt{gop(@bitor,a)}, bitwise OR of \texttt{a};
- \texttt{gop(@bitxor,a)}, bitwise XOR of \texttt{a}. 
SPMD supports some commands that allow the programmer to do message passing, in the MPI style:

- **labSend**, send data to another lab;
- **labReceive**, receive data from another lab;
- **labSendReceive**, interchange data with another lab.

For details, you will need to see the MATLAB HELP facility!
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In most cases, making use of parallelism requires some re-coding, perhaps even serious restructuring of your approach. Beginning with Version 4.0 (R2008a) of the Optimization Toolbox we can easily take advantage of parallelism in constructing finite-difference estimates of the gradient of the cost functional and the Jacobian of any nonlinear constraint functions.

Using the optimset command we simply set the flag UseParallel to (the string) always.

In the run_opt example we seek an optimal steering history for a boat moving in a spatially varying current. The control history is approximated as piecewise constant on a given time-grid. The optimization parameter is the vector of the values of the steering angle on the intervals. The cost functional and constraints depend on the final position of the boat in the plane.
The main work in evaluating these functions is the (numerical) integration of the dynamics with a prescribed steering history.

The dynamics are given by

\[ \dot{x}(t) = -\kappa y(t) + \cos(\theta(t)) \]
\[ \dot{y}(t) = \sin(\theta(t)) \]

with initial condition \( x(0) = y(0) = 0 \).

The problem is to maximize \( x(t_f) \) with the constraint \( y(t_f) > y_f \) (\( t_f, y_f, \) and \( \kappa \) are given).
function z_star = run_opt(f_name, n)
% Function to run a finite dimensional optimization problem
% based on a discretization of a Mayer problem in optimal control.

% f_name points to a user-supplied function with a single input argument
% n is a discretization parameter. The finite-dimensional problem arises
% by treating the (scalar) control as piecewise constant
% The function referenced by f_name must define the elements of
% the underlying optimal control problem. See 'zermelo' as an example.

% Problem data
PAR = feval(str2func(f_name), n);

% some lines omitted

% Algorithm set up
OPT = optimset(optimset('fmincon'),...'
    'LargeScale','off',...'
    'Algorithm','active-set',...'
    'Display','iter',...
    'UseParallel','Always');
h_cost = @(z) general_cost(z,PAR);
h_cnst = @(z) general_constraint(z,PAR);

% Run the algorithm
[z_star, f_star, exit] = ...
fmincon(h_cost, z0, [], [], [], [], LB, UB, h_cnst, OPT);
if exit >=0 && isfield(PAR,'plot')
    feval(PAR.plot, z_star, PAR)
end
The RUN_OPT Example: source material

A folder with the software and example output is in the parallel_matlab folder on your desktop. The folder looks like:
cell arrays are rectangular arrays, whose content can be any MATLAB variable, including a cell array

>> A = eye(2); B = ones(2); C = rand(3,4); D = 'a string';
>> G = { A B ; C D};
>> G

G =  [2x2 double]  [2x2 double]
     [3x4 double]  'a string'

>> isa(G, 'cell')

ans =  1
A cell array may be indexed in two ways:

1. \( G(1) \) - the result of **cell** indexing is a cell array
2. \( G\{1\} \) - the result of **content** indexing is the contents of the cell(s)

\[
\gg \text{F1 = G(1, 1:2)}
\]

\[
\text{F1 = [2x2 double] [2x2 double]}
\]

\[
\gg \text{isa(F1, 'cell')}
\]

\[
\text{ans = 1}
\]
Cell Arrays: Two ways of indexing

G{1} - the result of **content** indexing is the cell’s contents

```plaintext
>> F2 = G{1, 2}
F2=
    1  1
    1  1
```

```plaintext
>> whos
Name      Size Bytes  Class      Attributes
-------    ----  ------  --------  -------------
A         2x2   32     double
B         2x2   32     double
C         3x4   96     double
D         1x8   16     char
F1        1x2   184    cell
F2        2x2   32     double
G         2x2   416    cell
```
SPMD mode creates a composite object on the client. Composite objects are indexed in the same ways as cell arrays.

```matlab
>> spmd
V = eye(2) + (labindex -1);
end
>> V{1}
ans = 1 0
    0 1
>> V{2}
ans = 2 1
    1 2
>> whos
    Name      Size         Bytes  Class       Attributes
    V     1x2             373  Composite
```
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- **Codistributed Arrays**
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Codistributed arrays allow the user to build \((m \times n)\) matrices so that, for example, each 'lab' stores/operates on a contiguous block of columns. More general (rectangular) constructs are possible but are not covered here.

We shall demonstrate these ideas in pmode

\[
\text{>> pmode start 4}
\]

Starting pmode using the parallel configuration 'local'.
Waiting for parallel job to start...
Connected to a pmode session with 4 labs.

Many of the builtin Matlab matrix constructors can be assigned the class 'codistributed'. For example:

\[
M = \text{speye}(1000, \text{codistributor}());
\]
'codistributor' is the constructor and specifies which dimension is used to distribute the array. With no argument, we take the default, which is '1d' or one-dimensional. By default, two dimensional arrays are distributed by columns.

\texttt{codistributor(M)} returns information about the distributed structure of the array \texttt{M}.

If the number of columns is an integer multiple of the number of 'labs', then the (default) distribution of columns among the labs is obvious. Else we invoke \texttt{codistributor} (or other MATLAB supplied procedure).

\texttt{localPart(M)} returns the part of the codistributed array on this lab.
%%% run these in Matlab

```matlab
pmode start 4
M = speye(1000, codistributor())
M = ones(1000, codistributor())
codistributor(M)
```

```matlab
M = ones(1000, 1, codistributor())
codistributor(M)
```

%%%
One can construct local arrays on the labs and assemble them into a codistributed array:

%%% run these in Matlab
M = rand(100, 25) + labindex;
Mc = codistributed(M);
max(max(abs(M - localPart(Mc))))
Mc(12,13)
%%% 

Of course, in applications the construction on each lab will involve user-defined code. We will now demonstrate this idea for an unsteady heat equation in two space dimensions.
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An example: 2D unsteady heat equation

$$\sigma C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + F(x, y, t)$$

$$(x, y) \in \{(x, y) \mid 0 \leq x \leq L, \ 0 \leq y \leq w\} \subset \mathbb{R}^2, \ t > 0,$$

where:

- $F(x, y, t)$ is a specified source term,
- $\sigma > 0$ is the areal density of the material,
- $C_p > 0$ is the thermal capacitance of the material, and
- $k_x > 0$ ($k_y > 0$) is the conductivity in the $x$ direction (the $y$-direction).
Boundary conditions for our problem are:

\[
\frac{\partial T(x, 0)}{\partial y} + \frac{\partial T(x, w)}{\partial y} = 0 ,
\]

\[
k_x \frac{\partial T(L, y)}{\partial x} = f(y) ,
\]

\[
k_x \frac{\partial T(0, y)}{\partial x} = \alpha(y) \ (T(0, y) - \beta(y)) .
\]
We use backward Euler in time and finite-elements in space to arrive at

\[
\int_{\Omega} \left( T^{n+1} - T^n - \frac{\Delta t}{\sigma C_p} F(x, y, t_{n+1}) \right) \Psi \, d\omega \\
+ \frac{\Delta t}{\sigma C_p} \left[ \int_{\Omega} (k \nabla T^{n+1} \cdot \nabla \Psi) \, d\omega + \int_{\partial \Omega} (k \nabla T^{n+1} \cdot \hat{n}) \, \Psi \, d\sigma \right] = 0 ,
\]

where \( T^n(x, y) \triangleq T(n \Delta t, x, y) \), and \( \Psi \in H^1(\Omega) \) is a test function.
Imposing the specified boundary conditions, the boundary term evaluates to

$$
\int_{\partial \Omega} \left( k \nabla T^{n+1} \cdot \hat{n} \right) \psi \ d\sigma = \int_0^w f(y) \psi(L, y) \ dy \\
- \int_0^w \alpha(y) \left[ T^{n+1}(0, y) - \beta(y) \right] \psi(0, y) \ dy.
$$

Details are described in the 2D Heat ex.pdf file in the distribution material.
2D Heat Equation (cont’d)

We use quadratic functions on triangular elements.

Impose a regular $n_x \times n_y = ((2\ell + 1) \times (2m + 1))$ grid.

Using the odd-labeled points we generate $\ell m$ rectangles; diagonals divide these into $2 \ell m$ triangles.

Here’s the case $n_x = n_y = 5$ (8 elements, 25 grid points):
Seek an approximate solution: \( T_N^n(x, y) = \sum_{j=1}^{N} z_j^n \Phi_j(x, y) \).

\[
\sum_j \left[ \int_\Omega \Phi_j(x, y) \Phi_i(x, y) \, d\omega \right] z_j^{n+1} \\
+ \frac{\Delta t}{\sigma C_p} \left( \int_\Omega (k \nabla \Phi_j \cdot \nabla \Phi_i) \, d\omega + \int_0^w \alpha(y) \Phi_j(0, y) \Phi_i(0, y) \, dy \right) \\
- \sum_j \left[ \int_\Omega \Phi_j(x, y) \Phi_i(x, y) \, d\omega \right] z_j^n - \left[ \frac{\Delta t}{\sigma C_p} \int_\Omega F(x, y, t_{n+1}) \Phi_i \, d\omega \right] \\
- \frac{\Delta t}{\sigma C_p} \left[ \int_L^w f(y) \Phi_i(L, y) \, dy + \int_0^w \alpha(y) \beta(y) \Phi_i(0, y) \, dy \right] = 0
\]

In matrix terminology

\[
(M_1 + M_2) z^{n+1} - M_1 z^n + F(t_{n+1}) + b = 0.
\]
We began with a serial code for building $\mathbf{M}_1$, $\mathbf{M}_2$, $\mathbf{F}$ and $\mathbf{b}$. Here, we briefly note the changes to build codistributed versions of these.
function [M1, M2, F, b, x, e_conn] = assemb_co(param)
% The FEM equation for the temp. dist at time t_{n+1} satisfies
% (M_1 + M_2) z^{n+1} - M_1 z^n + F + b = 0

%%% Initialization & geometry
%-- lines omitted
%%% Set up codistributed structure

% column pointers and such for codistributed arrays
Vc = codcolon(1, n_equations);
IP = localPart(Vc); IP_1 = IP(1); IP_end = IP(end);
dPM = distributionPartition(codistributor(Vc));
col_shft = [0 cumsum(dPM(1:end-1))];

%%% local sparse arrays
M1_lab = sparse(n_equations, dPM(lab_index)); M2_lab = M1_lab;
b_lab = sparse(dPM(lab_index), 1); F_lab = b_lab;

%%% 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 = my_extract(nodes_local, IP_1, IP_end);
  if ~isempty(lab_nodes_local) % continue the calculation for this elmnt
    %-- calculate local arrays -- lines omitted
%% Assemble contributions into the global system matrices (on this lab) 
% 
for n_t = 1:nel_dof  % local DOF — test fcn 
  t_glb = nodes_local(n_t);  % global DOF — test fcn 
  for n_u = 1:size(lab_nodes_local, 1) 
    n_locj = lab_nodes_local(n_u, 1);  % local DOF in current n_el 
    n_glbj = lab_nodes_local(n_u, 2) ... 
      - col_shft(labindex);  % global DOF 
      M1_lab(t_glb, n_glbj) = M1_lab(t_glb, n_glbj) ... 
      + M1_loc(n_t, n_locj); 
    M2_lab(t_glb, n_glbj) = M2_lab(t_glb, n_glbj) ... 
      + param.dt*M2_loc(n_t, n_locj); 
  end 

  if t_glb >= IP_1 && t_glb <= IP_end  % is node on this lab? 
    t_loc = t_glb - col_shft(labindex); 
    b_lab(t_loc, 1) = b_lab(t_loc, 1) - param.dt*b_loc(n_t,1); 
    F_lab(t_loc, 1) = F_lab(t_loc, 1) - param.dt*F_loc(n_t,1); 
  end  % for n_t 
end  % if not empty 
end  % n_el 

%% Assemble the lab contributions in a codistributed format 
M1 = codistributed(M1_lab, codistributor('1d', 2)); 
M2 = codistributed(M2_lab, codistributor('1d', 2)); 
b = codistributed( b_lab, codistributor('1d', 1)); 
F = codistributed( F_lab, codistributor('1d', 1));
Example: $5 \times 5$ grid on 4 labs

There are 8 triangular elements, and 25 nodes. The nodes are color-coded for the four labs.

Note that lab 1 (green) requires evaluation on 4 of 8 elements, while lab 2 (blue) requires 7 of 8.

Clearly, our naive nodal assignment to labs leaves the computational load badly balanced.
%%% run these in Matlab

```matlab
% pmode start 4
Vc = codcolon(1, 25)
dPM = distributionPartition(codistributor(Vc))
col_shft = [ 0 cumsum(dPM(1:end-1))]
whos
```

%%%
% Script to assemble matrices for a 2D diffusion problem

%% set path
addpath './subs_source/oned'; addpath './subs_source/twod'

%% set parameter values and assemble arrays
param = p_data();
[M1, M2, F, b, x, e_conn] = assemb_co(param);

%% clean-up path
rmpath './subs_source/oned'; rmpath './subs_source/twod'

%% Steady state solutions
z_tmp = full(M2) \ full(F+b); % Temperature distribution
z_ss = gather(z_tmp, 1);

%% Plot and save a surface plot
if labindex == 1
    xx = x(1:param.nodesx, 1);
    yy = x(1:param.nodesx:,param.nodesx*param.nodesy, 2);
    figure
    surf(xx, yy, reshape(z_ss, param.nodesx, param.nodesy))
    xlabel('\textbf{x}'); ylabel('\textbf{y}'); zlabel('\textbf{T}');
    t_axis = axis;
    print -dpng fig_ss.png
end
close all
A folder with the software, example output and descriptive material is in the \texttt{parallel_matlab} folder on your desktop. The folder should look like:
Until recently, Advanced Research Computing at Virginia Tech had very limited support for MATLAB.

MATLAB was only available on the Sun cluster known as Dante. (The MathWorks dropped support for the SGI Altix system some years ago).

Although the Parallel Computing Toolbox was available, there were some incompatibilities between the system and the software, which meant that parallel performance was poor.

Because of strong user interest, a better platform was needed.
In June 2009, ARC received a new IBM iDataPlex cluster known as **Ithaca**.

Ithaca will be opened to the general computing community in October 2009. In the meantime, a limited number of “friendly users” will be able to work on the machine, trying it out, porting codes, and reporting problems.

Ithaca is an *expandable* system; as it takes over the load from System X and other research clusters, more racks will be added.
The current system has

- **84 nodes**, each with 24 GB of memory (some have 48 GB)
- **168 processors**, each node has two Intel Nehalem processors
- **672 cores**, each processor has 4 cores
Ithaca shares the `sysx` file system already used by System X and the other ARC computing clusters. Any files you stored or created on System X can be seen and used by Ithaca.

To copy files between Ithaca and your local system, use the `sftp` program:

```
sftp my_name@ithaca.arc.vt.edu

cd ithaca/my_project
put my_m_file.m
get my_output.txt

quit
```
For interactive access to Ithaca, log in using the `ssh` command.

```
ssh my_name@ithaca.arc.vt.edu
```

Especially if you are going to run MATLAB interactively, you will want to use the `-X` switch, to enable X-window graphics!

```
ssh -X my_name@ithaca.arc.vt.edu
```

If you don’t do this, and start MATLAB, you’ll get the warning:

```
Warning: No display specified.
You will not be able to display graphics on the screen.
```
MATLAB can be run interactively on Ithaca.

To access some of your M-files during the session, start the session from the directory that contains those files.

Start with the interactive command:

```
matlab
```

You will get the familiar interactive command window, which will stay until you enter **quit** or **exit**.

If you issue plot commands, the usual plot window will show up.
If you’ve enabled X Window graphics, MATLAB will open a separate command window. In that case, it’s really convenient to be able to move to the Ithaca command window and issue commands there as well.

But Ithaca won’t let you do this unless you use the & ("ampersand") switch at the end of the command that starts MATLAB:

```
matlab &
```

This means start up MATLAB, but also give me UNIX commandline access immediately. The MATLAB command window will be available by selecting it.
Even though Ithaca is a cluster, when you log in, you see only one node, which has 8 cores.

You can easily run parallel MATLAB locally, with up to 8 workers.

```
matlabpool open local 8
```

```
samson
```

```
matlabpool close
```

The "local" keyword refers to the local configuration. A configuration tells MATLAB how to get the workers you ask for.
When computing in parallel, it’s the cores that do the work.

When you log into Ithaca and start MATLAB, you have local access to one node, which has 8 cores, and that means you can get at most 8 MATLAB workers.

If more workers are desired, you have to tell MATLAB to find some more nodes and coordinate them.

MATLAB only knows how to do this if, in the `matlabpool` command, you replace the `local` configuration by the `ithaca` configuration which explains where all the nodes are and how to get them.
Start MATLAB;
Select the **Parallel** menu, then **Manage Configurations**;
Select the **File** menu, then **Import**;
Select the file `/apps/share/ithacaq.mat` and click **Import**;
Your configuration list should now include `local` and `ithaca`;
Double click on `ithaca`, which should open a dialogue box;
In **DataLocation** insert your PID in `/home/YOUR_USERNAME`;
In **SubmitArguments** replace `-lwalltime=HH:MM:SS`, by `-lwalltime=00:10:00`;
Click **OK** to save the configuration;
Click **Start Validation**;
Once validation has completed, exit MATLAB.
The time limit you specify for this configuration will apply to all jobs you submit. You can go back into the Parallel menu and change this value if you need to.

If the validation process fails, then there is something wrong with the configuration file, the other parameters you typed, file permissions, or the setup of MATLAB. Check your steps one more time, and then report the problem to ARC.

From now on, you have two configurations defined, local and ithaca. You choose the appropriate configuration on the matlabpool command.
If you want to run MATLAB on more than 8 cores, you need to use more than 1 node. The **ithaca** configuration takes care of getting the necessary nodes and starting up MATLAB workers on them. You specify the configuration in your **matlabpool** command:

```matlab
matlabpool open ithaca 16
samson
matlabpool close
```
If your MATLAB program takes a long time to run, or is complicated, it may make sense to run MATLAB “indirectly”. Technically, this is still an interactive session, but your command input will come from a file (perhaps “input.m”).

To keep MATLAB from trying to set up the command window you may want to include the -nodisplay switch.

The typical command gets a little complicated now:

matlab -nodisplay < input.m > output.txt &

The & at the end of the command line allows you to issue other commands while waiting for matlab to complete.
Suppose you want to run many jobs, or jobs that take a long time to start or run, and you don’t want to remain logged in to Ithaca, running MATLAB and waiting.

You can submit jobs to the ARC queueing system. The system will take care of running all the jobs on the available resources, and preserving the printed output in files. You can submit your jobs to the queue and log out.

The queueing system on Ithaca uses the same set of PBS commands to set time limits, number of nodes and so on.

What follows is an example of a job that runs a parallel MATLAB program under the queueing system.
#!/bin/bash
#PBS -lwalltime=00:05:00
#PBS -lnodes=2:ppn=8
#PBS -W group_list=matlab
#PBS -A matlab0001
#PBS -q ithaca_q@admin01
#PBS -lpartition=ITHACA

cd $PBS_O_WORKDIR
export PATH=/nfs/software/bin:$PATH

matlab -nodisplay < example_run.m > example_output.txt
You have been assigned an Ithaca account temporarily. These accounts are intended to let you carry out the class assignments, and familiarize yourself with the system. They will expire within a week.

Ithaca will be open to general users in October.

If you are interested in parallel MATLAB on Ithaca, and want to get an early start, you can participate in our Friendly User program, which will give you an account to develop, test and benchmark your programs.
MATLAB Parallel Computing

- Introduction
- Local Parallel Computing
- Parallelism with PARFOR
- The PRIME_NUMBER Example
- Behind the Magic
- Bumps in the Road
- The MD Example
- Parallelism with SPMD
- Parallel Computing with fmincon
- Codistributed Arrays
- A 2D Heat Equation
- Parallel MATLAB at Virginia Tech
- Conclusion
The new IBM cluster will encourage a parallel MATLAB community.

Any faculty, any graduate student will be able to request an account using:

**IBM System Account Request Application Form**

which will be available (once the system is ready) at:

http://www.arc.vt.edu/arc/UserAccounts.php

You’ll need your PID and password to access the form.
Users will find it convenient to work with MATLAB interactively for program development and debugging.

However, jobs that use many nodes or run for a long time are better handled by the queueing system.

The commands in your job file might move to the appropriate directory, start up MATLAB with an input command file. The output will be preserved in the queue log, or can be written to a separate text file.
This class is intended as an overview to parallel MATLAB and Ithaca.

The Mathworks has official training classes on parallel MATLAB.

If we can get 20 people to register, we can have the Mathworks give a half-day presentation on parallel MATLAB.

We hope that this class has given you enough information so that you can experiment with parallel MATLAB, and come to the MathWorks training session with some hard questions!
MATLAB Parallel Computing: Reminder

Please don’t forget!
**ITHACA** is an IBM iDataPlex cluster recently installed by Virginia Tech’s Advanced Research Computing facility.

It is intended to gradually take over the high performance computing load from System X.

**ITHACA** supports OpenMP, MPI and Parallel MATLAB programming.

- **Right Now:** Friendly users accepted for Ithaca *(talk to John Burkardt if you are interested,)*;
- **Mid October:** Ithaca opened to general users *(accounts given out through online application.)*.
MATLAB Training is available this fall.

These classes will be presented by the MathWorks. Some of these classes are tentative. Check the FDI website for details.

- **2 October**: Simulink (daylong);
- **3 October**: SimMechanics (daylong);
- **8 October**: MATLAB Programming Techniques.
- **8 October**: Parallel Computing with MATLAB.
- **29 October**: Parallel Computing with MATLAB (daylong).
- **19 November**: Real-time Data Acquisition and Control.
- **19 November**: Statistical Methods in MATLAB.