Using SpF to Achieve Petascale for Legacy Pseudospectral Applications

Dynamics of Planetary and Stellar Interiors Conference
July 28-31, 2014 — La Jolla, CA

Thomas Clune
Weiyuan Jiang

NASA Goddard Space Flight Center

July 29, 2014
Background/Motivation

NASA HEC supports at least 5 pseudospectral applications:

Spherical Geometry
- DYNAMO
- MoSST
- ASH

Cartesian Geometry
- HPS
- DDSCAT
Background/Motivation

NASA HEC supports at least 5 pseudospectral applications:

**Spherical Geometry**
- DYNAMO
- MoSST
- ASH

**Cartesian Geometry**
- HPS
- DDSCAT

All except ASH use a 1D decomposition:
Background/Motivation

NASA HEC supports at least 5 pseudospectral applications:

<table>
<thead>
<tr>
<th>Spherical Geometry</th>
<th>Cartesian Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>• DYNAMO</td>
<td>• HPS</td>
</tr>
<tr>
<td>• MoSST</td>
<td>• DDSCAT</td>
</tr>
<tr>
<td>• ASH</td>
<td></td>
</tr>
</tbody>
</table>

All except ASH use a 1D decomposition:

- limits scalability/performance
- constrains grid resolution
Background/Motivation

NASA HEC supports at least 5 pseudospectral applications:

<table>
<thead>
<tr>
<th>Spherical Geometry</th>
<th>Cartesian Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>• DYNAMO</td>
<td>• HPS</td>
</tr>
<tr>
<td>• MoSST</td>
<td>• DDSCAT</td>
</tr>
<tr>
<td>• ASH</td>
<td></td>
</tr>
</tbody>
</table>

All except ASH use a 1D decomposition:

• limits scalability/performance
• constrains **grid resolution**
Consequences of 1D decomposition

Scaling Legendre Transforms

- 1D Radial (T480x120L)
- 1D Wavenumber (T480x120L)
- 2D Extrapolation (T480x129)
Other motivations

Pseudospectral methods have an elegant structure that provides quite interesting challenges from a software design perspective.
Other motivations

Pseudospectral methods have an elegant structure that provides quite interesting challenges from a software design perspective

- Alternate between local computation and all-to-all communication
Other motivations

Pseudospectral methods have an elegant structure that provides quite interesting challenges from a software design perspective

- Alternate between *local* computation and all-to-all communication
- Complicated data structures (harmonic truncation)
Other motivations

Pseudospectral methods have an elegant structure that provides quite interesting challenges from a software design perspective

• Alternate between *local* computation and all-to-all communication
• Complicated data structures (harmonic truncation)
• Nontrivial load-balance
Pseudospectral methods have an elegant structure that provides quite interesting challenges from a software design perspective

- Alternate between *local* computation and all-to-all communication
- Complicated data structures (harmonic truncation)
- Nontrivial load-balance
- Most numerical calculations can be done with vendor-optimized libraries
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)

- **Support multiple geometries (sphere, box, ...?)**
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- Enable *decomposition independent* formulation of applications
- Allow user extensions/refinements (OO)
- Enable users to focus on *science*
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)

- Support multiple geometries (sphere, box, ...?)
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- Enable decomposition independent formulation of applications
- Allow user extensions/refinements (OO)
- Enable users to focus on science
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)
- Support multiple geometries (sphere, box, ...?)
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- Enable \textit{decomposition independent} formulation of applications
- Allow user extensions/refinements (OO)
- Enable users to focus on \textit{science}
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)

- Support multiple geometries (sphere, box, ...?)
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- **Support async communication, hybrid-parallelism and HW accelerators**
- Enable *decomposition independent* formulation of applications
- Allow user extensions/refinements (OO)
- **Enable users to focus on science**
Solution - SpF

SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)
- Support multiple geometries (sphere, box, ...?)
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- **Enable decomposition independent formulation of applications**
- Allow user extensions/refinements (OO)
- **Enable users to focus on science**
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)
- Support multiple geometries (sphere, box, ...?)
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- Enable \textit{decomposition independent} formulation of applications
- \textbf{Allow user extensions/refinements (OO)}
- Enable users to focus on \textit{science}
SpF (Spectral Framework) is a software framework tailor designed to maximize the performance and scalability of pseudospectral applications.

Specific design goals: (separation of concerns)
- Support multiple geometries (sphere, box, ...)?
- Manage: domain decomposition, transpose, and I/O operations
- Leverage optimized numerical libraries
- Support async communication, hybrid-parallelism and HW accelerators
- Enable decomposition independent formulation of applications
- Allow user extensions/refinements (OO)
- Enable users to focus on science
Benefits of adopting SpF

- Less duplication of effort
  - Parallel “transforms” — Legendre, LU Decomposition, etc.
  - Tedious/fragile transpose implementations
- Reduced effort to exploit new architectures/accelerators
- Readily adopt/share performance innovations within the community
Challenges and Complications

Nonlinear terms

FFT

Legendre

Chebychev

Implicit Update
Challenges and Complications

- Triangular
- Rhomboidal
- Trapezoidal (or pentagonal)
Each transform can be expressed as a union of independent, atomic (indivisible) numerical ‘kernels’ \( \{K_1, K_2, \ldots, K_n\} \).
SpF: The Secret Sauce

Each transform can be expressed as a union of independent, atomic (indivisible) numerical ‘kernels’ \( \{K_1, K_2, \ldots, K_n\} \).

These provide a natural partition of the computational domain:

\[
(X, d_x) = \left((\tilde{X}_q^1, d_x^1 \otimes q^1) \oplus (\tilde{X}_q^2, d_x^2 \otimes q^2) \oplus \ldots \oplus (\tilde{X}_q^n, d_x^n \otimes q^n)\right)
\]

\[
(Y, d_y) = \left((\tilde{Y}_q^1, d_y^1 \otimes q^1) \oplus (\tilde{Y}_q^2, d_y^2 \otimes q^2) \oplus \ldots \oplus (\tilde{Y}_q^n, d_y^n \otimes q^n)\right)
\]

\[Y = F(X) \implies \tilde{Y}_q^i = K_i(\tilde{X}_q^i), \ i = 1, 2, \ldots, n\]
Each transform can be expressed as a union of independent, atomic (indivisible) numerical ‘kernels’ \( \{ K_1, K_2, \ldots, K_n \} \).

These provide a natural partition of the computational domain:

\[
(X, d_x) = \left( (\tilde{X}_q^1, d_x^1 \otimes q^1) \oplus (\tilde{X}_q^2, d_x^2 \otimes q^2) \oplus \ldots \oplus (\tilde{X}_q^n, d_x^n \otimes q^n) \right)
\]

\[
(Y, d_y) = \left( (\tilde{Y}_q^1, d_y^1 \otimes q^1) \oplus (\tilde{Y}_q^2, d_y^2 \otimes q^2) \oplus \ldots \oplus (\tilde{Y}_q^n, d_y^n \otimes q^n) \right)
\]

\[
Y = F(X) \implies \tilde{Y}_q^i = K_i(\tilde{X}_q^i), i = 1, 2, \ldots, n
\]
SpF: Key Software Abstractions

- Kernel - Indivisible unit of algorithm
  - Most user customization is here
SpF: Key Software Abstractions

- Kernel - Indivisible unit of algorithm
  - Most user customization is here
- Permutor - *Automatic* generation of communication logic for global transposes
SpF: Key Software Abstractions

- Kernel - Indivisible unit of algorithm
  - Most user customization is here
- Permutor - *Automatic* generation of communication logic for global transposes
- Distributor - Responsible for domain decomposition (including load balance)
SpF: Key Software Abstractions

- **Kernel** - Indivisible unit of algorithm
  - Most user customization is here
- **Permutor** - *Automatic* generation of communication logic for global transposes
- **Distributor** - Responsible for domain decomposition (including load balance)
- **IndexSpace** - Describes *arbitrary* data layout within/across PEs
SpF: Key Software Abstractions

- Kernel - Indivisible unit of algorithm
  - Most user customization is here
- Permutor - *Automatic* generation of communication logic for global transposes
- Distributor - Responsible for domain decomposition (including load balance)
- IndexSpace - Describes arbitrary data layout within/across PEs
- Field - Local array and associated IndexSpace
  - Lingua franca within the framework
  - Input/output for kernel
SpF: Key Software Abstractions

- **Kernel** - Indivisible unit of algorithm
  - Most user customization is here
- **Permutor** - *Automatic* generation of communication logic for global transposes
- **Distributor** - Responsible for domain decomposition (including load balance)
- **IndexSpace** - Describes arbitrary data layout within/across PEs
- **Field** - Local array and associated IndexSpace
  - Lingua franca within the framework
  - Input/output for kernel
- **FieldList** - Local collection of Field objects
  - In/out for permutation
SpF: Key Software Abstractions

- Kernel - Indivisible unit of algorithm
  - Most user customization is here
- Permutor - *Automatic* generation of communication logic for global transposes
- Distributor - Responsible for domain decomposition (including load balance)
- IndexSpace - Describes *arbitrary* data layout within/across PEs
- Field - Local array and associated IndexSpace
  - Lingua franca within the framework
  - Input/output for kernel
- FieldList - Local collection of Field objects
  - In/out for permutation
- LinearSolver - Implicit updates
SpF: Key Software Abstractions

- **Kernel** - Indivisible unit of algorithm
  - Most user customization is here
- **Permutor** - *Automatic* generation of communication logic for global transposes
- **Distributor** - Responsible for domain decomposition (including load balance)
- **IndexSpace** - Describes arbitrary data layout within/across PEs
- **Field** - Local array and associated IndexSpace
  - Lingua franca within the framework
  - Input/output for kernel
- **FieldList** - Local collection of Field objects
  - In/out for permutation
- **LinearSolver** - Implicit updates
- **Integrator** - time integration (CN, AB, ...)

T. Clune
SpF - DPSIC 10/31
SpF: Implementation details

- Object-oriented design (ala Fortran 2003)
  - Applications built by extending SpF abstractions
  - User-extensions that can be shared by community
- Aggressive use of test-driven development (TDD) & pFUnit
  - More than 300 unit tests
  - Runs on at least 3 compilers (Intel, GNU, NAG)
- Demonstrated with multi-layer shallow water
- Not quite ready for distribution
  - Open source release planned (tedious paperwork)
  - Project-level release could be expedited
How SpF sees an application
use SpF_mod

class (IndexSpace) :: cartesian
type (RangeAxis) :: xAxis, yAxis, zAxis

xAxis = RangeAxis(’x’, nx)
yAxis = RangeAxis(’y’, ny)
zAxis = RangeAxis(’z’, nz)

allocate(cartesian, source= xAxis*yAxis*zAxis)
use Spf_mod

class (IndexSpace) :: cartesianBundle

type (RangeAxis) :: xAxis, yAxis, zAxis

type (StringAxis) :: qtys

xAxis = RangeAxis(‘x’, nx)
yAxis = RangeAxis(‘y’, ny)
zAxis = RangeAxis(‘z’, nz)

allocate(cartesianBundle, source= &
& xAxis*yAxis*zAxis*qtys)
IndexSpace - Triangular Truncation

```plaintext
use SpF_mod

class (IndexSpace) :: tDomain

class (OuterProductSpace) :: modeAxis

type (RangeAxis) :: rAxis

modeAxis = RangeAxis(’m’, 0, 0) * RangeAxis(’ell’, 0, Lmax)
Allocate(tDomain, source=mode)

do m = 1, mMax
    modeAxis = RangeAxis(’m’, m, m) * RangeAxis(’ell’, m, Lmax)
    allocate(tDomain, source= tDomain + modeAxis)
end do

allocate(tDomain, source= RangeAxis(’r’, nn)*tDomain)
```
Automating the transpose

First we translate the index space into a labelled table:

\[
\begin{array}{cccc}
\ell & m & r & f \\
0 & 0 & 1 & 'S' \\
1 & 0 & 1 & 'S' \\
\vdots & \vdots & \vdots & \vdots \\
10 & 7 & 10 & 'Z' \\
\end{array}
\]

\[
\begin{array}{cccc}
\ell & m & r & f \\
7 & 2 & 3 & 'W' \\
7 & 2 & 4 & 'W' \\
\vdots & \vdots & \vdots & \vdots \\
0 & 12 & 2 & 'P' \\
\end{array}
\]
Automating the transpose

Then we append process and offset metadata:

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( m )</th>
<th>( r )</th>
<th>( f )</th>
<th>( PE )</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>10</td>
<td>'Z'</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( m )</th>
<th>( r )</th>
<th>( f )</th>
<th>( PE )</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2</td>
<td>3</td>
<td>'W'</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>4</td>
<td>'W'</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
<td>\vdots</td>
</tr>
<tr>
<td>0</td>
<td>12</td>
<td>2</td>
<td>'P'</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>
Automating the transpose

Then we append process and offset metadata:

<table>
<thead>
<tr>
<th>ℓ</th>
<th>m</th>
<th>r</th>
<th>f</th>
<th>PE</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>10</td>
<td>'Z'</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

Then we “co-sort” the tables to find source/destination for each element:

<table>
<thead>
<tr>
<th>ℓ</th>
<th>m</th>
<th>r</th>
<th>f</th>
<th>p_{src}</th>
<th>δ_{src}</th>
<th>p_{dest}</th>
<th>δ_{dest}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>10</td>
<td>'Z'</td>
<td>8</td>
<td>15</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Automating the transpose

For a 2-phase (nested) transpose, we append the rank for each phase

<table>
<thead>
<tr>
<th>ℓ</th>
<th>m</th>
<th>r</th>
<th>f</th>
<th>PE₀</th>
<th>PE₁</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>'S'</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>10</td>
<td>'Z'</td>
<td>8</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ℓ</th>
<th>m</th>
<th>r</th>
<th>f</th>
<th>PE₀</th>
<th>PE₁</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2</td>
<td>3</td>
<td>'W'</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>4</td>
<td>'W'</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0</td>
<td>12</td>
<td>2</td>
<td>'P'</td>
<td>8</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

T. Clune  SpF - DPSIC  18/31
Primary configuration

• Azimuthal wavenumbers distributed over PEs
• Constraint $N_p \leq N_m$
• Supports variant spectral truncations and variant hyperviscosity terms
Author: Weijia Kuang

Primary configuration

- One dimensional Distribution over PEs at all stages
- Constraint: $N_p \leq N_m$
- Constraint: $N_p \leq N_r$
- Constraint: All Spherical transforms (Legendre and FFT) are in the same process
Adopting SpF - general strategy

1 Establish regression tests and data for baseline.
   • Invest in achieving *strong reproducibility*
   • Turn off optimization and turn on debugging flags

2 Proceed with incremental changes that preserve results

3 Commit to repository after each success.

4 Minor roundoff issues may be encountered
   • Isolate cause, then update baseline regression data
   • Bracket change in repository
Adopting SpF - copy to/from legacy data structures

1. Declare a FieldList object
2. Create a procedure that copies an array into a Field
3. For each contiguous array
   1. Define corresponding IndexSpace domain object
   2. Call append() method on FieldList
   3. Insert call to copy procedure just prior to use
Adopting SpF - Kernel Factory

1 Create a new module:
   1 Define a derived type that extends KernelFactory
   2 Implement methods that compute Kernel IndexSpace (I/O)
   3 Define a derived type that extends Kernel
   4 Implement apply() method that wraps actual computation

2 Declare and initialize in main code:
   1 new Factory defined above
   2 Distributor, Permutor
   3 TaskList, and 2 FieldLists (in and out)
   4 Build task list, and field lists using distributor and factory
   5 Build permutor object connecting previous transform to new

3 Use in main loop:
   1 Insert call to apply() method of TaskList object
Adoption status

MoSST
- Now uses SpF permutations

DYNAMO
- SpF conversion completed for
  - Legendre transforms
  - Quadratic convolution
  - Stream to vector (i.e. \( \{W, Z, \ldots\} \rightarrow \{v_r, v_\theta, \ldots\} \))
  - Permutations (including to/from legacy layout)
- Took \( \approx 1 \) week for expert (me)
  - Lots of ugly shortcuts
- Issues encountered with implicit update step
  - Could “cheat”
  - Will use experience to instead improve framework
Example - top declaration

```fortran
  type (SimpleMpiDistributor) :: d
  type (FieldList) :: leg_in, leg_out, NL_in, NL_out
  type (LegendreFactory) :: legFactory
  type (NL_ConvolutionFactory) :: NL_Factory
  type (PartitionedAlgorithm) :: legTasks, NL_tasks
  type (SimpleMpiIPermutor) :: perm
  class (IndexSpace) :: initialDomain

  d = SimpleMpiDistributor(MPI_communicator)
  legFactory = LegendreFactory(mMax=1023)
  NL_Factory = NL_ConvolutionFactory(ni, nk)
  initialDomain = ...
```
Example - initialization

```python
legTasks = d%distribute(legFactory, initialDomain)
leg_in = FieldList(legTasks, 'in')
leg_out = FieldList(legTasks, 'out')

NL_tasks = d%distribute(NL_Factory, leg_in)
NL_in = FieldList(NL_tasks, 'in')
NL_out = FieldList(NL_tasks, 'out')

perm = SimpleMpiPermutor(MPI_communicator, leg_out, NL_in)
```
Example - execute

1
2 call legTasks%apply(leg_in, leg_out)
3 call perm%permute(leg_out, NL_in)
4 call NL_tasks%apply(NL_in, NL_out)
5 ...
Variations
Variations

<table>
<thead>
<tr>
<th></th>
<th>Alternate load balancing strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>! type (SimpleMpiDistributor) :: d</td>
</tr>
<tr>
<td>2</td>
<td>! type (RoundRobinDistributor) :: d</td>
</tr>
</tbody>
</table>
Variations

! Alternate load balancing strategy
! type (SimpleMpiDistributor) :: d

type (RoundRobinDistributor) :: d

! Alternative permutation strategy
! type (SimpleMpiPermutor) :: perm

type (SomeOtherPermutor) :: perm
Variations

1 ! Alternate load balancing strategy
2 ! type (SimpleMpiDistributor) :: d
3 type (RoundRobinDistributor) :: d

5 ! Alternative permutation strategy
6 ! type (SimpleMpiPermutor) :: perm
7 type (SomeOtherPermutor) :: perm

9 ! Alternative Legendre implementation
10 ! type (LegendreFactory) :: legFactory
11 type (AltLegFactory) :: legFactory
Next steps

• Finish ports of DYNAMO, MoSST, HPS, DDSCAT
• Improve framework
  • Generalize/optimize Permutor classes
    • Allow for multiple sources
    • Allow for “subsetting”
    • Implement multiphase transpose (ala Nick Featherstone)
• Extend/improve kernels
  • Better mechanism for defining offsets
  • Allow for multiple sources/destinations
  • Allow for “fat” kernels that do internal communication (e.g. implicit treatment of coriolis)
• Release SpF as open source
Credits

- NASA High End Computing program for supporting this work
- Gary Glatmaier - for providing DYNAMO as an interesting challenge
Questions?