Constructing Parallel Data Distributions

Matthew Knepley, Michael Lange, and Gerard Gorman

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Mesh and Field Distribution

Suppose I want to distribute a mesh...

Mesh and Field Distribution

- Decide which cells go to which processes (partition)
- Tell processes how many cells are coming
- Send cell descriptions
- Mark *ghost* vertices/edges/faces
- Locally renumber/reorder

Suppose I want to distribute a field...

Mesh and Field Distribution

- Associate field values with parts of mesh
- Tell processes how many field values are coming
- Send field values
- Mark *ghost* values
- Locally renumber/reorder

Suppose I want to communicate ghost values...

Mesh and Field Distribution

- Construct map from owned values to ghost values
- Tell processes how many owned values are coming
- Send field values

Suppose I want to use a cell overlap...

Suppose I want many-to-many instead of one-to-many...

Suppose I want
Jacobian preallocation
instead of ghost values...

Parallel data distributions

can use a single interface

to first class objects.

Main Point

Parallel data distributions

can use a single interface

to first class objects.

Main Point

Parallel data distributions

can use a single interface

to first class objects.

Outline

Communication Automation

Point Space	**Dof Space**	**Section**	**SF**
Solution Dofs	Adjacent Dofs	Jacobian Layout →	Shared Adjacency
Mesh Points	Solution Dofs	Data Layout →	Shared Dofs
Mesh Points	Mesh Points	Topology →	Shared Topology
Processes	Mesh Points	Point Partition →	Shared Points
	Processes		Neighbors

Distribution Automation

We have two main tools:

PetscSection and PetscSF

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PetscSection and PetscSF

PetscSection

A PetscSection is a multimap

$$\mathrm{int} \longrightarrow \{\mathrm{int}\}$$

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$$\mathrm{int} \longrightarrow \{\mathrm{int}\}$$

which can represent **mesh topology**

$$\text{mesh point} \longrightarrow \{\text{mesh point}\}$$

PetscSection

A PetscSection is a multimap

$$\text{int} \longrightarrow \{\text{int}\}$$

which can represent **mesh partition**

$$\text{process} \longrightarrow \{\text{mesh point}\}$$

PetscSection

A PetscSection is a multimap

$$\text{int} \longrightarrow \{\text{int}\}$$

which can represent **data layout**

$$\text{mesh point} \longrightarrow \{\text{dof}\}$$

PetscSection

A PetscSection is a multimap

$$\text{int} \longrightarrow \{\text{int}\}$$

which can represent **Jacobian adjacency**

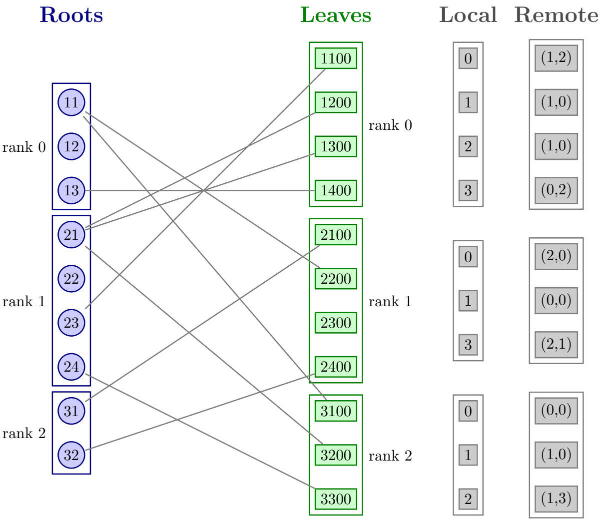
$$\text{dof} \longrightarrow \{\text{dof}\}$$

PetscSF

A PetscSF is a *star-forest*

$$\text{local dof (root)} \longrightarrow \{(\text{local dof},\ \text{process})\ (\text{leaf})\}$$

PetscSF


Roots
Leaves
Local
Remote
rank 0
11
12
13
rank 1
21
22
23
24
rank 2
31
32
1100
1200
1300
1400
rank 0
2100
2200
2300
2400
rank 1
3100
3200
3300
rank 2
0
1
2
3
0
1
3
0
1
2
(1,2)
(1,0)
(1,0)
(0,2)
(2,0)
(0,0)
(2,1)
(0,0)
(1,0)
(1,3)

Outline

Data Description

All data is understood as a function with

a domain consisting of *points*

and

a range consisting of *dofs*

Moving Data

In order to move data, we need

- a migration PetscSF
  - roots are old point distribution
  - leaves are new point distribution
- a PetscSection mapping points to dofs
  - in the old point distribution

Moving Data

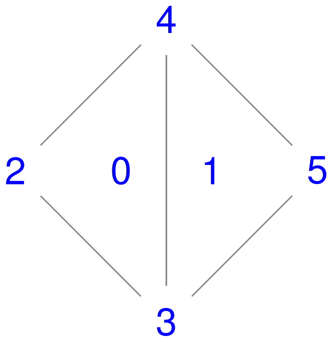
To redistribute the data, we

- redistribute the section
- derive a dof migration SF
  - Pushfoward of point migration SF over Section
- redistribute the values

Outline

Example
Field Data

Suppose that we have a P_1 discretization and want to distribute the data.



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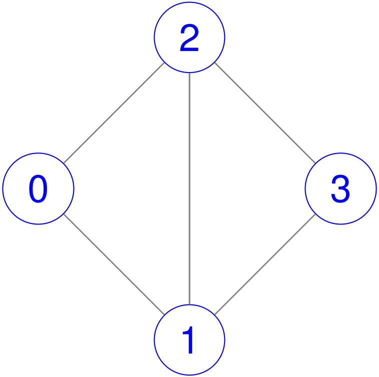
and want to distribute the data.



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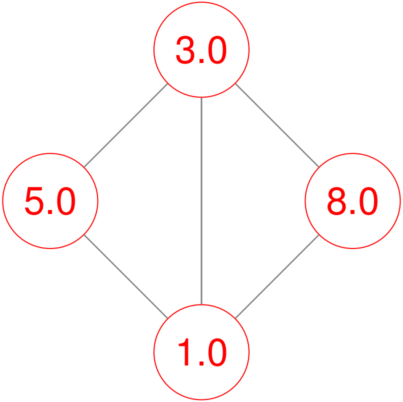


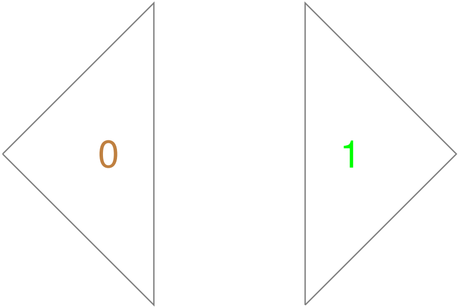
Example
Field Data

Suppose that we have a P_1 discretization
and want to distribute the data.

	Section		Vec
Proc 0	$2 \to \{1, 0\}$	$3 \to \{1, 1\}$	$\{5.0, 1.0, 3.0, 8.0\}$
	$4 \to \{1, 2\}$	$5 \to \{1, 3\}$	
Proc 1			$\{\}$

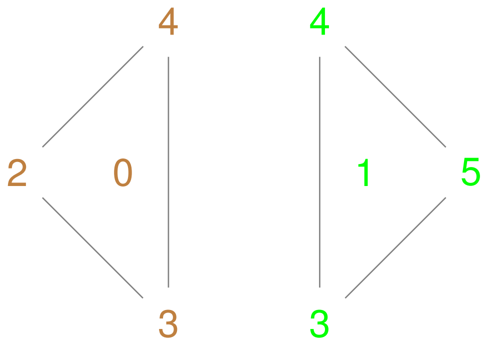
Partition

We create a partition of the cells,



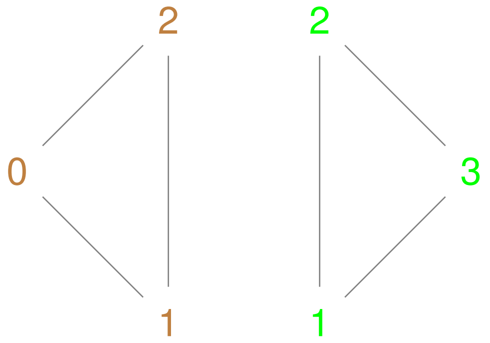
Partition

which induces a vertex partition



Partition

which induces a dof partition



Partition

and can be represented by a Section and IS

	Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{3, 3\}$	$\{0, 1, 2, 1, 2, 3\}$
Proc 1			$\{\}$

Bootstrap

Create a PetscSF that assumes everyone communicates:

Proc 0	Proc 1
$0 \to (p0, 0)$	$0 \to (p0, 1)$
$1 \to (p1, 0)$	$1 \to (p1, 1)$

Bootstrap

Create a PetscSF that assumes a broadcast from Proc 0:

Proc 0	Proc 1
$0 \to (p0, 0)$	$0 \to (p0, 1)$

Partition Inversion

Start with partition info at senders,

	Section		IS
Proc 0	$0 \to \{3, 0\}$	$1 \to \{3, 3\}$	$\{0, 1, 2, 1, 2, 3\}$
Proc 1	$0 \to \{0, 0\}$	$1 \to \{0, 0\}$	$\{\}$

but need partition info at receivers.

	Section		IS
Proc 0	$0 \to \{3, 0\}$	$1 \to \{0, 0\}$	$\{0, 1, 2\}$
Proc 1	$0 \to \{3, 0\}$	$1 \to \{0, 0\}$	$\{1, 2, 3\}$

```
DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
```

Partition Inversion

Start with partition info at senders,

	Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{3, 3\}$	$\{0, 1, 2, 1, 2, 3\}$
Proc 1	$0 \rightarrow \{0, 0\}$	$1 \rightarrow \{0, 0\}$	$\{\}$

but need partition info at receivers.

	Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{0, 0\}$	$\{0, 1, 2\}$
Proc 1	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{0, 0\}$	$\{1, 2, 3\}$

```
DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
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Partition Inversion

Start with partition info at senders,

	Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{3, 3\}$	$\{0, 1, 2, 1, 2, 3\}$
Proc 1	$0 \rightarrow \{0, 0\}$	$1 \rightarrow \{0, 0\}$	$\{\}$

but need partition info at receivers.

	Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{0, 0\}$	$\{0, 1, 2\}$
Proc 1	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{0, 0\}$	$\{1, 2, 3\}$

```
DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
```

Data Distribution

Now the serial data

	Section		Vec
Proc 0	$2 \to \{1, 0\}$	$3 \to \{1, 1\}$	$\{5.0, 1.0, 3.0, 8.0\}$
	$4 \to \{1, 2\}$	$5 \to \{1, 3\}$	
Proc 1			$\{\}$

can be distributed

	Section		Vec
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{5.0, 1.0, 3.0\}$
o	$3 \to \{1, 2\}$		
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{1.0, 3.0, 8.0\}$
	$3 \to \{1, 2\}$		

Data Distribution

using the same call on a new SF,

```
DistributeData(pointSF, dataSec, MPIU_SCALAR, data, newdataSec, newdata)
```

Notice the local renumbering of vertices.

can be distributed

	Section		Vec
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{5.0, 1.0, 3.0\}$
o	$3 \to \{1, 2\}$		
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{1.0, 3.0, 8.0\}$
	$3 \to \{1, 2\}$		

Data Distribution

Data distribution has three phases:

1. Distribute the Section
2. Create a new SF for the data
3. Distribute the data with SFBcast()

```
DistributeData(sf, secSource, dtype, dataSource, secTarget, dataTarget) {
  PetscSFDistributeSection(sf, secSource, remoteOff, secTarget);
  PetscSFCreateSectionSF(sf, secSource, remoteOff, secTarget, sfDof);
  PetscSFBcast(sfDof, dtype, dataSource, dataTarget);
}
```

Data Distribution
Phase I

The serial Section

	Serial Section	
Proc 0	$2 \to \{1, 0\}$	$3 \to \{1, 1\}$
	$4 \to \{1, 2\}$	$5 \to \{1, 3\}$
Proc 1		

is pushed over the point SF

Proc 0		Proc 1	
$0 \to (p0, 0)$	$1 \to (p0, 2)$	$0 \to (p0, 1)$	$1 \to (p0, 3)$
$2 \to (p0, 3)$	$3 \to (p0, 4)$	$2 \to (p0, 4)$	$3 \to (p0, 5)$

Data Distribution
Phase I

to give the parallel Section

Serial Section		Parallel Section	
$2 \rightarrow \{1, 0\}$	$3 \rightarrow \{1, 1\}$	$1 \rightarrow \{1, 0\}$	$2 \rightarrow \{1, 1\}$
$4 \rightarrow \{1, 2\}$	$5 \rightarrow \{1, 3\}$	$3 \rightarrow \{1, 2\}$	
		$1 \rightarrow \{1, 0\}$	$2 \rightarrow \{1, 1\}$
		$3 \rightarrow \{1, 2\}$	

is pushed over the point SF

Proc 0		Proc 1	
$0 \rightarrow (p0, 0)$	$1 \rightarrow (p0, 2)$	$0 \rightarrow (p0, 1)$	$1 \rightarrow (p0, 3)$
$2 \rightarrow (p0, 3)$	$3 \rightarrow (p0, 4)$	$2 \rightarrow (p0, 4)$	$3 \rightarrow (p0, 5)$

Data Distribution
Phase II

The point SF

Proc 0		Proc 1	
$0 \to (p0, 0)$	$1 \to (p0, 2)$	$0 \to (p0, 1)$	$1 \to (p0, 3)$
$2 \to (p0, 3)$	$3 \to (p0, 4)$	$2 \to (p0, 4)$	$3 \to (p0, 5)$

is expanded using the Section

	Section		
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$

Data Distribution
Phase II

to give a dof SF

Proc 0		Proc 1	
$0 \to (p0, 0)$	$1 \to (p0, 1)$	$0 \to (p0, 1)$	$1 \to (p0, 2)$
$2 \to (p0, 2)$		$2 \to (p0, 3)$	

is expanded using the Section

	Section		
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$

Data Distribution
Phase III

Now the serial data

	Serial Vec
Proc 0	$\{5.0, 1.0, 3.0, 8.0\}$
Proc 1	$\{\}$

is sent using the dof SF

Proc 0		Proc 1	
$0 \to (p0, 0)$	$1 \to (p0, 1)$	$0 \to (p0, 1)$	$1 \to (p0, 2)$
$2 \to (p0, 2)$		$2 \to (p0, 3)$	

Data Distribution
Phase III

to the parallel data distribution.

	Serial Vec	Parallel Vec
Proc 0	$\{5.0, 1.0, 3.0, 8.0\}$	$\{5.0, 1.0, 3.0\}$
Proc 1	$\{\}$	$\{1.0, 3.0, 8.0\}$

is sent using the dof SF

Proc 0		Proc 1	
$0 \rightarrow (p0, 0)$	$1 \rightarrow (p0, 1)$	$0 \rightarrow (p0, 1)$	$1 \rightarrow (p0, 2)$
$2 \rightarrow (p0, 2)$		$2 \rightarrow (p0, 3)$	

PetscSection Distribution

Section distribution has three phases:

1. Distribute the number of point dofs
2. Distribute the old dof offsets (used in dof SF)
3. Construct the Section locally

```
DistributeSection(sf, secSource, remoteOff, secTarget) {
  /* Calculate domain (chart) from local SF points */
  PetscSFBcast(sf, secSource.dof, secTarget.dof);
  /* Use remote offsets in PetscSFCreateSectionSF() */
  PetscSFBcast(sf, secSource.off, remoteOff);
  PetscSectionSetUp(secTarget);
}
```

PetscSF Distribution

```
DistributeSF(sfSource, sfMig, sfTarget) {
  PetscSFGetGraph(sfMig, Nr, Nl, leaves, NULL);
  for (p = 0; p < Nl; ++p) { /* Make bid to own all points we received */
    lowners[p].rank  = rank;
    lowners[p].index = leaves ? leaves[p] : p;
  }
  for (p = 0; p < Nr; ++p) { /* Flag so that MAXLOC ignores root value */
    rowners[p].rank  = -3;
    rowners[p].index = -3;
  }
  PetscSFReduce(sfMig, lowners, rowners, MAXLOC);
  PetscSFBcast(sfMig, rowners, lowners);
  for (p = 0, Ng = 0; p < Nl; ++p) {
    if (lowners[p].rank != rank) {
      ghostPoints[Ng] = leaves ? leaves[p] : p;
      remotePoints[Ng].rank  = lowners[p].rank;
      remotePoints[Ng].index = lowners[p].index;
      Ng++;
    }
  }
  PetscSFSetGraph(sfTarget, Np, Ng, ghostPoints, remotePoints);
}
```

Example
Jacobian Connectivity

We can use mesh topology to locally determine the nonzero pattern of the Jacobian,

	Serial Section		IS
Proc 0	$0 \to \{3, 0\}$	$1 \to \{4, 3\}$	{0, 1, 2, 0, 1, 2, 3,
	$2 \to \{4, 7\}$	$3 \to \{3, 11\}$	0, 1, 2, 3, 1, 2, 3}
Proc 1			

and using the same call on the dof SF,

```
DistributeData(dofSF, adjSec, MPIU_INT, adj, newadjSec, newadj);
```

Example
Jacobian Connectivity

it can be distributed.

	Serial Section		IS
Proc 0	$0 \rightarrow \{3, 0\}$	$1 \rightarrow \{4, 3\}$	{0, 1, 2, 0, 1, 2, 3, 0, 1, 2}
	$2 \rightarrow \{4, 7\}$		
Proc 1	$0 \rightarrow \{4, 0\}$	$1 \rightarrow \{4, 4\}$	{0, 1, 2, 3, 0, 1, 2, 3, 1, 2, 3}
	$2 \rightarrow \{3, 7\}$		

and using the same call on the dof SF,

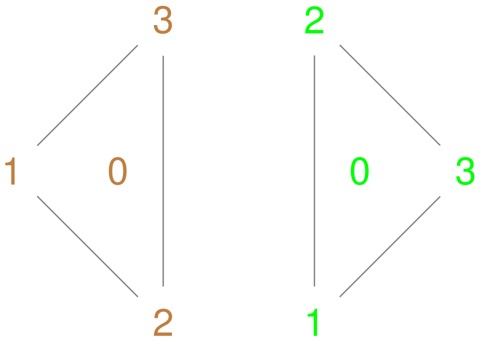
```
DistributeData(dofSF, adjSec, MPIU_INT, adj, newadjSec, newadj);
```

Outline

2 Moving Data
- P_1 Example
- Redistribution Example

Example
Redistribution

Suppose that we start with distributed P_1 and want to redistribute the data.



Example
Redistribution

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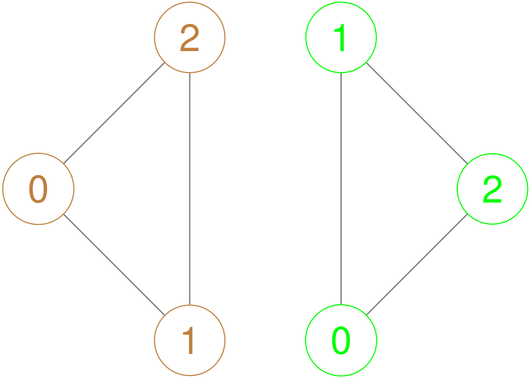

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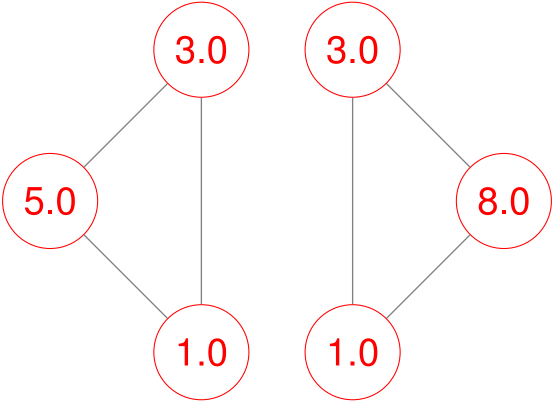

Example
Redistribution

Suppose that we start with distributed P_1
and want to redistribute the data.

	Local Section		Vec
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{5.0, 1.0, 3.0\}$
	$3 \to \{1, 2\}$		
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{1.0, 3.0, 8.0\}$
	$3 \to \{1, 2\}$		

Example
Redistribution

Suppose that we start with distributed P_1 and want to redistribute the data.

	Global Section		Vec
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$\{5.0, 1.0, 3.0\}$
	$3 \to \{1, 2\}$		
Proc 1	$1 \to \{1, -2\}$	$2 \to \{1, -3\}$	$\{8.0\}$
	$3 \to \{1, 3\}$		

Example
Redistribution

Suppose that we start with distributed P_1
and want to redistribute the data.

Point SF

Proc 0	Proc 1	
	$1 \to (p0, 2)$	$2 \to (p0, 3)$

Example
Redistribution

Suppose that we start with distributed P_1 and want to redistribute the data.

Dof SF

Proc 0	Proc 1
$0 \to (p0, 1)$	$1 \to (p0, 2)$

Partitioning

Again start with partition info at senders,

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

and get partition info at receivers.

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

using the same call and generic bootstrap SF.

```
DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
```

Partitioning

Again start with partition info at senders,

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

and get partition info at receivers.

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

using the same call and generic bootstrap SF.

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DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
```

Partitioning

Again start with partition info at senders,

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

and get partition info at receivers.

	Section		IS
Proc 0	$0 \to \{0, 0\}$	$1 \to \{4, 0\}$	$\{0, 1, 2, 3\}$
Proc 1	$0 \to \{4, 0\}$	$1 \to \{0, 4\}$	$\{0, 1, 2, 3\}$

using the same call and generic bootstrap SF.

```
DistributeData(procSF, partSec, MPIU_2INT, part, invpartSec, invpart);
```

Data Distribution
Phase I

The local Section

$$\begin{array}{ll} & \text{Local Section} \\ \text{Proc 0} & 1 \to \{1, 0\} \quad 2 \to \{1, 1\} \\ & 3 \to \{1, 2\} \\ \text{Proc 1} & 1 \to \{1, 0\} \quad 2 \to \{1, 1\} \\ & 3 \to \{1, 2\} \end{array}$$

is pushed over the migration point SF

$$\begin{array}{cc|cc} \multicolumn{2}{c}{\text{Proc 0}} & \multicolumn{2}{c}{\text{Proc 1}} \\ \hline 0 \to (p1, 0) & 1 \to (p1, 1) & 0 \to (p0, 0) & 1 \to (p0, 1) \\ 2 \to (p1, 2) & 3 \to (p1, 3) & 2 \to (p0, 2) & 3 \to (p0, 3) \end{array}$$

Data Distribution
Phase I

to give the new local Section

Old Section		New Section	
$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$
$3 \to \{1, 2\}$		$3 \to \{1, 2\}$	
$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$
$3 \to \{1, 2\}$		$3 \to \{1, 2\}$	

is pushed over the migration point SF

Proc 0		Proc 1	
$0 \to (p1, 0)$	$1 \to (p1, 1)$	$0 \to (p0, 0)$	$1 \to (p0, 1)$
$2 \to (p1, 2)$	$3 \to (p1, 3)$	$2 \to (p0, 2)$	$3 \to (p0, 3)$

Data Distribution
Phase II

The point SF

Proc 0		Proc 1	
$0 \to (p1, 0)$	$1 \to (p1, 1)$	$0 \to (p0, 0)$	$1 \to (p0, 1)$
$2 \to (p1, 2)$	$3 \to (p1, 3)$	$2 \to (p0, 2)$	$3 \to (p0, 3)$

is expanded using the Section

	Local Section		
Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$

Data Distribution

Phase II

to give a dof SF

Proc 0		Proc 1	
$0 \to (p1, 0)$	$1 \to (p1, 1)$	$0 \to (p0, 0)$	$1 \to (p0, 1)$
$2 \to (p1, 2)$		$2 \to (p0, 2)$	

is expanded using the Section

Local Section

Proc 0	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$
Proc 1	$1 \to \{1, 0\}$	$2 \to \{1, 1\}$	$3 \to \{1, 2\}$

Data Distribution
Phase III

Now the original data

	Old Vec
Proc 0	$\{5.0, 1.0, 3.0\}$
Proc 1	$\{1.0, 3.0, 8.0\}$

is sent using the dof SF

Proc 0		Proc 1	
$0 \rightarrow (p1, 0)$	$1 \rightarrow (p1, 1)$	$0 \rightarrow (p0, 0)$	$1 \rightarrow (p0, 1)$
$2 \rightarrow (p1, 2)$		$2 \rightarrow (p0, 2)$	

Data Distribution

Phase III

to the new data distribution.

	Old Vec	New Vec
Proc 0	$\{5.0, 1.0, 3.0\}$	$\{1.0, 3.0, 8.0\}$
Proc 1	$\{1.0, 3.0, 8.0\}$	$\{5.0, 1.0, 3.0\}$

is sent using the dof SF

Proc 0		Proc 1	
$0 \to (p1, 0)$	$1 \to (p1, 1)$	$0 \to (p0, 0)$	$1 \to (p0, 1)$
$2 \to (p1, 2)$		$2 \to (p0, 2)$	

Automation

We can automatically generate complex, parallel communication patterns for structured data

Automation

$$\text{Section} + \text{SF} \Longrightarrow \text{SF}$$

Automation

Partition + Bootstrap SF $\Longrightarrow$ Migration Point SF

Automation

Dof Section + Point SF $\Longrightarrow$
Migration Dof SF

Automation

Adjacency + Dof SF $\Longrightarrow$ Migration Adjacency SF

Automation

Topology + Point SF $\Longrightarrow$
Migration Topology SF

Automation

Simple Spec (FE, FV, FD) $\Longrightarrow$ Dof Section

Communication Automation

Point Space	**Dof Space**	**Section**	**SF**
Solution Dofs	Adjacent Dofs	Jacobian Layout →	Shared Adjacency
Mesh Points	Solution Dofs	Data Layout →	Shared Dofs
Mesh Points	Mesh Points	Topology →	Shared Topology
Processes	Mesh Points	Point Partition →	Shared Points
	Processes		Neighbors

Advantages

- Composable Abstractions
- Independent of
  - Dimension
  - Cell Shape
  - Discretization
- Localizes Optimization
- Extensible by User

Enabled Features

- Parallel Mesh Loads
- Parallel Load Balancing
- Arbitrary Mesh Overlap
- Arbitrary datatype support (DMNetwork)

Thank You!

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