

Introducing R: From Your Laptop to HPC and Big Data

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The pbdR Core Team

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112,896 Cores in 18,816 Nodes with 147 TB Memory

Support

This work used resources of the [Oak Ridge Leadership Computing Facility](#) at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725. This work also used resources of [National Institute for Computational Sciences](#) at the University of Tennessee, Knoxville, which is supported by the Office of Cyberinfrastructure of the U.S. National Science Foundation under Award No. ARRA-NSF-OCI-0906324 for NICS-RDAV center. This work used resources of the Newton HPC Program at the University of Tennessee, Knoxville.

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²University of Tennessee. Supported in part by the project “NICS Remote Data Analysis and Visualization Center” funded by the Office of Cyberinfrastructure of the U.S. National Science Foundation under Award No. ARRA-NSF-OCI-0906324 for NICS-RDAV center.

About This Presentation

Downloads

This presentation and supplemental materials are available at:

<http://r-pbd.org/tutorial>

Sample R scripts and pbs job scripts available on Nautilus from:
/lustre/medusa/proj/pbdR/tutorial/scripts.tar.gz

About This Presentation

Speaking Serial R with a Parallel Accent

The content of this presentation is based in part on the **pbdDEMO** vignette *Speaking Serial R with a Parallel Accent*

<http://goo.gl/HZkRt>

It contains more examples, and sometimes added detail.

About This Presentation

Installation Instructions

Installation instructions for setting up a pbdR environment are available:

<http://r-pbd.org/install.html>

This includes instructions for installing R, MPI, and pbdR.

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About This Presentation

Conventions For Code Presentation

We will use two different forms of syntax highlighting. One for displaying results from an interactive R session:

```
1 R> "interactive"  
2 [1] "interactive"
```

and one for presenting R scripts

```
1 "not interactive"
```

Contents

- 1 Introduction to R
- 2 pbdR
- 3 Introduction to pbdMPI
- 4 The Generalized Block Distribution
- 5 Basic Statistics Examples
- 6 Introduction to pbdDMAT and the DMAT Structure
- 7 Examples Using pbdDMAT
- 8 Wrapup

Contents

- 1 Introduction to R
 - What is R?
 - Basic Numerical Operations in R
 - R Syntax for Data Science: Not A Matlab Clone!

What is R?

- *lingua franca* for data analytics and statistical computing.
- Part programming language, part data analysis package.
- Dialect of S (Bell Labs).
- Syntax designed for data.

Who uses R?

Google, Pfizer, Merck, Bank of America, Shell^a, Oracle^b, Facebook, bing, Mozilla, okcupid^c, ebay^d, kickstarter^e, the New York Times^f

^ahttps://www.nytimes.com/2009/01/07/technology/business-computing/07program.html?_r=0

^b<http://www.oracle.com/us/corporate/features/features-oracle-r-enterprise-498732.html>

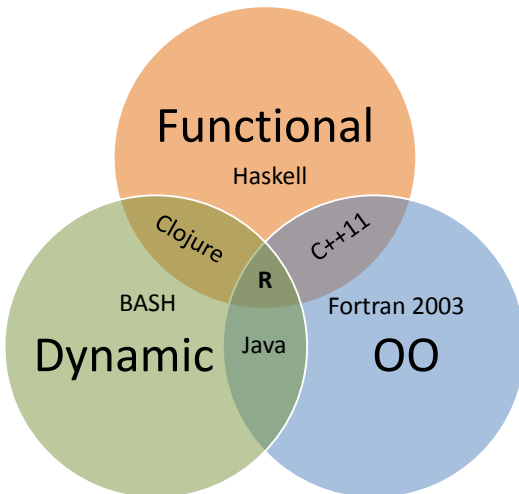
^c<http://www.revolutionanalytics.com/what-is-open-source-r/companies-using-r.php>

^d<http://blog.revolutionanalytics.com/2012/09/using-r-in-production-industry-experts-share-their-experiences.html>

^e<http://blog.revolutionanalytics.com/2012/09/kickstarter-facilitates-50m-in-indie-game-funding.html>

^f<http://blog.revolutionanalytics.com/2012/05/nyt-charts-the-facebook-ipo-with-r.html>

Language Paradigms



Data Types

- Storage: logical, int, double, double complex, character
- Structures: vector, matrix, array, list, dataframe
- Caveats: (Logical) TRUE, FALSE, NA

For the remainder of the tutorial, we will restrict ourselves to real number matrix computations.

Basics (1 of 2)

- The default method is to print:

```
1 R> sum
2 function (... , na.rm = FALSE) .Primitive("sum")
```

- Use <- for assignment:

```
1 R> x <- 1
2 R> x+1
3 [1] 2
```

- Naming rules: mostly like C.
- R is case sensitive.
- We use . the way most languages use _, e.g., La.svd() instead of La_svd().
- We use \$ (sometimes @) the way most languages use .

Basics (2 of 2)

- Use ? or ?? to search help

```

1 R> ?set.seed
2 R> ?comm.set.seed
3 No documentation for comm.set.seed in
  specified packages and libraries:
4 you could try ??comm.set.seed
5 R> ??comm.set.seed

```

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What is R?

Addons and Extras

R has the Comprehensive R Archive Network (CRAN), which is a package repository like CTAN and CPAN.

From R

```

1 install.packages("pbdMPI") # install
2 library(pbdMPI)           # load

```

From Shell

```

1 R CMD INSTALL pbdMPI_0.1-6.tar.gz

```



Basic Numerical Operations in R

Lists (1 of 1)

```

1 R> l <- list(a=1, b="a")
2 R> l
3 $a
4 [1] 1
5
6 $b
7 [1] "a"
8
9 R> l$a
10 [1] 1
11
12 R> list(x=list(a=1, b="a"), y=TRUE)
13 $x
14 $x$a
15 [1] 1
16
17 $x$b
18 [1] "a"
19
20
21 $y
22 [1] TRUE

```




Vectors and Matrices (1 of 2)

```

1 R> c(1, 2, 3, 4, 5, 6)
2 [1] 1 2 3 4 5 6
3
4 R> matrix(1:6, nrow=2, ncol=3)
5      [,1] [,2] [,3]
6 [1,]    1    3    5
7 [2,]    2    4    6
8
9 R> x <- matrix(1:6, nrow=2, ncol=3)
10
11 R> x[, -1]
12      [,1] [,2]
13 [1,]    3    5
14 [2,]    4    6
15
16 R> x[1, 1:2]
17 [1] 1 3

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Vectors and Matrices (2 of 2)

```
1 R> dim(x)
2 [1] 2 3
3
4 R> dim(x) <- NULL
5 R> x
6 [1] 1 2 3 4 5 6
7
8 R> dim(x) <- c(3,2)
9 R> x
10      [,1] [,2]
11 [1,]    1    4
12 [2,]    2    5
13 [3,]    3    6
```



Vector and Matrix Arithmetic (1 of 2)

```

1 R> 1:4 + 4:1
2 [1] 5 5 5 5
3
4 R> x <- matrix(0, nrow=2, ncol=3)
5
6 R> x + 1
7      [,1] [,2] [,3]
8 [1,]    1    1    1
9 [2,]    1    1    1
10
11 R> x + 1:3
12      [,1] [,2] [,3]
13 [1,]    1    3    2
14 [2,]    2    1    3

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```

Basic Numerical Operations in R

Vector and Matrix Arithmetic (2 of 2)

```

1 R> x <- matrix(1:6, nrow=2)
2
3 R> x*x
4      [,1] [,2] [,3]
5 [1,]    1    9   25
6 [2,]    4   16   36
7
8 R> x %*% x
9 Error in x %*% x : non-conformable arguments
10
11 R> t(x) %*% x
12      [,1] [,2] [,3]
13 [1,]    5   11   17
14 [2,]   11   25   39
15 [3,]   17   39   61
16
17 R> crossprod(x)
18      [,1] [,2] [,3]
19 [1,]    5   11   17
20 [2,]   11   25   39
21 [3,]   17   39   61

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Linear Algebra (1 of 2): Matrix Inverse

$$x_{n \times n} \text{ invertible} \iff \exists y_{n \times n} (xy = yx = Id_{n \times n})$$

```

1 R> x <- matrix(rnorm(5*5), nrow=5)
2 R> y <- solve(x)
3
4 R> round(x %*% y)
5      [,1] [,2] [,3] [,4] [,5]
6 [1,]    1    0    0    0    0
7 [2,]    0    1    0    0    0
8 [3,]    0    0    1    0    0
9 [4,]    0    0    0    1    0
10 [5,]    0    0    0    0    1

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Linear Algebra (2 of 2): Singular Value Decomposition

$$x = U\Sigma V^T$$

```

1 R> x <- matrix(rnorm(2*3), nrow=3)
2 R> svd(x)
3 $d
4 [1] 2.4050716 0.3105008
5
6 $u
7           [,1]      [,2]
8 [1,] 0.8582569 -0.1701879
9 [2,] 0.2885390  0.9402076
10 [3,] 0.4244295 -0.2950353
11
12 $v
13           [,1]      [,2]
14 [1,] -0.05024326 -0.99873701
15 [2,] -0.99873701  0.05024326

```

More than just a Matlab clone. . .

- Data science (machine learning, statistics, data mining, . . .) is mostly matrix algebra.

So what about Matlab/Python/Julia/ . . . ?

- The one you prefer depends more on your “religion” rather than differences in capabilities.
- As a *data analysis* package, R is king.

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Simple Statistics (1 of 2): Summary Statistics

```
1 R> x <- matrix(rnorm(30, mean=10, sd=3), nrow=10)
2
3 R> mean(x)
4 [1] 9.825177
5
6 R> median(x)
7 [1] 9.919243
8
9 R> sd(as.vector(x))
10 [1] 3.239388
11
12 R> colMeans(x)
13 [1] 9.661822 10.654686 9.159025
14
15 R> apply(x, MARGIN=2, FUN=sd)
16 [1] 2.101059 3.377347 4.087131
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Simple Statistics (2 of 2): Sample Covariance

$$\text{cov}(x_{n \times p}) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \mu_x)(x_i - \mu_x)^T$$

```

1 x <- matrix(rnorm(30), nrow=10)
2
3 # least recommended
4 cm <- colMeans(x)
5 crossprod(sweep(x, MARGIN=2, STATS=cm))
6
7 # less recommended
8 crossprod(scale(x, center=TRUE, scale=FALSE))
9
10 # recommended
11 cov(x)

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Advanced Statistics (1 of 2): Principal Components

PCA = centering + scaling + rotation (via SVD)

```

1 R> x <- matrix(rnorm(30), nrow=10)
2
3 R> prcomp(x, retx=TRUE, scale=TRUE)
4 Standard deviations:
5 [1] 1.1203373 1.0617440 0.7858397
6
7 Rotation:
8
9           PC1          PC2          PC3
10 [1,]  0.71697825 -0.3275365  0.6153552
11 [2,] -0.03382385  0.8653562  0.5000147
12 [3,]  0.69627447  0.3793133 -0.6093630

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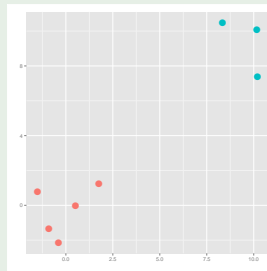
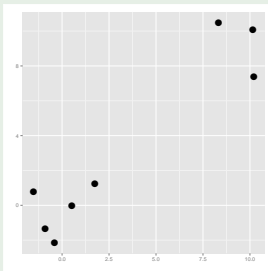
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R Syntax for Data Science: Not A Matlab Clone!

Advanced Statistics (2 of 2): k-Means Clustering



```
1 R> x <- rbind(matrix(rnorm(5*2), mean=0), ncol=2),
2               matrix(rnorm(3*2), mean=10), ncol=2))
```

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Advanced Statistics (2 of 2): k-Means Clustering

```

1 R> kmeans(x, centers=2)
2 K-means clustering with 2 clusters of sizes 5, 3
3
4 Cluster means:
5      [,1]      [,2]
6 1 -0.1080612 -0.2827576
7 2  9.5695365  9.3191892
8
9 Clustering vector:
10 [1] 1 1 1 1 1 2 2 2
11
12 Within cluster sum of squares by cluster:
13 [1] 14.675072  7.912641
14 (between_SS / total_SS =  93.9 %)
15
16 Available components:
17
18 [1] "cluster"      "centers"      "totss"
19      "withinss"    "tot.withinss"
20      "betweenss"   "size"

```

Contents

- 2 pbdR
 - The pbdR Project
 - pbdR Paradigms

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Programming with Big Data in R (pbdR)

Striving for *Productivity, Portability, Performance*

- Bridging high-performance C with high-productivity of R
- Scalable, big data analytics.
- *Free^a* R packages.
- Distributed data details implicitly managed.
- Methods have syntax *identical* to R.
- Powered by state of the art numerical libraries (MPI, ScaLAPACK, ...)



^aMPL, BSD, and GPL licensed

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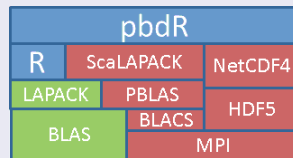
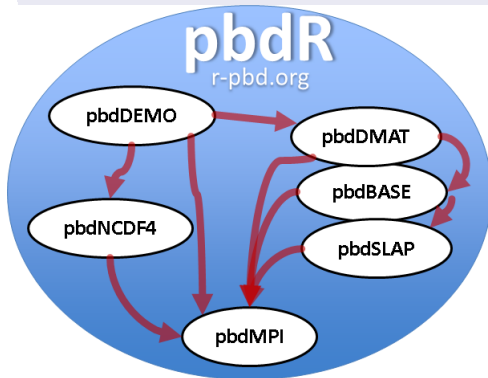
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The pbdR Project

pbdR Packages



pbdR on HPC Resources

pbdR is currently installed and maintained on:

- Nautilus, UTK
- Kraken, UTK
- Darter, UTK
- Newton, UTK
- Lens, ORNL
- tara, UMBC

If you are interested in maintaining pbdR, contact us at
RBigData@gmail.com


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Example Syntax

```

1 x <- x[-1, 2:5]
2 x <- log(abs(x) + 1)
3 xtx <- t(x) %*% x
4 ans <- svd(solve(xtx))

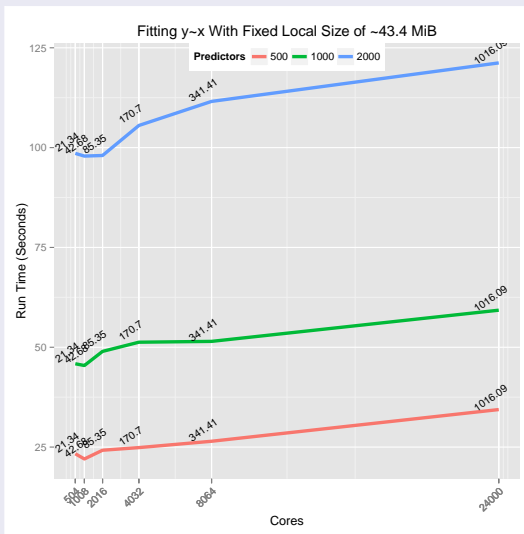
```

Look familiar?

The above runs on 1 core with R or 10,000 cores with pbdR



Least Squares Benchmark



pbdR Paradigms

Programs that use pbdR utilize:

- Batch execution
- Single Program/Multiple Data (SPMD) style

And generally utilize:

- Data Parallelism

Batch Execution

- Non-interactive
- Use

```
1 Rscript my_script.r
```

or

```
1 R CMD BATCH my_script.r
```

- In parallel:

```
1 mpirun -np 2 Rscript my_par_script.r
```

Single Program/Multiple Data (SPMD)

- Difficult to describe, easy to do...
- Only one program is written, executed in batch on all processors.
- Different processors are autonomous; there is no manager.
- The dominant programming model for large machines.

Contents

- 3 Introduction to pbdMPI
 - Managing a Communicator
 - Reduce, Gather, Broadcast, and Barrier
 - Other pbdMPI Tools

Message Passing Interface (MPI)

- *MPI*: Standard for managing communications (data and instructions) between different nodes/computers.
- *Implementations*: OpenMPI, MPICH2, Cray MPT, ...
- Enables parallelism (via communication) on distributed machines.
- *Communicator*: manages communications between processors.

MPI Operations (1 of 2)

- **Managing a Communicator:** Create and destroy communicators.
`init()` — initialize communicator
`finalize()` — shut down communicator(s)
- **Rank query:** determine the processor's position in the communicator.
`comm.rank()` — “who am I?”
`comm.size()` — “how many of us are there?”
- **Printing:** Printing output from various ranks.
`comm.print(x)`
`comm.cat(x)`
WARNING: only use these functions on *results*, never on yet-to-be-computed things.


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Quick Example 1

Rank Query: 1_rank.r

```

1 library(pbdMPI, quiet = TRUE)
2 init()
3
4 my.rank <- comm.rank()
5 comm.print(my.rank, all.rank=TRUE)
6
7 finalize()

```

Execute this script via:

```
1 mpirun -np 2 Rscript 1_rank.r
```

Sample Output:

```

1 COMM.RANK = 0
2 [1] 0
3 COMM.RANK = 1
4 [1] 1

```

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Quick Example 2

Hello World: 2_hello.r

```

1 library(pbdMPI, quiet=TRUE)
2 init()
3
4 comm.print("Hello, world")
5
6 comm.print("Hello again", all.rank=TRUE, quiet=TRUE)
7
8 finalize()

```

Execute this script via:

```
1 mpirun -np 2 Rscript 2_hello.r
```

Sample Output:

```

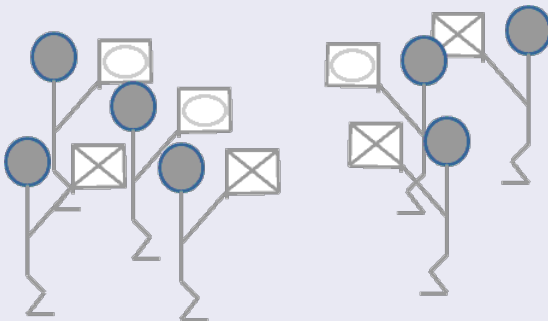
1 COMM.RANK = 0
2 [1] "Hello, world"
3 [1] "Hello again"
4 [1] "Hello again"

```

MPI Operations

- ① Reduce
- ② Gather
- ③ Broadcast
- ④ Barrier

Reductions — Combine results into single result



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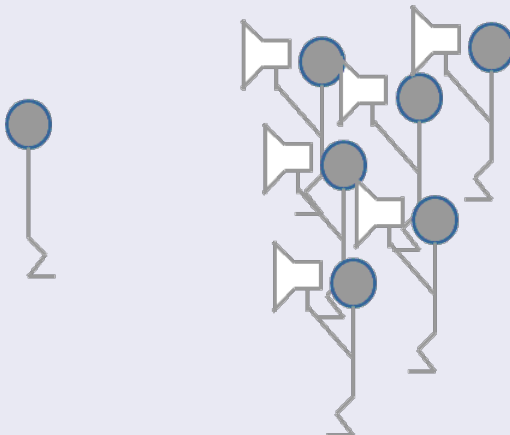
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Reduce, Gather, Broadcast, and Barrier

Gather — Many-to-one



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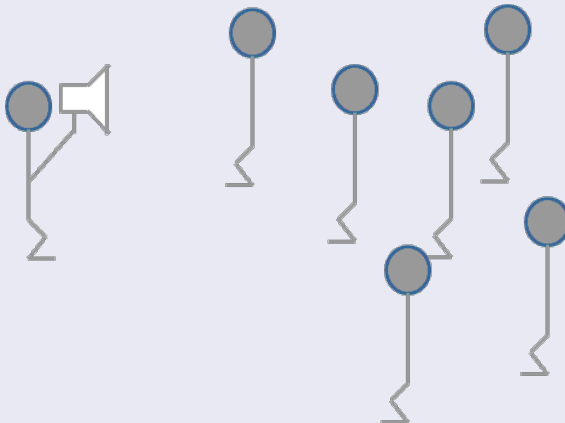
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Reduce, Gather, Broadcast, and Barrier

Broadcast — One-to-many



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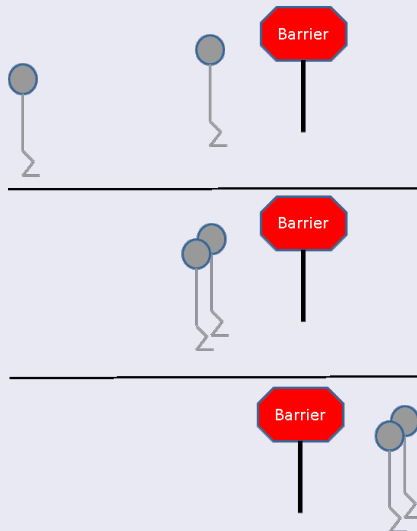
```

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Reduce, Gather, Broadcast, and Barrier

Barrier — Synchronization



MPI Operations (2 of 2)

- Reduction:** each processor has a number x ; add all of them up, find the largest/smallest,
`reduce(x, op='sum')` — reduce to one
`allreduce(x, op='sum')` — reduce to all
- Gather:** each processor has a number; create a new object on some processor containing all of those numbers.
`gather(x)` — gather to one
`allgather(x)` — gather to all
- Broadcast:** one processor has a number x that every other processor should also have.
`bcast(x)`
- Barrier:** “computation wall”; no processor can proceed until *all* processors can proceed.
`barrier()`

MPI Package Controls

The `.SPMD.CT` object allows for setting different package options with **pbdrMPI**. See the entry *SPMD Control* of the **pbdrMPI** manual for information about the `.SPMD.CT` object:

<http://cran.r-project.org/web/packages/pbdrMPI/pbdrMPI.pdf>

Random Seeds

pbdMPI offers a simple interface for managing random seeds:

- `comm.set.seed(diff=TRUE)` — Independent streams via the **rlecuyer** package.
- `comm.set.seed(seed=1234, diff=FALSE)` — All processors use the same seed `seed=1234`
- `comm.set.seed(diff=FALSE)` — All processors use the same seed, determined by processor 0 (using the system clock and PID of processor 0).

Other Helper Tools

pbBPI Also contains useful tools for Manager/Worker and task parallelism codes:

- **Task Subsetting:** Distributing a list of jobs/tasks
get.jid(n)
- ***ply:** Functions in the *ply family.
pbBApply(X, MARGIN, FUN, ...) — analogue of apply()
pbBLapply(X, FUN, ...) — analogue of lapply()
pbBSapply(X, FUN, ...) — analogue of sapply()

Quick Comments for Using pbdMPI

- 1 Start by loading the package:

```
1 library(pbdMPI, quiet = TRUE)
```

- 2 Always initialize before starting and finalize when finished:

```
1 init()
2
3 # ...
4
5 finalize()
```

Basic MPI Exercises

- 1 Experiment with Quick Examples 1 through 6, running them on 2, 4, and 8 processors.

Contents

- 4 The Generalized Block Distribution
 - The GBD Data Structure
 - GBD: Example 1
 - GBD: Example 2

Distributing Data

Problem: How to distribute the data

$$X = \begin{bmatrix} X_{1,1} & X_{1,2} & X_{1,3} \\ X_{2,1} & X_{2,2} & X_{2,3} \\ X_{3,1} & X_{3,2} & X_{3,3} \\ X_{4,1} & X_{4,2} & X_{4,3} \\ X_{5,1} & X_{5,2} & X_{5,3} \\ X_{6,1} & X_{6,2} & X_{6,3} \\ X_{7,1} & X_{7,2} & X_{7,3} \\ X_{8,1} & X_{8,2} & X_{8,3} \\ X_{9,1} & X_{9,2} & X_{9,3} \\ X_{10,1} & X_{10,2} & X_{10,3} \end{bmatrix}_{10 \times 3}$$

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Distributing a Matrix Across 4 Processors: Block Distribution

	Data	Processors
$X =$	$X_{1,1}$ $X_{1,2}$ $X_{1,3}$	0
	$X_{2,1}$ $X_{2,2}$ $X_{2,3}$	1
	$X_{3,1}$ $X_{3,2}$ $X_{3,3}$	2
	$X_{4,1}$ $X_{4,2}$ $X_{4,3}$	3
	$X_{5,1}$ $X_{5,2}$ $X_{5,3}$	
	$X_{6,1}$ $X_{6,2}$ $X_{6,3}$	
	$X_{7,1}$ $X_{7,2}$ $X_{7,3}$	
	$X_{8,1}$ $X_{8,2}$ $X_{8,3}$	
	$X_{9,1}$ $X_{9,2}$ $X_{9,3}$	
	$X_{10,1}$ $X_{10,2}$ $X_{10,3}$	

10×3


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The GBD Data Structure

Distributing a Matrix Across 4 Processors: Local Load Balance

	Data	Processors
$X =$	$X_{1,1}$ $X_{1,2}$ $X_{1,3}$	0
	$X_{2,1}$ $X_{2,2}$ $X_{2,3}$	1
	$X_{3,1}$ $X_{3,2}$ $X_{3,3}$	2
	$X_{4,1}$ $X_{4,2}$ $X_{4,3}$	3
	$X_{5,1}$ $X_{5,2}$ $X_{5,3}$	
	$X_{6,1}$ $X_{6,2}$ $X_{6,3}$	
	$X_{7,1}$ $X_{7,2}$ $X_{7,3}$	
	$X_{8,1}$ $X_{8,2}$ $X_{8,3}$	
	$X_{9,1}$ $X_{9,2}$ $X_{9,3}$	
	$X_{10,1}$ $X_{10,2}$ $X_{10,3}$	

10×3

The GBD Data Structure

Throughout the examples, we will make use of the Generalized Block Distribution, or GBD distributed matrix structure.

- ① GBD is *distributed*. No processor owns all the data.
- ② GBD is *non-overlapping*. Rows uniquely assigned to processors.
- ③ GBD is *row-contiguous*. If a processor owns one element of a row, it owns the entire row.
- ④ GBD is globally *row-major*, locally *column-major*.
- ⑤ GBD is often *locally balanced*, where each processor owns (almost) the same amount of data. But this is not required.
- ⑥ The last row of the local storage of a processor is adjacent (by global row) to the first row of the local storage of next processor (by communicator number) that owns data.
- ⑦ GBD is (relatively) easy to understand, but can lead to bottlenecks if you have many more columns than rows.

$x_{1,1}$	$x_{1,2}$	$x_{1,3}$
$x_{2,1}$	$x_{2,2}$	$x_{2,3}$
$x_{3,1}$	$x_{3,2}$	$x_{3,3}$
$x_{4,1}$	$x_{4,2}$	$x_{4,3}$
$x_{5,1}$	$x_{5,2}$	$x_{5,3}$
$x_{6,1}$	$x_{6,2}$	$x_{6,3}$
$x_{7,1}$	$x_{7,2}$	$x_{7,3}$
$x_{8,1}$	$x_{8,2}$	$x_{8,3}$
$x_{9,1}$	$x_{9,2}$	$x_{9,3}$
$x_{10,1}$	$x_{10,2}$	$x_{10,3}$

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GBD: Example 1

Understanding GBD: Global Matrix

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

Processors = 0 1 2 3 4 5

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GBD: Example 1

Understanding GBD: Load Balanced GBD

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

Processors = 0 1 2 3 4 5

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GBD: Example 1

Understanding GBD: Local View

[X ₁₁	X ₁₂	X ₁₃	X ₁₄	X ₁₅	X ₁₆	X ₁₇	X ₁₈	X ₁₉]	2×9
[	X ₂₁	X ₂₂	X ₂₃	X ₂₄	X ₂₅	X ₂₆	X ₂₇	X ₂₈	X ₂₉	]	2×9
[	X ₃₁	X ₃₂	X ₃₃	X ₃₄	X ₃₅	X ₃₆	X ₃₇	X ₃₈	X ₃₉	]	2×9
[	X ₄₁	X ₄₂	X ₄₃	X ₄₄	X ₄₅	X ₄₆	X ₄₇	X ₄₈	X ₄₉	]	2×9
[	X ₅₁	X ₅₂	X ₅₃	X ₅₄	X ₅₅	X ₅₆	X ₅₇	X ₅₈	X ₅₉	]	2×9
[	X ₆₁	X ₆₂	X ₆₃	X ₆₄	X ₆₅	X ₆₆	X ₆₇	X ₆₈	X ₆₉	]	2×9
[	X ₇₁	X ₇₂	X ₇₃	X ₇₄	X ₇₅	X ₇₆	X ₇₇	X ₇₈	X ₇₉	]	1×9
[X ₈₁	X ₈₂	X ₈₃	X ₈₄	X ₈₅	X ₈₆	X ₈₇	X ₈₈	X ₈₉]	1×9
[X ₉₁	X ₉₂	X ₉₃	X ₉₄	X ₉₅	X ₉₆	X ₉₇	X ₉₈	X ₉₉]	1×9

Processors = 0 1 2 3 4 5

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GBD: Example 2

Understanding GBD: Non-Balanced GBD

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

Processors = 0 1 2 3 4 5

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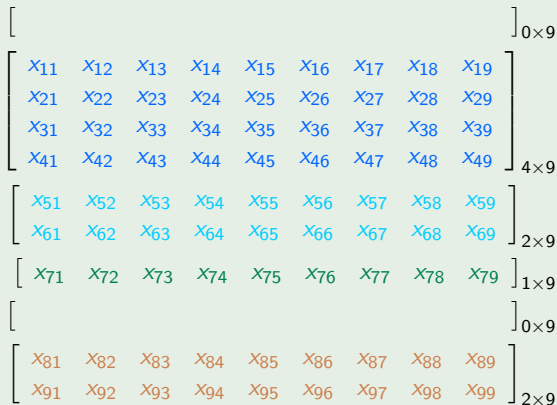
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GBD: Example 2

Understanding GBD: Local View



Processors = 0 1 2 3 4 5

Quick Comment for GBD

Local pieces of GBD distributed objects will be given the suffix `.gbd` to visually help distinguish them from global objects. This suffix carries no semantic meaning.

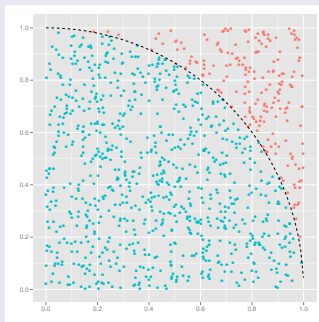
Contents

- 5 Basic Statistics Examples
 - pbdMPI Example: Monte Carlo Simulation
 - pbdMPI Example: Sample Covariance
 - pbdMPI Example: Linear Regression

Example 1: Monte Carlo Simulation

Sample N uniform observations (x_i, y_i) in the unit square $[0, 1] \times [0, 1]$. Then

$$\pi \approx 4 \left(\frac{\# \text{ Inside Circle}}{\# \text{ Total}} \right) = 4 \left(\frac{\# \text{ Blue}}{\# \text{ Blue} + \# \text{ Red}} \right)$$



Example 1: Monte Carlo Simulation GBD Algorithm

- 1 Let n be big-ish; we'll take $n = 50,000$.
- 2 Generate an $n \times 2$ matrix x of standard uniform observations.
- 3 Count the number of rows satisfying $x^2 + y^2 \leq 1$
- 4 Ask everyone else what their answer is; sum it all up.
- 5 Take this new answer, multiply by 4 and divide by n
- 6 If my rank is 0, print the result.

Example 1: Monte Carlo Simulation Code

Serial Code

```
1 N <- 50000
2 X <- matrix(runif(N * 2), ncol=2)
3 r <- sum(rowSums(X^2) <= 1)
4 PI <- 4*r/N
5 print(PI)
```

Parallel Code

```
1 library(pbdMPI, quiet = TRUE)
2 init()
3 comm.set.seed(diff=TRUE)
4
5 N.gbd <- 50000 / comm.size()
6 X.gbd <- matrix(runif(N.gbd * 2), ncol = 2)
7 r.gbd <- sum(rowSums(X.gbd^2) <= 1)
8 r <- allreduce(r.gbd)
9 PI <- 4*r/(N.gbd * comm.size())
10 comm.print(PI)
11
12 finalize()
```

Note

For the remainder, we will exclude loading, init, and finalize calls.

Example 2: Sample Covariance

$$\text{cov}(x_{n \times p}) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \mu_x)(x_i - \mu_x)^T$$

Example 2: Sample Covariance GBD Algorithm

- 1 Determine the total number of rows N .
- 2 Compute the vector of column means of the full matrix.
- 3 Subtract each column's mean from that column's entries in each local matrix.
- 4 Compute the crossproduct locally and reduce.
- 5 Divide by $N - 1$.

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Example 2: Sample Covariance Code

Serial Code

```

1 N <- nrow(X)
2 mu <- colSums(X) / N
3
4 X <- sweep(X, STATS=mu, MARGIN=2)
5 Cov.X <- crossprod(X) / (N-1)
6
7 print(Cov.X)

```

Parallel Code

```

1 N <- allreduce(nrow(X.gbd), op="sum")
2 mu <- allreduce(colSums(X.gbd) / N, op="sum")
3
4 X.gbd <- sweep(X.gbd, STATS=mu, MARGIN=2)
5 Cov.X <- allreduce(crossprod(X.gbd), op="sum") / (N-1)
6
7 comm.print(Cov.X)

```


Example 3: Linear Regression

Find β such that

$$\mathbf{y} = \mathbf{X}\beta + \epsilon$$

When \mathbf{X} is full rank,

$$\hat{\beta} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y}$$

Example 3: Linear Regression GBD Algorithm

- 1 Locally, compute $tx = x^T$
- 2 Locally, compute $A = tx * x$. Query every other processor for this result and sum up all the results.
- 3 Locally, compute $B = tx * y$. Query every other processor for this result and sum up all the results.
- 4 Locally, compute $A^{-1} * B$

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Example 3: Linear Regression Code

Serial Code

```

1 tX <- t(X)
2 A <- tX %*% X
3 B <- tX %*% y
4
5 ols <- solve(A) %*% B

```

Parallel Code

```

1 tX.gbd <- t(X.gbd)
2 A <- allreduce(tX.gbd %*% X.gbd, op = "sum")
3 B <- allreduce(tX.gbd %*% y.gbd, op = "sum")
4
5 ols <- solve(A) %*% B

```

MPI Exercises

- 1 Experiment with Statistics Examples 1 through 3, running them on 2, 4, and 8 processors.

Advanced MPI Exercises I

- 1 Write a script that will have each processor randomly take a sample of size 1 of TRUE and FALSE. Have each processor print its result.
- 2 Modify the script in Exercise 1 above to determine if any processors sampled TRUE. Do the same to determine if all processors sampled TRUE. In each case, print the result. Compare to the functions `comm.all()` and `comm.any()`.
- 3 Generate 50,000,000 (total) random normal values in parallel on 2, 4, and 8 processors. Time each run.

Advanced MPI Exercises II

- ④ Distribute the matrix `x <- matrix(1:24, nrow=12)` in GBD format across 4 processors and call it `x.spmc`.
 - ① Add `x.spmc` to itself.
 - ② Compute the mean of `x.spmc`.
 - ③ Compute the column means of `x.spmc`.

Contents

- 6 Introduction to pbdDMAT and the DMAT Structure
 - Introduction to Distributed Matrices
 - DMAT Distributions
 - pbdDMAT

Distributed Matrices

Most problems in data science are matrix algebra problems, so:

Distributed matrices \implies Handle Bigger data

Distributed Matrices

High level OOP allows *native* serial R syntax:

```
1 x <- x[-1, 2:5]
2 x <- log(abs(x) + 1)
3 xtx <- t(x) %*% x
4 ans <- svd(solve(xtx))
```

However...

Distributed Matrices

DMAT:

- Distributed **MAT**rix data structure.
- No single processor should hold all of the data.
- Block-cyclic matrix distributed across a 2-dimensional grid of processors.
- Very robust, but confusing data structure.

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Introduction to Distributed Matrices

Distributed Matrices



(a) Block



(b) Cyclic



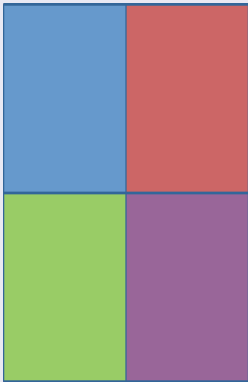
(c) Block-Cyclic

Figure: Matrix Distribution Schemes

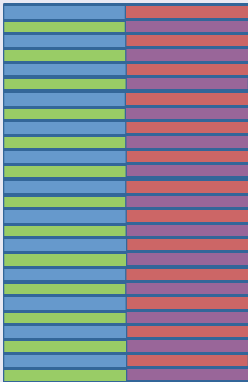
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Introduction to Distributed Matrices

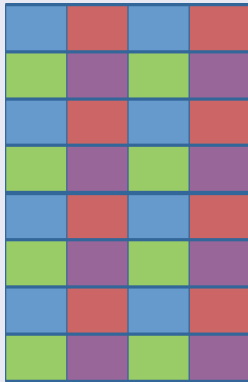
Distributed Matrices



(a) 2d Block



(b) 2d Cyclic



(c) 2d Block-Cyclic

Figure: Matrix Distribution Schemes Onto a 2-Dimensional Grid

Processor Grid Shapes

$$\begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix}^T$$

(a) 1×6

$$\begin{bmatrix} 0 & 1 & 2 \\ 3 & 4 & 5 \end{bmatrix}$$

(b) 2×3

$$\begin{bmatrix} 0 & 1 \\ 2 & 3 \\ 4 & 5 \end{bmatrix}$$

(c) 3×2

$$\begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix}$$

(d) 6×1

Table: Processor Grid Shapes with 6 Processors

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Distributed Matrices

The data structure is a special R class (in the OOP sense) called `ddmatrix`. It is the “under the rug” storage for a block-cyclic matrix distributed onto a 2-dimensional processor grid.

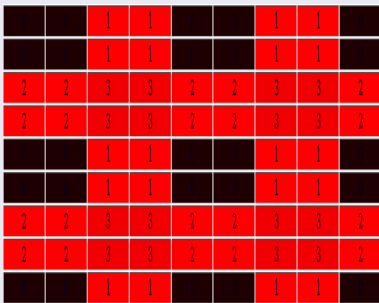
$$\text{ddmatrix} = \left\{ \begin{array}{ll} \text{Data} & \text{S4 local submatrix, an R matrix} \\ \text{dim} & \text{S4 dimension of the global matrix, a numeric pair} \\ \text{ldim} & \text{S4 dimension of the local submatrix, a numeric pair} \\ \text{bldim} & \text{S4 ScaLAPACK blocking factor, a numeric pair} \\ \text{CTXT} & \text{S4 BLACS context, an numeric singleton} \end{array} \right.$$

with prototype

$$\text{new("ddmatrix")} = \left\{ \begin{array}{ll} \text{Data} & = \text{matrix}(0.0) \\ \text{dim} & = \text{c}(1,1) \\ \text{ldim} & = \text{c}(1,1) \\ \text{bldim} & = \text{c}(1,1) \\ \text{CTXT} & = 0.0 \end{array} \right.$$

Distributed Matrices: The Data Structure

Example: an 9×9 matrix is distributed with a “block-cycling” factor of 2×2 on a 2×2 processor grid:



$$= \left\{ \begin{array}{ll} \text{Data} & = \text{matrix}(\dots) \\ \text{dim} & = \text{c}(9, 9) \\ \text{ldim} & = \text{c}(\dots) \\ \text{bldim} & = \text{c}(2, 2) \\ \text{CTXT} & = 0 \end{array} \right.$$

See <http://acts.nersc.gov/scalapack/hands-on/datadist.html>

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DMAT Distributions

Understanding Dmat: Global Matrix

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$


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DMAT: 1-dimensional Row Block

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ \hline X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ \hline X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 \\ 1 \\ 2 \\ 3 \end{vmatrix} = \begin{vmatrix} (0,0) \\ (0,1) \\ (1,0) \\ (1,1) \end{vmatrix}$$

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DMAT Distributions

DMAT: 2-dimensional Row Block

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ \hline X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 & 1 \\ 2 & 3 \end{vmatrix} = \begin{vmatrix} (0,0) & (0,1) \\ (1,0) & (1,1) \end{vmatrix}$$

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DMAT: 1-dimensional Row Cyclic

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 \\ 1 \\ 2 \\ 3 \end{vmatrix} = \begin{vmatrix} (0,0) \\ (0,1) \\ (1,0) \\ (1,1) \end{vmatrix}$$

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DMAT Distributions

DMAT: 2-dimensional Row Cyclic

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 & 1 \\ 2 & 3 \end{vmatrix} = \begin{vmatrix} (0,0) & (0,1) \\ (1,0) & (1,1) \end{vmatrix}$$

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DMAT Distributions

DMAT: 2-dimensional Block-Cyclic

$$X = \begin{bmatrix} \begin{array}{cc|cc|cc|cc|c} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \\ \hline X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \\ \hline X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \\ \hline X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \\ \hline X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{array} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 & 1 \\ 2 & 3 \end{vmatrix} = \begin{vmatrix} (0,0) & (0,1) \\ (1,0) & (1,1) \end{vmatrix}$$

The DMAT Data Structure

The more complicated the processor grid, the more complicated the distribution.

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DMAT: 2-dimensional Block-Cyclic with 6 Processors

$$X = \begin{bmatrix} \begin{array}{cc|cc|cc|cc|c} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} & X_{18} & X_{19} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} & X_{28} & X_{29} \end{array} \\ \hline \begin{array}{cc|cc|cc|cc|c} X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} & X_{38} & X_{39} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} & X_{48} & X_{49} \end{array} \\ \hline \begin{array}{cc|cc|cc|cc|c} X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} & X_{58} & X_{59} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} & X_{68} & X_{69} \end{array} \\ \hline \begin{array}{cc|cc|cc|cc|c} X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} & X_{78} & X_{79} \\ X_{81} & X_{82} & X_{83} & X_{84} & X_{85} & X_{86} & X_{87} & X_{88} & X_{89} \end{array} \\ \hline \begin{array}{cc|cc|cc|cc|c} X_{91} & X_{92} & X_{93} & X_{94} & X_{95} & X_{96} & X_{97} & X_{98} & X_{99} \end{array} \end{bmatrix}_{9 \times 9}$$

$$\text{Processor grid} = \begin{vmatrix} 0 & 1 & 2 \\ 3 & 4 & 5 \end{vmatrix} = \begin{vmatrix} (0,0) & (0,1) & (0,2) \\ (1,0) & (1,1) & (1,2) \end{vmatrix}$$

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Understanding DMAT: Local View

$\begin{bmatrix} X_{11} & X_{12} & X_{17} & X_{18} \\ X_{21} & X_{22} & X_{27} & X_{28} \\ X_{51} & X_{52} & X_{57} & X_{58} \\ X_{61} & X_{62} & X_{67} & X_{68} \\ X_{91} & X_{92} & X_{97} & X_{98} \end{bmatrix}$	5×4	$\begin{bmatrix} X_{13} & X_{14} & X_{19} \\ X_{23} & X_{24} & X_{29} \\ X_{53} & X_{54} & X_{59} \\ X_{63} & X_{64} & X_{69} \\ X_{93} & X_{94} & X_{99} \end{bmatrix}$	5×3	$\begin{bmatrix} X_{15} & X_{16} \\ X_{25} & X_{26} \\ X_{55} & X_{56} \\ X_{65} & X_{66} \\ X_{95} & X_{96} \end{bmatrix}$	5×2
$\begin{bmatrix} X_{31} & X_{32} & X_{37} & X_{38} \\ X_{41} & X_{42} & X_{47} & X_{48} \\ X_{71} & X_{72} & X_{77} & X_{78} \\ X_{81} & X_{82} & X_{87} & X_{88} \end{bmatrix}$	4×4	$\begin{bmatrix} X_{33} & X_{34} & X_{39} \\ X_{43} & X_{44} & X_{49} \\ X_{73} & X_{74} & X_{79} \\ X_{83} & X_{84} & X_{89} \end{bmatrix}$	4×3	$\begin{bmatrix} X_{35} & X_{36} \\ X_{45} & X_{46} \\ X_{75} & X_{76} \\ X_{85} & X_{86} \end{bmatrix}$	4×2

$$\text{Processor grid} = \begin{vmatrix} 0 & 1 & 2 \\ 3 & 4 & 5 \end{vmatrix} = \begin{vmatrix} (0,0) & (0,1) & (0,2) \\ (1,0) & (1,1) & (1,2) \end{vmatrix}$$


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The DMAT Data Structure

- DMAT is *distributed*. No one processor owns all of the matrix.
- DMAT is *non-overlapping*. Any piece owned by one processor is owned by no other processors.
- DMAT can be row-contiguous or not, depending on the processor grid and blocking factor used.
- DMAT is locally column-major and globally, it depends. . .
- GBD is a generalization of the one-dimensional block DMAT distribution. Otherwise there is no relation.
- DMAT is confusing, but very robust.

X ₁₁	X ₁₂	X ₁₃	X ₁₄	X ₁₅
X ₂₁	X ₂₂	X ₂₃	X ₂₄	X ₂₅
X ₃₁	X ₃₂	X ₃₃	X ₃₄	X ₃₅
X ₄₁	X ₄₂	X ₄₃	X ₄₄	X ₄₅
X ₅₁	X ₅₂	X ₅₃	X ₅₄	X ₅₅
X ₆₁	X ₆₂	X ₆₃	X ₆₄	X ₆₅
X ₇₁	X ₇₂	X ₇₃	X ₇₄	X ₇₅
X ₈₁	X ₈₂	X ₈₃	X ₈₄	X ₈₅
X ₉₁	X ₉₂	X ₉₃	X ₉₄	X ₉₅

Pros and Cons of This Data Structure

Pros

- Fast for distributed matrix computations

Cons

- Literally everything else

This is why we hide most of the distributed details.

The details are there if you want them (you don't want them).

Distributed Matrix Methods

pbdDMAT has over 100 methods with *identical* syntax to R:

- ``[, rbind(), cbind(), ...`
- `lm.fit(), prcomp(), cov(), ...`
- ``%*%`, solve(), svd(), norm(), ...`
- `median(), mean(), rowSums(), ...`

Serial Code

```
1 cov(x)
```

Parallel Code

```
1 cov(x)
```

Comparing pbdMPI and pbdDMAT

pbdMPI:

- MPI + sugar.
- GBD not the only structure **pbdMPI** can handle (just a useful convention).

pbdDMAT:

- More of a software package.
- DMAT structure *must* be used for **pbdDMAT**.
- If the data is not 2d block-cyclic compatible, DMAT will *definitely* give the wrong answer.

Quick Comments for Using pbdDMAT

- 1 Start by loading the package:

```
1 library(pbdDMAT, quiet = TRUE)
```

- 2 Always initialize before starting and finalize when finished:

```
1 init.grid()  
2  
3 # ...  
4  
5 finalize()
```

- 3 Distributed DMAT objects will be given the suffix `.dmat` to visually help distinguish them from global objects. This suffix carries no semantic meaning.

Contents

- 7 Examples Using pbdDMAT
 - Statistics Examples with pbdDMAT
 - RandSVD

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Statistics Examples with pbdDMAT

Sample Covariance

Serial Code

```

1 Cov.X <- cov(X)
2 print(Cov.X)

```

Parallel Code

```

1 Cov.X <- cov(X)
2 print(Cov.X)

```

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Statistics Examples with pbdDMAT

Linear Regression

Serial Code

```

1 tX <- t(X)
2 A <- tX %*% X
3 B <- tX %*% y
4
5 ols <- solve(A) %*% B
6
7 # or
8 ols <- lm.fit(X, y)

```

Parallel Code

```

1 tX <- t(X)
2 A <- tX %*% X
3 B <- tX %*% y
4
5 ols <- solve(A) %*% B
6
7 # or
8 ols <- lm.fit(X, y)

```



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Statistics Examples with pbdDMAT

Example 5: PCA

PCA: pca.r

```

1 library(pbdDMAT, quiet=T)
2 init.grid()
3
4 n <- 1e4
5 p <- 250
6
7 comm.set.seed(diff=T)
8 x.dmat <- ddmatrix("rnorm", nrow=n, ncol=p, mean=100, sd=25)
9
10 pca <- prcomp(x=x.dmat, retx=TRUE, scale=TRUE)
11 prop_var <- cumsum(pca$sdev)/sum(pca$sdev)
12 i <- max(min(which(prop_var > 0.9)) - 1, 1)
13
14 y.dmat <- pca$x[, 1:i]
15
16 comm.cat("\nCols: ", i, "\n", quiet=T)
17 comm.cat("%Cols: ", i/dim(x.dmat)[2], "\n\n", quiet=T)
18
19 finalize()

```

Execute this script via:

Sample Output:

```
1 mpirun -np 2 Rscript 5_pca.r
```

```

1 Cols: 221
2 %Cols: 0.884

```

Distributed Matrices

pbdDEMO contains many other examples of reading and managing GBD and DMAT data

Randomized SVD¹

PROTOTYPE FOR RANDOMIZED SVD

Given an $m \times n$ matrix A , a target number k of singular vectors, and an exponent q (say, $q = 1$ or $q = 2$), this procedure computes an approximate rank- $2k$ factorization $U\Sigma V^*$, where U and V are orthonormal, and Σ is nonnegative and diagonal.

Stage A:

- 1 Generate an $n \times 2k$ Gaussian test matrix Ω .
- 2 Form $Y = (AA^*)^q A\Omega$ by multiplying alternately with A and A^* .
- 3 Construct a matrix Q whose columns form an orthonormal basis for the range of Y .

Stage B:

- 4 Form $B = Q^* A$.
- 5 Compute an SVD of the small matrix: $B = \tilde{U}\Sigma V^*$.
- 6 Set $U = Q\tilde{U}$.

Note: The computation of Y in step 2 is vulnerable to round-off errors. When high accuracy is required, we must incorporate an orthonormalization step between each application of A and A^* ; see Algorithm 4.4.

ALGORITHM 4.4: RANDOMIZED SUBSPACE ITERATION

Given an $m \times n$ matrix A and integers ℓ and q , this algorithm computes an $m \times \ell$ orthonormal matrix Q whose range approximates the range of A .

- 1 Draw an $n \times \ell$ standard Gaussian matrix Ω .
- 2 Form $Y_0 = A\Omega$ and compute its QR factorization $Y_0 = Q_0 R_0$.
- 3 for $j = 1, 2, \dots, q$
- 4 Form $\tilde{Y}_j = A^* Q_{j-1}$ and compute its QR factorization $\tilde{Y}_j = \tilde{Q}_j \tilde{R}_j$.
- 5 Form $Y_j = A\tilde{Q}_j$ and compute its QR factorization $Y_j = Q_j R_j$.
- 6 end
- 7 $Q = Q_q$.

Serial R

```

1 randSVD <- function(A, k, q=3)
2 {
3   ## Stage A
4   Omega <- matrix(rnorm(n*2*k),
5                     nrow=n, ncol=2*k)
6   Y <- A %*% Omega
7   Q <- qr.Q(qr(Y))
8   At <- t(A)
9   for(i in 1:q)
10    {
11      Y <- At %*% Q
12      Q <- qr.Q(qr(Y))
13      Y <- A %*% Q
14      Q <- qr.Q(qr(Y))
15    }
16
17   ## Stage B
18   B <- t(Q) %*% A
19   U <- La.svd(B)$u
20   U <- Q %*% U
21   U[, 1:k]
22 }
```

¹Halko N, Martinsson P-G and Tropp J A 2011 Finding structure with randomness: probabilistic algorithms for constructing approximate matrix decompositions *SIAM Rev.* **53** 217–88

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```

RandSVD

Randomized SVD

Serial R

```

1 randSVD <- function(A, k, q=3)
2 {
3   ## Stage A
4   Omega <- matrix(rnorm(n*2*k),
5                   nrow=n, ncol=2*k)
6   Y <- A %*% Omega
7   Q <- qr.Q(qr(Y))
8   At <- t(A)
9   for(i in 1:q)
10    {
11      Y <- At %*% Q
12      Q <- qr.Q(qr(Y))
13      Y <- A %*% Q
14      Q <- qr.Q(qr(Y))
15    }
16
17   ## Stage B
18   B <- t(Q) %*% A
19   U <- La.svd(B)$u
20   U <- Q %*% U
21   U[, 1:k]
22 }

```

Parallel pbdR

```

1 randSVD <- function(A, k, q=3)
2 {
3   ## Stage A
4   Omega <- ddmatrix("rnorm",
5                   nrow=n, ncol=2*k)
6   Y <- A %*% Omega
7   Q <- qr.Q(qr(Y))
8   At <- t(A)
9   for(i in 1:q)
10    {
11      Y <- At %*% Q
12      Q <- qr.Q(qr(Y))
13      Y <- A %*% Q
14      Q <- qr.Q(qr(Y))
15    }
16
17   ## Stage B
18   B <- t(Q) %*% A
19   U <- La.svd(B)$u
20   U <- Q %*% U
21   U[, 1:k]
22 }

```

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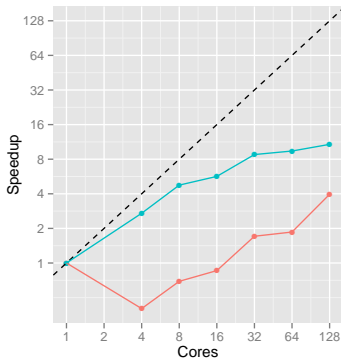
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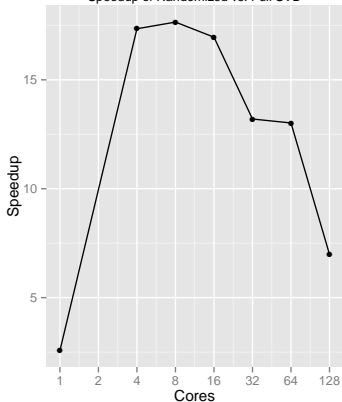
Randomized SVD

30 Singular Vectors from a 100,000 by 1,000 Matrix

Algorithm — full — randomized



30 Singular Vectors from a 100,000 by 1,000 Matrix
Speedup of Randomized vs. Full SVD



DMAT Exercises

- 1 Experiment with DMAT Examples 1 through 5, running them on 2 and 4 processors.

Advanced DMAT Exercises I

- ① Subsetting, selection, and filtering are basic matrix operations featured in R. The following may look silly, but it is useful for data processing. Let `x.dmat <- ddmatrix(1:30, 10, 3)`. Do the following:

- `y.dmat <- x.dmat[c(1, 5, 4, 3),]`
`y.dmat <- x.dmat[c(10:3, 5, 5),]`
`y.dmat <- x.dmat[1:5, 3:1]`
- `y.dmat <- x.dmat[x.dmat[, 2] > 13,]`
`y.dmat <- x.dmat[x.dmat[, 2] > x.dmat[, 3],]`
`y.dmat <- x.dmat[, x.dmat[2,] > x.dmat[3,]]`
`y.dmat <- x.dmat[c(1, 3, 5), x.dmat[, 2] > x.dmat[, 3]]`

Advanced DMAT Exercises II

- ② The method `crossprod()` is an optimized form of the crossproduct computation `t(x.dmat) %*% x.dmat`. For this exercise, let `x.dmat <- ddmatrix(1:30, nrow=10, ncol=3)`.
 - ① Verify that these computations really do produce the same results.
 - ② Time each operation. Which is faster?
- ③ The `prcomp()` method returns rotations for all components. Computationally verify by example that these rotations are orthogonal, i.e., that their crossproduct is the identity matrix.

Contents

8 Wrapup

The pbdR Project

- Our website: <http://r-pbd.org/>
- Email us at: RBigData@gmail.com
- Our google group: <http://group.r-pbd.org/>

Where to begin?

- The **pbdDEMO** package
<http://cran.r-project.org/web/packages/pbdDEMO/>
- The **pbdDEMO** Vignette: <http://goo.gl/HZkRt>

Thanks for coming!

Questions?