

pbdR: Harnessing HPC Research for Parallel Computing with R

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Oak Ridge National Laboratory and University of Tennessee

ISM HPCCON and ISM HPC on R Workshop, October 9-12, 2015
Institute of Statistical Mathematics, Tokyo, Japan



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Support

This material is based upon work supported by the National Science Foundation Division of Mathematical Sciences under Grant No. 1418195. This work used resources of the [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. This work also 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.



1 Introduction to HPC and Its View from R

- Three Basic Flavors of Parallel Hardware
- Cluster Computer Architectures
- A Quick Overview of Parallel Software
- Batch and Interactive
- Programming Models

2 pbdR

- The pbdR Project
- pbdMPI
- pbdDMAT
- RandSVD
- pbdMPI Example: Random Forest Prediction
- pbdMPI Example: Functional Data Analysis

3 pbdCS

- Client-Server Demo

4 Future Work

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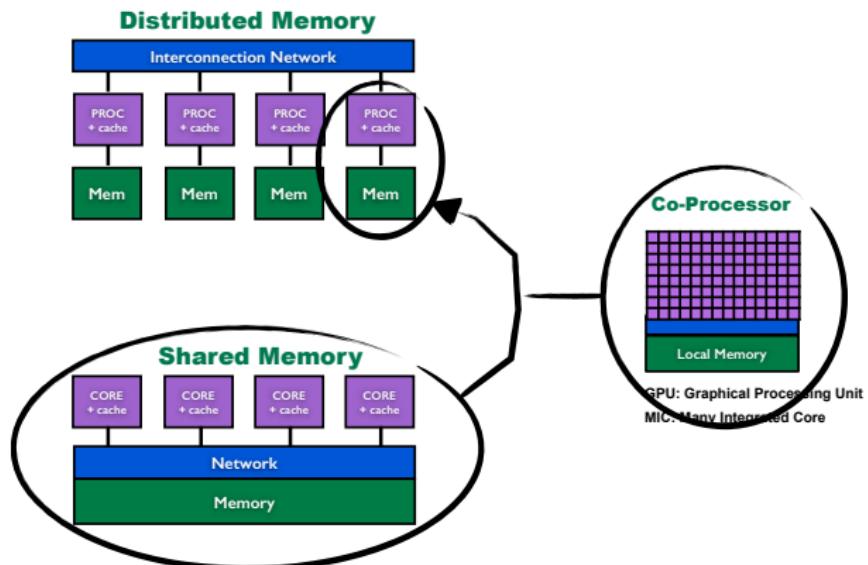


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Cores and Co-Processors to Nodes



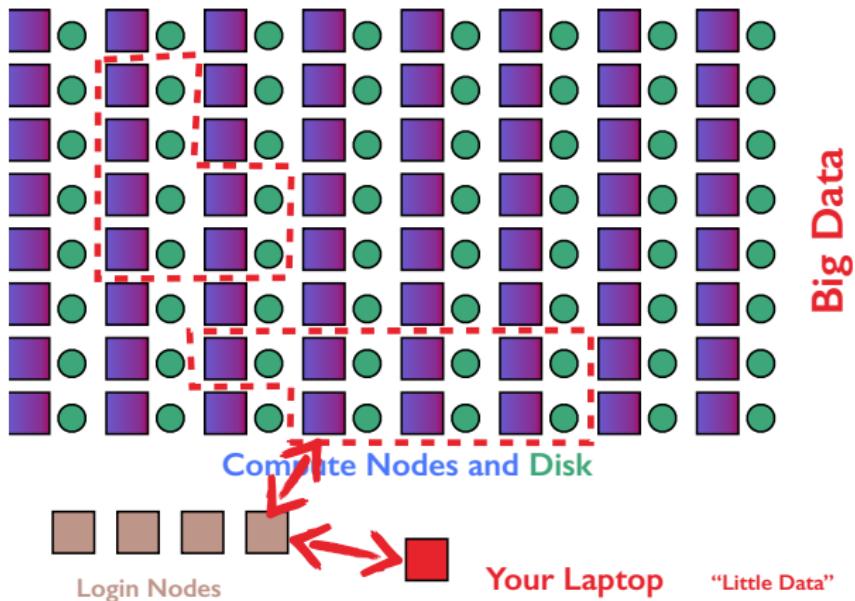
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Parallel Computing before Multicore

HPC “Beowulf” Clusters before 2005



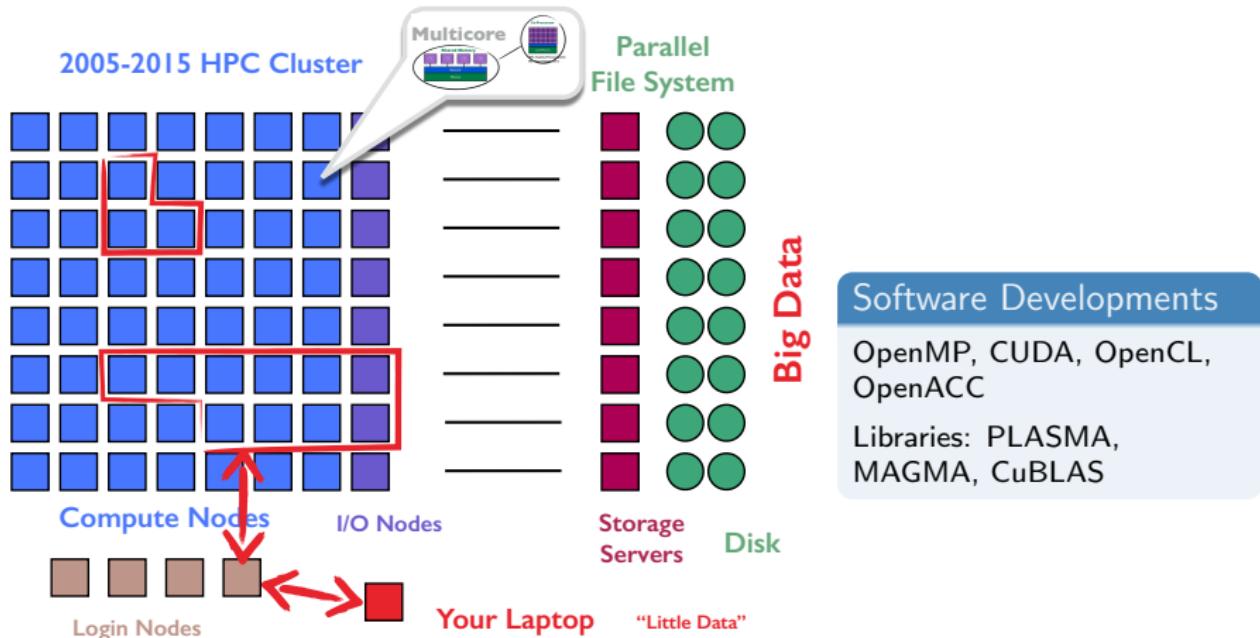
Software Developments:

MPI is mature, MapReduce emerges

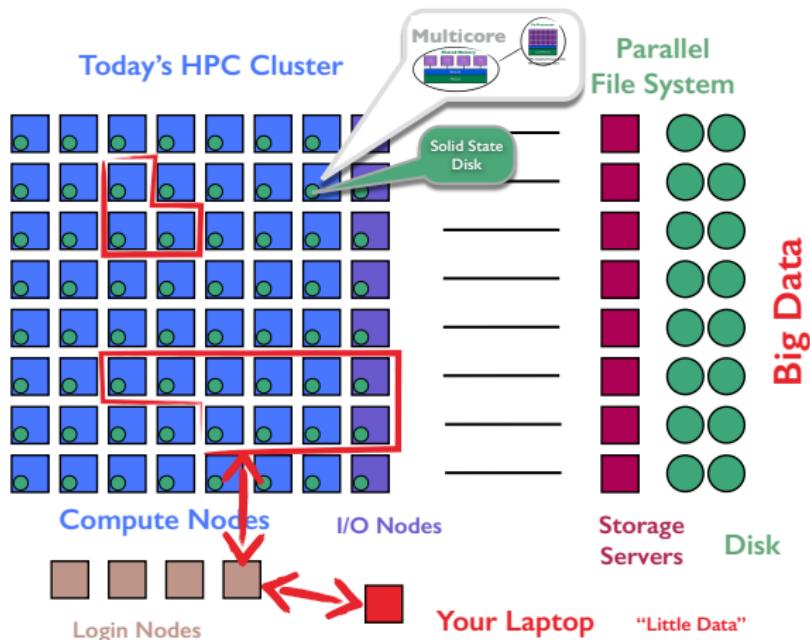
Parallel Libraries: PBLAS, ScaLAPACK, PETSc, etc.

Resource Manager: PBS mature, HADOOP emerges

Multicore Emerges and Clusters become Diskless



Adding NVRAM to New HPC Systems



Software Developments

Libraries: DPLASMA,
CombBLAS

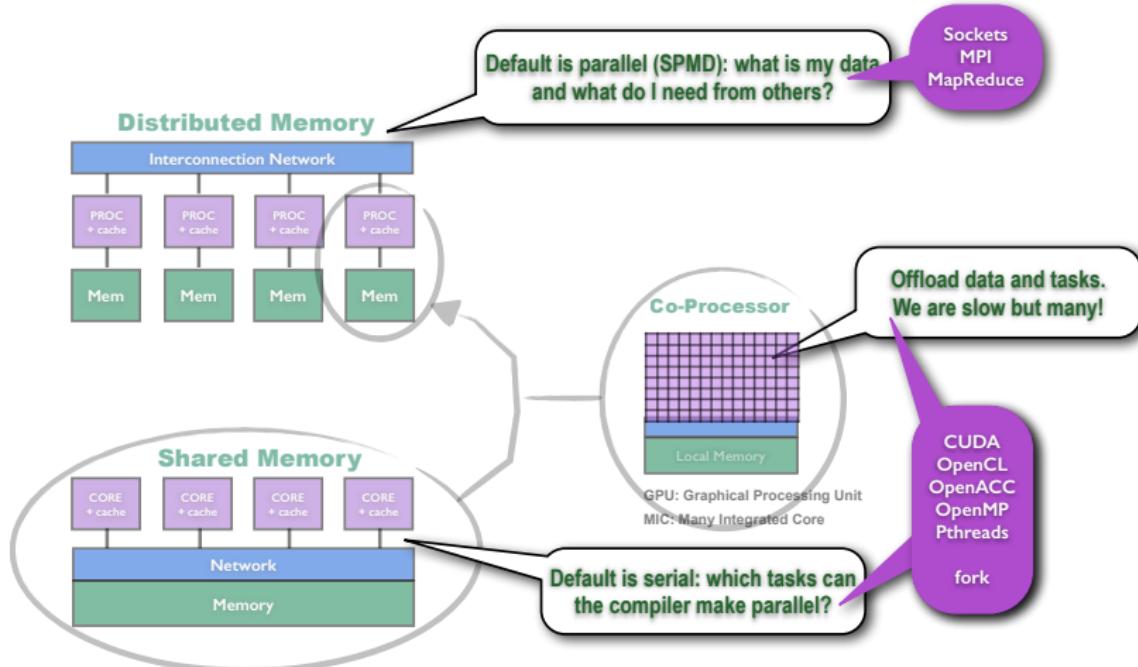
HADOOP fades, Spark
emerges

1 Introduction to HPC and Its View from R

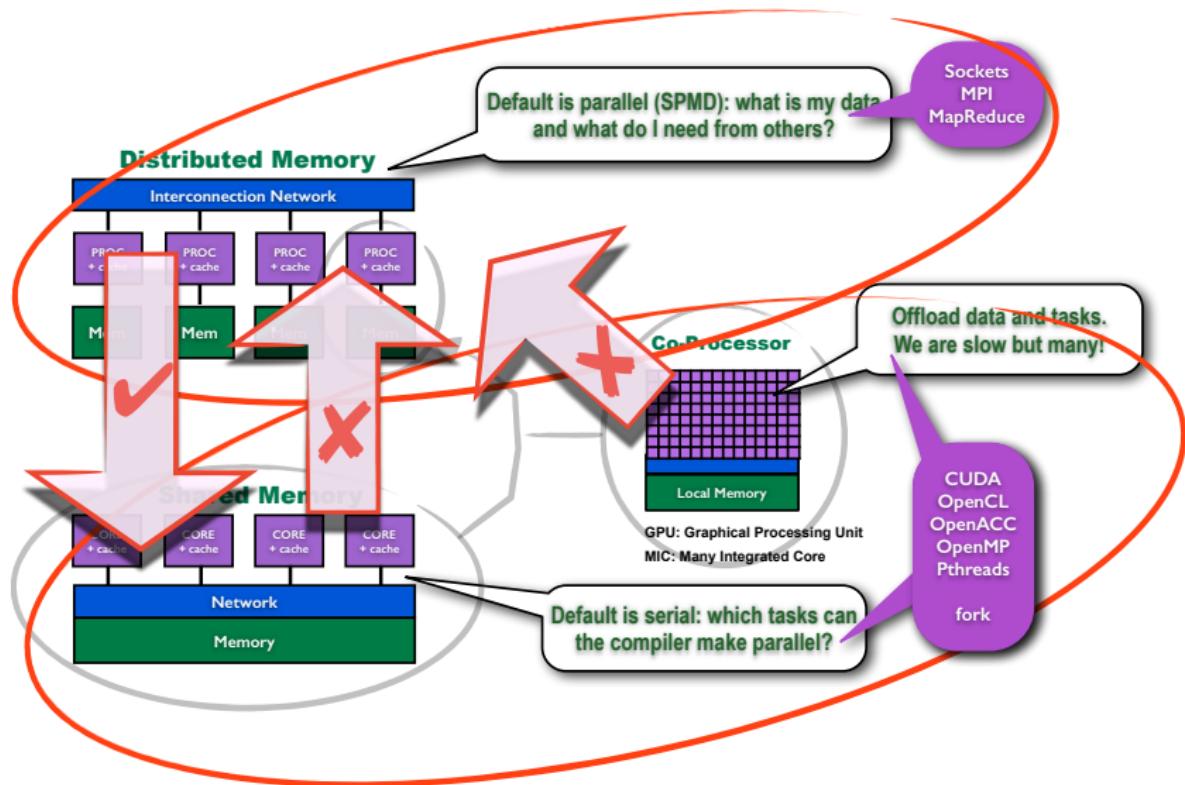
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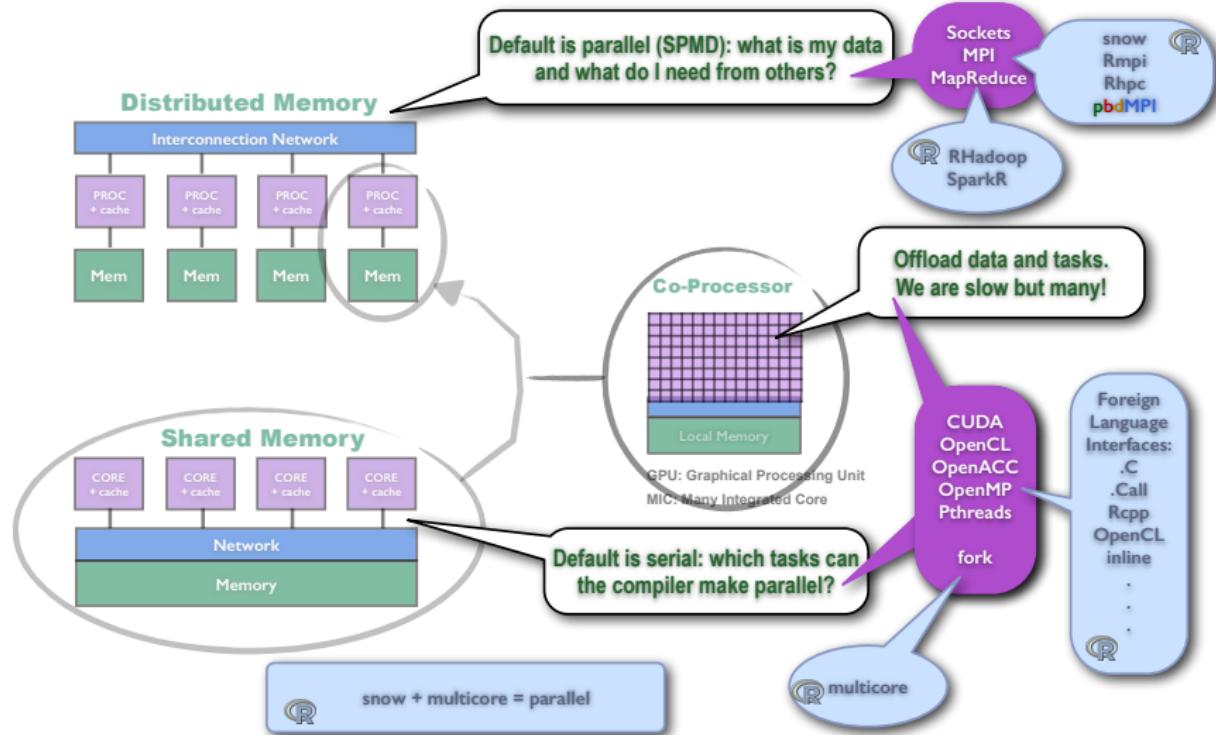
“Native” Programming Models and Tools



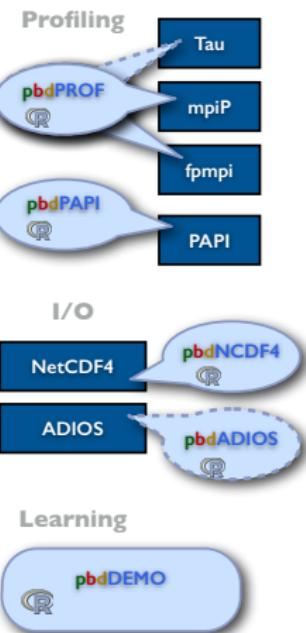
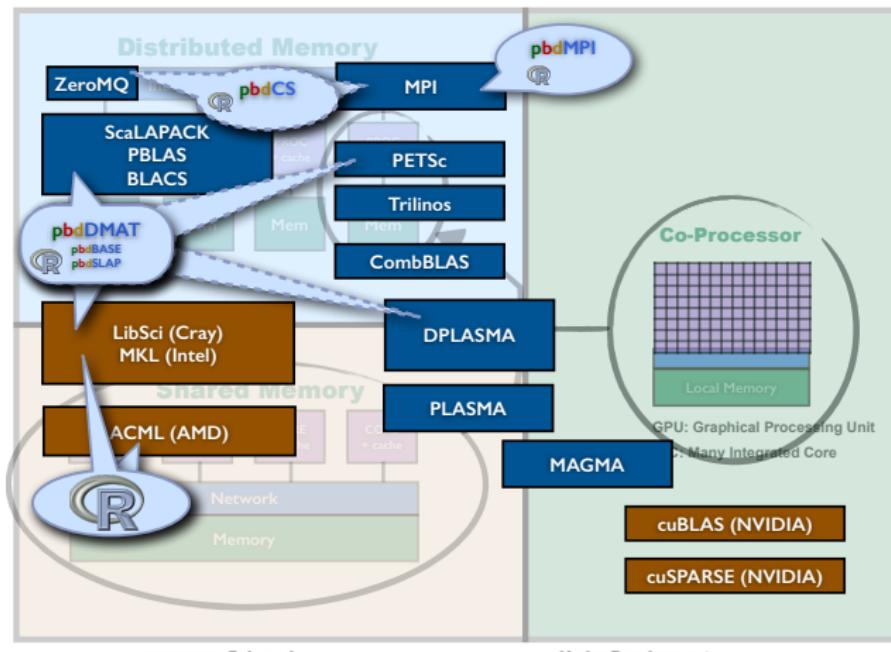
Distributed Programming Works in Shared Memory



R Interfaces to Low-Level Native Tools



R and **pbdR** Interfaces to HPC Libraries



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Data analysis is interactive!

- Data reduction to knowledge
- Iterative process with same data
 - Exploration, model construction
 - Diagnostics of fit and quantification of uncertainty
 - Interpretation
- S (and R) interactive “answer” to batch data analysis
- Efficient use of expensive people

Big platform computing is batch!

- Libraries built for batch computing
- Traditionally data generation by simulation science
- Efficient use of expensive platforms



High-Level Language: Batch and Interactive Distinction Blurred.

- A function is a “batch” script
- R “An interactive environment to use batch scripts”

Ideal solution: Interactive Client with a Batch Server

- Parallel visualization systems (VisIt and ParaView) are client-server (batch on server)
- Current **pbdR** packages address server side (batch)
- pbdCS 0.1-0 released on GitHub
 - Interactive SPMD
 - Based on ZeroMQ distributed messaging (pbdZMQ 0.1-1 on CRAN)
 - Bridge resource manager (pbdSCHED 0.1-0 on GitHub)
 - Site configuration file
 - Manage relationship of big data (server side) to little data (client side)



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Manager-Workers

- A serial program (Manager) divides up work and/or data
- Workers run in parallel without interaction
- Manager collects/combines results from workers
- Divide-Recombine fits this model



MapReduce

- A concept born of a search engine
- Decouples certain coupled problems with an intermediate communication - shuffle
- User writes two serial codes: Map and Reduce



MapReduce: a Parallel Search Engine Concept

Search MANY documents

Serve MANY users

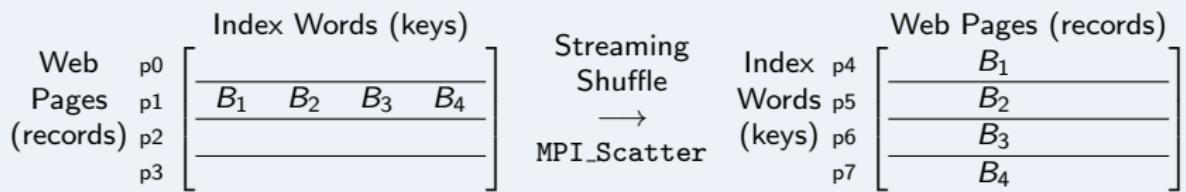
		Index Words (keys)			
Web	p0	A ₁	A ₂	A ₃	A ₄
Pages	p1	B ₁	B ₂	B ₃	B ₄
(records)	p2	C ₁	C ₂	C ₃	C ₄
	p3	D ₁	D ₂	D ₃	D ₄

		Web Pages (records)			
Shuffle	→	Index p0	Words p1	p2	p3
MPI_Alltoallv		(keys)	A ₁	B ₁	C ₁
			A ₂	B ₂	C ₂
			A ₃	B ₃	C ₃
			A ₄	B ₄	C ₄
					D ₁
					D ₂
					D ₃
					D ₄

Matrix transpose in another language?



Can use different sets of processors



MPI and MapReduce

Both Concepts are about Communication

- One makes communication explicit, gives choices
- The other hides communication, gives one choice (shuffle)



SPMD: Single Program Multiple Data

- The prevalent way of distributed programming
- Can handle tightly coupled parallel computations
- It is designed for batch computing
- There is usually no manager - rather, all cooperate
- Prime driver behind MPI specification



Early SPMD Work in Statistics: Crossproduct (Row-Block)

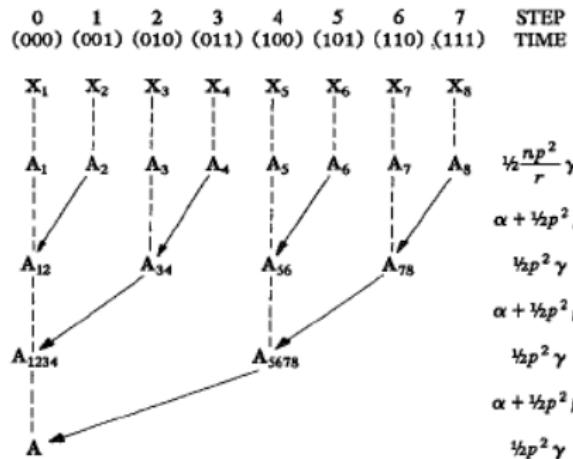


FIG. 4. Computation of $\mathbf{A} = \mathbf{X}\mathbf{X}$ on an 8-processor hypercube, with final result on processor 0.

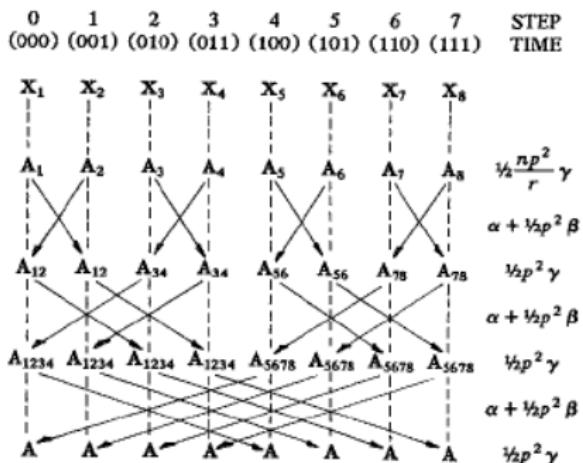


FIG. 6. Computation of $\mathbf{A} = \mathbf{X}\mathbf{X}$ on an 8-processor hypercube, with final result on all processors.

Hypercube: Individual send() and recv() over each dimension

Ostrouchov (1987). Parallel Computing on a Hypercube: An overview of the architecture and some applications. *Proceedings of the 19th Symposium on the Interface of Computer Science and Statistics*, p.27-32.

Simplified with MPI (and further with pbdMPI)

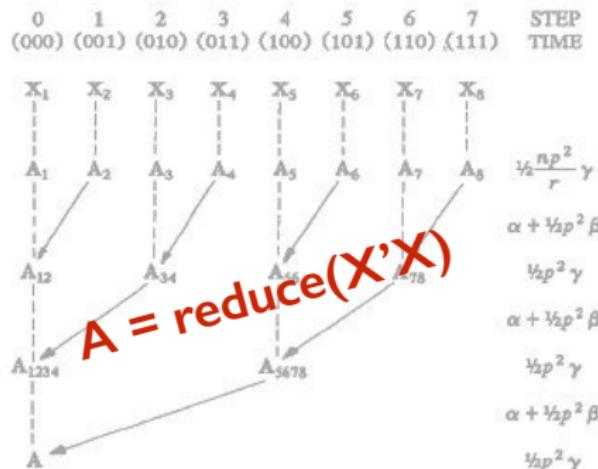


FIG. 4. Computation of $A = X'X$ on an 8-processor hypercube, with final result on processor 0.

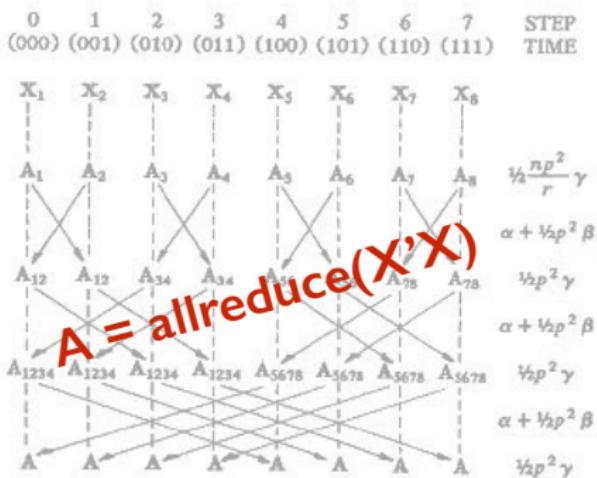


FIG. 6. Computation of $A = X'X$ on an 8-processor hypercube, with final result on all processors.

Architecture-specific vendor optimizations

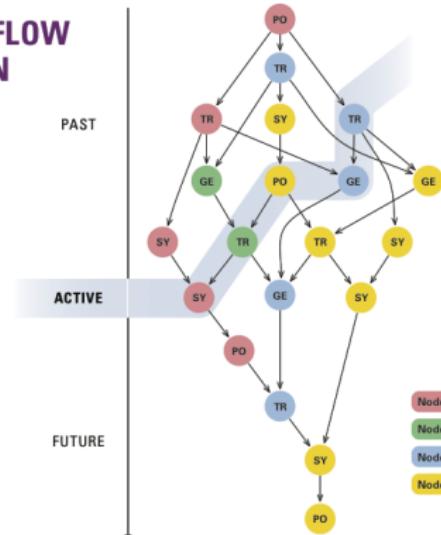
- Cray MPT
- SGI MPT

Data-flow: Parallel Runtime Scheduling and Execution Controller (PaRSEC)

EFFICIENT DATA FLOW REPRESENTATION

FEATURES

- Supports Distributed Heterogeneous Platforms
- Sustained Performance
- NUMA & Cache Aware Scheduling
- State-of-the-art Algorithms
- Capacity Level Scalability
- Performance Portability
- Implicit Communication
- Communication Overlapping



Graphic from icl.cs.utk.edu

Bosilca, G., Bouteiller, A., Danalis, A., Faverge, M., Herault, T., Dongarra, J. "PaRSEC: Exploiting Heterogeneity to Enhance Scalability," IEEE Computing in Science and Engineering, Vol. 15, No. 6, 36-45, November, 2013.

- Master data-flow controller runs distributed on all cores.
- Dynamic generation of current level in flow graph
- Effectively removes collective synchronizations

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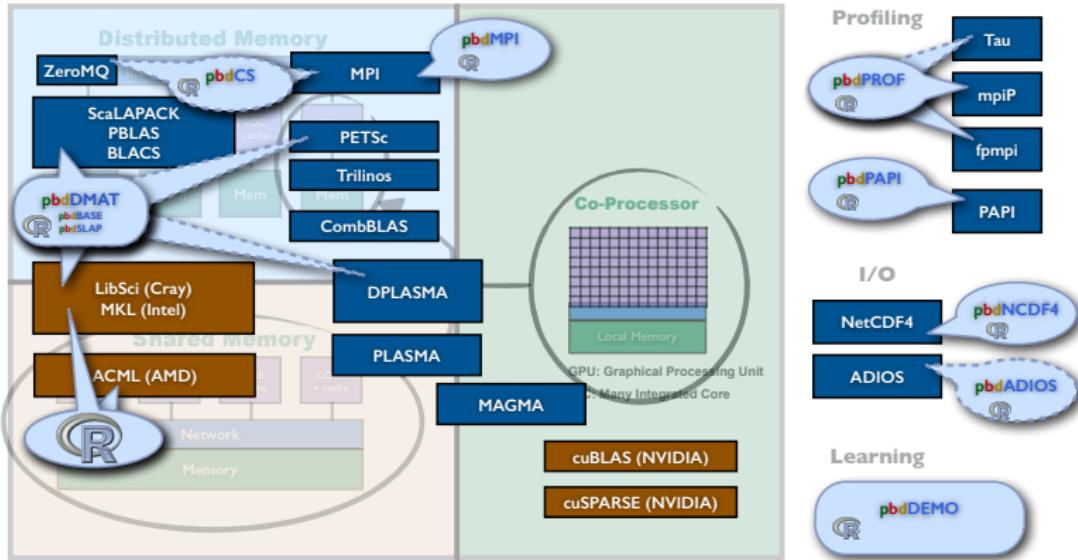
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pbdR Interfaces to Libraries: Sustainable Path



Why use HPC libraries?

- The libraries represent 30+ years of research by the HPC community
- *They're tested. They're fast. They're scalable.*
- Many science communities are invested in their API.
- HPC Simulation Science uses much of the same math as data analysis

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pbdMPI: Simplified, Extensible, and Fast Communication Operations

- S4 methods for collective communication: extensible to other R objects.
- Default methods (like `Robj` in **Rmpi**) check for data type: safe for general users.
- API is simplified: defaults in control objects.
- Array and matrix methods without serialization: faster than **Rmpi**.

pbdMPI (S4)	Rmpi
allgather	<code>mpi.allgather</code> , <code>mpi.allgatherv</code> , <code>mpi.allgather.Robj</code>
allreduce	<code>mpi.allreduce</code>
bcast	<code>mpi.bcast</code> , <code>mpi.bcast.Robj</code>
gather	<code>mpi.gather</code> , <code>mpi.gatherv</code> , <code>mpi.gather.Robj</code>
recv	<code>mpi.recv</code> , <code>mpi.recv.Robj</code>
reduce	<code>mpi.reduce</code>
scatter	<code>mpi.scatter</code> , <code>mpi.scatterv</code> , <code>mpi.scatter.Robj</code>
send	<code>mpi.send</code> , <code>mpi.send.Robj</code>



Integer? Not always obvious in R.

```
1 > is.integer(1)
2 [1] FALSE
3 > is.integer(2)
4 [1] FALSE
5 > is.integer(1:2)
6 [1] TRUE
```

pbdMPI lets R figure it out

Rmpi

```
1 # int
2 mpi.allreduce(x, type=1)
3 # double
4 mpi.allreduce(x, type=2)
```

pbdMPI

```
1 allreduce(x)
```



Single Program (SPMD): Runs Asynchronous Parallel

Rank Query Example

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 batch 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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Mapping a Matrix to Processors

Processor Grid Shapes

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

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

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

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

(a) 1×6

(b) 2×3

(c) 3×2

(d) 6×1

Table: Processor Grid Shapes with 6 Processors

2×3 block-cyclic grid on 6 processors: Global view “ddmatrix” class

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

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

2×3 block-cyclic grid on 6 processors: Local view “ddmatrix” class

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

$$\text{Processor grid} = \left| \begin{array}{ccc} 0 & 1 & 2 \\ 3 & 4 & 5 \end{array} \right| = \left| \begin{array}{ccc} (0,0) & (0,1) & (0,2) \\ (1,0) & (1,1) & (1,2) \end{array} \right|$$

pbdR Example Syntax

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

The above (and over 100 other functions) runs on 1 core with R
or 10,000 cores with pbdR ddmatrix class

```
1 > showClass("ddmatrix")
2 Class "ddmatrix" [package "pbdDMAT"]
3 Slots:
4 Name:      Data      dim      ldim      bldim      ICTXT
5 Class:    matrix numeric numeric numeric numeric
```

```
1 > x <- as.rowblock(x)
2 > x <- as.colblock(x)
3 > x <- redistribute(x, bldim=c(8, 8), ICTXT = 0)
```

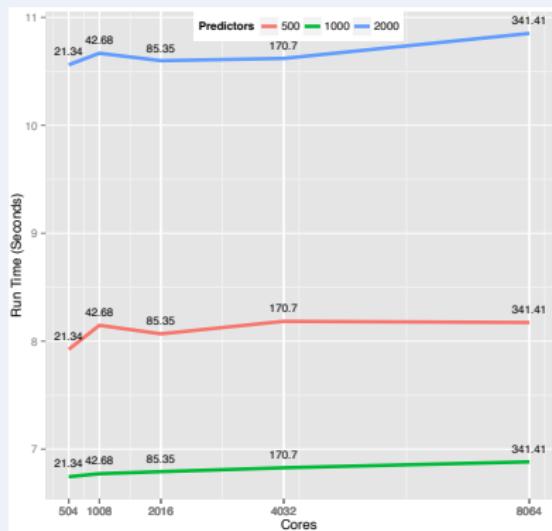
pbdDMAT Scalability Benchmarks

- Default choices throughout (no MKL, ACML, etc.)
- 1 core = 1 MPI process (Kraken: 6-core Opterons)
- Generate random matrix
 - Global Columns: 500, 1000, and 2000
 - Global Rows: fixed per core to make $43.4 MiB$
- Measure wall clock time
- “weak scaling” = global problem grows with core count

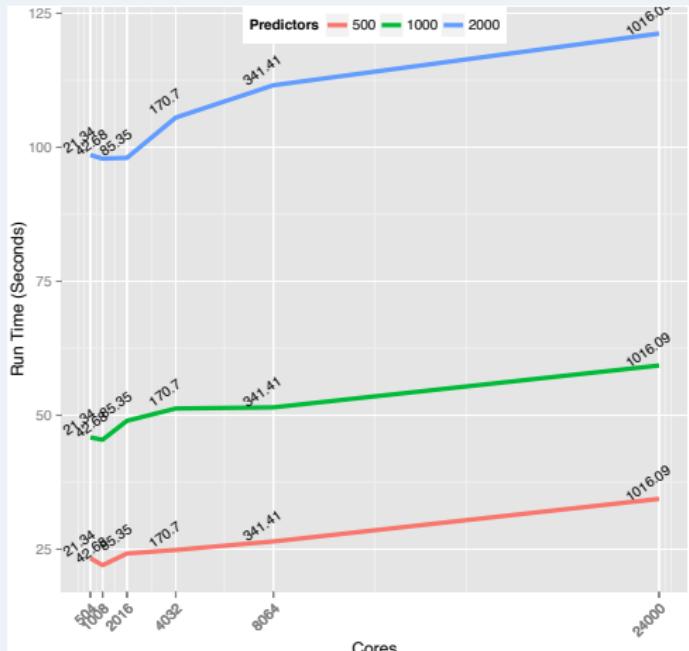


pbdDMAT Scalability Benchmarks

```
1 x <- ddmatrix("rnorm",
  nrow=n, ncol=p)
2 cov.x <- cov(x)
```

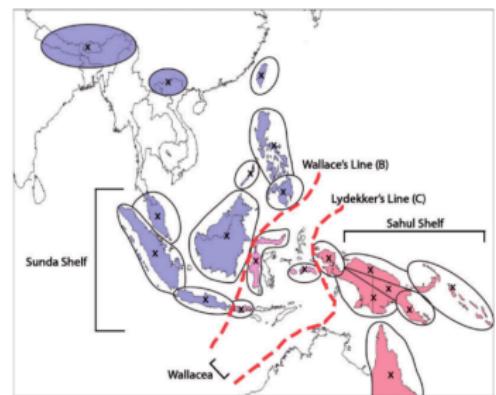
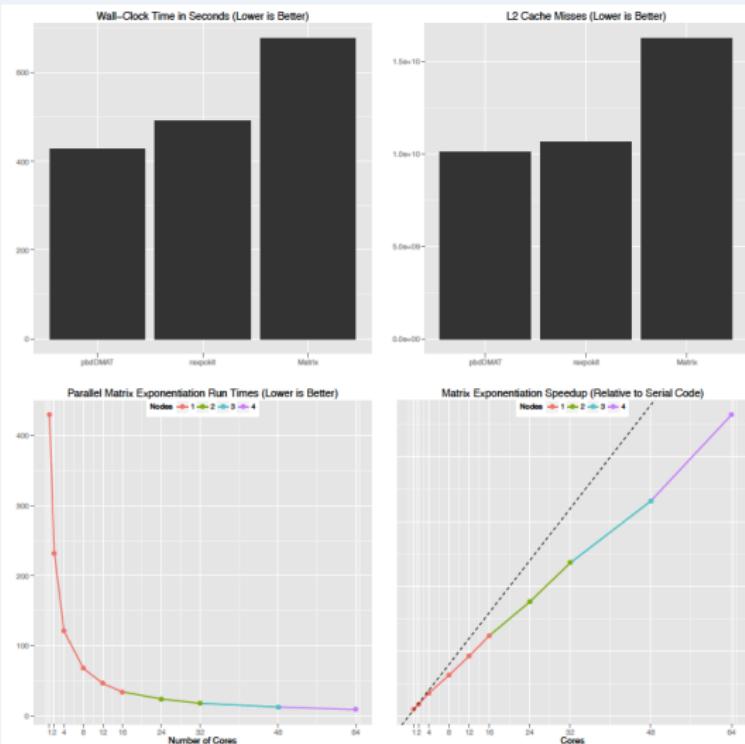


```
1 b <- ddmatrix("runif", nrow=p,
  ncol=1)
2 y <- x %*% b
3 b.hat <- lm.fit(x, y)$coefficients
```



Matrix Exponentiation (pbdDMAT)

- Fitting biogeography models requires many matrix exponentiations
- Benchmark: Matrix exponential of 5000×5000 matrix.
- R 3.1.0, Matrix 1.1-2, expokit 0.25, pbdDMAT 0.3-0
- Libs: Cray LibSci, NETLIB ScaLAPACK, Compilers: gnu 4.8.2
- Configuration: 1 thread == 1 MPI rank == 1 physical core



Schmidt and Matzke (2014) Distributed matrix exponentiation, The R User Conference (UseR! 2014), Los Angeles, CA, August 2014



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Randomized truncated 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, Martinsson, and Tropp. 2011. Finding structure with randomness: probabilistic algorithms for constructing approximate matrix decompositions *SIAM Review* 53 217–288

Randomized truncated SVD

Serial R

```

1 randSVD <- function(A, k, q=3)
2 {
3   ## Stage A
4   Omega <- matrix(rnorm(n*2*k),
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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 }
```

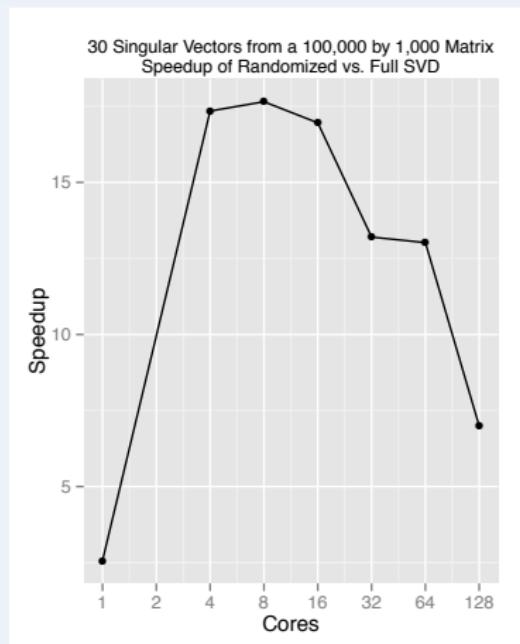
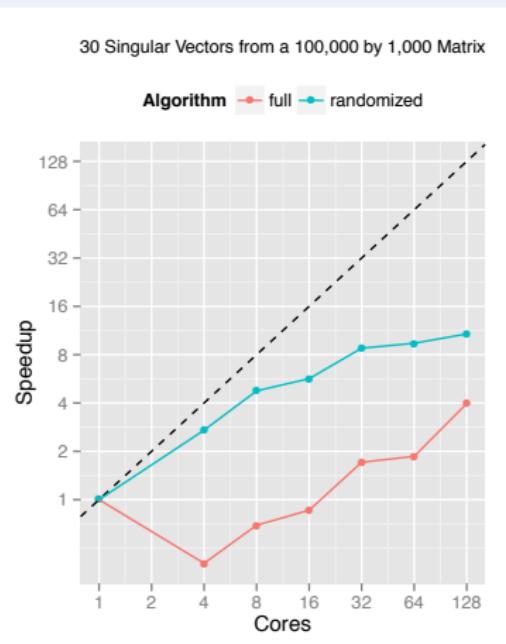
Parallel pbdR

```

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 }
```



From journal to scalable code and scaling data in one day.



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pbdR

- The pbdR Project
- pbdMPI
- pbdDMAT
- RandSVD
- **pbdMPI Example: Random Forest Prediction**
- pbdMPI Example: Functional Data Analysis



Letter Recognition Data

Example 1: Letter Recognition data from package **mlbench** ($20,000 \times 17$)



```
1 [ ,1] lettr capital letter
2 [ ,2] x.box horizontal position of box
3 [ ,3] y.box vertical position of box
4 [ ,4] width width of box
5 [ ,5] high height of box
6 [ ,6] onpix total number of on pixels
7 [ ,7] x.bar mean x of on pixels in box
8 [ ,8] y.bar mean y of on pixels in box
9 [ ,9] x2bar mean x variance
10 [ ,10] y2bar mean y variance
11 [ ,11] xybar mean x y correlation
12 [ ,12] x2ybr mean of  $x^2$  y
13 [ ,13] xy2br mean of x  $y^2$ 
14 [ ,14] x.ege mean edge count left to right
15 [ ,15] xegvy correlation of x.ege with y
16 [ ,16] y.ege mean edge count bottom to top
17 [ ,17] yegvx correlation of y.ege with x
```

P. W. Frey and D. J. Slate (Machine Learning Vol 6/2 March 91): "Letter Recognition Using Holland-style Adaptive Classifiers".

Example 1: Random Forest Algorithm

- ① Build simple regression trees from random subsets of columns
- ② Use model averaging for prediction
- ③ Package **randomForest** has a `combine()` function that enables the following parallel approach:
 - ① Everyone gets the same training data
 - ② Split regression tree building among processors (**randomForest**)
 - ③ Use `allgather` to bring built predictors to all
 - ④ Everyone combine predictors
 - ⑤ Split prediction work by blocks of rows
 - ⑥ Use `allreduce` to assess prediction
- ④ Steps (3) and (4) can be improved with a custom reduce/combine to take advantage of MPI vendor optimizations



Example 1: Random Forest Code

(Split learning by blocks of trees. Split prediction by blocks of rows.)

Serial Code 4_rf_s.r

```
1 library(randomForest)
2 library(mlbench)
3 data(LetterRecognition) # 26 Capital Letters Data 20,000 x 17
4 set.seed(seed=123)
5 n <- nrow(LetterRecognition)
6 n_test <- floor(0.2*n)
7 i_test <- sample.int(n, n_test) # Use 1/5 of the data to test
8 train <- LetterRecognition[-i_test, ]
9 test <- LetterRecognition[i_test, ]
10
11 ## train random forest
12 rf.all <- randomForest(lettr ~ ., train, ntree=500,
13                         norm.votes=FALSE)
14
15 ## predict test data
16 pred <- predict(rf.all, test)
17 correct <- sum(pred == test$lettr)
18 cat("Proportion Correct:", correct/(n_test), "\n")
```

Example 1: Random Forest Code

(Split learning by blocks of trees. Split prediction by blocks of rows.)

Parallel Code 4_rf_p.r

```
1 library(randomForest)
2 library(mlbench)
3 data(LetterRecognition)
4 comm.set.seed(seed=123, diff=FALSE) # same training data
5 n <- nrow(LetterRecognition)
6 n_test <- floor(0.2*n)
7 i_test <- sample.int(n, n_test) # Use 1/5 of the data to test
8 train <- LetterRecognition[-i_test, ]
9 test <- LetterRecognition[i_test, ] [get.jid(n_test), ]
10
11 comm.set.seed(seed=1e6*runif(1), diff=TRUE)
12 my.rf <- randomForest(lettr ~ ., train, ntree=500%/%comm.size(),
13                         norm.votes=FALSE)
13 rf.all <- do.call(combine, allgather(my.rf))
14
15 pred <- predict(rf.all, test)
16 correct <- allreduce(sum(pred == test$lettr))
17 comm.cat("Proportion Correct:", correct/(n_test), "\n")
```

Runs serial or on any number of cores

```
1 [beacon-login2 stats]$ time Rscript 4_rf_s.r
2 Proportion Correct: 0.96725
3 real 0m49.028s    user 0m48.626s    sys 0m0.335s
4 [beacon-login2 stats]$ time Rscript 4_rf_p.r
5 Proportion Correct: 0.96425
6 real 0m52.634s    user 0m51.914s    sys 0m0.598s
7 [beacon-login2 stats]$ time mpirun -np 2 Rscript 4_rf_p.r
8 Proportion Correct: 0.96425
9 real 0m28.349s    user 0m54.570s    sys 0m1.070s
10 [beacon-login2 stats]$ time mpirun -np 4 Rscript 4_rf_p.r
11 Proportion Correct: 0.963
12 real 0m16.380s    user 1m1.559s    sys 0m1.664s
13 [beacon-login2 stats]$ time mpirun -np 8 Rscript 4_rf_p.r
14 Proportion Correct: 0.963
15 real 0m11.010s    user 1m19.301s   sys 0m3.421s
16 [beacon-login2 stats]$ time mpirun -np 16 Rscript 4_rf_p.r
17 Proportion Correct: 0.9635
18 real 0m10.655s    user 2m32.508s   sys 0m6.624s
19 [beacon-login2 stats]$ time mpirun -np 32 Rscript 4_rf_p.r
20 Proportion Correct: 0.96325
21 real 0m21.692s    user 4m44.114s   sys 0m20.179s
```

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fda.usc Package

Profiling min.basis()

```
1 > summaryRprof()
2 $by.total
3
4 "min.basis"           total.time total.pct self.time self.pct
5 "type.CV"             6.54        53.08     0.02      0.16
6 "S.basis"              5.76        46.75     0.00      0.00
7 "drop"                  4.20        34.09     0.00      0.00
8 "norm.fdata"            4.20        34.09     0.00      0.00
9 "metric"                 4.18        33.93     1.04      8.44
10 "%*%"                   3.98        32.31     3.98      32.31
11 "getbasispenalty"       2.72        22.08     0.02      0.16
12 "bsplinepen"            2.68        21.75     0.36      2.92
13 "int.simpson2"          2.54        20.62     1.96     15.91
14 "t"                      2.10        17.05     0.10      0.81
15 "ppBspline"              1.60        12.99     0.82      6.66
16 . . .
```



Example: min.basis() 110 lines

SPMD: Add 5, change 3

```
1 min.basis <- function(fdataobj, type.CV = GCV.S, . . ., ...)  
2 {  
3     . . . 13 lines  
4     library(pbdMPI)  
5     init()  
6     my.k <- get.jid(lenlambda)  
7     my.gcv <- array(Inf, dim = c(lenbasis, length(my.k)))  
8     . . . 36 lines  
9     for (i in 1:lenbasis) {  
10         . . . 3 lines  
11         for (k in my.k) {  
12             S2 <- S.basis(tt, base, lambda[k])  
13             my.gcv[i, k - my.k[1] + 1] <-  
14                 type.CV(fdataobj, S = S2, W = W, trim =  
15                     par.CV$trim, draw = par.CV$draw, ...)  
16         }  
17     }  
18     gcv <- do.call(cbind, allgather(my.gcv))  
19     finalize()  
    . . . 48 lines
```

Contents

3 pbdCS

- Client-Server Demo



3 pbdCS

- Client-Server Demo



0MQ

Some explanation goes here The demo goes here



4 Future Work



Future Work

- Second year of a 3 year NSF grant to
 - Bring back interactivity via client/server (pbDCS 0.1-0)
 - Simplify parallel data input
 - Begin DPLASMA integration
 - Outreach to the statistics community
- DOE funding: In-situ or staging use with simulations
 - Machine learning from fusion simulation data
- Collaboration wishlist
 - RDD, HDFS, etc., file readers
 - Communicator integration with SparkR or Spark
 - Communicator integration with VisIt and ParaView
 - pbDCS integration with RStudio IDE
 - Instrumentation of various R packages with pbDR



Where to learn more?

- <http://r-pbd.org/>
- **pbdDEMO** vignette
- [Googlegroup:RBigDataProgramming](#)

