



# Linear Algebra Libraries

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# Linear Algebra Libraries

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# Part I

## Requirements

This document has been written to help in the choice of a linear algebra library to be included in Verdandi, a scientific library for data assimilation. The main requirements are

1. Portability: Verdandi should compile on BSD systems, Linux, MacOS, Unix and Windows. Beyond the portability itself, this often ensures that most compilers will accept Verdandi. An obvious consequence is that all dependencies of Verdandi must be portable, especially the linear algebra library.
2. High-level interface: the dependencies should be compatible with the building of the high-level interface (e. g. with SWIG, this implies that headers (.hxx) have to be separated from sources (.cxx)).
3. License: any dependency must have a license compatible with Verdandi licenses (GPL and LGPL).
4. C++ templates, sparse matrices and sparse vectors have to be supported.

Information reported here was collected from December 2008 to March 2009.

## Part II

# CPP Lapack

CPP Lapack is a C++ class wrapper for Blas and Lapack.

CPP Lapack	Distribution beta – Mar. 2005	Doc. updated in Mar. 2005
<a href="http://cpplapack.sourceforge.net/">http://cpplapack.sourceforge.net/</a>		
in development	4 developers	First release: Apr. 2004
License: GPL (GPL compatible)		

### *Types of matrices and vectors available*

- Real double-precision and complex double-precision vectors and matrices
- Real double-precision and complex double-precision band, symmetric and sparse matrices

### *Linear algebra operations available*

- Eigenvalues computation
- Linear systems solving
- SVD decomposition

### *Interface with other packages*

- Blas
- Lapack

### *Performance*

Almost the same as the performance of original Blas and Lapack

### *Portability: platforms and compilers supported*

Platform independent

### *Installation*

Requires Blas and Lapack

### *Miscellaneous*

- A few bugs and unsupported Blas and Lapack functions

### *Limitations*

- Templates not supported, float not supported
- Alpha version of sparse matrix classes with bugs (the authors advise developers not to use these classes in their code)
- No sparse vectors
- No separation between headers and sources

## Part III

# Eigen

Eigen is a C++ template library for linear algebra, part of the KDE project.

Eigen	Distribution 2.0-beta6 – soon released	Doc. updated in Jan. 2009
<a href="http://eigen.tuxfamily.org/">http://eigen.tuxfamily.org/</a>		
in development	7 contributors, 2 developers	First release: Dec. 2006
License: LGPL and GPL (GPL compatible)		

### *Types of matrices and vectors available*

- Dense and sparse matrices and vectors
- Plain matrices/vectors and abstract expressions
- Triangular and diagonal matrices
- Column-major (the default) and row-major matrix storage

### *Linear algebra operations available*

- Triangular, SVD, Cholesky, QR and LU solvers
- Eigen values/vectors solver for non-selfadjoint matrices
- Hessemberg decomposition
- Tridiagonal decomposition of a selfadjoint matrix

### *Interface with other packages*

For sparse matrices: TAUCS, umfpack, cholmod and SuperLU

### *Performance*

Very efficient, see benchmark: <http://eigen.tuxfamily.org/index.php?title=Benchmark>

### *Portability: platforms and compilers supported*

Standard C++ 98, compatible with any compliant compiler such as

- GCC, version 3.3 and newer
- MSVC (Visual Studio), 2005 and newer
- ICC, recent versions
- MinGW, recent versions

### *Installation*

No dependency

### *Miscellaneous*

- Templates supported
- Todo includes: interface to Lapack and eigensolver in non-selfadjoint case
- Examples of users:

KDE related projects such as screensavers, kglib, kglengine2d, solidkreator, painting and image editing

Avogadro, an opensource advanced molecular editor

VcgLib, C++ template library for the manipulation and processing of triangular and tetrahedral meshes

MeshLab, for the processing and editing of unstructured 3D triangular meshes and point cloud

The Yujin Robot company uses Eigen for the navigation and arm control of their next generation robots (switched from blitz, ublas and tvmet)

### *Limitations*

- Sparse matrices and vectors still experimental
- Eigen 2 is a beta version (Eigen 1 is the old stable version)

## Part IV

# Flens

Flens (Flexible Library for Efficient Numerical Solutions) is a C++ library for scientific computing providing interface for Blas and Lapack. Flens intends to be the building block of choice for the creation of serious scientific software in C++.

Flens	Distribution RC1 – Jul. 2007	Doc. updated in Feb. 2008
<a href="http://flens.sourceforge.net">http://flens.sourceforge.net</a>		
in development	9 developers	First release: 2004
License: BSD License (GPL compatible)		

### *Types of matrices and vectors available*

- General, triangular and symmetric matrix types
- Storage formats: full storage (store all elements), band storage (store only diagonals of a banded matrix), packed storage (store only the upper or lower triangular part)
- Sparse matrix types: general and symmetric, compressed row storage; random access for initialization

### *Linear algebra operations available*

- Linear systems solving using QR factorization
- Cg and Pcg methods

### *Interface with other packages*

Blas and Lapack

### *Performance*

- Natural mathematical notation: e. g. `y += 2 * transpose(A) * x + 1.5 * b + c` without sacrificing performances (see section 3 in Appendix)
- Very efficient, see benchmarks: <http://flens.sourceforge.net/session2/tut4.html>, [http://grh.mur.at/misc/sparselib\\_benchmark/report.html](http://grh.mur.at/misc/sparselib_benchmark/report.html), <http://flens.sourceforge.net/session1/tut9.html> and section 2.2

### *Portability: platforms and compilers supported*

- Tested on Mac OS X, Ubuntu Linux and a SUSE Opteron cluster
- GCC: version 4 or higher
- Intel C++ compiler (icc): version 9.1
- Pathscale (pathCC): GNU gcc version 3.3.1, PathScale 2.3.1 driver

### *Installation*

Requires Blas, Lapack and CBlas

### *Miscellaneous*

- Extensible: e. g. easy integration of user-defined matrix/vector types
- Flexible: e. g. generic programming of numerical algorithms
- Flens implements a view concept for vectors and dense matrices: a vector can reference a part of a vector, or also a row, column or diagonal of a matrix; you can apply to these views the same operations as for regular vectors and matrices.
- Templated matrices and vectors with several storage formats

### *Limitations*

- Lack of portability: not recently tested on Windows (once compiled with Microsoft Visual Studio Express compiler with minor modifications in the Flens code)
- No eigenvalues computation
- No sparse vectors
- No hermitian matrices

## Part V

# Gmm++

Gmm++ is a generic matrix template library inspired by MTL and ITL.

Gmm++	Distribution 3.1 – Sep. 2008	Doc. updated in Sep. 2008
<a href="http://home.gna.org/getfem/gmm_intro.html">http://home.gna.org/getfem/gmm_intro.html</a>		
in development	2 contributors and 2 developers	First release: Jun. 2002
License: LGPL (GPL compatible)		

### *Types of matrices and vectors available*

Sparse, dense and skyline vectors and matrices

### *Linear algebra operations available*

- Triangular solver, iterative generic solvers (Cg, BiCgStag, Qmr, Gmres) with preconditioners for sparse matrices (diagonal, based on MR iterations, ILU, ILUT, ILUTP, ILDLT, ILDLTT)
- Reference to sub-matrices (with sub-interval, sub-slice or sub-index) for any sparse dense or skyline matrix for read or write operations
- LU and QR factorizations for dense matrices
- Eigenvalues computation for dense matrices

### *Interface with other packages*

- Blas, Lapack or Atlas for better performance
- SuperLU 3.0 (sparse matrix direct solver) for sparse matrices

### *Performance*

Very efficient, see benchmarks: [http://grh.mur.at/misc/sparselib\\_benchmark/report.html](http://grh.mur.at/misc/sparselib_benchmark/report.html) and <http://eigen.tuxfamily.org/index.php?title=Benchmark>

### *Portability: platforms and compilers supported*

- Linux/x86 with g++ 3.x and g++ 4.x
- Intel C++ Compiler 8.0
- Linux/Itanium with g++
- MacOS X Tiger (with the python and matlab interface)
- Windows with MinGW and MSys (without the Python and Matlab interface)

### *Installation*

No special requirement

### *Miscellaneous*

- Templates supported
- Examples of users: IceTools, an open source model for glaciers; EChem++: a problem solving environment for electrochemistry
- Gmm++ is included in Getfem++, a generic and efficient C++ library for finite element methods, awarded by the second price at the "Trophées du Libre 2007" in the category of scientific softwares
- Provides a high-level interface to Python and Matlab via Mex-Files for Getfem++, covering some functionalities of Gmm++

### *Limitations*

- No separation between headers and sources (only header files)
- No eigenvalues computation for sparse matrices
- Gmm++ primary aim is not to be a standalone linear algebra library, but is more aimed at interoperability between several linear algebra packages.



## Part VI

# GNU Scientific Library (GSL)

GSL is a numerical library for C and C++ programmers. The library provides a wide range of mathematical routines covering subject areas such as linear algebra, Blas support and eigensystems.

GSL	Distribution GSL-1.12 – Dec. 2008	Doc. updated in Dec. 2008
<a href="http://www.gnu.org/software/gsl/">http://www.gnu.org/software/gsl/</a>		
in development	18 developers	First release: 1996
License: GPL (GPL compatible)		

### *Types of matrices and vectors available*

General vectors and matrices

### *Linear algebra operations available*

- Eigenvalues and eigenvectors computation
- Functions for linear systems solving: LU Decomposition, QR Decomposition, SVD Decomposition, Cholesky Decomposition, Tridiagonal Decomposition, Hessenberg Decomposition, Bidiagonalization, Householder Transformations, Householder solver for linear systems, Tridiagonal Systems, Balancing

### *Interface with other packages*

- Blas (level 1, 2 and 3)
- CBlas or Atlas
- Many extensions such as Marray, NEMO, LUSH (with full interfaces to GSL, Lapack, and Blas) and PyGSL

### *Performance*

Not evaluated

### *Portability: platforms and compilers supported*

- GNU/Linux with gcc – SunOS 4.1.3 and Solaris 2.x (Sparc) – Alpha GNU/Linux, gcc – HP-UX 9/10/11, PA-RISC, gcc/cc – IRIX 6.5, gcc – m68k NeXTSTEP, gcc – Compaq Alpha Tru64 Unix, gcc – FreeBSD, OpenBSD and NetBSD, gcc – Cygwin – Apple Darwin 5.4 – Hitachi SR8000 Super Technical Server, cc

### *Installation*

Easy to compile without any dependencies on other packages

### *Miscellaneous*

### *Limitations*

- Can be called from C++ but written in C
- No sparse matrices and vectors
- Templates not supported

## Part VII

# IT++

IT++ is a C++ library of mathematical, signal processing and communication routines. Templated vector and matrix classes are the core of the IT++ library, making its functionality similar to that of MATLAB and GNU Octave. IT++ makes an extensive use of existing open source libraries (e. g. Blas, Lapack, ATLAS and FFTW).

IT++	Distribution 4.0.6 – Oct. 2008	Doc. updated in Oct. 2008
<a href="http://itpp.sourceforge.net/">http://itpp.sourceforge.net/</a>		
in development	19 contributors and 11 developers	First release: 2001
License: GPL (not LGPL compatible)		

### *Types of matrices and vectors available*

- Diagonal, Jacobsthal, Hadamard and conference matrices
- Templated vectors and matrices
- Sparse vectors and matrices

### *Linear algebra operations available*

- Matrix decompositions such as eigenvalue, Cholesky, LU, Schur, SVD and QR
- Linear systems solving: over- and underdetermined, LU factorization and Cholesky factorization

### *Interface with other packages*

- Blas, Lapack and FFTW
- Optionally Atlas, MKL and ACML

### *Performance*

Not evaluated

### *Portability: platforms and compilers supported*

GNU/Linux, Sun Solaris, Microsoft Windows (with Cygwin, MinGW/MSYS or Microsoft Visual C++) and Mac OS X

### *Installation*

Packages available (Fedora RPM, Debian GNU/Linux and openSUSE)

### *Miscellaneous*

- Templates supported
- Separation between headers and sources

### *Limitations*

- Its main use is in simulation of communication systems and for performing research in the area of communications. It is also used in areas such as machine learning and pattern recognition.
- One important high-performance feature missing in IT++ is the ability to create "submatrix-views" and "shallow copies" of matrices, i.e. pass submatrices by reference -instead of by value (compared to Lapack++).

## Part VIII

# Lapack++

Lapack++ is a library for high performance linear algebra computations.

Lapack++	Distribution beta 2.5.2 – Jul. 2007	Doc. updated in Jul. 2007
<a href="http://lapackpp.sourceforge.net/">http://lapackpp.sourceforge.net/</a>		
in development	7 developers	First release: 1993
License: LGPL (GPL compatible)		

### *Types of matrices and vectors available*

- Int, long int, real and complex vectors and matrices
- Symmetric positive definite matrix
- Symmetric, banded, triangular and tridiagonal matrices

### *Linear algebra operations available*

- Linear systems solving for non-symmetric matrices, symmetric positive definite systems and solving linear least-square systems; using LU, Cholesky and QR matrix factorizations
- Symmetric eigenvalues computation
- SVN and QR decompositions

### *Interface with other packages*

- Blas
- Lapack

### *Performance*

High performance linear algebra computation

### *Portability: platforms and compilers supported*

- Linux/Unix: gcc2.95.x, gcc3.x and gcc4.x
- Windows 9x/NT/2000: MinGW and gcc3.x
- Windows 9x/NT/2000: Microsoft Visual Studio, .NET and MSVC
- Mac OS X

### *Installation*

Requires Blas, Lapack and a Fortran compiler

### *Miscellaneous*

- Template functions for matrices

### *Limitations*

- Templates not supported, float supported only for general matrices
- No sparse matrices
- No sparse vectors

## Part IX

# Matrix Template Library (MTL)

MTL is a generic component library developed specially for high performance numerical linear algebra. MTL includes matrix formats and functionality equivalent to level 3 Blas.

MTL 4	Distribution alpha 1 – Oct. 2007	Doc. updated in Nov. 2008
<a href="http://www.osl.iu.edu/research/mtl/mtl4/">http://www.osl.iu.edu/research/mtl/mtl4/</a>		
in development	4 developers	First release: 1998 (MTL2)
License: Copyright Indiana University (can be modified to become GPL compatible)		

### *Types of matrices and vectors available*

- Dense2D, morton\_dense and sparse matrices
- Arbitrary types can be used for matrix elements (float, double, complex)

### *Linear algebra operations available*

- Preconditioners: diagonal inversion, incomplete LU factorization without fill-in and incomplete Cholesky factorization without fill-in
- Solvers: triangular, conjugate gradient, BiCg, CgSquared and BiCgStab
- Iterative methods for solving linear systems thanks to the Iterative Template Library (ITL, last release in Oct. 2001): Chebyshev and Richardson iterations, generalized conjugate residual, generalized minimal residual and (transpose free) quasi-minimal residual without lookahead

### *Interface with other packages*

Blas (optionally Blitz++ thanks to ITL)

### *Performance*

- Natural mathematical notation without sacrificing performances:  $A = B * C$  dispatched to the appropriate Blas algorithm if available; otherwise an implementation in C++ is provided (also reasonably fast, usually reaching 60 percent peak)
- See benchmarks: [http://grh.mur.at/misc/sparselib\\_benchmark/report.html](http://grh.mur.at/misc/sparselib_benchmark/report.html), <http://eigen.tuxfamily.org/index.php?title=Benchmark> and <http://projects.opencascade.org/btl/>

### *Portability: platforms and compilers supported*

Can be compiled and used on any target platform with an ANSI C++ compiler

- Linux: g++ 4.0.1, g++ 4.1.1, g++ 4.1.2, g++ 4.2.0, g++ 4.2.1, g++ 4.2.2, icc 9.0
- Windows: VC 8.0 from Visual Studio 2005
- Macintosh: g++ 4.0.1

### *Installation*

Requires the Boost library included, optionally scon and a Blas library installed

### *Miscellaneous*

- Templates and generic programming
- A generic library has been built on top of MTL (ITL: <http://www.osl.iu.edu/research/itl/>)
- Developed from scratch but inspired by the design and implementation details of MTL 2 (interfacing Lapack; supporting sparse, banded, packed, diagonal, tridiagonal, triangle, symmetric matrices)

### *Limitations*

- No sparse vectors
- No eigenvalues computation

– No release since the alpha version in Oct. 2007

# Part X

## PETSc

PETSc, the Portable, Extensible Toolkit for Scientific computation, is a suite of data structures and routines for the scalable (parallel) solution of scientific applications modeled by partial differential equations.

PETSc	Distribution 2.3.3 – May 2007	Doc. updated in Jul. 2008
<a href="http://www.mcs.anl.gov/petsc/petsc-2/">http://www.mcs.anl.gov/petsc/petsc-2/</a>		
in development	11 developers	First release: Mar. 1999
License: Copyright University of Chicago (GPL compatible)		

### *Types of matrices and vectors available*

- Parallel vectors and matrices
- Several sparse matrices storages
- Symmetric, block diagonal and sequential matrices

### *Linear algebra operations available*

- Preconditioners: ILU, LU, Jacobi, block Jacobi, additive Schwartz and ICC
- Direct solvers: LU, Cholesky and QR
- Krylov subspace methods: GMRES, Chebychev, Richardson, conjugate gradients (Cg), CGSquard, BiCgStab, two variants of TFQMR, conjugate residuals and Lsqr
- Nonlinear solvers: Newton-based methods, line search and trust region
- Parallel timestepping solvers: Euler, Backward Euler and pseudo time stepping

### *Interface with other packages*

Blas, Lapack, ADIC/ADIFOR, AnaMod, BlockSolve95, BLOPEX, Chaco, DSCPACK, ESSL, Euclid, FFTW, Hypre, Jostle, Mathematica, Matlab, MUMPS, ParMeTiS, Party, PaStiX, PLapack, Prometheus, Scotch, SPAI, SPOOLES, SPRNG, Sundial/CVODE, SuperLU, Trilinos/ML, UMFPACK

### *Performance*

Optimal on parallel systems with high per-CPU memory performance

### *Portability: platforms and compilers supported*

Any compiler supporting ANSI C standard on Unix or Windows

### *Installation*

Requires Blas, Lapack, MPI and optional packages

### *Miscellaneous*

- Related packages using PETSc such as TAO, SLEPc, Prometheus, OpenFVM, OOFEM, DEAL.II and Python bindings (petsc4py and LINEAL)
- Scientific applications in many fields such as nano-simulations, cardiology, imaging and surgery, geosciences, environment, computational fluid dynamics, wave propagation and optimization

### *Limitations*

- No sparse vectors
- Not coded in C++ but in C
- Templates not supported, polymorphism used instead

## Part XI

# Seldon

Seldon is a C++ library for linear algebra. Seldon is designed to be efficient and convenient, which is notably achieved thanks to template classes.

Seldon	Distribution 2008-11-12 – Nov. 2008	Doc. updated in Nov. 2008
<a href="http://seldon.sourceforge.net/">http://seldon.sourceforge.net/</a>		
in development	2 developers	First release: Nov. 2004
License: GPL (GPL compatible)		

### *Types of matrices and vectors available*

- Dense and sparse vectors
- Dense matrices: several formats for rectangular, symmetric, hermitian and triangular
- Two sparse matrix forms: Harwell-Boeing and array of sparse vectors
- 3D arrays

### *Linear algebra operations available*

- Preconditioner of your own or by successive over-relaxations (SOR)
- Direct dense solvers: LU, QR, LQ and SVD decomposition
- Iterative solvers: BiCg, BiCgcr, BiCgStab, BiCgStabl, Cg, Cgne, Cgs, CoCg, Gcr, Gmres, Lsqr, MinRes, QCgs, Qmr, QmrSym, SYMmetric, Symmlq and TfQmr
- Eigenvalues and eigenvectors computation

### *Interface with other packages*

- Fully interfaced with Blas (level 1, 2 and 3) and Lapack, except for functions with banded matrices
- Direct sparse solvers: MUMPS, SuperLU and UmfPackLU

### *Performance*

Very efficient, see benchmarks in section [2.2](#)

### *Portability: platforms and compilers supported*

- Code fully compliant with the C++ standard
- OS Portable
- GNU GCC  $\geq 3$  (from 3.2 to 4.3 tested); Intel C++ compiler icc (icc 7.1 and 8.0 tested); compile with Microsoft Visual

### *Installation*

Requires Blas and CBlas

### *Miscellaneous*

- Thanks to templates, the solvers can be used for any type of matrix and preconditioning, not only Seldon matrices: very useful to perform a matrix-vector product when the matrix is not stored
- Provides a Python interface generated by SWIG
- Exception handling and several debug levels helpful while coding
- Good coverage of the interface to Blas and Lapack routines (see section [4](#))
- A few alternative functions provided in C++ if Blas is not available

### *Limitations*

- No band matrices

## Part XII

# SparseLib++

SparseLib++ is a C++ class library for efficient sparse matrix computations across various computational platforms.

SparseLib++	Distribution v.1.7 – after 1996	Doc. updated in 1996
<a href="http://math.nist.gov/sparselib++/">http://math.nist.gov/sparselib++/</a>		
minimal maintenance, not in development	3 authors, 0 developers	First release: 1994
License: Public domain (GPL compatible)		

### *Types of matrices and vectors available*

- Sparse double vectors
- Sparse double matrices with several storage formats: compressed row/column, compressed diagonal, coordinate formats, jagged diagonal, block compressed row and skyline

### *Linear algebra operations available*

- Preconditioners: incomplete LU, incomplete Cholesky and diagonal scaling
- Iterative solvers: SOR, Chebyshev iteration, BiCg, BiBgStab, Cg, Cgne, Cgnc, Cgnr, Gmres, MinRes and Qmr
- Sparse triangular system solver

### *Interface with other packages*

Blas

### *Performance*

Not evaluated

### *Portability: platforms and compilers supported*

Various computational platforms

### *Installation*

Requires Blas

### *Miscellaneous*

- Built upon sparse Blas (level 3)
- SparseLib++ matrices can be built out of nearly any C++ matrix/vector classes (it is shipped with the MV++ classes by default)

### *Limitations*

- Templates not supported (only double elements)
- No new feature since 1996, only maintenance
- No eigenvalues computation
- No dense vectors and matrices



## Part XIII

# Template Numerical Toolkit (TNT)

TNT is a collection of interfaces and reference implementations of numerical objects useful for scientific computing in C++. JAMA/C++ library (Java Matrix Package translated into C++) utilizes TNT for the lower-level operations to perform linear algebra operations.

TNT	Distribution v.3.0.11 – Jan. 2008	Doc. updated in 2003
<a href="http://math.nist.gov/tnt/">http://math.nist.gov/tnt/</a>		
active maintenance, not in development	2 authors, 0 developers	First release: Sep. 1999
License: Public domain (GPL compatible)		

### *Types of matrices and vectors available*

- Sparse matrices
- 1D, 2D and 3D arrays (row-major and column-major)

### *Linear algebra operations available*

Provided by JAMA/C++:

- SVD decomposition
- SVD, LU, QR and Cholesky solvers
- Eigenvalues computation

### *Interface with other packages*

None

### *Performance*

Not evaluated

### *Portability: platforms and compilers supported*

ANSI C++ compatibility: should work with most updated C++ compilers (tested by the authors with Microsoft Visual C++ v.5.0)

### *Installation*

By including header files

### *Miscellaneous*

Templates supported

### *Limitations*

- No sparse vectors
- No separation between headers and sources (only header files)
- Beta release since Jan. 2008

## Part XIV

# Trilinos

Trilinos provides algorithms and enabling technologies within an object-oriented software framework for large-scale, complex multi-physics engineering and scientific problems. Trilinos is a collection of interacting independent packages (package names are in *italic*).

Trilinos	Distribution 9.0.1 – Oct. 2008	Doc. updated in Oct. 2008
<a href="http://trilinos.sandia.gov/">http://trilinos.sandia.gov/</a>		
in development	34 developers	First release: Sept. 2003
License: LGPL (GPL compatible)		

### *Types of matrices and vectors available*

- Core kernel package (*Kokkos*)
- Dense, symmetric dense, sparse, block sparse, jagged-diagonal sparse matrices (*Epetra* and *EpetraExt*)
- Dense vectors and multivectors (*Epetra* and *EpetraExt*), sparse vectors (*Tpetra*)
- Integer and double elements (*Epetra* and *EpetraExt*), templates (*Tpetra*)

### *Linear algebra operations available*

- Preconditioners: ILU-type (*AztecOO* and *IFPACK*), Multilevel (*ML*), Block (*Meros*)

### – Linear solvers:

Direct dense solvers (*Epetra* and *Teuchos*: wrappers for selected Blas and Lapack routines, *Pliris*: LU solver on parallel platforms);

Krylov solvers (*AztecOO*: preconditioned Krylov solver, *Belos*: iterative solver, *Komplex*: for complex values);

Direct sparse solvers (*Amesos*: for DSCPACK, SuperLU, SuperLUDist and UMF-PACK);

SVD decomposition (*Epetra*)

### – Nonlinear solvers:

System solvers (*NOX*: globalized Newton methods such as line search and trust region methods, *LOCA*: computing families of solutions and their bifurcations for large-scale applications);

Optimization (*MOOCHO*: reduced-space successive quadratic programming (SQP) methods);

Time integration/Differential-algebraic equations (*Rythmos*)

- Eigensolver: block Krylov-Schur, block Davidson and locally-optimal block preconditioned conjugate gradient (*Anasazi*)

### *Interface with other packages*

- Uses Blas and Lapack

– Provides interfaces for Metis/ParMetis, SuperLU, Aztec, Mumps, Umfpack and soon PETS<sub>c</sub>

– Conjunction possible with SWIG, MPI, Expat (XML parser), METIS and ParMETIS

### *Performance*

*Epetra* provides classes to distribute vectors, matrices and other objects on a parallel (or serial) machine

### *Portability: platforms and compilers supported*

Linux, MAC OS X, Windows (under Cygwin), SGI64, DEC and Solaris

### *Installation*

Requires Blas and Lapack

### *Miscellaneous*

- Examples of users: SIERRA (Software Environment for Developing Complex Multi-physics Applications), SALINAS (structural dynamics finite element analysis), MPSalsa (high resolution 3D simulations with an equal emphasis on fluid flow and chemical kinetics modeling), Sundance (finite-element solutions of partial differential equations), DAKOTA (Design Analysis Kit for Optimization and Terascale Applications ; coding for uncertainty quantification, parameter estimation and sensitivity/variance analysis)
- Most of Trilinos functionalities available in a Python script
- A package of basic structures with templated types (*Tpetra*, first release distributed with 9.0.1)
- *EpetraExt* enables objects to be easily exported to MATLAB
- Trilinos is based on established algorithms at Sandia. The effort required to develop new algorithms and enabling technologies is substantially reduced because a common base provides an excellent starting point. Furthermore, many applications are standardizing on the Trilinos APIs: these applications have access to all Trilinos solver components without any unnecessary interface modifications.

### *Limitations*

- Not yet available: templates (except in an isolated package, *Teuchos*) and sparse vectors (*Tpetra* is still under heavy development, release planned in Mar./Apr. 2009)
- Impossible to build Trilinos under Windows without Cygwin (improved Windows support in a further release)
- Trilinos is a complex collection of interoperable packages and requires some careful configuration (with a suitable set of packages and options)

## Part XV

# uBlas

uBlas is a C++ template class library that provides Blas level 1, 2, 3 functionality for dense, packed and sparse matrices.

uBlas	Distribution 1.33.0 – Jul. 2008	Doc. updated in 2008
<a href="http://www.boost.org/doc/libs/1_35_0/libs/numeric/ublas/">http://www.boost.org/doc/libs/1_35_0/libs/numeric/ublas/</a>		
in development	5 developers	First release: 2008
License: Boost Software License (GPL compatible)		

### *Types of matrices and vectors available*

- Dense, unit and sparse (mapped, compressed or coordinate) vectors
- Dense, identity, triangular, banded, symmetric, hermitian, packed and sparse (mapped, compressed or coordinate) matrices

### *Linear algebra operations available*

- Submatrices and subvectors operations
- Triangular solver
- LU factorization

### *Interface with other packages*

Blas (level 1, 2 and 3)

### *Performance*

Optimized for large vectors and matrices, see benchmarks:

<http://flens.sourceforge.net/session2/tut4.html>,

<http://flens.sourceforge.net/session1/tut9.html>, <http://eigen.tuxfamily.org/index.php?tit>

<http://projects.opencascade.org/btl/> and and section 2.2

### *Portability: platforms and compilers supported*

OS Independent, requires a modern (ISO standard compliant) compiler such as GCC 3.2.3, 3.3.x, 3.4.x, 4.0.x; MSVC 7.1, 8.0; ICC 8.0, 8.1; Visual age 6; Codewarrior 9.4, 9.5

### *Installation*

Requires Blas

### *Miscellaneous*

- Templates supported
- Included in Boost C++ libraries
- Mathematical notation to ease the development (use of operator overloading)

### *Limitations*

- No eigenvalues computation
- Only basic linear algebra (no linear solving except triangular solver)
- The implementation assumes a linear memory address model
- Tuning focussed on dense matrices
- No separation between headers and sources (only header files)

## Part XVI

# Other Libraries

**Armadillo++** is a C++ linear algebra library providing matrices and vectors, interfacing Lapack and Atlas. : <http://arma.sourceforge.net/>.

*Limitations* — No templates (only double), early development (first release in Apr. 2008), no portability under Windows without Cygwin.

**Blitz++** is a C++ class library for scientific computing providing high performance by using template techniques. The current versions provide dense arrays and vectors, random number generators, and small vectors and matrices: <http://www.oonumerics.org/blitz/>.

*Limitations* — No sparse matrices and vectors. Barely relevant for linear algebra.

**CPPScaLapack** is a C++ class wrapper for BLACS, PBlas and ScaLapack with MPI. CPPScaLapack provides a user-friendly interface of high-speed parallel matrix calculation with Blas and Lapack technologies for programmers concerning with large-scale computing: <http://cppscalapack.sourceforge.net/>.

*Limitations* — Still an alpha program, no sparse matrices and vectors, no templates (only double-precision vectors and general matrices).

**CVM Class Library** provides vector and different matrices including square, band, symmetric and hermitian ones in Euclidean space of real and complex numbers. It utilizes Blas and Lapack. Contains different algorithms including solving of linear systems, singular value decomposition, non-symmetric and symmetric eigenvalue problem (including Cholesky and Bunch-Kaufman factorization), LU factorization, QR factorization: <http://www.cvmlib.com/>.

*Limitations* — Templates supported but distinction between real and complex types. No sparse matrices and vectors.

**IML++** (Iterative Methods Library) is a C++ templated library for solving linear systems of equations, capable of dealing with dense, sparse, and distributed matrices: <http://math.nist.gov/impl++/>.

*Limitations* — No matrices and vectors, only iterative solvers.

**LA library** is a C++ interface to Blas and Lapack providing also a general (sparse) matrix diagonalization, linear solver and exponentiation templates : <http://www.pittnerovi.com/la/>.

*Limitations* — Portability: tested only on Linux with a code not fully ANSI C++ compliant.

**LinAl** The library is based on STL techniques and uses STL containers for the storage of matrix data furthermore STL algorithms are used where feasible. Low level, algebraic operators as well as linear solvers and eigenvalue solvers are implemented, based on calls to Blas, Lapack and CGSOLX and LANCZOS: <http://linal.sourceforge.net/LinAl/Doc/linal.html>.

*Limitations* — No vectors, no sparse matrices.

**LinBox** is a C++ template library for exact, high-performance linear algebra computation with dense, sparse, and structured matrices over the integers and over finite fields: <http://www.linalg.org/>.

*Limitations* — Does not suit to real and complex values.

**MV++** is a small set of concrete vector and matrix classes specifically designed for high performance numerical computing, including interfaces to the computational kernels found in Blas: <http://math.nist.gov/mv++/>.

*Limitations* — Only building blocks to a larger-user level library such as SparseLib++ and Lapack++.

**Newmat** C++ library supports various matrix types. Only one element type (float or double) is supported. The library includes Cholesky decomposition, QR, triangularisation, singular value decomposition and eigenvalues of a symmetric matrix: [http://www.robertnz.net/nm\\_intro.htm](http://www.robertnz.net/nm_intro.htm).

*Limitations* — No sparse matrices and vectors, templates not supported.

**RNM** by Frédéric Hecht provides C++ classes for arrays with vectorial operations: <http://www.ann.jussieu.fr/~hecht/>.

*Limitations* — Only general matrices, no sparse matrices, no vectors, only one linear system solver (conjugate gradient), no English documentation.

**SL++ (Scientific Library)** is a C++ numerical library, composed of modules specialized in various fields of numerical computations: <http://ldeniau.home.cern.ch/ldeniau/html/sl++.html>.

*Limitations* — Not developed since 1998.

**TCBI (Temporary Base Class Idiom)** templated C++ numerical library implements basic data structures like complex numbers, dynamic vectors, static vectors, different types of matrices like full matrices, band matrices, sparse matrices, etc. It also includes some standard matrix solvers like Gauss-Jordan, LU-decomposition and Singular Value Decomposition and a set of powerful iterative solvers (Krylov subspace methods along with preconditioners). Also interfaces to netlib libraries such as CLapack or SuperLU. Its specificity is being exclusively written in C++, without needing to interface to Fortran code. The usual loss of performance associated with object-oriented languages has been avoided through not as obvious implementations of numerical base classes, avoiding unnecessary copying of objects. It can be thought of as some sort of reference counting done by the compiler at compile time. Supported on Linux/Unix with the GNU compiler, on Windows with the Microsoft Visual C++ (6, 7) compiler and with the Intel compiler: <http://plasimo.phys.tue.nl/TBCI/>.

*Limitations* — No interface to Blas and Lapack.

## Part XVII

# Links and Benchmarks

## 1 Links

Here are some Web portals related to numerical analysis software and linear algebra libraries:

- List of numerical analysis software (Wikipedia)  
[http://en.wikipedia.org/wiki/List\\_of\\_numerical\\_analysis\\_software](http://en.wikipedia.org/wiki/List_of_numerical_analysis_software)
- Numerical computing resources on the Internet (Indiana University)  
<http://www.indiana.edu/~statmath/bysubject/numerics.html>
- Scientific computing in object-oriented languages (community resources)  
<http://www.oonumerics.org/oon/>
- Scientific computing software (Master's Degrees in Applied Mathematics at École Centrale Paris) <http://norma.mas.ecp.fr/wikimas/ScientificComputingSoftware>

## 2 Benchmarks

### 2.1 Benchmarks for Linear Algebra Libraries

- Freely available software for linear algebra on the web – 2006 comparative statement  
<http://www.netlib.org/utk/people/JackDongarra/la-sw.html>
- Benchmark sparse matrices (tests for residual and random order initialization) – 2008  
<http://flens.sourceforge.net/session2/tut4.html>
- Some Blas Benchmarks – 2007 <http://flens.sourceforge.net/session1/tut9.html>
- Benchmark 2008 <http://eigen.tuxfamily.org/index.php?title=Benchmark>
- Benchmark of C++ Libraries for Sparse Matrix Computation – 2007  
[http://grh.mur.at/misc/sparselib\\_benchmark/report.html](http://grh.mur.at/misc/sparselib_benchmark/report.html)
- Benchmark for Templated Libraries project – 2003  
<http://projects.opencascade.org/btl/>

## 2.2 Benchmarks including Seldon

Platform: Intel Core 2 Duo CPU P9500, 2.53GHz, 6 MB cache, 4 GB Ram.  
Compiler: gcc version 4.3.2 (Ubuntu 4.3.2-1ubuntu12).  
Date: March 2009.

### 2.2.1 Benchmarks for Dense Matrix

Adapted from <http://flens.sourceforge.net/session1/tut9.html>

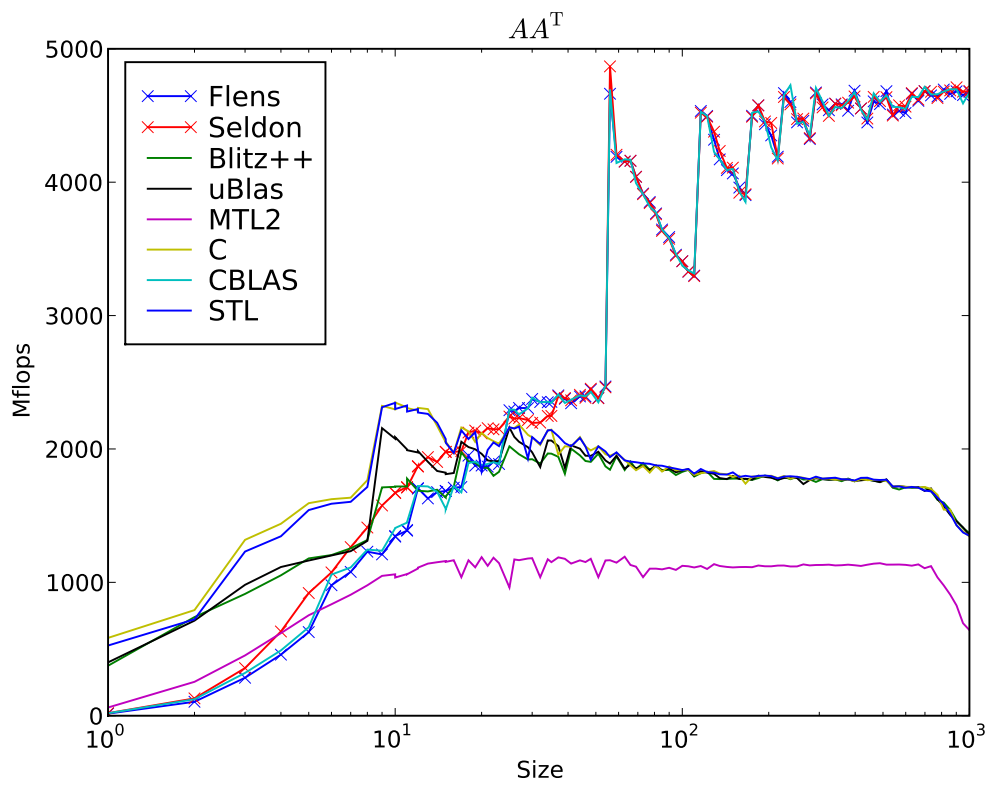


Figure 1:  $A \times A^T$  product for dense matrices.



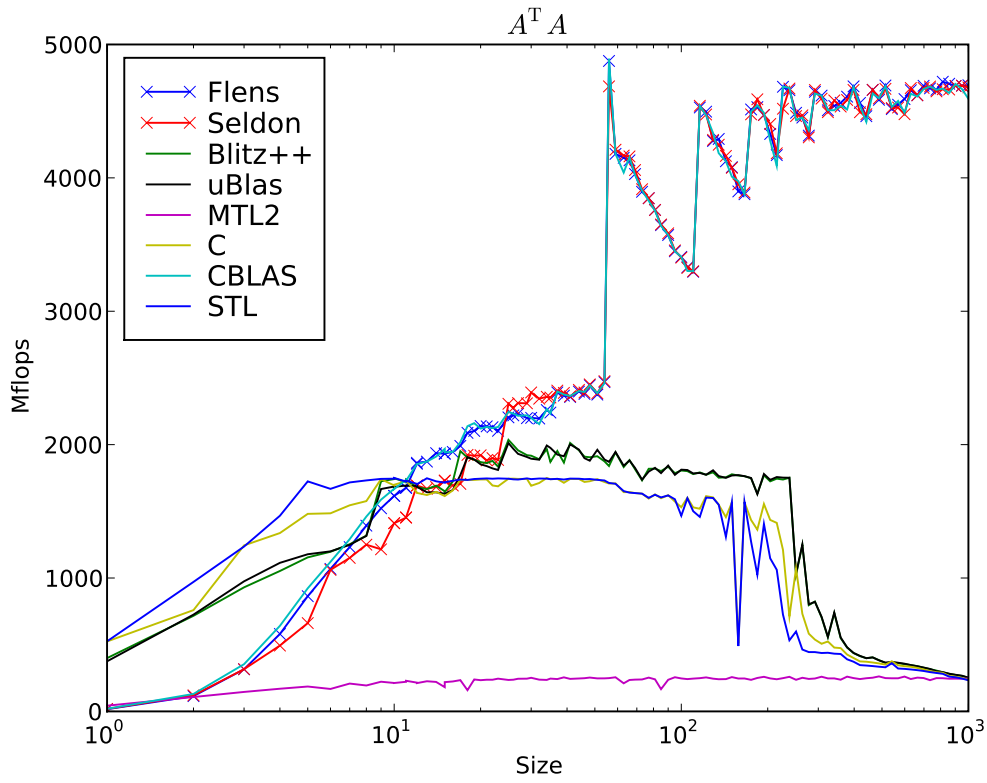


Figure 2:  $A^T A$  product for dense matrices.

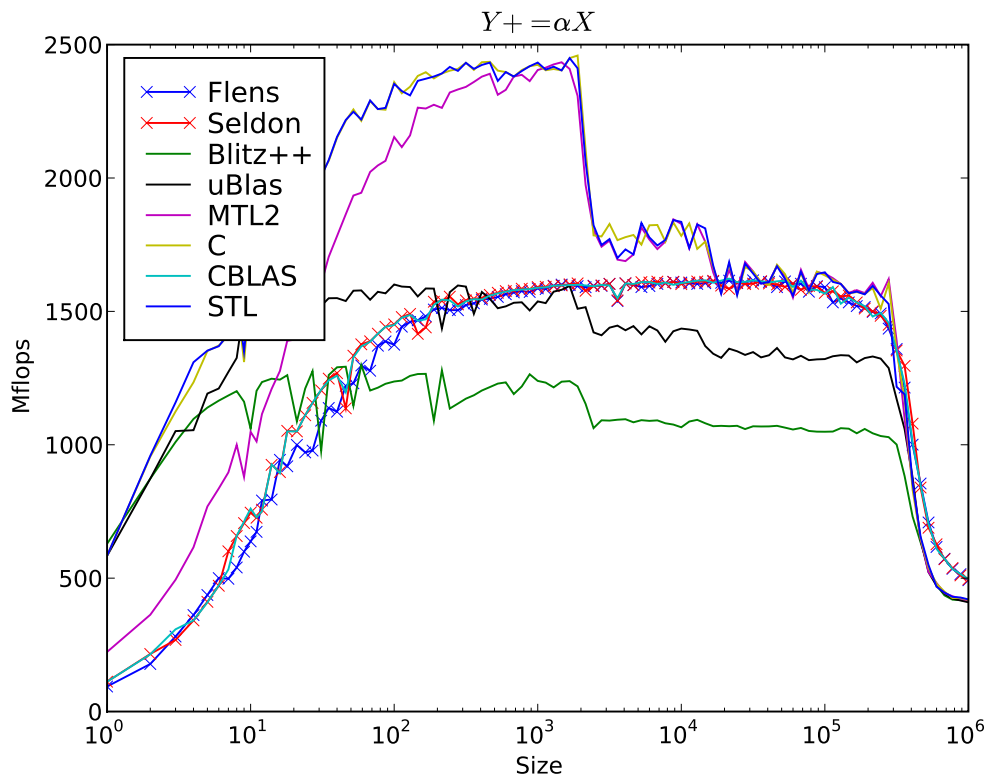


Figure 3:  $Y += \alpha * X$  for dense vectors.

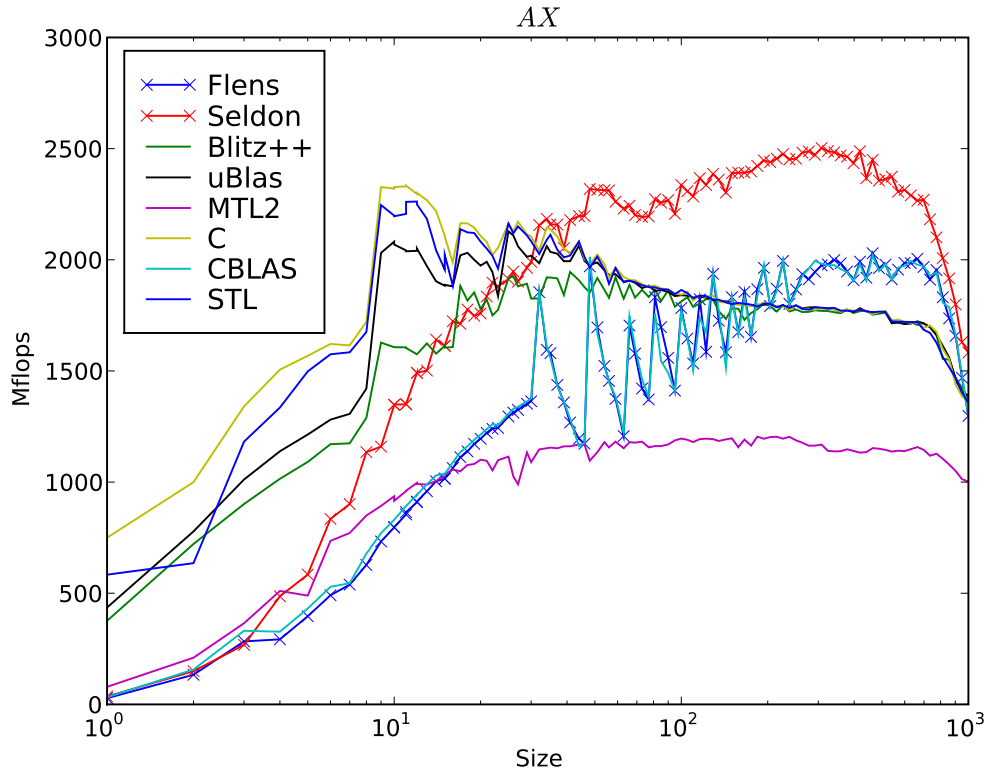


Figure 4: Matrix vector product for dense matrices and vectors.

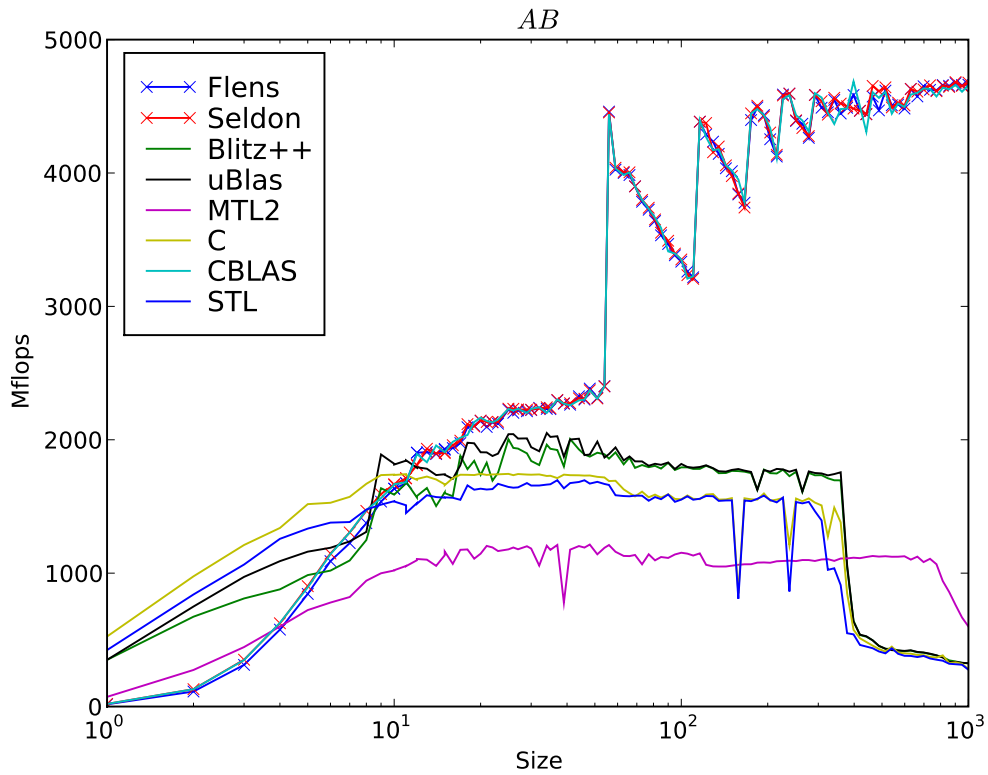


Figure 5: Matrix matrix product for dense matrices.

## 2.2.2 Benchmarks for Sparse Matrix

Adapted from <http://flens.sourceforge.net/session2/tut4.html>.

Compiled with -DNDEBUG -O3 options for g++.

Matrices of 1 000 000 lines.

1. Benchmark for sparse matrix, vector product with random initialization  
5 non zero elements per line on average. In CRS Flens format, the number of non zero values stored corresponds to the number of non zero values plus the number of empty lines (one 0 is inserted on the diagonal).

	Flens	Seldon
initialization	0.35s	1.48s
finalization	1.23s	
$y = Ax$	1.28s	1.3s
$y = A'x$	1.61s	1.49s

2. Benchmark with initialization in order and tridiagonal matrix  
3 non zero elements per line (except on first and last lines with only 2 non zero elements).

	Flens	Seldon (matrix built by hand)	Seldon (matrix built with a generic algorithm *)
initialization	0.28s	0.08s	0.1s
finalization	0.16s		
$y = Ax$	0.19s	0.18s	0.18s
$y = A'x$	0.22s	0.22s	0.22s

\*using MergeSort on already sorted vectors, instead of QuickSort used in random initialization case.

3. Benchmark for computation of the residual  
5 non zero elements per line on average.

	Flens	Seldon
initialization	1.34s	2.46s
finalization	1.25s	
computations $r = b - Ax$	1.39s	1.35s

## Acknowledgement

This document benefits from discussions with Vivien Mallet, Dominique Chapelle and Philippe Moireau, and also from corrections thanks to Xavier Clerc.

## Part XVIII

# Appendix

These sections deal with Flens distribution RC1 (Jul. 2007), Seldon distribution 2008-11-12 and Trilinos distribution 9.0.1 (Oct. 2008). The first two libraries satisfy the main requirements exposed in section I, and Trilinos was supposed to be a good reference as for the coverage of Blas and Lapack.

### 3 Flens Overloaded Operator Performance Compared to Seldon

Flens implements a user-friendly interface to Blas routines by overloading operators. For example, one can add vectors by using mathematical symbols:  $y = a + b + c$ . Here are a few tests to check if this does not imply any loss of performance in the computation.

In table 1 are presented CPU times measured with `std::clock()` for several operations, for RowMajor (R.) and ColMajor (C.) matrices. In the following, lower-case letters denote vectors and upper-case letters denote matrices.  $Y = A + B$  cannot be used for sparse matrices in Flens, so this has been tested only on general dense matrices.

In ColumnMajor format for Flens, the affectation operation  $Y = A$  costs much more (1.48s) than in RowMajor format (0.35s). This lack of performance slows down sum operations such as  $Y = A + B$ . This is due to a direct call to Blas to copy the data (a memory block copy in C++ is used in Seldon).

In ColumnMajor for Seldon, matrix vector product such as  $Y += \text{transpose}(A)*B$  is three times longer than in Flens. This is due to a call to a generic function instead of the Blas routine. Taking advantage of a local knowledge of Seldon (one of its authors, Vivien Mallet, is part of my team!), we have fixed this bug and got the same results as in Flens for  $y += \text{transpose}(A)*b$  and  $y += 2*\text{transpose}(A)*b + 1.5*c + d$ .

Table 1: Flens and Seldon performance benchmarks using overloaded operators.

Operation	Flens code	R.(s)	C.(s)	Seldon code	R.(s)	C.(s)
$y = a + b + c$	$y = a + b + c;$	1.16	1.17	$y = a; \text{Add}(b,y); \text{Add}(c,y);$	1.13	1.12
	$y = a; y += b; y += c;$	1.16	1.18			
	$y = a + b; y += c;$	1.17	1.18			
$y = a + b + c + d$	$y=a+b+c+d;$	1.58	1.59	$y=a; \text{Add}(b,y); \text{Add}(c,y); \text{Add}(d,y)$	1.52	1.54
	$y = a; y += b; y += c; y += d;$	1.6	1.58			
$y += 4a$	$y += 4a;$	4.11	4.07	$\text{Add}(4.,a,y);$	4.09	4.09
	$\text{axpy}(4, a, y);$	4.09	4.1			
$Y = A$	$Y = A;$	0.35	1.48	$Y = A;$	0.32	0.32
$Y = A + B$	$Y = A + B;$	0.78	2.92	$Y = A; \text{Add}(B,Y);$	0.76	1.89
	$Y = A; Y += B;$	0.78	2.93			
$Y = A + B + C$	$Y = A + B + C;$	1.21	4.41	$Y = A; \text{Add}(B,Y); \text{Add}(C,Y);$	1.24	3.44
	$Y = A + B; Y += C;$	1.22	4.35			
	$Y = A; Y += B; Y += C;$	1.21	4.35			
$Y = A + B + C + D$	$Y = A + B + C + D;$	1.63	5.78	$Y = A; \text{Add}(B,Y); \text{Add}(C,Y); \text{Add}(D,Y);$	1.7	4.95
	$Y = A; Y += B; Y += C; Y += D;$	1.62	5.78			
$y = Ax + b$	$y = Ax + b;$	1.64	2.09	$\text{Copy}(b,y); \text{MltAdd}(1.,A,x,1.,y);$	1.61	2.08
$y += A*b$	$y += A*b;$	1.63	2.07	$\text{MltAdd}(1.,A,b,1.,y);$	1.63	2.08
$y += \text{transpose}(A)*b$	$y += \text{transpose}(A)*b;$	2.05	1.63	$\text{MltAdd}(1.,\text{SeldonTrans},A,b,1.,y);$	6.64/2.05*	1.53
$y += 2\text{transpose}(A)*b + 1.5c + d$	$y += 2*\text{transpose}(A)*b + 1.5c + d;$	2.06	1.64	$\text{MltAdd}(2.,\text{SeldonTrans},A,b,1.,y); \text{Add}(1.5,c,y); \text{Add}(d,y);$	6.66/2.05*	1.52
$C += 1.5A*\text{transpose}(B)$	$C += 1.5A*\text{transpose}(B);$	43.18	43.3	$\text{MltAdd}(1.5,\text{SeldonNoTrans}, A,\text{SeldonTrans},B,1.,C);$	43.1	43.26

\* with the correction (see above for the explanation).

## 4 Flens, Seldon and Trilinos Content Comparisons

### 4.1 Available Matrix Types from Blas (Flens and Seldon)

F stands for Flens, S stands for Seldon. A black cell for an existing structure; a gray cell for no structure.

	F	S		F	S		F	S
GE - General			GB - General Band					
SY - SYmmetric			SB - Sym. Band			SP - Sym. Packed		
HE - HERmitian			HB - Herm. Band			HP - Herm. Packed		
TR - TRiangular			TB - Triang. Band			TP - Triang. Packed		

## 4.2 Available Interfaces to Blas and Lapack Routines (Flens and Seldon)

A black cell for an existing interface to a given routine; a gray cell for no interface.

### 1. Blas routines

	Flens	Seldon		Flens	Seldon		Flens	Seldon		Flens	Seldon
srotg			drotg			crotg			zrotg		
srotmg			drotmg			srot			drot		
csrot			zdrot			srotm			drotm		
sswap			dswap			cswap			zswap		
sscal			dscal			cscal			zscal		
csscal			zscal			scopy			dcopy		
ccopy			zcopy			saxpy			daxpy		
caxpy			zaxpy			sdot			ddot		
sdsdot			dsdot			cdotu			zdotu		
cdotc			zdotc			snrm2			dnrm2		
senrm2			dznrm2			sasum			dasum		
scasum			dzasum			isamax			idamax		
icamax			izamax			sgemv			dgemv		
cgemv			zgemv			sgbmv			dgbmv		
cgbmv			zgbmv			chemv			zhemv		
chbmv			zhbmv			chpmv			zhpmv		
ssymv			dsymv			ssbmv			dsbmv		
sspmv			dspmv			strmv			dtrmv		
ctrmv			ztrmv			stbmv			dtbmv		
ctbmv			ztbmv			stpmv			dtpmv		
ctpmv			ztpmv			strsv			dtrsv		
ctrsv			ztrsv			stbsv			dtbsv		
ctbsv			ztbsv			stpsv			dtps		
ctpsv			ztpsv			sger			dger		
cgeru			zgeru			cgerc			zgerc		
cher			zher			chpr			zhpr		
cher2			zher2			chpr2			zhpr2		
ssyr			dsyr			sspr			dspr		
ssyr2			dsyr2			sspr2			dspr2		
sgemm			dgemm			cgemm			zgemm		
ssymm			dsymm			csymm			zsymm		
chemm			zhemm			ssyrk			dsyrk		
csyrk			zsyrk			cherk			zherk		
ssyr2k			dsyr2k			csyr2k			zsyr2k		
cher2k			zher2k			strmm			dtrmm		
ctrmm			ztrmm			strsm			dtrsm		
ctrsm			ztrsm								

Blas	Flens	Seldon
Total	44	110
Coverage	30%	75%

2. Single precision real Lapack routines

	Flens	Seldon		Flens	Seldon		Flens	Seldon		Flens	Seldon
sgesv			sgbsv			sgtsv			sposv		
sppsv			spbsv			sptsv			ssysv		
sspsv			sgels			sgelsd			sgglse		
sggglm			ssyev			ssyevd			sspev		
sspevd			ssbev			ssbevd			sstev		
sstevd			sgees			sgeev			sgesvd		
sgesdd			ssygv			ssygvd			sspgv		
sspgvd			ssbgv			ssbgvd			sgegs		
sgges			sgegv			sggev			sggsvd		
sgesvx			sgbsvx			sgtsvx			sposvx		
sppsvx			spbsvx			sptsvx			ssysvx		
sspsvx			sgelsx			sgelsy			sgelss		
ssyevx			ssyevr			ssygvx			sspevx		
sspgvx			ssbevz			ssbgvx			sstevx		
sstevr			sgeesx			sggesx			sgeevx		
sggevx			sbdsdc			sbdsqr			sdisna		
sgbbrd			sgbcon			sgbequ			sgbrfs		
sgbtrf			sgbtrs			sgebak			sgebal		
sgebrd			sgecon			sgeequ			sgehrd		
sgelqf			sgeqlf			sgeqp3			sgeqpf		
sgeqrf			sgerfs			sgerqf			sgetrf		
sgetri			sgetrs			sggbak			sggbal		
sgghrd			sggqrf			sggrqf			sggsvp		
sgtcon			sgtrfs			sgttrf			sgttrs		
shgeqz			shsein			shseqr			sopgtr		
sopmtr			sorgbr			sorghr			sorglq		
sorgql			sorgqr			sorgrq			sorgtr		
sormbr			sormhr			sormlq			sormql		
sormqr			sormr3			sormrq			sormrz		
sormtr			spbcon			spbequ			spbrfs		
spbstf			spbtrf			spbtrs			spocon		
spoequ			sporfs			spotrf			spotri		
spotrs			sppcon			sppequ			spprfs		
spptrf			spptri			spptrs			sptcon		
spteqr			sptrfs			sptrf			spttrs		
ssbgst			ssbtrd			sspcon			sspgst		
ssprfs			ssptrd			ssptrf			ssptri		
ssptrs			sstebz			sstedc			sstegr		
sstein			ssteqr			ssterf			ssycon		
ssygst			ssyrfs			ssytrd			ssytrf		
ssytri			ssytrs			stbcon			stbrfs		
stbtrs			stgevc			stgexc			stgsen		
stgsja			stgsna			stgsyl			stpcon		
stprfs			stptri			stptrs			strcon		
strevc			strexc			strrfs			strsen		
strsna			strsyl			strtri			strtrs		
strzrf			strzrf								

Single real Lapack	Flens	Seldon
Total	15	36
Coverage	8%	19%



3. Double precision real Lapack routines

	Flens	Seldon	Flens	Seldon	Flens	Seldon	Flens	Seldon
dgesv	■		dsgesv		dgbsv	■	dgtsv	
dposv			dppsv		dpbsv		dptsv	
dsysv			dspsv		dgels	■	dgelsd	
dggls			dggglm		dsyev		dsyevd	
dspev		■	dspevd		dsbev		dsbevd	
dsteve			dsteve		dgees		dgeev	■
dgesvd	■		dgesdd		dsygv	■	dsygvd	
dspgv	■	■	dspgvd		dsbgv		dsbgvd	
dgegs			dgges		dgegv		dggev	■
dggsvd			dgesvx		dgbsvx		dgtsvx	
dposvx			dppsvx		dpbsvx		dptsvx	
dsysvx			dspsvx		dgelsx		dgelsy	
dgelss	■		dsyevx		dsyevr		dsygvx	
dspevx			dspgvx		dsbev		dsbgvx	
dstevx			dstevr		dgeesx		dggesx	
dgeevx			dggev		dbdsdc		dbdsqr	
ddisna			dgbbrd		dgbcon		dgebequ	
dgbfrs			dgbtrf	■	dgbtrs	■	dgebak	
dgebal			dgebrd		dgecon	■	dgeequ	■
dgehrd			dgelqf	■	dgeqlf	■	dgeqp3	■
dgeqpf			dgeqrf	■	dgerfs	■	dgerqf	
dgetrf	■		dgetri	■	dgetrs	■	dggbak	
dggbal			dggghrd		dggqrf		dggrqf	
dggsvp			dgtcon		dgtrfs		dgtrrf	
dgtrrs			dhgeqz		dhsein		dhseqr	
dopgtr			dopmtr		dorgbr		dorghr	
dorglq			dorgql		dorgqr	■	dorgrq	
dorgtr			dormbr		dormhr	■	dormlq	■
dormql			dormqr	■	dormr3		dormrq	
dormrz			dormtr		dpbcon		dpbequ	
dpbrfs			dpbstf		dpbtrf		dpbtrs	
dpocon			dpoequ		dporfs		dpotrf	
dpotri			dpotrs		dppcon		dppequ	
dpprfs			dpptrf		dpptri		dpptrs	
dptcon			dpteqr		dptrfs		dpttrf	
dpttrs			dsbgst		dsbtrd		dspcon	■
dspgst			dsprfs	■	dsptrd		dsptrf	■
dsptri		■	dsptrs	■	dstebe		dstedc	
dstegr			dstein		dsteqr		dsterf	
dsycon		■	dsygst		dsyrfs	■	dsytrd	
dsytrf		■	dsytri	■	dsytrs	■	dtbcon	
dtbrfs			dtbtrs	■	dtgevc		dtgexc	
dtgsen			dtgsja		dtgsna		dtgsyl	
dtpcon		■	dtpfrs	■	dtptri	■	dtptrs	■
dtrcon		■	dtrevc		dtrexc		dtrfrs	
dtrsen			dtrsna		dtrsyl		dtrtri	■
dtrtrs	■		dtzrqf		dtzrzf			

Double real Lapack	Flens	Seldon
Total	15	38
Coverage	8%	20%

4. Single precision complex Lapack routines

	Flens	Seldon		Flens	Seldon		Flens	Seldon		Flens	Seldon
cgesv			cgbsv			cgtsv			cposv		
cppsv			cpbsv			cptsv			csysv		
chesv			cspsv			chpsv			cgels		
cgelsd			cggls			cggglm			cheev		
cheevd			cheevr			chpev			chpevd		
chbev			chbevd			cgees			cgeev		
cgesvd			cgesdd			chegv			chegvd		
chpgv			chpgvd			chbgv			chbgvd		
cgegs			cgggs			cgeg			cgeev		
cggsvd			cgesvx			cgbsvx			cgtsvx		
cposvx			cpsvx			cpbsvx			cptsvx		
csysvx			chesvx			cspsvx			chpsvx		
cgelsx			cgelsy			cgelss			cheevx		
cheevr			chegvx			chpevx			chpgvx		
chbev			chbgvx			cgeesx			cggesx		
cgeevx			cgeevx			cbdsdc			cbdsqr		
cgbbrd			cgbcon			cgbequ			cgbrfs		
cgbrf			cgbrs			cgebak			cgebal		
cgebrd			cgecon			cgee			cgehrd		
cgelqf			cgeqlf			cgeqp3			cgeqpf		
cgeqrf			cgerfs			cgerqf			cgetrf		
cgetri			cgetrs			cggbak			cggbal		
cgghrd			cggqrf			cggqrf			cggsvp		
cgtrcon			cgtrfs			cgtrf			cgtrrs		
chgeqz			chsein			chseqr			cupgtr		
cupmtr			cungbr			cunghr			cunglq		
cungql			cungqr			cungrq			cungr		
cunmbr			cunmhr			cunmlq			cunmql		
cunmqr			cunmr3			cunmrq			cunmrz		
cunmtr			cpbcon			cpbequ			cpbrfs		
cpbstf			cpbrf			cpbrs			cpocon		
cpoequ			cporfs			cpotrf			cpotri		
cpotrs			cppcon			cppequ			cpprfs		
cpptrf			cpptri			cpptrs			cptcon		
cpteqr			cptrfs			cptrf			cptrrs		
chbgst			chbrd			cspecon			chpcon		
chpgst			csprfs			chprfs			chptrd		
csprf			chprf			csptri			chptri		
csprts			chptrs			cstedc			ctestr		
cstein			csteqr			csycon			checon		
chegst			csyrfs			cherfs			chetrd		
csytrf			chetrf			csytri			chetri		
csytrs			chetrs			ctbcon			ctbrfs		
ctbtrs			ctgevc			ctgexc			ctgsen		
ctgsja			ctgsna			ctgsyl			ctpcon		
ctprfs			ctptri			ctptrs			ctrcon		
ctrevc			ctrexc			ctrrfs			ctrsen		
ctrsna			ctrsyl			ctrtri			ctrtrs		
ctzrqf			ctzrzf								

Single complex Lapack	Flens	Seldon
Total	1	42
Coverage	1%	22%

5. Double precision complex Lapack routines

	Flens	Seldon		Flens	Seldon		Flens	Seldon		Flens	Seldon
zgesv			zgbsv			zgtsv			zposv		
zppsv			zpbsv			zptsv			zsysv		
zhesv			zspsv			zhpsv			zgels		
zgelsd			zggls			zggglm			zheev		
zheevd			zhpev			zhpevd			zhbev		
zhbev			zgees			zgeev			zgesvd		
zgesdd			zhegv			zhegv			zhpgv		
zhpgvd			zhbgv			zhbgvd			zgegs		
zggsv			zgegv			zgge			zggsvd		
zgesvx			zgbsvx			zgtsvx			zposvx		
zppsvx			zpbsvx			zptsvx			zsysvx		
zhesvx			zspsvx			zhpsvx			zgelsx		
zgelsy			zgelss			zheevx			zheevr		
zhegvx			zhpevx			zhpgvx			zhbev		
zhbgvx			zgeesx			zggsvx			zgeevx		
zggsvx			zbdsc			zbdscr			zgbbrd		
zgbcon			zgbqr			zgbtrf			zgbtrf		
zgbtr			zgbak			zgebrd			zgebrd		
zgecon			zgeeq			zgehrd			zgelqf		
zgeqlf			zgeqp3			zgeqpf			zgeqrf		
zgerfs			zgerqf			zgetrf			zgetri		
zgetrs			zggbr			zggbr			zggbrd		
zggqrf			zggqr			zggsvp			zgtcon		
zgrtrf			zgttrf			zgttr			zhgeqz		
zhsein			zhseqr			zupgtr			zupmtr		
zungbr			zungbr			zunglq			zungql		
zungqr			zungqr			zungtr			zunmbr		
zunmhr			zunmlq			zunmql			zunmqr		
zunmr3			zunmrq			zunmrz			zunmtr		
zpbcon			zpbqr			zpbtrf			zpbstf		
zpbtrf			zpbtr			zpocon			zpocon		
zporfs			zpotrf			zpotri			zpotrs		
zppcon			zppeqr			zpptrf			zpptrf		
zpptri			zpptr			zptcon			zpteqr		
zptrfs			zptrf			zptrs			zpbgst		
zpbtrd			zspcon			zhpcon			zhpgst		
zsprfs			zhprfs			zhptrd			zsptrf		
zhptrf			zsptri			zhptri			zsptrs		
zhptrs			zstedc			zstegr			zstein		
zsteqr			zsycon			zhecon			zhegst		
zsyrf			zherfs			zhtrd			zsytrf		
zhtrf			zsytri			zhtri			zsytrs		
zhtrrs			ztbcon			zbrfs			zbrfs		
ztgevc			ztgexc			ztgsen			ztgsja		
ztgsna			ztgsyl			ztpcon			ztptrf		
ztptri			ztptr			ztrcon			ztrvc		
ztrexc			ztrrf			ztrsen			ztrsn		
ztrsyl			ztrtri			ztrtr			ztrqf		
ztrzf											

Double complex Lapack	Flens	Seldon
Total	5	49
Coverage	3%	25%

### 4.3 Available Interfaces to Blas and Lapack Routines (Trilinos)

As a rough guide, here are some results for Trilinos. Several Trilinos packages offer at least a partial interface to Blas and Lapack routines: *Epetra*, *Teuchos*, *Amesos*, *AztecOO*, *ML*, *MOOCHO* and *Pliris*. The Trilinos column refers to all the packages tested together. This result is the maximum coverage and one should be careful for its interpretation. Indeed, some packages may not communicate together, with non compatible structures, and therefore could not be used together. Moreover, some of the interfaces may not be usable directly, only indirectly through other functions.

Blas	Trilinos	<i>Epetra</i>	<i>Teuchos</i>	<i>Amesos</i>	<i>AztecOO</i>	<i>ML</i>	<i>MOOCHO</i>	<i>Pliris</i>
Total	87	28	62	18	21	29	34	28
Coverage	60%	19%	42%	12%	14%	20%	23%	19%
Single real Lapack	Trilinos	<i>Epetra</i>	<i>Teuchos</i>	<i>Amesos</i>	<i>AztecOO</i>	<i>ML</i>	<i>MOOCHO</i>	<i>Pliris</i>
Total	57	44	44	4	8	32	1	1
Coverage	31%	24%	24%	2%	4%	17%	1%	1%
Double real Lapack	Trilinos	<i>Epetra</i>	<i>Teuchos</i>	<i>Amesos</i>	<i>AztecOO</i>	<i>ML</i>	<i>MOOCHO</i>	<i>Pliris</i>
Total	59	43	44	4	7	32	7	0
Coverage	32%	23%	24%	2%	4%	17%	4%	0%
Single complex Lapack	Trilinos	<i>Epetra</i>	<i>Teuchos</i>	<i>Amesos</i>	<i>AztecOO</i>	<i>ML</i>	<i>MOOCHO</i>	<i>Pliris</i>
Total	39	1	38	1	1	1	0	0
Coverage	20%	1%	20%	1%	1%	1%	0%	0%
Double complex Lapack	Trilinos	<i>Epetra</i>	<i>Teuchos</i>	<i>Amesos</i>	<i>AztecOO</i>	<i>ML</i>	<i>MOOCHO</i>	<i>Pliris</i>
Total	38	0	38	1	0	0	0	0
Coverage	20%	0%	20%	1%	0%	0%	0%	0%

## 5 Flens and Seldon Synoptic Comparison

	Flens		Seldon		See section
	—	+	—	+	
Portability	Not recently tested on Windows				
High-level interface				Python interface generated by SWIG	
C++ templates		Supported		Supported	
Matrix types	No hermitian matrices		No band matrices		
Sparse matrices		General and symmetric, compressed row storage		Harwell-Boeing and array of sparse vectors	
Sparse vectors	Not Supported			Supported	
Syntax		Natural mathematical notation			
Maintenance	Release candidate RC1 in Jul. 2007, last commit Jan. 2009			Latest release in Nov. 2008	
Blas and Lapack interface				Good coverage	4
Performance	Costly affectation in ColumnMajor format		One bug (fixed in later versions)	Better performance for dense matrix vector product	2.2 and 3
Vector and matrix views		Supported	Not supported		
Technical mastery				One author in my INRIA team!	
Eigenvalues computation	Not Supported			Eigenvalues and eigenvectors computation	