

# SANDIA REPORT

SAND2007-xxxx

Unlimited Release

Printed August 2007

## DRAFT: Meros User's Guide <sup>a</sup>

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<sup>a</sup>For **Meros**<sup>TM</sup> Version 2.0 in **Trilinos**<sup>TM</sup> Release 8.0



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## **DRAFT: Meros User's Guide**<sup>†</sup>

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### **Abstract**

meros abstract

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<sup>†</sup>For **Meros**<sup>™</sup> Version 2.0 in **Trilinos**<sup>™</sup> Release 8.0

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# 1 Getting Started

## 1.1 Downloading Meros and Trilinos

Meros is a package within the Trilinos Project and currently can be downloaded and built with Trilinos. The Trilinos software, including Meros, can be downloaded from

`http://trilinos.sandia.gov/`.

Follow the download instructions on the web site.

## 1.2 Licensing

Meros is available for download (through Trilinos) under the GNU Lesser General Public License [1].

## 1.3 Configuration, Compilation, and Installation

- System and software requirements
- Configuring and building Trilinos in general
- Configuring and building Meros within Trilinos
- Testing your build

Using the instructions here, your build of trilinos will have the following libraries: aztecoo, epetra, epetraext, ML, newpackage, nox teuchos, and thyra.

- cd into the trilinos directory.
- Make a build directory, e.g., `mkdir LINUX`.
- `cd LINUX`.
- Configure trilinos:
  1. If you do not want to use MPI:

```
{ ../configure --enable-teuchos --enable-amesos}
```
  2. To use MPI:

```
{ ../configure --enable-teuchos \  
  --enable-amesos --with-mpi-compilers=/usr/local/mpich/bin}
```

where your path to the mpi-compilers is specified.
- Build trilinos: `make`.

- If your build finished without errors, you should see the directory Trilinos/LINUX/packages/, with subdirectories below that for each individual library. Meros's subdirectory, meros, should contain files config.log, config.status, Makefile, and Makefile.export, and directories src and examples. Directory src contains object files and libmeros.a. Directory examples contains executables with extension .exe, symbolic links to the corresponding source code, and object files. Directory test is intended primarily for developers and can be ignored.
- Look in Trilinos/LINUX/packages/meros/examples for examples of how to use Meros. File Trilinos/packages/meros suggests how to use the examples.

Sample configure script for Meros:

```
BUILD_DIR='pwd'

../configure \
--enable-mpi \
--with-mpi-compilers="/usr/local/mpich-1.2.7_gcc3.4.3/bin" \
CXXFLAGS="-g -O0 -Wreturn-type" \
--with-libs="-lexpat" \
--disable-default-packages \
--enable-teuchos --enable-teuchos-extended \
--enable-teuchos-complex --enable-teuchos-abc --enable-teuchos-expat \
--enable-thyra \
--enable-thyra-examples \
--enable-epetra \
--enable-epetra-thyra \
--enable-epetraext \
--enable-epetraext-thyra \
--enable-ml \
--enable-ml-thyra \
--enable-aztecoo \
--enable-aztecoo-thyra \
--enable-ifpack \
--enable-ifpack-thyra \
--enable-nox \
--enable-stratimikos \
--enable-meros \
--enable-meros-examples \
--with-gnumake \
--with-install="/usr/bin/install -c -p" \
--prefix=$BUILD_DIR
```

## 2 Methods

### 2.1 Overview

Outline:

- Overview of problems Meros is intended to solve and the methods included
- Overview of PreconditionerFactory and how Meros extends from Thyra

Meros is a segregated preconditioning package within Trilinos [2]. Meros provides scalable block preconditioning for problems that couple simultaneous solution variables such as Navier-Stokes problems.

The initial focus of Meros is on preconditioners for the incompressible Navier-Stokes equations:

$$\begin{aligned} \eta \mathbf{u}_t - \nu \nabla^2 \mathbf{u} + (\mathbf{u} \cdot \text{grad}) \mathbf{u} + \text{grad } p &= \mathbf{f} \\ -\text{div } \mathbf{u} &= 0 \end{aligned} \quad (1)$$

on  $\Omega \subset \mathbb{R}^d$ ,  $d = 2$  or  $3$ . Here,  $\mathbf{u}$  is the  $d$ -dimensional velocity field, which is assumed to satisfy suitable boundary conditions on  $\partial\Omega$ ,  $p$  is the pressure, and  $\nu$  is the kinematic viscosity, which is inversely proportional to the Reynolds number. The value  $\eta = 0$  corresponds to the steady-state problem and  $\eta = 1$  to the case of unsteady flow. Linearization and discretization of (1) by finite elements, finite differences or finite volumes leads to a sequence of linear systems of equations of the form

$$\begin{bmatrix} F & B^T \\ B & -C \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ p \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ g \end{bmatrix}. \quad (2)$$

These systems, which are the primary focus of the Meros preconditioners, must be solved at each step of a nonlinear (Picard or Newton) iteration, or at each time step. Here,  $B$  and  $B^T$  are matrices corresponding to discrete divergence and gradient operators, respectively and  $F$  operates on the discrete velocity space.

This guide describes the use of a block preconditioner within the Meros package. The block preconditioners can be used to solve block linear systems of the type in (2). We will denote the velocity and pressure degrees of freedom as  $v$  and  $p$  respectively.

The user must supply the four subblocks  $F$ ,  $B^T$ ,  $B$ , and  $C$ . If the matrix  $C$  is not provided, it is assumed to be the zero matrix.  $F$  is the convection-diffusion-like operator of size  $v \times v$ ,  $B^T$  the pressure gradient of size  $v \times p$ ,  $B$  the divergence operator of size  $p \times v$ , and  $C$  is a stabilization matrix of size  $p \times p$ . Depending on the discretization  $C$  might be the zero matrix. For *div-stable* discretizations,  $C = 0$ . For mixed approximation methods that do not uniformly satisfy a discrete inf-sup condition, the matrix  $C$  is a nonzero *stabilization operator*.

Block preconditioners are useful for a number of reasons:

- Want the scalability and mesh-independence of multigrid
- Difficult to apply multigrid to the whole system
- Segregate blocks and apply multigrid separately to subproblems
- Requires a good Schur complement approximation

Meros 1.0 includes the following classes of methods:



- Approximate Commutator Methods
  1. Pressure Convection-Diffusion (Fp) methods
  2. Least Squares Commutator (LSC) methods
- Pressure-Projection Methods
  1. SIMPLE - Semi Implicit Methods for Pressure Linked Equations
  2. SIMPLEC

This guide describes the use of a block preconditioner within the Meros package. The block preconditioners in Meros are designed for block linear systems of the type

$$A = \begin{bmatrix} F & B^T \\ B & C \end{bmatrix} \begin{bmatrix} u \\ p \end{bmatrix} = \begin{bmatrix} f \\ g \end{bmatrix}$$

that usually arise from linearization and discretization of the incompressible Navier-Stokes equations. When using Meros, the sub matrices  $F, B, B^T, C$  and the vectors  $f$  and  $g$  are user supplied and  $u$  and  $p$  are vectors to be computed. Meros is intended to be used on large block sparse linear systems arising from partial differential equation (PDE) discretizations. While technically any block linear system can be considered, Meros should be used on linear systems that correspond to things that work well with multigrid methods (e.g. elliptic PDEs).

The methods in Meros are based on an LDU factorization of the saddlepoint system. The LDU factors of a saddle point system are given as follows:

$$\begin{bmatrix} A & B^T \\ B & C \end{bmatrix} = \begin{bmatrix} I & \\ BF^{-1} & I \end{bmatrix} \begin{bmatrix} F & \\ & -S \end{bmatrix} \begin{bmatrix} I & F^{-1}B^T \\ & I \end{bmatrix},$$

where  $S$  is the Schur complement  $S = BF^{-1}B^T - C$ .

## 2.2 Pressure Convection-Diffusion (PCD)

- Mathematical overview
- PCDPreconditionerFactory and PCDOperatorSource

In this section we describe the factory for building a pressure convection-diffusion style block preconditioner. This class of preconditioners were originally proposed by Kay, Loghin, and Wathen [3] and Silvester, Elman, Kay, and Wathen [4].

Meros currently implements the PCD preconditioner, a.k.a. Fp preconditioner.

The LDU factors of a saddle point system are given as follows:

$$\begin{bmatrix} A & B^T \\ B & C \end{bmatrix} = \begin{bmatrix} I & \\ BF^{-1} & I \end{bmatrix} \begin{bmatrix} F & \\ & -S \end{bmatrix} \begin{bmatrix} I & F^{-1}B^T \\ & I \end{bmatrix}, \quad (3)$$

where  $S$  is the Schur complement  $S = BF^{-1}B^T - C$ . A pressure convection-diffusion style preconditioner is then given by

$$P^{-1} = \begin{bmatrix} F & B^T \\ & -\tilde{S} \end{bmatrix}^{-1} = \begin{bmatrix} F^{-1} & \\ & I \end{bmatrix} \begin{bmatrix} I & -B^T \\ & I \end{bmatrix} \begin{bmatrix} I & \\ & -\tilde{S}^{-1} \end{bmatrix} \quad (4)$$

where for  $\tilde{S}$  is an approximation to the Schur complement  $S$ .

To apply the above preconditioner, we need a linear solver on the (0,0) block and an approximation to the inverse of the Schur complement.

To build a concrete preconditioner object, we will also need a 2x2 block Thyra matrix or the 4 separate blocks as either Thyra or Epetra matrices. If Thyra, assumes each block is a Thyra EpetraMatrix.

### 2.3 Least Squares Commutator (LSC)

- Mathematical overview
- LSCPreconditionerFactory and LSCOperatorSource

Factory for building least squares commutator style block preconditioner.

Note that the LSC preconditioner assumes that we are using a stable discretization on a uniform mesh.

The LDU factors of a saddle point system are given as follows:

$$\begin{bmatrix} A & B^T \\ B & C \end{bmatrix} = \begin{bmatrix} I & \\ BF^{-1} & I \end{bmatrix} \begin{bmatrix} F & \\ & -S \end{bmatrix} \begin{bmatrix} I & F^{-1}B^T \\ & I \end{bmatrix}, \quad (5)$$

where  $S$  is the Schur complement  $S = BF^{-1}B^T - C$ . A pressure convection-diffusion style preconditioner is then given by

$$P^{-1} = \begin{bmatrix} F & B^T \\ & -\tilde{S} \end{bmatrix}^{-1} = \begin{bmatrix} F^{-1} & \\ & I \end{bmatrix} \begin{bmatrix} I & -B^T \\ & I \end{bmatrix} \begin{bmatrix} I & \\ & -\tilde{S}^{-1} \end{bmatrix} \quad (6)$$

where for  $\tilde{S}$  is an approximation to the Schur complement  $S$ .

To apply the above preconditioner, we need a linear solver on the (0,0) block and an approximation to the inverse of the Schur complement.

To build a concrete preconditioner object, we will also need a 2x2 block Thyra matrix or the 4 separate blocks as either Thyra or Epetra matrices. If Thyra, assumes each block is a Thyra EpetraMatrix.

### 2.4 SIMPLE

- Mathematical overview
- SIMPLEPreconditionerFactory and SIMPLEOperatorSource

## 3 Examples

In this section, we go through several examples of using Meros as a preconditioner.

### 3.1 PCD Example

- brief explanation of the example
- walk through each step of setting up and solving with Meros
- can do code quotes with verbatim

### 3.2 LSC Example

```
// @HEADER
// *****
//
//           Meros: Segregated Preconditioning Package
//           Copyright (2004) Sandia Corporation
//
// Under terms of Contract DE-AC04-94AL85000, there is a non-exclusive
// license for use of this work by or on behalf of the U.S. Government.
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// Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307
// USA
// Questions? Contact Michael A. Heroux (maherou@sandia.gov)
//
// *****
// @HEADER

// saddle_lsc.cpp

// Example program that reads in Epetra matrices from files, creates a
// Meros Least Squares Commutator (LSC) preconditioner and does a
// solve.

#include "Teuchos_ConfigDefs.hpp"
```

```

#include "Teuchos_MPISession.hpp"
#include "Teuchos_GlobalMPISession.hpp"
#include "Teuchos_DefaultComm.hpp"
#include "Teuchos_ParameterList.hpp"
#include "Teuchos_ParameterXMLFileReader.hpp"
#include "Teuchos_RefCountPtr.hpp"

#include "Thyra_SolveSupportTypes.hpp"
#include "Thyra_LinearOpBase.hpp"
#include "Thyra_LinearOpBaseDecl.hpp"
#include "Thyra_VectorDecl.hpp"
#include "Thyra_VectorImpl.hpp"
#include "Thyra_VectorSpaceImpl.hpp"
#include "Thyra_LinearOperatorDecl.hpp"
#include "Thyra_LinearOperatorImpl.hpp"
#include "Thyra_SpmdVectorBase.hpp"
#include "Thyra_DefaultZeroLinearOp.hpp"
#include "Thyra_DefaultBlockedLinearOpDecl.hpp"
#include "Thyra_LinearOpWithSolveFactoryHelpers.hpp"
#include "Thyra_PreconditionerFactoryHelpers.hpp"
#include "Thyra_DefaultInverseLinearOpDecl.hpp"
#include "Thyra_DefaultInverseLinearOp.hpp"
#include "Thyra_PreconditionerFactoryBase.hpp"
#include "Thyra_DefaultPreconditionerDecl.hpp"
#include "Thyra_DefaultPreconditioner.hpp"
#include "Thyra_SingleRhsLinearOpWithSolveBase.hpp"
#include "Thyra_Aztec00LinearOpWithSolveFactory.hpp"

#ifdef HAVE_MPI
#include "Epetra_MpiComm.h"
#include "mpi.h"
#else
#include "Epetra_SerialComm.h"
#endif

#include "Epetra_Comm.h"
#include "Epetra_Map.h"
#include "Epetra_CrsMatrix.h"
#include "Epetra_Vector.h"

#include "EpetraExt_CrsMatrixIn.h"
#include "EpetraExt_VectorIn.h"

#include "Thyra_EpetraLinearOp.hpp"
#include "Thyra_EpetraThyraWrappers.hpp"

#include "Aztec00.h"
#include "Thyra_Aztec00LinearOpWithSolveFactory.hpp"
#include "Thyra_Aztec00LinearOpWithSolve.hpp"

#include "Meros_ConfigDefs.h"

```

```

#include "Meros_Version.h"
#include "Meros_LSCPreconditionerFactory.h"
#include "Meros_LSCOperatorSource.h"
#include "Meros_AztecSolveStrategy.hpp"
#include "Meros_InverseOperator.hpp"
#include "Meros_ZeroOperator.hpp"
#include "Meros_IdentityOperator.hpp"
#include "Meros_LinearSolver.hpp"

using namespace Teuchos;
using namespace EpetraExt;
using namespace Thyra;
using namespace Meros;

int main(int argc, char *argv[])
{
    GlobalMPISession mpiSession(&argc, &argv);

    // DEBUG 0 = no extra tests or printing
    // DEBUG 1 = print out basic diagnostics as we go.
    //           prints outer saddle system iterations, but not inner solves
    // DEBUG > 1 = test usage of some of the operators before proceeding
    //           prints inner and outer iterations
    int DEBUG = 1;

    // Get stream that can print to just root or all streams!
    Teuchos::RefCountPtr<Teuchos::FancyOStream>
        out = Teuchos::VerboseObjectBase::getDefaultOStream();

    // Epetra_Comm* Comm;
#ifdef HAVE_MPI
    Epetra_MpiComm Comm(MPI_COMM_WORLD);
    const int myRank = Comm.MyPID();
    const int numProcs = Comm.NumProc();
#else
    Epetra_SerialComm Comm;
    const int myRank = 0;
    const int numProcs = 1;
#endif

    if(DEBUG > 0)
    {
        if (myRank == 0)
        {
            cout << "Proc " << myRank << ": "
                 << "Number of processors = "
                 << numProcs << endl;
            cout << "Proc " << myRank << ": "
                 << Meros::Meros_Version() << endl;
        }
    }
}

```

```

}

try
{
    /* ----- Read in epetra matrices and rhs ----- */

    // Using Q1 matrix example; see Meros/examples/data/q1
    // (2,2 block (C block) is zero in this example)

    // Make necessary Epetra maps.
    // Need a velocity space map and a pressure space map.
    const Epetra_Map* velocityMap = new Epetra_Map(578, 0, Comm);
    const Epetra_Map* pressureMap = new Epetra_Map(192, 0, Comm);

    // Read matrix and vector blocks into Epetra_Crs matrices
    Epetra_CrsMatrix* FMatrix(0);
    char * filename = "../../../../../packages/meros/example/data/q1/Aq1.mm";
    MatrixMarketFileToCrsMatrix(filename,
                                *velocityMap,
                                *velocityMap, *velocityMap,
                                FMatrix);

    // cerr << "If you get Epetra ERROR -1 here, the file was not found"
    // << "Need to make symbolic link to data directory"
    // << endl;

    Epetra_CrsMatrix* BtMatrix(0);
    filename = "../../../../../packages/meros/example/data/q1/Btq1.mm";
    MatrixMarketFileToCrsMatrix(filename,
                                *velocityMap,
                                *velocityMap, *pressureMap,
                                BtMatrix);

    Epetra_CrsMatrix* BMatrix(0);
    filename = "../../../../../packages/meros/example/data/q1/Bq1.mm";
    MatrixMarketFileToCrsMatrix(filename,
                                *pressureMap,
                                *pressureMap, *velocityMap,
                                BMatrix);

    Epetra_Vector* rhsq1_vel(0);
    filename = "../../../../../packages/meros/example/data/q1/rhsq1_vel.mm";
    MatrixMarketFileToVector(filename,
                             *velocityMap,
                             rhsq1_vel);

    Epetra_Vector* rhsq1_press(0);
    filename = "../../../../../packages/meros/example/data/q1/rhsq1_press.mm";
    MatrixMarketFileToVector(filename,

```

```

        *pressureMap,
        rhsq1_press);

FMatrix->FillComplete();
BtMatrix->FillComplete(*pressureMap, *velocityMap);
BMatrix->FillComplete(*velocityMap, *pressureMap);

// Wrap Epetra operators into Thyra operators. To do this, we
// first wrap as Thyra core operators, then convert to the
// handle layer LinearOperators.

RefCountPtr<LinearOpBase<double> >
    tmpF = rcp(new EpetraLinearOp(rcp(FMatrix,false)));
const LinearOperator<double> F = tmpF;

RefCountPtr<LinearOpBase<double> >
    tmpBt = rcp(new EpetraLinearOp(rcp(BtMatrix,false)));
const LinearOperator<double> Bt = tmpBt;

RefCountPtr<LinearOpBase<double> >
    tmpB = rcp(new EpetraLinearOp(rcp(BMatrix,false)));
const LinearOperator<double> B = tmpB;

// Wrap Epetra vectors into Thyra vectors similarly by first
// wrapping to the Thyra core vector layer, then converting to
// the handle layer

RefCountPtr<const Thyra::VectorSpaceBase<double> > epetra_vs_press
    = Thyra::create_VectorSpace(rcp(pressureMap,false));
RefCountPtr<const Thyra::VectorSpaceBase<double> > epetra_vs_vel
    = Thyra::create_VectorSpace(rcp(velocityMap,false));

RefCountPtr<VectorBase<double> > rhs1
    = create_Vector(rcp(rhsq1_press, false), epetra_vs_press);
RefCountPtr<VectorBase<double> > rhs2
    = create_Vector(rcp(rhsq1_vel, false), epetra_vs_vel);

// Convert the vectors to handled vectors
RefCountPtr<VectorBase<double> > tmp1 = rhs1;
const Vector<double> rhs_press = tmp1;

RefCountPtr<VectorBase<double> > tmp2 = rhs2;
const Vector<double> rhs_vel = tmp2;

if(DEBUG > 1){
    // Test the wrapped operators
    cerr << "F matrix: description " << F.description() << endl;

```

```

cerr << "F domain: " << F.domain().dim()
    << ", F range: " << F.range().dim()
    << endl;
cerr << "B matrix: description " << B.description() << endl;
cerr << "B domain: " << B.domain().dim()
    << ", B range: " << B.range().dim()
    << endl;
cerr << "Bt matrix: description " << Bt.description() << endl;
cerr << "Bt domain: " << Bt.domain().dim()
    << ", Bt range: " << Bt.range().dim()
    << endl;

Vector<double> testvec1 = Bt * rhs_press;
cerr << "Bt * rhs_press = " << norm2(testvec1) << endl;

cerr << "domain size of B " << B.domain().dim() << endl;
cerr << "range size of B " << B.range().dim() << endl;
cerr << "size of testvec1 " << dim(testvec1) << endl;

Vector<double> testvec2 = B * testvec1;
cerr << "B * Bt * rhs_press = " << norm2(testvec2) << endl;

Vector<double> testvec3 = F * rhs_vel;
cerr << "F * rhs_vel = " << norm2(testvec3) << endl;

Vector<double> testvec4 = B * F * Bt * rhs_press;
cerr << "BFBt * rhs_press = " << norm2(testvec4) << endl;

}

// Get Thyra velocity and pressure spaces from the operators.
VectorSpace<double> velocitySpace = F.domain();
VectorSpace<double> pressureSpace = Bt.domain();

if(DEBUG > 0){
    cerr << "P" << myRank
        << ": vel space dim = " << velocitySpace.dim() << endl;
    cerr << "P" << myRank
        << ": press space dim = " << pressureSpace.dim() << endl;
}

// Make a zero operator on the small (pressure) space since the
// 2,2 block (C) is zero in this example.
// RefCountPtr<Thyra::LinearOpBase<double> > tmpZ =
// rcp(new DefaultZeroLinearOp<double>(tmpBt->domain(),
//                                     tmpBt->domain()));
// const LinearOperator<double> Z = tmpZ;
const LinearOperator<double> Z;

```



```

// Build the block saddle operator with F, Bt, B, and Z. This
// operator will be blockOp = [F Bt; B zero] (in Matlab
// notation).
LinearOperator<double> blockOp = block2x2(F, Bt, B, Z);

if(DEBUG > 1)
{
    // Test getting subblock components out of the block operator.
    LinearOperator<double> testF1 = blockOp.getBlock(0,0);
    LinearOperator<double> testBt1 = blockOp.getBlock(0,1);
    LinearOperator<double> testB1 = blockOp.getBlock(1,0);
    cerr << "Checking blocks after extracting them out the block op"
        << endl;
    cerr << "testF domain: " << testF1.domain().dim() << endl;
    cerr << "testF range: " << testF1.range().dim() << endl;
    cerr << "testBt domain: " << testBt1.domain().dim() << endl;
    cerr << "testBt range: " << testBt1.range().dim() << endl;
    cerr << "testB domain: " << testB1.domain().dim() << endl;
    cerr << "testB range: " << testB1.range().dim() << endl;

    Vector<double> testvec1 = testBt1 * rhs_press;
    cerr << "Bt * rhs_press = " << norm2(testvec1) << endl;

    Vector<double> testvec2 = testB1 * testvec1;
    cerr << "B * Bt * rhs_press = " << norm2(testvec2) << endl;

    Vector<double> testvec3 = testF1 * rhs_vel;
    cerr << "F * rhs_vel = " << norm2(testvec3) << endl;

    Vector<double> testvec4 = testB1 * testF1 * testBt1 * rhs_press;
    cerr << "BFBt * rhs_press = " << norm2(testvec4) << endl;
}

// Get the domain and range product spaces from the block operator.
VectorSpace<double> domain = blockOp.domain();
VectorSpace<double> range = blockOp.range();

// Build a product vector for the rhs and set the velocity and
// pressure components of the rhs with the vectors we previously
// read in from files and wrapped in Thyra.
Vector<double> rhs = range.createMember();
rhs.setBlock(0,rhs_vel);
rhs.setBlock(1,rhs_press);

// Build a solution vector and initialize it to zero.
Vector<double> solnblockvec = domain.createMember();
zeroOut(solnblockvec);

// We now have Thyra block versions of the saddle point system,
// rhs, and solution vector. Next we build the Meros LSC

```

```

// preconditioner.

/* ----- Build the Meros preconditioner factory -----*/

// Build a Least Squares Commutator (LSC) block preconditioner
// with Meros
//
// | inv(F) 0 | | I  -Bt | | I          |
// | 0      I | |      I | | -inv(X)|
//
// where inv(X) = inv(B*Bt) * B * F * Bt * inv(B*Bt)
// (velocity mass matrix is the identity in this example)
//
// We'll do this in 4 steps:
// 1) Build an Aztec00 ParameterList for inv(F) solve
// 2) Build an Aztec00 ParameterList for inv(B*Bt) solve
//    The Schur complement approximation inverse requires solves
//    on the composed operator B*Bt.
// 3) Make an LSCOperatorSource with blockOp (and Qu if needed)
// 4) Build the LSC block preconditioner factory

// 1) Build an Aztec00 ParameterList for inv(F) solve
//    This one corresponds to (unpreconditioned) GMRES

RefCountPtr<ParameterList>
    aztecFParams = rcp(new ParameterList("aztec00FSolverFactory"));

RefCountPtr<LinearOpWithSolveFactoryBase<double> > aztecFLoWsFactory;

if(DEBUG> 1)
{
    // Print out valid parameters and the existing default params.
    aztecFLoWsFactory = rcp(new Aztec00LinearOpWithSolveFactory());
    cerr << "\naztecFLoWsFactory.getValidParameters():\n" << endl;
    aztecFLoWsFactory->getValidParameters()->print(cerr, 0, true, false);
    cerr << "\nPrinting initial parameters. " << endl;
    aztecFLoWsFactory->setParameterList(aztecFParams);
    aztecFLoWsFactory->getParameterList()->print(cerr, 0, true, false);
}

// forward solve settings
aztecFParams->sublist("Forward Solve").set("Max Iterations", 100);
aztecFParams->sublist("Forward Solve").set("Tolerance", 10e-8);
// aztec00 solver settings
aztecFParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Solver", "GMRES");
aztecFParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Preconditioner", "none");

```

```

aztecFParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Size of Krylov Subspace", 100);

if(DEBUG > 1)
{
    // turn on Aztec00 output
    aztecFParams->sublist("Forward Solve")
        .sublist("Aztec00 Settings").set("Output Frequency", 10);
}

if(DEBUG > 1)
{
    // Print out the parameters we just set
    aztecFParams->setParameterList(aztecFParams);
    aztecFParams->getParameterList()->print(cerr, 0, true, false);
}

// 2) Build an Aztec00 ParameterList for inv(Ap) solve
// This one corresponds to unpreconditioned CG.

RefCountPtr<ParameterList>
    aztecBBtParams = rcp(new ParameterList("aztec00BBtSolverFactory"));

// forward solve settings
aztecBBtParams->sublist("Forward Solve").set("Max Iterations", 100);
aztecBBtParams->sublist("Forward Solve").set("Tolerance", 10e-8);
// aztec00 solver settings
aztecBBtParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Solver", "CG");
aztecBBtParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Preconditioner", "none");

if(DEBUG > 1)
{
    // turn on Aztec00 output
    aztecBBtParams->sublist("Forward Solve")
        .sublist("Aztec00 Settings").set("Output Frequency", 10);
}

if(DEBUG > 1)
{
    // Print out the parameters we just set
    RefCountPtr<LinearOpWithSolveFactoryBase<double> >
        aztecBBtLowsFactory = rcp(new Aztec00LinearOpWithSolveFactory());
    aztecBBtLowsFactory->setParameterList(aztecBBtParams);
    aztecBBtLowsFactory->getParameterList()->print(cerr, 0, true, false);
}

```

```

// 3) Make an LSCOperatorSource that contains blockOp
// The velocity mass matrix Qu is the identity in this example.
RefCountPtr<const LinearOpSourceBase<double> > myLSCopSrcRcp
    = rcp(new LSCOperatorSource(blockOp));

if(DEBUG > 1)
{
    // Test getting subblock components out of the operator source
    RefCountPtr<const LSCOperatorSource> lscOpSrcPtr
        = rcp_dynamic_cast<const LSCOperatorSource>(myLSCopSrcRcp);

    // Retrieve operators from the LSC operator source
    RefCountPtr<const LinearOpBase<double> > tmpBlockOp
        = lscOpSrcPtr->getOp();
    ConstLinearOperator<double> blockOp = tmpBlockOp;
    ConstLinearOperator<double> testF2 = blockOp.getBlock(0,0);
    ConstLinearOperator<double> testBt2 = blockOp.getBlock(0,1);
    ConstLinearOperator<double> testB2 = blockOp.getBlock(1,0);

    cerr << "Checking blocks after extracting them out the block op"
        << endl;
    cerr << "testF domain: " << testF2.domain().dim() << endl;
    cerr << "testF range: " << testF2.range().dim() << endl;
    cerr << "testBt domain: " << testBt2.domain().dim() << endl;
    cerr << "testBt range: " << testBt2.range().dim() << endl;
    cerr << "testB domain: " << testB2.domain().dim() << endl;
    cerr << "testB range: " << testB2.range().dim() << endl;

    Vector<double> testvec11 = testBt2 * rhs_press;
    cerr << "Bt * rhs_press = " << norm2(testvec11) << endl;

    Vector<double> testvec22 = testB2 * testvec11;
    cerr << "B * Bt * rhs_press = " << norm2(testvec22) << endl;

    Vector<double> testvec33 = testF2 * rhs_vel;
    cerr << "F * rhs_vel = " << norm2(testvec33) << endl;

    Vector<double> testvec44 = testB2 * testF2 * testBt2 * rhs_press;
    cerr << "BFBt * rhs_press = " << norm2(testvec44) << endl;
}

// 4) Build the LSC block preconditioner factory.
RefCountPtr<PreconditionerFactoryBase<double> > merosPrecFac
    = rcp(
        new LSCPreconditionerFactory(
            rcp(new Thyra::Aztec00LinearOpWithSolveFactory(aztecFParams)),
            rcp(new Thyra::Aztec00LinearOpWithSolveFactory(aztecBBtParams))
        )
    )

```

```

);

RefCountPtr<PreconditionerBase<double> > Prcp
    = merosPrecFac->createPrec();

merosPrecFac->initializePrec(myLSCopSrcRcp, &*Prcp);

// Checking that isCompatible and uninitializedPrec at least
// compile and throw the intended exceptions for now.
// merosPrecFac->uninitializePrec(&*Prcp, &myLSCopSrcRcp);
// bool passed;
// passed = merosPrecFac->isCompatible(*(myLSCopSrcRcp.get()));

/* --- Now build a solver factory for outer saddle point problem --- */

// Set up parameter list and Aztec00 solver
RefCountPtr<ParameterList> aztecSaddleParams
    = rcp(new ParameterList("aztec00SaddleSolverFactory"));

RefCountPtr<LinearOpWithSolveFactoryBase<double> >
    aztecSaddleLowsFactory = rcp(new Aztec00LinearOpWithSolveFactory());

double saddleTol = 1.0e-6;

// forward solve settings
aztecSaddleParams->sublist("Forward Solve").set("Max Iterations", 500);
aztecSaddleParams->sublist("Forward Solve").set("Tolerance", saddleTol);
// aztec00 solver settings
aztecSaddleParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Solver", "GMRES");
aztecSaddleParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Aztec Preconditioner", "none");
aztecSaddleParams->sublist("Forward Solve")
    .sublist("Aztec00 Settings").set("Size of Krylov Subspace", 500);

if(DEBUG > 0)
{
    // turn on Aztec00 output
    aztecSaddleParams->sublist("Forward Solve")
        .sublist("Aztec00 Settings").set("Output Frequency", 1);
}

aztecSaddleLowsFactory->setParameterList(aztecSaddleParams);

if(DEBUG > 0)
{
    // Print out the parameters we've set.
    aztecSaddleLowsFactory->getParameterList()->print(cerr, 0,
                                                    true, false);
}

```

```

    }

    // Set up the preconditioned inverse object and do the solve!
    RefCountPtr<LinearOpWithSolveBase<double> > rcpAztecSaddle
        = aztecSaddleLowsFactory->createOp();

    // LinearOperator<double> epetraBlockOp = makeEpetraOperator(blockOp);

    // initializePreconditionedOp<double>(*aztecSaddleLowsFactory,
    // epetraBlockOp.ptr(),
    // Prcp,
    // &*rcpAztecSaddle );

    // initializePreconditionedOp<double>(*aztecSaddleLowsFactory,
    // blockOp.ptr(),
    // Prcp,
    // &*rcpAztecSaddle );

    // RefCountPtr<LinearOpBase<double> > tmpSaddleInv
    // = rcp(new DefaultInverseLinearOp<double>(rcpAztecSaddle));

    // LinearOperator<double> saddleInv = tmpSaddleInv;
    // saddleInv.description();

    RefCountPtr<const LinearOpBase<double> > tmpPinv
        = Prcp->getRightPrecOp();
    ConstLinearOperator<double> Pinv = tmpPinv;

    LinearSolveStrategy<double> azSaddle
        = new AztecSolveStrategy(*(aztecSaddleParams.get()));

    ConstLinearOperator<double> saddleInv
= new InverseOperator<double>(blockOp * Pinv, azSaddle);

    // Do the solve!
    solnblockvec = saddleInv * rhs;

    // Check our results.
    Vector<double> residvec = blockOp * Pinv * solnblockvec - rhs;

    cerr << "norm of resid " << norm2(residvec) << endl;

    double normResvec = norm2(residvec);

    if(normResvec < 10.0*saddleTol)
{
    cerr << "Example PASSED!" << endl;
    return 0;
}

```

```

        else
    {
        cerr << "Example FAILED!" << endl;
        return 1;
    }

    } // end of try block

    catch(std::exception& e)
    {
        cerr << "Caught exception: " << e.what() << endl;
    }

    MPISession::finalize();

} // end of main()

```

### 3.3 SIMPLE Example

## A Bug Reporting and Enhancement Requests

If you have access to the Sandia Software Bugzilla system, please use the Bugzilla bug-tracking system. (Recommended)

To get started with Bugzilla for the first time:

- Go to the Sandia Software Bugzilla page: <http://software.sandia.gov/bugzilla/>
- Click on 'Open a new Bugzilla account'.
- Enter your e-mail address and name.
- Check your e-mail for your new password.
- Sign in with your new password.
- Configure your password and preferences how you want them. This can be done under 'Change password or user preferences' on the main page, or under 'Edit prefs' in the footer.

To submit a bug, fill out a Bugzilla bug report:

- Go to the Sandia Software Bugzilla page: <http://software.sandia.gov/bugzilla/>
- Click 'Enter a new bug report' on the main page, or 'New' in the footer.
- Choose the package in which you want to request a feature or report a bug/issue (or Trilinos if it applies to the entire Trilinos framework).
- Read the 'bug writing guidelines,' check the list of 'most frequently reported bugs,' and 'search' for the bug to see if the bug has already been submitted (in which case, it may be helpful to add a new comment to the existing report).
- Select the version number, component, platform, operating system, priority, and severity of the bug.
- Enter a concise, informative summary.
- Describe, in as much detail as possible, the feature you are requesting or the bug/issue you are reporting.

To find a bug, run a Bugzilla query:

- Go to the Sandia Software Bugzilla page: <http://software.sandia.gov/bugzilla/>
- Click 'Query existing bug reports' on the main page, or 'Query' in the footer.
- Select appropriate entries from any relevant fields.
- Click the 'Search' button.

If you do not have access to the Sandia Software Bugzilla system, please send an e-mail describing the bug in as much detail as possible to [vehowle@software.sandia.gov](mailto:vehowle@software.sandia.gov).



## **B Mailing Lists**

Meros maintains a number of email lists that users and developers can subscribe to. We recommend subscribing to the following mailing lists as appropriate.

- Meros-Announce Mailing List - Low-volume, primarily for Meros release announcements. (Highly Recommended)
- Meros-Users Mailing List - Discussion forum for users of Meros. (Recommended)
- Meros-Developers Mailing List - Discussion forum for Meros developers. (Developers)
- Meros-Checkins Mailing List - CVS Commit Message. (Active Developers)
- Meros-Regression Mailing List - Captures output from Meros automated regression tests. (Active Developers)
- mailing lists and their purposes
- how to subscribe/unsubscribe

## References

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- [3] D. KAY, D. LOGHIN, AND A. WATHEN, *A preconditioner for the steady-state Navier–Stokes equations*, SIAM J. Sci. Comput., 24 (2002), pp. 237–256.
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