IML++ v. 1.2
Iterative Methods Library
Reference Guide

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1 Introduction

The Iterative Methods Library, IML++, is a collection of algorithms implemented in C++ for solving both symmetric and nonsymmetric linear systems of equations by using iterative techniques.

One motivation for this package is that high level matrix algorithms, such as those found in Barrett et. al. [2], can be easily implemented with the template facilities of C++. For example, consider a preconditioned conjugate gradient algorithm, used to solve $Ax = b$, with preconditioner $M$. A comparison between the pseudo-code description of the algorithm and the body of a C++ routine used to implement the algorithm is shown in Figure 1. Notice that in the C++ code example, no mention of a specific matrix type (e.g. dense, sparse, distributed) is given. The operators such as * and + have been overloaded to work with matrix and vectors formats. Thus, the code fragment represents an interface and can be used with any matrix and vector classes which support these operations.

```c++
Initial \( r^{(0)} = b - Ax^{(0)} \)
for \( i = 1, 2, \ldots \)
    solve \( Mz^{(i-1)} = r^{(i-1)} \)
    \( \rho_{i-1} = r^{(i-1)^T}z^{(i-1)} \)
    if \( i = 1 \)
        \( p^{(1)} = z^{(0)} \)
    else
        \( \beta_{i-1} = \rho_{i-1}/\rho_{i-2} \)
        \( p^{(i)} = z^{(i-1)} + \beta_{i-1}p^{(i-1)} \)
    endif
endif
\( q^{(i)} = Ap^{(i)} \)
\( \alpha_i = \rho_{i-1}/p^{(i)^T}q^{(i)} \)
\( x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)} \)
\( r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)} \)
check convergence;
end
```

Figure 1: Comparison of an algorithm for the preconditioned conjugate gradient method in pseudocode and the corresponding IML++ routine.

The following iterative methods have been incorporated into IML++:

- Richardson Iteration
- Chebyshev Iteration
- Conjugate Gradient (CG)
- Conjugate Gradient Squared (CGS)
- BiConjugate Gradient (BiCG)
- BiConjugate Gradient Stabilized (BiCGSTAB)
- Generalized Minimum Residual (GMRES)
- Quasi-Minimal Residual Without Lookahead (QMR)

All of these methods are designed to be used in conjunction with a preconditioner.

In addition, IML++ provides SparseLib++ compatible implementations of the following preconditioners:

- Diagonal
- Incomplete LU (ILU)
- Incomplete Cholesky (IC)

The functions provided are fully templated \(^1\), so they can be used with any matrix and vector library that provide the required level of functionality (see Section 2), including distributed sparse and dense matrices. In effect, the details of the underlying data structure are separated from the mathematical algorithm. The result is a library of high level mathematical denotations that can run on a large variety of hardware platforms (e.g., distributed networks, multicomputers, as well as single node workstations) without modification.

The iterative methods functions and the preconditioner functions are described in detail in Section 4.

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\(^1\) There are two senses in which the word ‘templates’ is used in scientific computing. Templates as code exemplars is the meaning used in the context of [2]. Templates in the C++ sense indicates the more formal strategy for reusing skeletal code.
2 Requirements

Here we give description of the specific functions that matrix and vector classes must provide in order to be used with IML++. In order to make IML++ as useful (and portable) as possible to other matrix and/or vector packages, we have assumed only a minimal level of functionality.

To illustrate the functionality that IML++ functions require of other packages, it is helpful to look at an example. A typical IML++ function declaration looks like this:

```cpp
template <class Matrix, class Vector, class Preconditioner, class Real>
int CG ( const Matrix& A, Vector& x, const Vector& b, const Preconditioner& M, int& max_iter,
        Real& tol )
```

There are a few things to note about this declaration (which will be generic to most of the other IML++ functions). First, the function is fully templated. That is, the function can be called with any set of arguments that are members of classes that provide a minimum level of functionality (described below). In fact, since the objects passed to the function are only accessed through their member functions, the classes that are substituted for Matrix, Vector, and Preconditioner do not necessarily have to be actual matrices and vectors at all (e.g. they may just be utilized in a matrix-vector product); they only need to be able to carry out required interface computations listed below.

Matrices The Matrix class (corresponding to \(A\) in the linear system \(Ax = b\)) must supply the functions listed in Figure 2.

The matrices in the linear systems \(Ax = b\) are accessed only through the `operator*` and the `trans_mult()` member function. The return type in both cases is a Vector (the same type as the supplied argument). Note that not all of the IML++ functions will necessarily use `trans_mult()`.

The GMRES() routine in particular requires two matrices as input. The first (which will typically be a sparse matrix) corresponds to the matrix in the linear system \(Ax = b\). The second (typically a smaller, dense matrix) corresponds to the upper Hessenberg matrix \(H\) that is constructed during the GMRES iterations. Since the second matrix is used in a different way than the first, its class must supply different functionality. In particular, it must have `operator()` for accessing individual elements. For this matrix class, it is important to remember that IML++ uses the C/C++ convention of 0-based indexing. That is, \(A(0,0)\) is the first component of the matrix \(A\). Also, the type of a single matrix entry must be compatible with the type of single vector entry. That is, operations such as \(A(i,j)*x(j)\) must be able to be carried out. See the GMRES() man page for more information.
### Vectors

The `Vector` class must supply the following constructors in figure 3, together with fundamental operations listed in figures 4.

IML++ uses the C/C++ convention that vectors use 0-based indexing. That is, `x(0)` is the first component of the vector `x`. This is in contrast to Fortran, which uses 1-based indexing. Since (presumably) all users of this package will be using it with C and/or C++ matrices and vectors, this assumption should not be limiting in any way.

Scalars We use the convention that a scalar is the same type as a single component of a vector. In particular, the `dot()` function must return a scalar type which is the same type as a single component of a vector. That is, assignments of the form `x(0) = dot(x, y)` must be made without type conversion.

### Preconditioners

The `Preconditioner` class can be viewed as a simple wrapper around a user-defined function. These function may, for example, perform incomplete LU factorization, diagonal scaling, or nothing at all (corresponding to unpreconditioned case). A preconditioner matrix `M` is typically used to compute `M^{-1}x` or `(M^T)^{-1}x` during the course of a basic iteration, and thus can be seen as taking some input vector and return a corresponding vector. The corresponding C++ class must therefore provide the two fundamental capabilities listed in figure 5.

---

**Figure 3:** Interface requirements for constructors of `Vector` class.

<table>
<thead>
<tr>
<th>Constructor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>Vector()</code></td>
<td>Constructor for null (zero-length) <code>Vector</code></td>
</tr>
<tr>
<td><code>Vector(unsigned int n)</code></td>
<td>Constructor for <code>Vector</code> of length <code>n</code></td>
</tr>
</tbody>
</table>

**Figure 4:** Interface requirements for `Vector` operations.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator=(Vector)</code></td>
<td>Assignment of <code>Vector</code> to <code>Vector</code></td>
</tr>
<tr>
<td><code>operator=(Scalar)</code></td>
<td>Assignment of <code>Scalar</code> to all components of <code>Vector</code></td>
</tr>
<tr>
<td><code>Vector operator+(Vector)</code></td>
<td>Addition</td>
</tr>
<tr>
<td><code>Vector operator-(Vector)</code></td>
<td>Subtraction</td>
</tr>
<tr>
<td><code>Scalar operator*(Vector)</code></td>
<td>Multiplication of <code>Vector</code> by <code>Scalar</code></td>
</tr>
<tr>
<td><code>Vector operator[](int)</code></td>
<td>Element access</td>
</tr>
<tr>
<td><code>dot(Vector, Vector)</code></td>
<td><code>Vector</code> inner product</td>
</tr>
<tr>
<td><code>norm(Vector)</code></td>
<td><code>Vector</code> norm</td>
</tr>
</tbody>
</table>

**Figure 5:** Interface requirements for `Preconditioner` class.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>solve(Vector)</code></td>
<td>solve linear system</td>
</tr>
<tr>
<td><code>trans_solve(Vector)</code></td>
<td>solve transpose linear system</td>
</tr>
</tbody>
</table>
Preconditioners are accessed only through their `solve()` and `trans_solve()` member functions. The return type in both cases is a `Vector` (the same type as the supplied argument). Note that not all of the IML++ functions will use `trans_solve()`.

**Reals** At this time, all IML++ functions test the value of the residual norm against a specified tolerance to determine convergence. The type of the tolerance variable is templated so that either `float` or `double` can be used. The `norm()` function must return the `Real` type. Note that the elements of a `Vector` class can be complex or user-defined, so that `Real` type may be different than the `Scalar` type.
Summary

The following is a summary of necessary functions for use with IML++.

```
Vector()  
Vector(unsigned int n)  
Vector = Matrix operator*(Vector)  
Vector = Matrix::trans_mult(Vector)  
Vector = operator=(Vector)  
Vector = operator=(Scalar)  
Vector = Vector operator+(Vector)  
Vector = Vector operator-(Vector)  
Vector = Scalar operator*(Vector)  
Scalar = Vector operator()(int)  
Scalar = dot(Vector, Vector)  
Real = norm(Vector)  
Vector = Preconditioner::solve(Vector)  
Vector = Preconditioner::trans_solve(Vector)
```

Note that certain “optimized” operators such as += are not used by IML++. This may cause a slight loss of performance in certain applications. However, the advantage is increased portability of IML++. In order to use operators like += (if your package supplies them), you should replace occurrences of operations like \( \mathbf{x} = \mathbf{x} + \mathbf{y} \) with \( \mathbf{x} += \mathbf{y} \) in the text of the IML++ routines.

The test programs that come with IML++ use SparseLib++. When in doubt about the required functionality of other matrix and/or vector packages, refer to SparseLib++.
3 Using IML++

In order to use IML++, the user must supply matrix and vector classes (the functionality for which is described in Section 2). Typically, IML++ will be used with the matrix and vector packages together in a common program. IML++ is accessed by including the appropriate header files which provide the template declarations. The header files which provide the matrix and vector class declarations must also be included.
As an application example, the following code listing demonstrates the use of IML++ in conjunction with a publicly available matrix library, SparseLib++, to solve a linear system with CG. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using CG and a diagonal preconditioner. The modifications to this example which would be necessary to use it with different matrix and/or vector classes should be fairly obvious.

```cpp
#include <stdlib.h> // System includes
#include <iostream.h> //
#include "compcol_double.h" // Compressed column matrix header
#include "isib_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV_Vector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "cg.h" // IML++ CG template

int main(int argc, char * argv[]) {
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6; // Convergence tolerance
    int result, maxit = 150; // Maximum iterations

    CompCol_Mat_double A; // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data
    DiagPreconditioner_double D(A); // Create diagonal preconditioner

    result = CG(A, x, b, D, maxit, tol); // Solve system

    cout << "CG flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;

    return result;
}
```

The executable for this example can be made by compiling it and linking it with the object files for the matrix and vector classes. For compilation, be sure to use appropriate compiler directives so that all header and library files can be found.
The following is an example Makefile that could be used to create an executable file (called main) from the code in the above example. It assumes a directory structure similar to that of the SparseLib++ distribution.

```makefile
# Example Makefile

# The C++ compiler
CPP = g++

# The architecture
ARCH = sun4

# The top-level SparseLib++ directory
SPARSELIB = /usr/local/src/SparseLib++

# The various include directories
IML_INCLUDE = $(SPARSELIB)/iml/include
MV_INCLUDE = $(SPARSELIB)/mv/include
SPARSELIB_INCLUDE = $(SPARSELIB)/sparselib/include

# A list of all include directives for the compiler
INCLUDES = -I$(IML_INCLUDE) -I$(MV_INCLUDE) -I$(SPARSELIB_INCLUDE)

# The SparseLib++ library archive file
SPARSELIB_LIB = $(SPARSELIB)/sparselib/libs/$(ARCH)

# Libraries to be linked
LIBS = -L$(SPARSELIB_LIB) -lsparse$(CPP) -lm

# Rule to create executable main from main.o
main: main.o
  $(CPP) $(CPPFLAGS) -o main.o $(LIBS)

# Rule to create object main.o from main.cc
main.o: main.cc
  $(CPP) $(CPPFLAGS) $(INCLUDE_DIRS) -c main.cc

# Include dependencies
main.o: $(IML_INCLUDE)/cg.h $(SPARSELIB_INCLUDE)/diagpre.h $(SPARSELIB_INCLUDE)/compcol1.h $(SPARSELIB_INCLUDE)/readhh.h $(MV_INCLUDE)/vector.h $(MV_INCLUDE)/blas1.h

See the IML++ test directory for more examples.
```
4 Iterative Method Library Functions

In the following pages, we provide a detailed description of each of the iterative methods functions available in IML++. Each function is described in turn on a "man" page. For each function, we provide an example of its declaration, a detailed description of the function, its return values, an example of its usage, and cross references.
**Name**

BiCG — BiConjugate Gradient Iteration

**Declaration**

```cpp
#include "bicg.h"

template < class Matrix, class Vector, class Preconditioner, class Real >
int BiCG ( const Matrix& A, Vector& x, const Vector& b,
           const Preconditioner& M, int& max_iter, Real& tol )
```

**Description**

**BiCG** solves the unsymmetric linear system $Ax = b$ using the preconditioned BiConjugate Gradient method.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for the solution of the unsymmetric linear system $Ax = b$. In addition, $M$ specifies a preconditioner, $max\_iter$ specifies the maximum number of iterations that the method will take, and $tol$ specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if $\|r\|/\|b\| < tol$.

**Return Values**

A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations. A return value of 2 indicates that a breakdown occurred.

Upon return, the output arguments have the following values:

- $x$ approximate solution to $Ax = b$ computed at the final iteration
- $tol$ the value of the $\|r\|/\|b\|$ achieved after the final iteration
- $max\_iter$ the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with BiCG. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using BiCG and a diagonal preconditioner.

```c
#include <stdlib.h> // System includes
#include <iostream.h> //
#include "compcol_double.h" // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV_Vector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "bicg.h" // IML++ BiCG template

int main(int argc, char * argv[]) {
  if (argc < 2) {
    cerr << "Usage: " << argv[0] << " HBfile " << endl;
    exit(-1);
  }
  double tol = 1.e-6; // Convergence tolerance
  int result, maxit = 150; // Maximum iterations
  CompCol_Mat_double A; // Create a matrix
  readHB_mat(argv[1], &A); // Read matrix data
  VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
  readHB_rhs(argv[1], &b); // Read rhs data
  DiagPreconditioner_double D(A); // Create diagonal preconditioner
  result = BiCG(A, x, b, D, maxit, tol); // Solve system
  cout << "BiCG flag = " << result << endl;
  cout << "iterations performed: " << maxit << endl;
  cout << "tolerance achieved : " << tol << endl;
  return result;
}
```

See Also

SparseLib++
DiagPreconditioner

Name  
BiCGSTAB — BiConjugate Gradient Iteration Stabilized

Declaration  
#include "bicgstab.h"

template <class Matrix, class Vector, class Preconditioner, class Real>
in
BiCGSTAB (const Matrix& A, Vector& x, const Vector& b,  
const Preconditioner& M, int& max_iter, Real& tol)  

Description  
BiCGSTAB solves the unsymmetric linear system $Ax = b$ using the precondi-
tioned BiConjugate Gradient Stabilized method.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for
the solution of the unsymmetric linear system $Ax = b$. In addition, $M$ specifies
a preconditioner, $\text{max}_\text{iter}$ specifies the maximum number of iterations that the
method will take, and $\text{tol}$ specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance,
\text{i.e.}, if $\|r\|/\|b\| < \text{tol}$.

Return Values  
A return value of 0 indicates convergence to the specified tolerance within the
specified maximum number of iterations. A return value of 1 indicates that the
method did not reach the specified convergence tolerance in the maximum number
of iterations. A return value of 2 indicates that a breakdown occurred with $\rho_{i-1} =  
\langle \tilde{r}, r^{i-1} \rangle = 0$. A return value of 3 indicates that a breakdown occurred with $\omega_i =  
\langle t, s \rangle / \langle t, t \rangle = 0$.

Upon return, the output arguments have the following values:

\begin{itemize}
  \item $x$ approximate solution to $Ax = b$ computed at the final iteration
  \item $\text{tol}$ the value of the $\|r\|/\|b\|$ achieved after the final iteration
  \item $\text{max}_\text{iter}$ the number of iterations performed before return
\end{itemize}
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with BiCGSTAB. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using BiCGSTAB and a diagonal preconditioner.

```cpp
#include <stdlib.h> // System includes
#include <iostream.h> //
#include "compcol_double.h" // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MVector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "bicgstab.h" // IML++ BiCGSTAB template

int
main(int argc, char * argv[])
{
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6; // Convergence tolerance
    int result, maxit = 150; // Maximum iterations

    CompCol_Mat_double A; // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data

    DiagPreconditioner_double D(A); // Create diagonal preconditioner

    result = BiCGSTAB(A, x, b, D, maxit, tol); // Solve system

    cout << "BiCGSTAB flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;

    return result;
}
```

See Also

SparseLib++
DiagPreconditioner

Name  CG — Conjugate Gradient Iteration

Declaration  

```cpp
#include "cg.h"

template < class Matrix, class Vector, class Preconditioner, class Real >
int CG ( const Matrix& A, Vector& x, const Vector& b,
         const Preconditioner& M, int& max_iter, Real& tol )
```

Description  CG solves the symmetric positive-definite linear system $Ax = b$ using the preconditioned Conjugate Gradient method.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for the solution of the unsymmetric linear system $Ax = b$. In addition, $M$ specifies a preconditioner, $max_iter$ specifies the maximum number of iterations that the method will take, and $tol$ specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if $\|r\|/\|b\| < tol$.

Return Values  A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations.

Upon return, the output arguments have the following values:

- $x$  approximate solution to $Ax = b$ computed at the final iteration
- $tol$  the value of the $\|r\|/\|b\|$ achieved after the final iteration
- $max_iter$  the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with CG. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using CG and a diagonal preconditioner.

```cpp
#include <stdlib.h>  // System includes
#include <iostream.h> //

#include "compcol_double.h"  // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV_Vector level 1 BLAS
#include "icpre_double.h" // Diagonal preconditioner
#include "cg.h" // IML++ CG template

int main(int argc, char * argv[]) {
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6;  // Convergence tolerance
    int result, maxit = 150;  // Maximum iterations

    CompCol_Mat_double A;  // Create a matrix
    readHB_mat(argv[1], &A);  // Read matrix data
    VECTOR_double b, x(A.dim(1), 0.0);  // Create rhs, solution vectors
    readHB_rhs(argv[1], &b);  // Read rhs data

    ICPreconditioner_double M(A);  // Create IC preconditioner

    result = CG(A, x, b, M, maxit, tol);  // Solve system

    cout << "CG flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;

    return result;
}
```

See Also

SparseLib++
IC Preconditioner


Name: CGS — Conjugate Gradient Squared Iteration

Declaration:

```cpp
#include "cgs.h"

template < class Matrix, class Vector, class Preconditioner, class Real >
int CGS ( const Matrix& A, Vector& x, const Vector& b, 
          const Preconditioner& M, int& max_iter, Real& tol )
```

Description: CGS solves the unsymmetric linear system \( Ax = b \) using the preconditioned Conjugate Gradient Squared method.

This is a fully templated function.

On input, \( A \) specifies the matrix, \( b \) the right-hand side, and \( x \) the initial guess for the solution of the unsymmetric linear system \( Ax = b \). In addition, \( M \) specifies a preconditioner, \( max_iter \) specifies the maximum number of iterations that the method will take, and \( tol \) specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if \( \frac{\|r\|}{\|b\|} < tol \).

Return Values: A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations. A return value of 2 indicates that a breakdown occurred.

Upon return, the output arguments have the following values:

- \( x \) approximate solution to \( Ax = b \) computed at the final iteration
- \( tol \) the value of the \( \frac{\|r\|}{\|b\|} \) achieved after the final iteration
- \( max_iter \) the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with CGS. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using CGS and a diagonal preconditioner.

```c
#include <stdlib.h> // System includes
#include <iostream.h> //

#include "compcol_double.h" // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas_double.h" // MV_Vector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "cgs.h" // IML++ CGS template

int main(int argc, char * argv[]) {
  if (argc < 2) {
    cerr << "Usage: " " argv[0] HBfile " " endl;
    exit(-1);
  }

  double tol = 1.e-6; // Convergence tolerance
  int result, maxit = 150; // Maximum iterations

  CompCol_Mat_double A; // Create a matrix
  readHB_mat(argv[1], &A); // Read matrix data
  VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
  readHB_rhs(argv[1], &b); // Read rhs data

  DiagPreconditioner_double D(A); // Create diagonal preconditioner

  result = CGS(A, x, b, D, maxit, tol); // Solve system

  cout << "CGS flag = " << result << " endl;
  cout << "iterations performed: " " maxit << " endl;
  cout << "tolerance achieved : " " tol << " endl;

  return result;
}
```

See Also

SparseLib++
DiagPreconditioner


Version 1.2 22 May 1995
Name | CHEBY — Chebyshev Iteration

Declaration | 
| #include "cheby.h"

template < class Matrix, class Vector, class Preconditioner, class Real, class Type >
| int CHEBY ( const Matrix& A, Vector& x, const Vector& b, const Preconditioner& M, int& max_iter, Real& tol, Type eigmin, Type eigmax )

Description | CHEBY solves the unsymmetric linear system $Ax = b$ using the preconditioned Chebyshev iteration.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for the solution of the unsymmetric linear system $Ax = b$. In addition, $M$ specifies a preconditioner, $\text{max\_iter}$ specifies the maximum number of iterations that the method will take, and $\text{tol}$ specifies the convergence tolerance for the method. Finally, the parameters $\text{eigmin}$ and $\text{eigmax}$ are parameters provided to estimate an ellipse containing the spectrum of $A$. In the case of positive-definite $A$, these parameters are real and correspond to estimates of the minimal and maximal eigenvalues of $A$, respectively. Note that poor estimates for these values can cause poor convergence behavior (including divergence).

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if $\|r\|/\|b\| < \text{tol}$.

Return Values | A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations.

Upon return, the output arguments have the following values:

- $x$ approximate solution to $Ax = b$ computed at the final iteration
- $\text{tol}$ the value of the $\|r\|/\|b\|$ achieved after the final iteration
- $\text{max\_iter}$ the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with CHEBY. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using CHEBY and a diagonal preconditioner. The parameters eigmin and eigmax for this example are chosen based on an 8 × 8 discretization of the two-dimensional Poisson problem on the unit square.

```c++
#include <stdlib.h> // System includes
#include <iostream.h>
#include "compcol_double.h" // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV_Vector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "cheby.h" // IML++ Cheby template

int main(int argc, char * argv[])
{
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6; // Convergence tolerance
    int result, maxit = 300; // Maximum iterations
    double mineig = .01; // eigenvalue information
    double maxeig = 3; // (this info for 1a2d8 example)

    CompCol_Mat_double A; // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data

    DiagPreconditioner_double D(A); // Create diagonal preconditioner

    result = CHEBY(A, x, b, D, maxit, tol, mineig, maxeig); // Solve system

    cout << "cheby flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;

    return result;
}
```

See Also

SparseLib++
DiagPreconditioner


GMRES — Generalized Minimum Residual Iteration

#include "gmres.h"

template < class SMatrix, class Vector, class Preconditioner, class DMatrix, class Real >
int GMRES ( const SMatrix& A, Vector& x, const Vector& b, const Preconditioner& M, DMatrix& H, int& m, int& max_iter, Real& tol )

GMRES() solves the unsymmetric linear system \( Ax = b \) using the preconditioned Generalized Minimum Residual method.

This is a fully templated function.

On input, \( A \) specifies the matrix, \( b \) the right-hand side, and \( x \) the initial guess for the solution of the unsymmetric linear system \( Ax = b \). In addition, \( M \) specifies a preconditioner, \( H \) specifies a matrix to hold the coefficients of the upper Hessenberg matrix constructed by the GMRES iterations, \( m \) specifies the number of iterations for each restart, \( max \_iter \) specifies the maximum number of iterations that the method will take, and \( tol \) specifies the convergence tolerance for the method. Note that the size of \( H \) must be at least \( m \times m \).

GMRES() requires two matrices as input, \( A \) and \( H \). The matrix \( A \) (which will typically be a sparse matrix) corresponds to the matrix in the linear system \( Ax = b \). The matrix \( H \) (which will typically be a dense matrix) corresponds to the upper Hessenberg matrix \( H \) that is constructed during the GMRES iterations. Within GMRES, \( H \) is used in a different way than \( A \), so its class must supply different functionality. That is, \( A \) is only accessed through its matrix-vector and transpose-matrix-vector multiplication functions. On the other hand, GMRES solves a (dense upper triangular) linear system of equations based on \( H \). Therefore, the class to which \( H \) belongs (DMatrix) must provide \texttt{operator()} for element access. For this matrix class, it is important to remember that IML++ uses the C/C++ convention that matrices use 0-based indexing. That is, \( A(0,0) \) is the first component of the matrix \( A \). Also, the type of a single matrix entry must be compatible with the type of single vector entry. That is, operations such as \( A(i,j) \times a(j) \) must be able to be carried out.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if \( \| r \| / \| b \| < tol \).

A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations.
Upon return, the output arguments have the following values:

- $x$: approximate solution to $Ax = b$ computed at the final iteration
- $tow$: the value of the $\|r\|/\|b\|$ achieved after the final iteration
- $\text{max_iter}$: the number of iterations performed before return
- $H$: the upper triangular factor of the upper Hessenberg matrix constructed by GMRES
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with GMRES. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using GMRES and a diagonal preconditioner. A restart value of 32 is used. The matrix A is a sparse matrix and H is a dense matrix.

```cpp
#include <stdlib.h> // System includes
#include <iostream.h>
#include "compcol_double.h" // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV Vector level 1 BLAS
#include "ilupre_double.h" // Diagonal preconditioner
#include MATRIX_H // MV Matrix dense matrix header
#include "gmres.h" // IML++ GMRES template

int main(int argc, char * argv[]) {
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }
    double tol = 1.e-6; // Convergence tolerance
    int result, maxit = 150, restart = 32; // Maximum, restart iterations
    CompCol_Mat_double A; // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data
    MATRIX_double H(restart+1, restart, 0.0); // storage for upper Hessenberg H
    CompCol_ILUPreconditioner_double M(A); // Create ILU preconditioner
    result = GMRES(A, x, b, M, H, restart, maxit, tol); // Solve system
    cout << "GMRES flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;
    return result;
}
```

See Also

SparseLib++
ILUPreconditioner

Name  IR — Richardson Iteration

Declaration  
```cpp
#include "ir.h"

template <class Matrix, class Vector, class Preconditioner, class Real>
int IR ( const Matrix& A, Vector& x, const Vector& b,
         const Preconditioner& M, int& max_iter, Real& tol )
```

Description  IR solves the unsymmetric linear system $Ax = b$ using the preconditioned Richardson method.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for the solution of the unsymmetric linear system $Ax = b$. In addition, $M$ specifies a preconditioner, $max_iter$ specifies the maximum number of iterations that the method will take, and $tol$ specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if $\|r\|/\|b\| < tol$.

The iterative refinement algorithm is realized by taking $A$ to be the preconditioner (assuming class to which $A$ belongs has a `solve()` member function).

Return Values  A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations.

Upon return, the output arguments have the following values:

- $x$: approximate solution to $Ax = b$ computed at the final iteration
- $tol$: the value of the $\|r\|/\|b\|$ achieved after the final iteration
- $max_iter$: the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with IR. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved with IR and a diagonal preconditioner, i.e., with the Gauss-Jacobi iteration.

```cpp
#include <stdlib.h>    // System includes
#include <iostream>    //
#include "compcol/double.h"    // Compressed column matrix header
#include "iohb/double.h"      // Harwell-Boeing matrix I/O header
#include "mv blas1/double.h"   // MV Vector level 1 BLAS
#include "diagpre/double.h"    // Diagonal preconditioner
#include "ir.h"              // IML++ IR template

int main(int argc, char* argv[]) 
{
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6;     // Convergence tolerance
    int result, maxit = 300; // Maximum iterations
    CompCol_Mat_double A;   // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data
    DiagPreconditioner_double D(A); // Create diagonal preconditioner
    result = IR(A, x, b, D, maxit, tol); // Solve system

    cout << "IR flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;
    return result;
}
```

See Also

SparseLib++
DiagPreconditioner


Name: QMR — Quasi Minimal Residual Iteration (Without Look Ahead)

Declaration:

```cpp
#include "qmr.h"

template <class Matrix, class Vector, class Preconditioner1,
          class Preconditioner2, class Real>
int QMR ( const Matrix& A, Vector& x, const Vector& b,
          const Preconditioner& M1, const Preconditioner& M2,
          int& max_iter, Real& tol )
```

Description:

QMR solves the unsymmetric linear system $Ax = b$ using the preconditioned Quasi-Minimal Residual method.

This is a fully templated function.

On input, $A$ specifies the matrix, $b$ the right-hand side, and $x$ the initial guess for the solution of the unsymmetric linear system $Ax = b$. In addition, $M1$ and $M2$ specify preconditioners, $max_iter$ specifies the maximum number of iterations that the method will take, and $tol$ specifies the convergence tolerance for the method.

Convergence is achieved if the normalized residual is less than the specified tolerance, i.e., if $\frac{\|r\|}{\|b\|} < tol$.

Return Values:

A return value of 0 indicates convergence to the specified tolerance within the specified maximum number of iterations. A return value of 1 indicates that the method did not reach the specified convergence tolerance in the maximum number of iterations. A return value of 2 indicates that a breakdown associated with $\rho$ occurred. A return value of 3 indicates that a breakdown associated with $\beta$ occurred. A return value of 4 indicates that a breakdown associated with $\gamma$ occurred. A return value of 5 indicates that a breakdown associated with $\delta$ occurred. A return value of 6 indicates that a breakdown associated with $\epsilon$ occurred. A return value of 7 indicates that a breakdown associated with $\xi$ occurred.

Upon return, the output arguments have the following values:

- $x$ approximate solution to $Ax = b$ computed at the final iteration
- $tol$ the value of the $\frac{\|r\|}{\|b\|}$ achieved after the final iteration
- $max_iter$ the number of iterations performed before return
Example

The following example program uses IML++ in conjunction with SparseLib++ to solve a linear system with QMR. The program reads in a matrix and right-hand side stored in Harwell-Boeing format from the file specified in argv[1]. An initial guess of 0 is made for the solution and the system is solved using QMR and diagonal preconditioners.

```c
#include <stdlib.h>  // System includes
#include <iostream.h> //
#include "compcol_double.h"  // Compressed column matrix header
#include "iohb_double.h" // Harwell-Boeing matrix I/O header
#include "mv_blas1_double.h" // MV_Vector level 1 BLAS
#include "diagpre_double.h" // Diagonal preconditioner
#include "qmr.h" // IML++ QMR template

int main(int argc, char * argv[]) {
    if (argc < 2) {
        cerr << "Usage: " << argv[0] << " HBfile " << endl;
        exit(-1);
    }

    double tol = 1.e-6; // Convergence tolerance
    int result, maxit = 150; // Maximum iterations

    CompCol_Mat_double A; // Create a matrix
    readHB_mat(argv[1], &A); // Read matrix data
    VECTOR_double b, x(A.dim(1), 0.0); // Create rhs, solution vectors
    readHB_rhs(argv[1], &b); // Read rhs data

    DiagPreconditioner_double D(A); // Create diagonal preconditioner

    result = QMR(A, x, b, D, D, maxit, tol); // Solve system

    cout << "QMR flag = " << result << endl;
    cout << "iterations performed: " << maxit << endl;
    cout << "tolerance achieved : " << tol << endl;

    return result;
}
```

See Also

SparseLib++
DiagPreconditioner


5 References


A Code Listings

To demonstrate the elegance and power of using C++ for scientific computing, we include the complete text of each iterative method function in the following appendix. Note that in most cases, each function is completely specified on a single page.
Name  

`bicg.h` — BiConjugate Gradient Iteration template header file

Code  

```cpp
// Code

// biCG template
int BiCG(const Matrix &A, Vector &x, const Vector &b,
          const Preconditioner &M, int &max_iter, Real &tol)
{
    Real resid;
    Vector rho_1(1), rho_2(1), alpha(1), beta(1);
    Vector z, ztilde, p, ptilde, q, qtilde;
    Real normb = norm(b);
    Vector r = b - A * x;
    Vector rtilde = r;
    if (normb == 0.0)
        normb = 1;
    if ((resid = norm(r) / normb) <= tol) {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    for (int i = 1; i <= max_iter; i++) {
        z = M.solve(r);
        ztilde = M.trans_solve(rtilde);
        rho_1(0) = dot(z, rtilde);
        if (rho_1(0) == 0) {
            tol = norm(r) / normb;
            max_iter = i;
            return 2;
        }
        if (i == 1) {
            p = z;
            ptilde = ztilde;
        } else {
            beta(0) = rho_1(0) / rho_2(0);
            p = z + beta(0) * p;
            ptilde = ztilde + beta(0) * ptilde;
        }
        q = A * p;
        qtilde = A.trans_mult(ptilde);
        alpha(0) = rho_1(0) / dot(ptilde, q);
        x += alpha(0) * p;
        r -= alpha(0) * q;
        rtilde -= alpha(0) * qtilde;
        rho_2(0) = rho_1(0);
        if ((resid = norm(r) / normb) < tol) {
            tol = resid;
            max_iter = i;
            return 0;
        }
    }
    tol = resid;
    return 1;
}
```
**Name**

bicgsta.h — BiConjugate Gradient Stabilized Iteration template header file

**Code**

```cpp
template < class Matrix, class Vector, class Preconditioner, class Real >
int BiCGSTAB(const Matrix &A, Vector &x, const Vector &b,
              const Preconditioner &M, int &max_iter, Real &tol)
{
    Real resid;
    Vector rho_1(1), rho_2(1), alpha(1), beta(1), omega(1);
    Vector p, phat, s, shat, t, v;
    Real normb = norm(b);
    Vector r = b - A * x;
    Vector rtilde = r;
    if (normb == 0.0)
        normb = 1;
    if ((resid == norm(r) / normb) <= tol) {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    for (int i = 1; i <= max_iter; i++) {
        rho_1(0) = dot(rtilde, r);
        if (rho_1(0) == 0) {
            tol = norm(r) / normb;
            return 2;
        }
        if (i == 1)
            p = r;
        else {
            beta(0) = (rho_1(0)/rho_2(0)) * (alpha(0)/omega(0));
            p = r + beta(0) * (p - omega(0) * v);
        }
        phat = M.solve(p);
        v = A * phat;
        alpha(0) = rho_1(0) / dot(rtilde, v);
        s = r - alpha(0) * v;
        if ((resid = norm(s)/normb) < tol) {
            x += alpha(0) * phat;
            tol = resid;
            return 0;
        }
        shat = M.solve(s);
        t = A * shat;
        omega = dot(t,s) / dot(t,t);
        x += alpha(0) * phat + omega(0) * shat;
        r = s - omega(0) * t;
        rho_2(0) = rho_1(0);
        if ((resid = norm(r) / normb) < tol) {
            tol = resid;
            max_iter = i;
            return 0;
        }
    }
}
```

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if (omega(0) == 0) {
    tol = norm(r) / normb;
    return 3;
}

tol = resid;
return 1;
Name  

cg.h — Conjugate Gradient Iteration template header file

Code  

template < class Matrix, class Vector, class Preconditioner, class Real >  
int CG(const Matrix &A, Vector &x, const Vector &b,  
        const Preconditioner &M, int &max_iter, Real &tol)  
{
    Real resid;
    Vector p, z, q;
    Vector alpha(1), beta(1), rho(1), rho_1(1);
    Real normb = norm(b);
    Vector r = b - A*x;
    if (normb == 0.0)
        normb = 1;
    if ((resid = norm(r) / normb) <= tol) {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    for (int i = 1; i <= max_iter; i++) {
        z = M.solve(r);
        rho(0) = dot(r, z);
        if (i == 1)
            p = z;
        else {
            beta(0) = rho(0) / rho_1(0);
            p = z + beta(0) * p;
        }
        q = A*p;
        alpha(0) = rho(0) / dot(p, q);
        x += alpha(0) * p;
        r -= alpha(0) * q;
        if ((resid = norm(r) / normb) <= tol) {
            tol = resid;
            max_iter = i;
            return 0;
        }
        rho_1(0) = rho(0);
    }
    tol = resid;
    return 1;
}
Name
cgs.h — Conjugate Gradient Squared Iteration template header file

Code
template < class Matrix, class Vector, class Preconditioner, class Real >
int CGS(const Matrix &A, Vector &x, const Vector &b,
const Preconditioner &M, int &max_iter, Real &tol)
{
    Real resid;
    Vector rho_1(1), rho_2(1), alpha(1), beta(1);
    Vector p, phat, q, qhat, what, u, uhat;
    Real normb = norm(b);
    Vector r = b - A*x;
    Vector rtilde = r;
    if (normb == 0.0)
        normb = 1;
    if ( (resid = norm(r) / normb) <= tol )
    {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    for (int i = 1; i <= max_iter; i++)
    {
        rho_1(0) = dot(rtilde, r);
        if (rho_1(0) == 0)
        {
            tol = norm(r) / normb;
            return 2;
        }
        if (i == 1) {
            u = r;
            p = u;
        } else {
            beta(0) = rho_1(0) / rho_2(0);
            u = r + beta(0) * q;
            p = u + beta(0) * (q + beta(0) * p);
        }
        phat = M.solve(p);
        what = A*phat;
        alpha(0) = rho_1(0) / dot(rtilde, what);
        q = u - alpha(0) * what;
        uhat = M.solve(u + q);
        x += alpha(0) * uhat;
        qhat = A * uhat;
        r -= alpha(0) * qhat;
        rho_2(0) = rho_1(0);
        if ( ((resid = norm(r) / normb) < tol )
        {
            tol = resid;
            max_iter = i;
            return 0;
        }
    }
    tol = resid;
    return 1;
}
Name

`cheby.h` — Chebyshev Iteration template header file

Code

```cpp
template < class Matrix, class Vector, class Preconditioner, class Real, class Type >
int CHEBY(const Matrix &A, Vector &x, const Vector &b, const Preconditioner &M, int &max_iter, Real &tol,
        Type eigmin, Type eigmax)
{
    Real resid;
    Type alpha, beta, c, d;
    Vector p, q, z;
    Real normb = norm(b);
    Vector r = b - A * x;
    if (normb == 0.0)
        normb = 1;
    if ((resid == norm(r) / normb) <= tol) {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    c = (eigmax - eigmin) / 2.0;
    d = (eigmax + eigmin) / 2.0;
    for (int i = 1; i <= max_iter; i++) {
        z = M.solve(r); // apply preconditioner
        if (i == 1) {
            p = z;
            alpha = 2.0 / d;
        } else {
            beta = c * alpha / 2.0; // calculate new beta
            beta = beta * beta;
            alpha = 1.0 / (d - beta); // calculate new alpha
            p = z + beta * p; // update search direction
        }
        q = A * p;
        x += alpha * p; // update approximation vector
        r -= alpha * q; // compute residual
        if ((resid = norm(r) / normb) <= tol) {
            tol = resid;
            max_iter = i;
            return 0; // convergence
        }
    }
    tol = resid;
    return 1; // no convergence
}
```
### Name

gmres.h — GMRES Iteration template header file

### Code

```cpp
#include <math.h>
template <class Operator, class Vector, class Preconditioner,
          class Matrix, class Real>
int GMRES(const Operator &A, Vector &x, const Vector &b,
          const Preconditioner &M, Matrix &H, int &m, int &max_iter,
          Real &tol)
{
  Real resid;
  int i, j = 1, k;
  Vector s(m+1), cs(m+1), sn(m+1), w;
  Real normb = norm(M.solve(b));
  Vector r = M.solve(b - A * x);
  Real beta = norm(r);
  if (normb == 0.0)
    normb = 1;
  if ((resid = norm(r) / normb) <= tol) {
    tol = resid;
    max_iter = 0;
    return 0;
  }
  Vector *v = new Vector[m+1];
  while (j <= max_iter) {
    v[0] = r * (1.0 / beta);
    s = 0.0;
    s(0) = beta;
    for (i = 0; i < m && j <= max_iter; i++, j++) {
      w = M.solve(A * v[i]);
      for (k = 0; k < i; k++) {
        H(k, i) = dot(w, v[k]);
        w -= H(k, i) * v[k];
      }
      H(i+1, i) = norm(w);
      v[i+1] = w * (1.0 / H(i+1, i));
      for (k = 0; k < i; k++)
        ApplyPlaneRotation(H(k, i), H(k+1, i), cs(k), sn(k));
      GeneratePlaneRotation(H(i, i), H(i+1, i), cs(i), sn(i));
      ApplyPlaneRotation(H(i, i), H(i+1, i), cs(i), sn(i));
    }
    if ((resid = abs(s(i+1)) / normb) < tol) {
      Update(x, i, H, s, v);
      tol = resid;
      max_iter = j;
      delete[] v;
      return 0;
    }
  }
}
```

---

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Update(x, m - 1, H, s, v);
  r = M.solve(b - A * x);
  beta = norm(r);
  if ((resid = beta / normb) < tol) {
    tol = resid;
    max_iter = j;
    delete [] v;
    return 0;
  }
  tol = resid;
  delete [] v;
  return 1;
}

template <class Matrix, class Vector>
void Update(Vector &x, int k, Matrix &h, Vector &s, Vector v[])
{
  Vector y(s);
  for (int i = k; i >= 0; i--)
  {
    y(i) /= h(i, i);
    for (int j = i - 1; j >= 0; j--)
      y(j) /= h(j, i) * y(i);
  }
  for (int j = 0; j <= k; j++)
    x += v[j] * y(j);
}

template<class Real>
Real abs(Real x)
{
  return (x > 0 ? x : -x);
}

 template<class Real>
void GeneratePlaneRotation(Real &dx, Real &dy, Real &cs, Real &sn)
{
  if (dy == 0.0) {
    cs = 1.0;
    sn = 0.0;
  } else if (abs(dy) > abs(dx)) {
    Real temp = dx / dy;
    sn = 1.0 / sqrt(1.0 + temp*temp);
    cs = temp * sn;
  } else {
    Real temp = dy / dx;
    cs = 1.0 / sqrt(1.0 + temp*temp);
    sn = temp * cs;
  }
}
template<class Real>
void ApplyPlaneRotation(Real &dx, Real &dy, Real &cs, Real &sn)
{
    Real temp = cs * dx + sn * dy;
    dy = -sn * dx + cs * dy;
    dx = temp;
}
Name  
ir.h — Richardson Iteration template header file

Code  
```
template < class Matrix, class Vector, class Preconditioner, class Real >  
int IR(const Matrix &A, Vector &x, const Vector &b,  
       const Preconditioner &M, int &max_iter, Real &tol)  
{  
  Real resid;  
  Vector z;  
  Real normb = norm(b);  
  Vector r = b - A*x;  
  if (normb == 0.0)  
    normb = 1;  
  if ((resid = norm(r) / normb) <= tol) {  
    tol = resid;  
    max_iter = 0;  
    return 0;  
  }  
  for (int i = 1; i <= max_iter; i++) {  
    z = M.solve(r);  
    x += z;  
    r = b - A * x;  
    if ((resid = norm(r) / normb) <= tol) {  
      tol = resid;  
      max_iter = i;  
      return 0;  
    }  
  }  
  tol = resid;  
  return 1;  
}  
```
Name  

**qmr.h** — Quasi-Minimal Residual Iteration template header file

Code

```cpp
#include <math.h>

template <class Matrix, class Vector, class Preconditioner1, class Preconditioner2, class Real>
int QMR(const Matrix &A, Vector &x, const Vector &b, const Preconditioner1 &M1,
        const Preconditioner2 &M2, int &max_iter, Real &tol)
{
    Real resid;
    Vector rho(1), rho_1(i), xi(1), gamma(1), gamma_1(1), theta(1), theta_1(1);
    Vector eta(1), delta(1), ep(1), beta(1);
    Vector r, v_tld, y, w_tld, z;
    Vector v, w, y_tld, z_tld;
    Vector p, q, p_tld, d, s;
    Real normb = norm(b);
    r = b - A * x;
    if (normb == 0.0)
        normb = 1;
    if ((resid = norm(r) / normb) <= tol) {
        tol = resid;
        max_iter = 0;
        return 0;
    }
    v_tld = r;
    y = M1.solve(v_tld);
    rho(0) = norm(y);
    w_tld = r;
    z = M2.trans_solve(w_tld);
    xi(0) = norm(z);
    gamma(0) = 1.0;
    eta(0) = -1.0;
    theta(0) = 0.0;
    for (int i = 1; i <= max_iter; i++) {
        if (rho(0) == 0.0)
            return 2; // return on breakdown
        if (xi(0) == 0.0)
            return 7; // return on breakdown
        v = (1.0 / rho(0)) * v_tld;
        y = (1.0 / rho(0)) * y;
        w = (1.0 / xi(0)) * w_tld;
        z = (1.0 / xi(0)) * z;
        delta(0) = dot(z, y);
        if (delta(0) == 0.0)
            return 5; // return on breakdown
        y_tld = M2.solve(y);
        z_tld = M1.trans_solve(z);
```

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if (i > 1) {
  p = y_tld - (xi(0) * delta(0) / ep(0)) * p;
  q = z_tld - (rho(0) * delta(0) / ep(0)) * q;
} else {
  p = y_tld;
  q = z_tld;
}
p_tld = A * p;
ep(0) = dot(q, p_tld);
if (ep(0) == 0.0)
  return 6; // return on breakdown
beta(0) = ep(0) / delta(0);
if (beta(0) == 0.0)
  return 3; // return on breakdown
v_tld = p_tld - beta(0) * v;
y = M1.solve(v_tld);
rho_1(0) = rho(0);
rho(0) = norm(y);
w_tld = A.trans_mult(q) - beta(0) * w;
z = M2.trans_solve(w_tld);
xi(0) = norm(z);
gamma_1(0) = gamma(0);
theta_1(0) = theta(0);
theta(0) = rho(0) / (gamma_1(0) * beta(0));
gamma(0) = 1.0 / sqrt(1.0 + theta(0) * theta(0));
if (gamma(0) == 0.0)
  return 4; // return on breakdown
eta(0) = -eta(0) * rho_1(0) * gamma(0) * gamma(0) /
  (beta(0) * gamma_1(0) * gamma_1(0));
if (i > 1) {
  d = eta(0) * p + (theta_1(0) * theta_1(0) * gamma(0) * gamma(0)) * d;
  s = eta(0) * p_tld + (theta_1(0) * theta_1(0) * gamma(0) * gamma(0)) * s;
} else {
  d = eta(0) * p;
  s = eta(0) * p_tld;
}
x += d; // update approximation vector
r -= s; // compute residual
if ((resid = norm(r) / normb) <= tol) {
  tol = resid;
  max_iter = i;
  return 0;
}
tol = resid;
return 1; // no convergence