NAG Library Function Document

nag_real_sym_posdef_packed_lin_solve (f04bec)

1 Purpose

nag_real_sym_posdef_packed_lin_solve (f04bec) computes the solution to a real system of linear equations $AX = B$, where $A$ is an $n$ by $n$ symmetric positive definite matrix, stored in packed format, and $X$ and $B$ are $n$ by $r$ matrices. An estimate of the condition number of $A$ and an error bound for the computed solution are also returned.

2 Specification

```c
#include <nag.h>
#include <nagf04.h>
void nag_real_sym_posdef_packed_lin_solve (Nag_OrderType order,
                                      Nag_UploType uplo, Integer n, Integer nrhs,
                                      double ap[], double b[],
                                      Integer pdb, double *rcond, double *errbnd, NagError *fail)
```

3 Description

The Cholesky factorization is used to factor $A$ as $A = U^T U$, if $uplo = Nag_Upper$, or $A = LL^T$, if $uplo = Nag_Lower$, where $U$ is an upper triangular matrix and $L$ is a lower triangular matrix. The factored form of $A$ is then used to solve the system of equations $AX = B$.

4 References


5 Arguments

1: $order$ – Nag_OrderType
   $Input$
   $On entry$: the $order$ argument specifies the two-dimensional storage scheme being used, i.e., row-major ordering or column-major ordering. C language defined storage is specified by $order = Nag_RowMajor$. See Section 3.2.1.3 in the Essential Introduction for a more detailed explanation of the use of this argument.
   $Constraint$: $order = Nag_RowMajor$ or $Nag_ColMajor$.

2: $uplo$ – Nag_UploType
   $Input$
   $On entry$: if $uplo = Nag_Upper$, the upper triangle of the matrix $A$ is stored.
   If $uplo = Nag_Lower$, the lower triangle of the matrix $A$ is stored.
   $Constraint$: $uplo = Nag_Upper$ or $Nag_Lower$.

3: $n$ – Integer
   $Input$
   $On entry$: the number of linear equations $n$, i.e., the order of the matrix $A$.
   $Constraint$: $n \geq 0$. 
4: \( \text{nrhs} \) – Integer  
\( \text{Input} \)

On entry: the number of right-hand sides \( r \), i.e., the number of columns of the matrix \( B \).

Constraint: \( \text{nrhs} \geq 0 \).

5: \( \text{ap}[\text{dim}] \) – double  
\( \text{Input/Output} \)

Note: the dimension, \( \text{dim} \), of the array \( \text{ap} \) must be at least \( \max(1, \text{n} \times (\text{n} + 1)/2) \).

On entry: the \( n \) by \( n \) symmetric matrix \( A \). The upper or lower triangular part of the symmetric matrix is packed column-wise in a linear array. The \( j \)th column of \( A \) is stored in the array \( \text{ap} \) as follows:

The storage of elements \( A_{ij} \) depends on the \text{order} and \text{uplo} arguments as follows:

\begin{align*}
\text{if order} = \text{Nag\_ColMajor and uplo} = \text{Nag\_Upper}, & \quad A_{ij} \text{ is stored in } \text{ap}((j-1) \times j/2 + i - 1), \text{ for } i \leq j; \\
\text{if order} = \text{Nag\_ColMajor and uplo} = \text{Nag\_Lower}, & \quad A_{ij} \text{ is stored in } \text{ap}((2n - j) \times (j-1)/2 + i - 1), \text{ for } i \geq j; \\
\text{if order} = \text{Nag\_RowMajor and uplo} = \text{Nag\_Upper}, & \quad A_{ij} \text{ is stored in } \text{ap}((2n - i) \times (i-1)/2 + j - 1), \text{ for } i \leq j; \\
\text{if order} = \text{Nag\_RowMajor and uplo} = \text{Nag\_Lower}, & \quad A_{ij} \text{ is stored in } \text{ap}((i-1) \times i/2 + j - 1), \text{ for } i \geq j.
\end{align*}

On exit: if \text{fail\_code} = NE\_NOERROR or NE\_RCOND, the factor \( U \) or \( L \) from the Cholesky factorization \( \text{A} = U^T U \) or \( \text{A} = LL^T \), in the same storage format as \( \text{A} \).

6: \( \text{b}[\text{dim}] \) – double  
\( \text{Input/Output} \)

Note: the dimension, \( \text{dim} \), of the array \( \text{b} \) must be at least \( \max(1, \text{pdb} \times \text{nrhs}) \) when \text{order} = \text{Nag\_ColMajor}; \( \max(1, \text{n} \times \text{pdb}) \) when \text{order} = \text{Nag\_RowMajor}.

The \( (i, j) \)th element of the matrix \( B \) is stored in

\begin{align*}
\text{b}((j-1) \times \text{pdb} + i - 1) & \quad \text{when order} = \text{Nag\_ColMajor}; \\
\text{b}((i-1) \times \text{pdb} + j - 1) & \quad \text{when order} = \text{Nag\_RowMajor}.
\end{align*}

On entry: the \( n \) by \( r \) matrix of right-hand sides \( B \).

On exit: if \text{fail\_code} = NE\_NOERROR or NE\_RCOND, the \( n \) by \( r \) solution matrix \( X \).

7: \( \text{pdb} \) – Integer  
\( \text{Input} \)

On entry: the stride separating row or column elements (depending on the value of \text{order}) in the array \( \text{b} \).

Constraints:

\begin{align*}
\text{if order} = \text{Nag\_ColMajor, pdb} & \geq \max(1, \text{n}); \\
\text{if order} = \text{Nag\_RowMajor, pdb} & \geq \max(1, \text{nrhs}).
\end{align*}

8: \( \text{rcond} \) – double  
\( \text{Output} \)

On exit: if \text{fail\_code} = NE\_NOERROR or NE\_RCOND, an estimate of the reciprocal of the condition number of the matrix \( \text{A} \), computed as \( \text{rcond} = 1/(\|A\|_1 \|A^{-1}\|_1) \).

9: \( \text{errbnd} \) – double  
\( \text{Output} \)

On exit: if \text{fail\_code} = NE\_NOERROR or NE\_RCOND, an estimate of the forward error bound for a computed solution \( \hat{x} \), such that \( \|\hat{x} - x\|_1/\|x\|_1 \leq \text{errbnd} \), where \( \hat{x} \) is a column of the computed solution returned in the array \( \text{b} \) and \( x \) is the corresponding column of the exact solution \( X \). If \text{rcond} is less than machine precision, then \( \text{errbnd} \) is returned as unity.
6 Error Indicators and Warnings

**NE_ALLOC_FAIL**

Dynamic memory allocation failed.
See Section 3.2.1.2 in the Essential Introduction for further information.

**NE_BAD_PARAM**

On entry, argument \texttt{value} had an illegal value.

**NE_INT**

On entry, \( n = \texttt{value} \).
Constraint: \( n \geq 0 \).

On entry, \( nrhs = \texttt{value} \).
Constraint: \( nrhs \geq 0 \).

On entry, \( pdb = \texttt{value} \).
Constraint: \( pdb > 0 \).

**NE_INT_2**

On entry, \( pdb = \texttt{value} \) and \( n = \texttt{value} \).
Constraint: \( pdb \geq \max(1, n) \).

On entry, \( pdb = \texttt{value} \) and \( nrhs = \texttt{value} \).
Constraint: \( pdb \geq \max(1, nrhs) \).

**NE_INTERNAL_ERROR**

An internal error has occurred in this function. Check the function call and any array sizes. If the call is correct then please contact NAG for assistance.

An unexpected error has been triggered by this function. Please contact NAG.
See Section 3.6.6 in the Essential Introduction for further information.

**NE_NO_LICENCE**

Your licence key may have expired or may not have been installed correctly.
See Section 3.6.5 in the Essential Introduction for further information.

**NE_POS_DEF**

The principal minor of order \texttt{value} of the matrix \( A \) is not positive definite. The factorization has not been completed and the solution could not be computed.

**NE_RCOND**

A solution has been computed, but \texttt{rcond} is less than \texttt{machine precision} so that the matrix \( A \) is numerically singular.

7 Accuracy

The computed solution for a single right-hand side, \( \hat{x} \), satisfies an equation of the form

\[(A + E)\hat{x} = b,\]

where
\[ \|E\|_1 = O(\epsilon)\|A\|_1 \]
and \( \epsilon \) is the \textit{machine precision}. An approximate error bound for the computed solution is given by
\[ \|\hat{x} - x\|_1 \leq \kappa(A)\|E\|_1 /\|X\|_1, \]
where \( \kappa(A) = \|A^{-1}\|_1\|A\|_1 \), the condition number of \( A \) with respect to the solution of the linear equations. \texttt{nag_real_sym_posdef_packed_lin_solve} uses the approximation \( \|E\|_1 = \epsilon\|A\|_1 \) to estimate \texttt{errbnd}. See Section 4.4 of Anderson \textit{et al.} (1999) for further details.

8 Parallelism and Performance

\texttt{nag_real_sym_posdef_packed_lin_solve} is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

\texttt{nag_real_sym_posdef_packed_lin_solve} makes calls to BLAS and/or LAPACK routines, which may be threaded within the vendor library used by this implementation. Consult the documentation for the vendor library for further information.

Please consult the X06 Chapter Introduction for information on how to control and interrogate the OpenMP environment used within this function. Please also consult the Users’ Note for your implementation for any additional implementation-specific information.

9 Further Comments

The Integer allocatable memory required is \( n \), and the double allocatable memory required is \( 3 \times n \). Allocation failed before the solution could be computed.

The packed storage scheme is illustrated by the following example when \( n = 4 \) and \texttt{uplo} = Nag_Upper. Two-dimensional storage of the symmetric matrix \( A \):

\[
\begin{bmatrix}
  a_{11} & a_{12} & a_{13} & a_{14} \\
  a_{22} & a_{23} & a_{24} & \\
  a_{33} & a_{34} & \\
  a_{44} & 
\end{bmatrix}
\]

Packed storage of the upper triangle of \( A \):

\[
ap = [a_{11}, a_{12}, a_{22}, a_{13}, a_{23}, a_{33}, a_{14}, a_{24}, a_{34}, a_{44}]
\]

The total number of floating-point operations required to solve the equations \( AX = B \) is proportional to \((\frac{1}{3}n^3 + n^2r)\). The condition number estimation typically requires between four and five solves and never more than eleven solves, following the factorization.

In practice the condition number estimator is very reliable, but it can underestimate the true condition number; see Section 15.3 of Higham (2002) for further details.

The complex analogue of \texttt{nag_real_sym_posdef_packed_lin_solve} is \texttt{nag_herm_posdef_packed_lin_solve}.

10 Example

This example solves the equations
\[ AX = B, \]
where \( A \) is the symmetric positive definite matrix.
\[
A = \begin{pmatrix}
4.16 & -3.12 & 0.56 & -0.10 \\
-3.12 & 5.03 & -0.83 & 1.18 \\
0.56 & -0.83 & 0.76 & 0.34 \\
-0.10 & 1.18 & 0.34 & 1.18 \\
\end{pmatrix}
\quad \text{and} \quad
B = \begin{pmatrix}
8.70 & 8.30 \\
-13.35 & 2.13 \\
1.89 & 1.61 \\
-4.14 & 5.00 \\
\end{pmatrix}.
\]

An estimate of the condition number of \( A \) and an approximate error bound for the computed solutions are also printed.

### 10.1 Program Text

// * nag_real_sym_posdef_packed_lin_solve (f04bec) Example Program. *
// * Copyright 2014 Numerical Algorithms Group. *
// * Mark 8, 2004. */
#include <stdio.h>
#include <nag.h>
#include <nag_stdlib.h>
#include <nagf04.h>
#include <nagx04.h>

int main(void) {
    /* Scalars */
    double errbnd, rcond;
    Integer exit_status, i, j, n, nrhs, pdb;
    /* Arrays */
    char nag_enum_arg[40];
    double *ap = 0, *b = 0;
    /* Nag Types */
    NagError fail;
    Nag_OrderType order;
    Nag_UploType uplo;

    #ifdef NAG_COLUMN_MAJOR
    #define A_UPPER(I, J) ap[J*(J-1)/2 + I - 1]
    #define A_LOWER(I, J) ap[(2*n-J)*(J-1)/2 + I - 1]
    #define B(I, J) b[(J-1)*pdb + I - 1]
    order = Nag_ColMajor;
    #else
    #define A_LOWER(I, J) ap[I*(I-1)/2 + J - 1]
    #define A_UPPER(I, J) ap[(2*n-I)*(I-1)/2 + J - 1]
    #define B(I, J) b[(I-1)*pdb + J - 1]
    order = Nag_RowMajor;
    #endif

    exit_status = 0;
    INIT_FAIL(fail);
    printf("nag_real_sym_posdef_packed_lin_solve (f04bec) Example ",
            "Program Results\n\n");

    /* Skip heading in data file */
    #ifdef _WIN32
    scanf_s("%*[\n ]");
    #else
    scanf("%*[\n ]");
    #endif

    #ifdef _WIN32
    scanf_s("%NAG_IFMT%NAG_IFMT%*[\n ]", &n, &nrhs);
    #else
    scanf("%NAG_IFMT%NAG_IFMT%*[\n ]", &n, &nrhs);
    #endif

    return exit_status;
}
if (n > 0 && nrhs > 0)
{
    /* Allocate memory */
    if (!(ap = NAG_ALLOC(n*(n+1)/2, double)) ||
        !(b = NAG_ALLOC(n*nrhs, double)))
    {
        printf("Allocation failure\n");
        exit_status = -1;
        goto END;
    }
    #ifdef NAG_COLUMN_MAJOR
    pdb = n;
    #else
    pdb = nrhs;
    #endif
}
else
{
    printf("%s\n", "n and/or nrhs too small");
    exit_status = 1;
    return exit_status;
}
#endif
#ifdef _WIN32
    scanf_s("%39s%*\n ", nag_enum_arg, _countof(nag_enum_arg));
#else
    scanf("%39s%*\n ", nag_enum_arg);
#endif
/* nag_enum_name_to_value (x04nac).
* Converts NAG enum member name to value */
uplo = (Nag_UploType) nag_enum_name_to_value(nag_enum_arg);
/* Read the upper or lower triangular part of the matrix A from */
/* data file */
if (uplo == Nag_Upper)
{
    for (i = 1; i <= n; ++i)
    {
        for (j = i; j <= n; ++j)
        {
            #ifdef _WIN32
                scanf_s("%lf", &A_UPPER(i, j));
            #else
                scanf("%lf", &A_UPPER(i, j));
            #endif
        }
    }
    #ifdef _WIN32
        scanf_s("%*[\n ");
    #else
        scanf("%*[\n ");
    #endif
}
else
{
    for (i = 1; i <= n; ++i)
    {
        for (j = 1; j <= i; ++j)
        {
            #ifdef _WIN32
                scanf_s("%lf", &A_LOWER(i, j));
            #else
                scanf("%lf", &A_LOWER(i, j));
            #endif
        }
    }
    #ifdef _WIN32
        scanf_s("%*[\n ");
    #else
        scanf("%*[\n ");
    #endif
}
else
{
    for (i = 1; i <= n; ++i)
    {
        for (j = 1; j <= i; ++j)
        {
            #ifdef _WIN32
                scanf_s("%lf", &A_LOWER(i, j));
            #else
                scanf("%lf", &A_LOWER(i, j));
            #endif
        }
    }
    #ifdef _WIN32
        scanf_s("%*[\n ");
    #else
        scanf("%*[\n ");
    #endif
}
#else
    scanf("%*[\n"]
#endif

/* Read B from data file */
for (i = 1; i <= n; ++i)
{
    for (j = 1; j <= nrhs; ++j)
    {
        #ifdef _WIN32
            scanf_s("%lf", &B(i, j));
        #else
            scanf("%lf", &B(i, j));
        #endif
    }
    #ifdef _WIN32
        scanf_s("%*[\n"]
    #else
        scanf("%*[\n"]
    #endif
}

/* Solve the equations AX = B for X */
/* nag_real_sym_posdef_packed_lin_solve (f04bec).
* Computes the solution and error-bound to a real symmetric
* positive-definite system of linear equations, packed
* storage */
    nag_real_sym_posdef_packed_lin_solve(order, uplo, n, nrhs, ap, b, pdb,
                                           &rcond, &errbnd, &fail);
if (fail.code == NE_NOERROR)
{
    /* Print solution, estimate of condition number and approximate */
    /* error bound */
    /* nag_gen_real_mat_print (x04cac).
    * Print real general matrix (easy-to-use)
    */
    fflush(stdout);
    nag_gen_real_mat_print(order, Nag_GeneralMatrix, Nag_NonUnitDiag, n,
                           nrhs, b, pdb, "Solution", 0, &fail);
    if (fail.code != NE_NOERROR)
    {
        printf("Error from nag_gen_real_mat_print (x04cac).\n%s\n", fail.message);
        exit_status = 1;
        goto END;
    }
    printf("\n");
    printf("%s\%6s\%10.1e\n\n\n\n", "Estimate of condition number", "", 1.0/rcond);
    printf("%s\%6s\%10.1e\n\n", "Estimate of error bound for computed solutions", "", errbnd);
}
else if (fail.code == NE_RCOND)
{
    /* Matrix A is numerically singular. Print estimate of */
    /* reciprocal of condition number and solution */
    printf("%s\%6s\%10.1e\n\n\n\n", "Estimate of reciprocal of condition number", "", rcond);
    /* nag_gen_real_mat_print (x04cac), see above. */
    fflush(stdout);
    nag_gen_real_mat_print(order, Nag_GeneralMatrix, Nag_NonUnitDiag, n,
                           nrhs, b, pdb, "Solution", 0, &fail);
    if (fail.code != NE_NOERROR)
    {
        printf("Error from nag_gen_real_mat_print (x04cac).\n%s\n", fail.message);
        exit_status = 1;
    }
goto END;

} else if (fail.code == NE_POS_DEF)
{
    /* The matrix A is not positive definite to working precision */
    printf("%s"NAG_IFMT"%sn\n", "The leading minor of order ",
            fail.errnum, " is not positive definite");
}
else
{
    printf("Error from ",
            "nag_real_sym_posdef_packed_lin_solve (f04bec).\n%sn",
            fail.message);
    exit_status = 1;
    goto END;
}
END:
NAG_FREE(ap);
NAG_FREE(b);
return exit_status;

10.2 Program Data

nag_real_sym_posdef_packed_lin_solve (f04bec) Example Program Data

<table>
<thead>
<tr>
<th>n</th>
<th>nrhs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

:Values of n and nrhs

<table>
<thead>
<tr>
<th>uplo</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nag_Upper</td>
<td>-3.12</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>5.03</td>
<td>-0.83</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>0.34</td>
</tr>
</tbody>
</table>

:Value of uplo

<table>
<thead>
<tr>
<th>A</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

:End of matrix A

<table>
<thead>
<tr>
<th>B</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-13.35</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>1.89</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>-4.14</td>
<td>5.00</td>
</tr>
</tbody>
</table>

:End of matrix B

10.3 Program Results

nag_real_sym_posdef_packed_lin_solve (f04bec) Example Program Results

Solution

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>4.0000</td>
</tr>
<tr>
<td>2</td>
<td>-1.0000</td>
<td>3.0000</td>
</tr>
<tr>
<td>3</td>
<td>2.0000</td>
<td>2.0000</td>
</tr>
<tr>
<td>4</td>
<td>-3.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Estimate of condition number

9.7e+01

Estimate of error bound for computed solutions

1.1e-14