MUltifrontal Massively Parallel Solver
(MUMPS 5.0.0)
Users’ guide *

February 20, 2015

Abstract

This document describes the Fortran 90 and C user interfaces to MUMPS 5.0.0. We describe in detail the data structures, parameters, calling sequences, and error diagnostics. Basic example programs using MUMPS are also provided.

*Information on how to obtain updated copies of MUMPS can be obtained from the Web page http://mumps-solver.org/
## Contents

1 Introduction 4

2 Notes for users of previous versions of MUMPS 5
   2.1 Changelog .......................................................... 6
   2.2 Binary compatibility .............................................. 6
   2.3 Upgrading between MUMPS 4.10.0 to MUMPS 5.0.0 ............... 7
       2.3.1 Interface with the Metis and ParMetis orderings .......... 7
       2.3.2 Interface with the SCOTCH and PT-SCOTCH orderings ...... 7
       2.3.3 ICNTL(10): iterative refinement .......................... 7
       2.3.4 ICNTL(11): error analysis ................................... 7
       2.3.5 ICNTL(20): sparse right-hand sides ........................ 8
       2.3.6 License ......................................................... 8

3 Main functionalities of MUMPS 5.0.0 8
   3.1 Input matrix format ............................................... 8
   3.2 Preprocessing ..................................................... 8
   3.3 Post-processing facilities ....................................... 10
       3.3.1 Iterative refinement ......................................... 10
       3.3.2 Error analysis and statistics ................................ 10
   3.4 Null pivot detection ................................................ 11
   3.5 Computation of a solution of a deficient matrix and of a null space basis .......... 11
   3.6 Solving the transposed system .................................... 11
   3.7 Forward elimination during factorization .......................... 11
   3.8 Arithmetic versions ................................................ 12
   3.9 Numerical pivoting ................................................ 12
   3.10 The working host processor ...................................... 12
   3.11 MPI-free version .................................................. 13
   3.12 Combining MPI and multithreaded parallelism ...................... 13
   3.13 Out-of-core facility ................................................ 13
   3.14 Determinant ....................................................... 13
   3.15 Computing selected entries of A⁻¹ ................................ 14
   3.16 Reduce/condense a problem on an interface (Schur complement and reduced/condensed right-hand side) ........................................ 14

4 User interface and available routines 15

5 Application Program Interface 18
   5.1 General ............................................................. 18
       5.1.1 Initialization, Analysis, Factorization, Solve, Termination (JOB) .... 18
       5.1.2 Version number ................................................. 19
       5.1.3 Control of parallelism (COMM, PAR) .......................... 19
   5.2 Input Matrix ......................................................... 20
       5.2.1 Matrix type (SYM) ............................................... 20
       5.2.2 Matrix format .................................................. 20
       5.2.2.1 Centralized assembled matrix (ICNTL(5)=0 and ICNTL(18)=0) .......... 21
       5.2.2.2 Distributed assembled matrix (ICNTL(5)=0 and ICNTL(18)=1,2,3) ....... 22
       5.2.2.3 Elemental matrix (ICNTL(5)=1 and ICNTL(18)=0) ...................... 23
       5.2.3 Writing the input matrix to a file ............................. 24
   5.3 Preprocessing: permutation to zero-free diagonal and scaling .................. 24
       5.3.1 Permutation to a zero-free diagonal (ICNTL(6)) .................. 26
       5.3.2 Scaling (ICNTL(6) or ICNTL(8)) ................................ 26
   5.4 Preprocessing: symmetric permutations ................................ 27
       5.4.1 Symmetric permutation vector (ICNTL(7) and ICNTL(29)) ............ 28
       5.4.2 Given ordering (ICNTL(7)=1 and ICNTL(28)=1) ................. 29
5.5 Out-of-core (ICNTL(22)) .................................................. 29
5.6 Workspace parameters (ICNTL(14) and ICNTL(23)) and user workspace .......................... 30
5.7 Null pivot row detection .......................................................... 32
5.8 Discard matrix factors (ICNTL(31)) .............................................. 32
5.9 Computation of the determinant (ICNTL(33)) ..................................... 33
5.10 Forward elimination during factorization (ICNTL(32)) .............................. 34
5.11 Right-hand side and solution vectors/matrices .......................................... 34
  5.11.1 Dense right-hand side (ICNTL(20)=0) ..................................... 35
  5.11.2 Sparse right-hand side (ICNTL(20)=1,2,3) ................................ 36
  5.11.3 A particular case of sparse right-hand side: computing entries of \(A^{-1}\) (ICNTL(30)=1) ............................................................ 37
  5.11.4 Centralized solution (ICNTL(21)=0) ....................................... 38
  5.11.5 Distributed solution (ICNTL(21)=1) ..................................... 38
5.12 Schur complement with reduced or condensed right-hand side (ICNTL(19) and ICNTL(26)) .......................................................... 38
  5.12.1 Centralized Schur complement stored by rows (ICNTL(19)=1) .............. 39
  5.12.2 Distributed Schur complement (ICNTL(19)=2 or 3) ............................ 40
  5.12.3 Centralized Schur complement stored by columns (ICNTL(19)=2 or 3) .... 41
  5.12.4 Using partial factorization during solution phase (ICNTL(26)=0, 1 or 2) .... 42

6 Control parameters ................................................................. 44
  6.1 Integer control parameters ...................................................... 44
  6.2 Real/complex control parameters ................................................. 58
  6.3 Compatibility between options ................................................... 61

7 Information parameters ............................................................... 62
  7.1 Information local to each processor ............................................... 62
  7.2 Information available on all processors .......................................... 64

8 Error diagnostics ................................................................. 67

9 Calling MUMPS from C .............................................................. 70
  9.1 Array indices ................................................................. 70
  9.2 Issues related to the C and Fortran communicators .............................. 72
  9.3 Fortran I/O ................................................................. 72
  9.4 Runtime libraries ............................................................. 72
  9.5 Integer, real and complex datatypes in C and Fortran .......................... 72
  9.6 Sequential version ............................................................. 73

10 Scilab and MATLAB/Octave interfaces ........................................... 73

11 Examples of use of MUMPS ....................................................... 75
  11.1 An assembled problem .......................................................... 75
  11.2 An elemental problem ........................................................ 76
  11.3 An example of calling MUMPS from C ......................................... 78

12 License ................................................................. 79

13 Credits ................................................................. 79
1 Introduction

MUMPS (“Multifrontal Massively Parallel Solver”) is a package for solving systems of linear equations of the form $A x = b$, where $A$ is a square sparse matrix that can be either unsymmetric, symmetric positive definite, or general symmetric, on distributed memory computers. MUMPS implements a direct method based on a multifrontal approach which performs a Gaussian factorization

$$A = LU$$

where $L$ is a lower triangular matrix and $U$ an upper triangular matrix. If the matrix is symmetric then the factorization

$$A = LDL^T$$

where $D$ is block diagonal matrix with blocks of order 1 or 2 on the diagonal is performed. We refer the reader to the papers [5, 6, 9, 23, 24, 28, 35, 27, 14, 1, 40, 11, 36, 3, 30, 42, 15, 31, 39] for full details of the techniques used, algorithms and related research.

The system $Ax = b$ is solved in three main steps:

1. Analysis.
   During analysis, preprocessing (see Subsection 3.2), including an ordering based on the symmetrized pattern $A + A^T$, and a symbolic factorization are performed. During the symbolic factorization, a mapping of the multifrontal computational graph, the so called elimination tree [33], is computed and used to estimate the number of operations and memory necessary for factorization and solution. Both parallel and sequential implementations of the analysis phase are available. Let $A_{pre}$ denote the preprocessed matrix (further defined in Subsection 3.2).

2. Factorization.
   During factorization $A_{pre} = LU$ or $A_{pre} = LDL^T$, depending on the symmetry of the preprocessed matrix, is computed. The original matrix is first distributed (or redistributed) onto the processors depending on the mapping computed during the analysis. The numerical factorization is then a sequence of dense factorization on so called frontal matrices. In addition to standard threshold pivoting and two-by-two pivoting (not so standard in distributed memory codes) there is an option to perform static pivoting. The elimination tree also expresses independency between tasks and enables multiple fronts to be processed simultaneously. This approach is called multifrontal approach. After factorization, the factor matrices are kept distributed (in-core memory or on disk); they will be used at the solution phase.

3. Solution.
   The solution $x_{pre}$ of $LUX_{pre} = b_{pre}$ or $LDL^Tx_{pre} = b_{pre}$ where $x_{pre}$ and $b_{pre}$ are respectively the transformed solution $x$ and right-hand side $b$ associated to the preprocessed matrix $A_{pre}$, is obtained through a forward elimination step

$$Ly = b_{pre} \text{ or } LDy = b_{pre}.$$  \hspace{1cm} (3)

followed by a backward elimination step

$$Ux_{pre} = y \text{ or } L^Tx_{pre} = y.$$  \hspace{1cm} (4)

The solution $x_{pre}$ is finally postprocessed to obtain the solution $x$ of the original system $Ax = b$, where $x$ is either assembled on an identified processor (the host) or kept distributed on the working processors. Iterative refinement and backward error analysis are also postprocessing options of the solution phase.

Each of these 3 phases can be called separately (see Subsection 5.1.1). A special case is the one where the forward elimination step is performed during factorization (see Subsection 3.7), instead of during the solve phase. This allows accessing the $L$ factors right after they have been computed, with a better locality, and can avoid writing the $L$ factors to disk in an out-of-core context. In this case (forward elimination during factorization), only the backward elimination is performed during the solution phase.

The software is mainly written in Fortran 90 although a C interface is available (see Section 9). Scilab and MATLAB/Octave interfaces are also available in the case of sequential executions. The parallel
version of MUMPS requires MPI [41] for message passing and makes use of the BLAS [18, 19], BLACS, and ScALAPACK [17] libraries. The sequential version only relies on BLAS.

MUMPS exploits both parallelism arising from sparsity in the matrix $A$ and from dense factorization kernels. It distributes the work tasks among the processors, but an identified processor (the host) is required to perform most of the analysis phase, to distribute the incoming matrix to the other processors (slaves) in the case where the matrix is centralized, and to collect the solution if it is not kept distributed.

Several instances of MUMPS can be handled simultaneously. MUMPS allows the host processor to participate to the factorization and solve phases, just like any other processor (see Subsection 3.10).

For both the symmetric and the unsymmetric algorithms used in the code, we have chosen a fully asynchronous approach with dynamic scheduling of the computational tasks. Asynchronous communication is used to enable overlapping between communication and computation. Dynamic scheduling is used to accommodate numerical pivoting in the factorization and to remap work and data to appropriate processors at execution time. In fact, we combine the main features of static and dynamic approaches; we use the estimation obtained during the analysis to map some of the main computational tasks; the other tasks are dynamically scheduled at execution time. The main data structures (the original matrix and the factors) are similarly partially mapped during the analysis phase.

The main features of the MUMPS package include:

- various arithmetics (real or complex, single or double precision)
- input of the matrix in assembled format (distributed or centralized) or elemental format
- sequential or parallel analysis phase
- use of several built-in ordering algorithms, a tight interface to some external ordering packages such as PORD [38], SCOTCH [34] or METIS [29] (strongly recommended), and the possibility for the user to input a given ordering.
- scaling of the original matrix
- out-of-core capability
- detection of null pivots, basic estimate of rank deficiency and computation of a null space basis for symmetric matrices
- computation of a Schur complement matrix
- computation of the determinantal
- computation of selected entries of the inverse of $A$
- exploiting sparsity of the right-hand sides
- forward elimination during factorization
- solution of the transposed system
- error analysis
- iterative refinement

MUMPS is downloaded from the web site almost four times a day on average and has been run on very many machines, compilers and operating systems, although our experience is really only with UNIX-based systems. We have tested it extensively on many parallel computers. Please visit our website for recommendations, from our users, on how to use the solver on Windows platforms.

2 Notes for users of previous versions of MUMPS

The MUMPS 5.0.0 release has several new features and several bug fixes with respect to the previous release (see a list of changes in Subsection 2.1). We strongly advise to use the latest version.

In this section, we also describe backward compatibility issues and what should be done if you are using a version of MUMPS anterior to MUMPS 5.0.0 and if you would like to upgrade your application to use MUMPS 5.0.0.

We discuss binary compatibility in Subsection 2.2. Then we discuss in Subsection 2.3 some minor modifications to control parameters or to interfaces with ordering packages. Such control parameters are normally backward compatible, but it may happen that their range of possible values or their meaning has been slightly modified or extended. Please read this section if you are using an anterior version of MUMPS and want to use MUMPS 5.0.0.
2.1 ChangeLog

Changes from 4.10.0 to 5.0.0
* Userguide revisited
* Compatibility withmetis 5.1.0/parmetis 4.0.3, and with
  scotch/pt-scotch 6.0
* Matlab interface updated (scaling vectors (COLSCA, ROWSCA) and
  A-1 feature ICNTL(30) are now available)
* Improved sequential and parallel performance for computing selected entries of
  A-1 (ICNTL(30))
* Workspace for solve phase, of size B x N per processor (B: block
  size controlled by ICNTL(27)) divided by almost #procs. Default
  value of B increased.
* Parallel symmetric indefinite elemental matrices: improved numerical behaviour
* Performance of solve phase improved
* Finer control of error analysis and iterative refinement (ICNTL(11))
* Memory for analysis phase (mapping) reduced.
* Better support for 64-bit integers (see INSTALL file)
* Improvements and corrections to parallel analysis (ICNTL(28)),
  deterministic graph construction forced with -DDETERMINISTIC_PARALLEL_GRAPH
* Forward elimination (ICNTL(32)) can be done during factorization
* Possibility to use a workspace (WK_USER, LWK_USER) allocated by user
* Very occasional numerical bug in parallel out-of-core case
corrected (thanks to EDF and Samtech for the validation)
* More efficient processing of sparse right-hand-sides (see ICNTL(20))
* Count for entries in factors now include parallel root node
* Amalgamation of the assembly tree revisited
* Scaling arrays (COLSCA, ROWSCA) also returned at C interface level
* OOC_NB_FILE_TYPE is part of the MUMPS structure, for
  a better management of multiple OOC instances
* Warning +2 set only once (could lead to incorrect +4 in
  case of iterative refinement + error analysis)
* Warning +4 has disappeared from documentation (since it
  was never occurring -- JCN never modified on exit)
* Error code -16 now raised for the case N=0 even on distributed
  matrices (thanks to P.Jolivet for noticing this)
* Use BLAS3 routines for efficiency even in case of BLAS2 operations
  (~DMUMPS_USE_BLAS2 allows the use of BLAS2 routines for such
  operations)
* Message "problem with NIV2_FLOPS message" should no more occur
  (there was still an occasional problem in 4.10.0)
* Improved determinant computation (ICNTL(33)) in case of singular
  matrix + scaling (where zero pivots are excluded)
* Trace ’ PANEL: INIT and force STRAT_IO=’ suppressed
* Some OpenMP directives added (multithreaded BLAS still needed)
* Null pivot (ICNTL(24)) and null space detection ICNTL(25)) improved
  for unsymmetric matrices
* Fortran automatic arrays (e.g. in mumps_static_mapping.F) suppressed
  to avoid risks of stack overflows
* Routine names and filenames changed

2.2 Binary compatibility

In general, successive versions of the MUMPS package do not ensure binary compatibility. This means
that you should recompile your code if you use a new version of MUMPS.
2.3 Upgrading between MUMPS 4.10.0 to MUMPS 5.0.0

2.3.1 Interface with the Metis and ParMetis orderings

Since the release of MUMPS 4.10.0, the Metis API has changed. MUMPS 5.0.0 now assumes that Metis ≥ 5.1.0 or ParMetis ≥ 4.0.3 are installed, and that the newer versions of Metis/ParMetis are backward compatible with Metis 5.1.0/ParMetis 4.0.3.

It is however possible to continue using Metis versions ≤ 4.0.3 by forcing the compilation flag -Dmetis4, and to continue using ParMetis versions ≤ 3.2.0 by forcing the compilation flag -Dparmetis3.

Note that Metis 5.0.1/5.0.2/5.0.3 and ParMetis 4.0.1/4.0.2 have never been supported in MUMPS.

2.3.2 Interface with the SCOTCH and PT-SCOTCH orderings

MUMPS 4.10.0 was not compatible with SCOTCH 6.x. MUMPS 5.0.0 is compatible with both SCOTCH 5.1.x and SCOTCH 6.0.x and we recommend using the latest version of SCOTCH.

Since SCOTCH version 6.0.0, the PT-SCOTCH library does not include the SCOTCH library. So during the link phase, the SCOTCH library must be provided to MUMPS. It can be easily done by adding "-lscotch" to the LSCOTCH variable in your Makefile.inc file.

Unfortunately, there is a problem in the SCOTCH 6.0.0 package which is making it unusable with MUMPS. You should update your version of SCOTCH to 6.0.1 or later.

2.3.3 ICNTL(10): iterative refinement

In both MUMPS 4.10.0 and MUMPS 5.0.0, ICNTL(10) indicates the maximum number of iterative refinement steps during the solve phase, with a default value of 0 meaning no iterative refinement.

In MUMPS 4.10.0, if the user sets ICNTL(10) to a negative value, then the value was treated as 0, no iterative refinement. This is not the case with MUMPS 5.0.0, where negative values are interpreted differently (fixed number of iterative refinement steps).

This modification should not affect normal users, since it was not natural to reset ICNTL(10) to a negative value (instead of the default value of 0) in order to forbid iterative refinement in MUMPS 4.10.0.

2.3.4 ICNTL(11): error analysis

Whereas all positive values of ICNTL(11) were producing the same statistics in MUMPS 4.10.0, ICNTL(11)=1, ICNTL(11)=2 and ICNTL(11)> 2 now have a different behaviour in MUMPS 5.0.0, as shown in Table 1.

<table>
<thead>
<tr>
<th>ICNTL(11) value</th>
<th>MUMPS 4.10.0 meaning</th>
<th>MUMPS 5.0.0 meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0</td>
<td>No error analysis</td>
<td>No error analysis</td>
</tr>
<tr>
<td>0</td>
<td>No error analysis (default)</td>
<td>No error analysis (default)</td>
</tr>
<tr>
<td>1</td>
<td>Full statistics</td>
<td>Full statistics</td>
</tr>
<tr>
<td>2</td>
<td>Full statistics</td>
<td>Full statistics</td>
</tr>
<tr>
<td>&gt; 2</td>
<td>Full statistics</td>
<td>Main statistics (recommended)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Defaults to 0, no error analysis</td>
</tr>
</tbody>
</table>

Table 1: Backward compatibility issues between MUMPS 4.10.0 and MUMPS 5.0.0 for ICNTL(11). Full statistics include condition numbers estimates and forward error estimate, which are very expensive to compute.

The main reason for this change is that, because backward error analysis already provides a good indication of the quality of the computed solution, most users might not want to compute forward error analysis and condition numbers estimates in all cases.

1See http://gforge.inria.fr/projects/scotch/
2.3.5 ICNTL(20): sparse right-hand sides

The range of values for ICNTL(20) has been extended to better control an internal feature that exploits sparsity of the right-hand sides during the solution phase. This extension should be transparent in practice, since the authorized values for ICNTL(20) were 0 (dense right-hand side expected) and 1 (sparse right-hand sides expected) in MUMPS 4.10.0, which will be correctly interpreted in MUMPS 5.0.0.

One minor difference is in the interpretation of ICNTL(20)=2 or 3 in MUMPS 4.10.0. Whereas both values (2 and 3) are out-of-range values in MUMPS 4.10.0 and treated as 0 (dense right-hand side expected), they now also mean in MUMPS 5.0.0 that the right-hand sides should be provided in sparse form.

Another difference is in the treatment of duplicate entries in the sparse right-hand sides. In MUMPS 4.10.0 the last entry is used whereas in MUMPS 5.0.0 duplicate entries are summed.

We refer the reader to the description of ICNTL(20) for a precise description of sparse right-hand sides and an explanation of the differences between values 1, 2, and 3.

2.3.6 License

The license for public versions of MUMPS is CeCILL-C. See also Section 12.

3 Main functionalities of MUMPS 5.0.0

We describe here the main functionalities of the MUMPS solver. These functionalities are controlled by the components of the arrays mumps_par%ICNTL and mumps_par%CNTL. The user should refer to Section 5 and Section 6 for a complete description of the parameters that must be set or that are referred to in this section. The variables mentioned in this section are components of a structure mumps_par of type MUMPS_STRUCT (see Section 4). For the sake of clarity and when no confusion is possible, we refer to them only by their component name. For example, we use ICNTL to refer to mumps_par%ICNTL.

3.1 Input matrix format

MUMPS provides several possibilities to input the matrix. The selection is controlled by the parameters ICNTL(5) and ICNTL(18).

The input matrix can be supplied as assembled in coordinate format either on a single processor or distributed over the processors. Otherwise, it can be supplied in elemental format, but in this case it can be input only centrally on the host.

For full details on how these formats are handled by MUMPS, see Subsection 5.2.2.1 and Subsection 5.2.2.2, respectively for the assembled centralized and assembled distributed formats, and see Subsection 5.2.2.3 for the elemental format.

By default, the input matrix is assumed to be provided in assembled format and centralised on the host processor.

3.2 Preprocessing

During the analysis phase, it is possible to preprocess the matrix to make easier/cheaper the numerical factorization. The package offers a range of symmetric orderings to preserve sparsity, but also other preprocessing facilities: permuting to zero-free diagonal and prescaling. When all preprocessing options are activated, the preprocessed matrix $A_{pre}$ that will be effectively factored is:

$$A_{pre} = P D_r A Q_c D_c P^T,$$

where $P$ is a permutation matrix applied symmetrically, $Q_c$ is a (column) permutation and $D_r$ and $D_c$ are diagonal matrices for (respectively row and column) scaling. Note that when the matrix is symmetric, preprocessing is designed to preserve symmetry.

Preprocessing highly influences the performance (memory and time) of the factorization and solution steps. The default values correspond to an automatic setting performed by the package which depends on the ordering packages installed, the type of the matrix (symmetric or unsymmetric), the size of the matrix.
and the number of processors available. We thus strongly recommend the user to install all ordering packages to offer maximum choice to the automatic decision process.

- **Symmetric permutation:** $P$
  The symmetric permutation can be computed either sequentially, or in parallel. This option is controlled by \texttt{ICNTL(28)}. The sequential computation is controlled by \texttt{ICNTL(7)} whereas the parallel computation is controlled by \texttt{ICNTL(29)}.

  - In the case where the symmetric permutation is computed sequentially, an important range of ordering options is offered including the approximate minimum degree ordering (AMD, \cite{4}), an approximate minimum degree ordering with automatic quasi-dense row detection (QAMD, \cite{2}), an approximate minimum fill-in ordering (AMF), an ordering where bottom-up strategies are used to build separators by Jürgen Schulze from University of Paderborn (PORD, \cite{38}), the SCOTCH package \cite{34} from the University of Bordeaux 1, and the METIS package from Univ. of Minnesota \cite{29}. A user-supplied permutation can also be provided and the pivot order must be set by the user on the host in the array \texttt{PERM} (see Subsection 5.4.2).

  - When the symmetric permutation is computed in parallel, possible orderings are PT-SCOTCH and ParMetis if they have been installed by the user.

- **Permutations to a zero-free diagonal:** $Q_c$
  Controlled by \texttt{ICNTL(6)}, this permutation is recommended for very unsymmetric matrices to reduce fill-in and arithmetic cost, see \cite{20, 21}. For symmetric matrices this permutation can also be used to constrain the symmetric permutation $P$ (see \texttt{ICNTL(12)}). Furthermore, when numerical values are provided on entry to the analysis phase, \texttt{ICNTL(6)} may also build scaling vectors during the analysis, that will be either used or discarded depending on the scaling option \texttt{ICNTL(8)} (see next paragraph).

- **Row and column scalings:** $D_r$ and $D_c$
  Controlled by \texttt{ICNTL(8)}, this preprocessing improves the numerical accuracy and makes all estimations performed during analysis more reliable. A range of classical scalings are provided and can be automatically performed within the package either during the analysis phase or at the beginning of the factorization phase.

  Furthermore, preprocessing strategies for symmetric indefinite matrices, as described in \cite{22}, can be applied and also lead to scaling arrays; they are controlled by \texttt{ICNTL(12)}.
3.3 Post-processing facilities

3.3.1 Iterative refinement

A well known and simple technique to improve the accuracy of the solution of linear systems is the use of iterative refinement. It consists in refining an initial solution obtained after solution phase as described in Algorithm 1.

Let $x$ be the initial solution of $Ax = b$
Compute residual $r = b - Ax$

repeat
  Solve $A\Delta x = r$ using the computed factorization
  $x \leftarrow x + \Delta x$
  $r = b - Ax$
  Compute backward errors $\omega_1$ and $\omega_2$ (see Subsection 3.3.2)
until $\omega_1 + \omega_2 < \alpha$ or convergence is too slow

Algorithm 1: Iterative refinement. At each step, backward errors are computed and compared to $\alpha$, the stopping criterion (see CNTL(2)).

It has been shown [16] that with only two to three steps of iterative refinement the solution can often be significantly improved. For this reason, alternatively to Algorithm 1, a simple variant (see Algorithm 2) can be used with a fixed number of steps of iterative refinement and thus without convergence test.

Let $x$ be the initial solution of $Ax = b$
Compute residual $r = b - Ax$

for $i = 1$ to $t$
  Solve $A\Delta x = r$ using the computed factorization
  $x \leftarrow x + \Delta x$
  $r = b - Ax$
end for

Algorithm 2: Iterative refinement with a fixed number of steps.

The use of iterative refinement can be particularly useful if static pivoting has been used during factorization (see Subsection 3.9).

In MUMPS, iterative refinement can be optionally performed after the solution step using the parameter ICNTL(10).

3.3.2 Error analysis and statistics

MUMPS enables the user to perform classical error analysis based on the residuals. This option is controlled by ICNTL(11). We calculate an estimate of the sparse backward error using the theory and metrics developed in [16]. We use the notation $\bar{x}$ for the computed solution and a modulus sign on a vector or a matrix to indicate the vector or matrix obtained by replacing all entries by their moduli. The scaled residual

$$\frac{|b - A\bar{x}|_i}{(|b| + |A||\bar{x}|)_i}$$

is computed for all equations except those for which the numerator is nonzero and the denominator is small. For all these exceptional equations,

$$\frac{|b - A\bar{x}|_i}{(|A||\bar{x}|_i + \|A\|_\infty\|\bar{x}\|_\infty)}$$

(7)
is computed instead, where $A_i$ is row $i$ of $A$. The largest scaled residual (Equation (6)) is returned in $\text{RINFOG}(7)$ and the largest scaled residual (Equation (7)) is returned in $\text{RINFOG}(8)$. If all equations are in category (1), $\text{RINFOG}(8)$ is zero. Those two quantities respectively correspond to the two backward errors $\omega_1 = RINFOG(7)$ and $\omega_2 = RINFOG(8)$, as defined in [16]. Then, the computed solution $\bar{x}$ is the exact solution of the equation

$$(A + \delta A)x = (b + \delta b),$$

where

$$|\delta A_{ij}| \leq \max(\omega_1, \omega_2)|A|_{ij},$$

and $|\delta b_i| \leq \max(\omega_1|b|_i, \omega_2\|A\|_\infty\|\bar{x}\|_\infty)$. Note that $\delta A$ respects the sparsity of $A$ in the sense that $\delta A_{ij}$ is zero for structural zeros in $A$, i.e., when $A_{ij}=0$. Finally, if the user can afford a significantly more costly error analysis, condition numbers $\text{cond}_1$ and $\text{cond}_2$ for the linear system (not just the matrix) can also be returned in $\text{RINFOG}(10)$ and $\text{RINFOG}(11)$, respectively, together with an upper bound of the forward error of the computed solution in $\text{RINFOG}(9)$:

$$\|\delta x\|_\infty \leq \omega_1 \text{cond}_1 + \omega_2 \text{cond}_2 = RINFOG(7) \times RINFOG(10) + RINFOG(8) \times RINFOG(11) = RINFOG(9).$$

### 3.4 Null pivot detection

MUMPS gives the possibility to detect null pivots of a matrix during factorization. This option is controlled by ICNTL(24). The number of null pivots provides an estimate of the rank deficiency.

At the solution phase, one of the possible solution of the deficient system $AX = B$ can be computed using the control parameter ICNTL(25) (Subsection 3.5).

It is also possible to compute all or a part of the null vectors (that is the vectors solving $AX = 0$) associated to these null pivots using the same control parameter ICNTL(25).

### 3.5 Computation of a solution of a deficient matrix and of a null space basis

Using the ICNTL(25) parameter, MUMPS gives the possibility to compute one of the possible solutions of $AX = B$ of a symmetric matrix that has been found deficient during factorization if a zero-pivot detection option was requested (Subsection 3.4).

The same control parameter (ICNTL(25)) can be used to compute a part or the complete null space basis (that is $AX = 0$) of the matrix that has been found deficient during factorization.

### 3.6 Solving the transposed system

Given a sparse matrix $A$, the system $AX = B$ or $A^TX = B$ can be solved during the solve phase, where $A$ is a square matrix of order $n$ and $X$ and $B$ are matrices of order $n$ by $nrhs$. This is controlled by ICNTL(9). Note that in the case where the forward elimination (see Subsection 3.7) is performed during the factorization, solving the transposed system is not allowed.

### 3.7 Forward elimination during factorization

It is possible to perform the forward elimination (Subsection 5.10) of the right-hand sides (Equation (3)) during the factorization.

If the forward elimination is performed during the factorization, some factors may be discarded (Subsection 5.8) because in this case only the backward substitution (Equation (4)) needs to be performed during the solution phase. This option makes much sense in an out-of-core context (Subsection 3.13), where the solution phase involves loading factors from disk during both the forward (Equation (3)) and backward (Equation (4)) substitutions and can be particularly costly, or when the factors have to be used only once. Note that in the case where the forward elimination is performed during the factorization, solving the transposed system is not allowed.
3.8 Arithmetic versions

Several versions of the package MUMPS are available: REAL, DOUBLE PRECISION, COMPLEX, and DOUBLE COMPLEX.

To compile all or any particular version, please refer to the file named “INSTALL” at the root of the MUMPS distribution.

This document applies to all four arithmetics. In the following we use the conventions below:

1. the term real is used for REAL or DOUBLE PRECISION,
2. the term complex is used for COMPLEX or DOUBLE COMPLEX.

3.9 Numerical pivoting

The goal of pivoting is to ensure a good numerical accuracy during Gaussian elimination. A widely used technique is known as partial pivoting. Considering an unsymmetric matrix, at step \( i \) of the factorization we first determine \( k \) such that \( |a_{k,i}| = \max_{l=1:n} |a_{l,i}| \). Rows \( i \) and \( k \) are swapped in \( A \) (and the permutation information is stored in order to apply it to the right-hand side \( b \)) before dividing the column by the pivot and performing the rank-one update. The advantage of this approach is that it bounds the growth factor and improves the numerical stability.

Unfortunately, in the case of sparse matrices, numerical pivoting prevents a full static prediction of the structure of the factors: it dynamically modifies the structure of the factors, thus forcing the use of dynamic data structures. Numerical pivoting can thus have a significant impact on the fill-in and on the amount of floating-point operations. To limit the amount of numerical pivoting, and stick better to the sparsity predictions done during the symbolic factorization, partial pivoting can be relaxed, leading to the partial threshold pivoting strategy:

In the partial threshold pivoting strategy, a pivot \( a_{i,i} \) is accepted if it satisfies:

\[
|a_{i,i}| \geq u \times \max_{k=1:n} |a_{k,i}|
\]  

for a given value of \( u \), \( 0 \leq u \leq 1 \). This ensures a growth factor limited to \( 1 + 1/u \) for the corresponding step of Gaussian elimination. In practice, one often chooses \( u = 0.1 \) or \( u = 0.01 \) as a default threshold and this generally leads to a stable factorization. The threshold \( u \) can be set using CNTL(1).

It is possible to perform the pivot search on the row rather than on the column with similar stability.

In the multifrontal method, once a frontal matrix is formed, we cannot choose a pivot outside the fully-summed block, because the corresponding rows are not fully-summed. Once all possible pivots in the block of candidate pivots have been eliminated, if no other pivot satisfies the partial pivoting threshold, some rows and columns remain unfactored in the front. Those are then delayed to the frontal matrix of the parent, as part of the contribution block (delayed pivots). Note that because of the delayed pivots fill-in the parent node will occur.

The same type of approach is applied to the symmetric case, but with the constrain that we want to maintain the symmetry of the frontal matrices.

In order to avoid the complications due to numerical pivoting, perturbation techniques can be applied (static pivoting): a pivot smaller than a threshold in absolute value is replaced by this threshold. In this case it is recommended do use iterative refinement (see Subsection 3.3.1) to improve the approximate solution.

In MUMPS, static pivoting (CNTL(4)) and numerical pivoting (CNTL(1)) are combined at runtime. A comparison of approaches based on static pivoting with approaches based on numerical pivoting in the context of high-performance distributed solvers can be found in [10].

3.10 The working host processor

The host processor is the one with rank 0 in the communicator provided to MUMPS. By setting the variable PAR to 1 (see Subsection 5.1.3), MUMPS allows the host to participate in computations during the factorization and solve phases, just like any other processor. This allows MUMPS to run on a single processor and prevents the host processor being idle during the factorization and solve phases (as would be the case for PAR=0). We thus generally recommend using a working host processor (PAR=1).
The only case where it may be worth using $\text{PAR}=0$ is with a large centralized matrix on a purely distributed architecture with relatively small local memory: $\text{PAR}=1$ will lead to a memory imbalance because of the storage related to the initial matrix on the host.

### 3.11 MPI-free version

It is possible to use MUMPS with a single MPI process by limiting the number of processors to one, or by passing to the solver a communicator consisting of a single MPI process. However, the link phase still requires the MPI, BLACS, and ScalAPACK libraries in this case.

An MPI-free version of MUMPS is also available. For this, a special library is distributed that provides all external references needed by MUMPS for a sequential environment. MUMPS can thus be used in a simple sequential program, ignoring everything related to MPI. Details on how to build a purely sequential version of MUMPS are available in the INSTALL file available in the MUMPS distribution.

Remark that for the sequential version, the component $\text{PAR}$ must be set to 1 (see Subsection 5.1.3). Furthermore, the calling program should not make use of MPI: if the calling program is a parallel MPI code which requires sequential MUMPS, a parallel version of MUMPS must then be installed, to which a communicator consisting of a single process should be provided. Finally, the MPI-free version can make use of several cores by relying on multithreading (see Section 3.12).

### 3.12 Combining MPI and multithreaded parallelism

On SMP nodes or clusters of SMP nodes (multiprocessor nodes with a shared memory) or on multicore-based machines, a parallel shared memory BLAS library (also called multithreaded BLAS) is often available. Using multithreaded BLAS (between 2 and 8 threads per MPI process) can be significantly more efficient than running with MPI processes only. For example on a computer with 2 SMP nodes and 32 cores per node, we advise to run using 16 MPI processes with 4 threads per MPI process. The number of threads per MPI process in the BLAS can be defined by setting environment variables. Setting $\text{OMP_NUM_THREADS}$ is sometimes enough (e.g., with MKL BLAS). Please check since it depends on the parallel BLAS library used.

In order to get additional gains from MPI and multithreading, the code also includes preliminary experimental OpenMP directives, which can be activated with an OpenMP compiler. In that case, the number of threads is always controlled by the environment variable $\text{OMP_NUM_THREADS}$ and the multithreaded BLAS library should be compatible with OpenMP.

### 3.13 Out-of-core facility

An out-of-core (disk is used as an extension to main memory) facility is available in both sequential and parallel environments. This option is controlled by $\text{ICNTL(22)}$.

In this version only the factors are written to disk during the factorization phase and will be read each time a solution phase is requested. Our experience is that on a reasonably small number of processors this can significantly reduce the memory requirement while not increasing much the factorization time. The extra cost of the out-of-core feature is thus mainly during the solve phase, where factors have to be read from disk for both the forward elimination and the backward substitution. To significantly reduce the cost of the solve phase in an out-of-core context, we advise performing the forward elimination (see Equation (3)) during the factorization, if this is compatible with your usage of MUMPS (limited amount of dense right-hand sides, no iterative refinement or error analysis (see Subsection 3.7)).

### 3.14 Determinant

MUMPS has an option to compute the determinant of the input matrix. It is available for symmetric and unsymmetric matrices for all arithmetics (single, double, real, complex), and for all matrix input formats. This option is controlled by $\text{ICNTL(33)}$.

Let $n$ be the order of the matrix $A$, if $A = LU$ (unsymmetric matrices), then

$$
\text{det}(A) = \text{det}(L) \times \text{det}(U) = \prod_{i=1}^{n} U_{ii}
$$
If $A = LDL^t$ (symmetric matrices), then

$$\det(A) = \prod_{i=1}^{n} D_{ii}$$

The sign of the determinant is maintained by keeping track of all internal permutations. Scaling arrays are taken into account too, in case the matrix is scaled. To avoid overflows and guarantee an accurate computation, the mantissa and exponent are computed separately and renormalized when needed.

The determinant is computed when requested by the user. If the user is only interested in the determinant, he/she may tell MUMPS that the factor matrices can be discarded (see Subsection 5.8), significantly reducing the storage requirements.

### 3.15 Computing selected entries of $A^{-1}$

Several applications require the explicit computation of selected entries of the inverse of large sparse matrices. In most cases, many entries are requested, for example all diagonal entries. To compute column $j$ of the inverse, the equation $Ax = e_j$ can be used, where $e_j$ is the $j$th column of the identity matrix. One can obtain major savings if the structural zeros of $e_j$ are exploited or if only few entries of the $j$th column of the inverse are requested [40, 36, 11]. If an $LU$ factorization of $A$ had been computed, $a_{ij}^{-1}$, the $(i, j)$ entry of $A^{-1}$, is obtained by solving successively the two triangular systems:

$$y = L^{-1} e_j$$

$$a_{ij}^{-1} = (U^{-1} y)_i$$

MUMPS provides a functionality, controlled by ICNTL(30), to compute a set of entries of $A^{-1}$, while avoiding most of the computations on explicit zeros in Equations (9) and (10). The list of entries of $A^{-1}$ to be computed and the memory for those entries should be provided as a sparse right-hand side (see Subsection 5.11.2). In a parallel environment it is not so natural to combine parallelism and exploiting sparsity. Recent work based on [36, 12] to exploit parallelism is provided in this release.

### 3.16 Reduce/condense a problem on an interface (Schur complement and reduced/condensed right-hand side)

MUMPS provides the possibility to perform a partial factorization of the complete input matrix and to return the corresponding Schur matrix, that is the part of the matrix that has been updated but that is still to be factorized. This option is controlled by ICNTL(19).

Let us consider a partitioned matrix (here with an unsymmetric matrix) where the variables of $A_{2,2}$ correspond to the Schur variables and on which a partial factorization has been performed. In the following, and only for the sake of clearness, we have ordered all the variables belonging to the Schur last.

$$A = \begin{pmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{pmatrix} = \begin{pmatrix} L_{1,1} & 0 \\ L_{2,1} & I \end{pmatrix} \begin{pmatrix} U_{1,1} & U_{1,2} \\ 0 & S \end{pmatrix}$$

Thus the Schur complement, as returned by MUMPS, is such that $S = A_{2,2} - A_{2,1}A_{1,1}^{-1}A_{1,2}$.

The user must specify on entry to the analysis phase the list of indices of the Schur matrix, corresponding to the variables of $A_{2,2}$. MUMPS returns to the user, on exit of the factorization phase, the Schur complement matrix $S$, as a full matrix but with different type of distribution (see Subsection 5.12 for more details.)

This partial factorization can be used to solve $Ax = b$ in different ways using the ICNTL(26) parameter. It can be used to solve the linear system associated with the “interior” variables or to handle a reduced/condensed right-hand-side as described in the following discussion.
• **Compute a partial solution** \((\text{ICNTL}(26) = 0)\):

The solve is performed on the internal problem:

\[
A_{1,1}x_1 = b_1.
\]

Entries in the right-hand side corresponding to indices from the Schur matrix need not be set on entry and they are explicitly set to zero on output.

• **Solve the complete system in three steps**:

\[
\begin{pmatrix}
L_{1,1} & 0 \\
L_{2,1} & I
\end{pmatrix}
\begin{pmatrix}
U_{1,1} & U_{1,2} \\
0 & S
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix}
= 
\begin{pmatrix}
b_1 \\
b_2
\end{pmatrix}
\tag{12}
\]

First solving:

\[
\begin{pmatrix}
L_{1,1} & 0 \\
L_{2,1} & I
\end{pmatrix}
\begin{pmatrix}
y_1 \\
y_2
\end{pmatrix}
= 
\begin{pmatrix}
b_1 \\
b_2
\end{pmatrix}
\tag{13}
\]

And thereafter:

\[
\begin{pmatrix}
U_{1,1} & U_{1,2} \\
0 & S
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix}
= 
\begin{pmatrix}
y_1 \\
y_2
\end{pmatrix}
\tag{14}
\]

1. **Reduction/condensation phase** \((\text{ICNTL}(26) = 1)\):

The Equation (13) can be solved setting \(\text{ICNTL}(26) = 1\), and the intermediate \(y\) vector will be computed, but only the \(y_2\) vector is returned to the user. Note that \(y_2\) is often referred to as the reduced/condensed right-hand-side.

2. **Using the Schur matrix**:

Then after the solution \(Sx_2 = y_2\) has to be computed. It is the responsibility of the user to compute \(x_2\) using the Schur matrix \(S\) given on output of the factorization phase.

3. **Expansion phase** \((\text{ICNTL}(26) = 2)\):

Given \(x_2\) and \(y_1\), it is possible to compute \(x_1\), such that \(U_{1,1}x_1 = y_1 - U_{1,2}x_2\), using the option \(\text{ICNTL}(26) = 2\). Note that the package uses \(y_1\) computed (and stored in the main MUMPS structure) during the first step \((\text{ICNTL}(26) = 1)\) and provides the complete solution \(x\) on output.

Note that the Schur complement could be considered as an element contribution to the interface block in a domain decomposition approach. MUMPS could then be used to solve this interface problem using the element entry functionality.

## 4 User interface and available routines

In the Fortran 90 interface (see Section 9 for the C interface), there is a single user callable subroutine per arithmetic, called \([\text{SDCZ}]\text{MUMPS}\), that has a single parameter \text{mumps\_par} of Fortran 90 derived datatype \([\text{SDCZ}]\text{MUMPS\_STRUC}\) defined in \([\text{sdcz}]\text{mumps\_struc.h}\).

The interface is the same for the MPI-free version (see Subsection 3.11), only the compilation process and libraries need be changed. In the case of the parallel version, MPI must be initialized by the user before the first call to \([\text{SDCZ}]\text{MUMPS}\) is made.

The calling sequence for the DOUBLE PRECISION version may look as follows:

\(^{2}\text{We use the notation }[\text{SDCZ}]\text{MUMPS} \text{ to refer to } \text{SMUMPS, ZMUMPS or CMUMPS, corresponding to the REAL, DOUBLE PRECISION, COMPLEX and DOUBLE COMPLEX versions, respectively. Similarly }[\text{SDCZ}]\text{MUMPS\_STRUC} \text{ refers to either } \text{SMUMPS\_STRUC, DMUMPS\_STRUC, CMUMPS\_STRUC, or ZMUMPS\_STRUC, and }[\text{sdcz}]\text{mumps\_struc.h} \text{ to } \text{smumps\_struc.h, dmumps\_struc.h, cmumps\_struc.h or zmumps\_struc.h}.\)
INCLUDE 'mpif.h'
INCLUDE 'dmumps_struc.h'

INTEGER :: IERR
TYPE (DMUMPS_STRUCT) :: mumps_par
...
CALL MPI_INIT(IERR)
...
mumps_par%JOB = ... ! Set some arguments to the package: those
mumps_par%ICNTL(3)=6 ! are components of the mumps_par structure
...
CALL DMUMPS( mumps_par )
...
CALL MPI_FINALIZE(IERR)

For other arithmetics, dmumps_struc.h should be replaced by smumps_struc.h,
cmumps_struc.h, or zmumps_struc.h, and the 'D' in DMUMPS and DMUMPS_STRUCT by
'S','C' or 'Z'.

The variable mumps_par of datatype [SDCZ]MUMPS_STRUCT holds all the data for the problem. It
has many components, only some of which are of interest to the user. The other components are internal
to the package. Some of the components must only be defined on the host. Others must be defined
on all processors. The file [sdcz]mumps_struc.h defines the derived datatype and must always be
included in the program that calls MUMPS.

The interface to MUMPS consists in calling the subroutine [SDCZ]MUMPS with the appropriate
parameters set in mumps_par.

Components of the structure [SDCZ]MUMPS_STRUCT that are of interest to the user are shown in
Figure 1.

In the following, real/complex qualifies parameters that are real in the real version and complex in the
complex version, whereas real is used for parameters that are always real, even in the complex version of
MUMPS.
Figure 1: Main components of the structure [SDCZ]MUMPS_STRUC defined in [sdcz]mumps_struc.h.
5 Application Program Interface

In this section, we describe the main components of the variable mumps_par of datatype [SDC2]MUMPS_STRUCT (see Section 4), that must be set by the user, or that are returned to the user. The parameters controlling the activation of the main functionalities of the package are provided on input in the arrays ICNTL and CNTL. In each section, we describe in detail the entry of the ICNTL and CNTL related to the section. The entire list is given in Section 6. Statistics and various information parameters on output to the solver are then described in Section 7. Information parameters returned by the package might correspond to values local to each processor (mumps_par%INFO and mumps_par%INFOG) or might be global information and available on all processors (mumps_par%INFOG and mumps_par%INFO).

For the sake of clarity (and when no confusion is possible), we refer to components of the structure only by their component name; for example, we use ICNTL to refer to mumps_par%ICNTL.

5.1 General

5.1.1 Initialization, Analysis, Factorization, Solve, Termination (JOB)

JOB (integer) must be initialized by the user on all processors before a call to MUMPS. It controls the main actions taken by MUMPS. It is not altered by MUMPS. Possible values of JOB are:

–1 initializes an instance of the package. A call with JOB = –1 must be performed before any other call to the package on the same instance. It sets default values for other components of [SDC2]MUMPS_STRUCT (such as ICNTL), which may then be altered before subsequent calls to MUMPS. Note that three components of the structure must always be set by the user (on all processors) before a call with JOB = –1. These are

• COMM,
• SYM, and
• PAR.

Note that if the user wants to modify one of those three components then he/she must terminate the instance (call with JOB = –2) then reinitialize the instance (call with JOB = –1).

Furthermore, after a call with JOB = –1, the internal component MYID contains the rank of the calling processor in the communicator provided to MUMPS. Thus, the test “(MYID == 0)” may be used to identify the host processor (see Subsection 3.10).

Finally, the version number is returned in VERSION_NUMBER (see Subsection 5.1.2).

–2 terminates an instance of the package. All data structures associated in mumps_par with the instance, except those provided by the user, are deallocated. It should be called by the user only when no further calls to MUMPS with this instance are required. In order to avoid memory leaks, it must also be called before a further JOB = –1 call with the same argument mumps_par.

1 performs the analysis. In this phase, MUMPS chooses pivots from the diagonal using a selection criterion to preserve sparsity, using the pattern of the matrix A input by the user. Several formats and distributions onto the processors are available to input matrix (see Subsection 5.2.2). It subsequently constructs subsidiary information for the numerical factorization (a JOB=2 call).

An option exists for the user to input the pivotal sequence (ICNTL(7)=1, see Subsection 5.4) in which case only the necessary information for a JOB=2 call will be generated.

If a preprocessing based on the numerical values is requested (see Subsection 5.3 and ICNTL(6)), then the numerical values of the original matrix A must also be provided by the user during the analysis phase, and scaling vectors are optionally computed.

Note that a call to MUMPS with JOB=1 must be preceded by a call with JOB = –1 on the same instance.

2 performs the factorization. It uses the numerical values of the matrix A provided by the user (see Subsection 5.2.2) and the information from the analysis phase (JOB=1) to factorize the matrix A. The actual pivot sequence used during the factorization may slightly differ from the sequence returned by the analysis (see Subsection 5.4.1) if the matrix A is not diagonally dominant.
An option exists for the user to input scaling vectors or let MUMPS compute automatically such vectors (see Subsection 5.3.2 and ICNTL(8)) just before the numerical factorization.

A call to MUMPS with \( \text{JOB}=2 \) must be preceded by a call with \( \text{JOB}=1 \) on the same instance.

3 computes the solution. It uses the right-hand side(s) \( B \) provided by the user and the factors generated by the factorization (\( \text{JOB}=2 \)) to solve a system of equations \( AX = B \) or \( A^T X = B \). The pattern and values of the matrix should be passed unchanged since the last call to the factorization phase (see \( \text{JOB}=2 \)). Several possibilities are given to input the right-hand side matrix \( B \) and to output the solution matrix \( X \). The structure component mumps\_par\%RHS must be set by the user (on the host only) before a call with \( \text{JOB}=3 \) (see Subsection 5.11). This solution phase can also be used to compute the null space basis of singular matrices (see ICNTL(25)), provided that “null pivot” detection (ICNTL(24)) was on and that the deficiency obtained INFOG(28) was different from 0.

A call to MUMPS with \( \text{JOB}=3 \) must be preceded by a call with \( \text{JOB}=2 \) (or \( \text{JOB}=4 \)) on the same instance.

4 combines the actions of \( \text{JOB}=1 \) with those of \( \text{JOB}=2 \). It must be preceded by a call to MUMPS with \( \text{JOB} = -1 \) on the same instance.

5 combines the actions of \( \text{JOB}=2 \) and \( \text{JOB}=3 \). It must be preceded by a call to MUMPS with \( \text{JOB}=1 \) on the same instance.

6 combines the actions of calls with \( \text{JOB}=1, 2, \) and \( 3 \). It must be preceded by a call to MUMPS with \( \text{JOB} = -1 \) on the same instance.

Consecutive calls with \( \text{JOB}=2,3,5 \) on the same instance are possible.

### 5.1.2 Version number

\textbf{VERSION\_NUMBER (string)} is set by MUMPS to the version number of MUMPS after a call to the initialization phase (\( \text{JOB}=-1 \)).

For C users (see Section 9 for more general information), a macro MUMPS\_VERSION is also defined in the include files [sdcz]mumps\_c.h; it contains a string defining the version number. Typically, it is defined by: \#define MUMPS\_VERSION "5.0.0". This may be useful for users who wish to get the version number associated to the header file they include in their application (the component VERSION\_NUMBER of the structure may be badly initialized in case of incompatible alignment options or incorrect version of the header file).

### 5.1.3 Control of parallelism (\textbf{COMM}, \textbf{PAR})

\textbf{COMM (integer)} must be set by the user on all processors before the initialization phase (\( \text{JOB} = -1 \)) and must not be changed in further calls. It must be set to a valid MPI communicator that will be used for message passing inside MUMPS. It is not altered by MUMPS and a copy of the communicator is kept internally by the package until a call to the termination phase (\( \text{JOB} = -2 \)). The processor with rank 0 in this communicator is used by MUMPS as the \textbf{host} processor. Note that only the processors belonging to the communicator should call MUMPS.

\textbf{PAR (integer)} must be initialized by the user on all processors before the initialization phase (\( \text{JOB} = -1 \)) and is accessed by MUMPS only during this phase. It is not altered by MUMPS and its value is communicated internally to the other phases as required. Possible values for \( \text{PAR} \) are:

- \( 0 \) : The host is not involved in the parallel steps of the factorization and solve phases. The host will only hold the initial problem, perform symbolic computations during the analysis phase, distribute data, and collect results from other processors.
- \( 1 \) : The host is also involved in the parallel steps of the factorization and solve phases.

Other values are treated as 1.

Note that the value of \( \text{PAR} \) should be identical on all processors; if this is not the case, the value on processor 0 (the host) is used by the package.
If the initial problem is large and memory is an issue, PAR=1 is not recommended if the matrix is centralized on processor 0 because this can lead to memory imbalance, with processor 0 having a larger memory load than the other processors.

5.2 Input Matrix

5.2.1 Matrix type (SYM)

The user must set the variable SYM to indicate which kind of matrix has to be factorize and consequently, which factorization has to be performed.

SYM (integer) must be initialized by the user on all processors before the initialization phase (JOB = –1) and is accessed by MUMPS only during this phase. It is not altered by MUMPS. Its value is communicated internally to the other phases as required. Possible values for SYM are:

0: A is unsymmetric.
1: A is assumed to be symmetric positive definite so that pivots are taken from the diagonal without numerical pivoting during the factorization. With this option, non-positive definite matrices that do not require pivoting can also be treated in certain cases (see remark below).
2: A is general symmetric

Other values are treated as 0.

Note that the value of SYM should be identical on all processors; if this is not the case, the value on processor 0 is used by the package. For the complex version, the value SYM=1 is currently treated as SYM=2. We do not have a version for Hermitian matrices in this release of MUMPS.

Remark for symmetric matrices (SYM=1). When SYM=1 is indicated by the user, an LDL^T factorization (in opposition to Cholesky factorization which requires positive diagonal pivots) of matrix A is performed internally by the package, and numerical pivoting is switched off. Therefore, this setting works for classes of matrices more general than positive definite matrices, including matrices with negative pivots. However, this feature depends on the use of the ScaLAPACK library (see ICNTL(13)) to factorize the last dense block in the factorization of A. More precisely,

- if ScaLAPACK is allowed for the last dense block (default in parallel, ICNTL(13) =0), then the presence of negative pivots in the part of the factorization processed with ScaLAPACK (subroutine P_POTRF) will raise an error and the code -40 is then returned in INFOG(1);
- if ScaLAPACK is not used (ICNTL(13) >0, or sequential execution, or last dense block detected to be too small), then negative pivots are allowed and the factorization will work for some classes of non-positive definite matrices where numerical pivoting is not necessary, e.g., symmetric negative matrices.

The successful factorization of a symmetric matrix with SYM=1 is thus not an indication that the matrix provided was symmetric positive definite. In order to verify that a matrix is positive definite, the user can check that the number of negative pivots or inertia (INFOG(12)) is 0 on exit from the factorization phase. Another approach to suppress numerical pivoting on symmetric matrices which is compatible with the use of ScaLAPACK (see ICNTL(13)) consists in setting SYM=2 (general symmetric matrices) with the relative threshold for pivoting CNTL(1) set to 0 (recommended strategy).

5.2.2 Matrix format

The formats of the input matrix and its distribution onto the processors are controlled by ICNTL(5) and ICNTL(18), respectively.

ICNTL(5) controls the matrix input format

- **Phase**: accessed by the host and only during the analysis phase
- **Possible variables/arrays involved**: N, NZ, IRN, JCN, NZloc, IRNloc, JCNloc, A_loc, NELT, ELTPTR, ELTVAR, and A_ELTT
- **Possible values**:

Note that the value of SYM should be identical on all processors; if this is not the case, the value on processor 0 is used by the package. For the complex version, the value SYM=1 is currently treated as SYM=2. We do not have a version for Hermitian matrices in this release of MUMPS.
0: assembled format. The matrix must be input in the structure components \( N, \) \( NZ, \) \( IRN, \) \( JCN, \) and \( A \) if the matrix is centralized on the host (see Subsection 5.2.2.1) or in the structure components \( N, \) \( NZ, \) \( IRN_{\text{loc}}, \) \( JCN_{\text{loc}}, \) \( A_{\text{loc}} \) if the matrix is distributed (see Subsection 5.2.2.2).

1: elemental format. The matrix must be input in the structure components \( N, \) \( NELT, \) \( ELTPTR, \) \( ELTVAR, \) and \( A_{\text{ELT}} \) (see Subsection 5.2.2.3).

Default value: 0 (assembled format)

Related parameters: \( \text{ICNTL}(18) \)

Remarks: Note that parallel analysis (\( \text{ICNTL}(28) \) = 2) is only available for matrices in assembled format and, thus, an error will be raised for elemental matrices (\( \text{ICNTL}(5) \) = 1).

Elemental matrices can be input only centralized on the host (\( \text{ICNTL}(18) \) = 0).

\( \text{ICNTL}(18) \) defines the strategy for the distribution of the input matrix (only for assembled matrix).

Phase: accessed by the host during the analysis phase.

Possible values:

0: the input matrix is centralized on the host (see Subsection 5.2.2.1).

1: the user provides the structure of the matrix on the host at analysis, \textsc{MUMPS} returns a mapping and the user should then provide the matrix entries distributed according to the mapping on entry to the numerical factorization phase (see Subsection 5.2.2.2).

2: the user provides the structure of the matrix on the host at analysis, and the distributed matrix entries on all slave processors at factorization. Any distribution is allowed (see Subsection 5.2.2.2).

3: user directly provides the distributed matrix, pattern and entries, input both for analysis and factorization (see Subsection 5.2.2.2).

Other values are treated as 0.

Default value: 0 (input matrix centralized on the host)

Related parameters: \( \text{ICNTL}(5) \)

Remarks: In case of distributed matrix, we recommend options 2 or 3 that are easier to use.

5.2.2.1 Centralized assembled matrix (\( \text{ICNTL}(5) \) = 0 and \( \text{ICNTL}(18) \) = 0). In the following, an example of an unsymmetric 3x3 assembled matrix with 5 nonzeros is given.

\[
A = \begin{pmatrix}
    a_{11} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{pmatrix}
\]

Order of the matrix \( N = 3 \)

Nonzeros in the matrix \( NZ = 5 \)

array of row indices \( IRN[1:NZ] = [2, 3, 2, 1, 3] \)

array of col indices \( JCN[1:NZ] = [3, 1, 2, 1, 3] \)

array of values \( A[1:NZ] = [a_{23}, a_{31}, a_{22}, a_{11}, a_{33}] \)

Note that the elements of the matrix can be input in any order.

The following components of \( [\text{SDCZ}]\text{MUMPS}_\text{STRUC} \) hold the matrix in centralized assembled format:

\( \text{mumps}_\text{par}\%N \) (integer) is the order of the matrix \( A, \) \( N > 0. \) It must be set by the user on the host before analysis. It is not altered by \textsc{MUMPS}.

\( \text{mumps}_\text{par}\%NZ \) (integer) is the number of nonzero entries being input, \( NZ > 0. \) It must be set by the user on the host before analysis. It is not altered by \textsc{MUMPS}.

21
mumps_par%IRN and mumps_par%JCN (integer pointer arrays, dimension NZ) contain the row and column indices, respectively, for the matrix entries. They must be set by the user on the host before analysis. They are not altered by MUMPS.

mumps_par%A (real/complex pointer array, dimension NZ) must be set by the user in such a way that A(k) is the value of the entry in row IRN(k) and column JCN(k) of the matrix. It must be set before the factorization phase (JOB=2) or before analysis (JOB=1) if a numerical preprocessing option is requested (1 < ICNTL(6) < 7). A is not altered by MUMPS. Duplicate entries are summed and all entries with IRN(k) or JCN(k) out-of-range are ignored.

Note that, in the case of symmetric matrices (SYM=1 or 2), only half of the matrix should be provided. For example, only the lower triangular part of the matrix (including the diagonal) or only the upper triangular part of the matrix (including the diagonal) can be provided in IRN, JCN, and A. More precisely, a diagonal nonzero $a_{ii}$ must be provided as $A(k)=a_{ii}$, IRN(k)=JCN(k)=i, and a pair of off-diagonal nonzeros $a_{ij} = a_{ji}$ must be provided either as $A(k)=a_{ij}$ and IRN(k)=i, JCN(k)=j or vice-versa. Again, out-of-range entries are ignored and duplicate entries are summed. In particular, this means that if both $a_{ij}$ and $a_{ji}$ are provided, they will be summed.

5.2.2.2 Distributed assembled matrix (ICNTL(5) = 0 and ICNTL(18) = 1,2,3). When the matrix is in assembled format (ICNTL(5) = 0), we offer several options to distribute the matrix, defined by the control parameter ICNTL(18).

- only the matrix structure is provided on the host for the analysis phase and the matrix entries are provided for the numerical factorization, distributed across the processors
  - either according to a mapping supplied by the analysis (ICNTL(18) = 1),
  - or according to a user determined mapping (ICNTL(18) = 2);
- it is also possible to distribute the matrix pattern and the entries in any distribution in local triplets (ICNTL(18) = 3) for both analysis and factorization (recommended option for distributed entry)

The following components of the structure define the distributed assembled matrix input. They are valid for ICNTL(18) = 1,2,3, otherwise the user should refer to Subsection 5.2.2.1 for the centralized assembled matrix input.

The following components of [SDC2]MUMPS_STRUC hold the matrix in distributed assembled format:

mumps_par%N (integer) is the order of the matrix $A$, $N > 0$. It must be set by the user on the host before analysis. It is not altered by MUMPS.

mumps_par%NZ (integer) is the number of entries being input in the definition of $A$, $NZ > 0$. It must be set by the user on the host before analysis if ICNTL(18) = 1 or 2.

mumps_par%IRN and mumps_par%JCN (integer pointer array, dimension NZ) contain the row and column indices, respectively, for the matrix entries. They must be set by the user on the host before analysis if ICNTL(18) = 1, or 2. They can be deallocated by the user just after the analysis.

mumps_par%NZ_loc (integer) is the number of entries local to a processor. It must be defined on all processors in the case of the working host model of parallelism (PAR=1), and on all processors except the host in the case of the non-working host model of parallelism (PAR=0), before analysis if ICNTL(18) = 3, and before factorization if ICNTL(18) = 1 or 2.

mumps_par%IRN_loc and mumps_par%JCN_loc (integer pointer array, dimension NZ_loc) contain the global row and column indices, respectively, for the matrix entries. They must be defined on all processors if PAR=1, and on all processors except the host if PAR=0, before analysis if ICNTL(18) = 3, and before factorization if ICNTL(18) = 1 or 2.

mumps_par%A_loc (real/complex pointer array, dimension NZ_loc) must be defined before the factorization phase (JOB=2) on all processors if PAR = 1, and on all processors except the host if PAR = 0. The user must set $A_{loc}(k)$ to the value in row IRN_loc(k) and column JCN_loc(k).

If the calling application manages both local and global indices, the global indices must be provided.
mumps_par%MAPPING (integer array, dimension NZ) is returned by MUMPS on the host after the analysis phase as an indication of a preferred mapping if ICNTL(18) = 1. In that case, MAPPING(i) = IPROC means that entry IRN(i), JCN(i) should be provided on processor with rank IPROC in the MUMPS communicator. Remark that MAPPING is allocated by MUMPS, and not by the user. It will be freed during a call to MUMPS with JOB = -2.

We recommend the use of options ICNTL(18) = 2 or 3 because they are the simplest and most flexible options. Furthermore, these options (2 or 3) are in general almost as efficient as the more sophisticated (but more complicated for the user) option ICNTL(18) = 1.

Again, out-of-range entries are ignored and duplicate entries are summed. In particular, if an entry a_{ij} is provided both as (IRN_loc(k1), JCN_loc(k1), A_loc(k1)) on a process P1 and as (IRN_loc(k2), JCN_loc(k2), A_loc(k2)) on a process P2, the corresponding numerical value considered for a_{ij} is the sum of A_loc(k1) on P1 and A_loc(k2) on P2. This also means that it is possible to only perform local assemblies inside each MPI process and that entries that are common to several MPI processes (which may typically correspond to interface variables) will be summed internally by the MUMPS package without the user having to take care of communications to assemble those entries.

5.2.2.3 Elemental matrix (ICNTL(5) =1 and ICNTL(18) =0). In the following, an example of elemental matrix with two elements is given.

\[
\begin{bmatrix}
1 & -1 & 2 & 3 \\
2 & 1 & 1 & 1 \\
3 & 1 & 1 & 1 \\
\end{bmatrix}
\begin{bmatrix}
2 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
\end{bmatrix}
\begin{bmatrix}
3 & 2 & -1 & 3 \\
4 & 1 & 2 & -1 \\
5 & 3 & 2 & 1 \\
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
-1 & 2 & 3 & 0 & 0 \\
2 & 1 & 1 & 0 & 0 \\
1 & 1 & 3 & -1 & 3 \\
0 & 0 & 1 & 2 & -1 \\
0 & 0 & 3 & 2 & 1 \\
\end{bmatrix}
= A_1 + A_2
\]

• N=5 NELT=2 NVAR=6 \( A = \sum_{i=1}^{NELT} A_i \)
• ELTPTR [1:NELT+1] = 1 4 7
• ELTVAR [1:NVAR] = 1 2 3 3 4 5
• A_ELT [1:NVAL] = -1 2 1 2 1 3 1 1 2 1 3 -1 2 2 3 -1 1
• Remarks:
  - NVAR = ELTPTR(NELT+1)-1
  - Order of element i: \( S_i = ELTPTR(i + 1) - ELTPTR(i) \)
  - NVAL = \( \sum S_i^2 \) (unsymmetric) or \( S_i(S_i + 1)/2 \) (symmetric),
  - storage of elements in ELTVAR: by columns

In the current release of the package, a matrix in elemental format must be input centrally on the host (ICNTL(5) =1 and ICNTL(18) =0). The distributed elemental format is not currently available.

mumps_par%N (integer), mumps_par%NELT (integer), mumps_par%ELTPTR (integer pointer array, dimension NELT+1), mumps_par%ELTVAR (integer pointer array, dimension ELTPTR(NELT+1)-1), and mumps_par%A_ELT (real/complex pointer array) hold the matrix in elemental format. The following components of the MUMPS_STRUC hold the matrix in elemental format:

mumps_par%N (integer) is the order of the matrix A. N > 0. It is not altered by MUMPS.

mumps_par%NELT (integer) is the number of elements being input, NELT > 0. It is not altered by MUMPS.
mumps_par%ELTPTR (integer pointer array, dimension NELT+1) is such that ELTPTR(j) points to the position in ELTVAR of the first variable in element j, and ELTPTR(NELT+1) must be set to the position after the last variable of the last element. Note that ELTPTR(1) should be equal to 1. ELPTR is not altered by MUMPS.

mumps_par%ELTVAR (integer pointer array, dimension ELTPTR(NELT+1) – 1) must be set to the lists of variables of the elements. It is not altered by MUMPS. The variables for element j are stored in positions ELTPTR(j), . . . , ELTPTR(j+1) – 1. Out-of-range variables are ignored.

mumps_par%A ELT (real/complex pointer array) If \( N_p \) denotes ELTPTR(p+1)–ELTPTR(p), then the values for element j are stored in positions \( K_j + 1, \ldots, K_j + L_j \), where
\[
K_j = \sum_{p=1}^{j-1} N_p^2, \quad \text{and} \quad L_j = N_j^2 \quad \text{in the unsymmetric case (SYM = 0)}
\]
\[
K_j = \sum_{p=1}^{j-1} (N_p \cdot (N_p + 1))/2, \quad \text{and} \quad L_j = (N_j \cdot (N_j + 1))/2 \quad \text{in the symmetric case (SYM = 1 or 2)}.
\]
Only the lower triangular part is stored.

Values within each element are stored column-wise. Values corresponding to out-of-range variables are ignored and values corresponding to duplicate variables within an element are summed. A_EL'T is not accessed at the analysis phase (JOB = 1). Note that, although the elemental matrix may be symmetric or unsymmetric in value, its structure is always symmetric.

The components N, NELT, ELTPTR, and ELTVAR describe the pattern of the matrix and must be set by the user before the analysis phase (JOB = 1) and should be passed unchanged when later calling the factorization (JOB = 2) and solve (JOB = 3) phases. Component A_EL'T must be set before the factorization phase (JOB = 2).

5.2.3 Writing the input matrix to a file

If the input matrix is in assembled format (centralized or distributed), it is possible to write the matrix at the analysis phase into a file whose name is given in the variable “WRITE_PROBLEM”. The “matrix market” format is used to write the matrix.

mumps_par%WRITE_PROBLEM (string) must be set by the user before the analysis phase (JOB = 1).

If the matrix is distributed, each processor must initialize the variable WRITE_PROBLEM. Each processor will then write its share of the matrix in a file whose name is defined by the string “WRITE_PROBLEM” appended by the rank of the processor in the communicator passed to MUMPS.

Note that WRITE_PROBLEM should include both the path and the file name.

Furthermore, if a dense right-hand side RHS (see Subsection 5.11.1) is provided on the host before the analysis phase, it is also written in a file with the same name of the matrix file name (WRITE_PROBLEM) but appended by “.rhs”.

5.3 Preprocessing: permutation to zero-free diagonal and scaling

The permutation to a zero-free diagonal and the scalings are controlled by ICNTL(6) and ICNTL(8), respectively.

ICNTL(6) computes a permutation to permute the matrix to a zero-free diagonal and/or computes a matrix scaling.

\[\text{Phase: accessed by the host and only during sequential analysis (ICNTL(28) = 1)}\]

\[\text{Possible variables/arrays involved: optionally UNS_PERM, mumps_par%A, COLSCA and ROWSCA} \]

\[\text{Possible values:} \]
\[\text{0 : No column permutation is computed.} \]
\[\text{1 : The permuted matrix has as many entries on its diagonal as possible. The values on the diagonal are of arbitrary size.} \]

See [http://math.nist.gov/MatrixMarket/](http://math.nist.gov/MatrixMarket/)
2: The permutation is such that the smallest value on the diagonal of the permuted matrix is maximized. The numerical values of the original matrix, (mumps_par%A), must be provided by the user during the analysis phase.

3: Variant of option 2 with different performance. The numerical values of the original matrix (mumps_par%A) must be provided by the user during the analysis phase.

4: The sum of the diagonal entries of the permuted matrix is maximized. The numerical values of the original matrix (mumps_par%A) must be provided by the user during the analysis phase.

5: The product of the diagonal entries of the permuted matrix is maximized. Scaling vectors are also computed and stored in COLSCA and ROWSCA, if ICNTL(8) is set to -2 or 77. With these scaling vectors, the nonzero diagonal entries in the permuted matrix are one in absolute value and all the off-diagonal entries less than or equal to one in absolute value. For unsymmetric matrices, COLSCA and ROWSCA are meaningful on the permuted matrix A Q_e (see Equation (5)). For symmetric matrices, COLSCA and ROWSCA are meaningful on the original matrix A. The numerical values of the original matrix, mumps_par%A, must be provided by the user during the analysis phase.

6: Similar to 5 but with a different algorithm. The numerical values of the original matrix, mumps_par%A, must be provided by the user during the analysis phase.

7: Based on the structural symmetry of the input matrix and on the availability of the numerical values, the value of ICNTL(6) is automatically chosen by the software. Other values are treated as 0. On output from the analysis phase, INFOG(23) holds the value of ICNTL(6) that was effectively used.

Default value: 7 (automatic choice done by the package)

Incompatibility: If the matrix is symmetric positive definite (SYM = 1), or in elemental format(ICNTL(5) =1), or the parallel analysis is requested (ICNTL(28) =2) or the ordering is provided by the user (ICNTL(7) =1), or the Schur option (ICNTL(19) = 1, 2, or 3) is required, or the matrix is initially distributed (ICNTL(18) =1,2,3), then ICNTL(6) is treated as 0.

Related parameters: ICNTL(8), ICNTL(12)

Remarks: On assembled centralized unsymmetric matrices (ICNTL(5) =0, ICNTL(18) =0, SYM = 0), if ICNTL(6)=1, 2, 3, 4, 5, 6 a column permutation (based on weighted bipartite matching algorithms described in [20, 21]) is applied to the original matrix to get a zero-free diagonal. The user is advised to set ICNTL(6) to a nonzero value when the matrix is very unsymmetric in structure. On output during the analysis phase, when the column permutation is not the identity, the pointer UNS_PERM (internal data valid until a call to MUMPS with JOB=-2) provides access to the permutation on the host processor (see Subsection 5.3.1). Otherwise, the pointer is not associated.

The column permutation is such that entry a_i,perm(i) is on the diagonal of the permuted matrix.

On general assembled centralized symmetric matrices (ICNTL(5) =0, ICNTL(18) =0, SYM = 2), if ICNTL(6)=1, 2, 3, 4, 5, 6, the column permutation is internally used to determine a set of recommended 1 x 1 and 2 x 2 pivots (see [22] and the description of ICNTL(12) in Subsection 6.1 for more details). We advise either to let MUMPS select the strategy (ICNTL(6) = 7) or to set ICNTL(6) = 5 if the user knows that the matrix is for example an augmented system (which is a system with a large zero diagonal block). On output from the analysis the pointer UNS_PERM is not associated.

ICNTL(8) describes the scaling strategy

Phase: accessed by the host during analysis phase (that need be sequential ICNTL(28) =1) or on entry to numerical factorization phase

Possible variables/arrays involved: COLSCA, ROWSCA

Possible values:

-2: Scaling computed during analysis (see [20, 21] for the unsymmetric case and [22] for the symmetric case). The user has to provide the numerical values of the original matrix (mumps_par%A) on entry to the analysis.
-1: Scaling provided by the user. Scaling arrays must be provided in COLSCA and ROWSCA on entry to the numerical factorization phase by the user, who is then responsible for allocating and freeing them. If the input matrix is symmetric (SYM= 1 or 2), then the user should ensure that the array ROWSCA is equal to (or points to the same location as) the array COLSCA.

0: No scaling applied/computed.
1: Diagonal scaling computed during the numerical factorization phase,
3: Column scaling computed during the numerical factorization phase,
4: Row and column scaling based on infinite row/column norms, computed during the numerical factorization phase,
7: Simultaneous row and column iterative scaling based on [37] and [13] computed during the numerical factorization phase.
8: Similar to 7 but more rigorous and expensive to compute; computed during the numerical factorization phase.
77: Automatic choice of the value of ICNTL(8) done during analysis.

Default value: 77 (automatic choice done by the package)

Related parameters: ICNTL(6), ICNTL(12)

Remarks: If ICNTL(8) = 77, then an automatic choice of the scaling option may be performed, either during the analysis or the factorization. The effective value used for ICNTL(8) is returned in INFOG(33). If the scaling arrays are computed during the analysis, then they are ready to be used by the factorization phase. Note that scalings can be efficiently computed during analysis when requested (see ICNTL(6) and ICNTL(12)).

If the input matrix is symmetric (SYM= 1 or 2), then only options –2, –1, 0, 1, 7, 8 and 77 are allowed and other options are treated as 0.

If the input matrix is in elemental format (ICNTL(5) = 1), then only options –1 and 0 are allowed and other options are treated as 0.

If the initial assembled matrix is distributed (ICNTL(18)=1,2,3 and ICNTL(5) = 0), then only options 7, 8 and 77 are allowed, otherwise no scaling is applied.

### 5.3.1 Permutation to a zero-free diagonal (ICNTL(6))

On assembled centralized unsymmetric matrices (ICNTL(5)=0, ICNTL(18)=0, SYM = 0), if ICNTL(6)=1, 2, 3, 4, 5, 6 a column permutation (based on weighted bipartite matching algorithms described in [20, 21]) is applied to the original matrix to get a zero-free diagonal. The user is advised to set ICNTL(6) to a nonzero value when the matrix is very unsymmetric in structure, or to leave it to its default (automatic) value.

mumps_par%UNS_PERM (integer pointer array, dimension N) is returned on the host processor on output to the analysis phase for a centralized unsymmetric matrix, when a column permutation is requested (ICNTL(6) ≠0) and if it not the identity. For all other cases, the pointer is not associated. It is allocated internally by MUMPS and provides access to the permutation, and is such that entry $a_{i,perm(i)}$ is on the diagonal of the permuted matrix.

### 5.3.2 Scaling (ICNTL(6) or ICNTL(8))

mumps_par%COLSCA, mumps_par%ROWSCA (real pointer arrays, dimension N) are optional, column and row scaling arrays, respectively, required only by the host. Note that this arrays are real also in the complex version.

On input: If a scaling is provided by the user (ICNTL(8) = –1), these arrays must be allocated and initialized by the user on the host, before a call to the factorization phase (JOB=2).

On output:

If ICNTL(6)=5 or 6, and ICNTL(8) =–2 or 77, they are automatically allocated and computed by the package during the analysis phase.

Otherwise, they are automatically allocated and computed by the package during the factorization phase.
5.4 Preprocessing: symmetric permutations

The choice of the symmetric permutation $P$, the so-called ordering, from Equation (5) is managed by the control parameters $ICNTL(28)$, $ICNTL(7)$ and $ICNTL(29)$ defined below:

$ICNTL(28)$ determines whether a sequential or a parallel analysis is performed.

**Phase:** accessed by the host process during the analysis phase.

**Possible values:**

0: automatic choice.

1: sequential computation. In this case the ordering method is set by $ICNTL(7)$ and the $ICNTL(29)$ parameter is meaningless (choice of the parallel ordering tool).

2: parallel computation. A parallel ordering and parallel symbolic factorization will be performed if one of the parallel ordering tools (or all) are available. In this case $ICNTL(7)$ is meaningless.

Any other values will be treated as 0.

**Default value:** 0 (automatic choice)

**Incompatibility:** The parallel analysis is not available when the Schur complement feature is requested ($ICNTL(19)=1$), when a maximum transversal is requested on the input matrix (i.e., $ICNTL(6)=1, 2, 3, 4, 5$ or $6$) or when the input matrix is an unassembled matrices ($ICNTL(5)=1$).

**Related parameters:** $ICNTL(7), ICNTL(29)$

**Remarks:** Performing the analysis in parallel ($ICNTL(29)=2$) will enable saving both time and memory. Note that then the quality of the ordering depends on the number of processors used.

$ICNTL(7)$ computes a symmetric permutation (ordering) to determine the pivot order to be used for the factorization (see Subsection 3.2)

**Phase:** accessed by the host and only during the sequential analysis phase ($ICNTL(28)=1$).

**Possible variables/arrays involved:** PERM_IN, SYM_PERM

**Possible values:**

0: Approximate Minimum Degree (AMD) [4] is used.

1: The pivot order should be set by the user in PERM_IN, on the host processor. In that case, PERM_IN must be allocated on the host by the user and PERM_IN(i), (i=1, ... N) must hold the position of variable i in the pivot order.

2: Approximate Minimum Fill (AMF) is used,

3: SCOTCH$^\text{6}$ [34] package is used if previously installed by the user otherwise treated as 7.

4: PORD$^\text{6}$ [38] is used if previously installed by the user otherwise treated as 7.

5: the METIS$^\text{7}$ [29] package is used if previously installed by the user otherwise treated as 7.

6: Approximate Minimum Degree with automatic quasi-dense row detection (QAMD) is used.

7: Automatic choice by the software during analysis phase. This choice will depend on the ordering packages made available, on the matrix (type and size), and on the number of processors.

Other values are treated as 7.

**Default value:** 7 (automatic choice)

**Incompatibility:** $ICNTL(7)$ is meaningless if the parallel analysis is chosen ($ICNTL(28)=2$).

**Related parameters:** $ICNTL(28)$


$^\text{7}$Distributed within MUMPS by permission of J. Schulze (University of Paderborn).

$^\text{8}$See [http://glaros.dtc.umn.edu/gkhome/metis/metis/overview](http://glaros.dtc.umn.edu/gkhome/metis/metis/overview) to obtain a copy.
Remarks: Even when the ordering is provided by the user, the analysis must be performed before numerical factorization.

For assembled matrices (centralized or distributed) \((\text{ICNTL}(5)=0)\) all the options are available.
For elemental matrices \((\text{ICNTL}(5)=1)\), only options 0, 1, 5 and 7 are available, with option 7 leading to an automatic choice between AMD and METIS (options 0 or 5); other values are treated as 7.

If the user asks for a Schur complement matrix \((\text{ICNTL}(19)=1, 2, 3)\) and

- the matrix is assembled \((\text{ICNTL}(5)=0)\) then only options 0, 1, 5 and 7 are currently available. Other options are treated as 7.
- the matrix is elemental \((\text{ICNTL}(5)=1)\) only options 0, 1 and 7 are currently available. Other options are treated as 7 which will (currently) be treated as 0 (AMD).
- in both cases (assembled or elemental matrix) if the pivot order is given by the user \((\text{ICNTL}(7)=1)\) then the following property should hold: \(\text{PERM}_{\text{IN}}(\text{LISTVAR}_{\text{SCHUR}}(i)) = N - \text{SIZE}_{\text{SCHUR}} + i\), for \(i=1, \ldots, \text{SIZE}_{\text{SCHUR}}\).

For matrices with relatively dense rows, we highly recommend option 6 which may significantly reduce the time for analysis.

On output, the pointer array \(\text{SYM}_{\text{PERM}}\) provides access, on the host processor, to the symmetric permutation that is effectively computed during the analysis phase by the MUMPS package, and \(\text{INFOG}(7)\) to the ordering option that was effectively used. In fact, the option corresponding to \(\text{ICNTL}(7)\) may be forced by MUMPS when for example the ordering option chosen by the user is not compatible with the value of \(\text{ICNTL}(12)\) or the necessary package is not installed. \(\text{SYM}_{\text{PERM}}(i), i=1, \ldots, N\), holds the position of variable \(i\) in the pivot order, see Subsection 5.4.1 for a full description.

\(\text{ICNTL}(29)\) defines the parallel ordering tool to be used to compute the fill-in reducing permutation.

Phase: accessed by host process only during the parallel analysis phase \((\text{ICNTL}(28)=2)\).

Possible variables/arrays involved: \(\text{SYM}_{\text{PERM}}\)

Possible values:

0: automatic choice.
1: PT-SCOTCH is used to reorder the input matrix, if available.
2: ParMetis is used to reorder the input matrix, if available.

Default value: 0 (automatic choice)

Related parameters: \(\text{ICNTL}(28)\)

Remarks: On output, the pointer array \(\text{SYM}_{\text{PERM}}\) provides access, on the host processor, to the symmetric permutation that is effectively computed during the analysis phase, and \(\text{INFOG}(7)\) to the ordering option that was effectively used. \(\text{SYM}_{\text{PERM}}(i), i=1, \ldots, N\), holds the position of variable \(i\) in the pivot order, see Subsection 5.4.1 for a full description.

5.4.1 Symmetric permutation vector \((\text{ICNTL}(7)\) and \(\text{ICNTL}(29)\))

When the ordering is not provided by the user, the choice of the ordering strategy is controlled by \(\text{ICNTL}(7)\) in case of sequential analysis \((\text{ICNTL}(28)=1)\), and by \(\text{ICNTL}(29)\) in case of parallel analysis \((\text{ICNTL}(28)=2)\). In all cases (serial or parallel analysis, ordering computed internally or provided by the user, Schur complement, assembled or elemental matrix), the symmetric permutation of the variables that MUMPS relies on is returned to the user in the mumps.par\%SYM\_PERM array.

\text{mumps.par\%SYM\_PERM} (integer pointer array, dimension \(N\)) is allocated internally and returned on the host processor on output to the analysis phase. It contains the permutation that was effectively computed during the analysis phase and that will serve as a basis for the numerical factorization. It is such that \(\text{SYM\_PERM}(i)\) holds the position of variable \(i\) in the pivot order. For example, \(\text{SYM\_PERM}(12)=2\) means that variable 12 in the original matrix is the second
variable to be eliminated in the pivot order. In case a Schur complement was requested (see ICNTL(19)), the returned permutation also includes the variables from the Schur complement, so that: \( \text{SYM\_PERM} (\text{LISTVAR\_SCHUR}(i)) = \text{N-\_SIZE\_SCHUR} + i \), for \( 1 \leq i \leq \text{SIZE\_SCHUR} \) (see also Subsection 5.12).

5.4.2 Given ordering \((\text{ICNTL}(7) = 1\text{ and } \text{ICNTL}(28) = 1)\)

An ordering can optionally be provided by the user on input to the package. Even in this case, the analysis phase \((\text{JOB} = 1)\) must be performed before the numerical factorization. Note that this functionality is only available with the sequential analysis \((\text{ICNTL}(28) = 1)\).

\texttt{mumps\_par\%\_PERM\_IN} (integer pointer array, dimension \(N\)) must be allocated and initialized by the user on the host before the sequential analysis phase \((\text{JOB} = 1, \text{ICNTL}(28) = 1)\) when \text{ICNTL}(7) = 1. Although the input matrix can be provided in assembled or elemental format (see ICNTL(5)), \text{PERM\_IN} always defines the elimination order of the variables, not the elimination order of the elements. The user should define \text{PERM\_IN} such that \text{PERM\_IN}(i), \(i = 1, \ldots, N\) holds the position of variable \(i\) in the pivot order. For example, \text{PERM\_IN}(12) = 2 indicates that variable 12 in the original matrix is the second variable to be eliminated in the pivot order. In case a Schur complement is requested \((\text{ICNTL}(19) = 1, 2, 3)\), the permutation should also include the variables from the Schur complement, so that: \( \text{PERM\_IN}(\text{LISTVAR\_SCHUR}(i)) = \text{N-\_SIZE\_SCHUR} + i \), for \( 1 \leq i \leq \text{SIZE\_SCHUR} \) (see Subsection 5.12). In case of parallel analysis \((\text{ICNTL}(28) = 2)\), \text{PERM\_IN} is ignored. The input matrix can be centralized or distributed (see ICNTL(18)).

Remark that, in case of given ordering, although \text{PERM\_IN} is used, \text{SYM\_PERM} (see Subsection 5.4.1) will generally differ from \text{PERM\_IN} because \text{MUMPS} takes some freedom to reorganize the order of the computations for locality and efficiency. However, \text{PERM\_IN} and \text{SYM\_PERM} are equivalent orderings in terms of estimated factor size and estimated number of operations for the factorization.

5.5 Out-of-core \((\text{ICNTL}(22))\)

The decision to use the disk to store the matrix of factors is controlled by \text{ICNTL}(22). Only the value on the host node is significant.

\text{ICNTL}(22) \text{ controls the in-core/out-of-core (OOC) factorization and solve.}

\textit{Phase}: accessed by the host during the factorization phase.

\textit{Possible variables/arrays involved}: \text{OOC\_TMPDIR} and \text{OOC\_PREFIX}

\textit{Possible values}:

\begin{itemize}
  \item 0: In-core factorization and solution phases (default standard version).
  \item 1: Out-of-core factorization and solve phases. The complete matrix of factors is written to disk (see Subsection 3.13).
\end{itemize}

\textit{Default value}: 0 (in-core factorization)

\textit{Remarks}: The variables \text{OOC\_TMPDIR} and \text{OOC\_PREFIX} are used to indicate the directory and the prefix, respectively, where to store the factors. They must be set after the initialization phase \((\text{JOB} = -1)\) and before the factorization phase \((\text{JOB}=2, 4, 5 \text{ or } 6)\). Otherwise, \text{MUMPS} will use the \text{/tmp} directory and arbitrary file names.

\texttt{mumps\_par\%OOC\_TMPDIR} (string) can be provided by the user (on each processor) to control the directory where the out-of-core files will be stored. If not provided, the \text{/tmp} directory will be tried.

Note that it is also possible to provide the directory through environment variables. If \text{OOC\_TMPDIR} is not defined, then \text{MUMPS} checks for the environment variable \text{MUMPS\_OOC\_TMPDIR}. If not defined, then the directory \text{/tmp} is attempted.

\texttt{mumps\_par\%OOC\_PREFIX} (string) can be provided by the user (on each processor) to prefix the out-of-core files. If not provided, file names will be chosen automatically.
Note that it is also possible to provide the file names through environment variables. If `OOC_PREFIX` is not defined, then MUMPS checks for the environment variable `MUMPS_OOC_PREFIX`. If not defined, then MUMPS chooses the file names automatically.

5.6 Workspace parameters (ICNTL(14) and ICNTL(23)) and user workspace

The memory required to run the numerical phases (factorization and solve) is estimated during the analysis. The size of the workspace actually required during numerical factorization depends on the numerical characteristics of the matrix, and therefore on the numerical pivoting that may lead to extra storage, but also on algorithmic parameters such as the in-core/out-of-core strategies (ICNTL(22)), the memory relaxation parameter (ICNTL(14)) and the fact to discard the factor matrices during the factorization (ICNTL(31)).

Two main workarrays are allocated internally: IS and S (integer and real/complex workarray, respectively), that hold factors, active frontal matrices, and contribution blocks. In addition to these two large workarrays, other internal workarrays are used: for example, internal communication buffers in the parallel case, or integer arrays holding the structure of the assembly tree.

At the end of the analysis phase, the following estimations of the memory required to run the numerical phases are provided (note that these estimations take into account the value of the memory relaxation parameter ICNTL(14)):

**Estimated memory for the in-core strategy:**

- Estimated size in MegaBytes of the total working space locally requested by each processor: INFO(15)
- The maximum and sum over all processors: INFOG(16) and INFOG(17), respectively
- The size of the main real/complex workarray $S$: INFO(8). If INFO(8) is negative, then the absolute value corresponds to millions of real/complex entries needed in this workarray.

**Estimated memory for the out-of-core strategy:**

- Estimated size in MegaBytes of the total working space locally requested by each processor: INFO(17)
- The maximum and sum over all processors: INFOG(26) and INFOG(27) respectively
- The size of the main real/complex workarray $S$: INFO(20). If negative, then the absolute value corresponds to millions of real/complex entries needed in this workarray.

As a first general approach, we advise the user to rely on the estimations provided during the analysis phase. If the user wants to/must increase the allocated workspace (typically, because of numerical pivoting that leads to extra storage, or previous call to MUMPS that failed because of a lack of allocated memory), we describe in the following how the size of the workspace can be controlled.

- The user can modify the value of the memory relaxation parameter, ICNTL(14), that is designed to control the increase with respect to the estimations performed during analysis, in the size of all (integer and real/complex) workspace allocated during the numerical phase.
- The user can explicitly control the memory used by the package providing in ICNTL(23) the size of the total memory that is allowed to be used internally.

We provide the definitions of ICNTL(14) and ICNTL(23) below:

**ICNTL(14)** corresponds to the percentage increase in the estimated working space.

Phase: accessed by the host both during the analysis and the factorization phases.

Default value: 20 (which corresponds to a 20 % increase).

Related parameters: ICNTL(23)

Remarks: When significant extra fill-in is caused by numerical pivoting, increasing ICNTL(14) may help.
ICNTL(23) corresponds to the maximum size of the working memory in MegaBytes that MUMPS can allocate per working processor. It covers all internal integer and real (complex in the complex version) workspace.

*Phase:* accessed by the host at the beginning of the factorization phase and is only significant on the host.

*Possible values:*
- 0: each processor will allocate workspace based on the estimates computed during the analysis
- >0: maximum size of the working memory in MegaBytes per working processor to be allocated

*Default value:* 0

*Related parameters:* ICNTL(14)

*Remarks:* If ICNTL(23) is greater than 0 then MUMPS automatically computes the size of the internal workarrays such that the storage for all MUMPS internal data is equal to ICNTL(23). The relaxation ICNTL(14) is first applied to the internal integer workarray IS and to communication and I/O buffers; the remaining available space is given to the main (and most critical) real/complex internal workarray S holding the factors and the stack of contribution blocks. A lower bound of ICNTL(23) (if ICNTL(14) has not been modified since the analysis) is given by INFOG(16) if the factorization is in-core (ICNTL(22)=0), and by INFOG(26) if the factorization is out-of-core (ICNTL(22)=1).

If ICNTL(23) is left to its default value 0 then each processor will allocate for the factorization phase a workspace based on the estimates computed during the analysis (INFO(17) that is the estimate of the sum over all processors) if ICNTL(14) has not been modified since analysis, or larger if ICNTL(14) was increased. Note that these estimates are accurate in the sequential version of MUMPS, but they can be inaccurate in the parallel case, especially for the out-of-core version. Therefore, in parallel, we recommend to use ICNTL(23) and provide a value significantly larger than the maximum over all processors: INFOG(16) in the in-core case, or INFOG(26) in the out-of-core case.

Another possibility is that the user provides the real/complex workarray instead of using the internal main real/complex workarray S. The user workarray must be larger than INFO(8) (in-core factorization) or INFO(20) (out-of-core factorization), and a pointer array that points to that workspace must be provided. In this case, the value of ICNTL(23) is ignored.

We describe below the two parameters associated to this functionality:

mumps_par%LWK_USER (integer) is local to each processor if PAR=1, and on all processors except the host if PAR=0. It is accessed at the beginning of the numerical phases of MUMPS. Its default value is 0. At the beginning of the numerical phases, if the user sets LWK_USER to a nonzero value then LWK_USER will be define the size of the pointer array WK_USER. If negative, -LWK_USER is a lower bound of the number of entries in millions of the pointer array WK_USER so that \(\text{abs}(\text{LWK_USER}) \times 10^6 \leq \text{size}(\text{WK_USER})\) must hold.

If the numerical phases are in-core (ICNTL(22)=0), we recommend the user to set LWK_USER larger than INFO(8), otherwise an error with code --9 may occur. Moreover, the value of LWK_USER must not be modified between factorization and subsequent solution phases.

If the numerical phases are out-of-core (ICNTL(22)=1), we recommend LWK_USER to be larger than INFO(20). In this case, the user can reduce the value for LWK_USER between the factorization phase and the solve phase.

mumps_par%WK_USER is a real/complex pointer array that can point to the workspace provided by the user. It is only accessed by MUMPS when LWK_USER has been set by the user to a non-zero value. In that case, MUMPS will avoid the internal allocation of the main real/complex workarray S and use WK_USER instead.

Note that the type of WK_USER should follow the arithmetic: single precision for SMUMPS, double precision for DMUMPS, single complex for CMUMPS, and double complex for ZMUMPS.

If the factorization is in-core (ICNTL(22)=0), then WK_USER should not be modified between factorization and solution phases of MUMPS.
5.7 Null pivot row detection

It is possible to detect null pivots during the factorization by setting ICNTL(24) = 1. A pivot is considered as null if it is smaller than a threshold defined by CNTL(3).

At the end of the factorization mumps_par%INFOG(28) will contain the deficiency of the initial matrix and the array PIVNUL_LIST(1:INFOG(28)) will contain, on the host, the row indices corresponding to the null pivots, if INFOG(28) ≠ 0.

In order to be able to perform a solve step, the null pivot may be replaced by a huge fixation or by 1 (in this latter case the elements of the columns under the pivot are set to 0). The choice of the fixation value can be done with CNTL(5). In this way we will be able to compute one solution among the possible solutions of the deficient system AX = B (ICNTL(25) = 0) or a part of the null vectors (that is the vectors solving AX = 0, ICNTL(25) ≠ 0) associated to these null pivots.

ICNTL(24) controls the detection of “null pivot rows”.

Phase: accessed by the host during the factorization phase
Possible variables/arrays involved: PIVNUL_LIST
Possible values:
0: Nothing done. A null pivot will result in error INFO(1) = -10.
1: Null pivot row/column detection.

Other values are treated as 0.
Default value: 0 (no null pivot detection)
Incompatibility: This option is available only for symmetric matrices.
Related parameters: CNTL(3), CNTL(5), ICNTL(13), ICNTL(25).
Remarks:
CNTL(3) is used to compute the threshold to decide if a pivot row is “null”.
Null pivot rows are modified to enable the solution phase to provide one solution among the possible solutions of the numerically deficient matrix. The parameter CNTL(5) defines the fixation of null pivots.

Note that the list of row indices corresponding to null pivots is returned on the host in PIVNUL_LIST(1:INFOG(28)). The solution phase (JOB=3) can then be used to either provide a “regular” solution, that it is a possible solution of the complete system when the right-hand-side belongs to the span of the original matrix, or to compute the associated vectors of the null-space basis (see ICNTL(25)).

Note that when ScALAPACK is applied on the root node (see ICNTL(13) = 0), then exact null pivots on the root will stop the factorization (INFO(1) = -10) while if tiny pivots are present on the root node the ScALAPACK routine will factorize the root matrix. Computing the root node factorization sequentially (this can be forced by setting ICNTL(13) to 1) will help with the correct detection of null pivots but may degrade performance.

Related data:
mumps_par%INFOG(28) (integer) is set to the number of null pivots detected during the factorization step.
mumps_par%PIVNUL_LIST (integer array, dimension N) is set during the factorization phase to the row indices corresponding to the null pivots. It is also accessed during the solve phase.

5.8 Discard matrix factors (ICNTL(31))

In some cases the user may want to discard one or both factors during factorization. This can be done using the ICNTL(31) control parameter.

ICNTL(31) indicates which factors may be discarded during the factorization.
Phase: accessed by the host during the analysis phase.
Possible values:

0: all factors needed to perform the solution phase (JOB=3) are kept during the factorization phase. In general this means that both the L and U factors are kept. However, in case the forward elimination is performed during the factorization (ICNTL(32)=1) on unsymmetric matrices (SYM=0), the L factors are discarded because only the backward substitution will then be performed during the solution phase (JOB=3).

1: all factors are discarded during the factorization phase. The user is not interested in solving the linear system (Equations (3) or (4)) and will not call MUMPS solution phase (JOB=3). This option is meaningful when only statistics from the factorization, such as (for example) definiteness, value of the determinant, number of entries in factors after numerical pivoting, number of negative or null pivots are required. In this case, the memory allocated for the factorization will rely on the out-of-core estimates.

2: only the U factor is kept after factorization so that only a backward substitution is possible during the solve phase (JOB=3). This setting is only meaningful for unsymmetric matrices when:
   - the user is only interested in the computation of a null space basis (see ICNTL(25)) during the solve phase, or
   - the forward elimination is performed during the factorization (ICNTL(32)=1), in which case ICNTL(31)=0 and ICNTL(32) have the same behaviour.

Other values are treated as 0.

Default value: 0 (the factors needed for the solve are kept during the factorization phase).

Incompatibility: ICNTL(31) = 2 is meaningful only for unsymmetric matrices.

Related parameters: ICNTL(32), forward elimination during factorization, ICNTL(33), computation of the determinant, ICNTL(25) computation of a null space basis.

5.9 Computation of the determinant (ICNTL(33))

The user interested in computing the determinant of the matrix A can use the control parameter ICNTL(33). See Subsection 3.14 for details on how it will be computed.

ICNTL(33) computes the determinant of the input matrix.

Phase: accessed by the host during the factorization phase.

Possible values:

0: the determinant of the input matrix is not computed.

≠ 0: computes the determinant of the input matrix. The determinant is obtained by computing 
\[(a + ib) \times 2^c\] where 
\[a = \text{RINFOG}(12), b = \text{RINFOG}(13)\] and 
\[c = \text{INFOG}(34).\] In real arithmetic \(b = \text{RINFOG}(13)\) is equal to 0.

Default value: 0 (determinant is not computed)

Related parameters: ICNTL(31)

Remarks: In case a Schur complement was requested (see ICNTL(19)), elements of the Schur complement are excluded from the computation of the determinant so that the determinant is that of one of matrix \(A_{1,1}\) (using notations of Subsection 3.16).

Although we recommend to compute the determinant on non-singular matrices, null pivots (ICNTL(24)) and static pivots (CNTL(4)) are excluded from the determinant so that a non-zero determinant is still returned on singular or near-singular matrices. This determinant is then not unique and will depend on which equations were excluded.

Furthermore, we recommend to switch off scaling (ICNTL(8)) in such cases. If not (ICNTL(8) ≠ 0), we describe in the following the current behaviour of the package:

- if static pivoting (CNTL(4)) is activated: all entries of the scaling arrays ROWSCA and COLSCA are currently taken into account in the computation of the determinant.
- if the null pivot detection (ICNTL(24)) is activated, then entries of ROWSCA and COLSCA corresponding to pivots in PIVNUL_LIST are excluded from the determinant so that
  * for symmetric matrices (SYM=1 or 2), the returned determinant correctly corresponds to the matrix excluding rows and columns of PIVNUL_LIST.
  * for unsymmetric matrices (SYM=0), scaling may perturb the value of the determinant in case off-diagonal pivoting has occurred (INFOG(12) ≠ 0).

Note that if the user is interested in computing only the determinant, we recommend to discard the factors during factorization ICNTL(31).

### 5.10 Forward elimination during factorization (ICNTL(32))

This option makes much sense when the factors have to be used only once or in an out-of-core context (ICNTL(22)=1), where loading the factors from disk during the solution phase (JOB=3) involves loading factors during both the forward (Equation (3)) and backward (Equation (4)) substitutions and can be particularly costly. Note that if the forward elimination is performed during factorization, some factors may be discarded (ICNTL(31)).

ICNTL(32) performs the forward elimination of the right-hand sides (Equation (3)) during the factorization (JOB=2).

**Phase:** accessed by the host during the analysis phase.

**Possible variables/arrays involved:** RHS, NRHS, and LRHS

**Possible values:**

0: standard factorization not involving right-hand sides.

1: forward elimination (Equation (3)) of the right-hand side vectors is performed during factorization (JOB=2). The solve phase (JOB=3) will then only involve backward substitution (Equation (4)).

**Default value:** 0 (standard factorization)

**Incompatibility:** This option is incompatible with sparse right-hand sides (ICNTL(20)=1), with the solution of the transposed system (ICNTL(9) ≠ 1), and with the computation of entries of the inverse (ICNTL(30)).

Furthermore, iterative refinement (ICNTL(10)) and error analysis (ICNTL(11)) are disabled. Finally, the current implementation imposes that all right-hand sides are processed in one pass during the backward step. Therefore, the blocking size (ICNTL(27)) is ignored.

**Remarks:** The right-hand sides must be dense to use this functionality: RHS, NRHS, and LRHS should be provided as described in Subsection 5.11.1. They should be provided at the beginning of the factorization phase (JOB=2) rather than at the beginning of the solve phase (JOB=3). We advise to use this option only for a reasonable number of dense right-hand side vectors because of the additional storage required when this option is activated.

### 5.11 Right-hand side and solution vectors/matrices

MUMPS can solve the systems $AX = B$ or $A^TX = B$ where $X, B \in \mathbb{R}^{n \times nrhs}$. The $B$ matrix is referred to as the right-hand side and the $X$ matrix to as the solution.

MUMPS gives the option to input the right-hand side matrix $B$ in dense or in sparse format but always centralized on the host processor, and to output the solution matrix $X$ centralized or distributed, but always in dense format. Sparsity of the right-hand side can be exploited to accelerate the solution phase [11, 12, 36, 30]. Note that the first step of the solution phase involves the distribution (scatter step) of the right-hand side onto the processors. The cost of scatter can be highly reduce in when right-hand sides are sparse and provided in a sparse format.

Moreover, MUMPS can optionally compute some entries of the inverse $A^{-1}$ solving the system with a particular sparse right-hand side $B$ (see Subsection 5.11.3).
The formats of the right-hand side and of the solution vectors are controlled by $\text{ICNTL}(20)$ and $\text{ICNTL}(21)$, respectively.

**ICNTL(20)** determines the format (dense or sparse) of the right-hand side.

*Phase:* accessed by the host during the solve phase.

*Possible variables/arrays involved:* $\text{RHS}$, $\text{NRHS}$, $\text{LRHS}$, $\text{IRHS}\_\text{SPARSE}$, $\text{RHS}\_\text{SPARSE}$, $\text{IRHS}\_\text{PTR}$ and $\text{NZ}\_\text{RHS}$.

*Possible values:*

0: the right-hand side is in dense format in the structure component $\text{RHS}$, $\text{NRHS}$, $\text{LRHS}$ (see Subsection 5.11.1)

1, 2, 3: the right-hand side is in sparse format in the structure components $\text{IRHS}\_\text{SPARSE}$, $\text{RHS}\_\text{SPARSE}$, $\text{IRHS}\_\text{PTR}$ and $\text{NZ}\_\text{RHS}$.

1: The decision of exploiting sparsity of the right-hand side to accelerate the solution phase is done automatically.

2: Sparsity of the right-hand side is NOT exploited to improve solution phase.

3: Sparsity of the right-hand side is exploited during solution phase.

Values different from 0, 1, 2 or 3 are treated as 0. For a sparse right-hand side, the recommended value is 1.

*Default value:* 0 (dense right-hand sides)

*Incompatibility:* When $\text{ICNTL}(20)=0$ (dense right-hand side) and $\text{NRHS} > 1$ (multiple right-hand side) the functionalities related to iterative refinement ($\text{ICNTL}(10)$) and error analysis ($\text{ICNTL}(11)$) are currently disabled.

With sparse right-hand sides ($\text{ICNTL}(20)=1$), the forward elimination during the factorization ($\text{ICNTL}(32)=1$) is not currently available.

*Remarks:* For details on how to set the input parameters see Subsection 5.11.1 and Subsection 5.11.2. Please note that duplicate entries in the sparse right-hand sides are summed.

**ICNTL(21)** determines the distribution (centralized or distributed) of the solution vectors.

*Phase:* accessed by the host during the solve phase.

*Possible variables/arrays involved:* $\text{RHS}$, $\text{NZ}\_\text{RHS}$, $\text{ISOL}\_\text{loc}$ and $\text{SOL}\_\text{loc}$, $\text{LSOL}\_\text{loc}$

*Possible values:*

0: the solution vector is assembled and stored in the structure component $\text{RHS}$ (gather phase), that must have been allocated earlier by the user (see Subsection 5.11.4).

1: the solution vector is kept distributed on each slave processor in the structure components $\text{ISOL}\_\text{loc}$ and $\text{SOL}\_\text{loc}$. $\text{ISOL}\_\text{loc}$ and $\text{SOL}\_\text{loc}$ must then have been allocated by the user and must be of size at least $\text{INFO}(23)$, where $\text{INFO}(23)$ has been returned by $\text{MUMPS}$ at the end of the factorization phase (see Subsection 5.11.5).

Values different from 0 and 1 are currently treated as 0.

*Default value:* 0 (assembled centralized format)

*Incompatibility:* If the solution is kept distributed, error analysis and iterative refinement (controlled by $\text{ICNTL}(10)$ and $\text{ICNTL}(11)$) are not applied.

### 5.11.1 Dense right-hand side ($\text{ICNTL}(20)=0$)

In this case, the matrix $\mathbf{B}$ of size $n \times \text{nrhs}$ is input in a one dimensional array of size $\text{lrhs} \times \text{nrhs}$ where the leading dimension $\text{lrhs}$ must be $\geq n$, the dimension of the matrix $\mathbf{A}$.

The following components of the $\text{MUMPS}$ structure should be allocated by the user on the host before a call to $\text{MUMPS}$ with $\text{JOB}=3, 5, or 6$ (call including the solve) if forward and backward elimination are both computed during the solve ($\text{ICNTL}(32)=0$), or before a call to $\text{MUMPS}$ with $\text{JOB}=2, 4$ (call including the factorization) if the forward elimination is computed during the factorization ($\text{ICNTL}(32)=1$).
mumps_par%RHS (real/complex pointer array, dimension LRHS×NRHS) is a real (complex in the complex version) array. On entry RHS(i+(k-1)×LRHS) must hold the i-th component of the k-th column of the right-hand side matrix (1 ≤ k ≤ NRHS) of the equations being solved. On exit, if the solution matrix has to be centralized (ICNTL(21)=0), then RHS(i+(k-1)×LRHS) will hold the i-th component of the k-th column of the solution matrix, 1 ≤ k ≤ NRHS. Otherwise, if the solution matrix has to be distributed (ICNTL(21)=1), on exit to the package, RHS will not contain any significant data for the user, even if it may have been modified.

mumps_par%NRHS (integer) is an optional parameter that should be set by the user to the number of right-hand side vectors. Otherwise, the value 1 is assumed.

mumps_par%LRHS (integer) is an optional parameter that should be set by the user, in the case where NRHS is set by the user. In this case, it must hold the leading dimension of the array RHS and should be greater than or equal to N (the matrix dimension). Otherwise, a single-column right-hand side is assumed and LRHS is not accessed.

5.11.2 Sparse right-hand side (ICNTL(20)=1,2,3)

If the user wants to compute the solution with sparse right-hand sides, the right-hand side matrix should be input as a sparse matrix in column format. Sparsity of the right-hand side can be exploited to accelerate the solution phase (see [36, 30]). Since exploiting sparsity requires some extra preprocessing it can be switched off by the user setting ICNTL(20) to 2.

In the following, an example of a 4x2 matrix B with 5 nonzeros is provided.

\[
B = \begin{pmatrix}
a_{11} & a_{22} \\
a_{31} & a_{32} \\
a_{41} & \\
\end{pmatrix}
\]

- total nonzeros in B: NZ_RHS = 5
- number of columns B (n. of rhs vectors): NRHS = 2
- pointers to the columns: IRHS_PTR [1 : NRHS+1] = 1 4 6
- array of row indices: IRHS_SPARSE [1 : NZ_RHS] = 1 3 4 2 3
- array of values: RHS_SPARSE [1 : NZ_RHS] = a_{11} a_{31} a_{41} a_{22} a_{32}

The following input parameters should be defined on the host only before a call to MUMPS including the solve phase (JOB=3, 5, or 6):

mumps_par%NZ_RHS (integer) should hold the total number of non-zeros in all the right-hand side vectors.

mumps_par%NRHS (integer), if set, should hold the number of right-hand side vectors. If not set, the value 1 is assumed.

mumps_par%RHS_SPARSE (real/complex pointer array, dimension NZ_RHS) should hold the numerical values of the non-zero entries of each right-hand side vector. This means that the B matrix should be input by columns.

mumps_par%IRHS_SPARSE (integer pointer array, dimension NZ_RHS) should hold the indices of the non-zero inputs of each right-hand side vector.

mumps_par%IRHS_PTR (integer pointer array, dimension NRHS+1) is such that the i-th right-hand side vector is defined by its non-zero row indices IRHS_SPARSE(IRHS_PTR(i)…IRHS_PTR(i+1)-1) and the corresponding numerical values RHS_SPARSE(IRHS_PTR(i)…IRHS_PTR(i+1)-1). Note that IRHS_PTR(1)=1 and IRHS_PTR(NRHS+1)=NZ_RHS+1.

mumps_par%RHS (real/complex pointer array, dimension LRHS×NRHS) must be allocated by the user on the host if the output solution should be centralized (ICNTL(21)=0). On exit from a call to MUMPS it will hold the centralized solution (ICNTL(21)=0).
5.11.3 A particular case of sparse right-hand side: computing entries of \( A^{-1} \) 
\( (\text{ICNTL}(30) = 1) \)

It is possible to compute some selected entries of the inverse matrix \( A^{-1} \) (see Subsection 3.15) using the control parameter \( \text{ICNTL}(30) \).

Let us consider the example below, in which

\[
A^{-1} = \begin{pmatrix}
a_{11}^{-1} & a_{12}^{-1} & a_{13}^{-1} & a_{14}^{-1} \\
a_{21}^{-1} & a_{22}^{-1} & a_{23}^{-1} & a_{24}^{-1} \\
a_{31}^{-1} & a_{32}^{-1} & a_{33}^{-1} & a_{34}^{-1} \\
a_{41}^{-1} & a_{42}^{-1} & a_{43}^{-1} & a_{44}^{-1}
\end{pmatrix}
\]

denotes the inverse of the matrix \( A \).

We would like to compute the boldface elements:

\[
A^{-1} = \begin{pmatrix}
a_{11}^{-1} & a_{12}^{-1} & a_{13}^{-1} & a_{14}^{-1} \\
a_{21}^{-1} & a_{22}^{-1} & a_{23}^{-1} & a_{24}^{-1} \\
a_{31}^{-1} & a_{32}^{-1} & a_{33}^{-1} & a_{34}^{-1} \\
a_{41}^{-1} & a_{42}^{-1} & a_{43}^{-1} & a_{44}^{-1}
\end{pmatrix}
\]

On input, the following parameters should be allocated and initialized:

- total entries \( A^{-1} \) to be computed: \( \text{NZ} \_\text{RHS} = 4 \)
- number of columns \( A^{-1} \): \( \text{NRHS} = N = 4 \)
- pointers to the columns: \( \text{IRHS} \_\text{PTR} = [1 : N \_\text{RHS} + 1] = 1 \ 3 \ 4 \ 4 \ 5 \)
- array of row indices: \( \text{IRHS} \_\text{SPARSE} = [1 : N \_\text{RHS}] = 1 \ 3 \ 3 \ 4 \)

Note that column 3 will be considered as empty, because no elements have to be computed.

The following parameter should be allocated, but not initialized:

- array of values: \( \text{RHS} \_\text{SPARSE} = [1 : N \_\text{RHS}] \)

On output, the following parameters will hold the requested entries:

- total entries \( A^{-1} \) to be computed: \( \text{NZ} \_\text{RHS} = 4 \)
- number of columns \( A^{-1} \): \( \text{NRHS} = N = 4 \)
- pointers to the columns: \( \text{IRHS} \_\text{PTR} = [1 : N \_\text{RHS} + 1] = 1 \ 3 \ 4 \ 4 \ 5 \)
- array of row indices: \( \text{IRHS} \_\text{SPARSE} = [1 : N \_\text{RHS}] = 1 \ 3 \ 3 \ 4 \)
- array of values: \( \text{RHS} \_\text{SPARSE} = [1 : N \_\text{RHS}] = a_{11}^{-1} \ a_{31}^{-1} \ a_{32}^{-1} \ a_{44}^{-1} \)

\( \text{ICNTL}(30) \) computes a user-specified set of entries in the inverse \( A^{-1} \) of the original matrix.

**Phase:** accessed during the solution phase.

**Possible variables/arrays involved:** \( \text{NZ} \_\text{RHS}, \text{NRHS}, \text{RHS} \_\text{SPARSE}, \text{IRHS} \_\text{SPARSE}, \text{IRHS} \_\text{PTR} \)

**Possible values:**

- 0: no entries in \( A^{-1} \) are computed.
- 1: computes entries in \( A^{-1} \).

Other values are treated as 0.

**Default value:** 0 (no entries in \( A^{-1} \) are computed)

**Incompatibility:** Error analysis and iterative refinement will not be performed, even if the corresponding options are set (\( \text{ICNTL}(10) \) and \( \text{ICNTL}(11) \)). Because the entries of \( A^{-1} \) are returned in \( \text{RHS} \_\text{SPARSE} \) on the host, this functionality is incompatible with the distributed solution option (\( \text{ICNTL}(21) \)). Furthermore, computing entries of \( A^{-1} \) is not possible in the case of partial factorizations with a Schur complement (\( \text{ICNTL}(19) \)). Option to compute solution using \( A \) or \( A^T \) (\( \text{ICNTL}(9) \)) is meaningless and thus ignored.
Related parameters: ICNTL(27)

Remarks: When a set of entries of $A^{-1}$ is requested, the associated set of columns will be computed in blocks of size ICNTL(27). In an out-of-core context (ICNTL(22)=1), larger ICNTL(27) values will most likely decrease the amount of factors read from the disk and reduce the solution time [40, 36, 11]. In an in-core context, the effects might be mixed.

The user must specify on input to a call of the solve phase in the arrays IRHS_PTR and IRHS_SPARSE the target entries. The array RHS_SPARSE should be allocated but not initialized.

Note that since selected entries of the inverse of the matrix are requested, NRHS must be set to $N$. On output the arrays IRHS_PTR, IRHS_SPARSE and RHS_SPARSE will hold the requested entries. If duplicate target entries are provided then duplicate solutions will be returned.

When entries of $A^{-1}$ are requested (ICNTL(30) = 1), mumps_par%RHS needs not be allocated.

5.11.4 Centralized solution (ICNTL(21)=0)
The solution vector $X$ can be returned centralized on the host in both cases: dense or sparse right-hand side vectors. The matrix $X$ will be returned as a dense vector in the array mumps_par%RHS. For this reason the mumps_par%RHS should be allocated even when the right-hand side matrix $B$ is input in sparse format.

5.11.5 Distributed solution (ICNTL(21)=1)
On some networks with low bandwidth, and especially when there are many right-hand side vectors, centralizing the solution on the host processor might be a costly part of the solution phase. If this is critical to the user, this functionality allows the solution to be left distributed over the processors (ICNTL(21)=1). The solution should then be exploited in its distributed form by the user application.

Note that this option can be used only with JOB=3 and should not be used with JOB=5 or 6, because some parameters needed for this option must be set using information output by the factorization.

The following input parameters should be allocated by the user before the solve phase (JOB=3) on all processors in the case of the working host model of parallelism (PAR=1), and on all processors except the host in the case of the non-working host model of parallelism (PAR=0).

mumps_par%SOL_loc (real/complex pointer array, dimension LSOL_loc×NRHS where NRHS is either equal to 1 or corresponds to the value provided by the user in NRHS on the host) must be allocated by the user between the factorization and solve steps. Its leading dimension LSOL_loc should be larger than or equal to INFO(23), that is returned by the factorization phase.

On exit from the solve phase, SOL_loc(i+(k-1)×LSOL_loc) will contain the value corresponding to variable ISOL_loc(i) in the $k$th solution vector.

mumps_par%LSOL_loc (integer). LSOL_loc must be set to the leading dimension of SOL_loc (see above) and should be larger than or equal to INFO(23), that is returned by the factorization phase.

mumps_par%ISOL_loc (integer pointer array, of dimension at least INFO(23), that is returned by the factorization phase) must be allocated by the user between the factorization and solve steps.

On exit from the solve phase, ISOL_loc(i) contains the index of the variables for which the solution (in SOL_loc) is available on the local processor.

If successive calls to the solve phase (JOB=3) are performed for a given matrix, ISOL_loc will have the same contents for each of these calls.

Note that if the solution is kept distributed, then functionalities related to error analysis and iterative refinement (ICNTL(10) and ICNTL(11)) are currently not available.

5.12 Schur complement with reduced or condensed right-hand side (ICNTL(19) and ICNTL(26))
MUMPS gives the possibility to perform the partial factorization of the complete matrix and to return the Schur matrix, that is the part of the matrix still to be factorized. The Schur matrix will be returned as a full matrix, distributed in different ways (see Subsection 5.12.1, Subsection 5.12.3 and Subsection 5.12.2).
ICNTL(19) computes the Schur complement matrix.

Phase: accessed by the host during the analysis phase.

Possible variables/arrays involved: SIZE_SCHUR, LISTVAR_SCHUR, NPROW, NPCOL, MBLOCK, NBLOCK, SCHUR, SCHUR_MLOC, SCHUR_NLOC, and SCHUR_LLD

Possible values:

0: complete factorization. No Schur complement is returned.
1: the Schur complement matrix will be returned centralized by rows on the host after the factorization phase. On the host before the analysis phase, the user must set the integer variable SIZE_SCHUR to the size of the Schur matrix, the integer pointer array LISTVAR_SCHUR to the list of indices of the Schur matrix.
2 or 3: the Schur complement matrix will be returned distributed by columns: the Schur will be returned on the slave processors in the form of a 2D block cyclic distributed matrix (ScalAPACK style) after factorization. Workspace should be allocated by the user before the factorization phase in order for MUMPS to store the Schur complement (see SCHUR, SCHUR_MLOC, SCHUR_NLOC, and SCHUR_LLD in Subsection 5.12). On the host before the analysis phase, the user must set the integer variable SIZE_SCHUR to the size of the Schur matrix, the integer pointer array LISTVAR_SCHUR to the list of indices of the Schur matrix. The integer variables NPROW, NPCOL, MBLOCK, NBLOCK may also be defined (default values will otherwise be provided).

Values not equal to 1, 2 or 3 are treated as 0.

Default value: 0 (complete factorization)

Incompatibility: since the Schur complement is a partial factorization of the global matrix (with partial ordering of the variables provided by the user), the following options of MUMPS are incompatible with the Schur option: maximum transversal, scaling, iterative refinement, error analysis and parallel analysis.

Related parameters: ICNTL(7)

Remarks: If the ordering is given (ICNTL(7)=1) then the following property should hold: PERM_IN(LISTVAR_SCHUR(i)) = N-SIZE_SCHUR + i, for i=1, SIZE_SCHUR.

Note that, in order to have a centralized Schur complement matrix by columns (see Subsection 5.12.3), it is possible (and recommended) to use a particular case of the distributed Schur complement (ICNTL(19)=2 or 3), where the Schur complement is assigned to only one processor (NPCOL x NPROW = 1).

If ICNTL(19) = 1,2,3 the user should give on input on the host before the analysis phase the following parameters:

mumps_par%SIZE_SCHUR (integer) must be initialized to the number of variables defining the Schur complement. It is only accessed during the analysis phase and is not altered by MUMPS. Its value is communicated internally to the other phases as required. SIZE_SCHUR should be greater or equal to 0 and strictly smaller than N.

mumps_par%LISTVAR_SCHUR (integer pointer array, dimension SIZE_SCHUR) must be allocated and initialized by the user so that LISTVAR_SCHUR(i), i=1, ..., SIZE_SCHUR must hold the i-th variable of the Schur complement matrix. It is accessed during analysis (JOB=1) and it is not altered by MUMPS.

If a given ordering (Subsection 5.4.2, ICNTL(7) =1) is set by the user, the permutation should also include the variables of the Schur complement, so that: PERM_IN(LISTVAR_SCHUR(i))=N-SIZE_SCHUR+i, for 1 ≤ i ≤ SIZE_SCHUR.

5.12.1 Centralized Schur complement stored by rows (ICNTL(19)=1)

Note that this option is becoming obsolete and is not recommended anymore because the memory for the Schur is doubled and because it requires a copy or message transfer of the Schur computed internally by MUMPS into the SCHUR argument. If a centralized Schur complement is required, we refer the user to the Subsection 5.12.3 “Centralized Schur complement stored by columns” instead.
mumps\_par\%SCHUR is a \textbf{real} (\textbf{complex} in the complex version) 1-dimensional pointer array that should point to SIZE\_SCHUR $\times$ SIZE\_SCHUR locations in memory. It must be allocated by the user on the host (independently of the value of PAR) before the factorization phase. On output from the factorization phase, and on the host node, the 1-dimensional pointer array SCHUR of length SIZE\_SCHUR $\times$ SIZE\_SCHUR holds the (dense) Schur matrix of order SIZE\_SCHUR. Note that the order of the indices in the Schur matrix is identical to the order provided by the user in LISTVAR\_SCHUR and that the Schur matrix is stored by rows. If the matrix is symmetric then only the lower triangular part of the Schur matrix is provided (by rows) and the upper part is not significant. This can also be viewed as the upper triangular part stored by columns in which case the lower part is not defined.

5.12.2 Distributed Schur complement (ICNTL(19) = 2 or 3)\footnote{MUMPS gives the possibility to output the Schur complement matrix distributed onto the processors (ICNTL(19) = 2, 3) using a 2D block cyclic distribution (please refer to [17] (for example) for the notion of grid of processors and 2D block cyclic distributions) stored by columns.}

For symmetric matrices, if ICNTL(19) = 2, only the lower part of the Schur matrix is generated, otherwise, if ICNTL(19) = 3, the complete Schur matrix is generated.

For unsymmetric matrices MUMPS always provides the complete Schur matrix, so that ICNTL(19) = 2 and ICNTL(19) = 3 have the same effect.

\textit{On entry to the analysis phase} (JOB = 1), the following parameters should be defined on the host:

- mumps\_par\%NPROW, mumps\_par\%NPCOL, mumps\_par\%MBLOCK, and mumps\_par\%NBLOCK are integers corresponding to a 2D block cyclic grid of processors. If any of these quantities is smaller than or equal to zero or has not been defined by the user, or if NPROW $\times$ NPCOL is larger than the number of slave processors available (total number of processors if PAR = 1, total number of processors minus 1 if PAR = 0), then a grid shape will be computed by the analysis phase of MUMPS and NPROW, NPCOL, MBLOCK, NBLOCK will be overwritten on exit from the analysis phase. We briefly describe here the meaning of the four above parameters in a 2D block cyclic distribution:
  - NPROW is the number of rows of the process grid (or the number of processors in a column of the process grid),
  - NPCOL is the number of columns of the process grid (or the number of processors in a row of the process grid),
  - MBLOCK is the blocking factor used to distribute the rows of the Schur complement,
  - NBLOCK is the blocking factor used to distribute the columns of the Schur complement.

As in ScaLAPACK, we use a row-major process grid of processors, that is, process ranks (as provided to MUMPS in the MPI communicator) are consecutive in a row of the process grid. NPROW, NPCOL, MBLOCK and NBLOCK should be passed unchanged from the analysis phase to the factorization phase. If the matrix is symmetric (SYM = 1 or 2) and ICNTL(19) = 3 (see below), then the values of MBLOCK and NBLOCK should be equal.

\textit{On exit from the analysis phase}, the following two components are set by MUMPS on the first NPROW $\times$ NPCOL slave processors (the host is excluded if PAR = 0 and the processors with largest MPI ranks in the communicator provided to MUMPS may not be part of the grid of processors).

mumps\_par\%SCHUR\_MLOC is an integer giving the number of rows of the local Schur complement matrix on the concerned processor. It is equal to MAX(1, NUMROC(SIZE\_SCHUR, MBLOCK, myrow, 0, NPROW)), where
  - NUMROC is an integer function defined in most ScaLAPACK implementations (also used internally by the MUMPS package),
  - SIZE\_SCHUR, MBLOCK, NPROW have been defined earlier, and
  - myrow is defined as follows:
    - Let myid be the rank of the calling process in the communicator COMM provided to MUMPS. (myid can be returned by the MPI routine MPI\_COMM\_RANK.)
– if \( PAR = 1 \) \( myrow \) is equal to \( myid \) / \( NPCOL \),
– if \( PAR = 0 \) \( myrow \) is equal to \((myid − 1) / NPCOL\).

Note that an upperbound of the minimum value of leading dimension (\( SCHUR\_LLD \) defined below) is equal to \( ((\text{SIZE\_SCHUR}+\text{MBLOCK}-1)/\text{MBLOCK}+\text{NPROW}-1)/\text{NPROW}^*\text{MBLOCK} \).

\text{mumps\_par\%SCHUR\_NLOC} \) is an integer giving the number of columns of the local Schur complement matrix on the concerned processor. It is equal to \( \text{NUMROC(\text{SIZE\_SCHUR}, \text{NBLOCK}, mycol, 0, NPCOL) \), where} \)

- \( \text{SIZE\_SCHUR}, \text{NBLOCK}, \text{NPCOL} \) have been defined earlier, and
- \( mycol \) is defined as follows:
  Let \( myid \) be the rank of the calling process in the communicator \( \text{COMM} \) provided to \( \text{MUMPS} \).
  \( myid \) can be returned by the MPI routine \( \text{MPI\_COMM\_RANK} \).)
  – if \( PAR = 1 \) \( mycol \) is equal to \( \text{MOD}(myid, NPCOL) \),
  – if \( PAR = 0 \) \( mycol \) is equal to \( \text{MOD}(myid − 1, NPCOL) \).

On entry to the factorization phase (\( \text{JOB} = 2 \)), the user should give on input the following components of the structure:

\text{mumps\_par\%SCHUR\_LLD} \) (integer) should be set to the leading dimension of the local Schur complement matrix. It should be larger or equal to the local number of rows of that matrix, \( \text{SCHUR\_MLOC} \) (as returned by \( \text{MUMPS} \) on exit from the analysis phase on the processors that participate in the computation of the Schur). \( \text{SCHUR\_LLD} \) is not modified by \( \text{MUMPS} \).

\text{mumps\_par\%SCHUR} \) (real/complex one-dimensional pointer array) should be allocated by the user on the \( NPROW \times NPCOL \) first slave processors (the host is excluded if \( PAR=0 \) and the processors with largest MPI ranks in the communicator provided to \( \text{MUMPS} \) may not be part of the grid of processors). Its size should be at least equal to \( \text{SCHUR\_LLD} \times (\text{SCHUR\_NLOC} - 1) + \text{SCHUR\_MLOC} \), where \( \text{SCHUR\_MLOC}, \text{SCHUR\_NLOC}, \text{SCHUR\_LLD} \) have been defined above.

On exit from the factorization phase, the pointer array \( \text{SCHUR} \) contains the Schur complement, stored by columns, in the format corresponding to the 2D cyclic grid of \( NPROW \times NPCOL \) processors, with block sizes \( \text{MBLOCK} \) and \( \text{NBLOCK} \), and local leading dimensions \( \text{SCHUR\_LLD} \).

Note that if \( \text{ICNTL(19)} = 3 \) and the Schur is symmetric (\( \text{SYM}=1 \) or \( 2 \)), then the constraint \( \text{mumps\_par\%MBLOCK} = \text{mumps\_par\%NBLOCK} \) should hold.

Note that setting \( NPCOL \times NPROW = 1 \) will centralize the Schur complement matrix, stored by columns (instead of by rows as in the \( \text{ICNTL(19)} = 1 \) option). More details on this are presented in Subsection 5.12.3.

5.12.3 Centralized Schur complement stored by columns (\( \text{ICNTL(19)} = 2 \) or \( 3 \))

In order to have a centralized Schur complement matrix by columns, it is possible to use a particular case of the distributed Schur complement (\( \text{ICNTL(19)} = 2 \) or \( 3 \), see Subsection 5.12.2), where the Schur complement is only assigned to one processor (\( NPCOL \times \text{NPROW} = 1 \)). Therefore we refer the reader to the previous section for a detailed description of the parameters for using this option. This option is recommended compared to \( \text{ICNTL(19)} = 1 \) (centralized Schur complement by rows).

The Schur complement matrix will be available on the host node if \( PAR=1 \), and on the node with MPI identifier 1 (first working slave processor) if \( PAR=0 \).

Let us summarize a simple case of use, where the user wants a centralized Schur complement and where \( PAR=1 \) (working host node).

On top of \( \text{SIZE\_SCHUR} \) and \( \text{LISTVAR\_SCHUR} \) described earlier, the user should set the following parameters on the host on entry to the analysis phase:

\( NPROW = NPCOL = 1 \), in order to define a distribution that uses only one processor (the host, assuming that \( PAR=1 \));

\( \text{MBLOCK} = \text{NBLOCK} = 100 \). Those arguments must be provided and be strictly positive but their actual value will not change the distribution since \( NPROW=NPCOL=1 \).

\( \text{ICNTL(19)} = 2 \) or \( 3 \).
On entry to the factorization phase, the user should provide on the host:

\texttt{mumps\_par\%SCHUR\_LLD=SIZE\_SCHUR}: we consider here the simple case where the leading dimension of the Schur is equal to its order.

\texttt{mumps\_par\%SCHUR}, a real (complex in the complex version) one-dimensional pointer array of size \( \text{SIZE\_SCHUR} \times \text{SIZE\_SCHUR} \) that should be allocated by the user.

On exit from the factorization phase, the pointer array \texttt{SCHUR} available on the host contains the Schur complement. If the matrix is unsymmetric (\texttt{SYM}=0), then the settings \texttt{ICNTL(19)=2} and \texttt{ICNTL(19)=3} have an identical behaviour and the unsymmetric Schur complement is returned by columns (i.e., in column-major format). If the matrix is symmetric (\texttt{SYM}=1 or 2) and \texttt{ICNTL(19)=2}, then only the lower triangular part of the symmetric Schur is returned, stored by columns, and the upper triangular part should not be accessed. Note that this is equivalent to say that the upper triangular part is returned by rows and the lower triangular part is not accessed. If the matrix is symmetric (\texttt{SYM}=1 or 2) and \texttt{ICNTL(19)=3}, then both the lower and upper triangular parts are returned. Because the Schur complement is symmetric, this can be seen both as a row-major and as a column-major storage.

5.12.4 Using partial factorization during solution phase (\texttt{ICNTL(26) = 0, 1 or 2})

As explained in Subsection 3.16, when a Schur complement has been computed during the factorization phase, either the solution phase computes a solution on the internal problem (\texttt{ICNTL(26)=0}) or the complete problem can be used to first condensed the right-hand side on the Schur variables (\texttt{ICNTL(26)=1}). Then the condensed right-hand side is made available to the user for computing the local solution using the Schur matrix. This local solution corresponding to Schur variables can then be expanded to compute a global solution (\texttt{ICNTL(26)=2}).

\texttt{ICNTL(26)} drives the solution phase if a Schur complement matrix has been computed (\texttt{ICNTL(19) \neq 0}, see Subsection 3.16 for details)

\textit{Phase}: accessed by the host during the solution phase. It will be accessed also during factorization if the forward elimination is performed during factorization (\texttt{ICNTL(32)=1})

\textit{Possible variables/arrays involved}: \texttt{REDRHS}, \texttt{LREDRHS}

\textit{Possible values}:

0: standard solution phase on the internal problem; referring to the notations from Subsection 3.16, only the system \( A_1 \cdot x_1 = b_1 \) is solved and the entries of the right-hand side corresponding to the Schur are explicitly set to 0 on output.

1: condense/reduce the right-hand side on the Schur. Only a forward elimination is performed. The solution corresponding to the "internal" (non-Schur) variables is returned together with the reduced/condensed right-hand-side. The reduced right-hand side is made available on the host in the pointer array \texttt{REDRHS}, that must be allocated by the user. Its leading dimension \texttt{LREDRHS} must be provide, too.

2: expand the Schur local solution on the complete solution variables. \texttt{REDRHS} is considered to be the solution corresponding to the Schur variables. It must be allocated by the user as well as its leading dimension \texttt{LREDRHS} must be provided. The backward substitution is then performed with the given right-hand side to compute the solution associated with the "internal" variables. Note that the solution corresponding to the Schur variables is also made available in the main solution vector/matrix.

Values different from 1 and 2 are treated as 0.

\textit{Default value}: 0 (normal solution phase)

\textit{Incompatibility}: if \texttt{ICNTL(26) = 1 or 2}, then error analysis and iterative refinements are disabled (\texttt{ICNTL(11)} and \texttt{ICNTL(10)})

\textit{Related parameters}: \texttt{ICNTL(19)}, \texttt{ICNTL(32)}

\(^8\)As said above, we assume a working host model (\texttt{PAR}=1), otherwise this becomes processor 1 – please refer to the general description from paragraph “Distributed Schur Complement” above for more information.
Figure 2: Solving the complete system using the Schur complement matrix

\[
\begin{bmatrix}
L_{11} & \cdot & \cdot & \cdot & \cdot \\
L_{21} & I & \cdot & \cdot & \cdot \\
\cdot & \cdot & U_{11} & U_{12} & \cdot \\
\cdot & \cdot & S & X_1 & \cdot \\
\cdot & \cdot & \cdot & X_2 & \cdot \\
\end{bmatrix}
\begin{bmatrix}
NRHS \\
NRHS \\
\end{bmatrix}
= 
\begin{bmatrix}
B_1 \\
B_2 \\
\end{bmatrix}
\]

SIZE_SCHUR
SIZE_SCHUR

Remarks: If ICNTL(26) \(\neq 0\), then the user should provide workspace in the pointer array REDRHS, as well as a leading dimension LREDRHS (see Subsection 5.12). Note that if no Schur complement was computed, ICNTL(26) = 1 or 2 results in an error.

If the complete system should be solved using the Schur complement matrix (see Subsection 3.16, ICNTL(26) =1 or 2), then the following parameters must be defined on the host on entry to the solution step:

- input the right-hand side matrix \([B_1 B_2]^T\) (see Figure 2), the user can input the right-hand side matrix as a dense matrix (ICNTL(20) = 0, RHS, LRHS, NRHS, see Subsection 5.11.1) or as a sparse matrix (ICNTL(20) = 1, NZ_RHS, NRHS, RHS_SPARSE, IRHS_SPARSE, IRHS_PTR, see Subsection 5.11.2).

- mumps_par%LREDRHS is an optional integer parameter defining the leading dimension of the reduced right-hand side, REDRHS, that must be set by the user when NRHS is provided and it must be larger or equal to SIZE_SCHUR, the size of the Schur complement. Otherwise it will be considered equal to 1.

- mumps_par%REDRHS is a real (complex in the complex version) one-dimensional pointer array that should be allocated by the user before entering the solution phase. Its size should be at least equal to LREDRHS \(\times (\text{NRHS}-1) + \text{SIZE}_\text{SCHUR}\).

If the reduction/condensation phase should be performed (ICNTL(26) =1), then on exit from the solution phase, REDRHS(i+(k-1)*LREDRHS), i=1, ..., SIZE_SCHUR, k=1, ..., NRHS will hold the reduced right-hand side (the y_2 vector of Equation (13)).

If the expansion phase should be performed (ICNTL(26) =2), then REDRHS(i+(k-1)*LREDRHS), i=1, ..., SIZE_SCHUR, k=1, ..., NRHS must be set (on entry to the solution phase) to the solution on the Schur variables (the x_2 vector of Equation (14)). In this case (ie, ICNTL(26) =2) REDRHS is not altered by MUMPS.

Note that on exit, the solution matrix \([X_1 X_2]^T\), in Figure 2 is in the RHS vector.
6 Control parameters

On exit from the initialization call (\texttt{JOB} = \texttt{-1}), the control parameters are set to default values. If the user wishes to use values other than the defaults, the corresponding entries in \texttt{mumps.par\%ICNTL} and \texttt{mumps.par\%CNTL} should be reset after this initial call and before the call in which they are used.

6.1 Integer control parameters

\texttt{mumps.par\%ICNTL} is an integer array of dimension 40.

- \texttt{ICNTL(1)} is the output stream for error messages
- \texttt{ICNTL(2)} is the output stream for diagnostic printing, statistics, and warning message
- \texttt{ICNTL(3)} is the output stream for global information, collected on the host
- \texttt{ICNTL(4)} is the level of printing for error, warning, and diagnostic messages
- \texttt{ICNTL(5)} controls the matrix input format
- \texttt{ICNTL(6)} permutes the matrix to a zero-free diagonal and/or scale the matrix
- \texttt{ICNTL(7)} computes a symmetric permutation in case of sequential analysis
- \texttt{ICNTL(8)} describes the scaling strategy
- \texttt{ICNTL(9)} computes the solution using \( A \) or \( A^T \)
- \texttt{ICNTL(10)} applies the iterative refinement to the computed solution
- \texttt{ICNTL(11)} computes statistics related to an error analysis
- \texttt{ICNTL(12)} defines an ordering strategy for symmetric matrices
- \texttt{ICNTL(13)} controls the parallelism of the root node
- \texttt{ICNTL(14)} controls the percentage increase in the estimated working space
- \texttt{ICNTL(18)} defines the strategy for the distributed input matrix
- \texttt{ICNTL(19)} computes the Schur complement matrix
- \texttt{ICNTL(20)} determines the format (dense or sparse) of the right-hand sides
- \texttt{ICNTL(21)} determines the distribution (centralized or distributed) of the solution vectors
- \texttt{ICNTL(22)} controls the in-core/out-of-core (OOC) factorization and solve
- \texttt{ICNTL(23)} corresponds to the maximum size of the working memory in MegaBytes that \texttt{MUMPS} can allocate per working processor
- \texttt{ICNTL(24)} controls the detection of “null pivot rows”
- \texttt{ICNTL(25)} allows the computation of a solution of a deficient matrix and also of a null space basis
- \texttt{ICNTL(26)} drives the solution phase if a Schur complement matrix
- \texttt{ICNTL(27)} controls the blocking size for multiple right-hand sides
- \texttt{ICNTL(28)} determines whether a sequential or parallel computation of the ordering is performed
- \texttt{ICNTL(29)} defines the parallel ordering tool to be used to compute the fill-in reducing permutation
- \texttt{ICNTL(30)} computes a user-specified set of entries in the inverse \( A^{-1} \) of the original matrix
- \texttt{ICNTL(31)} indicates which factors may be discarded during the factorization
- \texttt{ICNTL(32)} performs the forward elimination of the right-hand sides during the factorization
- \texttt{ICNTL(33)} computes the determinant of the input matrix

\texttt{ICNTL(1)} is the output stream for error messages.

Possible values:

\[ \leq 0: \] these messages will be suppressed.
> 0 : is the output stream.  
*Default value*: 6 (standard output stream)

**ICNTL(2)** is the output stream for diagnostic printing, statistics, and warning messages.  
*Possible values*:
- \(\leq 0\): these messages will be suppressed.
- \(> 0\): is the output stream.  
*Default value*: 0

**ICNTL(3)** is the output stream for global information, collected on the host.  
*Possible values*:
- \(\leq 0\): these messages will be suppressed.
- \(> 0\): is the output stream.  
*Default value*: 6 (standard output stream)

**ICNTL(4)** is the level of printing for error, warning, and diagnostic messages.  
*Possible values*:
- \(\leq 0\): No messages output.
- 1: Only error messages printed.
- 2: Errors, warnings, and main statistics printed.
- 3: Errors and warnings and terse diagnostics (only first ten entries of arrays) printed.
- \(\geq 4\): Errors, warnings and information on input, output parameters printed.  
*Default value*: 2 (errors and warnings printed)

**ICNTL(5)** controls the matrix input format (see **Subsection 5.2.2**).  
*Phase*: accessed by the host and only during the analysis phase  
*Possible variables/arrays involved*: N, NZ, IRN, JCN, NZ_loc, IRN_loc, JCN_loc, A_loc, NELT, ELTPTR, ELTVAR, and A_ELTVAR  
*Possible values*:
- 0: assembled format. The matrix must be input in the structure components N, NZ, IRN, JCN, and A if the matrix is centralized on the host (see **Subsection 5.2.2.1**) or in the structure components N, NZ_loc, IRN_loc, JCN_loc, A_loc if the matrix is distributed (see **Subsection 5.2.2.2**).  
- 1: elemental format. The matrix must be input in the structure components N, NELT, ELTPTR, ELTVAR, and A_ELTVAR (see **Subsection 5.2.2.3**).  
*Default value*: 0 (assembled format)  
*Related parameters*: ICNTL(18)

*Remarks*: Note that parallel analysis (ICNTL(28) = 2) is only available for matrices in assembled format and, thus, an error will be raised for elemental matrices (ICNTL(5) = 1). Elemental matrices can be input only centralized on the host (ICNTL(18) = 0).

**ICNTL(6)** permutes the matrix to a zero-free diagonal and/or scale the matrix (see **Subsection 3.2** and **Subsection 5.3.2**).  
*Phase*: accessed by the host and only during sequential analysis (ICNTL(28) = 1)  
*Possible variables/arrays involved*: optionally UNS_PERM, mumps_par%A, COLSCA and RONSCA  
*Possible values*:
0: No column permutation is computed.
1: The permuted matrix has as many entries on its diagonal as possible. The values on the diagonal are of arbitrary size.
2: The permutation is such that the smallest value on the diagonal of the permuted matrix is maximized. The numerical values of the original matrix, (mumps_par%A), must be provided by the user during the analysis phase.
3: Variant of option 2 with different performance. The numerical values of the original matrix (mumps_par%A) must be provided by the user during the analysis phase.
4: The sum of the diagonal entries of the permuted matrix is maximized. The numerical values of the original matrix (mumps_par%A) must be provided by the user during the analysis phase.
5: The product of the diagonal entries of the permuted matrix is maximized. Scaling vectors are also computed and stored in COLSCA and ROWSCA, if ICNTL(8) is set to -2 or 77. With these scaling vectors, the nonzero diagonal entries in the permuted matrix are one in absolute value and all the off-diagonal entries less than or equal to one in absolute value. For unsymmetric matrices, COLSCA and ROWSCA are meaningful on the permuted matrix \( \mathbf{A} \mathbf{Q}_c \) (see Equation (5)). For symmetric matrices, COLSCA and ROWSCA are meaningful on the original matrix \( \mathbf{A} \). The numerical values of the original matrix, mumps_par%A, must be provided by the user during the analysis phase.
6: Similar to 5 but with a different algorithm. The numerical values of the original matrix, mumps_par%A, must be provided by the user during the analysis phase.
7: Based on the structural symmetry of the input matrix and on the availability of the numerical values, the value of ICNTL(6) is automatically chosen by the software.

Other values are treated as 0. On output from the analysis phase, INFOG(23) holds the value of ICNTL(6) that was effectively used.

Default value: 7 (automatic choice done by the package)

Incompatibility: If the matrix is symmetric positive definite (SYM = 1), or in elemental format (ICNTL(5) =1), or the parallel analysis is requested (ICNTL(28)=2) or the ordering is provided by the user (ICNTL(7)=1), or the Schur option (ICNTL(19) = 1, 2, or 3) is required, or the matrix is initially distributed (ICNTL(18)=1,2,3), then ICNTL(6) is treated as 0.

Related parameters: ICNTL(8), ICNTL(12)

Remarks: On assembled centralized unsymmetric matrices (ICNTL(5) =0, ICNTL(18)=0, SYM = 0), if ICNTL(6)=1, 2, 3, 4, 5, 6 a column permutation (based on weighted bipartite matching algorithms described in [20, 21]) is applied to the original matrix to get a zero-free diagonal. The user is advised to set ICNTL(6) to a nonzero value when the matrix is very unsymmetric in structure. On output to the analysis phase, when the column permutation is not the identity, the pointer UNS_PERM (internal data valid until a call to MUMPS with JOB=-2) provides access to the permutation on the host processor (see Subsection 5.3.1). Otherwise, the pointer is not associated.

The column permutation is such that entry \( a_i,perm(j) \) is on the diagonal of the permuted matrix.

On general assembled centralized symmetric matrices (ICNTL(5) =0, ICNTL(18)=0, SYM = 2), if ICNTL(6)=1, 2, 3, 4, 5, 6, the column permutation is internally used to determine a set of recommended 1x1 and 2x2 pivots (see [22] and the description of ICNTL(12) in Subsection 6.1 for more details). We advise either to let MUMPS select the strategy (ICNTL(6) = 7) or to set ICNTL(6) = 5 if the user knows that the matrix is for example an augmented system (which is a system with a large zero diagonal block). On output from the analysis the pointer UNS_PERM is not associated.

ICNTL(7) computes a symmetric permutation (ordering) to determine the pivot order to be used for the factorization in case of sequential analysis (ICNTL(28) =1). See Subsection 3.2 and Subsection 5.4.

Phase: accessed by the host and only during the sequential analysis phase (ICNTL(28) = 1).

Possible variables/arrays involved: PERM_IN, SYM_PERM

Possible values:
0: Approximate Minimum Degree (AMD) \([4]\) is used,
1: The pivot order should be set by the user in \texttt{PERM_in}, on the host processor. In that case, \texttt{PERM_in} must be allocated on the host by the user and \texttt{PERM_in}(i), \((i=1, \ldots N)\) must hold the position of variable \(i\) in the pivot order.
2: Approximate Minimum Fill (AMF) is used,
3: \texttt{SCOTCH}\(^9\) \([34]\) package is used if previously installed by the user otherwise treated as 7.
4: \texttt{PORD}\(^10\) \([38]\) is used if previously installed by the user otherwise treated as 7.
5: the \texttt{METIS}\(^11\) \([29]\) package is used if previously installed by the user otherwise treated as 7.
6: Approximate Minimum Degree with automatic quasi-dense row detection (QAMD) is used.
7: Automatic choice by the software during analysis phase. This choice will depend on the ordering packages made available, on the matrix (type and size), and on the number of processors.

Other values are treated as 7.

\textit{Default value:} 7 (automatic choice)

\textit{Incompatibility:} ICNTL(7) is meaningless if the parallel analysis is chosen \((ICNTL(28)=2)\).

\textit{Related parameters:} ICNTL(28)

\textit{Remarks:} Even when the ordering is provided by the user, the analysis must be performed before numerical factorization.

For \textit{assembled matrices} \((\text{centralized or distributed})\) \((ICNTL(5)=0)\) all the options are available.

For \textit{elemental matrices} \((ICNTL(5)=1)\), only options 0, 1, 5 and 7 are available, with option 7 leading to an automatic choice between AMD and METIS (options 0 or 5); other values are treated as 7.

If the user asks for a \textit{Schur complement matrix} \((ICNTL(19)=1, 2, 3)\) and

- the matrix is \textit{assembled} \((ICNTL(5)=0)\) then only options 0, 1, 5 and 7 are currently available. Other options are treated as 7.
- the matrix is \textit{elemental} \((ICNTL(5)=1)\) only options 0, 1 and 7 are currently available. Other options are treated as 7 which will (currently) be treated as 0 (AMD).
- in both cases (assembled or elemental matrix) if the pivot order is given by the user \((ICNTL(7)=1)\) then the following property should hold: \texttt{PERM_in(LISTVAR_SCHUR(i))} = \(N\)-\texttt{SIZE_SCHUR}+i, for \(i=1, \ldots \text{SIZE_SCHUR}\).

For matrices with \textit{relatively dense rows}, we highly recommend option 6 which may significantly reduce the time for analysis.

On output, the pointer array \texttt{SYM_PERM} provides access, on the host processor, to the symmetric permutation that is effectively computed during the analysis phase by the \texttt{MUMPS} package, and \texttt{INFOG(7)} to the ordering option that was effectively used. In fact, the option corresponding to ICNTL(7) may be forced by \texttt{MUMPS} when for example the ordering option chosen by the user is not compatible with the value of ICNTL(12) or the necessary package is not installed.

\texttt{SYM_PERM}(i), \(i=1, \ldots N\), holds the position of variable \(i\) in the pivot order, see \textbf{Subsection 5.4.1} for a full description.

\textbf{ICNTL(8) } describes the scaling strategy (see \textbf{Subsection 5.3}).

\textit{Phase:} accessed by the host during analysis phase (that need be sequential ICNTL(28)=1) or on entry to numerical factorization phase

\textit{Possible variables/arrays involved:} \texttt{COLSCA,ROWSCA}

\textit{Possible values :}

---

\(^9\)See \url{http://gforge.inria.fr/projects/scotch/} to obtain a copy.

\(^{10}\)Distributed within \texttt{MUMPS} by permission of J. Schulze (University of Paderborn).

\(^{11}\)See \url{http://glaros.dtc.umn.edu/gkhome/metis/metis/overview} to obtain a copy.
-2: Scaling computed during analysis (see [20, 21] for the unsymmetric case and [22] for the symmetric case). The user has to provide the numerical values of the original matrix (mumps_par%A) on entry to the analysis.

-1: Scaling provided by the user. Scaling arrays must be provided in COLSCA and ROWSCA on entry to the numerical factorization phase by the user, who is then responsible for allocating and freeing them. If the input matrix is symmetric (SYM= 1 or 2), then the user should ensure that the array ROWSCA is equal to (or points to the same location as) the array COLSCA.

0: No scaling applied/computed.

1: Diagonal scaling computed during the numerical factorization phase,

3: Column scaling computed during the numerical factorization phase,

4: Row and column scaling based on infinite row/column norms, computed during the numerical factorization phase,

7: Simultaneous row and column iterative scaling based on [37] and [13] computed during the numerical factorization phase,

8: Similar to 7 but more rigorous and expensive to compute; computed during the numerical factorization phase.

77: Automatic choice of the value of ICNTL(8) done during analysis.

Default value: 77 (automatic choice done by the package)

Related parameters: ICNTL(6), ICNTL(12)

Remarks: If ICNTL(8) = 77, then an automatic choice of the scaling option may be performed, either during the analysis or the factorization. The effective value used for ICNTL(8) is returned in INFOG(33). If the scaling arrays are computed during the analysis, then they are ready to be used by the factorization phase. Note that scalings can be efficiently computed during analysis when requested (see ICNTL(6) and ICNTL(12)).

If the input matrix is symmetric (SYM= 1 or 2), then only options –2, –1, 0, 1, 7, 8 and 77 are allowed and other options are treated as 0.

If the input matrix is in elemental format (ICNTL(5) = 1), then only options –1 and 0 are allowed and other options are treated as 0.

If the initial assembled matrix is distributed (ICNTL(18)=1,2,3 and ICNTL(5) = 0), then only options 7, 8 and 77 are allowed, otherwise no scaling is applied.

ICNTL(9) computes the solution using A or A^T.

Phase: accessed by the host during the solve phase.

Possible values:

1: AX = B is solved.

≠ 1: A^T X = B is solved.

Default value: 1

Related parameters: ICNTL(10), ICNTL(11), ICNTL(21), ICNTL(32)

Remarks: when a forward elimination is performed during the factorization (see ICNTL(32)) only ICNTL(9)=1 is allowed.

ICNTL(10) applies the iterative refinement to the computed solution.

Phase: accessed by the host during the solve phase.

Possible variables/arrays involved: NRHS

Possible values:

< 0: Fixed number of steps of iterative refinement. No stopping criterion is used.

0: No iterative refinement.

> 0: Maximum number of steps of iterative refinement. A stopping criterion is used, therefore a test for convergence is done at each step of the iterative refinement algorithm.
**Default value:** 0 (no iterative refinement)

**Related parameters:** CNTL(2)

**Incompatibility:** if ICNTL(21) =1 (solution kept distributed) or if ICNTL(32) =1 (forward elimination during factorization), or if NRHS >1 (multiple right hand sides), then ICNTL(10) is treated as 0.

**Remarks:** Note that if ICNTL(10)< 0, |ICNTL(10)| steps of iterative refinement are performed, without any test of convergence. This means that the iterative refinement may diverge, that is the solution instead of being improved may be worse from an accuracy point of view. But it has been shown [16] that with only two to three steps of iterative refinement the solution can often be significantly improved. So if the convergence test should not be done we recommend to set ICNTL(10) to -2 or -3.

See Subsection 3.3.1 for more details.

**ICNTL(11)** computes statistics related to an error analysis of the linear system solved (Ax = b or AT x = b (see ICNTL(9))).

**Phase:** accessed by the host and only during the solve phase.

**Possible variables/arrays involved:** NRHS

**Possible values:**
- 0 : no error analysis is performed (no statistics).
- 1 : compute all the statistics (very expensive).
- 2 : compute main statistics (norms, residuals, components of backward errors), but not the most expensive ones like (condition number and forward error estimates).

Values different from 0, 1, and 2 are treated as 0.

**Default value:** 0 (no statistics).

**Incompatibility:** if NRHS > 1, if ICNTL(32) =1 (forward elimination during factorization), or if ICNTL(21) =1 (solution kept distributed) then error analysis is not performed and ICNTL(11) is treated as 0.

**Related parameters:** ICNTL(9)

**Remarks:** The computed statistics are returned in various informational parameters, see also Subsection 3.3:

- If ICNTL(11)= 2, then the infinite norm of the input matrix (||A||∞ or ||AT||∞ in RINFOG(4)), the infinite norm of the computed solution (||x|| in RINFOG(5)), and the scaled residual ||Ax−b||∞ ||A||∞ ||x||∞ in RINFOG(6), a componentwise backward error estimate in RINFOG(7) and RINFOG(8) are computed.
- If ICNTL(11)= 1, then in addition to the above statistics also an estimate for the error in the solution in RINFOG(9), and condition numbers for the linear system in RINFOG(10) and RINFOG(11) are also returned.

If performance is critical, ICNTL(11) should be set to 0. If both performance is critical and statistics are requested, then ICNTL(11) should be set to 2. If ICNTL(11)=1, the error analysis is very costly (typically significantly more costly than the solve phase itself).

**ICNTL(12)** defines an ordering strategy for symmetric matrices (SYM = 2) (see [22] for more details) and is used in conjunction with ICNTL(6), to add constraints to the ordering algorithm (ICNTL(7) option).

**Phase:** accessed by the host and only during the analysis phase.

**Possible values:**
- 0 : automatic choice
1: usual ordering (nothing done)
2: ordering on the compressed graph associated with the matrix.
3: constrained ordering, only available with AMF (ICNTL(7)=2).

Other values are treated as 0.

Default value: 0 (automatic choice).

Incompatibility: If the matrix is unsymmetric (SYM=0) or symmetric definite positive matrices (SYM=1), or the matrix is in elemental format (ICNTL(5)=1), or the matrix is initially distributed (ICNTL(18)=1,2,3) or the ordering is provided by the user (ICNTL(7)=1), or the Schur option (ICNTL(19) ≠ 0) is required, ICNTL(12) is treated as 1 (nothing done).

Related parameters: ICNTL(6), ICNTL(7)

Remarks: If MUMPS detects some incompatibility between control parameters then it uses the following rules to automatically reset the control parameters. Firstly ICNTL(12) has a lower priority than ICNTL(7) so that if ICNTL(12) = 3 and the ordering required is not AMF then ICNTL(12) is internally treated as 2. Secondly ICNTL(12) has a higher priority than ICNTL(6) and ICNTL(8). Thus if ICNTL(12) = 2 and ICNTL(6) was not active (ICNTL(6)=0) then ICNTL(6) is treated as 5 if numerical values are provided, or as 1 otherwise. Furthermore, if ICNTL(12) = 3 then ICNTL(6) is treated as 5 and ICNTL(8) is treated as -2 (scaling computed during analysis).

On output from the analysis phase, INFOG(24) holds the value of ICNTL(12) that was effectively used. Note that INFOG(7) and INFOG(23) hold the values of ICNTL(7) and ICNTL(6) (respectively) that were effectively used.

ICNTL(13) controls the parallelism of the root node (enabling or not the use of ScaLAPACK) and also its splitting.

Phase: accessed by the host during the analysis phase.

Possible values:
≤ -1: treated as 0.
-1: force splitting of the root node in all cases (even sequentially)
0: parallel factorization of the root node. If the size of the root frontal node (last Schur complement to be factored) is larger than an internal threshold, then ScaLAPACK will be used for factoring it. Otherwise, the root node will be processed by a single MPI process.
> 0: forces a sequential factorization of the root node (ScaLAPACK will not be used). In this case if the number of working processors is strictly larger than ICNTL(13) then splitting of the root node is performed, in order to automatically recover part of the parallelism lost because the root node was processed sequentially.

Default value: 0 (parallel factorization on the root node)

Remarks: Processing the root sequentially (ICNTL(13) > 0) can be useful when the user is interested in the inertia of the matrix (see INFO(12) and INFOG(12)), or when the user wants to detect null pivots (see Subsection 5.7).
Although ICNTL(13) controls the efficiency of the factorization and solve phases, preprocessing work is performed during analysis and this option must be set on entry to the analysis phase.

ICNTL(14) controls the percentage increase in the estimated working space, see Subsection 5.6.

Phase: accessed by the host both during the analysis and the factorization phases.

Default value: 20 (which corresponds to a 20 % increase).

Related parameters: ICNTL(23)

Remarks: When significant extra fill-in is caused by numerical pivoting, increasing ICNTL(14) may help.
ICNTL(15-17) Not used in current version.

ICNTL(18) defines the strategy for the distributed input matrix (only for assembled matrix, see Subsection 5.2.2).

**Phase:** accessed by the host during the analysis phase.

**Possible values:**

- **0**: the input matrix is centralized on the host (see Subsection 5.2.2.1).
- **1**: the user provides the structure of the matrix on the host at analysis, MUMPS returns a mapping and the user should then provide the matrix entries distributed according to the mapping on entry to the numerical factorization phase (see Subsection 5.2.2.2).
- **2**: the user provides the structure of the matrix on the host at analysis, and the distributed matrix entries on all slave processors at factorization. Any distribution is allowed (see Subsection 5.2.2.2).
- **3**: user directly provides the distributed matrix, pattern and entries, input both for analysis and factorization (see Subsection 5.2.2.2).

Other values are treated as 0.

**Default value:** 0 (input matrix centralized on the host)

**Related parameters:** ICNTL(5)

**Remarks:** In case of distributed matrix, we recommend options 2 or 3 that are easier to use.

ICNTL(19) computes the Schur complement matrix (see Subsection 5.12).

**Phase:** accessed by the host during the analysis phase.

**Possible variables/arrays involved:** SIZE_SCHUR, LISTVAR_SCHUR, NPROW, NPCOL, MBLOCK, NBLOCK, SCHUR, SCHUR_MLOC, SCHUR_NLOC, and SCHUR_LLD

**Possible values:**

- **0**: complete factorization. No Schur complement is returned.
- **1**: the Schur complement matrix will be returned centralized by rows on the host after the factorization phase. On the host before the analysis phase, the user must set the integer variable SIZE_SCHUR to the size of the Schur matrix, the integer pointer array LISTVAR_SCHUR to the list of indices of the Schur matrix.
- **2** or **3**: the Schur complement matrix will be returned distributed by columns: the Schur will be returned on the slave processors in the form of a 2D block cyclic distributed matrix (ScalAPACK style) after factorization. Workspace should be allocated by the user before the factorization phase in order for MUMPS to store the Schur complement (see SCHUR, SCHUR_MLOC, SCHUR_NLOC, and SCHUR_LLD in Subsection 5.12). On the host before the analysis phase, the user must set the integer variable SIZE_SCHUR to the size of the Schur matrix, the integer pointer array LISTVAR_SCHUR to the list of indices of the Schur matrix. The integer variables NPROW, NPCOL, MBLOCK, NBLOCK may also be defined (default values will otherwise be provided).

Values not equal to 1, 2 or 3 are treated as 0.

**Default value:** 0 (complete factorization)

**Incompatibility:** since the Schur complement is a partial factorization of the global matrix (with partial ordering of the variables provided by the user), the following options of MUMPS are incompatible with the Schur option: maximum transversal, scaling, iterative refinement, error analysis and parallel analysis.

**Related parameters:** ICNTL(7)

**Remarks:** If the ordering is given (ICNTL(7)=1) then the following property should hold: PERM_IN(LISTVAR_SCHUR(i)) = N-SIZE_SCHUR+i, for i=1,SIZE_SCHUR.

Note that, in order to have a centralized Schur complement matrix by columns (see Subsection 5.12.3), it is possible (and recommended) to use a particular case of the distributed Schur complement (ICNTL(19)=2 or 3), where the Schur complement is assigned to only one processor (NPCOL x NPROW = 1).
**ICNTL(20)** determines the format (dense or sparse) of the right-hand sides

*Phase:* accessed by the host during the solve phase.

*Possible variables/arrays involved:* RHS, NRHS, LRHS, IRHS\_SPARSE, RHS\_SPARSE, IRHS\_PTR and NZ\_RHS.

*Possible values:*

0: the right-hand side is in dense format in the structure component RHS, NRHS, LRHS (see Subsection 5.11.1)

1,2,3: the right-hand side is in sparse format in the structure components IRHS\_SPARSE, RHS\_SPARSE, IRHS\_PTR and NZ\_RHS.

  1: The decision of exploiting sparsity of the right-hand side to accelerate the solution phase is done automatically.
  2: Sparsity of the right-hand side is NOT exploited to improve solution phase.
  3: Sparsity of the right-hand side is exploited during solution phase.

Values different from 0, 1, 2 or 3 are treated as 0. For a sparse right-hand side, the recommended value is 1.

*Default value:* 0 (dense right-hand sides)

*Incompatibility:* When ICNTL(20)=0 (dense right-hand side) and NRHS > 1 (multiple right-hand side) the functionalities related to iterative refinement (ICNTL(10)) and error analysis (ICNTL(11)) are currently disabled.

With sparse right-hand sides (ICNTL(20)=1), the forward elimination during the factorization (ICNTL(32)=1) is not currently available.

*Remarks:* For details on how to set the input parameters see Subsection 5.11.1 and Subsection 5.11.2. Please note that duplicate entries in the sparse right-hand sides are summed.

**ICNTL(21)** determines the distribution (centralized or distributed) of the solution vectors.

*Phase:* accessed by the host during the solve phase.

*Possible variables/arrays involved:* RHS, NZ\_RHS, ISOL\_loc and SOL\_loc, LSOL\_loc

*Possible values:*

0: the solution vector is assembled and stored in the structure component RHS (gather phase), that must have been allocated earlier by the user (see Subsection 5.11.4).

1: the solution vector is kept distributed on each slave processor in the structure components ISOL\_loc and SOL\_loc. ISOL\_loc and SOL\_loc must then have been allocated by the user and must be of size at least INFO(23), where INFO(23) has been returned by MUMPS at the end of the factorization phase (see Subsection 5.11.5).

Values different from 0 and 1 are currently treated as 0.

*Default value:* 0 (assembled centralized format)

*Incompatibility:* If the solution is kept distributed, error analysis and iterative refinement (controlled by ICNTL(10) and ICNTL(11)) are not applied.

**ICNTL(22)** controls the in-core/out-of-core (OOC) factorization and solve.

*Phase:* accessed by the host during the factorization phase.

*Possible variables/arrays involved:* OOC\_TMPDIR and OOC\_PREFIX

*Possible values:*

0: In-core factorization and solution phases (default standard version).

1: Out-of-core factorization and solve phases. The complete matrix of factors is written to disk (see Subsection 3.13).

*Default value:* 0 (in-core factorization)
Remarks: The variables OOC_TMPDIR and OOC_PREFIX are used to indicate the directory and the prefix, respectively, where to store the factors. They must be set after the initialization phase (JOB = -1) and before the factorization phase (JOB=2,4,5 or 6). Otherwise, MUMPS will use the /tmp directory and arbitrary file names.

ICNTL(23) corresponds to the maximum size of the working memory in MegaBytes that MUMPS can allocate per working processor, see Subsection 5.6 for more details.

Phase: accessed by the host at the beginning of the factorization phase and is only significant on the host.

Possible values:

- 0: each processor will allocate workspace based on the estimates computed during the analysis
- >0: maximum size of the working memory in MegaBytes per working processor to be allocated

Default value: 0

Related parameters: ICNTL(14)

Remarks: If ICNTL(23) is greater than 0 then MUMPS automatically computes the size of the internal workarrays such that the storage for all MUMPS internal data is equal to ICNTL(23). The relaxation ICNTL(14) is first applied to the internal integer workarray IS and to communication and I/O buffers; the remaining available space is given to the main (and most critical) real/complex internal workarray S holding the factors and the stack of contribution blocks. A lower bound of ICNTL(23) (if ICNTL(14) has not been modified since the analysis) is given by INFOG(16) if the factorization is in-core (ICNTL(22)=0), and by INFOG(26) if the factorization is out-of-core (ICNTL(22)=1).

If ICNTL(23) is left to its default value 0 then each processor will allocate for the factorization phase a workspace based on the estimates computed during the analysis (INFO(17) that is the estimate of the sum over all processors) if ICNTL(14) has not been modified since analysis, or larger if ICNTL(14) was increased. Note that these estimates are accurate in the sequential version of MUMPS, but they can be inaccurate in the parallel case, especially for the out-of-core version. Therefore, in parallel, we recommend to use ICNTL(23) and provide a value significantly larger than the maximum over all processors: INFOG(16) in the in-core case, or INFOG(26) in the out-of-core case.

ICNTL(24) controls the detection of “null pivot rows”.

Phase: accessed by the host during the factorization phase

Possible variables/arrays involved: PIVNUL_LIST

Possible values:

- 0: Nothing done. A null pivot will result in error INFO(1)=--10.
- 1: Null pivot row/column detection.

Other values are treated as 0.

Default value: 0 (no null pivot detection)

Incompatibility: This option is available only for symmetric matrices.

Related parameters: CNTL(3), CNTL(5), ICNTL(13), ICNTL(25),

Remarks: CNTL(3) is used to compute the threshold to decide if a pivot row is “null”.

Null pivot rows are modified to enable the solution phase to provide one solution among the possible solutions of the numerically deficient matrix. The parameter CNTL(5) defines the fixation of null pivots.

Note that the list of row indices corresponding to null pivots is returned on the host in PIVNUL_LIST(1:INFOG(28)). The solution phase (JOB=3) can then be used to either provide a “regular” solution, that it is a possible solution of the complete system when the right-hand-side
belongs to the span of the original matrix, or to compute the associated vectors of the null-space basis (see ICNTL(25)).

Note that when ScALAPACK is applied on the root node (see ICNTL(13) = 0), then exact null pivots on the root will stop the factorization (INFO(1) = -10) while if tiny pivots are present on the root node the ScALAPACK routine will factorize the root matrix. Computing the root node factorization sequentially (this can be forced by setting ICNTL(13) to 1) will help with the correct detection of null pivots but may degrade performance.

ICNTL(25) allows the computation of a solution of a deficient matrix and also of a null space basis.

Phase: accessed by the host during the solution phase

Possible variables/arrays involved: RHS, ISOL_loc and SOL_loc

Possible values:

0: A normal solution step is performed. If the matrix was found singular during factorization then one of the possible solutions is returned.

i: with 1 ≤ i ≤ INFOG(28). The i-th vector of the null space basis is computed.

-1: The complete null space basis is computed.

Default value: 0 (normal solution step)

Incompatibility: Iterative refinement, error analysis, and the option to solve the transpose system (ICNTL(9) ≠ 1) are ignored when the solution step is used to return vectors from the null space (ICNTL(25) ≠ 0).

Related parameters: ICNTL(21), ICNTL(24)

Remarks: Null space basis computation can be used when a zero-pivot detection option was requested (ICNTL(24) ≠ 0) during the factorization and when the matrix was found to be deficient (INFOG(28) > 0).

Note that when vectors from the null space are requested (ICNTL(25) ≠ 0), both centralized (ICNTL(21) = 0) and distributed (ICNTL(21) = 1) solutions options can be used. If the solution is centralized (ICNTL(21) = 0), then the null space vectors are returned to the user in the array RHS, allocated by the user on the host. If the solution is distributed (ICNTL(21) = 1), then the null space vectors are returned in the array SOL_loc, which must be allocated by the user on all working processors (see Subsection 5.11.5). In both cases, the number of columns of RHS or SOL_loc must be equal to the number of vectors requested, so that NRHS must be equal to:

- 1 if 1 ≤ ICNTL(25) ≤ INFOG(28)
- INFOG(28) if ICNTL(25) = -1.

ICNTL(26) drives the solution phase if a Schur complement matrix has been computed (ICNTL(19) ≠ 0), see Subsection 3.16 for details

Phase: accessed by the host during the solution phase. It will be accessed also during factorization if the forward elimination is performed during factorization (ICNTL(32) = 1)

Possible variables/arrays involved: REDRHS, LREDRHS

Possible values:

0: standard solution phase on the internal problem; referring to the notations from Subsection 3.16, only the system \( A_{11} x_1 = b_1 \) is solved and the entries of the right-hand side corresponding to the Schur are explicitly set to 0 on output.

1: condense/reduce the right-hand side on the Schur. Only a forward elimination is performed. The solution corresponding to the "internal" (non-Schur) variables is returned together with the reduced/condensed right-hand-side. The reduced right-hand side is made available on the host in the pointer array REDRHS, that must be allocated by the user. Its leading dimension LREDRHS must be provide, too.
2: expand the Schur local solution on the complete solution variables. REDRHS is considered to be the solution corresponding to the Schur variables. It must be allocated by the user as well as its leading dimension LREDRHS must be provided. The backward substitution is then performed with the given right-hand side to compute the solution associated with the “internal” variables. Note that the solution corresponding to the Schur variables is also made available in the main solution vector/matrix.

Values different from 1 and 2 are treated as 0.

Default value: 0 (normal solution phase)

Incompatibility: if ICNTL(26) = 1 or 2, then error analysis and iterative refinements are disabled (ICNTL(11) and ICNTL(10))

Related parameters: ICNTL(19), ICNTL(32)

Remarks: If ICNTL(26) ≠ 0, then the user should provide workspace in the pointer array REDRHS, as well as a leading dimension LREDRHS (see Subsection 5.12). Note that if no Schur complement was computed, ICNTL(26) = 1 or 2 results in an error.

**ICNTL(27)** controls the blocking size for multiple right-hand sides.

Phase: accessed by the host during the solution phase

Possible variables/arrays involved: id%NRHS

Possible values:

< 0: an automatic setting is performed by the solver:

(i) the blocksize = \( \min(id\%NRHS, -2 \times ICNTL(27)) \) if the factors are on disk \((ICNTL(22)=1)\);

(ii) the blocksize = \( \min(id\%NRHS, -ICNTL(27)) \) if the factors are in-core \((ICNTL(22)=0)\)

0: no blocking, it is treated as 1.

> 0: blocksize = \( \min(id\%NRHS,ICNTL(27)) \)

Default value: -8

Remarks: It influences both the memory usage (see INFOG(30) and INFOG(31)) and the solution time. Larger values of ICNTL(27) lead to larger memory requirements and a better performance (except if the larger memory requirements induce swapping effects). Tuning ICNTL(27) is critical, especially when factors are on disk \((ICNTL(22)=1)\) at the factorization stage) because factors must be accessed once for each block of right-hand sides.

**ICNTL(28)** determines whether a sequential or parallel computation of the ordering is performed (see Subsection 3.2 and Subsection 5.4).

Phase: accessed by the host process during the analysis phase.

Possible values:

0: automatic choice.

1: sequential computation. In this case the ordering method is set by \( ICNTL(7) \) and the \( ICNTL(29) \) parameter is meaningless (choice of the parallel ordering tool).

2: parallel computation. A parallel ordering and parallel symbolic factorization will be performed if one of the parallel ordering tools (or all) are available. In this case \( ICNTL(7) \) is meaningless.

Any other values will be treated as 0.

Default value: 0 (automatic choice)

Incompatibility: The parallel analysis is not available when the Schur complement feature is requested \((ICNTL(19)=1),\) when a maximum transversal is requested on the input matrix (i.e., \( ICNTL(6)=1, 2, 3, 4, 5 \) or 6) or when the input matrix is an unassembled matrices \((ICNTL(5)=1).\)
Related parameters: ICNTL(7), ICNTL(29)

Remarks: Performing the analysis in parallel (ICNTL(29) = 2) will enable saving both time and memory. Note that then the quality of the ordering depends on the number of processors used.

ICNTL(29) defines the parallel ordering tool (when ICNTL(28)=1) to be used to compute the fill-in reducing permutation. See Subsection 3.2 and Subsection 5.4.

Phase: accessed by host process only during the parallel analysis phase (ICNTL(28)=2).

Possible variables/arrays involved: SYM_PERM

Possible values:
0: automatic choice.
1: PT-SCOTCH is used to reorder the input matrix, if available.
2: ParMetis is used to reorder the input matrix, if available.

Default value: 0 (automatic choice)

Related parameters: ICNTL(28)

Remarks: On output, the pointer array SYM_PERM provides access, on the host processor, to the symmetric permutation that is effectively considered during the analysis phase, and INFOG(7) to the ordering option that was effectively used. SYM_PERM(i), (i=1, ... N) holds the position of variable i in the pivot order, see Subsection 5.4.1 for a full description.

ICNTL(30) computes a user-specified set of entries in the inverse $A^{-1}$ of the original matrix (see Subsection 5.11.3).

Phase: accessed during the solution phase.

Possible variables/arrays involved: NZ_RHS, NRHS, RHS_SPARSE, IRHS_SPARSE, IRHS_PTR

Possible values:
0: no entries in $A^{-1}$ are computed.
1: computes entries in $A^{-1}$.

Other values are treated as 0.

Default value: 0 (no entries in $A^{-1}$ are computed)

Incompatibility: Error analysis and iterative refinement will not be performed, even if the corresponding options are set (ICNTL(10) and ICNTL(11)). Because the entries of $A^{-1}$ are returned in RHS_SPARSE on the host, this functionality is incompatible with the distributed solution option (ICNTL(21)). Furthermore, computing entries of $A^{-1}$ is not possible in the case of partial factorizations with a Schur complement (ICNTL(19)). Option to compute solution using $A$ or $A^T$ (ICNTL(9)) is meaningless and thus ignored.

Related parameters: ICNTL(27)

Remarks: When a set of entries of $A^{-1}$ is requested, the associated set of columns will be computed in blocks of size ICNTL(27). In an out-of-core context (ICNTL(22)=1), larger ICNTL(27) values will most likely decrease the amount of factors read from the disk and reduce the solution time [40, 36, 11]. In an in-core context, the effects might be mixed.

The user must specify on input to a call of the solve phase in the arrays IRHS_PTR and IRHS_SPARSE the target entries. The array RHS_SPARSE should be allocated but not initialized. Note that since selected entries of the inverse of the matrix are requested, NRHS must be set to N. On output the arrays IRHS_PTR, IRHS_SPARSE and RHS_SPARSE will hold the requested entries. If duplicate target entries are provided then duplicate solutions will be returned.

When entries of $A^{-1}$ are requested (ICNTL(30) = 1), mumps_par%RHS needs not be allocated.

ICNTL(31) indicates which factors may be discarded during the factorization.

Phase: accessed by the host during the analysis phase.
Possible values:

0: all factors needed to perform the solution phase (\( \text{JOB}=3 \)) are kept during the factorization phase. In general this means that both the \( L \) and \( U \) factors are kept. However, in case the forward elimination is performed during the factorization (\( \text{ICNTL}(32)=1 \)) on unsymmetric matrices (\( \text{SYM}=0 \)), the \( L \) factors are discarded because only the backward substitution will then be performed during the solution phase (\( \text{JOB}=3 \)).

1: all factors are discarded during the factorization phase. The user is not interested in solving the linear system (Equations (3) or (4)) and will not call MUMPS solution phase (\( \text{JOB}=3 \)). This option is meaningful when only statistics from the factorization, such as (for example) definiteness, value of the determinant, number of entries in factors after numerical pivoting, number of negative or null pivots are required. In this case, the memory allocated for the factorization will rely on the out-of-core estimates.

2: only the \( U \) factor is kept after factorization so that only a backward substitution is possible during the solve phase (\( \text{JOB}=3 \)). This setting is only meaningful for unsymmetric matrices when:
   - the user is only interested in the computation of a null space basis (see \( \text{ICNTL}(25) \)) during the solve phase, or
   - the forward elimination is performed during the factorization (\( \text{ICNTL}(32)=1 \)), in which case \( \text{ICNTL}(31)=0 \) and \( \text{ICNTL}(32) \) have the same behaviour.

Other values are treated as 0.

Default value: 0 (the factors needed for the solve are kept during the factorization phase).

Incompatibility: \( \text{ICNTL}(31)=2 \) is meaningful only for unsymmetric matrices.

Related parameters: \( \text{ICNTL}(32) \), forward elimination during factorization, \( \text{ICNTL}(33) \), computation of the determinant, \( \text{ICNTL}(25) \) computation of a null space basis.

\( \text{ICNTL}(32) \) performs the forward elimination of the right-hand sides (Equation (3)) during the factorization (\( \text{JOB}=2 \)). (see Subsection 5.10).

Phase: accessed by the host during the analysis phase.

Possible variables/arrays involved: \( \text{RHS}, \text{NRHS}, \text{LRHS} \)

Possible values:

0: standard factorization not involving right-hand sides.

1: forward elimination (Equation (3)) of the right-hand side vectors is performed during factorization (\( \text{JOB}=2 \)). The solve phase (\( \text{JOB}=3 \)) will then only involve backward substitution (Equation (4)).

Default value: 0 (standard factorization)

Incompatibility: This option is incompatible with sparse right-hand sides (\( \text{ICNTL}(20)=1 \)), with the solution of the transposed system (\( \text{ICNTL}(9) \neq 1 \)), and with the computation of entries of the inverse (\( \text{ICNTL}(30) \)).

Furthermore, iterative refinement (\( \text{ICNTL}(10) \)) and error analysis (\( \text{ICNTL}(11) \)) are disabled. Finally, the current implementation imposes that all right-hand sides are processed in one pass during the backward step. Therefore, the blocking size (\( \text{ICNTL}(27) \)) is ignored.

Remarks: The right-hand sides must be dense to use this functionality: \( \text{RHS}, \text{NRHS}, \text{LRHS} \) should be provided as described in Subsection 5.11.1. They should be provided at the beginning of the factorization phase (\( \text{JOB}=2 \)) rather than at the beginning of the solve phase (\( \text{JOB}=3 \)). We advise to use this option only for a reasonable number of dense right-hand side vectors because of the additional storage required when this option is activated.

\( \text{ICNTL}(33) \) computes the determinant of the input matrix.

Phase: accessed by the host during the factorization phase.

Possible values:
0: the determinant of the input matrix is not computed.

\( \neq 0 \): computes the determinant of the input matrix. The determinant is obtained by computing 
\((a + ib) \times 2^c\) where \( a = \text{RINFOG}(12), b = \text{RINFOG}(13) \) and \( c = \text{INFOG}(34) \). In real arithmetic \( b = \text{RINFOG}(13) \) is equal to 0.

\textit{Default value:} 0 (determinant is not computed)

\textit{Related parameters:} ICNTL(31)

\textit{Remarks:} In case a Schur complement was requested (see ICNTL(19)), elements of the Schur complement are excluded from the computation of the determinant so that the determinant is that one of matrix \( A_{1,1} \) (using notations of Subsection 3.16).

Although we recommend to compute the determinant on non-singular matrices, null pivots (ICNTL(24)) and static pivots (CNTL(4)) are excluded from the determinant so that a non-zero determinant is still returned on singular or near-singular matrices. This determinant is then not unique and will depend on which equations were excluded.

Furthermore, we recommend to switch off scaling (ICNTL(8)) in such cases. If not (ICNTL(8) \( \neq 0 \)), we describe in the following the current behaviour of the package:

- if static pivoting (CNTL(4)) is activated: all entries of the scaling arrays ROWSCA and COLSCA are currently taken into account in the computation of the determinant.
- if the null pivot detection (ICNTL(24)) is activated, then entries of ROWSCA and COLSCA corresponding to pivots in PIVNUL_LIST are excluded from the determinant so that
  * for symmetric matrices (SYM=1 or 2), the returned determinant correctly corresponds to the matrix excluding rows and columns of PIVNUL_LIST.
  * for unsymmetric matrices (SYM=0), scaling may perturb the value of the determinant in case off-diagonal pivoting has occurred (INFOG(12) \( \neq 0 \)).

Note that if the user is interested in computing only the determinant, we recommend to discard the factors during factorization ICNTL(31).

ICNTL(34-40) are not used in the current version.

### 6.2 Real/complex control parameters

\textit{mumps.par\%CNTL} is a real (also real in the complex version) array of dimension 5.

\textbf{CNTL(1)} is the relative threshold for numerical pivoting. See Subsection 3.9

\textit{Phase:} accessed by the host during the factorization phase.

\textit{Possible values:}

\( < 0.0 \): values less than 0.0 are treated as 0.0

\( = 0.0 \): no numerical pivoting performed and the subroutine will fail if a zero pivot is encountered.

\( > 0.0 \): numerical pivoting performed.

For unsymmetric matrices values greater than 1.0 are treated as 1.0

For symmetric matrices values greater than 0.5 are treated as 0.5

\textit{Default value:}

0.01: for unsymmetric or general symmetric matrices

0.0: for symmetric positive definite matrices

\textit{Related parameters:} CNTL(4)

\textit{Remarks:} It forms a trade-off between preserving sparsity and ensuring numerical stability during the factorization. In general, a larger value of CNTL(1) increases fill-in but leads to a more accurate factorization.

Note that for \textit{diagonally dominant matrix}, setting CNTL(1) to zero will decrease the factorization time while still providing a stable decomposition.

\textbf{CNTL(2)} is the stopping criterion for iterative refinement.
Phase: accessed by the host during the solve phase.

Possible values: \( \geq 0 \)

Values \(< 0\) are treated as \(\sqrt{\epsilon}\), where \(\epsilon\) holds the machine precision and depends on the arithmetic version.

Default value: \(\sqrt{\epsilon}\)

Related parameters: ICNTL(10), RINFOG(7), RINFOG(8)

Remarks: Let \(\omega_1\) and \(\omega_2\) be the backward errors as defined in Subsection 3.3.2. Iterative refinement (Subsection 3.3.1) will stop when either the requested accuracy is reached \((\omega_1 + \omega_2 < \text{CNTL}(2))\) or when the convergence rate is too slow \((\omega_1 + \omega_2\) does not decrease by at least a factor of 5).

\(\text{CNTL}(3)\) it is used to determine if a pivot is null when the null pivot detection option is used (ICNTL(24) = 1)

Phase: accessed by the host during the numerical factorization phase.

Possible values: We define the threshold \(thres\) as follows.

\[
\begin{align*}
&> 0.0: \quad \text{thres} = \text{CNTL}(3) \times \|A_{\text{pre}}\| \\
&= 0.0: \quad \text{thres} = \epsilon \times 10^{-5} \times \|A_{\text{pre}}\| \\
&< 0.0: \quad \text{thres} = |\text{CNTL}(3)|
\end{align*}
\]

where \(A_{\text{pre}}\) is the preprocessed matrix to be factorized (see Equation (5)), \(\epsilon\) is the machine precision and \(\|\|\) is the infinite norm.

Default value: 0.0

Related parameters: ICNTL(24)

Remarks: When null pivot detection is enabled (ICNTL(24) = 1), CNTL(3) is the threshold used to determine if a pivot is null. A pivot is considered to be null if the infinite norm of its row/column is smaller than the threshold \(thres\).

\(\text{CNTL}(4)\) determines the threshold for static pivoting. See Subsection 3.9

Phase: accessed by the host, and must be set either before the factorization phase, or before the analysis phase.

Possible values:

\[
\begin{align*}
&< 0.0: \quad \text{static pivoting is not activated.} \\
&= 0.0: \quad \text{static pivoting is activated and the threshold value to define a small pivot is determined automatically.} \\
&> 0.0: \quad \text{static pivoting is activated and the magnitude of small pivots smaller than CNTL(4) will be set to CNTL(4).}
\end{align*}
\]

Default value: -1.0 (no static pivoting)

Related parameters: CNTL(1)

Remarks: By static pivoting (as in [32]) we mean replacing small pivots whose elimination should be postponed because of partial threshold pivoting and would thus result in an increase of our estimations (memory and operations), by a small perturbation of the original matrix controlled by CNTL(4).

\(\text{CNTL}(5)\) defines the fixation for null pivots and is effective only when null pivot detection is active (ICNTL(24) = 1).

Phase: accessed by the host during the numerical factorization phase.

Possible values:

\[
\begin{align*}
&\leq 0.0: \quad \text{In the symmetric case (SYM = 2) then the pivot column of the L factors is set to zero and the pivot entry in matrix D is set to one.}
\end{align*}
\]
> 0.0: when a pivot $piv$ is detected as null, in order to limit the impact of this pivot on the rest of the matrix, it is set to $\text{sign}(piv) \times \text{CNTL}(5) \times \|A_{\text{pre}}\|$, where $A_{\text{pre}}$ is the preprocessed matrix to be factored (see Equation (5)). We recommend setting $\text{CNTL}(5)$ to a large floating-point value (e.g. $10^{20}$).

Default value: 0.0

Related parameters: ICNTL(24)

$\text{CNTL(6-15)}$ are not used in the current version.
6.3 Compatibility between options

As shown above, the package has a lot of options and this gives an exponential amount of combinations of options. Almost all options are indeed compatible with each other but obviously a few of them are not, either because the implementation of some options is more complicated in some context, or because some algorithms cannot be applied or do not make sense under certain conditions. For each option and ICNTL parameter, the list of incompatibilities is normally given in the description of the option. The objective of this section is to provide to the user a more global view of the main incompatibilities.

Table 2 highlights the incompatibilities between functionalities and matrix input formats (functionalities which do not appear in this table are compatible with all matrix input formats).

<table>
<thead>
<tr>
<th>Functionality</th>
<th>(Control)</th>
<th>Matrix input format (ICNTL(18) and ICNTL(5))</th>
<th>Centralised</th>
<th>Assembled</th>
<th>Elemental</th>
<th>Distributed assembled (distr. elemental not avail.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsymmetric permutations</td>
<td>(ICNTL(6))</td>
<td>All options</td>
<td>Not available (ICNTL(6)=0)</td>
<td>Not available (ICNTL(6)=0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scalings</td>
<td>(ICNTL(8))</td>
<td>All options</td>
<td>Only option 1 (user-provided)</td>
<td>Only options 7, 8, or 1 (user-provided)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constrained/compressed orderings</td>
<td>(ICNTL(12))</td>
<td>All options</td>
<td>Not available (ICNTL(12)=0)</td>
<td>Not available (ICNTL(12)=0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of analysis</td>
<td>(ICNTL(28))</td>
<td>Sequential (parallel not available)</td>
<td>Sequential or parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schur complement</td>
<td>(ICNTL(19))</td>
<td>All options</td>
<td>All options but not compatible with Parallel analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Compatibilities between MUMPS functionalities and matrix-input formats.

In Table 3, we present the numerical limitations of the solver when ScaLAPACK is used on the final dense Schur complement of MUMPS.

<table>
<thead>
<tr>
<th>Numerical limitation</th>
<th>SCALAPACK</th>
<th>OFF</th>
<th>ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null pivot list</td>
<td></td>
<td>ok</td>
<td>null pivots on root node not available and failure if exact null pivot on root node</td>
</tr>
<tr>
<td>LDL factorization</td>
<td></td>
<td>ok</td>
<td>ok but LUPDGETRF performed on root node (no Scalapack LDL kernel)</td>
</tr>
<tr>
<td>Number of negative</td>
<td></td>
<td>ok</td>
<td>lowerbound (negative pivots not counted on root node)</td>
</tr>
<tr>
<td>pivots</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: MUMPS relies on ScaLAPACK to factorize the last dense Schur complement. If exact inertia (number of negative pivots) or null pivot list is critical, ScaLAPACK can be switched off, see ICNTL(13) although this might imply a small performance degradation.

Regarding the solve phase (JOB=3), iterative refinement and error analysis are incompatible with some options, as reported in Table 4. Although iterative refinement and error analysis could be performed externally to the package, they are provided by the package for convenience for all matrix formats but not for all situations. For example, they do not really make sense when computing something different from the solution of $Ax = b$ (e.g. entries of the inverse, null space basis, only forward substitution performed), or when the factors have been discarded during factorization.
<table>
<thead>
<tr>
<th>Functionality</th>
<th>Control</th>
<th>Iterative refinement</th>
<th>Error analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple right-hand sides</td>
<td>NRHS &gt; 1</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Distributed solution</td>
<td>ICNTL(21)</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Forward during factorization</td>
<td>ICNTL(32)</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Reduced right-hand sides/partial solution</td>
<td>ICNTL(26) = 1</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Discard some factors</td>
<td>ICNTL(31)</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Compute null space (*)</td>
<td>ICNTL(25)</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
<tr>
<td>Entries of $A^{-1}$</td>
<td>ICNTL(30)</td>
<td>Incomp.</td>
<td>Incomp.</td>
</tr>
</tbody>
</table>

Table 4: List of incompatibilities with postprocessing options at the end of the solve phase. (*) The null space estimate is only available for symmetric matrices.

Finally, note that orderings available for the sequential and the parallel analysis phase (see ICNTL(28)) are controlled by two different parameters (ICNTL(7) and ICNTL(29)), which have a different range of allowed values, so there is no incompatibility as such. But orderings based on minimum-degree (for example) are only available with the sequential analysis.

7 Information parameters

The parameters described in this section are returned by MUMPS and hold information that may be of interest to the user. Some of the information is local to each processor and some only on the host. If an error is detected (see Section 8), the information may be incomplete.

7.1 Information local to each processor

The arrays mumps.par%RINFO and mumps.par%INFO are local to each process.

mumps.par%RINFO is a double precision array of dimension 20. It contains the following local information on the execution of MUMPS:

RINFO(1) - after analysis: The estimated number of floating-point operations on the processor for the elimination process.
RINFO(2) - after factorization: The number of floating-point operations on the processor for the assembly process.
RINFO(3) - after factorization: The number of floating-point operations on the processor for the elimination process.
RINFO(4) - RINFO(20) are not used in the current version.

mumps.par%INFO is an integer array of dimension 40. It contains the following local information on the execution of MUMPS:

INFO(1) is 0 if the call to MUMPS was successful, negative if an error occurred (see Section 8), or positive if a warning is returned.
INFO(2) holds additional information about the error or the warning. If INFO(1) = -1, INFO(2) is the processor number (in communicator COMM) on which the error was detected.
INFO(3) - after analysis: Estimated size of the real/complex space needed on the processor to store the factors in memory if the factorization is performed in-core (ICNTL(22)=0). If INFO(3) is negative, then the absolute value corresponds to millions of real/complex entries used to store the factor matrices. If the user plans to perform an out-of-core factorization (ICNTL(22)=1), then a rough estimation of the size of the disk space in bytes of the files written by the concerned processor can be obtained by multiplying INFO(3) (or its absolute value multiplied by 1 million when negative) by 4, 8, 8, or 16 for single precision, double precision, single complex, and double complex arithmetics, respectively. The effective value will be returned in INFO(9) (see below), but only after the factorization.

INFO(4) - after analysis: Estimated integer space needed on the processor for factors.

INFO(5) - after analysis: Estimated maximum front size on the processor.

INFO(6) - after analysis: Number of nodes in the complete tree. The same value is returned on all processors.

INFO(7) - after analysis: Minimum estimated size of the main internal integer workarray IS to run the numerical factorization in-core.

INFO(8) - after analysis: Minimum estimated size of the main internal real/complex workarray S to run the numerical factorization in-core. If negative, then the absolute value corresponds to millions of real/complex entries needed in this workarray.

INFO(9) - after factorization: Size of the real/complex space used on the processor to store the factor matrices. If negative, then the absolute value corresponds to millions of real/complex entries used to store the factor matrices. In the case of an out-of-core execution (ICNTL(22)=1), the disk space in bytes of the files written by the concerned processor can be obtained by multiplying INFO(9) (or its absolute value multiplied by 1 million) by 4, 8, 8, or 16 for single precision, double precision, single complex, and double complex arithmetics, respectively.

INFO(10) - after factorization: Size of the integer space used on the processor to store the factor matrices.

INFO(11) - after factorization: Order of the largest frontal matrix processed on the processor.

INFO(12) - after factorization: Number of off-diagonal pivots selected on the processor if SYM=0 or number of negative pivots on the processor if SYM=1 or 2. If ICNTL(13)=0 (the default), this excludes pivots from the parallel root node treated by ScaLAPACK. (This means that the user should set ICNTL(13)=1 or use a single processor in order to get the exact number of off-diagonal or negative pivots rather than a lower bound.) Note that for complex symmetric matrices (SYM=1 or 2), INFO(12) will be 0. See also INFOG(12), which provides the total number of off-diagonal or negative pivots over all processors.

INFO(13) - after factorization: The number of postponed elimination because of numerical issues.

INFO(14) - after factorization: Number of memory compresses.

INFO(15) - after analysis: estimated size in MegaBytes of all working space to run the numerical phases (factorization/solve) in-core (ICNTL(22)=0 for the factorization). The maximum and sum over all processors are returned respectively in INFOG(16) and INFOG(17).

INFO(16) - after factorization: total size (in millions of bytes) of all MUMPS internal data allocated during the numerical factorization. This excludes the memory for WK_USER, in the case where WK_USER is provided.

INFO(17) - after analysis: estimated size in MegaBytes of all working space to run the numerical phases out-of-core (ICNTL(22)≠0) with the default strategy. The maximum and sum over all processors are returned respectively in INFOG(26) and INFOG(27).

INFO(18) - after factorization: local number of null pivots resulting from detected when ICNTL(24)=1.

INFO(19) - after analysis: Estimated size of the main internal integer workarray IS to run the numerical factorization out-of-core.
INFO(20) - after analysis: Estimated size of the main internal real/complex workarray S to run the numerical factorization \textit{out-of-core}. If negative, then the absolute value corresponds to \textit{millions} of real/complex entries needed in this workarray.

INFO(21) - after factorization: Effective space used in the main real/complex workarray S— or in the workarray \texttt{WK\_USER}, in the case where \texttt{WK\_USER} is provided. If negative, then the absolute value corresponds to \textit{millions} of real/complex entries needed in this workarray.

INFO(22) - after factorization: Size in millions of bytes of memory effectively used during factorization. This includes the memory effectively used in the workarray \texttt{WK\_USER}, in the case where \texttt{WK\_USER} is provided.

INFO(23) - after factorization: total number of pivots eliminated on the processor. In the case of a distributed solution (see \texttt{ICNTL(21)}), this should be used by the user to allocate solution vectors \texttt{ISOL\_loc} and \texttt{SOL\_loc} of appropriate dimensions (\texttt{ISOL\_loc} of size INFO(23), \texttt{SOL\_loc} of size \texttt{LSOL\_loc} × \texttt{NRHS} where \texttt{LSOL\_loc} ≥ INFO(23)) on that processor, between the factorization and solve steps.

INFO(24) - after analysis: estimated number of entries in factors on the processor. If negative, then the absolute value corresponds to \textit{millions} of entries in the factors. Note that in the unsymmetric case, \texttt{INFO(24)=INFO(3)}. In the symmetric case, however, \texttt{INFO(24) < INFO(3)}.

INFO(25) - After factorization: number of tiny pivots (number of pivots modified by static pivoting) detected on the processor.

INFO(26) - after solution: effective size in MegaBytes of all working space to run the solution phase. (The maximum and sum over all processors are returned respectively in \texttt{INFOG(30)} and \texttt{INFOG(31)}).

INFO(27) - after factorization: effective number of entries in factors on the processor. If negative, then the absolute value corresponds to \textit{millions} of entries in the factors. Note that in the unsymmetric case, \texttt{INFO(27)=INFO(9)}. In the symmetric case, however, \texttt{INFO(27) ≤ INFO(9)}. The total number of entries over all processors is available in \texttt{INFOG(29)}.

INFO(28) - INFO(40) are not used in the current version.

7.2 Information available on all processors

The arrays \texttt{mumps\_par\%RINFOG} and \texttt{mumps\_par\%INFOG}:

\texttt{mumps\_par\%RINFOG} is a double precision array of dimension 20. It contains the following global information on the execution of MUMPS:

\texttt{RINFOG(1)} - after analysis: The estimated number of floating-point operations (on all processors) for the elimination process.

\texttt{RINFOG(2)} - after factorization: The total number of floating-point operations (on all processors) for the assembly process.

\texttt{RINFOG(3)} - after factorization: The total number of floating-point operations (on all processors) for the elimination process.

\texttt{RINFOG(4) to RINFOG(11)} - after solve with error analysis: Only returned if \texttt{ICNTL(11) ≠ 0}. See description of \texttt{ICNTL(11)}.

\texttt{RINFOG(12)} - after factorization: if the computation of the determinant was requested (see \texttt{ICNTL(33)}), \texttt{RINFOG(12)} contains the real part of the determinant. The determinant may contain an imaginary part in case of complex arithmetic (see \texttt{RINFOG(13)}). It is obtained by multiplying \texttt{(RINFOG(12),RINFOG(13))} by 2 to the power \texttt{INFOG(34)}.

\texttt{RINFOG(13)} - after factorization: if the computation of the determinant was requested (see \texttt{ICNTL(33)}), \texttt{RINFOG(13)} contains the imaginary part of the determinant. The determinant is then obtained by multiplying \texttt{(RINFOG(12),RINFOG(13))} by 2 to the power \texttt{INFOG(34)}.

\texttt{RINFOG(14) - RINFOG(20)} are not used in the current version.
mumps_par\%INFOG is an integer array of dimension 40. It contains the following global information on the execution of MUMPS:

INFOG(1) is 0 if the call to MUMPS was successful, negative if an error occurred (see Section 8), or positive if a warning is returned.

INFOG(2) holds additional information about the error or the warning.

The difference between INFOG(1:2) and INFO(1:2) is that INFOG(1:2) is identical on all processors. It has the value of INFO(1:2) of the processor which returned with the most negative INFO(1) value. For example, if processor \( p \) returns with INFO(1) = --13, and INFO(2) = 10000, then all other processors will return with INFOG(1) = --13 and INFOG(2) = 10000, and with INFO(1) = --1 and INFO(2) = \( p \).

INFOG(3) - after analysis: Total (sum over all processors) estimated real/complex workspace to store the factor matrices. If negative, then the absolute value corresponds to \( \text{millions} \) of real/complex entries used to store the factor matrices. If the user plans to perform an out-of-core factorization (ICNTL(22) = 1), then a rough estimate of the total disk space in bytes (for all processors) can be obtained by multiplying INFOG(3) (or its absolute value multiplied by 1 million) by 4, 8, 8, or 16 for single precision, double precision, single complex, and double complex arithmetics, respectively. The effective value is returned in INFOG(9) (see below), but only after the factorization.

INFOG(4) - after analysis: Total (sum over all processors) estimated integer workspace to store the factor matrices.

INFOG(5) - after analysis: Estimated maximum front size in the complete tree.

INFOG(6) - after analysis: Number of nodes in the complete tree.

INFOG(7) - after analysis: the ordering method actually used. The returned value will depend on the type of analysis performed, e.g. sequential or parallel (see INFOG(32)). Please refer to ICNTL(7) and ICNTL(29) for more details on the ordering methods available in sequential and parallel analysis respectively.

INFOG(8) - after analysis: structural symmetry in percent (100 : symmetric, 0 : fully unsymmetric) of the (permuted) matrix. (-1 indicates that the structural symmetry was not computed which will be the case if the input matrix is in elemental form.)

INFOG(9) - after factorization: Total (sum over all processors) real/complex workspace to store the factor matrices. If negative, then the absolute value corresponds to the size in \( \text{millions} \) of real/complex entries used to store the factors. In case of an out-of-core factorization (ICNTL(22) = 1), the total disk space in bytes of the files written by all processors can be obtained by multiplying INFOG(9) (or its absolute value multiplied by 1 million) by 4, 8, 8, or 16 for single precision, double precision, single complex, and double complex arithmetics, respectively.

INFOG(10) - after factorization: Total (sum over all processors) integer workspace to store the factor matrices.

INFOG(11) - after factorization: Total number of off-diagonal pivots if SYM = 0 or total number of negative pivots (real arithmetic) if SYM = 1 or 2. If ICNTL(13) = 0 (the default) this excludes pivots from the parallel root node treated by ScaLAPACK. (This means that the user should set ICNTL(13) to a positive value, say 1, or use a single processor in order to get the exact number of off-diagonal or negative pivots rather than a lower bound.) Furthermore, when ICNTL(24) is set to 1 and SYM = 1 or 2, INFOG(12) excludes the null\(^{12}\) pivots, even if their sign is negative. In other words, a pivot cannot be both null and negative.

Note that if SYM = 1 or 2, INFOG(12) will be 0 for complex symmetric matrices.

INFOG(13) - after factorization: Total number of delayed pivots. A variable of the original matrix may be delayed several times between successive frontal matrices. In that case, it accounts for several delayed pivots. A large number (more that 10% of the order of the matrix) indicates numerical problems. Settings related to numerical preprocessing (ICNTL(6), ICNTL(8), ICNTL(12)) might then be modified by the user.

\(^{12}\)i.e., whose magnitude is smaller than the tolerance defined by CNTL(3).
INFOG(14) - after factorization: Total number of memory compresses.
INFOG(15) - after solution: Number of steps of iterative refinement.
INFOG(16) and INFOG(17) - after analysis: Estimated size (in million of bytes) of all MUMPS internal data for running factorization [in-core].
  - (16): value on the most memory consuming processor.
  - (17): sum over all processors.
INFOG(18) and INFOG(19) - after factorization: Size in millions of bytes of all MUMPS internal data allocated during factorization.
  - (18): value on the most memory consuming processor.
  - (19): sum over all processors.
Note that in the case where WK_USER is provided, the memory allocated by the user for the local arrays WK_USER is not counted in INFOG(18) and INFOG(19).
INFOG(20) - after analysis: Estimated number of entries in the factors. If negative the absolute value corresponds to millions of entries in the factors. Note that in the unsymmetric case, INFOG(20)=INFOG(3). In the symmetric case, however, INFOG(20) ≤ INFOG(3).
INFOG(21) and INFOG(22) - after factorization: Size in millions of bytes of memory effectively used during factorization.
  - (21): value on the most memory consuming processor.
  - (22): sum over all processors.
This includes the memory effectively used in the local workarrays WK_USER, in the case where the arrays WK_USER are provided.
INFOG(23) - After analysis: value of ICNTL(6) effectively used.
INFOG(24) - After analysis: value of ICNTL(12) effectively used.
INFOG(25) - After factorization: number of tiny pivots (number of pivots modified by static pivoting)
INFOG(26) and INFOG(27) - after analysis: Estimated size (in millions of bytes) of all MUMPS internal data for running factorization [out-of-core] (ICNTL(22) ≠ 0) for a given value of ICNTL(14) and for the default strategy.
  - (26): max over all processors
  - (27): sum over all processors
INFOG(28) - After factorization: number of null pivots encountered. See CNTL(3) for the definition of a null pivot.
INFOG(29) - After factorization: effective number of entries in the factors (sum over all processors).
If negative, then the absolute value corresponds to millions of entries in the factors. Note that in the unsymmetric case, INFOG(29)=INFOG(9). In the symmetric case, however, INFOG(29) ≤ INFOG(9).
INFOG(30) and INFOG(31) - after solution: Size in millions of bytes of memory effectively used during solution phase:
  - (30): max over all processors
  - (31): sum over all processors
INFOG(32) - after analysis: the type of analysis actually done (see ICNTL(28)). INFOG(32) has value 1 if sequential analysis was performed, in which case INFOG(7) returns the sequential ordering option used, as defined by ICNTL(7). INFOG(32) has value 2 if parallel analysis was performed, in which case INFOG(7) returns the parallel ordering used, as defined by ICNTL(29).
INFOG(33): effective value used for ICNTL(8). It is set both after the analysis and the factorization phases. If ICNTL(8)=77 on entry to the analysis and INFOG(33) has value 77 on exit from the analysis, then no scaling was computed during the analysis and the automatic decision will only be done during factorization (except if the user modifies ICNTL(8) to set a specific option on entry to the factorization).
INFOG(34): if the computation of the determinant was requested (see ICTL(33)), INFOG(34) contains the exponent of the determinant. See also RINFOG(12) and RINFOG(13): the determinant is obtained by multiplying \((\text{RINFOG}(12), \text{RINFOG}(13))\) by 2 to the power INFOG(34).

INFOG(35) - INFOG(40) are not used in the current version.

8 Error diagnostics

MUMPS uses the following mechanism to process errors that may occur during the parallel execution of the code. If, during a call to MUMPS, an error occurs on a processor, this processor informs all the other processors before they return from the call. In parts of the code where messages are sent asynchronously (for example the factorization and solve phases), the processor on which the error occurs sends a message to the other processors with a specific error tag. On the other hand, if the error occurs in a subroutine that does not use asynchronous communication, the processor propagates the error to the other processors.

On successful completion, a call to MUMPS will exit with the parameter mumps\_par\%INFOG(1) set to zero. A negative value for mumps\_par\%INFOG(1) indicates that an error has been detected on one of the processors. For example, if processor \(s\) returns with INFO(1) = --8 and INFO(2)=1000, then processor \(s\) ran out of integer workspace during the factorization and the size of the workspace should be increased by 1000 at least. The other processors are informed about this error and return with INFO(1) = --1 (i.e., an error occurred on another processor) and INFO(2)=s (i.e., the error occurred on processor \(s\)). If several processors raised an error, those processors do not overwrite INFO(1), i.e., only processors that did not produce an error will set INFO(1) to --1 and INFO(2) to the rank of the processor having the most negative error code.

The behaviour is slightly different for the global information parameters INFOG(1) and INFOG(2): in the previous example, all processors would return with INFOG(1) = --8 and INFOG(2)=1000.

The possible error codes returned in INFO(1) (and INFOG(1)) have the following meaning:

--1 An error occurred on processor INFO(2).
--2 NZ is out of range. INFO(2)=NZ.
--3 MUMPS was called with an invalid value for JOB. This may happen for example if the analysis (JOB=1) was not performed before the factorization (JOB=2), or the factorization was not performed before the solve (JOB=3), or the initialization phase (JOB=-1) was performed a second time on an instance not freed (JOB=-2). See description of JOB in Section 4. This error also occurs if JOB does not contain the same value on all processes on entry to MUMPS. INFO(2) is then set to the local value of JOB.
--4 Error in user-provided permutation array PERM\_IN at position INFO(2). This error may only occur on the host.
--5 Problem of real workspace allocation of size INFO(2) during analysis. The unit for INFO(2) is the number of real values (single precision for SMUMPS/CMUMPS, double precision for DMUMPS/ZMUMPS), in the Fortran “ALLOCATE” statement that did not succeed.
--6 Matrix is singular in structure. INFO(2) holds the structural rank.
--7 Problem of integer workspace allocation of size INFO(2) during analysis. The unit for INFO(2) is the number of integer values that MUMPS tried to allocate in the Fortran ALLOCATE statement that did not succeed.
--8 Main internal integer workarray IS too small for factorization. This may happen, for example, if numerical pivoting leads to significantly more fill-in than was predicted by the analysis. The user should increase the value of ICTL(14) before calling the factorization again (JOB=2).
--9 The main internal real/complex workarray S too small. If INFO(2) is positive, then the number of entries that are missing in S at the moment when the error is raised is available in INFO(2). If INFO(2) is negative, then its absolute value should be multiplied by 1 million. If an error --9 occurs, the user should increase the value of ICTL(14) before calling the factorization (JOB=2) again, except if ICTL(23) or LWK\_USER are provided, in which case ICTL(23) or LWK\_USER should be increased.

11. Internal real/complex workarray S too small for solution. If INFO(2) is positive, then the number of entries that are missing in S at the moment when the error is raised is available in INFO(2). If the numerical phases are out-of-core and LWK_USER is provided for the solution phase and is smaller than the value provided for the factorization, it should be increased by at least INFO(2). In other cases, please contact us.

12. Internal real/complex workarray S too small for iterative refinement. Please contact us.

13. Problem of workspace allocation of size INFO(2) during the factorization or solve steps. The size that the package tried to allocate with a Fortran ALLOCATE statement is available in INFO(2). If INFO(2) is negative, then the size that the package requested is obtained by multiplying the absolute value of INFO(2) by 1 million. In general, the unit for INFO(2) is the number of scalar entries of the type of the input matrix (real, complex, single or double precision).


15. Integer workarray IS too small for iterative refinement and/or error analysis. See error INFO(1) = -8.

16. N is out of range. INFO(2) = N.

17. The internal send buffer that was allocated dynamically by MUMPS on the processor is too small. The user should increase the value of I_CNTL(14) before calling MUMPS.

18. The internal reception buffer that was allocated dynamically by MUMPS is too small. INFO(2) holds the minimum size of the reception buffer required (in bytes). The user should increase the value of I_CNTL(14) before calling MUMPS again.

19. Value of PAR=0 is not allowed because only one processor is available; Running MUMPS in host-node mode (the host is not a slave processor itself) requires at least two processors. The user should either set PAR to 1 or increase the number of processors.

20. A pointer array is provided by the user that is either
   - not associated, or
   - has insufficient size, or
   - is associated and should not be associated (for example, RHS on non-host processors).

   INFO(2) points to the incorrect pointer array in the table below:

<table>
<thead>
<tr>
<th>INFO(2)</th>
<th>array</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IRN or ELTPTI</td>
</tr>
<tr>
<td>2</td>
<td>JCN or ELTVAR</td>
</tr>
<tr>
<td>3</td>
<td>PERM_IN</td>
</tr>
<tr>
<td>4</td>
<td>A or A_ELTI</td>
</tr>
<tr>
<td>5</td>
<td>ROWSCA</td>
</tr>
<tr>
<td>6</td>
<td>COLSCA</td>
</tr>
<tr>
<td>7</td>
<td>RHS</td>
</tr>
<tr>
<td>8</td>
<td>LISTVAR_SCHUR</td>
</tr>
<tr>
<td>9</td>
<td>SCHUR</td>
</tr>
<tr>
<td>10</td>
<td>RHS_SPARSE</td>
</tr>
<tr>
<td>11</td>
<td>IRHS_SPARSE</td>
</tr>
<tr>
<td>12</td>
<td>IRHS_PTR</td>
</tr>
<tr>
<td>13</td>
<td>ISOL_loc</td>
</tr>
<tr>
<td>14</td>
<td>SOL_loc</td>
</tr>
<tr>
<td>15</td>
<td>REDRHS</td>
</tr>
</tbody>
</table>

   21. MPI was not initialized by the user prior to a call to MUMPS with JOB = -1.

   22. NELT is out of range. INFO(2) = NELT.

   23. A problem has occurred in the initialization of the BLACS. This may be because you are using a vendor’s BLACS. Try using a BLACS version from netlib instead.

   24. LRHS is out of range. INFO(2) = LRHS.

   25. NZ_RHS and IRHS_PTR(NRHS+1) do not match. INFO(2) = IRHS_PTR(NRHS+1).

   26. IRHS_PTR(1) is not equal to 1. INFO(2) = IRHS_PTR(1).

   27. LSOL_loc is smaller than INFO(23). INFO(2) = LSOL_loc.
--30 SCHUR_LLD is out of range. INFO(2) = SCHUR_LLD.

--31 A 2D block cyclic symmetric (SYM=1 or 2) Schur complement is required with the option ICNTL(19)=3, but the user has provided a process grid that does not satisfy the constraint MBLOCK=NBLOCK. INFO(2) = MBLOCK-NBLOCK.

--32 Incompatible values of NRHS and ICNTL(25). Either ICNTL(25) was set to -1 and NRHS is different from INFG(28); or ICNTL(25) was set to i, 1 ≤ i ≤ INFG(28) and NRHS is different from 1. Value of NRHS is stored in INFO(2).

--33 ICNTL(26) was asked for during solve phase (or during the factorization – see ICNTL(32)) but the Schur complement was not asked for at the analysis phase (ICNTL(19)). INFO(2) = ICNTL(26).

--34 LREDRHS is out of range. INFO(2) = LREDRHS.

--35 This error is raised when the expansion phase is called (ICNTL(26) = 2) but reduction phase (ICNTL(26) = 1) was not called before. This error also occurs in case the reduction phase (ICNTL(26) = 1) is asked for at the solution phase (JOB=3) but the forward elimination was already performed during the factorization phase (JOB=2 and ICNTL(32)=1). INFO(2) contains the value of ICNTL(26).

--36 Incompatible values of ICNTL(25) and INFG(28). The value of ICNTL(25) is stored in INFO(2).

--37 Value of ICNTL(25) incompatible with some other parameter. with SYM or ICNTL(xx). If INFO(2)=0 then ICNTL(25) is incompatible with SYM: in current version, the null space basis functionality is not available for unsymmetric matrices (SYM=0). Otherwise, ICNTL(25) is incompatible with ICNTL(xx), and the index xx is stored in INFO(2).

--38 Parallel analysis was set (i.e., ICNTL(28)=2) but PT-SCOTCH or ParMetis were not provided.

--39 Incompatible values for ICNTL(28) and ICNTL(5) and/or ICNTL(19) and/or ICNTL(6). Parallel analysis is not possible in the cases where the matrix is unassembled and/or a Schur complement is requested and/or a maximum transversal is requested on the matrix.

--40 The matrix was indicated to be positive definite (SYM=1) by the user but a negative or null pivot was encountered during the processing of the root by ScaLAPACK. SYM=2 should be used.

--41 Incompatible value of LWK_USER between factorization and solution phases. This error may only occur when the factorization is in-core (ICNTL(22)=1), in which case both the contents of WK_USER and LWK_USER should be passed unchanged between the factorization (JOB=2) and solution (JOB=3) phases.

--42 ICNTL(32) was set to 1 (forward during factorization), but the value of NRHS on the host processor is incorrect: either the value of NRHS provided at analysis is negative or zero, or the value provided at factorization or solve is different from the value provided at analysis. INFO(2) holds the value of id%NRHS that was provided at analysis.

--43 Incompatible values of ICNTL(32) and ICNTL(xx). The index xx is stored in INFO(2).

--44 The solve phase (JOB=3) cannot be performed because the factors or part of the factors are not available. INFO(2) contains the value of ICNTL(31).

--45 NRHS ≤ 0. INFO(2) contains the value of NRHS.

--46 NZ_RHS ≤ 0. This is currently not allowed in case of reduced right-hand-side (ICNTL(26)=1) and in case entries of A⁻¹ are requested (ICNTL(30)=1). INFO(2) contains the value of NZ_RHS.

--47 Entries of A⁻¹ were requested during the solve phase (JOB=3, ICNTL(30)=1) but the constraint NRHS=0 is not respected. The value of NRHS is provided in INFO(2).

--48 A⁻¹ Incompatible values of ICNTL(30) and ICNTL(xx). xx is stored in INFO(2).

--49 SIZE_SCHUR has an incorrect value: SIZE_SCHUR < 0 or SIZE_SCHUR ≥ N, or SIZE_SCHUR was modified on the host since the analysis phase. The value of SIZE_SCHUR is provided in INFO(2).
an error occurred while computing the fill-reducing ordering during the analysis phase. This
commonly happens when an (external) ordering too returns an error code.

An integer overflow occurred during analysis. The integer is used to dimension an array whose
size is slightly larger than twice NZ.

Error in out-of-core management. See the error message returned on output unit ICNTL(1) for
more information.

A positive value of INFO(1) is associated with a warning message which will be output on unit
ICNTL(2) when ICNTL(4) ≥ 2.

Index (in IRN or JCN) out of range. Action taken by subroutine is to ignore any such entries and
continue. INFO(2) is set to the number of faulty entries. Details of the first ten are printed on unit
ICNTL(2).

During error analysis the max-norm of the computed solution was found to be zero.

Not used in current version.

Warning return from the iterative refinement routine. More than ICNTL(10) iterations are required.

Combinations of the above warnings will correspond to summing the constituent warnings.

9 Calling MUMPS from C

MUMPS is a Fortran 90 library, designed to be used from Fortran 90 rather than C. However a basic C
interface is provided that allows users to call MUMPS directly from C programs. Similarly to the Fortran
90 interface, the C interface uses a structure whose components match those in the MUMPS structure for
Fortran (Figure 1). Thus the description of the parameters in Sections 5 and 6 applies. Figure 3 shows the
C structure [SDCZ]MUMPS_STRUC_C. This structure is defined in the include file [sdcz]mumps_c.h
and there is one main routine per available arithmetic with the following prototype:

```c
void [sdcz]mumps_c([SDCZ]MUMPS_STRUC_C * idptr);
```

An example of calling MUMPS from C for a complex assembled problem is given in Subsection 11.3.
The following subsections discuss some technical issues that a user should be aware of before using the
C interface to MUMPS.

In the following, we suppose that id has been declared of type [SDCZ]MUMPS_STRUC_C.

9.1 Array indices

Arrays in C start at index 0 whereas they normally start at 1 in Fortran. Therefore, care must be taken when
providing arrays to the C structure. For example, the row indices of the matrix A, stored in IRN(1:NZ)
in the Fortran version should be stored in irn[0:nz-1] in the C version. (Note that the contents of
irn itself is unchanged with values between 1 and N.) One solution to deal with this is to define macros:

```c
#define ICNTL( i ) icntl[ (i) - 1 ]
#define A( i ) a[ (i) -1 ]
#define IRN( i ) irn[ (i) -1 ]
...
```

and then use the uppercase notation with parenthesis (instead of lowercase/brackets). In that case, the
 notation id.IRN(I), where I is in { 1, 2, ... NZ} can be used instead of id.irn[I-1]; this notation
then matches exactly with the description in Sections 5 and 6, where arrays are supposed to start at 1.

This can be slightly more confusing for elemental matrix input (see Subsection 5.2.2.3), where some
arrays are used to index other arrays. For instance, the first value in eltptr, eltptr[0], pointing
into the list of variables of the first element in eltvar, should be equal to 1. Effectively, using the
notation above, the list of variables for element j = 1 starts at location ELTVAR(ELTPTR(j)) =
ELTVAR(eltptr[j-1]) = eltvar[eltptr[j-1]-1].
typedef struct
{
    int sym, par, job;
    int comm_fortran; /* Fortran communicator */
    int icntl[40];
    real cntl[15];
    int n;
    /* Assembled entry */
    int nz; int *irn; int *jcn; real/complex *a;
    /* Distributed entry */
    int nz_loc; int *irn_loc; int *jcn_loc; real/complex *a_loc;
    /* Element entry */
    int nelt; int *eltptr; int *eltvar; real/complex *a_elt;
    /* Ordering, if given by user */
    int *perm_in;
    /* Scaling (input only in this version) */
    real/complex *colsca; real/complex *rowsca;
    /* RHS, solution, output data and statistics */
    real/complex *rhs, *redrhs, *rhs_sparse, *sol_loc;
    int *irhs_sparse, *irhs_ptr, *isol_loc;
    int nrhs, lrhs, lredrs, nz_rhs, lsol_loc;
    int info[40], infog[40];
    real rinfo[20], rinfo[20];
    int *sym_perm, *uns_perm;
    int *mapping;
    /* Schur */
    int size_schur; int *listvar_schur; real/complex *schur;
    int nprow, npcol, mblock, nblock, schur_lld, schur_mloc, schur_nloc;
    /* Version number */
    char version_number[80];
    char ooc_tmpdir[256], ooc_prefix[64];
    char write_problem[256];
    /* Internal parameters */
    int instance_number;
} [SDCZ]MUMPS_STRUCT_C;

Figure 3: Definition of the C structure [SDCZ]MUMPS_STRUCT_C. real/complex is used for data that can be either real or complex, real for data that stays real (float or double) in the complex version.
9.2 Issues related to the C and Fortran communicators

In general, C and Fortran communicators have a different datatype and are not directly compatible. For the C interface, MUMPS requires a Fortran communicator to be provided in id.comm_fortran. If, however, this field is initialized to the special value -987654, the Fortran communicator MPI_COMM_WORLD is used by default. If you need to call MUMPS based on a smaller number of processors defined by a C subcommunicator, then you should convert your C communicator to a Fortran one. This has not been included in MUMPS because it is dependent on the MPI implementation and thus not portable. For MPI2, and most MPI implementations, you may just do

\[
\text{id.comm\_fortran} = (\text{MUMPS\_INT}) \text{MPI\_Comm\_c2f}(\text{comm} \_\text{c});
\]

(Note that MUMPS\_INT is defined in [sdcz]mumps\_c.h and normally is an int.) For MPI implementations where the Fortran and the C communicators have the same integer representation

\[
\text{id.comm\_fortran} = (\text{MUMPS\_INT}) \text{comm} \_\text{c};
\]

should work. For some MPI implementations, check if \text{id.comm\_fortran} = MPIR\_FromPointer(\text{comm} \_\text{c}) can be used.

9.3 Fortran I/O

Diagnostic, warning and error messages (controlled by Icntl(1:4)/icnt1[0..3]) are based on Fortran file units. Use the value 6 for the Fortran unit 6 which corresponds to stdout. For a more general usage with specific file names from C, passing a C file handler is not currently possible. One solution would be to use a Fortran subroutine along the lines of the model below:

\[
\begin{align*}
&\text{SUBROUTINE OPENFILE( UNIT, NAME )} \\
&\text{INTEGER UNIT} \\
&\text{CHARACTER*(*) NAME} \\
&\text{OPEN(UNIT, file=NAME)} \\
&\text{RETURN} \\
&\text{END}
\end{align*}
\]

and have (in the C user code) a statement like

\[
\text{openfile( &mumps.par.ICNTL(1), name, name.length_byval)}
\]

(or slightly different depending on the C-Fortran calling conventions); something similar could be done to close the file.

9.4 Runtime libraries

The Fortran 90 runtime library corresponding to the compiler used to compile MUMPS is required at the link stage. One way to provide it is to perform the link phase with the Fortran compiler (instead of the C compiler or ld).

9.5 Integer, real and complex datatypes in C and Fortran

We assume that the int, float and double types are compatible with the Fortran INTEGER, REAL and DOUBLE PRECISION datatypes. If this were not the case, the files [dscz]mumps.prec.h or Makefiles would need to be modified accordingly.

Since not all C compilers define the complex datatype (this only appeared in the C99 standard), we define the following, compatible with the Fortran COMPLEX and DOUBLE COMPLEX types:

\[
\begin{align*}
\text{typedef struct \{float r,i;\} mumps\_complex; for simple precision (cmumps).} \\
\text{typedef struct \{double r,i;\} mumps\_double\_complex; for double precision (zmumps).}
\end{align*}
\]

Types for complex data from the user program should be compatible with those above.
9.6 Sequential version

The C interface to MUMPS is compatible with the sequential version; see Subsection 3.11.

10 Scilab and MATLAB/Octave interfaces

Thanks to Octave MEX compatibility, an Octave interface can be generated based on the MATLAB one. The documentation provided in this section also applies to the Octave case.

The main callable functions are

```plaintext
id = initmumps;
id = dmumps(id [,mat] );
id = zmumps(id [,mat] );
```

We have designed these interfaces such that their usage is as similar as possible to the existing C and Fortran interfaces to MUMPS. Only an interface to the sequential version of MUMPS is provided, thus only the parameters related to the sequential version of MUMPS are available. The main differences and characteristics are:

- The existence of a function `initmumps` (usage: `id=initmumps`) that builds an initial structure `id` in which `id.JOB` is set to -1 and `id.SYM` is set to 0 (unsymmetric solver by default).
- Only the double precision and double complex versions of MUMPS are interfaced, since they correspond to the arithmetics used in MATLAB/Scilab.
- The sparse matrix `A` is passed to the interface functions `dmumps` and `zmumps` as a Scilab/MATLAB object (parameters `ICNTL(5)`, `N`, `NZ`, `NELT`, ... are thus irrelevant).
- The right-hand side vector or matrix, possibly sparse, is passed to the interface functions `dmumps` and/or `zmumps` in the argument `id.RHS`, as a Scilab/MATLAB object (parameters `ICNTL(20)`, `NRHS`, `NZ_RHS`, ... are thus irrelevant).
- The Schur complement matrix, if required, is allocated within the interface and returned as a Scilab/MATLAB dense matrix. Furthermore, the parameters `SIZE_SCHUR` and `ICNTL(19)` need not be set by the user; they are set automatically depending on the availability and size of the list of Schur variables, `id.VAR_SCHUR`.
- We have chosen to use a new variable `id.SOL` to store the solution, instead of overwriting `id.RHS`.
- In the out-of-core case, functionalities allowing to control the directory and name of temporary files, can only be controlled through the environment variables `OOC_TMPDIR` and `OOC_PREFIX`—see Subsection 5.5.

Please refer to the report [25] for a more detailed description of these interfaces. Please also refer to the README file in directories MATLAB or Scilab of the main MUMPS distribution for more information on installation. For example, one important thing to note is that at installation, the user must provide the Fortran 90 runtime libraries corresponding to the compiled MUMPS package. This can be done in the makefile for the MATLAB interface (file `make.inc`) and in the builder for the Scilab interface (file `builder.sce`).

Finally, note that examples of usage of the MATLAB and the Scilab interfaces are provided in directories `MATLAB` and `SCILAB/examples`, respectively. In the following, we describe the input and output parameters of the function `[dz]mumps`, that are relevant in the context of this interface to the sequential version of MUMPS.

Input Parameters

- **mat**: sparse matrix which has to be provided as the second argument of `dmumps` if `id.JOB` is strictly larger than 0.
- **id.SYM**: controls the matrix type (symmetric positive definite, symmetric indefinite or unsymmetric) and it has do be initialized by the user before the initialization phase of MUMPS (see `id.JOB`). Its value is set to 0 after the call of `initmumps`.
• **id.JOB**: defines the action that will be realized by **MUMPS**: initialize, analyze and/or factorize and/or solve and release **MUMPS** internal C/Fortran data. It has to be set by the user before any call to **MUMPS** (except after a call to initmumps, which sets its value to -1).

• **id.ICNTL and id.CNTL**: define control parameters that can be set after the initialization call (id.JOB = -1). See Section “Control parameters” for more details. If the user does not modify an entry in id.ICNTL then **MUMPS** uses the default parameter. For example, if the user wants to use the AMD ordering, he/she should set id.ICNTL(7) = 0. Note that the following parameters are inhibited because they are automatically set within the interface: id.ICNTL(19) which controls the Schur complement option and id.ICNTL(20) which controls the format of the right-hand side. Note that parameters id.ICNTL(1:4) may not work properly depending on your compiler and your environment. In case of problem, we recommend to swith printing off by setting id.ICNL(1:4)=-1.

• **id.PERM**: corresponds to the given ordering option (see Section “Input and output parameters” for more details). Note that this permutation is only accessed if the parameter id.ICNTL(7) is set to 1.

• **id.COLSCA and id.ROWSCA**: are optional scaling arrays (see Section “Input and output parameters” for more details)

• **id.RHS**: defines the right-hand side. The parameter id.ICNTL(20) related to its format (sparse or dense) is automatically set within the interface. Note that id.RHS is not modified (as in **MUMPS**), the solution is returned in id.SOL.

• **id.VAR_SCHUR**: corresponds to the list of variables that appear in the Schur complement matrix (see Section “Input and output parameters” for more details).

• **id.REDRHS** (input parameter only if id.VAR_SCHUR was provided during the factorization and if ICNTL(26)=2 on entry to the solve phase): partial solution on the variables corresponding to the Schur complement. It is provided by the user and normally results from both the Schur complement and the reduced right-hand side that were returned by **MUMPS** in a previous call. When ICNTL(26)=2, **MUMPS** uses this information to build the solution id.SOL on the complete problem. See Section “Schur complement” for more details.

**Output Parameters**

• **id.SCHUR**: if id.VAR_SCHUR is provided of size SIZE_SCHUR, then id.SCHUR corresponds to a dense array of size (SIZE_SCHUR,SIZE_SCHUR) that holds the Schur complement matrix (see Section “Input and output parameters” for more details). The user does not have to initialize it.

• **id.REDRHS** (output parameter only if ICNTL(26)=1 and id.VAR_SCHUR was defined): Reduced right-hand side (or condensed right-hand side on the variables associated to the Schur complement). It is computed by **MUMPS** during the solve stage if ICNTL(26)=1. It can then be used outside **MUMPS**, together with the Schur complement, to build a solution on the interface. See Section “Schur complement” for more details.

• **id.INFOG and id.RINFOG**: information parameters (see Section “Information parameters”).

• **id.SYM_PERM**: corresponds to a symmetric permutation of the variables (see discussion regarding ICNTL(7) in Section “Control parameters”). This permutation is computed during the analysis and is followed by the numerical factorization except when numerical pivoting occurs.

• **id.UNS_PERM**: column permutation (if any) on exit from the analysis phase of **MUMPS** (see discussion regarding ICNTL(6) in Section “Control parameters”).

• **id.SOL**: dense vector or matrix containing the solution after **MUMPS** solution phase. Also contains the nullspace in case of null space computation, or entries of the inverse, in case of computation of inverse entries.

**Internal Parameters**

• **id.INST**: (**MUMPS** reserved component) **MUMPS** internal parameter.

• **id.TYPE**: (**MUMPS** reserved component) defines the arithmetic (complex or double precision).
11 Examples of use of MUMPS

11.1 An assembled problem

An example program illustrating a possible use of MUMPS on assembled DOUBLE PRECISION problems is given Figure 4.

```fortran
PROGRAM MUMPS_EXAMPLE
IMPLICIT NONE
INCLUDE 'mpif.h'
INCLUDE 'dmumps_struc.h'
TYPE (DMUMPS_STRUC) mumps_par
INTEGER IERR, I
CALL MPI_INIT (IERR)
C Define a communicator for the package.
! mumps_par%COMM = MPI_COMM_WORLD
C Initial an instance of the package
C for L U factorization (sym = 0, with working host)
mumps_par%JOB = -1
mumps_par%SYM = 0
mumps_par%PAR = 1
CALL DMUMPS(mumps_par)
C Define problem on the host (processor 0)
IF ( mumps_par%MYID .eq . 0 ) THEN
READ(5,*) mumps_par%N
READ(5,*) mumps_par%NZ
ALLOCATE( mumps_par%IRN ( mumps_par%NZ ) )
ALLOCATE( mumps_par%JCN ( mumps_par%NZ ) )
ALLOCATE( mumps_par%A( mumps_par%NZ ) )
ALLOCATE( mumps_par%BHS ( mumps_par%N ) )
DO I = 1 , mumps_par%NZ
   READ(5,*) mumps_par%IRN ( I ) , mumps_par%JCN ( I ) , mumps_par%A( I )
END DO
READ(5,*) ( id%RHS(I) , I =1 , id%N )
END IF
C Call package for solution
mumps_par%JOB = 6
CALL DMUMPS(mumps_par)
IF ( mumps_par%INFOG(1) .LT .0 ) THEN
   WRITE(6, '(A, A, I6, A, I9)') "ERROR: RETURN: ", mumps_par%INFOG(1), " ", mumps_par%INFOG(2)
   GO TO 500
END IF
C Solution has been assembled on the host
IF ( mumps_par%MYID .eq . 0 ) THEN
   WRITE(6, *) "Solution is:",( mumps_par%BHS(1), I=1, mumps_par%N )
END IF
C Deallocate user data
IF ( mumps_par%MYID .eq . 0 ) THEN
   DEALLOCATE( mumps_par%IRN )
   DEALLOCATE( mumps_par%JCN )
   DEALLOCATE( mumps_par%A )
   DEALLOCATE( mumps_par%BHS )
END IF
C Destroy the instance (deallocate internal data structures)
mumps_par%JOB = -2
CALL DMUMPS(mumps_par)
500 CALL MPI_FINALIZE (IERR)
STOP
END
```

Figure 4: Example program using MUMPS on an assembled DOUBLE PRECISION problem

Two files must be included in the program: mpif.h for MPI and mumps_struc.h for MUMPS. The file mumps_root.h must also be available because it is included in mumps_struc.h. The initialization and termination of MPI are performed in the user program via the calls to MPI_INIT and MPI_FINALIZE.

The MUMPS package is initialized by calling MUMPS with JOB = -1, the problem is read in by the host (in the components N, NZ, IRN, JCN, A, and RHS), and the solution is computed in RHS with a
call on all processors to MUMPS with \texttt{JOB=6}. Finally, a call to MUMPS with \texttt{JOB = -2} is performed to deallocate the data structures used by the instance of the package.

Thus for the assembled $5 \times 5$ matrix and right-hand side

$$
\begin{pmatrix}
2 & 3 & 4 & 6 \\
1 & -1 & 2 & 1 \\
-4 & 2 & 1 & 1 \\
-1 & 2 & 1 & 1 \\
2 & 1 & 1 & 1 \\
\end{pmatrix},
\begin{pmatrix}
20 \\
9 \\
6 \\
13 \\
\end{pmatrix}
$$

we could have as input

$\begin{array}{ll}
5 & : \text{N} \\
12 & : \text{NZ} \\
1 & 2 & 3.0 \\
2 & 3 & -3.0 \\
4 & 3 & 2.0 \\
5 & 5 & 1.0 \\
2 & 1 & 3.0 \\
1 & 1 & 2.0 \\
5 & 2 & 4.0 \\
3 & 4 & 2.0 \\
4 & 5 & 6.0 \\
3 & 2 & -1.0 \\
1 & 3 & 4.0 \\
3 & 3 & 1.0 & : \text{A} \\
12.0 & \\
13.0 & : \text{RHS} \\
\end{array}$

and we obtain the solution $\text{RHS}(i) = i, i = 1, \ldots, 5.$

### 11.2 An elemental problem

An example of a driver to use MUMPS for element \texttt{DOUBLE PRECISION} problems is given in Figure 5.

The calling sequence is similar to that for the assembled problem in Subsection 11.1 but now the host reads the problem in components \texttt{N}, \texttt{NELT}, \texttt{ELPTR}, \texttt{ELTVA}, \texttt{A_EL}, and \texttt{RHS}. Note that for elemental problems \texttt{ICNTL(5)} must be set to 1 and that elemental matrices always have a symmetric structure. For the two-element matrix and right-hand side

$$
\begin{pmatrix}
1 & 2 \\
2 & 3 \\
3 & 4 \\
4 & 5 \\
\end{pmatrix},
\begin{pmatrix}
-1 & 1 & 1 & 1 \\
2 & 1 & 1 & 1 \\
-2 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
\end{pmatrix},
\begin{pmatrix}
12 \\
23 \\
6 \\
22 \\
\end{pmatrix}
$$

we could have as input

$\begin{array}{ll}
5 & \\
2 & \\
6 & \\
18 & \\
1 & 4 & 7 \\
1 & 2 & 3 & 4 & 5 \\
-1.0 & 2.0 & 1.0 & 2.0 & 1.0 \\
1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\
1.0 & 2.0 & 1.0 & 3.0 & 1.0 \\
1.0 & 2.0 & 2.0 & 1.0 & 3.0 \\
-1.0 & 2.0 & 2.0 & 3.0 & 1.0 \\
12.0 & 7.0 & 23.0 & 6.0 & 22.0 \\
\end{array}$

and we obtain the solution $\text{RHS}(i) = i, i = 1, \ldots, 5.$
PROGRAM MUMS_EXAMPLE
IMPLICIT NONE
INCLUDE 'mpif.h'
INCLUDE 'dmumps_struct.h'

TYPE (DMUMPS_STRUCT) mumps_par

INTEGER I, IERR, LELTVAR, NA, ELT

CALL MPI_INIT(IERR)

C Define a communicator for the package
mumps_par%COMM = MPI_COMM_WORLD

C Ask for unsymmetric code
mumps_par%SYM = 0

C Host working
mumps_par%PAR = 1

C Initialize an instance of the package
mumps_par%JOB = -1
CALL DMUMPS(mumps_par)

C Define the problem on the host (processor 0)
IF (mumps_par%MYID .eq. 0) THEN
  READ(5,*) mumps_par%N
  READ(5,*) mumps_par%NELT
  READ(5,*) LELTVAR
  READ(5,*) NA, ELT
  ALLOCATE( mumps_par%EIPTPT ( mumps_par%NELT+1 ) )
  ALLOCATE ( mumps_par%ELTVAR ( LELTVAR ) )
  ALLOCATE ( mumps_par%A_EL ( NA, ELT ) )
  ALLOCATE ( mumps_par%RHS ( mumps_par%N ) )
  READ(5,*) ( mumps_par%EIPTPT(1) ,1=1, mumps_par%NELT+1 )
  READ(5,*) ( mumps_par%ELTVAR(1) ,1=1, LELTVAR )
  READ(5,*) ( mumps_par%A_EL(1,1) , NA, ELT )
  READ(5,*) ( mumps_par%RHS(1) ,1=1, mumps_par%N )
END IF

C Specify element entry
mumps_par%ICNTL(5) = 1

C Call package for solution
mumps_par%JOB = 6
CALL DMUMPS(mumps_par)

IF (mumps_par%INFOG(1) .LT. 0) THEN
  WRITE(6,'(A, A, I6 , A, I9)') "ERROR RETURN: ", mumps_par%INFOG(1),
& "mumps_par%INFOG(2)=" , mumps_par%INFOG(2)
  GO TO 500
END IF

C Solution has been assembled on the host
IF (mumps_par%MYID .eq. 0) THEN
  WRITE(6,'(A, A, A, A)') "Solution is ".(mumps_par%RHS(1),1=1,mumps_par%N)
C Deallocate user data
DEALLOCATE( mumps_par%EIPTPT )
DEALLOCATE( mumps_par%ELTVAR )
DEALLOCATE( mumps_par%A_EL )
DEALLOCATE( mumps_par%RHS )
END IF

C Destroy the instance (deallocate internal data structures)
mumps_par%JOB = -2
CALL DMUMPS(mumps_par)

500 CALL MPI_FINALIZE(IERR)
STOP
END

Figure 5: Example program using MUMPS on an elemental DOUBLE PRECISION problem.
11.3 An example of calling MUMPS from C

An example of a driver to use MUMPS from C is given in Figure 6.

```c
/* Example program using the C interface to the */
/* double precision version of MUMPS, dmumps_c. */
/* We solve the system A x = RHS with */
/* A = diag(1, 2) and RHS = \[1 4\]^T */
/* Solution is \[1 2\]^T */
#include <stdio.h>
#include "mpi.h"
#include "dmumps_c.h"
#define JOB_INIT -1
#define JOB_END -2
#define USE_COMM_WORLD -987654
int main(int argc , char **argv) {
    DMUMPS_STRUCT id;
    int n = 2;
    int nz = 2;
    int irn[2] = {1, 2};
    int jcn[2] = {1, 2};
    double a[2];
    double rhs[2];
    int myid , ierr ;
    ierr = MPI_Init(& argc , & argv);
    ierr = MPI_Comm_rank(MPI_COMM_WORLD , &myid);
    /* Define A and rhs */
    rhs[0] = 1.0 ; rhs[1] = 4.0 ;
    a[0] = 1.0 ; a[1] = 2.0 ;
    /* Initialize a MUMPS instance. Use MPI_COMM_WORLD. */
    id.job = JOB_INIT ; id.par = 1 ; id.sym = 0 ; id.comm_fortran = USE_COMM_WORLD ;
    dmumps_c(&id);
    /* Define the problem on the host */
    if ( myid == 0 ) {
        id.n = n ; id.nz = nz ; id.irn = irn ; id.jcn = jcn ;
        id.a = a ; id.rhs = rhs ;
    }
    #define ICNTL ( I ) icntl [ ( I ) − 1 ] /* macro s.t. indices match documentation */
    /* No outputs */
    /* Call the MUMPS package. */
    id.job = 6 ;
    dmumps_c(&id);
    /* Terminate instance */
    if ( myid == 0 ) {
        printf("Solution is \[ \%8.2f \%8.2f \]\n", rhs[0] , rhs[1] );
    } return 0 ;
}
```

Figure 6: Example program using MUMPS from C on an assembled problem.
12 License

Copyright 1991–2015 CERFACS, CNRS, ENS Lyon, INP Toulouse, Inria, University of Bordeaux.

This version of MUMPS is provided to you free of charge. It is released under the CeCILL-C license, http://www.cecill.info/licences/Licence_CeCILL-C_V1-en.html, except for the external and optional ordering PORD, in separate directory PORD, which is public domain (see PORD/README).

You can acknowledge (using references [1] and [2]) the contribution of this package in any scientific publication dependent upon the use of the package. Please use reasonable endeavours to notify the authors of the package of this publication.


As a counterpart to the access to the source code and rights to copy, modify and redistribute granted by the license, users are provided only with a limited warranty and the software’s author, the holder of the economic rights, and the successive licensors have only limited liability.

In this respect, the user’s attention is drawn to the risks associated with loading, using, modifying and/or developing or reproducing the software by the user in light of its specific status of free software, that may mean that it is complicated to manipulate, and that also therefore means that it is reserved for developers and experienced professionals having in-depth computer knowledge. Users are therefore encouraged to load and test the software’s suitability as regards their requirements in conditions enabling the security of their systems and/or data to be ensured and, more generally, to use and operate it in the same conditions as regards security.

The fact that you are presently reading this means that you have had knowledge of the CeCILL-C license and that you accept its terms.

13 Credits

This version of MUMPS has been developed by employees of CERFACS, ENS Lyon, INPT(ENSEEIHT)-IRIT, Inria and University of Bordeaux: Emmanuel Agullo, Patrick Amestoy, Maurice Bremond, Alfredo Buttari, Philippe Combes, Aurelia Fevre, Abdou Guermouche, Guillaume Joslin, Jacko Koster, Jean-Yves L’Excellent, Stephane Pralet, Chiara Puglisi, Francois-Henry Rouet, Wissam Sid-Lakhdar, Tzvetomila Slavova, Bora Ucar and Clement Weisbecker.
We are grateful to Caroline Bousquet, Indranil Chowdhury, Christophe Daniel, Iain Duff, Vincent Espirat, Gregoire Richard, Alexis Salzman, Miroslav Tuma and Christophe Voemel who have been contributing to this project.

We are also grateful to Juergen Schulze for letting us distribute PORD developed at the University of Paderborn. We thank Eddy Caron for the administration of a server used on a daily basis for MUMPS.

We want to thank the French ANR programme, the European community, Altair, EADS-IW, EDF, EMGS, ESI Group, LSTC, Michelin, SAMTECH (now Siemens), Total for their support.

We also thank the Lawrence Berkeley National Laboratory, PARALLAB (Bergen) and Rutherford Appleton Laboratory for research discussions that have certainly influenced this work.

Finally we want to thank the institutions that have provided access to their parallel machines: Centre Informatique National de l’Enseignement Superieur (CINES), CERFACS, CICT-CALMIP (Centre Interuniversitaire de Calcul de Toulouse), Federation Lyonnaise de Calcul Haute-Performance, Institut du Developpement et des Ressources en Informatique Scientifique (IDRIS), Lawrence Berkeley National Laboratory, Laboratoire de l’Informatique du Parallelisme, Inria, and PARALLAB.

References


