Intel® Math Kernel Library for Linux* OS

User's Guide

Intel® MKL - Linux* OS

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Getting Help and Support

Intel provides a support web site that contains a rich repository of self help information, including getting started tips, known product issues, product errata, license information, user forums, and more. Visit the Intel MKL support website at http://www.intel.com/software/products/support/.
Introducing the Intel® Math Kernel Library

Intel® Math Kernel Library (Intel® MKL) is a computing math library of highly optimized, extensively threaded routines for applications that require maximum performance. Intel MKL provides comprehensive functionality support in these major areas of computation:

- BLAS (level 1, 2, and 3) and LAPACK linear algebra routines, offering vector, vector-matrix, and matrix-matrix operations.
- The PARDISO* direct sparse solver, an iterative sparse solver, and supporting sparse BLAS (level 1, 2, and 3) routines for solving sparse systems of equations.
- ScalAPACK distributed processing linear algebra routines for Linux* and Windows* operating systems, as well as the Basic Linear Algebra Communications Subprograms (BLACS) and the Parallel Basic Linear Algebra Subprograms (PBLAS).
- Fast Fourier transform (FFT) functions in one, two, or three dimensions with support for mixed radices (not limited to sizes that are powers of 2), as well as distributed versions of these functions provided for use on clusters of the Linux* and Windows* operating systems.
- Vector Math Library (VML) routines for optimized mathematical operations on vectors.
- Vector Statistical Library (VSL) routines, which offer high-performance vectorized random number generators (RNG) for several probability distributions, convolution and correlation routines, and summary statistics functions.
- Data Fitting Library, which provides capabilities for spline-based approximation of functions, derivatives and integrals of functions, and search.
- Extended Eigensolver, a shared memory programming (SMP) version of an eigensolver based on the Feast Eigenvalue Solver.

For details see the Intel® MKL Reference Manual.

Intel MKL is optimized for the latest Intel processors, including processors with multiple cores (see the Intel MKL Release Notes for the full list of supported processors). Intel MKL also performs well on non-Intel processors.

For Linux* systems based on Intel® 64 Architecture, Intel MKL also includes support for the Intel® Many Integrated Core (Intel® MIC) Architecture and provides libraries to help you port your applications to Intel MIC Architecture.

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What's New

This User's Guide documents Intel® Math Kernel Library (Intel® MKL) 11.0 update 5. The document has been updated to reflect the following changes to the product:

- Support of heterogeneous clusters by the Intel® Optimized MP LINPACK Benchmark for Clusters (see Intel(R) Optimized MP LINPACK Benchmark for Clusters).

Additionally minor updates have been made to correct errors in the document.
The following term is used in reference to the operating system.

Linux* OS  This term refers to information that is valid on all supported Linux* operating systems.

The following notations are used to refer to Intel MKL directories.

<parent product directory>  The installation directory for the larger product that includes Intel MKL; for example, Intel® C++ Composer XE or Intel® Fortran Composer XE.

<mkl directory>  The main directory where Intel MKL is installed:

<mkl directory> = <parent product directory>/mkl.

Replace this placeholder with the specific pathname in the configuring, linking, and building instructions.

The following font conventions are used in this document.

**Italic**  Italic is used for emphasis and also indicates document names in body text, for example:

see *Intel MKL Reference Manual*.

**Monospace lowercase**  Indicates filenames, directory names, and pathnames, for example:

`./benchmarks/linpack`

**Monospace lowercase mixed with uppercase**  Indicates:

- Commands and command-line options, for example,

  `icc myprog.c -L$MKLPATH -I$MKLINCLUDE -lmkl -liomp5 -lpthread`

- Filenames, directory names, and pathnames, for example,

- C/C++ code fragments, for example,

  ```c
  a = new double [SIZE*SIZE];
  ```

**UPPERCASE MONOSPACE**  Indicates system variables, for example, `$MKLPATH`.

**Monospace italic**  Indicates a parameter in discussions, for example, `lda`.

When enclosed in angle brackets, indicates a placeholder for an identifier, an expression, a string, a symbol, or a value, for example, `<mkl directory>`. Substitute one of these items for the placeholder.

**[ items ]**  Square brackets indicate that the items enclosed in brackets are optional.

**{ item | item }**  Braces indicate that only one of the items listed between braces should be selected. A vertical bar ( | ) separates the items.
Related Information

To reference how to use the library in your application, use this guide in conjunction with the following documents:

- The *Intel® Math Kernel Library Reference Manual*, which provides reference information on routine functionalities, parameter descriptions, interfaces, calling syntaxes, and return values.
Getting Started

Optimization Notice

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Notice revision #20110804

Checking Your Installation

After installing the Intel® Math Kernel Library (Intel® MKL), verify that the library is properly installed and configured:

1. Intel MKL installs in the `<parent product directory>` directory.
   
   Check that the subdirectory of `<parent product directory>` referred to as `<mkl directory>` was created.

2. If you want to keep multiple versions of Intel MKL installed on your system, update your build scripts to point to the correct Intel MKL version.

3. Check that the following files appear in the `<mkl directory>/bin` directory and its subdirectories:
   
   mklvars.sh
   mklvars.csh
   ia32/mklvars_ia32.sh
   ia32/mklvars_ia32.csh
   intel64/mklvars_intel64.sh
   intel64/mklvars_intel64.csh

   Use these files to assign Intel MKL-specific values to several environment variables, as explained in Setting Environment Variables

4. To understand how the Intel MKL directories are structured, see Intel® Math Kernel Library Structure.

5. To make sure that Intel MKL runs on your system, launch an Intel MKL example, as explained in Using Code Examples.

See Also

Notational Conventions

Setting Environment Variables

See Also

Setting the Number of Threads Using an OpenMP* Environment Variable
Scripts to Set Environment Variables

When the installation of Intel MKL for Linux* OS is complete, set the INCLUDE, MKLROOT, LD_LIBRARY_PATH, MIC_LD_LIBRARY_PATH, MANPATH, LIBRARY_PATH, CPATH, and NLSPATH environment variables in the command shell using one of the script files in the bin subdirectory of the Intel MKL installation directory. The environment variable MIC_LD_LIBRARY_PATH specifies locations of shared objects for Intel® Many Integrated Core (Intel® MIC) Architecture.

Choose the script corresponding to your system architecture and command shell as explained in the following table:

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Shell</th>
<th>Script File</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA-32</td>
<td>C</td>
<td>ia32/mklvars_ia32.csh</td>
</tr>
<tr>
<td>IA-32</td>
<td>Bash and Bourne (sh)</td>
<td>ia32/mklvars_ia32.sh</td>
</tr>
<tr>
<td>Intel® 64</td>
<td>C</td>
<td>intel64/mklvars_intel64.csh</td>
</tr>
<tr>
<td>Intel 64</td>
<td>Bash and Bourne (sh)</td>
<td>intel64/mklvars_intel64.sh</td>
</tr>
<tr>
<td>All supported architectures</td>
<td>C</td>
<td>mklvars.csh</td>
</tr>
<tr>
<td>All supported architectures</td>
<td>Bash and Bourne (sh)</td>
<td>mklvars.sh</td>
</tr>
</tbody>
</table>

Running the Scripts

The parameters of the scripts specify the following:

- Architecture.
- Use of Intel MKL Fortran modules precompiled with the Intel® Fortran compiler. Supply this parameter only if you are using this compiler.
- Programming interface (LP64 or ILP64).

Usage and values of these parameters depend on the name of the script (regardless of the extension). The following table lists values of the script parameters.

<table>
<thead>
<tr>
<th>Script</th>
<th>Architecture (required, when applicable)</th>
<th>Use of Fortran Modules (optional)</th>
<th>Interface (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mklvars_ia32</td>
<td>n/a†</td>
<td>mod</td>
<td>n/a</td>
</tr>
<tr>
<td>mklvars_intel64</td>
<td>n/a</td>
<td>mod</td>
<td>lp64, default</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ilp64</td>
</tr>
<tr>
<td>mklvars</td>
<td>ia32</td>
<td>mod</td>
<td>lp64, default</td>
</tr>
<tr>
<td></td>
<td>intel64</td>
<td></td>
<td>ilp64</td>
</tr>
</tbody>
</table>

† Not applicable.

For example:

- The command
  
mklvars.sh ia32
  
sets the environment for Intel MKL to use the IA-32 architecture.

- The command
  
mklvars.sh intel64 mod ilp64
  
sets the environment for Intel MKL to use the Intel 64 architecture, ILP64 programming interface, and Fortran modules.
• The command
  mklvars.sh intel64 mod
  sets the environment for Intel MKL to use the Intel 64 architecture, LP64 interface, and Fortran modules.

• The command
  mklvars.sh mic lp64
  sets the environment for Intel MKL to use the Intel MIC Architecture and LP64 programming interface.

NOTE
Supply the parameter specifying the architecture first, if it is needed. Values of the other two parameters can be listed in any order.

See Also
High-level Directory Structure
Interface Libraries and Modules
Fortran 95 Interfaces to LAPACK and BLAS
Setting the Number of Threads Using an OpenMP* Environment Variable

Automating the Process of Setting Environment Variables

To automate setting of the INCLUDE, MKLROOT, LD_LIBRARY_PATH, MANPATH, LIBRARY_PATH, CPATH, and NLSPATH environment variables, add mklvars*.sh to your shell profile so that each time you login, the script automatically executes and sets the paths to the appropriate Intel MKL directories. To do this, with a local user account, edit the following files by adding the appropriate script to the path manipulation section right before exporting variables:

<table>
<thead>
<tr>
<th>Shell</th>
<th>Files</th>
<th>Commands</th>
</tr>
</thead>
</table>
| bash  | ~/.bash_profile, ~/.bash_login or ~/.profile | # setting up MKL environment for bash
       |                 | . <absolute_path_to_installed_MKL>/bin
       |                 |   [/<arch>]/mklvars[<arch>].sh [<arch>] [mod] [lp64|ilp64]            |
| sh    | ~/.profile     | # setting up MKL environment for sh
       |                 | . <absolute_path_to_installed_MKL>/bin
       |                 |   [/<arch>]/mklvars[<arch>].sh [<arch>] [mod] [lp64|ilp64]            |
| csh   | ~/.login       | # setting up MKL environment for sh
       |                 | . <absolute_path_to_installed_MKL>/bin
       |                 |   [/<arch>]/mklvars[<arch>].csh [<arch>] [mod] [lp64|ilp64]            |

In the above commands, replace <arch> with ia32 or intel64.

If you have super user permissions, add the same commands to a general-system file in /etc/profile (for bash and sh) or in /etc/csh.login (for csh).

CAUTION
Before uninstalling Intel MKL, remove the above commands from all profile files where the script execution was added. Otherwise you may experience problems logging in.

See Also
Scripts to Set Environment Variables
Compiler Support

Intel® MKL supports compilers identified in the Release Notes. However, the library has been successfully used with other compilers as well.

When building Intel MKL code examples for either C or Fortran, you can select a compiler: Intel®, GNU*, or PGI®.

Intel MKL provides a set of include files to simplify program development by specifying enumerated values and prototypes for the respective functions. Calling Intel MKL functions from your application without an appropriate include file may lead to incorrect behavior of the functions.

See Also
Include Files

Using Code Examples

The Intel MKL package includes code examples, located in the examples subdirectory of the installation directory. Use the examples to determine:

- Whether Intel MKL is working on your system
- How you should call the library
- How to link the library

The examples are grouped in subdirectories mainly by Intel MKL function domains and programming languages. For instance, the examples/spblas subdirectory contains a makefile to build the Sparse BLAS examples and the examples/vmlc subdirectory contains the makefile to build the C VML examples. You can find examples of Automatic Offload in the examples/mic_ao subdirectory and examples of Compiler Assisted Offload in examples/mic_offload subdirectory. Source code for the examples is in the next-level sources subdirectory.

See Also
High-level Directory Structure
Using Intel® Math Kernel Library on Intel® Xeon Phi™ Coprocessors

What You Need to Know Before You Begin Using the Intel® Math Kernel Library

<table>
<thead>
<tr>
<th>Target platform</th>
<th>Identify the architecture of your target machine:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• IA-32 or compatible</td>
</tr>
<tr>
<td></td>
<td>• Intel® 64 or compatible</td>
</tr>
</tbody>
</table>

**Reason:** Because Intel MKL libraries are located in directories corresponding to your particular architecture (see Architecture Support), you should provide proper paths on your link lines (see Linking Examples). To configure your development environment for the use with Intel MKL, set your environment variables using the script corresponding to your architecture (see Setting Environment Variables for details).

<table>
<thead>
<tr>
<th>Mathematical problem</th>
<th>Identify all Intel MKL function domains that you require:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• BLAS</td>
</tr>
<tr>
<td></td>
<td>• Sparse BLAS</td>
</tr>
<tr>
<td></td>
<td>• LAPACK</td>
</tr>
<tr>
<td></td>
<td>• PBLAS</td>
</tr>
<tr>
<td></td>
<td>• ScaLAPACK</td>
</tr>
</tbody>
</table>
• Sparse Solver routines
• Vector Mathematical Library functions (VML)
• Vector Statistical Library functions
• Fourier Transform functions (FFT)
• Cluster FFT
• Trigonometric Transform routines
• Poisson, Laplace, and Helmholtz Solver routines
• Optimization (Trust-Region) Solver routines
• Data Fitting Functions
• Extended Eigensolver Functions

**Reason:** The function domain you intend to use narrows the search in the *Reference Manual* for specific routines you need. Additionally, if you are using the Intel MKL cluster software, your link line is function-domain specific (see *Working with the Cluster Software*). Coding tips may also depend on the function domain (see *Other Tips and Techniques to Improve Performance*).

**Programming language**

Intel MKL provides support for both Fortran and C/C++ programming. Identify the language interfaces that your function domains support (see Intel® Math Kernel Library Language Interfaces Support).

**Reason:** Intel MKL provides language-specific include files for each function domain to simplify program development (see Language Interfaces Support, by Function Domain).

For a list of language-specific interface libraries and modules and an example how to generate them, see also Using Language-Specific Interfaces with Intel® Math Kernel Library.

**Range of integer data**

If your system is based on the Intel 64 architecture, identify whether your application performs calculations with large data arrays (of more than $2^{31}$-1 elements).

**Reason:** To operate on large data arrays, you need to select the ILP64 interface, where integers are 64-bit; otherwise, use the default, LP64, interface, where integers are 32-bit (see Using the ILP64 Interface vs. LP64 Interface).

**Threading model**

Identify whether and how your application is threaded:

• Threaded with the Intel compiler
• Threaded with a third-party compiler
• Not threaded

**Reason:** The compiler you use to thread your application determines which threading library you should link with your application. For applications threaded with a third-party compiler you may need to use Intel MKL in the sequential mode (for more information, see Sequential Mode of the Library and Linking with Threading Libraries).

**Number of threads**

Determine the number of threads you want Intel MKL to use.

**Reason:** Intel MKL is based on the OpenMP* threading. By default, the OpenMP* software sets the number of threads that Intel MKL uses. If you need a different number, you have to set it yourself using one of the available mechanisms. For more information, see Improving Performance with Threading.

**Linking model**

Decide which linking model is appropriate for linking your application with Intel MKL libraries:

• Static
• Dynamic
**Reason:** The link line syntax and libraries for static and dynamic linking are different. For the list of link libraries for static and dynamic models, linking examples, and other relevant topics, like how to save disk space by creating a custom dynamic library, see *Linking Your Application with the Intel® Math Kernel Library*.

**MPI used**

Decide what MPI you will use with the Intel MKL cluster software. You are strongly encouraged to use the latest available version of Intel® MPI.

**Reason:** To link your application with ScaLAPACK and/or Cluster FFT, the libraries corresponding to your particular MPI should be listed on the link line (see *Working with the Cluster Software*).
Optimization Notice

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Notice revision #20110804

Architecture Support

Intel® Math Kernel Library (Intel® MKL) for Linux® OS provides architecture-specific implementations for supported platforms. The following table lists the supported architectures and directories where each architecture-specific implementation is located.

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA-32 or compatible</td>
<td>&lt;mkl directory&gt;/lib/ia32</td>
</tr>
<tr>
<td>Intel® 64 or compatible</td>
<td>&lt;mkl directory&gt;/lib/intel64</td>
</tr>
<tr>
<td>Intel® Many Integrated Core (Intel® MIC)</td>
<td>&lt;mkl directory&gt;/lib/mic</td>
</tr>
</tbody>
</table>

See Also

High-level Directory Structure
Notational Conventions
Detailed Structure of the IA-32 Architecture Directories
Detailed Structure of the Intel® 64 Architecture Directories

High-level Directory Structure

<table>
<thead>
<tr>
<th>Directory</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;mkl directory&gt;</td>
<td>Installation directory of the Intel® Math Kernel Library (Intel® MKL)</td>
</tr>
<tr>
<td>bin</td>
<td>Scripts to set environmental variables in the user shell</td>
</tr>
<tr>
<td>bin/ia32</td>
<td>Shell scripts for the IA-32 architecture</td>
</tr>
<tr>
<td>bin/intel64</td>
<td>Shell scripts for the Intel® 64 architecture</td>
</tr>
<tr>
<td>benchmarks/linpack</td>
<td>Shared-memory (SMP) version of the LINPACK benchmark</td>
</tr>
<tr>
<td>benchmarks/mp_linpack</td>
<td>Message-passing interface (MPI) version of the LINPACK benchmark</td>
</tr>
<tr>
<td>Directory</td>
<td>Contents</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>examples</td>
<td>Examples directory. Each subdirectory has source and data files.</td>
</tr>
<tr>
<td>examples/mic_ao</td>
<td>Examples of automatic offloading Intel MKL computations to Intel® Xeon Phi™ coprocessors. Each subdirectory has source files.</td>
</tr>
<tr>
<td>examples/mic_offload</td>
<td>Examples of Compiler Assisted Offload of computations to Intel Xeon Phi coprocessors. Each subdirectory has source files.</td>
</tr>
<tr>
<td>include</td>
<td>INCLUDE files for the library routines, as well as for tests and examples</td>
</tr>
<tr>
<td>include/ia32</td>
<td>Fortran 95 .mod files for the IA-32 architecture and Intel® Fortran compiler</td>
</tr>
<tr>
<td>include/intel64/lp64</td>
<td>Fortran 95 .mod files for the Intel® 64 architecture, Intel Fortran compiler, and LP64 interface</td>
</tr>
<tr>
<td>include/intel64/ilp64</td>
<td>Fortran 95 .mod files for the Intel® 64 architecture, Intel Fortran compiler, and ILP64 interface</td>
</tr>
<tr>
<td>include/mic/lp64</td>
<td>Fortran 95 .mod files for the Intel® MIC architecture, Intel Fortran compiler, and LP64 interface</td>
</tr>
<tr>
<td>include/mic/ilp64</td>
<td>Fortran 95 .mod files for the Intel® MIC architecture, Intel Fortran compiler, and ILP64 interface</td>
</tr>
<tr>
<td>include/fftw</td>
<td>Header files for the FFTW2 and FFTW3 interfaces</td>
</tr>
<tr>
<td>interfaces/blas95</td>
<td>Fortran 95 interfaces to BLAS and a makefile to build the library</td>
</tr>
<tr>
<td>interfaces/fftw2x_cdft</td>
<td>MPI FFTW 2.x interfaces to the Intel MKL Cluster FFTs</td>
</tr>
<tr>
<td>interfaces/fftw3x_cdft</td>
<td>MPI FFTW 3.x interfaces to the Intel MKL Cluster FFTs</td>
</tr>
<tr>
<td>interfaces/fftw2xc</td>
<td>FFTW 2.x interfaces to the Intel MKL FFTs (C interface)</td>
</tr>
<tr>
<td>interfaces/fftw2xf</td>
<td>FFTW 2.x interfaces to the Intel MKL FFTs (Fortran interface)</td>
</tr>
<tr>
<td>interfaces/fftw3xc</td>
<td>FFTW 3.x interfaces to the Intel MKL FFTs (C interface)</td>
</tr>
<tr>
<td>interfaces/fftw3xf</td>
<td>FFTW 3.x interfaces to the Intel MKL FFTs (Fortran interface)</td>
</tr>
<tr>
<td>interfaces/lapack95</td>
<td>Fortran 95 interfaces to LAPACK and a makefile to build the library</td>
</tr>
<tr>
<td>lib/ia32</td>
<td>Static libraries and shared objects for the IA-32 architecture</td>
</tr>
<tr>
<td>lib/intel64</td>
<td>Static libraries and shared objects for the Intel® 64 architecture</td>
</tr>
<tr>
<td>lib/mic</td>
<td>Static libraries and shared objects for the Intel® MIC architecture</td>
</tr>
<tr>
<td>tests</td>
<td>Source and data files for tests.</td>
</tr>
<tr>
<td>tools</td>
<td>Tools and plug-ins</td>
</tr>
<tr>
<td>tools/builder</td>
<td>Tools for creating custom dynamically linkable libraries</td>
</tr>
</tbody>
</table>

**See Also**
Notational Conventions
Using Code Examples
Layered Model Concept

Intel MKL is structured to support multiple compilers and interfaces, different OpenMP* implementations, both serial and multiple threads, and a wide range of processors. Conceptually Intel MKL can be divided into distinct parts to support different interfaces, threading models, and core computations:

1. Interface Layer
2. Threading Layer
3. Computational Layer

You can combine Intel MKL libraries to meet your needs by linking with one library in each part layer-by-layer. Once the interface library is selected, the threading library you select picks up the chosen interface, and the computational library uses interfaces and OpenMP implementation (or non-threaded mode) chosen in the first two layers.

To support threading with different compilers, one more layer is needed, which contains libraries not included in Intel MKL:

- Compiler run-time libraries (RTL).

The following table provides more details of each layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Layer</td>
<td>This layer matches compiled code of your application with the threading and/or computational parts of the library. This layer provides:</td>
</tr>
<tr>
<td></td>
<td>• LP64 and ILP64 interfaces.</td>
</tr>
<tr>
<td></td>
<td>• Compatibility with compilers that return function values differently.</td>
</tr>
<tr>
<td></td>
<td>• A mapping between single-precision names and double-precision names for applications using Cray*-style naming (SP2DP interface).</td>
</tr>
<tr>
<td></td>
<td>SP2DP interface supports Cray-style naming in applications targeted for the Intel 64 architecture and using the ILP64 interface. SP2DP interface provides a mapping between single-precision names (for both real and complex types) in the application and double-precision names in Intel MKL BLAS and LAPACK. Function names are mapped as shown in the following example for BLAS functions SGETRF:</td>
</tr>
<tr>
<td></td>
<td>SGETRF -&gt; DGGETRF</td>
</tr>
<tr>
<td></td>
<td>DGGETRF -&gt; DGGETRF</td>
</tr>
<tr>
<td></td>
<td>CGGETRF -&gt; DZGETRF</td>
</tr>
<tr>
<td></td>
<td>DZGETRF -&gt; DZGETRF</td>
</tr>
<tr>
<td></td>
<td>Mind that no changes are made to double-precision names.</td>
</tr>
<tr>
<td>Threading Layer</td>
<td>This layer:</td>
</tr>
<tr>
<td></td>
<td>• Provides a way to link threaded Intel MKL with different threading compilers.</td>
</tr>
<tr>
<td></td>
<td>• Enables you to link with a threaded or sequential mode of the library.</td>
</tr>
<tr>
<td></td>
<td>This layer is compiled for different environments (threaded or sequential) and compilers (from Intel, GNU*, and so on).</td>
</tr>
<tr>
<td>Computational Layer</td>
<td>This layer is the heart of Intel MKL. It has only one library for each combination of architecture and supported OS. The Computational layer accommodates multiple architectures through identification of architecture features and chooses the appropriate binary code at run time.</td>
</tr>
<tr>
<td>Compiler Run-time Libraries (RTL)</td>
<td>To support threading with Intel® compilers, Intel MKL uses RTLs of the Intel® C++ Compiler or Intel® Fortran Compiler. To thread using third-party threading compilers, use libraries in the Threading layer or an appropriate compatibility library.</td>
</tr>
</tbody>
</table>

See Also

Using the ILP64 Interface vs. LP64 Interface
Linking Your Application with the Intel® Math Kernel Library
## Contents of the Documentation Directories

Most of Intel MKL documentation is installed in `<parent product directory>/Documentation/<locale>/mkl`. For example, the documentation in English is installed in `<parent product directory>/Documentation/en_US/mkl`. However, some Intel MKL-related documents are installed one or two levels up. The following table lists Intel MKL-related documentation.

<table>
<thead>
<tr>
<th>File name</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&lt;locale&gt;</code>/clicense or <code>&lt;locale&gt;</code>/flicense</td>
<td>Common end user license for the larger product that includes Intel MKL.</td>
</tr>
<tr>
<td>mklsupport.txt</td>
<td>Information on package number for customer support reference</td>
</tr>
<tr>
<td>Contents of <code>&lt;parent product directory&gt;/Documentation/&lt;locale&gt;/mkl</code> redist.txt</td>
<td>List of redistributable files</td>
</tr>
<tr>
<td>mkldocumentation.htm</td>
<td>Overview and links for the Intel MKL documentation</td>
</tr>
<tr>
<td>get_started.html</td>
<td>Brief introduction to Intel MKL</td>
</tr>
<tr>
<td>tutorials/mkl_mmx_c/index.htm</td>
<td>Getting Started Tutorials &quot;Using Intel® Math Kernel Library for Matrix Multiplication (C Language)&quot;</td>
</tr>
<tr>
<td>tutorials/mkl_mmx_f/index.htm</td>
<td>Getting Started Tutorials &quot;Using Intel® Math Kernel Library for Matrix Multiplication (Fortran Language)&quot;</td>
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<td>List of redistributable files</td>
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<td>Overview and links for the Intel MKL documentation</td>
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<tr>
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<td>Overview and links for the Intel MKL documentation</td>
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<tr>
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</tr>
</tbody>
</table>

† Included only in a localized Japanese version of the Intel® MKL. Please see the Release Notes for information on Intel MKL localization.


**See Also**

Notational Conventions
Linking Your Application with the Intel® Math Kernel Library

Optimization Notice

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Notice revision #20110804

Linking Quick Start

Intel® Math Kernel Library (Intel® MKL) provides several options for quick linking of your application, which depend on the way you link:

- Using the Intel® Composer XE compiler
  - see Using the -mkl Compiler Option.
- Explicit dynamic linking
  - see Using the Single Dynamic Library for how to simplify your link line.
- Explicitly listing libraries on your link line
  - see Selecting Libraries to Link with for a summary of the libraries.
- Using an interactive interface
  - see Using the Link-line Advisor to determine libraries and options to specify on your link or compilation line.
- Using an internally provided tool
  - see Using the Command-line Link Tool to determine libraries, options, and environment variables or even compile and build your application.

Using the -mkl Compiler Option

The Intel® Composer XE compiler supports the following variants of the -mkl compiler option:

- `-mkl` or `-mkl=parallel`
  - to link with standard threaded Intel MKL.
- `-mkl=sequential`
  - to link with sequential version of Intel MKL.
- `-mkl=cluster`
  - to link with Intel MKL cluster components (sequential) that use Intel MPI.

For more information on the -mkl compiler option, see the Intel Compiler User and Reference Guides.

On Intel® 64 architecture systems, for each variant of the -mkl option, the compiler links your application using the LP64 interface.
If you specify any variant of the -mkl compiler option, the compiler automatically includes the Intel MKL libraries. In cases not covered by the option, use the Link-line Advisor or see Linking in Detail.

See Also
Listing Libraries on a Link Line
Using the ILP64 Interface vs. LP64 Interface
Using the Link-line Advisor
Intel® Software Documentation Library for Intel® Composer XE documentation

Using the Single Dynamic Library
You can simplify your link line through the use of the Intel MKL Single Dynamic Library (SDL).

To use SDL, place libmkl_rt.so on your link line. For example:

```bash
icc application.c -lmkl_rt
```

SDL enables you to select the interface and threading library for Intel MKL at run time. By default, linking with SDL provides:

- LP64 interface on systems based on the Intel® 64 architecture
- Intel threading

To use other interfaces or change threading preferences, including use of the sequential version of Intel MKL, you need to specify your choices using functions or environment variables as explained in section Dynamically Selecting the Interface and Threading Layer.

Selecting Libraries to Link with
To link with Intel MKL:

- Choose one library from the Interface layer and one library from the Threading layer
- Add the only library from the Computational layer and run-time libraries (RTL)

The following table lists Intel MKL libraries to link with your application.

<table>
<thead>
<tr>
<th>Interface layer</th>
<th>Threading layer</th>
<th>Computational layer</th>
<th>RTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA-32 architecture, static linking</td>
<td>libmkl_intel.a</td>
<td>libmkl_intel_thread.a</td>
<td>libmkl_core.a</td>
</tr>
<tr>
<td>IA-32 architecture, dynamic linking</td>
<td>libmkl_intel.so</td>
<td>libmkl_intel_thread.so</td>
<td>libmkl_core.so</td>
</tr>
<tr>
<td>Intel® 64 architecture, static linking</td>
<td>libmkl_intel_lp64.a</td>
<td>libmkl_intel_thread.a</td>
<td>libmkl_core.a</td>
</tr>
<tr>
<td>Intel® 64 architecture, dynamic linking</td>
<td>libmkl_intel_lp64.so</td>
<td>libmkl_intel_thread.so</td>
<td>libmkl_core.so</td>
</tr>
<tr>
<td>Intel® Many Integrated Core (Intel® MIC) Architecture, static linking</td>
<td>libmkl_intel_lp64.a</td>
<td>libmkl_intel_thread.a</td>
<td>libmkl_core.a</td>
</tr>
</tbody>
</table>
The Single Dynamic Library (SDL) automatically links interface, threading, and computational libraries and thus simplifies linking. The following table lists Intel MKL libraries for dynamic linking using SDL. See Dynamically Selecting the Interface and Threading Layer for how to set the interface and threading layers at run time through function calls or environment settings.

<table>
<thead>
<tr>
<th>SDL</th>
<th>RTL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intel MIC Architecture, dynamic linking</strong></td>
<td></td>
</tr>
<tr>
<td>libmkl_intel_lpm64.so</td>
<td>libmkl_intel_thread.so</td>
</tr>
<tr>
<td><strong>IA-32 and Intel® 64 architectures</strong></td>
<td></td>
</tr>
<tr>
<td>libmkl_rt.so</td>
<td>libiomp5.so††</td>
</tr>
</tbody>
</table>

†† Use the Link-line Advisor to check whether you need to explicitly link the libiomp5.so RTL.

For exceptions and alternatives to the libraries listed above, see Linking in Detail.

**See Also**
Layered Model Concept
Using the Link-line Advisor
Using the -mkl Compiler Option
Working with the Intel® Math Kernel Library Cluster Software
Linking for Compiler Assisted Offload For special linking needed for Compiler Assisted Offload

**Using the Link-line Advisor**
Use the Intel MKL Link-line Advisor to determine the libraries and options to specify on your link or compilation line.

The latest version of the tool is available at http://software.intel.com/en-us/articles/intel-mkl-link-line-advisor. The tool is also available in the product.

The Advisor requests information about your system and on how you intend to use Intel MKL (link dynamically or statically, use threaded or sequential mode, etc.). The tool automatically generates the appropriate link line for your application.

**See Also**
Contents of the Documentation Directories for the location of the installed Link-line Advisor

**Using the Command-line Link Tool**
Use the command-line Link tool provided by Intel MKL to simplify building your application with Intel MKL.

The tool not only provides the options, libraries, and environment variables to use, but also performs compilation and building of your application.

The tool mkl_link_tool is installed in the `<mkl directory>/tools` directory.


**Linking Examples**

**See Also**
Using the Link-line Advisor
Examples for Linking with ScaLAPACK and Cluster FFT
Linking on IA-32 Architecture Systems

The following examples illustrate linking that uses Intel(R) compilers.
The examples use the .f Fortran source file. C/C++ users should instead specify a .cpp (C++) or .c (C) file and replace ifort with icc.

In these examples,
MKLPATH=$MKLROOT/lib/ia32,
MKLINCLUDE=$MKLROOT/include.

NOTE
If you successfully completed the Setting Environment Variables step of the Getting Started process, you can omit -I$MKLINCLUDE in all the examples and omit -L$MKLPATH in the examples for dynamic linking.

- **Static linking of myprog.f and parallel Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -Wl,--start-group $MKLPATH/libmkl_intel.a $MKLPATH/libmkl_intel_thread.a $MKLPATH/libmkl_core.a
  -Wl,--end-group -liomp5 -lpthread -lm

- **Dynamic linking of myprog.f and parallel Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel -lmkl_intel_thread -lmkl_core -liomp5 -lpthread -lm

- **Static linking of myprog.f and sequential version of Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -Wl,--start-group $MKLPATH/libmkl_intel.a $MKLPATH/libmkl_sequential.a $MKLPATH/libmkl_core.a
  -Wl,--end-group -lpthread -lm

- **Dynamic linking of myprog.f and sequential version of Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel -lmkl_sequential -lmkl_core -lpthread -lm

- **Dynamic linking of user code myprog.f and parallel or sequential Intel MKL (Call the mkl_set_threading_layer function or set value of the MKL_THREADING_LAYER environment variable to choose threaded or sequential mode):**
  ifort myprog.f -lmkl_rt

- **Static linking of myprog.f, Fortran 95 LAPACK interface, and parallel Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE -I$MKLINCLUDE/ia32
  -lmkl_lapack95
  -Wl,--start-group $MKLPATH/libmkl_intel.a $MKLPATH/libmkl_intel_thread.a $MKLPATH/libmkl_core.a
  -Wl,--end-group -liomp5 -lpthread -lm

- **Static linking of myprog.f, Fortran 95 BLAS interface, and parallel Intel MKL:**
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE -I$MKLINCLUDE/ia32
  -lmkl_blas95
  -Wl,--start-group $MKLPATH/libmkl_intel.a $MKLPATH/libmkl_intel_thread.a $MKLPATH/libmkl_core.a
  -Wl,--end-group -liomp5 -lpthread -lm

**See Also**
Fortran 95 Interfaces to LAPACK and BLAS
Examples for Linking a C Application
Examples for Linking a Fortran Application

Using the Single Dynamic Library

Linking with System Libraries for specifics of linking with a GNU or PGI compiler

Linking on Intel(R) 64 Architecture Systems

The following examples illustrate linking that uses Intel(R) compilers.

The examples use the .f Fortran source file. C/C++ users should instead specify a .cpp (C++) or .c (C) file and replace ifort with icc.

In these examples,
MKLPATH=$MKLROOT/lib/intel64,
MKLINCLUDE=$MKLROOT/include.

NOTE
If you successfully completed the Setting Environment Variables step of the Getting Started process, you can omit -I$MKLINCLUDE in all the examples and omit -L$MKLPATH in the examples for dynamic linking.

- Static linking of myprog.f and parallel Intel MKL supporting the LP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -Wl,--start-group $MKLPATH/libmkl_intel_lp64.a $MKLPATH/libmkl_intel_thread.a
  $MKLPATH/libmkl_core.a -Wl,--end-group -liomp5 -lpthread -lm
  ```
- Dynamic linking of myprog.f and parallel Intel MKL supporting the LP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel_lp64 -lmkl_intel_thread -lmkl_core
  -liomp5 -lpthread -lm
  ```
- Static linking of myprog.f and sequential version of Intel MKL supporting the LP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel_lp64 -lmkl_sequential -lmkl_core -lpthread -lm
  ```
- Dynamic linking of myprog.f and sequential version of Intel MKL supporting the LP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel_ilp64 -lmkl_intel_thread -lmkl_core -liomp5 -lpthread -lm
  ```
- Static linking of myprog.f and parallel Intel MKL supporting the ILP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
  -lmkl_intel_ilp64 -lmkl_intel_thread -lmkl_core -liomp5 -lpthread -lm
  ```
- Dynamic linking of myprog.f and parallel or sequential Intel MKL (Call appropriate functions or set environment variables to choose threaded or sequential mode and to set the interface):
  ```
  ifort myprog.f -lmkl_rt
  ```
- Static linking of myprog.f, Fortran 95 LAPACK interface, and parallel Intel MKL supporting the LP64 interface:
  ```
  ifort myprog.f -L$MKLPATH -I$MKLINCLUDE -I$MKLINCLUDE/intel64/lp64
  -lmkl_lapack95_lp64 -Wl,--start-group $MKLPATH/libmkl_intel_lp64.a $MKLPATH/
  libmkl_intel_thread.a
  $MKLPATH/libmkl_core.a -Wl,--end-group -liomp5 -lpthread -lm
  ```
- Static linking of myprog.f, Fortran 95 BLAS interface, and parallel Intel MKL supporting the LP64 interface:
ifort myprog.f -L$MKLPATH -I$MKLINCLUDE -I$MKLINCLUDE/intel64/lp64
-lmkl_blas95_lp64 -Wl,--start-group $MKLPATH/libmkl_intel_lp64.a $MKLPATH/libmkl_intel_thread.a
$MKLPATH/libmkl_core.a -Wl,--end-group -liomp5 -lpthread -lm

See Also
Fortran 95 Interfaces to LAPACK and BLAS
Examples for Linking a C Application
Examples for Linking a Fortran Application
Using the Single Dynamic Library
Linking with System Libraries for specifics of linking with a GNU or PGI compiler

Linking in Detail
This section recommends which libraries to link with depending on your Intel MKL usage scenario and provides details of the linking.

Listing Libraries on a Link Line
To link with Intel MKL, specify paths and libraries on the link line as shown below.

NOTE
The syntax below is for dynamic linking. For static linking, replace each library name preceded with "-l" with the path to the library file. For example, replace -lmkl_core with $MKLPATH/libmkl_core.a, where $MKLPATH is the appropriate user-defined environment variable.

<files to link>
-L<MKL path> -I<MKL include>
[-I<MKL include>/{ia32|intel64|{ilp64|lp64}}]
[-lmkl_blas(95|95_ilp64|95_lp64)]
[-lmkl_lapack(95|95_ilp64|95_lp64)]
[<cluster components>]
-lmkl_{intel|intel_ilp64|intel_lp64|intel_sp2dp|gf|gf_ilp64|gf_lp64}
-lmkl_{intel_thread|gnu_thread|pgi_thread|sequential}
-lmkl_core
-liomp5 [-lpthread] [-lm] [-ldl]

In case of static linking, enclose the cluster components, interface, threading, and computational libraries in grouping symbols (for example, -Wl,--start-group $MKLPATH/libmkl_cdft_core.a $MKLPATH/libmkl_blacs_intelmpi_ilp64.a $MKLPATH/libmkl_intel_ilp64.a $MKLPATH/libmkl_intel_thread.a $MKLPATH/libmkl_core.a -Wl,--end-group).

The order of listing libraries on the link line is essential, except for the libraries enclosed in the grouping symbols above.

See Also
Using the Link-line Advisor
Linking Examples
Working with the Intel® Math Kernel Library Cluster Software
Dynamically Selecting the Interface and Threading Layer

The Single Dynamic Library (SDL) enables you to dynamically select the interface and threading layer for Intel MKL.

Setting the Interface Layer

Available interfaces depend on the architecture of your system.

On systems based on the Intel® 64 architecture, LP64 and ILP64 interfaces are available. To set one of these interfaces at run time, use the `mkl_set_interface_layer` function or the `MKL_INTERFACE_LAYER` environment variable. The following table provides values to be used to set each interface.

<table>
<thead>
<tr>
<th>Interface Layer</th>
<th>Value of MKL_INTERFACE_LAYER</th>
<th>Value of the Parameter of mkl_set_interface_layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP64</td>
<td>LP64</td>
<td>MKL_INTERFACE_LP64</td>
</tr>
<tr>
<td>ILP64</td>
<td>ILP64</td>
<td>MKL_INTERFACE_ILP64</td>
</tr>
</tbody>
</table>

If the `mkl_set_interface_layer` function is called, the environment variable `MKL_INTERFACE_LAYER` is ignored.

By default the LP64 interface is used.

See the Intel MKL Reference Manual for details of the `mkl_set_interface_layer` function.

Setting the Threading Layer

To set the threading layer at run time, use the `mkl_set_threading_layer` function or the `MKL_THREADING_LAYER` environment variable. The following table lists available threading layers along with the values to be used to set each layer.

<table>
<thead>
<tr>
<th>Threading Layer</th>
<th>Value of MKL_THREADING_LAYER</th>
<th>Value of the Parameter of mkl_set_threading_layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel threading</td>
<td>INTEL</td>
<td>MKL_THREADING_INTEL</td>
</tr>
<tr>
<td>Sequential mode</td>
<td>SEQUENTIAL</td>
<td>MKL_THREADING_SEQUENTIAL</td>
</tr>
<tr>
<td>GNU threading</td>
<td>GNU</td>
<td>MKL_THREADING_GNU</td>
</tr>
<tr>
<td>PGI threading</td>
<td>PGI</td>
<td>MKL_THREADING_PGI</td>
</tr>
</tbody>
</table>

If the `mkl_set_threading_layer` function is called, the environment variable `MKL_THREADING_LAYER` is ignored.

By default Intel threading is used.

See the Intel MKL Reference Manual for details of the `mkl_set_threading_layer` function.

See Also

Using the Single Dynamic Library
Layered Model Concept
Directory Structure in Detail

Linking with Interface Libraries
Using the ILP64 Interface vs. LP64 Interface

The Intel MKL ILP64 libraries use the 64-bit integer type (necessary for indexing large arrays, with more than \(2^{31}-1\) elements), whereas the LP64 libraries index arrays with the 32-bit integer type.

The LP64 and ILP64 interfaces are implemented in the Interface layer. Link with the following interface libraries for the LP64 or ILP64 interface, respectively:

- `libmkl_intel_lp64.a` or `libmkl_intel_ilp64.a` for static linking
- `libmkl_intel_lp64.so` or `libmkl_intel_ilp64.so` for dynamic linking

The ILP64 interface provides for the following:

- Support large data arrays (with more than \(2^{31}-1\) elements)
- Enable compiling your Fortran code with the `-i8` compiler option

The LP64 interface provides compatibility with the previous Intel MKL versions because "LP64" is just a new name for the only interface that the Intel MKL versions lower than 9.1 provided. Choose the ILP64 interface if your application uses Intel MKL for calculations with large data arrays or the library may be used so in future. Intel MKL provides the same include directory for the ILP64 and LP64 interfaces.

Compiling for LP64/ILP64

The table below shows how to compile for the ILP64 and LP64 interfaces:

<table>
<thead>
<tr>
<th>Language</th>
<th>Compiling for ILP64</th>
<th>Compiling for LP64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortran</td>
<td>ifort -i8 -I&lt;mkl directory&gt;/include ...</td>
<td>ifort -I&lt;mkl directory&gt;/include ...</td>
</tr>
<tr>
<td>C or C++</td>
<td>icc -DMKL_ILP64 -I&lt;mkl directory&gt;/include ...</td>
<td>icc -I&lt;mkl directory&gt;/include ...</td>
</tr>
</tbody>
</table>

CAUTION

Linking of an application compiled with the `-i8` or `-DMKL_ILP64` option to the LP64 libraries may result in unpredictable consequences and erroneous output.

Coding for ILP64

You do not need to change existing code if you are not using the ILP64 interface.

To migrate to ILP64 or write new code for ILP64, use appropriate types for parameters of the Intel MKL functions and subroutines:

<table>
<thead>
<tr>
<th>Integer Types</th>
<th>Fortran</th>
<th>C or C++</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit integers</td>
<td>INTEGER*4 or INTEGER(KIND=4)</td>
<td>int</td>
</tr>
<tr>
<td>Universal integers for ILP64/ LP64:</td>
<td>INTEGER without specifying KIND</td>
<td>MKL_INT</td>
</tr>
<tr>
<td>- 64-bit for ILP64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Integer Types

<table>
<thead>
<tr>
<th></th>
<th>Fortran</th>
<th>C or C++</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal integers for ILP64/LP64:</td>
<td>INTEGER*8 or INTEGER(KIND=8)</td>
<td>MKL_INT64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFT interface integers for ILP64/LP64</td>
<td>INTEGER without specifying KIND</td>
<td>MKL_LONG</td>
</tr>
</tbody>
</table>

To determine the type of an integer parameter of a function, use appropriate include files. For functions that support only a Fortran interface, use the C/C++ include files *.h.

The above table explains which integer parameters of functions become 64-bit and which remain 32-bit for ILP64. The table applies to most Intel MKL functions except some VML and VSL functions, which require integer parameters to be 64-bit or 32-bit regardless of the interface:

- **VML**: The mode parameter of VML functions is 64-bit.

- **Random Number Generators (RNG):**
  - All discrete RNG except viRngUniformBits64 are 32-bit.
  - The viRngUniformBits64 generator function and vslSkipAheadStream service function are 64-bit.

- **Summary Statistics**: The estimate parameter of the vslsSSCompute/vsldSSCompute function is 64-bit.

Refer to the *Intel MKL Reference Manual* for more information.

To better understand ILP64 interface details, see also examples and tests.

### Limitations

All Intel MKL function domains support ILP64 programming but FFTW interfaces to Intel MKL:

- FFTW 2.x wrappers do not support ILP64.
- FFTW 3.2 wrappers support ILP64 by a dedicated set of functions plan_guru64.

### See Also

- High-level Directory Structure
- Include Files
- Language Interfaces Support, by Function Domain
- Layered Model Concept
- Directory Structure in Detail

### Linking with Fortran 95 Interface Libraries

The libmkl_blas95*.a and libmkl_lapack95*.a libraries contain Fortran 95 interfaces for BLAS and LAPACK, respectively, which are compiler-dependent. In the Intel MKL package, they are prebuilt for the Intel® Fortran compiler. If you are using a different compiler, build these libraries before using the interface.

### See Also

- Fortran 95 Interfaces to LAPACK and BLAS
- Compiler-dependent Functions and Fortran 90 Modules

### Linking with Threading Libraries
Sequential Mode of the Library

You can use Intel MKL in a sequential (non-threaded) mode. In this mode, Intel MKL runs unthreaded code. However, it is thread-safe (except the LAPACK deprecated routine ?lacon), which means that you can use it in a parallel region in your OpenMP* code. The sequential mode requires no compatibility OpenMP* run-time library and does not respond to the environment variable OMP_NUM_THREADS or its Intel MKL equivalents.

You should use the library in the sequential mode only if you have a particular reason not to use Intel MKL threading. The sequential mode may be helpful when using Intel MKL with programs threaded with some non-Intel compilers or in other situations where you need a non-threaded version of the library (for instance, in some MPI cases). To set the sequential mode, in the Threading layer, choose the *sequential.* library.

Add the POSIX threads library (pthread) to your link line for the sequential mode because the *sequential.* library depends on pthread.

See Also
Directory Structure in Detail
Improving Performance with Threading
Avoiding Conflicts in the Execution Environment
Linking Examples

Selecting the Threading Layer

Several compilers that Intel MKL supports use the OpenMP* threading technology. Intel MKL supports implementations of the OpenMP* technology that these compilers provide. To make use of this support, you need to link with the appropriate library in the Threading Layer and Compiler Support Run-time Library (RTL).

Each Intel MKL threading library provides support for an appropriate threading compiler (Intel®, GNU*, or PGI* compiler on Linux OS).

The RTL layer includes libiomp, the compatibility OpenMP* run-time library of the Intel compiler. In addition to the Intel compiler, libiomp provides support for more threading compilers on Linux OS (GNU). That is, a program threaded with a GNU compiler can safely be linked with Intel MKL and libiomp.

The table below explains what Intel MKL libraries and OpenMP* run-time libraries you should choose under different scenarios (static cases only):

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Application Threaded?</th>
<th>Threading Layer</th>
<th>RTL Recommended</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel</td>
<td>Does not matter</td>
<td>libmkl_intel_thread.a</td>
<td>libiomp5.so</td>
<td></td>
</tr>
<tr>
<td>PGI</td>
<td>Yes</td>
<td>libmkl_pgi_thread.a or libmkl_sequential.a</td>
<td>PGI* supplied</td>
<td>Use of libmkl_sequential.a removes threading from Intel MKL calls.</td>
</tr>
<tr>
<td>PGI</td>
<td>No</td>
<td>libmkl_intel_thread.a</td>
<td>libiomp5.so</td>
<td></td>
</tr>
<tr>
<td>PGI</td>
<td>No</td>
<td>libmkl_pgi_thread.a</td>
<td>PGI* supplied</td>
<td></td>
</tr>
<tr>
<td>GNU</td>
<td>Yes</td>
<td>libmkl_gnu_thread.a</td>
<td>libiomp5.so or GNU OpenMP run-time library</td>
<td>libiomp5 offers superior scaling performance.</td>
</tr>
<tr>
<td>GNU</td>
<td>Yes</td>
<td>libmkl_sequential.a</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
Linking Your Application with the Intel\textsuperscript{®} Math Kernel Library

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Application Threaded?</th>
<th>Threading Layer</th>
<th>RTL Recommended</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNU</td>
<td>No</td>
<td>sequential.a</td>
<td>libiomp5.so</td>
<td></td>
</tr>
<tr>
<td>other</td>
<td>Yes</td>
<td>libmkl_intel_thread.a</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>other</td>
<td>No</td>
<td>sequential.a</td>
<td>libiomp5.so</td>
<td></td>
</tr>
</tbody>
</table>

### Linking with Computational Libraries

If you are not using the Intel MKL cluster software, you need to link your application with only one computational library, depending on the linking method:

<table>
<thead>
<tr>
<th>Static Linking</th>
<th>Dynamic Linking</th>
</tr>
</thead>
<tbody>
<tr>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
</tbody>
</table>

### Computational Libraries for Applications that Use the Intel MKL Cluster Software

ScalAPACK and Cluster Fourier Transform Functions (Cluster FFTs) require more computational libraries, which may depend on your architecture.

The following table lists computational libraries for IA-32 architecture applications that use ScalAPACK or Cluster FFTs.

#### Computational Libraries for IA-32 Architecture

<table>
<thead>
<tr>
<th>Function domain</th>
<th>Static Linking</th>
<th>Dynamic Linking</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScalAPACK (^\d)</td>
<td>libmkl_scalapack_core.a</td>
<td>libmkl_scalapack_core.so</td>
</tr>
<tr>
<td></td>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
<tr>
<td>Cluster Fourier Transform Functions (^\d)</td>
<td>libmkl_cdft_core.a</td>
<td>libmkl_cdft_core.so</td>
</tr>
<tr>
<td></td>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
</tbody>
</table>

\(^\d\) Also add the library with BLACS routines corresponding to the MPI used.

The following table lists computational libraries for Intel\textsuperscript{®} 64 architecture applications that use ScalAPACK or Cluster FFTs.

#### Computational Libraries for the Intel\textsuperscript{®} 64 or Intel\textsuperscript{®} Many Integrated Core Architecture

<table>
<thead>
<tr>
<th>Function domain</th>
<th>Static Linking</th>
<th>Dynamic Linking</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScalAPACK, LP64 interface (^\d)</td>
<td>libmkl_scalapack_lp64.a</td>
<td>libmkl_scalapack_lp64.so</td>
</tr>
<tr>
<td></td>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
<tr>
<td>ScalAPACK, ILP64 interface (^\d)</td>
<td>libmkl_scalapack_ilp64.a</td>
<td>libmkl_scalapack_ilp64.so</td>
</tr>
<tr>
<td></td>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
<tr>
<td>Function domain</td>
<td>Static Linking</td>
<td>Dynamic Linking</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Cluster Fourier Transform Functions‡</td>
<td>libmkl_cdft_core.a</td>
<td>libmkl_cdft_core.so</td>
</tr>
<tr>
<td></td>
<td>libmkl_core.a</td>
<td>libmkl_core.so</td>
</tr>
</tbody>
</table>

‡ Also add the library with BLACS routines corresponding to the MPI used.

See Also
Linking with ScaLAPACK and Cluster FFTs
Using the Link-line Advisor
Using the ILP64 Interface vs. LP64 Interface

Linking with Compiler Run-time Libraries

Dynamically link libiomp5, the compatibility OpenMP* run-time library, even if you link other libraries statically.

Linking to the libiomp5 statically can be problematic because the more complex your operating environment or application, the more likely redundant copies of the library are included. This may result in performance issues (oversubscription of threads) and even incorrect results.

To link libiomp5 dynamically, be sure the LD_LIBRARY_PATH environment variable is defined correctly.

See Also
Scripts to Set Environment Variables
Layered Model Concept

Linking with System Libraries

To use the Intel MKL FFT, Trigonometric Transform, or Poisson, Laplace, and Helmholtz Solver routines, link also the math support system library by adding "-lm" to the link line.

On Linux OS, the libiomp5 library relies on the native pthread library for multi-threading. Any time libiomp5 is required, add -lpthread to your link line afterwards (the order of listing libraries is important).

NOTE
To link with Intel MKL statically using a GNU or PGI compiler, link also the system library libdl by adding -ldl to your link line. The Intel compiler always passes -ldl to the linker.

See Also
Linking Examples

Building Custom Shared Objects

Custom shared objects reduce the collection of functions available in Intel MKL libraries to those required to solve your particular problems, which helps to save disk space and build your own dynamic libraries for distribution.

The Intel MKL custom shared object builder enables you to create a dynamic library (shared object) containing the selected functions and located in the tools/builder directory. The builder contains a makefile and a definition file with the list of functions.
NOTE
The objects in Intel MKL static libraries are position-independent code (PIC), which is not typical for static libraries. Therefore, the custom shared object builder can create a shared object from a subset of Intel MKL functions by picking the respective object files from the static libraries.

## Using the Custom Shared Object Builder

To build a custom shared object, use the following command:

```shell
make target [<options>]
```

The following table lists possible values of `target` and explains what the command does for each value:

<table>
<thead>
<tr>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>libia32</td>
<td>The builder uses static Intel MKL interface, threading, and core libraries to build a custom shared object for the IA-32 architecture.</td>
</tr>
<tr>
<td>libintel64</td>
<td>The builder uses static Intel MKL interface, threading, and core libraries to build a custom shared object for the Intel® 64 architecture.</td>
</tr>
<tr>
<td>soia32</td>
<td>The builder uses the single dynamic library <code>libmkl_rt.so</code> to build a custom shared object for the IA-32 architecture.</td>
</tr>
<tr>
<td>sointel64</td>
<td>The builder uses the single dynamic library <code>libmkl_rt.so</code> to build a custom shared object for the Intel® 64 architecture.</td>
</tr>
<tr>
<td>help</td>
<td>The command prints Help on the custom shared object builder</td>
</tr>
</tbody>
</table>

The `<options>` placeholder stands for the list of parameters that define macros to be used by the makefile. The following table describes these parameters:

<table>
<thead>
<tr>
<th>Parameter [Values]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>interface</td>
<td>Defines whether to use LP64 or ILP64 programming interface for the Intel 64 architecture. The default value is lp64.</td>
</tr>
<tr>
<td>threading</td>
<td>Defines whether to use the Intel MKL in the threaded or sequential mode. The default value is parallel.</td>
</tr>
<tr>
<td>export</td>
<td>Specifies the full name of the file that contains the list of entry-point functions to be included in the shared object. The default name is <code>user_example_list</code> (no extension).</td>
</tr>
<tr>
<td>name = &lt;so name&gt;</td>
<td>Specifies the name of the library to be created. By default, the names of the created library is <code>mkl_custom.so</code>.</td>
</tr>
<tr>
<td>xerbla = &lt;error handler&gt;</td>
<td>Specifies the name of the object file <code>&lt;user_xerbla&gt;.o</code> that contains the user's error handler. The makefile adds this error handler to the library for use instead of the default Intel MKL error handler <code>xerbla</code>. If you omit this parameter, the native Intel MKL <code>xerbla</code> is used. See the description of the <code>xerbla</code> function in the Intel MKL Reference Manual on how to develop your own error handler.</td>
</tr>
<tr>
<td>MKLROOT = &lt;mkl directory&gt;</td>
<td>Specifies the location of Intel MKL libraries used to build the custom shared object. By default, the builder uses the Intel MKL installation directory.</td>
</tr>
</tbody>
</table>

All the above parameters are optional.

In the simplest case, the command line is `make ia32`, and the missing options have default values. This command creates the `mkl_custom.so` library for processors using the IA-32 architecture. The command takes the list of functions from the `user_list` file and uses the native Intel MKL error handler `xerbla`. 
An example of a more complex case follows:

make ia32 export=my_func_list.txt name=mkl_small xerbla=my_xerbla.o

In this case, the command creates the `mkl_small.so` library for processors using the IA-32 architecture. The command takes the list of functions from `my_func_list.txt` file and uses the user's error handler `my_xerbla.o`.

The process is similar for processors using the Intel® 64 architecture.

**See Also**
Using the Single Dynamic Library

---

**Composing a List of Functions**

To compose a list of functions for a minimal custom shared object needed for your application, you can use the following procedure:

1. Link your application with installed Intel MKL libraries to make sure the application builds.
2. Remove all Intel MKL libraries from the link line and start linking.
   
   Unresolved symbols indicate Intel MKL functions that your application uses.
3. Include these functions in the list.

   **Important**
   
   Each time your application starts using more Intel MKL functions, update the list to include the new functions.

**See Also**
Specifying Function Names

---

**Specifying Function Names**

In the file with the list of functions for your custom shared object, adjust function names to the required interface. For example, for Fortran functions append an underscore character "_" to the names as a suffix:

- `dgemm_`
- `ddot_`
- `dgetrf_`

For more examples, see domain-specific lists of functions in the `<mkl directory>/tools/builder` folder.

**NOTE**

The lists of functions are provided in the `<mkl directory>/tools/builder` folder merely as examples. See **Composing a List of Functions** for how to compose lists of functions for your custom shared object.

**TIP**

Names of Fortran-style routines (BLAS, LAPACK, etc.) can be both upper-case or lower-case, with or without the trailing underscore. For example, these names are equivalent:

- **BLAS**: `dgemm`, `DGEMM`, `dgemm_`, `DGEMM_`
- **LAPACK**: `dgetrf`, `DGETRF`, `dgetrf_`, `DGETRF_`.

Properly capitalize names of C support functions in the function list. To do this, follow the guidelines below:
1. In the mkl_service.h include file, look up a #define directive for your function
   (mkl_service.h is included in the mkl.h header file).

2. Take the function name from the replacement part of that directive.

   For example, the #define directive for the mkl_disable_fast_mm function is
   
   #define mkl_disable_fast_mm MKL_Disable_Fast_MM.

   Capitalize the name of this function in the list like this: MKL_Disable_Fast_MM.

   For the names of the Fortran support functions, see the tip.

---

**NOTE**

If selected functions have several processor-specific versions, the builder automatically includes them all in the custom library and the dispatcher manages them.

---

**Distributing Your Custom Shared Object**

To enable use of your custom shared object in a threaded mode, distribute libiomp5.so along with the custom shared object.
Managing Performance and Memory

Optimization Notice

Intel’s compilers may or may not optimize to the same degree for non-Intel microprocessors for
optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and
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the applicable product User and Reference Guides for more information regarding the specific instruction
sets covered by this notice.

Notice revision #20110804

Improving Performance with Threading

Intel MKL is extensively parallelized. See Threaded Functions and Problems for lists of threaded functions and
problems that can be threaded.

Intel MKL is thread-safe, which means that all Intel MKL functions (except the LAPACK deprecated routine ?
lacon) work correctly during simultaneous execution by multiple threads. In particular, any chunk of
threaded Intel MKL code provides access for multiple threads to the same shared data, while permitting only
one thread at any given time to access a shared piece of data. Therefore, you can call Intel MKL from
multiple threads and not worry about the function instances interfering with each other.

The library uses OpenMP* threading software, so you can use the environment variable OMP_NUM_THREADS to
specify the number of threads or the equivalent OpenMP run-time function calls. Intel MKL also offers
variables that are independent of OpenMP, such as MKL_NUM_THREADS, and equivalent Intel MKL functions
for thread management. The Intel MKL variables are always inspected first, then the OpenMP variables are
examined, and if neither is used, the OpenMP software chooses the default number of threads.

By default, Intel MKL uses the number of threads equal to the number of physical cores on the system.
To achieve higher performance, set the number of threads to the number of processors or physical cores, as
summarized in Techniques to Set the Number of Threads.

See Also
Managing Multi-core Performance

Threaded Functions and Problems
The following Intel MKL function domains are threaded:

- Direct sparse solver.
- LAPACK.
  For the list of threaded routines, see Threaded LAPACK Routines.
- Level1 and Level2 BLAS.
  For the list of threaded routines, see Threaded BLAS Level1 and Level2 Routines.
- All Level 3 BLAS and all Sparse BLAS routines except Level 2 Sparse Triangular solvers.
- All mathematical VML functions.
- FFT.
  For the list of FFT transforms that can be threaded, see Threaded FFT Problems.
Threaded LAPACK Routines

In the following list, ? stands for a precision prefix of each flavor of the respective routine and may have the value of s, d, c, or z.

The following LAPACK routines are threaded:

- **Linear equations, computational routines:**
- **Orthogonal factorization, computational routines:**
- **Singular Value Decomposition, computational routines:**
  - ?gesvd, ?bdsqr
- **Symmetric Eigenvalue Problems, computational routines:**
- **Generalized Nonsymmetric Eigenvalue Problems, computational routines:**
  - chgeqz/zhgeqz.

A number of other LAPACK routines, which are based on threaded LAPACK or BLAS routines, make effective use of parallelism:


Threaded BLAS Level1 and Level2 Routines

In the following list, ? stands for a precision prefix of each flavor of the respective routine and may have the value of s, d, c, or z.

The following routines are threaded for Intel® Core™2 Duo and Intel® Core™ i7 processors:

- **Level1 BLAS:**
- **Level2 BLAS:**
  - ?gemv, ?trmv, dsyr/ssyr, dsyr2/ssyr2, dsymv/ssymv

Threaded FFT Problems

The following characteristics of a specific problem determine whether your FFT computation may be threaded:

- rank
- domain
- size/length
- precision (single or double)
- placement (in-place or out-of-place)
- strides
- number of transforms
- layout (for example, interleaved or split layout of complex data)

Most FFT problems are threaded. In particular, computation of multiple transforms in one call (number of transforms > 1) is threaded. Details of which transforms are threaded follow.

**One-dimensional (1D) transforms**

1D transforms are threaded in many cases.

1D complex-to-complex (c2c) transforms of size N using interleaved complex data layout are threaded under the following conditions depending on the architecture:
<table>
<thead>
<tr>
<th>Architecture</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel® 64</td>
<td>( N ) is a power of 2, ( \log_2(N) &gt; 9 ), the transform is double-precision out-of-place, and input/output strides equal 1.</td>
</tr>
<tr>
<td>IA-32</td>
<td>( N ) is a power of 2, ( \log_2(N) &gt; 13 ), and the transform is single-precision.</td>
</tr>
<tr>
<td></td>
<td>( N ) is a power of 2, ( \log_2(N) &gt; 14 ), and the transform is double-precision.</td>
</tr>
<tr>
<td>Any</td>
<td>( N ) is composite, ( \log_2(N) &gt; 16 ), and input/output strides equal 1.</td>
</tr>
</tbody>
</table>

1D complex-to-complex transforms using split-complex layout are not threaded.

**Multidimensional transforms**

All multidimensional transforms on large-volume data are threaded.

### Avoiding Conflicts in the Execution Environment

Certain situations can cause conflicts in the execution environment that make the use of threads in Intel MKL problematic. This section briefly discusses why these problems exist and how to avoid them.

If you thread the program using OpenMP directives and compile the program with Intel compilers, Intel MKL and the program will both use the same threading library. Intel MKL tries to determine if it is in a parallel region in the program, and if it is, it does not spread its operations over multiple threads unless you specifically request Intel MKL to do so via the `MKL_DYNAMIC` functionality. However, Intel MKL can be aware that it is in a parallel region only if the threaded program and Intel MKL are using the same threading library.

If your program is threaded by some other means, Intel MKL may operate in multithreaded mode, and the performance may suffer due to overuse of the resources.

The following table considers several cases where the conflicts may arise and provides recommendations depending on your threading model:

<table>
<thead>
<tr>
<th>Threading model</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>You thread the program using OS threads (PTHREADS on Linux* OS).</td>
<td>If more than one thread calls Intel MKL, and the function being called is threaded, it may be important that you turn off Intel MKL threading. Set the number of threads to one by any of the available means (see Techniques to Set the Number of Threads).</td>
</tr>
<tr>
<td>You thread the program using OpenMP directives and/or pragmas and compile the program using a compiler other than a compiler from Intel.</td>
<td>This is more problematic because setting of the <code>OMP_NUM_THREADS</code> environment variable affects both the compiler’s threading library and <code>libiomp5</code>. In this case, choose the threading library that matches the layered Intel MKL with the OpenMP compiler you employ (see Linking Examples on how to do this). If this is not possible, use Intel MKL in the sequential mode. To do this, you should link with the appropriate threading library: <code>libmkl_sequential.a</code> or <code>libmkl_sequential.so</code> (see High-level Directory Structure).</td>
</tr>
<tr>
<td>There are multiple programs running on a multiple-cpu system, for example, a parallelized program that runs using MPI for communication in which each processor is treated as a node.</td>
<td>The threading software will see multiple processors on the system even though each processor has a separate MPI process running on it. In this case, one of the solutions is to set the number of threads to one by any of the available means (see Techniques to Set the Number of Threads). Section Intel(R) Optimized MP LINPACK Benchmark for Clusters discusses another solution for a Hybrid (OpenMP* + MPI) mode.</td>
</tr>
</tbody>
</table>

Using the `mkl_set_num_threads` and `mkl_domain_set_num_threads` functions to control parallelism of Intel MKL from parallel user threads may result in a race condition that impacts the performance of the application because these functions operate on internal control variables that are global, that is, apply to all threads. For example, if parallel user threads call these functions to set different numbers of threads for the same function domain, the number of threads actually set is unpredictable. To avoid this kind of data races, use the `mkl_set_num_threads_local` function (see the "Support Functions" chapter in the Intel MKL Reference Manual for the function description).
Techniques to Set the Number of Threads

Use the following techniques to specify the number of threads to use in Intel MKL:

- Set one of the OpenMP or Intel MKL environment variables:
  - OMP_NUM_THREADS
  - MKL_NUM_THREADS
  - MKL_DOMAIN_NUM_THREADS

- Call one of the OpenMP or Intel MKL functions:
  - omp_set_num_threads()
  - mkl_set_num_threads()
  - mkl_domain_set_num_threads()
  - mkl_set_num_threads_local()

When choosing the appropriate technique, take into account the following rules:

- The Intel MKL threading controls take precedence over the OpenMP controls because they are inspected first.
- A function call takes precedence over any environment settings. The exception, which is a consequence of the previous rule, is that a call to the OpenMP subroutine omp_set_num_threads() does not have precedence over the settings of Intel MKL environment variables such as MKL_NUM_THREADS. See Using Additional Threading Control for more details.
- You cannot change run-time behavior in the course of the run using the environment variables because they are read only once at the first call to Intel MKL.

Setting the Number of Threads Using an OpenMP* Environment Variable

You can set the number of threads using the environment variable OMP_NUM_THREADS. To change the number of threads, use the appropriate command in the command shell in which the program is going to run, for example:

- For the bash shell, enter:
  ```
  export OMP_NUM_THREADS=<number of threads to use>
  ```
- For the csh or tcsh shell, enter:
  ```
  setenv OMP_NUM_THREADS <number of threads to use>
  ```

See Also
Using Additional Threading Control

Changing the Number of Threads at Run Time

You cannot change the number of threads during run time using environment variables. However, you can call OpenMP API functions from your program to change the number of threads during run time. The following sample code shows how to change the number of threads during run time using the omp_set_num_threads() routine. See also Techniques to Set the Number of Threads.

The following example shows both C and Fortran code examples. To run this example in the C language, use the omp.h header file from the Intel(R) compiler package. If you do not have the Intel compiler but wish to explore the functionality in the example, use Fortran API for omp_set_num_threads() rather than the C version. For example, `omp_set_num_threads_( &i_one );`

```c
// ******* C language *******
#include "omp.h"
```
```c
#include "mkl.h"
#include <stdio.h>
#define SIZE 1000
int main(int argc, char *argv[]){
    double *a, *b, *c;
    a = (double*)malloc(sizeof(double)*SIZE*SIZE);
    b = (double*)malloc(sizeof(double)*SIZE*SIZE);
    c = (double*)malloc(sizeof(double)*SIZE*SIZE);
    double alpha=1, beta=1;
    int m=SIZE, n=SIZE, k=SIZE, lda=SIZE, ldb=SIZE, ldc=SIZE, i=0, j=0;
    char transa='n', transb='n';
    for( i=0; i<SIZE; i++){
        for( j=0; j<SIZE; j++){
            a[i*SIZE+j] = (double)(i+j);
            b[i*SIZE+j] = (double)(i*j);
            c[i*SIZE+j] = (double)0;
        }
        cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
                    m, n, k, alpha, a, lda, b, ldb, beta, c, ldc);
        printf("row\ta\tc
");
        for ( i=0;i<10;i++){
            printf("%d:	%f	%f
", i, a[i*SIZE], c[i*SIZE]);
        }
    }
    omp_set_num_threads(2);
    for( i=0; i<SIZE; i++){
        for( j=0; j<SIZE; j++){
            a[i*SIZE+j] = (double)(i+j);
            b[i*SIZE+j] = (double)(i*j);
            c[i*SIZE+j] = (double)0;
        }
        cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
                    m, n, k, alpha, a, lda, b, ldb, beta, c, ldc);
        printf("row\ta\tc
");
        for ( i=0;i<10;i++){
            printf("%d:	%f	%f
", i, a[i*SIZE], c[i*SIZE]);
        }
        free (a);
        free (b);
        free (c);
        return 0;
    }
}
```

```fortran
// ******* Fortran language *******
PROGRAM DGEMM_DIFF_THREADS
INTEGER N, I, J
PARAMETER (N=100)
REAL*8 A(N,N),B(N,N),C(N,N)
REAL*8 ALPHA, BETA
ALPHA = 1.1
BETA = -1.2
DO I=1,N
```
Using Additional Threading Control

Intel MKL-specific Environment Variables for Threading Control

Intel MKL provides optional threading controls, that is, the environment variables and support functions that are independent of OpenMP. They behave similar to their OpenMP equivalents, but take precedence over them in the meaning that the Intel MKL-specific threading controls are inspected first. By using these controls along with OpenMP variables, you can thread the part of the application that does not call Intel MKL and the library independently of each other.

These controls enable you to specify the number of threads for Intel MKL independently of the OpenMP settings. Although Intel MKL may actually use a different number of threads from the number suggested, the controls will also enable you to instruct the library to try using the suggested number when the number used in the calling application is unavailable.

NOTE
Sometimes Intel MKL does not have a choice on the number of threads for certain reasons, such as system resources.

Use of the Intel MKL threading controls in your application is optional. If you do not use them, the library will mainly behave the same way as Intel MKL 9.1 in what relates to threading with the possible exception of a different default number of threads.
Section "Number of User Threads" in the "Fourier Transform Functions" chapter of the Intel MKL Reference Manual shows how the Intel MKL threading controls help to set the number of threads for the FFT computation.

The table below lists the Intel MKL environment variables for threading control, their equivalent functions, and OMP counterparts:

<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Support Function</th>
<th>Comment</th>
<th>Equivalent OpenMP* Environment Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>MKL_NUM_THREADS</td>
<td>mkl_set_num_threads</td>
<td>Suggests the number of threads to use.</td>
<td>OMP_NUM_THREADS</td>
</tr>
<tr>
<td></td>
<td>mkl_set_num_threads</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>_local</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MKL_DOMAIN_NUM_THREADS</td>
<td>mkl_domain_set_num_threads</td>
<td>Suggests the number of threads for a particular function domain.</td>
<td></td>
</tr>
<tr>
<td>MKL_DYNAMIC</td>
<td>mkl_set_dynamic</td>
<td>Enables Intel MKL to dynamically change the number of threads.</td>
<td>OMP_DYNAMIC</td>
</tr>
</tbody>
</table>

NOTE
The functions take precedence over the respective environment variables. Therefore, if you want Intel MKL to use a given number of threads in your application and do not want users of your application to change this number using environment variables, set the number of threads by a call to mkl_set_num_threads(), which will have full precedence over any environment variables being set.

The example below illustrates the use of the Intel MKL function mkl_set_num_threads() to set one thread.

```c
// ******* C language *******
#include <omp.h>
#include <mkl.h>
...
mkl_set_num_threads( 1 );
```

```fortran
// ******* Fortran language *******
...
call mkl_set_num_threads( 1 )
```

See the Intel MKL Reference Manual for the detailed description of the threading control functions, their parameters, calling syntax, and more code examples.

**MKL_DYNAMIC**

The MKL_DYNAMIC environment variable enables Intel MKL to dynamically change the number of threads. The default value of MKL_DYNAMIC is TRUE, regardless of OMP_DYNAMIC, whose default value may be FALSE. When MKL_DYNAMIC is TRUE, Intel MKL tries to use what it considers the best number of threads, up to the maximum number you specify.

For example, MKL_DYNAMIC set to TRUE enables optimal choice of the number of threads in the following cases:
If the requested number of threads exceeds the number of physical cores (perhaps because of using the Intel® Hyper-Threading Technology), and MKL_DYNAMIC is not changed from its default value of TRUE, Intel MKL will scale down the number of threads to the number of physical cores.

If you are able to detect the presence of MPI, but cannot determine if it has been called in a thread-safe mode (it is impossible to detect this with MPICH 1.2.x, for instance), and MKL_DYNAMIC has not been changed from its default value of TRUE, Intel MKL will run one thread.

When MKL_DYNAMIC is FALSE, Intel MKL tries not to deviate from the number of threads the user requested. However, setting MKL_DYNAMIC=FALSE does not ensure that Intel MKL will use the number of threads that you request. The library may have no choice on this number for such reasons as system resources. Additionally, the library may examine the problem and use a different number of threads than the value suggested. For example, if you attempt to do a size one matrix-matrix multiply across eight threads, the library may instead choose to use only one thread because it is impractical to use eight threads in this event.

Note also that if Intel MKL is called in a parallel region, it will use only one thread by default. If you want the library to use nested parallelism, and the thread within a parallel region is compiled with the same OpenMP compiler as Intel MKL is using, you may experiment with setting MKL_DYNAMIC to FALSE and manually increasing the number of threads.

In general, set MKL_DYNAMIC to FALSE only under circumstances that Intel MKL is unable to detect, for example, to use nested parallelism where the library is already called from a parallel section.

**MKL_DOMAIN_NUM_THREADS**

The MKL_DOMAIN_NUM_THREADS environment variable suggests the number of threads for a particular function domain.

MKL_DOMAIN_NUM_THREADS accepts a string value &lt;MKL-env-string&gt;, which must have the following format:

&lt;MKL-env-string&gt; ::= &lt;MKL-domain-env-string&gt; [ &lt;delimiter&gt;&lt;MKL-domain-env-string&gt; ]

&lt;delimiter&gt; ::= [ &lt;space-symbol&gt;* ] ( &lt;space-symbol&gt; | &lt;comma-symbol&gt; | &lt;semicolon-symbol&gt; | &lt;colon-symbol&gt; ) [ &lt;space-symbol&gt;* ]

&lt;MKL-domain-env-string&gt; ::= &lt;MKL-domain-env-name&gt;&lt;uses&gt;&lt;number-of-threads&gt;

&lt;uses&gt; ::= [ &lt;space-symbol&gt;* ] ( &lt;space-symbol&gt; | &lt;equality-sign&gt; | &lt;comma-symbol&gt; ) [ &lt;space-symbol&gt;* ]

&lt;number-of-threads&gt; ::= &lt;positive-number&gt;

&lt;positive-number&gt; ::= &lt;decimal-positive-number&gt; | &lt;octal-number&gt; | &lt;hexadecimal-number&gt;

In the syntax above, values of &lt;MKL-domain-env-name&gt; indicate function domains as follows:

MKL_DOMAIN_ALL All function domains
MKL_DOMAIN_BLAS BLAS Routines
MKL_DOMAIN_FFT non-cluster Fourier Transform Functions
MKL_DOMAIN_VML Vector Mathematical Functions
MKL_DOMAIN_PARDISO PARDISO

For example,

MKL_DOMAIN_ALL 2 : MKL_DOMAIN_BLAS 1 : MKL_DOMAIN_FFT 4
MKL_DOMAIN_ALL=2 : MKL_DOMAIN_BLAS=1 : MKL_DOMAIN_FFT=4
MKL_DOMAIN_ALL=2, MKL_DOMAIN_BLAS=1, MKL_DOMAIN_FFT=4
MKL_DOMAIN_ALL=2; MKL_DOMAIN_BLAS=1; MKL_DOMAIN_FFT=4
The global variables MKL_DOMAIN_ALL, MKL_DOMAIN_BLAS, MKL_DOMAIN_FFT, MKL_DOMAIN_VML, and MKL_DOMAIN_PARDISO, as well as the interface for the Intel MKL threading control functions, can be found in the mkl.h header file.

The table below illustrates how values of MKL_DOMAIN_NUM_THREADS are interpreted.

<table>
<thead>
<tr>
<th>Value of MKL_DOMAIN_NUM_THREADS</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MKL_DOMAIN_ALL=4</td>
<td>All parts of Intel MKL should try four threads. The actual number of threads may be still different because of the MKL_DYNAMIC setting or system resource issues. The setting is equivalent to MKL_NUM_THREADS = 4.</td>
</tr>
<tr>
<td>MKL_DOMAIN_ALL=1, MKL_DOMAIN_BLAS =4</td>
<td>All parts of Intel MKL should try one thread, except for BLAS, which is suggested to try four threads.</td>
</tr>
<tr>
<td>MKL_DOMAIN_VML=2</td>
<td>VML should try two threads. The setting affects no other part of Intel MKL.</td>
</tr>
</tbody>
</table>

Be aware that the domain-specific settings take precedence over the overall ones. For example, the "MKL_DOMAIN_BLAS=4" value of MKL_DOMAIN_NUM_THREADS suggests trying four threads for BLAS, regardless of later setting MKL_NUM_THREADS, and a function call "mkl_domain_set_num_threads (4, MKL_DOMAIN_BLAS);", suggests the same, regardless of later calls to mkl_set_num_threads(). However, a function call with input "MKL_DOMAIN_ALL", such as "mkl_domain_set_num_threads (4, MKL_DOMAIN_ALL)"; is equivalent to "mkl_set_num_threads(4)", and thus it will be overwritten by later calls to mkl_set_num_threads. Similarly, the environment setting of MKL_DOMAIN_NUM_THREADS with "MKL_DOMAIN_ALL=4" will be overwritten with MKL_NUM_THREADS = 2.

Whereas the MKL_DOMAIN_NUM_THREADS environment variable enables you set several variables at once, for example, "MKL_DOMAIN_BLAS=4,MKL_DOMAIN_FFT=2", the corresponding function does not take string syntax. So, to do the same with the function calls, you may need to make several calls, which in this example are as follows:

```c
mkl_domain_set_num_threads ( 4, MKL_DOMAIN_BLAS );
mkl_domain_set_num_threads ( 2, MKL_DOMAIN_FFT );
```

### Setting the Environment Variables for Threading Control

To set the environment variables used for threading control, in the command shell in which the program is going to run, enter the `export` or `setenv` commands, depending on the shell you use.

For a bash shell, use the `export` commands:

```bash
export <VARIABLE NAME>=<value>
```

For example:

```bash
export MKL_NUM_THREADS=4
export MKL_DOMAIN_NUM_THREADS="MKL_DOMAIN_ALL=1, MKL_DOMAIN_BLAS=4"
export MKL_DYNAMIC=FALSE
```

For the csh or tcsh shell, use the `setenv` commands:

```bash
setenv <VARIABLE NAME> <value>
```

For example:

```bash
setenv MKL_NUM_THREADS 4
```
Calling Intel MKL Functions from Multi-threaded Applications

This section summarizes typical usage models and available options for calling Intel MKL functions from multi-threaded applications. These recommendations apply to any multi-threading environments: OpenMP®, Intel® Threading Building Blocks, POSIX* threads, and others.

Usage model: disable Intel MKL internal threading for the whole application

When used: Intel MKL internal threading interferes with application's own threading or may slow down the application.

Example: the application is threaded at top level, or the application runs concurrently with other applications.

Options:

• Link statically or dynamically with the sequential library
• Link with the Single Dynamic Library mkl_rt.so and select the sequential library using an environment variable or a function call:
  
  • Set MKL_THREADING_LAYER=sequential
  • Call mkl_set_threading_layer(MKL_THREADING_SEQUENTIAL)

• Link with a threading library, but disable Intel MKL threading using an environment variable or a function call:
  
  • set MKL_NUM_THREADS=1
  • call mkl_set_num_threads(1).

  In particular, use to temporarily disable Intel MKL threading at run time.
• Link with the Single Dynamic Library mkl_rt.so and select a threading library using an environment variable or a function call below, but disable threading as in the case above:
  
  • set MKL_THREADING_LAYER=intel
  • call mkl_set_threading_layer(MKL_THREADING_INTEL)

Usage model: partition system resources among application threads

When used: application threads are specialized for a particular computation.

Example: one thread solves equations on all cores but one, while another thread running on a single core updates a database.

Linking Options:

• Link statically or dynamically with a threading library
• Link with the Single Dynamic Library mkl_rt.so and select a threading library using an environment variable or a function call:
  
  • set MKL_THREADING_LAYER=intel
  • call mkl_set_threading_layer(MKL_THREADING_INTEL)

Other Options:

• Set the MKL_NUM_THREADS environment variable to a desired number of threads for Intel MKL.
• Set the MKL_DOMAIN_NUM_THREADS environment variable to a desired number of threads for Intel MKL for a particular function domain.

Use if the application threads work with different Intel MKL function domains.
Call `mkl_set_num_threads()`.
Use to globally set a desired number of threads for Intel MKL at run time.

Call `mkl_domain_set_num_threads()`.
Use if at some point application threads start working with different Intel MKL function domains.

Call `mkl_set_num_threads_local()`.
Use to sets the number of threads for Intel MKL called from a particular thread.

**NOTE**
If your application uses OpenMP* threading, you may need to provide additional settings:

- Set the environment variable `OMP_NESTED=true`, or alternatively call `omp_set_nested(1)`, to enable OpenMP nested parallelism.
- Set the environment variable `MKL_DYNAMIC=false`, or alternatively call `mkl_set_dynamic(0)`, to prevent Intel MKL from dynamically reducing the number of threads in nested parallel regions.

‡ For details of the mentioned functions, see the Support Functions section of the *Intel MKL Reference Manual*, available in the Intel Software Documentation Library.

### Optimization Notice

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#### See Also

- Linking with Threading Libraries
- Dynamically Selecting the Interface and Threading Layer
- Intel MKL-specific Environment Variables for Threading Control
- `MKL_DOMAIN_NUM_THREADS`
- Avoiding Conflicts in the Execution Environment
- Intel Software Documentation Library

### Other Tips and Techniques to Improve Performance

#### See Also

- Improving Performance on Intel Xeon Phi Coprocessors
- Tips for Intel® Many Integrated Core Architecture

#### Coding Techniques

To improve performance of your application that calls Intel MKL, align your arrays on 64-byte boundaries and ensure that the leading dimensions of the arrays are divisible by 64.

Additional conditions can improve performance for specific function domains.
LAPACK Packed Routines

The routines with the names that contain the letters HP, OP, PP, SP, TP, UP in the matrix type and storage position (the second and third letters respectively) operate on the matrices in the packed format (see LAPACK "Routine Naming Conventions" sections in the Intel MKL Reference Manual). Their functionality is strictly equivalent to the functionality of the unpacked routines with the names containing the letters HE, OR, PO, SY, TR, UN in the same positions, but the performance is significantly lower.

If the memory restriction is not too tight, use an unpacked routine for better performance. In this case, you need to allocate $N^2/2$ more memory than the memory required by a respective packed routine, where $N$ is the problem size (the number of equations).

For example, to speed up solving a symmetric eigenproblem with an expert driver, use the unpacked routine:

```
call dsyevx(jobz, range, uplo, n, a, lda, vl, vu, il, iu, abstol, m, w, z, ldz, work, lwork, iwork, ifail, info)
```

where $a$ is the dimension $lda$-by-$n$, which is at least $N^2$ elements, instead of the packed routine:

```
call dspevx(jobz, range, uplo, n, ap, vl, vu, il, iu, abstol, m, w, z, ldz, work, iwork, ifail, info)
```

where $ap$ is the dimension $N*(N+1)/2$.

See Also
Example of Data Alignment

Hardware Configuration Tips

Dual-Core Intel® Xeon® processor 5100 series systems

To get the best performance with Intel MKL on Dual-Core Intel® Xeon® processor 5100 series systems, enable the Hardware DPL (streaming data) Prefetcher functionality of this processor. To configure this functionality, use the appropriate BIOS settings, as described in your BIOS documentation.

Intel® Hyper-Threading Technology

Intel® Hyper-Threading Technology (Intel® HT Technology) is especially effective when each thread performs different types of operations and when there are under-utilized resources on the processor. However, Intel MKL fits neither of these criteria because the threaded portions of the library execute at high efficiencies using most of the available resources and perform identical operations on each thread. You may obtain higher performance by disabling Intel HT Technology.

If you run with Intel HT Technology enabled, performance may be especially impacted if you run on fewer threads than physical cores. Moreover, if, for example, there are two threads to every physical core, the thread scheduler may assign two threads to some cores and ignore the other cores altogether. If you are using the OpenMP® library of the Intel Compiler, read the respective User Guide on how to best set the thread affinity interface to avoid this situation. For Intel MKL, apply the following setting:

```
set KMP_AFFINITY=granularity=fine,compact,1,0
```

See Also
Improving Performance with Threading

Managing Multi-core Performance

You can obtain best performance on systems with multi-core processors by requiring that threads do not migrate from core to core. To do this, bind threads to the CPU cores by setting an affinity mask to threads. Use one of the following options:
• OpenMP facilities (recommended, if available), for example, the `KMP_AFFINITY` environment variable using the Intel OpenMP library
• A system function, as explained below

Consider the following performance issue:

• The system has two sockets with two cores each, for a total of four cores (CPUs)
• The two-thread parallel application that calls the Intel MKL FFT happens to run faster than in four threads, but the performance in two threads is very unstable

The following code example shows how to resolve this issue by setting an affinity mask by operating system means using the Intel compiler. The code calls the system function `sched_setaffinity` to bind the threads to the cores on different sockets. Then the Intel MKL FFT function is called:

```c
#define _GNU_SOURCE //for using the GNU CPU affinity
// (works with the appropriate kernel and glibc)
// Set affinity mask
#include <sched.h>
#include <stdio.h>
#include <unistd.h>
#include <omp.h>
int main(void) {
  int NCPUs = sysconf(_SC_NPROCESSORS_CONF);
  printf("Using thread affinity on %i NCPUs\n", NCPUs);
  #pragma omp parallel default(shared)
  {
    int tid = omp_get_thread_num();
    CPU_ZERO(&new_mask);
    // 2 packages x 2 cores/pkg x 1 threads/core (4 total cores)
    CPU_SET(tid==0 ? 0 : 2, &new_mask);
    if (sched_getaffinity(0, sizeof(was_mask), &was_mask) == -1) {
      printf("Error: sched_getaffinity(%d, sizeof(was_mask), &was_mask)\n", tid);
    }
    if (sched_setaffinity(0, sizeof(new_mask), &new_mask) == -1) {
      printf("Error: sched_setaffinity(%d, sizeof(new_mask), &new_mask)\n", tid);
    }
    printf("tid=%d new_mask=%08X was_mask=%08X\n", tid,
           *(unsigned int*)(&new_mask), *(unsigned int*)(&was_mask));
  }
  // Call Intel MKL FFT function
  return 0;
}
```

Compile the application with the Intel compiler using the following command:

```
icc test_application.c -openmp
```

where `test_application.c` is the filename for the application.

Build the application. Run it in two threads, for example, by using the environment variable to set the number of threads:

```
env OMP_NUM_THREADS=2 ./a.out
```

See the `Linux Programmer's Manual` (in man pages format) for particulars of the `sched_setaffinity` function used in the above example.
Operating on Denormals

The IEEE 754-2008 standard, "An IEEE Standard for Binary Floating-Point Arithmetic", defines denormal (or subnormal) numbers as non-zero numbers smaller than the smallest possible normalized numbers for a specific floating-point format. Floating-point operations on denormals are slower than on normalized operands because denormal operands and results are usually handled through a software assist mechanism rather than directly in hardware. This software processing causes Intel MKL functions that consume denormals to run slower than with normalized floating-point numbers.

You can mitigate this performance issue by setting the appropriate bit fields in the MXCSR floating-point control register to flush denormals to zero (FTZ) or to replace any denormals loaded from memory with zero (DAZ). Check your compiler documentation to determine whether it has options to control FTZ and DAZ. Note that these compiler options may slightly affect accuracy.

FFT Optimized Radices

You can improve the performance of Intel MKL FFT if the length of your data vector permits factorization into powers of optimized radices.

In Intel MKL, the optimized radices are 2, 3, 5, 7, 11, and 13.

Enabling Low-communication Algorithm in Cluster FFT

You may obtain a better performance of a one-dimensional Cluster FFT by enabling a low-communication Segment Of Interest FFT (SOI FFT) algorithm. To use this algorithm, you must set the MKL_CFFT_ENABLE_SOI environment variable to "1" or "yes".

CAUTION
While using fewer MPI communications, the SOI FFT algorithm incurs a minor loss of precision (about one decimal digit).

Using Memory Functions

Avoiding Memory Leaks in Intel MKL

When running, Intel MKL allocates and deallocates internal buffers to facilitate better performance. However, in some cases this behavior may result in memory leaks.

To avoid memory leaks, you can do either of the following:

- Set the MKL_DISABLE_FAST_MM environment variable to 1 or call the mkl_disable_fast_mm() function. Be aware that this change may negatively impact performance of some Intel MKL functions, especially for small problem sizes.
- Call the mkl_free_buffers() function or the mkl_thread_freeBuffers() function in the current thread.

For the descriptions of the memory functions, see the Intel MKL Reference Manual, available in the Intel Software Documentation Library.

See Also
Intel Software Documentation Library
Redefining Memory Functions

In C/C++ programs, you can replace Intel MKL memory functions that the library uses by default with your own functions. To do this, use the *memory renaming* feature.

Memory Renaming

Intel MKL memory management by default uses standard C run-time memory functions to allocate or free memory. These functions can be replaced using memory renaming.

Intel MKL accesses the memory functions by pointers `i_malloc`, `i_free`, `i_calloc`, and `i_realloc`, which are visible at the application level. These pointers initially hold addresses of the standard C run-time memory functions `malloc`, `free`, `calloc`, and `realloc`, respectively. You can programmatically redefine values of these pointers to the addresses of your application’s memory management functions.

Redirecting the pointers is the only correct way to use your own set of memory management functions. If you call your own memory functions without redirecting the pointers, the memory will get managed by two independent memory management packages, which may cause unexpected memory issues.

How to Redefine Memory Functions

To redefine memory functions, use the following procedure:

1. Include the `i_malloc.h` header file in your code. This header file contains all declarations required for replacing the memory allocation functions. The header file also describes how memory allocation can be replaced in those Intel libraries that support this feature.

2. Redefine values of pointers `i_malloc`, `i_free`, `i_calloc`, and `i_realloc` prior to the first call to MKL functions, as shown in the following example:

```c
#include "i_malloc.h"

... 

i_malloc = my_malloc;
i_calloc = my_calloc;
i_realloc = my_realloc;
i_free = my_free;
...

// Now you may call Intel MKL functions
```
The Intel® Math Kernel Library (Intel® MKL) provides broad support for Fortran and C/C++ programming. However, not all functions support both Fortran and C interfaces. For example, some LAPACK functions have no C interface. You can call such functions from C using mixed-language programming.

If you want to use LAPACK or BLAS functions that support Fortran 77 in the Fortran 95 environment, additional effort may be initially required to build compiler-specific interface libraries and modules from the source code provided with Intel MKL.

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### Using Language-Specific Interfaces with Intel® Math Kernel Library

This section discusses mixed-language programming and the use of language-specific interfaces with Intel MKL.

See also the "FFTW Interface to Intel® Math Kernel Library" Appendix in the Intel MKL Reference Manual for details of the FFTW interfaces to Intel MKL.

### Interface Libraries and Modules

You can create the following interface libraries and modules using the respective makefiles located in the interfaces directory.

<table>
<thead>
<tr>
<th>File name</th>
<th>Contains</th>
</tr>
</thead>
<tbody>
<tr>
<td>libmkl_blas95.a</td>
<td>Fortran 95 wrappers for BLAS (BLAS95) for IA-32 architecture.</td>
</tr>
<tr>
<td>libmkl_blas95_ilp64.a</td>
<td>Fortran 95 wrappers for BLAS (BLAS95) supporting LP64 interface.</td>
</tr>
<tr>
<td>libmkl_blas95_lp64.a</td>
<td>Fortran 95 wrappers for BLAS (BLAS95) supporting ILP64 interface.</td>
</tr>
<tr>
<td>libmkl_lapack95.a</td>
<td>Fortran 95 wrappers for LAPACK (LAPACK95) for IA-32 architecture.</td>
</tr>
<tr>
<td>libmkl_lapack95_lp64.a</td>
<td>Fortran 95 wrappers for LAPACK (LAPACK95) supporting LP64 interface.</td>
</tr>
<tr>
<td>File name</td>
<td>Contains</td>
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<tr>
<td>-----------</td>
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</tr>
<tr>
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<td>Fortran 95 wrappers for LAPACK (LAPACK95) supporting ILP64 interface.</td>
</tr>
<tr>
<td>libfftw2xc_intel.a</td>
<td>Interfaces for FFTW version 2.x (C interface for Intel compilers) to call Intel MKL FFTs.</td>
</tr>
<tr>
<td>libfftw2xc_gnu.a</td>
<td>Interfaces for FFTW version 2.x (C interface for GNU compilers) to call Intel MKL FFTs.</td>
</tr>
<tr>
<td>libfftw2xf_intel.a</td>
<td>Interfaces for FFTW version 2.x (Fortran interface for Intel compilers) to call Intel MKL FFTs.</td>
</tr>
<tr>
<td>libfftw2xf_gnu.a</td>
<td>Interfaces for FFTW version 2.x (Fortran interface for GNU compiler) to call Intel MKL FFTs.</td>
</tr>
<tr>
<td>libfftw3xc_intel.a</td>
<td>Interfaces for FFTW version 3.x (C interface for Intel compiler) to call Intel MKL FFTs.</td>
</tr>
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</tr>
<tr>
<td>libfftw3xf_gnu.a</td>
<td>Interfaces for FFTW version 3.x (Fortran interface for GNU compiler) to call Intel MKL FFTs.</td>
</tr>
<tr>
<td>libfftw2x_cdft_SINGLE.a</td>
<td>Single-precision interfaces for MPI FFTW version 2.x (C interface) to call Intel MKL cluster FFTs.</td>
</tr>
<tr>
<td>libfftw2x_cdft_DOUBLE.a</td>
<td>Double-precision interfaces for MPI FFTW version 2.x (C interface) to call Intel MKL cluster FFTs.</td>
</tr>
<tr>
<td>libfftw3x_cdft.a</td>
<td>Interfaces for MPI FFTW version 3.x (C interface) to call Intel MKL cluster FFTs.</td>
</tr>
<tr>
<td>libfftw3x_cdft_ilp64.a</td>
<td>Interfaces for MPI FFTW version 3.x (C interface) to call Intel MKL cluster FFTs supporting the ILP64 interface.</td>
</tr>
</tbody>
</table>

**Modules, in architecture- and interface-specific subdirectories of the Intel MKL include directory**

- **blas95.mod**: Fortran 95 interface module for BLAS (BLAS95).
- **lapack95.mod**: Fortran 95 interface module for LAPACK (LAPACK95).
- **f95_precision.mod**: Fortran 95 definition of precision parameters for BLAS95 and LAPACK95.
- **mk195_blas.mod**: Fortran 95 interface module for BLAS (BLAS95), identical to blas95.mod. To be removed in one of the future releases.
- **mk195_lapack.mod**: Fortran 95 interface module for LAPACK (LAPACK95), identical to lapack95.mod. To be removed in one of the future releases.
- **mk195_precision.mod**: Fortran 95 definition of precision parameters for BLAS95 and LAPACK95, identical to f95_precision.mod. To be removed in one of the future releases.
- **mkl_service.mod**: Fortran 95 interface module for Intel MKL support functions.

1 Prebuilt for the Intel® Fortran compiler

2 FFTW3 interfaces are integrated with Intel MKL. Look into `<mkl directory>/interfaces/fftw3x*/makefile` for options defining how to build and where to place the standalone library with the wrappers.
Fortran 95 Interfaces to LAPACK and BLAS

Fortran 95 interfaces are compiler-dependent. Intel MKL provides the interface libraries and modules precompiled with the Intel® Fortran compiler. Additionally, the Fortran 95 interfaces and wrappers are delivered as sources. (For more information, see Compiler-dependent Functions and Fortran 90 Modules). If you are using a different compiler, build the appropriate library and modules with your compiler and link the library as a user’s library:

1. Go to the respective directory `<mkl directory>/interfaces/blas95` or `<mkl directory>/interfaces/lapack95`
2. Type one of the following commands depending on your architecture:
   - For the IA-32 architecture,
     make libia32 INSTALL_DIR=<user dir>
   - For the Intel® 64 architecture,
     make libintel64 [interface=lp64|ilp64] INSTALL_DIR=<user dir>

**Important**
The parameter INSTALL_DIR is required.

As a result, the required library is built and installed in the `<user dir>/lib` directory, and the .mod files are built and installed in the `<user dir>/include/<arch>[/{lp64|ilp64}]` directory, where `<arch>` is one of {ia32, intel64}.

By default, the ifort compiler is assumed. You may change the compiler with an additional parameter of make:
make FC=<compiler>.

For example, the command
make libintel64 FC=pgf95 INSTALL_DIR=<userpgf95 dir> interface=lp64
builds the required library and .mod files and installs them in subdirectories of `<userpgf95 dir>`.

To delete the library from the building directory, use one of the following commands:

- For the IA-32 architecture,
  make cleania32 INSTALL_DIR=<user dir>
- For the Intel® 64 architecture,
  make cleanintel64 [interface=lp64|ilp64] INSTALL_DIR=<user dir>
- For all the architectures,
  make clean INSTALL_DIR=<user dir>

**CAUTION**
Even if you have administrative rights, avoid setting INSTALL_DIR=../.. or INSTALL_DIR=<mkl directory> in a build or clean command above because these settings replace or delete the Intel MKL prebuilt Fortran 95 library and modules.
Compiler-dependent Functions and Fortran 90 Modules

Compiler-dependent functions occur whenever the compiler inserts into the object code function calls that are resolved in its run-time library (RTL). Linking of such code without the appropriate RTL will result in undefined symbols. Intel MKL has been designed to minimize RTL dependencies.

In cases where RTL dependencies might arise, the functions are delivered as source code and you need to compile the code with whatever compiler you are using for your application.

In particular, Fortran 90 modules result in the compiler-specific code generation requiring RTL support. Therefore, Intel MKL delivers these modules compiled with the Intel compiler, along with source code, to be used with different compilers.

Mixed-language Programming with the Intel Math Kernel Library

Appendix A: Intel(R) Math Kernel Library Language Interfaces Support lists the programming languages supported for each Intel MKL function domain. However, you can call Intel MKL routines from different language environments.

See also these Knowledge Base articles:


Calling LAPACK, BLAS, and CBLAS Routines from C/C++ Language Environments

Not all Intel MKL function domains support both C and Fortran environments. To use Intel MKL Fortran-style functions in C/C++ environments, you should observe certain conventions, which are discussed for LAPACK and BLAS in the subsections below.

**CAUTION**

Avoid calling BLAS 95/LAPACK 95 from C/C++. Such calls require skills in manipulating the descriptor of a deferred-shape array, which is the Fortran 90 type. Moreover, BLAS95/LAPACK95 routines contain links to a Fortran RTL.

LAPACK and BLAS

Because LAPACK and BLAS routines are Fortran-style, when calling them from C-language programs, follow the Fortran-style calling conventions:

- Pass variables by *address*, not by *value*.
  
  Function calls in Example "Calling a Complex BLAS Level 1 Function from C++" and Example "Using CBLAS Interface Instead of Calling BLAS Directly from C" illustrate this.

- Store your data in Fortran style, that is, column-major rather than row-major order.

With row-major order, adopted in C, the last array index changes most quickly and the first one changes most slowly when traversing the memory segment where the array is stored. With Fortran-style column-major order, the last index changes most slowly whereas the first index changes most quickly (as illustrated by the figure below for a two-dimensional array).
For example, if a two-dimensional matrix $A$ of size $m \times n$ is stored densely in a one-dimensional array $B$, you can access a matrix element like this:

$A[i][j] = B[i*n+j]$ in C \hspace{1cm} (i=0, \ldots, m-1, j=0, \ldots, -1)$

$A(i,j) = B((j-1)*m+i)$ in Fortran \hspace{1cm} (i=1, \ldots, m, j=1, \ldots, n)$.

When calling LAPACK or BLAS routines from C, be aware that because the Fortran language is case-insensitive, the routine names can be both upper-case or lower-case, with or without the trailing underscore. For example, the following names are equivalent:

- LAPACK: dgetrf, DGETRF, dgetrf_, and DGETRF_
- BLAS: dgemm, DGEMM, dgemm_, and DGEMM_

See Example "Calling a Complex BLAS Level 1 Function from C++" on how to call BLAS routines from C.

See also the Intel(R) MKL Reference Manual for a description of the C interface to LAPACK functions.

### CBLAS

Instead of calling BLAS routines from a C-language program, you can use the CBLAS interface.

CBLAS is a C-style interface to the BLAS routines. You can call CBLAS routines using regular C-style calls. Use the `mkl.h` header file with the CBLAS interface. The header file specifies enumerated values and prototypes of all the functions. It also determines whether the program is being compiled with a C++ compiler, and if it is, the included file will be correct for use with C++ compilation. Example "Using CBLAS Interface Instead of Calling BLAS Directly from C" illustrates the use of the CBLAS interface.

### C Interface to LAPACK

Instead of calling LAPACK routines from a C-language program, you can use the C interface to LAPACK provided by Intel MKL.

The C interface to LAPACK is a C-style interface to the LAPACK routines. This interface supports matrices in row-major and column-major order, which you can define in the first function argument `matrix_order`. Use the `mkl.h` header file with the C interface to LAPACK. `mkl.h` includes the `mkl_lapacke.h` header file, which specifies constants and prototypes of all the functions. It also determines whether the program is being compiled with a C++ compiler, and if it is, the included file will be correct for use with C++ compilation. You can find examples of the C interface to LAPACK in the `examples/lapacke` subdirectory in the Intel MKL installation directory.

### Using Complex Types in C/C++

As described in the documentation for the Intel® Fortran Compiler XE, C/C++ does not directly implement the Fortran types `COMPLEX(4)` and `COMPLEX(8)`. However, you can write equivalent structures. The type `COMPLEX(4)` consists of two 4-byte floating-point numbers. The first of them is the real-number component, and the second one is the imaginary-number component. The type `COMPLEX(8)` is similar to `COMPLEX(4)` except that it contains two 8-byte floating-point numbers.
Intel MKL provides complex types MKL_Complex8 and MKL_Complex16, which are structures equivalent to the Fortran complex types COMPLEX(4) and COMPLEX(8), respectively. The MKL_Complex8 and MKL_Complex16 types are defined in the mkl_types.h header file. You can use these types to define complex data. You can also redefine the types with your own types before including the mkl_types.h header file. The only requirement is that the types must be compatible with the Fortran complex layout, that is, the complex type must be a pair of real numbers for the values of real and imaginary parts.

For example, you can use the following definitions in your C++ code:

```c
#define MKL_Complex8 std::complex<float>
```

and

```c
#define MKL_Complex16 std::complex<double>
```

See Example "Calling a Complex BLAS Level 1 Function from C++" for details. You can also define these types in the command line:

```c
-DMKL_Complex8="std::complex<float>"
-DMKL_Complex16="std::complex<double>"
```

### Calling BLAS Functions that Return the Complex Values in C/C++ Code

Complex values that functions return are handled differently in C and Fortran. Because BLAS is Fortran-style, you need to be careful when handling a call from C to a BLAS function that returns complex values. However, in addition to normal function calls, Fortran enables calling functions as though they were subroutines, which provides a mechanism for returning the complex value correctly when the function is called from a C program. When a Fortran function is called as a subroutine, the return value is the first parameter in the calling sequence. You can use this feature to call a BLAS function from C.

The following example shows how a call to a Fortran function as a subroutine converts to a call from C and the hidden parameter result gets exposed:

**Normal Fortran function call:**

```fortran
result = cdotc(n, x, 1, y, 1)
```

**A call to the function as a subroutine:**

```fortran
call cdotc(result, n, x, 1, y, 1)
```

**A call to the function from C:**

```c
cdotc(&result, &n, x, &one, y, &one)
```

**NOTE**

Intel MKL has both upper-case and lower-case entry points in the Fortran-style (case-insensitive) BLAS, with or without the trailing underscore. So, all these names are equivalent and acceptable: cdotc, CDOTC, cdotc_, and CDOTC_.

The above example shows one of the ways to call several level 1 BLAS functions that return complex values from your C and C++ applications. An easier way is to use the CBLAS interface. For instance, you can call the same function using the CBLAS interface as follows:

```c
cblas_cdotu(n, x, 1, y, 1, &result)
```

**NOTE**

The complex value comes last on the argument list in this case.

The following examples show use of the Fortran-style BLAS interface from C and C++, as well as the CBLAS (C language) interface:

- Example "Calling a Complex BLAS Level 1 Function from C"
- Example "Calling a Complex BLAS Level 1 Function from C++"
- Example "Using CBLAS Interface Instead of Calling BLAS Directly from C"
Example “Calling a Complex BLAS Level 1 Function from C”

The example below illustrates a call from a C program to the complex BLAS Level 1 function `zdotc()`. This function computes the dot product of two double-precision complex vectors.

In this example, the complex dot product is returned in the structure `c`.

```c
#include "mkl.h"
#define N 5
int main()
{  
    int n = N, inca = 1, incb = 1, i;
    MKL_Complex16 a[N], b[N], c;
    for( i = 0; i < n; i++ )
    {  
a[i].real = (double)i; a[i].imag = (double)i * 2.0;
    b[i].real = (double)(n - i); b[i].imag = (double)i * 2.0;
    }
    zdotc(&c, &n, a, &inca, b, &incb);
    printf( "The complex dot product is: ( %6.2f, %6.2f)\n", c.real, c.imag );
    return 0;
}
```

Example “Calling a Complex BLAS Level 1 Function from C++”

Below is the C++ implementation:

```cpp
#include <complex>
#include <iostream>
#define MKL_Complex16 std::complex<double>
#include "mkl.h"
#define N 5

int main()
{  
    int n, inca = 1, incb = 1, i;
    std::complex<double> a[N], b[N], c;
    n = N;
    for( i = 0; i < n; i++ )
    {  
a[i] = std::complex<double>(i,i*2.0);
    b[i] = std::complex<double>(n-i,i*2.0);
    }
    zdotc(&c, &n, a, &inca, b, &incb);
    std::cout << "The complex dot product is: " << c << std::endl;
    return 0;
}
```

Example “Using CBLAS Interface Instead of Calling BLAS Directly from C”

This example uses CBLAS:

```c
#include <stdio.h>
#include "mkl.h"
typedef struct{ double re; double im; } complex16;
#define N 5
int main()
{  
    int n, inca = 1, incb = 1, i;
    complex16 a[N], b[N], c;
    n = N;
    for( i = 0; i < n; i++ )
    {  
a[i].re = (double)i; a[i].im = (double)i * 2.0;
    b[i].re = (double)(n - i); b[i].im = (double)i * 2.0;
    }
```
Support for Boost uBLAS Matrix-matrix Multiplication

If you are used to uBLAS, you can perform BLAS matrix-matrix multiplication in C++ using Intel MKL substitution of Boost uBLAS functions. uBLAS is the Boost C++ open-source library that provides BLAS functionality for dense, packed, and sparse matrices. The library uses an expression template technique for passing expressions as function arguments, which enables evaluating vector and matrix expressions in one pass without temporary matrices. uBLAS provides two modes:

- Debug (safe) mode, default. Checks types and conformance.
- Release (fast) mode. Does not check types and conformance. To enable this mode, use the `NDEBUG` preprocessor symbol.

The documentation for the Boost uBLAS is available at www.boost.org.

Intel MKL provides overloaded `prod()` functions for substituting uBLAS dense matrix-matrix multiplication with the Intel MKL `gemm` calls. Though these functions break uBLAS expression templates and introduce temporary matrices, the performance advantage can be considerable for matrix sizes that are not too small (roughly, over 50).

You do not need to change your source code to use the functions. To call them:

- Include the header file `mkl_boost_ublas_matrix_prod.hpp` in your code (from the Intel MKL include directory)
- Add appropriate Intel MKL libraries to the link line.

The list of expressions that are substituted follows:

```
prod( m1, m2 )
prod( trans(m1), m2 )
prod( trans(conj(m1)), m2 )
prod( conj(trans(m1)), m2 )
prod( m1, trans(m2) )
prod( trans(m1), trans(m2) )
prod( trans(conj(m1)), trans(m2) )
prod( conj(trans(m1)), trans(m2) )
prod( m1, conj(trans(m2)) )
prod( trans(m1), conj(trans(m2)) )
prod( trans(conj(m1)), conj(trans(m2)) )
prod( conjugate(trans(m1)), conj(trans(m2)) )
```

These expressions are substituted in the release mode only (with `NDEBUG` preprocessor symbol defined). Supported uBLAS versions are Boost 1.34.1 and higher. To get them, visit www.boost.org.

A code example provided in the `<mkl directory>/examples/ublas/source/sylvester.cpp` file illustrates usage of the Intel MKL uBLAS header file for solving a special case of the Sylvester equation.
To run the Intel MKL ublas examples, specify the `BOOST_ROOT` parameter in the `make` command, for instance, when using Boost version 1.37.0:

```
make libia32 BOOST_ROOT = <your_path>/boost_1_37_0
```

See Also
Using Code Examples

**Invoking Intel MKL Functions from Java* Applications**

**Intel MKL Java* Examples**

To demonstrate binding with Java, Intel MKL includes a set of Java examples in the following directory:

```
<mkl directory>/examples/java
```

The examples are provided for the following MKL functions:

- `?gemm`, `?gemv`, and `?dot` families from CBLAS
- The complete set of non-cluster FFT functions
- ESSL\(^1\)-like functions for one-dimensional convolution and correlation
- VSL Random Number Generators (RNG), except user-defined ones and file subroutines
- VML functions, except `GetErrorCallBack`, `SetErrorCallBack`, and `ClearErrorCallBack`

You can see the example sources in the following directory:

```
<mkl directory>/examples/java/examples
```

The examples are written in Java. They demonstrate usage of the MKL functions with the following variety of data:

- 1- and 2-dimensional data sequences
- Real and complex types of the data
- Single and double precision

However, the wrappers, used in the examples, do not:

- Demonstrate the use of large arrays (>2 billion elements)
- Demonstrate processing of arrays in native memory
- Check correctness of function parameters
- Demonstrate performance optimizations

The examples use the Java Native Interface (JNI* developer framework) to bind with Intel MKL. The JNI documentation is available from [http://java.sun.com/javase/6/docs/technotes/guides/jni/](http://java.sun.com/javase/6/docs/technotes/guides/jni/).

The Java example set includes JNI wrappers that perform the binding. The wrappers do not depend on the examples and may be used in your Java applications. The wrappers for CBLAS, FFT, VML, VSL RNG, and ESSL-like convolution and correlation functions do not depend on each other.

To build the wrappers, just run the examples. The makefile builds the wrapper binaries. After running the makefile, you can run the examples, which will determine whether the wrappers were built correctly. As a result of running the examples, the following directories will be created in `<mkl directory>/examples/java`:

- `docs`
- `include`
- `classes`
- `bin`
- `_results`

The directories `docs`, `include`, `classes`, and `bin` will contain the wrapper binaries and documentation; the directory `_results` will contain the testing results.
For a Java programmer, the wrappers are the following Java classes:

- com.intel.mkl.CBLAS
- com.intel.mkl.DFTI
- com.intel.mkl.ESSL
- com.intel.mkl.VML
- com.intel.mkl.VSL

Documentation for the particular wrapper and example classes will be generated from the Java sources while building and running the examples. To browse the documentation, open the index file in the docs directory (created by the build script):

<example directory>/java/docs/index.html.

The Java wrappers for CBLAS, VML, VSL RNG, and FFT establish the interface that directly corresponds to the underlying native functions, so you can refer to the Intel MKL Reference Manual for their functionality and parameters. Interfaces for the ESSL-like functions are described in the generated documentation for the com.intel.mkl.ESSL class.

Each wrapper consists of the interface part for Java and JNI stub written in C. You can find the sources in the following directory:

<example directory>/java/wrappers.

Both Java and C parts of the wrapper for CBLAS and VML demonstrate the straightforward approach, which you may use to cover additional CBLAS functions.

The wrapper for FFT is more complicated because it needs to support the lifecycle for FFT descriptor objects. To compute a single Fourier transform, an application needs to call the FFT software several times with the same copy of the native FFT descriptor. The wrapper provides the handler class to hold the native descriptor, while the virtual machine runs Java bytecode.

The wrapper for VSL RNG is similar to the one for FFT. The wrapper provides the handler class to hold the native descriptor of the stream state.

The wrappers meet the JNI Specification versions 1.1 and 5.0 and should work with virtually every modern implementation of Java.

The examples and the Java part of the wrappers are written for the Java language described in "The Java Language Specification (First Edition)" and extended with the feature of "inner classes" (this refers to late 1990s). This level of language version is supported by all versions of the Sun Java Development Kit* (JDK*) developer toolkit and compatible implementations starting from version 1.1.5, or by all modern versions of Java.

The level of C language is "Standard C" (that is, C89) with additional assumptions about integer and floating-point data types required by the Intel MKL interfaces and the JNI header files. That is, the native float and double data types must be the same as JNI jfloat and jdouble data types, respectively, and the native int must be 4 bytes long.

1 IBM Engineering Scientific Subroutine Library (ESSL*).

See Also
Running the Java* Examples

Running the Java* Examples

The Java examples support all the C and C++ compilers that Intel MKL does. The makefile intended to run the examples also needs the make utility, which is typically provided with the Linux* OS distribution.

To run Java examples, the JDK* developer toolkit is required for compiling and running Java code. A Java implementation must be installed on the computer or available via the network. You may download the JDK from the vendor website.
The examples should work for all versions of JDK. However, they were tested only with the following Java implementations for all the supported architectures:

- J2SE* SDK 1.4.2, JDK 5.0 and 6.0 from Sun Microsystems, Inc. (http://sun.com/).
- JRockit* JDK 1.4.2 and 5.0 from Oracle Corporation (http://oracle.com/).

Note that the Java run-time environment* (JRE*) system, which may be pre-installed on your computer, is not enough. You need the JDK* developer toolkit that supports the following set of tools:

- java
- javac
- javah
- javadoc

To make these tools available for the examples makefile, set the JAVA_HOME environment variable and add the JDK binaries directory to the system PATH, for example, using the bash shell:

```bash
export JAVA_HOME=/home/<user name>/jdk1.5.0_09
echo PATH=${JAVA_HOME}/bin:${PATH}
```

You may also need to clear the JDK_HOME environment variable, if it is assigned a value:

```bash
unset JDK_HOME
```

To start the examples, use the makefile found in the Intel MKL Java examples directory:

```bash
make {soia32|sointel64|libia32|libintel64} [function=...] [compiler=...]
```

If you type the make command and omit the target (for example, soia32), the makefile prints the help info, which explains the targets and parameters.

For the examples list, see the examples.lst file in the Java examples directory.

**Known Limitations of the Java* Examples**

This section explains limitations of Java examples.

**Functionality**

Some Intel MKL functions may fail to work if called from the Java environment by using a wrapper, like those provided with the Intel MKL Java examples. Only those specific CBLAS, FFT, VML, VSL RNG, and the convolution/correlation functions listed in the Intel MKL Java Examples section were tested with the Java environment. So, you may use the Java wrappers for these CBLAS, FFT, VML, VSL RNG, and convolution/correlation functions in your Java applications.

**Performance**

The Intel MKL functions must work faster than similar functions written in pure Java. However, the main goal of these wrappers is to provide code examples, not maximum performance. So, an Intel MKL function called from a Java application will probably work slower than the same function called from a program written in C/C++ or Fortran.

**Known bugs**

There are a number of known bugs in Intel MKL (identified in the Release Notes), as well as incompatibilities between different versions of JDK. The examples and wrappers include workarounds for these problems. Look at the source code in the examples and wrappers for comments that describe the workarounds.
Obtaining Numerically Reproducible Results

Intel® Math Kernel Library (Intel® MKL) offers functions and environment variables that help you obtain Conditional Numerical Reproducibility (CNR) of floating-point results when calling the library functions from your application. These new controls enable Intel MKL to run in a special mode, when functions return bitwise reproducible floating-point results from run to run under the following conditions:

- Calls to Intel MKL occur in a single executable
- Input and output arrays in function calls are properly aligned
- The number of computational threads used by the library does not change in the run

It is well known that for general single and double precision IEEE floating-point numbers, the associative property does not always hold, meaning \((a+b)+c\) may not equal \(a+(b+c)\). Let’s consider a specific example. In infinite precision arithmetic \(2^{-63} + 1 + -1 = 2^{-63}\). If this same computation is done on a computer using double precision floating-point numbers, a rounding error is introduced, and the order of operations becomes important:

\[(2^{-63} + 1) + (-1) \approx 1 + (-1) = 0\]

versus

\[2^{-63} + (1 + (-1)) \approx 2^{-63} + 0 = 2^{-63}\]

This inconsistency in results due to order of operations is precisely what the new functionality addresses.

The application related factors that affect the order of floating-point operations within a single executable program include selection of a code path based on run-time processor dispatching, alignment of data arrays, variation in number of threads, threaded algorithms and internal floating-point control settings. You can control most of these factors by controlling the number of threads and floating-point settings and by taking steps to align memory when it is allocated (see the Getting Reproducible Results with Intel® MKL knowledge base article for details). However, run-time dispatching and certain threaded algorithms do not allow users to make changes that can ensure the same order of operations from run to run.

Intel MKL does run-time processor dispatching in order to identify the appropriate internal code paths to traverse for the Intel MKL functions called by the application. The code paths chosen may differ across a wide range of Intel processors and Intel architecture compatible processors and may provide differing levels of performance. For example, an Intel MKL function running on an Intel® Pentium® 4 processor may run one code path, while on the latest Intel® Xeon® processor it will run another code path. This happens because each unique code path has been optimized to match the features available on the underlying processor. One key way that the new features of a processor are exposed to the programmer is through the instruction set architecture (ISA). Because of this, code branches in Intel MKL are designated by the latest ISA they use for optimizations: from the Intel® Streaming SIMD Extensions 2 (Intel® SSE2) to the Intel® Advanced Vector Extensions (Intel® AVX). The feature-based approach introduces a challenge: if any of the internal floating-point operations are done in a different order or are re-associated, the computed results may differ.

Dispatching optimized code paths based on the capabilities of the processor on which the code is running is central to the optimization approach used by Intel MKL. So it is natural that consistent results require some performance trade-offs. If limited to a particular code path, performance of Intel MKL can in some circumstances degrade by more than a half. To understand this, note that matrix-multiply performance nearly doubled with the introduction of new processors supporting Intel AVX instructions. Even if the code branch is not restricted, performance can degrade by 10-20% because the new functionality restricts algorithms to maintain the order of operations.

**Optimization Notice**

Intel's compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or
Optimization Notice

Effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

Notice revision #20110804

Getting Started with Conditional Numerical Reproducibility

Intel MKL offers functions and environment variables to help you get reproducible results. You can configure Intel MKL using functions or environment variables, but the functions provide more flexibility.

The following specific examples introduce you to the conditional numerical reproducibility.

Intel CPUs supporting Intel AVX

To ensure Intel MKL calls return the same results on every Intel CPU supporting Intel AVX instructions:

1. Make sure that:
   - Your application uses a fixed number of threads
   - Input and output arrays in Intel MKL function calls are aligned properly

2. Do either of the following:
   - Call
     \[
     \text{mkl\_cbwr\_set(MKL\_CBWR\_AVX)}
     \]
   - Set the environment variable:
     \[
     \text{MKL\_CBWR\_BRANCH = AVX}
     \]

NOTE
On non-Intel CPUs and on Intel CPUs that do not support Intel AVX, this environment setting may cause results to differ because the AUTO branch is used instead, while the above function call returns an error and does not enable the CNR mode.

Intel CPUs supporting Intel SSE2

To ensure Intel MKL calls return the same results on every Intel CPU supporting Intel SSE2 instructions:

1. Make sure that:
   - Your application uses a fixed number of threads
   - Input and output arrays in Intel MKL function calls are aligned properly

2. Do either of the following:
   - Call
     \[
     \text{mkl\_cbwr\_set(MKL\_CBWR\_SSE2)}
     \]
   - Set the environment variable:
     \[
     \text{MKL\_CBWR\_BRANCH = SSE2}
     \]

NOTE
On non-Intel CPUs, this environment setting may cause results to differ because the AUTO branch is used instead, while the above function call returns an error and does not enable the CNR mode.
Intel or Intel compatible CPUs supporting Intel SSE2

On non-Intel CPUs, only the `MKL_CBWR_AUTO` and `MKL_CBWR_COMPATIBLE` options are supported for function calls and only `AUTO` and `COMPATIBLE` options for environment settings.

To ensure Intel MKL calls return the same results on all Intel or Intel compatible CPUs supporting Intel SSE2 instructions:

1. Make sure that:
   - Your application uses a fixed number of threads
   - Input and output arrays in Intel MKL function calls are aligned properly

2. Do either of the following:
   - Call
     ```
     mkl_cbwr_set(MKL_CBWR_COMPATIBLE)
     ```
   - Set the environment variable:
     ```
     MKL_CBWR_BRANCH = COMPATIBLE
     ```

**NOTE**
The special `MKL_CBWR_COMPATIBLE/COMPATIBLE` option is provided because Intel and Intel compatible CPUs have a few instructions, such as approximation instructions rcpps/rsqrtps, that may return different results. This option ensures that Intel MKL does not use these instructions and forces a single Intel SSE2 only code path to be executed.

Next steps

See [Specifying the Code Branches](#) for details of specifying the branch using environment variables.

See the following sections in the *Intel MKL Reference Manual*:

Support Functions for Conditional Numerical Reproducibility

PARDISO* - Parallel Direct Sparse Solver Interface

for how to configure the CNR mode of Intel MKL using functions.

See Also

Code Examples

**Specifying the Code Branches**

Intel MKL provides conditional numerically reproducible results for a code branch determined by the supported instruction set architecture (ISA). The values you can specify for the `MKL_CBWR` environment variable may have one of the following equivalent formats:

- `MKL_CBWR="<branch>"
- `MKL_CBWR="BRANCH=<branch>"

The `<branch>` placeholder specifies the CNR branch with one of the following values:

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUTO</td>
<td>CNR mode uses:</td>
</tr>
<tr>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>•</td>
<td>The standard ISA-based dispatching model on Intel processors while ensuring fixed cache sizes, deterministic reductions, and static scheduling</td>
</tr>
<tr>
<td>•</td>
<td>The branch corresponding to COMPATIBLE otherwise</td>
</tr>
</tbody>
</table>

CNR mode uses the branch for the following ISA:

<table>
<thead>
<tr>
<th>Branch</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPATIBLE</td>
<td>Intel® Streaming SIMD Extensions 2 (Intel® SSE2) without rcpps/rsqrtps instructions</td>
</tr>
<tr>
<td>SSE2</td>
<td>Intel® Streaming SIMD Extensions 3 (Intel® SSE3)</td>
</tr>
<tr>
<td>SSE3</td>
<td>Supplemental Streaming SIMD Extensions 3 (SSSE3)</td>
</tr>
<tr>
<td>SSE4_1</td>
<td>Intel® Streaming SIMD Extensions 4-1 (Intel® SSE4-1)</td>
</tr>
<tr>
<td>SSE4_2</td>
<td>Intel® Streaming SIMD Extensions 4-2 (Intel® SSE4-2)</td>
</tr>
<tr>
<td>AVX</td>
<td>Intel® Advanced Vector Extensions (Intel® AVX)</td>
</tr>
<tr>
<td>AVX2</td>
<td>Intel® Advanced Vector Extensions 2 (Intel® AVX2)</td>
</tr>
</tbody>
</table>

When specifying the CNR branch, be aware of the following:

- Reproducible results are provided under **certain conditions**.
- Settings other than **AUTO** or **COMPATIBLE** are available only for Intel processors. The code branch specified by **COMPATIBLE** is run on all non-Intel processors in the case of specific settings.
- To get the CNR branch optimized for the processor where your program is currently running, choose the value of **AUTO** or call the mkl_cbwr_get_auto_branch function.

Setting the MKL_CBWR environment variable or a call to an equivalent mkl_set_cbwr_branch function fixes the code branch and sets the reproducibility mode.

- If the value of the branch is incorrect or your processor does not support the specified branch, CNR ignores this value and uses the **AUTO** branch without providing any warning messages.
- Calls to functions that define the behavior of CNR must precede any of the math library functions that they control.
- Settings specified by the functions take precedence over the settings specified by the environment variable.

See the *Intel MKL Reference Manual* for how to specify the branches using functions.

**See Also**

Getting Started with Conditional Numerical Reproducibility

**Reproducibility Conditions**

Reproducible results are provided under these conditions:

- The number of threads is fixed and constant.

Specifically:

- If you are running your program on different processors, explicitly specify the number of threads.
- To ensure that your application has deterministic behavior with OpenMP* parallelization and does not adjust the number of threads dynamically at run time, set MKL_DYNAMIC and OMP_DYNAMIC to FALSE. This is especially needed if you are running your program on different systems.
• Input and output arrays are aligned on 128-byte boundaries.

Instead of the general 128-byte alignment, you can use a more specific alignment depending on the ISA. For example: 16-byte alignment suffices for Intel SSE2 or higher and 32-byte alignment suffices for Intel AVX or Intel AVX2. To ensure proper alignment of arrays, allocate memory for them using `mkl_malloc/mkl_calloc`.

See Also
MKL_DYNAMIC

Setting the Environment Variable for Conditional Numerical Reproducibility

The following examples illustrate the use of the `MKL_CBWR` environment variable. The first command in each list sets Intel MKL to run in the CNR mode based on the default dispatching for your platform. The other two commands in each list are equivalent and set the CNR branch to Intel AVX.

For the bash shell:

- `export MKL_CBWR="AUTO"
- `export MKL_CBWR="AVX"
- `export MKL_CBWR="BRANCH=AVX"

For the C shell (csh or tcsh):

- `setenv MKL_CBWR "AUTO"
- `setenv MKL_CBWR "AVX"
- `setenv MKL_CBWR "BRANCH=AVX"

See Also
Specifying the Code Branches

Code Examples

The following simple programs show how to obtain reproducible results from run to run of Intel MKL functions. See the Intel MKL Reference Manual for more examples.

C Example of CNR

```c
#include <mkl.h>
int main(void) {
  int my_cbwr_branch;
  /* Align all input/output data on 128-byte boundaries */
  /* to get reproducible results of Intel MKL function calls */
  void *darray;
  int darray_size=1000;
  /* Set alignment value in bytes */
  int alignment=128;
  /* Allocate aligned array */
  darray = mkl_malloc (sizeof(double)*darray_size, alignment);
  /* Find the available MKL_CBWR_BRANCH automatically */
  my_cbwr_branch = mkl_cbwr_get_auto_branch();
  /* User code without Intel MKL calls */
  /* Piece of the code where CNR of Intel MKL is needed */
  /* The performance of Intel MKL functions might be reduced for CNR mode */

  if (mkl_cbwr_set(my_cbwr_branch)) {
    printf("Error in setting MKL_CBWR_BRANCH! Aborting\n");
    return;
  }
  /* CNR calls to Intel MKL + any other code */
```
Fortran Example of CNR

PROGRAM MAIN
  INCLUDE 'mkl.fi'
  INTEGER*4 MY_CBWR_BRANCH
  INTEGER*8 MKL_MALLOC
  DOUBLE PRECISION DARRAY
  INTEGER*4 ALIGNMENT
  INTEGER*8 ALIGNMENT

  ! Align all input/output data on 128-byte boundaries
  ! to get reproducible results of Intel MKL function calls
  ! Declare Intel MKL memory allocation routine
  #ifdef _IA32
    INTEGER MKL_MALLOC
  #else
    INTEGER*8 MKL_MALLOC
  #endif
  EXTERNAL MKL_MALLOC, MKL_FREE
  POINTER (P_DARRAY,DARRAY(1))
  INTEGER DARRAY_SIZE
  PARAMETER (DARRAY_SIZE=1000)
  ! Set alignment value in bytes
  INTEGER ALIGNMENT
  PARAMETER (ALIGNMENT=128)

  ! Allocate aligned array
  P_DARRAY = MKL_MALLOC (%VAL(8*DARRAY_SIZE), %VAL(ALIGNMENT));
  ! Find the available MKL_CBWR_BRANCH automatically
  MY_CBWR_BRANCH = MKL_CBWR_GET_AUTO_BRANCH()
  ! User code without Intel MKL calls
  ! Piece of the code where CNR of Intel MKL is needed
  ! The performance of Intel MKL functions may be reduced for CNR mode
  IF (MKL_CBWR_SET (MY_CBWR_BRANCH) .NE. MKL_CBWR_SUCCESS) THEN
    PRINT *, "Error in setting MKL_CBWR_BRANCH! Aborting…"
    RETURN
  ENDIF

  ! CNR calls to Intel MKL + any other code
  CALL MKL_FREE(P_DARRAY)

END
This section provides coding tips for managing data alignment and version-specific compilation.

**Example of Data Alignment**

Needs for best performance with Intel MKL or for reproducible results from run to run of Intel MKL functions require alignment of data arrays. The following example shows how to align an array on 64-byte boundaries. To do this, use `mkl_malloc()` in place of system provided memory allocators, as shown in the code example below.

**Aligning Addresses on 64-byte Boundaries**

```c
// ******* C language *******
... 
#include <stdlib.h>
#include <mkl.h>
... 
void *darray;
int workspace;
// Set value of alignment
int alignment=64;
... 
// Allocate aligned workspace
darray = mkl_malloc( sizeof(double)*workspace, alignment );
... 
// call the program using MKL
mkl_app( darray );
... 
// Free workspace
mkl_free( darray );
```

```fortran
! ******* Fortran language *******
... 
! Set value of alignment
integer alignment
parameter (alignment=64)
... 
! Declare Intel MKL routines
#ifdef _IA32
integer mkl_malloc
#else
integer*8 mkl_malloc
#endif
external mkl_malloc, mkl_free, mkl_app
... 
! Allocate aligned workspace
p_wrk = mkl_malloc( %val(8*workspace), %val(alignment) )
... 
! call the program using Intel MKL
call mkl_app( darray )
... 
! Free workspace
call mkl_free(p_wrk)
```
Using Predefined Preprocessor Symbols for Intel® MKL Version-Dependent Compilation

Preprocessor symbols (macros) substitute values in a program before it is compiled. The substitution is performed in the preprocessing phase.

The following preprocessor symbols are available:

<table>
<thead>
<tr>
<th>Predefined Preprocessor Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTEL_MKL</strong></td>
<td>Intel MKL major version</td>
</tr>
<tr>
<td><strong>INTEL_MKL_MINOR</strong></td>
<td>Intel MKL minor version</td>
</tr>
<tr>
<td><strong>INTEL_MKL_UPDATE</strong></td>
<td>Intel MKL update number</td>
</tr>
<tr>
<td>INTEL_MKL_VERSION</td>
<td>Intel MKL full version in the following format:</td>
</tr>
</tbody>
</table>
|                              | \[
| \text{INTEL\_MKL\_VERSION} = \]
|                              | \left(\text{\_INTEL\_MKL\_}\ast100+\text{\_INTEL\_MKL\_MINOR}\right)\ast100+\text{\_INTEL\_MKL\_UPDATE}\right) |

These symbols enable conditional compilation of code that uses new features introduced in a particular version of the library.

To perform conditional compilation:

1. Include in your code the file where the macros are defined:
   - mkl.h for C/C++
   - mkl.fi for Fortran

2. [Optionally] Use the following preprocessor directives to check whether the macro is defined:
   - #ifdef, #endif for C/C++
   - \!DEC$IF DEFINED, \!DEC$ENDIF for Fortran

3. Use preprocessor directives for conditional inclusion of code:
   - #if, #endif for C/C++
   - \!DEC$IF, \!DEC$ENDIF for Fortran

Example

This example shows how to compile a code segment conditionally for a specific version of Intel MKL. In this case, the version is 10.3 Update 4:

**C/C++:**

```c
#include "mkl.h"
#define INTEL_MKL_VERSION
#if INTEL_MKL_VERSION == 100304
  // Code to be conditionally compiled
#endif
#endif
```

**Fortran:**

```fortran
include "mkl.fi"
!DEC$IF DEFINED INTEL_MKL_VERSION
!DEC$IF INTEL_MKL_VERSION .EQ. 100304
  * Code to be Conditionally compiled
!DEC$ENDIF
!DEC$ENDIF
```
Working with the Intel® Math Kernel Library Cluster Software

Optimization Notice

Intel's compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

Notice revision #20110804

Linking with ScaLAPACK and Cluster FFTs

The Intel MKL ScaLAPACK and Cluster FFTs support MPI implementations identified in the Intel MKL Release Notes.

To link a program that calls ScaLAPACK or Cluster FFTs, you need to know how to link a message-passing interface (MPI) application first.

Use mpi scripts to do this. For example, mpicc or mpif77 are C or FORTRAN 77 scripts, respectively, that use the correct MPI header files. The location of these scripts and the MPI library depends on your MPI implementation. For example, for the default installation of MPICH, /opt/mpich/bin/mpicc and /opt/mpich/bin/mpif77 are the compiler scripts and /opt/mpich/lib/libmpich.a is the MPI library.

Check the documentation that comes with your MPI implementation for implementation-specific details of linking.

To link with Intel MKL ScaLAPACK and/or Cluster FFTs, use the following general form:

```
<MPI linker script> <files to link> \n-L <MKL path> [-Wl,--start-group] <MKL cluster library> \n<BLACS> <MKL core libraries> [-Wl,--end-group]
```

where the placeholders stand for paths and libraries as explained in the following table:

<table>
<thead>
<tr>
<th>Placeholders</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;MKL cluster library&gt;</td>
<td>One of ScaLAPACK or Cluster FFT libraries for the appropriate architecture and programming interface (LP64 or ILP64). Available libraries are listed in Directory Structure in Detail. For example, for the IA-32 architecture, it is either –lmkl_scalapack_core or –lmkl_cdft_core.</td>
</tr>
<tr>
<td>&lt;BLACS&gt;</td>
<td>The BLACS library corresponding to your architecture, programming interface (LP64 or ILP64), and MPI used. Available BLACS libraries are listed in Directory Structure in Detail. For example, for the IA-32 architecture, choose one of –lmkl_blacs, –lmkl_blacs_intelmpi, or –lmkl_blacs_openmpi, depending on the MPI; specifically, for Intel MPI, choose –lmkl_blacs_intelmpi.</td>
</tr>
<tr>
<td>&lt;MKL core libraries&gt;</td>
<td>&lt;MKL LAPACK &amp; MKL kernel libraries&gt; for ScaLAPACK, and &lt;MKL kernel libraries&gt; for Cluster FFTs.</td>
</tr>
<tr>
<td>&lt;MKL kernel libraries&gt;</td>
<td>Processor optimized kernels, threading library, and system library for threading support, linked as described in Listing Libraries on a Link Line.</td>
</tr>
</tbody>
</table>
The LAPACK library and MKL kernel libraries.

A linker script that corresponds to the MPI version.

For example, if you are using Intel MPI, want to statically link with ScaLAPACK using the LP64 interface, and have only one MPI process per core (and thus do not use threading), specify the following linker options:

```
-L$MKLPATH -I$MKLINCLUDE -Wl,--start-group $MKLPATH/libmkl_scalapack_lp64.a $MKLPATH/libmkl_blacs_intelmpi_lp64.a $MKLPATH/libmkl_intel_lp64.a $MKLPATH/libmkl_sequential.a $MKLPATH/libmkl_core.a -static_mpi -Wl,--end-group -lpthread -lm
```

**NOTE**
Grouping symbols `-Wl,--start-group` and `-Wl,--end-group` are required for static linking.

**TIP**
Use the Link-line Advisor to quickly choose the appropriate set of MKL cluster Library, BLACS, and MKL core libraries.

See Also
Linking Your Application with the Intel® Math Kernel Library
Examples for Linking with ScaLAPACK and Cluster FFT

**Setting the Number of Threads**

The OpenMP* software responds to the environment variable `OMP_NUM_THREADS`. Intel MKL also has other mechanisms to set the number of threads, such as `MKL_NUM_THREADS` or `MKL_DOMAIN_NUM_THREADS` environment variables (see Using Additional Threading Control).

Make sure that the relevant environment variables have the same and correct values on all the nodes. Intel MKL does not set the default number of threads to one, but depends on the OpenMP libraries used with the compiler to set the default number. For the threading layer based on the Intel compiler (libmkl_intel_thread.a), this value is the number of CPUs according to the OS.

**CAUTION**
Avoid over-prescribing the number of threads, which may occur, for instance, when the number of MPI ranks per node and the number of threads per node are both greater than one. The number of MPI ranks per node multiplied by the number of threads per node should not exceed the number of hardware threads per node.

If you are using your login environment to set an environment variable, such as `OMP_NUM_THREADS`, remember that changing the value on the head node and then doing your run, as you do on a shared-memory (SMP) system, does not change the variable on all the nodes because `mpirun` starts a fresh default shell on all the nodes. To change the number of threads on all the nodes, in `.bashrc`, add a line at the top, as follows:

```
OMP_NUM_THREADS=1; export OMP_NUM_THREADS
```
You can run multiple CPUs per node using MPICH. To do this, build MPICH to enable multiple CPUs per node. Be aware that certain MPICH applications may fail to work perfectly in a threaded environment (see the Known Limitations section in the Release Notes). If you encounter problems with MPICH and setting of the number of threads is greater than one, first try setting the number of threads to one and see whether the problem persists.

**See Also**

Techniques to Set the Number of Threads

---

### Using Shared Libraries

All needed shared libraries must be visible on all nodes at run time. To achieve this, set the `LD_LIBRARY_PATH` environment variable accordingly.

If Intel MKL is installed only on one node, link statically when building your Intel MKL applications rather than use shared libraries.

The Intel® compilers or GNU compilers can be used to compile a program that uses Intel MKL. However, make sure that the MPI implementation and compiler match up correctly.

---

### Building ScaLAPACK Tests

To build ScaLAPACK tests:

- For the IA-32 architecture, add `libmkl_scalapack_core.a` to your link command.
- For the Intel® 64 or Intel® Many Integrated Core architecture, add `libmkl_scalapack_lp64.a` or `libmkl_scalapack_ilp64.a`, depending on the desired interface.

---

### Examples for Linking with ScaLAPACK and Cluster FFT

This section provides examples of linking with ScaLAPACK and Cluster FFT.

Note that a binary linked with ScaLAPACK runs the same way as any other MPI application (refer to the documentation that comes with your MPI implementation). For instance, the script `mpirun` is used in the case of MPICH2 and OpenMPI, and a number of MPI processes is set by `-np`. In the case of MPICH 2.0 and all Intel MPIs, start the daemon before running your application; the execution is driven by the script `mpiexec`.

For further linking examples, see the support website for Intel products at http://www.intel.com/software/products/support/.

**See Also**

Directory Structure in Detail

---

### Examples for Linking a C Application

These examples illustrate linking of an application under the following conditions:

- Main module is in C.
- You are using the Intel® C++ Compiler.
- You are using MPICH2.
- The `PATH` environment variable contains a directory with the MPI linker scripts.
- `$MKLPATH` is a user-defined variable containing `<mkl_directory>/lib/ia32`.

To link with ScaLAPACK for a cluster of systems based on the IA-32 architecture, use the following link line:

```
mpicc <user files to link> \
  -L$MKLPATH
```
To link with Cluster FFT for a cluster of systems based on the IA-32 architecture, use the following link line:

```plaintext
mpicc <user files to link>
   -Wl,--start-group
   $MKLPATH/libmkl_cdft_core.a
   $MKLPATH/libmkl_blacs_intelmpi.a
   $MKLPATH/libmkl_intel.a
   $MKLPATH/libmkl_intel_thread.a
   $MKLPATH/libmkl_core.a
   -Wl,--end-group
   -liomp5 -lpthread
```

See Also
Linking with ScaLAPACK and Cluster FFTs
Using the Link-line Advisor

Examples for Linking a Fortran Application
These examples illustrate linking of an application under the following conditions:

- Main module is in Fortran.
- Intel® Fortran Compiler is used.
- Intel® MPI is used.
- The PATH environment variable contains a directory with the MPI linker scripts.
- $MKLPATH is a user-defined variable containing <mkl directory>/lib/intel64.

To link with ScaLAPACK for a cluster of systems based on the Intel® 64 architecture, use the following link line:

```plaintext
mpiifort <user files to link>
   -L$MKLPATH
   -lmkl_scalapack_lp64
   -lmkl_blacs_intelmpi_lp64
   -lmkl_intel_lp64 -lmkl_intel_thread -lmkl_core
   -liomp5 -lpthread
```

To link with Cluster FFT for a cluster of systems based on the Intel® 64 architecture, use the following link line:

```plaintext
mpiifort <user files to link>
   -Wl,--start-group
   $MKLPATH/libmkl_cdft_core.a
   $MKLPATH/libmkl_blacs_intelmpi_ilp64.a
   $MKLPATH/libmkl_intel_ilp64.a
   $MKLPATH/libmkl_intel_thread.a
   $MKLPATH/libmkl_core.a
   -Wl,--end-group
   -liomp5 -lpthread
```

See Also
Linking with ScaLAPACK and Cluster FFTs
Using the Link-line Advisor
Using Intel® Math Kernel Library on Intel® Xeon Phi™ Coprocessors

Intel® Math Kernel Library (Intel® MKL) offers two sets of libraries to support Intel® Many Integrated Core (Intel® MIC) Architecture:

- For the host computer based on Intel® 64 or compatible architecture and running a Linux* operating system
- For Intel® Xeon Phi™ coprocessors

You can control how Intel MKL offloads computations to Intel® Xeon Phi™ coprocessors. Either you can offload computations automatically or use Compiler Assisted Offload:

- **Automatic Offload.**
  
  On Linux* OS running on Intel® 64 or compatible architecture systems, Automatic Offload automatically detects the presence of coprocessors based on Intel MIC Architecture and automatically offloads computations that may benefit from additional computational resources available. This usage model enables you to call Intel MKL routines as you would normally do with minimal changes to your program. The only change needed to enable Automatic Offload is either the setting of an environment variable or a single function call. For details see Automatic Offload.

- **Compiler Assisted Offload.**
  
  This usage model enables you to use the Intel compiler and its offload pragma support to manage the functions and data offloaded to a coprocessor. Within an offload region, you should specify both the input and output data for the Intel MKL functions to be offloaded. After linking with the Intel MKL libraries for Intel MIC Architecture, the compiler provided run-time libraries transfer the functions along with their data to a coprocessor to carry out the computations. For details see Compiler Assisted Offload.

In addition to offloading computations to coprocessors, you can call Intel MKL functions from an application that runs natively on a coprocessor. Native execution occurs when an application runs entirely on Intel MIC Architecture. Native mode is a fast way to make an existing application run on Intel MIC Architecture with minimal changes to the source code. For more information, see Running Intel MKL on an Intel Xeon Phi Coprocessor in Native Mode.

Intel MKL ScaLAPACK and Cluster FFT can benefit from yet another usage model offered by the Intel® MPI Library. The Intel MPI Library treats each Intel Xeon Phi coprocessor as a regular node in a cluster of Intel® Xeon® processors and Intel Xeon Phi coprocessors. To run your application on a coprocessor, you can specify an MPI rank on the coprocessor, build the application for Intel MIC Architecture, and launch the built executable from the host computer or the coprocessor. For usage details of the MPI on coprocessors, see documentation for the Intel MPI Library, available in the Intel Software Documentation Library. For details of building MPI applications that use Intel MKL, see Using ScaLAPACK and Cluster FFT on Intel Xeon Phi Coprocessors.

Intel MKL functionality offers different levels of support for Intel MIC Architecture:

- Optimized
- Supported

Please see the Intel MKL Release Notes for details.

<table>
<thead>
<tr>
<th>Optimization Notice</th>
</tr>
</thead>
</table>

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Automatic Offload provides performance improvements with fewer changes to the code than Compiler Assisted Offload. If you are executing a function on the host CPU, Intel MKL running in the Automatic Offload mode may offload part of the computations to one or multiple Intel Xeon Phi coprocessors without you explicitly offloading computations. By default, Intel MKL determines the best division of the work between the host CPU and coprocessors. However, you can specify a custom work division.

To enable Automatic Offload and control the division of work, use environment variables or support functions. See the *Intel MKL Reference Manual* for detailed descriptions of the support functions.

**Important**
Use of Automatic Offload does not require changes in your link line.

### Automatic Offload Controls

The table below lists the environment variables for Automatic Offload and the functions that cause similar results. See the *Intel MKL Reference Manual* for detailed descriptions of the functions. To control the division of work between the host CPU and Intel Xeon Phi coprocessors, the environment variables use a fractional measure ranging from zero to one.

<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Support Function</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MKL_MIC_ENABLE</td>
<td>mkl_mic_enable</td>
<td>Enables Automatic Offload.</td>
<td>1</td>
</tr>
<tr>
<td>OFFLOAD_DEVICES</td>
<td>None</td>
<td>OFFLOAD_DEVICES is a common setting for Intel MKL and Intel® Compilers. It specifies a list of coprocessors to be used for any offload, including Intel MKL Automatic Offload. In particular, this setting may help you to configure the environment for an MPI application to run Intel MKL in the Automatic Offload mode. If this variable is not set, all the coprocessors available on the system are used for Automatic Offload. A comma-separated list of integers, each ranging from 0 to the largest number of an Intel Xeon Phi coprocessor on the system, with the maximum of 31. Values out of this range are ignored. Moreover, if the list contains any non-integer data, the list is ignored completely as if the environment variable were not set at all. For example, if your system has 4 Intel Xeon Phi coprocessors and the value of the list is 1,3, Intel MKL uses only coprocessors 1 and 3 for Automatic Offload, and Intel MKL support functions and environment variables refer to these coprocessors as coprocessors 0 and 1.</td>
<td></td>
</tr>
<tr>
<td>Environment Variable</td>
<td>Support Function</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>OFFLOAD_ENABLE ORSL</td>
<td>None</td>
<td>Enables the mode in which Intel MKL and Intel Compilers synchronize their accesses to coprocessors. Set this variable if your application uses both Compiler Assisted and Automatic Offload but does not implement its own synchronization.</td>
<td>1</td>
</tr>
<tr>
<td>MKL_HOST_WORKDIVISION</td>
<td>mkl_mic_set_workdivision</td>
<td>Specifies the fraction of work for the host CPU to do.</td>
<td>A floating-point number ranging from 0.0 to 1.0. For example, the value could be 0.2 or 0.33. Intel MKL ignores negative values and treats values greater than 1 as 1.0.</td>
</tr>
<tr>
<td>MKL_MIC&lt;number&gt;_WORKDIVISION</td>
<td>mkl_mic_set_workdivision</td>
<td>Specifies the fraction of work to do on a specific Intel Xeon Phi coprocessor. Here &lt;number&gt; is an integer ranging from 0 to the system.</td>
<td>See MKL_HOST_WORKDIVISION</td>
</tr>
</tbody>
</table>

You can set this environment variable if Automatic Offload is enabled by the environment setting or function call.

Setting this variable to an empty value is equivalent to completely disabling Automatic Offload regardless of the value of MKL_MIC_ENABLE.

After setting this environment variable, Intel MKL support functions and environment variables refer to the specified coprocessors by their indexes in the list, starting with zero.

For more information, refer to the Intel® Compiler User and Reference Guides.
<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Support Function</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MKL_MIC_MAX_MEMORY</td>
<td>mkl_mic_set_max_memory</td>
<td>Specifies the maximum coprocessor memory reserved for Automatic Offload computations on all of the Intel Xeon Phi coprocessors on the system. Each process that performs Automatic Offload computations uses additional coprocessor memory specified by the environment variable.</td>
<td>Memory size in Kilobytes (K), megabytes (M), gigabytes (G), or terabytes (T). For example, MKL_MIC_MAX_MEMORY = 4096M limits the coprocessor memory reserved for Automatic Offload computations to 4096 megabytes or 4 gigabytes. Setting MKL_MIC_MAX_MEMORY = 4G specifies the same amount of memory in gigabytes.</td>
</tr>
<tr>
<td>MKL_MIC_&lt;number&gt;_MAX_MEMORY</td>
<td>mkl_mic_set_max_memory</td>
<td>Specifies the maximum coprocessor memory reserved for Automatic Offload computations on a specific Intel Xeon Phi coprocessor on the system. Here &lt;number&gt; is an integer ranging from 0 to the largest number of an Intel Xeon Phi coprocessor on the system, with the maximum of 31. For example, if the system has two Intel Xeon Phi coprocessors, &lt;number&gt; can be 0 or 1.</td>
<td>Memory size in Kilobytes (K), megabytes (M), gigabytes (G), or terabytes (T). For example, MKL_MIC_MAX_MEMORY = 4096M limits the coprocessor memory reserved for Automatic Offload computations to 4096 megabytes or 4 gigabytes. Setting MKL_MIC_MAX_MEMORY = 4G specifies the same amount of memory in gigabytes.</td>
</tr>
<tr>
<td>MIC_OMP_NUM_THREADS</td>
<td>mkl_mic_set_device_num_threads</td>
<td>Specifies the maximum number of threads to use for Automatic Offload computations on all the Intel Xeon Phi coprocessors on the system.</td>
<td>An integer greater than 0.</td>
</tr>
<tr>
<td>MIC_&lt;number&gt;_OMP_NUM_THREADS</td>
<td>mkl_mic_set_device_num_threads</td>
<td>Specifies the maximum number of threads to use for Automatic Offload computations on a specific Intel Xeon Phi coprocessor on the system.</td>
<td>An integer greater than 0.</td>
</tr>
<tr>
<td>Environment Variable</td>
<td>Support Function</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>OFFLOAD_REPORT</td>
<td>mkl_mic_set_offload_report</td>
<td>OFFLOAD_REPORT is a common setting for Intel MKL and Intel® Compilers. It specifies the profiling report level for any offload, including Intel MKL Automatic Offload. For more information, refer to the Intel® Compiler User and Reference Guides.</td>
<td>An integer ranging from 0 to 2: 0 - No reporting, default. 1 - The report includes: - The name of the function called in the Automatic Offload (AO) mode. - Effective work division. The value of -1 indicates that the hint, that is, the work division specified by the mkl_mic_set_workdivision function or the appropriate MKL_*_WORKDIVISION environment variable was ignored in this function call. - The time spent on the host CPU during the call. - The time spent on each available Intel Xeon Phi coprocessor during the call. 2 - In addition to the above information, the report includes: - The amounts of data transferred to and from each available coprocessor during the call.</td>
</tr>
<tr>
<td>LD_LIBRARY_PATH</td>
<td>None</td>
<td>Search path for host-side dynamic libraries.</td>
<td>Must contain the path to host-side Intel MIC Platform Software Stack libraries used by Intel MKL. The default path is /opt/intel/mic/coi/host-linux-release/lib.</td>
</tr>
<tr>
<td>MIC_LD_LIBRARY_PATH</td>
<td>None</td>
<td>Search path for coprocessor-side dynamic libraries.</td>
<td>Must contain: - The path to coprocessor-side Intel MIC Platform Software Stack libraries used by Intel MKL. The default path is /opt/intel/mic/coi/device-linux-release/lib.</td>
</tr>
</tbody>
</table>
The path to Intel MKL coprocessor-side libraries. The default path is `<mkl directory>/lib/mic`.

- Settings specified by the functions take precedence over the settings specified by the respective environment variables.
- Intel MKL interprets the values of `MKL_HOST_WORKDIVISION`, `MKL_MIC_WORKDIVISION`, and `MKL_MIC_<number>_WORKDIVISION` as guidance toward dividing work between coprocessors, but the library may choose a different work division if necessary.
- For LAPACK routines, setting the fraction of work to any value other than 0.0 enables the specified processor for Automatic Offload mode. However, Intel MKL LAPACK does not use the value specified to divide the workload. For example, setting the fraction to 0.5 has the same effect as setting the fraction to 1.0.

### Setting Environment Variables for Automatic Offload

**Important**

To use Automatic Offload:

- If you completed the Setting Environment Variables step of the Getting Started process, `MKL_MIC_ENABLE` is the only environment variable that you need to set.
- Otherwise, you must also set the `LD_LIBRARY_PATH` and `MIC_LD_LIBRARY_PATH` environment variables.

To set the environment variables for Automatic Offload mode, described in Automatic Offload Controls, use the appropriate commands in your command shell:

- For the bash shell, set the appropriate environment variable(s) as follows:

  ```bash
  export MKL_MIC_ENABLE=1
  export OFFLOAD_DEVICES=<list>
  For example: export OFFLOAD_DEVICES=1,3
  export MKL_HOST_WORKDIVISION=<value>
  For example: export MKL_HOST_WORKDIVISION=0.2
  export MKL_MIC_<number>_WORKDIVISION=<value>
  For example: export MKL_MIC_2_WORKDIVISION=0.33
  export MKL_MIC_<number>_MAX_MEMORY=<value>
  For example: export MKL_MIC_0_MAX_MEMORY=2G
  export MIC_OMP_NUM_THREADS=<value>
  ```
export MIC_<number>_OMP_NUM_THREADS=<value>

For example: export MIC_0_OMP_NUM_THREADS=240

export OFFLOAD_REPORT=<level>

For example: export OFFLOAD_REPORT=2

export LD_LIBRARY_PATH="/opt/intel/mic/coi/host-linux-release/lib:${LD_LIBRARY_PATH}"


- For the C shell (csh or tcsh), set the appropriate environment variable(s) as follows:

  setenv MKL_MIC_ENABLE 1
  setenv OFFLOAD_DEVICES <list>

  For example: setenv OFFLOAD_DEVICES 1,3
  setenv OFFLOAD_ENABLE_ORSL 1
  setenv MKL_HOST_WORKDIVISION <value>

  For example: setenv MKL_HOST_WORKDIVISION 0.2
  setenv MKL_MIC_WORKDIVISION <value>
  setenv MKL_MIC_<number>_WORKDIVISION <value>

  For example: setenv MKL_MIC_2_WORKDIVISION 0.33
  setenv MKL_MIC_MAX_MEMORY <value>
  setenv MKL_MIC_<number>_MAX_MEMORY <value>

  For example: setenv MKL_MIC_0_MAX_MEMORY 2G
  setenv MIC_<number>_OMP_NUM_THREADS <value>

For example: setenv MIC_0_OMP_NUM_THREADS 240
  setenv OFFLOAD_REPORT <level>

  For example: setenv OFFLOAD_REPORT 2

  setenv LD_LIBRARY_PATH "/opt/intel/mic/coi/host-linux-release/lib:${LD_LIBRARY_PATH}"


See Also

Automatic Offload Controls
Detailed Directory Structure of the lib/mic Directory

Compiler Assisted Offload

Compiler Assisted Offload is a method to offload computations to Intel Xeon Phi coprocessors that uses the Intel® compiler and its offload pragma support to manage the functions and data offloaded. See Intel® Compiler User and Reference Guides for more details.

Important

The Intel compilers support Intel MIC Architecture starting with version 13.
Examples of Compiler Assisted Offload

The following are examples of Compiler Assisted Offload. Please see Intel® Compiler User and Reference Guide for more details.

These examples show how to call Intel MKL from offload regions that are executed on coprocessors based on Intel MIC Architecture and how to reuse data that already exists in the memory of the coprocessor and thus minimize data transfer.

Fortran

```fortran
! Upload A and B to the card, and do not deallocate them after the
!pragma. C is uploaded and downloaded back, but the allocated memory
!is retained
!DEC$ ATTRIBUTES OFFLOAD : MIC :: SGEMM
!DEC$ OFFLOAD TARGET( MIC:0 ) IN( N ), &
!DEC$ IN( A: LENGTH( N * N ) ALLOC_IF(.TRUE.) FREE_IF(.FALSE.)), &
!DEC$ IN( B: LENGTH( N * N ) ALLOC_IF(.TRUE.) FREE_IF(.FALSE.)), &
!DEC$ INOUT( C: LENGTH( N * N ) ALLOC_IF(.TRUE.) FREE_IF(.FALSE.))
CALL SGEMM( 'N', 'N', N, N, N, 1.0, A, B, N, 1.0, C, N )

! Change C here

! Reuse A and B on the card, and upload the new C. Free all the
!memory on the card
!DEC$ ATTRIBUTES OFFLOAD : MIC :: SGEMM
!DEC$ OFFLOAD TARGET( MIC:0 ) IN( N ), &
!DEC$ NOCOPY( A: LENGTH( N * N ) ALLOC_IF(.FALSE.) FREE_IF(.TRUE.)), &
!DEC$ NOCOPY( B: LENGTH( N * N ) ALLOC_IF(.FALSE.) FREE_IF(.TRUE.)), &
!DEC$ INOUT( C: LENGTH( N * N ) ALLOC_IF(.FALSE.) FREE_IF(.TRUE.))
CALL SGEMM( 'N', 'N', N, N, N, 1.0, A, B, N, -1.0, C, N )
```

C

```c
/* Upload A and B to the card, and do not deallocate them after the pragma.
 * C is uploaded and downloaded back, but the allocated memory is retained. */
#pragma offload target(mic:0) \
    in(A: length(matrix_elements) alloc_if(1) free_if(0)) \
    in(B: length(matrix_elements) alloc_if(1) free_if(0)) \
    in(transa, transb, N, alpha, beta) \
    inout(C:length(matrix_elements) alloc_if(1) free_if(0))
{ 
    sgemm(&transa, &transb, &N, &alpha, A, &N, B, &N, 
         &beta, C, &N);
}

/* Change C here */

/* Reuse A and B on the card, and upload the new C. Free all the memory on
 * the card. */
#pragma offload target(mic:0) \
    nocopy(A: length(matrix_elements) alloc_if(0) free_if(1)) \
    nocopy(B: length(matrix_elements) alloc_if(0) free_if(1)) \
    in(transa, transb, N, alpha, beta) \
    inout(C:length(matrix_elements) alloc_if(0) free_if(1))
{ 
    sgemm(&transa, &transb, &N, &alpha, A, &N, B, &N, 
         &beta, C, &N);
}
```

See Also

Intel® Software Documentation Library for Intel® Compiler User and Reference Guides
Linking for Compiler Assisted Offload

Intel MKL provides both static and dynamic libraries for coprocessors based on Intel MIC Architecture, but the Single Dynamic Library is unavailable for the coprocessors.

See Selecting Libraries to Link with for libraries to list on your link line in the simplest case.

See Detailed Directory Structure of the lib/mic Directory for a full list of libraries provided in the <mkl directory>/lib/mic directory.

You can link either static or dynamic host-side libraries and either static or dynamic coprocessor-side libraries independently.

To run applications linked dynamically with the host-side and coprocessor-side libraries, perform the Setting Environment Variables step of the Getting Started process. In addition to other environment variables, it sets:

- **LD_LIBRARY_PATH** to contain `<mkl directory>/lib/intel64`
- **MIC_LD_LIBRARY_PATH** to contain `<mkl directory>/lib/mic`

To make Intel MKL functions available on the coprocessor side, provide the `-offload-attribute-target=mic` option on your link line.

**Important**
Because Intel MKL provides both LP64 and ILP64 interfaces, ensure that the host and coprocessor-side executables use the same interface or cast all 64-bit integers to 32-bit integers (or vice-versa) before calling coprocessor-side functions in your application.

The following examples illustrate linking for compiler assisted offload to Intel Xeon Phi coprocessors.

The examples use a `.f` (Fortran) source file and Intel® Fortran Compiler. C/C++ users should instead specify a `.cpp` (C++) or `.c` (C) file and replace `ifort` with `icc`.

If you successfully completed the Setting Environment Variables step of the Getting Started process, you can omit the `-I$MKLROOT/include` parameter in these examples:

- **Static linking of myprog.f, host-side and coprocessor-side libraries for parallel Intel MKL using LP64 interface:**

  ```
  ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
  -Wl,--start-group $MKLROOT/lib/intel64/libmkl_intel_lp64.a
  $MKLROOT/lib/intel64/libmkl_intel_thread.a
  $MKLROOT/lib/intel64/libmkl_core.a -Wl,--end-group
  -openmp -lpthread -lm
  -offload-option,mic,compiler,"-Wl,--start-group $MKLROOT/lib/mic/libmkl_intel_lp64.a
  $MKLROOT/lib/mic/libmkl_intel_thread.a $MKLROOT/lib/mic/libmkl_core.a
  -Wl,--end-group"
  ```

  or

  ```
  ifort myprog.f -offload-attribute-target=mic -static-intel -mkl
  ```

- **Dynamic linking of myprog.f, host-side and coprocessor-side libraries for parallel Intel MKL using LP64 interface:**

  ```
  ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
  -L$MKLROOT/lib/intel64
  -lmkl_intel_lp64 -lmkl_intel_thread
  -lmkl_core -openmp -lpthread -lm
  -offload-option,mic,compiler,"-L$MKLROOT/lib/mic -lmkl_intel_lp64 -lmkl_intel_thread
  -lmkl_core"
  ```

  or

  ```
  ifort myprog.f -offload-attribute-target=mic -l intel -mkl
  ```
ifort myprog.f -offload-attribute-target=mic -mkl

• Static linking of myprog.f, host-side and coprocessor-side libraries for parallel Intel MKL using ILP64 interface:

    ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
                  -Wl,--start-group $MKLROOT/lib/intel64/libmkl_intel_ilp64.a
                  $MKLROOT/lib/intel64/libmkl_intel_thread.a
                  $MKLROOT/lib/intel64/libmkl_core.a -Wl,--end-group
                  -openmp -lpthread -lm
                  -offload-option,mic,compiler,"-Wl,--start-group
                  $MKLROOT/lib/mic/libmkl_intel_ilp64.a $MKLROOT/lib/mic/libmkl_intel_thread.a
                  $MKLROOT/lib/mic/libmkl_core.a -Wl,--end-group"

• Dynamic linking of myprog.f, host-side and coprocessor-side libraries for parallel Intel MKL using ILP64 interface:

    ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
                  -L$MKLROOT/lib/intel64
                  -lmkl_intel_ilp64 -lmkl_intel_thread
                  -lmkl_core -openmp -lpthread -lm
                  -offload-option,mic,compiler,"-L$MKLROOT/lib/mic -lmkl_intel_ilp64
                  -lmkl_intel_thread -lmkl_core"

• Static linking of myprog.f, host-side and coprocessor-side libraries for sequential version of Intel MKL using LP64 interface:

    ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
                  -Wl,--start-group $MKLROOT/lib/intel64/libmkl_intel_lp64.a
                  $MKLROOT/lib/intel64/libmkl_sequential.a
                  $MKLROOT/lib/intel64/libmkl_core.a -Wl,--end-group -lm
                  -offload-option,mic,compiler,"-Wl,--start-group $MKLROOT/lib/mic/libmkl_intel_lp64.a
                  $MKLROOT/lib/mic/libmkl_sequential.a $MKLROOT/lib/mic/libmkl_core.a -Wl,--end-group"

• Dynamic linking of myprog.f, host-side and coprocessor-side libraries for sequential version of Intel MKL using LP64 interface:

    ifort myprog.f -I$MKLROOT/include -offload-attribute-target=mic
                  -L$MKLROOT/lib/intel64
                  -lmkl_intel_lp64 -lmkl_sequential -lmkl_core -lm
                  -offload-option,mic,compiler,"-L$MKLROOT/lib/mic -lmkl_intel_lp64
                  -lmkl_sequential -lmkl_core"

See Also
Linking Your Application with the Intel® Math Kernel Library
Linking with System Libraries
Using the Link-line Advisor

Using Automatic Offload and Compiler Assisted Offload in One Application

You can use Automatic Offload and Compiler Assisted Offload in the same application. However, to avoid oversubscription of computational resources of the coprocessors, synchronize Intel MKL and Intel Compiler accesses to coprocessors using either of these techniques:

• In your code, manually synchronize #pragma offload regions and calls of Intel MKL functions that support Automatic Offload.
• Set the OFFLOAD_ENABLE_ORSL environment variable to 1 to enable automatic synchronization.
Running Intel MKL on an Intel Xeon Phi Coprocessor in Native Mode

Some applications can benefit from running on Intel Xeon Phi coprocessors in native mode. In this mode, the application runs directly on a coprocessor and its Linux* operating system without being offloaded from a host system. To run on Intel MIC Architecture in the native mode, an application requires minimal changes to the source code.

Because in the native mode the code runs exclusively on a coprocessor, binaries built for native runs contain only the code to be run on a coprocessor. Intel compilers provide a specialized option to support building applications to be run in the native mode.

To build an application that calls Intel MKL and natively run it on a coprocessor, you need to perform these high-level steps:

1. On the host system, compile and build the application using the `-mmic` option.
2. Transfer the executable and all the dynamic libraries it requires to the coprocessor:
   - The Intel MKL libraries in the `<mkl directory>/lib/mic directory`.
   - `libiomp5.so` in the `<parent product directory>/compiler/lib/mic directory`.
3. Use the Secure Shell (SSH) or Telnet protocol to execute on the coprocessor and add the paths to the dynamic libraries transferred to the coprocessor in step 2 and to the value of the `LD_LIBRARY_PATH` environment variable.
4. Set OpenMP* thread affinity and the `OMP_NUM_THREADS` environment variable.
5. Execute just as you would on a standard Linux* system.

For more information, see Intel® Compiler User and Reference Guides, available in the Intel Software Documentation Library.

See Also
- Detailed Directory Structure of the lib/mic Directory
- Improving Performance on Intel Xeon Phi Coprocessors
- Intel Software Documentation Library

Using ScaLAPACK and Cluster FFT on Intel Xeon Phi Coprocessors

Intel MKL ScaLAPACK and Cluster FFT support only Intel MPI Library on Intel Xeon Phi coprocessors.

The Intel MPI library can treat each Intel Xeon Phi coprocessor as a regular node in a cluster of processors based on Intel 64 architecture and Intel Xeon Phi coprocessors and enables a straightforward way to run an MPI application on clusters that contain both processors and coprocessors as compute nodes.

The documentation for the Intel MPI library recommends the following steps to run an MPI application on the specific Intel Xeon Phi coprocessor and the host node if the nodes are properly specified on the cluster and the network protocols and environment are properly set up:

1. Build the application for the Intel 64 architecture.
2. Build the application for the Intel MIC Architecture.
3. Launch the application from the host computer.

**NOTE**
If you need to run the application on the coprocessor only, you can alternatively launch it from the coprocessor.

For more details, check the Intel MPI Library documentation, available in the Intel Software Documentation Library.

To run a dynamically linked application natively, perform the Setting Environment Variables step of the Getting Started process. In addition to other environment variables, it sets:
● LD_LIBRARY_PATH to contain <mkl directory>/lib/intel64
● MIC_LD_LIBRARY_PATH to contain <mkl directory>/lib/mic

When building your application that uses Intel MKL ScaLAPACK or Cluster FFT, follow the linking guidelines in the Linking with ScaLAPACK and Cluster FFTs, but be aware that only Intel compiler and Intel MPI are supported, and only Intel threading layer is provided for Intel MKL. You can find a full list of Intel MKL libraries for Intel MIC architecture in Detailed Directory Structure of the lib mic Directory. Be aware that coprocessors run a Unix* operating system.

**TIP**
Use the Link-line Advisor to quickly choose the appropriate set of libraries and linker options.

**See Also**
Linking Your Application with the Intel® Math Kernel Library
Intel Software Documentation Library

**Examples of Linking with ScaLAPACK and Cluster FFT for Intel(R) Many Integrated Core Architecture**

**Examples of Linking a C Application**
These examples illustrate linking of an application for Intel MIC Architecture under the following conditions:

- The application uses Intel MKL ScaLAPACK or Cluster FFT.
- Main module is in C.
- `<path to mpi binaries>` is the path to Intel MPI binaries for Intel MIC Architecture.
- You are using the Intel® C++ Compiler.
- Your programming interface is LP64.

See the Intel MKL Release Notes for details of system requirements.

To link with ScaLAPACK for native runs on a cluster of systems based on the Intel MIC architecture, use the following link line:

```
<path to mpi binaries>/mpicc -mmic <files to link> \
   -L$MKLROOT/lib/mic \
   -lmkl_scalapack_lp64 \
   -lmkl_b lens_intelmpi lp64 \
   -lmkl_intel lp64 -lmkl_intel_thread -lmkl_core \
   -liomp5 -lpthread -lm
```

To link with Cluster FFT for native runs on a cluster of systems based on the Intel MIC architecture, use the following link line:

```
<path to mpi binaries>/mpicc -mmic <files to link> \
   -Wl,--start-group
   $MKLROOT/lib/mic/libmkl_cdft_core.a \
   $MKLROOT/lib/mic/libmkl_b lens_intelmpi lp64.a \
   $MKLROOT/lib/mic/libmkl_intel_lp64.a \
   $MKLROOT/lib/mic/libmkl_intel_thread.a \
   $MKLROOT/lib/mic/libmkl_core.a \
   -Wl,--end-group
   -liomp5 -lpthread -lm
```

**See Also**
Working with the Intel® Math Kernel Library Cluster Software
Using the Link-line Advisor
Examples of Linking a Fortran Application

These examples illustrate linking of an application for Intel MIC Architecture under the following conditions:

- The application uses Intel MKL ScaLAPACK or Cluster FFT.
- Main module is in Fortran.
- `<path to mpi binaries>` is the path to Intel MPI binaries for Intel MIC Architecture.
- You are using the Intel® Fortran Compiler.
- Your programming interface is LP64.

See the Intel MKL Release Notes for details of system requirements.

To link with ScaLAPACK for native runs on a cluster of systems based on the Intel MIC architecture, use the following link line:

```bash
<path to mpi binaries>/mpiifort -mmic <files to link> \
    -L$MKLROOT/lib/mic \
    -lmkl_scalapack_lp64 \
    -lmkl_blacs_intelmpi_lp64 \
    -lmkl_intel_lp64 -lmkl_intel_thread -lmkl_core \
    -liomp5 -lpthread -lm
```

To link with Cluster FFT for native runs on a cluster of systems based on the Intel MIC architecture, use the following link line:

```bash
<path to mpi binaries>/mpiifort -mmic <files to link> \
    -Wl,--start-group \
    $MKLROOT/lib/mic/libmkl_cdft_core.a \
    $MKLROOT/lib/mic/libmkl_blacs_intelmpi_lp64.a \
    $MKLROOT/lib/mic/libmkl_intel_lp64.a \
    $MKLROOT/lib/mic/libmkl_intel_thread.a \
    $MKLROOT/lib/mic/libmkl_core.a \
    -Wl,--end-group \
    -liomp5 -lpthread -lm
```

See Also

Working with the Intel® Math Kernel Library Cluster Software
Using the Link-line Advisor

Threading Behavior of Intel MKL on Intel MIC Architecture

To avoid performance drops caused by oversubscribing Intel Xeon Phi coprocessors, Intel MKL limits the number of threads it uses to parallelize computations:

- For native runs on coprocessors, Intel MKL uses $4 \times \text{Number-of-Phi-Cores}$ threads by default and scales down the number of threads back to this value if you request more threads and MKL_DYNAMIC is true.
- For runs that offload computations, Intel MKL uses $4 \times (\text{Number-of-Phi-Cores} - 1)$ threads by default and scales down the number of threads back to this value if you request more threads and MKL_DYNAMIC is true.
- If you request fewer threads than the default number, Intel MKL will use the requested number.

Here \textit{Number-of-Phi-Cores} is the number of cores per coprocessor.

See Also

MKL_DYNAMIC
Automatic Offload Controls
Techniques to Set the Number of Threads
Improving Performance on Intel Xeon Phi Coprocessors

To improve performance of Intel MKL on Intel Xeon Phi coprocessors, use the following tips, which are specific to Intel MIC Architecture. General performance improvement recommendations provided in Coding Techniques also apply.

Memory Allocation

Performance of many Intel MKL routines improves when input and output data reside in memory allocated with 2MB pages because this enables you to address more memory with less pages and thus reduce the overhead of translating between virtual and physical memory addresses compared to memory allocated with the default page size of 4K. For more information, refer to Intel® 64 and IA-32 Architectures Optimization Reference Manual and Intel® 64 and IA-32 Architectures Software Developer’s Manual (connect to http://www.intel.com/ and enter the name of each document in the Find Content text box).

To allocate memory with 2MB pages, you can use the mmap system call with the MAP_HUGETLB flag. You can alternatively use the libhugetlbfs library. See the white paper at http://software.intel.com/sites/default/files/Large_pages_mic_0.pdf for more information.

To enable allocation of memory with 2MB pages for data of size exceeding 2MB and transferred with offload pragmas, set the MIC_USE_2MB_BUFFERS environment variable to an appropriate value. This setting ensures that all pointer-based variables whose run-time length exceeds this value will be allocated in 2MB pages. For example, with MIC_USE_2MB_BUFFERS=64K, variables with run-time length exceeding 64 KB will be allocated in 2MB pages. For more details, see Intel® Compiler User and Reference Guides, available in the Intel Software Documentation Library.

Specifying the maximum amount of memory on a coprocessor that can be used for Automatic Offload computations typically enhances the performance by enabling Intel MKL to reserve and keep the memory on the coprocessor during Automatic Offload computations. You can specify the maximum memory by setting the MKL_MIC_MAX_MEMORY environment variable to a value such as 2 GB.

OpenMP and Threading Settings

To improve performance of Intel MKL routines, use the following OpenMP and threading settings:

- For BLAS, LAPACK, and Sparse BLAS:
  Set KMP_AFFINITY=compact,granularity=fine

- For FFT:
  Set KMP_AFFINITY=scatter,granularity=fine and use a number of threads depending on the total size of the input and output data for the transform:
  - A power of two, if the total size is less than Number-of-Phi-Cores/2 MB
  - 4*Number-of-Phi-Cores, if the total size is not less than Number-of-Phi-Cores/2 MB

  Here Number-of-Phi-Cores is the number of Intel Xeon Phi coprocessors on the system.


Data Alignment and Leading Dimensions

To improve performance of Intel MKL FFT functions, follow these recommendations:

- Align the first element of the input data on 64-byte boundaries
- For two- or higher-dimensional single-precision transforms, use leading dimensions (strides) divisible by 8 but not divisible by 16
- For two- or higher-dimensional double-precision transforms, use leading dimensions divisible by 4 but not divisible by 8

For other Intel MKL function domains, use general recommendations for data alignment.
See Also
Examples of Compiler Assisted Offload
Intel Software Documentation Library
Configuring Your Integrated Development Environment to Link with Intel(R) Math Kernel Library

Configuring the Eclipse* IDE CDT to Link with Intel MKL

This section explains how to configure the Eclipse* Integrated Development Environment (IDE) C/C++ Development Tools (CDT) to link with Intel® Math Kernel Library (Intel® MKL).

**TIP**
After configuring your CDT, you can benefit from the Eclipse-provided code assist feature. See Code/Context Assist description in the CDT Help for details.

To configure your Eclipse IDE CDT to link with Intel MKL, you need to perform the steps explained below. The specific instructions for performing these steps depend on your version of the CDT and on the tool-chain/compiler integration. Refer to the CDT Help for more details.

To configure your Eclipse IDE CDT, do the following:

1. Open **Project Properties** for your project.
2. Add the Intel MKL include path, that is, `<mkl directory>/include`, to the project's include paths.
3. Add the Intel MKL library path for the target architecture to the project's library paths. For example, for the Intel® 64 architecture, add `<mkl directory>/lib/intel64`.
4. Specify the names of the Intel MKL libraries to link with your application. For example, you may need the following libraries: `mkl_intel_lp64`, `mkl_intel_thread`, `mkl_core`, and `iomp5`.

**NOTE**
Because compilers typically require library names rather than file names, omit the "lib" prefix and "a" or "so" extension.

See Also
Selecting Libraries to Link with Linking in Detail
Intel® Optimized LINPACK Benchmark for Linux® OS

Intel® Optimized LINPACK Benchmark is a generalization of the LINPACK 1000 benchmark. It solves a dense (real*8) system of linear equations (Ax=b), measures the amount of time it takes to factor and solve the system, converts that time into a performance rate, and tests the results for accuracy. The generalization is in the number of equations (N) it can solve, which is not limited to 1000. It uses partial pivoting to assure the accuracy of the results.

Do not use this benchmark to report LINPACK 100 performance because that is a compiled-code only benchmark. This is a shared-memory (SMP) implementation which runs on a single platform. Do not confuse this benchmark with:

- MP LINPACK, which is a distributed memory version of the same benchmark.
- LINPACK, the library, which has been expanded upon by the LAPACK library.

Intel provides optimized versions of the LINPACK benchmarks to help you obtain high LINPACK benchmark results on your genuine Intel processor systems more easily than with the High Performance Linpack (HPL) benchmark.

Additional information on this software, as well as on other Intel® software performance products, is available at http://www.intel.com/software/products/.

Contents of the Intel® Optimized LINPACK Benchmark

The Intel Optimized LINPACK Benchmark for Linux® OS contains the following files, located in the ./.benchmarks/linpack/ subdirectory of the Intel® Math Kernel Library (Intel® MKL) directory:

<table>
<thead>
<tr>
<th>File in ./benchmarks/linpack/</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>xlinpack_xeon32</td>
<td>The 32-bit program executable for a system based on Intel® Xeon® processor or Intel® Xeon® processor MP with or without Streaming SIMD Extensions 3 (SSE3).</td>
</tr>
<tr>
<td>xlinpack_xeon64</td>
<td>The 64-bit program executable for a system with Intel Xeon processor using Intel® 64 architecture. This program may accelerate execution by using Intel® Xeon Phi™ coprocessors if they are available on the system.</td>
</tr>
<tr>
<td>xlinpack_mic</td>
<td>The 64-bit program executable for a native run on an Intel Xeon Phi coprocessor.</td>
</tr>
</tbody>
</table>
### File in ./benchmarks/linpack/

<table>
<thead>
<tr>
<th>File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>runme_xeon32</td>
<td>A sample shell script for executing a pre-determined problem set for xlinpack_xeon32.</td>
</tr>
<tr>
<td>runme_xeon64</td>
<td>A sample shell script for executing a pre-determined problem set for xlinpack_xeon64.</td>
</tr>
<tr>
<td>runme_xeon64_ao</td>
<td>A sample shell script for executing a pre-determined problem set for xlinpack_xeon64. The script enables acceleration by offloading computations to Intel Xeon Phi coprocessors available on the system.</td>
</tr>
<tr>
<td>runme_mic</td>
<td>A sample shell script for executing a pre-determined problem set for xlinpack_mic.</td>
</tr>
<tr>
<td>lininput_xeon32</td>
<td>Input file for a pre-determined problem for the runme_xeon32 script.</td>
</tr>
<tr>
<td>lininput_xeon64</td>
<td>Input file for a pre-determined problem for the runme_xeon64 script.</td>
</tr>
<tr>
<td>lininput_xeon64_ao</td>
<td>Input file for a pre-determined problem for the runme_xeon64_ao script.</td>
</tr>
<tr>
<td>lininput_mic</td>
<td>Input file for a pre-determined problem for the runme_mic script.</td>
</tr>
<tr>
<td>help.lpk</td>
<td>Simple help file.</td>
</tr>
<tr>
<td>xhelp.lpk</td>
<td>Extended help file.</td>
</tr>
</tbody>
</table>

These files are not available immediately after installation and appear as a result of execution of an appropriate runme script.

<table>
<thead>
<tr>
<th>File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lin_xeon32.txt</td>
<td>Result of the runme_xeon32 script execution.</td>
</tr>
<tr>
<td>lin_xeon64.txt</td>
<td>Result of the runme_xeon64 script execution.</td>
</tr>
<tr>
<td>lin_xeon64_ao.txt</td>
<td>Result of the runme_xeon64_ao script execution.</td>
</tr>
<tr>
<td>lin_mic.txt</td>
<td>Result of the runme_mic script execution.</td>
</tr>
</tbody>
</table>

### See Also

**High-level Directory Structure**

**Running the Software**

To obtain results for the pre-determined sample problem sizes on a given system, type one of the following, as appropriate:

```
./runme_xeon32
./runme_xeon64
./runme_xeon64_ao
./runme_mic
```

To run the software for other problem sizes, see the extended help included with the program. Extended help can be viewed by running the program executable with the `-e` option:

```
./xlinpack_xeon32 -e
./xlinpack_xeon64 -e
./xlinpack_mic -e
```
The pre-defined data input files `lininput_xeon32`, `lininput_xeon64`, `lininput_xeon64_ao`, and `lininput_mic` are provided merely as examples. Different systems have different numbers of processors or amounts of memory and thus require new input files. The extended help can be used for insight into proper ways to change the sample input files.

Each input file requires at least the following amount of memory:

- `lininput_xeon32`: 2 GB
- `lininput_xeon64`: 16 GB
- `lininput_xeon64_ao`: 8 GB
- `lininput_mic`: 8 GB

If the system has less memory than the above sample data input requires, you may need to edit or create your own data input files, as explained in the extended help.

The Intel Optimized LINPACK Benchmark determines the optimal number of threads to use. To run a different number, you can set the `OMP_NUM_THREADS` or `MKL_NUM_THREADS` environment variable inside a sample script. If you run the Intel Optimized LINPACK Benchmark without setting the number of threads, it defaults to the number of physical cores.

### Optimization Notice

Intel’s compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

Notice revision #20110804

### Known Limitations of the Intel® Optimized LINPACK Benchmark

The following limitations are known for the Intel Optimized LINPACK Benchmark for Linux® OS:

- Intel Optimized LINPACK Benchmark is threaded to effectively use multiple processors. So, in multi-processor systems, best performance will be obtained with the Intel® Hyper-Threading Technology turned off, which ensures that the operating system assigns threads to physical processors only.
- If an incomplete data input file is given, the binaries may either hang or fault. See the sample data input files and/or the extended help for insight into creating a correct data input file.

### Intel® Optimized MP LINPACK Benchmark for Clusters

#### Overview of the Intel Optimized MP LINPACK Benchmark

The Intel® Optimized MP LINPACK Benchmark for Clusters (Intel® Optimized MP LINPACK Benchmark) is based on modifications and additions to High-Performance LINPACK (HPL) 2.1 (http://www.netlib.org/benchmark/hpl) from Innovative Computing Laboratories (ICL) at the University of Tennessee, Knoxville. The Intel Optimized MP LINPACK Benchmark can be used for TOP500 runs (see http://www.top500.org). To use the benchmark you need be familiar with HPL usage. The Intel Optimized MP LINPACK Benchmark provides some additional enhancements designed to make the HPL usage more convenient and to use Intel® Message-Passing Interface (MPI) settings that may enhance performance. The `.benchmarks/mp_linpack` directory adds techniques to minimize search times frequently associated with long runs.

The Intel® Optimized MP LINPACK Benchmark implements the Massively Parallel (MP) LINPACK benchmark using HPL code. It solves a random dense system of linear equations ($Ax=b$) in `real*8` precision, measures the amount of time it takes to factor and solve the system, converts that time into a performance rate, and
tests the results for accuracy. You are not limited to solving a number of equations $N$ equal to 1000 because the implementation can be generalized to solve any size system of equations that meets the restrictions imposed by the MPI implementation chosen. The benchmark uses proper random number generation technique and full row pivoting to ensure the accuracy of the results.

Do not use this benchmark to report LINPACK 100 performance. Do not confuse this benchmark with:

- LINPACK, the library, which has been expanded upon by the LAPACK library.
- Intel Optimized LINPACK Benchmark, which is a shared memory (SMP) version of the same benchmark. While the Intel Optimized MP LINPACK Benchmark can be run on both a single node and a cluster, the Intel Optimized LINPACK Benchmark can only be run on a single node.

Intel provides optimized versions of the LINPACK benchmarks to help you obtain high LINPACK benchmark results on your systems based on genuine Intel processors more easily than with the standard HPL benchmark. Use the Intel Optimized MP LINPACK Benchmark to benchmark your cluster. The prebuilt binaries require Intel\textsuperscript{\textregistered} MPI library be installed on the cluster. The run-time version of Intel MPI is free and can be downloaded from http://www.intel.com/software/products/.

The Intel package includes software developed at the University of Tennessee, Knoxville, ICL, and neither the University nor ICL endorse or promote this product. Although HPL 2.1 is redistributable under certain conditions, this particular package is subject to the Intel MKL license.

Intel MKL has introduced a new hybrid build functionality into MP LINPACK, while continuing to support the previous, non-hybrid build. The term hybrid refers to special optimizations added to take advantage of mixed OpenMP*/MPI parallelism.

If you want to use one MPI process per node and to achieve further parallelism by means of OpenMP, use the hybrid build. In general, the hybrid build is useful when the number of MPI processes per core is less than one. If you want to rely exclusively on MPI for cross-node parallelism and use one MPI process per core, use the non-hybrid build.

In addition to supplying certain hybrid prebuilt binaries, Intel MKL supplies some hybrid prebuilt libraries for Intel\textsuperscript{\textregistered} MPI to take advantage of the additional OpenMP optimizations.

To enable you to offload computations from recent Intel\textsuperscript{\textregistered} Xeon\textsuperscript{\textregistered} processors to between zero and eight Intel\textsuperscript{\textregistered} Xeon Phi\textsuperscript{\texttrademark} coprocessors, Intel MKL supplies a hybrid offload binary. Because you can run only a few MPI processes on a single node, use this binary in hybrid mode and not in non-hybrid mode.

**NOTE**
If you are unsure which pre-built binary to use, start with the hybrid offload binaries, even when the system does not have any Intel Xeon Phi coprocessors. Always start with the hybrid offload binaries because they provide more optimizations than hybrid binaries.

If you want to use an MPI version other than Intel MPI, you can do so by using the MP LINPACK source code provided. You can use the source code to build a non-hybrid version that may be used in a hybrid mode, but it would be missing some of the optimizations added to the hybrid version.

Non-hybrid builds are the default of the source code makefiles provided. In some cases, the use of the hybrid mode is required for external reasons. If you have a choice, the hybrid offload code may be faster. To use the non-hybrid code in a hybrid mode, use the threaded version of Intel MKL BLAS, link with a thread-safe MPI (for example: use the -mt_mpi option with Intel MPI library), and call the MPI\_init\_thread() function so that MPI is thread-safe.

Intel MKL provides prebuilt binaries that are linked against Intel MPI libraries either statically or dynamically.

**NOTE**
Performance of statically and dynamically linked prebuilt binaries may be different. The performance of both depends on the version of Intel MPI you are using.

You can build binaries statically linked against a particular version of Intel MPI by yourself.
Intel's compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

Notice revision #20110804

Usage Modes of Intel Optimized MP LINPACK Benchmark for Intel® Xeon Phi™ Coprocessors

Intel MKL supports Intel® Xeon Phi™ coprocessors in these modes:

- Native
- Hybrid Offload

For details of the Native mode, see Using Intel® Math Kernel Library on Intel® Xeon Phi™ Coprocessors.

The Hybrid Offload mode combines use of different parallelization methods and offloading computations to coprocessors. In this mode, the host processor uses fewer cores for MPI than the total number of physical cores, also uses OpenMP* or POSIX threads, and offloads chunks of the problem to the Intel Xeon Phi coprocessor.

Native mode is required to run MPI processes directly on the Intel Xeon Phi coprocessors. If the MPI processes run solely on the Intel® Xeon® processors, the coprocessors are used in an offload mode.

In many cases, the host Intel Xeon processor has more memory than the Intel Xeon Phi coprocessor. Therefore, the MPI processes have access to more memory when run on the host processors than on the coprocessors.

HPL code is homogeneous by nature: it requires that each MPI process runs in an environment with similar CPU and memory constraints. If for some reason, one node is twice as powerful as another node, in the past you could balance this only by running two MPI processes on the faster node.

Intel MKL now supports heterogeneous Intel Optimized MP LINPACK Benchmark. Heterogeneity means that Intel MKL supports a data distribution that can be balanced to the performance requirements of each node if there is enough memory on that node to support any additional work. The Intel Optimized MP LINPACK Benchmark supports:

- Intra-node heterogeneity,
  where a node includes different processing units with different compute capabilities. To use intra-node heterogeneity, where work is shared between the Intel Xeon processors and Intel Xeon Phi coprocessors, use the hybrid offload techniques.
- Inter-node heterogeneity,
  where the nodes themselves can differ. For information on how to configure Intel MKL to use the inter-node heterogeneity, see Heterogeneous Intel Optimized MP LINPACK Benchmark.

To maximize performance, increase the memory on the host processor or processors (64 GB per coprocessor is ideal) and run a large problem and large block-size. Such runs offload pieces of work to the coprocessors. Although this method increases the PCIe bus traffic, it is worthwhile for solving a problem that is large enough.

If the amount of memory on the host processor is small, you might get the best performance by running natively instead of offloading.
## Contents of the Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark includes the entire HPL 2.1 distribution, but with modifications to several files, and files specific to the Intel Optimized MP LINPACK Benchmark. All the files are located in the `./benchmarks/mp_linpack/` subdirectory of the Intel MKL directory. Files specific to the Intel Optimized MP LINPACK Benchmark are listed below.

<table>
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<th>Directory/File in &lt;mkl directory&gt;/benchmarks/mp_linpack/</th>
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<td>Make.ia32</td>
<td>Sample architecture makefile for processors using the IA-32 architecture and Linux OS.</td>
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<td>Make.intel64</td>
<td>Sample architecture makefile for processors using the Intel® 64 architecture and Linux OS.</td>
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<td>Make.mic</td>
<td>Sample architecture makefile for native runs on Intel® Xeon Phi™ coprocessors.</td>
</tr>
<tr>
<td>HPL.dat</td>
<td>A duplicate of <code>testing/ptest/HPL.dat</code> in the top-level directory.</td>
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### Prebuilt executables for simple performance testing.

- **bin_intel/ia32/xhpl_ia32**: Prebuilt binary for the IA-32 architecture and Linux OS. Statically linked against Intel® MPI.
- **bin_intel/ia32/xhpl_ia32_dynamic**: Prebuilt binary for the IA-32 architecture and Linux OS. Dynamically linked against Intel® MPI.
- **bin_intel/intel64/xhpl_intel64**: Prebuilt binary for the Intel® 64 architecture and Linux OS. Statically linked against Intel® MPI.
- **bin_intel/intel64/xhpl_intel64_dynamic**: Prebuilt binary for the Intel® 64 architecture and Linux OS. Dynamically linked against Intel® MPI.
- **bin_intel/intel64/xhpl_offload_intel64**: Prebuilt binary for first generation Intel® Core™ i3/Intel® Core™ i5/Intel® Core™ i7 and later processors, offload mode, and Linux OS. This binary is statically linked against Intel® MPI. The binary accelerates execution by offloading computations to Intel Xeon Phi coprocessors if they are available on the system and is optimized for hybrid offloads.
- **bin_intel/intel64/xhpl_offload_intel64_dynamic**: Prebuilt binary for first generation Intel® Core™ i3/Intel® Core™ i5/Intel® Core™ i7 and later processors, offload mode, and Linux OS. This binary is dynamically linked against Intel® MPI. The binary accelerates execution by offloading computations to Intel Xeon Phi coprocessors if they are available on the system and is optimized for hybrid offloads.
- **bin_intel/mic/xhpl_mic**: Prebuilt binary for native runs on Intel Xeon Phi coprocessors. Statically linked against Intel® MPI.
- **bin_intel/mic/xhpl_mic_dynamic**: Prebuilt binary for native runs on Intel Xeon Phi coprocessors. Dynamically linked against Intel® MPI.
- **bin_intel/ia32/xhpl_hybrid_ia32**: Prebuilt hybrid binary for the IA-32 architecture and Linux OS. Statically linked against Intel® MPI.
- **bin_intel/ia32/xhpl_hybrid_ia32_dynamic**: Prebuilt hybrid binary for the IA-32 architecture and Linux OS. Dynamically linked against Intel® MPI.
## Directory/File in `<mkl directory>/benchmarks/mp_linpack/`

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<td>Prebuilt hybrid binary for the Intel® 64 architecture and Linux OS. Statically linked against Intel® MPI.</td>
</tr>
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<td>bin_intel/intel64/</td>
<td>Prebuilt hybrid binary for the Intel® 64 architecture and Linux OS. Dynamically linked against Intel® MPI.</td>
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<td>bin_intel/mic/xhpl_hybrid_mic</td>
<td>Prebuilt hybrid binary for native runs on Intel Xeon Phi coprocessors. Statically linked against Intel® MPI.</td>
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## Prebuilt libraries

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<td>Prebuilt library with the hybrid version of MP LINPACK for the IA-32 architecture and Intel MPI.</td>
</tr>
<tr>
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## Run scripts and examples of input files

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<td>Sample run script for the IA-32 architecture and a pure MPI binary statically linked against Intel MPI.</td>
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<td>Sample run script for the IA-32 architecture and a pure MPI binary dynamically linked against Intel MPI.</td>
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<td>bin_intel/ia32/HPL_serial.dat</td>
<td>Example of an MP LINPACK benchmark input file for a pure MPI binary and the IA-32 architecture.</td>
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<td>bin_intel/ia32/runme_hybrid_ia32</td>
<td>Sample run script for the IA-32 architecture and a hybrid binary statically linked against Intel MPI.</td>
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<tr>
<td>bin_intel/intel64/runme_intel64</td>
<td>Sample run script for the Intel® 64 architecture and a pure MPI binary statically linked against Intel MPI.</td>
</tr>
<tr>
<td>runme_intel64.</td>
<td></td>
</tr>
<tr>
<td>bin_intel/intel64/runme_intel64_dynamic</td>
<td>Sample run script for the Intel® 64 architecture and a pure MPI binary dynamically linked against Intel MPI.</td>
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<tr>
<td>runme_intel64.</td>
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<td>bin_intel/intel64/runme_intel64_ao</td>
<td>Sample run script for the Intel® 64 architecture and an offload binary statically linked against Intel MPI.</td>
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<td>bin_intel/intel64/HPL_serial.dat</td>
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<td>Example of an MP LINPACK benchmark input file for a hybrid binary and</td>
<td><code>bin_intel/intel64/ HPL_hybrid.dat</code></td>
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<tr>
<td>the Intel® 64 architecture.</td>
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<tr>
<td>Sample run script for native runs on Intel Xeon Phi</td>
<td><code>bin_intel/mic/runme_hybrid_mic</code></td>
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<tr>
<td>coprocessors and a hybrid binary statically linked against Intel MPI.</td>
<td><code>bin_intel/mic/ runme_hybrid_mic_dynamic</code></td>
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<td>Example of an MP LINPACK benchmark input file for a hybrid binary and</td>
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<td>native runs on Intel Xeon Phi coprocessors.</td>
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</tr>
<tr>
<td>Sample utility that tests the DGEMM speed across the cluster.</td>
<td><code>nodeperf.c</code></td>
</tr>
</tbody>
</table>

‡ For a list of supported versions of the Intel MPI Library, see system requirements in the Intel MKL Release Notes.

See Also

High-level Directory Structure

Compile Options Specific to the Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark has some additional compile options available over the standard HPL 2.1 distribution. These new options are:

ASYOUGO: Provides non-impacting performance information while runs proceed. There are only a few outputs and this information does not impact performance. This can be useful for runs that otherwise can execute for hours without providing any information.

ASYOUGO2: Provides additional performance information at a modest performance cost by intercepting every DGEMM call.

ASYOUGO2_DISPLAY: Displays the performance of all the significant DGEMM calls in the run.

ENDEARLY: Displays performance hints and then terminates the run early.

FASTSWAP: Inserts the LAPACK-optimized DLASWP into the HPL code. You can experiment with this to determine best results.

HYBRID: Establishes the Hybrid OpenMP/MPI mode of MP LINPACK, enabling the use of threaded Intel MKL and prebuilt MP LINPACK hybrid libraries.

**CAUTION**

Use this option only with an Intel® compiler and the Intel® MPI library version 3.1 or higher.
Building the Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark contains a few sample architecture makefiles, which you can edit to fit your configuration. Specifically:

- Set TOPdir to the directory where the Intel Optimized MP LINPACK Benchmark is being built.
- (Optional) Set MPI variables: MPdir, MPinc, and MPlib.
- Specify the location of Intel MKL and of files to be used (LAdir, LAinc, LAlib).
- Adjust compiler and compiler/linker options.
- Specify the architecture by setting the architecture parameter arch for the make command:
  - ia32 - for MPI processes to run on a 32-bit host processor.
  - intel64 - for MPI processes to run on a 64-bit host processor and use the Intel MKL hybrid offload methodology if Intel Xeon Phi coprocessors are available on the cluster.
  - mic - for MPI processes to run only on the Intel Xeon Phi coprocessors.

In this case, the makefile creates pure native mode binaries. Note that this option is limited by the size of memory on the coprocessors. For more details, see MP LINPACK Usage Modes for Intel Xeon Phi Coprocessors.

- By default, the non-hybrid version of MP LINPACK is built. To build a different version, set the version parameter for the make command to hybrid or offload, as appropriate.

  For example:
  ```
  make arch=intel64 version=offload install
  ```

The makefile creates the binary in the bin/<arch> subdirectory of your mp_linpack directory (for example, bin/intel64).

The makefiles contain common values for some sample cases, such as Linux systems based on the Intel® 64 architecture. To change these values, you must be familiar with building an HPL and picking appropriate values for the variables in the makefiles.

Ease-of-use Command-line Parameters

The Intel Optimized MP LINPACK Benchmark supports command-line parameters for HPL that help you to avoid making small changes in the HPL.dat input files every time you do a new run.

Placeholders in this command line illustrate these parameters:

```bash
./xhpl -n <problem size> -m <memory size in Mbytes> -b <block size> -p <grid row dimn> -q <grid column dimn>
```

For more command-line parameters, see Heterogeneous Intel Optimized MP LINPACK Benchmark.

If you want to run for \( N=10000 \) on a 1x3 grid, execute this command, provided that the other parameters in HPL.dat are correct:

```bash
$ ./xhpl -n 10000 -p 1 -q 3
```

By using the m parameter you can scale by the memory size instead of the problem size. The m parameter only refers to the size of the matrix storage and not to the coprocessor memory size or other buffers. So if you want to use matrices that fit in 50000 Mbytes with \( NB=1024 \) on 16 nodes, 32 nodes, and 128 nodes, execute these commands:

```bash
$ ./xhpl -m 50000 -b 1024 -p 4 -q 4
$ ./xhpl -m 50000 -b 1024 -p 4 -q 8
$ ./xhpl -m 50000 -b 1024 -p 8 -q 16
```
Heterogeneous Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark supports both inter-node and intra-node heterogeneity. Only the hybrid offload version of the prebuilt binaries supports node-to-node heterogeneity.

Intel MKL achieves heterogeneous support by distributing the matrix data unequally between the nodes. You do not need to run a different number of MPI processes on the faster nodes. Heterogeneous support works by running only one MPI process per node and assigning more work to the more powerful nodes. The heterogeneous factor command-line parameter $f$ controls the amount of work to be assigned to the more powerful nodes:

```
$ ./xhpl -n 100000 -b 1024 -p 8 -q 16 -f <heterogeneous factor>
```

The heterogeneous factor does not need to be an integer. If the heterogeneous factor is 2.5, roughly 2.5 times the work will be put on the more powerful nodes. The heterogeneous factor is an important tuning parameter. The more work you put on the more powerful nodes, the more memory you might be wasting on the other nodes. Intel MKL achieves load balance by distributing the work unevenly. You can balance for speed or balance for memory, but not both. If your cluster includes many different types of nodes, you may need multiple heterogeneous factors.

Suppose you have a cluster with 32 GB per node, but some of the nodes are twice as fast, so you put twice as much work on them. Because they only have 32 GB per node as well, all the other nodes must be treated as 16 GB nodes, and effectively waste half the memory. Note that wasting memory might require a smaller problem size, which lowers the overall performance.

Let $P$ be the number of rows and $Q$ the number of columns in your processor grid ($P\times Q$). The work must be homogeneous within each processor column because vertical operations, such as pivoting, are synchronizing operations.

When there are two different types of nodes, use MPI to process all the faster nodes first, and make sure the "PMAP process mapping" (line 9) of HPL.dat is set to 1, for Column-major mapping. Because all the nodes must be the same within a process column, the number of faster nodes must always be a multiple of $P$, and you can specify the faster nodes by setting the number of process columns $C$ for the faster nodes with the $c$ command-line parameter:

```
$ ./xhpl -n 100000 -b 1024 -p 8 -q 16 -f <heterogeneous factor> -c <number of faster processor columns>
```

Use both $f$ and $c$ command-line parameters together. The $-f 1.0 -c 0$ setting returns you to the default homogeneous behavior.

To understand how to choose the problem size $N$ for a heterogeneous run, first consider a homogeneous system, where you might choose $N$ as follows:

$$N \sim= \sqrt{\text{Memory Utilization} \times P \times Q \times \text{Memory Size in GBytes} / 8}$$

$\text{Memory Utilization}$ is usually around 0.8 for homogeneous Intel Xeon processor systems. With Intel Xeon Phi coprocessors involved, $\text{Memory Utilization}$ is probably around 0.7 due to extra buffers needed for communication.

On a heterogeneous system, you might apply a different formula for $N$ for each "cluster" of nodes that are the same and take the minimum $N$ involved. Suppose you have a cluster with only one heterogeneous factor $F$ and the number of processor columns (out of the total $Q$) in the group with that heterogeneous factor equal to $C$. That group contains $P\times C$ nodes. First compute the sum of the parts: $S = F\times P\times C + P\times (Q-C)$. Note that $S=P\times Q$, $F=1$, and $C=Q$ on a homogeneous system. So take $N$ as

$$N \sim= \sqrt{\text{Memory Utilization} \times P \times Q \times ((F\times P\times C)/S) \times \text{Memory Size in GBytes} / 8}$$

or simply scale down the value of $N$ for the homogeneous system by $\sqrt{F\times P\times C/S}$.

**Example**

Suppose the cluster has 100 nodes each having 64 GB of memory, and 20 of the nodes are 2.7 times as powerful as the other 80. Run one MPI process per node for a total of 100 MPI processes. Assume a square processor grid $P=Q=10$, which conveniently divides up the faster nodes evenly. Normally, the HPL documentation recommends choosing a matrix size that consumes 80 percent of available memory. If $N$ is the size of the matrix, the matrix consumes $8N^2/(P\times Q)$. So a homogeneous run might look like:
Unfortunately, the HPL from Netlib runs this problem as slow as the slowest node, and all the extra performance potential from the faster nodes is lost. However, if you redistribute the matrix and run the heterogeneous Intel Optimized MP LINPACK Benchmark, you can take advantage of the faster nodes. But because some of the nodes will contain 2.7 times as much data as the other nodes, you must shrink the problem size (unless the faster nodes also happen to have 2.7 times as much memory). Instead of 0.8*64GB*100 total memory size, we have only 0.8*64GB*20 + 0.8*64GB/2.7*80 total memory, which is less than half the original space. So the problem size in this case would be 526000. If the faster nodes are faster because of the presence of Intel Xeon Phi coprocessors (intra-node heterogeneity), you might need to choose a larger block size as well (which reduces scalability to some extent). Because \( P = 10 \) and there are 20 faster nodes, two processor columns are faster. If you arrange MPI to send these nodes first to the application, the command line looks like:

```bash
$ ./xhpl -n 526000 -b 1024 -p 10 -q 10 -f 2.7 -c 2
```

The \( m \) parameter may be misleading for heterogeneous calculations, because it calculates the problem size assuming all the nodes have the same amount of data.

While it suffices to provide \( f \) and \( c \) command-line parameters if you need one heterogeneous factor, to support multiple heterogeneous factors, you must add lines to the \texttt{HPL.dat} input as explained below.

For example, if there are three different types of nodes in a cluster and you need at least two heterogeneous factors:

1. Add these lines to the end of the \texttt{HPL.dat}:

   
   ```
   1          number of heterogeneous factors
   0 3 2.7   [start_column, stop_column, heterogeneous factor for that range]
   ```

   NOTE
   Numbering of processor columns starts at 0. The start and stopping numbers must be between 0 and \( Q-1 \) (inclusive).

   You can also perform this step instead of providing the command-line parameters if you need only one heterogeneous factor.

   2. For two heterogeneous factors, change the number in the first row above from 1 to 2 and follow that line with two lines specifying the start column, stopping column, and heterogeneous factor.

   When choosing parameters for heterogeneous support in \texttt{HPL.dat}, primarily focus on the most powerful nodes. However, the larger the heterogeneous factor, the more balanced the cluster may be from a performance viewpoint, but the more imbalanced from a memory viewpoint. At some point, further performance balancing might affect the memory too much. If this is the case, try to reduce any changes done for the faster nodes (such as in block sizes). Experiment with values in \texttt{HPL.dat} carefully because wrong values may greatly hinder performance.

   When tuning on a heterogeneous cluster, do not immediately attempt a heterogeneous run, but do the following:

   1. Break the cluster down into multiple homogeneous clusters.
   2. Make heterogeneous adjustments for performance balancing. For instance, if you have two different sets of nodes where one is three times as powerful as the other, it must do three times the work.
   3. Figure out the approximate size of the problem (per node) that you can run on each piece.
   4. Do some homogeneous runs with those problem sizes per node and the final block size needed for the heterogeneous run and find the best parameters.
   5. Use these parameters for an initial heterogeneous run.
Running the Intel Optimized MP LINPACK Benchmark

See Also
Building the Intel Optimized MP LINPACK Benchmark

Running the Benchmark on One Node
To run the Intel Optimized MP LINPACK Benchmark binary on a cluster node, follow the steps below.

**NOTE**
While these instructions assume the Intel® 64 architecture, they are more widely applicable. The instructions directly apply to first generation Intel® Core™ i3/Intel® Core™ i5/Intel® Core™ i7 or later Intel® processors. For IA-32 architecture processors and for earlier Intel® 64 architecture processors, omit the `version` parameter of the `make` command. For IA-32 architecture processors, also adjust directory names and the value of the `arch` parameter.

1. Load the necessary environment variables for Intel MKL, Intel MPI, and the Intel® compiler and build the binary:
   ```bash
   <parent product directory>/bin/compilervars.sh intel64
   <mpi directory>/bin64/mpivars.sh
   <mkl directory>/bin/mklvars.sh intel64
   make arch=intel64 version=offload
   ```
2. Change directory to `bin/intel64`:
   ```bash
   /bin/intel64
   ```
   This directory contains files:
   - `xhpl` - the Intel® 64 architecture binary.
   - `HPL.dat` - the HPL input data set.
3. Execute the binary for a small test run:
   ```bash
   ./xhpl
   ```
4. Modify the `HPL.dat` file to match the memory on the host processor by increasing the value in line 6 before `Ns`:
   - For 16 GB: 12000 Ns
   - For 32 GB: 56000 Ns
   - For 64 GB: 83000 Ns
   In general, you can compute the memory required to store the matrix (which does not count numerous buffers) as $8 \times N \times N / (P \times Q)$ bytes, where $N$ is the problem size, and $P$ and $Q$ are the process grids in `HPL.dat`. HPL documentation generally recommends choosing a problem size that fills 80% of memory, but you can sometimes use more.
5. Execute the binary again and take note of the new result.
   ```bash
   ./xhpl
   ```
   For specifics of running hybrid offload binaries, see *Running Hybrid Offload Binaries*.

See Also
Notational Conventions
Building the Intel Optimized MP LINPACK Benchmark
Expanding the Benchmark to Two or More Nodes

Expanding the Benchmark to Two or More Nodes
To run the Intel Optimized MP LINPACK Benchmark on multiple nodes, you need to use MPI and either modify the `HPL.dat` or use command-line parameters as explained in this section.
NOTE
While these instructions assume the Intel® 64 architecture, they are more widely applicable. The
instructions directly apply to first generation Intel® Core™ i3/Intel® Core™ i5/Intel® Core™ i7 or later
Intel® processors. For IA-32 architecture processors and for earlier Intel® 64 architecture processors,
omit the version parameter of the make command. For IA-32 architecture processors, also adjust
directory names and the value of the arch parameter.

To expand runs of the Intel Optimized MP LINPACK Benchmark to more nodes, perform these steps:

1. Load the necessary environment variables for Intel MKL, Intel MPI, and the Intel® compiler and build
   the binary:

   ```
   <parent product directory>/bin/compilervars.sh intel64
   <mpi directory>/bin64/mpivars.sh
   <mkl directory>/bin/mklvars.sh intel64
   make arch=intel64 version=offload
   ```

2. Change directory to bin/intel64:

   ```
   cd <mkl directory>/benchmarks/mp_linpack/bin/intel64
   ```

   This directory contains files:
   - `xhpl` - the Intel® 64 architecture binary.
   - `HPL.dat` - the HPL input data set.

3. In the HPL.dat file, set the problem size N to 10000. Because this setting is for a test run, the problem
   size should be small.

4. In the HPL.dat file, set the parameters Ps and Qs so that Ps * Qs equals the number of nodes. For
   example, for 2 nodes, set Ps to 1 and Qs to 2. It is easier to achieve optimal result if Ps = Qs, so
   choose them as close to each other as possible so that Ps ≤ Qs.

The resulting HPL.dat file for 2 nodes is as follows:

```
HPLinpack benchmark input file
Innovative Computing Laboratory, University of Tennessee
HPL.out output file name (if any)
6 device out (6=stdout,7=stderr,file)
1 # of problems sizes (N)
10000 Ns
1 # of NBs
1280 NBs
1 PMAP process mapping (0=Row-,1=Column-major)
1 # of process grids (P x Q)
1 Ps
2 Qs
16.0 threshold
1 # of panel fact.
2 PFACTs (0=left, 1=Crout, 2=Right)
1 # of recursive stopping criterium
4 NBMINs (> 1)
1 # of panels in recursion
2 NDIVs
1 # of recursive panel fact.
1 RFACTs (0=left, 1=Crout, 2=Right)
1 # of broadcast
0 BCASTs (0=1rg,1=1rM,2=2rg,3=2rM,4=Lng,5=LnM)
1 # of lookahead depth
1 DEPTHS (>0)
0 SWAP (0=bin-exch,1=long,2=mix)
1 swapping threshold
1 L1 in (0=transposed,1=no-transposed) form
1 U in (0=transposed,1=no-transposed) form
0 Equilibration (0=no,1=yes)
8 memory alignment in double (> 0)
```
The resulting **HPL.dat** file for 4 nodes is as follows:

```
HPLinpack benchmark input file
Innovative Computing Laboratory, University of Tennessee
HPL.out      output file name (if any)
           device out (6=stdout,7=stderr,file)
       # of problems sizes (N)
     10000     Ns
       1 # of NBs
      1280     NBs
       1   PMAP process mapping (0=Row-,1=Column-major)
       1 # of process grids (P x Q)
       2 Ps
       2 Qs
   16.0 threshold
       1 # of panel fact
       2 PFACTs (0=left, 1=Crout, 2=Right)
       1 # of recursive stopping criterium
       4 NBMINs (> 1)
       1 # of panels in recursion
       2 NDIVs
       1 # of recursive panel fact.
       1 RFACTs (0=left, 1=Crout, 2=Right)
       1 # of broadcast
       0 BCASTs (0=1rg,1=1rM,2=2rg,3=2rM,4=Lng,5=LnM)
       1 # of lookahead depth
       1 DEPTHs (> 0)
       0 SWAP (0=bin-exch,1=long,2=mix)
       1 swapping threshold
       1 L1 in (0=transposed,1=no-transposed) form
       1 U  in (0=transposed,1=no-transposed) form
       0 Equilibration (0=no,1=yes)
       8 memory alignment in double (> 0)
```

Alternatively, launch with `-n`, `-p`, `-q` parameters and leave the HPL.dat file as is.

**5.** Run the **xhpl** binary under MPI control on two nodes:

```
mpirun --perhost 1 -n 2 -hosts Node1,Node2 \
   -genv MIC_LD_LIBRARY_PATH $MIC_LD_LIBRARY_PATH \
   -genv LD_LIBRARY_PATH $LD_LIBRARY_PATH ./xhpl
```

**6.** Rerun the HPL test increasing the size of the problem until the matrix size uses about 80% of the available memory. To do this, either modify `Ns` in HPL.dat or use the `-m` command-line parameter.

For specifics of running hybrid offload binaries, see [Running Hybrid Offload Binaries](#).

---

**See Also**

- Notational Conventions
- Building the Intel Optimized MP LINPACK Benchmark
- Running the Benchmark on One Node
- Improving Performance of Your Cluster
- Ease-of-use Command-line Parameters

**Running Hybrid Offload Binaries**

Hybrid offload binaries of the Intel Optimized MP LINPACK Benchmark inform you how many Intel Xeon Phi coprocessors are detected during the run. The output early prints a line like this:

```
Number of Intel Xeon Phi coprocessors: 1
```

**NOTE**

This number counts only one Intel Xeon Phi coprocessor per MPI process.
If Intel Xeon Phi coprocessors are available on your cluster and you expect offloading to occur, but the number printed is zero, it is likely that the correct compiler environment was not loaded. Specifically, check whether the `LD_LIBRARY_PATH` environment variable contains shared libraries `libcoi_host.so.0` and `libscif.so.0`, which are installed by the Intel® Manycore Platform Software Stack (Intel® MPSS).

When running the Intel Optimized MP LINPACK Benchmark, you can use the standard Intel MKL environment variables to adjust the behavior of your runs. However not all the environment variables are available for the hybrid offload binaries, which use a different set of environment variables.

### Optimization Notice

Intel's compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

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### See Also

- Usage Modes of Intel Optimized MP LINPACK Benchmark for Intel® Xeon Phi™ Coprocessors
- Running the Benchmark on One Node
- Expanding the Benchmark to Two or More Nodes

### Improving Performance of Your Cluster

While it is relatively easy to get high performance of the HPL test on a single node, it is more complicated in a cluster. To achieve high performance of the test in a cluster, follow these steps, provided all the needed installations are done on each node:

1. Reboot all nodes.
2. Ensure all nodes are in identical conditions.
   
   To do this, run single-node Stream and HPL LINPACK or the Intel MKL program `nodeperf` on every node. Ensure results are within 2% of each other (problem size must be large enough depending on memory size and CPU speed). Investigate nodes with low performance for hardware/software problems.
3. Check that your cluster interconnects are working. Run a test over the complete cluster using an MPI test for bandwidth and latency. The IMB and Microway* Linkchecker tests of Intel MPI are two of many benchmarking methods that can be useful for this step.
4. Run an HPL benchmark on pairs of two or four nodes and ensure results are within 4% of each other. The problem size must be large enough depending on the memory size and CPU speed (for example, refer here).
5. Run a small HPL workload over the complete cluster to ensure correctness.
6. Increase the problem size and run the real test load. Rerun at the real size at least three times.
7. In case of problems go back to step 2.

Each step is important, so skipping a step like 4, you can waste a lot of time.

Before making a heterogeneous inter-node run, always run its homogeneous equivalent first. If you are using Intel Xeon Phi coprocessors in an offload mode for intra-node heterogeneity, first run on the Intel Xeon processors alone.
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Notice revision #20110804

See Also
Expanding the Benchmark to Two or More Nodes
Heterogeneous Intel Optimized MP LINPACK Benchmark

More Details of the Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark does Gaussian elimination with row pivoting to compute an LU decomposition of the matrix. If $P$ is a permutation matrix representing row pivots, then $PA = LU$ where $L$ is a lower unit triangular matrix and $U$ is an upper triangular matrix. The algorithm is blocked to increase cache reuse of the data. The sequential algorithm closest to the Intel Optimized MP LINPACK Benchmark is DGETRF from LAPACK or PDGETRF from ScaLAPACK, referred to by the generic name *GETRF. However, *GETRF retains $L$, which is not necessary in the Intel Optimized MP LINPACK Benchmark. A system of equations $Ax = b$ can be solved with *GETRF by performing these steps:

1. Compute $PA = LU$
2. Solve $Ly = Pb$ for $y$
3. Solve $Ux = y$ for $x$

$L$ to the left can be discarded if $b$ is replaced with $y$ above while going through the problem. This saves a forward solve at the end (which is not so critical), and it means that as long as you do an LU decomposition on the column-augmented system $[A|b]$, when doing pivots you can skip pivoting to the left while using a right-looking algorithm.

**NOTE**
While it is acceptable in the Intel Optimized MP LINPACK Benchmark to skip pivoting to the left, the LAPACK and ScaLAPACK *GETRF algorithms must add pivoting to the left if step 2 might be used later.

*GETRF makes several BLAS calls. Assuming $N$ is the problem size and $NB$ is the column block size used in the blocking above, then as long as $N$ is sufficiently greater than $NB$, most of the floating-point operations (FLOPs) are found in *GEMM. Some FLOPs may also be present in *TRSM. Although other BLAS calls may be necessary, these are the performance critical functions. *GETRF does computation in one of three spots: *GEMM, *TRSM, and a local LU factorization.

*GEMM overwrites $C$ with
\[ \alpha \cdot \text{op}(A) \cdot \text{op}(B) + \beta \cdot C. \]
\( \alpha \) and \( \beta \) are both scalars, and $A$, $B$, and $C$ are matrices. \( \text{op}(A) \) denotes $A$ or the transpose of $A$ and similarly for \( \text{op}(B) \). \( \text{op}(A) \) is an $m \times k$ matrix, \( \text{op}(B) \) is a $k \times n$ matrix, and $C$ is an $m \times n$ matrix.

Assuming that $N$ is the global problem size and that the matrix is distributed on a 2-dimensional (2D) block cyclic mapping on a $P$ by $Q$ processor grid with the block size $NB$, initial values of $m$, $n$, and $k$ for the first few *GEMM calls are $m \approx N/P$, $n \approx N/Q$, and $k = NB$.

The number of FLOPs executed in *GEMM for each block iteration starts off at approximately $2*N*N*NB/(P*Q)$. The size of each *GEMM may decrease, depending on whether the node in question owns the previous block row or block column.
*TRSM solves a triangular system of equations of size \(NB\) by \(NB\), with typically \(N/Q\) solution vectors to compute. It has roughly \(NB^2(N/Q)\) FLOPs. So, as long as \(N \gg P*NB\), there is more work in *GEMM than in *TRSM.

Additionally, each iteration does a local LU-factorization that starts at the size \(N/P\) by \(NB\). Although the row pivoting along the entire column has to be done, the computation is the same as factoring an \(NBxNB\) matrix, which is approximately \(2*NB^2*NB/3\) FLOPs. If \(N \gg P*NB\), there are fewer FLOPs in this computation than in *TRSM.

HPL requires row pivoting, which, while it does not involve FLOPs, can still be time consuming. It is not acceptable to replace the random matrix generator of HPL with a matrix that requires less pivoting (for example, a diagonally dominant matrix).

It is also necessary to get the data around the 2D \(P \times Q\) grid since each node needs this data to do the work for row pivoting. Each node in the \(P \times Q\) grid can be represented as the pair \((i, j)\) where \(0 \leq i < P\), and \(0 \leq j < Q\).

The algorithm involves a horizontal broadcast and a vertical broadcast across the grid.

The horizontal broadcast (which contains pivot information and the \(A\) matrix of the above *GEMM) is usually ring broadcast along \(Q\) nodes. For example, node \((2,3)\) has to get data to every other node in the block row given by \((2, j)\). The reason for using a ring broadcast, as opposed to a tree broadcast, is that horizontal motion in the grid can often be overlapped with other operations. The broadcast itself consumes time, but some of this effect can be hidden, depending on the input parameters.

The vertical broadcast (which contains the \(B\) matrix of the above *GEMM) is usually a tree broadcast along \(P\) nodes because processor columns must be synchronized. In many HPL configurations, \(P \leq 2Q\) is chosen.

For details of broadcasting in HPL, see www.netlib.org/benchmark/hpl/algorithm.html#bcast.

The other communication is the pivoting itself.

The offload portion of the code is typically some piece of the *GEMM or *TRSM because they have the highest ratio of FLOPs to data and data must move across the PCIe bus.

The fastest way to offload *GEMM is to send some portion of \(A\) and \(B\) to the coprocessor and have the coprocessor return \(C\) (assuming that \(\beta\) was zero) in an Intel Xeon Phi coprocessor native *DGEMM call.

\(NB\) must be larger than is required for Intel\(^\text{®}\) Xeon\(^\text{®}\) processors alone. Choosing 400 for \(NB\) offers no acceleration through offloading. However, choosing a value larger than 960 for \(NB\) has proven to offer considerable acceleration.

Large values of \(NB\) require extra memory on the host processor and coprocessor. If this memory is low, the problem size \(N\) does not satisfy the inequality \(N \gg NB\). In that event, it is better not to use the offload version of the Intel Optimized MP LINPACK Benchmark.

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**Configuring the Hybrid Offload Version of the Intel Optimized MP LINPACK Benchmark**

The most significant parameters in **HPL.dat** are \(N\), \(NB\), \(P\) and \(Q\). Specify them as follows, as well as some other parameters:

- \(P\) and \(Q\) - the number of rows and columns in the process grid, respectively.

\(P*Q\) must be the number of MPI processes that HPL is using.
For the hybrid offload version of the Intel Optimized MP LINPACK Benchmark, keep \( P \) and \( Q \) roughly the same size.

**NOTE**
This setting is different from settings recommended for most HPL implementations, which usually recommend to choose \( P < Q \) and possibly with the 1:4 ratio.

- **NB** - block size of the data distribution.
  
The table below shows recommended values of \( NB \) for processors based on Intel\(^\circ\) microarchitecture code named Sandy Bridge or Ivy Bridge and for different numbers of Intel Xeon Phi coprocessors. The values may vary and depend on the PCI Express settings and performance of main memory.

<table>
<thead>
<tr>
<th>No coprocessors</th>
<th>1 coprocessor</th>
<th>2 coprocessors</th>
<th>3 coprocessors</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>960</td>
<td>1024</td>
<td>1200</td>
</tr>
</tbody>
</table>

- **\( N \)** - the problem size:
  
  - For homogeneous runs, choose \( N \) divisible by \( NB*\text{LCM}(P,Q) \), where \( \text{LCM} \) is the least common multiple of the two numbers.
  
  - For heterogeneous runs, refer to [Heterogeneous Intel Optimized MP LINPACK Benchmark](#).

Note that increasing \( N \) usually increases performance, but the size of \( N \) is bounded by memory.

- Other parameters.
  
  To use Intel MKL BPUSH algorithm for horizontal broadcast, in line 23 of `HPL.dat`, set the `BCASTs` parameter to 6.

---

### Environment Variables for the Hybrid Offload

The table below lists Intel MKL environment variables to control runs of the Intel Optimized MP LINPACK Benchmark in the hybrid offload mode. Each of these environment variables has a default value. Use them with hybrid builds of the benchmark.

**NOTE**
While these environment variables impact performance of the hybrid offload binaries, they do not impact performance of other binaries. Environment variables for automatic offload, listed in [Automatic Offload Controls](#), do not impact performance or behavior of the hybrid offload binaries.

<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
</table>
| HPL_LARGEPAGE        | Defines the memory mapping to be used for both the Intel Xeon processor and Intel Xeon Phi coprocessors. | 0 or 1:  
  - 0 - normal memory mapping, default.  
  - 1 - memory mapping with large pages (2 MB per page mapping). It may increase performance. |
| HPL_LOG              | Controls the level of detail for the HPL output. | An integer ranging from 0 to 2:  
  - 0 - no log is displayed (printed).  
  - 1 - only one root node displays a log, exactly the same as the \text{ASYOUGO} option provides. |
<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HPL_HOST_CORE, HPL_HOST_NODE</strong></td>
<td>Specifies cores or Non-Uniform Memory Access (NUMA) nodes to be used. <strong>HPL_HOST_NODE</strong> requires NUMA mode to be enabled. You can check whether it is enabled by the <code>numactl --hardware</code> command. The default behavior is autodetection of the core or NUMA node.</td>
<td>A list of integers ranging from 0 to the largest number of a core or NUMA node in the cluster and separated as explained in example 3.</td>
</tr>
<tr>
<td><strong>HPL_SWAPWIDTH</strong></td>
<td>Specifies width for each swap operation.</td>
<td>16 or 32. The default is 16.</td>
</tr>
<tr>
<td><strong>HPL_MIC_DEVICE</strong></td>
<td>Specifies Intel Xeon Phi coprocessor(s) to be used. All available Intel Xeon Phi coprocessors are used by default. <strong>NOTE</strong> To avoid oversubscription of resources that might occur if you use multiple MPI processes per node, set this environment variable to specify which coprocessors each MPI process should use.</td>
<td>A comma-separated list of integers, each ranging from 0 to the largest number of an Intel Xeon Phi coprocessor on the node.</td>
</tr>
<tr>
<td><strong>HPL_PNUMMICS</strong></td>
<td>Specifies the number of Intel Xeon Phi coprocessors to be used. The <strong>HPL_MIC_DEVICE</strong> environment variable takes precedence over <strong>HPL_PNUMMICS</strong>, and the value of <strong>HPL_PNUMMICS</strong> is ignored if you set <strong>HPL_MIC_DEVICE</strong>. The default behavior is autodetection of the number of coprocessors.</td>
<td>An integer ranging from 0 to the number of Intel Xeon Phi coprocessors in the node. If the value is 0, the core ignores all Intel Xeon Phi coprocessors.</td>
</tr>
</tbody>
</table>
| **HPL_MIC_CORE, HPL_MIC_NODE** | Specifies which CPU core will be used for an Intel Xeon Phi coprocessor. Each Intel Xeon Phi coprocessor needs a dedicated CPU core. By setting these variables for an Intel Xeon Phi coprocessor, you reserve:  
- **HPL_MIC_CORE** - a specific core.  
- **HPL_MIC_NODE** - one of the cores on the specified NUMA node. | An integer ranging from 0 to the largest number of a core or NUMA node for the coprocessor. Can be provided in a comma-separated list, each integer corresponding to one coprocessor. |
<table>
<thead>
<tr>
<th>Environment Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPL_MIC_NUMCORES</td>
<td>Number of cores to be used for an Intel Xeon Phi coprocessor. All the</td>
<td>An integer ranging from 1 to the number of cores of the</td>
</tr>
<tr>
<td></td>
<td>coprocessor cores are used by default, which produces best performance.</td>
<td>coprocessor.</td>
</tr>
<tr>
<td></td>
<td>See example 5 for details.</td>
<td></td>
</tr>
<tr>
<td>HPL_MIC_SHAREMODE</td>
<td>Specifies whether and how an Intel Xeon Phi coprocessor is shared among</td>
<td>An integer ranging from 0 to 2:</td>
</tr>
<tr>
<td></td>
<td>two MPI processes.</td>
<td>• 0 - no sharing, default</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 1 - the lower half of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 2 - the upper half of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cores will be used for the MPI process.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPL_MIC_EXQUEUES</td>
<td>Specifies the queue size on an Intel Xeon Phi coprocessor. Using a larger</td>
<td>An integer ranging from 0 to 128. The default is 64.</td>
</tr>
<tr>
<td></td>
<td>number is typically better while it increases the memory consumption for</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the Intel Xeon Phi coprocessor.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If out of memory errors are encountered, try a lower number.</td>
<td></td>
</tr>
<tr>
<td>HPL_MIC_WIDTH</td>
<td>Computation width for Intel Xeon Phi DGEMM/DTRSM. If the Intel Xeon Phi</td>
<td>16 or 32. The default is 32.</td>
</tr>
<tr>
<td></td>
<td>coprocessor memory is insufficient, change the settings as follows:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Reduce HPL_MIC_WIDTH to 16.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. If Intel Xeon Phi coprocessor still reports a memory allocation error:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Reduce the value of the HPL_MIC_EXQUEUES environment variable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• If the node has more than two Intel Xeon Phi coprocessors, use twice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>larger P, the number of rows in the processor grid.</td>
<td></td>
</tr>
</tbody>
</table>
3. If memory allocation errors are still reported, keep reducing the problem size \( N \) until the errors are no longer reported.

You can set HPL environment variables using the \texttt{PMI\_RANK} and \texttt{PMI\_SIZE} environment variables of the Intel MPI library, and you can create a shell script to automate the process.

### Examples

<table>
<thead>
<tr>
<th>#</th>
<th>Settings</th>
<th>Behavior of the Intel Optimized MP Linpack Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nothing specified</td>
<td>xhpl uses all Intel Xeon processors and all Intel Xeon Phi coprocessors in the cluster.</td>
</tr>
<tr>
<td>2</td>
<td>\texttt{HPL_PNUMMICS=0}</td>
<td>xhpl ignores Intel Xeon Phi coprocessors and works as a regular HPL.</td>
</tr>
<tr>
<td>3</td>
<td>\texttt{HPL_MIC_DEVICE=0,2}</td>
<td>Only Intel Xeon Phi coprocessors 0 and 2 and Intel Xeon processor cores 1,2,3,8,9, and 10 are used.</td>
</tr>
<tr>
<td></td>
<td>\texttt{HPL_HOST_CORE=1-3,8-10}</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>\texttt{HPL_HOST_NODE=1}</td>
<td>Only cores on NUMA node 1 are used.</td>
</tr>
<tr>
<td>5</td>
<td>\texttt{HPL_MIC_DEVICE=0,1}</td>
<td>Only Intel Xeon Phi coprocessors 0 and 1 are used:</td>
</tr>
<tr>
<td></td>
<td>\texttt{HPL_MIC_SHAREMODE=0,2}</td>
<td>• On the coprocessor 0, all cores are used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• On the coprocessor 1, the upper half of the cores is used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For a 61-core Intel Xeon Phi coprocessor, the upper half includes cores 31-61.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>This setting is useful to share an Intel Xeon Phi coprocessor among two MPI processes for an odd number of Intel Xeon Phi coprocessors.</td>
</tr>
</tbody>
</table>

### See Also

#### Compile Options Specific to the Intel Optimized MP LINPACK Benchmark

To benchmark a cluster, follow the sequence of steps below (some of them are optional). Pay special attention to the iterative steps 3 and 4. They make a loop that searches for HPL parameters (specified in \texttt{HPL.dat}) that enable you to maximize the performance of your cluster.

1. Install HPL and make sure HPL is functional on all the nodes.
2. (Optional) Run \texttt{nodeperf.c} (included in the distribution) to see the performance of \texttt{DGEMM} on all the nodes.

Compile \texttt{nodeperf.c} with your MPI and Intel MKL. For example:

```bash
mpiicc -O3 nodeperf.c -L$MKLPATH $MKLPATH/libmkl_intel_lp64.a \ -Wl,--start-group $MKLPATH/libmkl_intel_thread.a \ $MKLPATH/libmkl_core.a -Wl,--end-group -lpthread -o nodeperf
```
Launching `nodeperf` on all the nodes is especially helpful in a very large cluster. `nodeperf` enables quick identification of a potential problem spot without numerous small runs of the Intel Optimized MP LINPACK Benchmark around the cluster in search of a bad node. It goes through all the nodes, one at a time, and reports the performance of `DGEMM` followed by the host identifier. Therefore, the higher the `DGEMM` performance, the faster that node was performing.

3. Edit `HPL.dat` to fit your cluster needs. See the HPL documentation for more information. Note, however, that you should use at least 4 nodes.

4. Make an HPL run, using compile options such as `ASYOUGO`, `ASYOUGO2`, or `ENDEARLY` to aid in your search. These options enable you to gain insight into the performance sooner than HPL would normally give this insight.

When doing so, follow these recommendations:

- Use the Intel Optimized MP LINPACK Benchmark, which is a patched version of HPL, to save time in the search.
  
  All the features impacting performance are optional in the Intel Optimized MP LINPACK Benchmark. That is, if you do not use the new options to reduce search time, these features are disabled. The primary purpose of the additions is to assist you in finding solutions.

  While HPL requires a long time to search for many different parameters, in the Intel Optimized MP LINPACK Benchmark, the goal is to get the best possible number.

  Given that the input is not fixed, there is a large parameter space you must search over. An exhaustive search of all possible inputs is improbably large even for a powerful cluster. The Intel Optimized MP LINPACK Benchmark optionally prints information on performance as it proceeds. You can also terminate early.

- Save time by compiling with `-DENDEARLY` `-DASYOUGO2` and using a negative threshold (do not use a negative threshold on the final run that you intend to submit as a TOP500 entry). Set the threshold in line 13 of the HPL 2.1 input file `HPL.dat`.

- If you are going to run a problem to completion, do it with `-DASYOUGO`.

5. Using the quick performance feedback, return to step 3 and iterate until you are sure that the performance is as good as possible.

**See Also**

Options to Reduce Search Time

Running large problems to completion on large numbers of nodes can take many hours. The search space for the Intel Optimized LINPACK Benchmark is also large: you can vary several parameters to improve performance, such as problem size, block size, grid layout, lookahead steps, factorization methods, and so on. You might not want to run a large problem to completion only to discover that it ran 0.01% slower than your previous best problem.

Use the following options to reduce the search time:

- `-DASYOUGO`
- `-DENDEARLY`
- `-DASYOUGO2`

Use `-DASYOUGO2` cautiously because it has a marginal performance impact. To see `DGEMM` internal performance, compile with `-DASYOUGO2` and `-DASYOUGO2_DISPLAY`. These options provide useful `DGEMM` performance information at the cost of around 0.2% performance loss.

If you want to use the original HPL, simply omit these options and recompile from scratch. To do this, try "make arch=<arch> clean_arch_all".

**-DASYOUGO**

-`DASYOUGO` gives performance data as the run proceeds. The performance always starts off higher and then drops because the LU decomposition slows down as it goes. So the `ASYOUGO` performance estimate is usually an overestimate, but it gets more accurate as the problem proceeds. The greater the lookahead step, the less accurate the first number may be. `ASYOUGO` tries to estimate where execution is in the LU decomposition...
that Intel Optimized LINPACK Benchmark performs, and this is always an overestimate as compared to \texttt{ASYOUGO2}, which measures actually achieved \texttt{DGEMM} performance. Note that the \texttt{ASYOUGO} output is a subset of the information that \texttt{ASYOUGO2} provides. Refer to the description of the \texttt{-DENDEARLY} option below for the details of the output.

\textbf{-DENDEARLY}

\texttt{-DENDEARLY} terminates the problem after a few steps, so that you can set up 10 or 20 HPL runs without monitoring them, see how they all do, and then only run the fastest ones to completion. \texttt{-DENDEARLY} assumes \texttt{-ASYOUGO}. You can define both, but it is not necessary. To avoid the residual check for a problem that terminates early, set the threshold parameter in \texttt{HPL.dat} to a negative number when testing \texttt{ENDEARLY}. It also sometimes gives more information to compile with \texttt{-ASYOUGO2} when using \texttt{-DENDEARLY}.

**Usage notes on \texttt{-DENDEARLY} follow:**

- \texttt{-DENDEARLY} stops the problem after a few iterations of \texttt{DGEMM} on the block size (the bigger the blocksize, the further it gets). It prints only five or six updates, whereas \texttt{-ASYOUGO} prints about 46 or so output elements before the problem completes.

- Performance for \texttt{-ASYOUGO} and \texttt{-DENDEARLY} always starts off at one speed, slowly increases, and then slows down toward the end (reflecting the progress of the LU decomposition). \texttt{-DENDEARLY} is likely to terminate before it starts to slow down.

- \texttt{-DENDEARLY} terminates the problem early with an HPL Error exit. It means that you need to ignore the missing residual results, which are wrong because the problem never completed. However, you can get an idea what the initial performance was, and if it is acceptable, run the problem to completion without \texttt{-DENDEARLY}. To avoid the error check, you can set the threshold parameter in \texttt{HPL.dat} to a negative number.

- Though \texttt{-DENDEARLY} terminates early, HPL treats the problem as completed and computes GFLOP rating as though the problem ran to completion. Ignore this erroneously high rating.

- The bigger the problem, the more accurately the last update that \texttt{-DENDEARLY} returns is close to what happens when the problem runs to completion. \texttt{-DENDEARLY} is a poor approximation for small problems. It is for this reason that you should use \texttt{ENDEARLY} in conjunction with \texttt{ASYOUGO2}, because \texttt{ASYOUGO2} reports actual \texttt{DGEMM} performance, which can be a closer approximation to problems just starting.

\textbf{-ASYOUGO2}

\texttt{-ASYOUGO2} gives detailed single-node \texttt{DGEMM} performance information. It captures all \texttt{DGEMM} calls (if you use Fortran BLAS) and records their data. Because of this, the routine has a marginal performance overhead. Unlike \texttt{-ASYOUGO}, which does not impact performance, \texttt{-ASYOUGO2} interrupts every \texttt{DGEMM} call to monitor its performance. You should be aware of this overhead, although for big problems, it is less than 0.2%.

A sample \texttt{ASYOUGO2} output appears as follows:

\begin{verbatim}
Col=001280 Fract=0.050 Mflops=42454.99 (DT=9.5 DF=34.1 DMF=38322.78).
\end{verbatim}

\textbf{NOTE} The values of Col, Fract, and Mflops are also produced for \texttt{ASYOUGO} and \texttt{ENDEARLY}.

In this example, the problem size is 16000 and a block size is 128. After processing 10 blocks, or 1280 columns (Col), an output was sent to the screen. Here, the fraction of columns completed (Fract) is 1280/16000=0.08. Only up to 111 outputs are printed, at various places through the matrix decomposition:

\begin{verbatim}
0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040 0.045 0.050 0.055 0.060 0.065 0.070
0.075 0.080 0.085 0.090 0.095 0.100 0.105 0.110 0.115 0.120 0.125 0.130 0.135 0.140
0.145 0.150 0.155 0.160 0.165 0.170 0.175 0.180 0.185 0.190 0.195 0.200 0.205 0.210
0.215 0.220 0.225 0.230 0.235 0.240 0.245 0.250 0.255 0.260 0.265 0.270 0.275 0.280
0.285 0.290 0.295 0.300 0.305 0.310 0.315 0.320 0.325 0.330 0.335 0.340 0.345 0.350
\end{verbatim}
However, this problem size is so small and the block size so big by comparison that as soon as it prints the value for 0.045, it was already through 0.08 fraction of the columns. On a really big problem, the fractional number is more accurate.

-DASYOUGO2 never prints more than the 112 numbers above. So, smaller problems have fewer than 112 updates, and the biggest problems have precisely 112 updates.

Mflops is an estimate based on the number of columns of the LU decomposition being completed. However, with lookahead steps, sometimes that work is not actually completed when the output is made. Nevertheless, this is a good estimate for comparing identical runs.

The three parenthesized numbers are ASYUOGO2 add-ins that impact performance. DT is the total time that processor 0 has spent in DGEMM. DF is the number of billion operations that have been performed in DGEMM by one processor. Therefore, the performance of processor 0 (in GFLOPs) in DGEMM is always DF/DT. Using the number of DGEMM FLOPs as a basis instead of the number of LU FLOPs, you get a lower bound on performance of the run by looking at DMF, which can be compared to Mflops above.

Note that when using the performance monitoring tools described in this section to compare different HPL.dat input data sets, you should be aware that the pattern of performance drop-off that LU experiences is sensitive to sizes of input data. For instance, when you try very small problems, the performance drop-off from the initial values to end values is very rapid. The larger the problem, the less the drop-off, and it is probably safe to use the first few performance values to estimate the difference between a problem size 700000 and 701000, for instance. Another factor that influences the performance drop-off is the relationship of the grid dimensions (P and Q). For big problems, the performance tends to fall off less from the first few steps when P and Q are roughly equal. You can make use of a large number of parameters, such as broadcast types, and change them so that the final performance is determined very closely by the first few steps.

Use of these tools can increase the amount of data you can test.

See Also
Optimizing the Result on a Cluster
## Language Interfaces Support, by Function Domain

The following table shows language interfaces that Intel® Math Kernel Library (Intel® MKL) provides for each function domain. However, Intel MKL routines can be called from other languages using mixed-language programming. See Mixed-language Programming with Intel® MKL for an example of how to call Fortran routines from C/C++.

<table>
<thead>
<tr>
<th>Function Domain</th>
<th>FORTRAN 77 interface</th>
<th>Fortran 90/95 interface</th>
<th>C/C++ interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Linear Algebra Subprograms (BLAS)</td>
<td>Yes</td>
<td>Yes</td>
<td>via CBLAS</td>
</tr>
<tr>
<td>BLAS-like extension transposition routines</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Sparse BLAS Level 1</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Sparse BLAS Level 2 and 3</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LAPACK routines for solving systems of linear equations</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LAPACK routines for solving least-squares problems, eigenvalue and singular value problems, and Sylvester’s equations</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Auxiliary and utility LAPACK routines</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Parallel Basic Linear Algebra Subprograms (PBLAS)</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ScaLAPACK routines</td>
<td>Yes</td>
<td></td>
<td>†</td>
</tr>
<tr>
<td>DSS/PARDISO* solvers</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Other Direct and Iterative Sparse Solver routines</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vector Mathematical Library (VML) functions</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vector Statistical Library (VSL) functions</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fourier Transform functions (FFT)</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Cluster FFT functions</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Trigonometric Transform routines</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Fast Poisson, Laplace, and Helmholtz Solver (Poisson Library) routines</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Optimization (Trust-Region) Solver routines</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Data Fitting functions</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Extended Eigensolver functions</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Support functions (including memory allocation)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

† Supported using a mixed language programming call. See Intel® MKL Include Files for the respective header file.
Include Files

The table below lists Intel MKL include files.

**NOTE**
The `.f90` include files supersede the `.f77` include files and can be used for FORTRAN 77 as well as for later versions of Fortran. However, the `.f77` files are kept for backward compatibility.

<table>
<thead>
<tr>
<th>Function domain</th>
<th>Fortran Include Files</th>
<th>C/C++ Include Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>All function domains</td>
<td>mkl.fi</td>
<td>mkl.h</td>
</tr>
<tr>
<td>BLACS Routines</td>
<td></td>
<td>mkl_blacs.h‡‡</td>
</tr>
<tr>
<td>BLAS Routines</td>
<td>blas.f90</td>
<td>mkl_blas.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_blas.fi†</td>
<td></td>
</tr>
<tr>
<td>BLAS-like Extension Transposition Routines</td>
<td>mkl_trans.fi†</td>
<td>mkl_trans.h‡</td>
</tr>
<tr>
<td>CBLAS Interface to BLAS</td>
<td></td>
<td>mkl_cblas.h‡</td>
</tr>
<tr>
<td>Sparse BLAS Routines</td>
<td>mkl_spblas.fi†</td>
<td>mkl_spblas.h‡</td>
</tr>
<tr>
<td>LAPACK Routines</td>
<td>lapack.f90</td>
<td>mkl_lapack.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_lapack.fi†</td>
<td></td>
</tr>
<tr>
<td>C Interface to LAPACK</td>
<td></td>
<td>mkl_lapacke.h‡</td>
</tr>
<tr>
<td>PBLAS Routines</td>
<td></td>
<td>mkl_pblas.h‡‡</td>
</tr>
<tr>
<td>ScaLAPACK Routines</td>
<td></td>
<td>mkl_scalapack.h‡‡</td>
</tr>
<tr>
<td>All Sparse Solver Routines</td>
<td>mkl_solver.f90</td>
<td>mkl_solver.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_solver.fi†</td>
<td></td>
</tr>
<tr>
<td>PARDISO</td>
<td>mkl_pardiso.f90</td>
<td>mkl_pardiso.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_pardiso.fi†</td>
<td></td>
</tr>
<tr>
<td>DSS Interface</td>
<td>mkl_dss.f90</td>
<td>mkl_dss.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_dss.fi†</td>
<td></td>
</tr>
<tr>
<td>RCI Iterative Solvers</td>
<td></td>
<td>mkl_rci.h‡</td>
</tr>
<tr>
<td>ILU Factorization</td>
<td>mkl_rci.fi†</td>
<td></td>
</tr>
<tr>
<td>Optimization Solver Routines</td>
<td></td>
<td>mkl_rci.h‡</td>
</tr>
<tr>
<td>Vector Mathematical Functions</td>
<td>mkl_vml.90</td>
<td>mkl_vml.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_vml.fi†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mkl_vml.f77</td>
<td></td>
</tr>
<tr>
<td>Vector Statistical Functions</td>
<td>mkl_vsl.f90</td>
<td>mkl_vsl.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_vsl.fi†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mkl_vsl.f77</td>
<td></td>
</tr>
<tr>
<td>Fourier Transform Functions</td>
<td>mkl_dfti.f90</td>
<td>mkl_dfti.h‡</td>
</tr>
<tr>
<td>Cluster Fourier Transform Functions</td>
<td>mkl_cdft.f90</td>
<td>mkl_cdft.h‡‡</td>
</tr>
<tr>
<td>Partial Differential Equations Support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function domain</td>
<td>Fortran Include Files</td>
<td>C/C++ Include Files</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Trigonometric Transforms</td>
<td>mkl_trig_transforms.f90</td>
<td>mkl_trig_transform.h†</td>
</tr>
<tr>
<td>Poisson Solvers</td>
<td>mkl_poisson.f90</td>
<td>mkl_poisson.h†</td>
</tr>
<tr>
<td>Data Fitting Functions</td>
<td>mkl_df.f90</td>
<td>mkl_df.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_df.f77</td>
<td></td>
</tr>
<tr>
<td>Extended Eigensolver Functions</td>
<td>mkl_solvers_ee.fi†</td>
<td>mkl_solvers_ee.h‡</td>
</tr>
<tr>
<td>Support functions</td>
<td>mkl_service.f90</td>
<td>mkl_service.h‡</td>
</tr>
<tr>
<td></td>
<td>mkl_service.fi†</td>
<td></td>
</tr>
<tr>
<td>Declarations for replacing memory allocation functions. See Redefining Memory Functions for details.</td>
<td></td>
<td>i_malloc.h</td>
</tr>
</tbody>
</table>

† You can use the mkl.fi include file in your code instead.
‡ You can include the mkl.h header file in your code instead.
‡‡ Also include the mkl.h header file in your code.

See Also
Language Interfaces Support, by Function Domain
Support for Third-Party Interfaces

FFTW Interface Support

Intel® Math Kernel Library (Intel® MKL) offers two collections of wrappers for the FFTW interface (www.fftw.org). The wrappers are the superstructure of FFTW to be used for calling the Intel MKL Fourier transform functions. These collections correspond to the FFTW versions 2.x and 3.x and the Intel MKL versions 7.0 and later.

These wrappers enable using Intel MKL Fourier transforms to improve the performance of programs that use FFTW without changing the program source code. See the "FFTW Interface to Intel® Math Kernel Library" appendix in the Intel MKL Reference Manual for details on the use of the wrappers.

**Important**

For ease of use, FFTW3 interface is also integrated in Intel MKL.
Tables in this section show contents of the Intel(R) Math Kernel Library (Intel(R) MKL) architecture-specific directories.

**Optimization Notice**

Intel's compilers may or may not optimize to the same degree for non-Intel microprocessors for optimizations that are not unique to Intel microprocessors. These optimizations include SSE2, SSE3, and SSSE3 instruction sets and other optimizations. Intel does not guarantee the availability, functionality, or effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-dependent optimizations in this product are intended for use with Intel microprocessors. Certain optimizations not specific to Intel microarchitecture are reserved for Intel microprocessors. Please refer to the applicable product User and Reference Guides for more information regarding the specific instruction sets covered by this notice.

Notice revision #20110804

**Detailed Structure of the IA-32 Architecture Directories**

<table>
<thead>
<tr>
<th>File</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interface layer</strong></td>
<td></td>
</tr>
<tr>
<td>libmkl_intel.a</td>
<td>Interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_blas95.a</td>
<td>Fortran 95 interface library for BLAS for the Intel® Fortran compiler</td>
</tr>
<tr>
<td>libmkl_lapack95.a</td>
<td>Fortran 95 interface library for LAPACK for the Intel Fortran compiler</td>
</tr>
<tr>
<td>libmkl_gf.a</td>
<td>Interface library for the GNU* Fortran compiler</td>
</tr>
<tr>
<td><strong>Threading layer</strong></td>
<td></td>
</tr>
<tr>
<td>libmkl_intel_thread.a</td>
<td>Threading library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_gnu_thread.a</td>
<td>Threading library for the GNU Fortran and C compilers</td>
</tr>
<tr>
<td>libmkl_pgi_thread.a</td>
<td>Threading library for the PGI* compiler</td>
</tr>
<tr>
<td>libmkl_sequential.a</td>
<td>Sequential library</td>
</tr>
<tr>
<td><strong>Computational layer</strong></td>
<td></td>
</tr>
<tr>
<td>libmkl_core.a</td>
<td>Kernel library for the IA-32 architecture</td>
</tr>
<tr>
<td>libmkl_scalapack_core.a</td>
<td>ScaLAPACK routines</td>
</tr>
<tr>
<td>libmkl_cdft_core.a</td>
<td>Cluster version of FFT functions</td>
</tr>
<tr>
<td><strong>Run-time Libraries (RTL)</strong></td>
<td></td>
</tr>
</tbody>
</table>

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### Dynamic Libraries in the `lib/ia32` Directory

<table>
<thead>
<tr>
<th>File</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>libmkl_blacs.a</td>
<td>BLACS routines for MPICH.</td>
</tr>
<tr>
<td>libmkl_blacs_intelmpi.a</td>
<td>BLACS routines for Intel MPI and MPICH2</td>
</tr>
<tr>
<td>libmkl_blacs_openmpi.a</td>
<td>BLACS routines for OpenMPI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>File</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>libmkl_rt.so</td>
<td>Single Dynamic Library</td>
</tr>
</tbody>
</table>

#### Interface layer

- **libmkl_intel.so**: Interface library for the Intel compilers
- **libmkl_gf.so**: Interface library for the GNU Fortran compiler

#### Threading layer

- **libmkl_intel_thread.so**: Threading library for the Intel compilers
- **libmkl_gnu_thread.so**: Threading library for the GNU Fortran and C compilers
- **libmkl_pgi_thread.so**: Threading library for the PGI* compiler
- **libmkl_sequential.so**: Sequential library

#### Computational layer

- **libmkl_core.so**: Library dispatcher for dynamic load of processor-specific kernel library
- **libmkl_p4.so**: Pentium® 4 processor kernel library
- **libmkl_p4p.so**: Kernel library for the Intel® Pentium® 4 processor with Intel® Streaming SIMD Extensions 3 (Intel® SSE3), including Intel® Core™ Duo and Intel® Core™ Solo processors.
- **libmkl_p4m.so**: Kernel library for processors based on the Intel® Core™ microarchitecture (except Intel® Core™ Duo and Intel® Core™ Solo processors, for which mkl_p4p.so is intended)
- **libmkl_p4m3.so**: Kernel library for the Intel® Core™ i7 processors
- **libmkl_vml_ia.so**: VML/VSL/DF default kernel for newer Intel® architecture processors
- **libmkl_vml_p4.so**: VML/VSL/DF part of Pentium® 4 processor kernel
- **libmkl_vml_p4m.so**: VML/VSL/DF for processors based on the Intel® Core™ microarchitecture
- **libmkl_vml_p4m2.so**: VML/VSL/DF for 45nm Hi-k Intel® Core™2 and Intel Xeon® processor families
- **libmkl_vml_p4m3.so**: VML/VSL/DF for the Intel® Core™ i7 processors
- **libmkl_vml_p4p.so**: VML/VSL/DF for Pentium® 4 processor with Intel SSE3
### Directory Structure in Detail

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<thead>
<tr>
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<tbody>
<tr>
<td>libmkl_vml_avx.so</td>
<td>VML/VSL/DF optimized for the Intel® Advanced Vector Extensions (Intel® AVX)</td>
</tr>
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<td>libmkl_vml_cmpt.so</td>
<td>VML/VSL/DF library for conditional numerical reproducibility</td>
</tr>
<tr>
<td>libmkl_scalapack_core.so</td>
<td>ScaLAPACK routines</td>
</tr>
<tr>
<td>libmkl_cdft_core.so</td>
<td>Cluster version of FFT functions</td>
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<td>BLACS routines for Intel MPI and MPICH2</td>
</tr>
<tr>
<td>locale/en_US/mkl_msg.cat</td>
<td>Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English</td>
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## Detailed Structure of the Intel® 64 Architecture Directories

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<td></td>
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<td>LP64 interface library for the Intel compilers</td>
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<tr>
<td>libmkl_intel_ilp64.a</td>
<td>ILP64 interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_intel_sp2dp.a</td>
<td>SP2DP interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_blas95_lp64.a</td>
<td>Fortran 95 interface library for BLAS for the Intel® Fortran compiler. Supports the LP64 interface</td>
</tr>
<tr>
<td>libmkl_blas95_ilp64.a</td>
<td>Fortran 95 interface library for BLAS for the Intel® Fortran compiler. Supports the ILP64 interface</td>
</tr>
<tr>
<td>libmkl_lapack95_lp64.a</td>
<td>Fortran 95 interface library for LAPACK for the Intel® Fortran compiler. Supports the LP64 interface</td>
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<tr>
<td>libmkl_lapack95_ilp64.a</td>
<td>Fortran 95 interface library for LAPACK for the Intel® Fortran compiler. Supports the ILP64 interface</td>
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<tr>
<td>libmkl_gf_lp64.a</td>
<td>LP64 interface library for the GNU Fortran compilers</td>
</tr>
<tr>
<td>libmkl_gf_ilp64.a</td>
<td>ILP64 interface library for the GNU Fortran compilers</td>
</tr>
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<td></td>
</tr>
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<td>Threading library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_gnu_thread.a</td>
<td>Threading library for the GNU Fortran and C compilers</td>
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<td>libmkl_pgi_thread.a</td>
<td>Threading library for the PGI compiler</td>
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<td>libmkl_sequential.a</td>
<td>Sequential library</td>
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<td>Kernel library for the Intel® 64 architecture</td>
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<td>libmkl_scalapack_lp64.a</td>
<td>ScaLAPACK routine library supporting the LP64 interface</td>
</tr>
<tr>
<td>libmkl_scalapack_ilp64.a</td>
<td>ScaLAPACK routine library supporting the ILP64 interface</td>
</tr>
<tr>
<td>libmkl_cdft_core.a</td>
<td>Cluster version of FFT functions.</td>
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<tr>
<td>libmkl_blacs_ilp64.a</td>
<td>ILP64 version of BLACS routines for MPICH.</td>
</tr>
<tr>
<td>libmkl_blacs_intelmpi_lp64.a</td>
<td>LP64 version of BLACS routines for Intel MPI and MPICH2</td>
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<tr>
<td>libmkl_blacs_intelmpi_ilp64.a</td>
<td>ILP64 version of BLACS routines for Intel MPI and MPICH2</td>
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<tr>
<td>libmkl_blacs_openmpi_lp64.a</td>
<td>LP64 version of BLACS routines supporting OpenMPI.</td>
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<tr>
<td>libmkl_blacs_openmpi_ilp64.a</td>
<td>ILP64 version of BLACS routines supporting OpenMPI.</td>
</tr>
<tr>
<td>libmkl_blacs_sgimpt_lp64.a</td>
<td>LP64 version of BLACS routines supporting SGI MPT.</td>
</tr>
<tr>
<td>libmkl_blacs_sgimpt_ilp64.a</td>
<td>ILP64 version of BLACS routines supporting SGI MPT.</td>
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<tr>
<td>libmkl_rt.so</td>
<td>Single Dynamic Library</td>
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#### Interface layer

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<thead>
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<th>File</th>
<th>Contents</th>
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<tr>
<td>libmkl_intel lp64.so</td>
<td>LP64 interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_intel ilp64.so</td>
<td>ILP64 interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_intel_sp2dp.so</td>
<td>SP2DP interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_gf lp64.so</td>
<td>LP64 interface library for the GNU Fortran compilers</td>
</tr>
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<td>libmkl_gf ilp64.so</td>
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#### Threading layer

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<td>Threading library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_gnu_thread.so</td>
<td>Threading library for the GNU Fortran and C compilers</td>
</tr>
<tr>
<td>libmkl_pgi_thread.so</td>
<td>Threading library for the PGI* compiler</td>
</tr>
<tr>
<td>libmkl_sequential.so</td>
<td>Sequential library</td>
</tr>
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#### Computational layer

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<tr>
<th>File</th>
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<tbody>
<tr>
<td>libmkl_core.so</td>
<td>Library dispatcher for dynamic load of processor-specific kernel</td>
</tr>
</tbody>
</table>
### Detailed Directory Structure of the lib/mic Directory

<table>
<thead>
<tr>
<th>File</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>libmkl_def.so</td>
<td>Default kernel library</td>
</tr>
<tr>
<td>libmkl_mc.so</td>
<td>Kernel library for processors based on the Intel® Core™ microarchitecture</td>
</tr>
<tr>
<td>libmkl_mc3.so</td>
<td>Kernel library for the Intel® Core™ i7 processors</td>
</tr>
<tr>
<td>libmkl_avx.so</td>
<td>Kernel optimized for the Intel® Advanced Vector Extensions (Intel® AVX).</td>
</tr>
<tr>
<td>libmkl_vml_def.so</td>
<td>Vector Math Library (VML)/Vector Statistical Library (VSL)/Data Fitting (DF) part of default kernels</td>
</tr>
<tr>
<td>libmkl_vml_p4n.so</td>
<td>VML/VSL/DF for the Intel® Xeon® processor using the Intel® 64 architecture</td>
</tr>
<tr>
<td>libmkl_vml_mc.so</td>
<td>VML/VSL/DF for processors based on the Intel® Core™ microarchitecture</td>
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<td>ILP64 version of BLACS routines for Intel MPI and MPICH2</td>
</tr>
<tr>
<td>locale/en_US/mkl_msg.cat</td>
<td>Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English</td>
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### Static Libraries

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<td>libmkl_intel_ilp64.a</td>
<td>ILP64 interface library for the Intel compilers</td>
</tr>
<tr>
<td>libmkl_blas95_lp64.a</td>
<td>Fortran 95 interface library for BLAS and Intel® Fortran compiler. Supports the LP64 interface.</td>
</tr>
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<td>Contents</td>
</tr>
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<td>--------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
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<td>Sequential library</td>
</tr>
<tr>
<td>libmkl_core.a</td>
<td>Core computation library</td>
</tr>
<tr>
<td>libmkl_scalapack_lp64.a</td>
<td>Static library with LP64 versions of ScaLAPACK routines</td>
</tr>
<tr>
<td>libmkl_scalapack_ilp64.a</td>
<td>Static library with ILP64 versions of ScaLAPACK routines</td>
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<td>Static library with cluster FFT functions</td>
</tr>
<tr>
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<td>Static library with LP64 versions of BLACS routines for Intel MPI</td>
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<td>Static library with ILP64 versions of BLACS routines for Intel MPI</td>
</tr>
<tr>
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<td></td>
</tr>
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<td>libmkl_ao_worker.so</td>
<td>The Intel® MIC Architecture library to implement the Automatic Offload mode</td>
</tr>
<tr>
<td>libmkl_intel_lp64.so</td>
<td>LP64 interface library for the Intel compilers</td>
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<td>Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English</td>
</tr>
<tr>
<td>locale/ja_JP/mkl_msg.cat</td>
<td>Catalog of Intel MKL messages in Japanese. Available only if the Intel® C++ Composer XE or Intel® Fortran Composer XE that includes Intel MKL provides Japanese localization. Please see the Release Notes for this information.</td>
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