Intel® Math Kernel Library for Linux*

Developer Guide

Intel® MKL 2017 - Linux*

Revision: 055

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Contents

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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. The library provides Fortran and C programming language interfaces. Intel MKL C language interfaces can be called from applications written in either C or C++, as well as in any other language that can reference a C interface.

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.
- ScaLAPACK distributed processing linear algebra routines, as well as the Basic Linear Algebra Communications Subprograms (BLACS) and the Parallel Basic Linear Algebra Subprograms (PBLAS).
- Intel MKL PARDISO (a direct sparse solver based on Parallel Direct Sparse Solver PARDISO*), an iterative sparse solver, and supporting sparse BLAS (level 1, 2, and 3) routines for solving sparse systems of equations, as well as a distributed version of Intel MKL PARDISO solver provided for use on clusters.
- 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.
- Vector Mathematics (VM) routines for optimized mathematical operations on vectors.
- Vector Statistics (VS) 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.
- Deep Neural Network (DNN) primitive functions with C language interface.

For details see the *Intel® MKL Developer Reference*.

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

NOTE
It is your responsibility when using Intel MKL to ensure that input data has the required format and does not contain invalid characters. These can cause unexpected behavior of the library.

The library requires subroutine and function parameters to be valid before being passed. While some Intel MKL routines do limited checking of parameter errors, your application should check for NULL pointers, for example.

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What's New

This Developer Guide documents Intel® Math Kernel Library (Intel® MKL) 2017 Update 2.

The Developer Guide has been updated with the following changes to the product and document enhancements:

- Coding techniques to improve performance of an application that calls Intel MKL are explained for Intel® Xeon Phi™ processor x200 product family, codenamed Knights Landing. For more details, see Coding Techniques.
- The `MKL_NUM_STRIPES` environment variable has been added to control the Intel MKL threading algorithm for `?gemm` functions. For details, see `MKL_NUM_STRIPES`.
- All Vector Mathematics functions are now threaded with Intel® Threaded Building Blocks (Intel® TBB). For more details, see Functions Threaded with Intel Threading Building Blocks.
- The instruction set architecture that Intel MKL dispatches by default has changed from Intel® Advanced Vector Extensions 2 to Intel® Advanced Vector Extensions 512. For more details, see Instruction Set Specific Dispatching on Intel® Architectures .

Additionally, minor updates have been made to fix inaccuracies in the document.

Notational Conventions

The following term is used in reference to the operating system.

Linux*	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 directory>	The installation directory that includes Intel MKL directory; for example, the directory for Intel® Parallel Studio XE Composer Edition.
<mkl directory>	The main directory where Intel MKL is installed: *<mkl directory>*=*<parent 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 Developer Reference*.
`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,
	`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 Developer Reference*, which provides *reference* information on routine functionalities, parameter descriptions, interfaces, calling syntaxes, and return values.
- The *Intel® Math Kernel Library for Linux* OS Release Notes*.

Getting Started

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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 directory>* directory.

   Check that the subdirectory of *<parent 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:

   mklvars.sh

   mklvars.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 Structure of the Intel® Math Kernel Library.
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* 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 Architecture (Intel® MIC Architecture).

Choose the script corresponding to your command shell:

Shell	Script File
C	`mklvars.csh`
Bash and Bourne (sh)	`mklvars.sh`

The scripts accept the parameters, explained in the following table:

Setting Specified	Required (Yes/No)	Possible Values	Comment

Architecture	Yes, when applicable	`ia32`
		`intel64`
		`mic`	

Use of Intel MKL Fortran modules precompiled with the Intel® Fortran compiler	No	`mod`	Supply this parameter only if you are using this compiler.
Programming interface (LP64 or ILP64)	No	`lp64`, default `ilp64`	

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:

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

In the above commands, the architecture parameter `<arch>` is one of {`ia32|intel64|mic`}.

If you have super user permissions, add the same commands to a general-systemfile 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

If an Intel MKL component that you selected during installation includes code examples, these examples are provided in a separate archive. Extract the examples from the archives before use.

For each component, the examples are grouped in subdirectories mainly by Intel MKL function domains and programming languages. For instance, the `blas` subdirectory (extracted from the `examples_core` archive) contains a makefile to build the BLAS examples and the `vmlc` subdirectory contains the makefile to build the C examples for Vector Mathematics functions. You can find examples of Automatic Offload in the `mic_ao` subdirectory (extracted from the `examples_mic` archive) and examples of Compiler Assisted Offload in the `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

Target platform	Identify the architecture of your target machine: • IA-32 or compatible • Intel® 64 or compatible **Reason:** Because Intel MKL libraries are located in directories corresponding to your particular architecture (seeArchitecture 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 Scripts to Set Environment Variables Setting Environment Variables for details).
Mathematical problem	Identify all Intel MKL function domains that you require: • BLAS • Sparse BLAS • LAPACK • PBLAS • ScaLAPACK • Sparse Solver routines • Parallel Direct Sparse Solvers for Clusters • Vector Mathematics functions (VM) • Vector Statistics functions (VS) • 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 *Intel MKL Developer Reference* 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 Intel® Math Kernel Library 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 Appendix A: 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).
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 Linking with Threading Libraries).
Number of threads	If your application uses an OpenMP* threading run-time library, determine the number of threads you want Intel MKL to use. **Reason:** By default, the OpenMP* run-time library sets the number of threads for Intel MKL. 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 Intel® Math Kernel Library Cluster Software).

Structure of the Intel® Math Kernel Library 2

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Architecture Support

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

Architecture	Location
IA-32 or compatible	*<mkl directory>*/lib/ia32_lin
Intel® 64 or compatible	*<mkl directory>*/lib/intel64_lin
Intel® Many Integrated Core Architecture (Intel® MIC Architecture)	*<mkl directory>*/lib/intel64_lin_mic

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

Directory	Contents
<mkl directory>	Installation directory of the Intel® Math Kernel Library (Intel® MKL)
Subdirectories of *<mkl directory>*	
bin	Scripts to set environmental variables in the user shell
bin/ia32	Shell scripts for the IA-32 architecture
bin/intel64	Shell scripts for the Intel® 64 architecture
benchmarks/linpack	Shared-memory (SMP) version of the LINPACK benchmark

Directory	Contents
benchmarks/mp_linpack	Message-passing interface (MPI) version of the LINPACK benchmark
benchmarks/hpcg	Intel® High Performance Conjugate Gradient Benchmark (Intel® HPCG)
examples	Source and data files for Intel MKL examples. Provided in archives corresponding to Intel MKL components selected during installation.
include	Include files for the library routines and examples
include/ia32	Fortran 95 .mod files for the IA-32 architecture and Intel® Fortran compiler
include/intel64/lp64	Fortran 95 .mod files for the Intel® 64 architecture, Intel Fortran compiler, and LP64 interface
include/intel64/ilp64	Fortran 95 .mod files for the Intel® 64 architecture, Intel Fortran compiler, and ILP64 interface
include/mic/lp64	Fortran 95 .mod files for the Intel® MIC Architecture, Intel Fortran compiler, and LP64 interface
include/mic/ilp64	Fortran 95 .mod files for the Intel® MIC Architecture, Intel Fortran compiler, and ILP64 interface
include/fftw	Header files for the FFTW2 and FFTW3 interfaces
interfaces/blas95	Fortran 95 interfaces to BLAS and a makefile to build the library
interfaces/fftw2x_cdft	MPI FFTW 2.x interfaces to the Intel MKL Cluster FFT
interfaces/fftw3x_cdft	MPI FFTW 3.x interfaces to the Intel MKL Cluster FFT
interfaces/fftw2xc	FFTW 2.x interfaces to the Intel MKL FFT (C interface)
interfaces/fftw2xf	FFTW 2.x interfaces to the Intel MKL FFT (Fortran interface)
interfaces/fftw3xc	FFTW 3.x interfaces to the Intel MKL FFT (C interface)
interfaces/fftw3xf	FFTW 3.x interfaces to the Intel MKL FFT (Fortran interface)
interfaces/lapack95	Fortran 95 interfaces to LAPACK and a makefile to build the library
lib/ia32_lin	Static libraries and shared objects for the IA-32 architecture
lib/intel64_lin	Static libraries and shared objects for the Intel® 64 architecture
lib/intel64_lin_mic	Static libraries and shared objects for the Intel® MIC Architecture
tools	Tools and plug-ins
tools/builder	Tools for creating custom dynamically linkable libraries

See Also
Notational Conventions
Using Code Examples

Layered Model Concept

Intel MKL is structured to support multiple compilers and interfaces, both serial and multi-threaded modes, different implementations of threading run-time libraries, 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.

To support threading with different compilers, you also need to use an appropriate threading run-time library (RTL). These libraries are provided by compilers and are not included in Intel MKL.

The following table provides more details of each layer.

Layer	Description
Interface Layer	This layer matches compiled code of your application with the threading and/or computational parts of the library. This layer provides: • LP64 and ILP64 interfaces. • Compatibility with compilers that return function values differently.
Threading Layer	This layer: • Provides a way to link threaded Intel MKL with supported compilers. • Enables you to link with a threaded or sequential mode of the library. This layer is compiled for different environments (threaded or sequential) and compilers (from Intel, GNU*, and PGI*).
Computational Layer	This layer accommodates multiple architectures through identification of architecture features and chooses the appropriate binary code at run time.

See Also

Using the ILP64 Interface vs. LP64 Interface
Linking Your Application with the Intel® Math Kernel Library
Linking with Threading Libraries

Linking Your Application with the Intel® Math Kernel Library 3

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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® Parallel Studio XE Composer Edition 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®Parallel Studio XE Composer Edition compiler supports the following variants of the `-mkl` compiler option:

`-mkl` or `-mkl=parallel`	to link with a certain Intel MKL threading layer depending on the threading option provided: • For `-qopenmp` the OpenMP threading layer for Intel compilers • For `-tbb` the Intel® Threading Building Blocks (Intel® TBB) threading layer
`-mkl=sequential`	to link with sequential version of Intel MKL.

`-mkl=cluster`	to link with Intel MKL cluster components (sequential) that use Intel MPI.

NOTE
The `-qopenmp` option has higher priority than `-tbb` in choosing the Intel MKL threading layer for linking.

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® compiler 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:

```
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:

- Intel LP64 interface on systems based on the Intel® 64 architecture
- Intel interface on systems based on the IA-32 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.

	Interface layer	Threading layer	Computational layer	RTL
IA-32 architecture, static linking	`libmkl_intel.a`	`libmkl_intel_thread.a`	`libmkl_core.a`	`libiomp5.so`

	Interface layer	Threading layer	Computational layer	RTL
IA-32 architecture, dynamic linking	libmkl_intel.so	libmkl_intel_thread.so	libmkl_core.so	libiomp5.so
Intel® 64 architecture, static linking	libmkl_intel_lp64.a	libmkl_intel_thread.a	libmkl_core.a	libiomp5.so
Intel® 64 architecture, dynamic linking	libmkl_intel_lp64.so	libmkl_intel_thread.so	libmkl_core.so	libiomp5.so
Intel® Many Integrated Core Architecture (Intel® MIC Architecture), static linking	libmkl_intel_lp64.a	libmkl_intel_thread.a	libmkl_core.a	libiomp5.so
Intel MIC Architecture, dynamic linking	libmkl_intel_lp64.so	libmkl_intel_thread.so	libmkl_core.so	libiomp5.so

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.

	SDL	RTL
IA-32 and Intel® 64 architectures	libmkl_rt.so	libiomp5.so[††]

[††]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 documentation directory of 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, and so on). The tool automatically generates the appropriate link line for your application.

See Also

High-level Directory Structure

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.

See the knowledge base article at http://software.intel.com/en-us/articles/mkl-command-line-link-tool for more information.

Linking Examples

See Also
Using the Link-line Advisor
Examples of Linking for Clusters

Linking on IA-32 Architecture Systems

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

Most 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=$MKLROOT/lib/ia32_lin`,
`MKLINCLUDE=$MKLROOT/include`.

> **NOTE**
> If you successfully completed the Scripts to Set Environment Variables 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 OpenMP* threaded 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 OpenMP* threaded 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 `myprog.f` and OpenMP* threaded 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 OpenMP* threaded 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 OpenMP* threaded 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
```

- Static linking of `myprog.c` and Intel MKL threaded with Intel® Threading Building Blocks (Intel® TBB), provided that the `LIBRARY_PATH` environment variable contains the path to Intel TBB library:

```
icc myprog.c -I$MKLINCLUDE -Wl,--start-group $MKLPATH/libmkl_intel.a $MKLPATH/
libmkl_tbb_thread.a $MKLPATH/libmkl_core.a -Wl,--end-group -ltbb -lstdc++
-lpthread -lm
```

- Dynamic linking of `myprog.c` and Intel MKL threaded with Intel TBB, provided that the `LIBRARY_PATH` environment variable contains the path to Intel TBB library:

```
icc myprog.c -L$MKLPATH -I$MKLINCLUDE -lmkl_intel -lmkl_tbb_thread -lmkl_core -ltbb
-lstdc++ -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 compiler

Linking on Intel(R) 64 Architecture Systems

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

Most 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=$MKLROOT/lib/intel64_lin`,
`MKLINCLUDE=$MKLROOT/include`.

> **NOTE**
> If you successfully completed the Scripts to Set Environment Variables 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 OpenMP* threaded 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 OpenMP* threaded 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
-Wl,--start-group $MKLPATH/libmkl_intel_lp64.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 supporting the LP64 interface:

```
ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
-lmkl_intel_lp64 -lmkl_sequential -lmkl_core -lpthread -lm
```

- Static linking of `myprog.f` and OpenMP* threaded Intel MKL supporting the ILP64 interface:

```
ifort myprog.f -L$MKLPATH -I$MKLINCLUDE
-Wl,--start-group $MKLPATH/libmkl_intel_ilp64.a $MKLPATH/libmkl_intel_thread.a
$MKLPATH/libmkl_core.a -Wl,--end-group -liomp5 -lpthread -lm
```

- Dynamic linking of `myprog.f` and OpenMP* threaded 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 user code `myprog.f` and OpenMP* threaded 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 OpenMP* threaded 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 OpenMP* threaded 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
```

- Static linking of `myprog.c` and Intel MKL threaded with Intel® Threading Building Blocks (Intel® TBB), provided that the `LIBRARY_PATH` environment variable contains the path to Intel TBB library:

```
icc myprog.c -L$MKLPATH -I$MKLINCLUDE -Wl,--start-group $MKLPATH/libmkl_intel_lp64.a
$MKLPATH/libmkl_tbb_thread.a $MKLPATH/libmkl_core.a -Wl,--end-group -ltbb -lstdc++
-lpthread -lm
```

- Dynamic linking of `myprog.c` and Intel MKL threaded with Intel TBB, provided that the `LIBRARY_PATH` environment variable contains the path to Intel TBB library:

```
icc myprog.c -L$MKLPATH -I$MKLINCLUDE-lmkl_intel_lp64 -lmkl_tbb_thread -lmkl_core
-ltbb -lstdc++ -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|tbb_thread|sequential}
-lmkl_core
[-liomp5] [-lpthread] [-lm] [-ldl] [-ltbb -lstdc++]
```

In the 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

To set the interface layer at run time, use the `mkl_set_interface_layer` function or the `MKL_INTERFACE_LAYER` environment variable.

Available interface layers depend on the architecture of your system.

The following table lists available interface layers for Intel® 64 architecture along with the values to be used to set each layer.

Specifying the Interface Layer for Intel® 64 Architecture

Interface Layer	Value of MKL_INTERFACE_LAYER	Value of the Parameter of mkl_set_interface_layer
Intel LP64, default	LP64	MKL_INTERFACE_LP64
Intel ILP64	ILP64	MKL_INTERFACE_ILP64
GNU* LP64	GNU,LP64	MKL_INTERFACE_LP64+MKL_INTERFACE_GNU
GNU ILP64	GNU,ILP64	MKL_INTERFACE_ILP64+MKL_INTERFACE_GNU

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

See the *Intel MKL Developer Reference* for details of the mkl_set_interface_layer function.

The following table lists available interface layers for IA-32 architecture along with the values to be used to set each layer.

Specifying the Interface Layer for IA-32 Architecture

Interface Layer	Value of MKL_INTERFACE_LAYER	Value of the Parameter of mkl_set_interface_layer
Intel, default	LP64	MKL_INTERFACE_LP64
GNU	GNU,LP64	MKL_INTERFACE_LP64+MKL_INTERFACE_GNU
	or	or
	GNU	MKL_INTERFACE_GNU

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.

Specifying the Threading Layer

Threading Layer	Value of MKL_THREADING_LAYER	Value of the Parameter of mkl_set_threading_layer
Intel threading, default	INTEL	MKL_THREADING_INTEL
Sequential mode of Intel MKL	SEQUENTIAL	MKL_THREADING_SEQUENTIAL
GNU threading†	GNU	MKL_THREADING_GNU
PGI threading†	PGI	MKL_THREADING_PGI
Intel TBB threading	TBB	MKL_THREADING_TBB

† Not supported by the SDL for Intel® Many Integrated Core Architecture.

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

See the *Intel MKL Developer Reference* 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:

Fortran	
Compiling for ILP64	`ifort -i8 -I<mkl directory>/include ...`
Compiling for LP64	`ifort -I<mkl directory>/include ...`

C or C++	
Compiling for ILP64	`icc -DMKL_ILP64 -I<mkl directory>/include ...`
Compiling for LP64	`icc -I<mkl directory>/include ...`

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:

Integer Types	Fortran	C or C++
32-bit integers	`INTEGER*4` or `INTEGER(KIND=4)`	`int`
Universal integers for ILP64/ LP64: • 64-bit for ILP64 • 32-bit otherwise	`INTEGER` without specifying `KIND`	`MKL_INT`
Universal integers for ILP64/ LP64: • 64-bit integers	`INTEGER*8` or `INTEGER(KIND=8)`	`MKL_INT64`
FFT interface integers for ILP64/ LP64	`INTEGER` without specifying `KIND`	`MKL_LONG`

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 Vector Mathematics and Vector Statistics functions, which require integer parameters to be 64-bit or 32-bit regardless of the interface:

- **Vector Mathematics:** The *mode* parameter of the 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 Developer Reference* for more information.

To better understand ILP64 interface details, see also examples.

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.x 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

Intel MKL threading layer defines how Intel MKL functions utilize multiple computing cores of the system that the application runs on. You must link your application with one appropriate Intel MKL library in this layer, as explained below. Depending on whether this is a threading or a sequential library, Intel MKL runs in a parallel or sequential mode, respectively.

In the *parallel mode*, Intel MKL utilizes multiple processor cores available on your system, uses the OpenMP* or Intel TBB threading technology, and requires a proper threading run-time library (RTL) to be linked with your application. Independently of use of Intel MKL, the application may also require a threading RTL. You should link not more than one threading RTL to your application. Threading RTLs are provided by your compiler. Intel MKL provides several threading libraries, each dependent on the threading RTL of a certain compiler, and your choice of the Intel MKL threading library must be consistent with the threading RTL that you use in your application.

The OpenMP RTL of the Intel® compiler is the `libiomp5.so` library, located under *<parent directory>*`/compiler/lib`. This RTL is compatible with the GNU* compilers (gcc and gfortran). You can find additional information about the Intel OpenMP RTL at https://www.openmprtl.org.

The Intel TBB RTL of the Intel® compiler is the `libtbb.so` library, located under *<parent directory>*`/tbb/lib`. You can find additional information about the Intel TBB RTL at https://www.threadingbuildingblocks.org.

In the *sequential mode*, Intel MKL runs unthreaded code, does not require an threading RTL, and does not respond to environment variables and functions controlling the number of threads. Avoid using the library in the sequential mode unless you have a particular reason for that, such as the following:

- Your application needs a threading RTL that none of Intel MKL threading libraries is compatible with
- Your application is already threaded at a top level, and using parallel Intel MKL only degrades the application performance by interfering with that threading
- Your application is intended to be run on a single thread, like a message-passing Interface (MPI) application

It is critical to link the application with the proper RTL. The table below explains what library in the Intel MKL threading layer and what threading RTL you should choose under different scenarios:

Application		Intel MKL		RTL Required
Uses OpenMP	**Compiled with**	**Execution Mode**	**Threading Layer**	

no	any compiler	parallel	Static linking:
			`libmkl_intel_thread.a`
			Dynamic linking:
			`libmkl_intel_thread.so`
				`libiomp5.so`

no	any compiler	parallel	Static linking:
			`libmkl_tbb_thread.a`
			Dynamic linking:
			`libmkl_tbb_thread.so`
				`libtbb.so`

no	any compiler	sequential	Static linking: `libmkl_`	none[†]

Application		Intel MKL		RTL Required
Uses OpenMP	**Compiled with**	**Execution Mode**	**Threading Layer**	

			`sequential.a`
			Dynamic linking:
			`libmkl_sequential.so`	

yes	Intel compiler	parallel	Static linking:
			`libmkl_intel_thread.a`
			Dynamic linking:
			`libmkl_intel_thread.so`
				`libiomp5.so`

yes	GNU compiler	parallel	Recommended!
			Static linking:
			`libmkl_intel_thread.a`
			Dynamic linking:
			`libmkl_intel_thread.so`
				`libiomp5.so`

yes	GNU compiler	parallel	Static linking:
			`libmkl_gnu_thread.a`
			Dynamic linking:
			`libmkl_gnu_thread.so`
				GNU OpenMP RTL

yes	PGI* compiler	parallel	Static linking:
			`libmkl_pgi_thread.a`
			Dynamic linking:
			`libmkl_pgi_thread.so`
				PGI OpenMP RTL

yes	any other compiler	parallel	Not supported. Use Intel MKL in the sequential mode.	

† For the sequential mode, add the POSIX threads library `(libpthread)` to your link line because the `libmkl_sequential.a` and `libmkl_sequential.so` libraries depend on `libpthread`.

See Also
Layered Model Concept
Notational Conventions

Linking with Computational Libraries

If you are not using the Intel MKL ScaLAPACK and Cluster Fast Fourier Transforms (FFT), you need to link your application with only one computational library, depending on the linking method:

Static Linking	Dynamic Linking
libmkl_core.a	libmkl_core.so

Computational Libraries for Applications that Use ScaLAPACK or Cluster FFT

ScaLAPACK and Cluster FFT 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 FFT.

Computational Libraries for IA-32 Architecture

Function domain	Static Linking	Dynamic Linking
ScaLAPACK †	libmkl_scalapack_core.a libmkl_core.a	libmkl_scalapack_core.so libmkl_core.so
Cluster Fourier Transform Functions†	libmkl_cdft_core.a libmkl_core.a	libmkl_cdft_core.so libmkl_core.so

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

The following table lists computational libraries for Intel® 64 or Intel® Many Integrated Core Architecture applications that use ScaLAPACK or Cluster FFT.

Computational Libraries for the Intel® 64 or Intel® Many Integrated Core Architecture

Function domain	Static Linking	Dynamic Linking
ScaLAPACK, LP64 interface‡	libmkl_scalapack_lp64.a libmkl_core.a	libmkl_scalapack_lp64.so libmkl_core.so
ScaLAPACK, ILP64 interface‡	libmkl_scalapack_ilp64.a libmkl_core.a	libmkl_scalapack_ilp64.so libmkl_core.so
Cluster Fourier Transform Functions‡	libmkl_cdft_core.a libmkl_core.a	libmkl_cdft_core.so libmkl_core.so

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

See Also

Linking with Intel MKL Cluster Software
Using the Link-line Advisor
Using the ILP64 Interface vs. LP64 Interface

Linking with Compiler Run-time Libraries

Dynamically link `libiomp5` or `libtbb` 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` or `libtbb` 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 HelmholtzSolver routines, link also the math support system library by adding "`-lm`" to the link line.

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).

The `libtbb` library relies on the compiler `libstdc++` library for C++ support. Any time `libtbb` is required, add `-lstdc++` 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:

`make target [<options>]`

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

Value	Comment
`libia32`	The builder uses static Intel MKL interface, threading, and core libraries to build a custom shared object for the IA-32 architecture.
`libintel64`	The builder uses static Intel MKL interface, threading, and core libraries to build a custom shared object for the Intel® 64 architecture.
`soia32`	The builder uses the single dynamic library `libmkl_rt.so` to build a custom shared object for the IA-32 architecture.
`sointel64`	The builder uses the single dynamic library `libmkl_rt.so` to build a custom shared object for the Intel® 64 architecture.

Value	Comment
help	The command prints Help on the custom shared object builder

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

Parameter [Values]	Description
interface = {lp64|ilp64}	Defines whether to use LP64 or ILP64 programming interfacefor the Intel 64architecture.The default value is lp64.
threading = {parallel| sequential}	Defines whether to use the Intel MKL in the threaded or sequential mode. The default value is parallel.
export = *<file name>*	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 user_example_list (no extension).
name = *<so name>*	Specifies the name of the library to be created. By default, the names of the created library is mkl_custom.so.
xerbla = *<error handler>*	Specifies the name of the object file *<user_xerbla>*.o 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 *xerbla*. If you omit this parameter, the native Intel MKL *xerbla* is used. See the description of the *xerbla* function in the Intel MKL Developer Reference on how to develop your own error handler.
MKLROOT = *<mkl directory>*	Specifies the location of Intel MKL libraries used to build the custom shared object. By default, the builder uses the Intel MKL installation directory.

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

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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

Improving Performance with Threading

Intel® Math Kernel Library (Intel® MKL) is extensively parallelized. See OpenMP* Threaded Functions and Problems and Functions Threaded with Intel® Threading Building Blocks 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.

If you are using OpenMP* threading technology, 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 OpenMP threads equal to the number of physical cores on the system.

If you are using the Intel TBB threading technology, the OpenMP threading controls, such as the `OMP_NUM_THREADS` environment variable or `MKL_NUM_THREADS` function, have no effect. Use the Intel TBB application programming interface to control the number of threads.

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

OpenMP* Threaded Functions and Problems

The following Intel MKL function domains are threaded with the OpenMP* technology:

- Direct sparse solver.
- LAPACK.

  For a list of threaded routines, see LAPACK Routines.
- Level1 and Level2 BLAS.

  For a list of threaded routines, see BLAS Level1 and Level2 Routines.

- All Level 3 BLAS and all Sparse BLAS routines except Level 2 Sparse Triangular solvers.
- All Vector Mathematics functions (except service functions).
- FFT.

  For a list of FFT transforms that can be threaded, see Threaded FFT Problems.

LAPACK Routines

In this section, `?` 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 with OpenMP*:

- Linear equations, computational routines:
  - Factorization: `?getrf`, `?getrfnpi`, `?gbtrf`, `?potrf`, `?pptrf`, `?sytrf`, `?hetrf`, `?sptrf`, `?hptrf`
  - Solving: `?dttrsb`, `?gbtrs`, `?gttrs`, `?pptrs`, `?pbtrs`, `?pttrs`, `?sytrs`, `?sptrs`, `?hptrs`, `?tptrs`, `?tbtrs`
- Orthogonal factorization, computational routines:
  `?geqrf`, `?ormqr`, `?unmqr`, `?ormlq`, `?unmlq`, `?ormql`, `?unmql`, `?ormrq`, `?unmrq`
- Singular Value Decomposition, computational routines:
  `?gebrd`, `?bdsqr`
- Symmetric Eigenvalue Problems, computational routines:
  `?sytrd`, `?hetrd`, `?sptrd`, `?hptrd`, `?steqr`, `?stedc`.
- 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 OpenMP* parallelism:
`?gesv`, `?posv`, `?gels`, `?gesvd`, `?syev`, `?heev`, `cgegs/zgegs`, `cgegv/zgegv`, `cgges/zgges`, `cggesx/zggesx`, `cggev/zggev`, `cggevx/zggevx`, and so on.

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 with OpenMP* for Intel® Core™2 Duo and Intel® Core™ i7 processors:

- Level1 BLAS:
  `?axpy`, `?copy`, `?swap`, `ddot/sdot`, `cdotc`, `drot/srot`
- 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 with OpenMP*:

- 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:

Architecture	Conditions
Intel® 64	*N* is a power of 2, $log_2(N) > 9$, the transform is double-precision out-of-place, and input/output strides equal 1.
IA-32	*N* is a power of 2, $log_2(N) > 13$, and the transform is single-precision.
	N is a power of 2, $log_2(N) > 14$, and the transform is double-precision.
Any	*N* is composite, $log_2(N) > 16$, and input/output strides equal 1.

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

Multidimensional transforms

All multidimensional transforms on large-volume data are threaded.

Functions Threaded with Intel® Threading Building Blocks

In this section, `?` stands for a precision prefix or suffix of the routine name and may have the value of `s`, `d`, `c`, or `z`.

The following Intel MKL function domains are threaded with Intel® Threading Building Blocks (Intel® TBB):

- LAPACK.

  For a list of threaded routines, see LAPACK Routines.
- Entire Level3 BLAS.
- Fast Poisson, Laplace, and Helmholtz Solver (Poisson Library).
- All Vector Mathematics functions (except service functions).
- Intel MKL PARDISO, a direct sparse solver based on Parallel Direct Sparse Solver (PARDISO*).

  For details, see Intel MKL PARDISO Steps.
- Sparse BLAS.

  For a list of threaded routines, see Sparse BLAS Routines.

LAPACK Routines

The following LAPACK routines are threaded with Intel TBB:
`?geqrf`, `?gelqf`, `?getrf`, `?potrf`, `?unmqr*`, `?ormqr*`, `?unmrq*`, `?ormrq*`, `?unmlq*`, `?ormlq*`, `?unmql*`, `?ormql*`, `?sytrd`, `?hetrd`, `?syev`, `?heev`, and `?latrd`.

A number of other LAPACK routines, which are based on threaded LAPACK or BLAS routines, make effective use of Intel TBB threading:
`?getrs`, `?gesv`, `?potrs`, `?bdsqr`, and `?gels`.

Intel MKL PARDISO Steps

Reordering and factorization steps of the solver are threaded with Intel TBB. In the solving step, call the routines sequentially.

Sparse BLAS Routines

The Sparse BLAS inspector-executor application programming interface routines `mkl_sparse_?_mv` are threaded with Intel TBB for the general compressed sparse row (CSR) and block sparse row (BSR) formats.

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 your program is parallelized by other means than Intel® OpenMP* run-time library (RTL) and Intel TBB RTL, several calls to Intel MKL may operate in a multithreaded mode at the same time and result in slow performance due to overuse of machine resources.

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

Threading model	Discussion
You parallelize the program using the technology other than Intel OpenMP and Intel TBB (for example: `pthreads` on Linux*).	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).
You parallelize the program using OpenMP directives and/or pragmas and compile the program using a non-Intel compiler.	To avoid simultaneous activities of multiple threading RTLs, link the program against the Intel MKL threading library that matches the compiler you use (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: `libmkl_sequential.a` or `libmkl_sequential.so` (see Appendix C: Directory Structure in Detail).
You thread the program using Intel TBB threading technology and compile the program using a non-Intel compiler.	To avoid simultaneous activities of multiple threading RTLs, link the program against the Intel MKL TBB threading library and Intel TBB RTL if it matches the compiler you use. If this is not possible, use Intel MKL in the sequential mode. To do this, link with the appropriate threading library: `libmkl_sequential.a` or `libmkl_sequential.so` (see Appendix C: Directory Structure in Detail).
You run multiple programs calling Intel MKL on a multiprocessor system, for example, a program parallelized using a message-passing interface (MPI).	The threading RTLs from different programs you run may place a large number of threads on the same processor on the system and therefore overuse the machine resources. 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® Optimized MP LINPACK Benchmark for Clusters discusses another solution for a Hybrid (OpenMP* + MPI) mode.

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 Developer Reference* for the function description).

See Also

Using Additional Threading Control
Linking with Compiler Run-time Libraries

Techniques to Set the Number of Threads

Use the following techniques to specify the number of OpenMP 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()`

NOTE
A call to the `mkl_set_num_threads` or `mkl_domain_set_num_threads` function changes the number of OpenMP threads available to all in-progress calls (in concurrent threads) and future calls to Intel MKL and may result in slow Intel MKL performance and/or race conditions reported by run-time tools, such as Intel® Inspector.

To avoid such situations, use the mkl_set_num_threads_local function (see the "Support Functions" section in the *Intel MKL Developer Reference* for the function description).

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.

If you use the Intel TBB threading technology, read the documentation for the `tbb::task_scheduler_init` class at https://www.threadingbuildingblocks.org/documentation to find out how to specify the number of threads.

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 OpenMP 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 OpenMP* Threads at Run Time

You cannot change the number of OpenMP threads at run time using environment variables. However, you can call OpenMP routines to do this. Specifically, the following sample code shows how to change the number of threads during run time using the `omp_set_num_threads()` routine. For more options, see also Techniques to Set the Number of Threads.

The example is provided for both C and Fortran languages. To run the example in C, 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 language *******
#include "omp.h"
#include "mkl.h"
#include <stdio.h>
#define SIZE 1000
int main(int args, 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\n");
for ( i=0;i<10;i++){
printf("%d:\t%f\t%f\n", i, a[i*SIZE], c[i*SIZE]);
}
omp_set_num_threads(1);
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\n");
for ( i=0;i<10;i++){
printf("%d:\t%f\t%f\n", 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\n");
for ( i=0;i<10;i++){
printf("%d:\t%f\t%f\n", i, a[i*SIZE],
c[i*SIZE]);
```

```
}
free (a);
free (b);
free (c);
return 0;
}
```

```
// ******* 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
DO J=1,N
A(I,J) = I+J
B(I,J) = I*j
C(I,J) = 0.0
END DO
END DO
CALL DGEMM('N','N',N,N,N,ALPHA,A,N,B,N,BETA,C,N)
print *,'Row A C'
DO i=1,10
write(*,'(I4,F20.8,F20.8)') I, A(1,I),C(1,I)
END DO
CALL OMP_SET_NUM_THREADS(1);
DO I=1,N
DO J=1,N
A(I,J) = I+J
B(I,J) = I*j
C(I,J) = 0.0
END DO
END DO
CALL DGEMM('N','N',N,N,N,ALPHA,A,N,B,N,BETA,C,N)
print *,'Row A C'
DO i=1,10
write(*,'(I4,F20.8,F20.8)') I, A(1,I),C(1,I)
END DO
CALL OMP_SET_NUM_THREADS(2);
DO I=1,N
DO J=1,N
A(I,J) = I+J
B(I,J) = I*j
C(I,J) = 0.0
END DO
END DO
CALL DGEMM('N','N',N,N,N,ALPHA,A,N,B,N,BETA,C,N)
print *,'Row A C'
DO i=1,10
write(*,'(I4,F20.8,F20.8)') I, A(1,I),C(1,I)
END DO
STOP
END
```

Using Additional Threading Control

Intel MKL-specific Environment Variables for OpenMP Threading Control

Intel MKL provides environment variables and support functions to control Intel MKL threading independently of OpenMP. The Intel MKL-specific threading controls take precedence over their OpenMP equivalents. Use the Intel MKL-specific threading controls to distribute OpenMP threads between Intel MKL and the rest of your program.

NOTE
Some Intel MKL routines may use fewer OpenMP threads than suggested by the threading controls if either the underlying algorithms do not support the suggested number of OpenMP threads or the routines perform better with fewer OpenMP threads because of lower OpenMP overhead and/or better data locality. Set the `MKL_DYNAMIC` environment variable to `FALSE` or call `mkl_set_dynamic(0)` to use the suggested number of OpenMP threads whenever the algorithms permit and regardless of OpenMP overhead and data locality.

Section "Number of User Threads" in the "Fourier Transform Functions" chapter of the *Intel MKL Developer Reference* 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:

Environment Variable	Support Function	Comment	Equivalent OpenMP* Environment Variable
`MKL_NUM_THREADS`	`mkl_set_num_threads` `mkl_set_num_threads_local`	Suggests the number of OpenMP threads to use.	`OMP_NUM_THREADS`
`MKL_DOMAIN_NUM_THREADS`	`mkl_domain_set_num_threads`	Suggests the number of OpenMP threads for a particular function domain.	
`MKL_DYNAMIC`	`mkl_set_dynamic`	Enables Intel MKL to dynamically change the number of OpenMP threads.	`OMP_DYNAMIC`

NOTE
Call `mkl_set_num_threads()` to force Intel MKL to use a given number of OpenMP threads and prevent it from reacting to the environment variables `MKL_NUM_THREADS`, `MKL_DOMAIN_NUM_THREADS`, and `OMP_NUM_THREADS`.

The example below shows how to force Intel MKL to use one thread:

```
// ******* C language *******

#include <mkl.h>
```

```
...
mkl_set_num_threads ( 1 );
```

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

See the *Intel MKL Developer Reference* 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 may use fewer OpenMP threads than 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), Intel MKL scales down the number of OpenMP threads to the number of physical cores.
- If you are able to detect the presence of a message-passing interface (MPI), but cannot determine whether it has been called in a thread-safe mode, Intel MKL runs one OpenMP thread.

When MKL_DYNAMIC is FALSE, Intel MKL uses the suggested number of OpenMP threads whenever the underlying algorithms permit. 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.

If Intel MKL is called from an OpenMP parallel region in your program, Intel MKL uses only one thread by default. If you want Intel MKL to go parallel in such a call, link your program against an OpenMP threading RTL supported by Intel MKL and set the environment variables:

- OMP_NESTED to TRUE
- OMP_DYNAMIC and MKL_DYNAMIC to FALSE
- MKL_NUM_THREADS to some reasonable value

With these settings, Intel MKL uses MKL_NUM_THREADS threads when it is called from the OpenMP parallel region in your program.

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 OpenMP threads for a particular function domain.

MKL_DOMAIN_NUM_THREADS accepts a string value <MKL-env-string>, which must have the following format:

<MKL-env-string> ::= *<MKL-domain-env-string>* { *<delimiter><MKL-domain-env-string>* }

<delimiter> ::= [*<space-symbol>**] (*<space-symbol>* | *<comma-symbol>* | *<semicolon-symbol>* | *<colon-symbol>*) [*<space-symbol>**]

<MKL-domain-env-string> ::= *<MKL-domain-env-name><uses><number-of-threads>*

<MKL-domain-env-name> ::= MKL_DOMAIN_ALL | MKL_DOMAIN_BLAS | MKL_DOMAIN_FFT | MKL_DOMAIN_VML | MKL_DOMAIN_PARDISO

<uses> ::= [*<space-symbol>**] (*<space-symbol>* | *<equality-sign>* | *<comma-symbol>*) [*<space-symbol>**]

<number-of-threads> ::= *<positive-number>*

<positive-number> ::= *<decimal-positive-number>* | *<octal-number>* | *<hexadecimal-number>*

In the syntax above, values of *<MKL-domain-env-name>* 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 Mathematics (VM)
MKL_DOMAIN_PARDISO	Intel MKL PARDISO, a direct sparse solver based on Parallel Direct Sparse Solver (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
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.

Value of MKL_DOMAIN_NUM_THREADS	Interpretation
MKL_DOMAIN_ALL=4	All parts of Intel MKL should try four OpenMP 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.
MKL_DOMAIN_ALL=1, MKL_DOMAIN_BLAS=4	All parts of Intel MKL should try one OpenMP thread, except for BLAS, which is suggested to try four threads.
MKL_DOMAIN_VML=2	VM should try two OpenMP threads. The setting affects no other part of Intel MKL.

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 OpenMP 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:

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

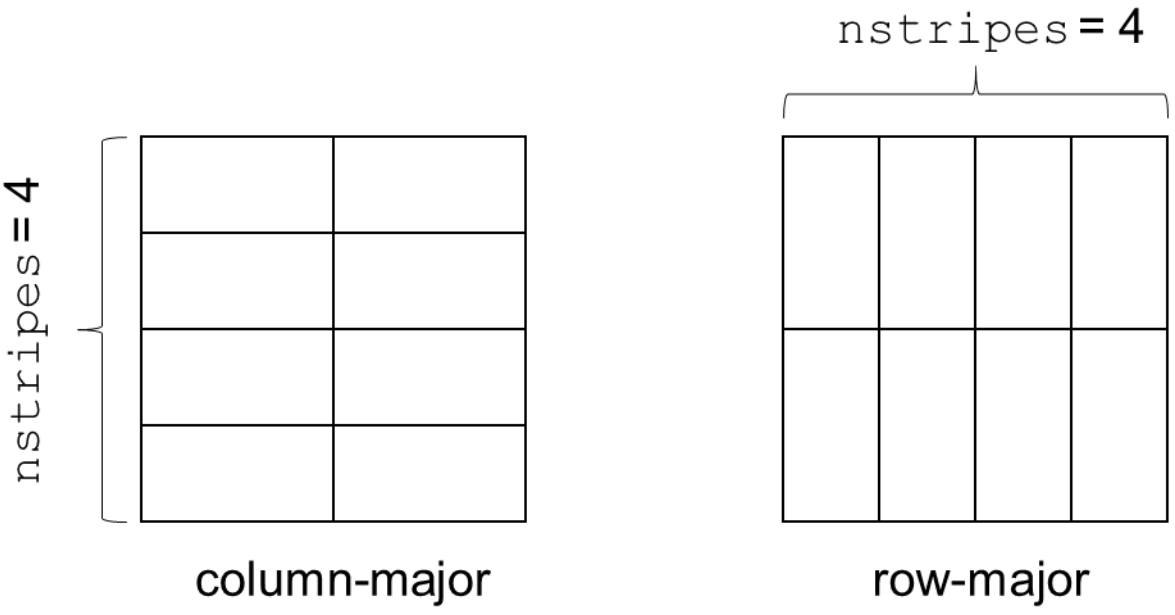
MKL_NUM_STRIPES

The MKL_NUM_STRIPES environment variable controls the Intel MKL threading algorithm for ?gemm functions. When MKL_NUM_STRIPES is set to a positive integer value *nstripes*, Intel MKL tries to use a number of partitions equal to *nstripes* along the leading dimension of the output matrix.

The following table explains how the value *nstripes* of MKL_NUM_STRIPES defines the partitioning algorithm used by Intel MKL for ?gemm output matrix; *max_threads_for_mkl* denotes the maximum number of OpenMP threads for Intel MKL:

Value of MKL_NUM_STRIPES	Partitioning Algorithm
1 < *nstripes* < (*max_threads_for_mkl*/2)	2D partitioning with the number of partitions equal to *nstripes*: • Horizontal, for column-major ordering. • Vertical, for row-major ordering.
nstripes = 1	1D partitioning algorithm along the opposite direction of the leading dimension.
nstripes≥ (*max_threads_for_mkl*/2)	1D partitioning algorithm along the leading dimension.
nstripes < 0	The default Intel MKL threading algorithm.

The following figure shows the partitioning of an output matrix for *nstripes* = 4 and a total number of 8 OpenMP threads for column-major and row-major orderings:



You can use support functions mkl_set_num_stripes and mkl_get_num_stripes to set and query the number of stripes, respectively.

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:

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

For example:

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

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

```
setenv <VARIABLE NAME><value>.
```

For example:

```
setenv MKL_NUM_THREADS 4
setenv MKL_DOMAIN_NUM_THREADS "MKL_DOMAIN_ALL=1, MKL_DOMAIN_BLAS=4"
setenv MKL_DYNAMIC FALSE
setenv MKL_NUM_STRIPES 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)` ‡

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` or `MKL_THREADING_LAYER=tbb`
- call `mkl_set_threading_layer(MKL_THREADING_INTEL)` or `mkl_set_threading_layer(MKL_THREADING_TBB)`

Other Options for OpenMP Threading:

- Set the `MKL_NUM_THREADS` environment variable to a desired number of OpenMP threads for Intel MKL.
- Set the `MKL_DOMAIN_NUM_THREADS` environment variable to a desired number of OpenMP 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 OpenMP 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 set the number of OpenMP 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 OpenMP threads in nested parallel regions.

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

See Also

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

Using 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
```

If you are using the Intel TBB threading technology, read the documentation on the `tbb::affinity_partitioner` class at https://www.threadingbuildingblocks.org/documentation to find out how to affinitize Intel TBB threads.

Managing Multi-core Performance

You can obtain best performance on systems with multi-core processors by requiring thatthreads do not migrate from core to core. To do this, bind threads to the CPU cores bysetting an affinity mask to threads. Use one of the following options:

- OpenMP facilities (if available), for example, the`KMP_AFFINITY`environment variable using the Intel OpenMP library
- A system function, as explained below
- Intel TBB facilities (if available), for example, the `tbb::affinity_partitioner` class (for details, see https://www.threadingbuildingblocks.org/documentation)

Consider the following performance issue:

- The system has two sockets with two cores each, for a total of four cores (CPUs).
- The application sets the number of OpenMP threads to two and calls Intel MKL to perform a Fourier transform. This call takes considerably different amounts of time from run to run.

To resolve this issue, before calling Intel MKL, set an affinity mask for each OpenMP thread using the `KMP_AFFINITY` environment variable or the `sched_setaffinity` system function. The following code example shows how to resolve the issue by setting an affinity mask by operating system means using the Intel compiler. The code calls the function`sched_setaffinity`to bind the threads tothecoreson different sockets. Then the Intel MKLFFT functionis called:

```
#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)
    {
        cpu_set_t new_mask;
        cpu_set_t was_mask;
        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.

Improving Performance for Small Size Problems

The overhead of calling an Intel MKL function for small problem sizes can be significant when the function has a large number of parameters or internally checks parameter errors. To reduce the performance overhead for these small size problems, the Intel MKL *direct call* feature works in conjunction with the compiler to preprocess the calling parameters to supported Intel MKL functions and directly call or inline special optimized small-matrix kernels that bypass error checking. For a list of functions supporting direct call, see Limitations of the Direct Call.

To activate the feature, do the following:

- Compile your C or Fortran code with the preprocessor macro depending on whether a threaded or sequential mode of Intel MKL is required by supplying the compiler option as explained below:

Intel MKL Mode	Macro	Compiler Option
Threaded	MKL_DIRECT_CALL	-DMKL_DIRECT_CALL
Sequential	MKL_DIRECT_CALL_SEQ	-DMKL_DIRECT_CALL_SEQ

- For Fortran applications:
  - Enable preprocessor by using the `-fpp` option for Intel® Fortran Compiler and `–Mpreprocess` option for PGI* compilers.
  - Include the Intel MKL Fortran include file `mkl_direct_call.fi`.

Intel MKL skips error checking and intermediate function calls if the problem size is small enough (for example: a call to a function that supports direct call, such as `dgemm`, with matrix ranks smaller than 50).

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Using MKL_DIRECT_CALL in C Applications

The following examples of code and link lines show how to activate direct calls to Intel MKL kernels in C applications:

- Include the `mkl.h` header file:

```
#include "mkl.h"
int main(void) {

// Call Intel MKL DGEMM

return 0;
}
```

- For multi-threaded Intel MKL, compile with `MKL_DIRECT_CALL` preprocessor macro:

```
icc -DMKL_DIRECT_CALL -std=c99 your_application.c -Wl,--start-group $(MKLROOT)/lib/intel64/
libmkl_intel_lp64.a
$(MKLROOT)/lib/intel64/libmkl_core.a
$(MKLROOT)/lib/intel64/libmkl_intel_thread.a -Wl,--end-group -lpthread -lm -openmp -I$(MKLROOT)/
include
```

- To use Intel MKL in the sequential mode, compile with `MKL_DIRECT_CALL_SEQ` preprocessor macro:

```
icc -DMKL_DIRECT_CALL_SEQ -std=c99 your_application.c -Wl,--start-group $(MKLROOT)/lib/intel64/
libmkl_intel_lp64.a
$(MKLROOT)/lib/intel64/libmkl_core.a
$(MKLROOT)/lib/intel64/libmkl_sequential.a -Wl,--end-group -lpthread -lm -I$(MKLROOT)/include
```

Using MKL_DIRECT_CALL in Fortran Applications

The following examples of code and link lines show how to activate direct calls to Intel MKL kernels in Fortran applications:

- Include `mkl_direct_call.fi`, to be preprocessed by the Fortran compiler preprocessor

```
#     include "mkl_direct_call.fi"
      program   DGEMM_MAIN
....
*      Call Intel MKL DGEMM
....
      call sub1()
      stop 1
      end

*     A subroutine that calls DGEMM
      subroutine sub1
```

```
*      Call Intel MKL DGEMM

      end
```

- For multi-threaded Intel MKL, compile with `-fpp` option for Intel Fortran compiler (or with `-Mpreprocess` for PGI compilers) and with `MKL_DIRECT_CALL` preprocessor macro:

```
ifort -DMKL_DIRECT_CALL -fpp your_application.f -Wl,--start-group
$(MKLROOT)/lib/intel64/libmkl_intel_lp64.a
$(MKLROOT)/lib/intel64/libmkl_core.a $(MKLROOT)/lib/intel64/libmkl_intel_thread.a -Wl,--end-group
-lpthread -lm -openmp -I$(MKLROOT)/include
```

- To use Intel MKL in the sequential mode, compile with `-fpp` option for Intel Fortran compiler (or with `-Mpreprocess` for PGI compilers) and with `MKL_DIRECT_CALL_SEQ` preprocessor macro:

```
ifort -DMKL_DIRECT_CALL_SEQ -fpp your_application.f -Wl,--start-group
$(MKLROOT)/lib/intel64/libmkl_intel_lp64.a
$(MKLROOT)/lib/intel64/libmkl_core.a $(MKLROOT)/lib/intel64/libmkl_sequential.a -Wl,--end-group
-lpthread -lm -I$(MKLROOT)/include
```

Limitations of the Direct Call

Directly calling the Intel MKL kernels has the following limitations:

- If the `MKL_DIRECT_CALL` or `MKL_DIRECT_CALL_SEQ` macro is used, Intel MKL may skip error checking.

  Important
  With a limited error checking, you are responsible for checking the correctness of function parameters to avoid unsafe and incorrect code execution.

- The feature is only available for the following functions:
  - BLAS: `?gemm`, `?gemm3m`, `?syrk`, `?trsm`, `?axpy`, and `?dot`
  - LAPACK: `?getrf`, `?getrs`, and `?getri` (available for C applications only)
- Intel MKL Verbose mode, Conditional Numerical Reproducibility, and BLAS95 interfaces are not supported.
- GNU* Fortran compilers are not supported.
- For C applications, you must enable mixing declarations and user code by providing the `-std=c99` option for Intel® compilers.
- In a fixed format Fortran source code compiled with PGI compilers, the lines containing Intel MKL functions must end at least seven columns before the line ending column, usually, in a column with the index not greater than 72 – 7 = 65.

  NOTE
  The direct call feature substitutes the names of Intel MKL functions with longer counterparts, which can cause the lines to exceed the column limit for a fixed format Fortran source code compiled with PGI compilers. Because the compilers ignore any part of the line that exceeds the limit, the behavior of the program can be unpredictable.

Other Tips and Techniques to Improve Performance

See Also

Managing Performance of the Cluster Fourier Transform Functions

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

Coding Techniques

This section discusses coding techniques to improve performance on processors based on supported architectures including Intel® Many Integrated Core Architecture. See Improving Performance on Intel Xeon Phi Coprocessors for tips to improve performance on Intel® Xeon Phi™ coprocessors.

To improve performance, properly align arrays in your code. Additional conditions can improve performance for specific function domains.

Data Alignment and Leading Dimensions

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/*element_size*, where *element_size* is the number of bytes for the matrix elements (4 for single-precision real, 8 for double-precision real and single-precision complex, and 16 for double-precision complex) . For more details, see Example of Data Alignment.

For Intel® Xeon Phi™ processor x200 product family, codenamed Knights Landing, align your matrices on 4096-byte boundaries and set the leading dimension to the following integer expression:
(((*n* * *element_size* + 511) / 512) * 512 + 64) /*element_size*,
where *n* is the matrix dimension along the leading dimension.

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 Developer Reference). 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

Managing Performance of the Cluster Fourier Transform Functions

Improving Intel(R) MKL Performance on Specific Processors

Dual-Core Intel® Xeon® Processor 5100 Series

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.

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.

Fast Fourier Transform Optimized Radices

You can improve the performance of Intel MKL Fourier Transform Functions 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.

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_free_buffers()` function in the current thread.

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

See Also

Intel Software Documentation Library

Using High-bandwidth Memory with Intel MKL

To achieve maximum performance, Intel MKL may use the memkind library (https://github.com/memkind/memkind), which enables controlling memory characteristics and partitioning the heap between different kinds of memory. By default Intel MKL memory manager tries to allocate memory to Multi-Channel Dynamic Random Access Memory (MCDRAM) using the memkind library on the 2nd generation Intel® Xeon Phi™ product family (for more details of MCDRAM, see https://software.intel.com/en-us/articles/mcdram-high-bandwidth-memory-on-knights-landing-analysis-methods-tools). If allocation of memory to MCDRAM is not possible at the moment, Intel MKL memory manager falls back to a regular system allocator.

By default the amount of MCDRAM available for Intel MKL is unlimited. To control the amount of MCDRAM available for Intel MKL, do either of the following:

- Call

  `mkl_set_memory_limit (MKL_MEM_MCDRAM, <limit_in_mbytes>)`

- Set the environment variable:
  - For the bash shell:

    `MKL_FAST_MEMORY_LIMIT="<limit_in_mbytes>"`
  - For a C shell (csh or tcsh):

    `setenv MKL_FAST_MEMORY_LIMIT "<limit_in_mbytes>"`

The setting of the limit affects all Intel MKL functions, including user-callable memory functions such as `mkl_malloc`. Therefore, if an application calls `mkl_malloc`, `mkl_calloc`, or `mkl_realloc`, which always tries to allocate memory to MCDRAM, make sure that the limit is sufficient.

If you replace Intel MKL memory management functions with your own functions (for details, see Redefining Memory Functions), Intel MKL uses your functions and does not work with the memkind library directly.

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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

In addition to the memkind library, 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. 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:

```
#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
```

See Also

Using High-bandwidth Memory with Intel MKL

Language-specific Usage Options

5

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 Developer Reference 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.

File name	Contains
Libraries, in Intel MKL architecture-specific directories	
`libmkl_blas95.a`[1]	Fortran 95 wrappers for BLAS (BLAS95) for IA-32 architecture.
`libmkl_blas95_ilp64.a`[1]	Fortran 95 wrappers for BLAS (BLAS95) supporting LP64 interface.
`libmkl_blas95_lp64.a`[1]	Fortran 95 wrappers for BLAS (BLAS95) supporting ILP64 interface.
`libmkl_lapack95.a`[1]	Fortran 95 wrappers for LAPACK (LAPACK95) for IA-32 architecture.
`libmkl_lapack95_lp64.a`[1]	Fortran 95 wrappers for LAPACK (LAPACK95) supporting LP64 interface.

File name	Contains
libmkl_lapack95_ilp64.a[1]	Fortran 95 wrappers for LAPACK (LAPACK95) supporting ILP64 interface.
libfftw2xc_intel.a[1]	Interfaces for FFTW version 2.x (C interface for Intel compilers) to call Intel MKL FFT.
libfftw2xc_gnu.a	Interfaces for FFTW version 2.x (C interface for GNU compilers) to call Intel MKL FFT.
libfftw2xf_intel.a	Interfaces for FFTW version 2.x (Fortran interface for Intel compilers) to call Intel MKL FFT.
libfftw2xf_gnu.a	Interfaces for FFTW version 2.x (Fortran interface for GNU compiler) to call Intel MKL FFT.
libfftw3xc_intel.a[2]	Interfaces for FFTW version 3.x (C interface for Intel compiler) to call Intel MKL FFT.
libfftw3xc_gnu.a	Interfaces for FFTW version 3.x (C interface for GNU compilers) to call Intel MKL FFT.
libfftw3xf_intel.a[2]	Interfaces for FFTW version 3.x (Fortran interface for Intel compilers) to call Intel MKL FFT.
libfftw3xf_gnu.a	Interfaces for FFTW version 3.x (Fortran interface for GNU compilers) to call Intel MKL FFT.
libfftw2x_cdft_SINGLE.a	Single-precision interfaces for MPI FFTW version 2.x (C interface) to call Intel MKL cluster FFT.
libfftw2x_cdft_DOUBLE.a	Double-precision interfaces for MPI FFTW version 2.x (C interface) to call Intel MKL cluster FFT.
libfftw3x_cdft.a	Interfaces for MPI FFTW version 3.x (C interface) to call Intel MKL cluster FFT.
libfftw3x_cdft_ilp64.a	Interfaces for MPI FFTW version 3.x (C interface) to call Intel MKL cluster FFT supporting the ILP64 interface.
Modules, in architecture- and interface-specific subdirectories of the Intel MKL include directory	
blas95.mod[1]	Fortran 95 interface module for BLAS (BLAS95).
lapack95.mod[1]	Fortran 95 interface module for LAPACK (LAPACK95).
f95_precision.mod[1]	Fortran 95 definition of precision parameters for BLAS95 and LAPACK95.
mkl_service.mod[1]	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.

See Also

Fortran 95 Interfaces to LAPACK and BLAS

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:
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® 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:

- http://software.intel.com/en-us/articles/performance-tools-for-software-developers-how-do-i-use-intel-mkl-with-java for how to call Intel MKL from Java* applications.
- http://software.intel.com/en-us/articles/how-to-use-boost-ublas-with-intel-mkl for how to perform BLAS matrix-matrix multiplication in C++ using Intel MKL substitution of Boost* uBLAS functions.
- http://software.intel.com/en-us/articles/intel-mkl-and-third-party-applications-how-to-use-them-together for a list of articles describing how to use Intel MKL with third-party libraries and applications.

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.

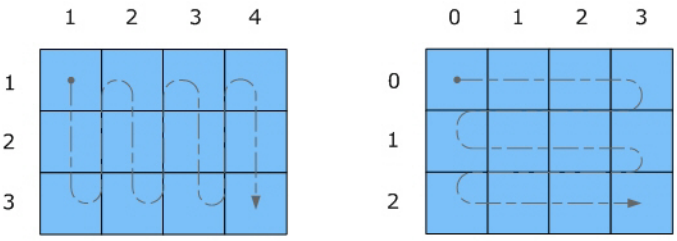
CAUTION
Avoid calling BLAS 95/LAPACK 95 from C/C++. Such calls require skills in manipulating the descriptor of a deferred-shape array, which is the Fortran 90 type. Moreover, BLAS95/LAPACK95 routines contain links to a Fortran RTL.

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).



A: Column-major order (Fortran-style) B: Row-major order (C-style)

For example, if a two-dimensional matrix A of size `mxn` 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 (`i=0, ... , m-1, j=0, ... , -1`)

`A(i,j) = B((j-1)*m+i)` in Fortran (`i=1, ... , m, j=1, ... , 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 Developer Reference 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, 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:

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

and

```
#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:

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

See Also

Intel® Software Documentation Library for the Intel® Fortran Compiler documentation

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

A call to the function as a subroutine: `call cdotc( result, n, x, 1, y, 1)`

A call to the function from 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:

```
cblas_cdotc( 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`.

```
#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:

```
#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:

```
#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;
}
cblas_zdotc_sub(n, a, inca, b, incb, &c );
printf( "The complex dot product is: ( %6.2f, %6.2f)\n", c.re, c.im );
```

```
return 0;
}
```

Obtaining Numerically Reproducible Results

6

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
- 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:

$(2^{-63} + 1) + (-1) \simeq 1 + (-1) = 0$

versus

$2^{-63} + (1 + (-1)) \simeq 2^{-63} + 0 = 2^{-63}$

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 2 (Intel® AVX2). 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 AVX2 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 effectiveness of any optimization on microprocessors not manufactured by Intel. Microprocessor-

Optimization Notice
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.

While these examples recommend aligning input and output data, you can supply unaligned data to Intel MKL functions running in the CNR mode, but refer to Reproducibility Conditions for details related to data alignment.

Intel CPUs supporting Intel AVX2

To ensure Intel MKL calls return the same results on every Intel CPU supporting Intel AVX2 instructions:

1. Make sure that your application uses a fixed number of threads
2. (Recommended) Properly align input and output arrays in Intel MKL function calls
3. Do either of the following:
   - Call

     ```
     mkl_cbwr_set(MKL_CBWR_AVX2)
     ```
   - Set the environment variable:

     ```
     export MKL_CBWR = AVX2
     ```

NOTE
On non-Intel CPUs and on Intel CPUs that do not support Intel AVX2, 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
2. (Recommended) Properly align input and output arrays in Intel MKL function calls
3. Do either of the following:
   - Call

     ```
     mkl_cbwr_set(MKL_CBWR_SSE2)
     ```
   - Set the environment variable:

     ```
     export MKL_CBWR = 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
2. (Recommended) Properly align input and output arrays in Intel MKL function calls
3. Do either of the following:
   - Call

     ```
     mkl_cbwr_set(MKL_CBWR_COMPATIBLE)
     ```
   - Set the environment variable:

     ```
     export MKL_CBWR = 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 Developer Reference*:

Support Functions for Conditional Numerical Reproducibility	for how to configure the CNR mode of Intel MKL using functions.
Intel MKL PARDISO - Parallel Direct Sparse Solver Interface	for how to configure the CNR mode for PARDISO.

See Also

Code Examples

Specifying 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:

Value	Description
`AUTO`	CNR mode uses the standard ISA-based dispatching model while ensuring fixed cache sizes, deterministic reductions, and static scheduling

Value	Description
	CNR mode uses the branch for the following ISA:
COMPATIBLE	Intel® Streaming SIMD Extensions 2 (Intel® SSE2) without rcpps/ rsqrtps instructions
SSE2	Intel SSE2
SSE3	DEPRECATED. Intel® Streaming SIMD Extensions 3 (Intel® SSE3). This setting is kept for backward compatibility and is equivalent to SSE2.
SSSE3	Supplemental Streaming SIMD Extensions 3 (SSSE3)
SSE4_1	Intel® Streaming SIMD Extensions 4-1 (Intel® SSE4-1)
SSE4_2	Intel® Streaming SIMD Extensions 4-2 (Intel® SSE4-2)
AVX	Intel® Advanced Vector Extensions (Intel® AVX)
AVX2	Intel® Advanced Vector Extensions 2 (Intel® AVX2)

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

- Reproducible results are provided under Reproducibility Conditions.
- Settings other than AUTO or COMPATIBLE are available only for Intel processors.
- 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 or operating system does not support the specified ISA, 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 Developer Reference* for how to specify the branches using functions.

See Also

Getting Started with Conditional Numerical Reproducibility

Reproducibility Conditions

To get reproducible results from run to run, ensure that the number of threads is fixed and constant. Specifically:

- If you are running your program with OpenMP* parallelization 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.
- If you are running your program with the Intel® Threading Building Blocks parallelization, numerical reproducibility is not guaranteed.

- As usual, you should align your data, even in CNR mode, to obtain the best possible performance. While CNR mode also fully supports unaligned input and output data, the use of it might reduce the performance of some Intel MKL functions on earlier Intel processors. Refer to coding techniques that improve performance for more details.
- Conditional Numerical Reproducibility does not ensure that bitwise-identical NaN values are generated when the input data contains NaN values.
- If dynamic memory allocation fails on one run but succeeds on another run, you may fail to get reproducible results between these two runs.

See Also

MKL_DYNAMIC
Coding Techniques

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 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 Developer Reference* for more examples.

C Example of CNR

```
#include <mkl.h>
int main(void) {
    int my_cbwr_branch;
    /* Align all input/output data on 64-byte boundaries */
    /* "for best performance of Intel MKL */
    void *darray;
    int darray_size=1000;
    /* Set alignment value in bytes */
    int alignment=64;
    /* 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 the "IF" statement below is commented out, Intel MKL will run in a regular mode, */
    /* and data alignment will allow you to get best performance */
    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 */
    /* Free the allocated aligned array */
    mkl_free(darray);
}
```

Fortran Example of CNR

```
    PROGRAM MAIN
    INCLUDE 'mkl.fi'
    INTEGER*4 MY_CBWR_BRANCH
! Align all input/output data on 64-byte  boundaries
! "for best performance of Intel MKL
! Declare Intel MKL memory allocation routine
#ifdef _IA32
    INTEGER MKL_MALLOC
#else
    INTEGER*8 MKL_MALLOC
#endif
    EXTERNAL MKL_MALLOC, MKL_FREE
    DOUBLE PRECISION DARRAY
    POINTER (P_DARRAY,DARRAY(1))
    INTEGER DARRAY_SIZE
    PARAMETER (DARRAY_SIZE=1000)
! Set alignment value in bytes
    INTEGER ALIGNMENT
    PARAMETER (ALIGNMENT=64)
! 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 the "IF" statement below is commented out, Intel MKL will run in a regular mode,
! and data alignment will allow you to get best performance
    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
! Free the allocated aligned array
    CALL MKL_FREE(P_DARRAY)

    END
```

Use of CNR with Unaligned Data in C

```
#include <mkl.h>
int main(void) {
     int my_cbwr_branch;
     /* If it is not possible to align all input/output data on 64-byte boundaries */
     /* to achieve performance, use unaligned IO data with possible performance */
```

```
     /* penalty */
     /* Using unaligned IO data */
     double *darray;
     int darray_size=1000;
     /* Allocate array, malloc aligns data on 8/16-byte boundary only */
     darray = (double *)malloc (sizeof(double)*darray_size);
     /* 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 the "IF" statement below is commented out, Intel MKL will run in a regular mode, */
     /* and you will NOT get best performance without data alignment */
     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 */
     /* Free the allocated array */
     free(darray);
```

Use of CNR with Unaligned Data in Fortran

```
     PROGRAM MAIN
     INCLUDE 'mkl.fi'
     INTEGER*4 MY_CBWR_BRANCH
! If it is not possible to align all input/output data on 64-byte boundaries
! to achieve performance, use unaligned IO data with possible performance
! penalty
     DOUBLE PRECISION, DIMENSION(:), ALLOCATABLE :: DARRAY
     INTEGER DARRAY_SIZE, STATUS
     PARAMETER (DARRAY_SIZE=1000)
! Allocate array with undefined alignment
     ALLOCATE(DARRAY(DARRAY_SIZE));
! 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 the "IF" statement below is commented out, Intel MKL will run in a regular mode,
! and you will NOT get best performance without data alignment
     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
! Free the allocated array
     DEALLOCATE(DARRAY)
     END
```

Coding Tips

7

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 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 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
...
double precision darray
pointer (p_wrk,darray(1))
integer workspace
...
```

```
! 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:

Predefined Preprocessor Symbol	Description
`__INTEL_MKL__`	Intel MKL major version
`__INTEL_MKL_MINOR__`	Intel MKL minor version
`__INTEL_MKL_UPDATE__`	Intel MKL update number
`INTEL_MKL_VERSION`	Intel MKL full version in the following format: `INTEL_MKL_VERSION = (__INTEL_MKL__*100+__INTEL_MKL_MINOR__)*100+__INTEL_MKL_UPDATE__`

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

To perform conditional compilation:

1. Depending on your compiler, include in your code the file where the macros are defined:

C/C++ compiler:	`mkl_version.h`, or `mkl.h`, which includes `mkl_version.h`
Intel®Fortran compiler:	`mkl.fi`
Any Fortran compiler with enabled preprocessing:	`mkl_version.h` Read the documentation for your compiler for the option that enables preprocessing.

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 11.2 Update 4:

Intel®Fortran Compiler:

```
include "mkl.fi"
!DEC$IF DEFINED INTEL_MKL_VERSION
!DEC$IF INTEL_MKL_VERSION .EQ. 110204
*     Code to be conditionally compiled
!DEC$ENDIF
!DEC$ENDIF
```

C/C++ Compiler. Fortran Compiler with Enabled Preprocessing:

```
#include "mkl.h"
#ifdef INTEL_MKL_VERSION
#if INTEL_MKL_VERSION ==  110204
...     Code to be conditionally compiled
#endif
#endif
```

8 Managing Output

Using Intel MKL Verbose Mode

If your application calls Intel MKL functions, you may want to know what computational functions are called, what parameters are passed to them, and how much time is spent to execute the functions. Your application can print this information to a standard output device if Intel MKL Verbose mode is enabled. Functions that can print this information are referred to as *verbose-enabled* functions. While not all Intel MKL functions are verbose-enabled, see *Intel MKL Release Notes* for the Intel MKL function domains that support the Verbose mode.

In the Verbose mode, every call of a verbose-enabled function finishes with printing a human readable line describing the call. If the application is terminated during the function call, no information for that function is printed. The first call to a verbose-enabled function also prints a version information line.

To enable the Intel MKL Verbose mode for an application, do one of the following:

- Set the environment variable `MKL_VERBOSE` to 1.
- Call the support function `mkl_verbose`(1).

The function call `mkl_verbose`(0) disables the Verbose mode. Enabling or disabling the Verbose mode using the function call takes precedence over the environment setting. For a full description of the `mkl_verbose` function, see the *Intel MKL Developer Reference*, available in the Intel® Software Documentation Library.

Intel MKL Verbose mode is not a thread-local but a global state. It means that if an application changes the mode from multiple threads, the result is undefined.

> **WARNING**
> The performance of an application may degrade with the Verbose mode enabled, especially when the number of calls to verbose-enabled functions is large, because every call to a verbose-enabled function requires an output operation.

See Also

Intel Software Documentation Library

Version Information Line

In the Intel MKL Verbose mode, the first call to a verbose-enabled function prints a version information line. The line begins with the `MKL_VERBOSE` character string and uses spaces as delimiters. The format of the rest of the line may change in a future release.

The following table lists information contained in a version information line and provides available links for more information:

Information	Description	Related Links
Intel MKL version.	This information is separated by a comma from the rest of the line.	
Operating system.	Possible values: • `Lnx` for Linux* OS • `Win` for Windows* OS	

Information	Description	Related Links
	• `OSX` for macOS*	
The host CPU frequency.		
Intel MKL interface layer used by the application.	Possible values: • No value on systems based on the IA-32 architecture. • `lp64` or `ilp64` on systems based on the Intel® 64 architecture.	Using the ILP64 Interface vs. LP64 Interface
Intel MKL threading layer used by the application.	Possible values: `intel_thread`, `gnu_thread`, `tbb_thread`, `pgi_thread`, or `sequential`.	Linking with Threading Libraries
The number of Intel® Xeon Phi™ coprocessors detected.	Nothing is printed if no coprocessors are detected. The number printed is prefixed with `NMICDev:` . Intel MKL attempts to detect the coprocessors unless it runs in the sequential mode because Automatic Offload functionality is only provided by threaded Intel MKL.	Automatic Offload

The following is an example of a version information line:

```
MKL_VERBOSE Intel(R) MKL 11.2 Beta build 20131126 for Intel(R) 64 architecture Intel(R)
Advanced Vector Extensions (Intel(R) AVX) Enabled Processor, Lnx 3.10GHz lp64
intel_thread NMICDev:2
```

Call Description Line

In Intel MKL Verbose mode, each verbose-enabled function called from your application prints a call description line. The line begins with the `MKL_VERBOSE` character string and uses spaces as delimiters. The format of the rest of the line may change in a future release.

The following table lists information contained in a call description line and provides available links for more information:

Information	Description	Related Links
The name of the function.	Although the name printed may differ from the name used in the source code of the application (for example, the `cblas_` prefix of CBLAS functions is not printed), you can easily recognize the function by the printed name.	
Values of the arguments.	• The values are listed in the order of the formal argument list. The list directly follows the function name, it is parenthesized and comma-separated. • Arrays are printed as addresses (to see the alignment of the data). • Integer scalar parameters passed by reference are printed by value. Zero values are printed for `NULL` references. • Character values are printed without quotes. • For all parameters passed by reference, the values printed are the values *returned by the function*. For example, the printed value of the *`info`* parameter of a LAPACK function is its value after the function execution.	

Information	Description	Related Links
Time taken by the function.	• The time is printed in convenient units (seconds, milliseconds, and so on), which are explicitly indicated. • The time may fluctuate from run to run. • The time printed may occasionally be larger than the time actually taken by the function call, especially for small problem sizes and multi-socket machines. To reduce this effect, bind threads that call Intel MKL to CPU cores by setting an affinity mask.	Managing Multi-core Performance for options to set an affinity mask.
Value of the `MKL_CBWR` environment variable.	The value printed is prefixed with `CNR:`	Getting Started with Conditional Numerical Reproducibility
Value of the `MKL_DYNAMIC` environment variable.	The value printed is prefixed with `Dyn:`	`MKL_DYNAMIC`
Status of the Intel MKL memory manager.	The value printed is prefixed with `FastMM:`	Avoiding Memory Leaks in Intel MKL for a description of the Intel MKL memory manager
OpenMP* thread number of the calling thread.	The value printed is prefixed with `TID:`	
Values of Intel MKL environment variables defining the general and domain-specific numbers of threads, separated by a comma.	The first value printed is prefixed with `NThr:`	Intel MKL-specific Environment Variables for Threading Control
Value of the `MKL_HOST_WORKDIVISION` environment variable.	The value printed is prefixed with `WDiv:HOST:`	Automatic Offload Controls
Values of the `MKL_MIC_<number>_WORKDIVISION` environment variables for each Intel® Xeon Phi™ coprocessor available on the system, where `<number>` is the number of the coprocessor.	The first value printed is prefixed with `WDiv:<number>:`	Automatic Offload Controls

The following is an example of a call description line:

```
MKL_VERBOSE DGEMM(n,n,
1000,1000,240,0x7ffff708bb30,0x7ff2aea4c000,1000,0x7ff28e92b000,240,0x7ffff708bb38,0x7f
f28e08d000,1000) 1.66ms CNR:OFF Dyn:1 FastMM:1 TID:0 NThr:16,FFT:2 WDiv:HOST:-1.000
WDiv:0:-1.000 WDiv:1:-1.000
```

The following information is not printed because of limitations of Intel MKL Verbose mode:

- Input values of parameters passed by reference if the values were changed by the function.

  For example, if a LAPACK function is called with a workspace query, that is, the value of the *lwork* parameter equals -1 on input, the call description line prints the result of the query and not -1.
- Return values of functions.

  For example, the value returned by the function `ilaenv` is not printed.
- Floating-point scalars passed by reference.

Working with the Intel® Math Kernel Library Cluster Software

9

Intel® Math Kernel Library (Intel® MKL) includes distributed memory function domains for use on clusters:

- ScaLAPACK
- Cluster Fourier Transform Functions (Cluster FFT)
- Parallel Direct Sparse Solvers for Clusters (Cluster Sparse Solver)

ScaLAPACK, Cluster FFT, and Cluster Sparse Solver are only provided for the Intel® 64 and Intel® Many Integrated Core architectures.

Important
ScaLAPACK, Cluster FFT, and Cluster Sparse Solver function domains are not installed by default. To use them, explicitly select the appropriate component during installation.

Linking with Intel MKL Cluster Software

The Intel MKL ScaLAPACK, Cluster FFT, and Cluster Sparse Solver support MPI implementations identified in the *Intel MKL Release Notes*.

To link a program that calls ScaLAPACK, Cluster FFT, or Cluster Sparse Solver, 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 MPICH3, `/opt/mpich/bin/mpicc` and `/opt/mpich/bin/mpif90` are the compiler scripts and `/opt/mpich/lib/libmpi.a` is the MPI library.

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

To link with ScaLAPACK, Cluster FFT, and/or Cluster Sparse Solver, use the following general form:

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

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

<MKL cluster library>	One of libraries for ScaLAPACK or Cluster FFT and appropriate architecture and programming interface (LP64 or ILP64). Available libraries are listed in Appendix C: Directory Structure in Detail. For example, for the LP64 interface, it is –`lmkl_scalapack_lp64` or –`lmkl_cdft_core`. Cluster Sparse Solver does not require an additional computation library.
<BLACS>	The BLACS library corresponding to your architecture, programming interface (LP64 or ILP64), and MPI used. Available BLACS libraries are listed in Appendix C: Directory Structure in Detail. Specifically, choose one of –`lmkl_blacs_intelmpi_lp64` or –`lmkl_blacs_intelmpi_ilp64`.
<MKL core libraries>	Processor optimized kernels, threading library, and system library for threading support, linked as described in Listing Libraries on a Link Line.
<MPI linker script>	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 Using 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 of Linking for Clusters

Setting the Number of OpenMP* Threads

The OpenMP* run-time library responds to the environment variable `OMP_NUM_THREADS`. Intel MKL also has other mechanisms to set the number of OpenMP threads, such as the `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 OpenMP 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 OpenMP threads, which may occur, for instance, when the number of MPI ranks per node and the number of OpenMP threads per node are both greater than one. The number of MPI ranks per node multiplied by the number of OpenMP 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 OpenMP 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 OpenMP threads is greater than one, first try setting the number of threads to one and see whether the problem persists.

Important
For Cluster Sparse Solver, set the number of OpenMP threads to a number greater than one because the implementation of the solver only supports a multithreaded algorithm.

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.

Interaction with the Message-passing Interface

To improve performance of cluster applications, it is critical for Intel MKL to use the optimal number of threads, as well as the correct thread affinity. Usually, the optimal number is the number of available cores per node divided by the number of MPI processes per node. You can set the number of threads using one of the available methods, described in Techniques to Set the Number of Threads.

If the number of threads is not set, Intel MKL checks whether it runs under MPI provided by the Intel® MPI Library. If this is true, the following environment variables define Intel MKL threading behavior:

- `I_MPI_THREAD_LEVEL`
- `MKL_MPI_PPN`
- `I_MPI_NUMBER_OF_MPI_PROCESSES_PER_NODE`
- `I_MPI_PIN_MAPPING`
- `OMPI_COMM_WORLD_LOCAL_SIZE`
- `MPI_LOCALNRANKS`

The threading behavior depends on the value of `I_MPI_THREAD_LEVEL` as follows:

- 0 or undefined.

  Intel MKL considers that thread support level of Intel MPI Library is `MPI_THREAD_SINGLE` and defaults to sequential execution.
- 1, 2, or 3.

  This value determines Intel MKL conclusion of the thread support level:

- 1 - `MPI_THREAD_FUNNELED`
- 2 - `MPI_THREAD_SERIALIZED`
- 3 - `MPI_THREAD_MULTIPLE`

In all these cases, Intel MKL determines the number of MPI processes per node using the other environment variables listed and defaults to the number of threads equal to the number of available cores per node divided by the number of MPI processes per node.

Important
Instead of relying on the discussed implicit settings, explicitly set the number of threads for Intel MKL.

See Also

Managing Multi-core Performance
Intel® Software Documentation Library for more information on Intel MPI Library

Using a Custom Message-Passing Interface

While different message-passing interface (MPI) libraries are compatible at the application programming interface (API) level, they are often incompatible at the application binary interface (ABI) level. Therefore, Intel MKL provides a set of prebuilt BLACS libraries that support certain MPI libraries, but this, however, does not enable use of Intel MKL with other MPI libraries. To fill this gap, Intel MKL additionally includes the MKLMPI adaptor, which provides an MPI-independent ABI to Intel MKL. The adaptor is provided as source code. To use Intel MKL with an MPI library that is not supported by default, you can use the adapter to build custom static or dynamic BLACS libraries and use them similarly to the prebuilt libraries.

Building a Custom BLACS Library

The MKLMPI adaptor is located in the *<mkl directory>*`/interfaces/mklmpi` directory.

To build a custom BLACS library, from the above directory run the `make` command.

For example: the command

```
make libintel64
```

builds a static custom BLACS library `libmkl_blacs_custom_lp64.a` using the MPI compiler from the current shell environment. Look into the *<mkl directory>*`/interfaces/mklmpi/makefile` for targets and variables that define how to build the custom library. In particular, you can specify the compiler through the `MPICC` variable.

For more control over the building process, refer to the documentation available through the command

```
make help
```

Using a Custom BLACS Library

Use custom BLACS libraries exactly the same way as you use the prebuilt BLACS libraries, but pass the custom library to the linker. For example, instead of passing the `libmkl_blacs_intelmpi_lp64.a` library, pass `libmkl_blacs_custom_lp64.a`.

See Also

Linking with Intel MKL Cluster Software

Examples of Linking for Clusters

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

Note that a binary linked with the Intel MKL cluster function domains 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 or higher and OpenMPI, and the number of MPI processes is set by `-np`. In the case of MPICH2 or higher and Intel MPI, 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.
- Intel MKL functions use LP64 interfaces.
- The `PATH` environment variable contains a directory with the MPI linker scripts.
- `$MKLPATH` is a user-defined variable containing *<mkl_directory>*`/lib/intel64_lin`.

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

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

```
mpicc <user files to link>                \
   -Wl,--start-group                      \
   $MKLPATH/libmkl_cdft_core.a            \
   $MKLPATH/libmkl_blacs_intelmpi_lp64.a  \
   $MKLPATH/libmkl_intel_lp64.a           \
   $MKLPATH/libmkl_intel_thread.a         \
   $MKLPATH/libmkl_core.a                 \
   -Wl,--end-group                        \
   -liomp5 -lpthread
```

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

```
mpicc <user files to link>                    \
   -L$MKLPATH                                 \
   -lmkl_blacs_intelmpi_lp64                  \
   -lmkl_intel_lp64                           \
   -lmkl_intel_thread -lmkl_core              \
   -liomp5 -lpthread
```

See Also

Linking with Intel MKL Cluster Software
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.
- You are using the Intel® Fortran Compiler.
- You are using the Intel MPI library.
- Intel MKL functions use LP64 interfaces.
- The `PATH` environment variable contains a directory with the MPI linker scripts.
- `$MKLPATH` is a user-defined variable containing *<mkl_directory>*`/lib/intel64_lin`.

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

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

```
mpiifort <user files to link>                      \
   -Wl,--start-group                               \
   $MKLPATH/libmkl_cdft_core.a                     \
   $MKLPATH/libmkl_blacs_intelmpi_lp64.a           \
   $MKLPATH/libmkl_intel_lp64.a                    \
   $MKLPATH/libmkl_intel_thread.a                  \
   $MKLPATH/libmkl_core.a                          \
   -Wl,--end-group                                 \
   -liomp5 -lpthread
```

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

```
mpiifort <user files to link>                      \
   -Wl,--start-group                               \
   $MKLPATH/libmkl_blacs_intelmpi_lp64.a           \
   $MKLPATH/libmkl_intel_lp64.a                    \
   $MKLPATH/libmkl_intel_thread.a                  \
   $MKLPATH/libmkl_core.a                          \
   -Wl,--end-group                                 \
```

```
-liomp5 -lpthread
```

See Also

Linking with Intel MKL Cluster Software

Using the Link-line Advisor

Using Intel® Math Kernel Library on Intel® Xeon Phi™ Coprocessors

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

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

Automatic Offload

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 Developer Reference* for detailed descriptions of the support functions.

Important
Use of Automatic Offload does not require changes in your link line. However, be aware that Automatic Offload supports only OpenMP* threaded Intel MKL.

Automatic Offload Controls

The table below lists the environment variables for Automatic Offload and the functions that cause *similar* results. See the *Intel MKL Developer Reference* 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.

Environment Variable	Support Function	Description	Value
`MKL_MIC_ENABLE`	`mkl_mic_enable`	Enables Automatic Offload (AO).	1
`OFFLOAD_DEVICES`	None	`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 AO. In particular, this setting may help you to configure the environment for an MPI application to run Intel MKL in the AO mode. If this variable is not set, all the coprocessors available on the system are used for AO.	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 AO, and Intel MKL support functions and environment variables refer to these coprocessors as coprocessors 0 and 1.

Environment Variable	Support Function	Description	Value
		You can set this environment variable if AO is enabled by the environment setting or function call. Setting this variable to an empty value is equivalent to completely disabling AO 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*.	
OFFLOAD_ENABLE_ORSL	None	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 AO but does not implement its own synchronization.	1
MKL_HOST_WORKDIVISION	mkl_mic_set_workdivision	Specifies the fraction of work for the host CPU to do.	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.
MKL_MIC_WORKDIVISION	mkl_mic_set_workdivision	Specifies the fraction of work to do on all the Intel Xeon Phi coprocessors on the system.	See MKL_HOST_WORKDIVISION
MKL_MIC_*<number>*_WORKDIVISION	mkl_mic_set_workdivision	Specifies the fraction of work to do on a specific Intel Xeon Phi coprocessor. Here *<number>* is an integer ranging from 0 to the largest number of an Intel Xeon Phi coprocessor on the	See MKL_HOST_WORKDIVISION

Environment Variable	Support Function	Description	Value
		system, with the maximum of 31. For example, if the system has two Intel Xeon Phi coprocessors, *<number>* can be 0 or 1.	
MKL_MIC_ MAX_MEMORY	mkl_mic_set_ max_memory	Specifies the maximum coprocessor memory reserved for AO computations on all of the Intel Xeon Phi coprocessors on the system. Each process that performs AO computations uses additional coprocessor memory specified by the environment variable.	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 AO computations to 4096 megabytes or 4 gigabytes. Setting MKL_MIC_MAX_MEMORY = 4G specifies the same amount of memory in gigabytes.
MKL_MIC_*<number>*_ MAX_MEMORY	mkl_mic_set_ max_memory	Specifies the maximum coprocessor memory reserved for AO computations on a specific Intel Xeon Phi coprocessor on the system. Here *<number>* 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, *<number>* can be 0 or 1.	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 AO computations to 4096 megabytes or 4 gigabytes. Setting MKL_MIC_MAX_MEMORY = 4G specifies the same amount of memory in gigabytes.
MKL_MIC_ REGISTER_ MEMORY	mkl_mic_ register_ memory	Enables/disables the mkl_malloc function running in AO mode to register allocated memory. If AO is disabled, this setting has no effect. Setting this environment variable to 1 may improve performance if the same memory region allocated by mkl_malloc is passed multiple times to Intel MKL functions enabled for AO (for a list of AO enabled functions, see *Intel MKL Release Notes*).	Desired behavior of mkl_malloc: 0 - not register allocated memory 1 - register allocated memory

Environment Variable	Support Function	Description	Value
MKL_MIC_RESOURCE_LIMIT	mkl_mic_set_resource_limit	Specifies how much of the computational resources of Intel Xeon Phi coprocessors can be used by the calling process. Use this environment variable if you need to share Intel Xeon Phi coprocessor cores automatically across multiple processes that call Intel MKL in the AO mode. For example, this might be useful in MPI applications. Actual reservation is made during a call to an Intel MKL AO function.	A floating-point number ranging from 0.0 to 1.0. Special values: • 0.0 - do not share Intel Xeon Phi coprocessors across multiple processes. Default. • MKL_MPI_PPN - enable special fully automated mode for MPI applications. In this mode Intel MKL tries to read the number of MPI processes per node (*ppn*) from the environment variables passed to the process by MPI. If this attempt is successful, Intel MKL sets the actual resource limit to 1.0/*ppn*. **NOTE** For Intel® MPI Library, Open MPI, and IBM Platform MPI, Intel MKL automatically detects *ppn*. For other MPI implementations, use the MKL_MPI_PPN environment variable to set *ppn*. Examples: 1. Two 61-core Intel Xeon Phi coprocessors are available on the system. Three processes simultaneously set MKL_MIC_RESOURCE_LIMIT=0.34 and then call dpotrf in AO mode. As a result, one process receives 40 cores from coprocessor 1, another process receives 40 cores from coprocessor 2, and the remaining process receives cores from each of the two coprocessors for a total of 40 cores. 2. Two 58-core Intel Xeon Phi coprocessors are available on the system. The user makes these settings MKL_MIC_1_WORKDIVISION=0.0 MKL_MIC_PPN=4 MKL_MIC_RESOURCE_LIMIT=MKL_MPI_PPN

Environment Variable	Support Function	Description	Value
			and then runs an MPI application with Intel MKL AO calls. As a result, each MPI process receives 14 cores on Intel Xeon Phi coprocessor 0 because the user excluded coprocessor 1 from computations by setting zero workdivision for it.
MIC_OMP_ NUM_THREADS	mkl_mic_set_ device_num_ threads	Specifies the maximum number of OpenMP* threads to use for AO computations on all the Intel Xeon Phi coprocessors on the system.	An integer greater than 0.
MIC_*<number>*_ OMP_NUM_ THREADS	mkl_mic_set_ device_num_ threads	Specifies the maximum number of OpenMP threads to use for AO computations on a specific Intel Xeon Phi coprocessor on the system. Here *<number>* 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, *<number>* can be 0 or 1.	An integer greater than 0.
OFFLOAD_ REPORT	mkl_mic_set_ offload_report	OFFLOAD_REPORT is a common setting for Intel MKL and Intel® Compilers. It specifies the profiling report level for any offload, including Intel MKL AO. For more information, refer to the *Intel® Compiler User and Reference Guides*. Note that the mkl_mic_set_offload _report function enables you to turn profile reporting on/off at run time but does not change the reporting level.	An integer ranging from 0 to 2: 0 - No reporting, default. 1 - The report includes: • The name of the function called in the AO mode. • Effective work division. The value of -1 indicates that the hint, that is, the work division specified by the mkl_mic_set_workdivison 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.

Environment Variable	Support Function	Description	Value
			2 - In addition to the above information, the report includes: • The amounts of data transferred to and from each available coprocessor during the call.
LD_LIBRARY_PATH	None	Specifies the search path for host-side dynamic libraries.	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.
MIC_LD_LIBRARY_PATH	None	Specifies the search path for coprocessor-side dynamic libraries.	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. • The path to Intel MKL coprocessor-side libraries. The default path is *<mkl directory>*/lib/mic.
MKL_MIC_THRESHOLDS_?GEMM	None	Specifies matrix size thresholds for ?GEMM computations in the AO mode.	Three comma-separated integers: *M*, *N*, *K*. If this environment variable is set, any call to a ?GEMM function with problem sizes M_1, N_1, and K_1 tries to offload computations only if $M_1>M$, $N_1>N$, and $K_1>K$. This setting is only a hint, and Intel MKL may decide to not offload computations depending on the problem size and environment. Example: To set the thresholds to *M*=2000, *N*=1000, *K*=500 for DGEMM, set MKL_MIC_THRESHOLDS_DGEMM=2000,1000,500.

- 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 AO 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.

See Also

Setting Environment Variables for Automatic Offload
Intel® Software Documentation Library for Intel® Compiler User and Reference Guides

Setting Environment Variables for Automatic Offload

Important
To use Automatic Offload:

- If you completed the Scripts to Set Environment Variables 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:

  ```
  export MKL_MIC_ENABLE=1
  ```

  ```
  export OFFLOAD_DEVICES=<list>
  ```

  For example: `export OFFLOAD_DEVICES=1,3`

  ```
  export OFFLOAD_ENABLE_ORSL=1
  ```

  ```
  export MKL_HOST_WORKDIVISION=<value>
  ```

  For example: `export MKL_HOST_WORKDIVISION=0.2`

  ```
  export MKL_MIC_WORKDIVISION=<value>
  ```

  ```
  export MKL_MIC_<number>_WORKDIVISION=<value>
  ```

  For example: `export MKL_MIC_2_WORKDIVISION=0.33`

  ```
  export MKL_MIC_MAX_MEMORY=<value>
  ```

  ```
  export MKL_MIC_<number>_MAX_MEMORY=<value>
  ```

  For example: `export MKL_MIC_0_MAX_MEMORY=2G`

  ```
  export MKL_MIC_REGISTER_MEMORY=1
  ```

  ```
  export MKL_MIC_RESOURCE_LIMIT=<value>
  ```

  For example: `export MKL_MIC_RESOURCE_LIMIT=0.34`

  ```
  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}"
  ```

  ```
  export MIC_LD_LIBRARY_PATH="/opt/intel/mic/coi/device-linux-release/lib:$
  {MKLROOT}/lib/mic:${MIC_LD_LIBRARY_PATH}"
  ```

  ```
  export MKL_MIC_THRESHOLDS_?GEMM="<N>,<M>,<K>"
  ```

  For example: `export MKL_MIC_THRESHOLDS_?GEMM="2000,1000,500"`

- For a 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 MKL_MIC_REGISTER_MEMORY 1`

  `setenv MKL_MIC_RESOURCE_LIMIT <value>`

  For example: `setenv MKL_MIC_RESOURCE_LIMIT 0.34`

  `setenv MIC_OMP_NUM_THREADS <value>`

  `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}"
  ```

  ```
  setenv MIC_LD_LIBRARY_PATH "/opt/intel/mic/coi/device-linux-release/lib:$
  {MKLROOT}/lib/mic:${MIC_LD_LIBRARY_PATH}"
  ```

  `setenv MKL_MIC_THRESHOLDS_?GEMM "<N>,<M>,<K>"`

  For example: `setenv MKL_MIC_THRESHOLDS_?GEMM "2000,1000,500"`

See Also

Automatic Offload Controls

Detailed Directory Structure of the lib/intel64_lin_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.

See Also

Automatic Offload

Running Intel MKL on an Intel Xeon Phi Coprocessor in Native Mode

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

```
c     Upload A and B to the card, and do not deallocate them after the
c     pragma. C is uploaded and downloaded back, but the allocated memory
c     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, N, B, N, 1.0, C, N )

c     Change C here

c     Reuse A and B on the card, and upload the new C. Free all the
c     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, N, B, N, -1.0, C, N )
```

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, &N, &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, &N, &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/intel64_win_intel64_lin_mic Directory for a full list of libraries provided in the *<mkl directory>*/lib/intel64_lin_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 Scripts to Set Environment Variables 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_lin
- MIC_LD_LIBRARY_PATH to contain *<mkl directory>*/lib/intel64_lin_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 Scripts to Set Environment Variables 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_lin/libmkl_intel_lp64.a
$MKLROOT/lib/intel64_lin/libmkl_intel_thread.a
$MKLROOT/lib/intel64_lin/libmkl_core.a -Wl,--end-group
-openmp -lpthread -lm
-offload-option,mic,compiler,"-Wl,--start-group $MKLROOT/lib/intel64_lin_mic/
libmkl_intel_lp64.a
$MKLROOT/lib/intel64_lin_mic/libmkl_intel_thread.a
$MKLROOT/lib/intel64_lin_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_lin
-lmkl_intel_lp64 -lmkl_intel_thread
-lmkl_core -openmp -lpthread -lm
```

```
-offload-option,mic,compiler,"-L$MKLROOT/lib/intel64_lin_mic
-lmkl_intel_lp64 -lmkl_intel_thread -lmkl_core"
```

or

```
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_lin/libmkl_intel_ilp64.a
$MKLROOT/lib/intel64_lin/libmkl_intel_thread.a
$MKLROOT/lib/intel64_lin/libmkl_core.a -Wl,--end-group
-openmp -lpthread -lm
-offload-option,mic,compiler,"-Wl,--start-group
$MKLROOT/lib/intel64_lin_mic/libmkl_intel_ilp64.a $MKLROOT/lib/intel64_lin_mic/
libmkl_intel_thread.a
$MKLROOT/lib/intel64_lin_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_lin
-lmkl_intel_ilp64 -lmkl_intel_thread
-lmkl_core -openmp -lpthread -lm
-offload-option,mic,compiler,"-L$MKLROOT/lib/intel64_lin_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_lin/libmkl_intel_lp64.a
$MKLROOT/lib/intel64_lin/libmkl_sequential.a
$MKLROOT/lib/intel64_lin/libmkl_core.a -Wl,--end-group -lm
-offload-option,mic,compiler,"-Wl,--start-group $MKLROOT/lib/intel64_lin_mic/
libmkl_intel_lp64.a
$MKLROOT/lib/intel64_lin_mic/libmkl_sequential.a $MKLROOT/lib/intel64_lin_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_lin
-lmkl_intel_lp64 -lmkl_sequential -lmkl_core -lm
-offload-option,mic,compiler,"-L$MKLROOT/lib/intel64_lin_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 the 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.

See Also

Automatic Offload
Compiler Assisted Offload

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/intel64_lin_mic` directory.
   - `libiomp5.so` in the *<parent directory>*`/compiler/lib/intel64_lin_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 the number of threads and the thread affinity using your threading run-time library.
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/intel64_lin_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 Scripts to Set Environment Variables 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_lin`
- `MIC_LD_LIBRARY_PATH` to contain `<mkl directory>/lib/intel64_lin_mic`

When building your application that uses Intel MKL ScaLAPACK or Cluster FFT, follow the linking guidelines in the Linking with Intel MKL Cluster Software, but be aware of Intel MKL specifics on Intel Xeon Phi coprocessors:

- Only Intel compiler and Intel MPI are supported
- Only OpenMP threading layer for Intel compilers and Intel® Threading Building Blocks (Intel® TBB) threading layer are provided

You can find a full list of Intel MKL libraries for Intel MIC Architecture in Detailed Directory Structure of the lib/intel64_win_intel64_lin_mic Directory. Be aware that coprocessors run a Unix* operating system.

TIP
Use the Using 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.
- You are using the Intel® C++ Compiler.
- Your programming interface is LP64.
- `<path to mpi binaries>` is the path to Intel MPI binaries for Intel MIC Architecture.
- `$MKLPATH` is a user-defined variable that contains `$MKLROOT/lib/intel64_lin_mic`

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$MKLPATH \
-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:

```
<path to mpi binaries>/mpicc -mmic <files to link> \
-Wl,--start-group \
$MKLPATH/libmkl_cdft_core.a \
$MKLPATH/libmkl_blacs_intelmpi_lp64.a \
$MKLPATH/libmkl_intel_lp64.a \
$MKLPATH/libmkl_intel_thread.a \
$MKLPATH/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.
- You are using the Intel® Fortran Compiler.
- Your programming interface is LP64.
- *<path to mpi binaries>* is the path to Intel MPI binaries for Intel MIC Architecture.
- `$MKLPATH` is a user-defined variable that contains `$MKLROOT/lib/intel64_lin_mic`.

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>/mpiifort -mmic <files to link> \
-L$MKLPATH \
-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:

```
<path to mpi binaries>/mpiifort -mmic <files to link> \
-Wl,--start-group \
$MKLPATH/libmkl_cdft_core.a \
$MKLPATH/libmkl_blacs_intelmpi_lp64.a \
$MKLPATH/libmkl_intel_lp64.a \
$MKLPATH/libmkl_intel_thread.a \
$MKLPATH/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 OpenMP threads it uses to parallelize computations:

- For native runs on coprocessors, Intel MKL uses 4**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*(*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 *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.

For more information, see the Knowledge Base article at http://software.intel.com/en-us/articles/performance-tips-of-using-intel-mkl-on-intel-xeon-phi-coprocessor.

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.

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.

Number of Threads

For FFT, 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**0.5 MB
– 4**Number-of-Phi-Cores,* if the total size is greater than *Number-of-Phi-Cores**0.5 MB

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

For more information, see Improving Performance with Threading and SettingDetermining the Number of OpenMP* Threads.

OpenMP Thread Affinity

To improve performance of Intel MKL routines, set `KMP_AFFINITY=balanced` for all function domains.

Intel® Threading Building Blocks Facilities

To improve performance of Intel MKL routines, use the `tbb::affinity_partitioner` class.

To adjust the number of threads (for example, see Number of Threads for FFT), use the `tbb::task_scheduler_init` class.

For more information, see the Intel® TBB documentation at https://www.threadingbuildingblocks.org/documentation.

See Also

Examples of Compiler Assisted Offload
Intel Software Documentation Library

Managing Behavior of the Intel(R) Math Kernel Library with Environment Variables

11

Managing Behavior of Function Domains

Setting the Default Mode of Vector Math with an Environment Variable

Intel® Math Kernel Library (Intel® MKL) enables overriding the default setting of the Vector Mathematics (VM) global mode using the `MKL_VML_MODE` environment variable.

Because the mode is set or can be changed in different ways, their precedence determines the actual mode used. The settings and function calls that set or change the VM mode are listed below, with the precedence growing from lowest to highest:

1. The default setting
2. The `MKL_VML_MODE` environment variable
3. A call `vmlSetMode` function
4. A call to any VM function other than a service function

For more details, see the Vector Mathematical Functions section in the *Intel MKL Developer Reference* and the description of the `vmlSetMode` function in particular.

To set the `MKL_VML_MODE` environment variable, use the following command in your command shell:

- For the bash shell:

  `export MKL_VML_MODE=<mode-string>`
- For a C shell (csh or tcsh):

  `setenv MKL_VML_MODE <mode-string>`

In these commands, *<mode-string>* controls error handling behavior and computation accuracy, consists of one or several comma-separated values of the *mode* parameter listed in the table below, and meets these requirements:

- Not more than one accuracy control value is permitted
- Any combination of error control values except `VML_ERRMODE_DEFAULT` is permitted
- No denormalized numbers control values are permitted

Values of the *mode* Parameter

Value of *mode*	Description
Accuracy Control	
`VML_HA`	high accuracy versions of VM functions
`VML_LA`	low accuracy versions of VM functions
`VML_EP`	enhanced performance accuracy versions of VM functions
Denormalized Numbers Handling Control	
`VML_FTZDAZ_ON`	Faster processing of denormalized inputs is enabled.
`VML_FTZDAZ_OFF`	Faster processing of denormalized inputs is disabled.
Error Mode Control	
`VML_ERRMODE_IGNORE`	No action is set for computation errors.

Value of *mode*	Description
VML_ERRMODE_STDERR	On error, the error text information is written to *stderr*.
VML_ERRMODE_EXCEPT	On error, an exception is raised.
VML_ERRMODE_CALLBACK	On error, an additional error handler function is called.
VML_ERRMODE_DEFAULT	On error, an exception is raised and an additional error handler function is called.

These commands provide an example of valid settings for the MKL_VML_MODE environment variable in your command shell:

- For the bash shell:

```
export MKL_VML_MODE=VML_LA,VML_ERRMODE_ERRNO,VML_ERRMODE_STDERR
```

- For a C shell (csh or tcsh):

```
setenv MKL_VML_MODE VML_LA,VML_ERRMODE_ERRNO,VML_ERRMODE_STDERR
```

NOTE
VM ignores the MKL_VML_MODE environment variable in the case of incorrect or misspelled settings of *mode*.

Managing Performance of the Cluster Fourier Transform Functions

Performance of Intel MKL Cluster FFT (CFFT) in different applications mainly depends on the cluster configuration, performance of message-passing interface (MPI) communications, and configuration of the run. Note that MPI communications usually take approximately 70% of the overall CFFT compute time. For more flexibility of control over time-consuming aspects of CFFT algorithms, Intel MKL provides the MKL_CDFT environment variable to set special values that affect CFFT performance. To improve performance of your application that intensively calls CFFT, you can use the environment variable to set optimal values for you cluster, application, MPI, and so on.

The MKL_CDFT environment variable has the following syntax, explained in the table below:

```
MKL_CDFT=option1[=value1],option2[=value2],…,optionN[=valueN]
```

Important
While this table explains the settings that usually improve performance under certain conditions, the actual performance highly depends on the configuration of your cluster. Therefore, experiment with the listed values to speed up your computations.

Option	Possible Values	Description
alltoallv	0 (default)	Configures CFFT to use the standard MPI_Alltoallv function to perform global transpositions.
	1	Configures CFFT to use a series of calls to MPI_Isend and MPI_Irecv instead of the MPI_Alltoallv function.
	4	Configures CFFT to merge global transposition with data movements in the local memory. CFFT performs global transpositions by calling MPI_Isend and MPI_Irecv in this case. Use this value in a hybrid case (MPI + OpenMP), especially when the number of processes per node equals one.
wo_omatcopy	0	Configures CFFT to perform local FFT and local transpositions separately.

Option	Possible Values	Description
		CFFT usually performs faster with this value than with `wo_omatcopy` = 1 if the configuration parameter `DFTI_TRANSPOSE` has the value of `DFTI_ALLOW`. See the *Intel MKL Developer Reference* for details.
	1	Configures CFFT to merge local FFT calls with local transpositions. CFFT usually performs faster with this value than with `wo_omatcopy` = 0 if `DFTI_TRANSPOSE` has the value of `DFTI_NONE`.
	-1 (default)	Enables CFFT to decide which of the two above values to use depending on the value of `DFTI_TRANSPOSE`.
`enable_soi`	Not applicable	A flag that enables low-communication Segment Of Interest FFT (SOI FFT) algorithm for one-dimensional complex-to-complex CFFT, which requires fewer MPI communications than the standard nine-step (or six-step) algorithm. **CAUTION** While using fewer MPI communications, the SOI FFT algorithm incurs a minor loss of precision (about one decimal digit).

The following example illustrates usage of the environment variable assuming the bash shell:

```
export MKL_CDFT=wo_omatcopy=1,alltoallv=4,enable_soi
mpirun -ppn 2 -n 16 ./mkl_cdft_app
```


Instruction Set Specific Dispatching on Intel® Architectures

Intel MKL automatically queries and then dispatches the code path supported on your Intel® processor to the optimal instruction set architecture (ISA) by default. The `MKL_ENABLE_INSTRUCTIONS` environment variable or the `mkl_enable_instructions` support function enables you to dispatch to an ISA-specific code path of your choice. For example, you can run the Intel® Advanced Vector Extensions (Intel® AVX) code path on an Intel processor based on Intel® Advanced Vector Extensions 2 (Intel® AVX2), or you can run the Intel® Streaming SIMD Extensions 4-2 (Intel® SSE4-2) code path on an Intel AVX-enabled Intel processor. This feature is not available on non-Intel processors.

In some cases Intel MKL also provides support for upcoming architectures ahead of hardware availability, but the library does not automatically dispatch the code path specific to an upcoming ISA by default. If for your exploratory work you need to enable an ISA for an Intel processor that is not yet released or if you are working in a simulated environment, you can use the `MKL_ENABLE_INSTRUCTIONS` environment variable or `mkl_enable_instructions` support function.

The following table lists possible values of MKL_ENABLE_INSTRUCTIONS alongside the corresponding ISA supported by a given processor. MKL_ENABLE_INSTRUCTIONS dispatches to the default ISA if the ISA requested is not supported on the particular Intel processor. For example, if you request to run the Intel AVX512 code path on a processor based on Intel AVX2, Intel MKL runs the Intel AVX2 code path. The table also explains whether the ISA is dispatched by default on the processor that supports this ISA.

Value of MKL_ENABLE_INSTRUCTIONS	ISA	Dispatched by Default
AVX512	Intel AVX-512 for systems based on Intel® Xeon® processors	Yes
AVX512_MIC	Intel AVX-512 for systems based on Intel® Xeon Phi™ processors and coprocessors	Yes
AVX2	Intel AVX2	Yes
AVX	Intel AVX	Yes
SSE4_2	Intel SSE4-2	Yes

For more details about the mkl_enable_instructions function, including the argument values, see the *Intel MKL Developer Reference*.

For example:

- To configure the library not to dispatch more recent architectures than Intel AVX2, do one of the following:
  - Call

    ```
    mkl_enable_instructions(MKL_ENABLE_AVX2)
    ```
  - Set the environment variable:
    - For the bash shell:

      ```
      export MKL_ENABLE_INSTRUCTIONS=AVX2
      ```
    - For a C shell (csh or tcsh):

      ```
      setenv MKL_ENABLE_INSTRUCTIONS AVX2
      ```

NOTE
Settings specified by the mkl_enable_instructions function take precedence over the settings specified by the MKL_ENABLE_INSTRUCTIONS environment variable.

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

Configuring Your Integrated Development Environment to Link with Intel(R) Math Kernel Library

12

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_lin.
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® Math Kernel Library Benchmarks

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Optimization Notice
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Intel® Optimized LINPACK Benchmark for Linux*

Intel® Optimized LINPACK Benchmark for Linux* 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/.

Acknowledgement

This product includes software developed at the University of Tennessee, Knoxville, Innovative Computing Laboratories.

Contents of the Intel® Optimized LINPACK Benchmark

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

File in `./benchmarks/linpack/`	Description
`xlinpack_xeon32`	The 32-bit program executable for a system based on Intel® Xeon® processor or Intel® Xeon® processor MP with or without Intel® Streaming SIMD Extensions 3 (SSE3).

File in ./benchmarks/linpack/	Description
xlinpack_xeon64	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.
xlinpack_mic	The 64-bit program executable for a native run on an Intel Xeon Phi coprocessor.
runme_xeon32	A sample shell script for executing a pre-determined problem set for xlinpack_xeon32.
runme_xeon64	A sample shell script for executing a pre-determined problem set for xlinpack_xeon64.
runme_xeon64_ao	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.
runme_mic	A sample shell script for executing a pre-determined problem set for xlinpack_mic.
lininput_xeon32	Input file for a pre-determined problem for the runme_xeon32 script.
lininput_xeon64	Input file for a pre-determined problem for the runme_xeon64 script.
lininput_xeon64_ao	Input file for a pre-determined problem for the runme_xeon64_ao script.
lininput_mic	Input file for a pre-determined problem for the runme_mic script.
help.lpk	Simple help file.
xhelp.lpk	Extended help file.
These files are not available immediately after installation and appear as a result of execution of an appropriate runme script.	
lin_xeon32.txt	Result of the runme_xeon32 script execution.
lin_xeon64.txt	Result of the runme_xeon64 script execution.
lin_xeon64_ao.txt	Result of the runme_xeon64_ao script execution.
lin_mic.txt	Result of the runme_mic script execution.

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 examples. Different systems have different numbers of processors or amounts of memory and therefore require new input files. The extended help can give 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 OpenMP 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

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Notice revision #20110804

Known Limitations of the Intel® Optimized LINPACK Benchmark

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

- Intel Optimized LINPACK Benchmark supports only OpenMP threading
- 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) and

for benchmarking your cluster. To use the benchmark you need to be familiar with HPL usage. The Intel Optimized MP LINPACK Benchmark provides some enhancements designed to make the HPL usage more convenient and to use Intel® Message-Passing Interface (MPI) settings to improve performance.

The Intel Optimized MP LINPACK Benchmark measures the amount of time it takes to factor and solve a random dense system of linear equations (*Ax=b*) in `real*8` precision, converts that time into a performance rate, and tests the results for accuracy. The benchmark uses random number generation and full row pivoting to ensure the accuracy of the results.

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. The prebuilt binaries require Intel® MPI library be installed on the cluster. The run-time version of Intel MPI library is free and can be downloaded from http://www.intel.com/software/products/ .

NOTE
Intel Optimized MP LINPACK Benchmark prebuilt binaries cannot run with the symmetric model of the Intel MPI library, where the MPI ranks reside on the host and the coprocessors. For details, see the article at https://software.intel.com/en-us/articles/using-the-intel-mpi-library-on-intel-xeon-phi-coprocessor-systems.

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® Math Kernel Library (Intel® MKL) license.

Intel MKL provides prebuilt binaries that are linked against Intel MPI libraries either statically or dynamically. In addition, binaries linked with a customized MPI implementation can be created using the Intel MKL MPI wrappers.

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 or dynamically linked against a particular version of Intel MPI by yourself.

HPL code is homogeneous by nature: it requires that each MPI process runs in an environment with similar CPU and memory constraints. The Intel Optimized MP LINPACK Benchmark supports heterogeneity, meaning that the data distribution can be balanced to the performance requirements of each node, provided that there is enough memory on that node to support additional work. For information on how to configure Intel MKL to use the internode heterogeneity, see Heterogeneous Support in the Intel Optimized MP LINPACK Benchmark.

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

The Intel Optimized MP LINPACK Benchmark supports first- and second-generation Intel® Xeon Phi™ coprocessors in offload modes, where the MPI processes are run on the host Intel® Xeon® processor. The second-generation Intel Xeon Phi processor is also supported in native mode, where the MPI processes are run directly on the Intel Xeon Phi processor. The offload mode combines use of different parallelization methods and offloading computations to coprocessors. This mode can be advantageous if the host Intel Xeon processor has more memory than the Intel Xeon Phi coprocessor because the MPI processes have access to more memory when run on the host processors than on the coprocessors. To maximize performance, increase the memory on the host processor or processors (64 GB per coprocessor is ideal) and run a large problem using a large block size. Such runs offload pieces of work to the coprocessors. Although this method increases the PCI Express bus traffic, it is worthwhile for solving a problem that is large enough.

See Also
Offloading to Intel Xeon Phi Coprocessors

Contents of the Intel Optimized MP LINPACK Benchmark

The Intel Optimized MP LINPACK Benchmark includes prebuilt binaries linked with Intel® MPI library. For a customized MPI implementation, tools are also included to build a binary using Intel MKL MPI wrappers. All the files are located in the `./benchmarks/mp_linpack/` subdirectory of the Intel MKL directory.

File in *<mkl directory>*`/benchmarks/mp_linpack/`	**Contents**
`COPYRIGHT`	Original Netlib HPL copyright document.
`readme.txt`	Information about the files provided.
Prebuilt executables for performance testing	
`xhpl_intel64_dynamic`	Prebuilt binary for the Intel® 64 architecture dynamically linked against Intel MPI library[‡]. The binary accelerates execution by offloading computations to Intel Xeon Phi coprocessors if they are available on the system.
`xhpl_intel64_static`	Prebuilt binary for the Intel® 64 architecture statically linked against Intel MPI library. The binary accelerates execution by offloading computations to Intel Xeon Phi coprocessors if they are available on the system.
Run scripts and an input file example	
`runme_intel64_dynamic`	Sample run script for the Intel® 64 architecture and binary dynamically linked against Intel MPI library.
`runme_intel64_static`	Sample run script for the Intel® 64 architecture and binary statically linked against Intel MPI library.
`runme_intel64_prv`	Script that sets HPL environment variables. It is called by `runme_intel64_static` and `runme_intel64_dynamic`.
`HPL.dat`	Example of an HPL configuration file.
Prebuilt libraries and utilities for building with a customized MPI implementation	
`libhpl_intel64.a`	Library file required to build Intel Optimized MP LINPACK Benchmark for the Intel® 64 architecture with a customized MPI implementation.
`HPL_main.c`	Source code required to build Intel Optimized MP LINPACK Benchmark for the Intel® 64 architecture with a customized MPI implementation.
`build.sh`	Build script for creating Intel Optimized MP LINPACK Benchmark for the Intel® 64 architecture with a customized MPI implementation.

[‡] 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

Building the Intel Optimized MP LINPACK Benchmark for a Customized MPI Implementation

The Intel Optimized MP LINPACK Benchmark contains a sample build script `build.sh`. If you are using a customized MPI implementation, this script builds a binary using Intel MKL MPI wrappers. To build the binary, follow these steps:

1. Specify the location of Intel MKL to be used (`MKLROOT`)
2. Set up your MPI environment
3. Run the script `build.sh`

See Also

Contents of the Intel Optimized MP LINPACK Benchmark

Building the Netlib HPL from Source Code

The source code for Intel Optimized MP LINPACK Benchmark is not provided. However, you can download reference Netlib HPL source code from http://www.netlib.org/benchmark/hpl/ . To build the HPL:

1. Download and extract the source code.
2. Copy the makefile:

   ```
   $> cp setup/Make.Linux_Intel64 .
   ```
3. Edit `Make.Linux_Intel64` as appropriate
4. Build the HPL binary:

   ```
   $> make arch=Linux_Intel64
   ```
5. Check that the built binary is available in the `bin/Linux_Intel64` directory.

NOTE
Intel Optimized MP LINPACK Benchmark may contain additional optimizations compared to the reference Netlib HPL implementation.

See Also

Contents of the Intel Optimized MP LINPACK Benchmark

Configuring Parameters

The most significant parameters in `HPL.dat` are *P, Q, NB*, and *N*. Specify them as follows:

- *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.

  Choose $P \leq Q$.
- *NB* - the block size of the data distribution.

  The table below shows recommended values of *NB* for different Intel® processors:

Processor	*NB*
Intel® Xeon® Processor X56*/E56*/E7-*/E7*/X7* (codenamed Nehalem or Westmere)	256
Intel Xeon Processor E26*/E26* v2 (codenamed Sandy Bridge or Ivy Bridge)	256
Intel Xeon Processor E26* v3/E26* v4 (codenamed Haswell or Broadwell)	192
Intel® Core™ i3/i5/i7-6* Processor (codenamed Skylake Client)	192

Processor	*NB*
Intel® Xeon Phi™ Processor 72* (codenamed Knights Landing)	336
Intel Xeon Processor supporting Intel® Advanced Vector Extensions 512 (Intel® AVX-512) instructions (codenamed Skylake Server)	384

For recommended values of *NB* when offloading to one or more Intel Xeon Phi coprocessors, see Offloading to Intel Xeon Phi Coprocessors.

- *N* - the problem size:
  - For homogeneous runs, choose *N* divisible by *NB*LCM(P,Q)*, where *LCM* is the least common multiple of the two numbers.
  - For heterogeneous runs, see Heterogeneous Support in the Intel Optimized MP LINPACK Benchmark for how to choose *N*.

NOTE
Increasing *N* usually increases performance, but the size of *N* is bounded by memory. In general, you can compute the memory required to store the matrix (which does not count internal buffers) as 8*N*N/(P*Q) bytes, where *N* is the problem size and *P* and *Q* are the process grids in `HPL.dat`. A general rule of thumb is to choose a problem size that fills 80% of memory. When offloading to Intel Xeon Phi coprocessors, you may choose a problem size that fills 70% of memory, to leave room for additional buffers needed for offloading. Choose *N* and *NB* such that *N* > > *NB*.

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 file every time you do a new run.

Placeholders in this command line illustrate these parameters:

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

You can also use command-line parameters with the sample runme scripts. For example:

```
./runme_intel64_dynamic -m <memory size in Mbytes> -b <block size> -p <grid row dimn> -q <grid column dimn>
```

For more command-line parameters, see Heterogeneous Support in the 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` and the script are correct:

```
./runme_intel64_dynamic -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*=256 on 16 nodes, adjust the script to set the total number of MPI processes to 16 and execute this command:

```
./runme_intel64_dynamic -m 50000 -b 256 -p 4 -q 4
```

Running the Intel Optimized MP LINPACK Benchmark

To run the Intel Optimized MP LINPACK Benchmark on multiple nodes or on one node with multiple MPI processes, you need to use MPI and either modify `HPL.dat` or use Ease-of-use Command-line Parameters. The following example describes how to run the dynamically-linked prebuilt Intel Optimized MP LINPACK Benchmark binary using the script provided. To run other binaries, adjust the steps accordingly; specifically, change line 58 of `runme_intel64_dynamic` to point to the appropriate binary.

1. Load the necessary environment variables for the Intel MPI Library and Intel® compiler:

   ```
   <parent directory>/bin/compilervars.sh intel64
   ```

   ```
   <mpi directory>/bin64/mpivars.sh
   ```

2. In `HPL.dat`, set the problem size *N* to 10000. Because this setting is for a test run, the problem size should be small.
3. For better performance, enable non-uniform memory access (NUMA) on your system and configure to run an MPI process for each NUMA socket as explained below.

   NOTE
   High-bandwidth Multi-Channel Dynamic Random Access Memory (MCDRAM) on the second-generation Intel Xeon Phi processors may appear to be a NUMA node. However, because there are no CPUs on this node, do not run an MPI process for it.

   - Refer to your BIOS settings to enable NUMA on your system.
   - Set the following variables at the top of the `runme_intel64_dynamic` script according to your cluster configuration:

`MPI_PROC_NUM`	The total number of MPI processes.
`MPI_PER_NODE`	The number of MPI processes per each cluster node.

   - In the `HPL.dat` file, set the parameters *Ps* and *Qs* so that *Ps* * *Qs* equals the number of MPI processes. For example, for 2 processes, set *Ps* to 1 and *Qs* to 2. Alternatively, leave the `HPL.dat` file as is and launch with `-p` and `-q` command-line parameters.
4. Execute `runme_intel64_dynamic` script:

   ```
   ./runme_intel64_dynamic
   ```

5. Rerun the 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 line 6 of `HPL.dat` or use the `-n` command-line parameter:

   - For 16 GB: `40000 Ns`
   - For 32 GB: `56000 Ns`
   - For 64 GB: `83000 Ns`

See Also

Notational Conventions
Building the Intel Optimized MP LINPACK Benchmark for a Customized MPI Implementation
Building the Netlib HPL from Source Code
Offloading to Intel Xeon Phi Coprocessors
Using High-bandwidth Memory with Intel MKL

Offloading to Intel Xeon Phi Coprocessors

Intel Optimized MP LINPACK Benchmark reacts to `MKL_MIC_ENABLE` and `OFFLOAD_DEVICES` environment variables for automatic offload to Intel Xeon Phi coprocessors. They also inform you how many Intel Xeon Phi coprocessors are detected during the run. The top of the output has a line like this:

```
Number of Intel(R) Xeon Phi(TM) coprocessors: 1
```

This is the number of Intel Xeon Phi coprocessors 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).

You can use environment variables to adjust the behavior of your runs. For a list of supported environment variables, see Environment Variables. The variable `NUMMIC` refers to the number of Intel Xeon Phi coprocessors per cluster node. You can use `HPL_MIC_DEVICE` and `HPL_MIC_SHAREMODE` environment

variables to share the Intel Xeon Phi coprocessors among MPI processes. The scripts`runme_intel64_dynamic` and `runme_intel64_static` set these environment variables for you for a given number of MPI ranks per node.

Adjust the block size *NB* and problem size *N* parameters as appropriate. The table below shows recommended values of *NB* for different numbers of Intel Xeon Phi coprocessors per node. The values may vary and depend on the PCI Express settings and performance of main memory.

1 coprocessor	2 coprocessors	3 coprocessors
960	1024	1200

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* > > *NB*. In that event, it is better not to use the Intel Optimized MP LINPACK Benchmark in an offload mode.

Heterogeneous Support in the Intel Optimized MP LINPACK Benchmark

Intel Optimized MP LINPACK Benchmark achieves heterogeneous support by distributing the matrix data unequally between the nodes. The heterogeneous factor command-line parameter `f` controls the amount of work to be assigned to the more powerful nodes, while the command-line parameter `c` controls the number of process columns for the faster nodes:

```
./xhpl -n <problem size> -b <block size> -p <grid row dimn> -q <grid column dimn> -f
<heterogeneous factor> -c <number of faster processor columns>
```

If the heterogeneous factor is 2.5, roughly 2.5 times the work will be put on the more powerful nodes. The more work you put on the more powerful nodes, the more memory you might be wasting on the other nodes if all nodes have equal amount of memory. If your cluster includes many different types of nodes, you may need multiple heterogeneous factors.

Let *P* be the number of rows and *Q* the number of columns in your processor grid (*PxQ*). The work must be *homogeneous* within each processor column because vertical operations, such as pivoting or panel factorization, 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. The `-f 1.0 -c 0` setting corresponds 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 ~= sqrt(Memory Utilization * P * Q * Memory Size in Bytes / 8)*

Memory Utilization is usually around 0.8 for homogeneous Intel Xeon processor systems. With Intel Xeon Phi coprocessors involved, *Memory Utilization* is around 0.7 due to extra buffers needed for communication. On a heterogeneous system, you might apply a different formula for *N* for each set of nodes that are the same and then choose the minimum *N* over all sets. 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*C* nodes. First compute the sum of the parts: *S =F*P*C + P*(Q-C)*. Note that on a homogeneous system *S=P*Q,F*=1, and *C=Q*. Take *N* as

*N ~= sqrt(Memory Utilization * P * Q * ((F*P*C)/S) * Memory Size in Bytes / 8)*

or simply scale down the value of *N* for the homogeneous system by *sqrt(F*P*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 8*N*^2/(*P*Q*) bytes. So a homogeneous run might look like:

```
./xhpl -n 820000 -b 256 -p 10 -q 10
```

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 size, 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, 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:

```
./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.

WARNING
The number of faster nodes must be *C***P*. If the number of faster nodes is not divisible by *P*, you might not be able to take advantage of the extra performance potential by giving the faster nodes extra work.

While it suffices to simply provide `f` and `c` command-line parameters if you need only one heterogeneous factor, you must add lines to the `HPL.dat` input to support multiple heterogeneous factors. For the above example (two processor columns have nodes that are 2.7 times faster), instead of passing `f` and `c` command-line parameters you can modify the `HPL.dat` input file by adding these two lines to the end:

```
1         number of heterogeneous factors
0 1 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).

If instead there are three different types of nodes in a cluster and you need at least 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 `HPL.dat`, primarily focus on the most powerful nodes. 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 `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.

Environment Variables

The table below lists Intel MKL environment variables to control runs of the Intel Optimized MP LINPACK Benchmark.

Environment Variable	Description	Value
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. • 1 - only one root node displays a log, exactly the same as the ASYOUGO option provides. • 2 - the most detailed log is displayed. All *P* root nodes in the processor column that owns the current column block display a log.
HPL_HOST_CORE, HPL_HOST_NODE	Specifies cores or Non-Uniform Memory Access (NUMA) nodes to be used. HPL_HOST_NODE requires NUMA mode to be enabled. You can check whether it is enabled by the numactl --hardware command. The default behavior is auto-detection of the core or NUMA node.	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.
HPL_SWAPWIDTH	Specifies width for each swap operation.	16 or 24. The default is 24.
HPL_MIC_DEVICE	Specifies Intel Xeon Phi coprocessor(s) to be used. All available Intel Xeon Phi coprocessors are used by default. **NOTE** 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.	A comma-separated list of integers, each ranging from 0 to the largest number of an Intel Xeon Phi coprocessor on the node.
HPL_PNUMMICS	Specifies the number of Intel Xeon Phi coprocessors to be used. The HPL_MIC_DEVICE environment variable takes precedence over	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.

Environment Variable	Description	Value
	HPL_PNUMMICS, and the value of HPL_PNUMMICS is ignored if you set HPL_MIC_DEVICE. The default behavior is auto-detection of the number of coprocessors.	
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. While the default for HPL_MIC_CORE is some core, the default for HPL_MIC_NODE is a core that the coprocessor shares with the same 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.
HPL_MIC_NUMCORES	Specifies the number of cores to be used for an Intel Xeon Phi coprocessor. All the coprocessor cores are used by default, which produces best performance.	An integer ranging from 1 to the number of cores of the coprocessor.
HPL_MIC_SHAREMODE	Specifies whether and how an Intel Xeon Phi coprocessor is shared among two MPI processes. See example 5 for details.	An integer ranging from 0 to 2: • 0 - no sharing, default • 1 - the lower half of the cores will be used for the MPI process. • 2 - the upper half of the cores will be used for the MPI process.
HPL_MIC_EXQUEUES	Specifies the queue size on an Intel Xeon Phi coprocessor. Using a larger number is typically better while it increases the memory consumption for the Intel Xeon Phi coprocessor. If out of memory errors are encountered, try a lower number.	An integer ranging from 0 to 512. The default is 128.

You can set Intel Optimized MP LINPACK Benchmark environment variables using the PMI_RANK and PMI_SIZE environment variables of the Intel MPI library, and you can create a shell script to automate the process.

Examples of Environment Settings

#	Settings	Behavior of the Intel Optimized MP Linpack Benchmark
1	Nothing specified	All Intel Xeon processors and all Intel Xeon Phi coprocessors in the cluster are used.
2	`HPL_PNUMMICS=0`	Intel Xeon Phi coprocessors are not used.
3	`HPL_MIC_DEVICE=0,2` `HPL_HOST_CORE=1-3,8-10`	Only Intel Xeon Phi coprocessors 0 and 2 and Intel Xeon processor cores 1,2,3,8,9, and 10 are used.
4	`HPL_HOST_NODE=1`	Only Intel Xeon processor cores on NUMA node 1 are used.
5	`HPL_MIC_DEVICE=0,1` `HPL_MIC_SHAREMODE=0,2`	Only Intel Xeon Phi coprocessors 0 and 1 are used: • On the coprocessor 0, all cores are used. • On the coprocessor 1, the upper half of the cores is used. For a 61-core Intel Xeon Phi coprocessor, the upper half includes cores 31-61. This setting is useful to share an Intel Xeon Phi coprocessor among two MPI processes for an odd number of Intel Xeon Phi coprocessors.

Improving Performance of Your Cluster

To improve cluster performance, follow these steps, provided all required software is installed on each node:

1. Reboot all nodes.
2. Ensure all nodes are in identical conditions and no zombie processes are left running from prior HPL runs. To do this, run single-node Stream and Intel Optimized MP LINPACK Benchmark on every node. Ensure results are within 10% 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, such as one found in the Intel® MPI Benchmarks package.
4. Run an Intel Optimized MP LINPACK Benchmark on pairs of two or four nodes and ensure results are within 10% of each other. The problem size must be large enough depending on the memory size and CPU speed.
5. Run a small problem size over the complete cluster to ensure correctness.
6. Increase the problem size and run the real test load.
7. In case of problems go back to step 2.

Before making a heterogeneous run, always run its homogeneous equivalent first. If you are using Intel Xeon Phi coprocessors in an offload mode, first run on the Intel Xeon processors alone.

See Also

Heterogeneous Support in the Intel Optimized MP LINPACK Benchmark

Intel® Optimized High Performance Conjugate Gradient Benchmark

Overview of the Intel Optimized HPCG

The Intel® Optimized High Performance Conjugate Gradient Benchmark (Intel® Optimized HPCG) provides an implementation of the HPCG benchmark (http://hpcg-benchmark.org) optimized for Intel® processors and Intel® Xeon Phi™ coprocessors with Intel® Advanced Vector Extensions (Intel® AVX) and Intel® Advanced Vector Extensions 2 (Intel® AVX2) support. The HPCG Benchmark is intended to complement the High Performance LINPACK benchmark used in the TOP500 (http://www.top500.org) system ranking by providing a metric that better aligns with a broader set of important cluster applications.

The HPCG benchmark implementation is based on a 3-dimensional (3D) regular 27-point discretization of an elliptic partial differential equation. The implementation calls a 3D domain to fill a 3D virtual process grid for all the available MPI ranks. HPCG uses the preconditioned conjugate gradient method (CG) to solve the intermediate systems of equations and incorporates a local and symmetric Gauss-Seidel preconditioning step that requires a triangular forward solve and a backward solve. A synthetic multi-grid V-cycle is used on each preconditioning step to make the benchmark better fit real-world applications. HPCG implements matrix multiplication locally, with an initial halo exchange between neighboring processes. The benchmark exhibits irregular accesses to memory and fine-grain recursive computations that dominate many scientific workloads (for details, see http://www.sandia.gov/~maherou/docs/HPCG-Benchmark.pdf).

The Intel® Optimized HPCG contains source code of the HPCG v2.4 reference implementation with the modifications necessary to include Intel® architecture optimizations, prebuilt benchmark executables and four dynamic libraries with kernels of sparse matrix-vector multiplication (SpMV), symmetric Gauss-Seidel smoother (SYMGS), and Gauss-Seidel preconditioner (GS) optimized for Intel AVX, Intel AVX2, and Intel Xeon Phi coprocessors. You can use this package to evaluate the performance of distributed-memory systems based on any generation of Intel® Xeon® processor E3 family, Intel® Xeon® processor E5 family, Intel® Xeon® processor E7 family, and Intel Xeon Phi coprocessor family.

The SpMV and GS kernels are implemented using an inspector-executor model. The inspection step chooses the best algorithm for the input matrix and converts the matrix to a special internal representation to achieve high performance at the execution step.

Versions of the Intel Optimized HPCG

The Intel Optimized HPCG package includes prebuilt HPCG benchmark for Intel MPI 4.1.3 or higher. All the files of the benchmark are located in the `./benchmarks/hpcg` subdirectory of the Intel MKL directory. The following versions of the benchmark are available:

File in `./benchmarks/hpcg/bin`	**Description**
`xhcg_avx`	The Intel AVX optimized version of the benchmark, optimized for systems based on the first and the second generations of Intel Xeon processor E3 family, Intel Xeon processor E5 family, or Intel Xeon processor E7 family.
`xhcg_avx2`	The Intel AVX2 optimized version of the benchmark, optimized for systems based on Intel Xeon E3-xxxx v3 processor and future Intel processors with Intel AVX2 support. Running the Intel AVX optimized version of the benchmark on an Intel AVX2 enabled system produces non-optimal performance. The Intel AVX2 optimized version of the benchmark does not run on systems that do not support Intel AVX2.
`xhcg_mic`	The Intel Xeon Phi coprocessor optimized version of the benchmark, to be used for native runs on Intel Xeon Phi coprocessors. It can also be used along with the Intel AVX optimized version or Intel AVX2 optimized version for symmetric runs. A symmetric run involves `xhpcg_mic` running on the Intel Xeon Phi coprocessors and `xhpcg_avx` or `xhpcg_avx2` running on Intel Xeon processors. MPI ranks can be on both Intel Xeon processor hosts and Intel Xeon Phi coprocessors. This version works only with Intel® MPI.

File in ./benchmarks/hpcg/bin	Description
xhcg_offload	The Intel Xeon Phi coprocessor optimized version for the offload mode. This version runs on Intel Xeon system and offloads computations to Intel Xeon Phi coprocessor(s). Unlike in the Intel Xeon Phi optimized version, MPI ranks are only on the Intel Xeon processor hosts and not on the Intel Xeon Phi coprocessors. Running this version of the benchmark requires the Redistributable Libraries package for the Intel® Parallel Studio XE Composer Edition (for details, see https://software.intel.com/en-us/articles/redistributables-for-intel-parallel-studio-xe-2015-composer-edition-for-linux). For the supported versions of Intel Parallel Studio XE Composer Edition, see Intel MKL System Requirements.

The Intel Optimized HPCG package also includes the source code and libraries necessary to build the following versions of the benchmark for other MPI implementations, such as SGI MPT*, MPICH2, or Open MPI: Intel AVX optimized version, Intel AVX2 optimized version, and Intel Xeon Phi coprocessor optimized version for offload mode. Build instructions are available in the QUICKSTART file included with the package. Intel Xeon Phi coprocessor optimized version for native runs is available only for Intel MPI library.

See Also

High-level Directory Structure

Getting Started with Intel Optimized HPCG

To start working with the benchmark, follow the instructions below:

1. On a cluster file system, unpack the Intel Optimized HPCG package to a directory accessible by all nodes. Read and accept the license as indicated in readme.txt file included in the package.
2. Change directory to hpcg/bin.
3. Determine which prebuilt version of the benchmark is best for your system or follow QUICKSTART instructions to build a version of the benchmark for your MPI implementation. When doing this, note that native runs on Intel Xeon Phi coprocessors and symmetric runs require Intel® MPI and only offload versions of the benchmark for Intel Xeon Phi coprocessors can be built with other MPI implementations.
4. Ensure the following:
   - Intel® C/C++ Compiler and MPI run-time libraries are available through the LD_LIBRARY_PATH environment variable.
   - To run the benchmark on Intel Xeon Phi coprocessors, Intel® Manycore Platform Software Stack (Intel® MPSS) run-time libraries are available through the MIC_LD_LIBRARY_PATH environment variable.
   - To run the offload version of the benchmark, Intel® Parallel Studio XE Composer Edition or its Redistributable Library package is installed (for details, see https://software.intel.com/en-us/articles/redistributables-for-intel-parallel-studio-xe-2015-composer-edition-for-linux). For the supported versions of Intel Parallel Studio XE Composer Edition, see Intel MKL System Requirements.
5. Run the chosen version of the benchmark as explained below:
   - The Intel AVX and Intel AVX2 optimized versions perform best with one process per socket and one OpenMP* thread per core skipping hyper-threads: set the affinity as KMP_AFFINITY=granularity=fine,compact,1,0. Specifically, for a 128-node cluster with two Intel Xeon Processor E5-2697 v3 per node, run the executable as follows:

```
#> I_MPI_ADJUST_ALLREDUCE=5 mpiexec.hydra -machinefile .machinefile -n
512 -perhost 2 env OMP_NUM_THREADS=14
KMP_AFFINITY=granularity=fine,compact,1,0 bin/xhpcg_avx2 --n=168
```

- The Intel Xeon Phi coprocessor optimized version for the offload mode performs best with one MPI process per coprocessor and four threads for each Intel Xeon Phi coprocessor core with a single core left free. Specifically, for a 128-node cluster with two Intel Xeon Phi coprocessors 7120D per node, run the executable as follows:

```
#> I_MPI_ADJUST_ALLREDUCE=5 mpiexec.hydra –machinefile .machinefile -n
256 –perhost 2 env –u OMP_NUM_THREADS –u KMP_AFFINITY
MIC_OMP_NUM_THREADS=240
MIC_LD_LIBRARY_PATH=./bin/lib/mic:$MIC_LD_LIBRARY_PATH
LD_LIBRARY_PATH=./bin/lib/mic:./bin/lib/intel64:$LD_LIBRARY_PATH
./bin/xhpcg_offload --n=168
```

- In the symmetric mode, choose the number of MPI processes per host and per coprocessor to balance the performance of the processes. Specifically, for a 128-node cluster with one Intel Xeon Phi coprocessor 7120D per node, two MPI ranks per host, and two MPI ranks per coprocessor, run the executable as follows:

```
#> I_MPI_ADJUST_ALLREDUCE=5 mpiexec.hydra –machinefile .machinefile -n
256 –perhost 2 env OMP_NUM_THREADS=14
KMP_AFFINITY=granularity=fine,compact,1,0 ./bin/xhpcg_avx2 --n=144 : -n 256
–perhost 2 env OMP_NUM_THREADS=120
KMP_AFFINITY=compact ./bin/xhpcg_mic --n=144
```

  For symmetric runs, `.machinefile` must include the list of Intel Xeon processor hosts followed by the list of Intel Xeon Phi coprocessors.

6. When the benchmark completes execution, which usually takes a few minutes, find the YAML file with official results in the current directory. The performance rating of the benchmarked system is in the last section of the file:

```
HPCG result is VALID with a GFLOP/s rating of: [GFLOP/s]
```

Choosing Best Configuration and Problem Sizes

The performance of the Intel Optimized HPCG depends on many system parameters including, but not limited to, hardware configuration of the host, number and configuration of coprocessors, and MPI implementation used. To get the best performance for a specific system configuration, choose the combination of the following parameters as explained below:

- The number of MPI processes per host and OpenMPI threads per process
- Local problem size
- Execution mode, if Intel Xeon Phi coprocessors are available

On Intel Xeon processor-based clusters, use the Intel AVX or Intel AVX2 optimized version of the benchmark depending on the supported instruction set and run one MPI process per CPU socket and one OpenMP* thread per physical CPU core skipping simultaneous multithreading (SMT) threads.

Intel Xeon Phi coprocessor-enabled systems support symmetric and offload execution modes. In the offload mode, the benchmark uses the host for MPI communication and offloads computational work to the Intel Xeon Phi coprocessors. In the symmetric mode, MPI ranks run on both Intel Xeon processors and Intel Xeon Phi coprocessors, which potentially results in better performance. Offload mode uses fewer MPI processes per system and scales better for large runs. Native mode requires more MPI processes per node to achieve good balancing, which may however lead to limited scalability.

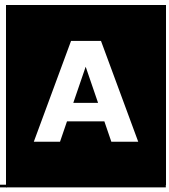
On systems with a single Intel Xeon Phi coprocessor, use the symmetric execution mode with one MPI process per socket and two MPI processes per coprocessor. On the Intel Xeon processor host, each process should run one OpenMP thread per processor core skipping hyper-threads. On the Intel Xeon Phi coprocessor, each process should run four OpenMP threads per core with one core left free. For example: on Intel Xeon Phi coprocessor 7120D, which has 61 cores, each of two MPI processes should run 120 OpenMP threads.

On systems with two or more Intel Xeon Phi coprocessors, offload mode works best with two MPI processes per coprocessor. Set the number of OpenMP threads for coprocessors to four for each coprocessor core and leave one core free. For example: on Intel Xeon Phi coprocessor 7120D, which has 61 cores, each MPI process should run 120 OpenMP threads.

Intel Xeon Phi coprocessors may have 57, 60, or 61 cores, depending on the specific model, with each core supporting four threads. Set the number of OpenMP processes in benchmark runs with Intel Xeon Phi coprocessors to use all cores but one and reserve that one for MPI or offload communications. For example: for 61-core coprocessors, the benchmark should use 240 threads.

For best performance, use the problem size that is large enough to better utilize available cores, but not too large, so that all tasks fit the available memory.

Intel® Math Kernel Library Language Interfaces Support



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 the Intel Math Kernel Library for an example of how to call Fortran routines from C/C++.

Function Domain	Fortran int erface	C/C++ interface
Basic Linear Algebra Subprograms (BLAS)	Yes	through CBLAS
BLAS-like extension transposition routines	Yes	Yes
Sparse BLAS Level 1	Yes	through CBLAS
Sparse BLAS Level 2 and 3	Yes	Yes
LAPACK routines for solving systems of linear equations	Yes	Yes
LAPACK routines for solving least-squares problems, eigenvalue and singular value problems, and Sylvester's equations	Yes	Yes
Auxiliary and utility LAPACK routines	Yes	Yes
Parallel Basic Linear Algebra Subprograms (PBLAS)	Yes	
ScaLAPACK	Yes	†
Direct Sparse Solvers/ Intel MKL PARDISO, a direct sparse solver based on Parallel Direct Sparse Solver (PARDISO*)	Yes	Yes
Parallel Direct Sparse Solvers for Clusters	Yes	Yes
Other Direct and Iterative Sparse Solver routines	Yes	Yes
Vector Mathematics (VM)	Yes	Yes
Vector Statistics (VS)	Yes	Yes
Fast Fourier Transforms (FFT)	Yes	Yes
Cluster FFT	Yes	Yes
Trigonometric Transforms	Yes	Yes
Fast Poisson, Laplace, and Helmholtz Solver (Poisson Library)	Yes	Yes
Optimization (Trust-Region) Solver	Yes	Yes
Data Fitting	Yes	Yes
Deep Neural Network (DNN) functions		Yes

Function Domain	Fortran interface	C/C++ interface
Extended Eigensolver	Yes	Yes
Support functions (including memory allocation)	Yes	Yes

† Supported using a mixed language programming call. See Include Files for the respective header file.

Include Files

The table below lists Intel MKL include files.

Function Domain/ Purpose	Fortran Include Files	C/C++ Include Files
All function domains	mkl.fi	mkl.h
BLACS		mkl_blacs.h‡‡
BLAS	blas.f90 mkl_blas.fi†	mkl_blas.h‡
BLAS-like Extension Transposition Routines	mkl_trans.fi†	mkl_trans.h‡
CBLAS Interface to BLAS		mkl_cblas.h‡
Sparse BLAS	mkl_spblas.fi†	mkl_spblas.h‡
LAPACK	lapack.f90 mkl_lapack.fi†	mkl_lapack.h‡
C Interface to LAPACK		mkl_lapacke.h‡
PBLAS		mkl_pblas.h‡‡
ScaLAPACK		mkl_scalapack.h‡‡
Intel MKL PARDISO	mkl_pardiso.f90 mkl_pardiso.fi†	mkl_pardiso.h‡
Parallel Direct Sparse Solvers for Clusters	mkl_cluster_sparse_solver.f90	mkl_cluster_sparse_solver.h‡
Direct Sparse Solver (DSS)	mkl_dss.f90 mkl_dss.fi†	mkl_dss.h‡
RCI Iterative Solvers ILU Factorization	mkl_rci.f90 mkl_rci.fi†	mkl_rci.h‡
Optimization Solver	mkl_rci.f90 mkl_rci.fi†	mkl_rci.h‡
Vector Mathematics	mkl_vml.90 mkl_vml.fi†	mkl_vml.h‡
Vector Statistics	mkl_vsl.f90 mkl_vsl.fi†	mkl_vsl.h‡
Fast Fourier Transforms	mkl_dfti.f90	mkl_dfti.h‡

Function Domain/ Purpose	Fortran Include Files	C/C++ Include Files
Cluster Fast Fourier Transforms	mkl_cdft.f90	mkl_cdft.h‡‡
Partial Differential Equations Support		
Trigonometric Transforms	mkl_trig_transforms.f90	mkl_trig_transform.h‡
Poisson Solvers	mkl_poisson.f90	mkl_poisson.h‡
Data Fitting	mkl_df.f90	mkl_df.h‡
Deep Neural Networks		mkl_dnn.h‡
Extended Eigensolver	mkl_solvers_ee.fi†	mkl_solvers_ee.h‡
Support functions	mkl_service.f90 mkl_service.fi†	mkl_service.h‡
Declarations for replacing memory allocation functions. See Redefining Memory Functions for details.		i_malloc.h
Auxiliary macros to determine the version of Intel MKL at compile time.	mkl_version	mkl_version‡

† 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 B

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 Developer Reference for details on the use of the wrappers.

Important
For ease of use, FFTW3 interface is also integrated in Intel MKL.

Directory Structure in Detail

C

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

Static Libraries in the `lib/ia32_lin` Directory

Some of the libraries in this directory are optional. However, some optional libraries are installed by default, while the rest are not. To get those libraries that are not installed by default, explicitly select the specified optional component during installation.

File	Contents	Optional Component	
		Name	Installed by Default
Interface Layer			
`libmkl_intel.a`	Interface library for the Intel compilers. Also use for other supported compilers that do not have a specialized Intel MKL interface library.		
`libmkl_blas95.a`	Fortran 95 interface library for BLAS for the Intel® Fortran compiler.	Fortran 95 interfaces for BLAS and LAPACK	Yes
`libmkl_lapack95.a`	Fortran 95 interface library for LAPACK for the Intel Fortran compiler.	Fortran 95 interfaces for BLAS and LAPACK	Yes
`libmkl_gf.a`	Interface library for the GNU* Fortran compiler.	GNU* Compiler Collection support	Yes
Threading Layer			

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_intel_thread.a	OpenMP threading library for the Intel compilers		
libmkl_tbb_thread.a	Intel® Threading Building Blocks (Intel® TBB) threading library for the Intel compilers	Intel TBB threading support	Yes
libmkl_gnu_thread.a	OpenMP threading library for the GNU Fortran and C compilers	GNU* Compiler Collection support	Yes
libmkl_sequential.a	Sequential library		
Computational Layer			
libmkl_core.a	Kernel library for the IA-32 architecture		

Dynamic Libraries in the lib/ia32_lin Directory

Some of the libraries in this directory are optional. However, some optional libraries are installed by default, while the rest are not. To get those libraries that are not installed by default, explicitly select the specified optional component during installation.

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_rt.so	Single Dynamic Library		
Interface Layer			
libmkl_intel.so	Interface library for the Intel compilers. Also use for other supported compilers that do not have a specialized Intel MKL interface library.		
libmkl_gf.so	Interface library for the GNU Fortran compiler	GNU* Compiler Collection support	Yes
Threading Layer			
libmkl_intel_thread.so	OpenMP threading library for the Intel compilers		
libmkl_tbb_thread.so	Intel TBB threading library for the Intel compilers	Intel TBB threading support	Yes
libmkl_gnu_thread.so	OpenMP threading library for the GNU Fortran and C compilers	GNU* Compiler Collection support	Yes

File	Contents	Optional Component	
		Name	Installed by Default
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_p4m.so	Kernel library for Intel® Supplemental Streaming SIMD Extensions 3 (Intel® SSSE3) enabled processors		
libmkl_p4m3.so	Kernel library for Intel® Streaming SIMD Extensions 4.2 (Intel® SSE4.2) enabled processors		
libmkl_avx.so	Kernel library for Intel® Advanced Vector Extensions (Intel® AVX) enabled processors		
libmkl_avx2.so	Kernel library for Intel® Advanced Vector Extensions 2 (Intel® AVX2) enabled processors		
libmkl_avx512.so	Kernel library for Intel® Advanced Vector Extensions 512 (Intel® AVX-512) enabled processors		
libmkl_vml_p4.so	Vector Mathematics (VM)/Vector Statistics (VS)/Data Fitting (DF) part of Pentium® 4 processor kernel		
libmkl_vml_p4m.so	VM/VS/DF for Intel® SSSE3 enabled processors		
libmkl_vml_p4m2.so	VM/VS/DF for 45nm Hi-k Intel® Core™2 and Intel Xeon® processor families		
libmkl_vml_p4m3.so	VM/VS/DF for Intel® SSE4.2 enabled processors		

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_vml_avx.so	VM/VS/DF optimized for Intel® AVX enabled processors		
libmkl_vml_avx2.so	VM/VS/DF optimized for Intel® AVX2 enabled processors		
libmkl_vml_avx512.so	VM/VS/DF optimized for Intel® AVX-512 enabled processors		
libmkl_vml_ia.so	VM/VS/DF default kernel for newer Intel® architecture processors		
libmkl_vml_cmpt.so	VM/VS/DF library for conditional numerical reproducibility		
Message Catalogs			
locale/en_US/mkl_msg.cat	Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English		
locale/ja_JP/mkl_msg.cat	Catalog of Intel MKL messages in Japanese. Available only if Intel MKL provides Japanese localization. Please see the Release Notes for this information.		

Detailed Structure of the Intel® 64 Architecture Directories

Static Libraries in the lib/intel64_lin Directory

Some of the libraries in this directory are optional. However, some optional libraries are installed by default, while the rest are not. To get those libraries that are not installed by default, explicitly select the specified optional component during installation.

File	Contents	Optional Component	
		Name	Installed by Default
Interface Layer			
libmkl_intel_lp64.a	LP64 interface library for the Intel compilers. Also use for other supported		

File	Contents	Optional Component	
		Name	Installed by Default
	compilers that do not have a specialized Intel MKL interface library		
libmkl_intel_ilp64.a	ILP64 interface library for the Intel compilers. Also use for other supported compilers that do not have a specialized Intel MKL interface library		
libmkl_blas95_lp64.a	Fortran 95 interface library for BLAS for the Intel® Fortran compiler. Supports the LP64 interface	Fortran 95 interfaces for BLAS and LAPACK	Yes
libmkl_blas95_ilp64.a	Fortran 95 interface library for BLAS for the Intel® Fortran compiler. Supports the ILP64 interface	Fortran 95 interfaces for BLAS and LAPACK	Yes
libmkl_lapack95_lp64.a	Fortran 95 interface library for LAPACK for the Intel® Fortran compiler. Supports the LP64 interface	Fortran 95 interfaces for BLAS and LAPACK	Yes
libmkl_lapack95_ilp64.a	Fortran 95 interface library for LAPACK for the Intel® Fortran compiler. Supports the ILP64 interface	Fortran 95 interfaces for BLAS and LAPACK	Yes
libmkl_gf_lp64.a	LP64 interface library for the GNU Fortran compilers	GNU* Compiler Collection support	Yes
libmkl_gf_ilp64.a	ILP64 interface library for the GNU Fortran compilers	GNU* Compiler Collection support	Yes
Threading Layer			
libmkl_intel_thread.a	OpenMP threading library for the Intel compilers		
libmkl_tbb_thread.a	Intel TBB threading library for the Intel compilers	Intel TBB threading support	Yes
libmkl_gnu_thread.a	OpenMP threading library for the GNU Fortran and C compilers	GNU* Compiler Collection support	Yes

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_pgi_thread.a	OpenMP threading library for the PGI compiler	PGI* Compiler support	
libmkl_sequential.a	Sequential library		
Computational Layer			
libmkl_core.a	Kernel library for the Intel® 64 architecture		
Cluster Libraries			
libmkl_scalapack_lp64.a	ScaLAPACK routine library supporting the LP64 interface	Cluster support	
libmkl_scalapack_ilp64.a	ScaLAPACK routine library supporting the ILP64 interface	Cluster support	
libmkl_cdft_core.a	Cluster version of FFT functions.	Cluster support	
libmkl_blacs_intelmpi_lp64.a	LP64 version of BLACS routines for Intel® MPI Library and MPICH2 or higher.	Cluster support	
libmkl_blacs_intelmpi_ilp64.a	ILP64 version of BLACS routines for Intel MPI Library and MPICH2 or higher.	Cluster support	
libmkl_blacs_openmpi_lp64.a	LP64 version of BLACS routines supporting Open MPI.	Cluster support	
libmkl_blacs_openmpi_ilp64.a	ILP64 version of BLACS routines supporting Open MPI.	Cluster support	
libmkl_blacs_sgimpt_lp64.a	LP64 version of BLACS routines supporting SGI Message-passing Interface Toolkit* (MPT).	Cluster support	
libmkl_blacs_sgimpt_ilp64.a	ILP64 version of BLACS routines supporting SGI MPT.	Cluster support	

Dynamic Libraries in the lib/intel64_lin Directory

Some of the libraries in this directory are optional. However, some optional libraries are installed by default, while the rest are not. To get those libraries that are not installed by default, explicitly select the specified optional component during installation.

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_rt.so	Single Dynamic Library		
Interface Layer			
libmkl_intel_lp64.so	LP64 interface library for the Intel compilers. Also use for other supported compilers that do not have a specialized Intel MKL interface library		
libmkl_intel_ilp64.so	ILP64 interface library for the Intel compilers. Also use for other supported compilers that do not have a specialized Intel MKL interface library		
libmkl_gf_lp64.so	LP64 interface library for the GNU Fortran compilers	GNU* Compiler Collection support	Yes
libmkl_gf_ilp64.so	ILP64 interface library for the GNU Fortran compilers	GNU* Compiler Collection support	Yes
Threading Layer			
libmkl_intel_thread.so	OpenMP threading library for the Intel compilers		
libmkl_tbb_thread.so	Intel TBB threading library for the Intel compilers	Intel TBB threading support	Yes
libmkl_gnu_thread.so	OpenMP threading library for the GNU Fortran and C compilers	GNU* Compiler Collection support	Yes
libmkl_pgi_thread.so	OpenMP threading library for the PGI* compiler	PGI* Compiler support	
libmkl_sequential.so	Sequential library		
Computational Layer			
libmkl_core.so	Library dispatcher for dynamic load of processor-specific kernel		
libmkl_def.so	Default kernel library		
libmkl_mc.so	Kernel library for Intel® Supplemental Streaming SIMD Extensions 3 (Intel® SSSE3) enabled processors		

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_mc3.so	Kernel library for Intel® Streaming SIMD Extensions 4.2 (Intel® SSE4.2) enabled processors		
libmkl_avx.so	Kernel library for Intel® Advanced Vector Extensions (Intel® AVX) enabled processors		
libmkl_avx2.so	Kernel library for Intel® Advanced Vector Extensions 2 (Intel® AVX2) enabled processors		
libmkl_avx512.so	Kernel library for dispatching Intel® Advanced Vector Extensions 512 (Intel® AVX-512) on Intel® Xeon® processors		
libmkl_avx512_mic.so	Kernel library for dispatching Intel® Advanced Vector Extensions 512 (Intel® AVX-512) on Intel® Xeon Phi™ processors and coprocessors		
libmkl_vml_def.so	Vector Mathematics (VM)/Vector Statistics (VS)/Data Fitting (DF) part of default kernels		
libmkl_vml_mc.so	VM/VS/DF for Intel® SSSE3 enabled processors		
libmkl_vml_mc2.so	VM/VS/DF for 45nm Hi-k Intel® Core™2 and Intel® Xeon® processor families		
libmkl_vml_mc3.so	VM/VS/DF for Intel® SSE4.2 enabled processors		
libmkl_vml_avx.so	VM/VS/DF optimized for Intel® AVX enabled processors		
libmkl_vml_avx2.so	VM/VS/DF optimized for Intel® AVX2 enabled processors		

File	Contents	Optional Component	
		Name	Installed by Default
libmkl_vml_avx512.so	VM/VS/DF optimized for Intel® AVX-512 on Intel® Xeon® processors		
libmkl_vml_avx512_mic.so	VM/VS/DF optimized for Intel® AVX-512 on Intel® Xeon Phi™ processors and coprocessors		
libmkl_vml_cmpt.so	VM/VS/DF library for conditional numerical reproducibility		
Cluster Libraries			
libmkl_scalapack_lp64.so	ScaLAPACK routine library supporting the LP64 interface	Cluster support	
libmkl_scalapack_ilp64.so	ScaLAPACK routine library supporting the ILP64 interface	Cluster support	
libmkl_cdft_core.so	Cluster version of FFT functions.	Cluster support	
libmkl_blacs_intelmpi_lp64.so	LP64 version of BLACS routines for Intel® MPI Library and MPICH2 or higher.	Cluster support	
libmkl_blacs_intelmpi_ilp64.so	ILP64 version of BLACS routines for Intel MPI Library and MPICH2 or higher.	Cluster support	
libmkl_blacs_openmpi_lp64.so	LP64 version of BLACS routines for Open MPI.	Cluster support	
libmkl_blacs_openmpi_ilp64.so	ILP64 version of BLACS routines for Open MPI.	Cluster support	
libmkl_blacs_sgimpt_lp64.so	LP64 version of BLACS routines for SGI MPI Toolkit* (MPT)	Cluster support	
libmkl_blacs_sgimpt_ilp64.so	ILP64 version of BLACS routines for SGI MPT.	Cluster support	
Message Catalogs			
locale/en_US/mkl_msg.cat	Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English		
locale/ja_JP/mkl_msg.cat	Catalog of Intel MKL messages in Japanese. Available only if Intel MKL provides Japanese		

File	Contents	Optional Component	
		Name	Installed by Default
	localization. Please see the Release Notes for this information.		

Detailed Directory Structure of the lib/intel64_lin_mic Directory

File	Contents
Static Libraries	
libmkl_intel_lp64.a	LP64 interface library for the Intel compilers
libmkl_intel_ilp64.a	ILP64 interface library for the Intel compilers
libmkl_blas95_lp64.a	Fortran 95 interface library for BLAS and Intel® Fortran compiler. Supports the LP64 interface.
libmkl_blas95_ilp64.a	Fortran 95 interface library for BLAS and Intel Fortran compiler. Supports the ILP64 interface.
libmkl_lapack95_lp64.a	Fortran 95 interface library for LAPACK and Intel Fortran compiler. Supports the LP64 interface.
libmkl_lapack95_ilp64.a	Fortran 95 interface library for LAPACK and Intel Fortran compiler. Supports the ILP64 interface.
libmkl_intel_thread.a	OpenMP threading library for the Intel compilers
libmkl_tbb_thread.a	Intel TBB threading library for the Intel compilers
libmkl_sequential.a	Sequential library
libmkl_core.a	Core computation library
libmkl_scalapack_lp64.a	Static library with LP64 versions of ScaLAPACK routines
libmkl_scalapack_ilp64.a	Static library with ILP64 versions of ScaLAPACK routines
libmkl_cdft_core.a	Static library with cluster FFT functions
libmkl_blacs_intelmpi_lp64.a	Static library with LP64 versions of BLACS routines for Intel MPI
libmkl_blacs_intelmpi_ilp64.a	Static library with ILP64 versions of BLACS routines for Intel MPI
Dynamic Libraries	
libmkl_rt.so	Single Dynamic Library
libmkl_ao_worker.so	The Intel® MIC Architecture library to implement the Automatic Offload mode
libmkl_intel_lp64.so	LP64 interface library for the Intel compilers
libmkl_intel_ilp64.so	ILP64 interface library for the Intel compilers
libmkl_intel_thread.so	OpenMP threading library for the Intel compilers

File	Contents
libmkl_tbb_thread.so	Intel TBB threading library for the Intel compilers
libmkl_sequential.so	Sequential library
libmkl_core.so	Core computation library
libmkl_scalapack_lp64.so	Dynamic library with LP64 versions of ScaLAPACK routines
libmkl_scalapack_ilp64.so	Dynamic library with ILP64 versions of ScaLAPACK routines
libmkl_cdft_core.so	Dynamic library with cluster FFT functions
libmkl_blacs_intelmpi_lp64.so	Dynamic library with LP64 versions of BLACS routines for Intel MPI
libmkl_blacs_intelmpi_ilp64.so	Dynamic library with ILP64 versions of BLACS routines for Intel MPI
locale/en_US/mkl_msg.cat	Catalog of Intel® Math Kernel Library (Intel® MKL) messages in English
locale/ja_JP/mkl_msg.cat	Catalog of Intel MKL messages in Japanese. Available only if Intel MKL provides Japanese localization. Please see the Release Notes for this information.

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