Agenda

Introduction
Optimizations and Reports
Floating point Model
OpenMP SIMD
KNL Memory and Floating Point
Why Use Intel® Compilers?

Compatibility
- Multiple OS Support: Windows®, Linux®, OS X®
- Integration into development environments: Visual Studio® in Windows®, Eclipse® in Linux®, Xcode® in OS X®
- Compatible with most versions of the GNU® Compiler collection (gcc)
- Source and binary compatibility with Microsoft Visual C++® Compilers
- Most features from C99 Standard (C Compilers)
- Full C++11 Standard support, some features from C++14 supported (C++ Compilers)
- Fortran 2003, Many features from Fortran 2008
- Support for Draft Fortran 2015 features

Parallelism
- Explicit Vector Programming (OpenMP®)
- Extensive OpenMP® 4.1 support
- C++ Multithreading Library (Intel® TBB)
Why Use Intel® Compilers?

Performance
- Code generation tuned for latest microarchitecture
- New instructions enable new opportunities (SSE, AVX, AVX2, AVX-512)
- Domain specific performance libraries (Intel® MKL, Intel® IPP)
- Data analytics acceleration library (Intel® DAAL)

Optimization
- Optimizing compilers
- Automatic vectorization
- Intel‘s optimized version of libm (Intel® Math Library libimf)
## Common Optimization Options

<table>
<thead>
<tr>
<th>Optimization Options</th>
<th>Windows*</th>
<th>Linux*, OS X*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disable optimization</td>
<td>/Od</td>
<td>-O0</td>
</tr>
<tr>
<td>Optimize for speed (no code size increase)</td>
<td>/O1</td>
<td>-O1</td>
</tr>
<tr>
<td>Optimize for speed (default)</td>
<td>/O2</td>
<td>-O2</td>
</tr>
<tr>
<td>High-level loop optimization</td>
<td>/O3</td>
<td>-O3</td>
</tr>
<tr>
<td>Create symbols for debugging</td>
<td>/Zi</td>
<td>-g</td>
</tr>
<tr>
<td>Multi-file inter-procedural optimization</td>
<td>/Qipo</td>
<td>-ipo</td>
</tr>
<tr>
<td>Profile guided optimization (multi-step build)</td>
<td>/Qprof-gen</td>
<td>-prof-gen</td>
</tr>
<tr>
<td></td>
<td>/Qprof-use</td>
<td>-prof-use</td>
</tr>
<tr>
<td>Optimize for speed across the entire program (“prototype switch”)</td>
<td>/fast</td>
<td>-fast</td>
</tr>
<tr>
<td><strong>fast options definitions changes over time!</strong></td>
<td>same as: /O3 /Qipo /Qprec-div, /fp:fast=2 /QxHost)</td>
<td>same as: Linux: -ipo –O3 -no-prec-div –static –fp-model fast=2 -xHost OS X: -ipo -mdynamic-no-pic -O3 -no-prec-div -fp-model fast=2 -xHost</td>
</tr>
<tr>
<td>OpenMP support</td>
<td>/Qopenmp</td>
<td>-qopenmp</td>
</tr>
<tr>
<td>Automatic parallelization</td>
<td>/Qparallel</td>
<td>-parallel</td>
</tr>
</tbody>
</table>
Compiler Reports – Optimization Report

- Enables the optimization report and controls the level of details
  - `/Qopt-report[:n], -qopt-report[=n]`
  - When used without parameters, full optimization report is issued on stdout with details level 2

- Control destination of optimization report
  - `/Qopt-report-file:<filename>, -qopt-report=<filename>`
  - By default, without this option, a `<filename>.optrpt` file is generated.

- Subset of the optimization report for specific phases only
  - `/Qopt-report-phase[:list], -qopt-report-phase[=list]`
  
  Phases can be:
  - `all` – All possible optimization reports for all phases (default)
  - `loop` – Loop nest and memory optimizations
  - `vec` – Auto-vectorization and explicit vector programming
  - `par` – Auto-parallelization
  - `openmp` – Threading using OpenMP
  - `ipo` – Interprocedural Optimization, including inlining
  - `pgo` – Profile Guided Optimization
  - `cg` – Code generation
  - `offload` – offload of data and/or execution to Intel® MIC Architecture or to Intel® Graphics Technology

Note: “offload” does not report on optimizations for MIC, it reports on data that are offloaded.
High-Level Optimization (HLO)

Compiler switches: 
/O2, -O2 (default), /O3, -O3

- O3 is suited to applications that have loops that do many floating-point calculations or process large data sets.
- Some of the optimizations are the same as at O2, but are carried out more aggressively. Some poorly suited applications might run slower at O3 than O2

Loop level optimizations
- loop unrolling, cache blocking, prefetching

More aggressive dependency analysis
- Determines whether or not it’s safe to reorder or parallelize statements

Scalar replacement
- Goal is to reduce memory by replacing with register references
Interprocedural Optimizations (IPO)

Multi-pass Optimization

- Interprocedural optimizations performs a static, topological analysis of your application!
- `ip:` Enables inter-procedural optimizations for current source file compilation
- `ipo:` Enables inter-procedural optimizations across files
  - Can inline functions in separate files
  - Especially many small utility functions benefit from IPO

<table>
<thead>
<tr>
<th>Windows*</th>
<th>Linux*</th>
</tr>
</thead>
<tbody>
<tr>
<td>/Qip</td>
<td>-ip</td>
</tr>
<tr>
<td>/Qipo</td>
<td>-ipo</td>
</tr>
</tbody>
</table>

Enabled optimizations:
- Procedure inlining (reduced function call overhead)
- Interprocedural dead code elimination, constant propagation and procedure reordering
- Enhances optimization when used in combination with other compiler features
- Much of ip (including inlining) is enabled by default at option O2
Interprocedural Optimizations (IPO)
Usage: Two-Step Process

### Compiling

<table>
<thead>
<tr>
<th>Operating System</th>
<th>Command Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux*</td>
<td>icc -c -ipo main.c func1.c func2.c</td>
</tr>
<tr>
<td>Windows*</td>
<td>icl -c /Qipo main.c func1.c func2.c</td>
</tr>
</tbody>
</table>

### Linking

<table>
<thead>
<tr>
<th>Operating System</th>
<th>Command Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux*</td>
<td>icc -ipo main.o func1.o func2.o</td>
</tr>
<tr>
<td>Windows*</td>
<td>icl /Qipo main.o func1.o func2.obj</td>
</tr>
</tbody>
</table>
Interprocedural Optimizations
Extends optimizations across file boundaries

**Without IPO**

- Compile & Optimize → file1.c
- Compile & Optimize → file2.c
- Compile & Optimize → file3.c
- Compile & Optimize → file4.c

**With IPO**

- Compile & Optimize

**Without IPO**

- Compile & Optimize → file1.c
- Compile & Optimize → file4.c
- Compile & Optimize → file2.c
- Compile & Optimize → file3.c

**With IPO**

- Compile & Optimize

<table>
<thead>
<tr>
<th>/Qip, -ip</th>
<th>Only between modules of one source file</th>
</tr>
</thead>
<tbody>
<tr>
<td>/Qipo, -ipo</td>
<td>Modules of multiple files/whole application</td>
</tr>
</tbody>
</table>
Auto-Vectorization
SIMD – Single Instruction Multiple Data

• Scalar mode
  – one instruction produces one result

• SIMD processing
  – with SSE or AVX instructions
  – one instruction can produce multiple results

```
for (i=0; i<=MAX; i++)
c[i]=a[i]+b[i];
```

```
\begin{align*}
a[i] &+ b[i] \\
a &+ b \\
a+b &
\end{align*}
```

```
\begin{align*}
\end{align*}
```
Vectorization is Achieved through SIMD Instructions & Hardware

**Intel® SSE**
- Vector size: 128bit
- Data types:
  - 8, 16, 32, 64 bit integers
  - 32 and 64bit floats
- VL: 2, 4, 8, 16

**Intel® AVX**
- Vector size: 256bit
- Data types:
  - 8, 16, 32, 64 bit integer
  - 32 and 64 bit float
- VL: 4, 8, 16, 32

**Intel® AVX-512, Intel® MIC Architecture**
- Vector size: 512bit
- Data types:
  - 32bit integer
  - 32 and 64 bit float
- VL: 8, 16
  - Xi, Yi & results 32-bit integer
Automatic Vectorization by Compiler

Intel Compiler will auto vectorize the source code for you if it can

Pros:

- Minimal effort required
- Maintainable – source code is not changed
- Portable across Intel SIMD architectures
- Optimal performance is possible in best cases
- Scales forward!

Cons:

- Compiler is conservative; will not risk generating code that could possibly be unsafe

\[ \Rightarrow \textbf{Advanced optimization techniques help to improve Data Level Parallelization using Vectorization} \]

More Vectorization details in a separate training module
Processor Specific Optimizations

Processor specific extensions switches:

/\texttt{arch:<target>} (Microsoft compatible), \texttt{\textendash m<target>} (Linux*, OS X*)

- No Intel processor check
- No Intel specific optimizations

/\texttt{Qx<target>}, \texttt{\textendash x<target>}

- Intel specific optimizations
- Processor-check added to main-program

/\texttt{Qax<target>}, \texttt{\textendash ax<target>}

- Intel specific optimizations
- Autodispatch switch \texttt{a} for generating one or more additional optimized code paths

/\texttt{QxHost}, \texttt{\textendash xHost}

- Generates optimized code targeted for execution on the system you compile on
# Compiler Based Vectorization

## Extension Specification

<table>
<thead>
<tr>
<th>Feature</th>
<th>SIMD Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>May generate Intel® Streaming SIMD Extensions 2 (Intel® SSE2) instructions as available in initial Pentium® 4 or compatible non-Intel processors</td>
<td>SSE2</td>
</tr>
<tr>
<td>May generate Intel® Streaming SIMD Extensions 3 (Intel® SSE3) instructions as available in Pentium® 4 or compatible non-Intel processors</td>
<td>SSE3</td>
</tr>
<tr>
<td>May generate Supplemental Streaming SIMD Extensions 3 (SSSE3) instructions as available in Intel® Core™2 Duo processors</td>
<td>SSSE3</td>
</tr>
<tr>
<td>May generate Intel® SSE4.1 instructions as first introduced in Intel® 45nm Hi-K next generation Intel Core™ micro-architecture</td>
<td>SSE4.1</td>
</tr>
<tr>
<td>May generate Intel® SSE4.2 Accelerated String and Text Processing instructions as available in the previous generation Intel® Core™ processor family</td>
<td>SSE4.2</td>
</tr>
<tr>
<td>Like SSSE3 (or SSE4.2) but optimizes for the Intel® Atom™ processors which support SSSE3 (or SSE4.2)</td>
<td>ATOM_SSSE3 (ATOM_SSE4.2)</td>
</tr>
<tr>
<td>May generate Intel® Advanced Vector Extensions (Intel® AVX) as available in 2nd generation Intel® Core™ processor family</td>
<td>AVX</td>
</tr>
<tr>
<td>May generate Intel® Advanced Vector Extension (Intel® AVX) instructions including instructions offered by the 3rd generation Intel® Core processor</td>
<td>CORE-AVX-I</td>
</tr>
</tbody>
</table>
## Compiler Based Vectorization
### Extension Specification cont’d

<table>
<thead>
<tr>
<th>Feature</th>
<th>SIMD Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>May generate Intel® Advanced Vector Extension (Intel® AVX) instructions including instructions offered by the 3rd generation Intel® Core processor</td>
<td>CORE-AVX-I</td>
</tr>
<tr>
<td>May generate Intel® Advanced Vector Extension 2 (Intel® AVX2) instructions as available in the 4th generation Intel® Core™ processor family</td>
<td>CORE-AVX2</td>
</tr>
<tr>
<td>May generate Intel® Advanced Vector Extensions 512 (Intel® AVX-512) Foundation, Conflict Detection, Exponential/Reciprocal and Prefetch instructions for Intel® processors, and the instructions enabled with CORE-AVX2. Optimizes for Intel® processors that support Intel® AVX-512 instructions.</td>
<td>MIC-AVX512</td>
</tr>
<tr>
<td>May generate Intel® AVX-512 Foundation, Conflict Detection, Doubleword and Quadword, Byte and Word instructions and Intel® AVX-512 Vector Length Extensions for Intel® processors, and the instructions enabled with CORE-AVX2. Optimizes for Intel® processors that support Intel® AVX-512 instructions.</td>
<td>CORE-AVX512</td>
</tr>
<tr>
<td>May generate Intel® AVX-512 Foundation, Conflict Detection instructions, as well as the instructions enabled with CORE-AVX2. Optimizes for Intel® processors that support Intel® AVX-512 instructions.</td>
<td>COMMON-AVX512</td>
</tr>
</tbody>
</table>
Example of New Optimization Report

$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr foo.c

Begin optimization report for: foo

Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(4,3)  
**Multiversioned v1**

remark #25231: Loop multiversioned for Data Dependence
remark #15135: vectorization support: reference theta has unaligned access
remark #15135: vectorization support: reference sth has unaligned access
remark #15127: vectorization support: unaligned access used inside loop body
remark #15145: vectorization support: unroll factor set to 2
remark #15164: vectorization support: number of FP up converts: single to double precision 1
remark #15165: vectorization support: number of FP down converts: double to single precision 1
remark #15002: LOOP WAS VECTORIZED
remark #36066: unmasked unaligned unit stride loads: 1
remark #36067: unmasked unaligned unit stride stores: 1

.... (loop cost summary) ....
remark #25018: Estimate of max trip count of loop=32

LOOP END

LOOP BEGIN at foo.c(4,3)  
**Multiversioned v2**

remark #15006: loop was not vectorized: non-vectorizable loop instance from multiversioning

LOOP END

#include <math.h>
void foo (float * theta, float * sth) {
    int i;
    for (i = 0; i < 128; i++)
        sth[i] = sin(theta[i]+3.1415927);
}
Optimization Report Example

$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr -fargument-noalias foo.c

Begin optimization report for: foo
  Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(4,3)
  remark #15135: vectorization support: reference theta has unaligned access
  remark #15135: vectorization support: reference sth has unaligned access
  remark #15127: vectorization support: unaligned access used inside loop body
  remark #15145: vectorization support: unroll factor set to 2
  remark #15164: vectorization support: number of FP up converts: single to double precision 1
  remark #15165: vectorization support: number of FP down converts: double to single precision 1
  remark #15002: LOOP WAS VECTORIZED
  remark #36066: unmasked unaligned unit stride loads: 1
  remark #36067: unmasked unaligned unit stride stores: 1
  remark #36091: --- begin vector loop cost summary ---
  remark #36092: scalar loop cost: 114
  remark #36093: vector loop cost: 55.750
  remark #36094: estimated potential speedup: 2.040
  remark #36095: lightweight vector operations: 10
  remark #36096: medium-overhead vector operations: 1
  remark #36098: vectorized math library calls: 1
  remark #36103: type converts: 2
  remark #36104: --- end vector loop cost summary ---
  remark #25018: Estimate of max trip count of loop=32

LOOP END

#include <math.h>
void foo (float * theta, float * sth) {
  int i;
  for (i = 0; i < 128; i++)
    sth[i] = sin(theta[i]+3.1415927);
}

( /Qalias-args- on Windows* )
Optimization Report Example

$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr -fargument-noalias foo.c

Begin optimization report for: foo

Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(4,3)
remark #15135: vectorization support: reference theta has unaligned access
remark #15135: vectorization support: reference sth has unaligned access
remark #15127: vectorization support: unaligned access used inside loop body
remark #15002: LOOP WAS VECTORIZED
remark #36066: unmasked unaligned unit stride loads: 1
remark #36067: unmasked unaligned unit stride stores: 1
remark #36091: --- begin vector loop cost summary ---
remark #36092: scalar loop cost: 111
remark #36093: vector loop cost: 28.000
remark #36094: estimated potential speedup: 3.950
remark #36095: lightweight vector operations: 9
remark #36098: vectorized math library calls: 1
remark #36104: --- end vector loop cost summary ---
remark #25018: Estimate of max trip count of loop=32
LOOP END

#include <math.h>
void foo (float * theta, float * sth) {
    int i;
    for (i = 0; i < 128; i++)
        sth[i] = sinf(theta[i]+3.1415927f);
}
Optimization Report Example

$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr -fargument-noalias -xavx foo.c

Begin report for: foo

Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(4,3)
remark #15135: vectorization support: reference theta has unaligned access
remark #15135: vectorization support: reference sth has unaligned access
remark #15127: vectorization support: unaligned access used inside loop body
remark #15002: LOOP WAS VECTORIZED
remark #36066: unmasked unaligned unit stride loads: 1
remark #36067: unmasked unaligned unit stride stores: 1
remark #36091: --- begin vector loop cost summary ---
remark #36092: scalar loop cost: 110
remark #36093: vector loop cost: 15.370
remark #36094: estimated potential speedup: 7.120
remark #36095: lightweight vector operations: 9
remark #36098: vectorized math library calls: 1
remark #36104: --- end vector loop cost summary ---
remark #25018: Estimate of max trip count of loop=16
LOOP END

#include <math.h>
void foo (float * theta, float * sth) {
  int i;
  for (i = 0; i < 128; i++)
    sth[i] = sinf(theta[i]+3.1415927f);
}

Optimization Notice
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Optimization Report Example

```
$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr -fargument-noalias -xavx foo.c

Begin optimization report for: foo

Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(6,3)
remark #15134: vectorization support: reference theta has aligned access
remark #15134: vectorization support: reference sth has aligned access
remark #15002: LOOP WAS VECTORIZED
remark #36064: unmasked aligned unit stride loads: 1
remark #36065: unmasked aligned unit stride stores: 1
remark #36091: --- begin vector loop cost summary ---
remark #36092: scalar loop cost: 110
remark #36093: vector loop cost: 13.620
remark #36094: estimated potential speedup: 8.060
remark #36095: lightweight vector operations: 9
remark #36098: vectorized math library calls: 1
remark #36104: --- end vector loop cost summary ---
remark #25018: Estimate of max trip count of loop=16
LOOP END
```

```c
#include <math.h>
void foo (float * theta, float * sth) {
    int i;
    __assume_aligned(theta,32);
    __assume_aligned(sth,32);
    for (i = 0; i < 128; i++)
        sth[i] = sinf(theta[i]+3.1415927f);
}
```
Optimization Report Example

$ icc -c -qopt-report=4 -qopt-report-phase=loop,vec -qopt-report-file=stderr -fargument-noalias -xavx foo.c

Begin optimization report for: foo

Report from: Loop nest & Vector optimizations [loop, vec]

LOOP BEGIN at foo.c(7,3)
remark #15134: vectorization support: reference theta has aligned access
remark #15134: vectorization support: reference sth has aligned access
remark #15002: LOOP WAS VECTORIZED
remark #36064: unmasked aligned unit stride loads: 1
remark #36065: unmasked aligned unit stride stores: 1
remark #36083: unmasked aligned streaming stores: 1
remark #36091: --- begin vector loop cost summary ---
remark #36092: scalar loop cost: 110
remark #36093: vector loop cost: 13.620
remark #36094: estimated potential speedup: 8.070
remark #36095: lightweight vector operations: 9
remark #36098: vectorized math library calls: 1
remark #36104: --- end vector loop cost summary ---
remark #25018: Estimate of max trip count of loop=250000
remark #15158: vectorization support: streaming store was generated for sth

LOOP END

#include <math.h>
void foo (float * theta, float * sth) {
  int i;
  __assume_aligned(theta,32);
  __assume_aligned(sth,32);
  for (i = 0; i < 2000000; i++)
    sth[i] = sinf(theta[i]+3.1415927f);
}
Compiler Floating-Point (FP) Model

The Floating Point options allow to control the optimizations on floating-point data. These options can be used to tune the performance, level of accuracy or result consistency.

**Accuracy**
Produce results that are “close” to the correct value
   – Measured in relative error, possibly ulps (units in the last place)

**Reproducibility**
Produce consistent results
   – From one run to the next
   – From one set of build options to another
   – From one compiler to another
   – From one platform to another

**Performance**
Produce the most efficient code possible
   – Default, primary goal of Intel® Compilers

These objectives usually conflict! Wise use of compiler options lets you control the tradeoffs.
Compiler Floating-Point Model

Problem Statement

Numerical FP results change from run-to-run:

```
C:\Users\me>test.exe
4.012345678901111

C:\Users\me>test.exe
4.012345678902222
```

Numerical results change between different systems:

**Intel® Xeon® Processor E5540**

```
C:\Users\me>test.exe
4.012345678901111

C:\Users\me>test.exe
4.012345678901111
```

**Intel® Xeon® Processor E3-1275**

```
C:\Users\me>test.exe
4.012345678902222

C:\Users\me>test.exe
4.012345678902222
```
Why Reproducible FP Results?

**Technical/legacy**
Software correctness is determined by comparison to previous (baseline) results.

**Debugging/porting**
When developing and debugging, a higher degree of run-to-run stability is required to find potential problems.

**Legal**
Accreditation or approval of software might require exact reproduction of previously defined results.

**Customer perception**
Developers may understand the technical issues with reproducibility but still require reproducible results since end users or customers will be disconcerted by the inconsistencies.
Why Results Vary I

Basic problem:

- FP numbers have **finite resolution** and
- **Rounding** is done for each (intermediate) result

Caused by algorithm:
Conditional numerical computation for different systems and/or input data can have unexpected results

Non-deterministic task/thread scheduler:
Asynchronous task/thread scheduling has best performance but reruns use different threads

Alignment (heap & stack):
If alignment is not guaranteed and changes between reruns the data sets could be computed differently (e.g. vector loop prologue & epilogue of unaligned data)

⇒ User controls those (direct or indirect)
Why Results Vary II

Order of FP operations has impact on rounded result, e.g.

\((a+b)+c \neq a+(b+c)\)

\[2^{-63} + 1 + -1 = 2^{-63}\] (mathematical result)

\[2^{-63} + 1) + -1 \approx 0\] (correct IEEE result)

\[2^{-63} + (1 + -1) \approx 2^{-63}\] (correct IEEE result)

Constant folding: \(X + 0 \Rightarrow X\) or \(X \ast 1 \Rightarrow X\)

Multiply by reciprocal: \(A/B \Rightarrow A \ast (1/B)\)

Approximated transcendental functions (e.g. \(\text{sqrt}(\ldots), \text{sin}(\ldots), \ldots\))

Flush-to-zero (for SIMD instructions)

Contractions (e.g. FMA)

Different code paths (e.g. SIMD & non-SIMD or Intel AVX vs. SSE)

\(\Rightarrow\) **Subject of Optimizations by Compiler & Libraries**
Compiler Optimizations

Why compiler optimizations:
- Provide best performance
- Make use of processor features like SIMD (vectorization)
- In most cases performance is more important than FP precision and reproducibility
- Use faster FP operations (not legacy x87 coprocessor)

FP model of compiler limits optimizations and provides control about FP precision and reproducibility:

Default is "fast"

Controlled via:
- Linux*, OS X*: `-fp-model`
- Windows*: `/fp:`
FP Model I

FP model does more:

- Value safety
- Floating-point expression evaluation
- Precise floating-point exceptions
- Floating-point contractions
- Floating-point unit (FPU) environment access
FP Model II

FP model settings:

- **precise**: allows value-safe optimizations only
- **source/double/extended**: intermediate precision for FP expression eval.
- **except**: enables strict floating point exception semantics
- **strict**: enables access to the FPU environment disables floating point contractions such as fused multiply-add (fma) instructions implies “precise” and “except”
- **fast[=1] (default)**:
  - Allows value-unsafe optimizations compiler chooses precision for expression evaluation
  - Floating-point exception semantics not enforced
  - Access to the FPU environment not allowed
  - Floating-point contractions are allowed
- **fast=2**: some additional approximations allowed

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### FP Model - Comparison

<table>
<thead>
<tr>
<th>Key</th>
<th>Value Safety</th>
<th>Expression Evaluation</th>
<th>FPU Environ. Access</th>
<th>Precise FP Exceptions</th>
<th>FP contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>precise source double extended</td>
<td>Safe</td>
<td>Varies Source Double Extended</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>strict</td>
<td>Safe</td>
<td>Varies</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>fast=1 (default)</td>
<td>Unsafe</td>
<td>Unknown</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>fast=2</td>
<td>Very Unsafe</td>
<td>Unknown</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>except except-</td>
<td><em>/</em>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* These modes are unaffected. `-fp-model except[-]` only affects the precise FP exceptions mode.

** It is illegal to specify `--fp-model except` in an unsafe value safety mode.
FP Model - Example

Using `-fp-model [precise|strict]`:

- Disables reassociation
- Enforces standard conformance (left-to-right)
- May carry a significant performance penalty

Disabling of reassociation also impacts vectorization (e.g. partial sums)!

```cpp
#include <iostream>
#define N 100

int main() {
    float a[N], b[N];
    float c = -1., tiny = 1.e-20F;

    for (int i=0; i<N; i++) a[i]=1.0;
    for (int i=0; i<N; i++) {
        a[i] = a[i] + c + tiny;
        b[i] = 1/a[i];
    }

    std::cout << "a = " << a[0] << "   b = " << b[0] << "\n";
}
```
Other FP Options I

- Linux*, OS X*: \(-[\text{no-}]\text{ftz}\), Windows*: \(/\text{Qftz}\) [-]
  Flush denormal results to zero

- Linux*, OS X*: \(-[\text{no-}]\text{prec-div}\), Windows*: \(/\text{Qprec-div}\) [-]
  Improves precision of floating point divides

- Linux*, OS X*: \(-[\text{no-}]\text{prec-sqrt}\), Windows*: \(/\text{Qprec-sqrt}\) [-]
  Improves precision of square root calculations

- Linux*, OS X*: \(-\text{fimf-precision}=\text{name}\), Windows*: \(/\text{Qimf-precision}:\text{name}\)
  \text{high, medium, low}: Controls accuracy of math library functions

- Linux*, OS X*: \(-\text{fimf-arch-consistency}=\text{true}\), Windows*: \(/\text{Qimf-arch-consistency}:\text{true}\)
  Math library functions produce consistent results on different processor types of the same architecture
Other FP Options II

- Linux*, OS X*: \texttt{-fpe0}, Windows*: /fpe:0
  Unmask floating point exceptions (Fortran only) and disable generation of denormalized numbers

- Linux*, OS X*: \texttt{-fp-trap=common}, Windows*: /Qfp-trap:common
  Unmask common floating point exceptions (C/C++ only)

- Linux*, OS X*: \texttt{-[no-]}fast-transcendentals, Windows*: /Qfast-transcendentals[-]
  Enable/disable fast math functions

- ...
Recommendation

• The **default FP model** is fast but has less precision/reproducibility (vectorization)

• The **strict FP model** has best precision/reproducibility but is slow (no vectorization; x87 legacy)

• For best trade-off between precision, reproducibility & performance use:
  Linux*, OS X*: `-fp-model precise -fp-model source`
  Windows*: `/fp:precise /fp:source`
  Approx. 12-15% slower performance for SPECCPU2006fp

• Don’t mix math libraries from different compiler versions!

• Using different processor types (of same architecture), specify:
  Linux*, OS X*: `-fimf-arch-consistency=true`
  Windows*: `/Qimf-arch-consistency:true`

More information:
How to Align Data   (Fortran)

Align array on an “n”-byte boundary (n must be a power of 2)

!dir$ attributes align:n :: array

• Works for dynamic, automatic and static arrays (not in common)

For a 2D array, choose column length to be a multiple of n, so that consecutive columns have the same alignment (pad if necessary)

-align array32byte     compiler tries to align all array types

And tell the compiler...

!dir$ vector aligned    OR
!$omp simd aligned( var [,var...]:<n>)

• Asks compiler to vectorize, assuming all array data accessed in loop are aligned for targeted processor
  • May cause fault if data are not aligned

!dir$ assume_aligned array:n     [,array2:n2, ...]

• Compiler may assume array is aligned to n byte boundary
  • Typical use is for dummy arguments
  • Extension for allocatable arrays in next compiler version

n=16 for Intel® SSE, n=32 for Intel® AVX, n=64 for Intel® AVX-512
How to Align Data (C/C++)

Allocate memory on heap aligned to n byte boundary:

```c
void* _mm_malloc(int size, int n)
int posix_memalign(void **p, size_t n, size_t size)
void* aligned_alloc(size_t alignment, size_t size) (C11)
#include <aligned_new> (C++11)
```

Alignment for variable declarations:

```c
__attribute__((aligned(n))) var_name or __declspec(align(n)) var_name
```

And tell the compiler...

`#pragma vector aligned`

- Asks compiler to vectorize, overriding cost model, and assuming all array data accessed in loop are aligned for targeted processor
- May cause fault if data are not aligned

```c
__assume_aligned(array, n)
```

- Compiler may assume array is aligned to n byte boundary

n=64 for Intel® Xeon Phi™ coprocessors, n=32 for Intel® AVX, n=16 for Intel® SSE
Pragma SIMD

• **Pragma SIMD:**
The `simd` construct can be applied to a loop to indicate that the loop can be transformed into a SIMD loop (that is, multiple iterations of the loop can be executed concurrently using SIMD instructions). [OpenMP* 4.0 API: 2.8.1]

• **Syntax:**

```
#pragma omp simd [clause [,clause]...]  
for-loop
```

• For-loop has to be in “canonical loop form” (see OpenMP 4.0 API:2.6)
  - Random access iterators required for induction variable (integer types or pointers for C++)
  - Limited test and in-/decrement for induction variable
  - Iteration count known before execution of loop
  - …
Pragma SIMD Clauses

- `safelen(n1[,n2] ...)`: Variables must be power of 2: The compiler can assume a vectorization for a vector length of `n1, n2, ...` to be safe.
- `private(v1, v2, ...)`: Variables private to each iteration
  - `lastprivate(...)`: Last value is copied out from the last iteration instance.
- `linear(v1:step1, v2:step2, ...)`: For every iteration of the original scalar loop `v1` is incremented by `step1`, ... etc. Therefore it is incremented by `step1 * vector length` for the vectorized loop.
- `reduction(operator:v1, v2, ...)`: Variables `v1, v2, ...` etc. are reduction variables for operation `operator`.
- `collapse(n)`: Combine nested loops – collapse them.
- `aligned(v1:base, v2:base, ...)`: Tell variables `v1, v2, ...` are aligned; (default is architecture specific alignment).
Pragma SIMD Example

Ignore data dependencies, indirectly mitigate control flow dependence & assert alignment:

```c
#include <stdio.h>

void vec1(float *a, float *b, int off, int len)
{
    #pragma omp simd safelen(32) aligned(a:64, b:64)
    for(int i = 0; i < len; i++)
    {
        a[i] = (a[i] > 1.0) ?
                a[i] * b[i] :
                a[i + off] * b[i];
    }
}
```

LOOP BEGIN at simd.cpp(4,5)
remark #15388: vectorization support: reference a has aligned access  [ simd.cpp(6,9) ]
remark #15388: vectorization support: reference b has aligned access  [ simd.cpp(6,9) ]
...
remark #15301: OpenMP SIMD LOOP WAS VECTORIZED
...
LOOP END
SIMD-Enabled Functions

• SIMD-Enabled Function (aka. declare simd construct):
The declare simd construct can be applied to a function […] to enable the creation of one or more versions that can process multiple arguments using SIMD instructions from a single invocation from a SIMD loop. [OpenMP* 4.0 API: 2.8.2]

• Syntax:
  #pragma omp declare simd [clause [,clause]…] function definition or declaration

• Intent:
  Express work as scalar operations (kernel) and let compiler create a vector version of it. The size of vectors can be specified at compile time (SSE, AVX, …) which makes it portable!

• Remember:
  Both the function definition as well as the function declaration (header file) need to be specified like this!
SIMD-Enabled Function Clauses

- **simdlen(len)**
  len must be power of 2: Allow as many elements per argument (default is implementation specific)

- **linear(v1:step1, v2:step2, ...)**
  Defines v1, v2, ... to be private to SIMD lane and to have linear (step1, step2, ...) relationship when used in context of a loop

- **uniform(a1, a2, ...)**
  Arguments a1, a2, ... etc. are not treated as vectors (constant values across SIMD lanes)

- **inbranch, notinbranch**: SIMD-enabled function called only inside branches or never

- **aligned(a1:base, a2:base, ...)**: Tell arguments a1, a2, ... are aligned; (default is architecture specific alignment)
SIMD-Enabled Function Example

Ignore data dependencies, indirectly mitigate control flow dependence & assert alignment:

```c
#pragma omp declare simd simdlen(16) notinbranch uniform(a, b, off)
float work(float *a, float *b, int i, int off)
{
    return (a[i] > 1.0) ? a[i] * b[i] : a[i + off] * b[i];
}

void vec2(float *a, float *b, int off, int len)
{
    #pragma omp simd safelen(64) aligned(a:64, b:64)
    for(int i = 0; i < len; i++)
    { a[i] = work(a, b, i, off); }
}
```

INLINE REPORT: (vec2(float *, float *, int, int)) [4/9=44.4%] simd.cpp(8,1)
-> INLINE: (12,16) work(float *, float *, int, int) (isz = 18) (sz = 31)

LOOP BEGIN at simd.cpp(10,5)
    remark #15388: vectorization support: reference a has aligned access [ simd.cpp(4,20) ]
    remark #15388: vectorization support: reference b has aligned access [ simd.cpp(4,20) ]
    ...
    remark #15301: OpenMP SIMD LOOP WAS VECTORIZED
    ...
LOOP END
KNL High Bandwidth Memory

Adapting software to make best use of KNL MCDRAM
High Bandwidth On-Package Memory API

API is open-sourced (BSD licenses)
- https://github.com/memkind; also part of XPPSL at https://software.intel.com/articles/xeon-phi-software
- User jemalloc API underneath

malloc replacement:

```c
#include <memkind.h>

hbw_check_available()
hbw_malloc, _calloc, _realloc,... (memkind_t kind, ...)
hbw_free()
hbw_posix_memalign(), _posix_memalign_psize()
hbw_get_policy(), _set_policy()

ld ... -ljemalloc -l numa -lmemkind -lpthread
```
HBW API for Fortran, C++

Fortran:

!DIR$ ATTRIBUTES FASTMEM :: data_object1,
  - Flat or hybrid mode only
  - More Fortran data types may be supported eventually
    - Global, local, stack or heap;
    - Currently just allocatable arrays (16.0) and pointers (17.0)
    - OpenMP private copies: preview in 17.0 update 1
    - Must remember to link with libmemkind!

Possible addition in a future compiler:
  - Placing FASTMEM directive before ALLOCATE statement
  - Instead of ALLOCATABLE declaration

C++: can pass hbw_malloc() etc.

standard allocator replacement for e.g. STL like

#include <hbw_allocator.h>
std::vector<int, hbw::allocator::allocate>

Available already, working on documentation
Use Fortran 2003 C-interoperability features to call memkind API

```fortran
interface
  function hbw_check_available() result(avail) bind(C,name='hbw_check_available')
    use iso_c_binding
    implicit none
    integer(C_INT) :: avail
  end function hbw_check_available
end interface

integer :: istat
istat = hbw_check_available()
if (istat == 0) then
  print *, 'HBM available'
else
  print *, 'ERROR, HBM not available, return code=', istat
end if
```
How much HBM is left?

#include <memkind.h>

int hbw_get_size(int partition, size_t * total, size_t * free) { // partition=1 for HBM
    memkind_t kind;

    int stat = memkind_get_kind_by_partition(partition, &kind);
    if(stat==0) stat = memkind_get_size(kind, total, free);
    return stat;
}

Fortran interface:

interface
function hbw_get_size(partition, total, free) result(istat) bind(C, name='hbw_get_size')
    use iso_c_binding
    implicit none
    integer(C_INT) :: istat
    integer(C_INT), value :: partition
    integer(C_SIZE_T) :: total, free
end function hbw_get_size
end interface

HBM doesn't show as “used” until first access after allocation
What Happens if HBW Memory is Unavailable? (Fortran)

In 16.0: silently default over to regular memory

New Fortran intrinsic in module IFCORE in 17.0:

```fortran
integer(4) FOR_GET_HBW_AVAILABILITY() returns values:
```

- `FOR_K_HBW_NOT_INITIALIZED` (= 0)
  - Automatically triggers initialization of internal variables
  - In this case, call a second time to determine availability

- `FOR_K_HBW_AVAILABLE` (= 1)

- `FOR_K_HBW_NO_ROUTINES` (= 2) e.g. because libmemkind not linked

- `FOR_K_HBW_NOT_AVAILABLE` (= 3)
  - does not distinguish between HBW memory not present; too little HBW available; and failure to set MEMKIND_HBW_NODES

New RTL diagnostics when ALLOCATE to fast memory cannot be honored:

- 183/4 warning/error libmemkind not linked
- 185/6 warning/error HBW memory not available

Severe errors 184, 186 may be returned in STAT field of ALLOCATE statement
Controlling What Happens if HBM is Unavailable (Fortran)

In 16.0: you can’t

New Fortran intrinsic in module IFCORE in 17.0:

integer(4) FOR_SET_FASTMEM_POLICY(new_policy)

input arguments:

- FOR_FASTMEM_INFO (= 0) return current policy unchanged
- FOR_FASTMEM_NORETRY (= 1) error if unavailable (default)
- FOR_FASTMEM_RETRY_WARN (= 2) warn if unavailable, use default memory
- FOR_FASTMEM_RETRY (= 3) if unavailable, silently use default memory

returns previous HBW policy

Environment variables (to be set before program execution):

- FOR_FASTMEM_NORETRY =T/F default False
- FOR_FASTMEM_RETRY =T/F default False
- FOR_FASTMEM_RETRY_WARN =T/F default False
Getting consistent floating-point results when moving to the Intel® Xeon Phi™ x200 processor family from Intel® Xeon® processors or from Intel® Xeon Phi™ x100 Coprocessors
Floating-Point Reproducibility

- `fp-model precise` disables most value-unsafe optimizations (especially reassociations)

- The primary way to get consistency between different platforms (including KNL) or different optimization levels

- Does not prevent differences due to:
  - Different implementations of math functions
  - Use of fused multiply-add instructions (FMAs)

- Floating-point results on Intel® Xeon Phi™ x100 coprocessors may not be bit-for-bit identical to results obtained on Intel® Xeon® processors or on KNL
Disabled by -fp-model precise

Vectorization of loops containing transcendental functions
Fast, approximate division and square roots
Flush-to-zero of denormals
Vectorization of reduction loops
Other reassociations
  (including hoisting invariant expressions out of loops)
Evaluation of constant expressions at compile time
…
Math functions

Implementation of math functions may differ between different processors

- For consistency of math functions between KNL and Intel® Xeon® processors, use
  
  `-fimf-arch-consistency=true` for both

- Not available for KNC
  - `-fp-model precise` (or `-fimf-precision=high`) should get you close

- These options come at a cost in performance
FMAs

The most common cause of differences between Intel® Xeon® processors and Intel® Xeon Phi™ x100 coprocessors or KNL

- Not disabled by -fp-model precise
- Can disable for testing with -no-fma
- Or by function-wide pragma or directive:
  
  #pragma float_control(fma,off)
  
  !dir$ nofma

  - With some impact on performance
- -fp-model strict disables FMAs, amongst other things
  - But on KNC, results in non-vectorizable x87 code
- The fma() intrinsic in C should always give a result with a single rounding, even on processors with no FMA instruction
FMAs

Can cause issues even when both platforms support them (e.g. Haswell and KNL)

- Optimizer may not generate them in the same places
  - No language rules
- FMAs may break the symmetry of an expression:

\[
\begin{align*}
  c &= a; \\
  d &= -b; \\
  \text{result} &= a \cdot b + c \cdot d; \\
  \text{result} &= fma(c, d, (a \cdot b)) \\
  \text{result} &= fma(a, b, (c \cdot d))
\end{align*}
\]

If FMAs are supported, the compiler may convert to either

result = fma(c, d, (a*b)) or result = fma(a, b, (c*d))

Because of the different roundings, these may give results that are non-zero and/or different from each other.
Reproducibility: the bottom line (for Intel64)

/fp:precise /Qfma- /Qimf-arch-consistency:true (Windows*)
-fp-model precise -no-fma -fimf-arch-consistency=true (Linux* or OS X*)

- Recommended for best reproducibility
  - Also for IEEE compliance
  - And for language standards compliance (C, C++ and Fortran)

- This isn’t very intuitive
  - a single switch will do all this in the 17.0 compiler
  - -fp-model consistent (/fp:consistent on Windows*)
Prefetching for KNL

Hardware prefetcher is more effective than for KNC
Software (compiler-generated) prefetching is off by default
- Like for Intel® Xeon® processors
- Enable by -qopt-prefetch=[1-5]

KNL has gather/scatter prefetch
- Enable auto-generation to L2 with -qopt-prefetch=5
  - Along with all other types of prefetch, in addition to h/w prefetcher – careful.
- Or hint for specific prefetches
  - !DIR$ PREFETCH var_name [ : type : distance ]
  - Needs at least -qopt-prefetch=2
- Or call intrinsic
  - _mm_prefetch((char *) &a[i], hint);   C
  - MM_PREFETCH(A, hint)                      Fortran
Gather Prefetch Example

void foo(int n, int* A, int *B, int *C)  
{  
    // pragma_prefetch var:hint:distance
#pragma prefetch A:1:3      // prefetch to L2 cache  3 iterations ahead
#pragma vector aligned
#pragma simd
    for(int i=0; i<n; i++)
        C[i] = A[B[i]];
}

icc -O3 -xmic-avx512 -qopt-prefetch=3 -qopt-report=4 -qopt-report-file=stderr -c -S emre5.cpp

remark #25033: Number of indirect prefetches=1, dist=2
remark #25035: Number of pointer data prefetches=2, dist=8
remark #25150: Using directive-based hint=1, distance=3 for indirect memory reference  [ emre5.cpp(…
remark #25540: Using gather/scatter prefetch for indirect memory reference, dist=3  [ emre5.cpp(9,12) ]
remark #25143: Inserting bound-check around lfetches for loop

% grep gatherpf emre5.s
    vgatherpf1dps (%rsi,%zmm0){%k1}                              #9.12 c7 stall 2
% grep prefetch emre5.s
# mark_description ".-O3 -xmic-avx512 -qopt-prefetch=3 -qopt-report=4 -qopt-report-file=stderr -c -S -g";
prefetcht0 512(%r9,%rcx)                                      #9.14 c1
prefetcht0 512(%r9,%r8)                                      #9.5 c7
Additional Resources (Optimization)

Webinars:
https://software.intel.com/articles/further-vectorization-features-of-the-intel-compiler-webinar-code-samples

Vectorization Guide (C):

Explicit Vector Programming in Fortran:
https://software.intel.com/articles/explicit-vector-programming-in-fortran

Initially written for Intel® Xeon Phi™ coprocessors, but also applicable elsewhere:
https://software.intel.com/articles/vectorization-essential

Compiler User Forums at http://software.intel.com/forums
Thank you!
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