Floating-point control in the Intel C/C++ compiler and libraries
or
Why doesn’t my application always give the same answer?

Martyn Corden
Developer Products Division
Software Solutions Group
Intel Corporation
February 2012
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Notice revision #20110804
Agenda

- Overview
- Floating Point (FP) Model
  - Comparisons with gcc
- Performance impact
- Runtime math libraries
Overview

• The finite precision of floating-point operations leads to an inherent uncertainty in the results of a floating-point computation
  – Results may vary within this uncertainty

• Nevertheless, may need reproducibility beyond this uncertainty
  – For reasons of Quality Assurance, e.g. when porting, optimizing, etc

• The right compiler options can deliver consistent, closely reproducible results whilst preserving good performance
  – Across IA-32, Intel® 64 and other IEEE-compliant platforms
  – Across optimization levels
  – -fp-model is the recommended high level control for the Intel Compiler
Floating Point (FP) Programming Objectives

- **Accuracy**
  - Produce results that are “close” to the correct value
  - Measured in relative error, possibly in ulp

- **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

These options usually conflict!
Judicious use of compiler options lets you control the tradeoffs.
Different compilers have different defaults.
Agenda

- Overview
- Floating Point (FP) Model
- Performance impact
- Runtime math libraries
Floating Point Semantics

- The –fp-model (/fp:) switch lets you choose the floating point semantics at a coarse granularity. It lets you specify the compiler rules for:
  - **Value safety** (main focus)
  - FP expression evaluation
  - FPU environment access
  - Precise FP exceptions
  - FP contractions (fused multiply-add)

- Also pragmas in C99 standard
  - #pragma STDC FENV_ACCESS etc

- Old switches such as –mp now deprecated
  - Less consistent and incomplete; don’t use
The \texttt{-fp-model} switch for \texttt{icc}

- \texttt{-fp-model}
  - \texttt{fast} [=1]  allows value-unsafe optimizations (default)
  - \texttt{fast} = 2  allows additional approximations
  - \texttt{precise}  value-safe optimizations only
    (also source, double, extended)
  - \texttt{except}   enable floating point exception semantics
  - \texttt{strict}   precise + except + disable fma +
    don’t assume default floating-point environment

- Replaces old switches \texttt{-mp}, \texttt{-fp-port}, etc (don’t use!)

- \texttt{-fp-model precise} \texttt{-fp-model source}
  - recommended for ANSI/IEEE standards compliance, C++ & Fortran
  - “source” is default with “precise” on Intel 64 Linux
GCC option

- `-f[no-]fast-math` is high level option
  - It is off by default (different from icc)
- Components control similar features:
  - Value safety (`-funsafe-math-optimizations`)
    - includes reassociation
  - Reproducibility of exceptions
  - assumptions about floating-point environment
  - Assumptions about exceptional values
- also sets abrupt/gradual underflow (FTZ)
- For more detail, check
  http://gcc.gnu.org/wiki/FloatingPointMath
## Value Safety

- In SAFE mode, the compiler may not make any transformations that could affect the result, e.g. all the following are prohibited.

<table>
<thead>
<tr>
<th>Transformation</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x / x ) (\equiv) 1.0</td>
<td>(x) could be 0.0, (\infty), or NaN</td>
</tr>
<tr>
<td>( x - y ) (\equiv) (-(y - x))</td>
<td>If (x) equals (y), (x - y) is +0.0 while (-(y - x)) is -0.0</td>
</tr>
<tr>
<td>( x - x ) (\equiv) 0.0</td>
<td>(x) could be (\infty) or NaN</td>
</tr>
<tr>
<td>( x * 0.0 ) (\equiv) 0.0</td>
<td>(x) could be -0.0, (\infty), or NaN</td>
</tr>
<tr>
<td>( x + 0.0 ) (\equiv) (x)</td>
<td>(x) could be -0.0</td>
</tr>
<tr>
<td>((x + y) + z) (\equiv) (x + (y + z))</td>
<td>General reassociation is not value safe</td>
</tr>
<tr>
<td>((x == x)) (\equiv) true</td>
<td>(x) could be NaN</td>
</tr>
</tbody>
</table>

- UNSAFE (fast) mode is the icc default
- VERY UNSAFE mode enables riskier transformations
Value Safety

Affected Optimizations include:

- Reassociation
- Flush-to-zero
- Expression Evaluation, various mathematical simplifications
- Approximate divide and sqrt
- Math library approximations
Reassociation

- Addition & multiplication are “associative” (& distributive)
  - \( a + b + c = (a+b) + c = a + (b+c) \)
  - \( a\times b + a\times c = a \times (b+c) \)
- These transformations are equivalent mathematically
  - but not in finite precision arithmetic

- Reassociation can be disabled in its entirety
  - \( \Rightarrow \) for standards conformance (C left-to-right)
  - Use `-fp-model precise`
- May carry a significant performance penalty other optimizations also disabled
Example (see exercises)

“tiny” is intended to keep $a[i] > 0$

but... optimizer hoists constant expression $(c + \text{tiny})$ out of loop
 tiny gets “rounded away” wrt $c$

```
icc -O1 reassoc.cpp; ./a.out
a = 0 b = inf
icc -fp-model precise reassoc.cpp; ./a.out
a = 1e-20 b = 1e+20
```

```
g++ reassoc.cpp; ./a.out
a = 1e-20 b = 1e+20
g++ -O3 -ffast-math reassoc.cpp; ./a.out
a = 0 b = inf
```

```
#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";
}
```
Denormalized numbers and Flush-to-Zero (FTZ)

- Denormals extend the (lower) range of IEEE floating-point values, at the cost of:
  - Reduced precision
  - Reduced performance (can be 100 X for ops with denormals)

- If your application creates but does not depend on denormal values, setting these to zero may improve performance ("abrupt underflow", or "flush-to-zero",)
  - Done in SSE or AVX hardware, so fast
  - Happens by default at –O1 or higher (for icc, not gcc)
  - -no-ftz or –fp-model precise will prevent
    - Must compile main with this switch to have an effect
    - -fp-model precise -ftz to get “precise” without denormals
  - Not available for x87, denormals always generated
    - (unless trapped and set to zero in software – very slow)

- For gcc, -ffast-math sets abrupt underflow (FTZ)
  - But –O3 -ffast-math reverts to gradual underflow
Reductions

- Parallel implementations imply reassociation (partial sums)
  - Not value safe, but can give substantial performance advantage
  - -fp-model precise
    - disables vectorization of reductions
    - does not affect OpenMP* or MPI* reductions
      These remain value-unsafe 
        (programmer’s responsibility)

```c
float Sum(const float A[], int n)
{
    float sum = 0;
    for (int i = 0; i < n; i++)
        sum = sum + A[i];
    return sum;
}
```

```c
float Sum(const float A[], int n)
{
    int n4 = n - n % 4;
    float sum = 0, sum1 = 0, sum2 = 0, sum3 = 0;
    for (int i = 0; i < n4; i += 4) {
        sum = sum + A[i];
        sum1 = sum1 + A[i + 1];
        sum2 = sum2 + A[i + 2];
        sum3 = sum3 + A[i + 3];
    }
    sum = sum + sum1 + sum2 + sum3;
    for (; i < n; i++) sum = sum + A[i];
    return sum;
}
```
Reproducibility of Reductions in OpenMP*

• Each thread has its own partial sum
  – Breakdown, & hence results, depend on number of threads
  – Partial sums are summed at end of loop
  – Order of partial sums is undefined (OpenMP standard)
    – First come, first served
    – Result may vary from run to run (even for same # of threads)
    – For both gcc and icc
    – Can be more accurate than serial sum
  – For icc, option to define the order of partial sums (tree)
    – Makes results reproducible from run to run
    – export KMP_FORCE_REDUCTION=tree
      – May also help accuracy
      – Possible slight performance impact, depends on context
      – Requires static scheduling, fixed number of threads
      – currently undocumented
      – See example
FP Expression Evaluation

- In the following expression, what if a, b, c, and d are mixed data types (single and double for example)
  \[ a = (b + c) + d \]

Four possibilities for intermediate rounding, (corresponding to C99 FLT_EVAL_METHOD)

- Indeterminate (-fp-model fast)
- Use precision specified in source (-fp-model source)
- Use double precision (C/C++ only) (-fp-model double)
- Use long double precision (C/C++ only) (-fp-model extended)

- Or platform-dependent default (-fp-model precise)
  - Defaults to -fp-model source on Intel64
  - Recommended for most purposes

- The expression evaluation method can significantly impact performance, accuracy, and portability
The Floating Point Unit (FPU) Environment

- FP Control Word Settings
  - Rounding mode (nearest, toward +∞, toward -∞, toward 0)
  - Exception masks, status flags
    (inexact, underflow, overflow, divide by zero, denormal, invalid)
  - Flush-to-zero (FTZ), Denormals-are-zero (DAZ)
  - x87 precision control (single, double, extended)  [don’t mess!]

- Affected Optimizations, e.g.
  - Constant folding
  - FP speculation
  - Partial redundancy elimination
  - Common subexpression elimination
  - Dead code elimination
  - Conditional transform, e.g.
    if (c) x = y; else x = z;  \( \Rightarrow \)  x = (c) ? y : z;
FPU Environment Access

- When access disabled (default):
  - Compiler assumes default FPU environment
    - Round-to-nearest
    - All exceptions masked
    - No FTZ/DAZ
  - Compiler assumes program will NOT read status flags

- If user might change the default FPU environment, inform compiler by setting FPU environment access mode!!
  - Access may only be enabled in value-safe modes, by:
    - `fp-model strict` or
    - `#pragma STDC FENV_ACCESS ON`
  - Compiler treats control settings as unknown
  - Compiler preserves status flags
  - Some optimizations are disabled
Precise FP Exceptions

- When Disabled (default):
  - Code may be reordered by optimization
  - FP exceptions might not occur in the “right” places

- When enabled by
  -fp-model strict
  -fp-model except
  #pragma float_control(except, on)
  - The compiler must account for the possibility that any FP operation might throw an exception
    - Disables optimizations such as FP speculation
    - May only be enabled in value-safe modes
    - (more complicated for x87)
  - Does not unmask exceptions
    - Must do that separately, e.g.
      -fp-trap=common for C
      or functions calls such as feenableexcept()
      -fpe0 or set_halting_mode() for Fortran
Example

double x., zero = 0.;
  feenableexcept
  (FE_DIVBYZERO);
  for( int i = 0; i < 20;
    i++ )
    x = zero ? (1./zero) :
    zero;

Problem: F-P exception from (1./zero) despite explicit protection
  - The invariant (1./zero) gets speculatively hoisted out of loop by
    optimizer, but the “?” alternative does not
  - exception occurs before the protection can kick in
  - NOTE: does not occur for AVX due to masked vector operations

Solution: Disable optimizations that lead to the premature exception
  - icc -fp-model precise -fp-model except (or icc -fp-model strict)
    disables all optimizations that could affect FP exception semantics
  - icc -fp-speculation safe
    disables just speculation where this could cause an exception
  - #pragma float_control around the affected code block (see doc)
Floating Point Contractions

- affects the generation of FMA instructions on Intel® MIC architecture and Intel® AVX2 (-xcore-avx2)
  - Enabled by default or -fma, disable with –no-fma
  - Disabled by –fp-model strict or C/C++ #pragma
  - -[no-]fma switch overrides –fp-model setting
  - Intel compiler does NOT support 4-operand AMD*-specific fma instruction)

- When enabled:
  - The compiler may generate FMA for combined multiply/add
    - Faster, more accurate calculations
    - Results may differ in last bit from separate multiply/add

- When disabled:
  - -fp-model strict, #pragma fp_contract(off) or –no-fma
  - The compiler must generate separate multiply/add with intermediate rounding
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**Typical Performance Impact of -fp-model source**

- Measured on SPECCPU2006fp benchmark suite:
  - -O2 or -O3
  - Geomean reduction due to
    -fp-model precise -fp-model source
    **in range 12% - 15%**

- Intel Compiler XE 2011 (12.0)
- Measured on Intel Xeon® 5650 system with dual, 6-core processors at 2.67Ghz, 24GB memory, 12MB cache, SLES* 10 x64 SP2

**Use -fp-model source (/fp:source) to improve floating point reproducibility whilst limiting performance impact**
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Math Library Functions

- Different implementations may not have the same accuracy
  - On Intel 64:
    - libsvml for vectorized loops
    - libimf (libm) elsewhere
    - Processor-dependent code within libraries, selected at runtime
    - Inlining was important for Itanium, to get software pipelining, but unimportant for Intel 64 since can vectorize with libsvml

- No official standard (yet) dictates accuracy or how results should be rounded (except for division & sqrt)

-fp-model precise helps generate consistent math calls
  - eg within loops, between kernel & prolog/epilog
  - Remove or reduce dependency on alignment
  - May prevent vectorization unless use -fast-transcendentals
    - When may differ from non-vectorized loop
New math library features (12.x compiler)

• Select minimum precision
  – Currently for libsvml (vector); scalar libimf normally “high”
    -fimf-precision=<high|medium|low>
    – Default is off (compiler chooses)
    – Typically high for scalar code, medium for vector code
    – “low” typically halves the number of mantissa bits
      – Potential performance improvement
    – “high” ~0.55 ulp; “medium” < 4 ulp (typically 2)

• -fimf-arch-consistency=<true | false>
  – Will produce consistent results on all microarchitectures or processors within the same architecture
  – Run-time performance may decrease
  – Default is false (even with -fp-model precise !)
Math Libraries – known issues

- Differences could potentially arise between:
  - Different compiler releases, due to algorithm improvements
    - Use -fimf-precision
    - another workaround, use later RTL with both compilers
  - Different platforms, due to different algorithms or different code paths at runtime
    - Libraries detect run-time processor internally
    - Independent of compiler switches
    - use -fimf-arch-consistency=true

- Expected accuracy is maintained
  - 0.55 ulp for libimf
  - < 4 ulp for libsvml (default for vectorized loops)

- Adherence to an eventual standard for math functions would improve consistency but at a cost in performance.
Intel® Math Kernel Library

• Linear algebra, FFTs, sparse solvers, statistical, ...
  – Highly optimized, vectorized
  – Threaded internally using OpenMP*
  – Repeated runs may not give identical results

• Coming soon: **Conditional BitWise Reproducibility**
  – Repeated runs give identical results under certain conditions:
    – Same number of threads
    – OMP_SCHEDULE=static (the default)
    – Same OS and architecture (e.g. Intel 64)
    – Same microarchitecture, or specify a minimum microarchitecture
    – Consistent data alignment
  – Call `mkl_bwr_set(...)"
Further Information

- Microsoft Visual C++* Floating-Point Optimization

- The Intel® C++ and Fortran Compiler Documentation, “Floating Point Operations”

- “Consistency of Floating-Point Results using the Intel® Compiler”

# Quick Overview of Primary Switches

<table>
<thead>
<tr>
<th>Primary Switches</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>/fp:keyword</code></td>
<td>`fast[-1</td>
</tr>
<tr>
<td><code>-fp-model keyword</code></td>
<td>Controls floating point semantics</td>
</tr>
<tr>
<td><code>/Qftz[-]</code></td>
<td><code>-[no-]ftz</code></td>
</tr>
<tr>
<td>Other switches</td>
<td></td>
</tr>
<tr>
<td><code>/Qfp-speculation keyword</code></td>
<td><code>fast</code>, <code>safe</code>, <code>strict</code>, <code>off</code> floating point speculation control</td>
</tr>
<tr>
<td><code>-fp-speculation keyword</code></td>
<td></td>
</tr>
<tr>
<td><code>/Qprec-div[-]</code></td>
<td><code>-[no-]prec-div</code></td>
</tr>
<tr>
<td>/Qprec-sqrt[-]</td>
<td><code>-[no-]prec-sqrt</code></td>
</tr>
<tr>
<td>/Qfma[-]</td>
<td><code>-[no-]fma</code></td>
</tr>
<tr>
<td>/Qfp-trap:...</td>
<td><code>-fp-trap=common</code></td>
</tr>
<tr>
<td>/fpe:0</td>
<td><code>-fpe0</code></td>
</tr>
<tr>
<td>/Qfp-port</td>
<td><code>-fp-port</code></td>
</tr>
<tr>
<td>/Qprec</td>
<td><code>-mp1</code></td>
</tr>
<tr>
<td>/Op[-]</td>
<td><code>-mp [-nofltconsistency]</code></td>
</tr>
<tr>
<td><code>Other switches</code></td>
<td></td>
</tr>
<tr>
<td><code>/Qprec</code></td>
<td><code>-mp1</code></td>
</tr>
<tr>
<td><code>/Op[-]</code></td>
<td><code>-mp [-nofltconsistency]</code></td>
</tr>
<tr>
<td><code>Deprecated; use /fp:source etc instead</code></td>
<td></td>
</tr>
</tbody>
</table>
## Floating-point representations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single</th>
<th>Double</th>
<th>Quad or Extended Precision (IEEE_X)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format width in bits</td>
<td>32</td>
<td>64</td>
<td>128</td>
</tr>
<tr>
<td>Sign width in bits</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>mantissa</td>
<td>23 (24 implied)</td>
<td>52 (53 implied)</td>
<td>112 (113 implied)</td>
</tr>
<tr>
<td>Exponent width in bits</td>
<td>8</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Max binary exponent</td>
<td>+127</td>
<td>+1023</td>
<td>+16383</td>
</tr>
<tr>
<td>Min binary exponent</td>
<td>- 126</td>
<td>- 1022</td>
<td>-16382</td>
</tr>
<tr>
<td>Exponent bias</td>
<td>+127</td>
<td>+1023</td>
<td>+16383</td>
</tr>
<tr>
<td>Max value</td>
<td>(\approx 3.4 \times 10^{38})</td>
<td>(\approx 1.8 \times 10^{-308})</td>
<td>(\approx 1.2 \times 10^{-4932})</td>
</tr>
<tr>
<td>Value (Min normalized)</td>
<td>(\approx 1.2 \times 10^{-38})</td>
<td>(\approx 2.2 \times 10^{-308})</td>
<td>(\approx 3.4 \times 10^{-4932})</td>
</tr>
<tr>
<td>Value (Min denormalized)</td>
<td>(\approx 1.4 \times 10^{-45})</td>
<td>(\approx 4.9 \times 10^{-324})</td>
<td>(\approx 6.5 \times 10^{-4966})</td>
</tr>
</tbody>
</table>
## Special FP number representations

- **Single precision representations**

<table>
<thead>
<tr>
<th></th>
<th>1 Sign bit</th>
<th>8 Exponent bits</th>
<th>(1)+23 Significand bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>zero</td>
<td>0 or 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>denormalized</td>
<td>0 or 1</td>
<td>0</td>
<td>(0.)xxxxx...</td>
</tr>
<tr>
<td>normalized</td>
<td>0 or 1</td>
<td>1-254</td>
<td>(1.)xxxxx...</td>
</tr>
<tr>
<td>infinity</td>
<td>0 or 1</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>Signalling NaN (SNaN)</td>
<td>No meaning</td>
<td>255</td>
<td>(1.)0xxxx...</td>
</tr>
<tr>
<td>Quiet Nan (QNaN)</td>
<td>No Meaning</td>
<td>255</td>
<td>(1.)1xxxx...</td>
</tr>
</tbody>
</table>
Flush-To-Zero and Denormal FP Values

- A **normalized** FP number has leading binary bit and an exponent in the range accommodated by number of bits in the exponent.
- example:
  
  \[ 0.171865_{10} = 1/8 + 1/32 + 1/64 \]
  
  \[ = 0.001011_2 \]
  
  normalized = \( 1.011_2 \times 2^{-3} \)

- Exponent is stored in 8 bits single or 11 bits double: mantissa in 23 bits single, 52 bits double
- exponent biased by 127 (single precision)
- leading sign bit – normalized “1.” bit implied, not physically stored (1.011 stored as 011)

0 01111100 011000000000000000000000
Flush-To-Zero and Denormal FP Values

- What happens if the number is close to zero BUT exponent X in the $2^{-x}$ won’t fit in 8 or 11 bits?
- $2^{-128}$ for example in single precision
- Cannot represent in a NORMALIZED fashion:
  - $1/2^{127} = 0.00...001_2$ (126 zeros after the binary point and a binary 1)
  - $= 1.0_2 \times 2^{-128}$
- But -128 won’t fit in a 127 biased 8-bit exponent value!
- Solution: DENORMAL representation
- Exponent is -126 (all zeros), NO implied leading 1.
- 0 00000000 1000000000000000000000000
Flush-To-Zero and Denormal FP Values

• “Underflow” is when a very small number is created that cannot be represented. “Gradual underflow” is when values are created that can be represented as denormal
• Denormals do not include as many significant digits
• Gradual loss of precision as denormal values get closer to zero

• OK, fine, I like these denormal numbers, they carry some precision – why are denormals an issue?
  – UNFORTUNATELY denormals can cause 100x loss of performance

• Solution: set any denormal to zero: FLUSH TO ZERO
  – Keeps performance up, tradeoff is some loss of precision
-prec-div and -prec-sqrt Options

- Both override the -fp-model settings
- Default is -no-prec-sqrt, and somewhere between -prec-div and -no-prec-div

[-no]-prec-div /Qprec-div[-]
- Enables[disables] various divide optimizations
  - x / y ⇔ x * (1.0 / y)
  - Approximate divide and reciprocal

[-no]-prec-sqrt /Qprec-sqrt[-]
- Enables[disables] approximate sqrt and reciprocal sqrt
-[no-]fast-transcendentals

The compiler frequently optimizes calls of math library functions (like exp, sinf) in loops

- Uses SVML (short vector math library) to vectorize loops
- Uses the XMM direct call routines,
  e.g. exp → ___libm_sse2_exp (IA-32 only)
  - Uses fast in-lined implementations

This switch “-[no]fast-transcendental” can be used to overwrite default behavior

- Behavior related to settings of fp-model and other switches – see reference manual!!