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

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Agenda

- Overview
- Floating Point (FP) Model
  - Comparisons with gcc
- Performance impact
- Runtime math libraries
- Intel® Xeon Phi™ Coprocessors – what's different

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.

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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 –fp-model switch for icc

- **-fp-model**
  - fast [=1] allows value-unsafe optimizations (default)
  - fast=2 allows additional approximations
  - precise value-safe optimizations only
  - source | double | extended imply "precise" unless overridden
    see "FP Expression Evaluation" for more detail
  - except enable floating point exception semantics
  - strict precise + except + disable fma +
    don't assume default floating-point
    environment

- Replaces old switches –mp, -fp-port, etc (don't use!)

- **-fp-model precise -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)
  - It is turned on by -Ofast
- 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 backup or 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.

x / x ⇔ 1.0	x could be 0.0, ∞, or NaN
x – y ⇔ - (y – x)	If x equals y, x – y is +0.0 while – (y – x) is -0.0
x – x ⇔ 0.0	x could be ∞ or NaN
x * 0.0 ⇔ 0.0	x could be -0.0, ∞, or NaN
x + 0.0 ⇔ x	x could be -0.0
(x + y) + z ⇔ x + (y + z)	General reassociation is not value safe
(x == x) ⇔ true	x could be NaN

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*b + a*c = a * (b+c)
- These transformations are equivalent ***mathematically***
  - but <u>***not***</u> in finite precision arithmetic
- Reassociation can be disabled in its entirety
  - ⇒ for standards conformance (C left-to-right)
  - Use **-fp-model precise**
  - May carry a significant performance penalty (other optimizations also disabled)
- Parentheses are respected only in value-safe mode!
  - -assume protect_parens compromise (Fortran only)
- See exercises for an example derived from a real app

Example (see exercises)

"tiny" is intended to keep a[i]>0

but… optimizer hoists constant expression (c+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 Intel® SSE or Intel® 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
      - except those mandated by Intel® Cilk Plus
    - does not affect OpenMP* or MPI* reductions

      These remain value-unsafe

      (programmer's responsibility)

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

```
float Sum( const float A[], int n )
{
   int i, n4 = n-n%4;
   float sum=0,sum1=0,sum2=0,sum3=0;
   for (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 & ifort, option to define the order of partial sums (tree algorithm)
    - Makes results reproducible from run to run
    - export KMP_DETERMINISTIC_REDUCTION=yes (in 13.0)
      - May also help accuracy
      - Possible slight performance impact, depends on context
      - Requires static scheduling, fixed number of threads
      - Default for large numbers of threads

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   (evaluation at compile time)
  - FP speculation
  - Partial redundancy elimination
  - Common subexpression elimination
  - Dead code elimination
  - Conditional transform, e.g.

    if (c) x = y; else x = z; ➔   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
- If you forget this, you might get **completely** wrong results!
  - Eg from math functions, if you change default rounding mode

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
- Compiler thinks safe, because exceptions are masked by default
- exception occurs before the protection can kick in
  - may not occur for Intel® AVX, which have masked vector instructions

Solution: Disable optimizations that lead to the premature exception

- icc –fp-model strict
  warns compiler that F-P defaults have been modified
- #pragma STDC FENV_ACCESS ON does likewise
- icc –fp-speculation safe
  disables just speculation where this could cause an exception

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 ieee_set_halting_mode() for Fortran

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
  - NOT disabled by –fp-model precise
  - -[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 less important for Intel 64 since can vectorize with libsvml
      - Used for some division and square root implementations

- 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 – potential 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*
  - By default, repeated runs may not give identical results
- **C**onditional **B**it**W**ise **R**eproducibility (new)
  - 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_cbwr_set(MKL_CBWR_COMPATIBLE)`
  - Or set environment variable `MKL_CBWR_BRANCH="COMPATIBLE"`
  - In Intel® Composer XE 2013

Intel® Threading Building Blocks

- A C++ template library for parallelism
  - Dynamic scheduling of user-defined tasks
  - Supports parallel_reduce() pattern
  - Repeated runs may not give identical results

- "Community preview" feature for reproducibiity:
  - **parallel_deterministic_reduce()**
  - In Intel® Composer XE 2013
  - Repeated runs give identical results provided the user-supplied body yields consistent results
    - Independent of the number of threads
      - Simple partitioner always breaks up work in the same way
    - But results may differ from a serial reduction
    - May be some impact on performance

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Floating-Point Behavior on the Intel® Xeon Phi™ Coprocessor

- Floating-point exception flags are set by KCi vector instructions
  - the flags can be read
  - unmasking and trapping is not supported.
  - attempts to unmask will result in seg fault
  - -fpe0 (Fortran) and -fp-trap (C) are disabled
  - -fp-model except or strict will yield (slow!) x87 code that supports unmasking and trapping of floating-point exceptions
- Denormals are supported by KCi (but slow, like host)
  - Needs –no-ftz or –fp-model precise (like host)
- 512 bit vector transcendental math functions available (SVML)
  - Division and square root implementations still settling down
  - Both SVML and fast inlined divide and sqrt sequences available
  - Many options to select different implementations
  - See Differences in floating-point arithmetic between Intel(R) Xeon processors and the Intel Xeon Phi(TM) coprocessor for details and status

Comparing Floating-Point Results between Intel® Xeon processors and the Intel® Xeon Phi™ Coprocessor

- Different architectures – expect some differences
  - Different optimizations
  - Use of fused multiply-add (FMA)
  - Different implementations of math functions
- To minimize differences (e.g. for debugging)
  - Build with –fp-model precise (both architectures)
  - Build with –no-fma (Intel® MIC architecture)
  - Select high accuracy math functions
    - (e.g. -fimf-precision=high; default with –fp-model precise)
  - Choose reproducible parallel reductions (slides 15 & 28)
    - Or run sequentially, if you have the patience…
  - Remember, the true uncertainty of your result is probably much greater!

Further Information

- Microsoft Visual C++* Floating-Point Optimization http://msdn2.microsoft.com/en-us/library/aa289157(vs.71).aspx
- The Intel® C++ and Fortran Compiler Documentation, "Floating Point Operations"
- "Consistency of Floating-Point Results using the Intel® Compiler" http://software.intel.com/en-us/articles/consistency-of-floating-point-results-using-the-intel-compiler/
- "Differences in Floating-Point Arithmetic between Intel® Xeon® Processors and the Intel® Xeon Phi™ Coprocessor" http://software.intel.com/sites/default/files/article/326703/floating-point-differences-sept11.pdf
- Goldberg, David: "What Every Computer Scientist Should Know About Floating-Point Arithmetic" Computing Surveys, March 1991, pg. 203

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Quick Overview of Primary Switches

Primary Switches	Description
/fp:keyword **-fp-model *keyword***	***fast**[=**1**|2], precise, source, double, extended, except, strict* *Controls floating point semantics*
/Qftz[-] -[no-]ftz	*Flushes denormal results to Zero*
Some Other switches	
/Qfp-speculation *keyword* -fp-speculation *keyword*	***fast**, safe, strict, off* *floating point speculation control*
/Qprec-div[-] -[no-]prec-div	*Improves precision of floating point divides*
/Qprec-sqrt[-] -[no-]prec-sqrt	*Improves precision of square root calculations*
/Qfma[-] -[no-]fma	*Enable[Disable] use of fma instructions*
/Qfp-trap:… -fp-trap=common	*Unmask floating point exceptions (C/C++ only)*
/fpe:0 -fpe0	*Unmask floating point exceptions (Fortran only)*
/Qfp-port -fp-port	*Round floating point results to user precision*
/Qprec -mp1	*More consistent comparisons & transcendentals*
/Op[-] -mp [-nofltconsistency]	*Deprecated; use /fp:source etc instead*

Floating-point representations

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

Special FP number representations

- Single precision representations

	1 Sign bit	8 Exponent bits	(1)+23 Significand bits
zero	0 or 1	0	0
denormalized	0 or 1	0	(0.)xxxxx…
normalized	0 or 1	1-254	(1.)xxxxx…
infinity	0 or 1	255	0
Signalling NaN (SNaN)	No meaning	255	(1.)0xxxx…
Quiet Nan (QNaN)	No Meaning	255	(1.)1xxxx…

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 01100000000000000000000

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 10000000000000000000000

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 and dynamic range

–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)

  – May sometimes use 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 !!

gcc options

- -ffast-math implies
  - -fno-math-errno
  - -funsafe-math-optimizations
  - -ffinite-math-only
  - -fno-rounding-math
  - -fno-signaling-nans
  - -fcx-limited-range
  - & sets __FAST_MATH__

- -funsafe-math-optimizations implies
  - -fno-signed-zeros
  - -fassociative-math
  - -fno-trapping-math
  - -freciprocal-math

Math Functions on the Intel® Xeon Phi™ Coprocessor

- Faster, more approximate versions of math functions can still be obtained with –fp-model precise by adding

  -fast-transcendentals –no-prec-div –no-prec-sqrt

  – See Differences in floating-point arithmetic between Intel(R) Xeon processors and the Intel Xeon Phi(TM) coprocessor for details and status

- Switches for finer control of math function accuracy:
  - -fimf-precision=<high|medium|low> [:func1,func2,…]
  - -fimf-max-error
  - -fimf-accuracy-bits
  - -fimf-absolute-error
  - -fimf-domain-exclusion

Math Functions on the Intel® Xeon Phi™ Coprocessor

- Math functions have special branches and code to handle "exceptional" arguments
  - Faster versions possible if this can be skipped
- -fimf-domain-exclusion= <value>; the bits of <value> indicate domains for which the compiler need not generate special code
  - 1 extreme values (close to singularities or infinities; denormals)
  - 2 NaNs
  - 4 infinities
  - 8 denormals
  - 16 zeros
  - E.g. -fimf-domain-exclusion=31 excludes all of these for all functions
- Can be restricted to specific functions, e.g.
  - -fimf-domain-exclusion=15:/sqrt,sqrtf gives fast, inlined versions of single & double precision square root
- -fp-model-fast=2 implies –fimf-domain-exclusion=15