COMPILER OPTIMIZATIONS

What's New for Intel compilers 19.1?

Advance Support for Intel® Architecture – Use Intel compiler to generate optimized code for Intel Atom® processor through Intel® Xeon® Scalable processor and Intel® Xeon Phi™ processor families

Achieve Superior Parallel Performance – Vectorize & thread your code (using OpenMP*) to take full advantage of the latest SIMD-enabled hardware, including Intel® Advanced Vector Extensions 512 (Intel® AVX-512)

What's New in C++

Initial C++20, and full C++ 17 enabled

- Enjoy advanced lambda and constant expression support
- Standards-driven parallelization for C++ developers

Initial OpenMP* 5.0, and full OpenMP* 4.5 support

- Modernize your code by using the latest parallelization specifications

What's New in Fortran

Substantial Fortran 2018 support

- Enjoy enhanced C-interoperability features for effective mixed language development
- Use advanced coarray features to parallelize your modern Fortran code

Initial OpenMP* 5.0, and substantial OpenMP* 4.5 support

- Customize your reduction operations by user-defined reductions

Common optimization options

	Linux*
Disable optimization	-O0
Optimize for speed (no code size increase)	-O1
Optimize for speed (default)	-O2
High-level loop optimization	-O3
Create symbols for debugging	-g
Multi-file inter-procedural optimization	-ipo
Profile guided optimization (multi-step build)	-prof-gen -prof-use
Optimize for speed across the entire program ("prototype switch") ***fast* options definitions changes over time!**	-fast same as: -ipo –O3 -no-prec-div –static –fp-model fast=2 -xHost)
OpenMP support	-qopenmp
Automatic parallelization	-parallel

High-Level Optimizations

Basic Optimizations with icc -O…

-O0 no optimization; sets -g for debugging

-O1 scalar optimizations
excludes optimizations tending to increase code size

-O2 **default** for icc/icpc (except with -g)
includes **auto-vectorization**; some loop transformations, e.g. unrolling, loop interchange;
inlining within source file;
start with this (after initial debugging at -O0)

-O3 more aggressive loop optimizations
including cache blocking, loop fusion, prefetching, …
suited to applications with loops that do many floating-point calculations or process large data sets

InterProcedural Optimizations (IPO)

Multi-pass Optimization

`icc -ipo`

Analysis and optimization across function and/or source file boundaries, e.g.

- Function inlining; constant propagation; dependency analysis; data & code layout; etc.

2-step process:

- Compile phase – objects contain intermediate representation
- “Link” phase – compile and optimize over all such objects
- Seamless: linker automatically detects objects built with -ipo and their compile options
- May increase build-time and binary size
- But build can be parallelized with `-ipo=n`
- Entire program need not be built with IPO, just hot modules

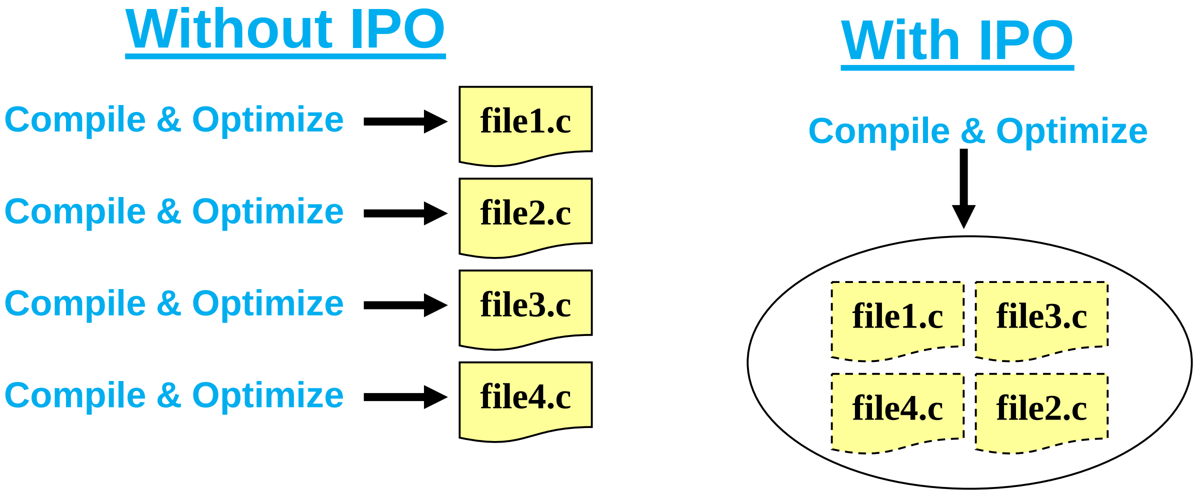
Particularly effective for applications with many smaller functions

Get report on inlined functions with `-qopt-report-phase=ipo`

InterProcedural Optimizations

Extends optimizations across file boundaries

`-ip`	Only between modules of one source file
`-ipo`	Modules of multiple files/whole application



Profile-Guided Optimizations (PGO)

Static analysis leaves many questions open for the optimizer like:

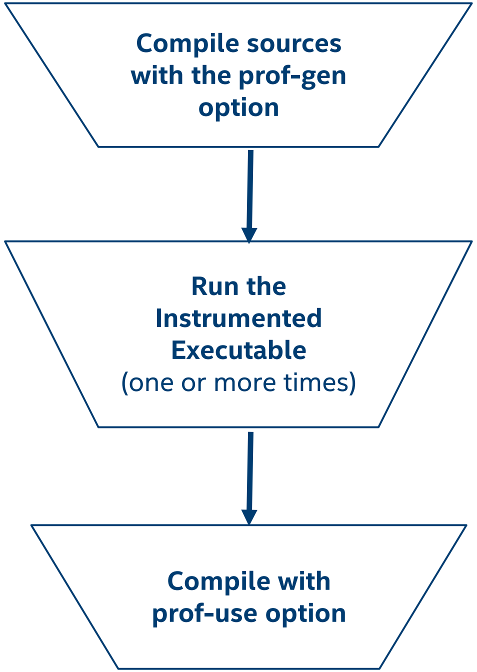
- How often is x > y
- What is the size of count
- Which code is touched how often

```
if (x > y)
     do_this();
 else
     do that();
```

```
for(i=0; i<count; ++i)
do_work();
```

Use execution-time feedback to guide (final) optimization
Enhancements with PGO:

- More accurate branch prediction
- Basic block movement to improve instruction cache behavior
- Better decision of functions to inline (help IPO)
- Can optimize function ordering
- Switch-statement optimization
- Better vectorization decisions



PGO Usage: Three-Step Process

Step 1

Compile + link to add instrumentation
`icc -prof-gen prog.c -o prog`

Instrumented executable:
`prog`

Step 2

Execute instrumented program
`./prog` (on a typical dataset)

Dynamic profile:
`12345678.dyn`

Step 3

Compile + link using feedback
`icc -prof-use prog.c -o prog`

Merged .dyn files:
`pgopti.dpi`

Optimized executable:
`prog`

Math Libraries

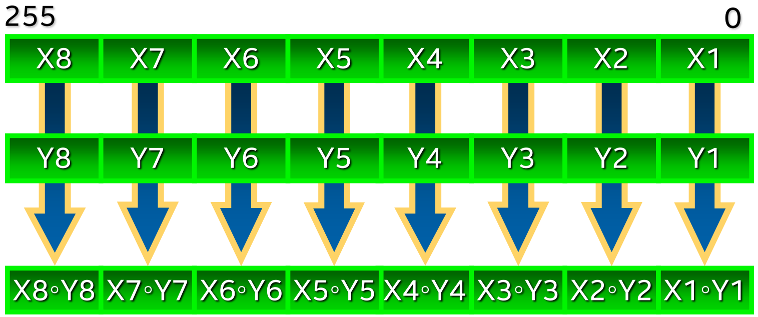
icc comes with Intel's optimized math libraries

- libimf (scalar) and libsvml (scalar & vector)
- Faster than GNU* libm
- Driver links libimf automatically, ahead of libm
- Additional functions (replace math.h by mathimf.h)

Don't link to libm explicitly! -lm

- May give you the slower libm functions instead
- Though the Intel driver may try to prevent this
- gcc needs -lm, so it is often found in old makefiles

SIMD Types for Intel® Architecture



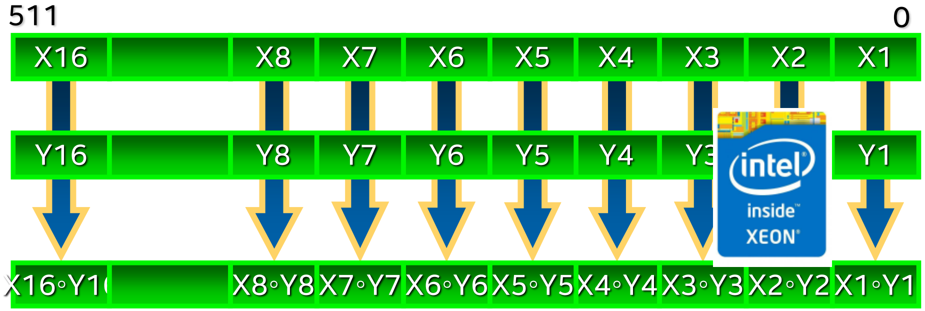
AVX

Vector size: **256 bit**

Data types:

- 8, 16, 32, 64 bit integer
- 32 and 64 bit float

VL: 4, 8, 16, 32



Intel® AVX-512

Vector size: **512 bit**

Data types:

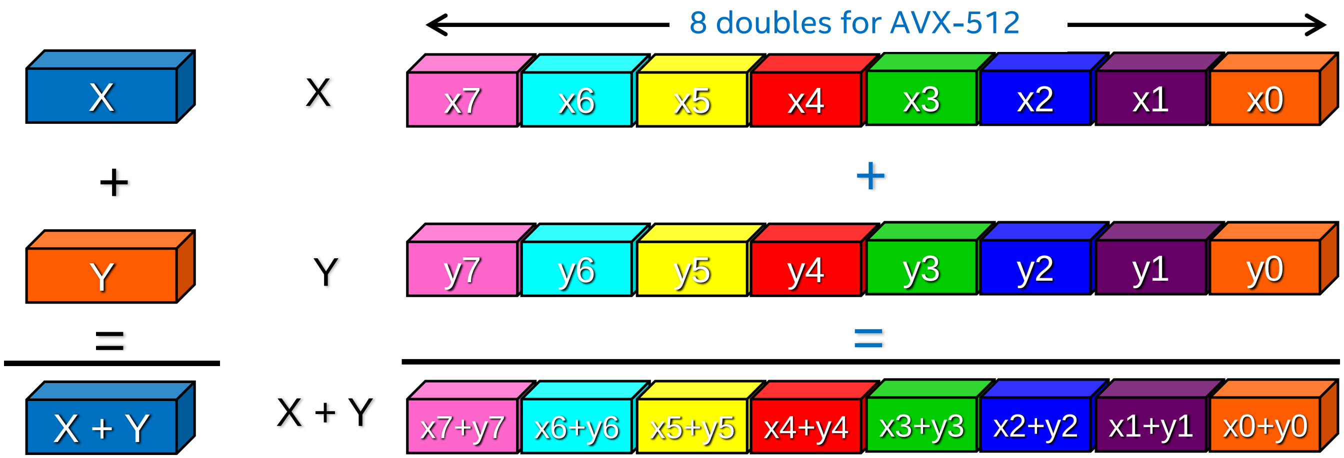
- 8, 16, 32, 64 bit integer
- 32 and 64 bit float

VL: 8, 16, 32, 64

SIMD: Single Instruction, Multiple Data

```
for (i=0; i<n; i++) z[i] = x[i] + y[i];
```

- Scalar mode
  - one instruction produces one result
  - E.g. vaddss, (vaddsd)
- Vector (SIMD) mode
  - one instruction can produce multiple results
  - E.g. vaddps, (vaddpd)



Many ways to vectorize

Compiler:
Auto-vectorization (no change of code)

Compiler:
Auto-vectorization hints (`#pragma vector`, …)

Compiler:
Explicit vectorization with OpenMP* 4.0 & later

SIMD intrinsic class
(e.g.: `F32vec`, `F64vec`, …)

Vector intrinsic
(e.g.: `_mm_fmadd_pd(…)`, `_mm_add_ps(…)`, …)

Assembler code
(e.g.: `[v]addps`, `[v]addss`, …)

Ease of use

Programmer control

Basic Vectorization Switches I

- Requirement: -O2 or higher
- -x<feature>
  - Might enable Intel processor specific optimizations
  - Processor-check added to “main” routine:
    Application errors in case SIMD feature missing or non-Intel processor with appropriate/informative message
- -ax<features>
  - Multiple code paths: baseline and optimized/processor-specific
  - Optimized code paths for Intel processors defined by <features>
  - Multiple SIMD features/paths possible, e.g.: -axSSE2,AVX,AVX2
  - Baseline code path defaults to –msse2
  - The baseline code path can be modified by –m<feature> or –x<feature>

Basic Vectorization Switches II

- -m<feature>
  - Neither check nor specific optimizations for Intel processors:
    Application optimized for both Intel and non-Intel processors for selected SIMD feature
- Default for Linux: -msse2
  - Activated implicitly
  - Implies the need for a target processor with at least Intel® SSE2
- Special switch: -xHost
  - Compiler checks SIMD features of current host processor (where built on) and makes use of latest SIMD feature available
  - Code only executes on processors with same SIMD feature or later as on build host
  - As for -x<feature> , if "main" routine is built with –xHost or the final executable only runs on Intel processors

Compiler Reports – Optimization Report

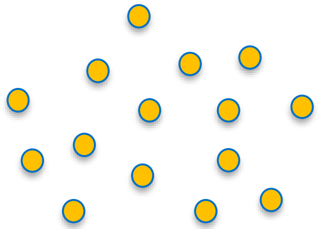
- -qopt-report[=n]: tells the compiler to generate an optimization report
  - n: (Optional) Indicates the level of detail in the report. You can specify values 0 through 5. If you specify zero, no report is generated. For levels n=1 through n=5, each level includes all the information of the previous level, as well as potentially some additional information. Level 5 produces the greatest level of detail. If you do not specify n, the default is level 2, which produces a medium level of detail.
- -qopt-report-phase[=list]: specifies one or more optimizer phases for which optimization reports are generated.
  - loop: the phase for loop nest optimization
  - vec: the phase for vectorization
  - par: the phase for auto-parallelization
  - all: all optimizer phases
- -qopt-report-filter=string: specified the indicated parts of your application, and generate optimization reports for those parts of your application.

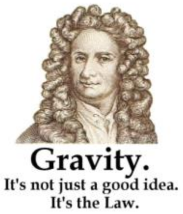
Lab: Nbody gravity simulation

Let's consider a distribution of point masses located at `r_1,…,r_n` and have masses `m_1,…,m_n`

We want to calculate the position of the particles after a certain time interval using the Newton law of gravity

```
struct Particle
{
  public:
    Particle() { init();}
    void init()
    {
      pos[0] = 0.; pos[1] = 0.; pos[2] = 0.;
      vel[0] = 0.; vel[1] = 0.; vel[2] = 0.;
      acc[0] = 0.; acc[1] = 0.; acc[2] = 0.;
      mass   = 0.;
    }
    real_type pos[3];
    real_type vel[3];
    real_type acc[3];
    real_type mass;
};
```





$$\vec{F}_{ij} = \frac{G m_i m_j}{|\vec{r}_j - \vec{r}_i|^3} (\vec{r}_j - \vec{r}_i)$$

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} = m\frac{d^2\vec{x}}{dt^2}$$

Lab: Nbody kernel implementation

```
GSimulation.cpp:
...
for (i = 0; i < n; i++) {                                    // update acceleration
     for (j = 0; j < n; j++) {
          real_type distance, dx, dy, dz;
          real_type distanceSqr = 0.0;
          real_type distanceInv = 0.0;

          dx = particles[j].pos[0] - particles[i].pos[0];
          dy = particles[j].pos[1] - particles[i].pos[1];
          dz = particles[j].pos[2] - particles[i].pos[2];

          distSqr = dx*dx + dy*dy + dz*dz + softeningSquared;
          distInv = 1.0 / sqrt(distanceSqr);
          particles[i].acc[0] += dx * G * particles[j].mass * distInv * distInv * distInv;
          particles[i].acc[1] += …
          particles[i].acc[2] += …
     }
}
...
```

Exercise 1 – nbody-demo/ver0

- module load intel64/19.1up01
- Go to the folder nbody-demo/ver0
  - Take a look on the code to learn data structures, main loops, Flops calculation, etc.
- Type *make* to compile code

```
icpc -g -std=c++11 -O2  -o nbody.x GSimulation.o main.o
```

- Type *make run* to run the test and measure the timing.

```
./nbody.x
```

- If everything works fine, you should see the following results:

Exercise 1 – nbody-demo/ver0

```
Run the default test case on CPU:
./nbody.x
===============================
 Initialize Gravity Simulation
 nPart = 16000; nSteps = 10; dt = 0.1
------------------------------------------------
 s        dt       kenergy     time (s)    GFlops
------------------------------------------------
 1        0.1      26.405      5.1986      1.4281
 2        0.2      313.77      5.2053      1.4263
 3        0.3      926.56      5.3105      1.398
 4        0.4      1866.4      5.2772      1.4069
 5        0.5      3135.6      5.1825      1.4326
 6        0.6      4737.6      5.1845      1.432
 7        0.7      6676.6      5.1921      1.4299
 8        0.8      8957.7      5.2037      1.4267
 9        0.9      11587       5.2009      1.4275
 10       1        14572       5.1825      1.4326

# Number Threads         : 1
# Total Time (s)         : 52.139
# Average Performance : 1.4233 +- 0.012399
===============================
```

- Observe how the performance changes according to the number of particles: `./nbody.x 8000`
- Is the perfomance saturating?
- What is the maximum perfomance?
- Has the code performance issues?

Exercise 1 – nbody-demo/ver0

```
Run the default test case on CPU:
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===============================
```

- Observe how the performance changes according to the number of particles: `./nbody.x 8000`
- Is the perfomance saturating?
- What is the maximum perfomance?
- Has the code performance issues?
- Generate the compiler report:

  `make REPORT=yes`

  or

  `icpc -g -std=c++11 -O2` **`-qopt-report=5`** `-o nbody.x GSimulation.cpp main.cpp`

Exercise 1 – nbody-demo/ver0

```
LOOP BEGIN at GSimulation.cpp(127,20)
   remark #15542: loop was not vectorized: inner loop
was already vectorized

   LOOP BEGIN at GSimulation.cpp(130,5)
      remark #15542: loop was not vectorized: inner
loop was already vectorized
.....

remark #15417: vectorization support: number of FP up
converts: single precision to double precision 1   [
GSimulation.cpp(143,4) ]

....
remark #15300: LOOP WAS VECTORIZED
         remark #15452: unmasked strided loads: 6
         remark #15475: --- begin vector cost summary
---
         remark #15476: scalar cost: 145
         remark #15477: vector cost: 79.500
         remark #15478: estimated potential speedup:
1.820
         remark #15487: type converts: 23
```

- Observe how verbose is the report looking at the file: `GSimulation.optrpt`
  - `2974 number of lines`
- You can filter the report by running: `make REPORT=yes FILTER=yes`

  ```
  -qopt-report-phase=vec
  -qopt-report-
  filter="GSimulation.cpp,125-175"
  ```

- Look at the `Makefile` for more details on the compiler options used
- Open the new report file and read the results

Exercise 1 – nbody-demo/ver0

- How can we improve the performance using only the compiler?
  - Use different compiler options and try to target the underlying architecture:
  - -xCORE-AVX2 or -xHost
  - -O3
  - -ipo
  - -prof-gen and -prof-use
  - -parallel
- Explain why some options don't bring additional speed-up. Try some more tests here:

  git clone https://github.com/ivorobts/compiler-optimization.git

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