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Лабораторна робота № 3

Тема: «Дослідження оптимізації коду з використанням векторних розширень CPU»

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Київ 2020

Хід роботи

1. Отримайте доступ на обчислювальний кластер для роботи з Intel Compiler.

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2. Завантажте файли Intel® C++ Compiler - Using Auto-Vectorization Tutorial (https://software.intel.com/en-us/product-code-samples?topic=20813) на свій комп'ютер та в домашню директорію користувача обчислювального кластеру.

3. Використовуючи інструкції в readme.html ознайомтесь та виконайте Tutorial на обчислювальному кластері
   Замість інструкцій в пункті "Setting the Environment Variables" завантажте оточення компілятора шляхом виконання команди: ml icc
   Виконуйте завдання на робочих вузлах кластеру замість вхідної ноди. По-перше процесори робочих вузлів мають набагато більше розширень. По-друге виконання компіляції та запуску на вхідній ноді заважає іншим користувачам, що призведе до блокування вашого аккаунту та автоматичного незарахування лабораторної роботи.
   Рекомендований варіант виконання роботи - використання інтерактивних задач в системі планування:
   [manf@plus7 ~]$ qsub -I -l nodes=1:ppn=1,walltime=00:30:00
   KNU:WN:s4 [manf ~]$ ml icc

```
Last login: Thu Jun  4 09:03:33 EEST 2020 on pts/8
[tb078@plus7 ~]$ qsub -I -l nodes=1:ppn=1,walltime=00:30:00
qsub: waiting for job 2732367 to start
qsub: job 2732367 ready

autoscratch: creating directory '/mnt/work/tb078'
autoscratch: creating directory '/mnt/scratch/tb078'
KNU:  :s4 [tb078 ~]$ pwd
/home/grid/testbed/tb078
```

```
KNU:  :s4 [tb078 lab3]$ ls
ITAC  advisor  cluster_checker  compiler_c  compiler_f  index.html  inspector  ipp  ipsxe2019_samples_lin_20190327.tgz
KNU:  :s4 [tb078 lab3]$ history
    1  quit
    2  exit
    3  pwd
    4  ml icc
    5  ls- la
    6  ls -la
    7  mkdir lab3
    8  cd lab3/
    9  wget https://software.intel.com/sites/defaut/files/ipsxe2019_samples_lin_20190327.tgz
   10  wget https://software.intel.com/sites/default/files/ipsxe2019_samples_lin_20190327.tgz
   11  tar -xvf ipsxe2019_samples_lin_20190327.tgz
   12  {Sls
   13  ls
```

```
KNU:  :s4 [tb078 vec_samples]$ cd src/
KNU:  :s4 [tb078 src]$ ls
Driver.c  Multiply.c  Multiply.h
```

Establishing a Performance Baseline

To set a performance baseline for the improvements that follow in this tutorial, compile your sources from the `src` directory with these compiler options:

```
icc -O1 -std=c99 Multiply.c Driver.c -o MatVector
```

Execute `MatVector` and record the execution time reported in the output. This is the baseline against which subsequent improvements will be measured.

```
KNU:  :s4 [tb078 src]$ icc -O1 -std=c99 Multiply.c Driver.c -o MatVector
KNU:  :s4 [tb078 src]$ ls
Driver.c  MatVector  Multiply.c  Multiply.h
```

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 101
Execution time is 12.974 seconds
GigaFlops = 1.572524
Sum of result = 195853.999899
```

A vectorization report shows what loops in your code were vectorized and explains why other loops were not vectorized. To generate a vectorization report, use the qopt-report-phase=vec compiler options together with qopt-report=1 or qopt-report=2.

Together with qopt-report-phase=vec, qopt-report=1 generates a report with the loops in your code that were vectorized while qopt-report-phase=vec with qopt-report=2 generates a report with both the loops in your code that were vectorized and the reason that other loops were not vectorized.

Because vectorization is turned off with the O1 option, the compiler does not generate a vectorization report. To generate a vectorization report, compile your project with the O2, qopt-report-phase=vec, qopt-report=1 options:

```
KNU:  :s4 [tb078 src]$ icc -std=c99 -O2 -D NOFUNCCALL -qopt-report=1 -qopt-report-phase=vec Multiply.c Driver.c -o MatVector
icc: remark #10397: optimization reports are generated in *.optrpt files in the output location
KNU:  :s4 [tb078 src]$ ls
Driver.c  Driver.optrpt  MatVector  Multiply.c  Multiply.h  Multiply.optrpt
```

Recompile the program and then execute MatVector. Record the new execution time. The reduction in time is mostly due to auto-vectorization of the inner loop at line 145 noted in the vectorization report matvec.optrpt:

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 101
Execution time is 4.467 seconds
GigaFlops = 4.567637
Sum of result = 195853.999899
```

Multiply.optrpt:

```
KNU:  :s4 [tb078 src]$ cat Multiply.optrpt
Intel(R) Advisor can now assist with vectorization and show optimization
  report messages with your source code.
See "https://software.intel.com/en-us/intel-advisor-xe" for details.


Begin optimization report for: matvec(int, int, double (*)[*], double *, double *)

    Report from: Vector optimizations [vec]


LOOP BEGIN at Multiply.c(37,5)
   remark #25460: No loop optimizations reported

   LOOP BEGIN at Multiply.c(49,9)
      remark #25460: No loop optimizations reported
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
   <Remainder>
   LOOP END
LOOP END
===========================================================================
```

qopt-report=2 with qopt-report-phase=vec,loop returns a list that also includes loops that were not vectorized or multi-versioned, along with the reason that the compiler did not vectorize them or multi-version the loop.

Recompile your project with the qopt-report=2 and qopt-report-phase=vec,loop options.

```
KNU:  :s4 [tb078 src]$ icc -std=c99 -O2 -D NOFUNCCALL -qopt-report-phase=vec,loop -qopt-report=2 Multiply.c Driver.c -o MatVector
icc: remark #10397: optimization reports are generated in *.optrpt files in the output location
```

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 101
Execution time is 4.469 seconds
GigaFlops = 4.565483
Sum of result = 195853.999899
```

The vectorization report Multiply.optrpt indicates that the loop at line 37 in Multiply.c did not vectorize because it is not the innermost loop of the loop nest. Two versions of the innermost loop at line 49 were generated, and one version was vectorized.

```
LOOP BEGIN at Multiply.c(37,5)
   remark #15541: outer loop was not auto-vectorized: consider using SIMD directive

   LOOP BEGIN at Multiply.c(49,9)
      remark #15344: loop was not vectorized: vector dependence prevents vectorization. First dependence is shown below. Use level 5 report for details
      remark #15346: vector dependence: assumed FLOW dependence between b[i] (50:13) and b[i] (50:13)
      remark #25439: unrolled with remainder by 2
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
   <Remainder>
   LOOP END
LOOP END
```

Remove the -D NOFUNCCALL to restore the call to matvec(), then add the -D NOALIAS option to the command line.

```
Sum of result = 195853.999899
KNU:  :s4 [tb078 src]$ icc -std=c99 -qopt-report=2 -qopt-report-phase=vec -D NOALIAS Multiply.c Driver.c -o MatVector
icc: remark #10397: optimization reports are generated in *.optrpt files in the output location
KNU:  :s4 [tb078 src]$
```

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 101
Execution time is 5.020 seconds
GigaFlops = 4.064306
Sum of result = 195853.999899
```

This conditional compilation replaces the loop in the main program with a function call. Execute MatVector and record the execution time reported in the output. Multiply.optrpt now shows:

```
KNU:  :s4 [tb078 src]$ cat Multiply.optrpt
Intel(R) Advisor can now assist with vectorization and show optimization
  report messages with your source code.
See "https://software.intel.com/en-us/intel-advisor-xe" for details.


Begin optimization report for: matvec(int, int, double (*)[*], double *__restrict__, double *)

    Report from: Vector optimizations [vec]


LOOP BEGIN at Multiply.c(37,5)
   remark #15542: loop was not vectorized: inner loop was already vectorized

   LOOP BEGIN at Multiply.c(49,9)
   <Peeled loop for vectorization>
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
      remark #15300: LOOP WAS VECTORIZED
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
   <Alternate Alignment Vectorized Loop>
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
   <Remainder loop for vectorization>
   LOOP END
LOOP END
================================================================================
```

The vectorizer can generate faster code when operating on aligned data. In this activity you will improve performance by aligning the arrays a, b, and x in Driver.c on a 16-byte boundary so that the vectorizer can use aligned load instructions for all arrays rather than the slower unaligned load instructions and can avoid runtime tests of alignment. Using the ALIGNED macro will modify the declarations of a, b, and x in Driver.c using the aligned attribute keyword

Recompile the program after adding the ALIGNED macro to ensure consistently aligned data. Use -qopt-report=4 to see the change in aligned references.

```
==========================================================================
KNU:  :s4 [tb078 src]$ icc -std=c99 -qopt-report=4 -qopt-report-phase=vec -D NOALIAS -D ALIGNED Multiply.c Driver.c -o MatVector
icc: remark #10397: optimization reports are generated in *.optrpt files in the output location
```

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 102
Execution time is 4.618 seconds
GigaFlops = 4.418266
Sum of result = 195853.999899
```

Multiply.optrpt after adding -D ALIGNED shows:

```
KNU:  :s4 [tb078 src]$ cat Multiply.optrpt
Intel(R) Advisor can now assist with vectorization and show optimization
  report messages with your source code.
See "https://software.intel.com/en-us/intel-advisor-xe" for details.

Intel(R) C Intel(R) 64 Compiler for applications running on Intel(R) 64, Version 18.0.5.274 Build 20180823

Compiler options: -std=c99 -qopt-report=4 -qopt-report-phase=vec -D NOALIAS -D ALIGNED -o MatVector

Begin optimization report for: matvec(int, int, double (*)[*], double *__restrict__, double *)

    Report from: Vector optimizations [vec]


LOOP BEGIN at Multiply.c(37,5)
   remark #15542: loop was not vectorized: inner loop was already vectorized

   LOOP BEGIN at Multiply.c(49,9)
      remark #15388: vectorization support: reference a[i][j] has aligned access   [ Multiply.c(50,21) ]
      remark #15388: vectorization support: reference x[j] has aligned access   [ Multiply.c(50,31) ]
      remark #15305: vectorization support: vector length 2
      remark #15399: vectorization support: unroll factor set to 4
      remark #15309: vectorization support: normalized vectorization overhead 0.594
      remark #15300: LOOP WAS VECTORIZED
      remark #15448: unmasked aligned unit stride loads: 2
      remark #15475: --- begin vector cost summary ---
      remark #15476: scalar cost: 10
      remark #15477: vector cost: 4.000
      remark #15478: estimated potential speedup: 2.410
      remark #15488: --- end vector cost summary ---
   LOOP END

   LOOP BEGIN at Multiply.c(49,9)
   <Remainder loop for vectorization>
      remark #15388: vectorization support: reference a[i][j] has aligned access   [ Multiply.c(50,21) ]
      remark #15388: vectorization support: reference x[j] has aligned access   [ Multiply.c(50,31) ]
      remark #15335: remainder loop was not vectorized: vectorization possible but seems inefficient. Use vector always directive or -vec-threshold0 to override
      remark #15305: vectorization support: vector length 2
      remark #15309: vectorization support: normalized vectorization overhead 2.417
   LOOP END
LOOP END
==========================================================================
```

The compiler may be able to perform additional optimizations if it is able to optimize across source line boundaries. These may include, but are not limited to, function inlining. This is enabled with the -ipo option.

Recompile the program using the -ipo option to enable interprocedural optimization.

```
Driver.c  Driver.optrpt  MatVector  Multiply.c  Multiply.h  Multiply.optrpt  ipo_out.optrpt
KNU:  :s4 [tb078 src]$ icc -std=c99 -qopt-report=2 -qopt-report-phase=vec -D NOALIAS -D ALIGNED -ipo Multiply.c Driver.c -o MatVector
icc: remark #10397: optimization reports are generated in *.optrpt files in the output location
```

```
KNU:  :s4 [tb078 src]$ ./MatVector

ROW:101 COL: 102
Execution time is 4.329 seconds
GigaFlops = 4.712376
Sum of result = 195853.999899
```

Note that the vectorization messages now appear at the point of inlining in Driver.c (line 150) and this is found in the file ipo_out.optrpt.

```
KNU:  :s4 [tb078 src]$ cat ipo_out.optrpt
Intel(R) Advisor can now assist with vectorization and show optimization
  report messages with your source code.
See "https://software.intel.com/en-us/intel-advisor-xe" for details.


Begin optimization report for: main()

    Report from: Vector optimizations [vec]


LOOP BEGIN at Driver.c(152,16)
   remark #15542: loop was not vectorized: inner loop was already vectorized

   LOOP BEGIN at Multiply.c(37,5) inlined into Driver.c(150,9)
      remark #15542: loop was not vectorized: inner loop was already vectorized

      LOOP BEGIN at Multiply.c(49,9) inlined into Driver.c(150,9)
         remark #15300: LOOP WAS VECTORIZED
      LOOP END

      LOOP BEGIN at Multiply.c(49,9) inlined into Driver.c(150,9)
      <Remainder loop for vectorization>
         remark #15335: remainder loop was not vectorized: vectorization possible but seems inefficient. Use vector always directive or -vec-threshold0 to override
      LOOP END
   LOOP END
LOOP END

LOOP BEGIN at Driver.c(74,5) inlined into Driver.c(159,5)
   remark #15300: LOOP WAS VECTORIZED
LOOP END

LOOP BEGIN at Driver.c(74,5) inlined into Driver.c(159,5)
<Remainder loop for vectorization>
LOOP END
===========================================================================
```

```
================================================================================

Begin optimization report for: init_matrix(int, int, double, double (*)[102])

    Report from: Vector optimizations [vec]


LOOP BEGIN at Driver.c(47,5)
   remark #15542: loop was not vectorized: inner loop was already vectorized

   LOOP BEGIN at Driver.c(48,9)
      remark #15300: LOOP WAS VECTORIZED
   LOOP END

   LOOP BEGIN at Driver.c(48,9)
   <Remainder loop for vectorization>
   LOOP END
LOOP END

LOOP BEGIN at Driver.c(53,9)
   remark #15300: LOOP WAS VECTORIZED
LOOP END

LOOP BEGIN at Driver.c(53,9)
<Remainder loop for vectorization>
LOOP END
================================================================================

Begin optimization report for: init_array(int, double, double *)

    Report from: Vector optimizations [vec]


LOOP BEGIN at Driver.c(62,5)
   remark #15300: LOOP WAS VECTORIZED
LOOP END

LOOP BEGIN at Driver.c(62,5)
<Remainder loop for vectorization>
LOOP END
================================================================================
```

4. Оберіть будь-яку неінтрерактивну консольну програму мовою C/C++ (унікальну в межах групи, в гуглі більше ніж 50 програм)

Взята одна із програм з минулорічної практики, яка виконує дії з матрицями.
https://github.com/HleBASS/CS_labs/blob/master/Lab3/myprog.cpp

Напишіть сценарій, що:
Компілює програму з різними оптимізаціями (-O) та виміряйте час її роботи. Якщо час досить малий - вимірюйте час роботи 1000 (чи 1000000) запусків алгоритму в циклі. Час роботи можна виміряти утилітою time.
Отримує перелік всіх розширень процесору що підтримуються
Для кожного розширення компілює Intel-компілятором окремий варіант оптимізованого коду (наприклад -x SSE2)
Вимірює час виконання кожного варіанта оптимізованої програми
Запустіть задачу в планувальник обчислювального кластеру 5 разів (для статистики на різних нодах)
[manf@plus7 ~]$ qsub -N MyJob -l nodes=1:ppn=1,walltime=00:30:00 script.sh

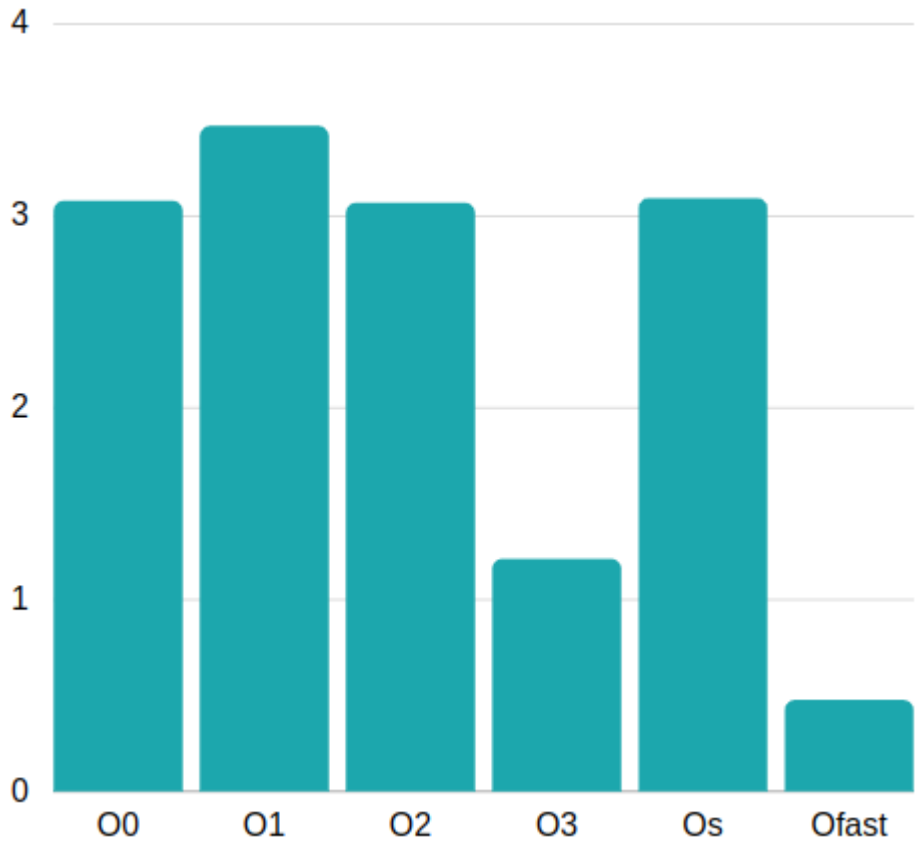
Побудуйте графіки залежності часу від різних варіантів компіляції.

Був написаний скрипт, який замірює час виконання циклу з 100 запусків виконання оптимізованої програми.

https://github.com/HleBASS/CS_labs/blob/master/Lab3/script.sh

Час виконання програми скомпільованої з різними прапорцями.

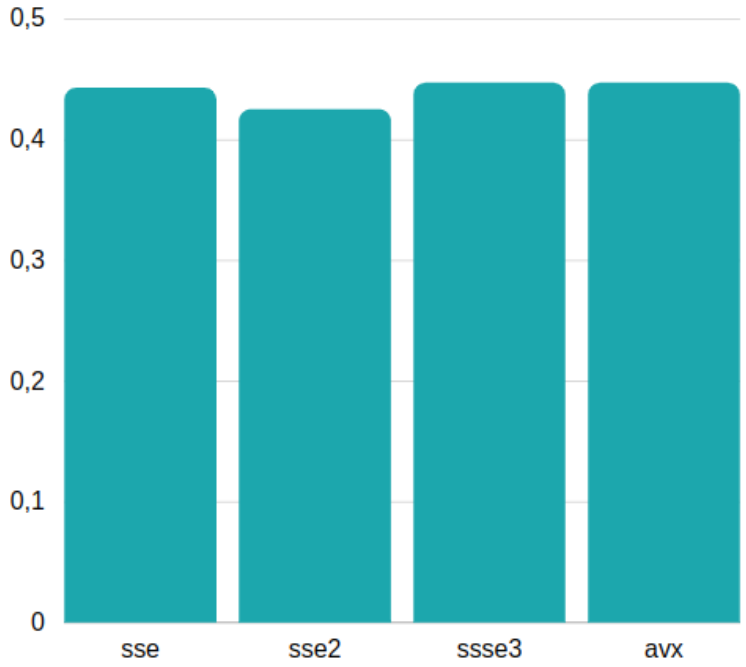
Номер запуску \ прапорець	O0	O1	O2	O3	Os	Ofast
1	3.059	3.98	3.033	1.228	3.107	0.485
2	3.054	3.102	3.049	1.182	3.073	0.438
3	3.079	3.114	3.078	1.199	3.085	0.454
4	3.073	3.99	3.065	1.198	3.06	0.492
5	3.122	3.143	3.107	1.241	3.128	0.499
average	3.077	3.466	3.066	1.209	3.09	0.474



Результат з -Ofast прапорцем і різними розширеннями:

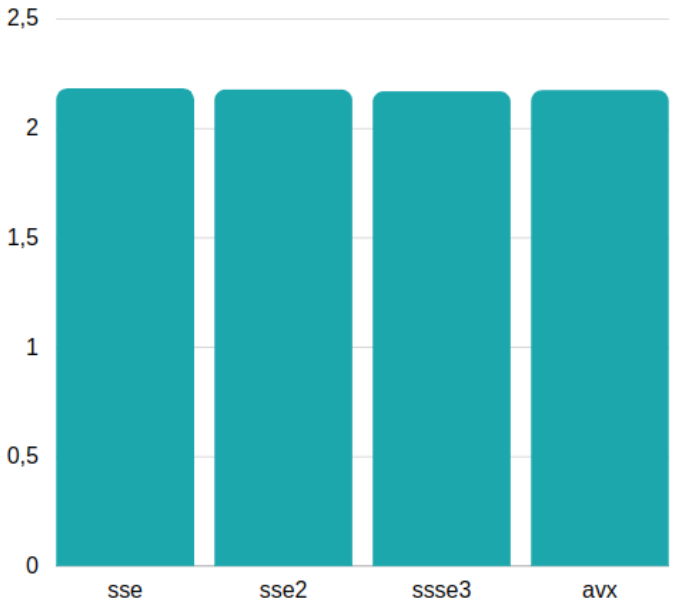
Номер запуску \ розширення	sse	sse2	ssse3	avx
1	0.452	0.452	0.452	0.453
2	0.427	0.323	0.437	0.438
3	0.422	0.436	0.434	0.434
4	0.455	0.457	0.453	0.456
5	0.457	0.456	0.459	0.456
average	0.443	0.425	0.447	0.447

В даному
випадку за допомогою розширень вдалося зекономити ще ~43% часу виконання програми.



Result with -O1 flag and different extensions:

Номер запуску \ розширення	sse	sse2	ssse3	avx
1	2.218	2.184	2.183	2.183
2	2.143	2.149	2.129	2.155
3	2.154	2.152	2.143	2.149
4	2.193	2.199	2.188	2.191
5	2.197	2.193	2.197	2.194
average	2.181	2.176	2.168	2.174



Висновок: В даній лабораторній роботі було ознайомлено з автоматичною векторизацією в паралельних обчисленнях. Було проведено оптимізацію коду з використанням векторних розширень CPU компілятора Intel на прикладі програми, яка виконує заповнення масивів.