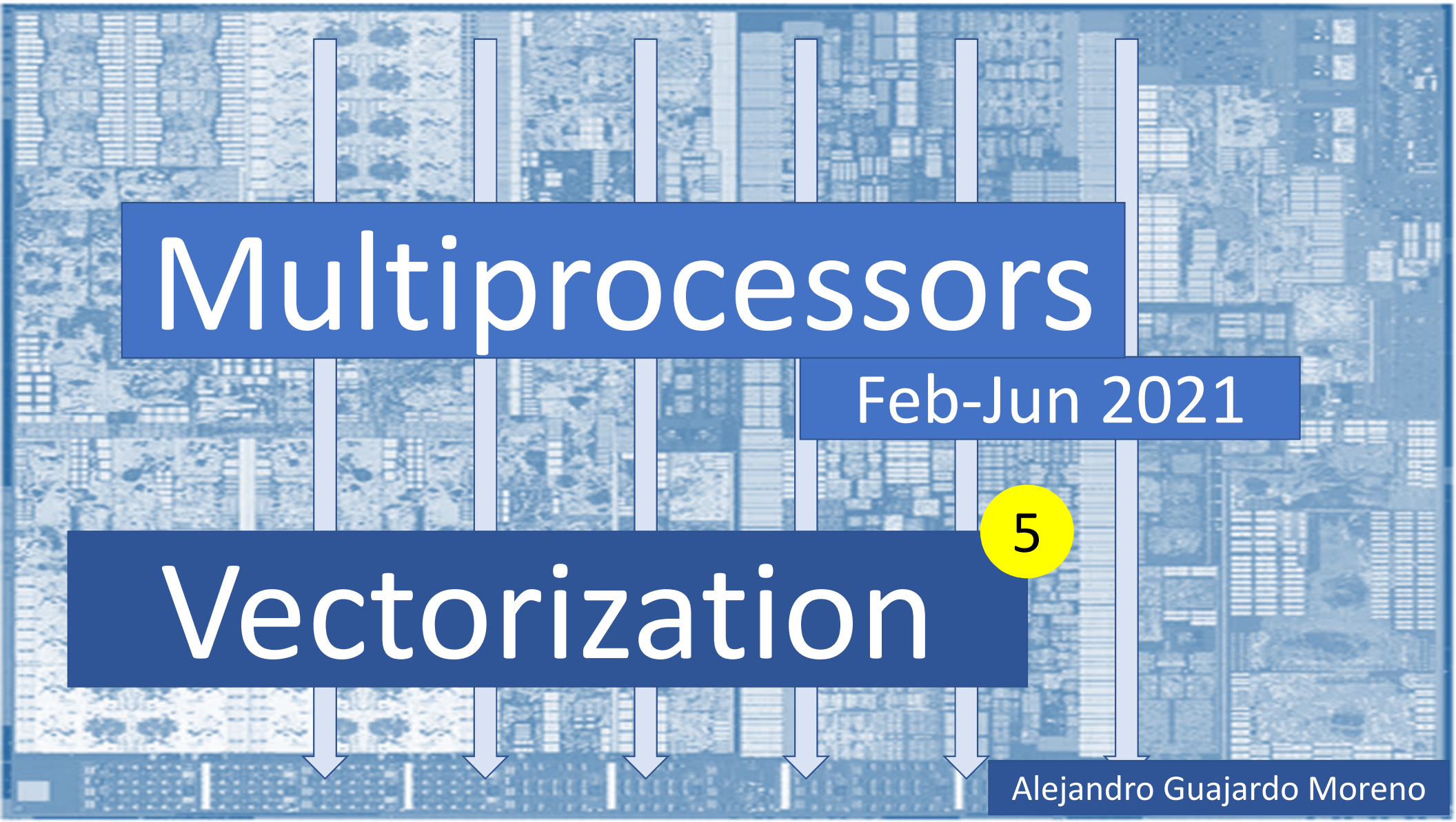

Multiprocessors
Feb-Jun 2021
5
Vectorization
Alejandro Guajardo Moreno

From last class…

Understand why Memory Alignment is important. Read the following:
https://software.intel.com/en-us/articles/data-alignment-to-assist-vectorization
https://en.wikipedia.org/wiki/Data_structure_alignment
https://docs.microsoft.com/en-us/cpp/c-runtime-library/reference/aligned-malloc?view=vs-2019
Look for the file "Single Threaded Array Addition (FLOATS)s" in Canvas.
1.- Document the time it took to process the loop BEFORE changing the code. Run 5 times the program. Average the 5 results. This will be your BASELINE for comparisons (The ## in "Results verified!!! (##)").
2.- Rewrite the loop commented "//This loop can be optimized using Intrinsics" using Intrinsics. First use SSE (128-bit) Instruction Set Extensions. Run it 5 times and average the runs. Document the time it took to process the loop.
3.- Change again the loop and now use AVX (256-bit) Instruction Set Extensions. Run 5 times, average and document.
4.- Upload to the platform a Word or PDF Document which includes:
- 1 Table comparing the times it took to run each case and the % of improvement vs. your BASELINE.
- Your conclusions.
5.- Upload your Visual Studio Solution or GCC's code of both SSE and AVX (You can add a menu to the program to choose which code to execute or leave commented one of the codes).
Note: Use what you learned on Memory Alignment. You may have to use __declspec(align()) when defining your variables, depending on the Intrinsics used.
Note 2: You might want to use the Intrinsics: _load_ps(), _loadu_ps(), _store_ps() or _storeu_ps().

Solution…

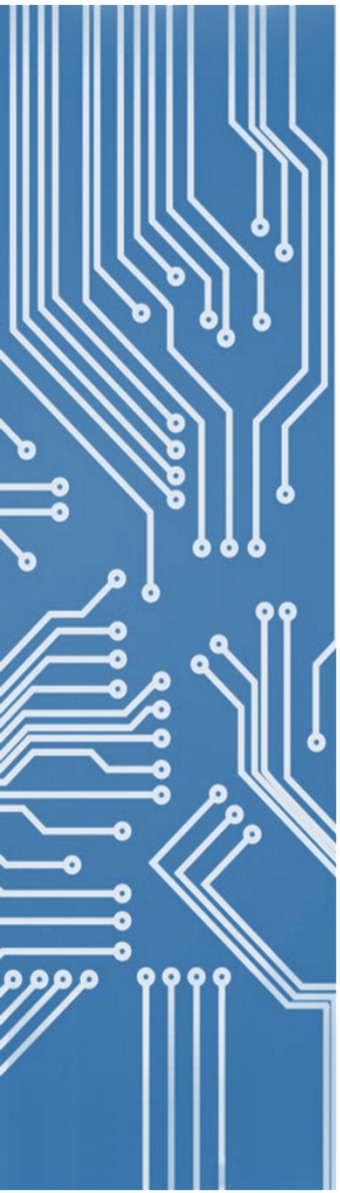
```
// No Vector
for (i = 0; i < elements; i++)
        C[i] = A[i] + B[i];
```

	BASELINE	SSE	AVX
1	306		
2	302		
3	305		
4	302		
5	303		
AVG	303.6		
%	-		

Solution…

```
// Using SSE Extensions
for (i = 0; i < elements; i += 4) {
        __m128 a = _mm_loadu_ps(&A[i]);
        __m128 b = _mm_loadu_ps(&B[i]);
        __m128 sum4 = _mm_add_ps(a, b);
        _mm_storeu_ps(&C[i], sum4);
}
```

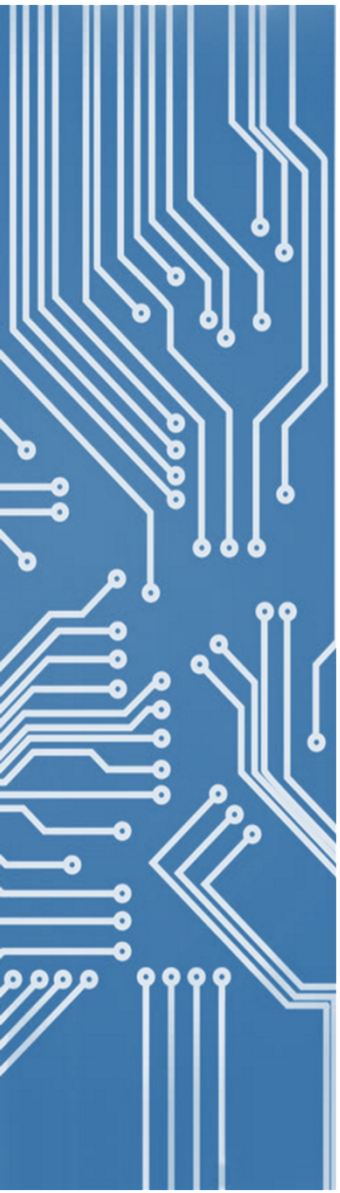
	BASELINE	SSE	AVX
1	306	94	
2	302	98	
3	305	96	
4	302	96	
5	303	95	
AVG	303.6	95.8	
%	-	317%	



Solution…

```
// Using AVX/AVX2 Extensions
for (i = 0; i < elements; i += 8) {
        __m256 a = _mm256_loadu_ps(&A[i]);
        __m256 b = _mm256_loadu_ps(&B[i]);
        __m256 sum4 = _mm256_add_ps(a, b);
        _mm256_storeu_ps(&C[i], sum4);
}
```

	BASELINE	SSE	AVX
1	306	94	79
2	302	98	79
3	305	96	76
4	302	96	78
5	303	95	77
AVG	303.6	95.8	77.8
%	-	317%	390%



Conclusions and notes…

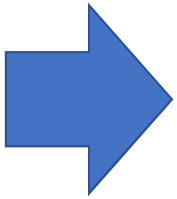
- Not the best option, but the most simple: Use unaligned loads and stores: loadu/storeu
- When using SSE or AVX, change your cycles, depending on your type of data:

```
for (i = 0; i < elements; i++)
        SSE => for (i = 0; i < elements; i += 4) //Valid for floats or ints.
                AVX => for (i = 0; i < elements; i += 8)
```

- The best option: ALIGN your data in memory.
- If we go from scalar to SSE, why don´t we see a 4x improvement?
    - Performance of the instruction (CPI)
    - Memory alignment
    - Cache Hits

Memory Alignment (Windows) – aligned_malloc()

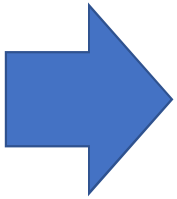
```
//Array creation
size_t datasize = sizeof(float) * elements;
A = (float*)malloc(datasize);
B = (float*)malloc(datasize);
C = (float*)malloc(datasize);

//Add loop
for (i = 0; i < elements; i++)
        C[i] = A[i] + B[i];

//Memory deallocation
free(A);
free(B);
free(C);
```



```
size_t  alignment = 16;

//Array creation
size_t datasize = sizeof(float) * elements;
A = (float*) _aligned_malloc(datasize,alignment);
B = (float*) _aligned_malloc(datasize,alignment);
C = (float*) _aligned_malloc(datasize,alignment);

//Add loop
for (i=0; i< elements/4 ; i++)
{
        Aint = _mm_load_ps(A + i*4);
        Bint = _mm_load_ps(B + i*4);
        Cint = _mm_add_ps(Aint, Bint);
        _mm_store_ps(C + i*4, Cint);
}

//Memory deallocation
_aligned_free(A);
_aligned_free(B);
_aligned_free(C);
```

Memory Alignment (Linux/GCC) – aligned_alloc()

```
//Array creation
size_t datasize = sizeof(float) * elements;
A = (float*)malloc(datasize);
B = (float*)malloc(datasize);
C = (float*)malloc(datasize);

//Add loop
for (i = 0; i < elements; i++)
        C[i] = A[i] + B[i];

//Memory deallocation
free(A);
free(B);
free(C);
```

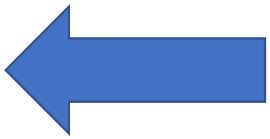


```
size_t  alignment = 16;

//Array creation
size_t datasize = sizeof(float) * elements;
A = (float*) aligned_alloc(alignment,datasize);
B = (float*) aligned_alloc(alignment,datasize);
C = (float*) aligned_alloc(alignment,datasize);

//Add loop
for (i=0; i< elements/4 ; i++)
{
        Aint = _mm_load_ps(A + i*4);
        Bint = _mm_load_ps(B + i*4);
        Cint = _mm_add_ps(Aint, Bint);
        _mm_store_ps(C + i*4, Cint);
}

//Memory deallocation
free(A);
free(B);
free(C);
```

Remember?

Other functions

- Logics (AND, OR, XOR, NOT, …)
- Cache support:
  - `_mm_prefecth(···)`
  - `_mm_stream_ps(···)`
- … and many others.

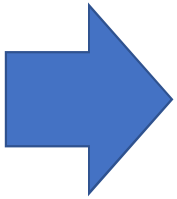


Like…

Aligned Memory Allocation!

Memory Alignment (Intrinsics Win/Linux) - _mm_malloc

```
//Array creation
size_t datasize = sizeof(float) * elements;
A = (float*)malloc(datasize);
B = (float*)malloc(datasize);
C = (float*)malloc(datasize);

//Add loop
for (i = 0; i < elements; i++)
        C[i] = A[i] + B[i];

//Memory deallocation
free(A);
free(B);
free(C);
```



```
size_t datasize = sizeof(float) * elements;

//Array creation
A = (float*)_mm_malloc(datasize, 16);
B = (float*)_mm_malloc(datasize, 16);
C = (float*)_mm_malloc(datasize, 16);

//Add loop
for (i = 0; i < elements; i += 4)
{
        __m128 a = _mm_load_ps(&A[i]);
        __m128 b = _mm_load_ps(&B[i]);
        __m128 sum4 = _mm_add_ps(a, b);
        _mm_store_ps(&C[i], sum4);
}

//Memory Deallocation
_mm_free(A);
_mm_free(B);
_mm_free(C);
```

Structure Alignment (Windows) - __declspec(align())

```
#include <stdio.h>
#include <stdlib.h>

#define SIZE 1024

int main() {

int __declspec(align(32)) A[SIZE];
int __declspec(align(32)) B[SIZE];

for (int i = 0; i < SIZE; i++)
   A[i] = B[i] = i;

for (int i = 0; i < SIZE; i++)
   A[i] = A[i] + B[i];

for (int i = 0; i < 1024; i++)
   printf("%2d %2d %2d\n", i, A[i],
B[i]);

return 0;
}
```

Align a structure in memory from its creation…

Structure Alignment (GCC) - __attribute__ ((aligned ()))

```
#include <stdio.h>
#include <stdlib.h>

#define SIZE 1024

int main() {

int A[SIZE] __attribute__ ((aligned (32)));
int B[SIZE] __attribute__ ((aligned (32)));

for (int i = 0; i < SIZE; i++)
   A[i] = B[i] = i;

for (int i = 0; i < SIZE; i++)
   A[i] = A[i] + B[i];

for (int i = 0; i < 1024; i++)
   printf("%2d %2d %2d\n", i, A[i], B[i]);

return 0;
}
```

Align a structure in memory from its creation…

Options for vectorization

Assembly language

```
..B8.5
  MOVAPS a(,%rdx,4), %xmm0
  ADDPA b(,%rdx,4), %xmm0
  MOVAPS %xmm0, c(,%rdx,4)
  ADDQ $4, %rdx
  CMPQ $rdi, %rdx
  JL ..B8.5
```

Explicit Vectorization

Intrinsic Functions

- Middle ground Assembly ⇔ C
- Direct Access to processor instructions
- Retain C Syntax

```
void ejemplo(){
    __m128 rA, rB, rC;
    for (int i = 0; i<LEN; i+=4){
        rA = _mm_load_ps(&a[i]);
        rB = _mm_load_ps(&b[i]);
        rC = _mm_add_ps(rA,rB);
        _mm_store_ps(&c[i], rC);
    }
}
```

Automatic Vectorization

Source code in C language.
+ Vectorizing compiler (#pragma).
&/| Vectorizing compiler options (/arch)

```
#pragma xyz
for (i=0; i<LEN; i++)
        c[i] = a[i] + b[i];
```

Auto-vectorization

Consider the following code:

```c
#include <stdio.h>
#include <stdlib.h>

#define SIZE 1024

int main() {

int __declspec(align(32)) A[SIZE];
int __declspec(align(32)) B[SIZE];

for (int i = 0; i < SIZE; i++)
   A[i] = B[i] = i;

// This loop will be auto-vectorized
for (int i = 0; i < SIZE; i++)
   A[i] = A[i] + B[i];

for (int i = 0; i < 1024; i++)
   printf("%2d %2d %2d\n", i, A[i], B[i]);

return 0;
}
```

- Normal C code
- Data is aligned.
- Compiler should take care of it.

Auto-vectorization

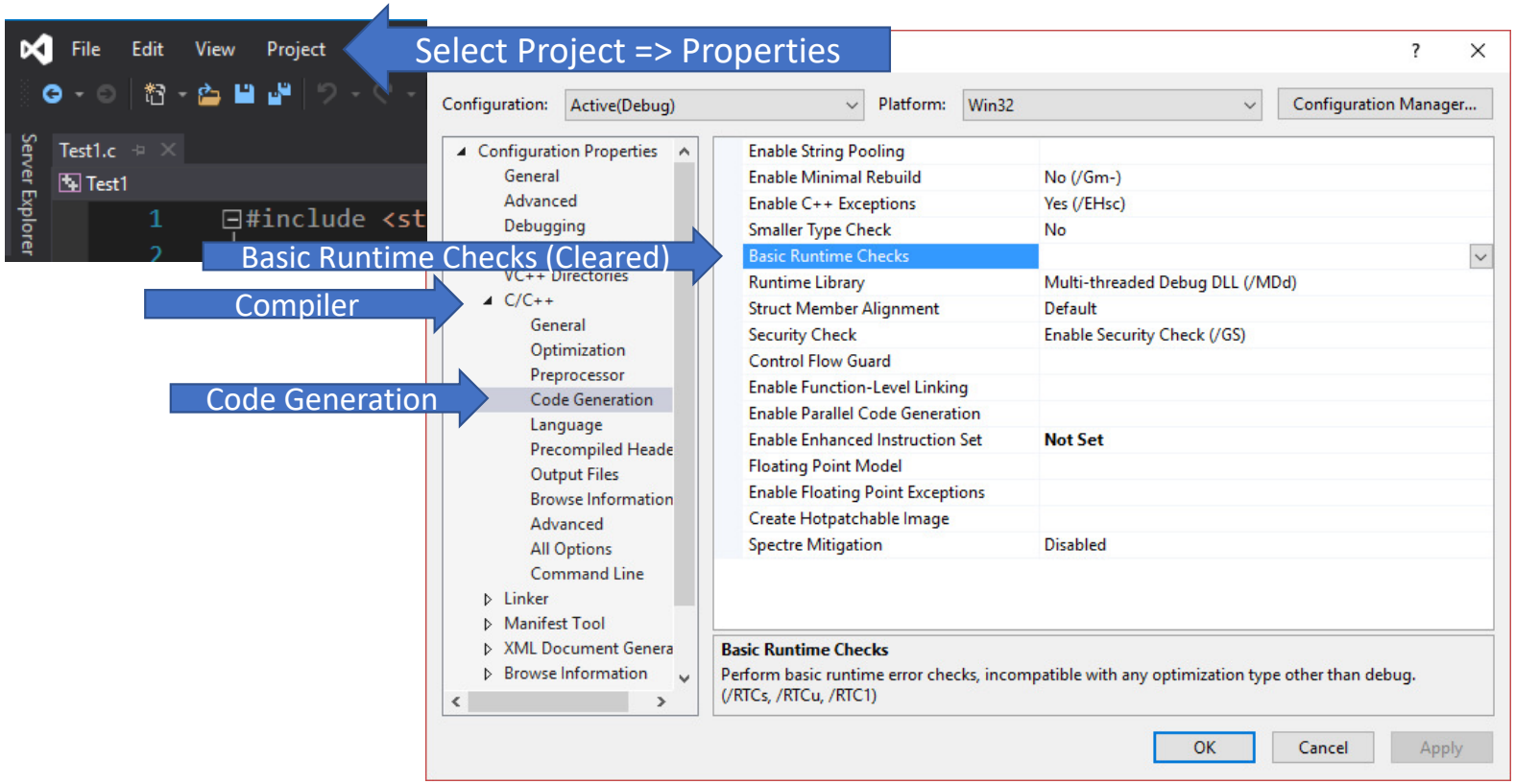
```
        // This loop will be auto-vectorized
        for (int i = 0; i < SIZE; i++)
00151076  xor         ecx,ecx
00151078  jmp         main+30h (0151080h)
0015107A  lea         ebx,[ebx]
            A[i] = A[i] + B[i];
00151080  mov         eax,dword ptr [esp+ecx+1040h]
00151087  add         dword ptr [esp+ecx+40h],eax
0015108B  mov         eax,dword ptr [esp+ecx+1044h]
00151092  add         dword ptr [esp+ecx+44h],eax
00151096  mov         eax,dword ptr [esp+ecx+1048h]
0015109D  add         dword ptr [esp+ecx+48h],eax
            A[i] = A[i] + B[i];
001510A1  mov         eax,dword ptr [esp+ecx+104Ch]
001510A8  add         dword ptr [esp+ecx+4Ch],eax
001510AC  add         ecx,10h
001510AF  cmp         ecx,1000h
001510B5  jl          main+30h (0151080h)
```

If it is auto-vectorizing, why do we see General Registers?

✓Just some configuration needed.

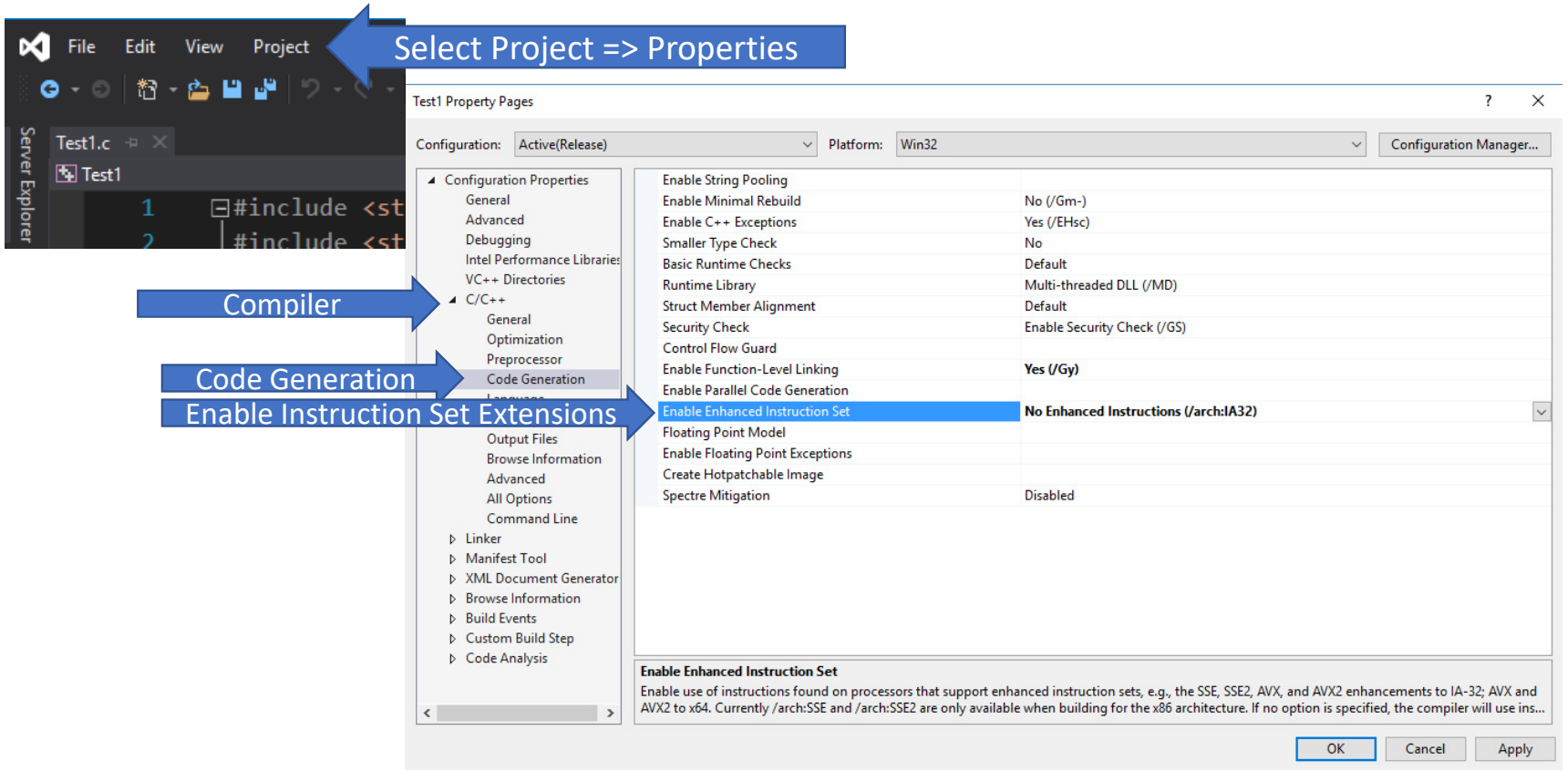
Auto-vectorization

Let´s enable the compiler´s ability to generate vectorized code:



Auto-vectorization

Let´s enable the compiler´s ability to generate vectorized code:



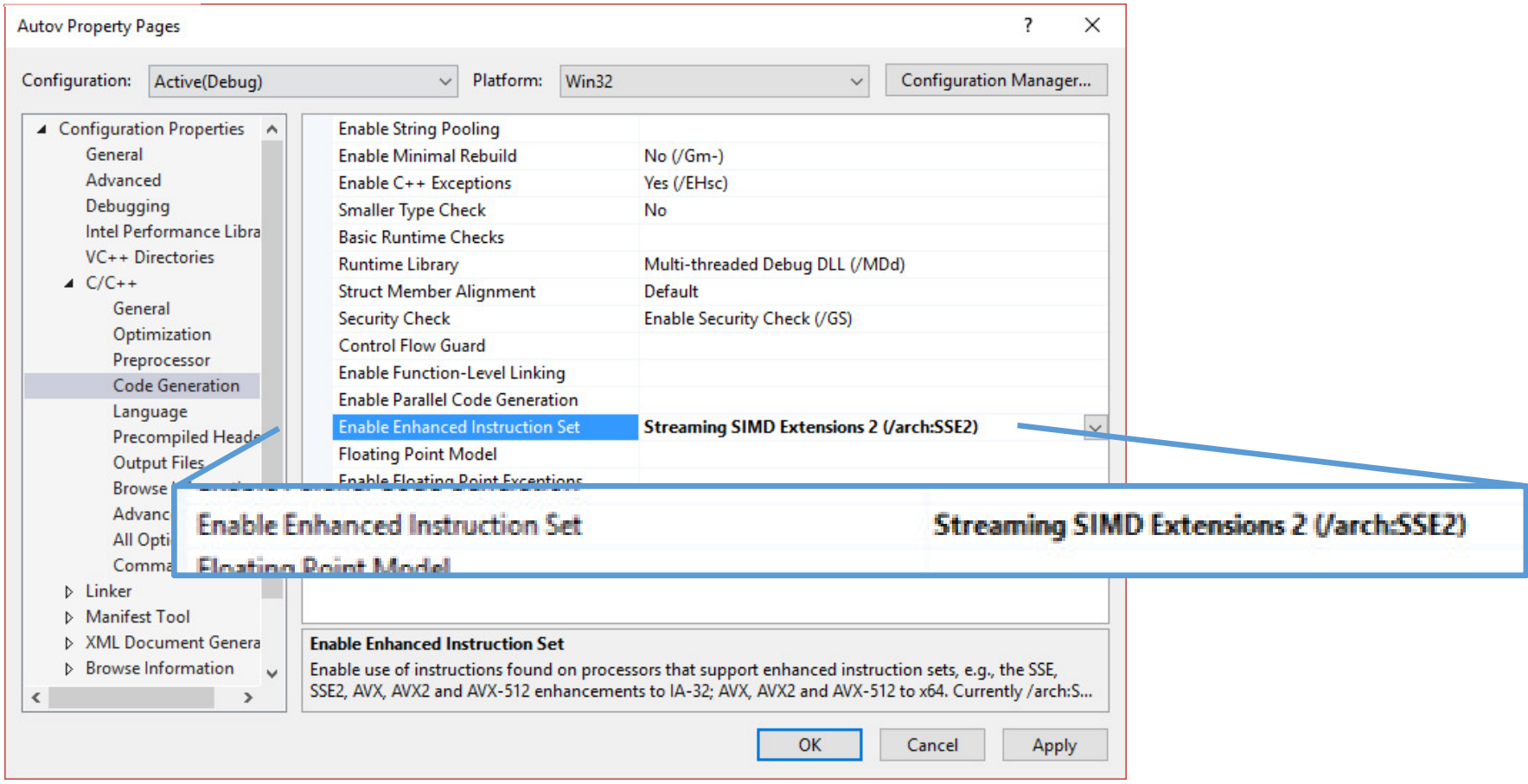
Auto-vectorization

Enable Enhanced Instruction Set:

This option is adding a compiler flag: /arch

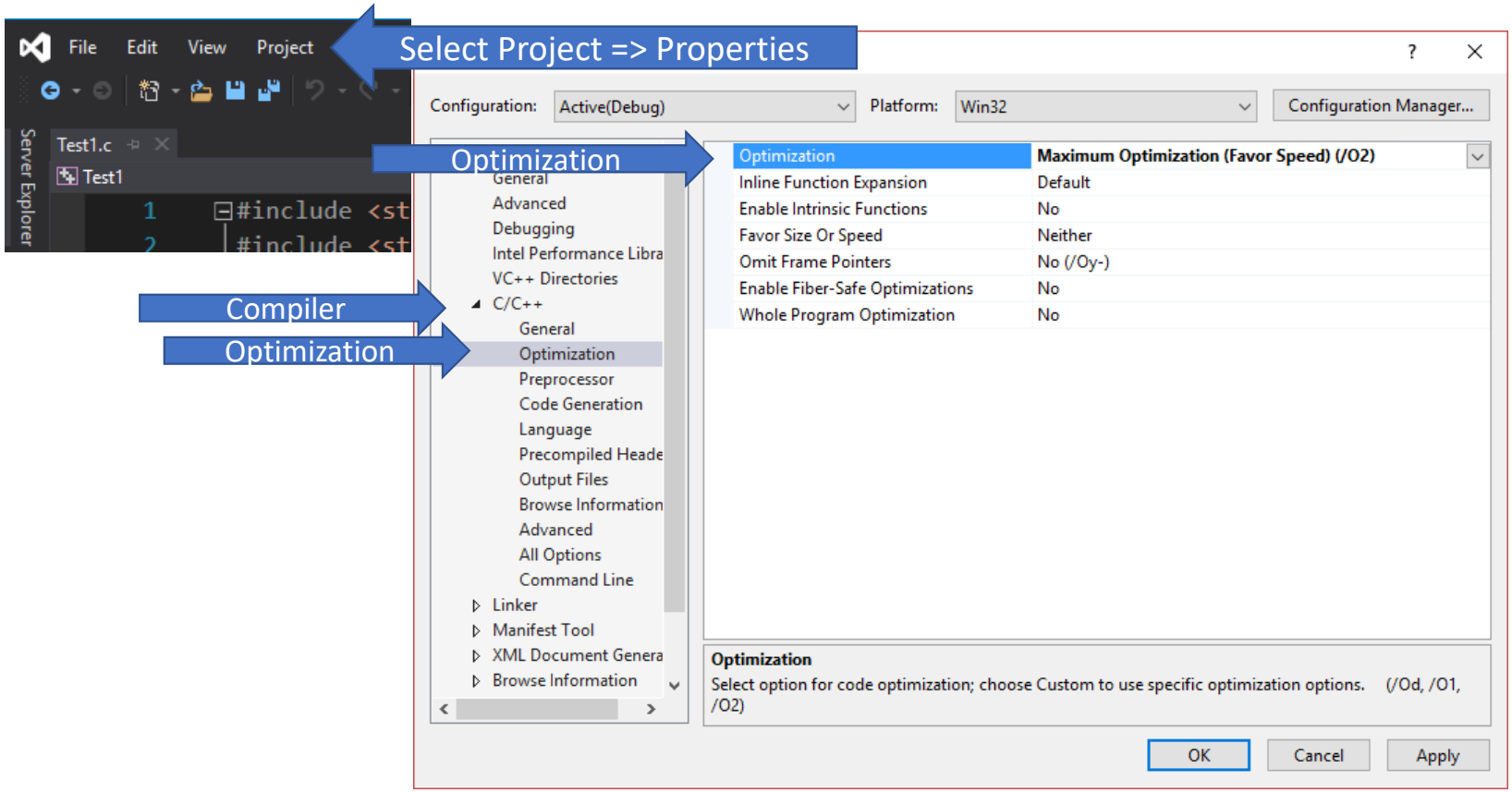
- Streaming SIMD Extensions (/arch:SSE)
- Streaming SIMD Extensions 2 (/arch:SSE2)
- Advanced Vector Extensions (/arch:AVX)
- Advanced Vector Extensions 2 (/arch:AVX2)
- No Enhanced Instructions (/arch:IA32)

Auto-vectorization



Auto-vectorization

Let´s enable the compiler´s ability to generate vectorized code:



Auto-vectorization

```
        // This loop will be auto-vectorized
        for (int i = 0; i < SIZE; i++)
00DE10F0  xor         eax,eax
            A[i] = A[i] + B[i];
00DE10F2  movups      xmm0,xmmword ptr [esp+eax+40h]
00DE10F7  movups      xmm1,xmmword ptr [esp+eax+1040h]
00DE10FF  paddd       xmm1,xmm0
00DE1103  movups      xmmword ptr [esp+eax+40h],xmm1
00DE1108  movups      xmm0,xmmword ptr [esp+eax+50h]
00DE110D  movups      xmm1,xmmword ptr [esp+eax+1050h]
00DE1115  paddd       xmm1,xmm0
00DE1119  movups      xmmword ptr [esp+eax+50h],xmm1
00DE111E  movups      xmm0,xmmword ptr [esp+eax+60h]
00DE1123  movups      xmm1,xmmword ptr [esp+eax+1060h]
00DE112B  paddd       xmm1,xmm0
00DE112F  movups      xmmword ptr [esp+eax+60h],xmm1
00DE1134  movups      xmm0,xmmword ptr [esp+eax+70h]
00DE1139  movups      xmm1,xmmword ptr [esp+eax+1070h]
00DE1141  paddd       xmm1,xmm0
00DE1145  movups      xmmword ptr [esp+eax+70h],xmm1
00DE114A  add         eax,40h
00DE114D  cmp         eax,1000h
00DE1152  jl          main+0A2h (0DE10F2h)
```

Is it auto-vectorizing?

✓ Yes

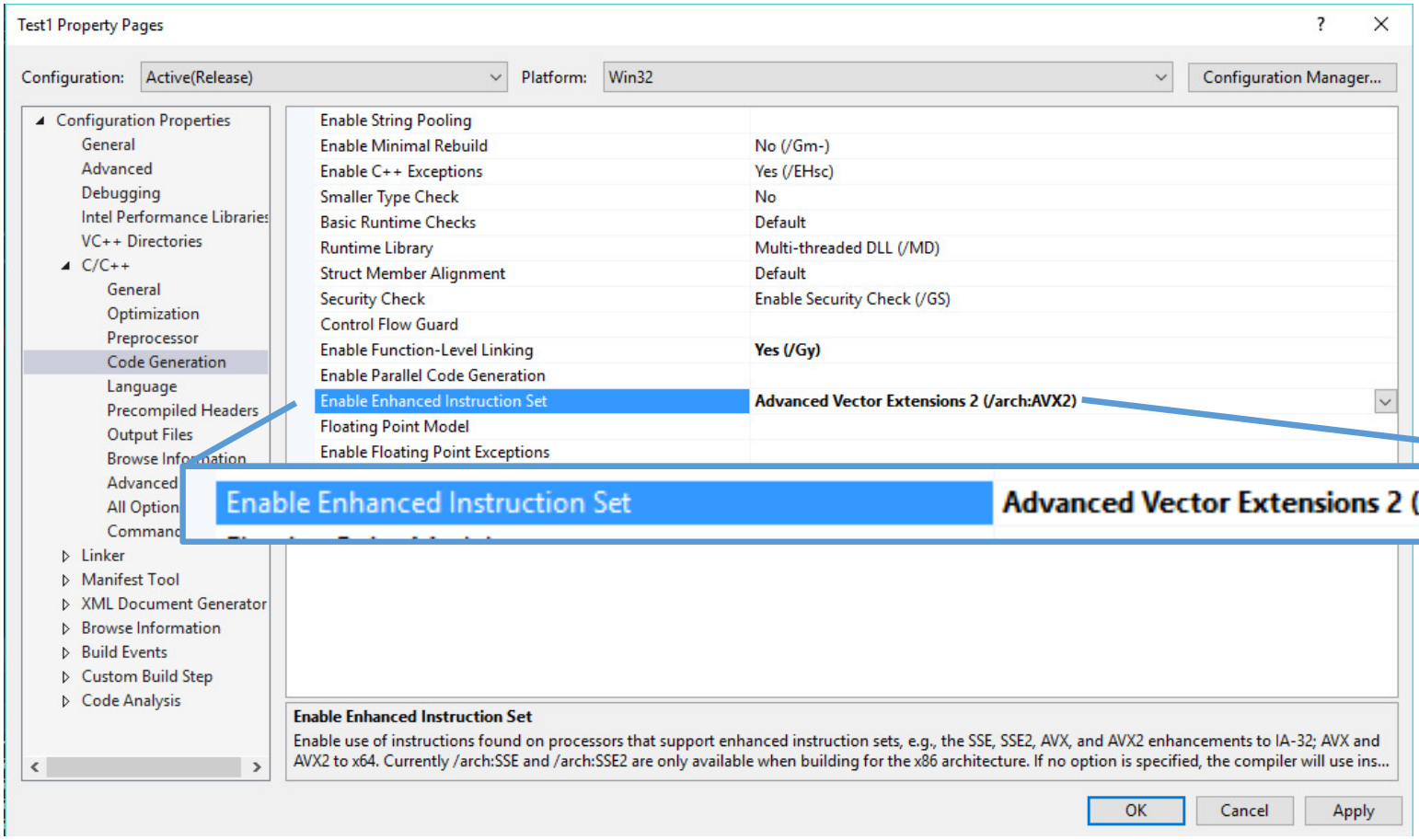
What registers is it using?

✓ SSE 128-bit.

Is it working as expected?

✓ Yes

Auto-vectorization



Auto-vectorization

```
        // This loop will be auto-vectorized
        for (int i = 0; i < SIZE; i++)
01141103  xor         eax,eax
01141105  nop         word ptr [eax+eax]
            A[i] = A[i] + B[i];
01141110  vmovdqu     ymm0,ymmword ptr [esp+eax+1040h]
01141119  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+40h]
0114111F  vmovdqu     ymmword ptr [esp+eax+40h],ymm0
01141125  vmovdqu     ymm0,ymmword ptr [esp+eax+1060h]
0114112E  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+60h]
01141134  vmovdqu     ymmword ptr [esp+eax+60h],ymm0
0114113A  vmovdqu     ymm0,ymmword ptr [esp+eax+1080h]
01141143  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+80h]
0114114C  vmovdqu     ymmword ptr [esp+eax+80h],ymm0
01141155  vmovdqu     ymm0,ymmword ptr [esp+eax+10A0h]
0114115E  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+0A0h]
01141167  vmovdqu     ymmword ptr [esp+eax+0A0h],ymm0
01141170  sub         eax,0FFFFFF80h
01141173  cmp         eax,1000h
01141178  jl          main+0C0h (01141110h)
```

Is it auto-vectorizing?

✓ Yes

What registers is it using?

✓ AVX 256-bit.

Is it working as expected?

✓ Yes

Auto-vectorization

```
        // This loop will be auto-vectorized
        for (int i = 0; i < SIZE; i++)
00DE10F0  xor         eax,eax
            A[i] = A[i] + B[i];
00DE10F2  movups      xmm0,xmmword ptr [esp+eax+40h]
00DE10F7  movups      xmm1,xmmword ptr [esp+eax+1040h]
00DE10FF  paddd       xmm1,xmm0
00DE1103  movups      xmmword ptr [esp+eax+40h],xmm1
00DE1108  movups      xmm0,xmmword ptr [esp+eax+50h]
00DE110D  movups      xmm1,xmmword ptr [esp+eax+1050h]
00DE1115  paddd       xmm1,xmm0
00DE1119  movups      xmmword ptr [esp+eax+50h],xmm1
00DE111E  movups      xmm0,xmmword ptr [esp+eax+60h]
00DE1123  movups      xmm1,xmmword ptr [esp+eax+1060h]
00DE112B  paddd       xmm1,xmm0
00DE112F  movups      xmmword ptr [esp+eax+60h],xmm1
00DE1134  movups      xmm0,xmmword ptr [esp+eax+70h]
00DE1139  movups      xmm1,xmmword ptr [esp+eax+1070h]
00DE1141  paddd       xmm1,xmm0
00DE1145  movups      xmmword ptr [esp+eax+70h],xmm1
00DE114A  add         eax,40h
00DE114D  cmp         eax,1000h
00DE1152  jl          main+0A2h (0DE10F2h)
```

```
        // This loop will be auto-vectorized
        for (int i = 0; i < SIZE; i++)
01141103  xor         eax,eax
01141105  nop         word ptr [eax+eax]
            A[i] = A[i] + B[i];
01141110  vmovdqu     ymm0,ymmword ptr [esp+eax+1040h]
01141119  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+40h]
0114111F  vmovdqu     ymmword ptr [esp+eax+40h],ymm0
01141125  vmovdqu     ymm0,ymmword ptr [esp+eax+1060h]
0114112E  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+60h]
01141134  vmovdqu     ymmword ptr [esp+eax+60h],ymm0
0114113A  vmovdqu     ymm0,ymmword ptr [esp+eax+1080h]
01141143  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+80h]
0114114C  vmovdqu     ymmword ptr [esp+eax+80h],ymm0
01141155  vmovdqu     ymm0,ymmword ptr [esp+eax+10A0h]
0114115E  vpaddd      ymm0,ymm0,ymmword ptr [esp+eax+0A0h]
01141167  vmovdqu     ymmword ptr [esp+eax+0A0h],ymm0
01141170  sub         eax,0FFFFFF80h
01141173  cmp         eax,1000h
01141178  jl          main+0C0h (01141110h)
```

Auto-vectorization in GCC

Consider the following code:

```
#include <stdio.h>
#include <stdlib.h>

#define SIZE 1024

int main() {

int A[SIZE] __attribute__((aligned(32)));
int B[SIZE] __attribute__((aligned(32)));

for (int i = 0; i < SIZE; i++)
   A[i] = B[i] = i;

// This loop will be auto-vectorized
for (int i = 0; i < SIZE; i++)
   A[i] = A[i] + B[i];

for (int i = 0; i < 1024; i++)
   printf("%2d %2d %2d\n", i, A[i], B[i]);

return 0;
}
```

- Normal C code
- Data is aligned.
- Compiler should take care of it.

Auto-vectorization

```
0x0000000000000719 <+111>:   cmpl   $0x3ff,-0x203c(%rbp)
0x0000000000000723 <+121>:   jle    0x6df <main+53>
0x0000000000000725 <+123>:   movl   $0x0,-0x2038(%rbp)
0x000000000000072f <+133>:   jmp    0x769 <main+191>
0x0000000000000731 <+135>:   nop
0x0000000000000732 <+136>:   mov    -0x2038(%rbp),%eax
0x0000000000000738 <+142>:   cltq
-Type <return> to continue, or q <return> to quit---
0x000000000000073a <+144>:   mov    -0x2030(%rbp,%rax,4),%edx
0x0000000000000741 <+151>:   mov    -0x2038(%rbp),%eax
0x0000000000000747 <+157>:   cltq
0x0000000000000749 <+159>:   mov    -0x1030(%rbp,%rax,4),%eax
0x0000000000000750 <+166>:   add    %eax,%edx
0x0000000000000752 <+168>:   mov    -0x2038(%rbp),%eax
0x0000000000000758 <+174>:   cltq
0x000000000000075a <+176>:   mov    %edx,-0x2030(%rbp,%rax,4)
0x0000000000000761 <+183>:   nop
0x0000000000000762 <+184>:   addl   $0x1,-0x2038(%rbp)
0x0000000000000769 <+191>:   cmpl   $0x3ff,-0x2038(%rbp)
0x0000000000000773 <+201>:   jle    0x731 <main+135>
0x0000000000000775 <+203>:   movl   $0x0,-0x2034(%rbp)
0x000000000000077f <+213>:   jmp    0x7bf <main+277>
0x0000000000000781 <+215>:   mov    -0x2034(%rbp),%eax
```

If it is auto-vectorizing, why do we see General Registers?

✓Just some configuration needed.

Auto-vectorization

First of all, turn on optimization flag:

-O

What optimization do you want?

A: Auto-vectorization!

-O -ftree-vectorize

```
push   %r10
push   %rbx
sub    $0x2038,%rsp
mov    %fs:0x28,%rax
mov    %rax,-0x38(%rbp)
xor    %eax,%eax
movdqa 0x152(%rip),%xmm0        # 0x860
movdqa 0x15a(%rip),%xmm1        # 0x870
movaps %xmm0,-0x1050(%rbp,%rax,1)
movaps %xmm0,-0x2050(%rbp,%rax,1)
add    $0x10,%rax
paddd  %xmm1,%xmm0
cmp    $0x1000,%rax
jne    0x716 <main+60>
mov    $0x0,%eax
nop
mov    -0x1050(%rbp,%rax,1),%edx
add    %edx,-0x2050(%rbp,%rax,1)
```

Example: $ gcc autovec.c -o autovec -O -ftree-vectorize

Auto-vectorization

Want AVX auto-vectorization optimizations?

Simple: -mavx2

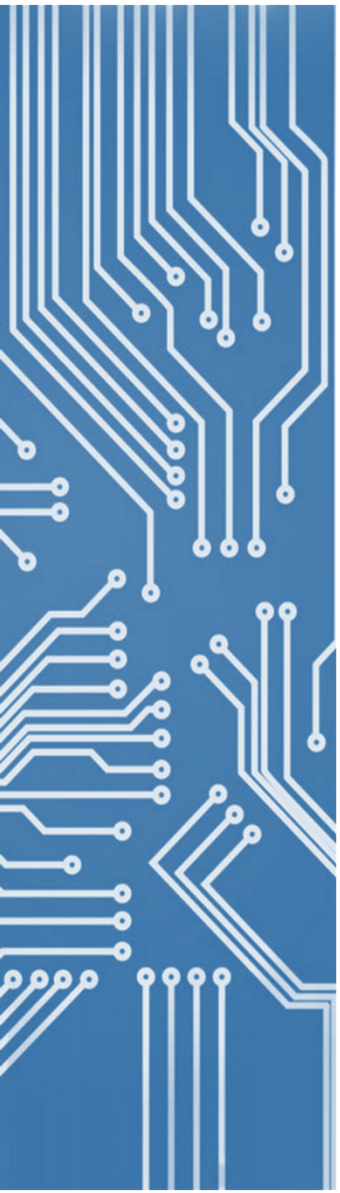
```
xor    %eax,%eax
vmovdqa 0x152(%rip),%ymm0        # 0x860
vmovdqa 0x16a(%rip),%ymm1        # 0x880
vmovdqa %ymm0,-0x1050(%rbp,%rax,1)
vmovdqa %ymm0,-0x2050(%rbp,%rax,1)
add    $0x20,%rax
vpaddd %ymm1,%ymm0,%ymm0
cmp    $0x1000,%rax
```

What about AVX-512?

-mavx512f

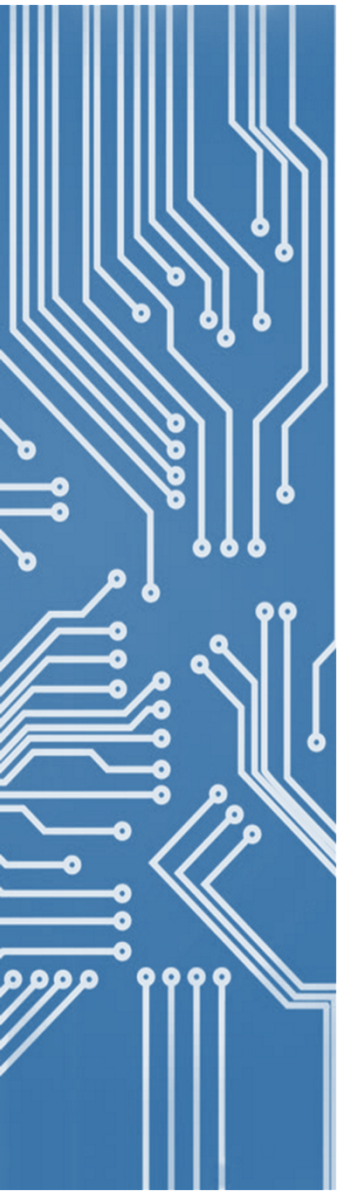
```
mov    $0x0,%esi
vmovdqa64 0x1ee(%rip),%zmm1        # 0x980
vmovdqa64 %zmm0,(%r8,%rdx,1)
vmovdqu32 %zmm0,(%rdi,%rdx,1)
add    $0x1,%esi
add    $0x40,%rdx
vpaddd %zmm1,%zmm0,%zmm0
```

Example: $ gcc autovec.c -o autovec -O -ftree-vectorize -mavx2



Auto-vectorization

Ok, so now we know the compiler auto-vectorizes. Is there a way to know without disassembling the code every time?



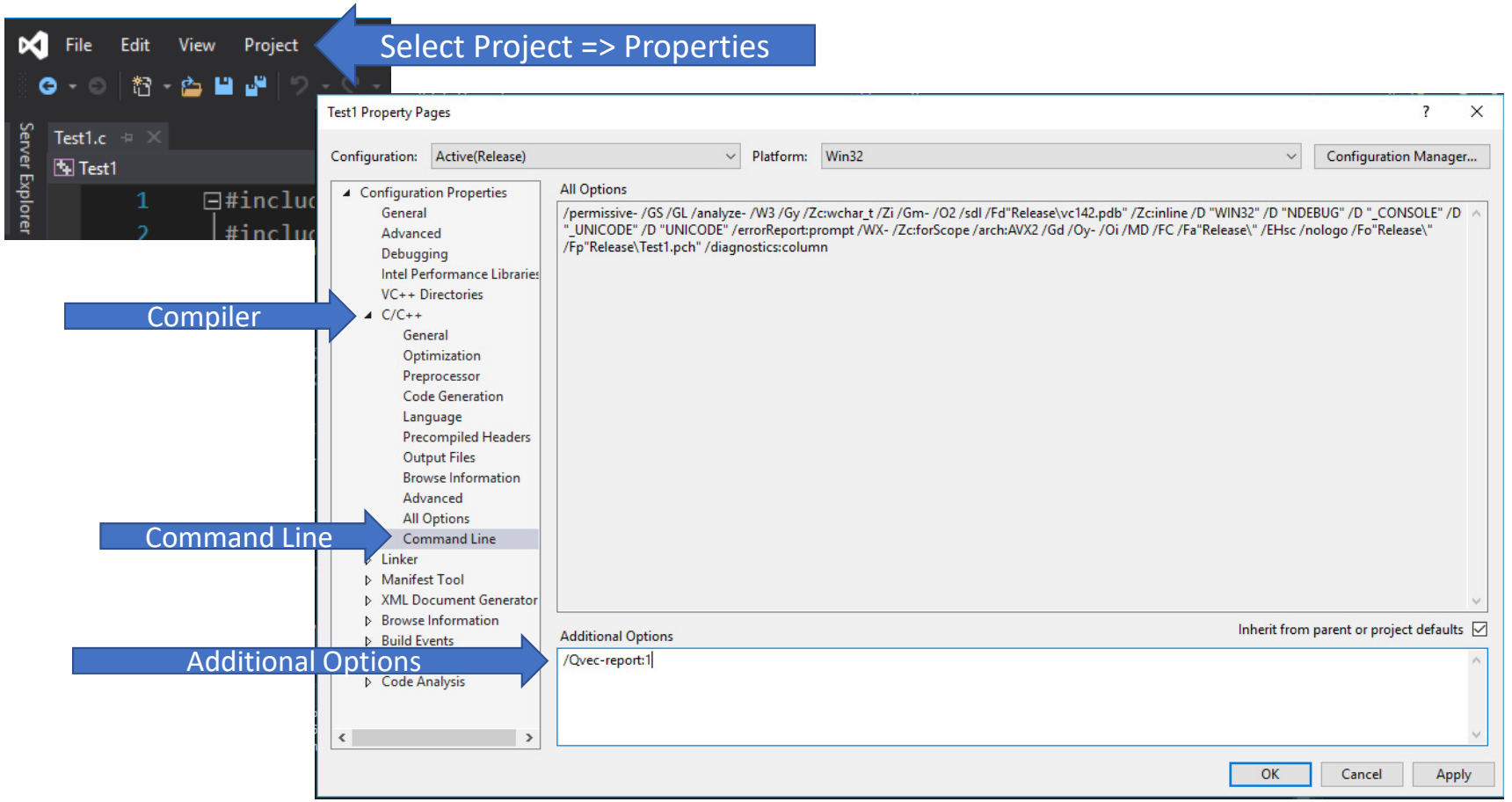
Auto-vectorization report (Windows)

/Qvec-report:{1}{2}

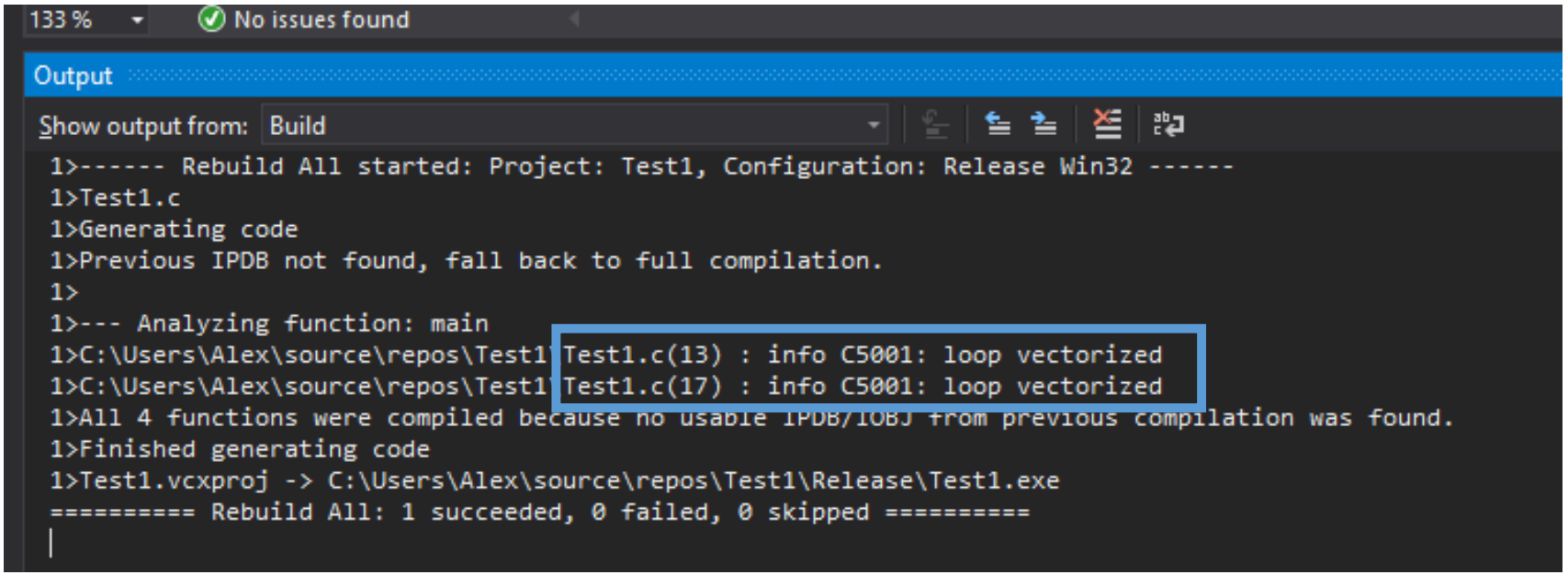
/Qvec-report:1

Outputs an informational message for loops that are vectorized.

Auto-vectorization report (Windows)



Auto-vectorization report (Windows)



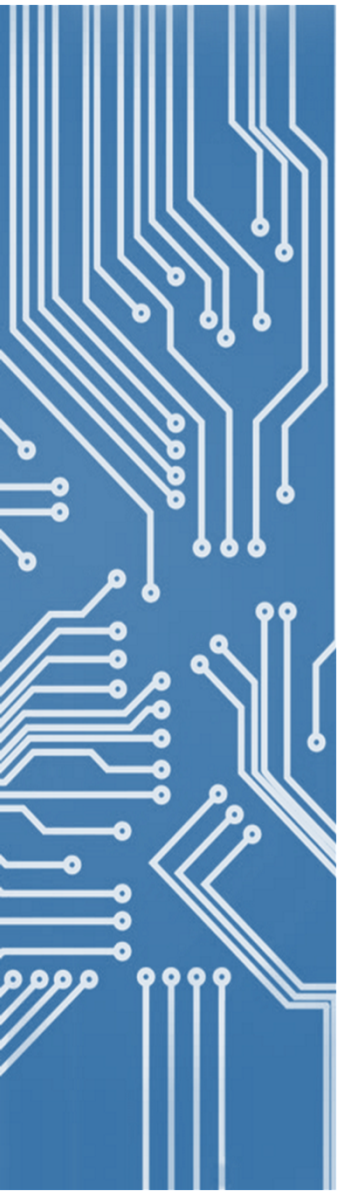
Auto-vectorization report (GCC)

-fopt-info-vec[=file.ext]

-fopt-info-vec

Outputs an informational message for loops that are vectorized.

```
mp@multiprocesadores:~/multiprocs$ gcc autovec.c -o autovec -O -ftree-vectorize -mavx2 -fopt-info-vec
autovec.c:11:1: note: loop vectorized
```



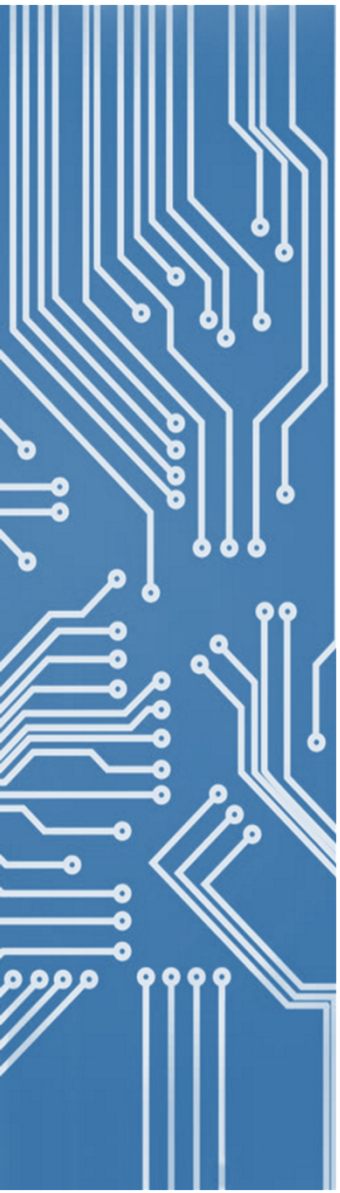
Lets try this!

1

Recall Homework code **Single Threaded Array Addition (FLOATs)**?

Single Threaded Array Addition (FLOATs)

1.- Check your project properties and make sure No Enhanced Instructions (/arch:IA32 or no –O option) is selected.
2.- Run the program and take note of the time needed to run.
3.- Now change your project's properties and enable Streaming SIMD Extensions 2 (/arch:SSE2 or -O -ftree-vectorize)
4.- Run the program and take note of the time.
5.- Compare the times and give a conclusion.



Lets try this!

1

Continue with the same code…

1.- Now change your project's properties and enable Advanced Vector Extensions 2 (/arch:AVX2)

2.- Run the program again and take note of the time.

3.- Disable your Enhanced Instruction Sets (/arch:IA32)

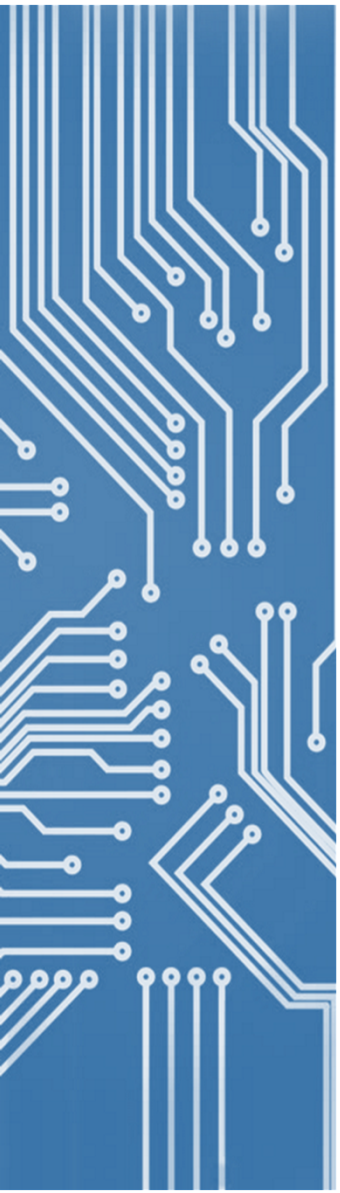
4.- Replace the code with your 128-bit Intrinsics.

5.- Run the program and take note of the time.

6.- Replace the code with your 256-bit Intrinsics.

7.- Run the program again and take note of the time.

8.- Compare the times and give a conclusion.



Lets try this!

1

No enhancements	SSE2 Auto	SSE Intrin	AVX Auto	AVX Intrin
172	48	55	46	46

- ✓ Auto-vectorized code is better than no vectorization at all (*not always).
- ✓ Sometimes, using Intrinsics you can get better performance (you, the programmer, have to know what you are doing).
- ✓ Why is SSE Autovectorization better than Intrinsics?
  - ✓ Cache hits, using storeu instead of store or bad alignment.

Auto-vectorization

So… **Auto-vectorization:**

The forced question…

Why assembly and Intrinsics!?

VS

VS

Auto-vectorization **Intrinsics** **Assembly Language**

Thank you!

See you next time!