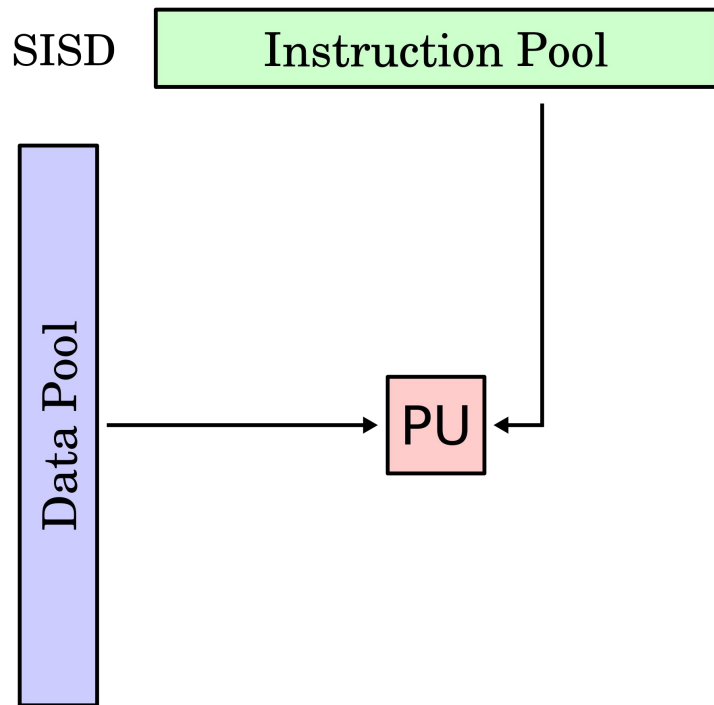


Vectorization

Parallel Programming

21 Oct 2021

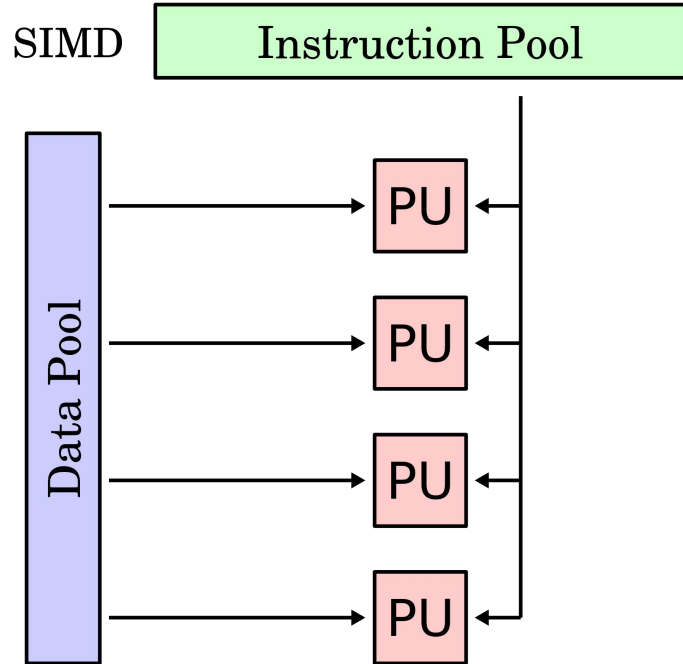
How CPU Execute an Instruction



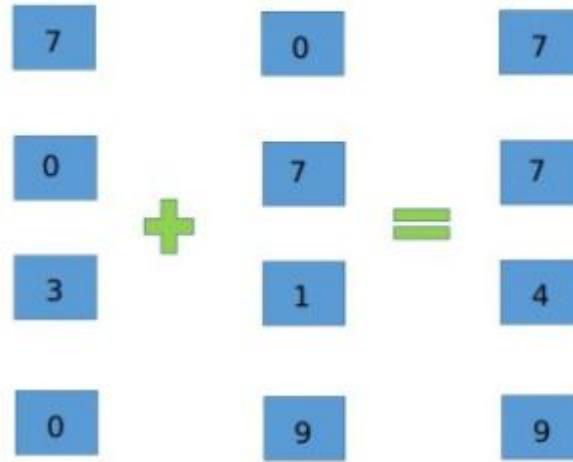
For loop

7	+	0	=	7
0	+	7	=	7
3	+	1	=	4
0	+	知乎 @Gerrfield	=	

How CPU Execute an Instruction



Vectorization



When to use Vector Instruction Set?

- A part of codes which are executed many times
 - ▷ In a loop
- There are no data dependency between each iteration
 - ▷ Data dependency:
 - ▷ In iteration i , it needs the result of iteration $i-1$ to calculate its result

When to use Vector Instruction Set?

■ Vectorizable

```
void multiply_and_add(int *a, int *b, int *c, int *d, long long size) {  
    for (long long i = 0; i < size; i++) {  
        a[i] = b[i] * c[i] + d[i];  
    }  
}
```

- ▷ Some observations
 - ▷ In each iteration, the result of $a[i]$ is independent with each other
 - ▷ The same instructions are executed many times on different data

When to use Vector Instruction Set?

- Non-vectorizable

```
double norm2(int *a, long long size) {  
    double result = 0.0;  
    for (long long i = 0; i < size; i++) {  
        result += a[i] * a[i];  
    }  
    return sqrt(result);  
}  
  
long long Fibonacci(long long ind) {  
    long long *result = (long long*)malloc(sizeof(long long) * (ind + 2));  
    result[1] = 1;  
    result[2] = 1;  
    for (int i = 3; i <= ind; i++) {  
        result[i] = result[i - 1] + result[i - 2];  
    }  
    return result[ind];  
}
```

Vector Instruction Sets

- MMX
- SSE
- FMA
- AVX

Vector Instruction Sets

- MMX
- SSE
 - ▷ Streaming SIMD Extensions
 - ▷ Versions: SSE, SSE2, SSE3, SSSE3, SSE4.1, SSE4.2
 - ▷ Calculate 128-bit data in an instruction (include integer & floating point)
 - ▷ 8x 16-bit short ⇐ 8x faster
 - ▷ 4x 32-bit integer ⇐ 4x faster
 - ▷ 4x 32-bit floating-point number ⇐ 4x faster
 - ▷ 2x 64-bit double-point number ⇐ 2x faster

Vector Instruction Sets

- SSE
 - ▷ 16 registers (XMM00~XMM15)
 - ▷ SSE: only 32-bit floating point
 - ▷ SSE2: double, long long, int, char
 - ▷ Newer SSE only adds more kinds of instruction

Vector Instruction Sets

- FMA

- ▷ Fused Multiply-Add
 - ▷ $\underline{a} = b * c + d$
- ▷ Versions: FMA4, FMA3
- ▷ 128-bit and 256-bit of FMA operations
- ▷ FMA4:
 - ▷ 4-operand instructions, only supported by AMD CPU
- ▷ FMA3:
 - ▷ 3-operand instructions (\underline{a} could only be b , c , or d)
Ex: $b = b * c + d$

Vector Instruction Sets

- AVX
 - ▷ Advanced Vector eXtensions

Width	256-bit vector instructions	512-bit vector instructions
Version	AVX, AVX2(extension of AVX)	AVX512
Register	16 (YMM00~YMM15)	32 (ZMM00~ZMM31)

- More bits: More data could be calculated at a time
- More registers: More complex calculation is supported

Check Hardware Support

- Linux command: `lscpu | grep -i $instruction_set`
 - where `$instruction_set` could be `mmx`, `sse`, `sse2`, `sse3`, `ssse3`, `sse4_1`, `sse4_2`, `avx`, `avx2`, `avx512`
- Most CPUs released after 2011 support AVX instructions

```
$ lscpu | grep sse
```

Flags:

```
fpu vme de pse tsc msr pae mce cx8 apic sep mtr  
r pge mca cmov pat pse36 clflush dts acpi mmx fxsr sse sse2 ss ht tm pbe syscall  
nx pdpe1gb rdtscp lm constant_tsc arch_perfmon pebs bts rep_good nopl xtopology  
nonstop_tsc cpuid aperfmperf pni pclmulqdq dtes64 monitor ds_cpl vmx smx est tm  
2 ssse3 cx16 xtpr pdcm pcid dca sse4_1 sse4_2 popcnt aes lahf_lm epb pti ssbd ib  
rs ibpb stibp tpr_shadow vnmi flexpriority ept vpid dtherm ida arat flush_lld
```

Automatic Vectorization

- GCC
 - Vectorization is enabled by the flag **-ftree-vectorize**
 - Enabled by default with flag **-O3**
 - Add compiler flag **-fopt-info-vec-all** to see vectorization log
 - Add flag **-march=native** to use instructions supported by the local CPU
 - Add **#pragma GCC ivdep** to code to declare that there are no data dependency in the following loop

Automatic Vectorization

```
mpicc -O3 -march=native -fopt-info-vec-all array.c -o array
array.c:8:3: optimized: loop vectorized using 16 byte vectors
array.c:8:3: optimized: loop versioned for vectorization because of possible aliasing
array.c:7:6: note: vectorized 1 loops in function.
array.c:32:3: optimized: loop vectorized using 16 byte vectors
array.c:32:3: optimized: loop versioned for vectorization because of possible aliasing
array.c:16:3: missed: couldn't vectorize loop
/usr/lib/gcc/x86_64-pc-linux-gnu/9.1.0/include/emmintrin.h:703:10: missed: not vectorize
d: no vectype for stmt: _40 = MEM[(const __m128i_u * {ref-all})_3];
scalar_type: const __m128i_u
array.c:13:6: note: vectorized 1 loops in function.
```

- See more: [link](#)
- LLVM Compiler: [link](#)

Vectorize Loop with Intel Intrinsics

- Intel Intrinsics Guide: [link](#)
 - Check the instruction set you want to use
 - Use keyword to search
 - Check the variable type & operation
- Procedure
 - Load data from memory to the special registers
 - Perform vector instructions
 - Save data from the special registers to memory

intel® Intrinsics Guide

The Intel Intrinsics Guide is an interactive reference tool for Intel intrinsic instructions, which are C style functions that provide access to many Intel instructions - including Intel® SSE, AVX, AVX-512, and more - without the need to write assembly code.

Technologies

- ☐ MMX
- ☒ SSE
- ☒ SSE2
- ☒ SSE3
- ☒ SSE3
- ☒ SSE4.1
- ☒ SSE4.2
- ☐ AVX
- ☐ AVX2
- ☐ FMA
- ☐ AVX-512
- ☐ KNC
- ☐ SVML
- ☐ Other

Categories

- ☐ Application-Targeted
- ☐ Arithmetic
- ☐ Bit Manipulation
- ☐ Cast
- ☐ Compare
- ☐ Convert
- ☐ Cryptography
- ☐ Elementary Math Functions
- ☐ General Support
- ☐ Load

load

```
__m128i _mm_lddqu_si128 (__m128i const* mem_addr)
```

Synopsis

```
__m128i _mm_lddqu_si128 (__m128i const* mem_addr)
#include <pmmintrin.h>
Instruction: lddqu xmm, m128
CPUID Flags: SSE3
```

Description

Load 128-bits of integer data from unaligned memory into dst. This intrinsic may perform better than `_mm_loadu_si128` when the data crosses a cache line boundary.

Operation

```
dst[127:0] := MEM[mem_addr+127:mem_addr]
```

```
void _mm_lfence (void)
__m128d _mm_load_pd (double const* mem_addr)
__m128d _mm_load_pd1 (double const* mem_addr)
__m128 _mm_load_ps (float const* mem_addr)
__m128 _mm_load_ps1 (float const* mem_addr)
__m128d _mm_load_sd (double const* mem_addr)
__m128i _mm_load_si128 (__m128i const* mem_addr)
__m128 _mm_load_ss (float const* mem_addr)
__m128d _mm_load1_pd (double const* mem_addr)
__m128 _mm_load1_ps (float const* mem_addr)
```

Vectorize Loop with Intel Intrinsics

- Original

```
void multiply_and_add(int *a, int *b, int *c, int *d, long long size) {  
    for (long long i = 0; i < size; i++) {  
        a[i] = b[i] * c[i] + d[i];  
    }  
}
```


Vectorize Loop with Intel Intrinsics

1. Check CPU support
 - ▶ Up to SSE4.2, no FMA (on apollo)
2. Load data from memory to the special registers
 - ▶ Use 128-bit instruction set & integer \Rightarrow `__m128i`
 - ▶ Load data (check Intel Intrinsics Guide) \Rightarrow `_mm_lddqu_si128`

```
__m128i _mm_lddqu_si128 (__m128i const* mem_addr)
```

`lddqu`

Synopsis

```
__m128i _mm_lddqu_si128 (__m128i const* mem_addr)  
#include <pmmintrin.h>  
Instruction: lddqu xmm, m128  
CPUID Flags: SSE3
```

Description

Load 128-bits of integer data from unaligned memory into `dst`. This intrinsic may perform better than `_mm_loadu_si128` when the data crosses a cache line boundary.

Operation

```
dst[127:0] := MEM[mem_addr+127:mem_addr]
```

Vectorize Loop with Intel Intrinsics

3. Perform vector instructions

- No FMA \Rightarrow cannot do multiplication and addition in 1 instruction
- Perform multiplication first, then addition

```
__m128i _mm_mullo_epi32 (__m128i a, __m128i b)
```

Synopsis

```
__m128i _mm_mullo_epi32 (__m128i a, __m128i b)
#include <smmintrin.h>
Instruction: pmulld xmm, xmm
CUID Flags: SSE4.1
```

Description

Multiply the packed 32-bit integers in `a` and `b`, producing intermediate 64-bit integers, and store the low 32 bits of the intermediate integers in `dst`.

Operation

```
FOR j := 0 to 3
  i := j*32
  tmp[63:0] := a[i+31:i] * b[i+31:i]
  dst[i+31:i] := tmp[31:0]
ENDFOR
```

`pmulld`

```
__m128i _mm_add_epi32 (__m128i a, __m128i b)
```

Synopsis

```
__m128i _mm_add_epi32 (__m128i a, __m128i b)
#include <emmintrin.h>
Instruction: paddq xmm, xmm
CUID Flags: SSE2
```

Description

Add packed 32-bit integers in `a` and `b`, and store the results in `dst`.

Operation

```
FOR j := 0 to 3
  i := j*32
  dst[i+31:i] := a[i+31:i] + b[i+31:i]
ENDFOR
```

Vectorize Loop with Intel Intrinsics

4. Save data from the special registers to memory

```
void _mm_store_si128 (__m128i* mem_addr, __m128i a)
```

Synopsis

```
void _mm_store_si128 (__m128i* mem_addr, __m128i a)
#include <emmintrin.h>
Instruction: movdqa m128, xmm
CPUID Flags: SSE2
```

Description

Store 128-bits of integer data from `a` into memory. `mem_addr` must be aligned on a 16-byte boundary or a general-protection exception may be generated.

Operation

```
MEM[mem_addr+127:mem_addr] := a[127:0]
```

```

14 void multiply_and_add_sse42(int *a, int *b, int *c, int *d, long long size) {
15     long long size1 = (size >> 2) << 2;
16     long long i = 0;
17     for (; i < size1; i += 4) {
18         // 1. Declare variable to store 128-bit data with 4 integers
19         __m128i as;
20         __m128i bs = _mm_lddqu_si128((__m128i const*)&b[i]);
21         __m128i cs = _mm_lddqu_si128((__m128i const*)&c[i]);
22         __m128i ds = _mm_lddqu_si128((__m128i const*)&d[i]);
23
24         // 2. Perform SSE multiply & add instructions
25         as = _mm_mullo_epi32(bs, cs);
26         as = _mm_add_epi32(as, ds);
27
28         // 3. Store result back to memory
29         _mm_store_si128((__m128i*)&a[i], as);
30     }
31
32     // Dealing with the remaining parts
33     for (long long i = size1; i < size; i++) {
34         a[i] = b[i] * c[i] + d[i];
35     }
36 }

```

Promise the vectorized loop is aligned to 128 bits

Dealing with the remaining data

Hint

- Theoretically, use SIMD instruction can improve performance
 - ▷ With SSE instruction, it could be about 2x~8x faster
- SSE~AVX2 intrinsics is supported by gcc, but only Intel Compiler supports AVX512 intrinsics
 - ▷ Try it by yourself!!!
- Take advantage of auto-vectorization
- You can use any intrinsics in your homework