

Optimization Pipelines

Luca Tornatore - I.N.A.F.



“Foundation of HPC - basic” course



DATA SCIENCE &
SCIENTIFIC COMPUTING
2022-2023 @ Università di Trieste



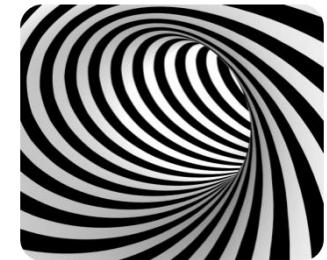
Outline



Pipelines



Branches



Loops



How to increase the CPU performance

If we define the *performance* of a CPU as the number of instructions it can deliver in, say, a second, there are basically two strategies:

1. we increase the number of times a CPU operates per second, i.e. its *clock*. That indeed happened in the past, as we have seen.
In abstract sense, this amounts to keep its design and hurry it up.
2. we change the design of the CPU, trying to increase the number of instructions that in average it delivers every “time” it operates, i.e. the number of instructions per cycle that the CPU can dispatch. This second approach has no tension with the first, since both can be pursued at the same time.
In this lecture we focus on this second way: what is the design change that makes it possible and how to exploit it from the programmer’s point of view.



| Increasing the “productivity”

A way to increase the throughput of instructions that a CPU can complete in time is called *pipelining*, which exploits the mutual independence among the different simpler operations needed to complete a single CPU's instruction.

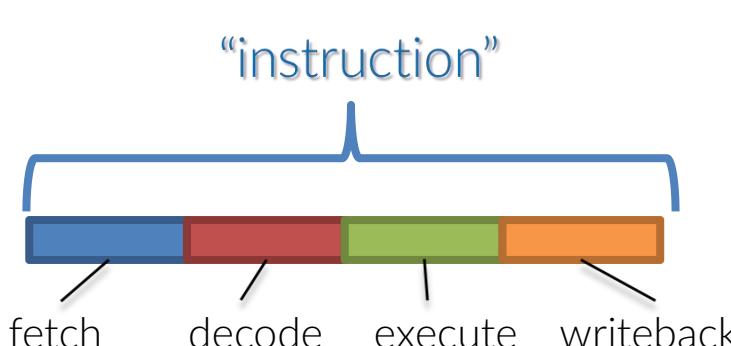
This technique is about **increasing the average number of instructions delivered per cpu's cycle, i.e. its throughput**, not about rendering the single instructions faster.



Atomic instructions

It would be obvious to think that an “instruction” is a kind of *atomic* operation that the CPU perform as a whole. Indeed that was true until the mid of the 80s.

If you think carefully about it, it is easy to understand that actually an “instruction” involves at least the following *independent* steps:

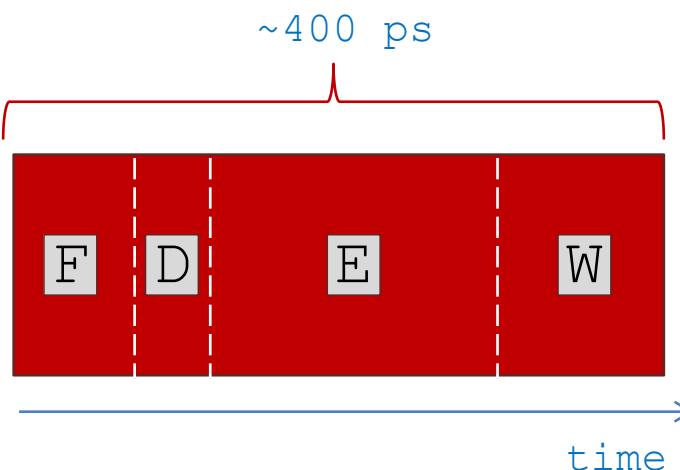


1. **Fetching**
it must be recalled from memory/lcache
2. **Decoding:**
it must be “understood and interpreted”
3. **Execution**
4. **Writeback :**
the result must be accounted in memory ()



Pipelines

Atomic instructions ?



If all the four stages take ~400ps, we then would obtain a **throughput** of 2.5GIPS (giga-instructions per second).

400ps is also the total time required to get a result from an instruction, and so it is the **latency** of the instruction, or the **delay** between two subsequent instructions.

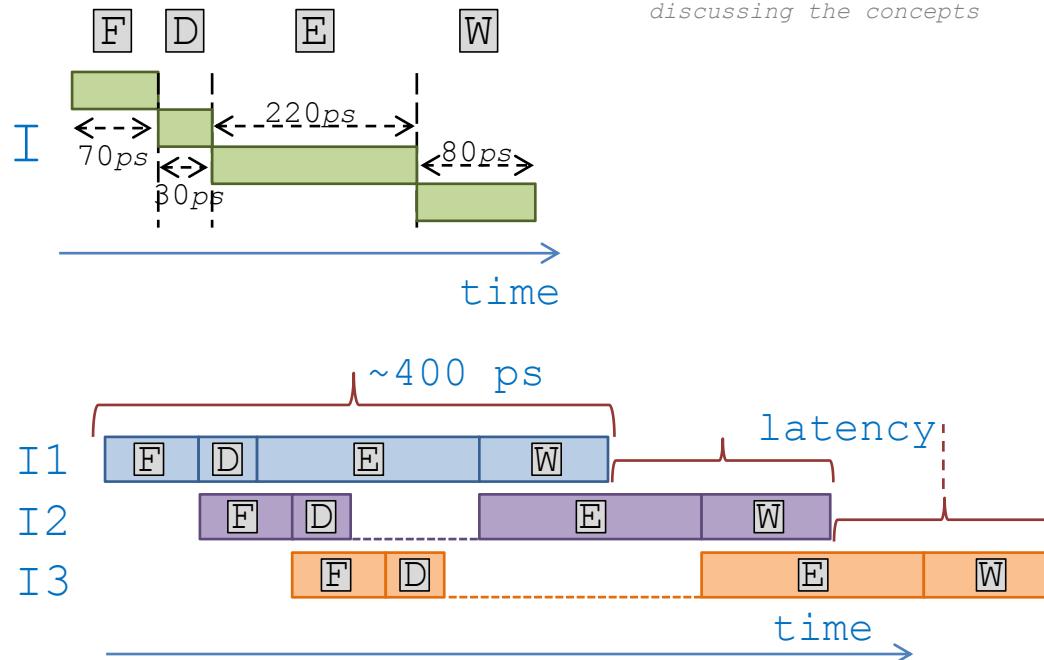
However, if we were able to “detach” the four stages, we could organize things differently, like in a car-building chain, or even at the mensa of the university.



Pipelines

Pipelines

Note: all the timing estimates are hypothetical for the purpose of discussing the concepts



If many independent logical units exist to perform each step, they could operate subsequently on different instructions:

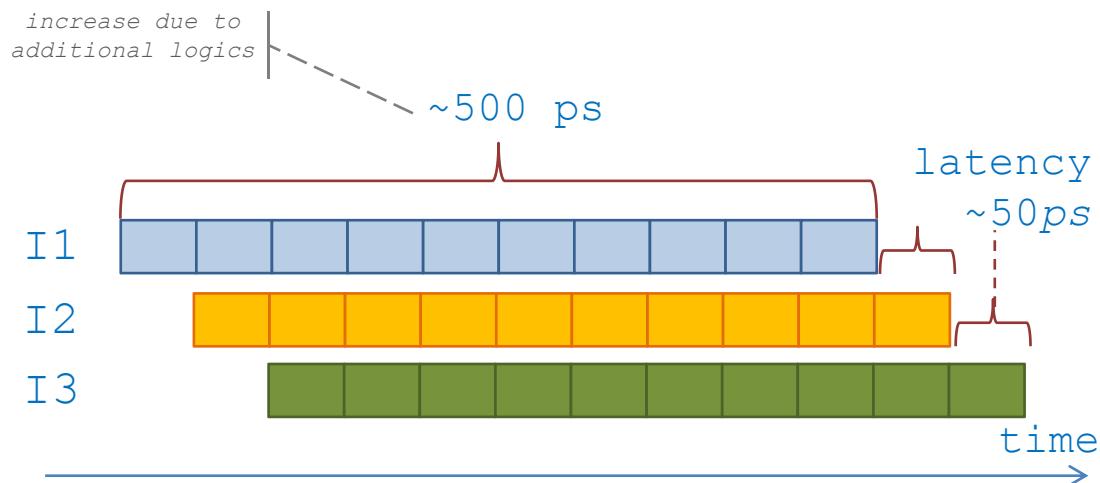
If the stage delays are not uniform, the throughput is limited by the latency $F + (D+E) - (F+D) = E \sim 220\text{ps}$, which means we have a throughput of $\sim 4.5\text{GIPS}$ just because of logic units separation.



Pipelines

Therefore, introducing the instructions pipelining, we can increase the **throughput** of our system by a large factor.

However, the efficiency of the pipelines is limited by its longest stage: the better option would be to have all equal stages, for instance further subdividing each stage – especially the most demanding ones (*).



Now the throughput of our system has increased to 1 instruction retired every 50ps, i.e. 20GIPS

(*) this is called *superpipelining*: modern CPUs may have 10-20 stages per pipeline.



Pipelines are about throughput

Pipelining is then about increasing the throughput of a system, and as we have seen it could be really effective.

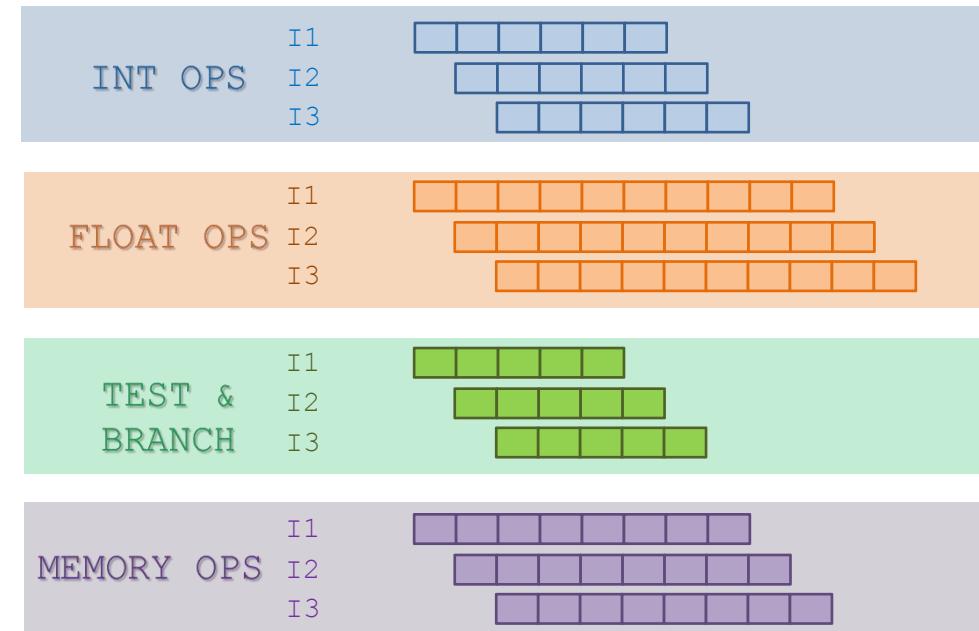
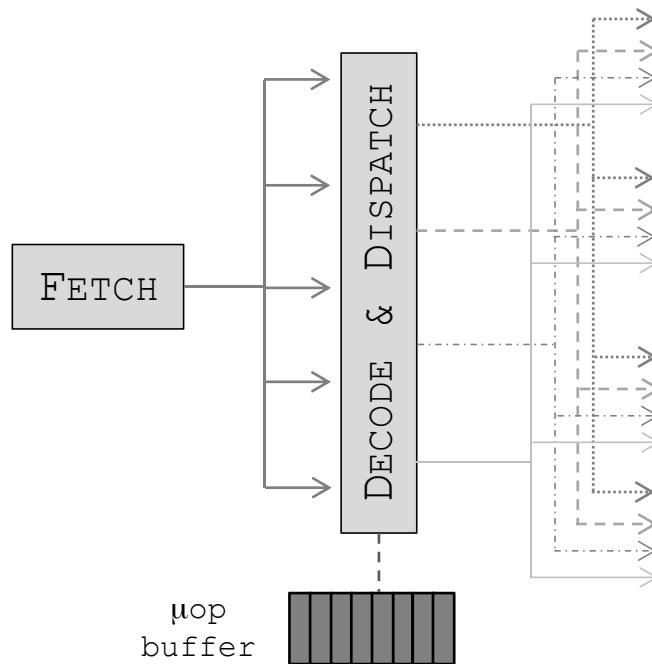
However, there is more that can be done working on the **execution stage** that, of course, encompasses a large number of different *functional units*, performing a **different and independent tasks**.

With an enhancement of the decode/dispatch stage, we can address multiple pipelines that can be active at the same time:



Pipelines

Multiple pipelines





Pipelines are about throughput

Let's have a look at an example. A given CPU has a clock of 2GHz, i.e. a single cycle lasts 0.5ns; let's suppose that its instructions have the following latencies:

ALU 3 cycles

BRANCH 5 cycles

MEMORY
ACCESS 4 cycles

Let's say that in a given average code, the frequency of those instructions are 20%, 30% and 50% respectively. Then, the average delivery (cycles-per-instructions, CPI) of this CPU-code pair is:

$$20\% \times 3\text{cyc} + 30\% \times 5\text{cyc} + 50\% \times 4\text{cyc} = 0.2 \times 3\text{cyc} + 0.3 \times 5\text{cyc} + 0.5 \times 4\text{cyc} = 4.1 \text{ CPI}$$

Note that a different code, with frequencies (80%,10%,10%; then a much more *arithmetic-intensive* one) would obtain, on the same CPU,

$$0.8 \times 3\text{cyc} + 0.1 \times 5\text{cyc} + 0.1 \times 4\text{cyc} = 3.3 \text{ CPI}$$



Pipelines are about throughput

Then let's say that we pipeline all the instructions in the previous CPU, in such a perfect way that all the stages require exactly the same time, i.e. 1 CPU cycle.

As a consequence, after the initial delay due to the latency of the first instruction, our CPU now is able to deliver 1 instruction per cycle, i.e. has a CPI = 1

Let's also define the gain in performance as

$$gain = \frac{\langle CPI_{np} \rangle}{\langle CPI_p \rangle}$$

where the subscripts *np* and *p* mean *non-pipelined* and *pipelined*, respectively, and the <> brackets mean “average”.

Then, the performance increase of the two hypothetical codes mentioned in the previous slide on this new CPU is **×4.1** and **×3.3**.



Pipelines are about throughput

However, due to the implementation some overhead is unavoidable, and let's say that it amounts to 0.1ns. Then, our pipelined cycle now lasts 0.6ns instead of 0.5ns. The real performance gain, as measured in wall clock time, is actually limited by this overhead:

$$\frac{clock_{np} \times \langle CPI_{np} \rangle}{clock_p \times \langle CPI_p \rangle} = \frac{0.5ns \times \langle CPI_{np} \rangle}{0.6ns \times \langle CPI_p \rangle} = \boxed{0.83 \times \frac{\langle CPI_{np} \rangle}{\langle CPI_p \rangle}}$$

The pipelining, then, although increases the throughput of the CPU renders each single instructions a little bit slower due to the overhead that comes with the pipelining itself.



Pipelines latency

The number of cycles between when an instruction's execution stage begins and when its result is available for other instructions usage, is the *latency* of the instruction and it grows with the pipeline deepness (the number of stages).

Typical latencies in modern processors (read the manual of yours) range from 1cyc for integer ops, to 1-5cyc for add and mul flop to $\geq 10\text{-}20$ for div flop, ~ 50 for trigonometric or exponential functions.

Latency for memory loads can be severely troublesome, because they are highly unpredictable and they block all other operations making it difficult to fill the delay with some other ops.



| The real pipelines performance

In a perfect world, as we have seen until now, where all the stage of a pipeline are perfectly equilibrated and the pipeline implementation has no overhead at all, the theoretical maximum gain from the ILP due to the pipelining is simply

$$gain = \frac{\langle CPI_{np} \rangle}{\langle CPI_p \rangle}$$

However, at least there is some overhead (the 0.1ns in the previous example) due to the pipeline's implementation details and to the managing of some other factors we'll see in the next slides.



| The real pipelines performance

There are 3 majors type of *hazards* that impact on the pipelines performance, lowering their theoretical gain:

1. *Structural hazards*
2. *Data hazards*
3. *Control hazards*

When a pipeline incurs in an hazard, it *stalls* until the hazard is solved. Normally, instructions issued before the hazard continue while all those issued after the one stalled, stall too.

A more realistic model for the improvement from pipelining is then

$$\text{speedup} = \frac{\langle CPI_{np} \rangle}{1 + \langle SCPI_p \rangle} \left(= \frac{\text{PIPELINE DEPTH}}{1 + \langle SCPI_p \rangle} \right)$$

where $\langle SCPI \rangle$ means “average stalled cycles per instruction” and the last equality holds in the simplest case in which all the instructions require the same # of cycles, which in turn are proportional to the pipeline’s number of stages #stages.



Structural hazards

these happens when there are not enough hardware units that can cope with the request of instructions execution.

Furthermore, some instructions are deemed (or forced to be) more *uncommon*, and so privilege has been given to the more common ones (i.e. the CPU are designed under the “optimize the common case” principle).

A typical example: the multiplication/summation (the common ones) vs. the division (the uncommon one).



Pipeline hazards

Some instructions are deemed (or forced to be) more *uncommon*, and so privilege has been given to the more common ones.

A typical example: the multiplication/summation (the common ones) vs. the division (the uncommon one).

From the Intel's manual
"Architectures Optimization"

Instruction	Latency ¹				Throughput			
CPUID	06_4E,06 _5E	06_3D/4 7/56	06_3C/4 5/46/3F	06_3A, 06_3E	06_4E,06 _5E	06_3D/4 7/56	06_3C/4 5/46/3F	06_3A, 06_3E
Lock CMPXCHG8B m64	22	19	19	24	22	19	19	24
Lock CMPXCHG16B m128	32	28	28	29	32	28	28	29
DEC/INC	1	2	2	2	0.25	0.25	0.25	0.33
IMUL r64, r64	3	3	3	3	1	1	1	1
IMUL r64 ¹¹	4, 5	3, 4	3, 4	3, 4	1	1	1	1
IMUL r32	5	4	4	4	1	1	1	1
IDIV r64 (RDX!= 0) ⁹					~85-100	~85-100	~85-100	~85-100
IDIV r32 ¹⁰					~20-26	~20-26	~20-26	~19-25
LEA	1	1	1	1	0.5	0.5	0.5	0.5

In the table above you can appreciate how much different the latency and the throughput (i.e., in the Intel's manual language "The number of clock cycles required to wait before the issue ports are free to accept the same instruction again", somehow the reciprocal of the one we are using here) of different instructions (in evidence: integer multiplication and integer division) can be. That induces you to avoid as much as possible some instructions, depending on the architecture you run.



Data hazards

These happen, due to the out-of-order execution (i.e. the mixing of different stages from different instructions), when the result computed by the i^{th} instruction is used by one or more following instructions, or when there is some conflict about the memory location to be used by more than one result:

Note about
notation →

"**ins**" : instruction
"**reg**" : register

"**i**" is an ins that in
the source code
comes
semantically
before the ins "**j**"

1. **Read After Write (RAW)**; when ins j reads the reg r that should hold the result from ins i before it could write it (wrong value is read by j).
2. **Write After Read (WAR)**; when ins i reads the reg r after ins j writes it (wrong value is read by i).
3. **Write After Write (WAW)**; when ins i writes the reg r after the ins j writes in the same reg (the wrong value is propagated).



Control hazards

These happen because of conditional execution, i.e. whenever there is a branch in the control flow due to a condition (i.e. *if-then*) whose evaluation may, or may not, result in a jump in the code or in the data. We have seen several details in the lecture about, exactly, branches.

The problem is, basically, that either you can not fill adequately the pipeline because in view of a condition you do not know which branch will be taken, or, when you can do speculative execution (i.e. you have a branch prediction), your speculation results to be wrong and it is necessary to flush the pipeline entirely.

This is one of the main cause of performance loss in modern superscalar/out-of-order CPUs. The logics for the runtime branch predictor occupies a large space on processor chips but it definitely is worth it.



Pipelines hazards

A very long pipeline, then, is not much more effective than a shorter one due to the real intrinsic nature of the codes that run on the CPUs.

The hazards we have just described are actually very common (very rarely a program is a stream of totally independent instructions with no jumps) and so the full exploitation of superscalarity + superpipelining is never reached.

Basically, that's the reason why we do not have 100-stage deep pipelines.

And the reason why branching is a performance-killer, too.



As we have seen, modern processor may be able to “perform more than one operations at a time”, through super-pipelining operations.

As for what concerns the programmer’s perspective, codes must be written so to make the pipelines saturation as effective as possible.

```
for (int i = 0; i < N; i++)  
    S += a[i] * b[i];
```

This way S is both read and written (the S as input in iteration i depends on S as output of iteration $i-1$) and the FP pipeline is difficult to be exploited (iteration i must unavoidably wait for iteration $i-1$ to end, which takes ~3-6 cycles at least)



Make things easier for the compiler and the CPU

```
for (i = 0; i < N; i += 2) {  
    sum0 += a[i] * b[i];  
    sum1 += a[i+1] * b[i+1]; }
```

Unrolling make it possible for the CPU to saturate the pipelines.

v. A

```
for (i = 0; i < N; i += 2) {  
    double tmp0 = a[i] * b[i];  
    double tmp1 = a[i+1] * b[i+1];  
    sum0 += tmp0;  
    sum1 += tmp1; }
```

Separate load and multiply from addition

v. B



[SCO/examples_on_pipelines/reduction/](#)



Make things easier for the compiler and the CPU

```
for (i = 0; i < N; i += 4) {  
    sum0 += a[i] * b[i];  
    sum1 += a[i+1] * b[i+1];  
    sum2 += a[i+2] * b[i+2];  
    sum3 += a[i+3] * b[i+3]; }
```

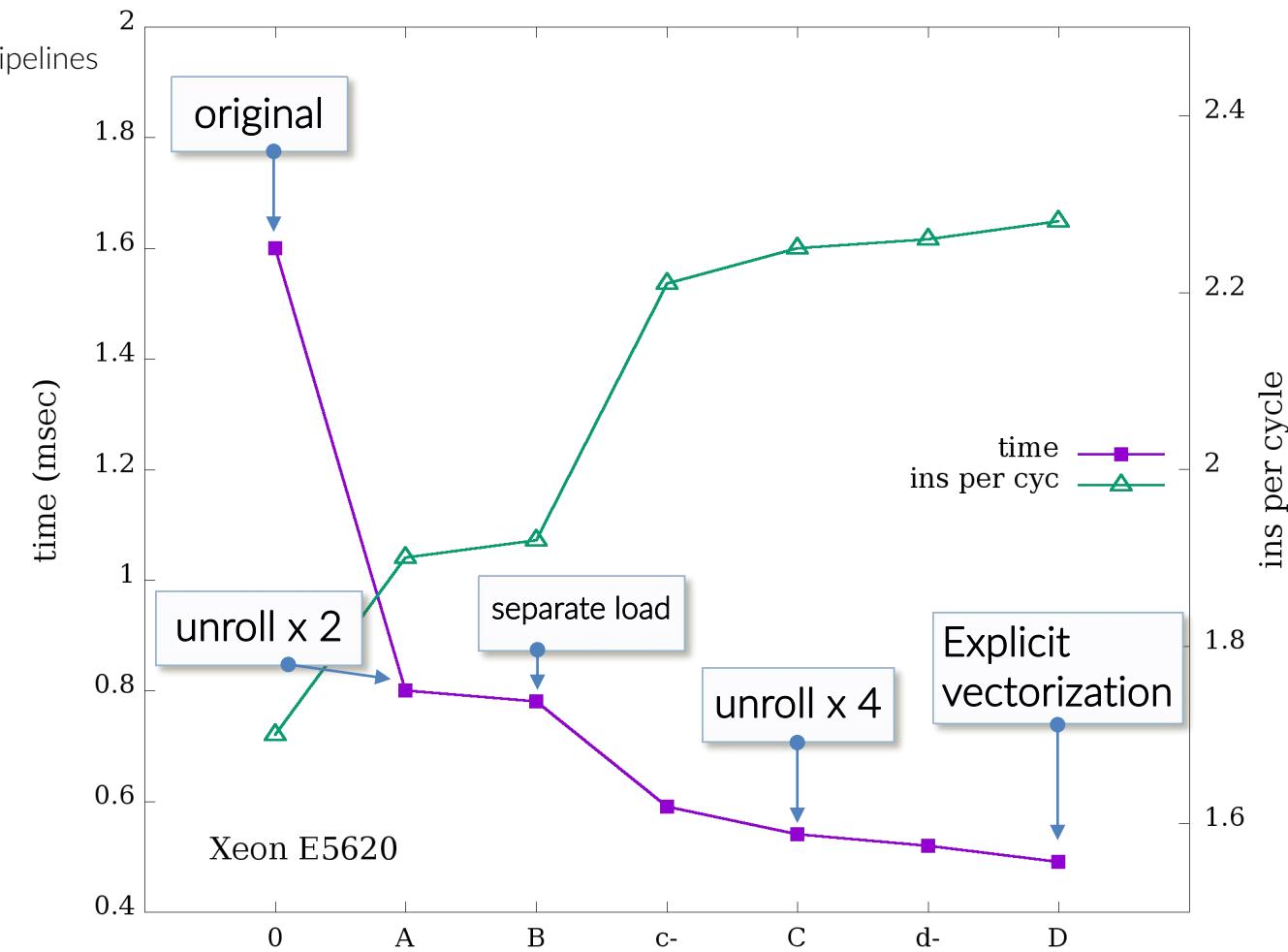
More unrolling may work even better

v. C

```
typedef double v4df __attribute__ ((vector_size (4*sizeof(double))));  
v4df array1, array2;  
v4df sum;  
for (i = 0; i < N/4; i++)  
    sum += array1[i] * array2[i];
```

Explicit vectorization

v. D





Hands-on

Let us now look in more detail to what happens at assembler level, so to understand in deeper details why some implementations are more effective than others.

We will use `-O0`, for the usual reason: with such simple kernels, compilers are very good (not all equally good..) in optimizing the code, and differences among improved version are more vagues.

*...that **does NOT** relieve you of knowing how to write not-that-bad code..*



v0

```
for (int i = 0; i < N; i++)  
    S += a[i] * b[i];
```



SCO/examples_on_pipelines
combine_2_arrays



Comparison btw 2 compilers

v0

```
.LB3365:  
##      for ( int i = 0; i < N; i++ )  
    cmpl    %ebx, %r14d  
    jge     .LB3366  
## lineno: 185  
.LN20:  
  
    movslq  %r14d, %rax  
    movq    -72(%rbp), %rcx  
    vmovsd  (%rcx,%rax,8), %xmm0  
  
    vmovsd  -32(%rbp), %xmm1  
  
    vfmaadd132sd    (%r12,%rax,8), %xmm1, %xmm0  
  
    vmovsd  %xmm0, -32(%rbp)  
  
    addl    $1, %r14d  
    jmp     .LB3365
```

```
.L8:  
# v0.c:185:    sum += array1[i] * array2[i];  
    mov    eax, DWORD PTR -136[rbp]          # tmp158, i  
    cdqe  
    lea    rdx, 0[0+rax*8]  
    mov    rax, QWORD PTR -96[rbp] # tmp159, array1  
    add    rax, rdx  
    vmovsd xmm1, QWORD PTR [rax]  
    mov    eax, DWORD PTR -136[rbp]  
    cdqe  
    lea    rdx, 0[0+rax*8] # _23,  
    mov    rax, QWORD PTR -88[rbp] # tmp161, array2  
    add    rax, rdx  
    vmovsd xmm0, QWORD PTR [rax]  
    vmulsd xmm0, xmm1, xmm0  
    vmovsd xmm1, QWORD PTR -104[rbp]        # tmp163, sum  
    vaddsd xmm0, xmm1, xmm0  
    vmovsd QWORD PTR -104[rbp], xmm0       # sum, tmp162  
    inc    DWORD PTR -136[rbp]          # i  
# v0.c:184:    for ( int i = 0; i < N; i++ )  
    mov    eax, DWORD PTR -136[rbp]          # tmp164, i  
    cmp    eax, DWORD PTR -148[rbp]        # tmp164, N  
    jl     .L8
```

PGI 2018.10

GCC 8.2.0



Comparison btw 2 compilers

```
.LB3365:  
##    for ( int i = 0; i < N; i++ )  
    cmpl    %ebx, %r14d  
    jge     .LB3366  
##    lineno: 185  
.LN20:  
  
    movsq  %r14d, %rax  
    novq   -72(%rbp), %rcx  
    vnmovsd (%rcx,%rax,8), %xmm0  
    vnmovsd -32(%rbp), %xmm1  
    vfmaddsd2sd (%r12,%rax,8), %xmm1, %xmm0  
    vnmovsd %xmm0, -32(%rbp)  
  
    addl    $1, %r14d  
    jnp     .LB3365
```

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% pgi/v0_papi_00 50000000  
generating 100000000 numbers..done  
sum is 1.24993e+07  
time is :0.176009 (min 0.175734, std dev 0.00054682, all 1.76643)  
transfer rate was 4.23 GB/sec ( 28.34% of theoretical max that is 15 GB/sec)  
IPC: 1  
[ time: 0.176sec - ins: 5e+08 ]
```

```
.LB:  
# v0.c:185:    sum += array1[i] * array2[i];  
    mov    eax, DWORD PTR -136[rbp]      # tmp158, i  
    cdqe  
    lea    rdx, [0+rax*8]  
    mov    rax, QWORD PTR -96[rbp] # tmp159, array1  
    add    rax, rdx  
    vnmovsd xmm1, QWORD PTR [rax]  
    mov    eax, DWORD PTR -136[rbp]  
    cdqe  
    lea    rdx, [0+rax*8] # _Z3sum  
    mov    rax, QWORD PTR -88[rbp] # tmp161, array2  
    add    rax, rdx  
    vnmovsd xmm0, QWORD PTR [rax]  
    vnmulsd xmm0, xmm1, xmm0  
    vnmovsd xmm1, QWORD PTR -104[rbp] # tmp163, sum  
    vaddsd xmm0, xmm1, xmm0  
    vnmovsd QWORD PTR -104[rbp], xmm0 # sum, tmp162  
    lnc    DWORD PTR -136[rbp], %i  
    # v0.c:184:    for ( int i = 0; i < N; i++ )  
    mov    eax, DWORD PTR -136[rbp]      # tmp164, i  
    cmp    eax, DWORD PTR -148[rbp]      # tmp164, N  
    jl     .LB
```

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v0_papi_00 50000000  
generating 100000000 numbers..done  
sum is 1.24993e+07  
time is :0.190236 (min 0.189567, std dev 0.000538453, all 1.90762)  
transfer rate was 3.92 GB/sec ( 26.22% of theoretical max that is 15 GB/sec)  
IPC: 1.9  
[ time: 0.1902sec - ins: 1.00158e+09 ]
```

Note: no optimization has been used in both cases



Comments on the previous slides

The PGI compiler has opted for using specialised fused multiply-addition instruction (`fmaadd`) that allows for a more compact code, but with an IPC of 1 (which basically means that the code occupies 1 pipeline at a time).

The gcc compiler, instead, opts for a redundant code (the 2 subsequent blocks `mov | cdqe | lea | mov | add | vmosd`) that can involve 2 pipelines, and separate multiplication and addition.

Both compilers could be induced to generate different and more efficient code playing with their options (the default behaviour can differ among different compilers).

The result is more or less equivalent from the point of view of the run-time due to the fact that the code generated by gcc is larger (more instructions) but it is dispatched to more pipelines (larger IPC).

NOTE: the IPC is a good metric, but it must be understood in a larger context. I.e. a larger IPC is good, but how good is the code depends on what instructions are being executed.



| Turning on the optimization

Let's have a preview of how the generated code changes..

```
.L8:  
# v0.c:185:    sum += array1[i] * array2[i];  
    mov    eax, DWORD PTR -136[rbp]      # tmp158, i  
    cdqe  
    lea    rdx, 0[0+rax*8]  
    mov    rax, QWORD PTR -96[rbp] # tmp159, array1  
    add    rax, rdx  
    vmovsd xmm1, QWORD PTR [rax]  
    mov    eax, DWORD PTR -136[rbp]  
    cdqe  
    lea    rdx, 0[0+rax*8] # _23,  
    mov    rax, QWORD PTR -88[rbp] # tmp161, array2  
    add    rax, rdx  
    vmovsd xmm0, QWORD PTR [rax]  
    vmulsd xmm0, xmm1, xmm0  
    vmovsd xmm1, QWORD PTR -104[rbp]      # tmp163,  
    vaddsd xmm0, xmm1, xmm0  
    vmovsd QWORD PTR -104[rbp], xmm0      # sum, tmp  
    inc    DWORD PTR -136[rbp]      # i  
# v0.c:184:        for ( int i = 0; i < N; i++ )  
    mov    eax, DWORD PTR -136[rbp]      # tmp164,  
    cmp    eax, DWORD PTR -148[rbp]      # tmp164,  
    jl     .L8
```

```
-00          for (int i = 0; i < N; i++)  
                      S += a[i] * b[i];  
  
.L8:  
# v0.c:55:    sum += array1[i] * array2[i];  
    vmovupd ymm5, YMMWORD PTR 0[r13+rax]  
    vmulpd  ymm0, ymm5, YMMWORD PTR [r15+rax]  
    add    rax, 32 # ivtmp.18,  
    vaddsd  xmm4, xmm0, xmm4  
    vunpckhpd   xmm1, xmm0, xmm0  
    vextractf128  xmm0, ymm0, 0x1  
    vaddsd  xmm1, xmm1, xmm4  
# v0.c:55:    sum += array1[i] * array2[i];  
    vaddsd  xmm1, xmm0, xmm1  
    vunpckhpd   xmm0, xmm0, xmm0  
    vaddsd  xmm4, xmm1, xmm0  
    cmp    rax, r12  
    jne    .L8    #,
```



Turning on the optimization

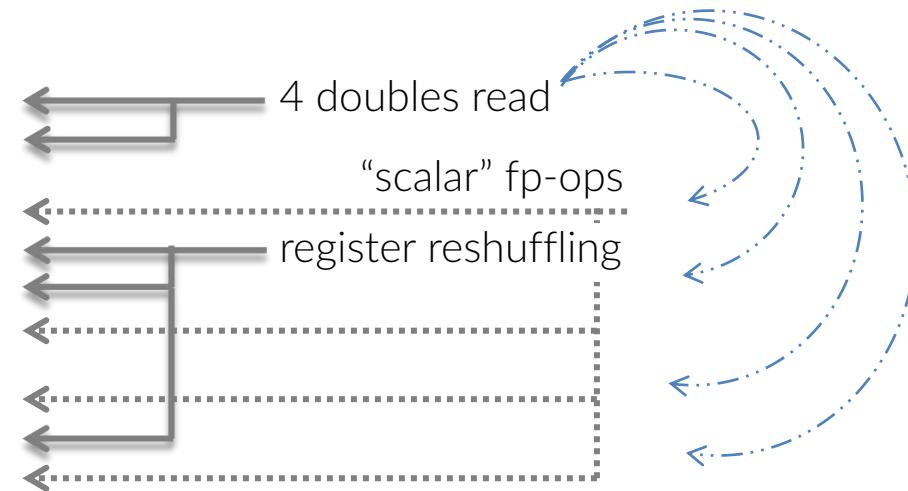
.L8:

```
# v0.c:55:    sum += array1[i] * array2[i];
vmovupd    ymm5, YMMWORD PTR 0[r13+rax]
vmulpd    ymm0, ymm5, YMMWORD PTR [r15+rax]
add        rax, 32 # ivtmp.18,
vaddsd    xmm4, xmm0, xmm4
vunpckhpd  xmm1, xmm0, xmm0
vextractf128  xmm0, ymm0, 0x1
vaddsd    xmm1, xmm1, xmm4
# v0.c:55:    sum += array1[i] * array2[i];
vaddsd    xmm1, xmm0, xmm1
vunpckhpd  xmm0, xmm0, xmm0
vaddsd    xmm4, xmm1, xmm0
cmp        rax, r12
jne        .L8      #,
```

v0

```
for (int i = 0; i < N; i++)
  s += a[i] * b[i];
```

gcc 8.2 on SkyLake
-O3 -march=native



HINT FOR IMPROVEMENT :

data are fetched with vector instructions,
then processed in a mixed way



Comments on the previous slides

Looking at the assembler generated by the compiler may be useful to understand where to direct optimization efforts.

In the previous slide, the compiler (with `-O3 -march=native`) chooses to fetch data from memory with a vector instruction, loading 4 doubles at a time (note that it uses the instruction for *unaligned memory*^(*): `vmovupd`).

But however can not really exploit the ILP (Instruction-Level parallelism) due to the data dependency intrinsic in how we wrote the loop.

That's why the best first step is to exhibit the possible parallelism, for instance either by unrolling or by a different accumulation (v1 and v3 in the following slides).

(*)you should remember what alignment is from the lecture about memory allocation



V* profile - 00



time is 0.217358 (min 0.216092, std dev 0.000667496)			
transfer rate was 3.43 GB/sec (22.95% of theoretical max that is 15 GB/sec)			
503,469,659	cycles..	#	0.37 insn per cycle (+- 12.99%)
185,027,735	instructions..		(+- 17.44%)
time is 0.139794 (min 0.139124, std dev 0.000733397)			
transfer rate was 5.33 GB/sec (35.68% of theoretical max that is 15 GB/sec)			
394,225,210	cycles..	#	0.52 insn per cycle (+- 9.57%)
204,046,712	instructions..		(+- 27.62%)
time is 0.119491 (min 0.117614, std dev 0.00116417)			
transfer rate was 6.24 GB/sec (41.75% of theoretical max that is 15 GB/sec)			
1,183,361,839	cycles..	#	0.70 insn per cycle (+- 6.59%)
824,904,000	instructions..		(+- 8.66%)
time is 0.0805418 (min 0.0798115, std dev 0.00128884)			
transfer rate was 9.25 GB/sec (61.93% of theoretical max that is 15 GB/sec)			
288,211,800	cycles..	#	0.32 insn per cycle (+- 1.80%)
92,540,296	instructions..		(+- 3.80%)



V* profile - O3

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v0_papi_03n 50000000
generating 100000000 numbers..done
sum is 1.24993e+07
time is :0.104058 (min 0.103508, std dev 0.000375562, all 1.04728)
transfer rate was 7.16 GB/sec ( 47.94% of theoretical max that is 15 GB/sec)
    IPC: 0.65
    [ time: 0.1041sec - ins: 1.50004e+08 ]
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v1_papi_03n 50000000
generating 100000000 numbers..done ( 1.27)
pipeline demonstrator, step 1:
- unroll 2 times

sum is 1.24993e+07
time is :0.0755591 (min 0.0750261, std dev 0.000291917, all 0.762576)
transfer rate was 9.86 GB/sec ( 66.02% of theoretical max that is 15 GB/sec)
    IPC: 1.2
    [ time: 0.07556sec - ins: 1.93753e+08 ]
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v3_papi_03n 50000000
generating 100000000 numbers..done (in 1.08sec)
pipeline demonstrator, step 3:

sum is 1.24993e+07
time is :0.0545231 (min 0.0544507, std dev 8.46002e-05, all 0.545244)
transfer rate was 13.7 GB/sec ( 91.49% of theoretical max that is 15 GB/sec)
    IPC: 1.1
    [ time: 0.0545sec - ins: 1.6e+08 ]%
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v3c_papi_03n 50000000
generating 100000000 numbers..done (in 1.27sec)
pipeline demonstrator, step 3:
- unroll 2 times +
- separate mul and sum
- separate accumulations

sum is 1.24993e+07
time is :0.0527944 (min 0.0526688, std dev 0.000107074, all 0.53314)
transfer rate was 14.1 GB/sec ( 94.49% of theoretical max that is 15 GB/sec)
    IPC: 1.2
    [ time: 0.0528sec - ins: 1.75e+08 ]
```



| V* profile - O3 + vectorisation

There's a lot of improvement in such a simple kernel, but why IPC even decreased?

Hint: the code becomes memory-bound (look at the memory transfer rate).

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v6_papi_03n 50000000
generating 100000000 numbers..done (in 1.27sec)
sum is 1.24993e+07
time is: 0.0647406 (min 0.0642672, std dev 0.00017916, all 0.654759)
transfer rate was 11.5 GB/sec ( 77.05% of theoretical max that is 15 GB/sec)
    IPC: 0.8
        [ time: 0.06475sec - ins: 1.00003e+08 ]
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v6_intrinsics_papi_03n 50000000
generating 100000000 numbers..done (in 1.1sec)
sum is 1.24993e+07
time is: 0.0504149 (min 0.0468492, std dev 0.00132376, all 0.509429)
transfer rate was 14.8 GB/sec ( 98.95% of theoretical max that is 15 GB/sec)
    IPC: 0.67
        [ time: 0.05042sec - ins: 7.50003e+07 ]
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v8_papi_03n 50000000
generating 100000000 numbers..done (in 1.11sec)
sum is 1.24993e+07
time is: 0.0499751 (min 0.0466076, std dev 0.00124928, all 0.499767)
transfer rate was 14.9 GB/sec ( 99.82% of theoretical max that is 15 GB/sec)
    IPC: 0.56
        [ time: 0.04998sec - ins: 6.25002e+07 ]
```

Comparison: v0 - v1

v0

```
for ( int i = 0; i < N; i++ )
    sum += array1[i] * array2[i];
```

v1

```
for ( int i = 0; i < N-1; i+=2 )
    // simply unrolling 2 times, exposes the fact that at least
    // 2 elements of the array can be processed independently
{
    sum1 += array1[ i ] * array2[ i ];
    sum2 += array1[ i+1 ] * array2[ i+1 ];
}
if ( N % 2 )
    sum = array1[ N-1 ] * array2[ N-1 ];
```



Comparison:

v0

```
.L8:  
# v0.c:185:    sum += array1[i] * array2[i];  
    mov    eax, DWORD PTR -136[rbp]      # tmp158, i  
    cdqe  
    lea    rdx, 0[0+rax*8]  
    mov    rax, QWORD PTR -96[rbp] # tmp159, array1  
    add    rax, rdx  
    vmovsd xmm1, QWORD PTR [rax]  
    mov    eax, DWORD PTR -136[rbp]  
    cdqe  
    lea    rdx, 0[0+rax*8] # 23,  
    mov    rax, QWORD PTR -88[rbp] # tmp161, array2  
    add    rax, rdx  
    vmovsd xmm0, QWORD PTR [rax]  
    vmulsd xmm0, xmm1, xmm0  
    vmovsd xmm1, QWORD PTR -104[rbp]      # tmp163, sum  
    vaddsd xmm0, xmm1, xmm0  
    vmovsd QWORD PTR -104[rbp], xmm0      # sum, tmp162  
    inc    DWORD PTR -136[rbp]      # i  
# v0.c:184:    for ( int i = 0; i < N; i++ )  
    mov    eax, DWORD PTR -136[rbp]      # tmp164, i  
    cmp    eax, DWORD PTR -148[rbp]      # tmp164, N  
    jl    .L8
```

gcc 8.2.0, no optimization

v1

```
.L10:  
# v1_aligned.c:91:    sum1 += array1[ i ] * array2[ i ];  
    movl   -148(%rbp), %eax      # i, tmp186  
    cltq  
    leaq   0(%rax,8), %rdx  
    movq   -96(%rbp), %rax # array1, tmp187  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm1  
    movl   -148(%rbp), %eax      # i, tmp188  
    cltq  
    leaq   0(%rax,8), %rdx  
    movq   -88(%rbp), %rax # array2, tmp189  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm0  
    vmulsd %xmm0, %xmm1, %xmm0  
    vmovsd -112(%rbp), %xmm1      # sum1, tmp191  
    vaddsd %xmm0, %xmm1, %xmm0  
    vmovsd %xmm0, -112(%rbp)      # tmp190, sum1  
    movl   -148(%rbp), %eax      # i, tmp192  
    cltq  
    incq   %rax  
    leaq   0(%rax,8), %rdx  
    movq   -96(%rbp), %rax # array1, tmp193  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm1  
    movl   -148(%rbp), %eax      # i, tmp194  
    cltq  
    incq   %rax  
    leaq   0(%rax,8), %rdx  
    movq   -88(%rbp), %rax # array2, tmp195  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm0  
    vmulsd %xmm0, %xmm1, %xmm0  
    vmovsd -104(%rbp), %xmm1      # sum2, tmp197  
    vaddsd %xmm0, %xmm1, %xmm0  
    vmovsd %xmm0, -104(%rbp)  
    addl   $2, -148(%rbp) #, i  
.L9:  
# v1_aligned.c:87:    for ( int i = 0; i < N-1; i+=2 )  
    movl   -164(%rbp), %eax      # N, tmp198  
    decl   %eax      # _42  
    cmpl   %eax, -148(%rbp)      # i  
    jl    .L10
```



Comparison:

v0

```
.L8:  
# v0.c:185:    sum += array1[i] * array2[i];  
    mov    eax, DWORD PTR -136[rbp]      # tmp158, i  
    cdqe  
    lea    rdx, [0+rax*8]  
    mov    rax, QWORD PTR -96[rbp] # tmp159, array1  
    add    rax, rdx  
    vmovsd xmm1, QWORD PTR [rax]  
    mov    eax, DWORD PTR -136[rbp]  
    cdqe  
    lea    rdx, [0+rax*8] # _23,  
    mov    rax, QWORD PTR -88[rbp] # tmp161, array2  
    add    rax, rdx  
    vmovsd xmm0, QWORD PTR [rax]  
    vmulsd xmm0, xmm1, xmm0  
    vmovsd xmm1, QWORD PTR -104[rbp]      # tmp163, sum  
    vaddsd xmm0, xmm1, xmm0  
    vmovsd QWORD PTR -104[rbp], xmm0      # sum, tmp162  
    inc    DWORD PTR -136[rbp]      # i  
    .L8  
# v0.c:184:  
    for ( int i = 0; i < N; i++ )  
        mov    eax, DWORD PTR -136[rbp]      # tmp164, i  
        cmp    eax, DWORD PTR -148[rbp]      # tmp164, N  
        jl     .L8
```

v1

```
.L10:  
# v1_aligned.c:91:    sum1 += array1[ i ] * array2[ i ];  
    movl   -148(%rbp), %eax      # i, tmp186  
    cltq  
    leaq   0(%rax,8), %rdx  
    movq   -96(%rbp), %rax # array1, tmp187  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm1  
    movl   -148(%rbp), %eax      # i, tmp188  
    cltq  
    leaq   0(%rax,8), %rdx  
    movq   -88(%rbp), %rax # array2, tmp189  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm0  
    vmulsd %xmm0, %xmm1, %xmm0  
    vmovsd -112(%rbp), %xmm1      # sum1, tmp191  
    vaddsd %xmm0, %xmm1, %xmm0  
    vmovsd %xmm0, -112(%rbp)      # tmp190, sum1  
    movl   -148(%rbp), %eax      # i, tmp192  
    cltq  
    incq   %rax  
    leaq   0(%rax,8), %rdx  
    movq   -96(%rbp), %rax # array1, tmp193  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm1  
    movl   -148(%rbp), %eax      # i, tmp194  
    cltq  
    incq   %rax  
    leaq   0(%rax,8), %rdx  
    movq   -88(%rbp), %rax # array2, tmp195  
    addq   %rdx, %rax  
    vmovsd (%rax), %xmm0  
    vmulsd %xmm0, %xmm1, %xmm0  
    vmovsd -104(%rbp), %xmm1      # sum2, tmp197  
    vaddsd %xmm0, %xmm1, %xmm0  
    vmovsd %xmm0, -104(%rbp)  
    addl   $2, -148(%rbp) #, i  
.L9:  
# v1_aligned.c:87:    for ( int i = 0; i < N-1; i+=2 )  
    movl   -164(%rbp), %eax      # N, tmp198  
    decl   %eax      # _42  
    cmpl   %eax, -148(%rbp)      # i  
.L10
```

The v1 version looks twice as longer (i.e.: more instructions to be executed), actually it really looks like the same code was copied & pasted below the original segment.

How does it come that the result is a faster execution?



Comparison: v0 – v1

The point is clearer considering the output of the PAPI instrumented code, that returns the IPC. Clearly, the 2fold unroll makes the CPU able to better exploit more than 1 logical units at a time.

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v0_papi_00 50000000
generating 100000000 numbers..done
sum is 1.24993e+07
time is :0.191208 (min 0.190616, std dev 0.00053432, all 1.91787)
transfer rate was 3.9 GB/sec ( 26.09% of theoretical max that is 15 GB/sec)
    IPC: 1.9
        [ time: 0.1912sec - ins: 1.00158e+09 ]
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v1_papi_00 50000000
generating 100000000 numbers..done ( 0.965)
pipeline demonstrator, step 1:
- unroll 2 times

sum is 1.24993e+07
time is :0.125749 (min 0.12396, std dev 0.00142263, all 1.26349)
transfer rate was 5.92 GB/sec ( 39.67% of theoretical max that is 15 GB/sec)
    IPC: 2.8
        [ time: 0.1258sec - ins: 9.76578e+08 ]
```



Refining v1

v1

```
for ( int i = 0; i < N-1; i+=2 )
    // simply unrolling 2 times, exposes the fact that at least
    // 2 elements of the array can be processed independently
{
    sum1 += array1[ i ] * array2[ i ];
    sum2 += array1[ i+1 ] * array2[ i+1 ];
}
if ( N % 2 )
    sum = array1[ N-1 ] * array2[ N-1 ];
```

v1b

```
double register sum0 = 0;
double register sum1 = 0;

double register * restrict a1 = __builtin_assume_aligned(array1, 32);
double register * restrict a2 = __builtin_assume_aligned(array2, 32);

tstart = CPU_TIME;
#pragma ivdep
for( int i = 0 ; i < N-1; i+=2 )
{
    sum0 += *(a1++) * *(a2++);
    sum1 += *(a1++) * *(a2++);
}
if( N%2 )
    sum = *a1 * *a2;
```

| Refining v1

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v1_papi_00 50000000
generating 100000000 numbers..done ( 0.973)
pipeline demonstrator, step 1:
- unroll 2 times

sum is 1.24993e+07
time is 0.125593 (min 0.125287, std dev 0.000476174, all 1.26231)
transfer rate was 5.93 GB/sec ( 39.72% of theoretical max that is 15 GB/sec)
    IPC: 2.8
    [ time: 0.1256sec   ins: 9.76578e+08 ]
```

```
luca@GGG:~/code/HPC_lectures/pipeline/2018% ./v1b_papi_00 50000000
generating 100000000 numbers.. done (in 0.973sec)
pipeline demonstrator, step 1b:
- unroll 2 times +
- align memory +
- minimize ptr arithmetic

sum is 1.24993e+07
time is 0.0977905 (min 0.0972945, std dev 0.000712555, all 0.977921)
transfer rate was 7.62 GB/sec ( 51.01% of theoretical max that is 15 GB/sec)
    IPC: 2.1
    [ time: 0.0978sec   ins: 5.76578e+08 ]
```



Refining: v3

Let's go further in trying to make it clear for the CPU about the possible ILP

```
#pragma ivdep
for ( int i = 0; i < N_4; i+=4 )
{
    sum += array1[i] * array2[i] +
        array1[i+1] * array2[i+1] +
        array1[i+2] * array2[i+2] +
        array1[i+3] * array2[i+3];
}

for ( int i = N_4; i < N; i++ )
    sum += array1[i] * array2[i];
```

v3

prefetching

#pragma

```
double register a;
double register b;
a = array1[0] * array2[0];
#pragma ivdep
for ( int i = 0; i < N_4; i+=4 )
{
    DO_NOT_OPTIMIZE;
    b = array1[i+4] * array2[i+4];
    DO_NOT_OPTIMIZE;
    sum += a +
        array1[i+1] * array2[i+1] +
        array1[i+2] * array2[i+2] +
        array1[i+3] * array2[i+3];
    a = b;
}

for ( int i = N_4; i < N; i++ )
    sum += array1[i] * array2[i];
```

v3b



Refining: vectorisation



Advanced

With the following statement you can define a vector type in gcc

```
typedef double v4df __attribute__ ((vector_size (4*sizeof(double))));  
typedef union {  
    v4df V;  
    double v[4];  
}v4df_u;
```

- By creating this union, you can access the single doubles within the vector
- This is the actual vector, made up by 4 doubles. You can not access the single elements.



Refining: vectorisation



Advanced

What is this
strange stuff
about ?

The loop is re-written
here in its simplest
form.

Now, however, the
variables are vectors.

```
#ifdef __GNUC_SOURCE
    v4df sum_ = {0, 0, 0, 0};
#else
    v4df sum_ = {0};
#endif
    v4df register mytmp;
    v4df register tmp = *((v4df*)&array1[0]) * *((v4df*)&array2[0]);

    int N_4 = N/4;
    int N_4 = N_4*4;
    tstart = CPU_TIME;
#pragma ivdep
    for( int i = 1; i <= N_4; i++)
    {
        _DO_NOT_OPTIMIZE_BEGIN;
        mytmp = *((v4df*)array1 + i) * *((v4df*)array2 + i);
        _DO_NOT_OPTIMIZE_END;
        sum_ += tmp;
        tmp = mytmp;
    }

    for ( int i = N_4; i < N; i++ )
        sum += array1[ i ] * array2[ i ];
}
```



Refining: vectorisation with intrinsics



Advanced

With the following statements you prepare the ground to use intrinsics, both types and functions.

Vector type
with 256bits
(AVX)

You can
initialize
it as an
array

The FMA in
vector AVX
flavour

Why am I
defining those
macros ?

```
#elif defined ( __AVX__ ) || defined ( __AVX2__ )  
  
#define V_DSIZE 4  
typedef __m256d vd;  
vd _dzero_ = {0, 0, 0, 0};  
#define MUL_ADD( A1, A2, R ) _mm256_fmad_pd( (A1), (A2), (R) )
```

Intrinsics are an API, exposed by the compiler^(*), that provide direct access to vector instructions and types.

(*) they are no compiler-dependent: look at <https://software.intel.com/sites/landingpage/IntrinsicsGuide/> for Intel's intrinsics



Refining: vectorisation with intrinsics



As before, the loop is re-written here in its simplest form.

It also looks very similar to the previous one.

The variables are still vectors.

Note the usage of macros: the code is still valid both for AVX512 or SSE

```
vd sum__attribute__ ((aligned(64)));
sum_ = _dzero_;

vd * restrict A1 __attribute__ ((aligned(64)));
vd * restrict A2 __attribute__ ((aligned(64)));
A1 = (vd*)array1 ;
A2 = (vd*)array2 ;

int N__ = N / V_DSIZE;
int N_ = N__ * V_DSIZE;

tstart = CPU_TIME;

#pragma ivdep
for( int i = 0; i < N__; i++)
    sum_ = MUL_ADD( A1[i], A2[i], sum_ );

for ( int i = N__; i < N; i++)
    sum += array1[ i ] * array2[ i ];
```





Hands-on / 2

Let's consider the polynomial evaluation:

$$a_0 + a_1 \times x + a_2 \times x^2 + \cdots + a_n \times x^n$$

Naïve implementation

```
double res = a[0];
double x_pwr = x;
for ( int i = 1; i <= n; i++ )
{
    res += a[i] * x_pwr;
    x_pwr *= x;
}
```

Horner's implementation

```
double res = a[n];
for ( int i = n-1; i >= 0; i-- )
    res += a[i] + res * x;
```



SCO/examples_on_pipelines
polynomial_evaluation/

exercise: although Horner's implementation requires less FP operations, on a modern CPU the naïve implementation outperforms it. Why is it so ?

that's all, have fun

"So long
and thanks
for all the fish"