Advanced Systems Lab

Spring 2025

Lecture: Intel Core Family, microarchitecture, execution units, Apple M

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Organization

Research project: Deadline *March 7th*

Finding team: fastcode-forum@lists.inf.ethz.ch

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Today

Architecture/Microarchitecture: *What is the difference?*

In detail: Intel Skylake

Derivation of runtime bounds

Execution units, latency and throughput

Brief: Apple M series

Definitions

Architecture (also instruction set architecture = ISA): The parts of a processor design that one needs to understand to write assembly code

Examples: instruction set specification, registers

Counterexamples: cache sizes and core frequency

Example ISAs

- *x86*
- *ARM*
- *MIPS*
- *POWER*
- *SPARC*

Some assembly code

```
ipf:
    xorps   %xmm1, %xmm1
    xorl    %ecx, %ecx
    jmp     .L8
.L10:
    movslq  %ecx,%rax
    incl    %ecx
    movss (%rsi,%rax,4), %xmm0
    mulss (%rdi,%rax,4), %xmm0
    addss   %xmm0, %xmm1
.L8:
    cmpl    %edx, %ecx
    jl      .L10
    movaps  %xmm1, %xmm0
    ret
```

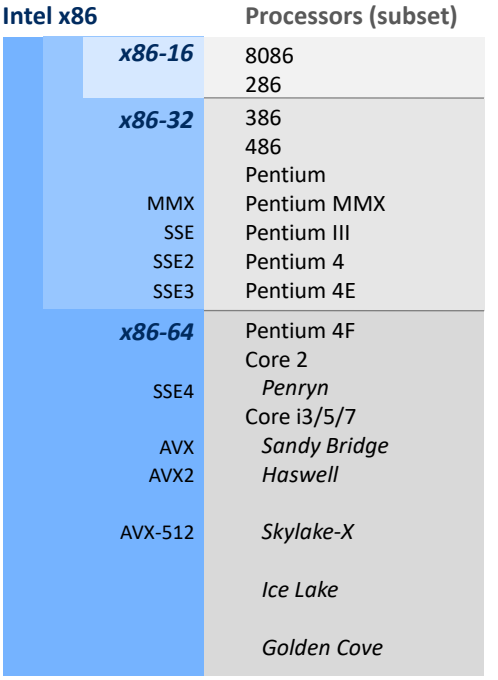
MMX:
Multimedia extension

SSE:
Streaming SIMD extension

AVX:
Advanced vector extensions

Backward compatible:
Old binary code (≥ 8086) runs on newer processors.

New code to run on old processors?
Depends on compiler flags.



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SIMD (Single Instruction Multiple Data) Vector Extensions

What is it?

- *Extension of the ISA. Data types and instructions for the parallel computation on short (length 2–8) vectors of integers or floats*

4-way

- *Names: MMX, SSE, SSE2, …, AVX, …*

We will have an extra lecture on vector instructions

- *What are the challenges?*
- *How to use them efficiently*

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FMA = Fused Multiply-Add

$x = x + y \cdot z$

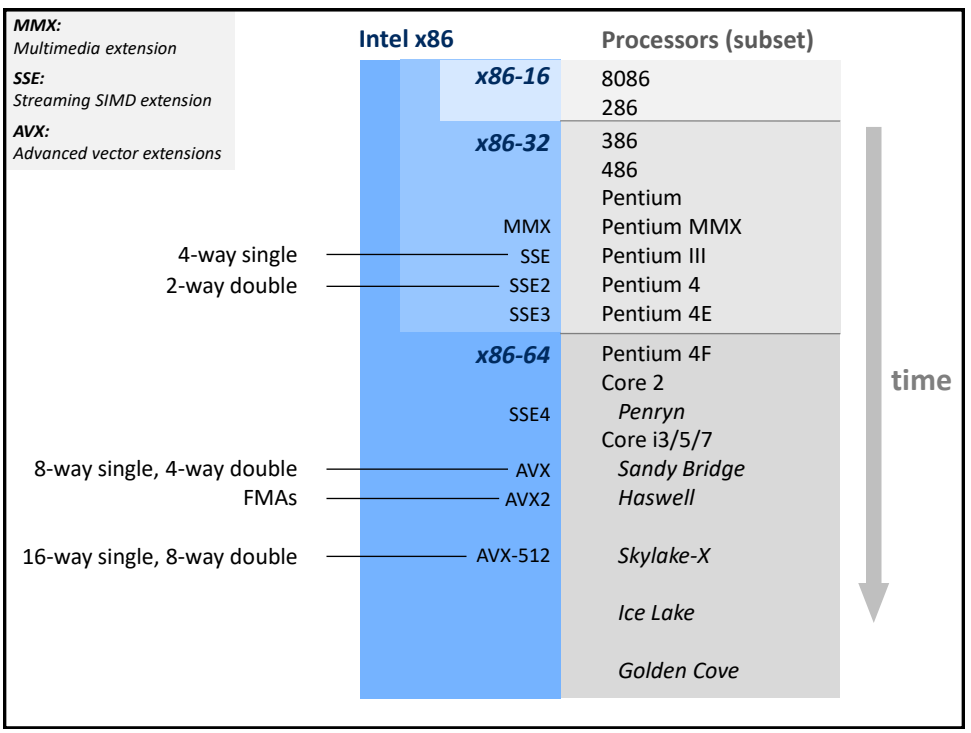
Done as one operation, i.e., involves only one rounding step

Better accuracy than sequence of mult and add

Natural pattern in many algorithms

```
/* matrix multiplication; A, B, C are n x n matrices of doubles */
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    for (k = 0; k < n; k++)
      C[i*n+j] += A[i*n+k]*B[k*n+j];
```

Exists only recently in Intel processors



Definitions

Microarchitecture: Implementation of the architecture

Examples: Caches, cache structure, CPU frequency, details of the virtual memory system

Examples

- *Intel processors (Wikipedia)*
- *AMD processors (Wikipedia)*

Intel's Tick-Tock Model

Core family

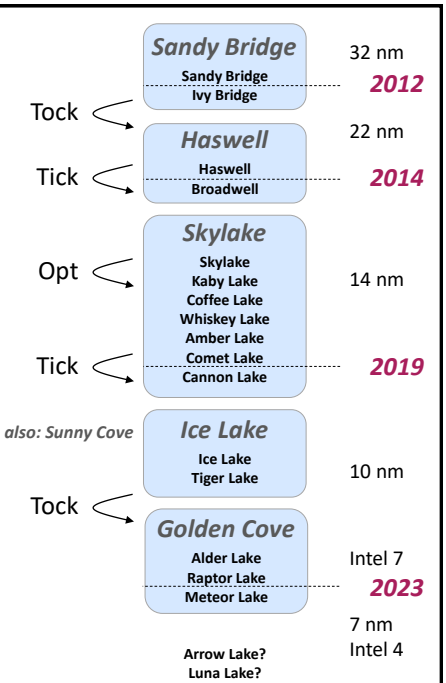
Tock: New microarchitecture
Tick: Shrink of process technology

2016: Tick-tock model got discontinued

Now:
process (tick)
architecture (tock)
optimization (opt)

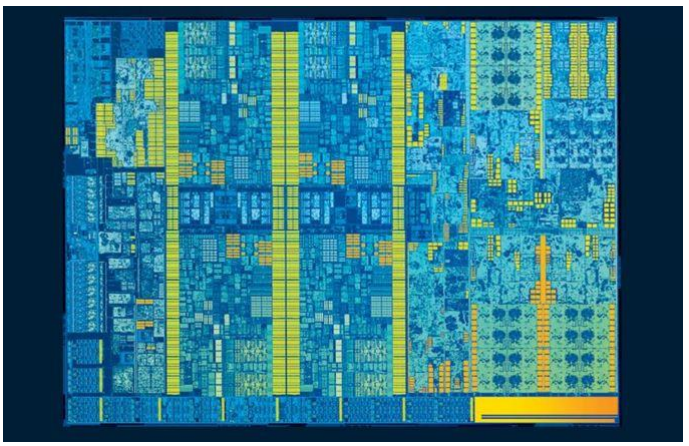
On the right:

- *Extracted from wiki link above*
- *Gray: main architectures*
- *Small/black: name of step*
- *Focus on desktop/mobile*
- *Intel 7 is 10 nm but claims density comparable to 7 nm*



Pictures: Intel

Intel Processors: Example Skylake



http://www.anandtech.com

Detailed information about Intel processors

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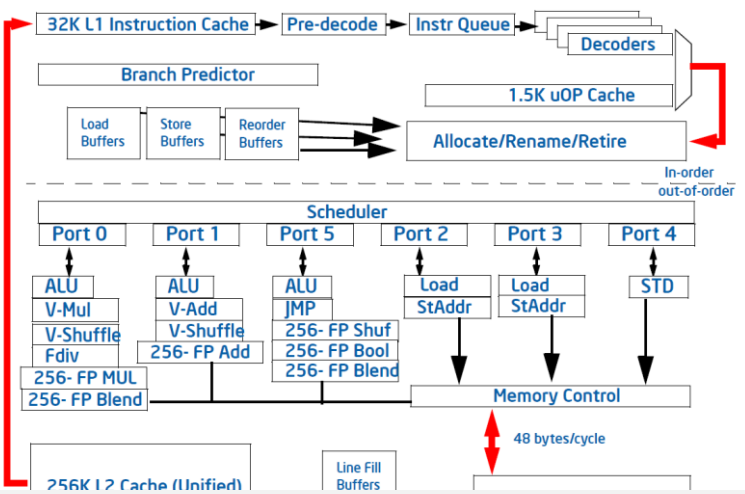
Microarchitecture: The View of the Computer Architect



we take the software developer's view …

Source: *Intel Architectures Optimization Reference Manual*

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Distribute microarchitecture abstraction

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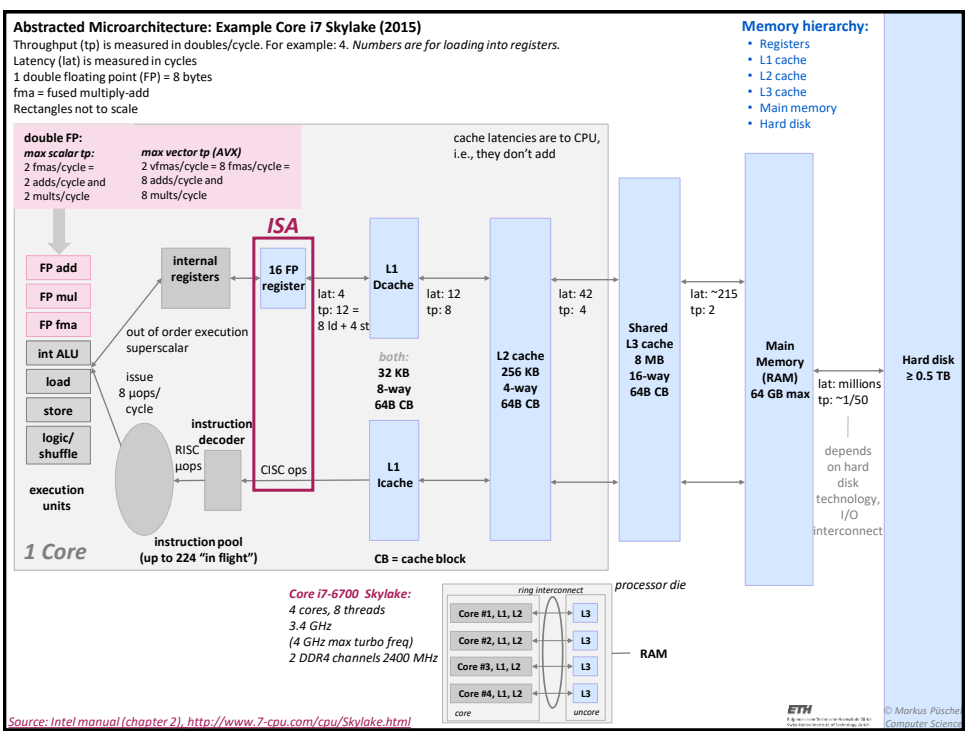

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Runtime Lower Bounds (Cycles) on Skylake

```
/* x, y are vectors of doubles of length n, alpha is a double  */
for (i = 0; i < n; i++)
  x[i] = x[i] + alpha*y[i];
```

		maximal achievable percentage of (vector) peak performance
Number flops?	**2n**	
Runtime bound no vector ops:	**n/2**	
Runtime bound vector ops:	**n/8**	
consider reads only: Runtime bound data in L1:	**n/4**	**50**
Runtime bound data in L2:	**n/4**	**50**
Runtime bound data in L3:	**n/2**	**25**
Runtime bound data in main memory:	**n**	**12.5**

Runtime dominated by data movement: Memory-bound

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Runtime Lower Bounds (Cycles) on Skylake

```
/* matrix multiplication; A, B, C are n x n matrices of doubles */
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    for (k = 0; k < n; k++)
      C[i*n+j] += A[i*n+k]*B[k*n+j];
```

Number flops?	**$2n^3$**
Runtime bound no vector ops:	**$n^3/2$**
Runtime bound vector ops:	**$n^3/8$**
consider reads only: Runtime bound data in L1:	**$3n^2/8$**
…	
Runtime bound data in main memory:	**$3n^2/2$**

Runtime dominated by data operations (except very small n): Compute-bound

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Operational Intensity

Definition: Given a program P, assume cold (empty) cache

$$\textit{Operational intensity: } I(n) = \frac{W(n)}{Q(n)}$$

W(n): #flops (input size n)

Q(n): #bytes transferred cache ↔ memory (for input size n)

Lower bounds for Q(n) yield upper bounds for I(n)

Sometimes we only consider reads from memory:
$Q_{read}(n) \le Q(n)$ and thus $I_{read}(n) \ge I(n)$

Operational Intensity (Cold Cache)

```
/* x, y are vectors of doubles of length n, alpha is a double  */
for (i = 0; i < n; i++)
  x[i] = x[i] + alpha*y[i];
```

Operational intensity (reads only):

- *Flops: W(n)* **= 2n**
- *Memory transfers (doubles):* **≥ 2n (just from the reads)**
- *Reads (bytes): $Q_{read}(n)$* **≥ 16n**
- *Operational intensity: $I(n) \le I_{read}(n)$* **$= W(n)/Q_{read}(n) \le 1/8$**

Operational Intensity (Cold Cache)

```
/* matrix multiplication; A, B, C are n x n matrices of doubles */
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    for (k = 0; k < n; k++)
      C[i*n+j] += A[i*n+k]*B[k*n+j];
```

Operational intensity (reads only):

- *Flops: W(n)* **$= 2n^3$**
- *Memory transfers (doubles):* **$\geq 3n^2$ (just from the reads)**
- *Reads (bytes): $Q_{read}(n)$* **$\geq 24n^2$**
- *Operational intensity: $I(n) \leq I_{read}(n)$* **$= W(n)/Q_{read}(n) \leq n/12$**

Compute/Memory Bound

A function/piece of code is:

- ***Compute bound*** *if it has high operational intensity*
- ***Memory bound*** *if it has low operational intensity*

A more exact definition depends on the given platform

More details later: Roofline model

Superscalar Processor

Definition: A superscalar processor can issue and execute *multiple instructions in one cycle*. The instructions are retrieved from a sequential instruction stream and are usually scheduled dynamically.

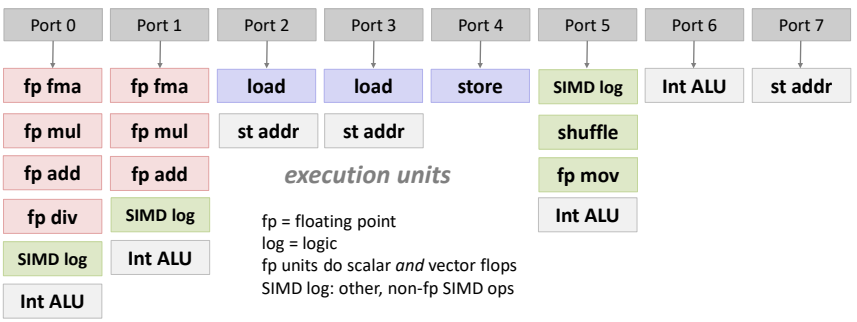
Benefit: Superscalar processors can take advantage of *instruction level parallelism (ILP)* that many programs have

Most CPUs since about 1998 are superscalar

Intel: since Pentium Pro

Simple embedded processors are usually not superscalar

Execution Units and Ports (Skylake)



Execution Unit (fp)	Latency [cycles]	Throughput [ops/cycle]	1/Throughput [cycles/issue]
fma	4	2	0.5
mul	4	2	0.5
add	4	2	0.5
div (scalar)	14	1/4	4
div (4-way)	14	1/8	8

- Every port can issue one instruction/cycle
- ***Intel calls 1/throughput the throughput!***
- Same exec units for scalar and vector flops
- Same latency/throughput for scalar (one double) and AVX vector (four doubles) flops, except for div
- Check Agner Fog's tables (pp. 278ff)

Table 2.11 & 2.12 in Intel® 64 and IA-32 Architectures Optimization Reference Manual: Volume 1
Intel Throughput and Latency (Table 7-8. 256-bit Intel® AVX Instructions)

Notes on Previous Slide

The availability of more than one port makes the processor superscalar

Execution units behind different ports can start an operation in the same cycle (superscalar)

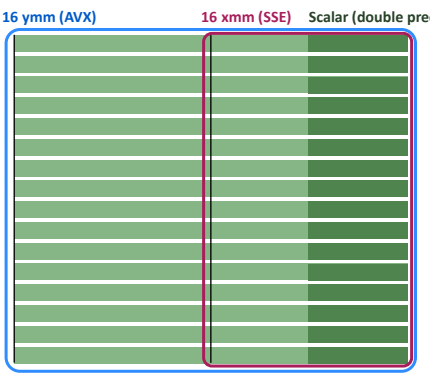
Execution units behind the same port cannot start an operation in the same cycle

Adds, Mults and FMAs have throughput of 2 because they have 2 units behind 2 different ports. Each of these units has a throughput of 1

An execution unit with throughput 1 is called fully pipelined

By default the compiler does not use FMAs for single adds or mults

Floating Point Registers



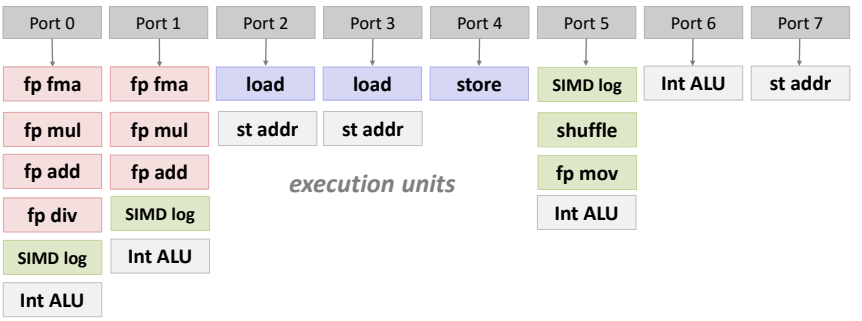
Each register:
256 bits =
4 doubles =
8 singles

FP add in assembly:
addsd (scalar double)
addpd (SSE vector)
vaddpd (AVX vector)

Same 16 registers for scalar FP, SSE and AVX

Scalar (non-vector) double precision FP code uses the bottom quarter

Explains why throughput and latency is usually the same for vector and scalar operations



How many cycles are at least required (no vector ops)?

A function with n adds and n mults in the C code	*n/2*
A function with n add and n mult instructions in the assembly code	*n*
A function with n adds in the C code	*n/2*
A function with n add instructions in the assembly code	*n/2*
A function with n adds and n/2 mults in the C code	*n/2*

Unless specified otherwise, operations are always floating point operations I this course

Comments on Intel Skylake Lake µarch

Peak performance: 16 double precision flops/cycle (only reached if SIMD FMA)

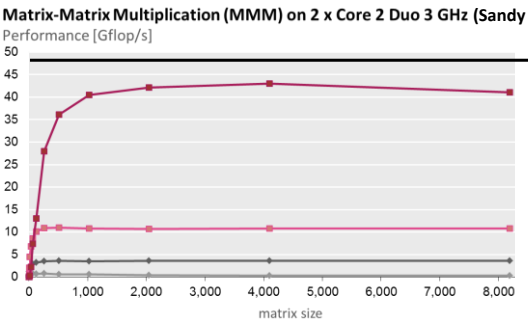
- *Peak perf. mults: 2 mults/cycle (scalar 2 flops/cycle, SIMD AVX 8 flops/cycle)*
- *Peak perf. adds: 2 adds/cycle (scalar 2 flop/cycle, SIMD AVX 8 flops/cycle)*

L1 bandwidth: two 32-byte loads *and* one 32-byte store per cycle

Shared L3 cache organized as multiple cache slices for better scalability with number of cores, thus access time is non-uniform

Shared L3 cache in a different clock domain (uncore)

Example: Peak Performance



Peak performance of this computer:
4 cores x
2-way SSE x
1 add and 1 mult/cycle
= 16 flops/cycle
= 48 Gflop/s

About M1 Processor

Release: November 2020

8 cores: 4 High-performance and 4 energy-efficient cores

ISA: ARMv8.4 (includes NEON 128-bit vector extension)

Microarchitecture: *Firestorm* (High-performance) and *Icestorm* (Energy-efficient)

Technology: 5nm

Successors (released in October 2021):

- *M1 Pro: Same as M1 but with 10 cores and twice L3 cache.*
- *M1 Max: Same as M1 Pro but with twice L3 cache (also bigger GPU).*

Cache	M1 (Firestorm)	M1 (Icestorm)
L1-I	192K	128K
L1-D	128K	64K
L2	12M Shared by four Firestorm cores	4M Shared by Icestorm cores
L3 (SLC)	16M, 24M (Pro) or 48M (Max). Shared by all cores and GPU.	

https://en.wikichip.org/wiki/apple/mx/m1
https://en.wikipedia.org/wiki/Apple_M1

Firestorm Microarchitecture

Integer ports:
1: alu + flags + branch + addr + msr/mrs nzcv + mrs
2: alu + flags + branch + addr + msr/mrs nzcv + ptrauth
3: alu + flags + mov-from-simd/fp?
4: alu + mov-from-simd/fp?
5: alu + mul + div
6: alu + mul + madd + crc + bfm/extr

Load and store ports:
7: store + amx
8: load/store + amx
9: load
10: load

FP/SIMD ports:
11: fp/simd
12: fp/simd
13: fp/simd + fcsel + to-gpr
14: fp/simd + fcsel + to-gpr + fcmp/e + fdiv + …

Instruction	Latency [cycles]	Throughput [ops/cycle]	1/Throughput [cycles/issue]
fma	4	4	0.25
add	3	4	0.25
mul	4	4	0.25
div	10	1	1
load		3	0.33
store		2	0.5

Latency and throughput of FP instructions in double precision. The numbers are the same for scalar and vector instructions.

This information is based on black-box reverse engineering (micro-benchmarking)
https://dougallj.github.io/applecpu/firestorm.html

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Icestorm Microarchitecture

Integer ports:
1: alu + br + mrs
2: alu + br + div + ptrauth
3: alu + mul + bfm + crc

Load and store ports:
4: load/store + amx
5: load

FP/SIMD ports:
6: fp/simd
7: fp/simd + fcsel + to-gpr + fcmp/e + fdiv + …

Instruction	Latency [cycles]	Throughput [ops/cycle]	1/Throughput [cycles/issue]
fma	4	2	0.5
add	3	2	0.5
mul	4	2	0.5
div (scalar) div (2-way)	10 11	1 0.5	1 2
load		2	0.5
store		1	1

Latency and throughput of FP instructions in double precision. The numbers are the same for scalar and vector instructions except for div.

This information is based on black-box reverse engineering
https://dougallj.github.io/applecpu/icestorm.html

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Apple M2 (5 nm, June 2022)

https://en.wikipedia.org/wiki/Apple_M2

Apple M3 (3 nm, October 2023)

https://en.wikipedia.org/wiki/Apple_M3

Apple M4 (3 nm, May 2024)

https://en.wikipedia.org/wiki/Apple_M4

Some information on units in Apple developer's guide (requires account)

See semester project by F. Sidler on measuring instructions on M3

For the perf cores, the previous M1 lat/tp table for the performance cores seems to be the same for M3 (and thus likely for M2)

Summary

Architecture vs. microarchitecture

To optimize code one needs to understand a suitable abstraction of the microarchitecture and its key quantitative characteristics

- *Memory hierarchy with throughput and latency info*
- *Execution units with port, throughput, and latency info*

Lower bounds on runtime can be derived

- *Based on data movement from/to cache/memory*
- *Based on: (arithmetic) instruction mix in code + throughput and port information*

Operational intensity:

- *High = compute bound = runtime dominated by data operations*
- *Low = memory bound = runtime dominated by data movement*