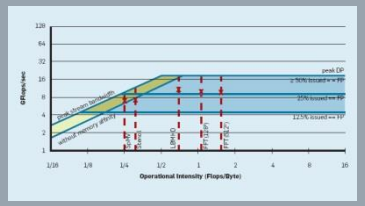
NHR FAU

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

“Simple” performance modeling: The Roofline Model

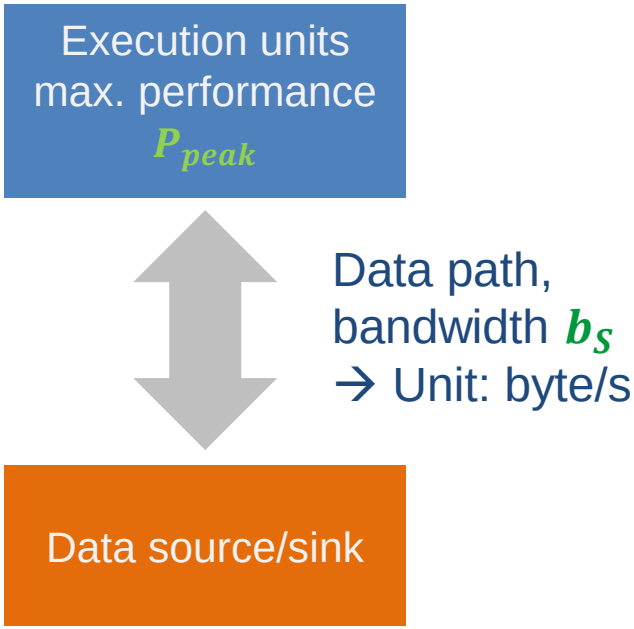
Loop-based performance modeling: Execution vs. data transfer



High Performance Computing

A simple performance model for loops

Simplistic view of the hardware:



Simplistic view of the software:

```
! may be multiple levels
do i = 1,<sufficient>
  <complicated stuff doing
    N flops causing
    V bytes of data transfer>
enddo
```

Computational intensity $I = \frac{N}{V}$

→ Unit: flop/byte

Naïve Roofline Model

How fast can tasks be processed? P **[flop/s]**

The bottleneck is either

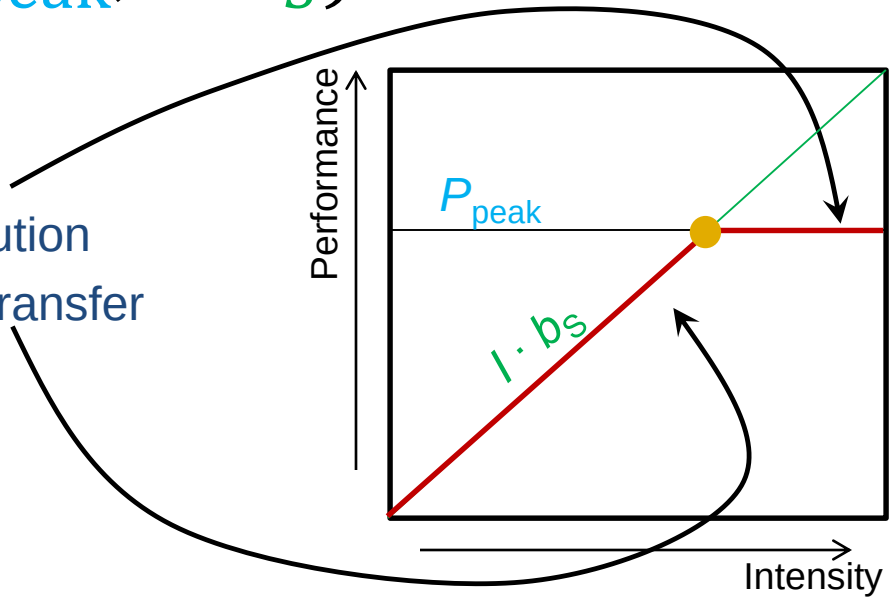
- The execution of work: P_{peak} [flop/s]
- The data path: $I \cdot b_S$ [flop/byte x byte/s]

$$P = \min(P_{\text{peak}}, I \cdot b_S)$$

This is the "Naïve Roofline Model"

- High intensity: P limited by execution
- Low intensity: P limited by data transfer
- "Knee" at $P_{max} = I \cdot b_S$:
  Best use of resources

- Roofline is an "optimistic" model ("light speed")



Apply the naive Roofline model in practice

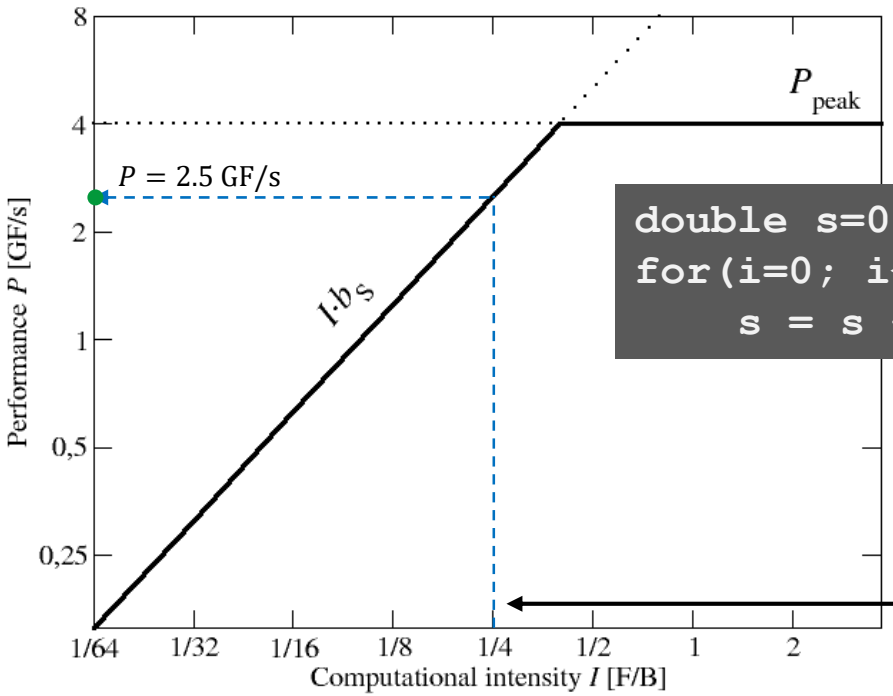
- Machine parameter #1: Peak performance: $P_{peak}\ \left[\frac{F}{s}\right]$
- Machine parameter #2: Memory bandwidth: $b_S\ \left[\frac{B}{s}\right]$
- Code characteristic: Computational intensity: $I\ \left[\frac{F}{B}\right]$

Machine properties:

$$\boldsymbol{P_{peak}} = 4\,\frac{\mathrm{GF}}{\mathrm{s}}$$

$$\boldsymbol{b_S} = 10\,\frac{\mathrm{GB}}{\mathrm{s}}$$

Application property: I




```
double s=0, a[];
for(i=0; i<N; ++i) {
    s = s + a[i] * a[i];}
```

$$I = \frac{2\,F}{8\,B} = 0.25\,{}^{F}/_{B}$$

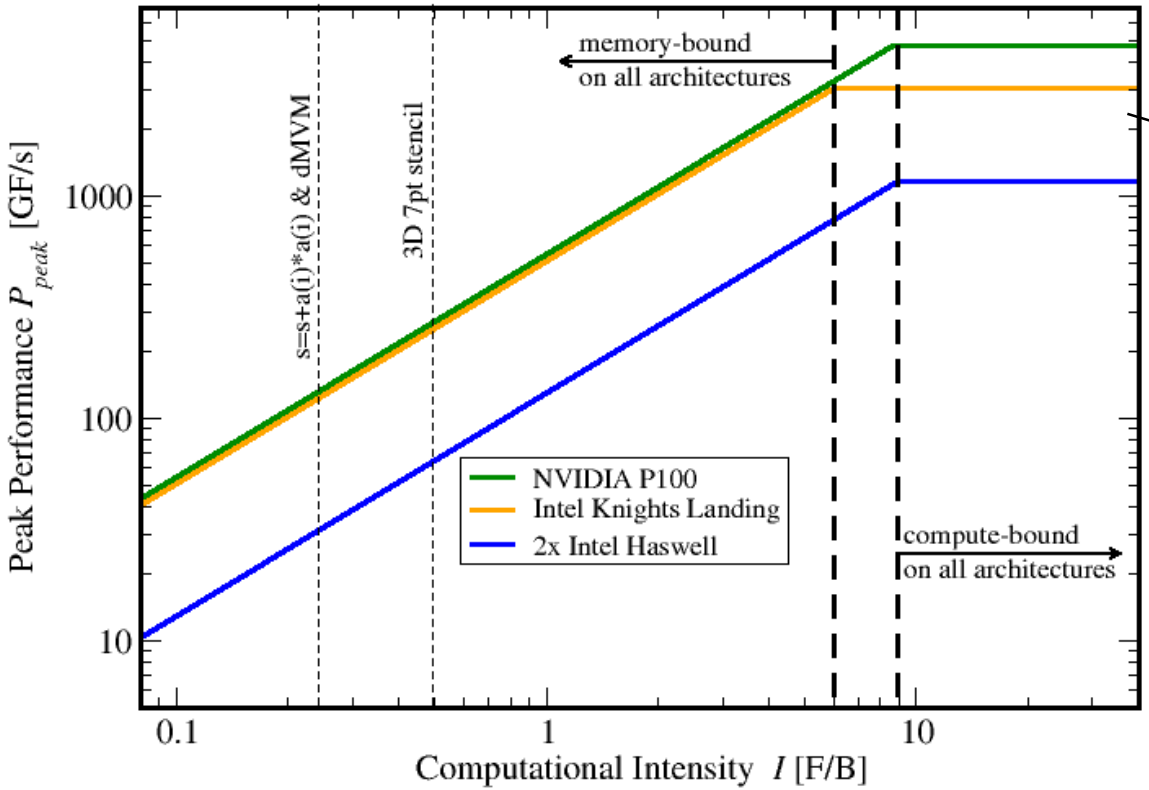
Prerequisites for the Roofline Model

- **The roofline formalism is based on some (crucial) prerequisites:**
  - There is a clear concept of "work" vs. "traffic"
    - "work" = flops, updates, iterations…
    - "traffic" = required data to do "work"
  - Machine input parameters: Peak Performance and Peak Bandwidth
    Application/kernel is expected to achieve is limits theoretically

- **Assumptions behind the model:**
  - Data transfer and core execution overlap perfectly!
    - **Either** the limit is core execution **or** it is data transfer
    - **Slowest limiting factor "wins";** all others are assumed to have no impact
  - Latency effects are ignored, i.e., perfect streaming mode
  - "Steady-state" code execution (no wind-up/-down effects)

The Roofline Model in computing – Basics

Compare capabilities of different machines:



Assuming double precision –
for single precision:
$P_{peak} \rightarrow 2 \cdot P_{peak}$

- Roofline always provides upper bound – but is it realistic?
- If code is not able to reach this limit (e.g., contains add operations only), machine parameters need to be redefined (e.g., $P_{peak} \rightarrow P_{peak}/2$)

A refined Roofline Model

1. P_{max} = Applicable peak performance of a loop, assuming that data comes from the level 1 cache (this is not necessarily P_{peak})
   → e.g., P_{max} = 176 GFlop/s

2. I = Computational intensity ("work" per byte transferred) over the slowest data path utilized (code balance $B_C = I^{-1}$)
   → e.g., I = 0.167 Flop/Byte → B_C = 6 Byte/Flop

3. b_S = Applicable (saturated) peak bandwidth of the slowest data path utilized
   → e.g., b_S = 56 GByte/s

Expected performance:

$$P = \min(P_{\text{max}}, I \cdot b_S) = \min\left(P_{\text{max}}, \frac{b_S}{B_C}\right)$$

[Byte/s]

[Byte/Flop]

R.W. Hockney and I.J. Curington: $f_{1/2}$: A parameter to characterize memory and communication bottlenecks. Parallel Computing 10, 277-286 (1989). DOI: 10.1016/0167-8191(89)90100-2

W. Schönauer: Scientific Supercomputing: Architecture and Use of Shared and Distributed Memory Parallel Computers. Self-edition (2000)

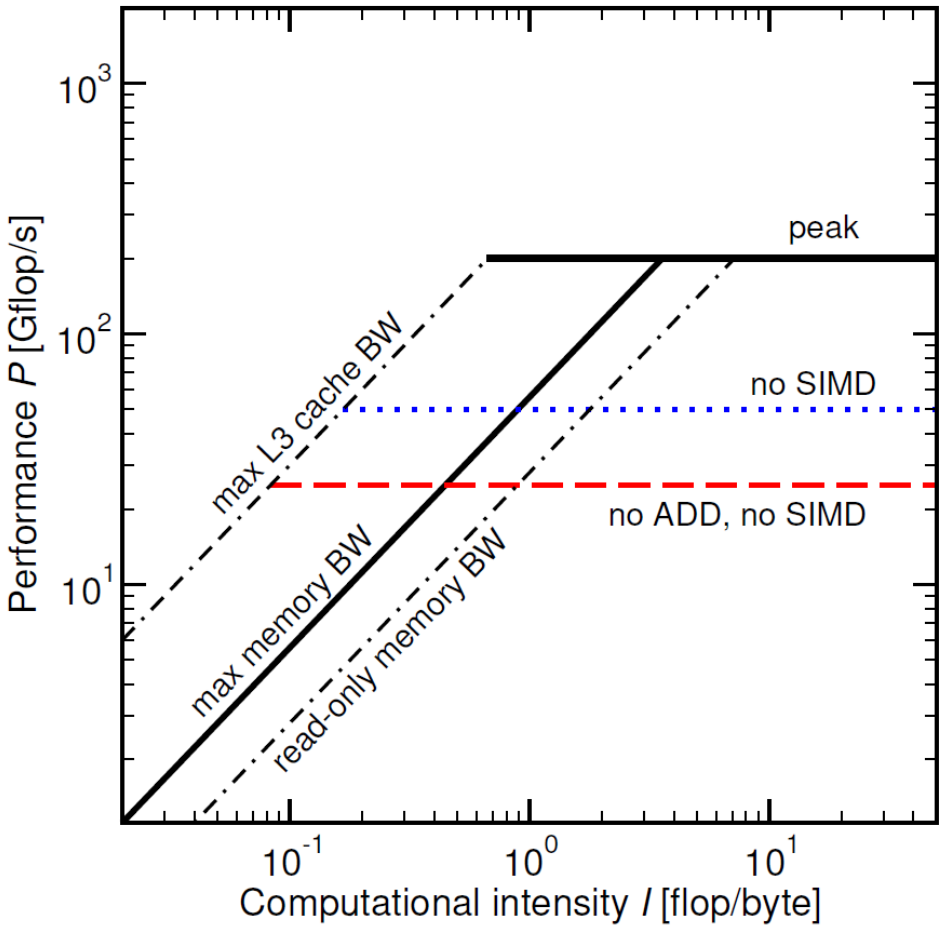
S. Williams: Auto-tuning Performance on Multicore Computers. UCB Technical Report No. UCB/EECS-2008-164. PhD thesis (2008)

Refined Roofline model: graphical representation

Multiple ceilings may apply

- Different bandwidths /data paths
  → different inclined ceilings
- Different P_{max}
  → different flat ceilings

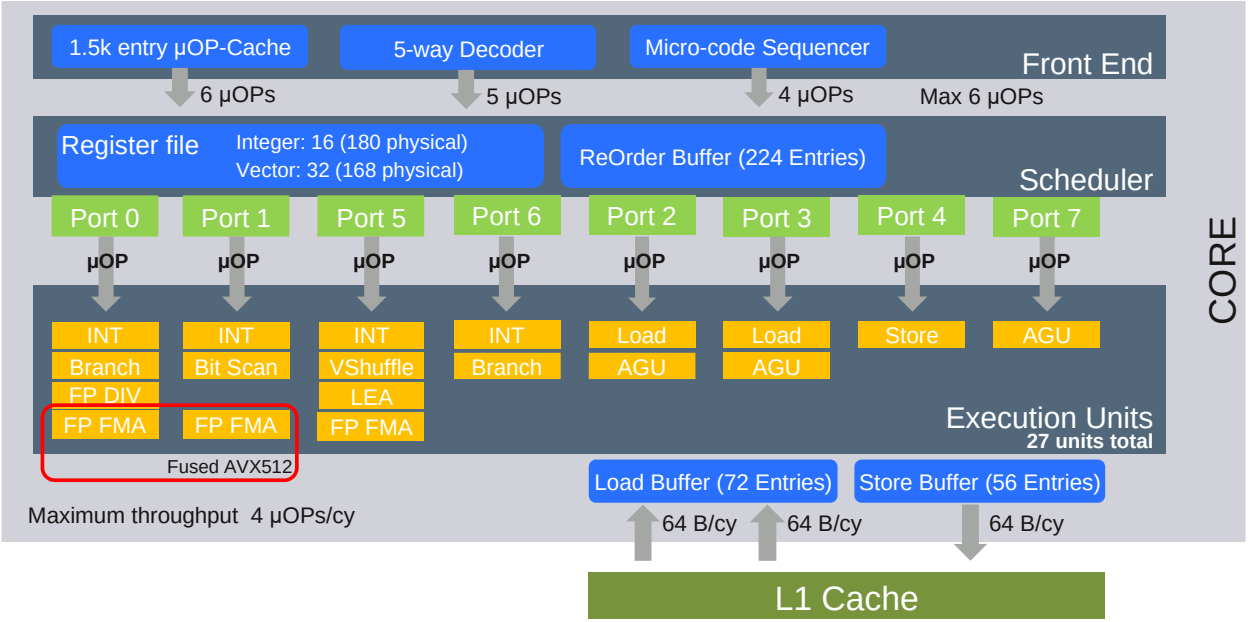
  In fact, P_{max} should always come from code analysis; generic ceilings are usually impossible to attain



Complexities of in-core execution (P_{max})

Multiple bottlenecks:

- Decode/retirement throughput
- Port contention (direct or indirect)
- Arithmetic pipeline stalls (dependencies)
- Overall pipeline stalls (branching)
- L1 Dcache bandwidth (LD/ST throughput)
- Scalar vs. SIMD execution
- L1 Icache (LD/ST) bandwidth
- Alignment issues
- …



Skylake

Tool for P_{max} analysis: OSACA
http://tiny.cc/OSACA
DOI: 10.1109/PMBS49563.2019.00006
DOI: 10.1109/PMBS.2018.8641578

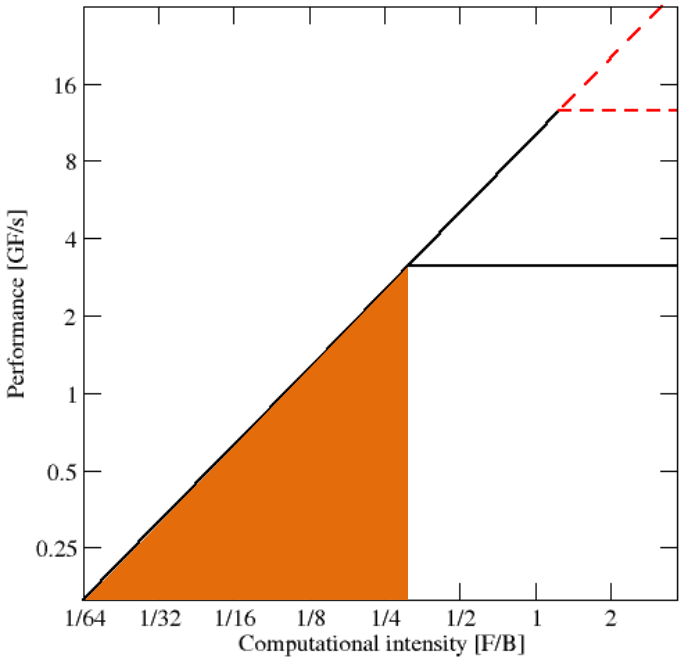
Factors to consider in the Roofline Model

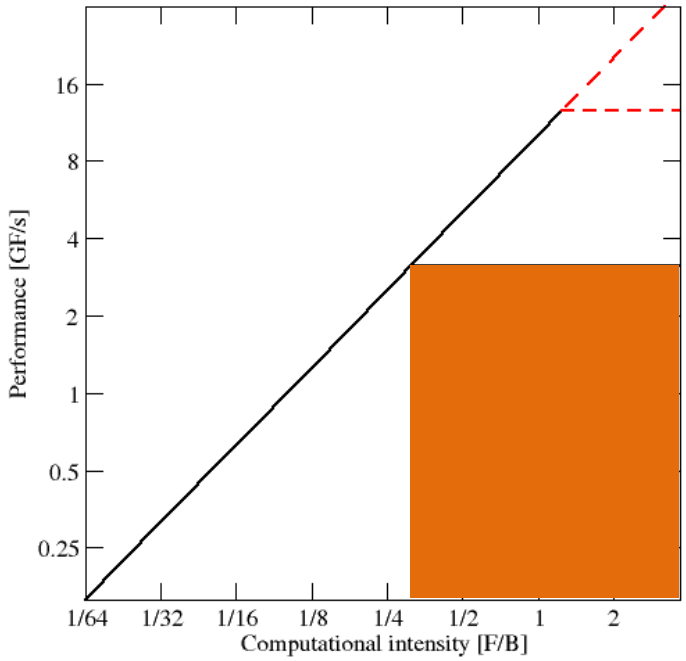
Bandwidth-bound (simple case)

1. Accurate traffic calculation (write-allocate, strided access, …)
2. Practical ≠ theoretical BW limits
3. Saturation effects → consider full socket only

Core-bound (may be complex)

1. Multiple bottlenecks: LD/ST, arithmetic, pipelines, SIMD, execution ports
2. Limit is linear in # of cores

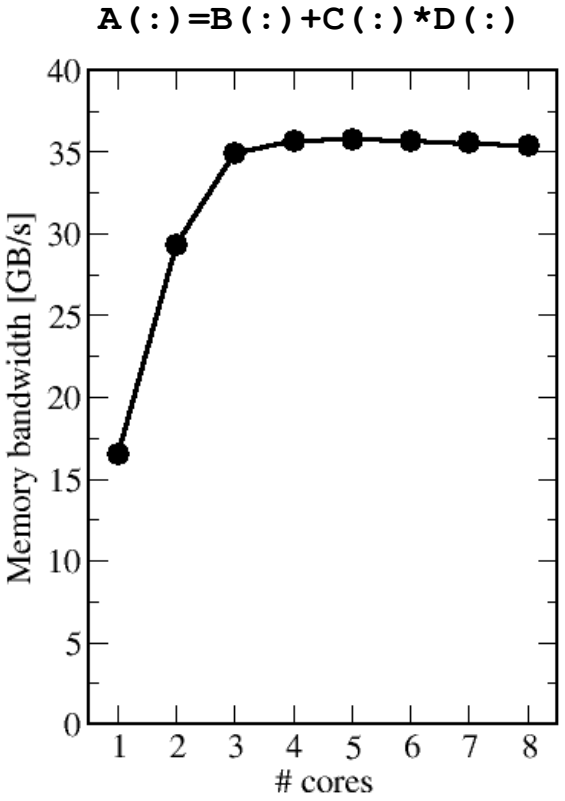




Shortcomings of the roofline model

- **Saturation effects in multicore chips are not explained**
  - Reason: "saturation assumption"
  - Cache line transfers and core execution do sometimes not overlap perfectly
  - It is not sufficient to measure single-core STREAM to make it work
  - Only increased "pressure" on the memory interface can saturate the bus
    → need more cores!
- **In-cache performance is not correctly predicted**
- **The ECM performance model gives more insight:**

G. Hager, J. Treibig, J. Habich, and G. Wellein: Exploring performance and power properties of modern multicore chips via simple machine models. Concurrency and Computation: Practice and Experience (2013). DOI: 10.1002/cpe.3180 Preprint: arXiv:1208.2908

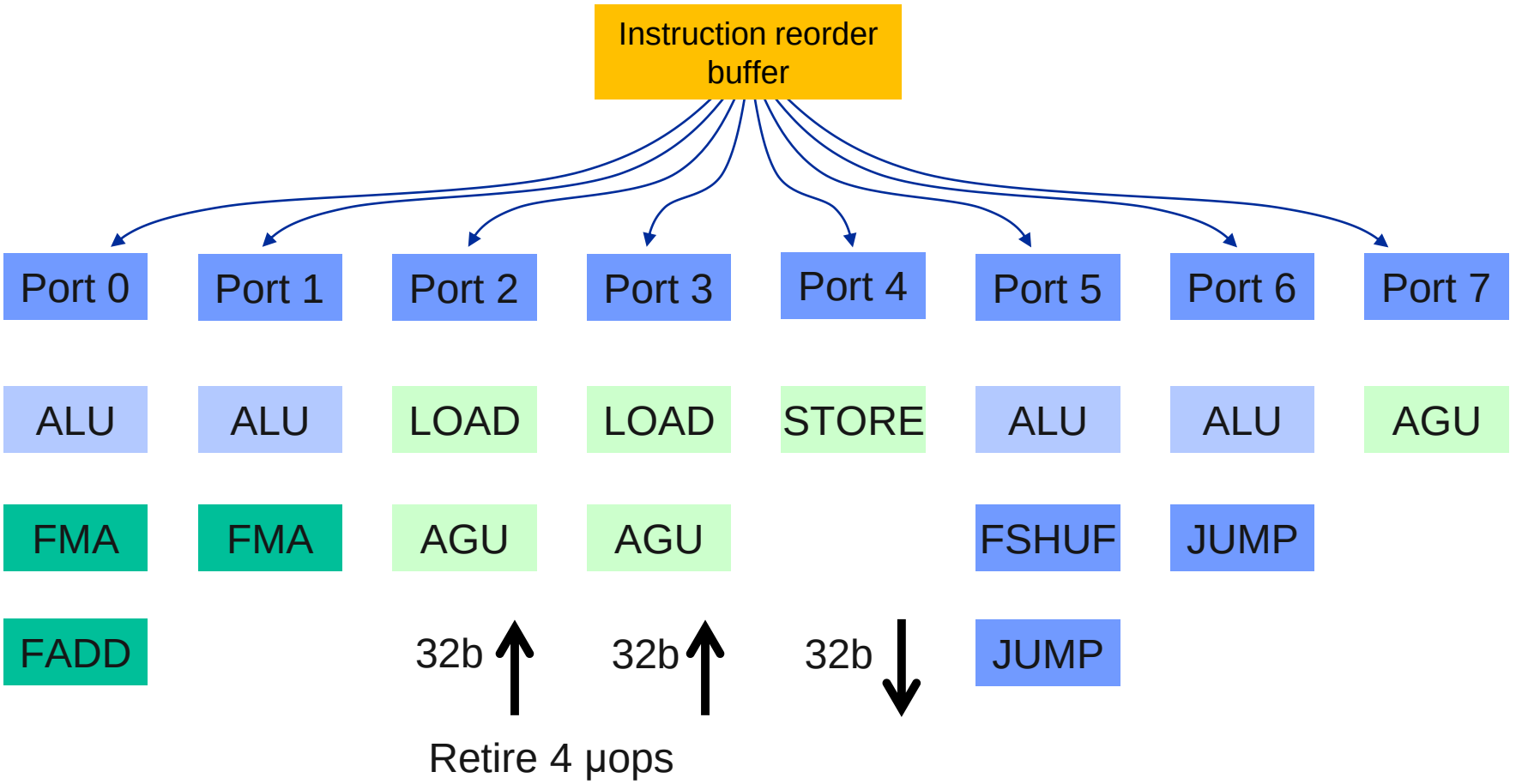


Hardware features of (some) Intel Xeon processors

Microarchitecture	Ivy Bridge EP	Broadwell EP	Cascade Lake SP
Introduced	09/2013	03/2016	04/2019
Cores	≤ 12	≤ 22	≤ 28
LD/ST throughput per cy:			
AVX(2), AVX512	1 LD + ½ ST	2 LD + 1 ST	2 LD + 1 ST
SSE/scalar	2 LD || 1 LD & 1 ST		
ADD throughput	1 / cy	1 / cy	2 / cy
MUL throughput	1 / cy	2 / cy	2 / cy
FMA throughput	N/A	2 / cy	2 / cy
L1-L2 data bus	32 B/cy	64 B/cy	64 B/cy
L2-L3 data bus	32 B/cy	32 B/cy	16+16 B/cy
L1/L2 per core	32 KiB / 256 KiB	32 KiB / 256 KiB	32 KiB / 1 MiB
LLC	2.5 MiB/core inclusive	2.5 MiB/core inclusive	1.375 MiB/core exclusive
Memory	4ch DDR3	4ch DDR3	6ch DDR4
Memory BW (meas.)	~ 48 GB/s	~ 62 GB/s	~ 115 GB/s

Estimating per-core P_{max} on a given architecture

Haswell/Broadwell port scheduler model:



Haswell/Broadwell

Zeroth order throughput limits on Haswell

- **Per cycle with AVX, SSE, or scalar**
  - 2 LOAD instructions **AND** 1 STORE instruction
  - 2 instructions selected from the following five:
    - 2 FMA (fused multiply-add)
    - 2 MULT
    - 1 ADD
  - **Overall maximum of 4 instructions per cycle**
    - In practice, 3 is more realistic
    - µ-ops may be a better indicator for short loops
- **Remember: one AVX instruction handles**
  - 4 DP operands or
  - 8 SP operands

- **First order correction**
  - Typically only two LD/ST instructions per cycle due to one AGU handling “simple” addresses only
  - See SIMD chapter for more about memory addresses

Example: P_{max} of vector triad on Haswell

```
double  *A, *B, *C, *D;
for (int i=0; i<N; i++) {
   A[i] = B[i] + C[i] * D[i];
}
```

Assembly code (AVX2+FMA, no additional unrolling):

```
..B2.9:
   vmovupd      ymm2, [rdx+rax*8]          # LOAD
   vmovupd      ymm1, [r12+rax*8]          # LOAD
   vfmadd213pd ymm1, ymm2, [rbx+rax*8]  # LOAD+FMA
   vmovupd      [rdi+rax*8], ymm2          # STORE
   add          rax,4
   cmp          rax,r11
   jb           ..B2.9
# remainder loop omitted
```

Iterations are independent → throughput assumption justified!

Best-case execution time?

Example: P_{max} of vector triad on Haswell

```
double  *A, *B, *C, *D;
for (int i=0; i<N; i++) {
   A[i] = B[i] + C[i] * D[i];
}
```

Minimum number of cycles to process **one AVX-vectorized iteration** (equivalent to 4 scalar iterations) on one core?

→ Assuming full throughput:

Cycle 1: LOAD + LOAD + STORE
Cycle 2: LOAD + LOAD + FMA + FMA
Cycle 3: LOAD + LOAD + STORE

Answer: 1.5 cycles

Example: P_{max} of vector triad on Haswell@2.3

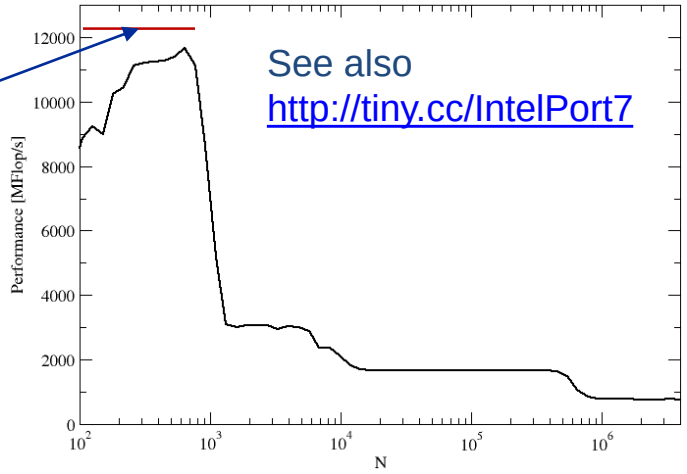
```
double  *A, *B, *C, *D;
for (int i=0; i<N; i++) {
   A[i] = B[i] + C[i] * D[i];
}
```

What is the **performance in GFlops/s per core** and the bandwidth in GBytes/s?

One AVX iteration (1.5 cycles) does 4 x 2 = 8 flops:

$$2.3 \cdot 10^9 \text{ cy/s} \cdot \frac{8 \text{ flops}}{1.5 \text{ cy}} = \mathbf{12.27} \frac{\mathbf{Gflops}}{\mathbf{s}}$$

$$12.27 \frac{\text{Gflops}}{\text{s}} \cdot 16 \frac{\text{bytes}}{\text{flop}} = 196 \frac{\text{Gbyte}}{\text{s}}$$



See also
http://tiny.cc/IntelPort7

Vector triad `A(:)=B(:)+C(:)*D(:)` on a 2.3 GHz 14-core Haswell chip

Consider full chip (14 cores):

Memory bandwidth: b_S = **50 GB/s**

Code balance (incl. write allocate):
B_c = (4+1) Words / 2 Flops = 20 B/F → ***I* = 0.05 F/B**

→ $I \cdot b_S$ **= 2.5 GF/s** (0.5% of peak performance)

P_{peak} / core = 36.8 Gflop/s ((8+8) Flops/cy x 2.3 GHz)
P_{max} / core = 12.27 Gflop/s (see prev. slide)

→ P_{max} **= 14 * 12.27 Gflop/s =172 Gflop/s** (33% peak)

$$P = \min(P_{\max}, I \cdot b_S) = \min(172, 2.5)\ \mathrm{GFlop/s} = 2.5\ \mathrm{GFlop/s}$$

Code balance: more examples

```
double a[], b[];
for(i=0; i<N; ++i) {
    a[i] = a[i] + b[i];}
```

B_C = 24B / 1F = 24 B/F

I = 0.042 F/B

```
double a[], b[];
for(i=0; i<N; ++i) {
    a[i] = a[i]+ s * b[i];}
```

B_C = 24B / 2F = 12 B/F

I = 0.083 F/B

Scalar – can be kept in register

```
float s=0, a[];
for(i=0; i<N; ++i) {
    s = s + a[i] * a[i];}
```

B_C = 4B / 2F = 2 B/F

I = 0.5 F/B

Scalar – can be kept in register

```
float s=0, a[], b[];
for(i=0; i<N; ++i) {
    s = s + a[i] * b[i];}
```

B_C = 8B / 2F = 4 B/F

I = 0.25 F/B

Scalar – can be kept in register

Machine balance for hardware characterization

- **For quick comparisons the concept of machine balance is useful**

$$B_m = \frac{b_S}{P_{\text{peak}}}$$

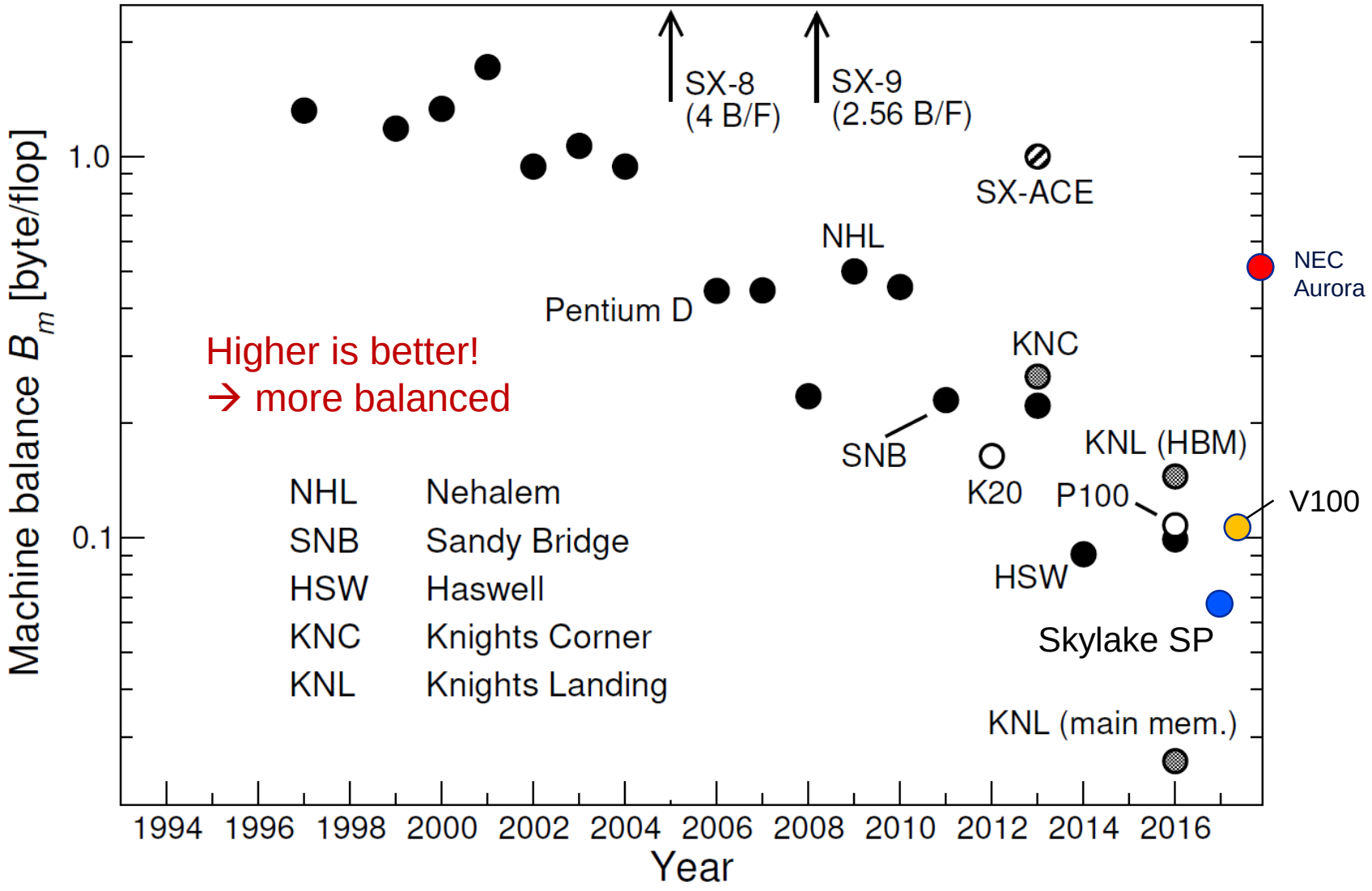
- Machine Balance = How much input data can be delivered for each FP operation? ("Memory Gap characterization")
  - Assuming balanced MULT/ADD
- Rough estimate: $B_m \ll B_c$ → strongly memory-bound code

- **Typical values (main memory):**

Intel Haswell 14-core 2.3 GHz
B_m = 60 GB/s / (14 x 2.3 x 16) GF/s ≈ **0.12 B/F**

Intel Skylake 24-core 2.3 GHz ≈ **0.06 B/F**
Nvidia P100 ≈ **0.10 B/F**
Nvidia V100 ≈ **0.10 B/F**
Intel Xeon Phi Knights Landing (MCDRAM) ≈ **0.18 B/F**

Machine balance over time



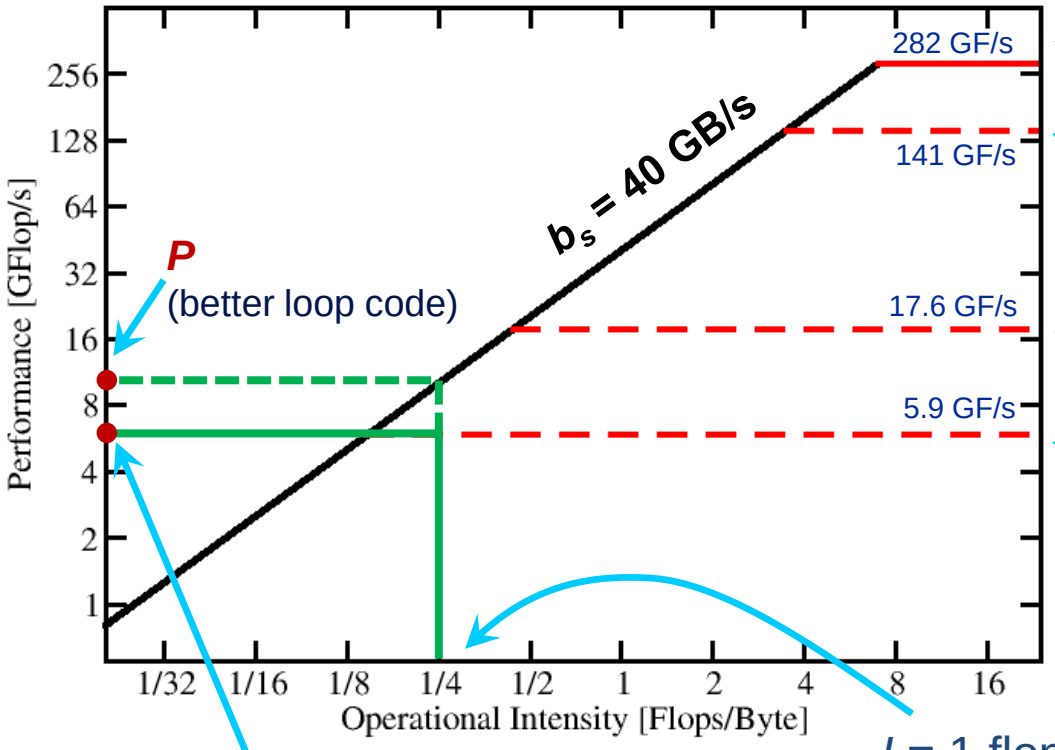
http://www.nec.com/en/press/201710/global_20171025_01.html

A not so simple Roofline example

Example: `do i=1,N; s=s+a(i); enddo`

in single precision on an 8-core 2.2 GHz Sandy Bridge socket @ "large" N

$$P = \min(P_{\max}, I \cdot b_S)$$



Machine peak (ADD+MULT) Out of reach for this code

ADD peak (best possible code)

no SIMD

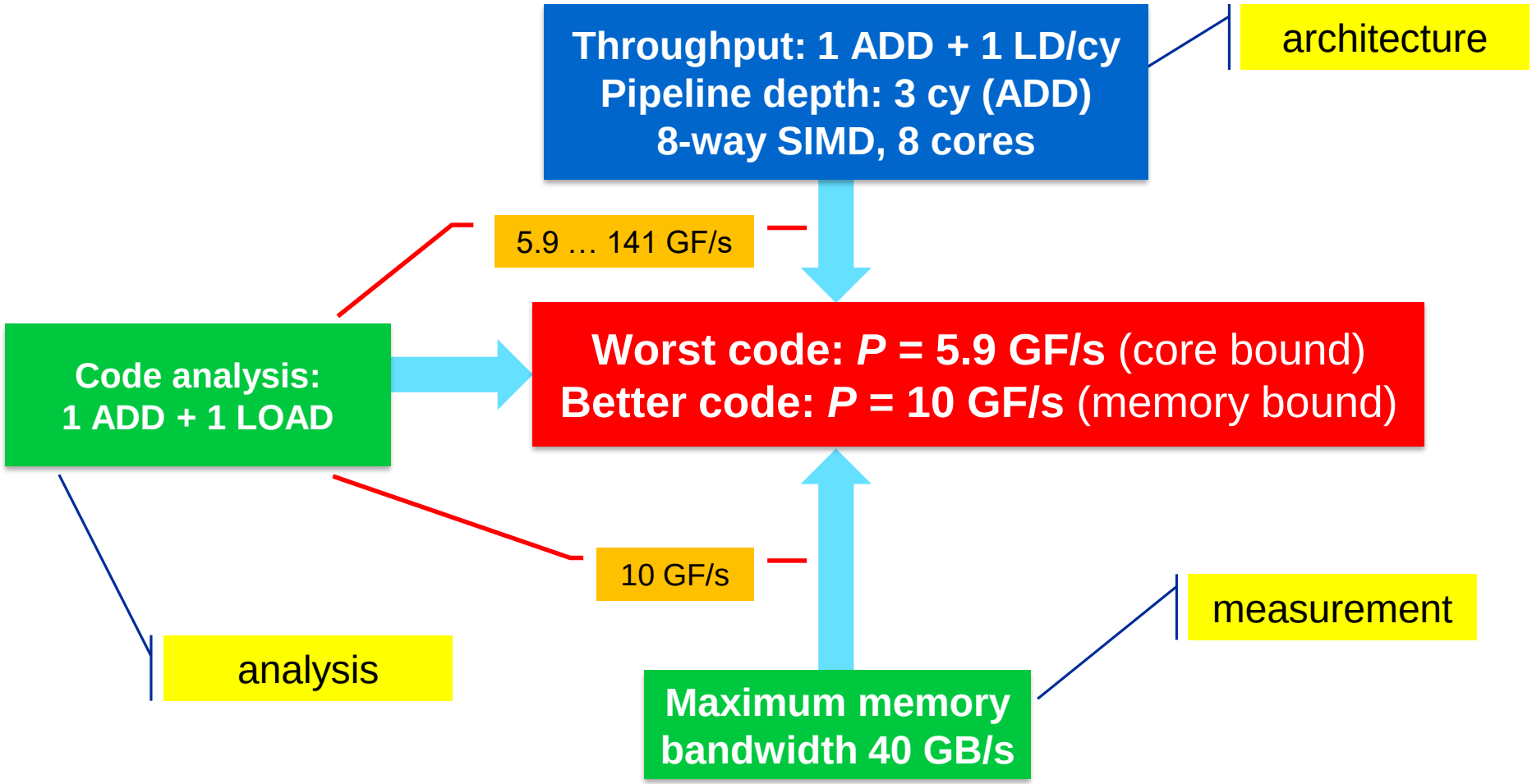
3-cycle latency per ADD if not unrolled

See architecture intro

I = 1 flop / 4 byte (SP!)

Input to the roofline model

… on the example of `do i=1,N; s=s+a(i); enddo`
in single precision



Tracking code optimizations in the Roofline Model

1. Hit the BW bottleneck by good serial code
   (e.g., Ninja C++ → Fortran)
2. Increase intensity to make better use of BW bottleneck
   (e.g., spatial loop blocking [see later])
3. Increase intensity and go from memory bound to core bound
   (e.g., temporal blocking)
4. Hit the core bottleneck by good serial code
   (e.g., `-fno-alias` [see later])