Advanced Systems Lab

Spring 2023

Lecture: Roofline model

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Operational Intensity Again

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

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)

Asymptotic bounds on I(n)

- *Vector sum: y = x + y* — O(1)
- *Matrix-vector product: y = Ax* — O(1)
- *Fast Fourier transform* — O(log(n)) → O(log(γ)) ← (not explained)
- *Matrix-matrix product: C = AB + C* — O(n) → O(sqrt(γ))

Cache lecture
γ = size LLC (last level cache)
Known to be optimal

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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*

The roofline model makes this more precise

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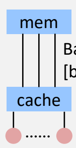
Roofline model/plot (Williams et al. 2008)

Platform model



Bandwidth β [bytes/cycle] ← carefully measured

- raw bandwidth from manual unattainable (maybe 60% is)
- Stream benchmark may be conservative

p cores

Each with peak performance π [flops/cycle]

Algorithm/program model (n is the input size)

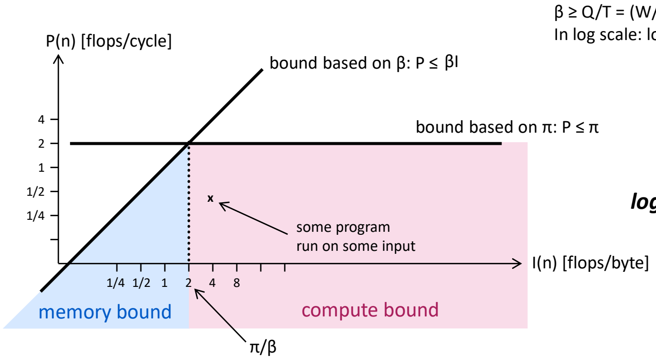
Work	W(n) [flops]
Data movement: *(mem ↔ cache)*	Q(n) [bytes]
Runtime:	T(n) [cycles]

Derived:

Operational intensity	I(n) = W(n)/Q(n) [flops/byte]
Performance:	P(n) = W(n)/T(n) [flops/cycle]

Example: one core, $\pi = 2$, $\beta = 1$, no SIMD

Bound based on β:
$\beta \geq Q/T = (W/T)/(W/Q) = P/I$
In log scale: $\log_2(P) \leq \log_2(\beta) + \log_2(I)$



log-log scale!

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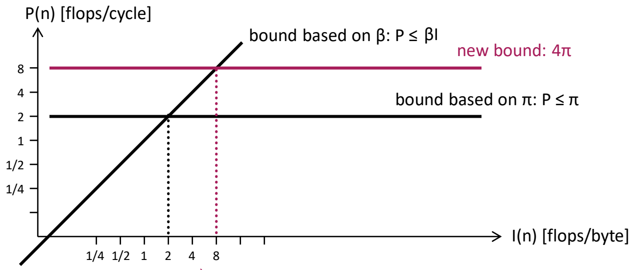
Roofline Plots

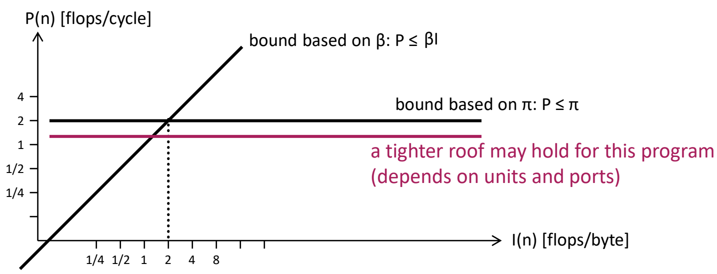
What happens if we introduce 4-way SIMD?



If β does not change:
more programs become memory bound

Roofline Plots

What if a program has an uneven mix of operations (e.g., 20% mults and 80% adds)?



Roofline Measurements

Tool developed in our group (code may need an update)
(G. Ofenbeck, R. Steinmann, V. Caparros-Cabezas, D. Spampinato)
http://www.spiral.net/software/roofline.html

Example plots follow

Estimate operational intensity I = W/Q (cold cache):

- *daxpy:* $y = \alpha x+y$ W = 2n Q = 3n doubles = 24n bytes I = 1/12
- *dgemv:* $y = Ax + y$ W = $2n^2$ Q ≈ n^2 doubles = $8n^2$ bytes I ≈ 1/4
- *dgemm:* $C = AB + C$ W = $2n^3$ Q ≥ $4n^2$ doubles = $32n^2$ bytes I ≤ n/16
- *FFT*

Note:

- *For daxpy and dgemv, Q is determined by compulsory misses.*
- *For dgemm, more misses than compulsory misses occur for larger sizes.*
  If $3n^2 \le \gamma$ (cache size), equality should hold above.

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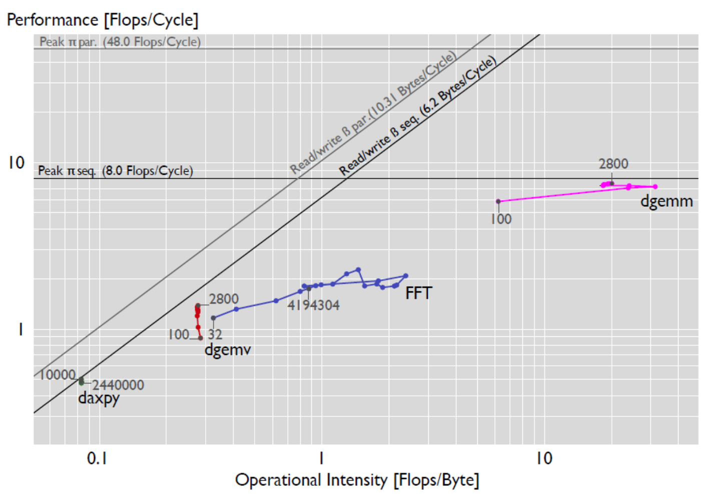
Roofline Measurements

Core i7 Sandy Bridge, 6 cores
*Code: Intel MKL, **sequential***
Cold cache



What happens when we go to parallel code?

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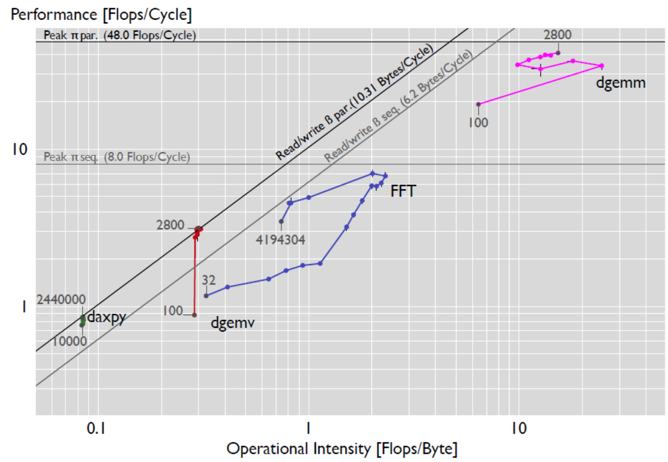
Roofline Measurements

Core i7 Sandy Bridge, 6 cores
*Code: Intel MKL, **parallel***
Cold cache



What happens when we measure with warm cache?

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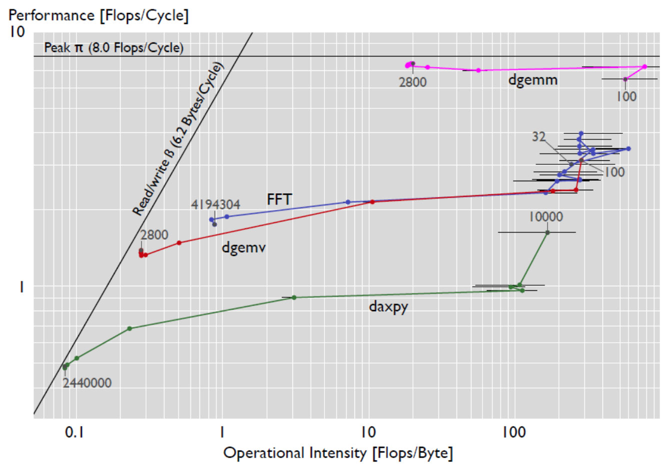
Roofline Measurements

Core i7 Sandy Bridge, 6 cores
*Code: Intel MKL, **sequential***
Warm cache



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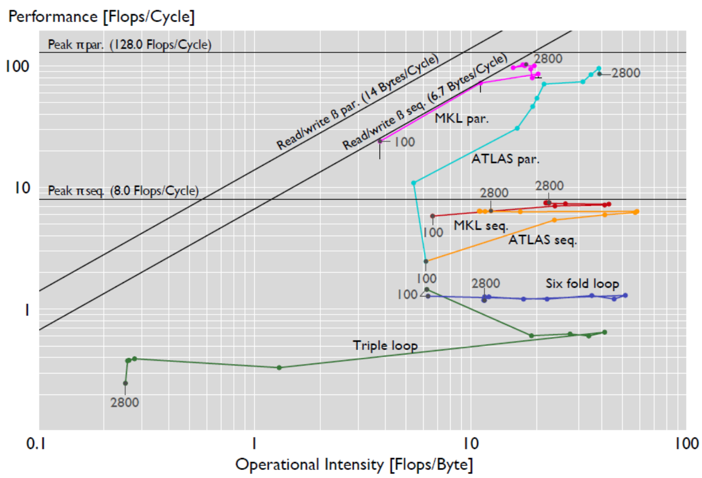
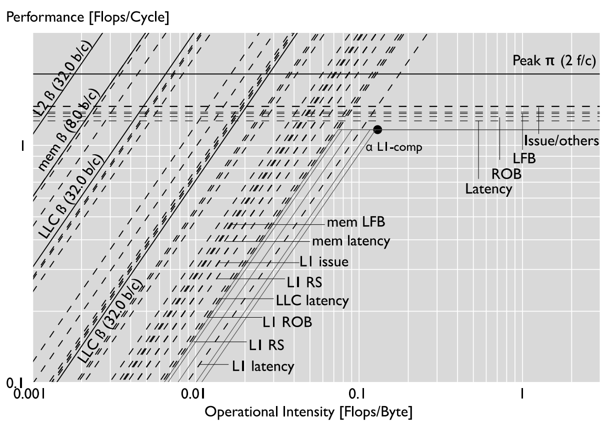
Core i7 Sandy Bridge, 6 cores
Code: Various MMM
Cold cache

Roofline Measurements



MMM: Different implementations

Generalized Roofline Model



Website and tool: https://acl.inf.ethz.ch/research/ERM/

Caparrós Cabezas and P. **Extending the Roofline Model: Bottleneck Analysis with Microarchitectural Constraints,** Proc. IISWC, pp. 222-231, 2014

Summary

Roofline plots distinguish between memory and compute bound

Can be instantiated for different scenarios (e.g., computation on GPU, data in CPU memory)

Can be used on for back-of-the-envelope computations on paper

Measurements difficult (performance counters) but doable

Easier variant just consider reads: Q_{read}, β_{read}

Interesting insights: *use in your project!*