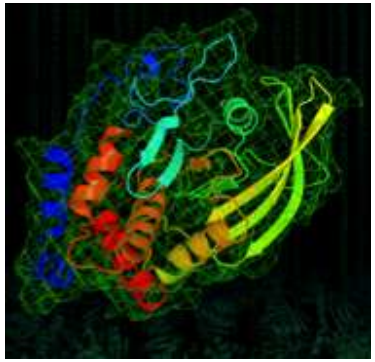
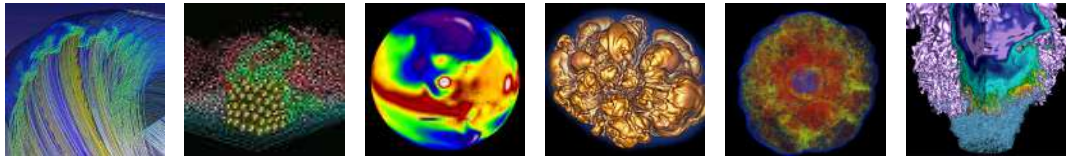
Introduction to the Roofline Model





Charlene Yang

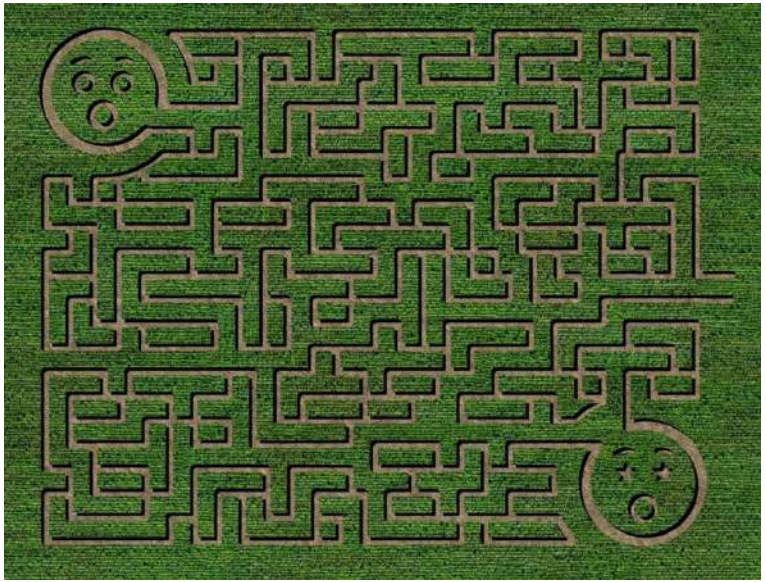
Lawrence Berkeley National Laboratory

Jun 16 2019, Frankfurt

U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

Performance Models

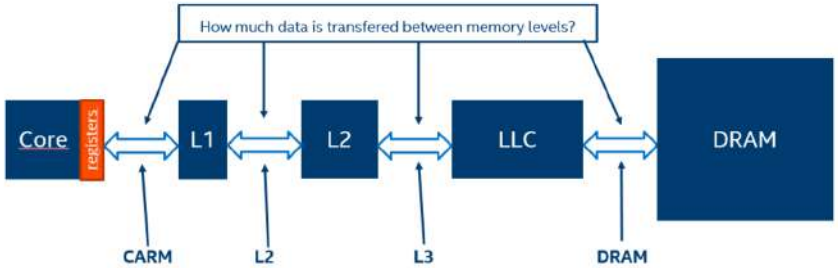


The Maze of Performance Optimization

The Map !!!

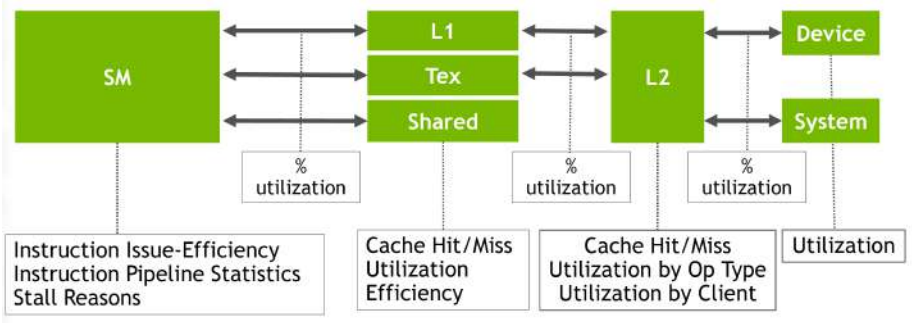
Performance Models

Modern architectures are complicated!



Intel Haswell CPU[1]

NVIDIA Volta GPU[2]



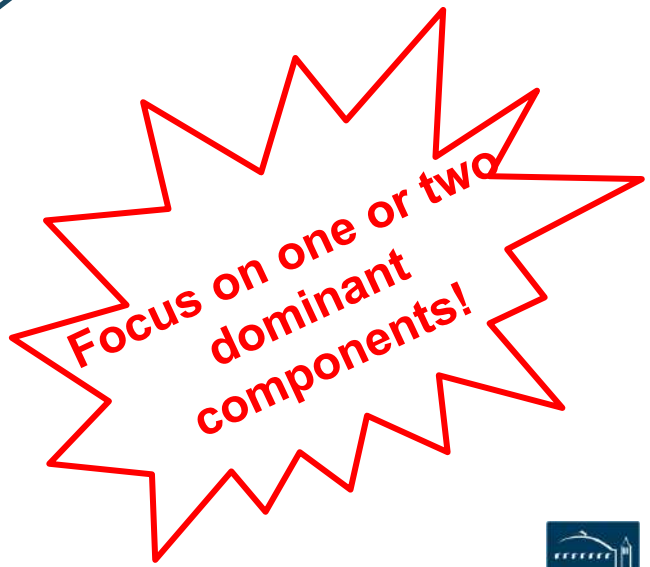
1. https://software.intel.com/en-us/articles/integrated-roofline-model-with-intel-advisor
2. http://on-demand.gputechconf.com/gtc/2016/presentation/s6659-avinash-baliga-perfworks.pdf

Performance Models

- **Many components contribute to the kernel run time**
- **An interplay of application characteristics and machine characteristics**

#FP operations	FLOP/s
Cache data movement	Cache GB/s
DRAM data movement	DRAM GB/s
PCIe data movement	PCIe bandwidth
MPI Message Size	Network Bandwidth
MPI Send:Wait ratio	Network Gap
#MPI Wait's	Network Latency
IO	File systems

Roofline Model



Roofline Performance Model

- Sustainable performance is bound by

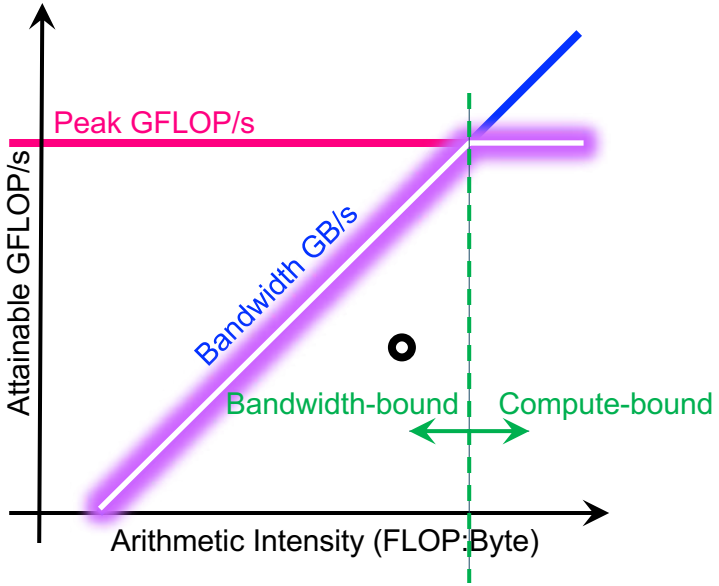
$$\text{GFLOP/s} = \min \begin{cases} \text{Peak GFLOP/s} \\ \text{AI} * \text{Peak GB/s} \end{cases}$$

- Arithmetic Intensity (AI) =

FLOPs / Bytes

- How did this come about?

→ A CPU DRAM example

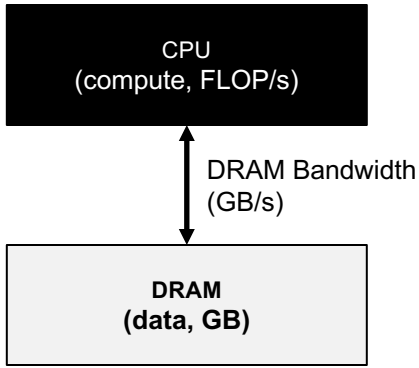


Transition @ AI ==
Peak GFLOP/s / Peak GB/s ==
'Machine Balance'

(CPU DRAM) Roofline

- One could hope to always attain peak performance (FLOP/s)
- However, finite locality (reuse) and bandwidth limit performance.
- Assume:
  - Idealized processor/caches
  - Cold start (data in DRAM)

$$\text{Time} = \max \begin{cases} \#\text{FP ops} / \text{Peak GFLOP/s} \\ \#\text{Bytes} / \text{Peak GB/s} \end{cases}$$



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- Assume:
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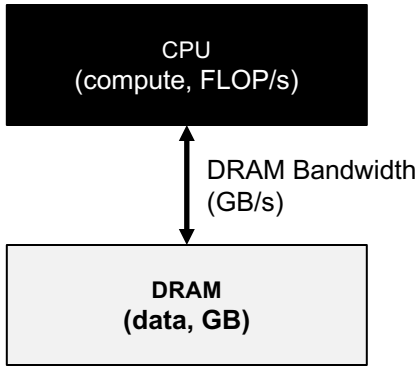
$$\frac{\text{Time}}{\#\text{FP ops}} = \max \begin{cases} 1 \,/\, \text{Peak GFLOP/s} \\ \#\text{Bytes} \,/\, \#\text{FP ops} \,/\, \text{Peak GB/s} \end{cases}$$



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- However, finite locality (reuse) and bandwidth limit performance.
- Assume:
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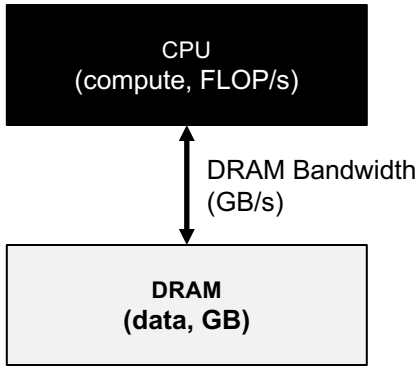
  - Cold start (data in DRAM)

$$\frac{\#\text{FP ops}}{\text{Time}} = \min \begin{cases} \text{Peak GFLOP/s} \\ (\#\text{FP ops} / \#\text{Bytes}) * \text{Peak GB/s} \end{cases}$$



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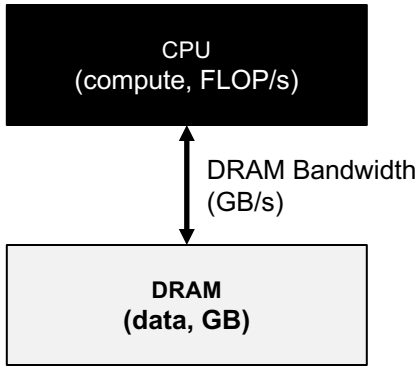


GFLOP/s = min { Peak GFLOP/s ; AI * Peak GB/s }

Arithmetic Intensity (AI) = FLOPs / Bytes (as presented to DRAM)

Roofline Performance Model

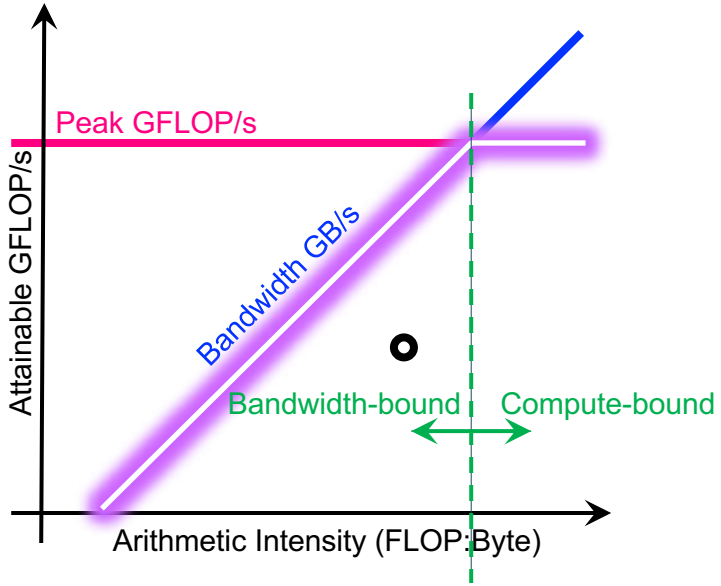
- Thus we obtain the model as

$$\text{GFLOP/s} = \min \begin{cases} \text{Peak GFLOP/s} \\ \text{AI} * \text{Peak GB/s} \end{cases}$$

where Arithmetic Intensity (AI) is

FLOPs / Bytes

- Machine Balance (FLOPs/Byte) =
  8.9 (V100, DP, HBM) or **5.1** (KNL, DP, HBM)



Transition @ AI ==
Peak GFLOP/s / Peak GB/s ==
'Machine Balance'

Roofline Performance Model

- A throughput-oriented model
  - tracks rates not times, i.e. GFLOP/s, GB/s, not seconds

- An abstraction over
  - architectures, ISA (CPU, GPU, Haswell, KNL, Pascal, Volta)
  - programming models, programming languages
  - numerical algorithms, problem sizes

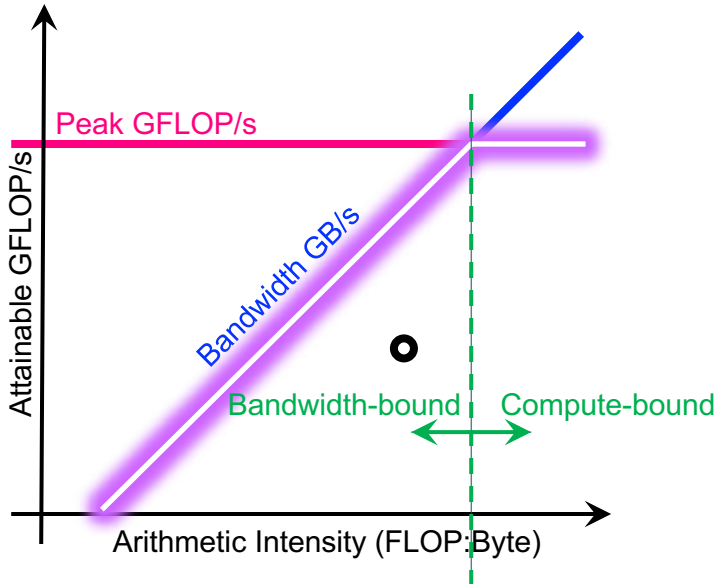
- In log-log scale to easily extrapolate performance along Moore's Law

More Advanced on Roofline

Roofline Performance Model

- This is a single Roofline
- What about the memory hierarchy, different execution configurations, and instruction mixes?

→ Hierarchical Roofline
→ Multiple compute ceilings

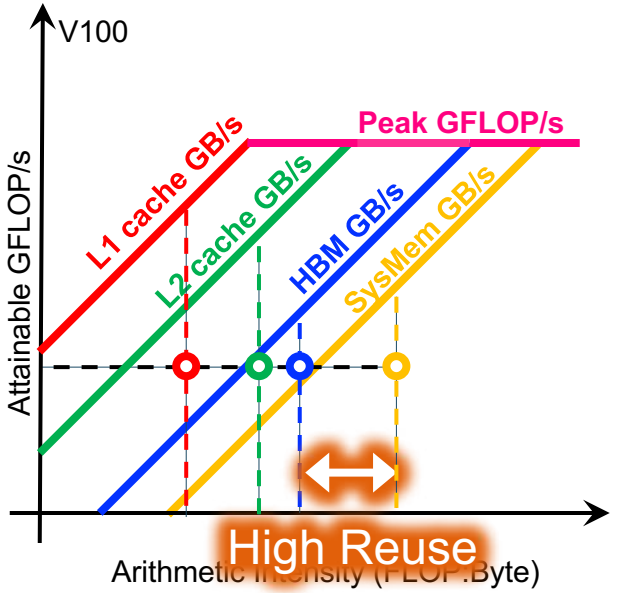


Transition @ AI ==
Peak GFLOP/s / Peak GB/s ==
'Machine Balance'

Hierarchical Roofline

- Superposition of multiple Rooflines
  - Incorporate full memory hierarchy
  - Arithmetic Intensity =

    FLOPs / Bytes$_{\text{L1/L2/HBM/SysMem}}$



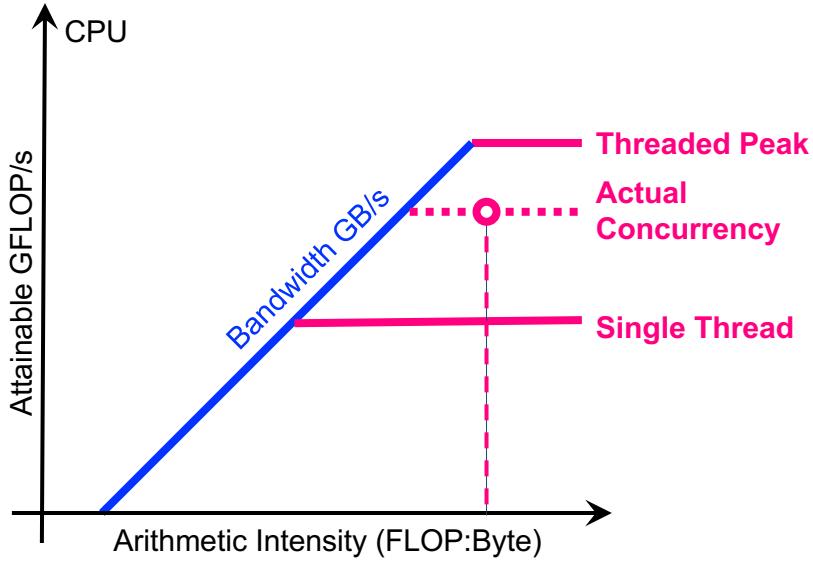
- Each kernel will have multiple AI's

  but one observed GFLOP/s performance

- Hierarchical Roofline tells you about **cache locality**

Multiple Compute Ceilings

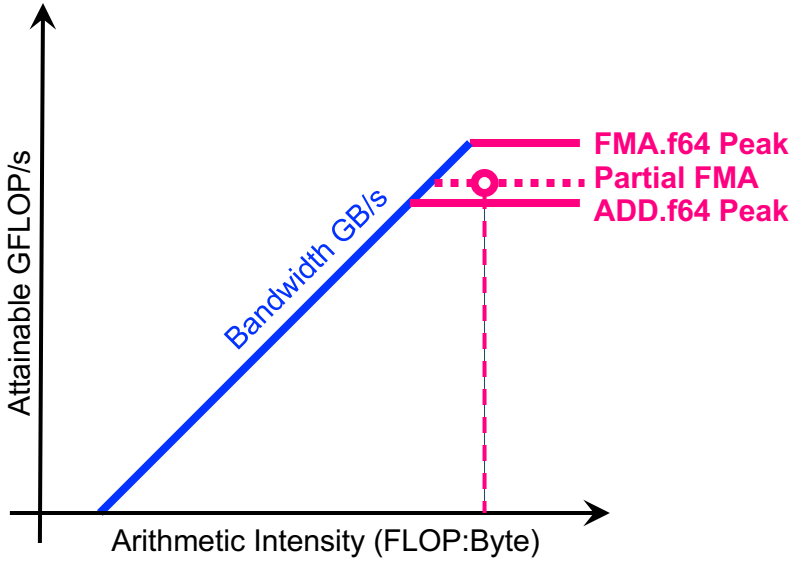
- Impact of **execution configuration**
- Concurrency affects your peak
  - OpenMP thread concurrency
  - SM occupancy
  - load balance
  - threadblock/thread configuration



- Performance is bound by the **actual concurrency** ceiling

Multiple Compute Ceilings

- Impact of **instruction mix**
- Applications are usually a mix of FMA.f64, ADD.f64, MUL.f64…
- Performance is a **weighted** average … bound by a **partial FMA** ceiling



Roofline Drives Optimization

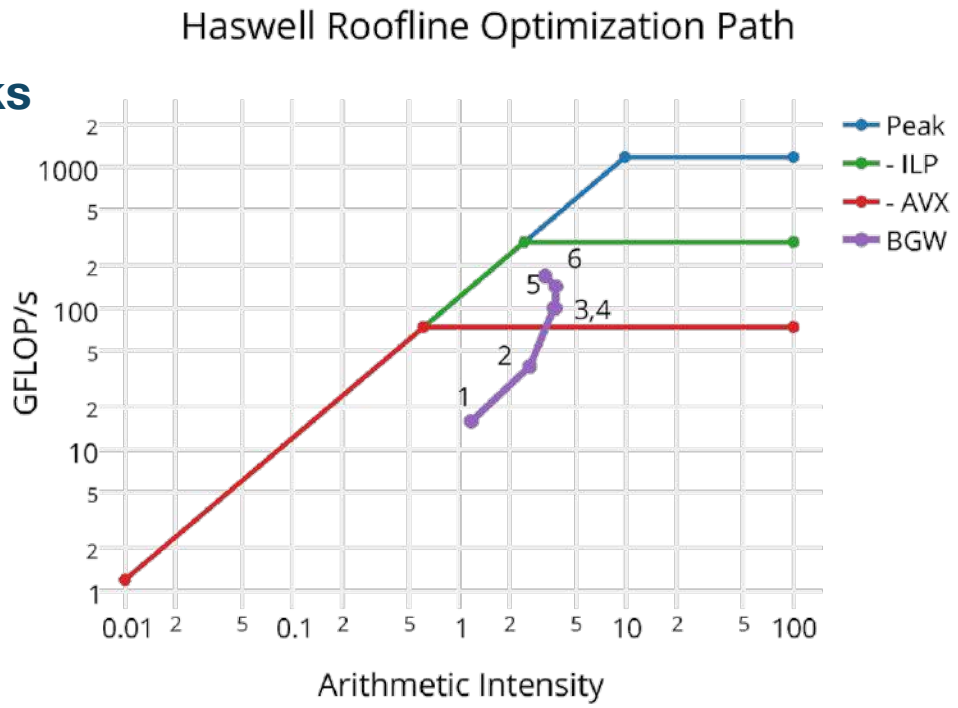
Roofline Performance Model

The Roofline Model

- helps you identify the bottlenecks
- guides you through optimization
- tells you when to stop

An example:

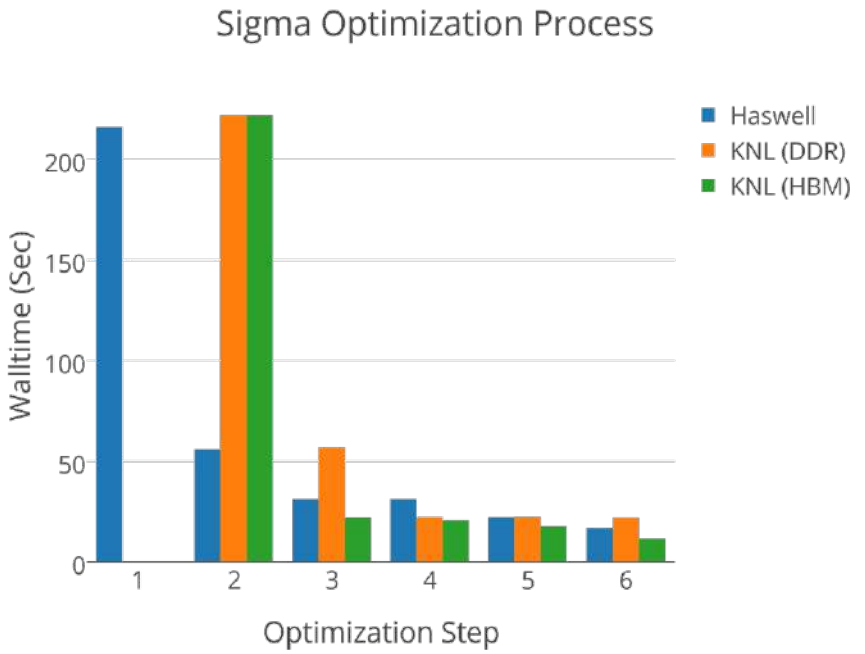
- NESAP for Cori - BerkeleyGW



Roofline Example: BerkeleyGW

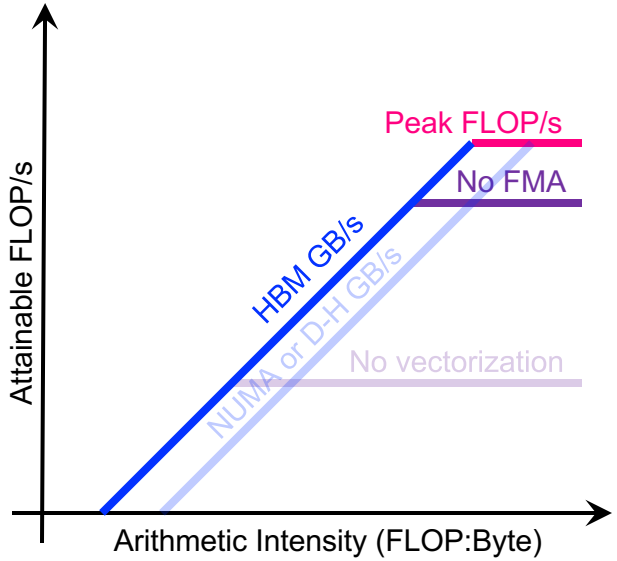
Optimization Path for Kernel-C (Sigma):

1. Add OpenMP
2. Initial Vectorization
   - loop reordering
   - conditional removal
3. Cache-Blocking
4. Improved Vectorization
   - divides
5. Hyper-threading



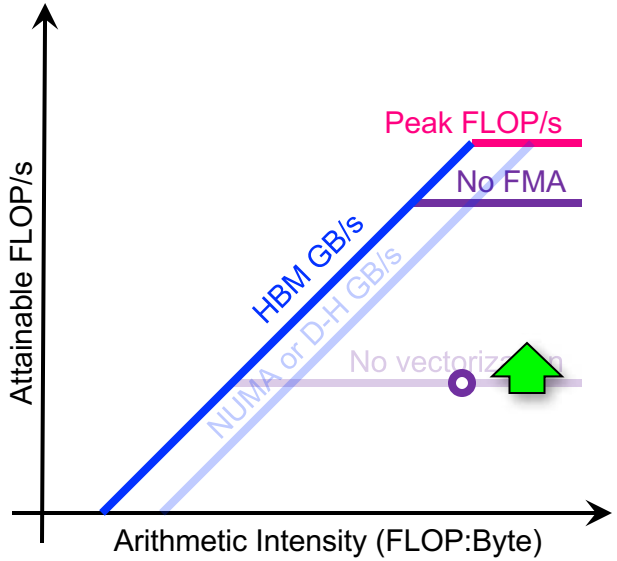
General Optimization Strategy

- **Broadly speaking, three approaches to improving performance:**



General Optimization Strategy

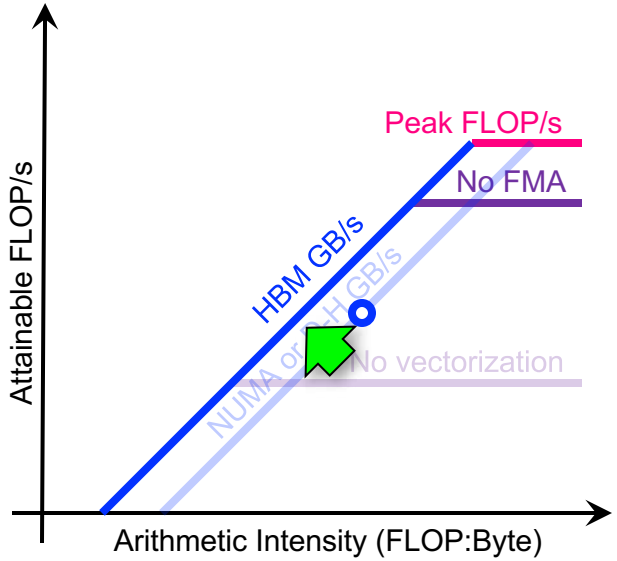
- Broadly speaking, three approaches to improving performance:
- Maximize compute performance
  - multithreading
  - vectorization
  - increase SM occupancy
  - utilize FMA instructions
  - minimize thread divergence



General Optimization Strategy

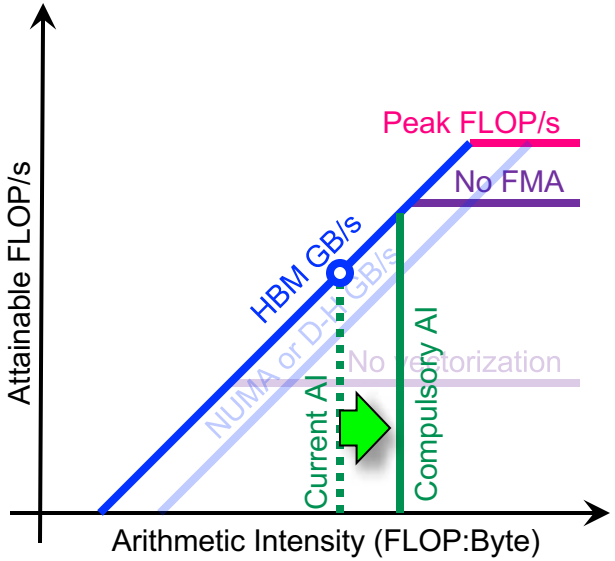
- Broadly speaking, three approaches to improving performance:
- Maximize compute performance

- Maximize memory bandwidth
  - utilize higher-level caches
  - NUMA-aware allocation
  - avoid H-D transfers
  - avoid uncoalesced memory access



General Optimization Strategy

- Broadly speaking, three approaches to improving performance:
- Maximize compute performance
- Maximize memory bandwidth
- Improve AI
  - minimize data movement
  - exploit cache reuse



Roofline Data Collection

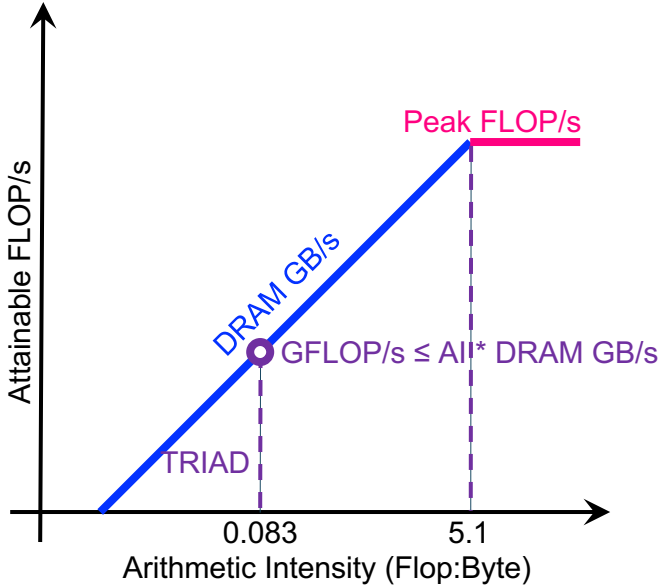
Pen and Paper

- **Example #1: STREAM Triad**

```
for(i=0;i<N;i++){
  Z[i] = X[i] + alpha*Y[i];
}
```

- 2 FLOPs per iteration
- Transfer 24 bytes per iteration
  - read X[i], Y[i], and write Z[i]

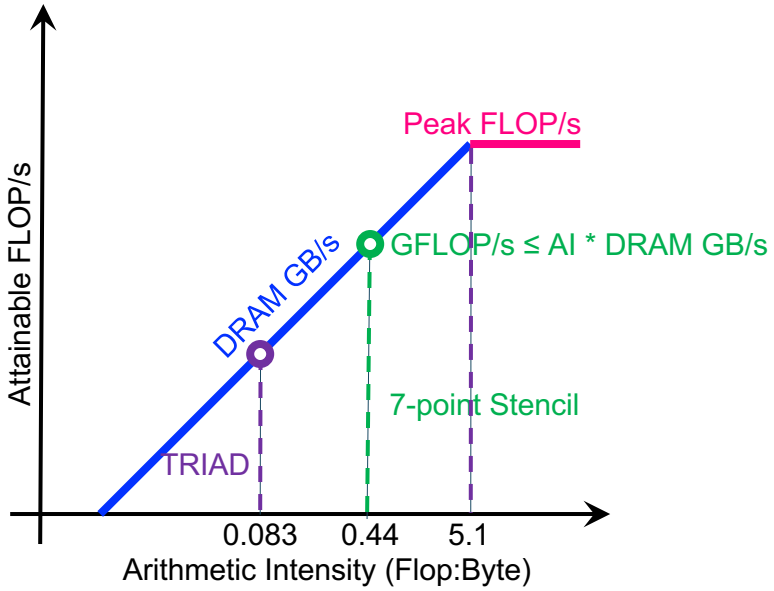
- **AI = 0.083 FLOPs per byte**
- **Memory bound**



Pen and Paper

- **Example #2: 7-pt stencil**
  - 7 FLOPs; 8 memory references (7 reads, 1 store) per pt
  - Cache can filter all but 1 read and 1 write per pt
  - AI = 0.44 FLOPs per byte
  - Memory bound, but 5x the GFLOP/s rate

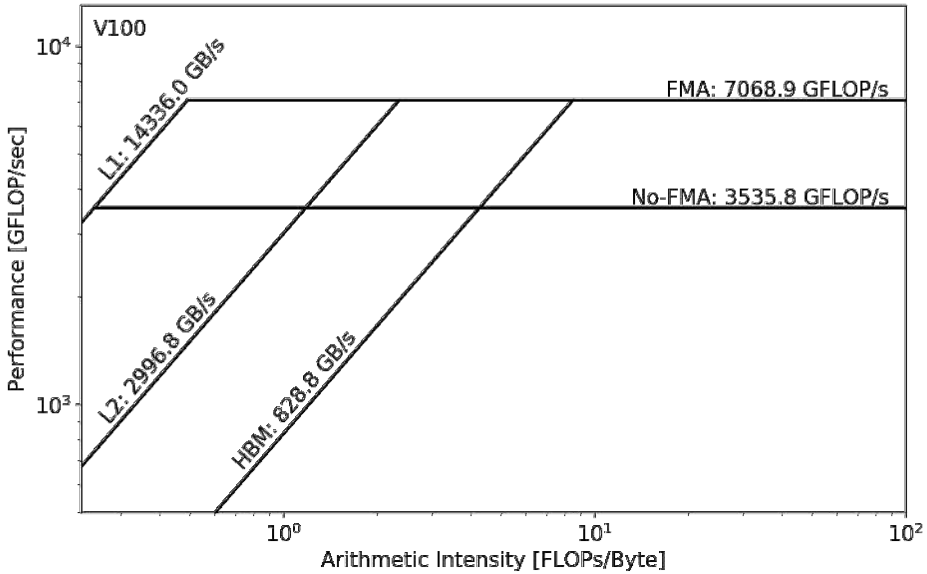
```
for(k=1;k<dim+1;k++){
for(j=1;j<dim+1;j++){
for(i=1;i<dim+1;i++){
  new[k][j][i] = -6.0*old[k  ][j  ][i  ]
                     + old[k  ][j  ][i-1]
                     + old[k  ][j  ][i+1]
                     + old[k  ][j-1][i  ]
                     + old[k  ][j+1][i  ]
                     + old[k-1][j  ][i  ]
                     + old[k+1][j  ][i  ];
}}}
```



Pen and Paper

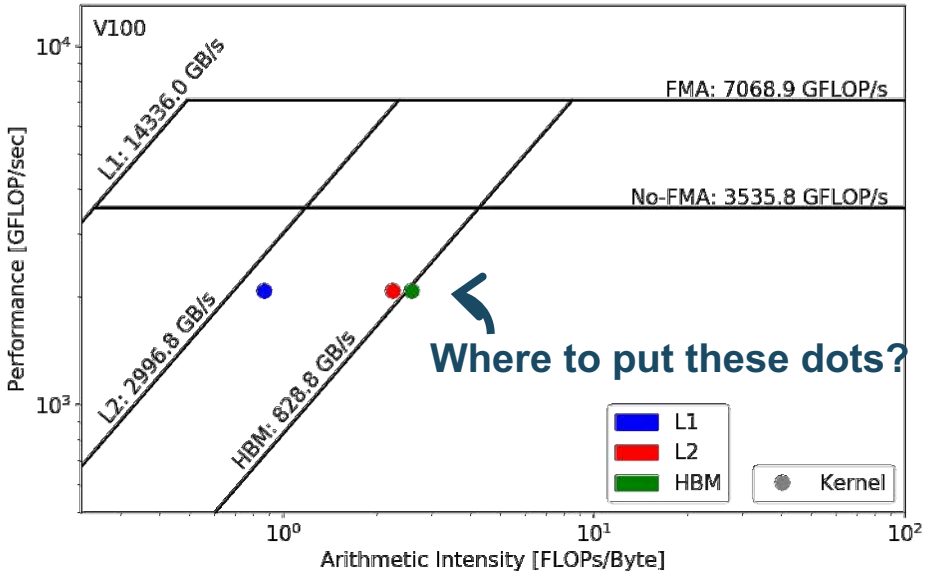
- Not scalable for real-life applications
- Millions of lines of code; mix of different languages
- Complicated modern architecture
  - memory hierarchy, caching effects
  - ISA
- Different problem sizes

We Need Tools!

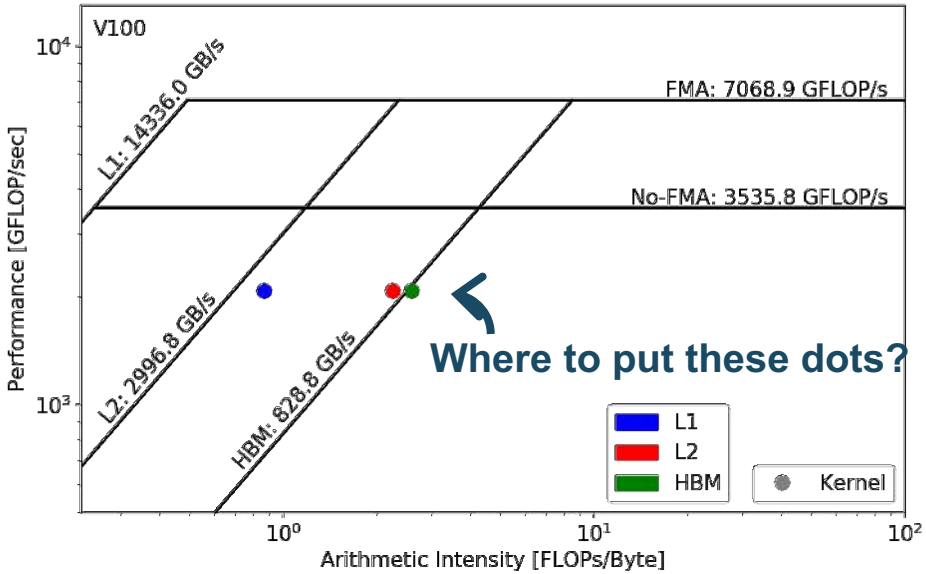


- **Roofline ceilings**
  - **vendor specifications**
  - **empirical measurements**
    - **ERT**
    - https://bitbucket.org/berkeleylab/cs-roofline-toolkit

We Need Tools!



We Need Tools!



Require three raw measurements:

- **Runtime**
- **FLOPs**
- **Bytes (on each cache level)**

In order to calculate AI and GFLOP/s:

$$\text{Arithmetic Intensity} = \frac{\text{FLOPs}}{\text{Data Movement}}$$

(FLOPs/Byte)

$$\text{Performance} = \frac{\text{FLOPs}}{\text{Runtime}}$$

(GFLOP/s)

Methodology to Construct Roofline

1. **Collect Roofline ceilings**
   - **compute** (FMA/no FMA) and **bandwidth** (DRAM, L2, …)
   - ERT: https://bitbucket.org/berkeleylab/cs-roofline-toolkit
2. **Collect application performance**
   - **FLOPs**, **bytes** (DRAM, L2, …), **runtime**
   - SDE, VTune, LIKWID, Advisor, nvprof, …
3. **Plot Roofline with Python Matplotlib (or other tools of your preference)**
   - **arithmetic intensity**, **GFLOP/s** performance, **ceilings**
   - example scripts: https://github.com/cyanguwa/nersc-roofline

Automated Data Collection

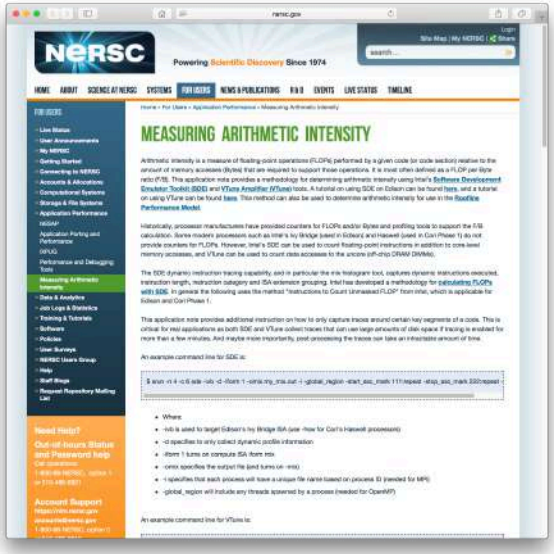
Data Collection on Intel CPUs

The not-so-automated way 1:

- Intel SDE for FLOPs (emulation)
- Intel VTune for DRAM bytes (HW counters)
- Runtime

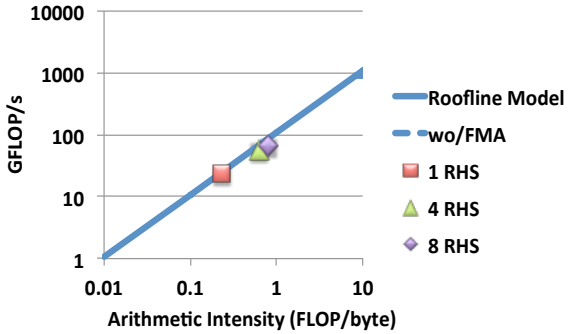
- DRAM Roofline only

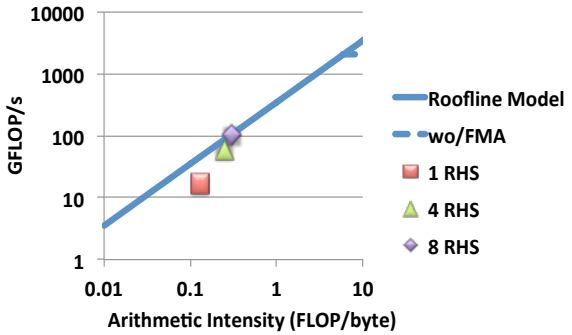
- Used by NESAP for Cori
  - NERSC Exascale Science Application Program
  - http://www.nersc.gov/users/application-performance/measuring-arithmetic-intensity/



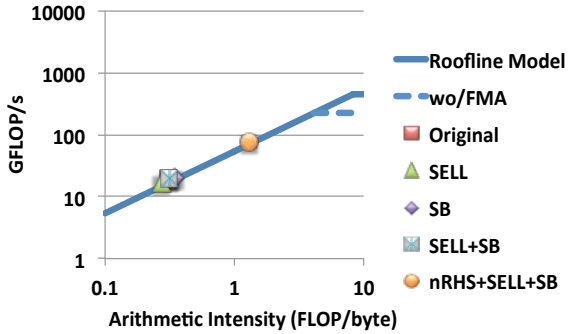
Data Collection on Intel CPUs

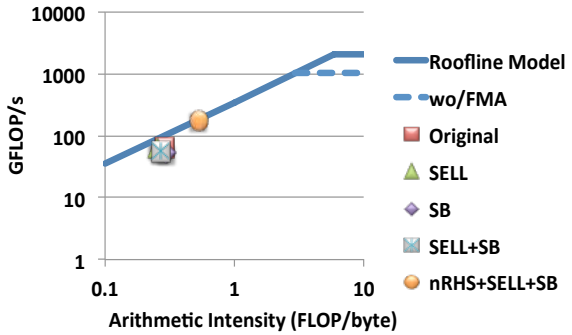
MFDn



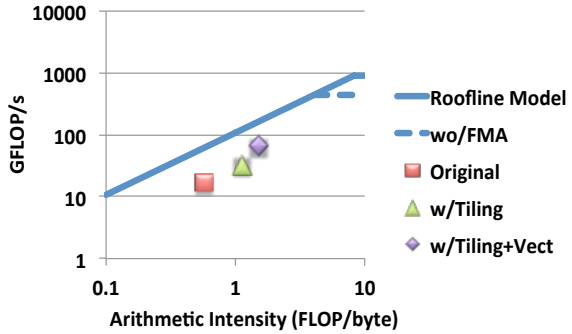


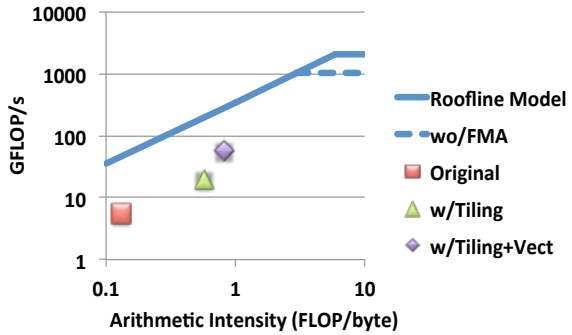
EMGeo





PICSAR





2P HSW

KNL

DRAM Rooflines of NESAP Codes

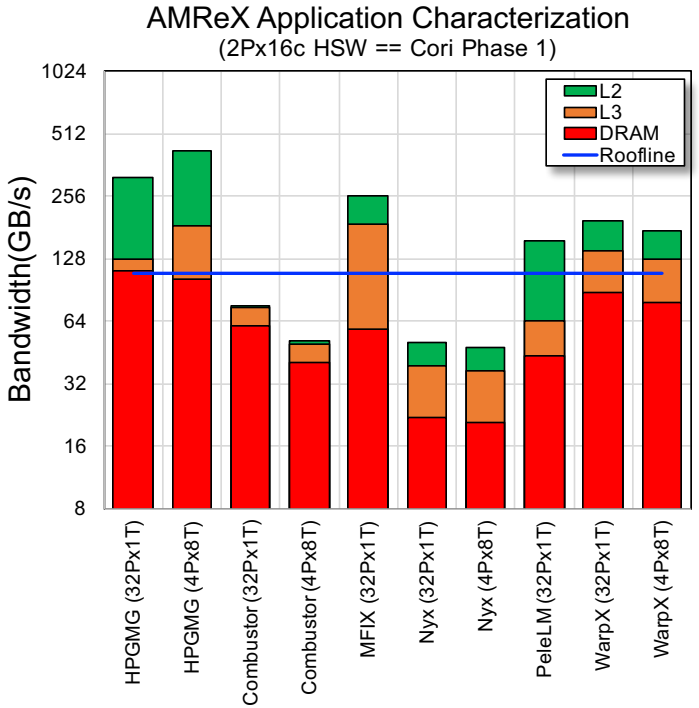
Data Collection on Intel CPUs

The not-so-automated way 2:

- **LIWID for FLOPs and bytes**
  - **Both are based on HW counters**
- **Runtime**

- **Hierarchical Roofline**

- **Limited by quality of HW counters**
- **High-level characterization, no callstack**



https://github.com/RRZE-HPC/likwid

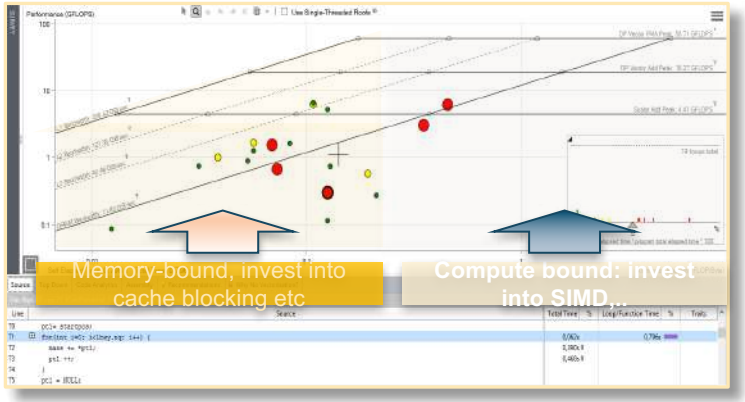
Data Collection on Intel CPUs

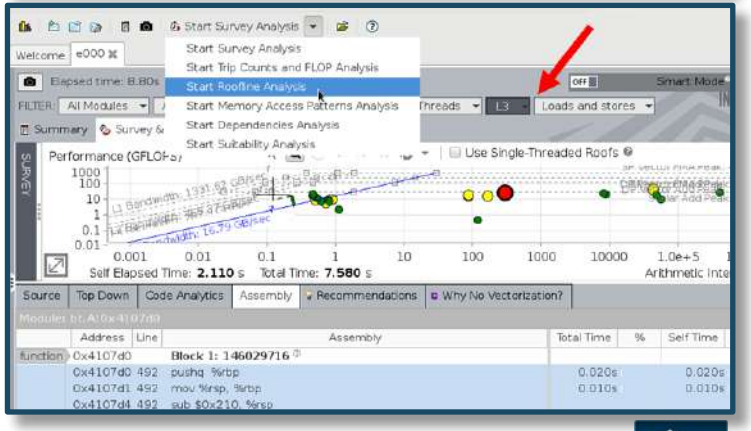
The fully automated way:

- Intel Advisor, Roofline feature
- Instrument applications **automatically**
  - one dot per loop nest/function
- **FLOPs**, **bytes** and **runtime**

- **Hierarchical** Roofline

- Integrates with other Advisor capabilities
- Benchmarks target system





Data Collection on NVIDIA GPUs

- Still very manual at this stage, but…
- Runtime:
  - Internal timers or `nvprof --print-gpu-trace`
- FLOPs:
  - DP/SP/HP counters and metrics, `nvprof --metrics 'flop_count_dp/sp/hp'` or `` `tensor_precision_fu_utilization' ``
- Bytes for different cache levels:
  - Bytes = (read transactions + write transactions) x transaction size
  - `nvprof --metrics 'metric_name'` e.g. `gld/gst_transactions`
- **Hierarchical Roofline**

Summary

- The Roofline Model formulizes the interaction between machine characteristics and application characteristics, and guides optimization
  - Peak computational throughput and bandwidth
  - Arithmetic intensity, cache locality, instruction mix…

- Automate Roofline data collection
  - Intel CPUs
    - Intel SDE + Intel VTune, Intel Advisor
  - NVIDIA GPUs
    - nvprof, Nsight Compute

More in the next few talks!

Reference

- S. Williams, A. Waterman and D. Patterson, “Roofline: An Insightful Visual Performance Model for Multicore Architectures,” *Communications of the ACM*, vol. 52, no. 4, pp. 65–76, 2009
- LBNL CRD Roofline Research:
  https://crd.lbl.gov/departments/computer-science/PAR/research/roofline
- Empirical Roofline Toolkit (ERT):
  https://bitbucket.org/berkeleylab/cs-roofline-toolkit
- Python scripts for plotting manually-collected Roofline:
  https://github.com/cyanguwa/nersc-roofline/tree/master/Plotting

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Thank You