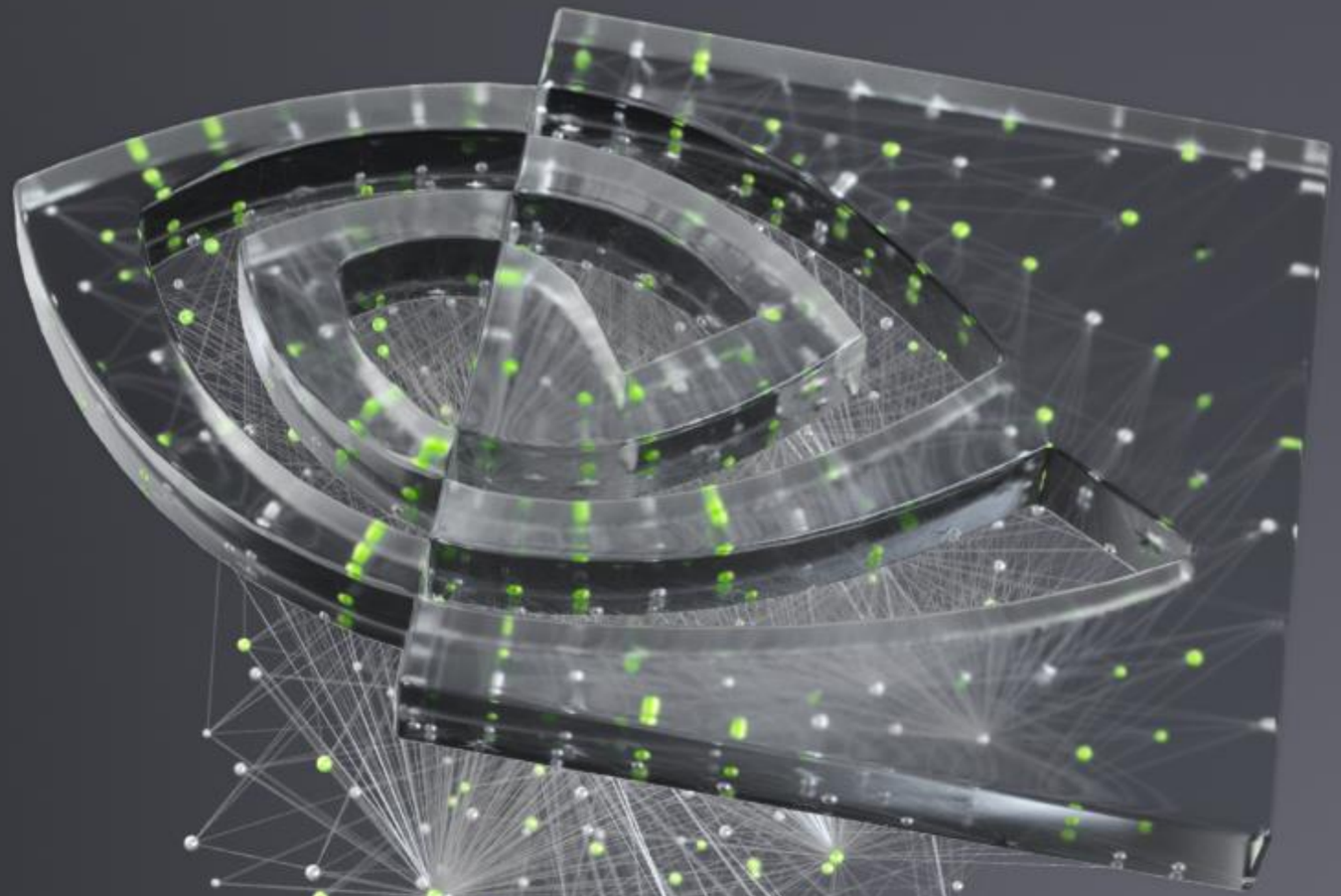
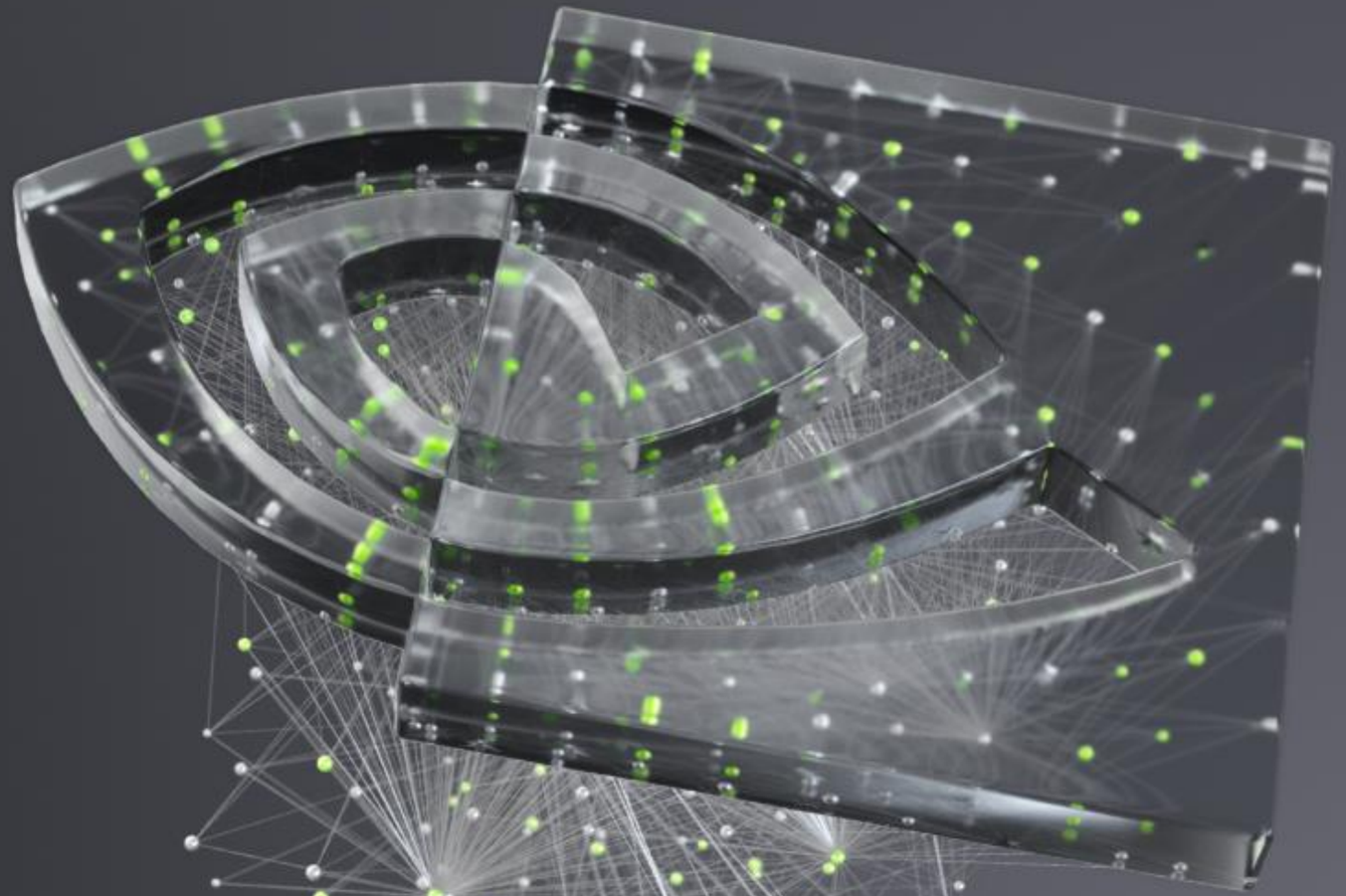


HOW GPU COMPUTING WORKS

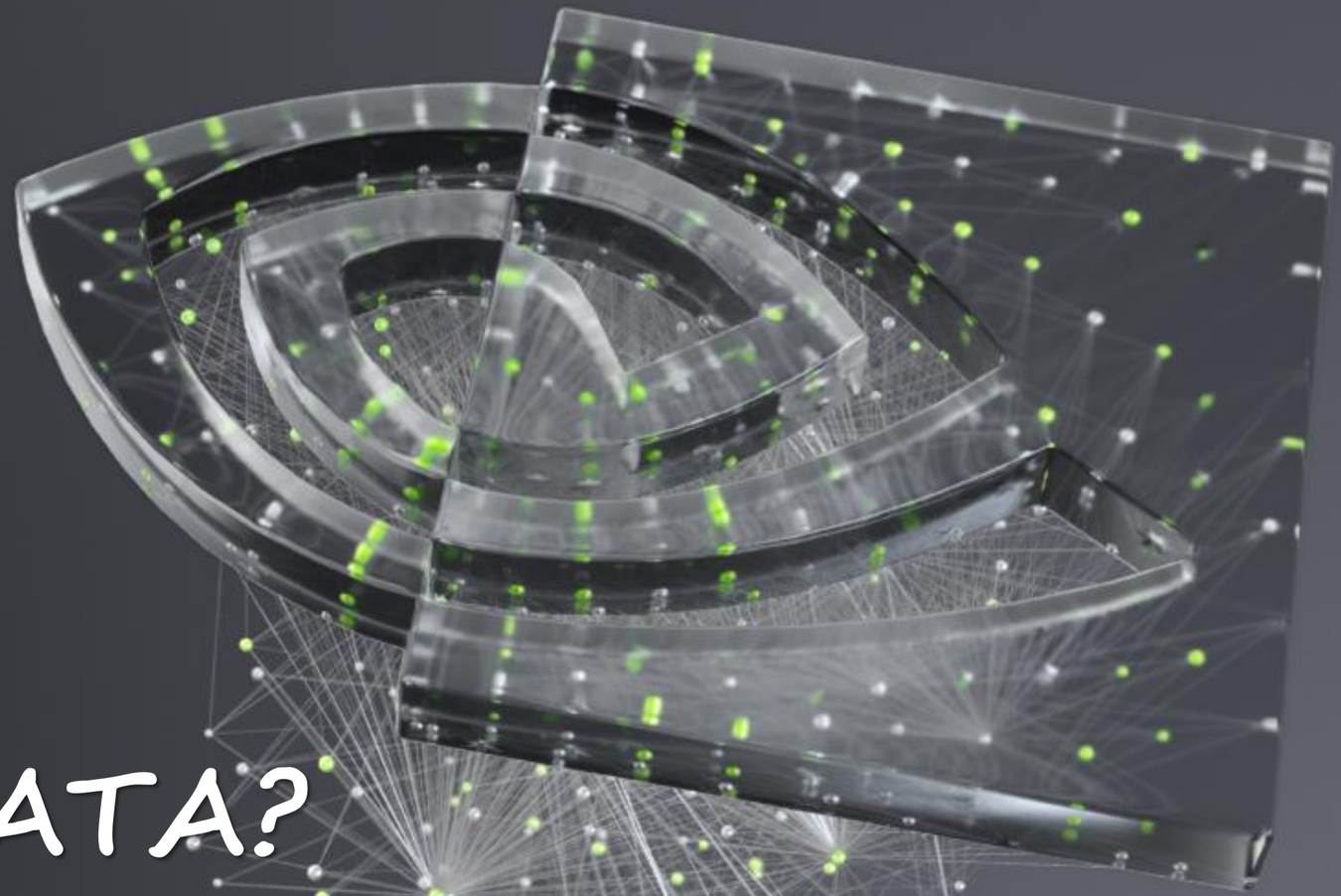
Stephen Jones, GTC 2021



NVIDIA

WHY ~~HOW~~ GPU COMPUTING WORKS

Stephen Jones, GTC 2021



NVIDIA

WHERE'S MY DATA?

WHY HOW GPU COMPUTING WORKS

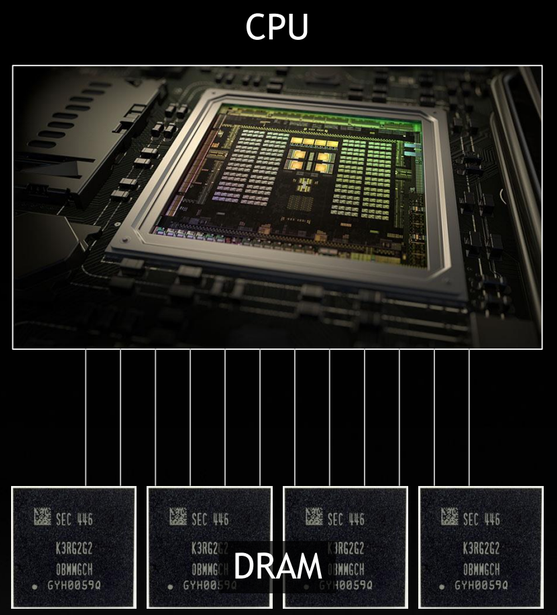
Stephen Jones, GTC 2021

NOBODY CARES ABOUT FLOPs

REALLY

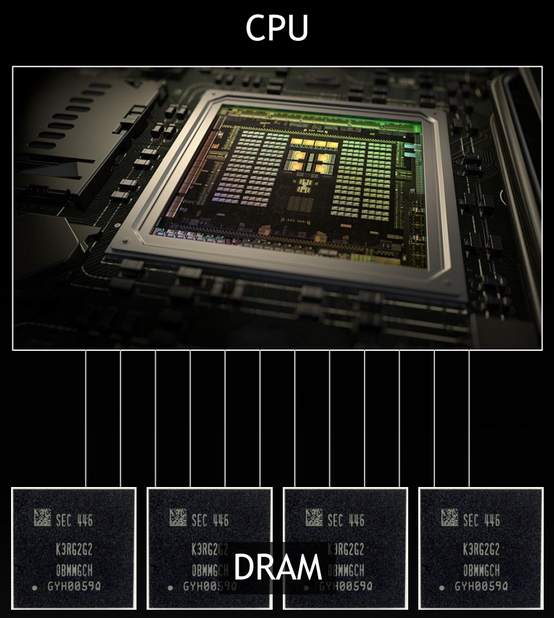
ALMOST NOBODY CARES ABOUT FLOPs

^


CPU
SEC 446
K3RG2G2
DRAM

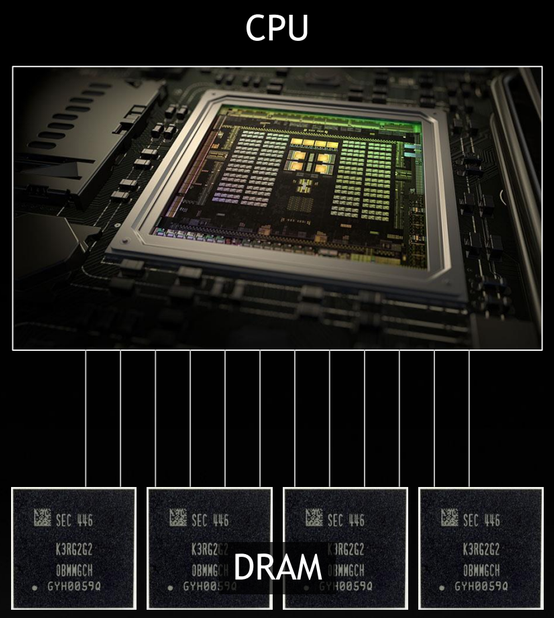
2000 GFLOPs FP64

200 GBytes / sec



2000 GFLOPs FP64

200 GBytes / sec
= 25 Giga-FP64 / sec
(because FP64 = 8 bytes)



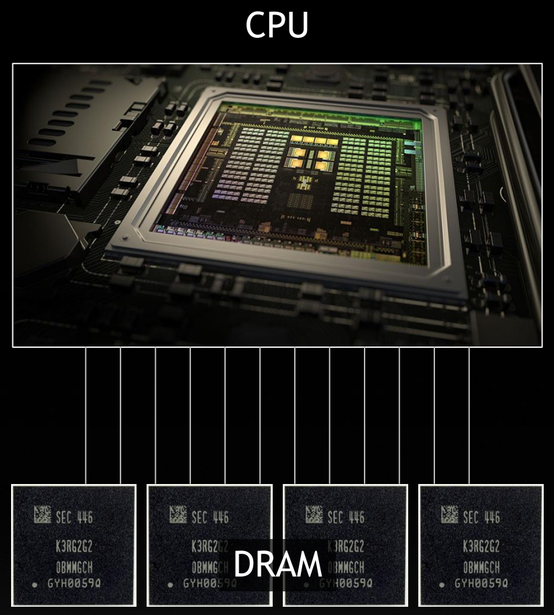
THIS IS COMPUTE INTENSITY

How many operations must I do on some data to make it worth the cost of loading it?

$$\text{Required Compute Intensity} = \frac{\text{FLOPs}}{\text{Data Rate}} = \mathbf{80}$$

2000 GFLOPs FP64

200 GBytes / sec
= 25 Giga-FP64 / sec
(because FP64 = 8 bytes)



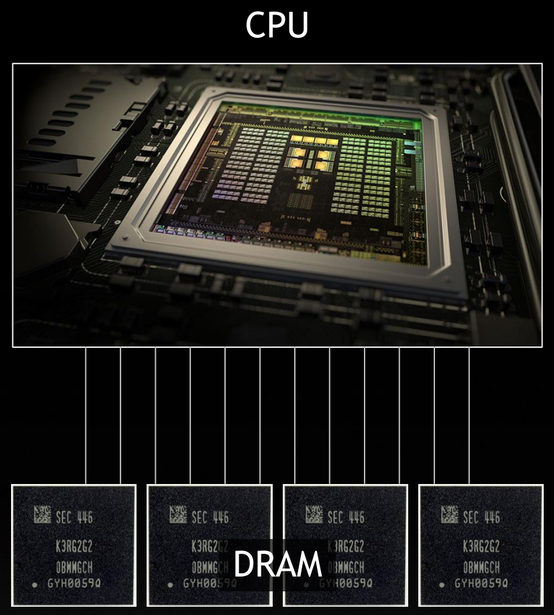
THIS IS COMPUTE INTENSITY

How many operations must I do on some data to make it worth the cost of loading it?

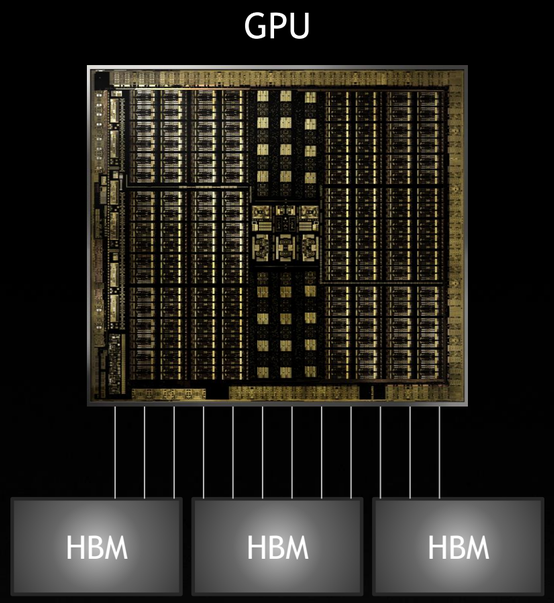
$$\text{Required Compute Intensity} = \frac{\text{FLOPs}}{\text{Data Rate}} = \mathbf{80}$$

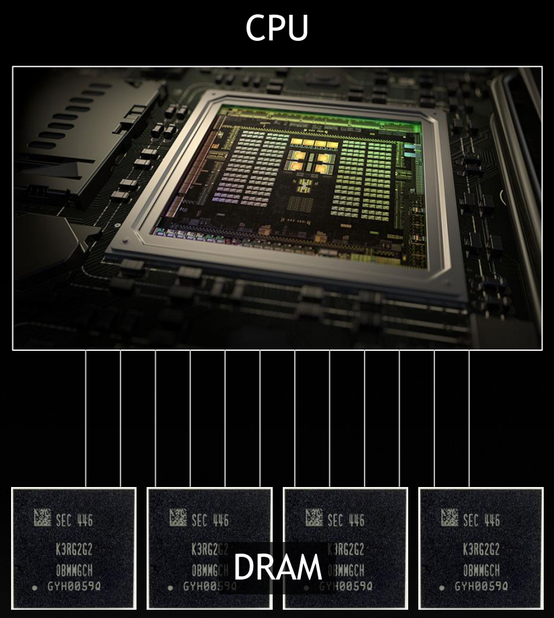
2000 GFLOPs FP64

200 GBytes / sec
= 25 Giga-FP64 / sec
(because FP64 = 8 bytes)



So for every number I load from memory, I need to do **80** operations on it to break even





	NVIDIA A100	Intel Xeon 8280	AMD Rome 7742
Peak FP64 GigaFLOPs	19500	2190	2300
Memory B/W (GB/sec)	1555	131	204
Compute Intensity	100	134	90

REALLY

ALMOST NOBODY CARES ABOUT FLOPs

^

...BECAUSE WE SHOULD REALLY BE CARING ABOUT

MEMORY BANDWIDTH

REALLY

ALMOST NOBODY CARES ABOUT FLOPs

^

...BECAUSE WE SHOULD REALLY BE CARING ABOUT

~~MEMORY BANDWIDTH~~ LATENCY

DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)

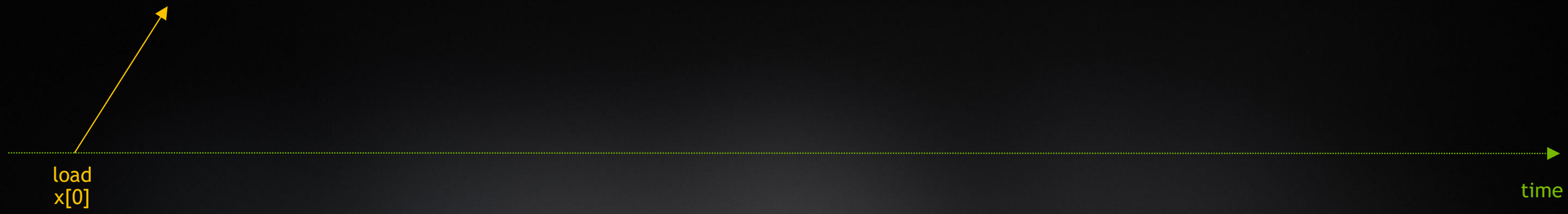
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)



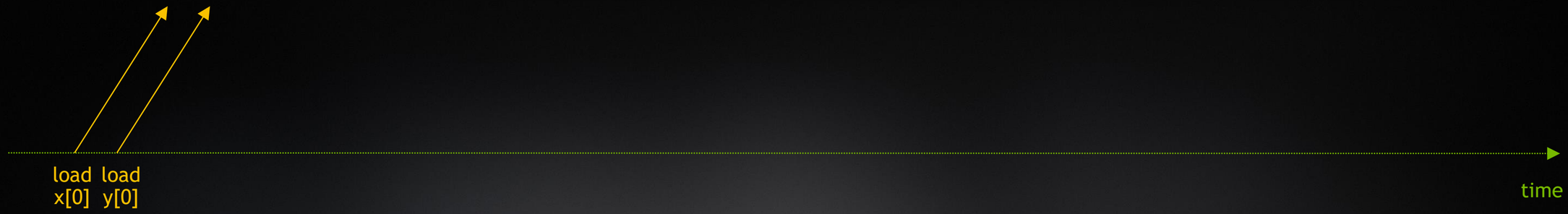
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)



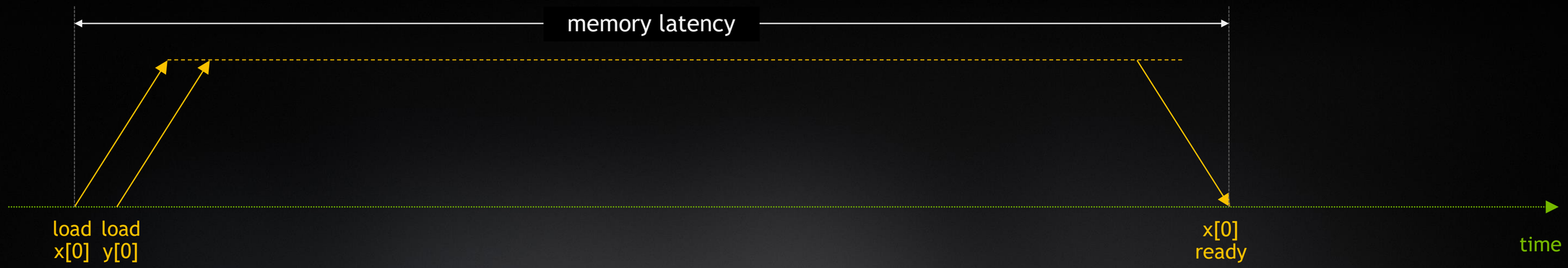
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)



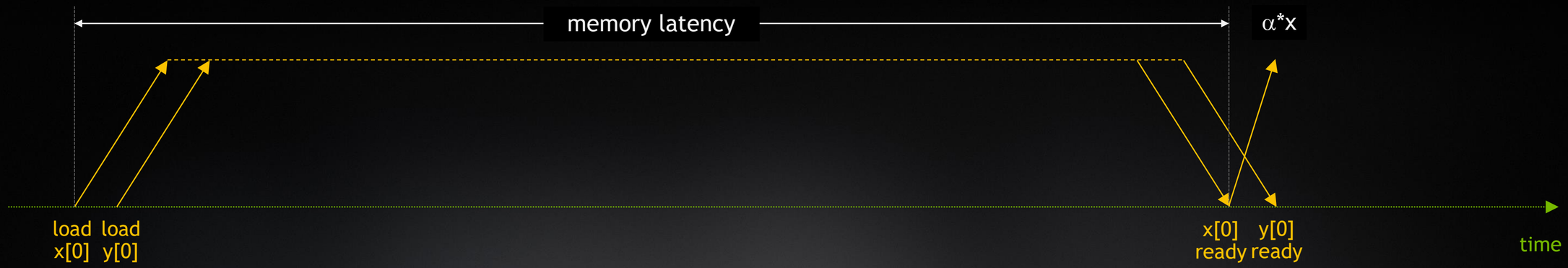
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)



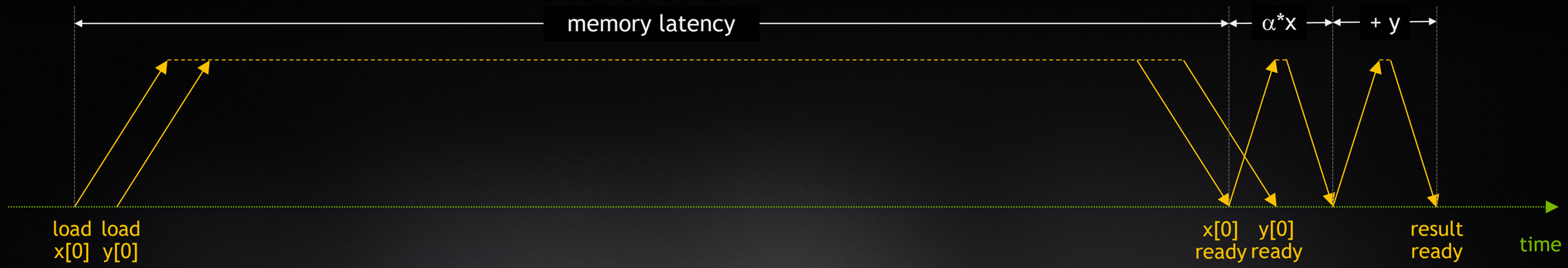
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

2 FLOPs: multiply & add

2 memory loads: x[i] & y[i] (per element)

Single operation: FMA (fused multiply-add)



SPEED OF LIGHT = 300,000,000 M/S

SPEED OF LIGHT = 300,000,000 M/S

COMPUTER CLOCK = 3,000,000,000 Hz

SPEED OF LIGHT = 300,000,000 M/S

COMPUTER CLOCK = 3,000,000,000 Hz

So in 1 clock tick light travels 100mm (~4 inches)

SPEED OF LIGHT = 300,000,000 M/S

COMPUTER CLOCK = 3,000,000,000 Hz

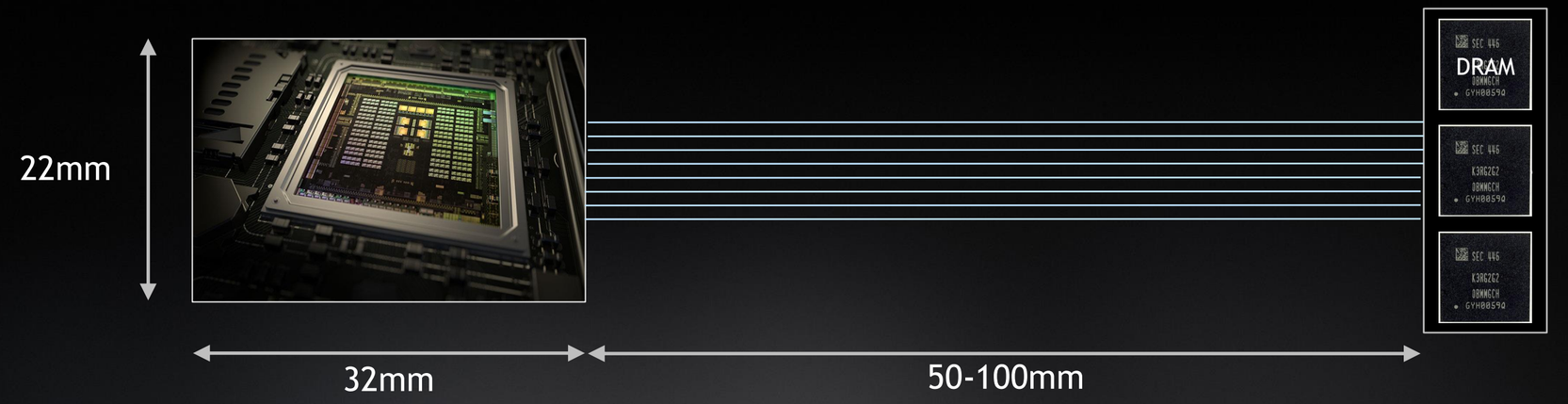
SPEED OF ELECTRICITY IN SILICON = 60,000,000 M/S

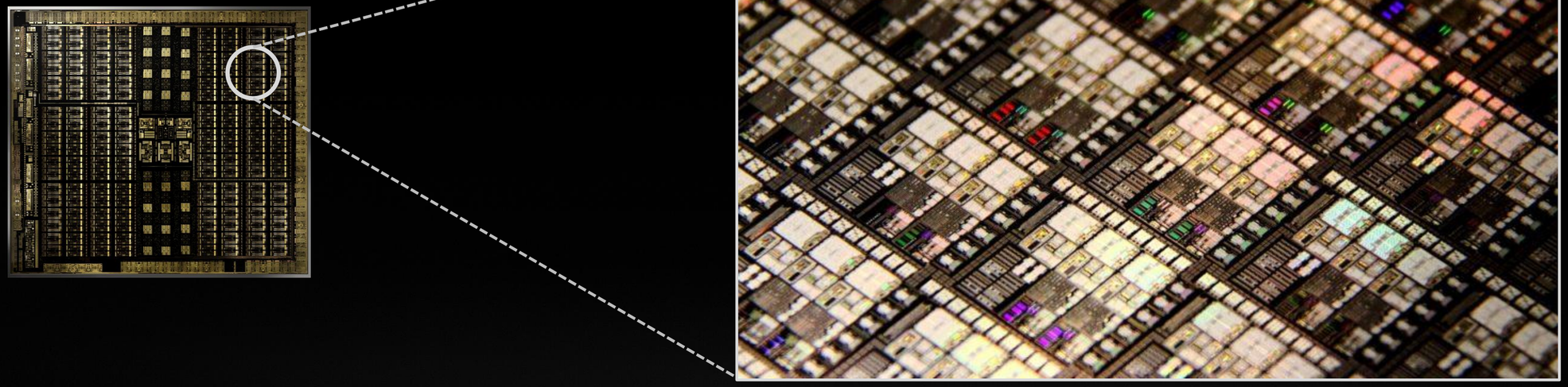
So in 1 clock tick **electricity** travels 20mm (~0.8 inches)

SPEED OF LIGHT = 300,000,000 M/S

COMPUTER CLOCK = 3,000,000,000 Hz

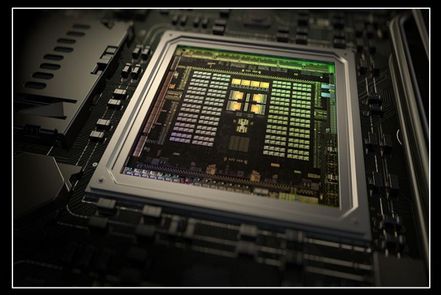
SPEED OF ELECTRICITY IN SILICON = 60,000,000 M/S





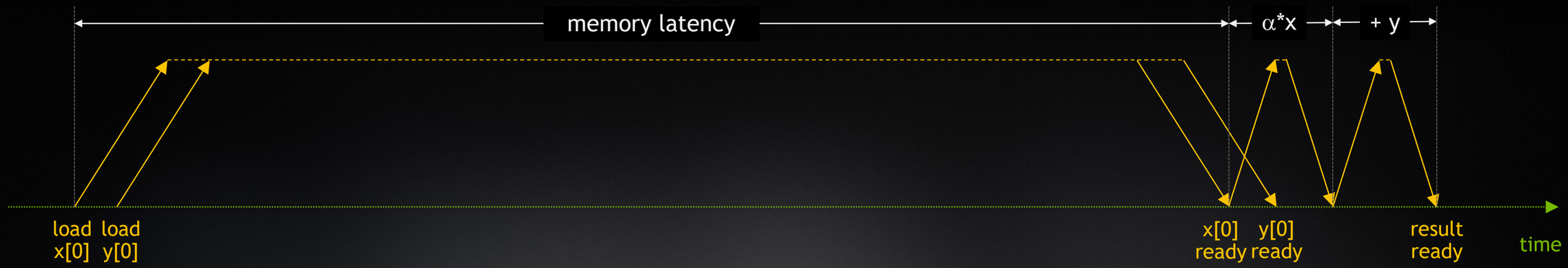
DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

Intel Xeon 8280



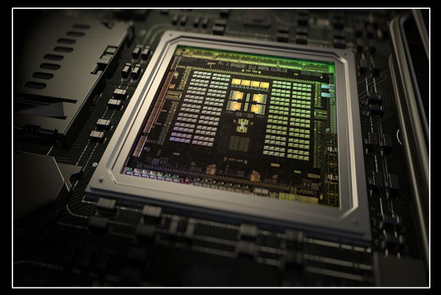
Memory bandwidth: 131 GB/sec

Memory latency: 89 ns



DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

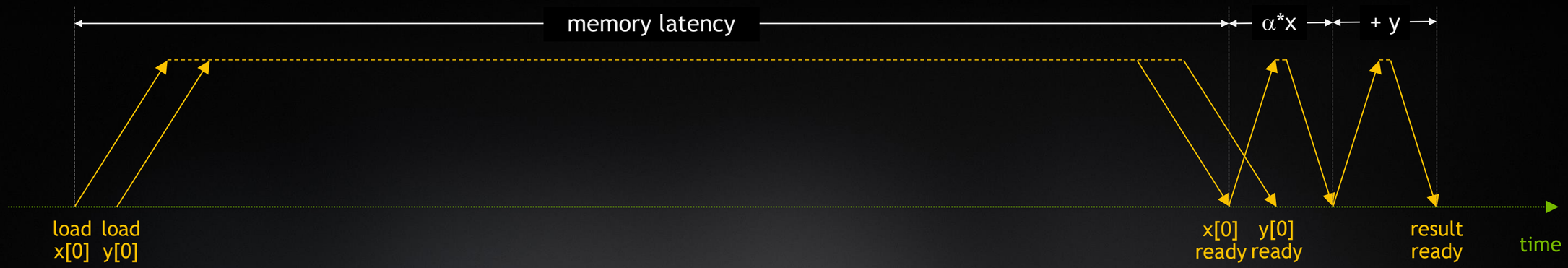
Intel Xeon 8280



Memory bandwidth: 131 GB/sec

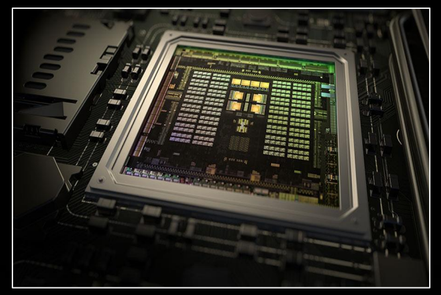
Memory latency: 89 ns

11,659 bytes can be moved in 89ns



DAXPY: $\alpha\underline{X} + \underline{Y} = \underline{Z}$

Intel Xeon 8280



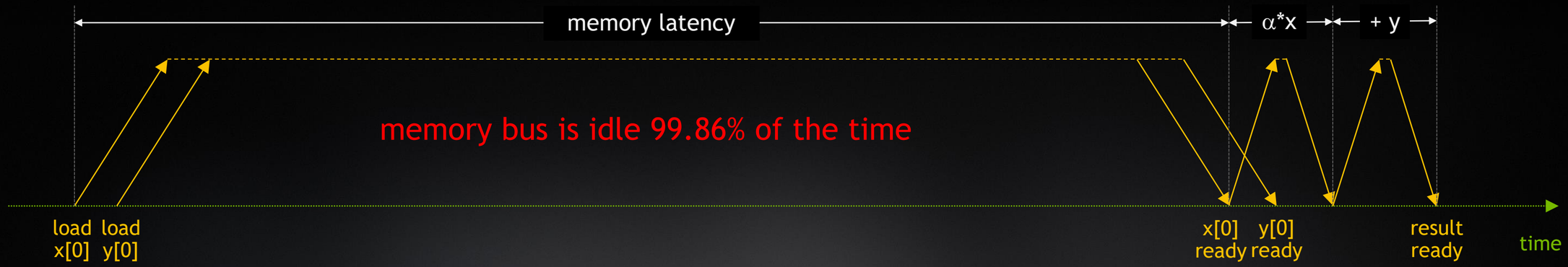
Memory bandwidth: 131 GB/sec

Memory latency: 89 ns

11,659 bytes can be moved in 89ns

daxpy moves 16 bytes per 89ns latency

Memory efficiency = 0.14%



COMPARISON OF DAXPY* EFFICIENCY ON DIFFERENT CHIPS

	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	131
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	11,659
Memory efficiency	0.0025%	0.064%	0.14%

**daxpy* moves 16 bytes per latency

SO WHAT CAN WE DO ABOUT IT?

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

11,659 bytes can be moved in 89ns

daxpy moves 16 bytes per 89ns latency

Memory efficiency = 0.14%

To keep memory bus busy, we must run $\frac{11,659}{16}$ = **729** iterations at once

LOOP UNROLLING

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i += 8 )
    {
        y[i+0] = alpha * x[i+0] + y[i+0];
        y[i+1] = alpha * x[i+1] + y[i+1];
        y[i+2] = alpha * x[i+2] + y[i+2];
        y[i+3] = alpha * x[i+3] + y[i+3];
        y[i+4] = alpha * x[i+4] + y[i+4];
        y[i+5] = alpha * x[i+5] + y[i+5];
        y[i+6] = alpha * x[i+6] + y[i+6];
        y[i+7] = alpha * x[i+7] + y[i+7];
    }
}
```

Compilers rarely unroll a loop 729 times

Just one thread issuing all these commands

One thread cannot hold 729 outstanding loads

To keep memory bus busy, we must run $\frac{11{,}659}{16}$ = **729** iterations at once

THE ONLY OPTION IS THREADS

```
void daxpy(int n, double alpha, double *x, double *y)
{
    parallel for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

Each thread issues load operations independently

Ideally requires 729 threads

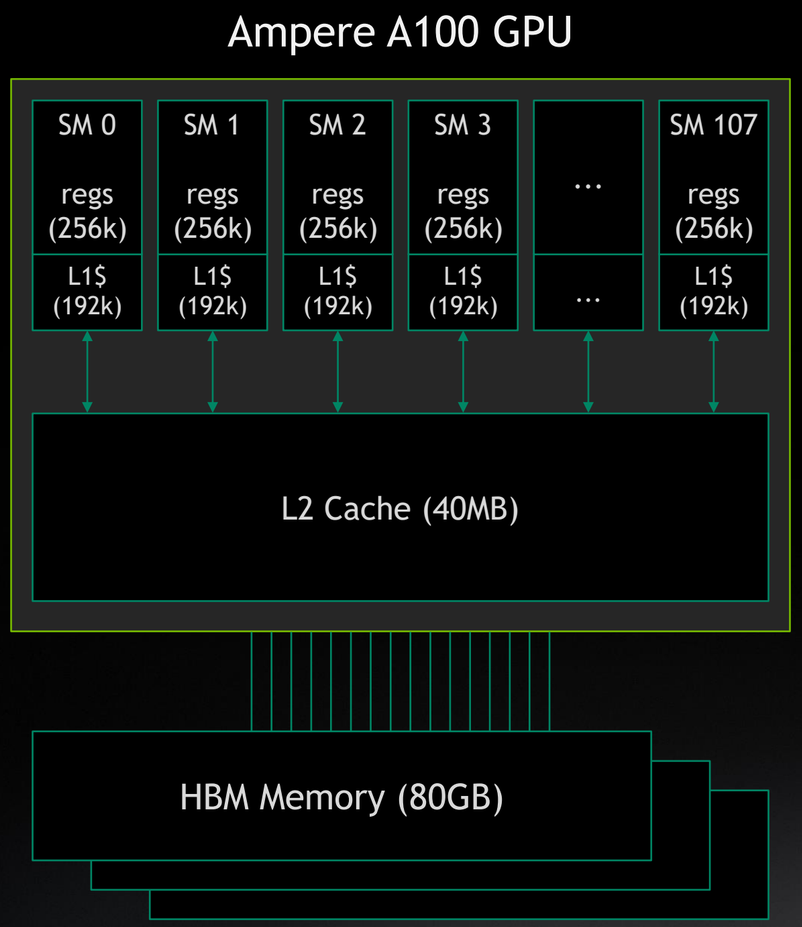
Limited by max threads & memory requests

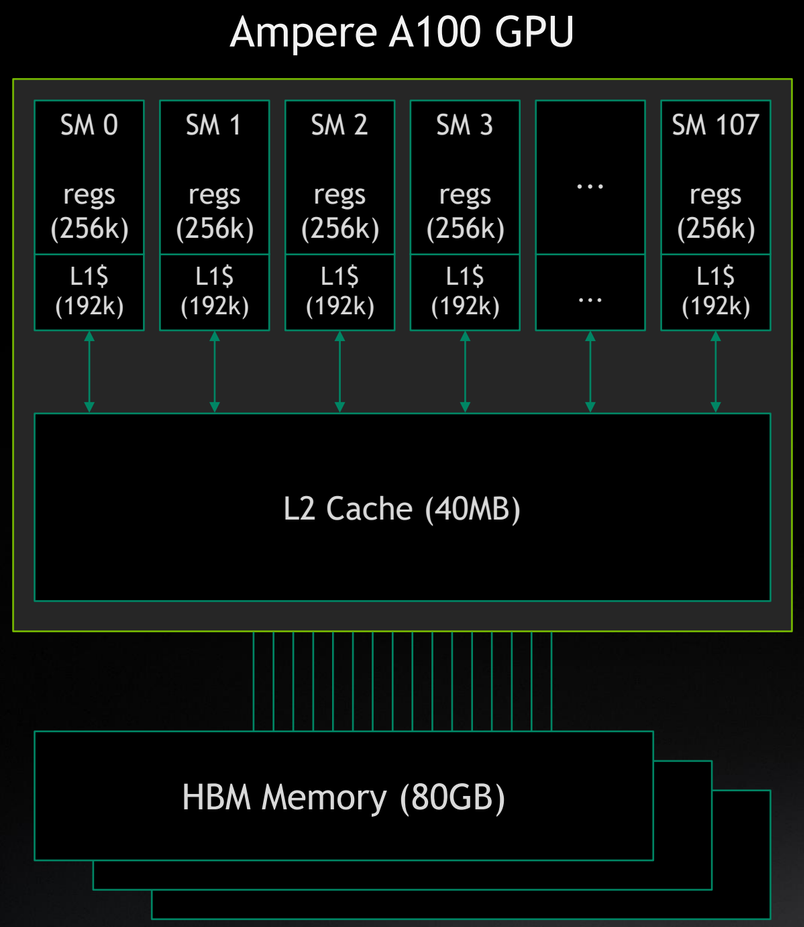
To keep memory bus busy, we must run $\frac{11{,}659}{16}$ = **729** iterations at once

COMPARISON OF DAXPY* EFFICIENCY ON DIFFERENT CHIPS

	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	**5.6x**	**1.3x**	**1.2x**

**daxpy* moves 16 bytes per latency


Ampere A100 GPU
SM 0
regs (256k)
L1$ (192k)
SM 1
regs (256k)
L1$ (192k)
SM 2
regs (256k)
L1$ (192k)
SM 3
regs (256k)
L1$ (192k)
…
…
SM 107
regs (256k)
L1$ (192k)
L2 Cache (40MB)
HBM Memory (80GB)



108 Streaming Multiprocessors (SMs)

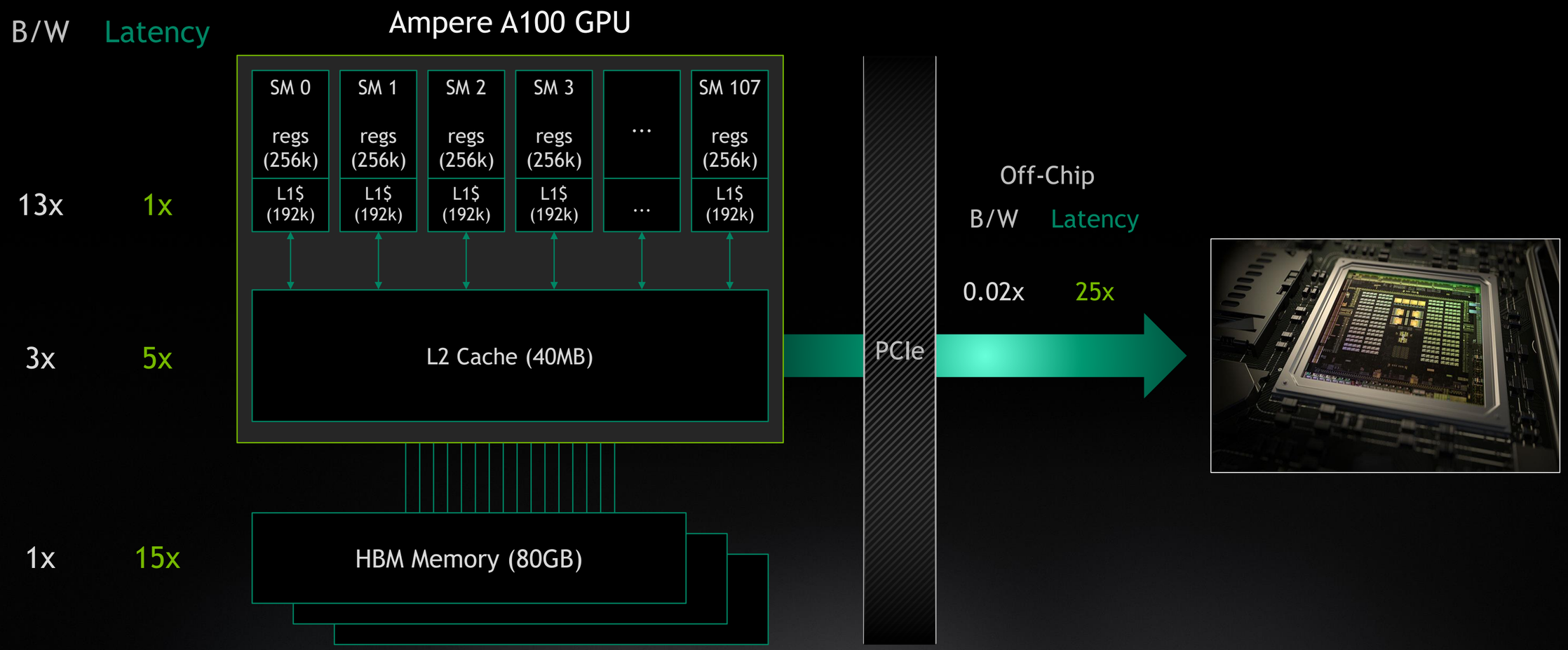
256kB Register File per SM (27MB total)

192kB L1 Cache & Shared Memory per SM (20MB total)

40MB L2 cache shared across all SMs

caches

80GB High Bandwidth Memory

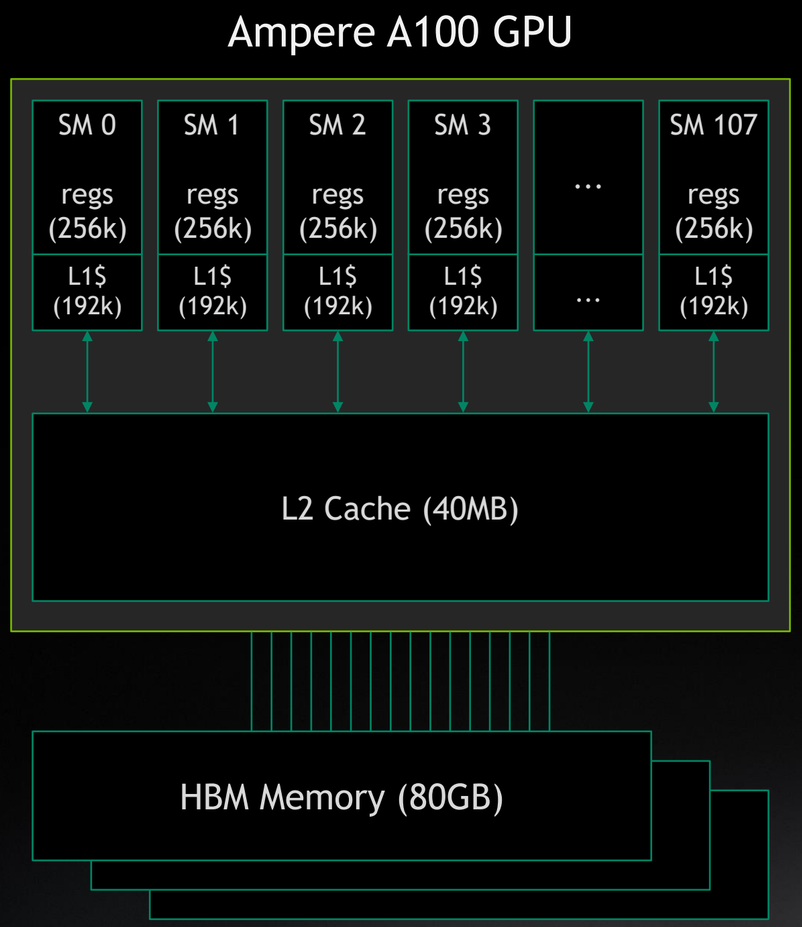

B/W
Latency
Ampere A100 GPU
SM 0
regs (256k)
L1$ (192k)
SM 1
regs (256k)
L1$ (192k)
SM 2
regs (256k)
L1$ (192k)
SM 3
regs (256k)
L1$ (192k)
...
...
SM 107
regs (256k)
L1$ (192k)
13x
1x
L2 Cache (40MB)
3x
5x
HBM Memory (80GB)
1x
15x
PCIe
Off-Chip
B/W
Latency
0.02x
25x

B/W Latency

13x 1x

3x 5x

1x 15x



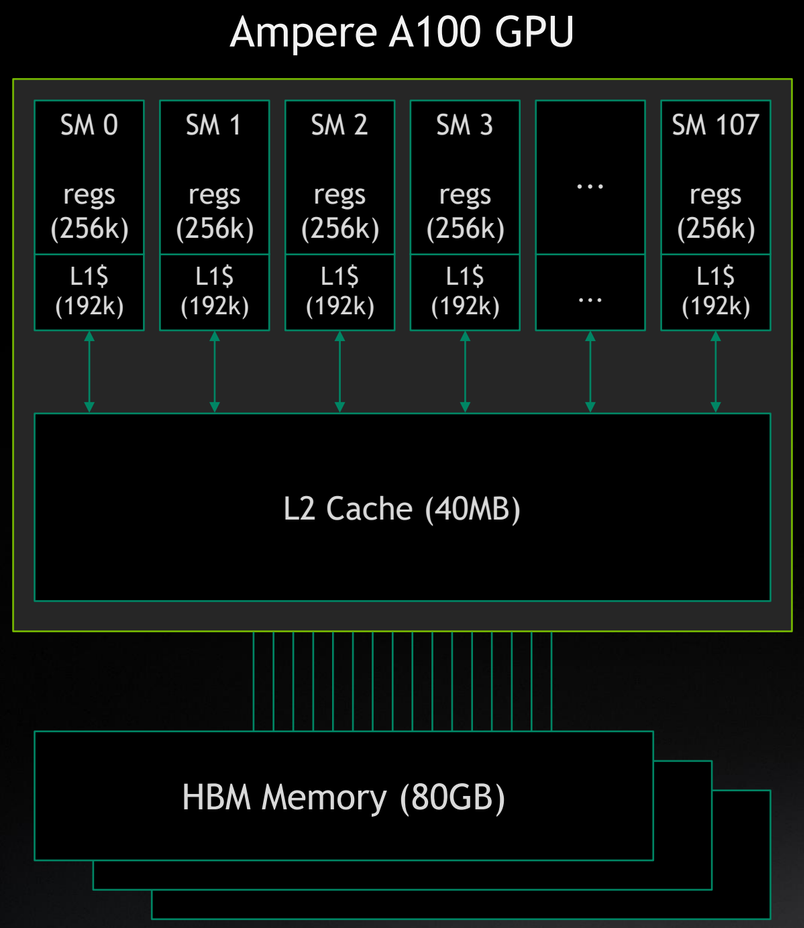
Data Location	Bandwidth (GB/sec)	Compute Intensity
L1 Cache	19,400	8
L2 Cache	4,000	39
HBM	1,555	100
NVLink	300	520
PCIe	25	6240

B/W Latency

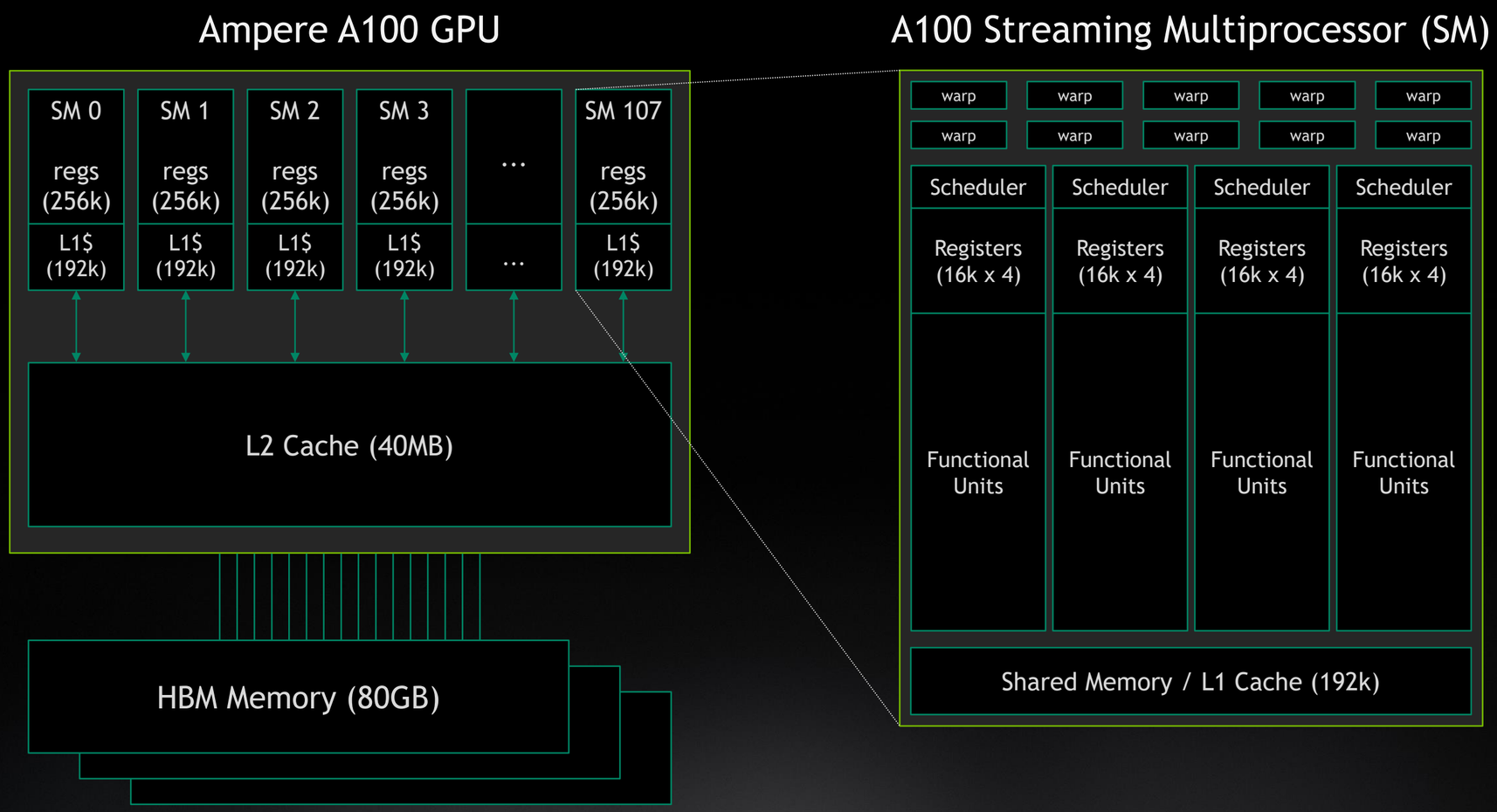
13x 1x

3x 5x

1x 15x



Data Location	Latency (ns)	Threads Required
L1 Cache	27	32,738
L2 Cache	150	37,500
HBM	404	39,264
NVLink	700	13,125
PCIe	1470	2297

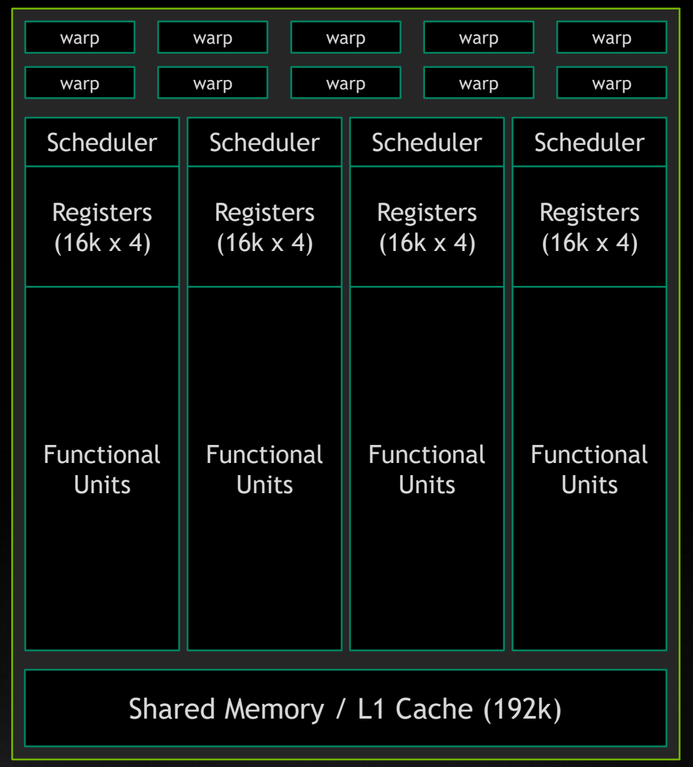


The GPU runs threads in groups of 32 - each group is known as a **warp**

THE GPU'S SECRET SAUCE: OVERSUBSCRIPTION

	Per SM	On A100
Total Threads	2048	221,184
Total Warps	64	6,912
Active Warps	4	432
Waiting Warps	60	6,480
Active Threads	128	13,824
Waiting Threads	1,920	207,360

A100 Streaming Multiprocessor (SM)



64 warps/SM

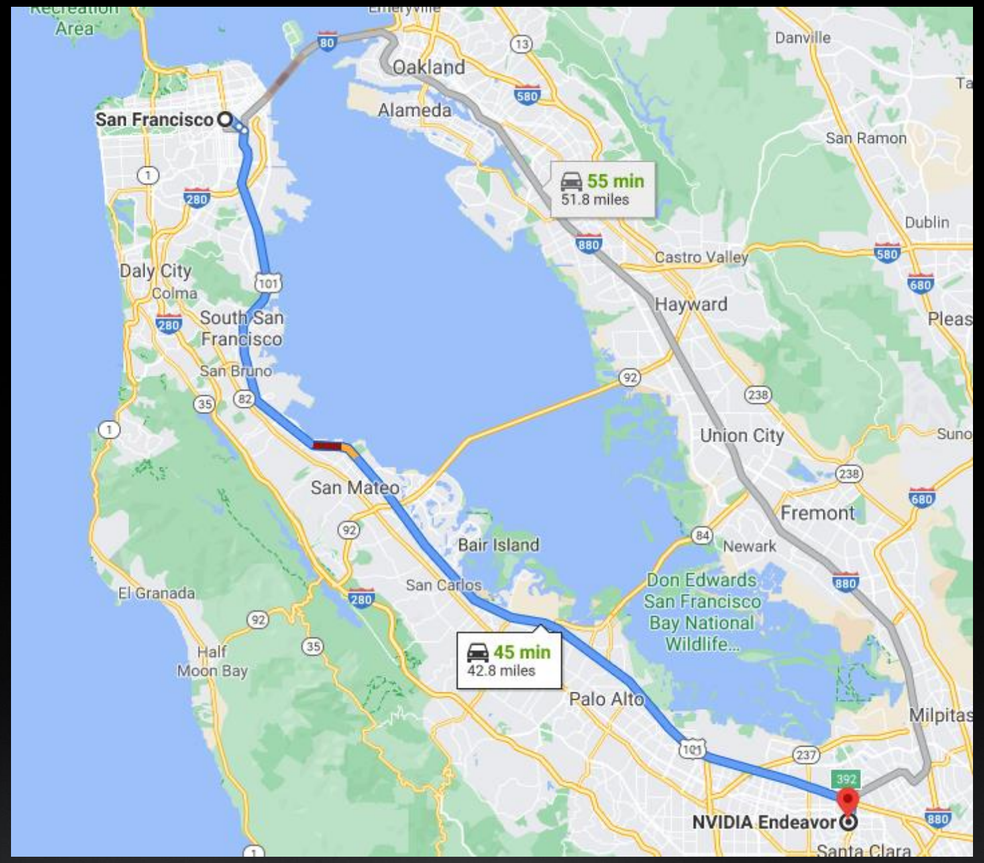
4x concurrent warp exec

64k x 4-byte registers

192KB L1/shared memory (configurable split)

The GPU can switch from one warp to the next in a **single clock cycle**

THROUGHPUT VS. LATENCY



San Francisco

Millbrae

Burlingame

Belmont

Redwood City

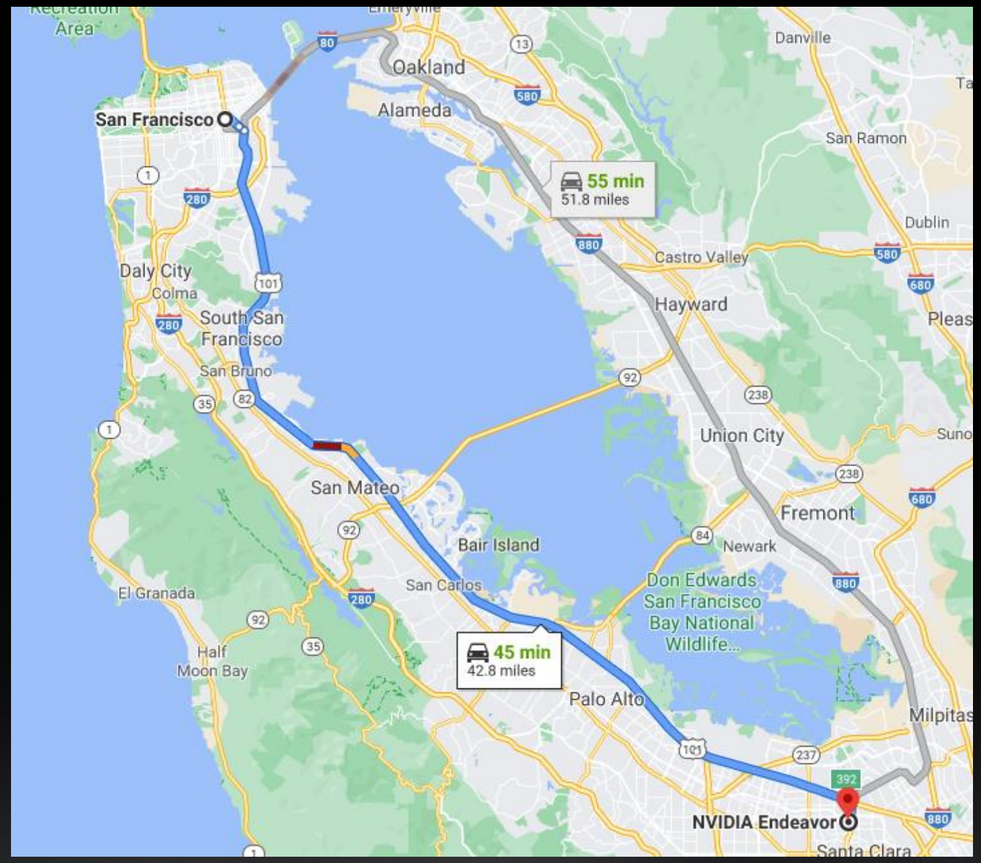
Palo Alto

Mountain View

Sunnyvale

NVIDIA

73 Minutes



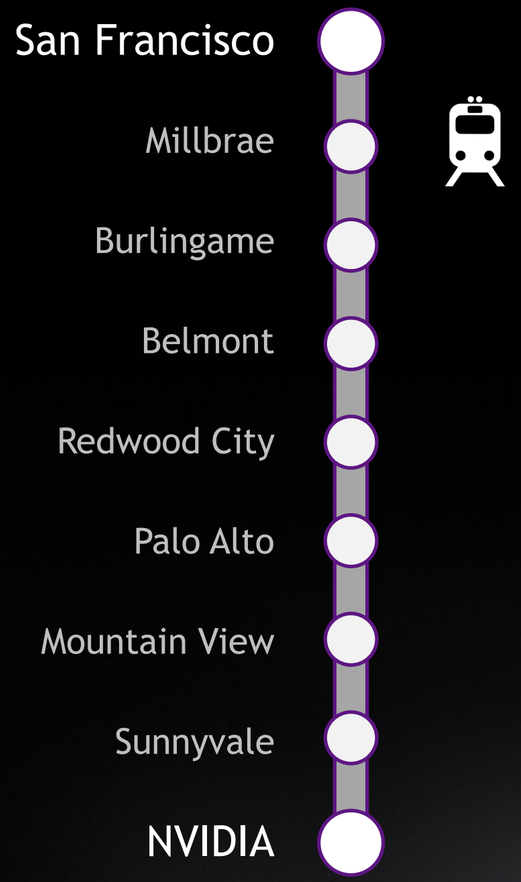
San Francisco

NVIDIA

45 Minutes

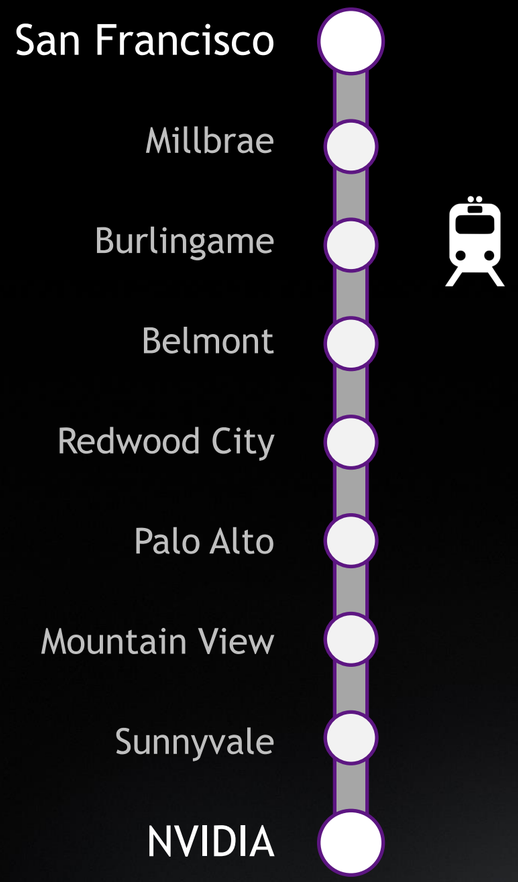
73 Minutes

45 Minutes



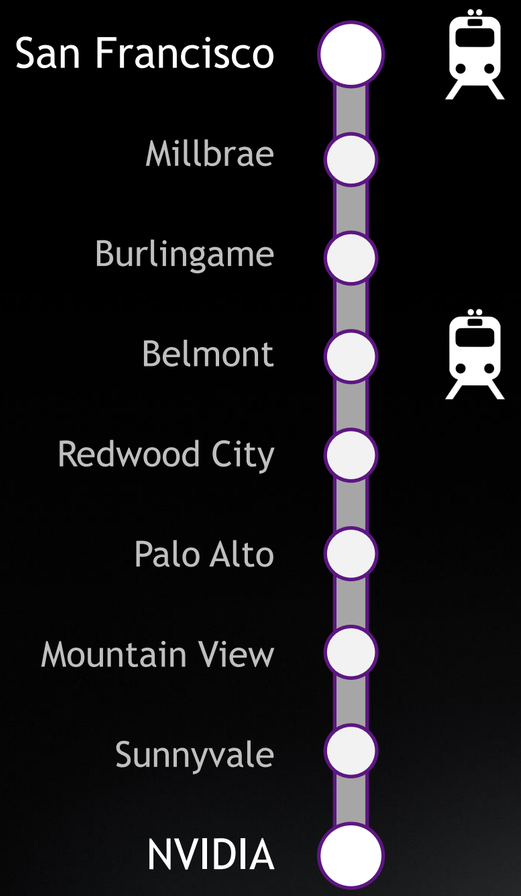
73 Minutes

45 Minutes



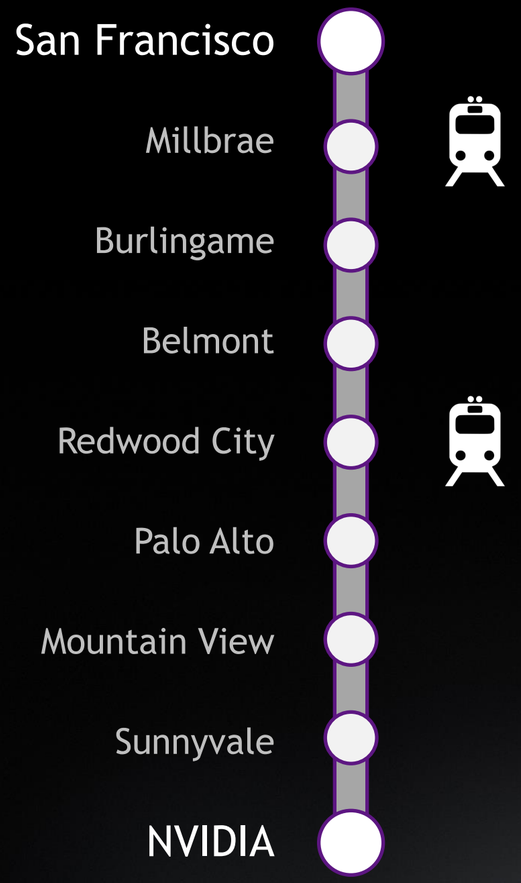
73 Minutes

45 Minutes



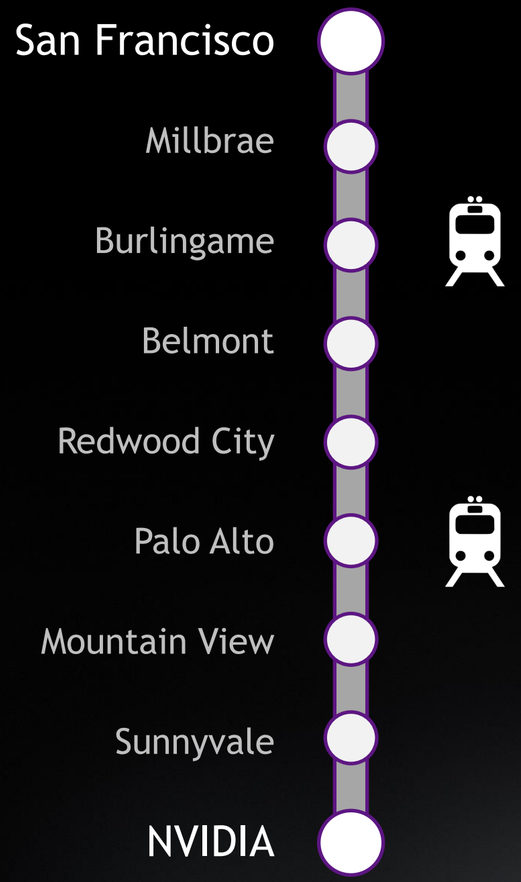
73 Minutes

45 Minutes



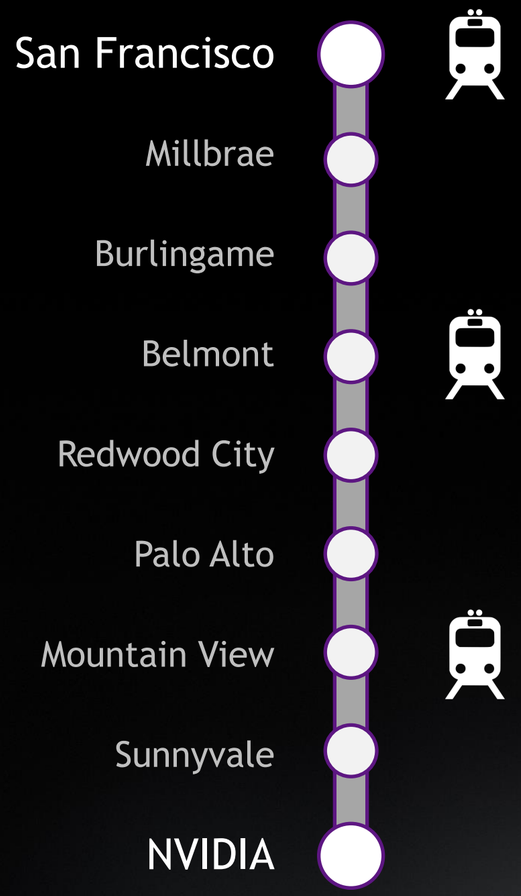
73 Minutes

45 Minutes



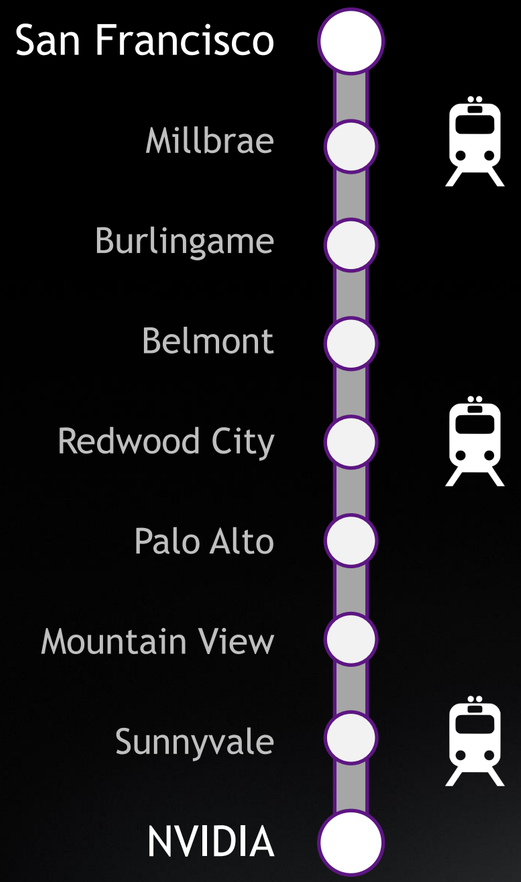
73 Minutes

45 Minutes



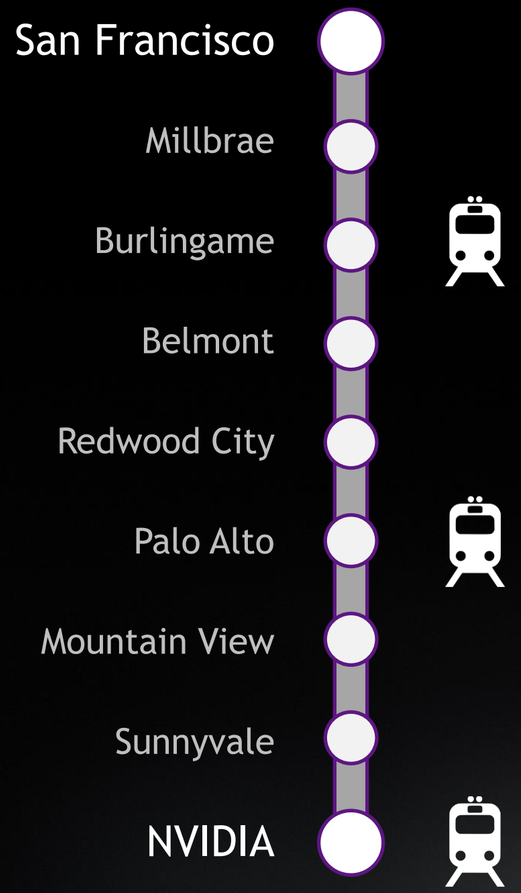
73 Minutes

45 Minutes

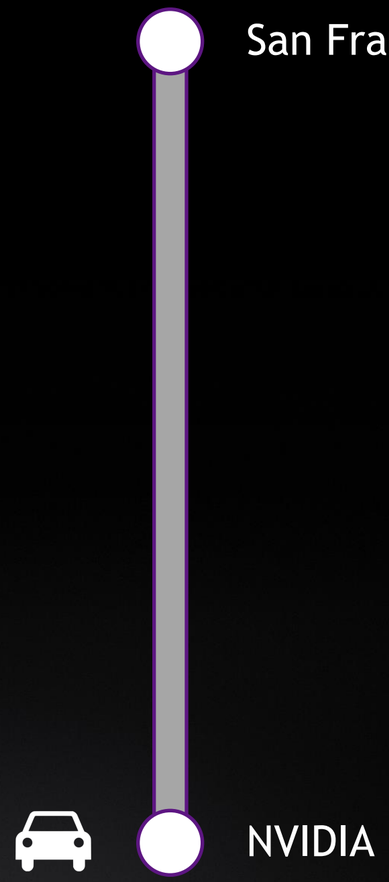


73 Minutes

45 Minutes



73 Minutes



45 Minutes

San Francisco

Millbrae

Burlingame

Belmont

Redwood City

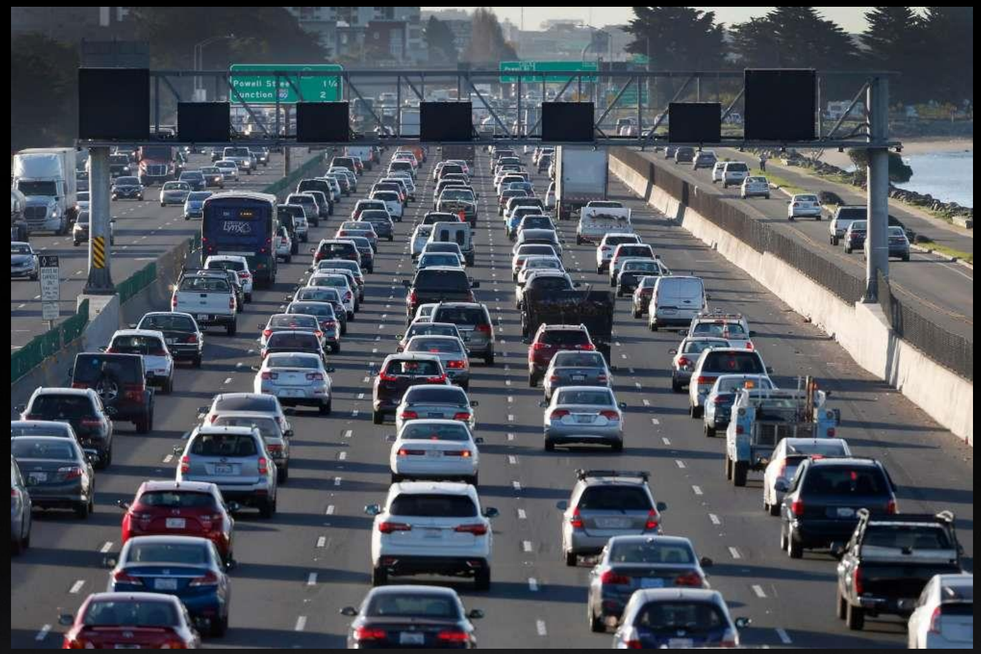
Palo Alto

Mountain View

Sunnyvale

NVIDIA

73 Minutes



San Francisco

NVIDIA

45 Minutes

San Francisco

Millbrae

Burlingame

Belmont

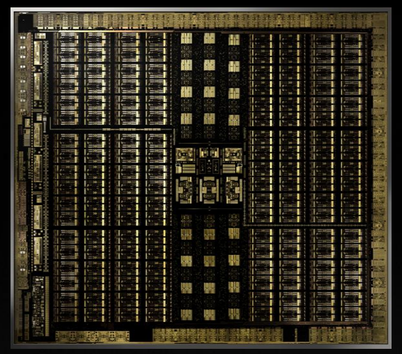
Redwood City

Palo Alto

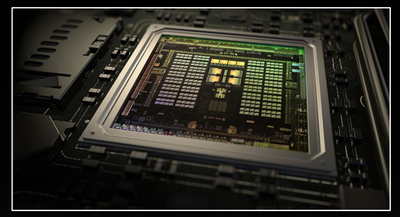
Mountain View

Sunnyvale

NVIDIA



73 Minutes

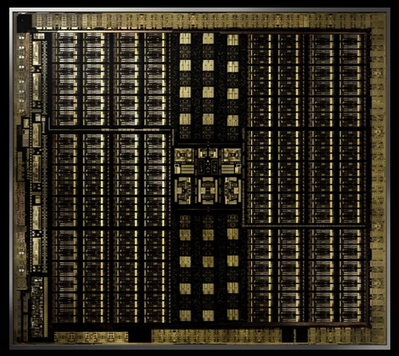


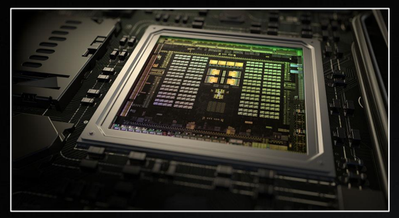
San Francisco

NVIDIA

45 Minutes

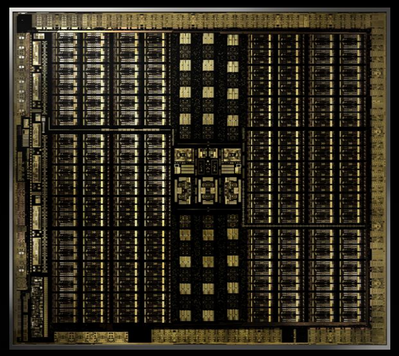
OVERSUBSCRIPTION MEANS KEEPING THE GPU BUSY

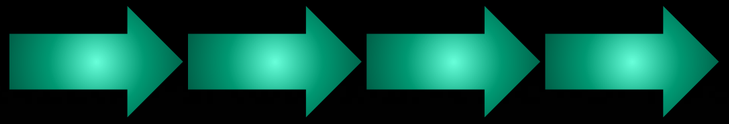


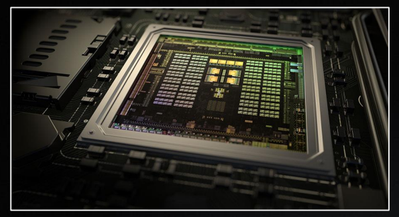


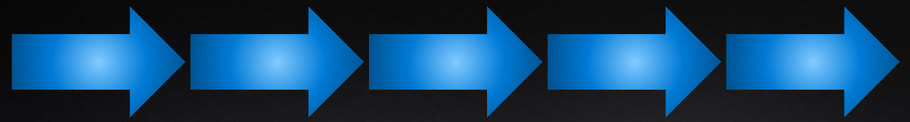
time

CPU/GPU ASYNCHRONY IS FUNDAMENTAL







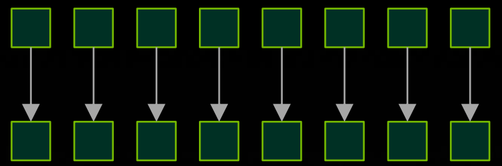


Synchronous

Asynchronous

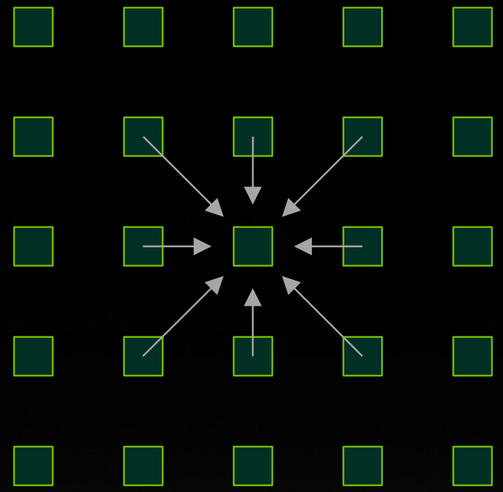
BUT NOT ALL THREADS WANT TO WORK INDEPENDENTLY

In fact, threads are very rarely completely independent



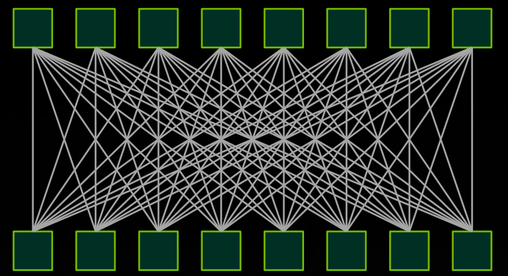
Element-wise

DAXPY



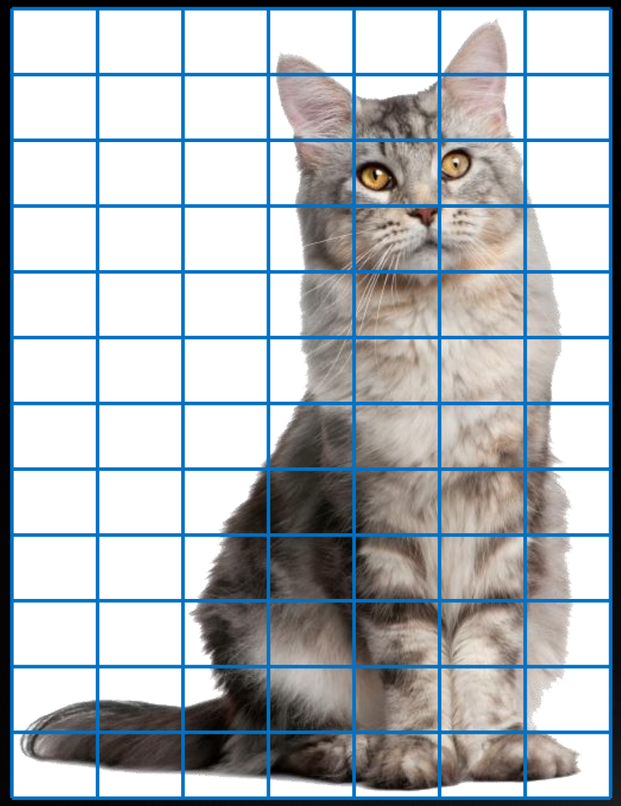
Local

Convolution

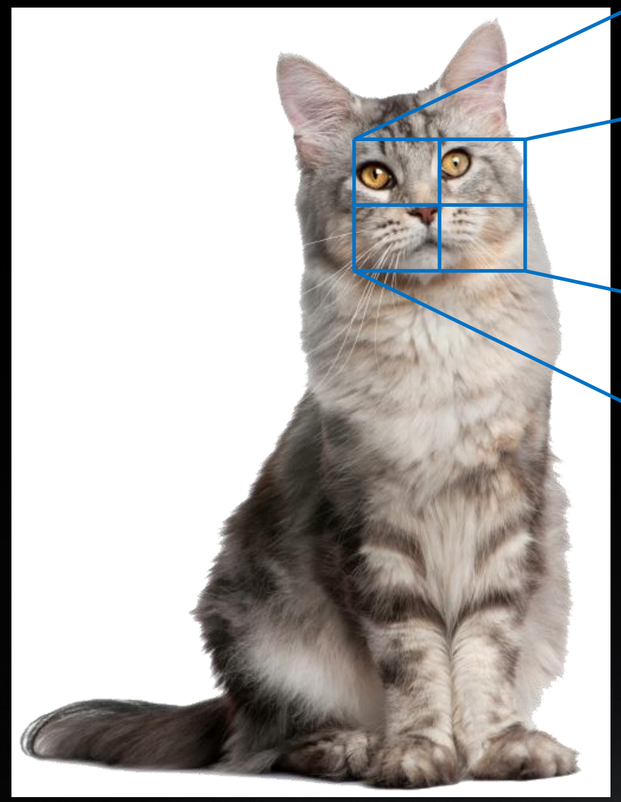


All-to-All

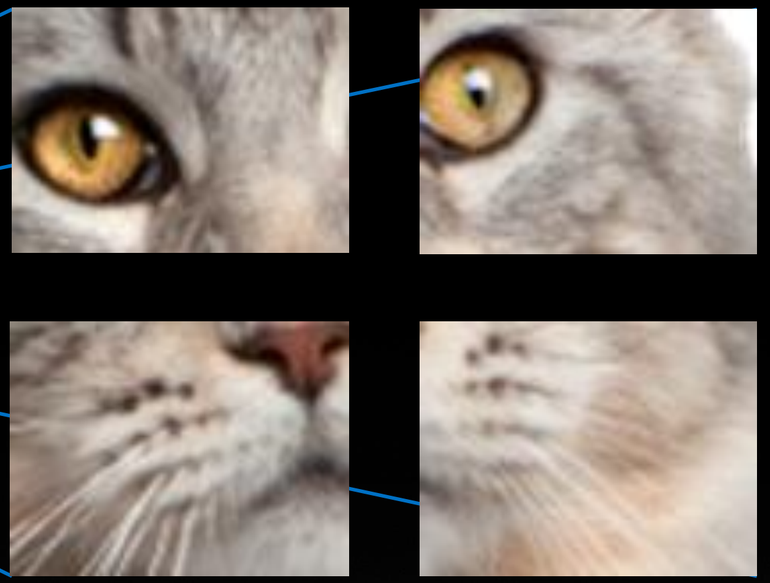
Fourier Transform



1. Overlay with a grid



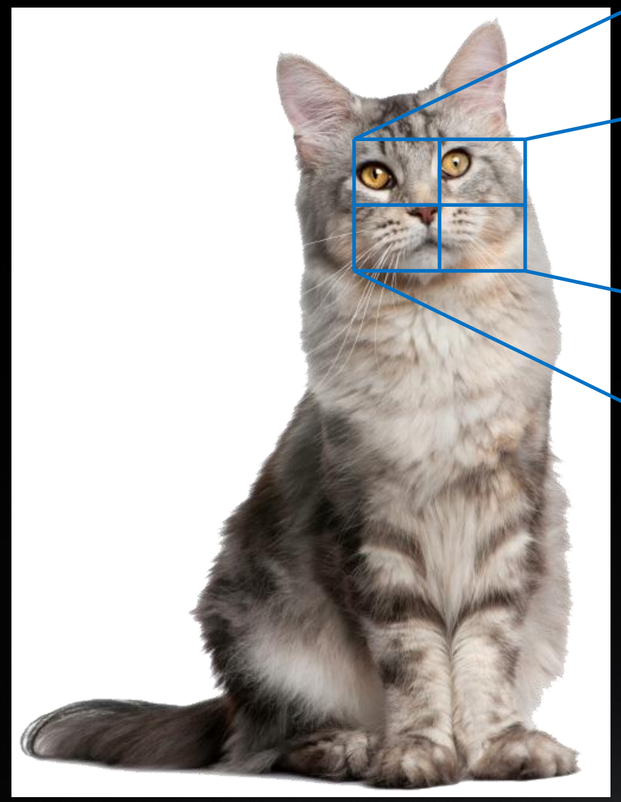
1. Overlay with a grid



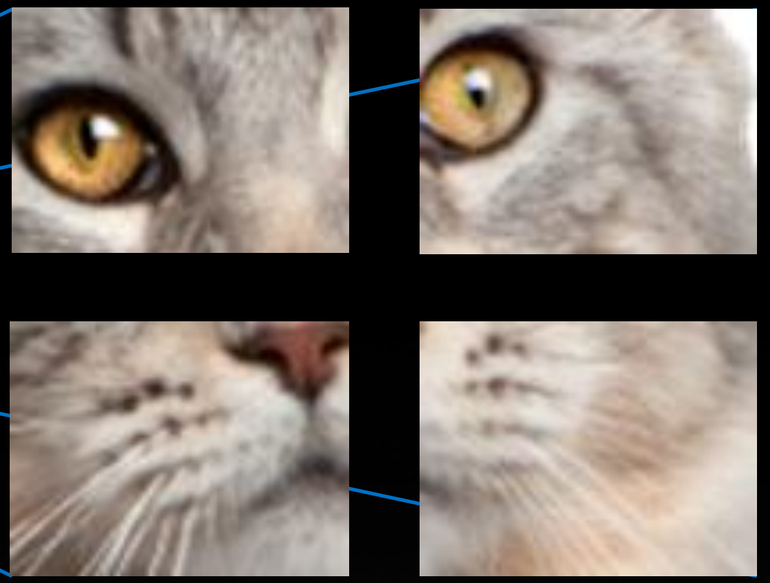
2. Operate on blocks within the grid

Blocks execute **independently**

GPU is **oversubscribed** with blocks



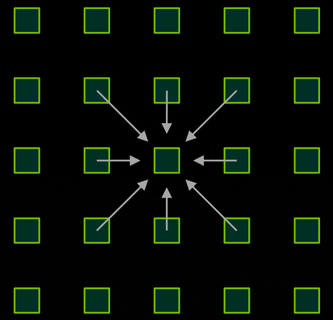
1. Overlay with a grid



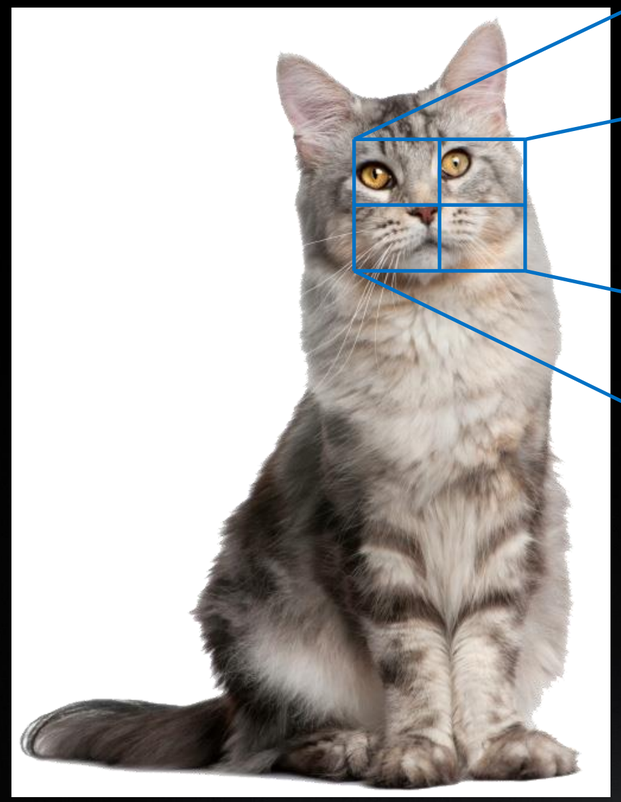
2. Operate on blocks within the grid

Blocks execute **independently**

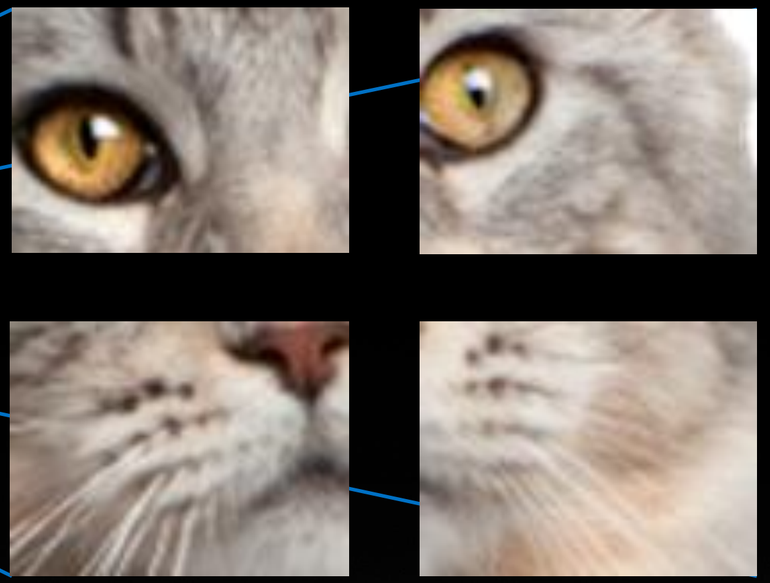
GPU is **oversubscribed** with blocks



3. Many threads work together in each block for **local** data sharing



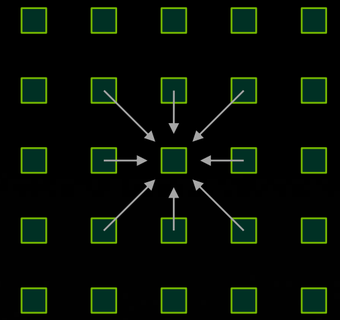
1. Overlay with a grid



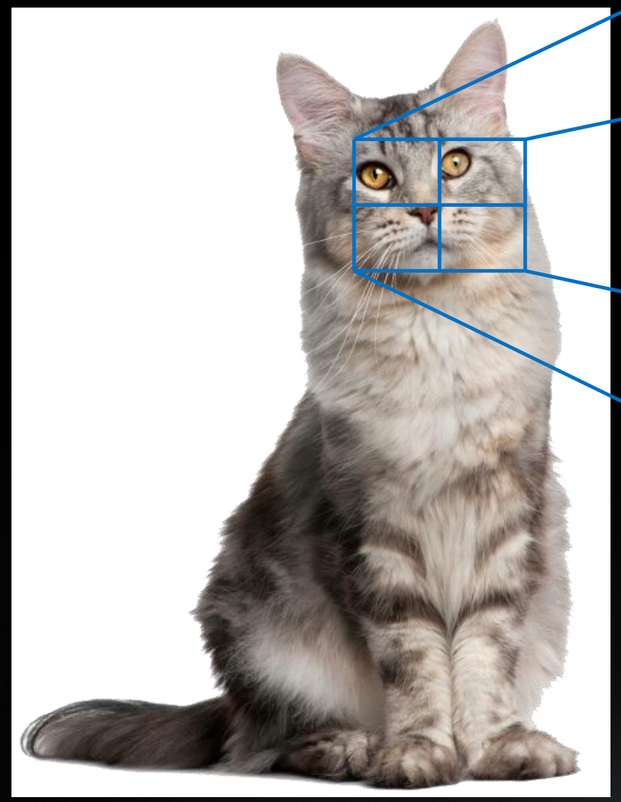
2. Operate on blocks within the grid

Blocks execute **independently**

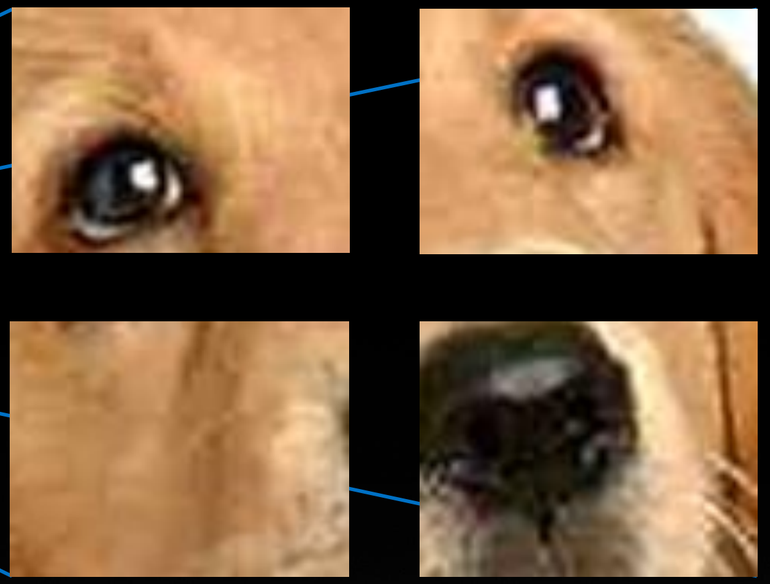
GPU is **oversubscribed** with blocks



3. Many threads work together in each block for **local** data sharing



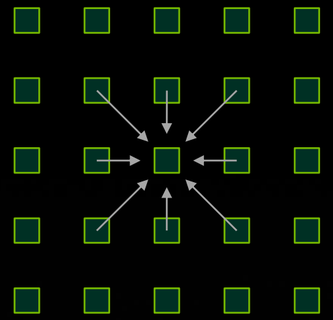
1. Overlay with a grid



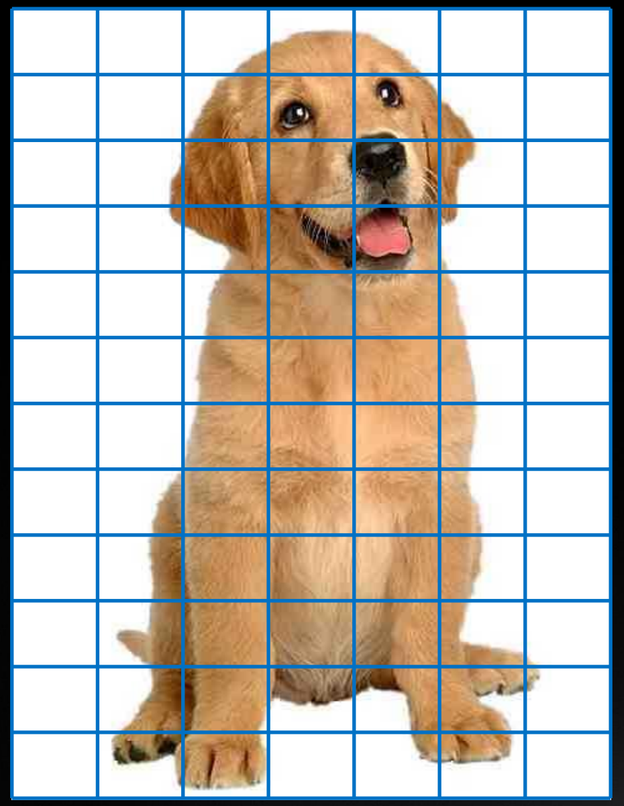
2. Operate on blocks within the grid

Blocks execute **independently**

GPU is **oversubscribed** with blocks



3. Many threads work together in each block for **local** data sharing

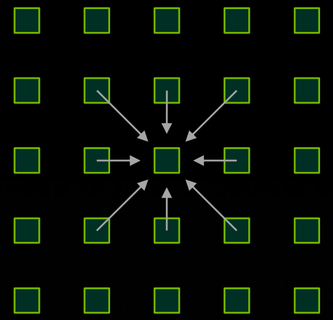


1. Overlay with a grid

2. Operate on blocks within the grid

Blocks execute **independently**

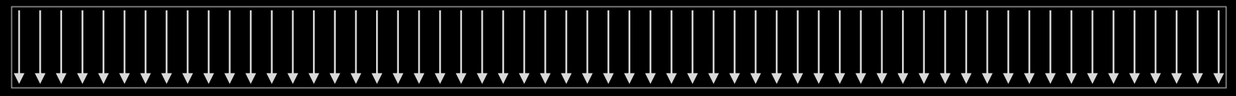
GPU is **oversubscribed** with blocks



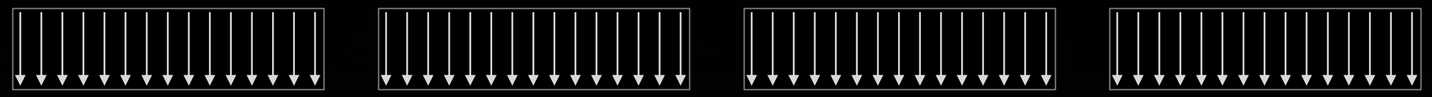
3. Many threads work together in each block for **local** data sharing

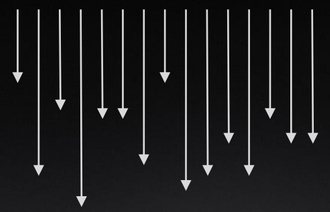
CUDA'S HIERARCHICAL EXECUTION MODEL

A grid represents all work to be done



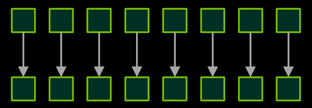
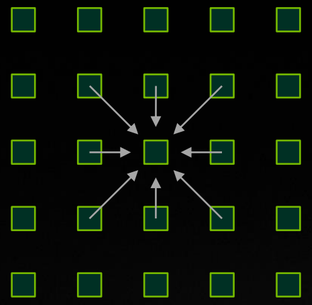
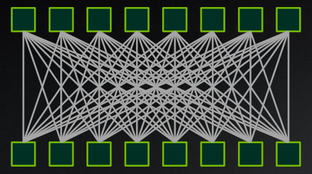
The grid comprises many blocks with an equal number of threads

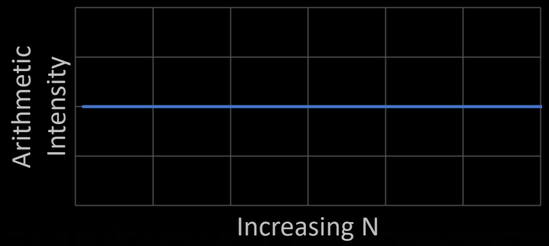


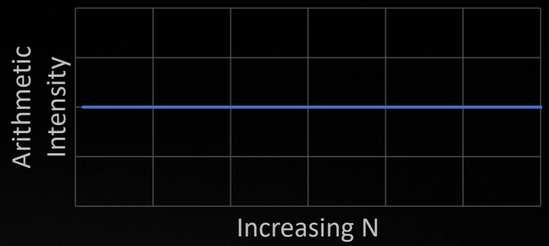


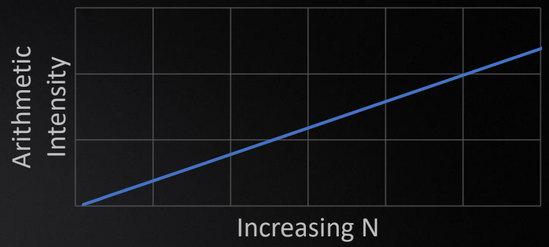
Threads within a block run independently
but may synchronize to exchange data

BEATING COMPUTE INTENSITY IS ALL ABOUT SCALING

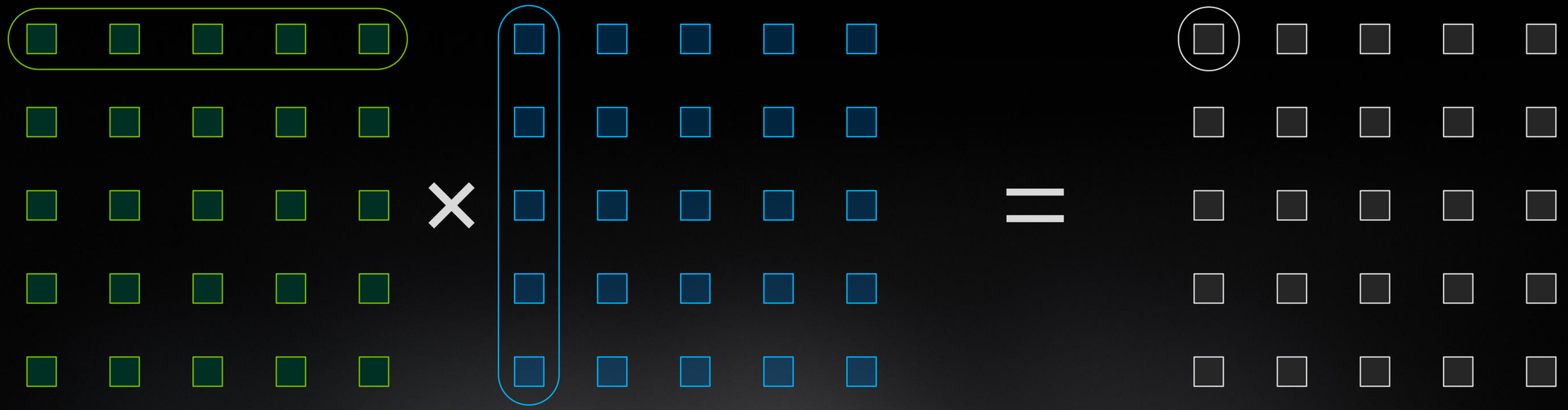
		Data Scales As	Compute Scales As	Intensity Scales As
Element-wise		O(N)	O(N)	O(1)
Local		$O(N^2)$	$O(N^2)$	O(1)
All-to-All		O(N)	$O(N^2)$	O(N)



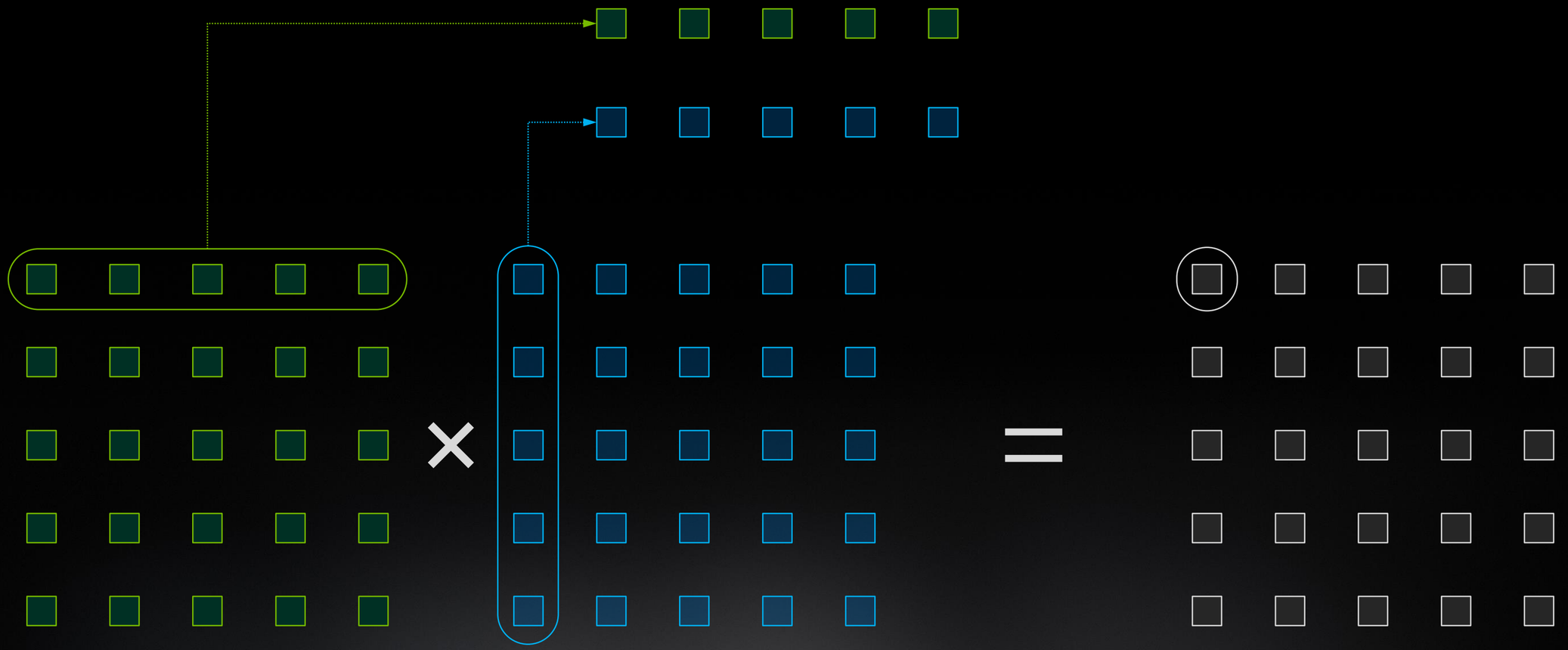




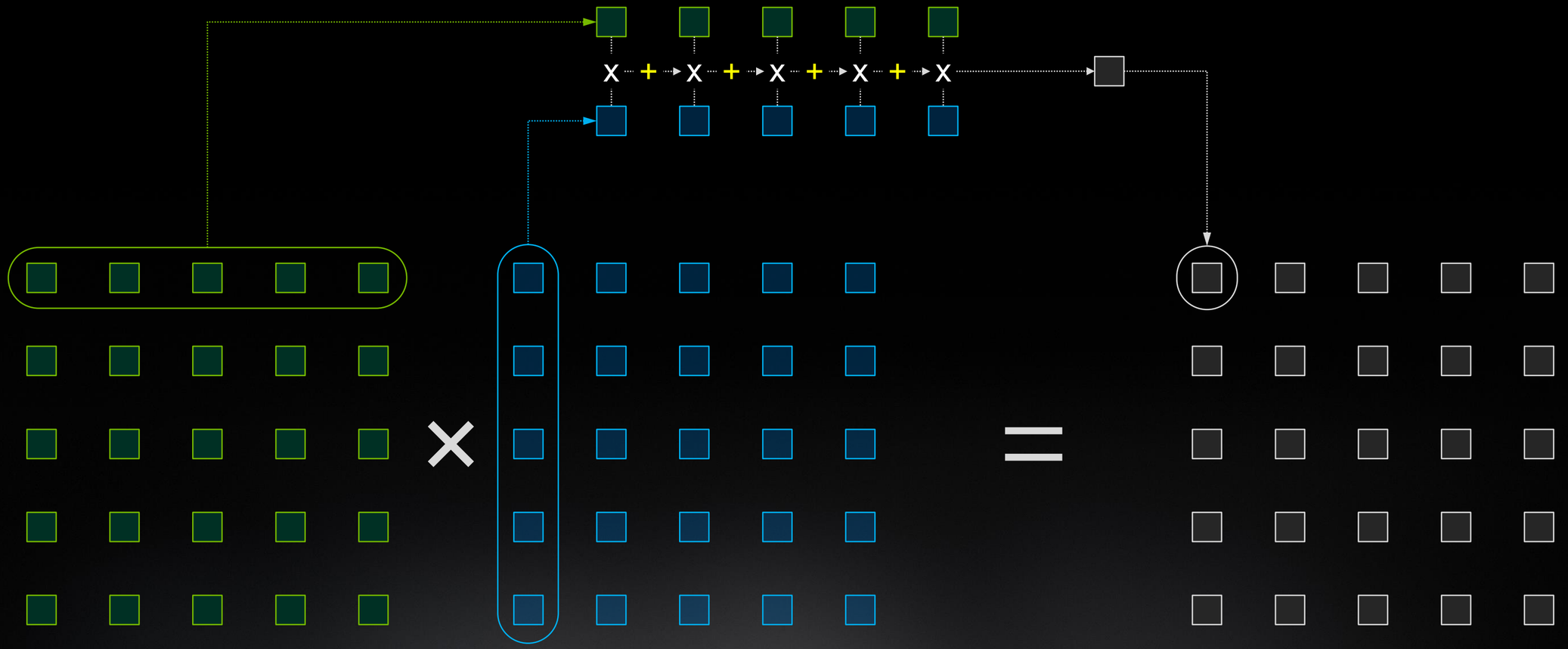
MATRIX MULTIPLICATION



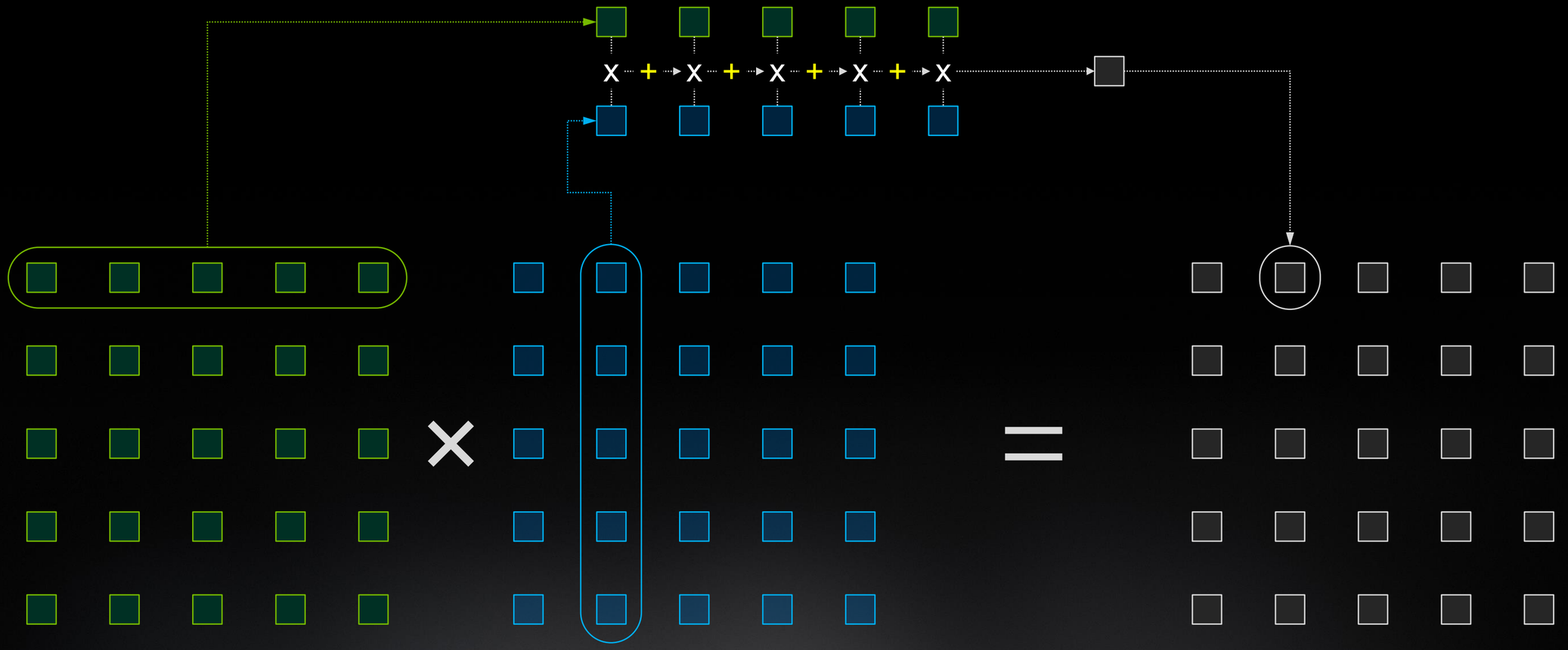
MATRIX MULTIPLICATION



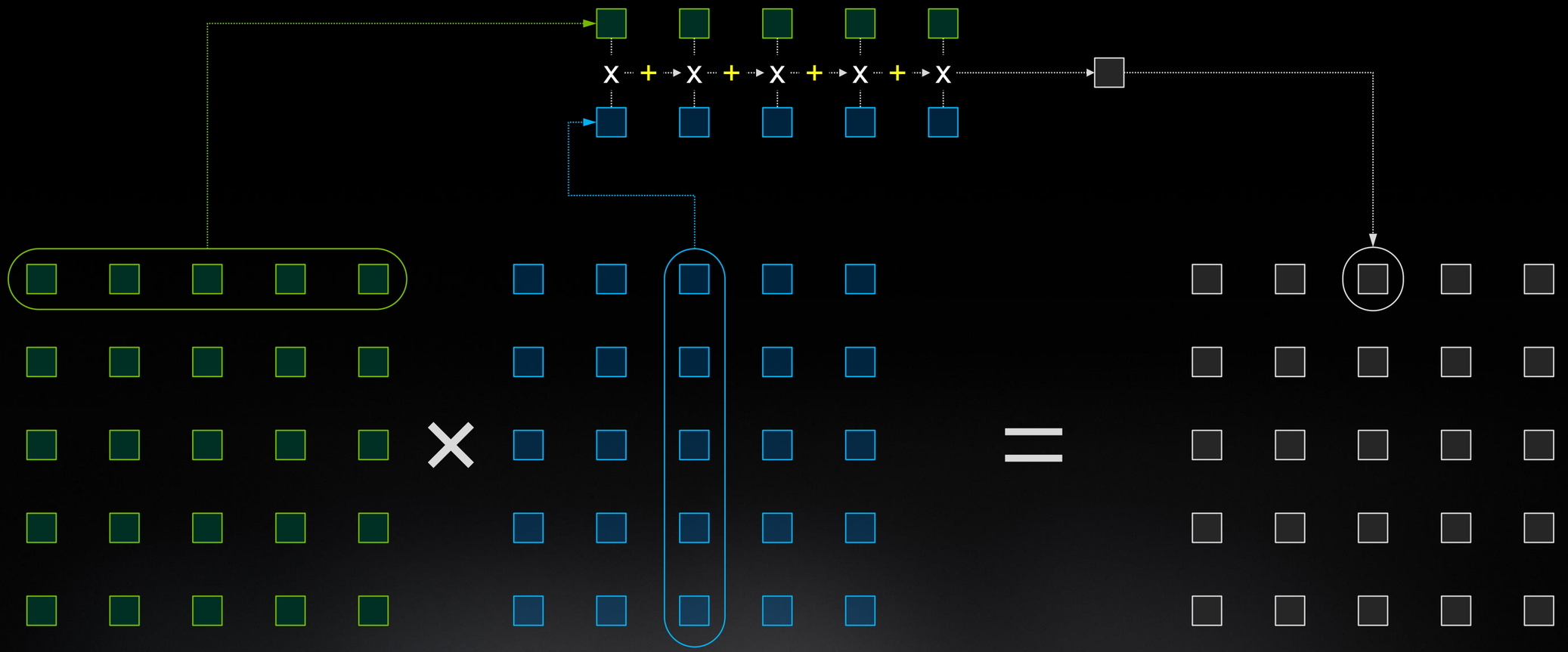
MATRIX MULTIPLICATION



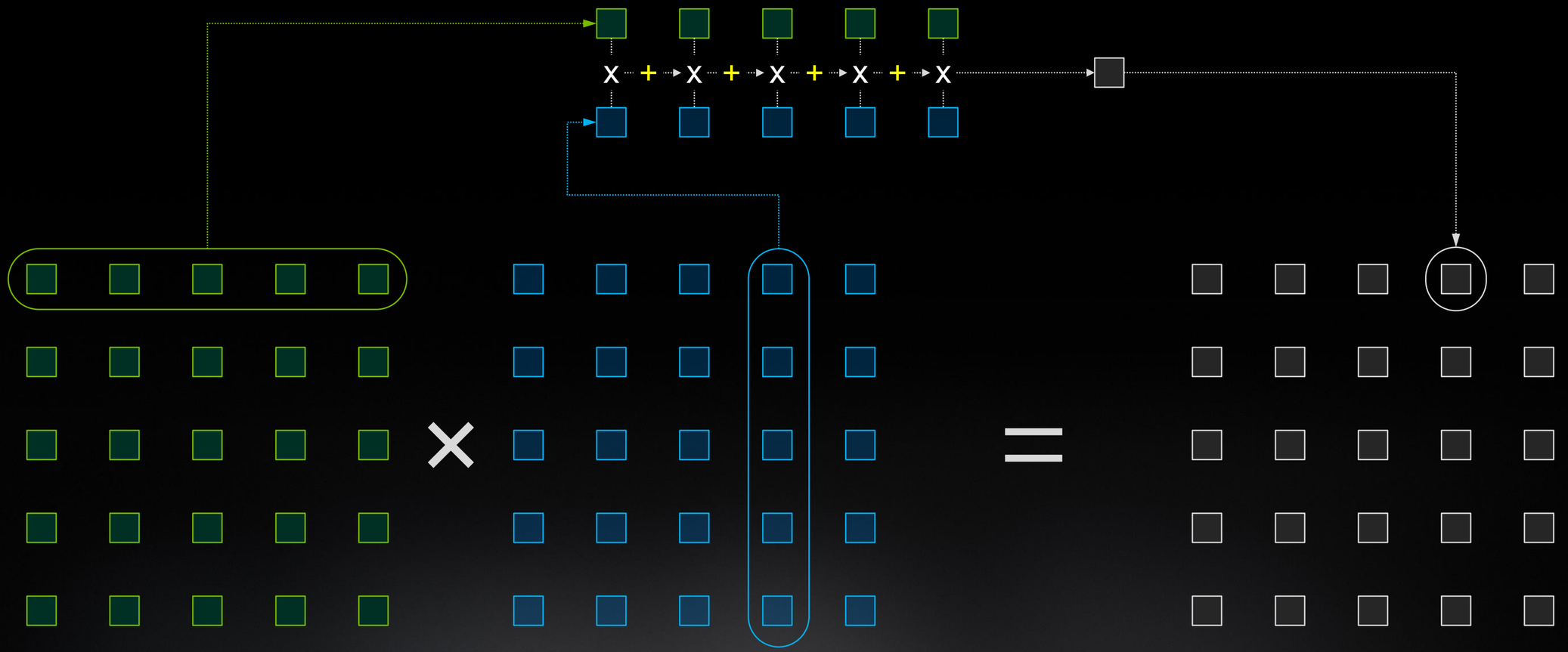
MATRIX MULTIPLICATION



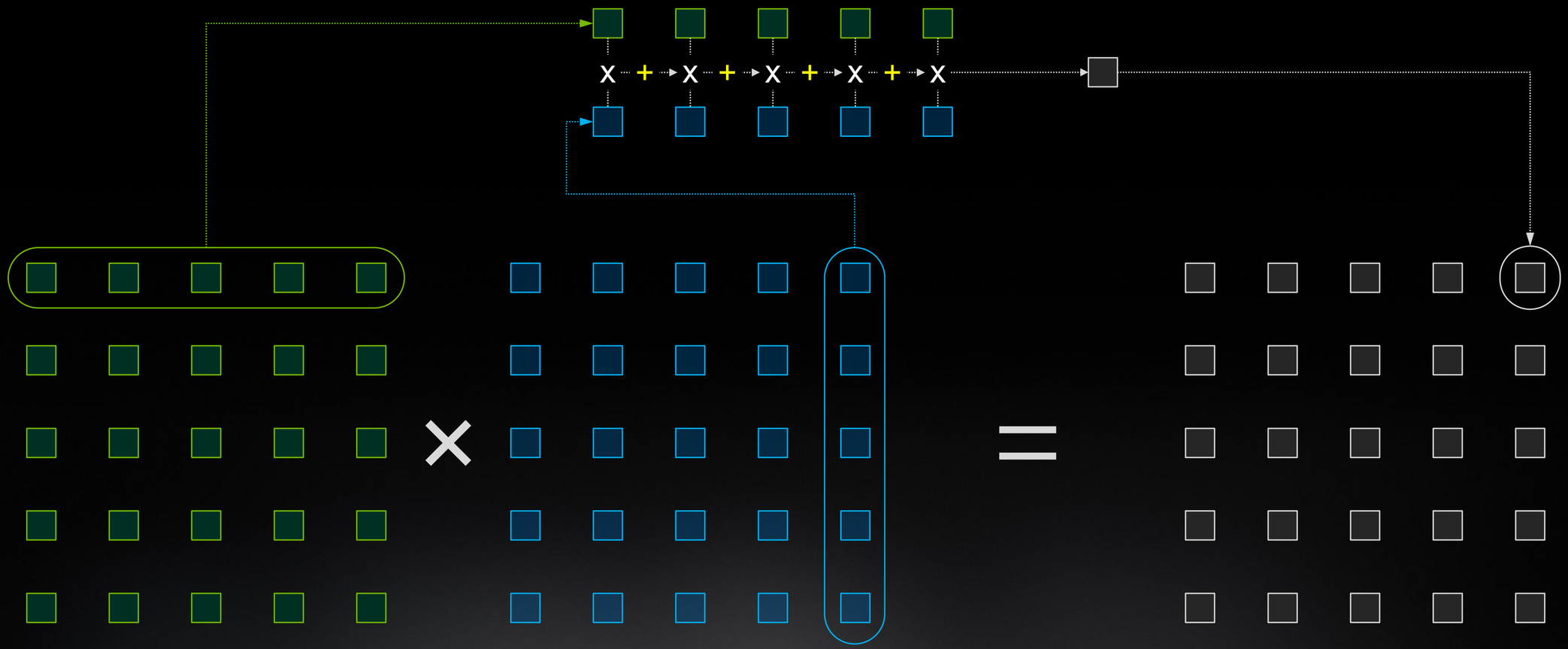
MATRIX MULTIPLICATION



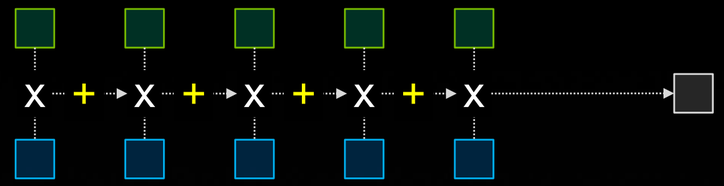
MATRIX MULTIPLICATION



MATRIX MULTIPLICATION



ARITHMETIC INTENSITY OF MATRIX MULTIPLICATION



For an NxN matrix

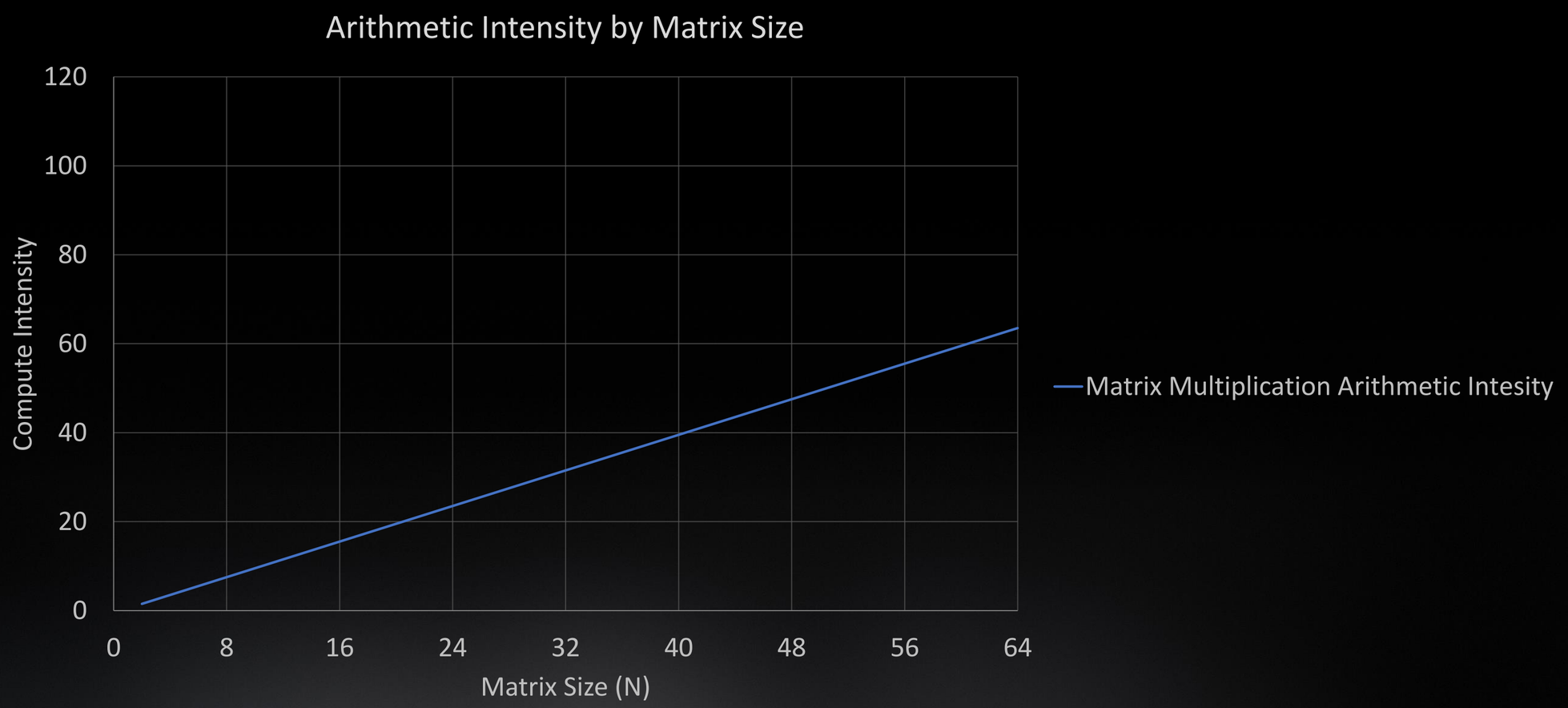
- N row elements multiply with N column elements
- N additions create the final result
- This is done N^2 times, once for each result element

Arithmetic complexity is therefore: **N^2 x (2N) = $2N^3$ = $O(N^3)$**

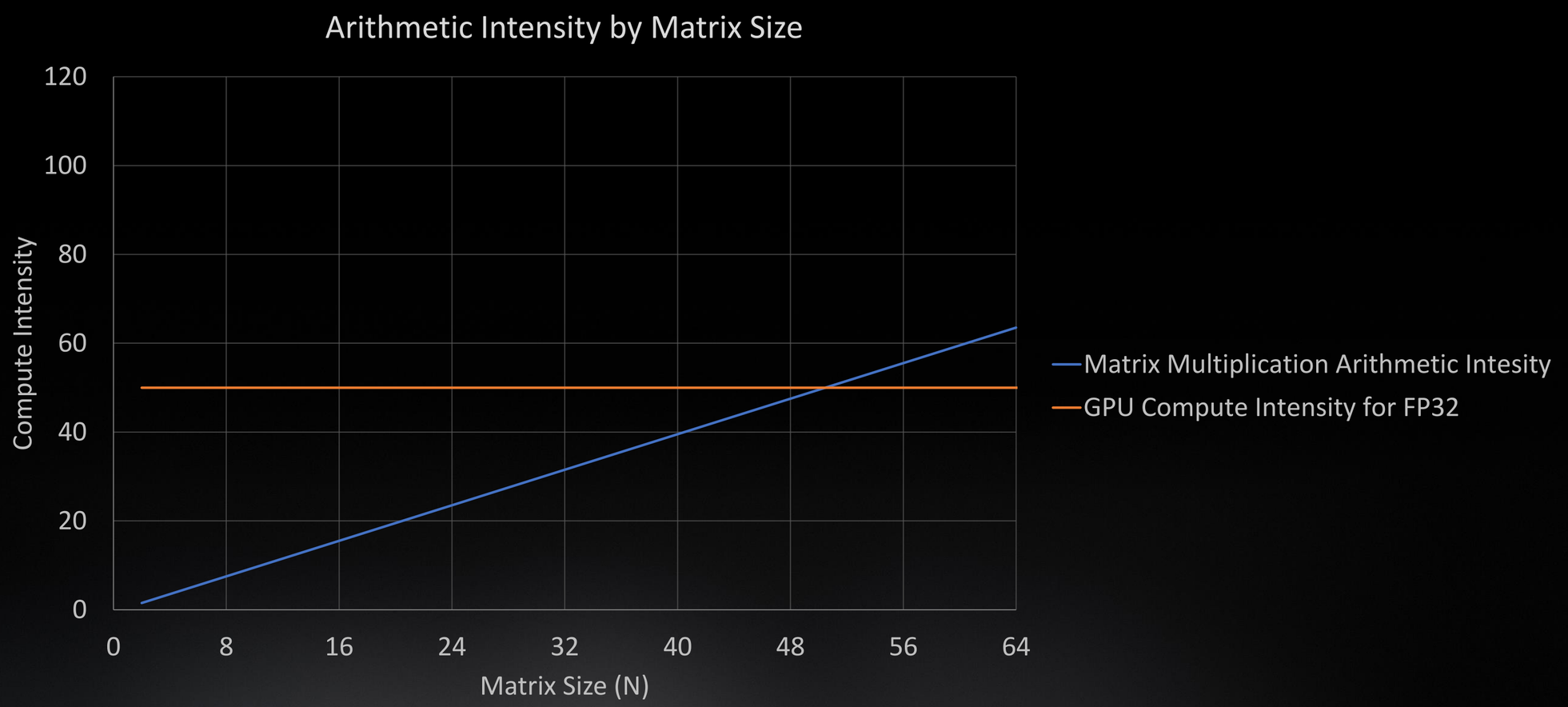
Number of data loads: **$O(N^2)$**

Arithmetic intensity scales as: **N^3 / N^2 = $O(N)$**

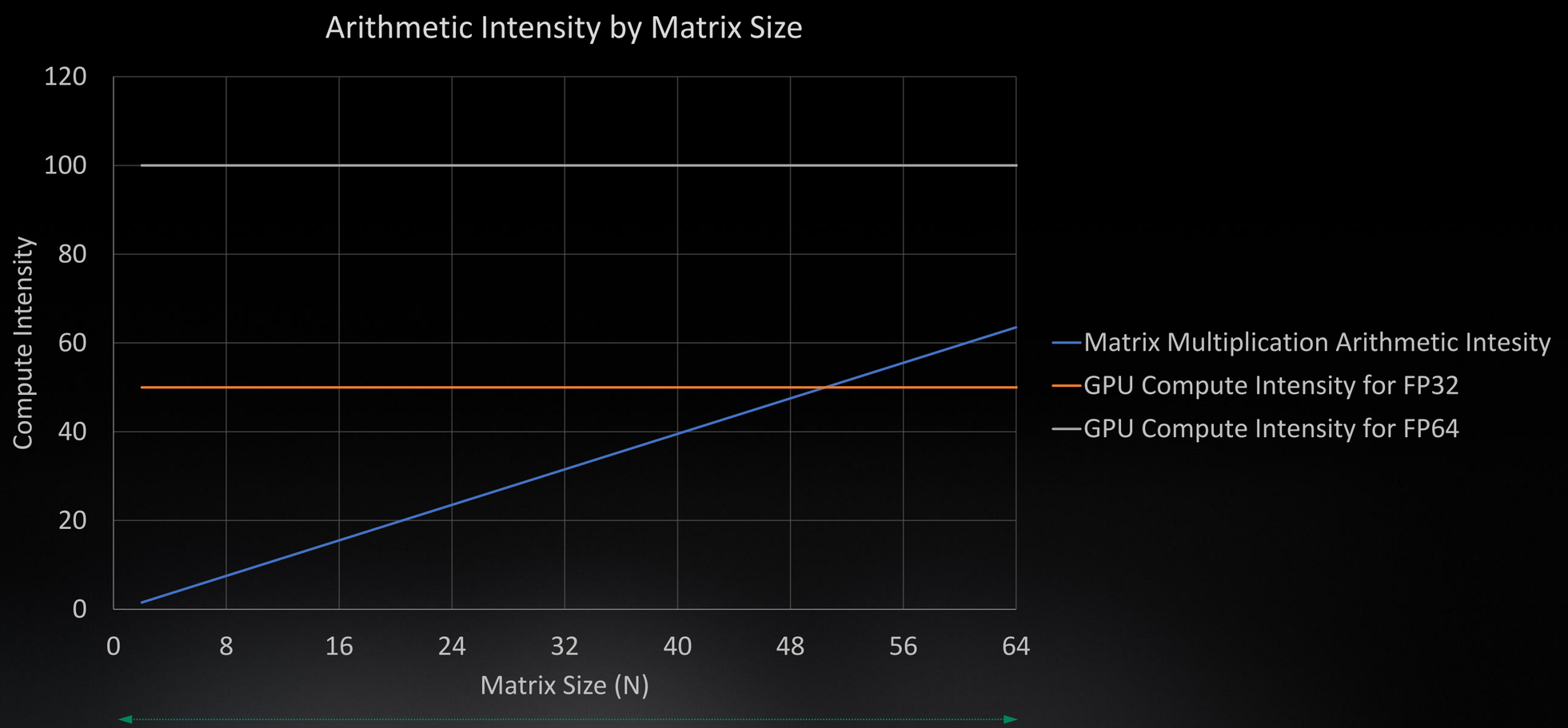
ALGORITHMIC EFFICIENCY OF MMA



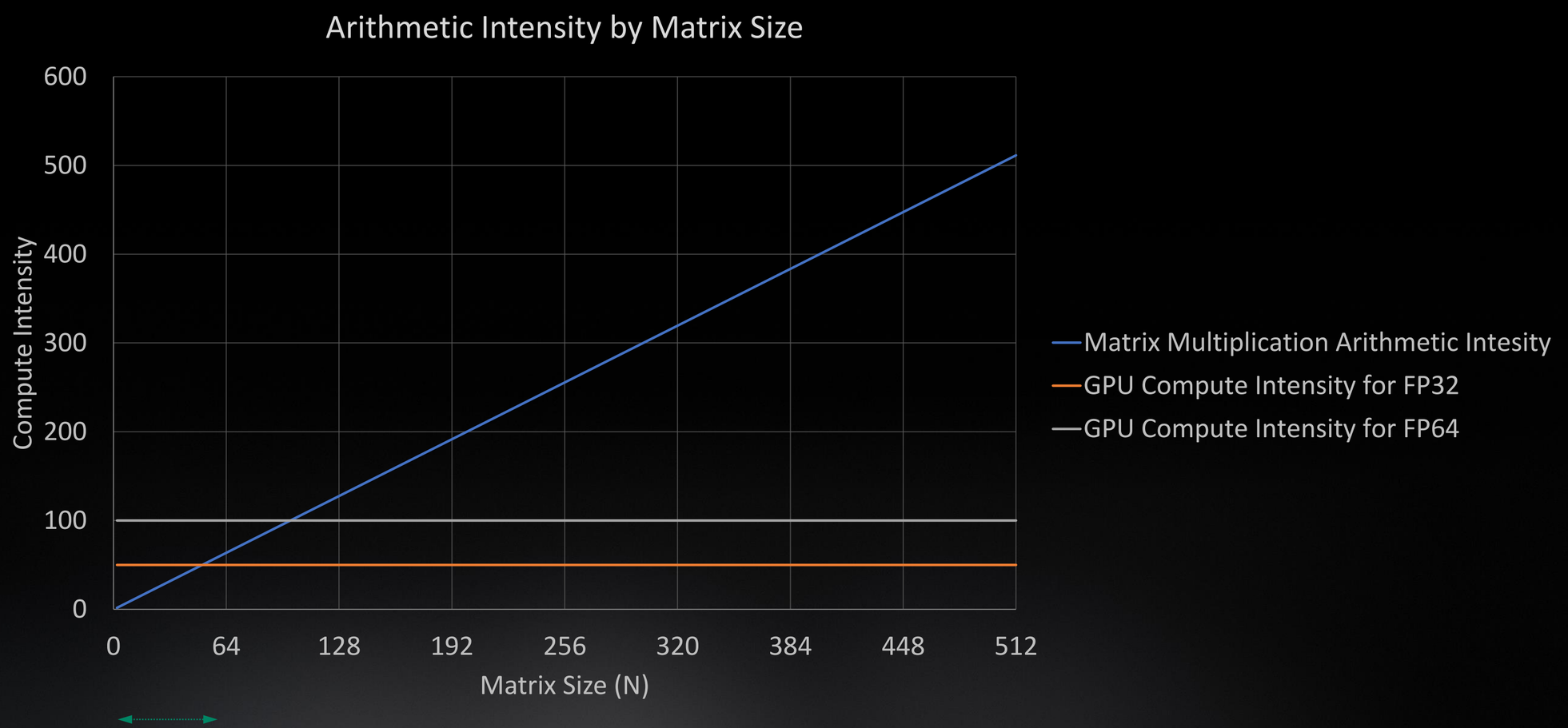
ALGORITHMIC EFFICIENCY OF MMA



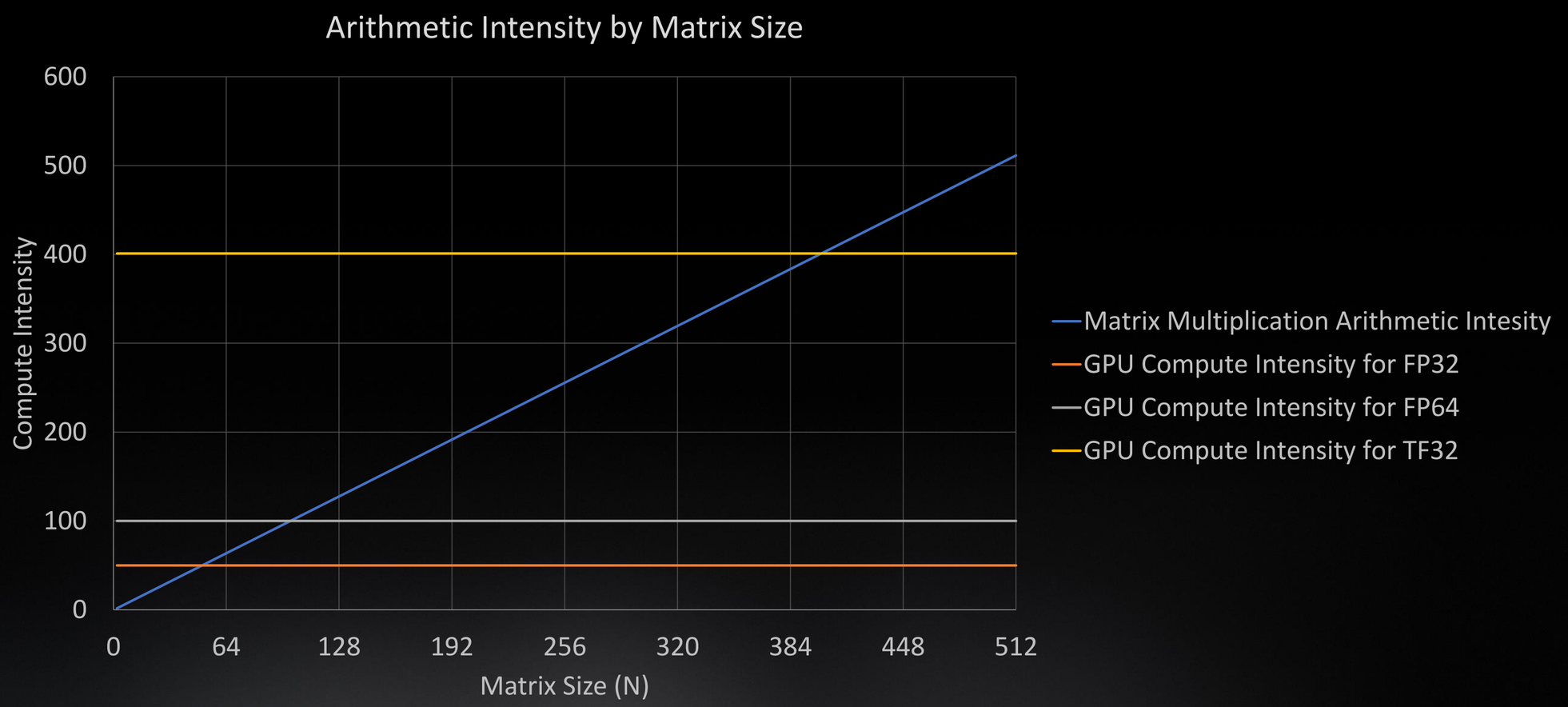
ALGORITHMIC EFFICIENCY OF MMA



ALGORITHMIC EFFICIENCY OF MMA



ALGORITHMIC EFFICIENCY OF MMA



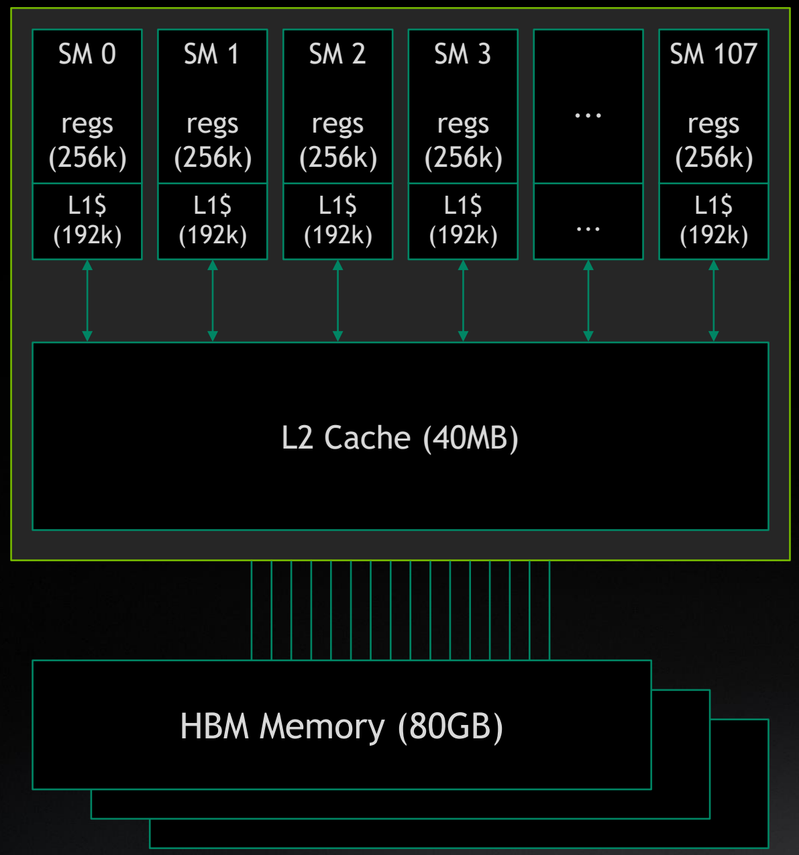
WORKING WITH SMALLER MATRICES

B/W Latency

13x 1x

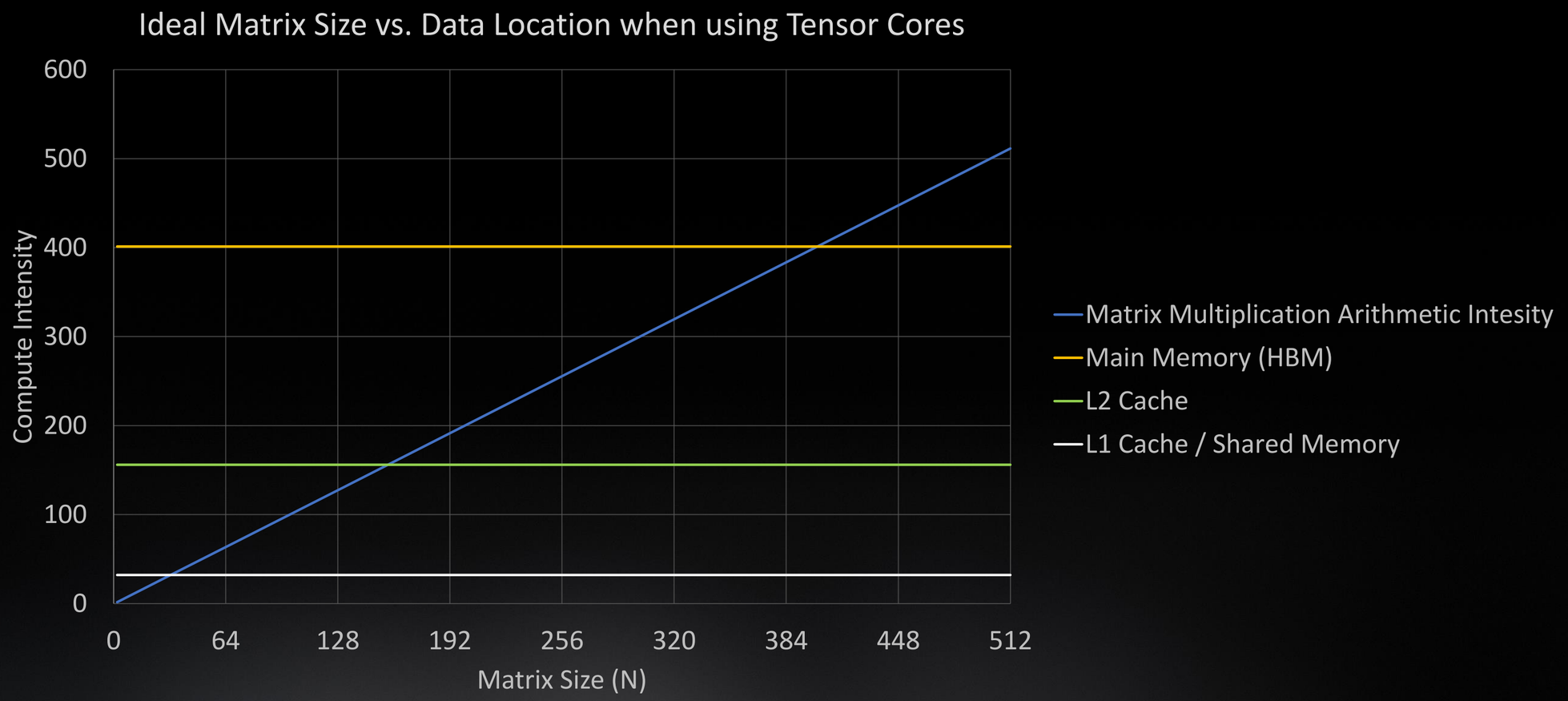
3x 5x

1x 15x



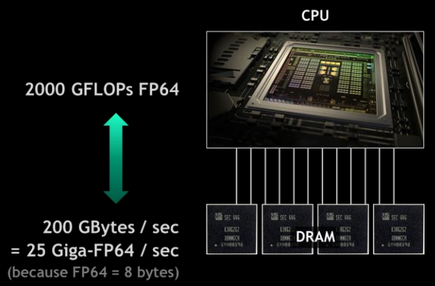
Data Location	Bandwidth (GB/sec)	Compute Intensity	Tensor Core Compute Intensity
L1 / Shared	19,400	8	32
L2 Cache	4,000	39	156
HBM	1,555	100	401
NVLink	300	520	2080
PCIe	25	6240	24960

WORKING WITH SMALLER MATRICES

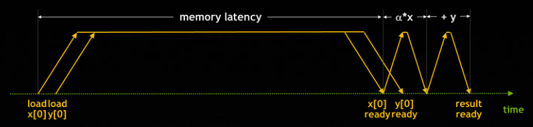


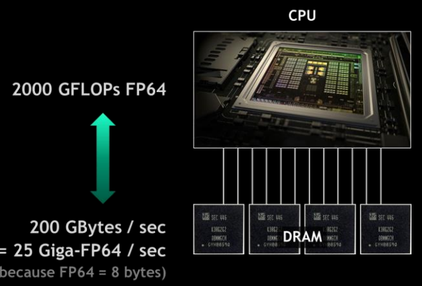
2000 GFLOPs FP64

200 GBytes / sec
= 25 Giga-FP64 / sec
(because FP64 = 8 bytes)

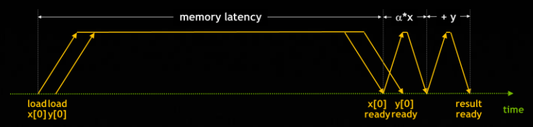



```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

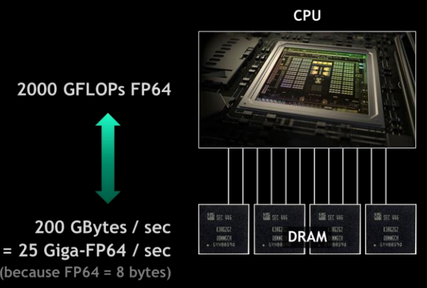




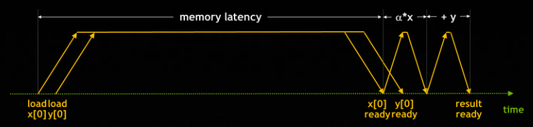

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```



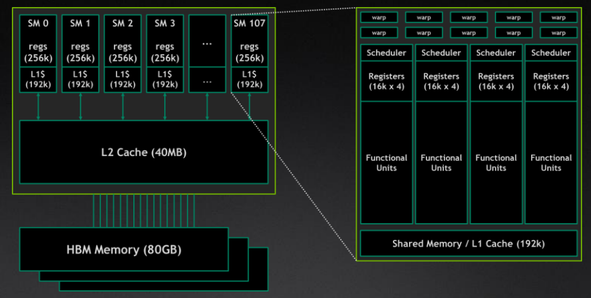
	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x

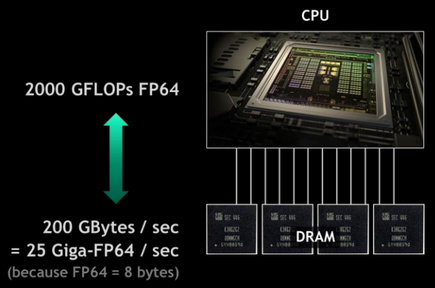



```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

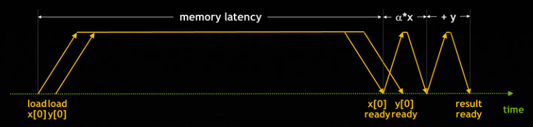


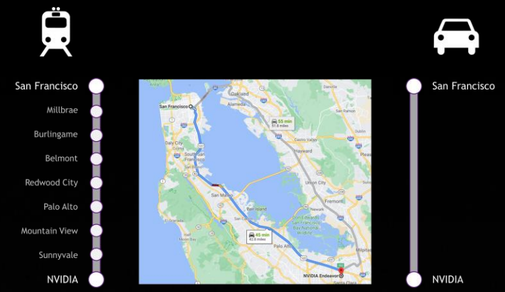
	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x



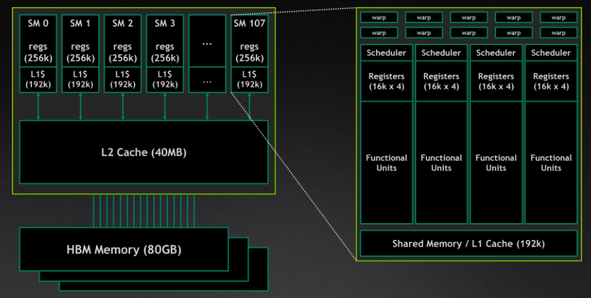


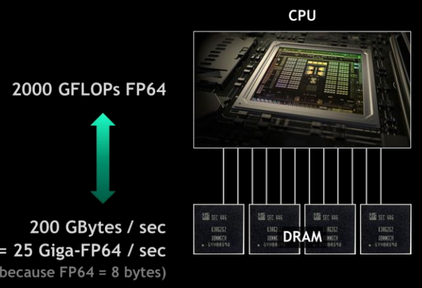

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

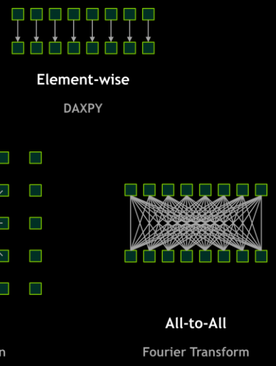




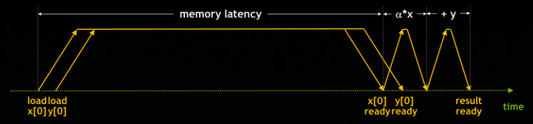
	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x

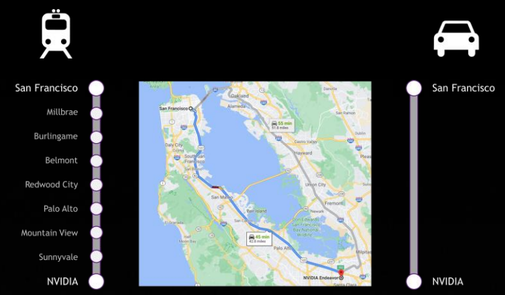




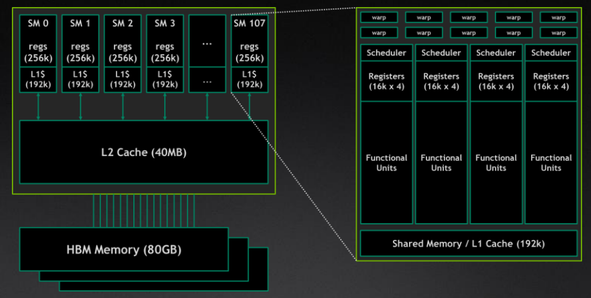


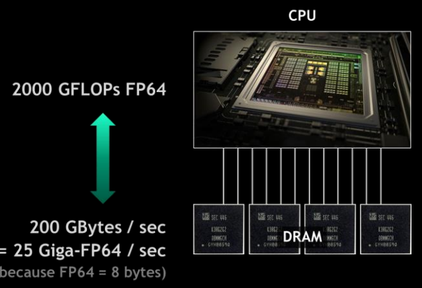

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

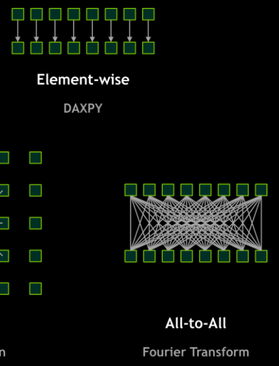


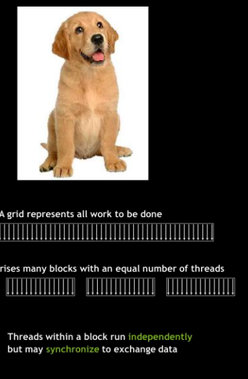


	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x

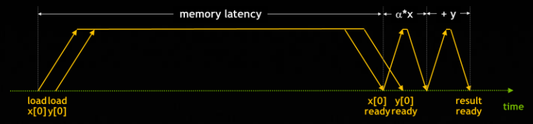


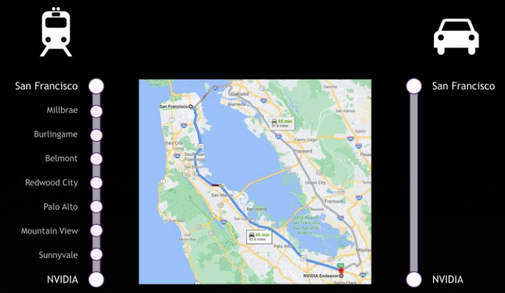




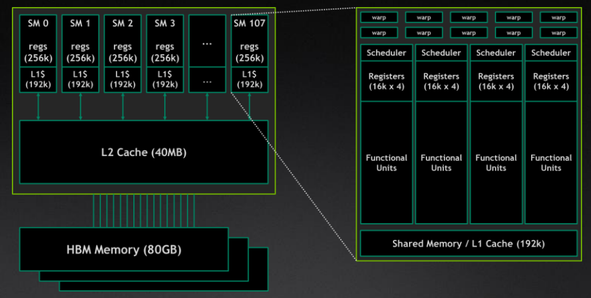


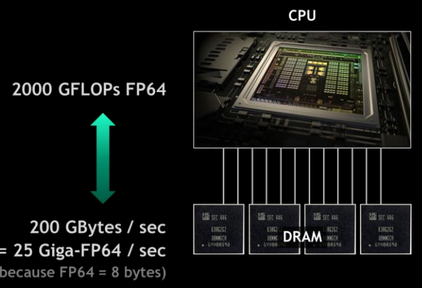

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

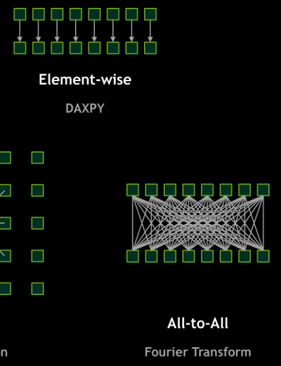


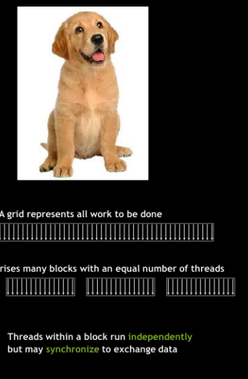


	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x

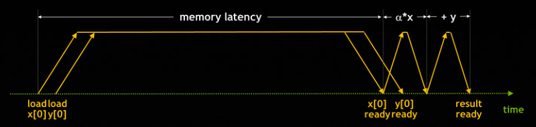


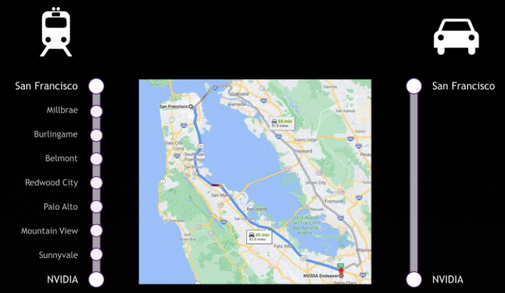


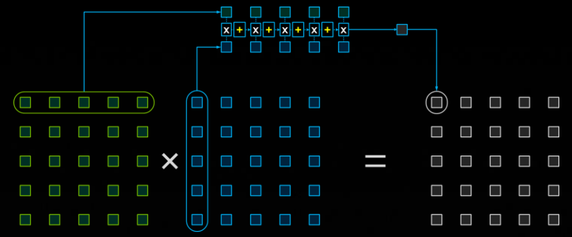




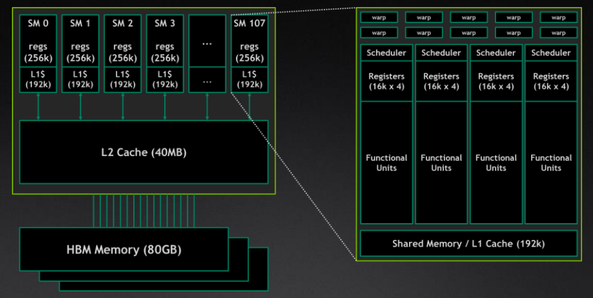

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

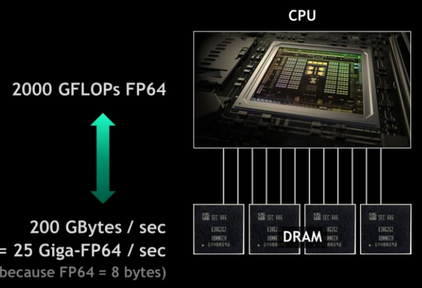


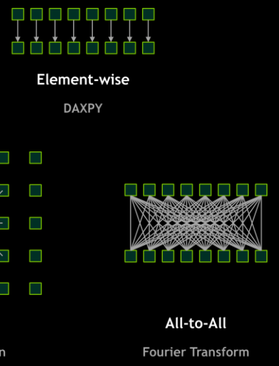


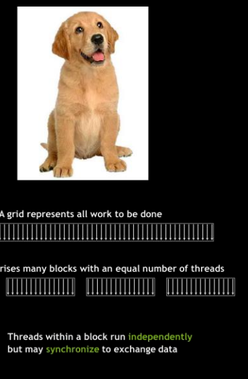


	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x

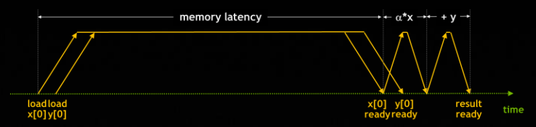


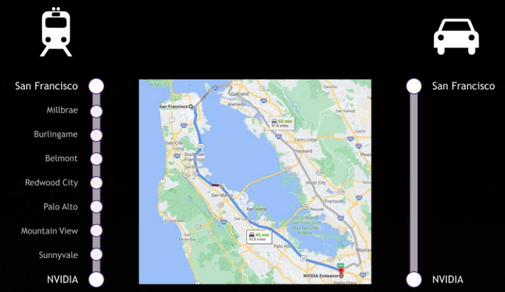


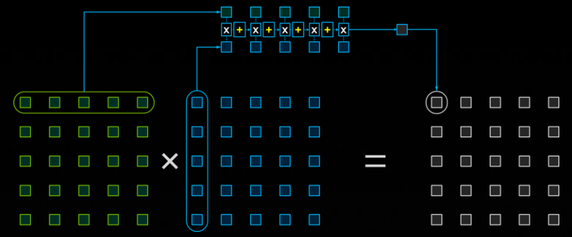




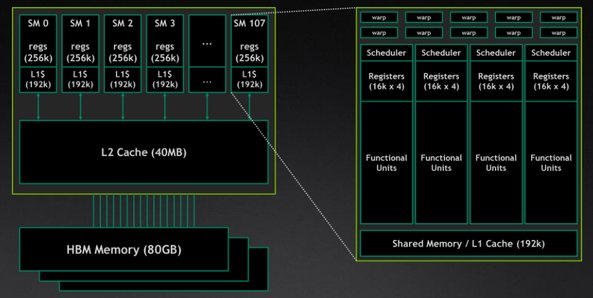

```
void daxpy(int n, double alpha, double *x, double *y)
{
    for( i = 0; i < n; i++ )
    {
        y[i] = alpha * x[i] + y[i];
    }
}
```

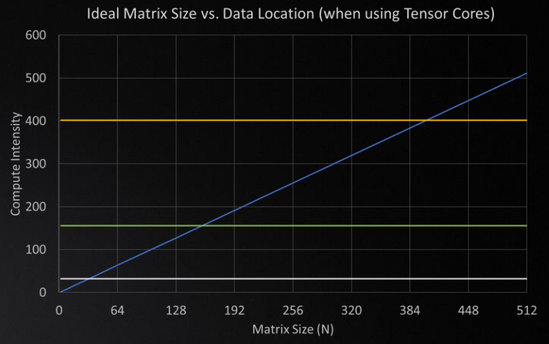


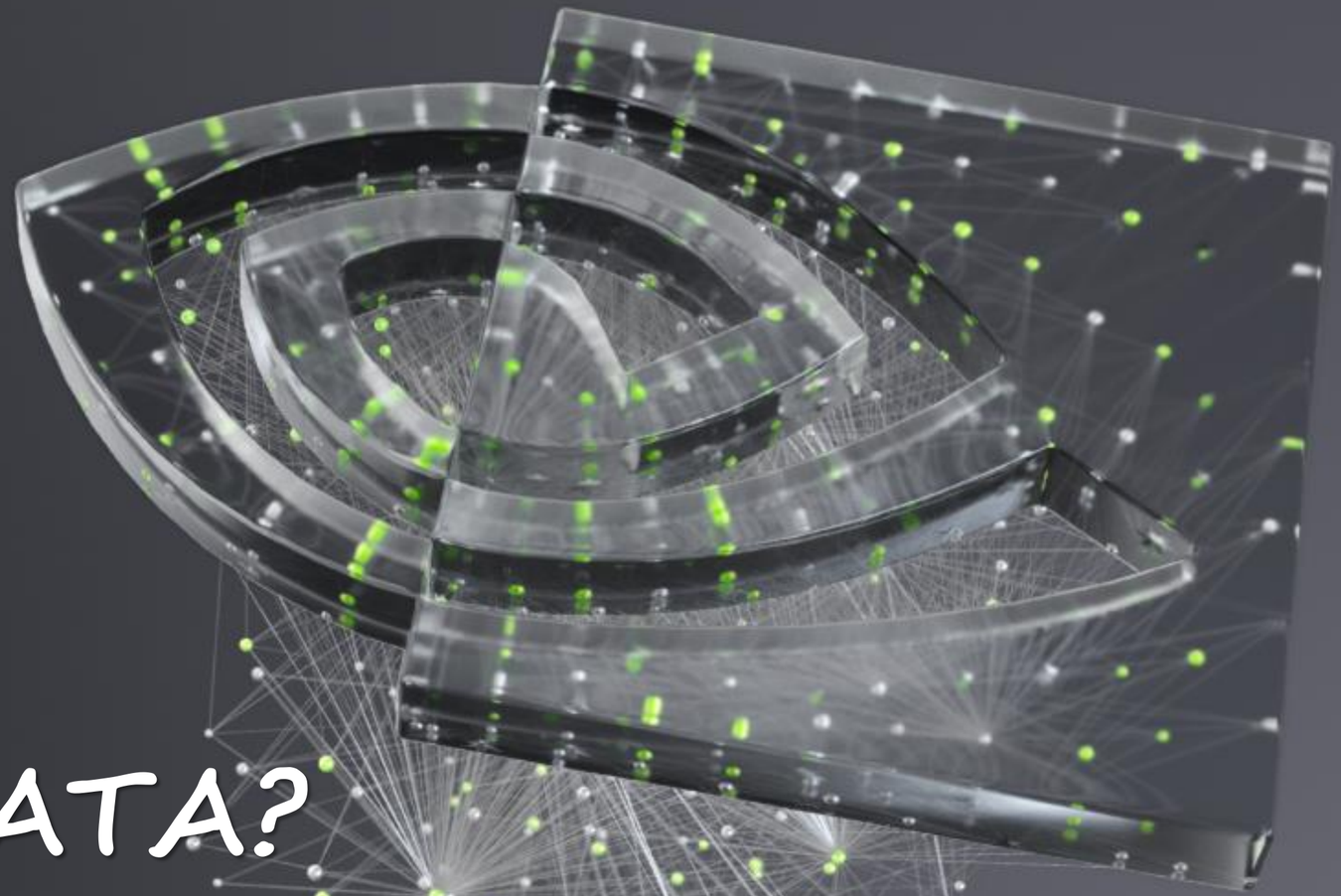




	NVIDIA A100	AMD Rome 7742	Intel Xeon 8280
Memory B/W (GB/sec)	1555	204	143
DRAM Latency (ns)	404	122	89
Peak bytes per latency	628,220	24,888	12,727
Memory efficiency	0.0025%	0.064%	0.13%
Threads required	39,264	1,556	729
Threads available	221,184	2048	896
Thread ratio	5.6x	1.3x	1.2x







NVIDIA

WHERE'S MY DATA?

WHY HOW GPU COMPUTING WORKS

Stephen Jones, GTC 2021