# GPU 101

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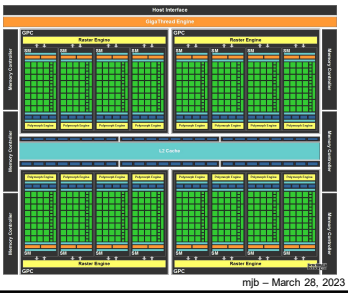



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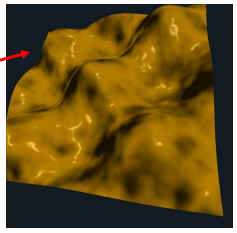
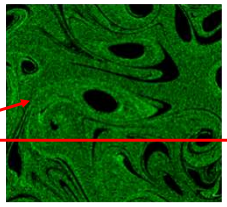
## How Have You Been Able to Gain Access to GPU Power?

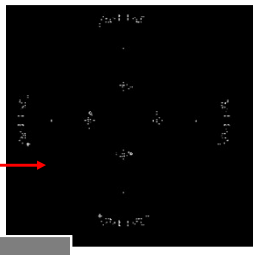
**There have been three ways:**

1. Write a graphics display program (≥ 1985)

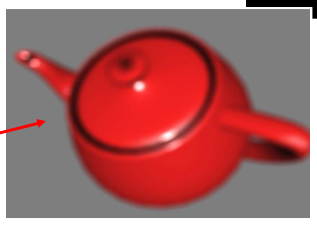


2. Write an application that looks like a graphics display program, but uses the fragment shader to do some per-node computation (≥ 2002)





3. Write in OpenCL or CUDA, which looks like C++ (≥ 2006)



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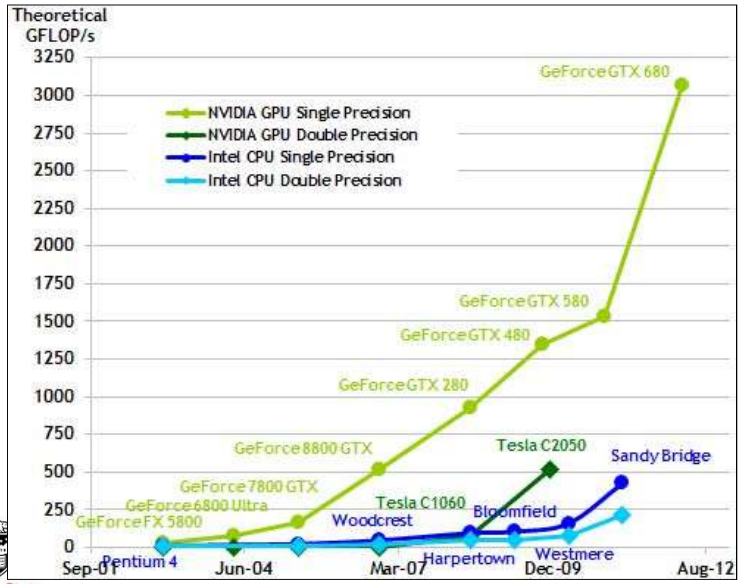
## Why do we care about GPU Programming?
## A History of GPU vs. CPU Performance

3

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## Why do we care about GPU Programming?
## A History of GPU vs. CPU Performance

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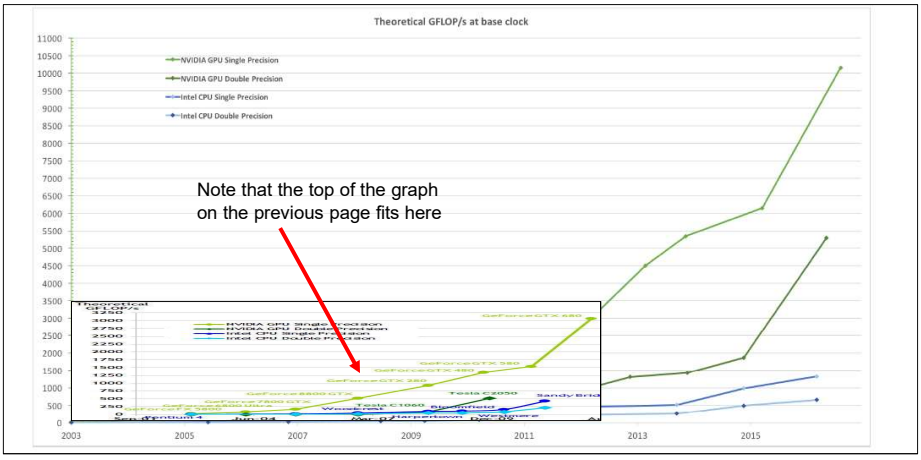


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## The "Core-Score". How can this be?

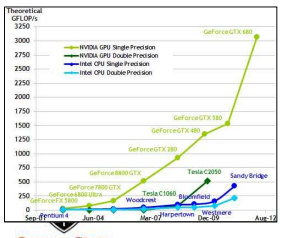


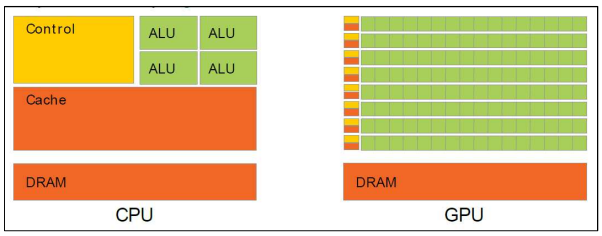



## Why have GPUs Been Outpacing CPUs in Performance?

Due to the nature of graphics computations, GPU chips are customized to stream **regular data**. General CPU chips must be able to handle **irregular data**.

Another reason is that GPU chips do not need the significant amount of **cache** space that occupies much of the real estate on general-purpose CPU chips. The GPU die real estate can then be re-targeted to hold more cores and thus to produce more processing power.

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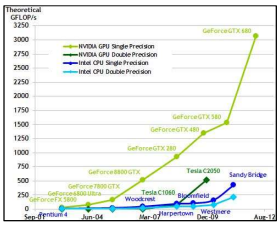
## Why have GPUs Been Outpacing CPUs in Performance?

Another reason is that general CPU chips contain on-chip logic to do **branch prediction** and **out-of-order execution.** This, too, takes up chip die space.

But, CPU chips can handle more general-purpose computing tasks.

So, which is better, a CPU or a GPU?

***It depends on what you are trying to do!***

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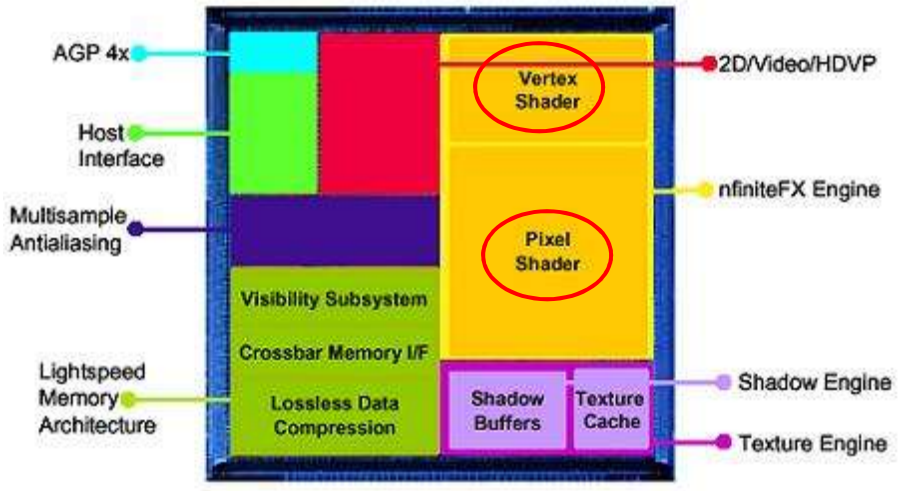
## Originally, GPU Devices were very task-specific

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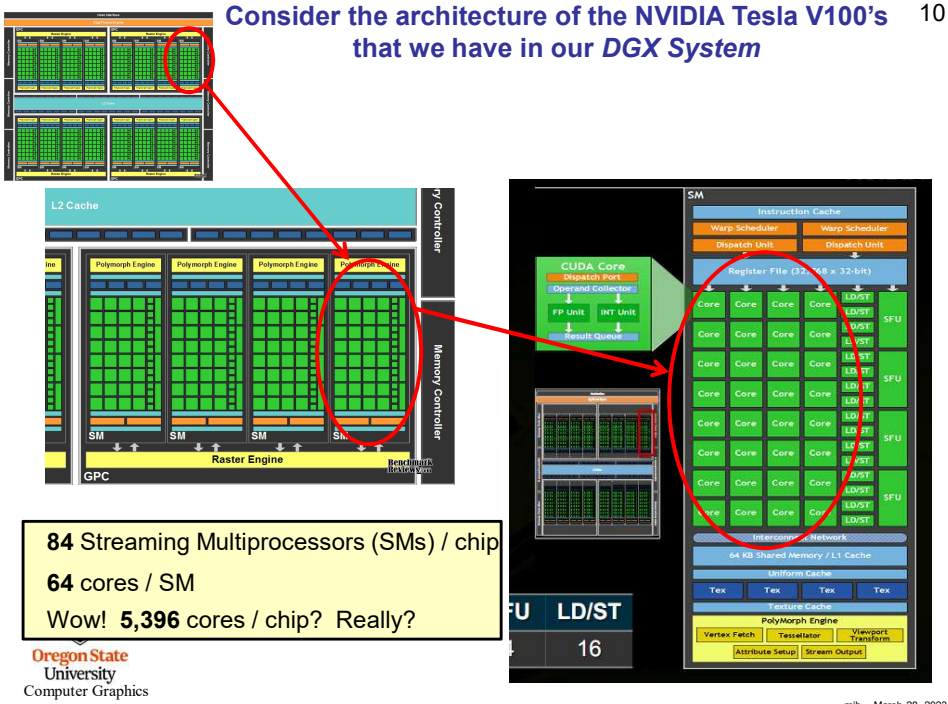
## Today's GPU Devices are not task-specific






## Consider the architecture of the NVIDIA Tesla V100's that we have in our *DGX System*




**84** Streaming Multiprocessors (SMs) / chip

**64** cores / SM

Wow! **5,396** cores / chip? Really?

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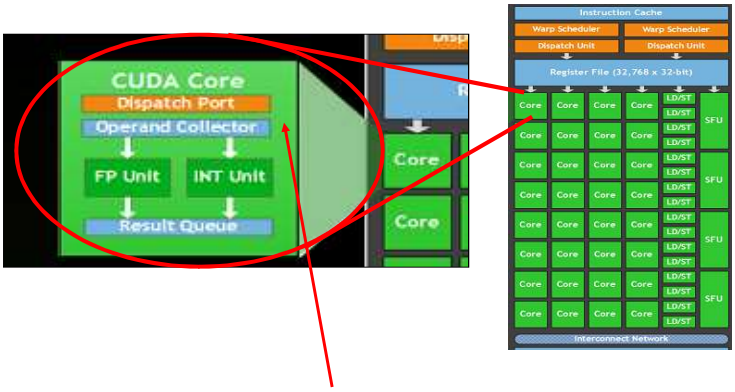
## What is a "Core" in the GPU Sense?




Look closely, and you'll see that NVIDIA really calls these "CUDA Cores"

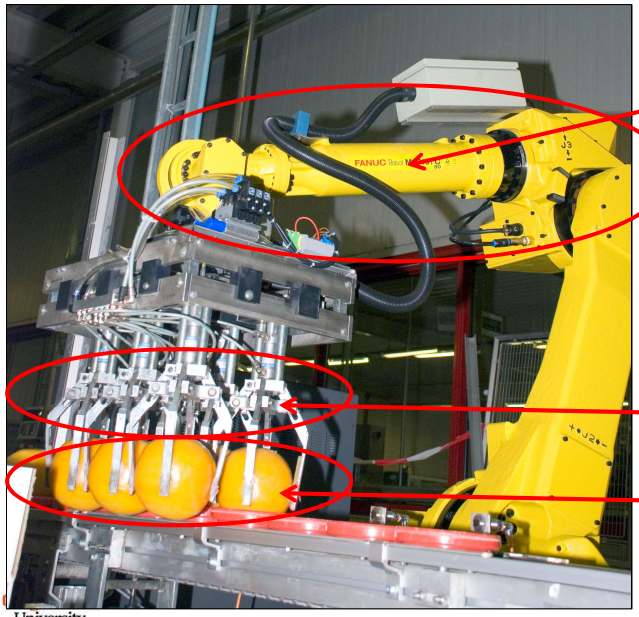
Look even more closely and you'll see that these CUDA Cores have no control logic – they are **pure compute units**. (The surrounding SM has the control logic.)

Other vendors refer to these as "Lanes". You might also think of them as 64-way SIMD.





## A Mechanical Equivalent…




http://news.cision.com

## How Many Robots Do You See Here?

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12? 72? Depends what you count as a "robot".





## A Spec Sheet Example

| NVIDIA Card 4000 Series | Number of CUDA Cores | Size of Power Supply ** | Memory Type | Memory Interface Width | Memory Bandwidth GB/sec | Base Clock Speed | Boost Clock Speed | NOTES |
|---|---|---|---|---|---|---|---|---|
| RTX-4080 | 9728 | 750 watt | GDDR6X | 256 bit | 716.8 GB/s | 2.21 GHz | 2.51 GHz | 16 GB of Memory |
| RTX-4090 | 16384 | 850 watt | GDDR6X | 384 bit | 1008 GB/s | 2.23 GHz | 2.52 GHz | 24 GB of Memory |

| NVIDIA Card 3000 Series | Number of CUDA Cores | Size of Power Supply ** | Memory Type | Memory Interface Width | Memory Bandwidth GB/sec | Base Clock Speed | Boost Clock Speed | NOTES |
|---|---|---|---|---|---|---|---|---|
| RTX-3050 | 2560 | 550 watt | GDDR6 | 128 bit | 224 GB/s | 1550 MHz | 1780 MHz | Standard with 8 GB of Memory |
| RTX-3060 | 3584 | 550 watt | GDDR6 | 192 bit | 384 GB/s | 1320 MHz | 1780 MHz | Standard with 12 GB of Memory |
| RTX-3060 Ti | 4864 | 600 watt | GDDR6 | 256 bit | 448 GB/s | 1410 MHz | 1670 MHz | Standard with 8 GB of Memory |
| RTX-3070 | 5888 | 650 watt | GDDR6 | 256 bit | 448 GB/s | 1580 MHz | 1770 MHz | Standard with 8 GB of Memory |
| RTX-3070 Ti | 6144 | 750 watt | GDDR6X | 256 bit | 608 GB/s | 1500 MHz | 1730 MHz | Standard with 8 GB of Memory |
| RTX-3080 | 8704 | 750 watt | GDDR6X | 320 bit | 760 GB/s | 1440 MHz | 1710 MHz | Standard with 10 GB of Memory |
| RTX-3080 Ti | 10240 | 750 watt | GDDR6X | 384 bit | 912 GB/s | 1370 MHz | 1670 MHz | Standard with 12 GB of Memory |
| RTX-3090 | 10496 | 750 watt | GDDR6X | 384 bit | 936 GB/s | 1400 MHz | 1700 MHz | Standard with 24 GB of Memory |
| RTX-3090 Ti | 10572 | 850 watt | GDDR6X | 384 bit | 936 GB/s | 1670 MHz | 1860 MHz | Standard with 24 GB of Memory |

| NVIDIA Card 2000 Series | Number of CUDA Cores | Size of Power Supply ** | Memory Type | Memory Interface Width | Memory Bandwidth GB/sec | Base Clock Speed | Boost Clock Speed | NOTES |
|---|---|---|---|---|---|---|---|---|
| RTX-2060 | 1920 | 500 watt | GDDR6 | 192 bit | 336 GB/s | 1365 MHz | 1680 MHz | Standard with 6 GB of Memory |
| RTX-2060 Super | 2176 | 550 watt | GDDR6 | 256 bit | 448 GB/s | 1470 MHz | 1650 MHz | Standard with 8 GB of Memory |
| RTX-2070 | 2304 | 550 watt | GDDR6 | 256 bit | 448 GB/s | 1410 MHz | 1620 MHz | Standard with 8 GB of Memory |
| RTX-2070 Super | 2560 | 650 watt | GDDR6 | 256 bit | 448 GB/s | 1605 MHz | 1770 MHz | Standard with 8 GB of Memory |
| RTX-2080 | 2944 | 650 watt | GDDR6 | 256 bit | 448 GB/s | 1515 MHz | 1710 MHz | Standard with 8 GB of Memory |
| RTX-2080 Super | 3072 | 650 watt | GDDR6 | 256 bit | 496 GB/s | 1650 MHz | 1815 MHz | Standard with 8 GB of Memory |
| RTX-2080 Ti | 4352 | 650 watt | GDDR6 | 352 bit | 616 GB/s | 1350 MHz | 1545 MHz | Standard with 11 GB of Memory |
| Titan RTX | 4608 | 650 watt | GDDR6 | 384 bit | 672 GB/s | 1350 MHz | 1770 MHz | Standard with 24 GB of Memory |

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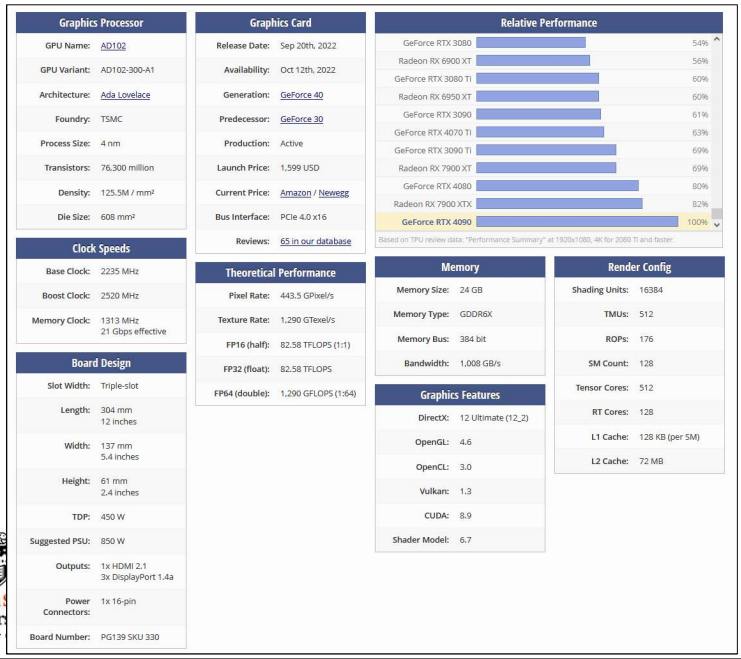
# NVIDIA 4090 Spec Sheet



**Graphics Processor**

| | |
|---|---|
| GPU Name: | AD102 |
| GPU Variant: | AD102-300-A1 |
| Architecture: | Ada Lovelace |
| Foundry: | TSMC |
| Process Size: | 4 nm |
| Transistors: | 76,300 million |
| Density: | 125.5M / mm² |
| Die Size: | 608 mm² |

**Graphics Card**

| | |
|---|---|
| Release Date: | Sep 20th, 2022 |
| Availability: | Oct 12th, 2022 |
| Generation: | GeForce 40 |
| Predecessor: | GeForce 30 |
| Production: | Active |
| Launch Price: | 1,599 USD |
| Current Price: | Amazon / Newegg |
| Bus Interface: | PCIe 4.0 x16 |
| Reviews: | 65 in our database |

**Relative Performance**

| | |
|---|---|
| GeForce RTX 3080 | 54% |
| Radeon RX 6900 XT | 56% |
| GeForce RTX 3080 Ti | 60% |
| Radeon RX 6950 XT | 60% |
| GeForce RTX 3090 | 61% |
| GeForce RTX 4070 Ti | 63% |
| GeForce RTX 3090 Ti | 69% |
| Radeon RX 7900 XT | 69% |
| GeForce RTX 4080 | 80% |
| Radeon RX 7900 XTX | 82% |
| GeForce RTX 4090 | 100% |

Based on TPU review data. "Performance Summary" at 1920x1080, 4K for 2080 Ti and faster.

**Clock Speeds**

| | |
|---|---|
| Base Clock: | 2235 MHz |
| Boost Clock: | 2520 MHz |
| Memory Clock: | 1313 MHz<br>21 Gbps effective |

**Theoretical Performance**

| | |
|---|---|
| Pixel Rate: | 443.5 GPixel/s |
| Texture Rate: | 1,290 GTexel/s |
| FP16 (half): | 82.58 TFLOPS (1:1) |
| FP32 (float): | 82.58 TFLOPS |
| FP64 (double): | 1,290 GFLOPS (1:64) |

**Memory**

| | |
|---|---|
| Memory Size: | 24 GB |
| Memory Type: | GDDR6X |
| Memory Bus: | 384 bit |
| Bandwidth: | 1,008 GB/s |

**Render Config**

| | |
|---|---|
| Shading Units: | 16384 |
| TMUs: | 512 |
| ROPs: | 176 |
| SM Count: | 128 |
| Tensor Cores: | 512 |
| RT Cores: | 128 |
| L1 Cache: | 128 KB (per SM) |
| L2 Cache: | 72 MB |

**Board Design**

| | |
|---|---|
| Slot Width: | Triple-slot |
| Length: | 304 mm<br>12 inches |
| Width: | 137 mm<br>5.4 inches |
| Height: | 61 mm<br>2.4 inches |
| TDP: | 450 W |
| Suggested PSU: | 850 W |
| Outputs: | 1x HDMI 2.1<br>3x DisplayPort 1.4a |
| Power Connectors: | 1x 16-pin |
| Board Number: | PG139 SKU 330 |

**Graphics Features**

| | |
|---|---|
| DirectX: | 12 Ultimate (12_2) |
| OpenGL: | 4.6 |
| OpenCL: | 3.0 |
| Vulkan: | 1.3 |
| CUDA: | 8.9 |
| Shader Model: | 6.7 |



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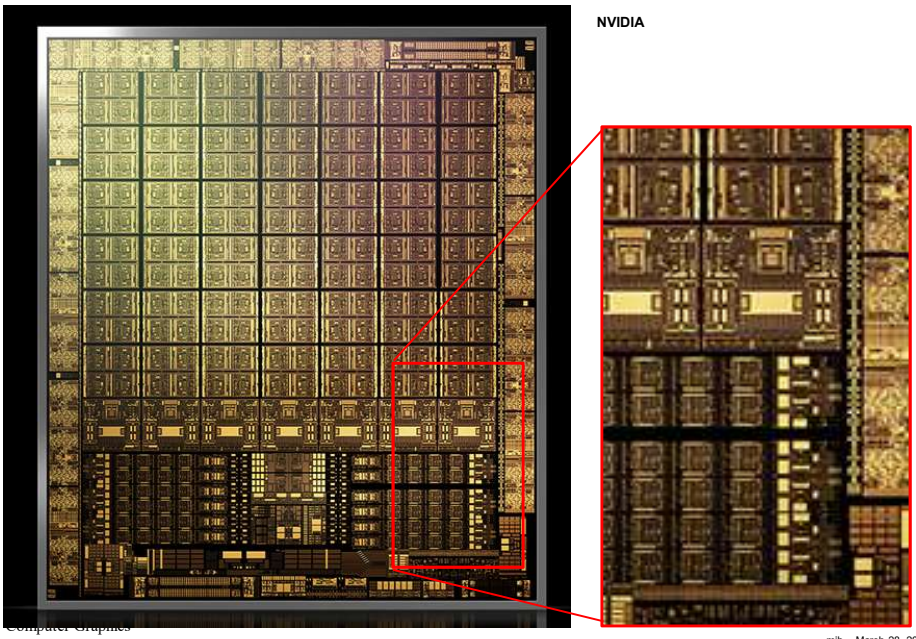
# NVIDIA's Ampere Chip



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## The Bottom Line is This

It is obvious that it is difficult to *directly* compare a CPU with a GPU. They are optimized to do different things.

So, let's use the information about the architecture as a way to consider what CPUs should be good at and what GPUs should be good at

| CPU | GPU |
|---|---|
| General purpose programming | Data parallel programming |
| Multi-core under user control | Little user control |
| Irregular data structures | Regular data structures |
| Irregular flow control | Regular Flow Control |

BTW,
The general term in the OpenCL world for an SM is a **Compute Unit**.
The general term in the OpenCL world for a CUDA Core is a **Processing Element**.

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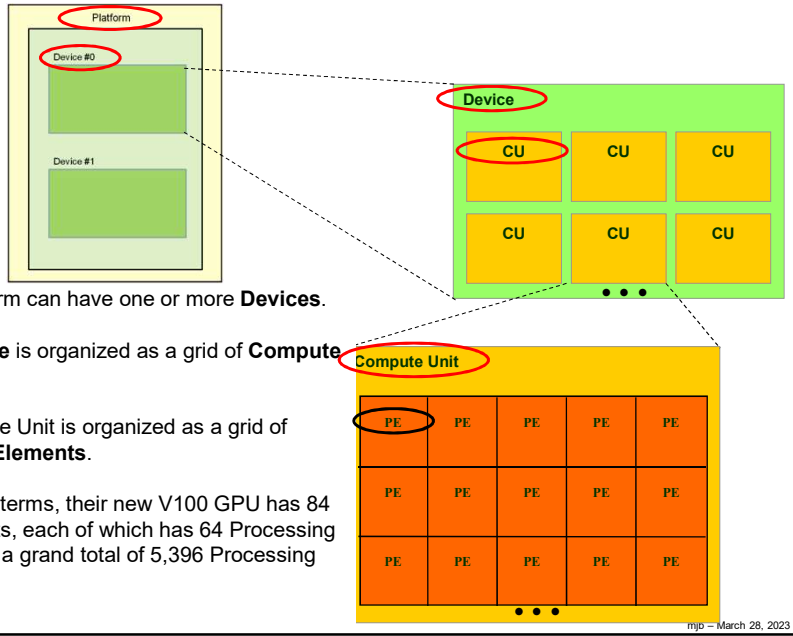
## Compute Units and Processing Elements are Arranged in Grids




A GPU Platform can have one or more **Devices**.

A GPU **Device** is organized as a grid of **Compute Units.**

Each Compute Unit is organized as a grid of **Processing Elements**.

So in NVIDIA terms, their new V100 GPU has 84 Compute Units, each of which has 64 Processing Elements, for a grand total of 5,396 Processing Elements.

## Thinking ahead to CUDA and OpenCL…



## How can GPUs execute General C Code Efficiently?

• Ask them to do what they do best. Unless you have a very intense **Data Parallel** application, don't even think about using GPUs for computing.

• GPU programs expect you to not just have a few threads, but to have ***thousands*** of them!

• Each thread executes the same program (called the *kernel*), but operates on a different small piece of the overall data

• Thus, you have many, many threads, all waking up at about the same time, all executing the same kernel program, all hoping to work on a small piece of the overall problem.

• CUDA and OpenCL have built-in functions so that each thread can figure out which thread number it is, and thus can figure out what part of the overall job it's supposed to do.

• When a thread gets blocked somehow (a memory access, waiting for information from another thread, etc.), the processor switches to executing another thread to work on.

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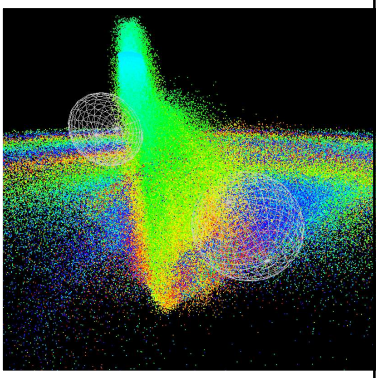
## So, the Trick is to Break your Problem into Many, Many Small Pieces



**Particle Systems** are a great example.

1. Have one thread per *each particle*.
2. Put all of the initial parameters into an array in GPU memory.
3. Tell each thread what the current **Time** is.
4. Each thread then computes its particle's position, color, etc. and writes it into arrays in GPU memory.
5. The CPU program then initiates OpenGL drawing of the information in those arrays.

Note: once setup, the data never leaves GPU memory!



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## Something New – Tensor Cores




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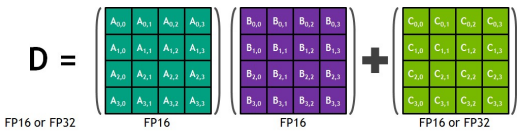
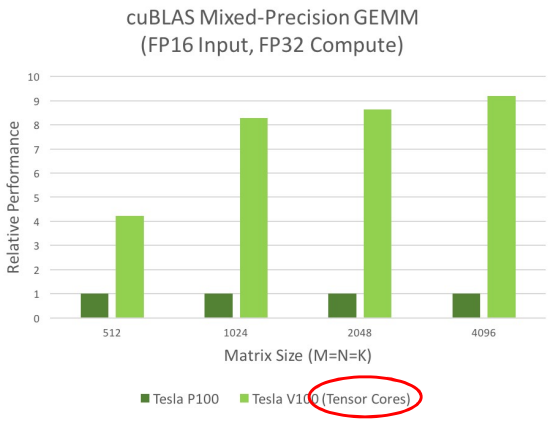
## Tensor Cores Accelerate Fused-Multiply-Add Arithmetic



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## What is Fused Multiply-Add?



Many scientific and engineering computations take the form:
**D = A + (B*C);**

A "normal" multiply-add would likely handle this as:
**tmp = B*C;**
**D = A + tmp;**

A "fused" multiply-add does it all at once, that is, when the low-order bits of B*C are ready, they are immediately added into the low-order bits of A at the same time the higher-order bits of B*C are being multiplied.

Consider a Base 10 example: **789 + ( 123*456 )**

```
   123
 x 456
 ------
   738
  615
 492
 ------
 + 789
 ------
 56,877
```

Can start adding the 9 the moment the 8 is produced!



**Note: "Normal" A+(B*C) ≠ "FMA" A+(B*C)**



## There are Two Approaches to Combining CPU and GPU Programs



1. Combine both the CPU and GPU code in the same file. The CPU compiler compiles its part of that file. The GPU compiler compiles just its part of that file.
2. Have two separate programs: a .cpp and a .somethingelse that get compiled separately.

### Advantages of Each

1. The CPU and GPU sections of the code know about each others' intents. Also, they can share common structs, #define's, etc.
2. It's potentially cleaner to look at each section by itself. Also, the GPU code can be easily used in combination with other CPU programs.

### Who are we Talking About Here?

1 = NVIDIA's CUDA

2 = Khronos's OpenCL



**We will talk about each of these separately – stay tuned!**

## Looking ahead: If threads all execute the same program, what happens on flow divergence?



```
if( a > b )
        Do This;
else
        Do That;
```

1. The line "if( a > b )" creates a vector of Boolean values giving the results of the if-statement for each thread. This becomes a "mask".
2. Then, the GPU executes all parts of the divergence:
   Do This;
   Do That;
3. During that execution, anytime a value wants to be stored, the mask is consulted and the storage only happens if that thread's location in the mask is the right value.

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- GPUs were originally designed for the streaming-ness of computer graphics
- Now, GPUs are also used for the streaming-ness of data-parallel computing
- GPUs are better for some things. CPUs are better for others.

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## Dismantling a Graphics Card



This is an Nvidia 1080 ti card – one that died on us. It willed its body to education.




## Dismantling a Graphics Card

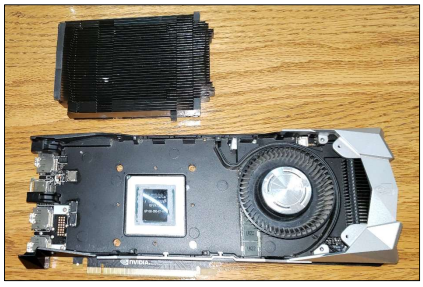


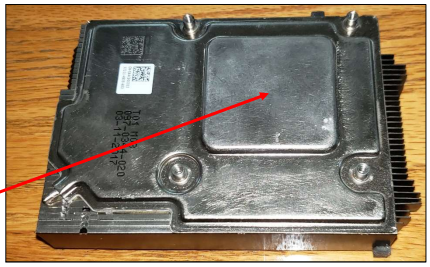
Removing the covers:

## Dismantling a Graphics Card



Removing the heat sink:





This transfers heat from the GPU Chip to the cooling fins

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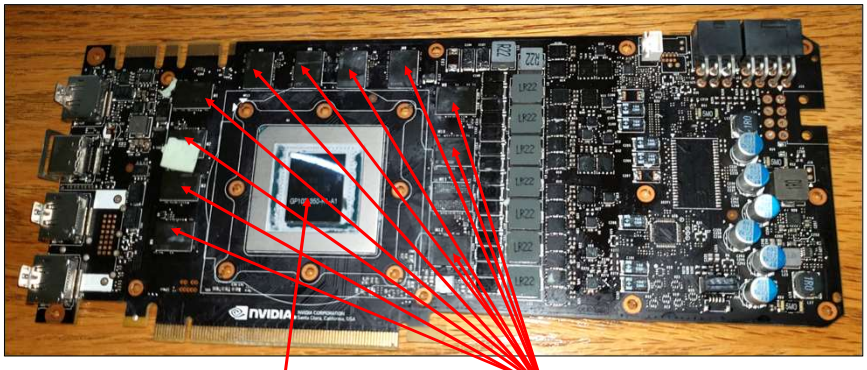
## Dismantling a Graphics Card



Removing the fan assembly reveals the board:

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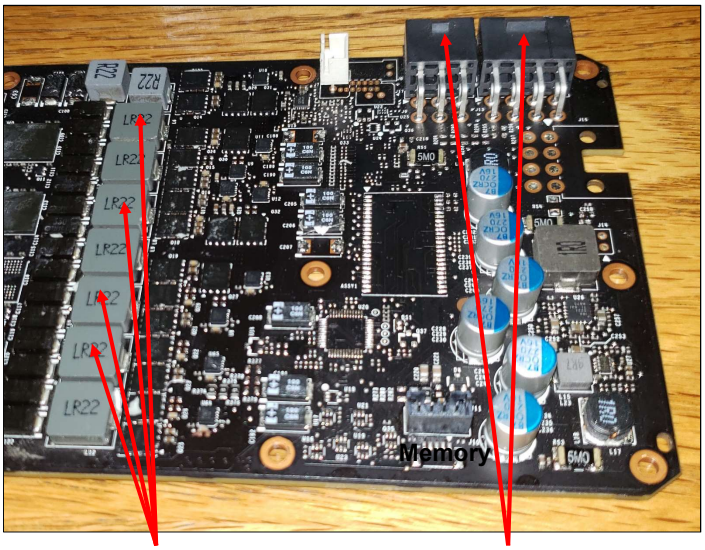
## Dismantling a Graphics Card



Power half of the board:

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**Power distribution**

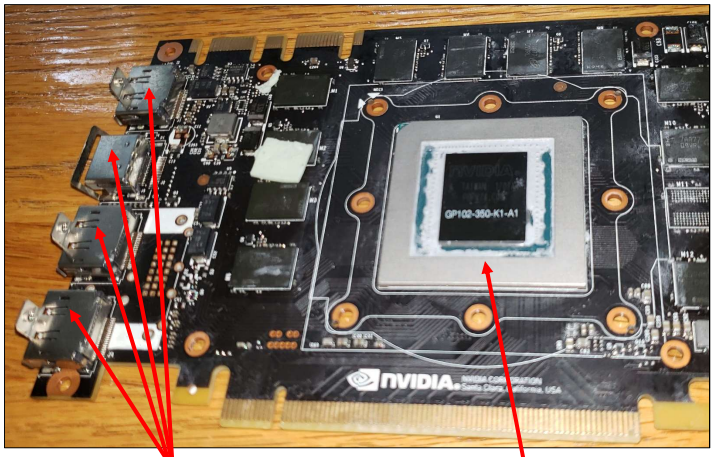
**Power input**



## Dismantling a Graphics Card



Graphics half of the board:

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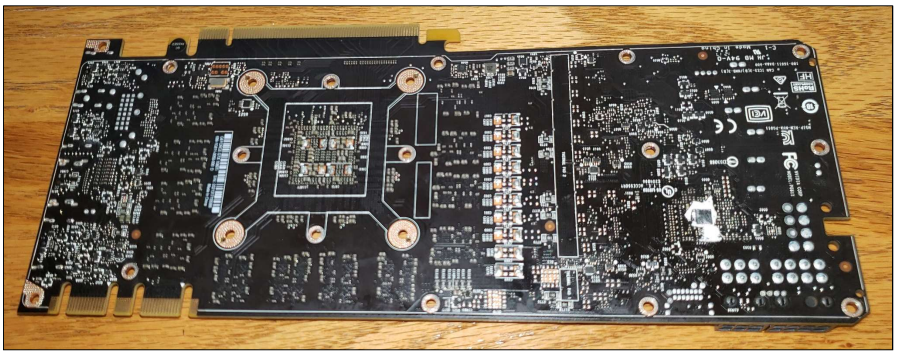
**Video out**

**GPU Chip**
**This one contains 7.2 billion transistors!**
**The newer cards contain 70+ billion transistors.**
**(Thank you, Moore's Law)**

## Dismantling a Graphics Card



Underside of the board:

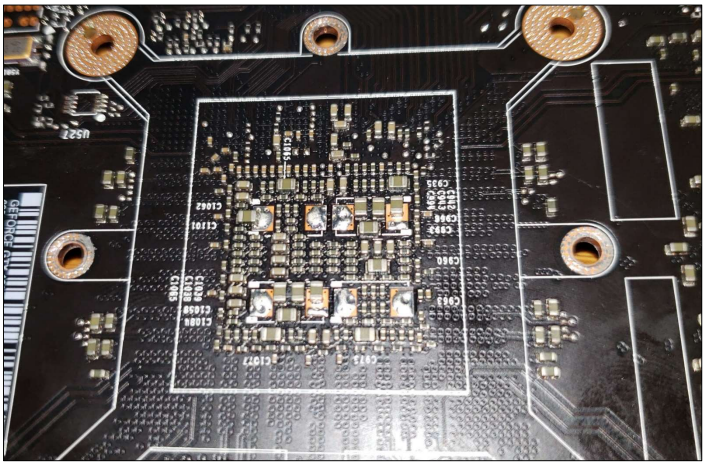




## Dismantling a Graphics Card



Underside of where the GPU chip attaches:



Here is a fun video of someone explaining the different parts of this same card:
https://www.youtube.com/watch?v=dSCNf9DIBGE