HOCHSCHULE FURTWANGEN UNIVERSITY HFU

CODE3

Summer semester 2025

Prof. Dr.-Ing. Uwe Hahne

A trip down the 3D graphics pipeline

Learning goals: Lecture 01 (May 13th)

Get an overview of what happens during rendering.

Get to know the basic terms, typical hardware and standard APIs.

What is a pipeline?

- Input → Command chain → Output
- Chain of command consists of several stages
- The steps must be executed sequentially for a single data element
- For a larger amount of data, each stage can be executed in **parallel.** executed in parallel

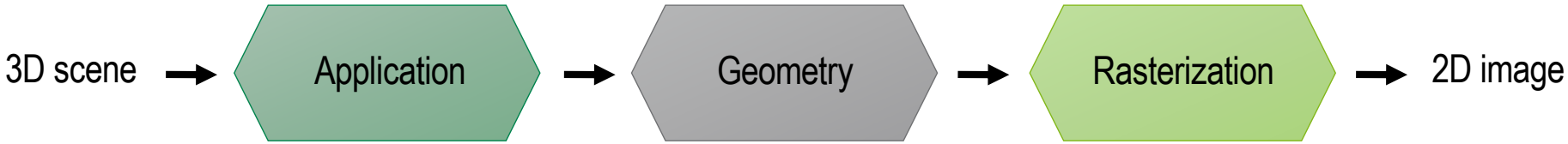
Pipeline [microprocessors]: refers to a type of "assembly line" with which the processing of machine commands is broken down into subtasks that are executed in parallel for several commands.

Definitions: www.wikipedia.de

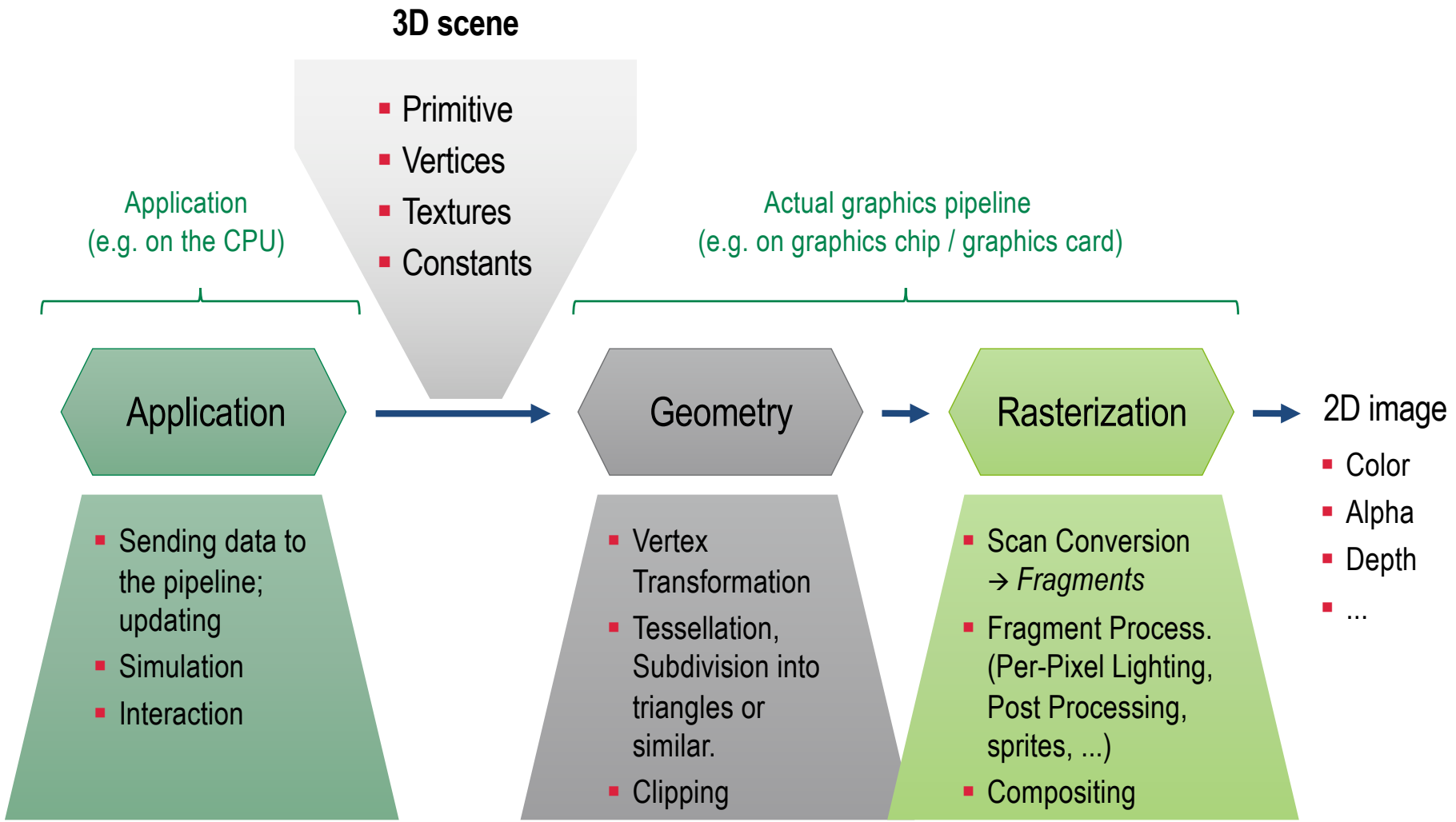
What is a graphics pipeline?

- Input: 3D scene description (polygons, transformations, ...)
- Output: 2D image
- What are the levels / what is the chain of command?

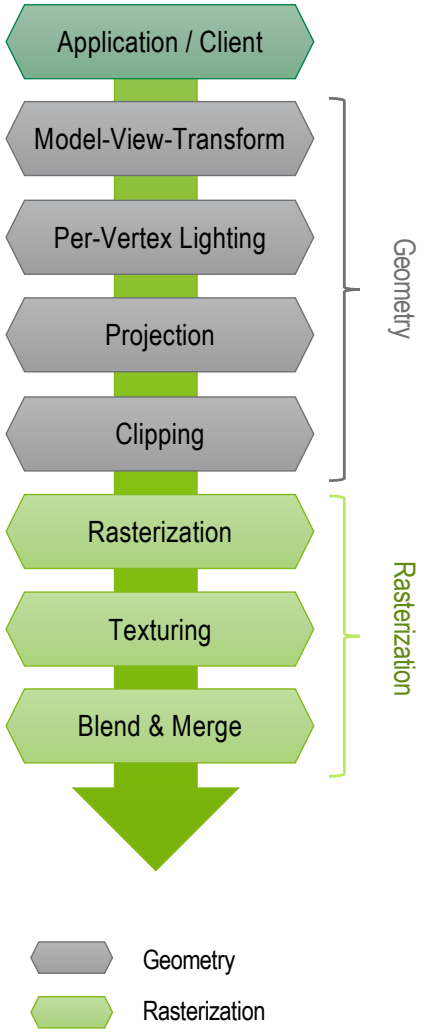
Conceptual model of the graphics pipeline



Conceptual model of the graphics pipeline



Classic graphics pipeline



- Functionality was hard-wired (fixed function pipeline)
- Configuration through many model parameters
  - Modelview matrix
  - Projection matrix
  - Light and material properties
  - Texturing modes
  - Alpha blending modes
  - Fog modes
  - ...

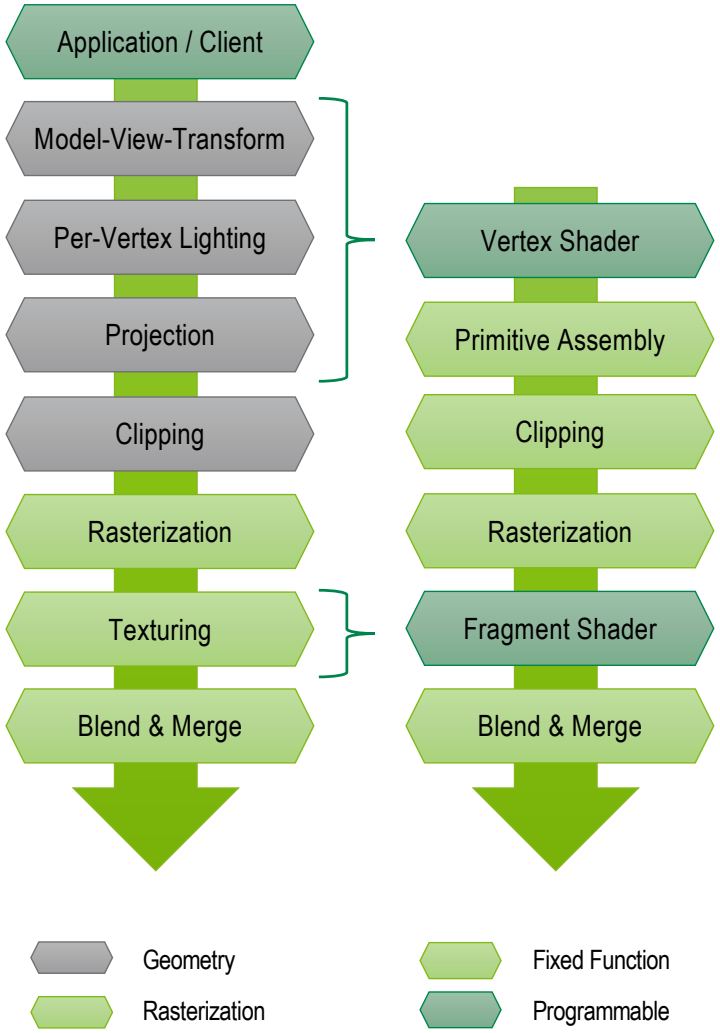
```
glMatrixMode(GL_MODELVIEW);
glMultMatrix(...);
```

```
glLight(GL_LIGHT0, GL_POSITION, {5,4,-1,1} );
glLight(GL_LIGHT0, GL_DIFFUSE, {1,1,1} );
```

```
glAlphaFunc(GL_GREATER, 0.2);
```

```
glFog(GL_FOG_MODE, GL_EXP);
glFog(GL_FOG_COLOR, {1,1,1} );
```

From the classic to the programmable pipeline




```
// this is a shader executed in the pipeline
void main() {
  outPos = modelViewMatrix * inPos;
  normal = normalMatrix * inNormal;
  outColor = phong(outPos,normal);
  outPos = projectionMatrix * outPos;
}
```

Programmable shaders

- Since OpenGL 2.0 / DirectX 8.0 (2004/2000)
- Replace parts of the fixed function pipeline
- Pipeline becomes more flexible
  - Other lighting models
  - Other uses of textures and alpha blending
  - Realize effects directly *in the pipeline* using shaders

From graphics computers to programmable GPUs

1981 - 200x: Silicon Graphics (SGI) graphics workstations

- 1987 SGI "4D" series → most popular computer for animation
- 1992 MIPS R4000, use of one of the first 64-bit processors

1996: 3DFX Vodoo, first PC graphics card

1999: Transform & Lighting (T&L) Unit

- NVIDIA Geforce 256 "the world's first GPU"; Pipeline on a single chip

2001: GeForce 3: First fixed-length Vertex Programs

2006-2011: Hardware tessellation

- Distribution through DirectX 11 and OpenGL 4.1

2011-2013: Compute Shaders

- For general, massively parallel calculations

2014: New proprietary low-level APIs

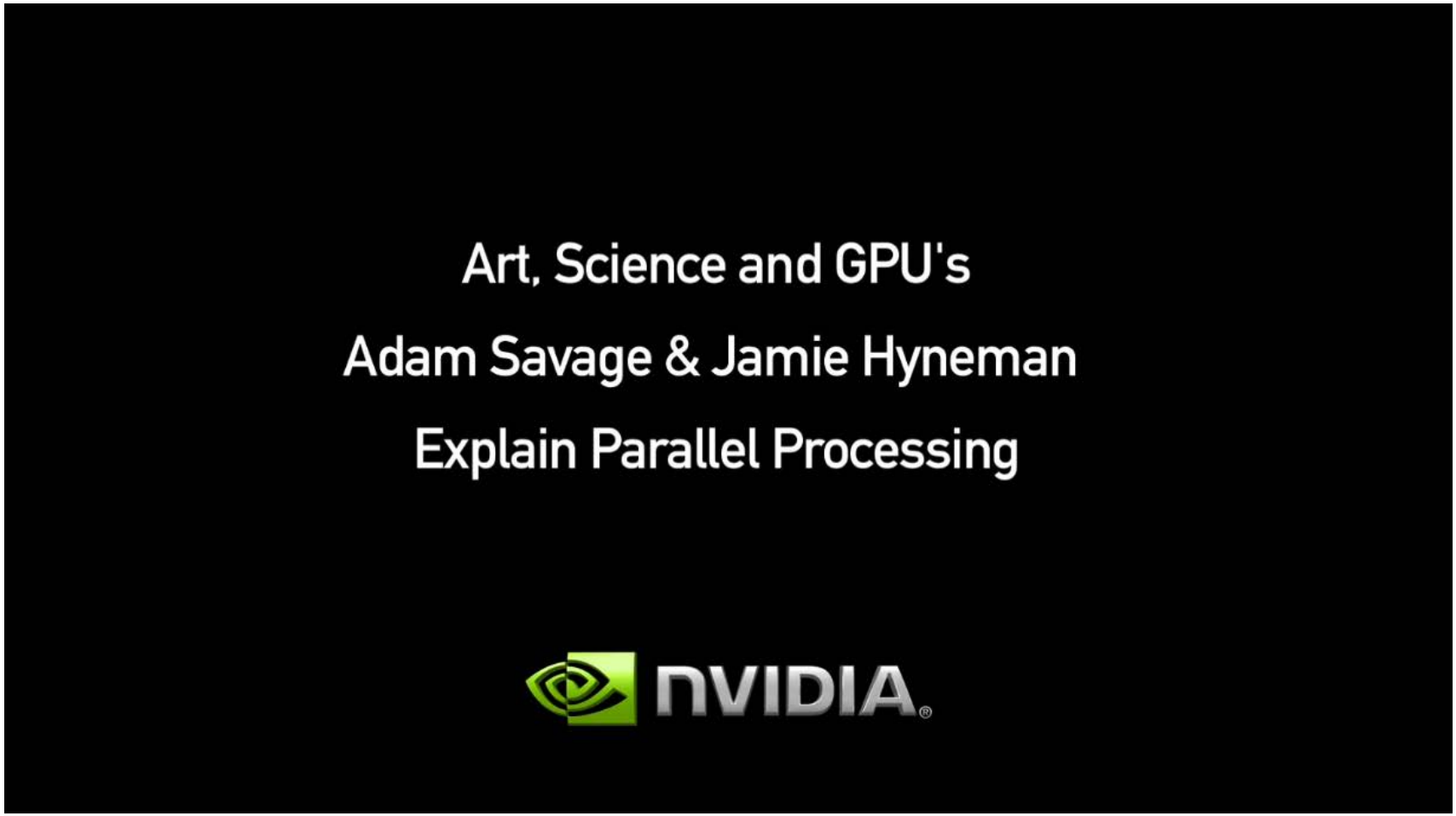
- AMD *Mantle, NVIDIA Cuda*
- Apple *Metal*
- Design goal: less "ballast" than OpenGL / DirectX
- DirectX 12 and Vulkan: similar design goals

1999
15 million triangles/sec.
480 million pixels/sec.

2010
100,000 million vertices/sec. *
40,000 million pixels/sec.

* See this side node about GPU performance measures

Graphics hardware



From https://blogs.nvidia.com/blog/2009/12/16/whats-the-difference-between-a-cpu-and-a-gpu/

Inside view of a computer

Inside view of a computer

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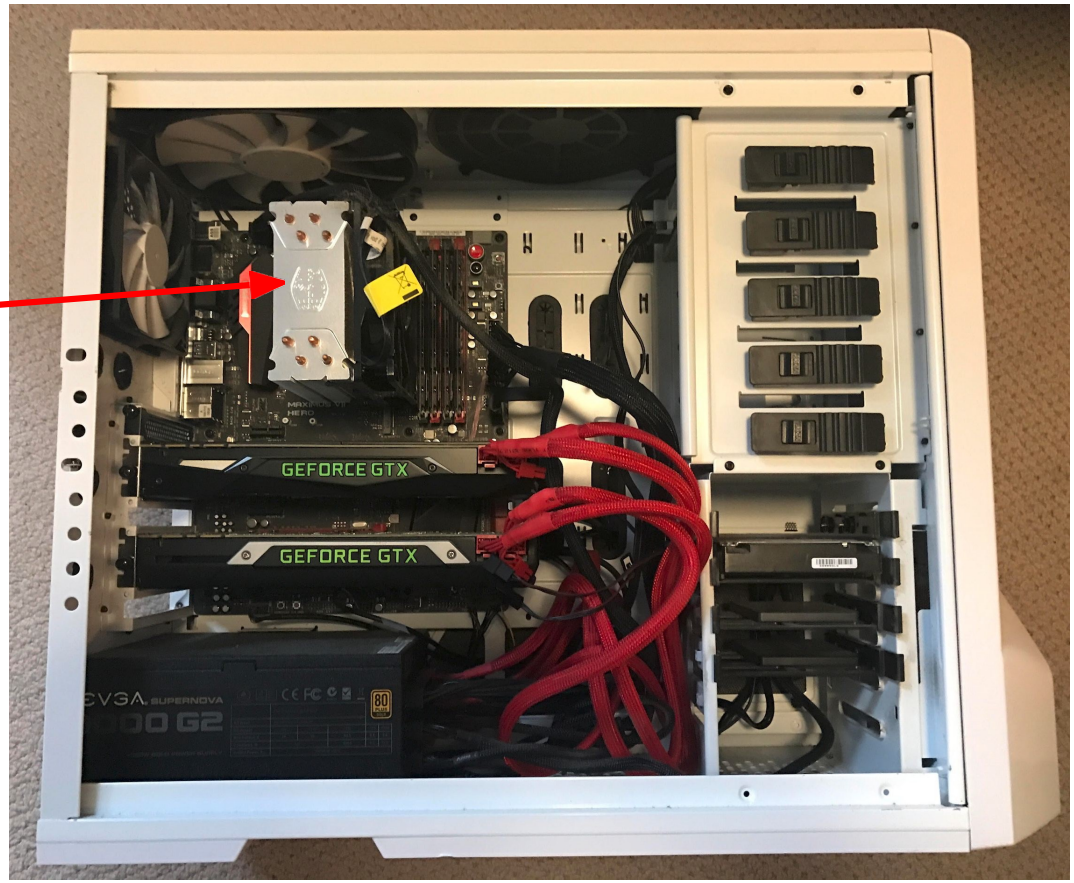
Find the CPU!

(central processing unit)



Inside view of a computer

Find the GPUs!

(graphics processing unit)

CPU vs GPU

	Cores	Clock Speed	Memory	Price	Speed (throughput)
CPU (Intel Core i9-7900k)	10	4.3 GHz	System RAM	$385	~640 GFLOPS FP32
GPU (NVIDIA RTX 3090)	10496	1.6 GHz	24 GB GDDR6X	$1499	~35.6 TFLOPS FP32

CPU: Fewer cores, but each core is much faster and more powerful; ideal for sequential tasks

GPU: More cores, but each core is much slower and "dumber"; ideal for parallel tasks

A graphics pipeline (anno 2004) in hardware

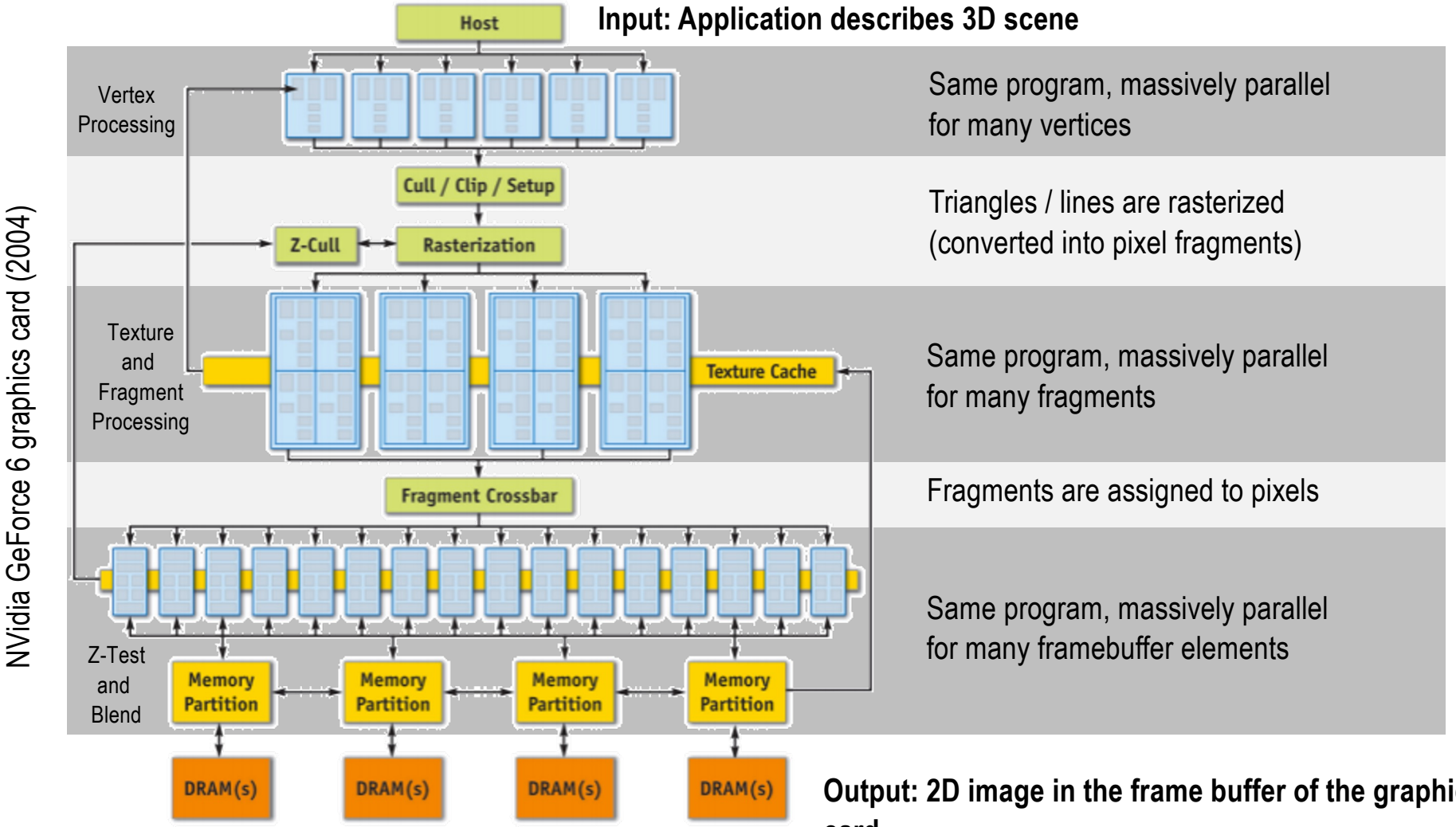


Image source: GPU Gems 2 (2005), ftp://download.nvidia.com/developer/GPU_Gems_2/GPU_Gems2_ch30.pdf

Graphics pipeline: SIMD = Single Instruction, Multiple Data

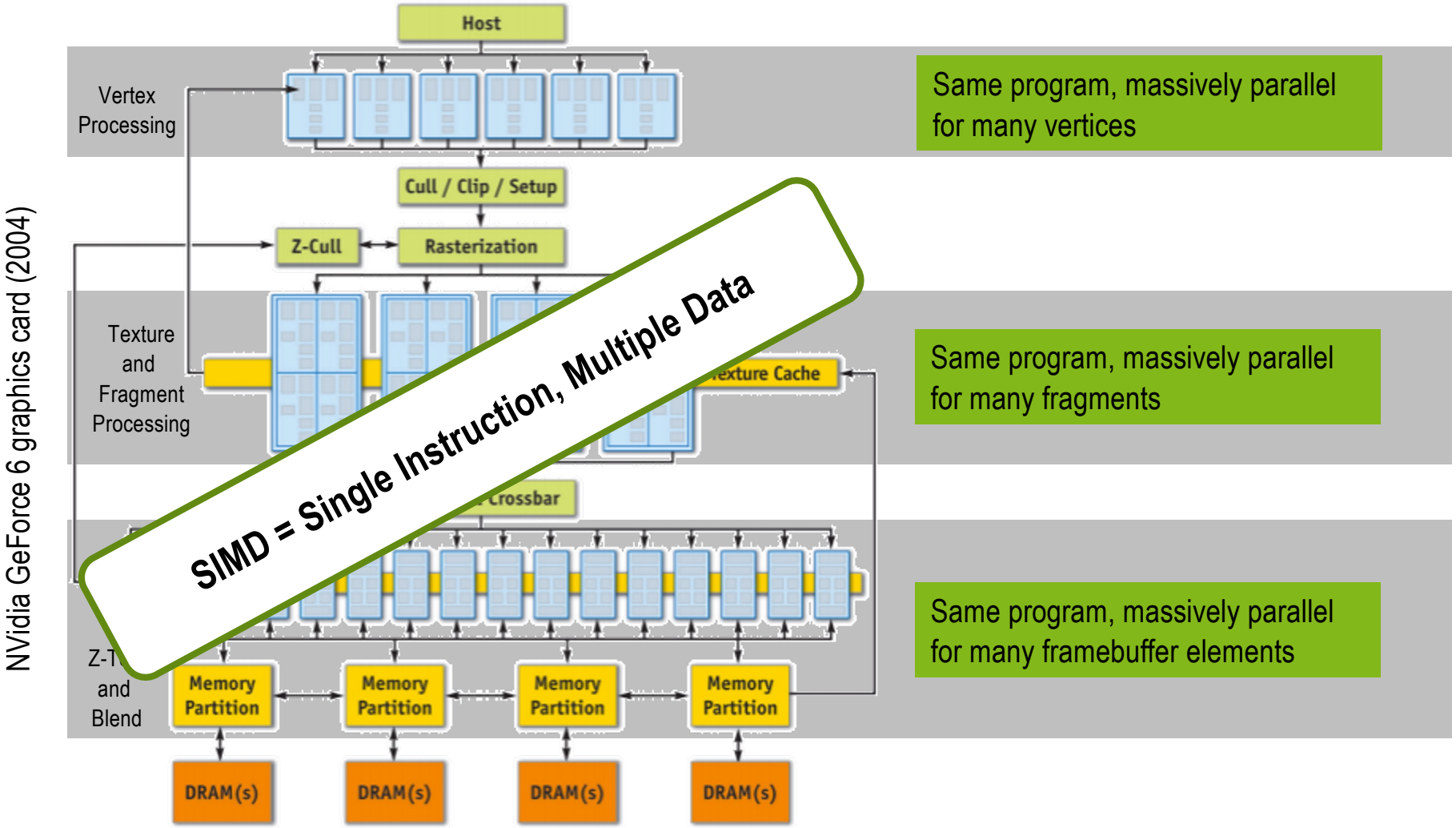


Image source: GPU Gems 2 (2005), ftp://download.nvidia.com/developer/GPU_Gems_2/GPU_Gems2_ch30.pdf

Example: NVIDIA Jetson TX2 mobile chipset (2017)

	TX2 NX
Technical data of the graphics processor	
NVIDIA Pascal™ (number of computing units)	256
Technical data of the memory *:	
Standard memory configuration	4 x 4 GB LPDDR
Speed	51.2 GB/s
Power consumption	7.5 / 15 watts

*** Shared CPU+GPU memory**

Example high-end GPU: NVIDIA RTX 3080 Ti (2021)

	GeForce RTX 3080 Ti
Technical data of the graphics processor	
NVIDIA CUDA computing units®	10.240
Boost clock (GHz)	1,67
Base clock rate (GHz)	1,37
Technical data of the memory:	
Standard memory configuration	12 GB GDDR6X
Width of the memory interface	384 bit
Speed	76 - 84 GB/s *
Power consumption	350 watts

10,000+ shader cores running in parallel!

*** Approximation from Wikipedia**

Example high-end GPU: NVIDIA Titan RTX (2021)

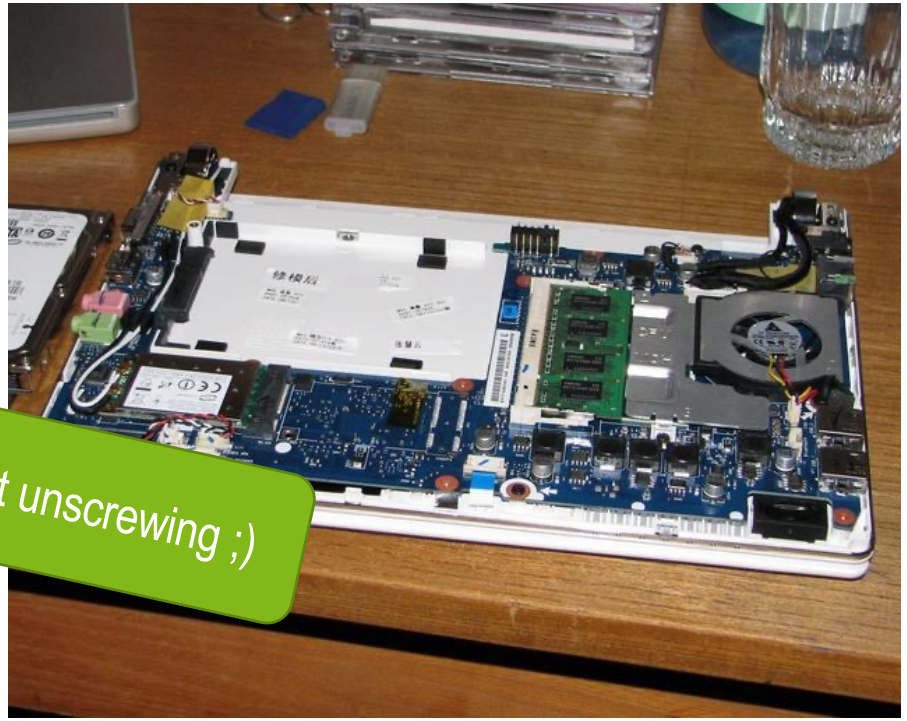
	Titan RTX
Technical data of the graphics processor	
NVIDIA CUDA computing units®	4608 + 576 Tensor Cores + 72 RT Cores
Boost clock (GHz)	1,77
Base clock rate (GHz)	1,35
Technical data of the memory:	
Standard memory configuration	24 GB GDDR6X
Width of the memory interface	384 bit
Speed	672 GB/s
Power consumption	280 watts *

Different specialized cores!

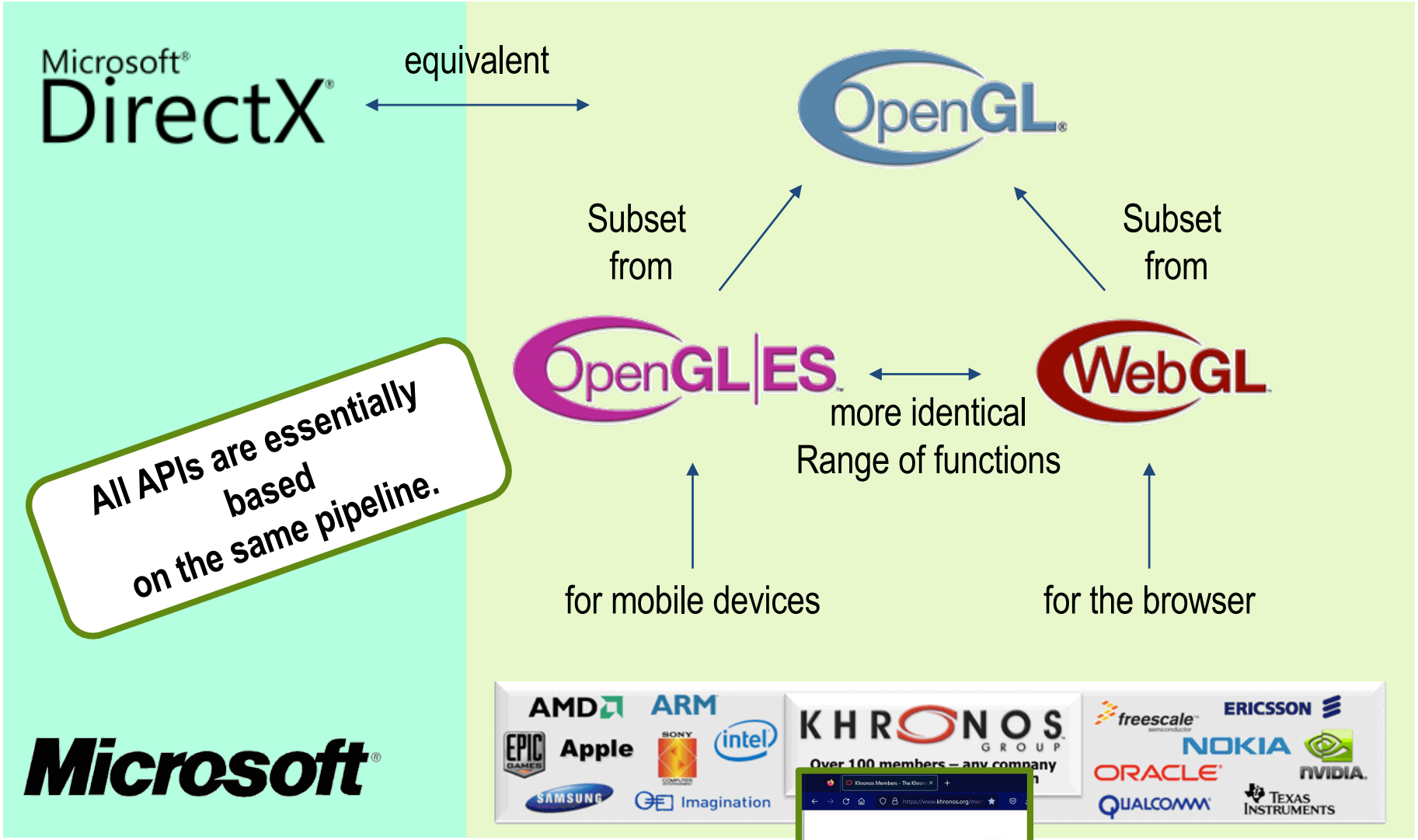
*** Thermal design power**

Task

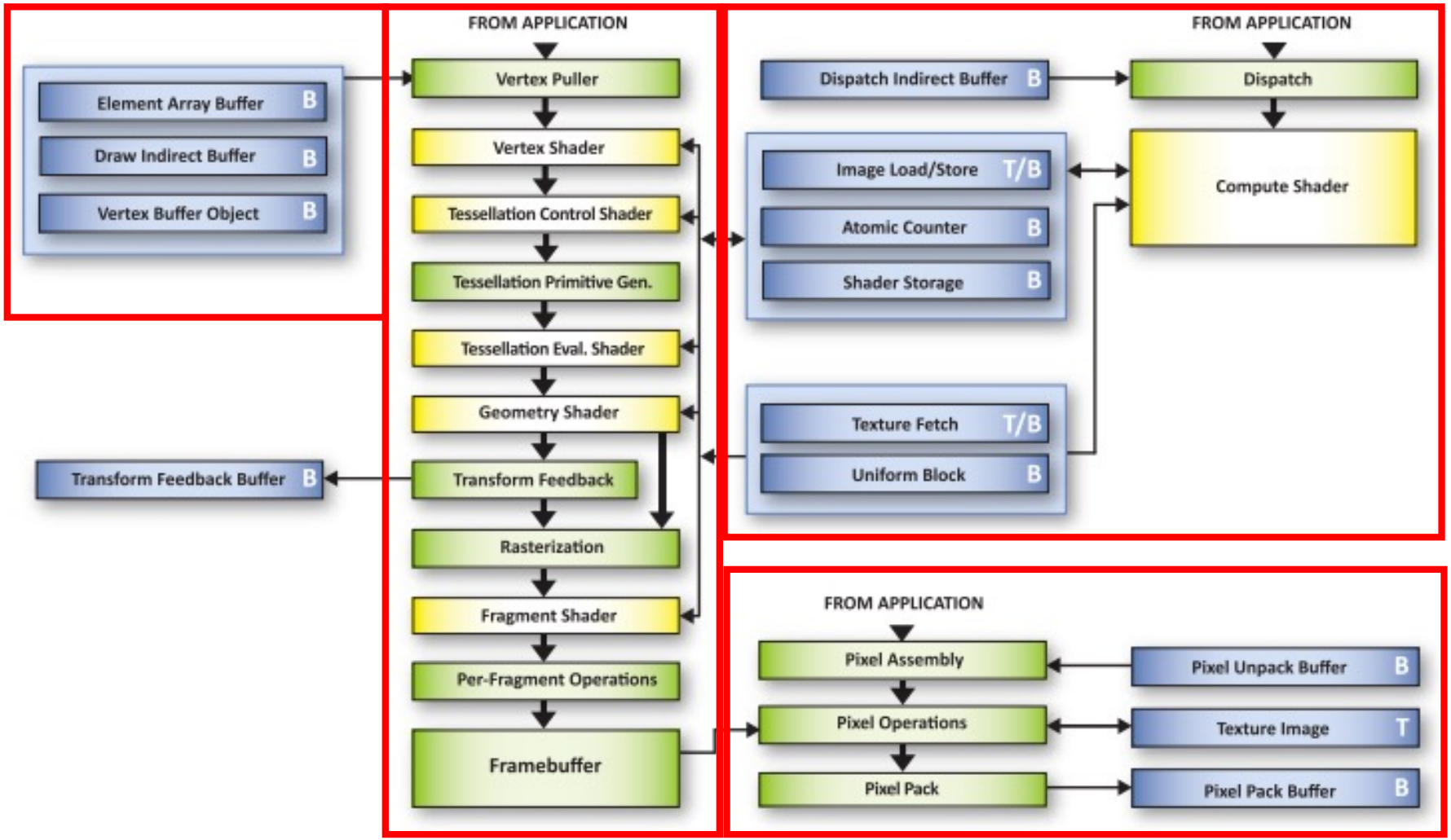
Take your laptop or smartphone and find out which CPU and GPU are installed in it.



Standard low level APIs for 3D graphics

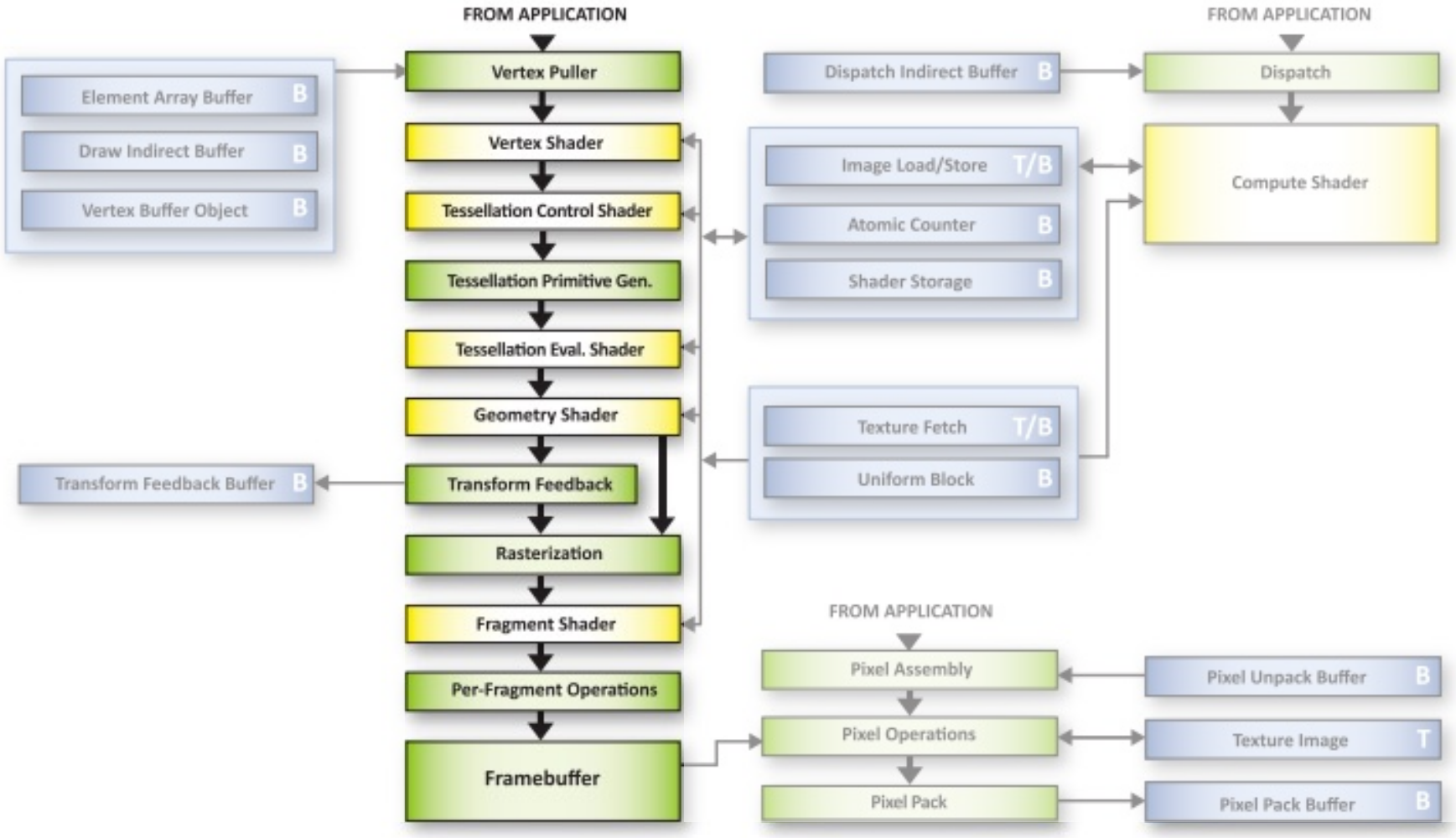


Complete OpenGL 4.6 pipeline (2017)



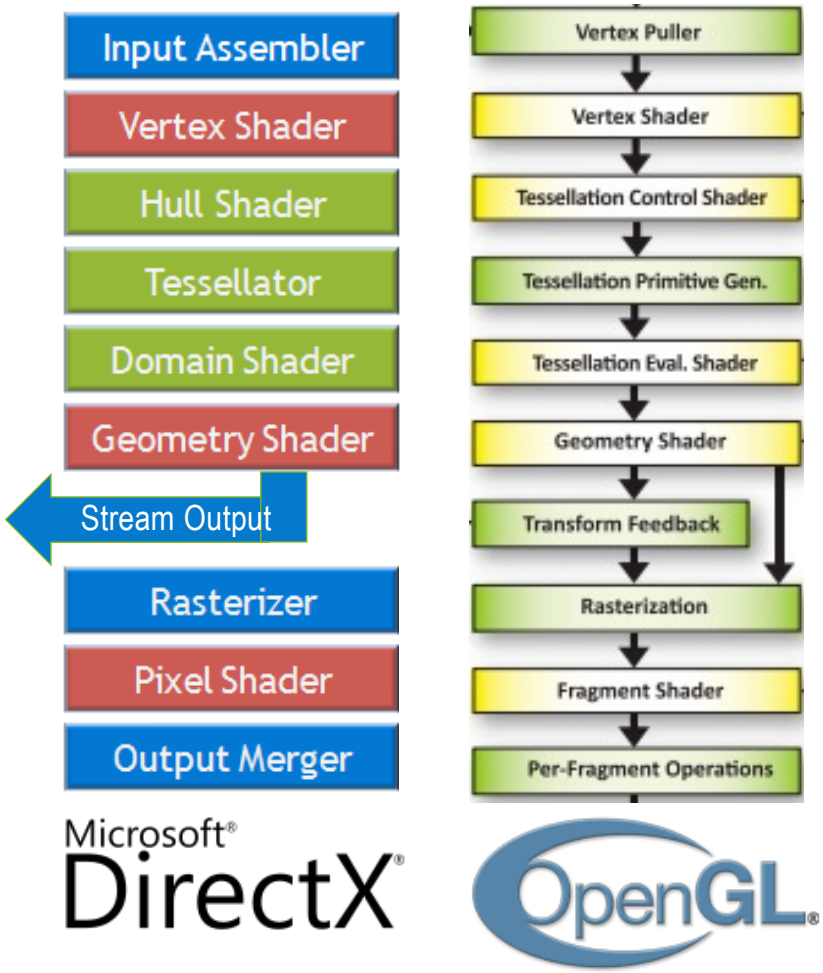
http:

The core of the OpenGL pipeline



http:

DirectX 11 vs. OpenGL 4 Pipeline



The two pipelines are very similar, except for terminology

- "Input Assembler" = "Vertex Pulling"
- "Hull Shader" = "Tesselation Control Shader"
- ...

The simple reason for this:

- Both standards are developed for the latest graphics hardware
- Differences are usually only temporary until one standard has caught up with the other

Sources: Microsoft, Khronos Group

OpenGL vs Vulkan

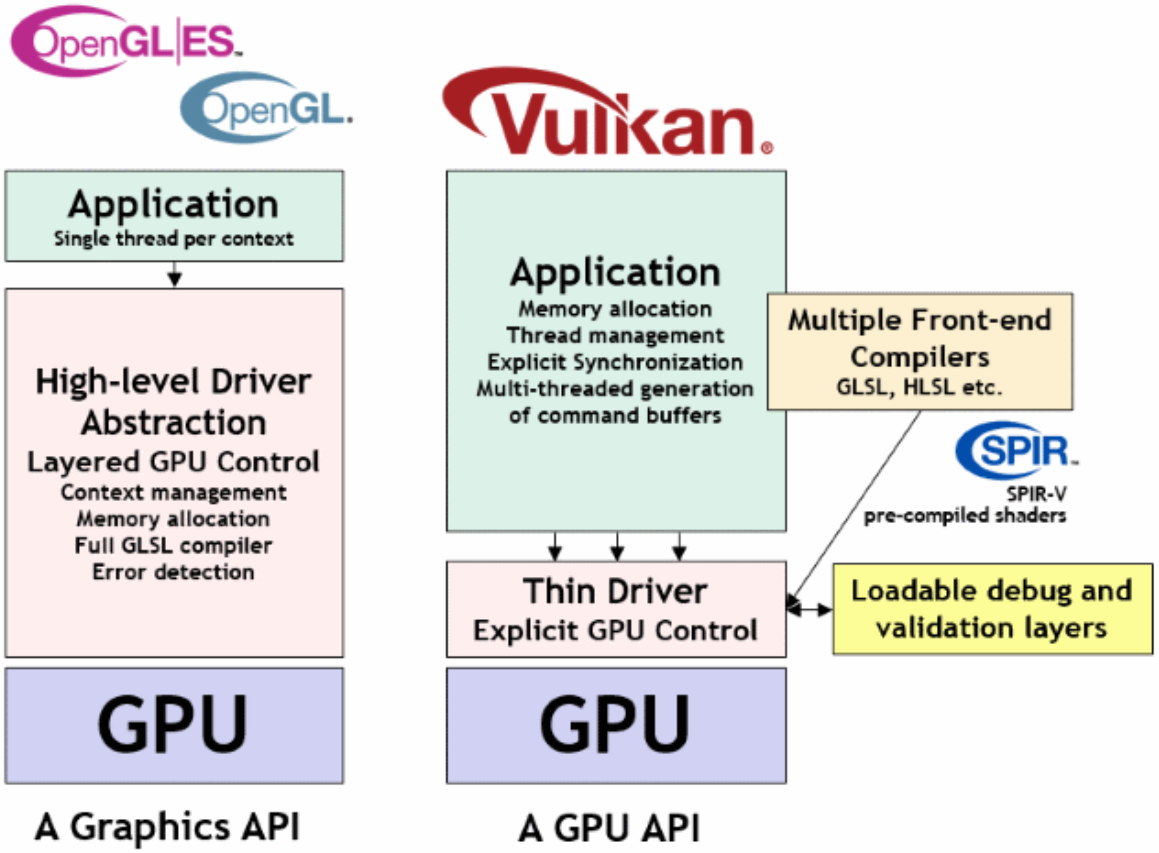
Vulkan: Performance, Predictability, Portability

Complex drivers cause overhead and inconsistent behavior across vendors

Always active error handling

Full GLSL preprocessor and compiler in driver

OpenGL vs. OpenGL ES



Simpler drivers - application has the best knowledge for holistic optimization - no 'driver magic'

Explicit creation of API objects before usage - efficient, predictable execution

Easier portability - no fighting with different vendor heuristics

Validation and debug layers loaded only when needed

SPIR-V intermediate language: shading language flexibility

Unified API across mobile and desktop platforms

Multiple graphics, command and DMA queues

Source: Khronos Group

About Vulkan

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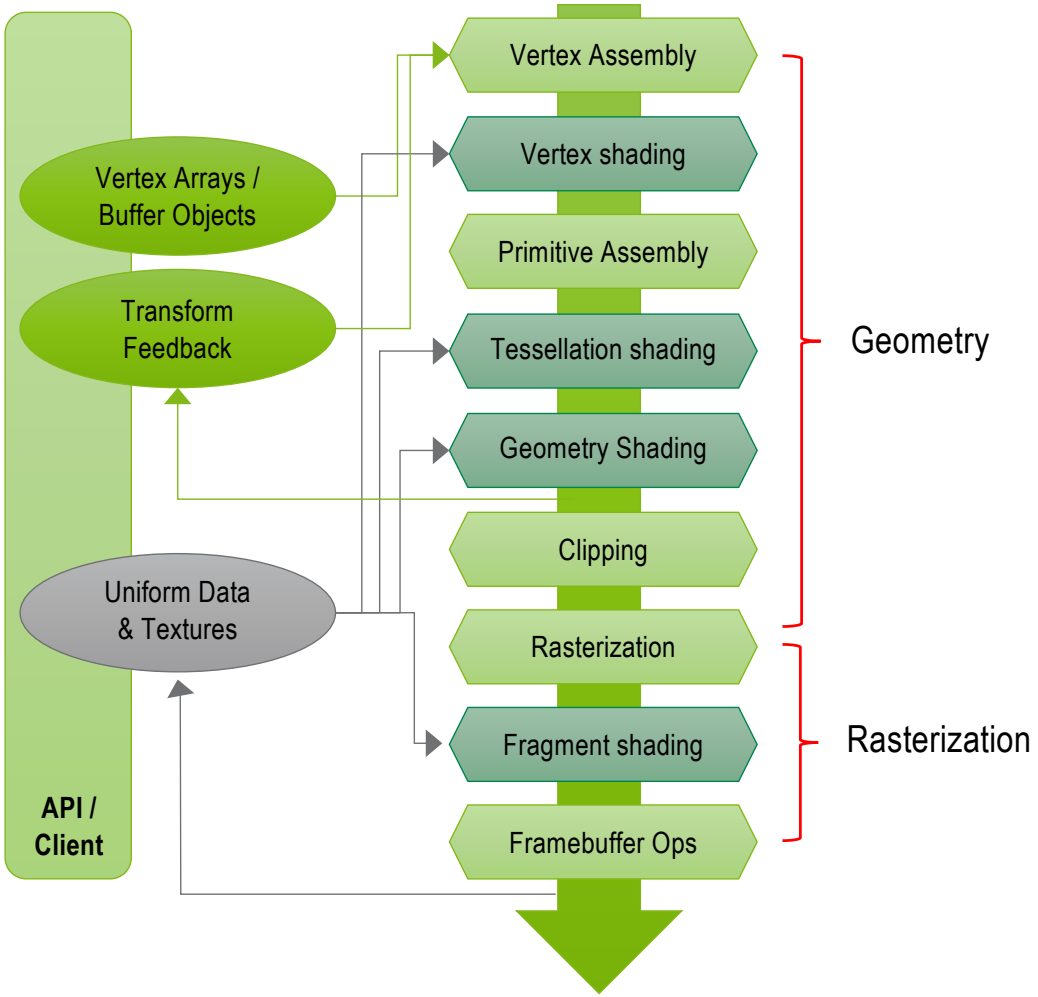
"Vulkan is not well-suited to simple test applications; neither is it a suitable aid for teaching graphics concepts."
— Graham Sellers, in the book *"Vulkan Programming Guide"*

The (simplified) pipeline model of OpenGL

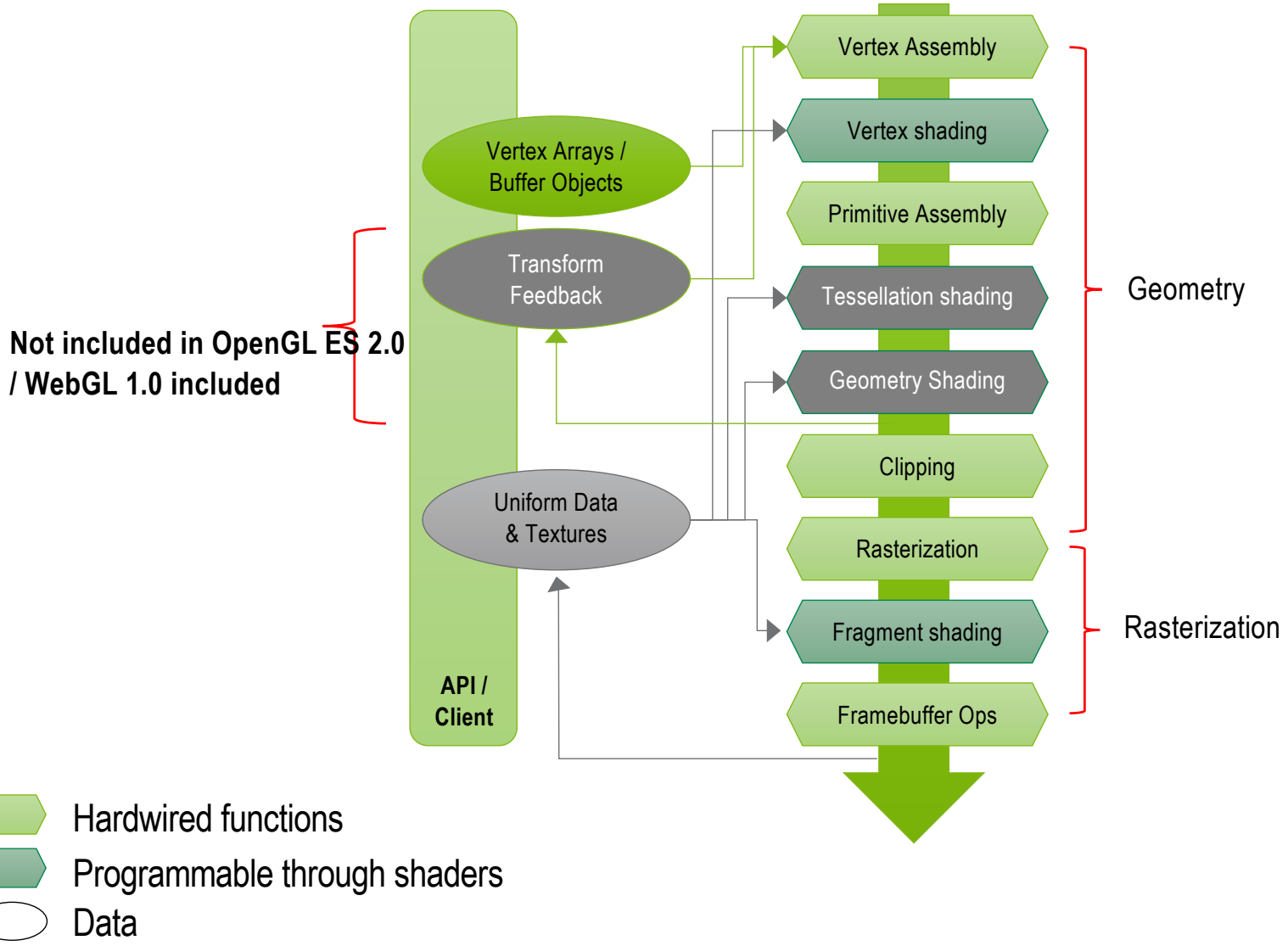


Hardwired functions

Programmable through shaders

Data

The (simplified) pipeline model of OpenGL



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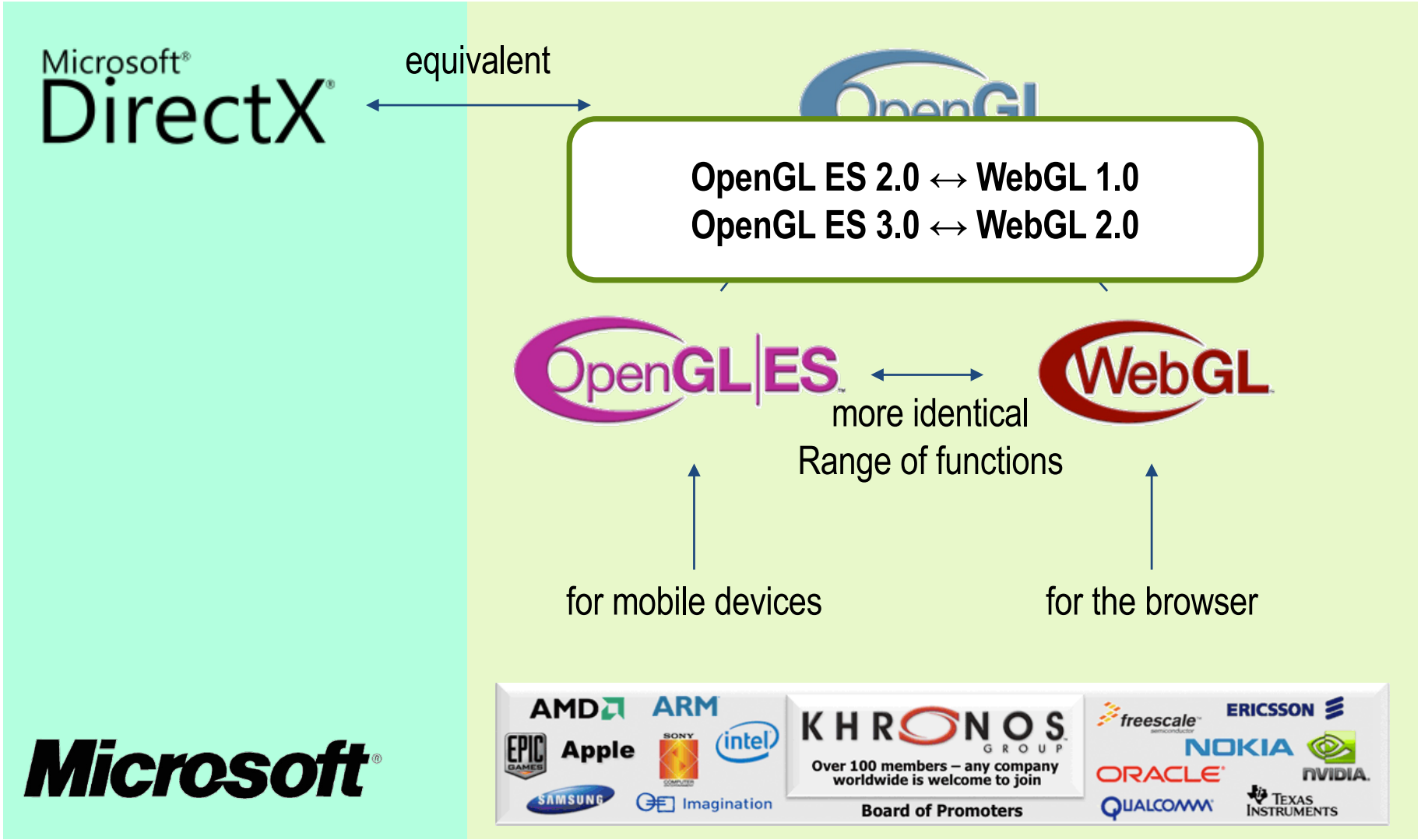

Task: Check learning objective

Did you get an overview of what happens during rendering?

- Write all the basic terms, typical hardware and standard APIs that you can remember on a card (5 min).

- Find a partner and explain the terms to each other. Collect all the cards that you could not explain (well enough) and send the open questions to your instructor.