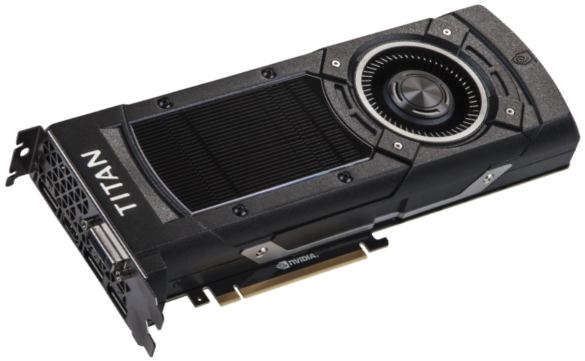


Computer Graphics

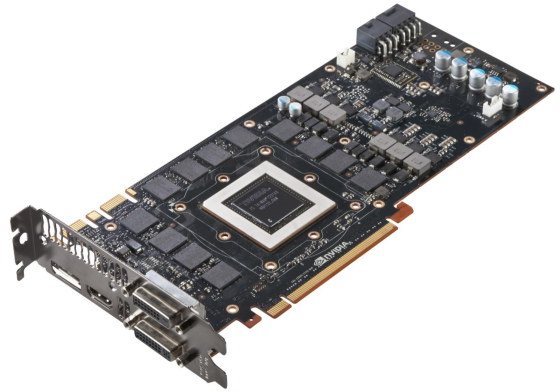
Accelerating 3D Graphics With Dedicated Hardware

Tobias Isenberg

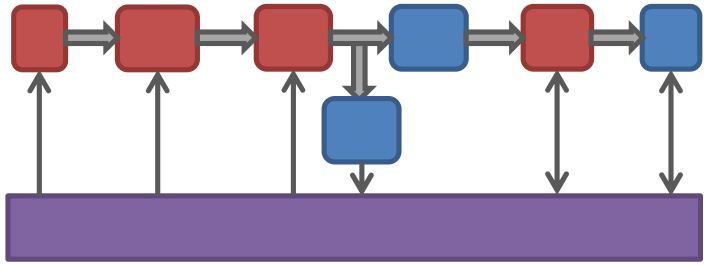
informatics mathematics Inria

Overview

- introduction to graphics hardware

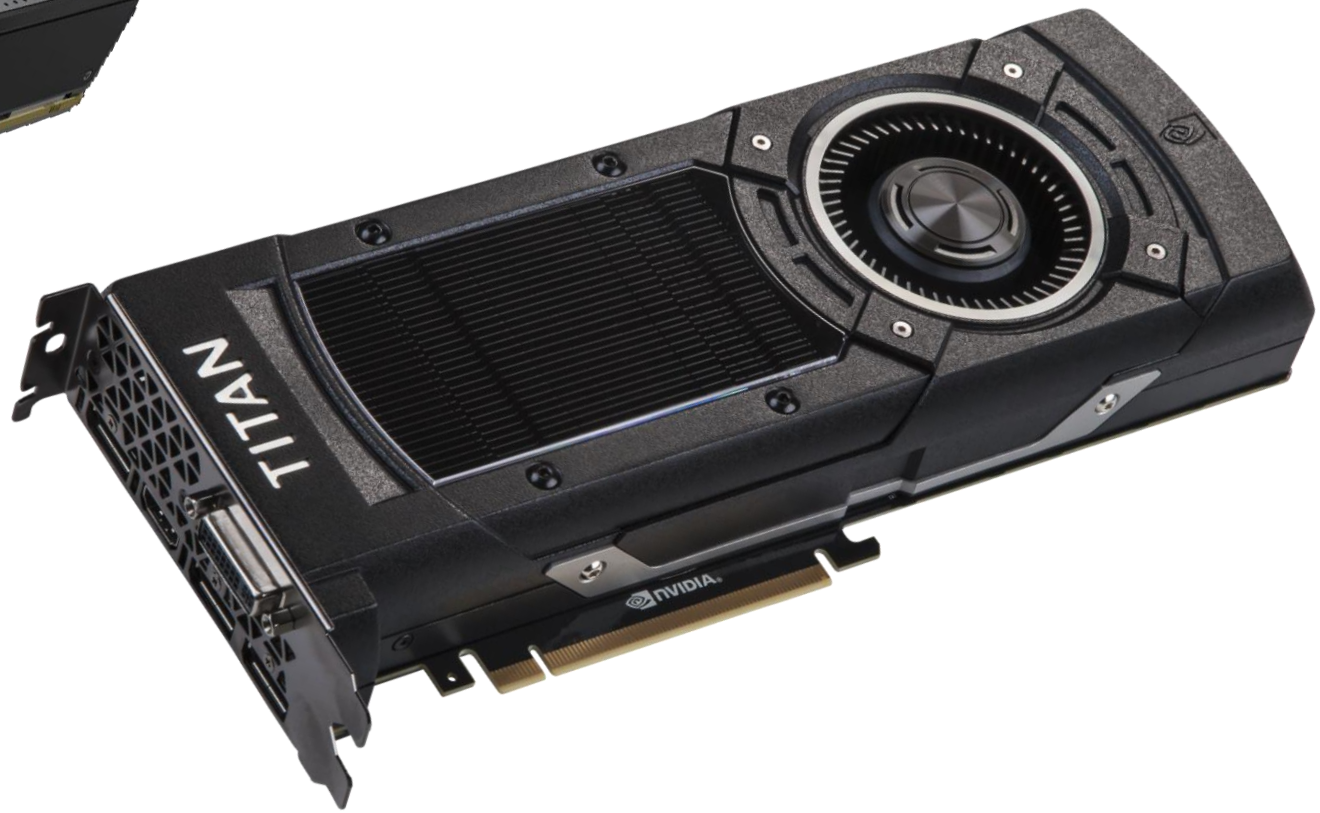


- the graphics hardware (rendering) pipeline



- general purpose computation on the GPU (GPGPU)

What is graphics hardware?



[ATI/nVidia]

What is graphics hardware?

- rendering traditionally implemented on CPU (C/C++/ASM)
- late 90's: several companies (nVidia, ATI, 3Dfx) started releasing consumer hardware to remove rendering from CPU

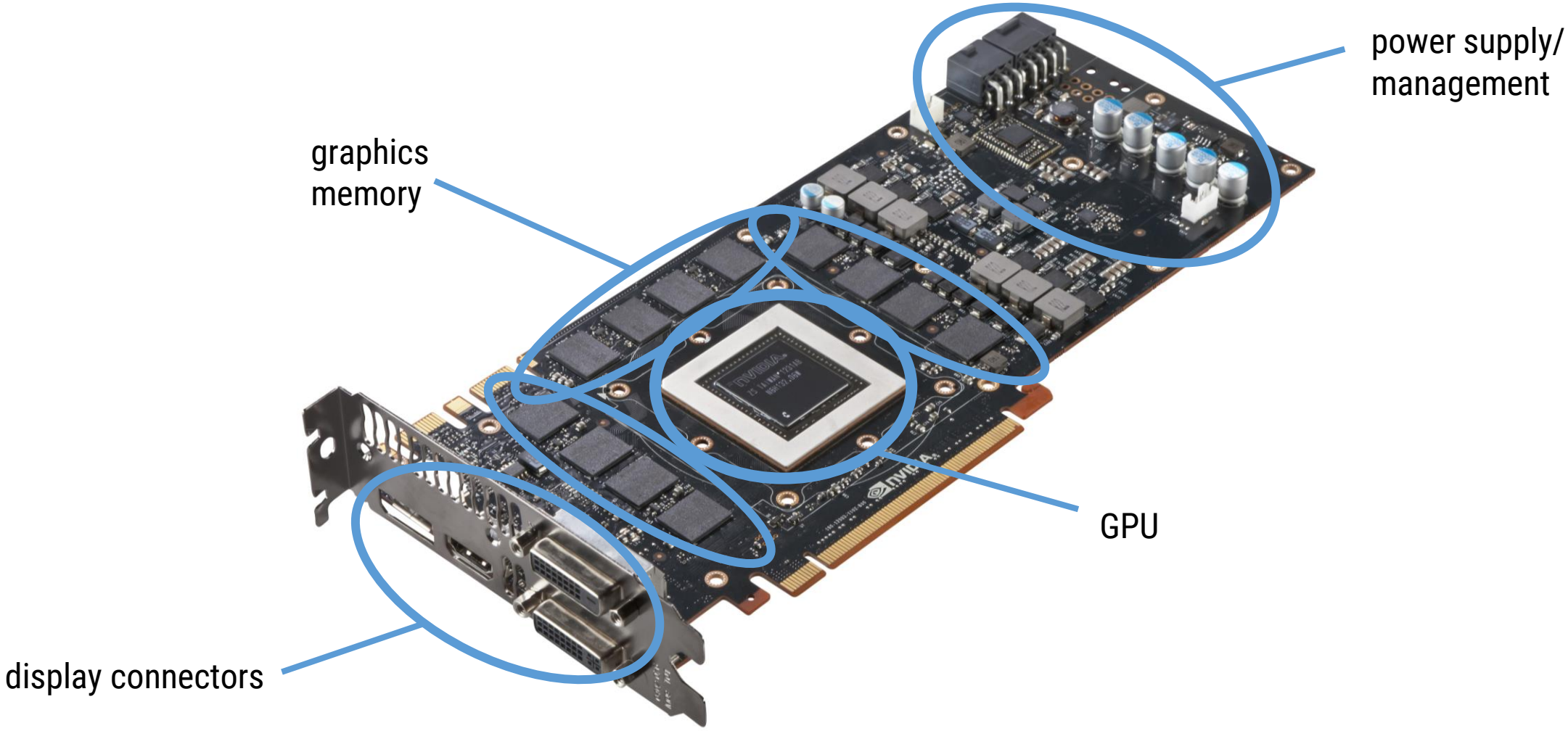



1990s

What is graphics hardware?

- today: all desktops/laptops with dedicated graphics hardware
  - application logic still controlled by CPU
  - assets (3D meshes, texture maps, …) uploaded to GPU at start up
  - CPU issues rendering commands to GPU
  - GPU performs rendering (transformations, lighting, etc.)
  - results sent directly to the display

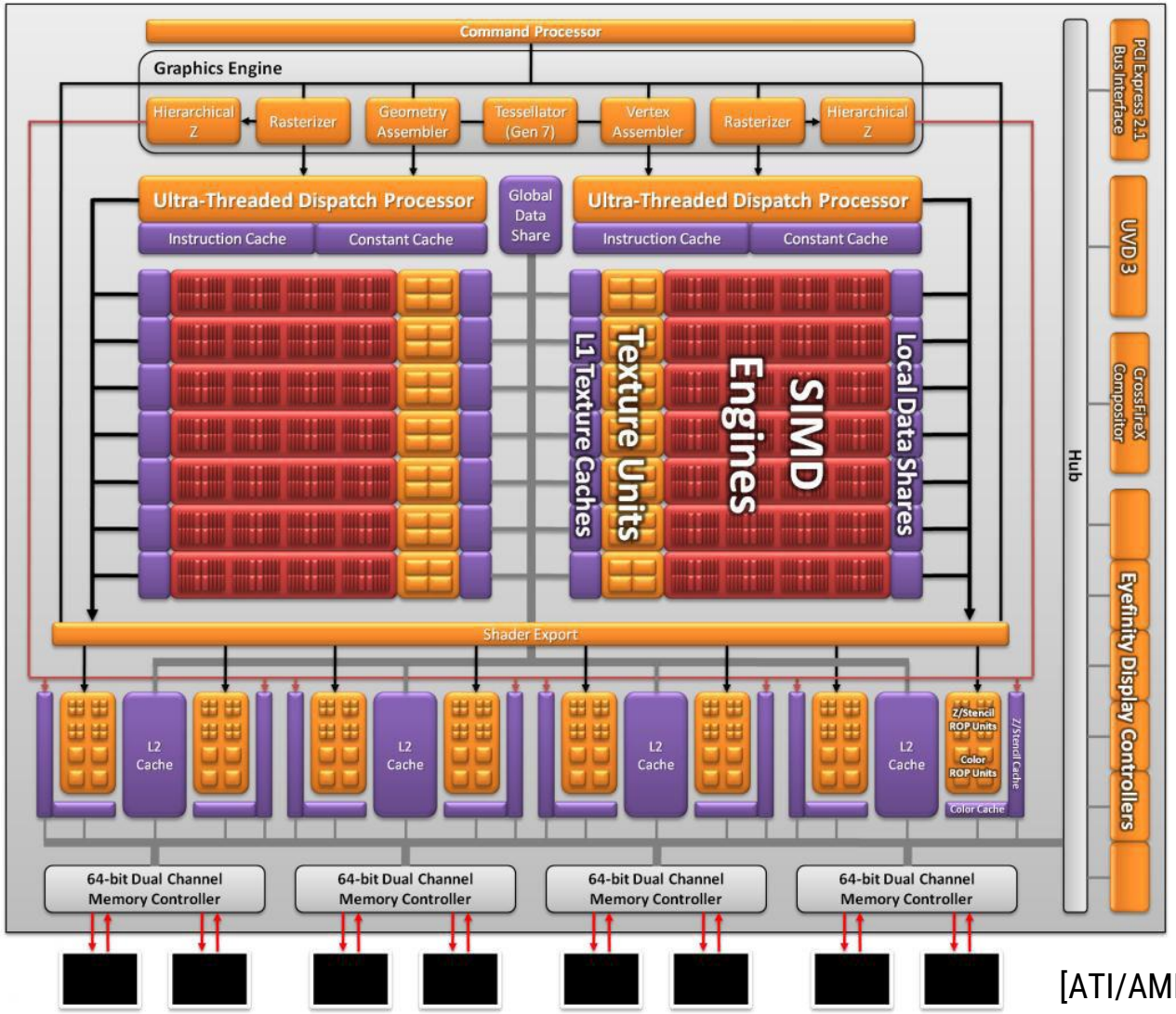
Why is graphics hardware effective?



[nVidia]

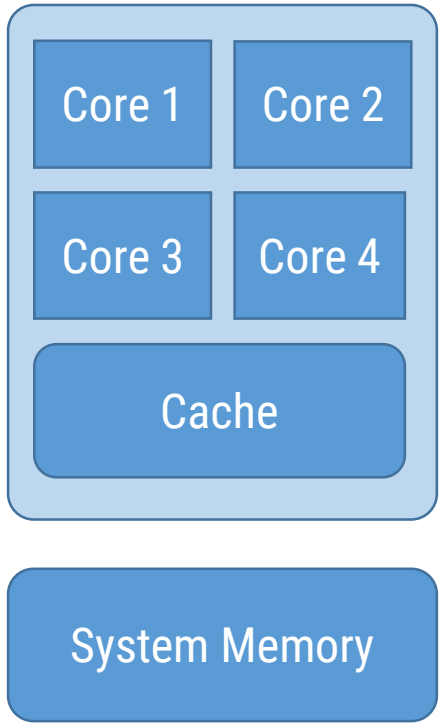
Why is graphics hardware effective?

- example: AMD ATI Radeon HD 5870 (1600 cores)
- graphics engine: fixed-function hardware
- SIMD engines: single instruction, multiple data
  - i.e., lots of simple cores
  - massive parallel processing
  - perfect for graphics tasks

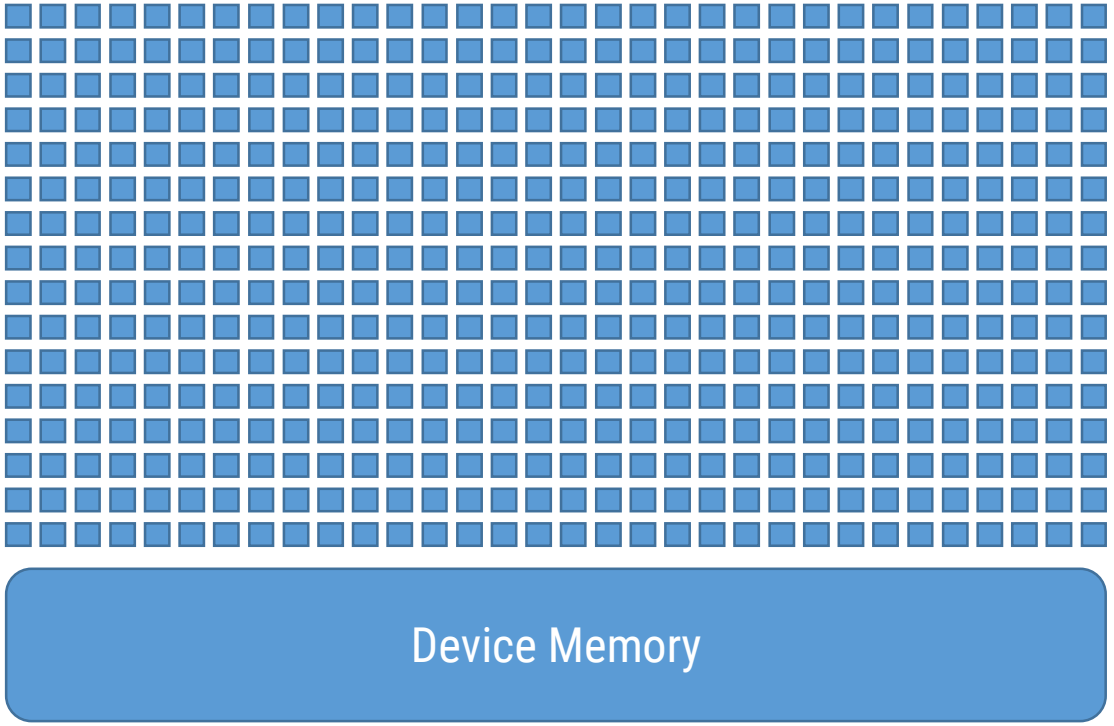


[ATI/AMD]

Why is graphics hardware effective?



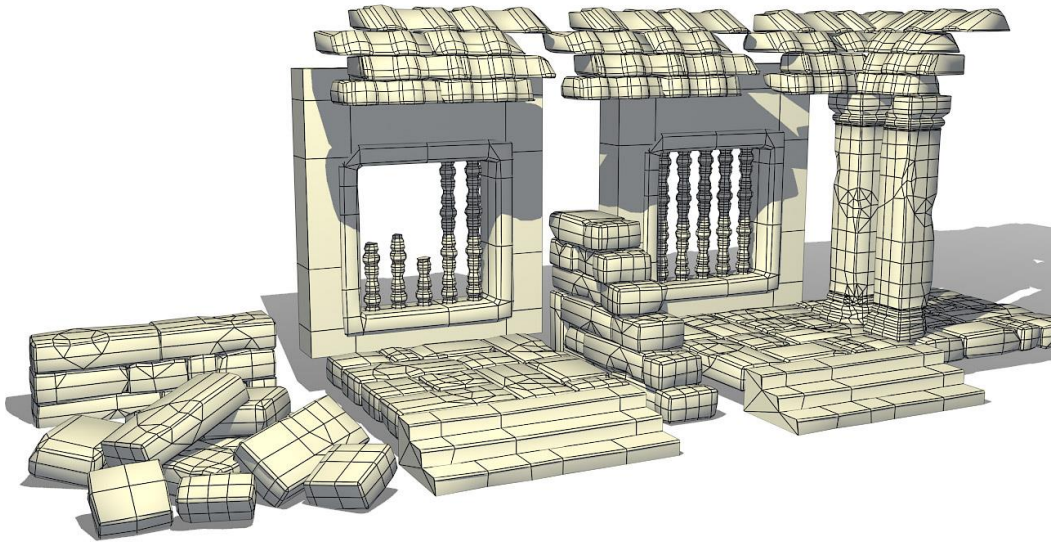
CPU: multiple cores



GPU: hundreds to thousands of cores

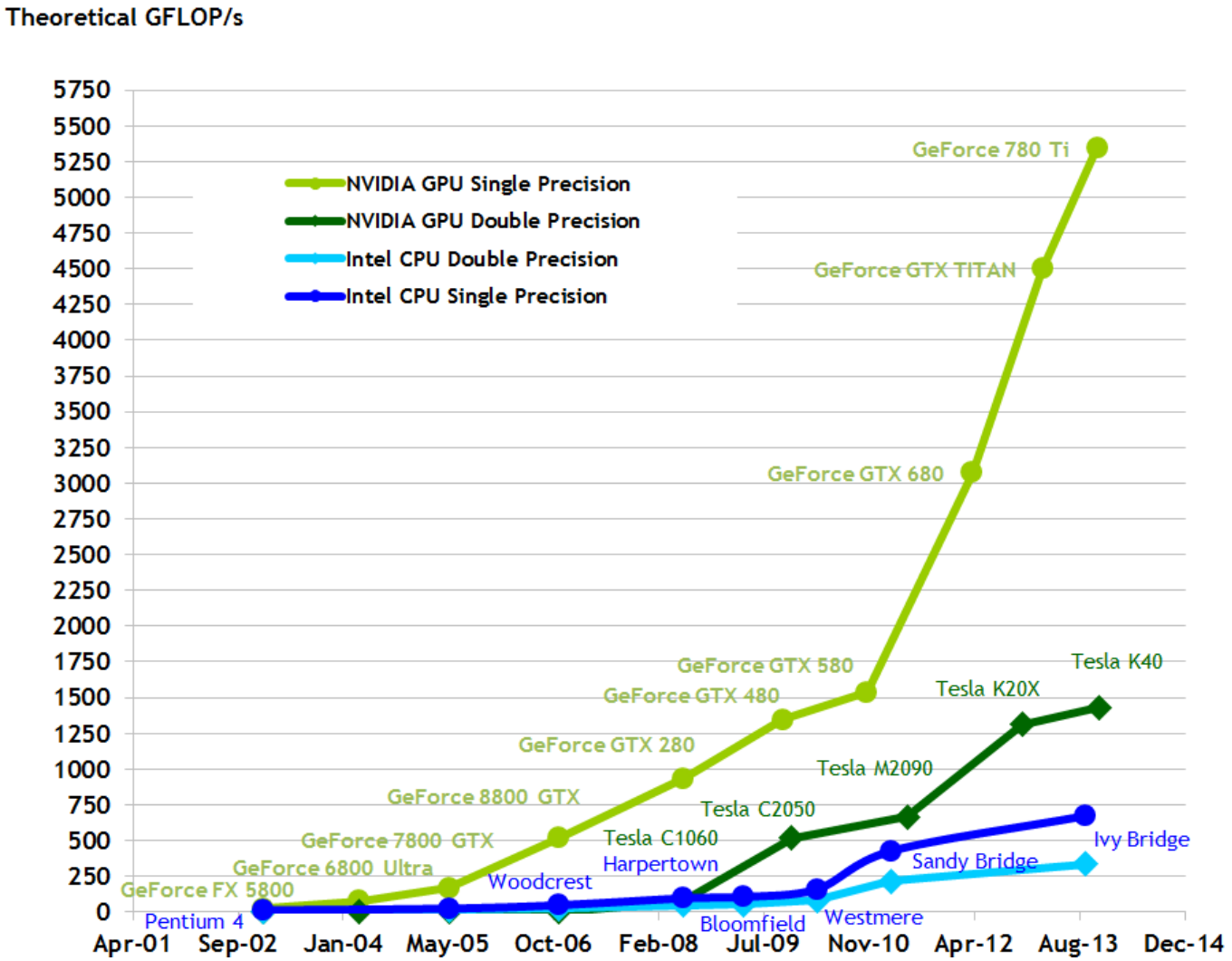
Why is graphics hardware effective?

- 3D rendering can easily be parallelized:
  - meshes contain thousands of vertices & more; for each vertex we:
    - transform (object space → eye/camera space → screen space)
    - light (compute vectors, attenuation, etc.)
    - various other tasks …
  - rendered images have millions of pixels; for each pixel/fragment we:
    - interpolate coordinates/normals
    - perform texture mapping
    - perform blending
    - compute illumination
    - various other tasks …



Why is graphics hardware effective?

- GPU throughput increasing faster than CPU throughput

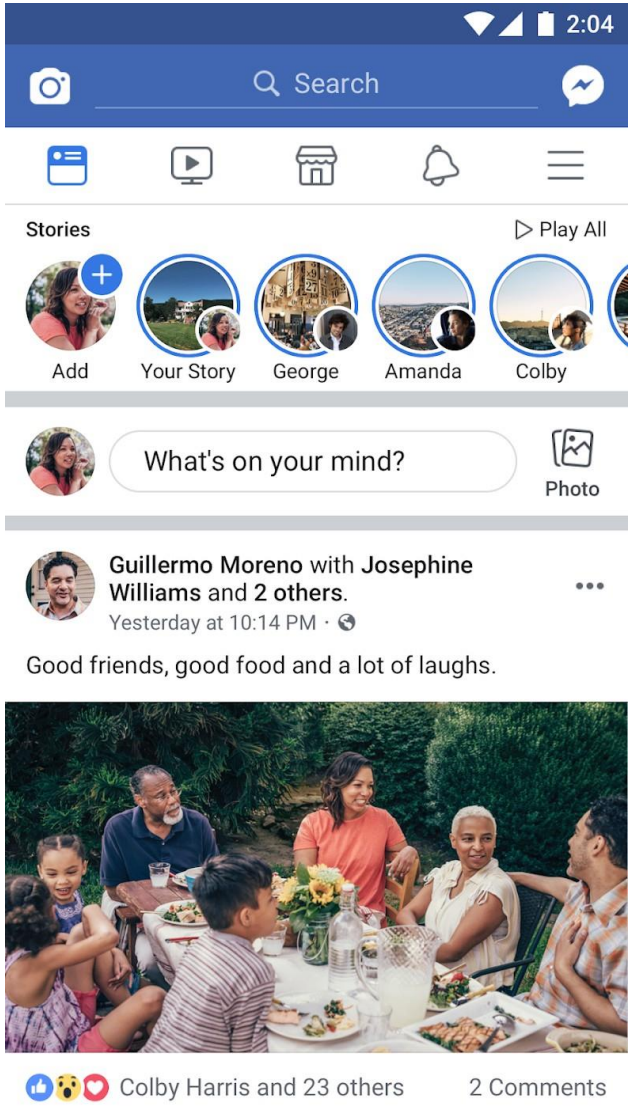


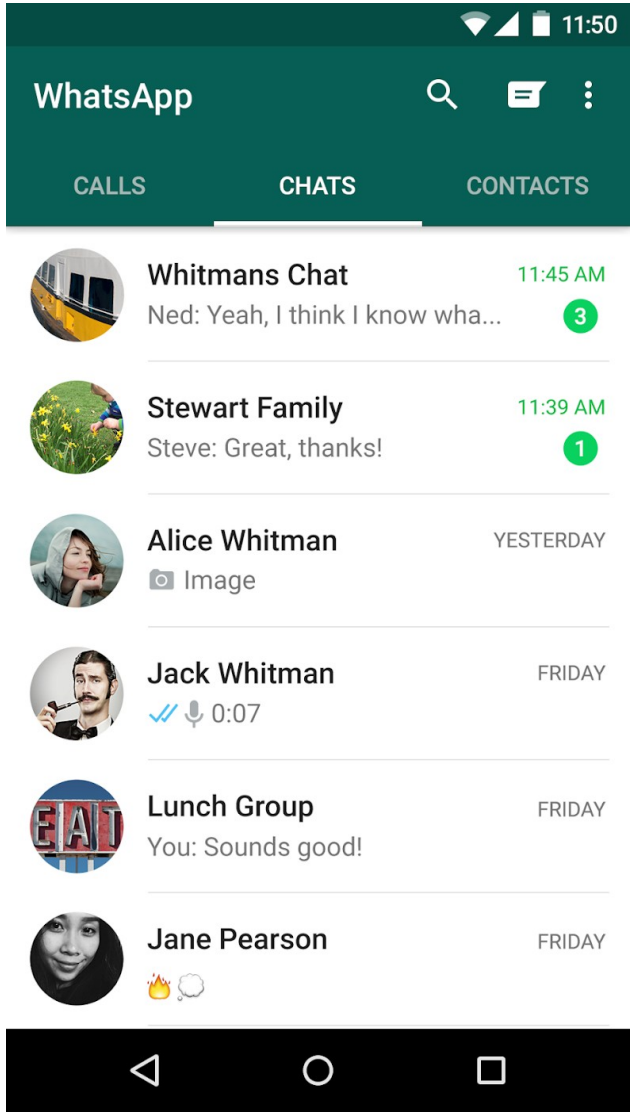
[nVidia]

Virtually all rendering requires GPUs

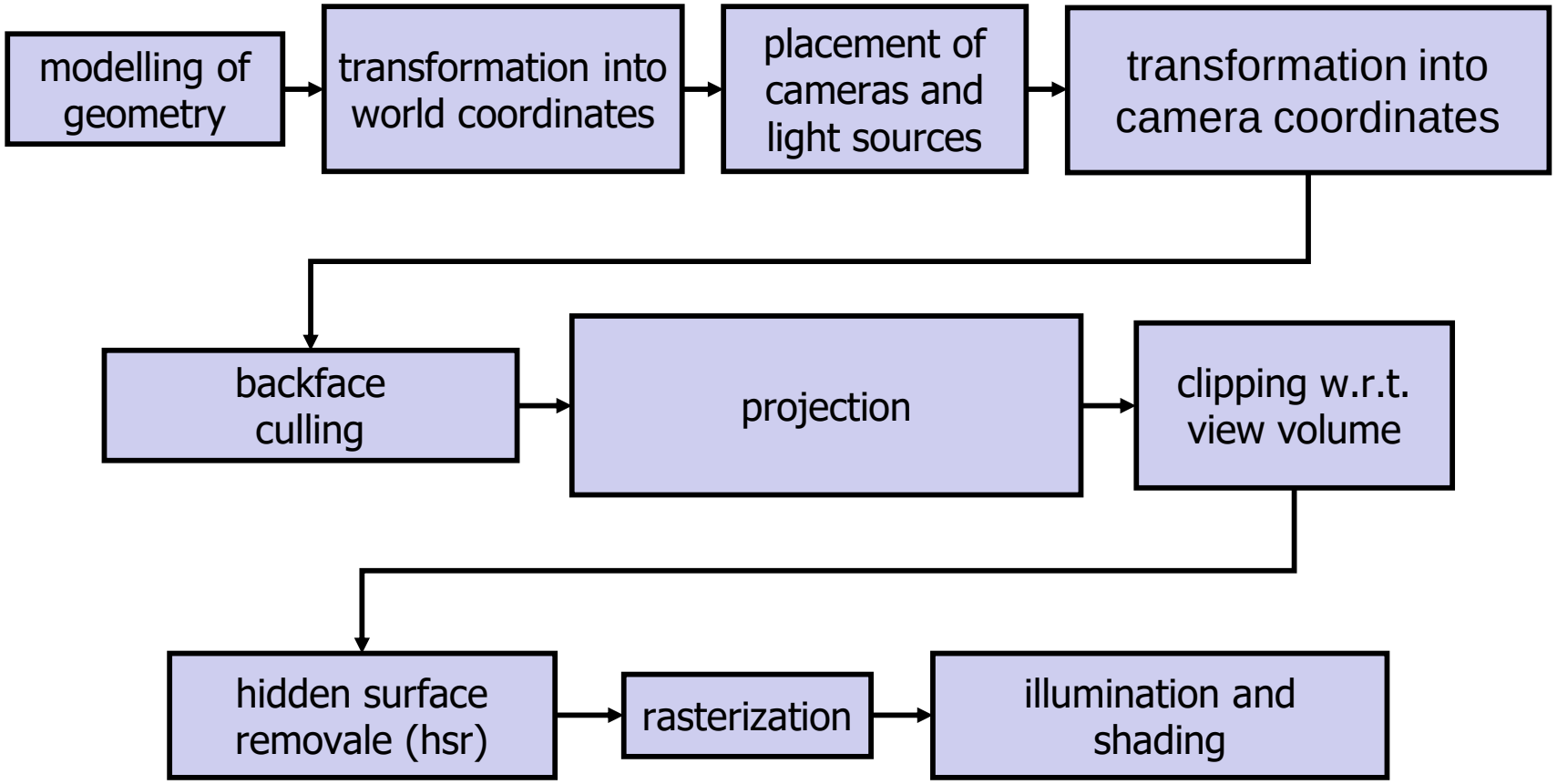
[EA]

Virtually all rendering requires GPUs



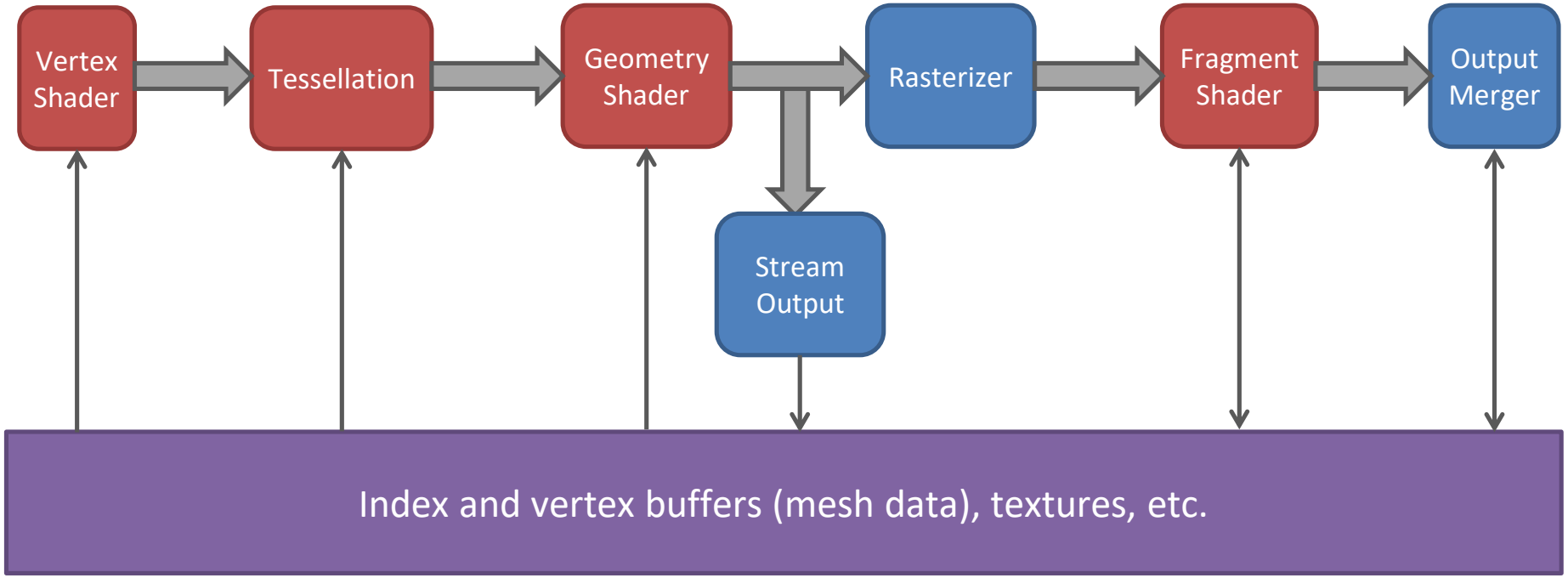


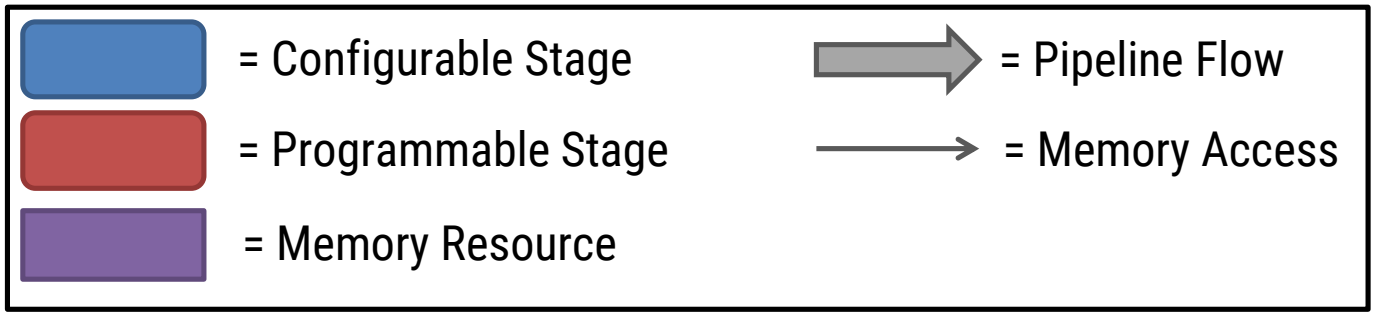
The computer graphics pipeline



- traditional pipeline can closely be mapped to the modern hardware/GPU pipeline

The graphics hardware pipeline





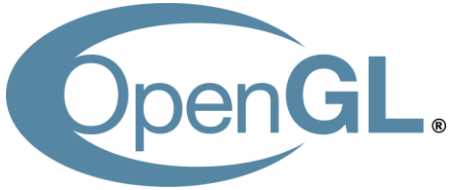
Note: terminology can vary between APIs; for example, OpenGL uses the term 'fragment shader', while Direct3D uses the term 'pixel shader'

Controlling the pipeline (CPU)

- graphics API: programmer submits data/commands to GPU
  - OpenGL: open standard maintained by the Khronos group
  - OpenGL ES: cut-down version for use on embedded systems
  - Direct3D: developed by Microsoft for their systems
  - Vulkan: successor to OpenGL by the Khronos group

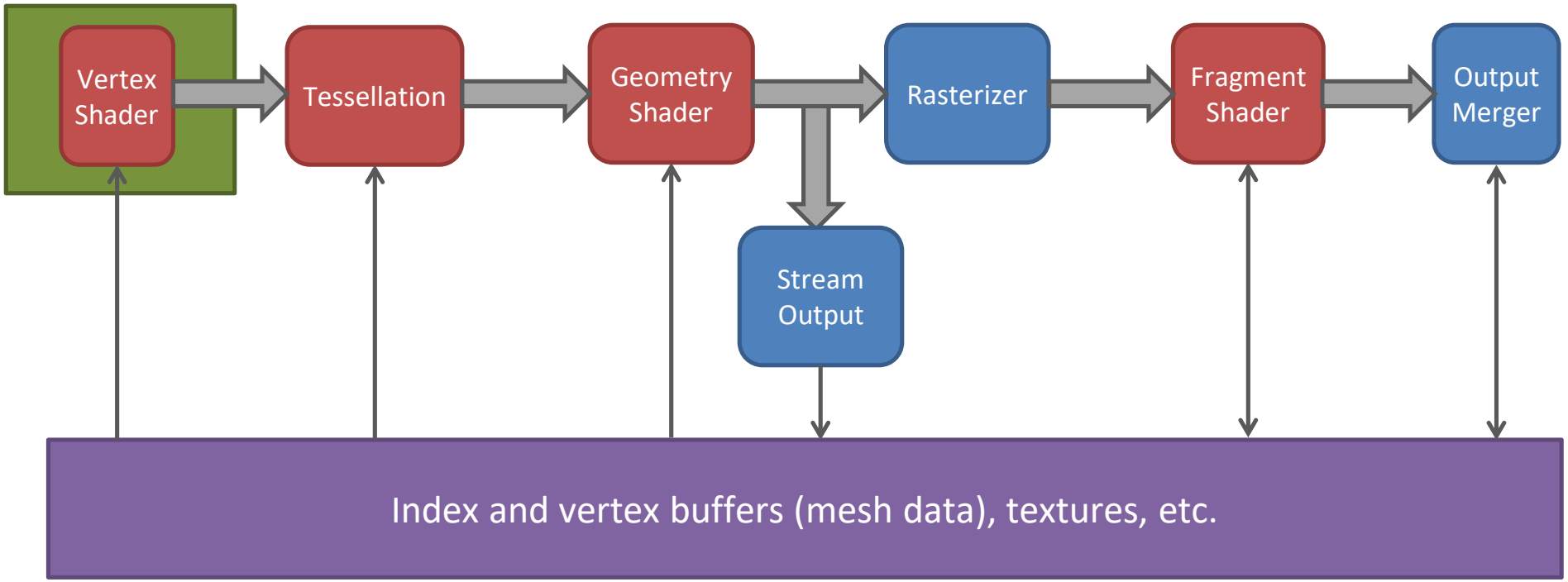
- APIs are constantly evolving, e.g.:
  - OpenGL 1.0 (1992): only configurable; some stages still missing
  - OpenGL 2.0 (2004): vertex and fragment stages programmable
  - OpenGL 3.0 (2008): added geometry shader as a programmable stage
  - OpenGL 4.0 (2010): added tessellation support as a programmable stage

Using an API

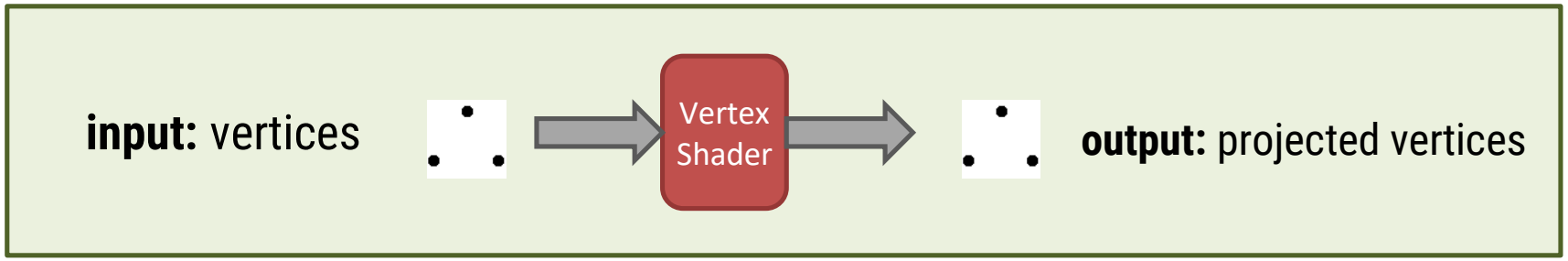


- before rendering commences, load relevant data onto the GPU
  - glGenBuffers(...), glBindBuffer(...), glBufferData(...), etc.
- also set up shaders for the programmable pipeline stages
  - glCreateShader(...), glShaderSource(...), glCompileShader(...), etc.
- once set up is complete, issue rendering commands
  - glDrawArrays, etc.

Vertex shader

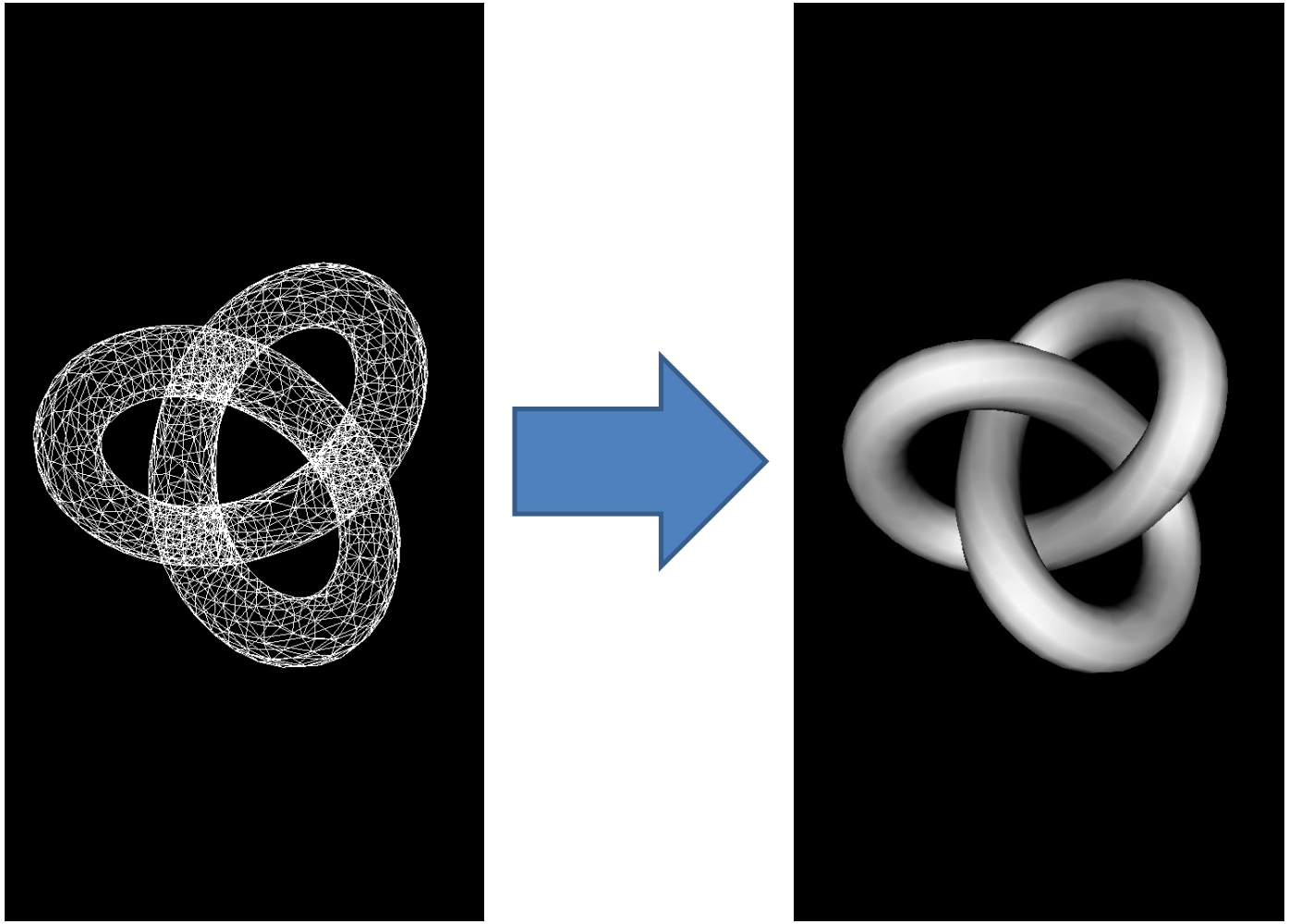


Vertex shader



- one of the first pipeline stages to become fully programmable (OpenGL 2.0)
- executed for each vertex in the in input data
- most important role—apply transformations:
  - transform vertex into eye/camera space
  - project vertex into clip space
  - possibly lighting (illumination) calculations (Gouraud shading)

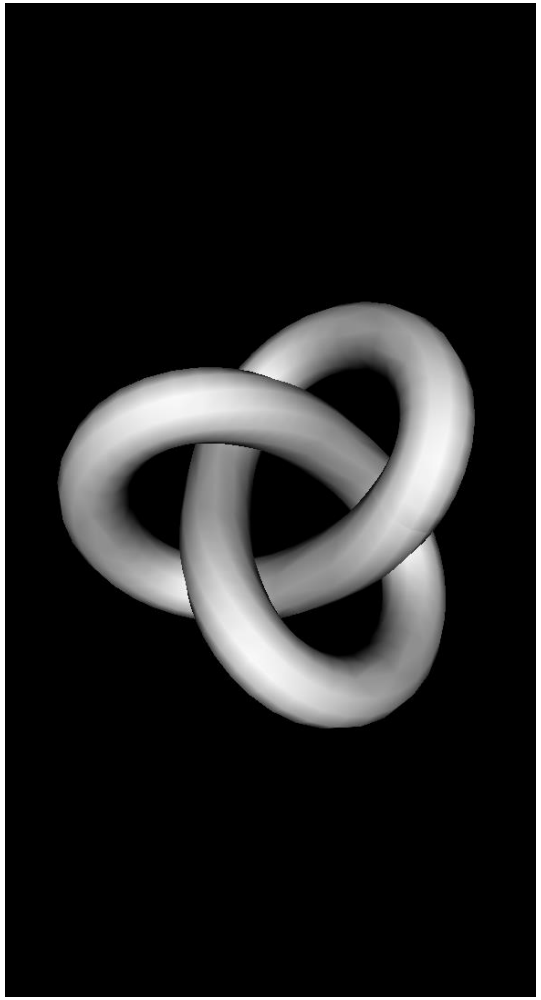
Vertex shader: Example



Vertex shader: Example

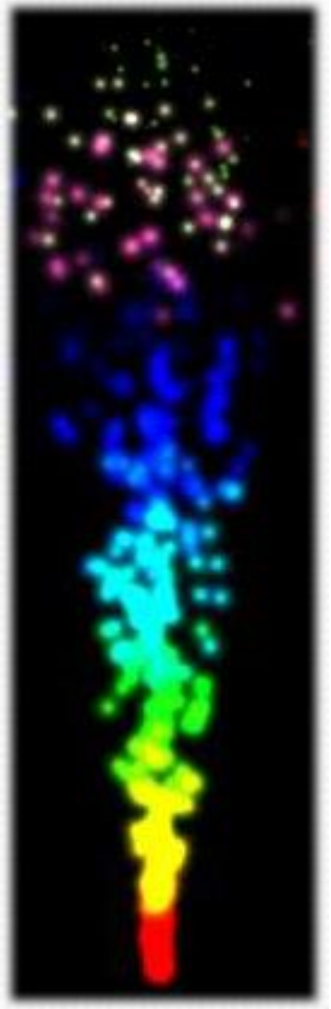
- per-vertex diffuse lighting (Gouraud)

```
void main()
{
  // compute the diffuse light intensity
  vec3 normal = normalize(gl_NormalMatrix * gl_Normal);
  vec3 lightDir = normalize(vec3(gl_LightSource[0].position));
  float NdotL = max(dot(normal, lightDir), 0.0);
  vec4 diffuseLight = NdotL * gl_FrontMaterial.diffuse * gl_LightSource[0].diffuse;

  // assign the results to variables to be passed to the next stage
  gl_FrontColor = diffuseLight;
  gl_TexCoord[0] = gl_MultiTexCoord0;
  gl_Position = gl_ProjectionMatrix * gl_ModelViewMatrix * gl_Vertex;
}
```



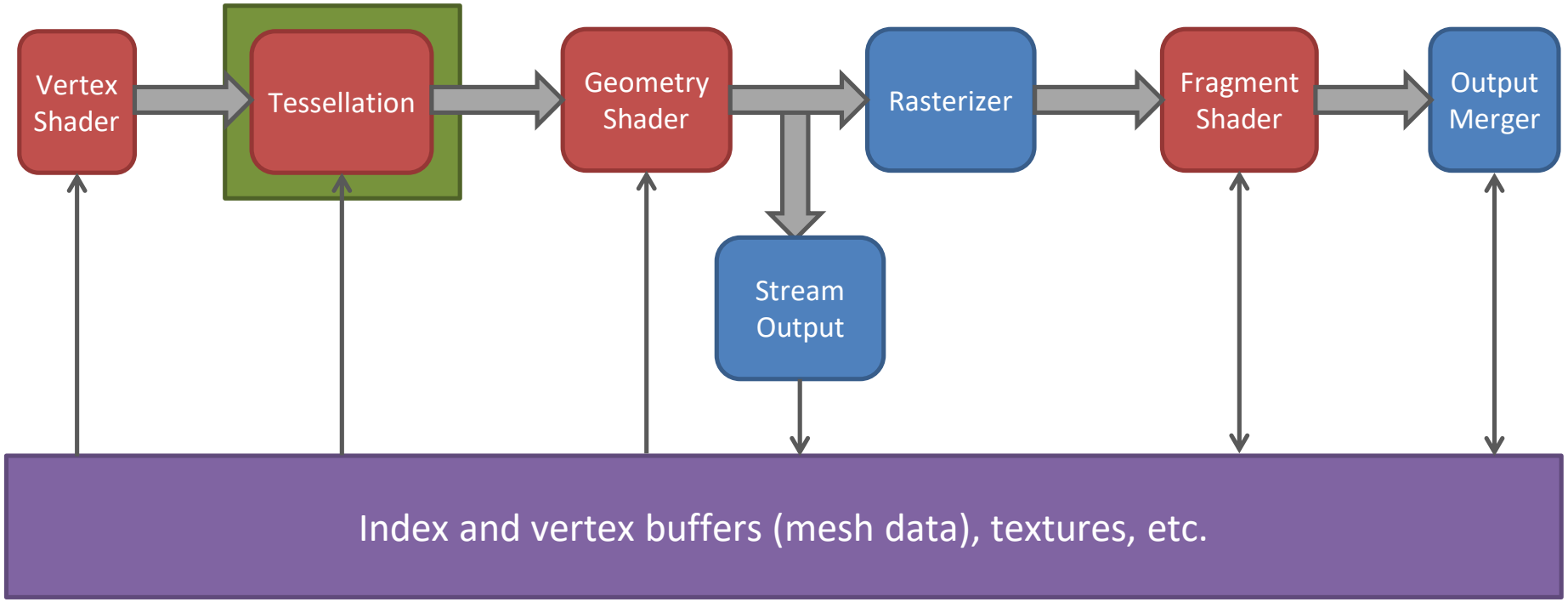
Vertex shader: Advanced uses

- particle systems
  - each particle modelled as single vertex
  - position and colour changed over time by the vertex shader
- animation
  - time passed to shader to animate the mesh
  - key-frame animation:
    shader blends between predefined frames
  - skeletal animation:
    - each vertex is attached to a ‘bone’
    - CPU updates bone transformation
    - vertex shader applies this to each vertex

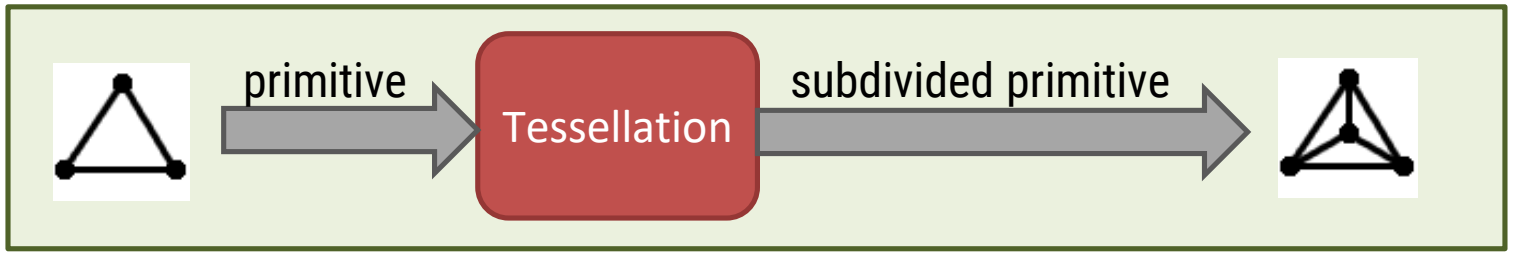


Vertex shader: Character animation

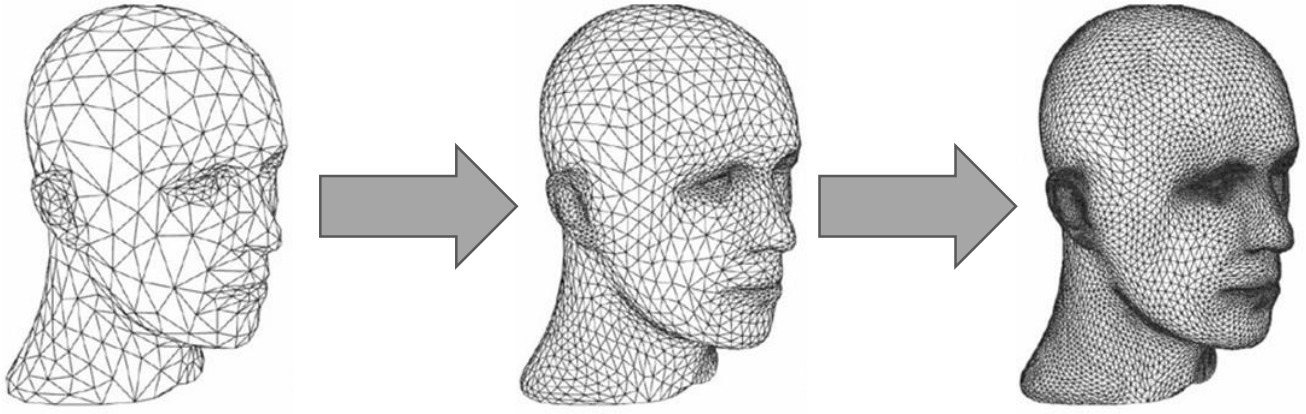
Tessellation shader



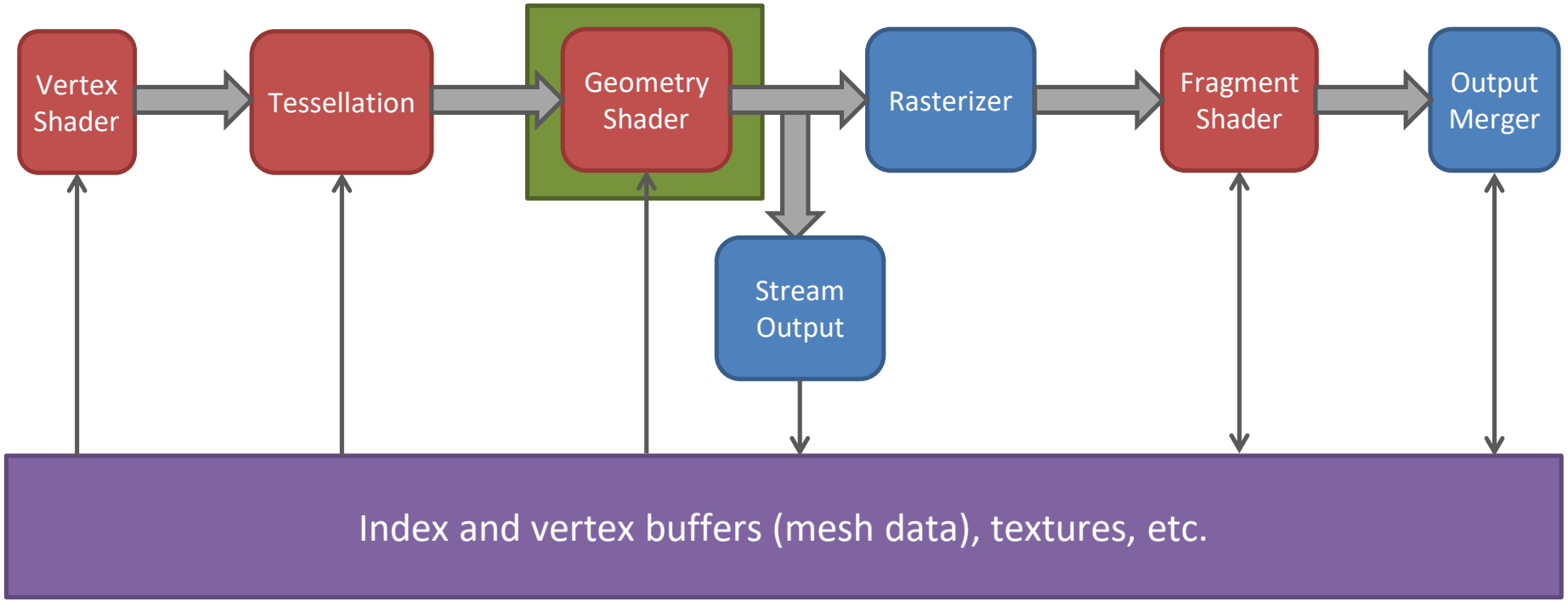
Tessellation shader



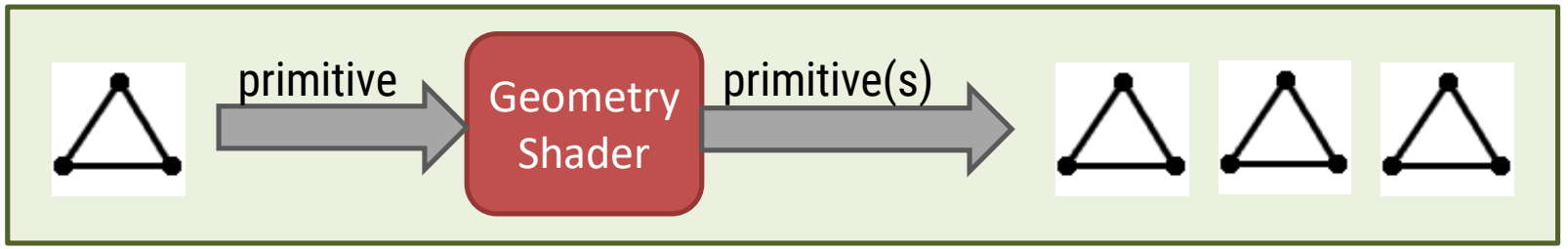
- later addition to the hardware pipeline (OpenGL 4.0)
- used to increase the number of primitives via subdivision
- programmable, so various subdivision approaches possible
- effective when combined with *displacement mapping*



Geometry shader

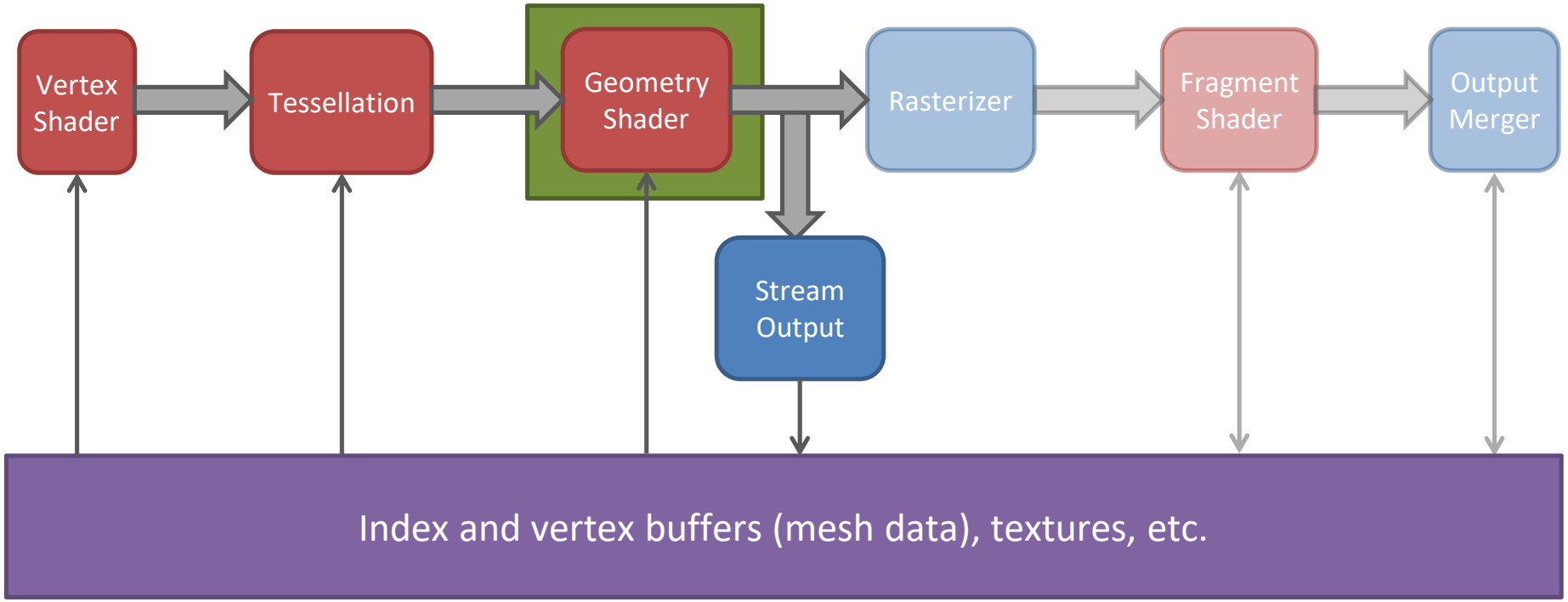


Geometry shader

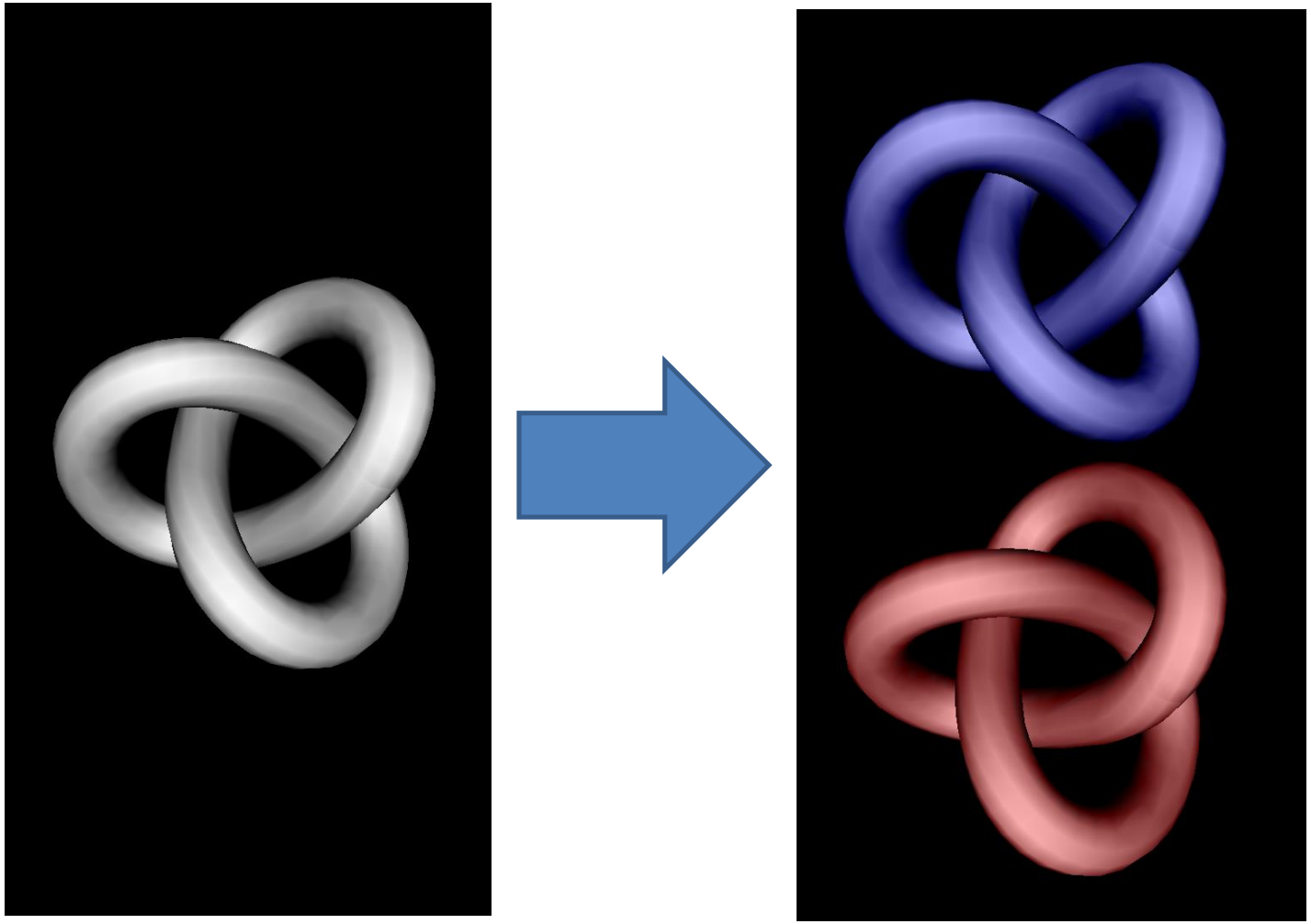


- later addition to the pipeline (OpenGL 3.0)
- operates on primitives (e.g., lines and triangles)
  - input: usually the set of vertices the primitive consists off
  - shader has access to adjacency information
  - mesh processing algorithms such as smoothing and simplification
- multiple output primitives for each input primitive possible
- modified geometry can also be saved to memory (*stream out*)

Geometry shader: Stream output

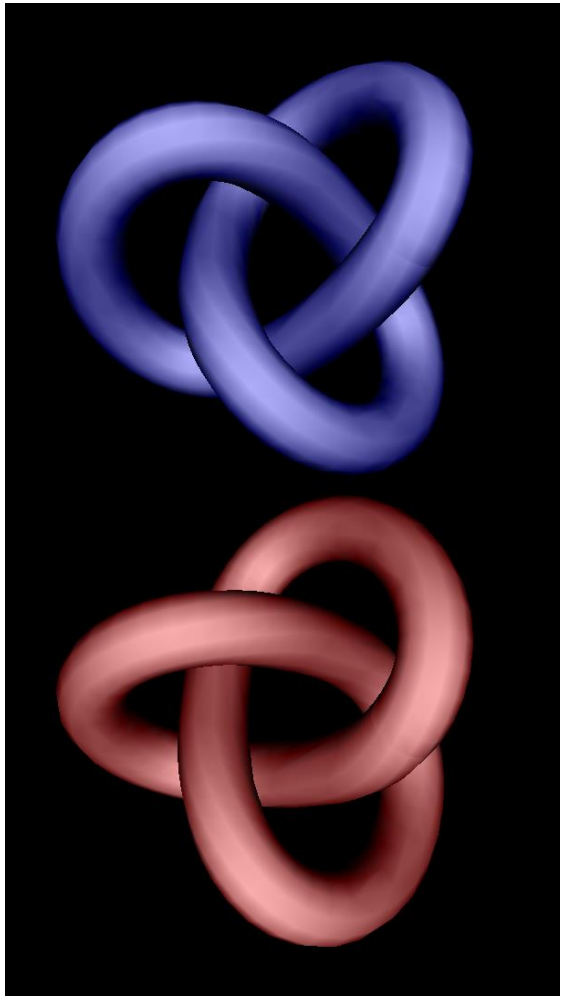


Geometry shader: Duplication example



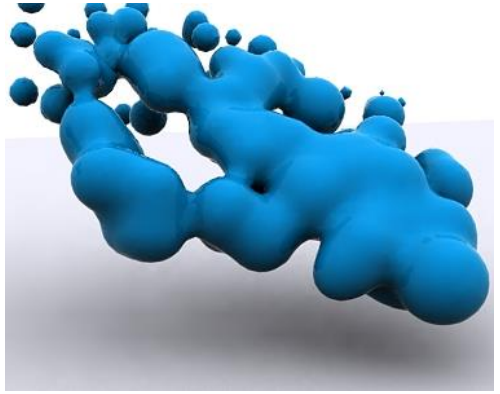
Geometry shader: Duplication example

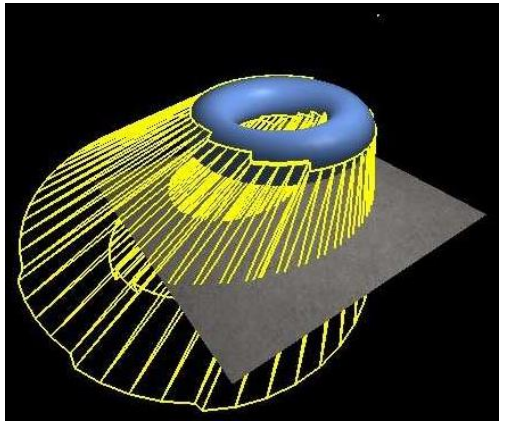
```
void main(void)
{
  // output a copy tinted blue and raised up
  for(int i=0; i<gl_VerticesIn; i++) {
    gl_Position = gl_PositionIn[i] + vec4(0.0, 250.0, 0.0, 0.0);
    gl_FrontColor = gl_FrontColorIn[i] - vec4(0.3, 0.3, 0.0, 0.0);
    gl_TexCoord[0] = gl_TexCoordIn[i][0];   EmitVertex();
  }
  EndPrimitive();

  // output a copy tinted red and lowered down
  for(int i=0; i<gl_VerticesIn; i++) {
    gl_Position = gl_PositionIn[i] - vec4(0.0, 250.0, 0.0, 0.0);
    gl_FrontColor = gl_FrontColorIn[i] - vec4(0.0, 0.3, 0.3, 0.0);
    gl_TexCoord[0] = gl_TexCoordIn[i][0];    EmitVertex();
  }
  EndPrimitive();
}
```



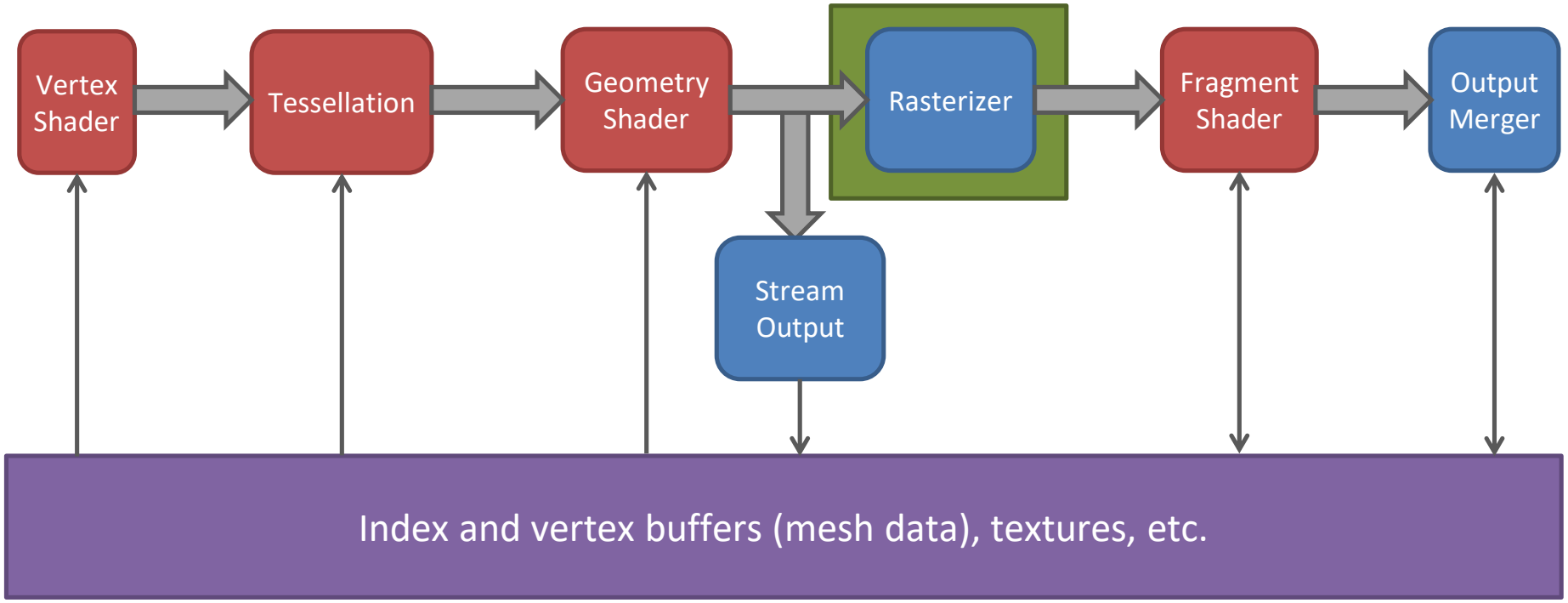
Geometry shader: Advanced uses

- procedural geometry
  - can also generate primitives procedurally
  - e.g., metaballs; mathematical surface which that can be evaluated on the GPU
- particle systems
  - particles usually drawn as quad (requires four vertices)
  - send a single point, shader expands it into a quad
- shadow volume extrusion
  - extrude object boundary in shader, reduces CPU load
  - boundary used to determine what is in shadow

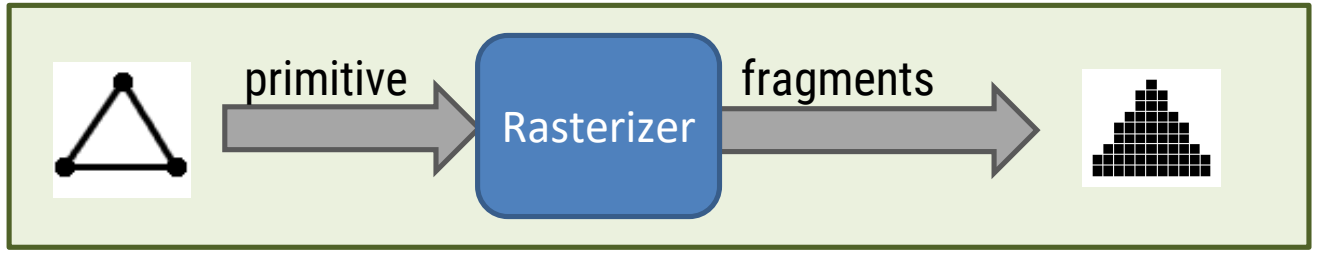




Rasterizer

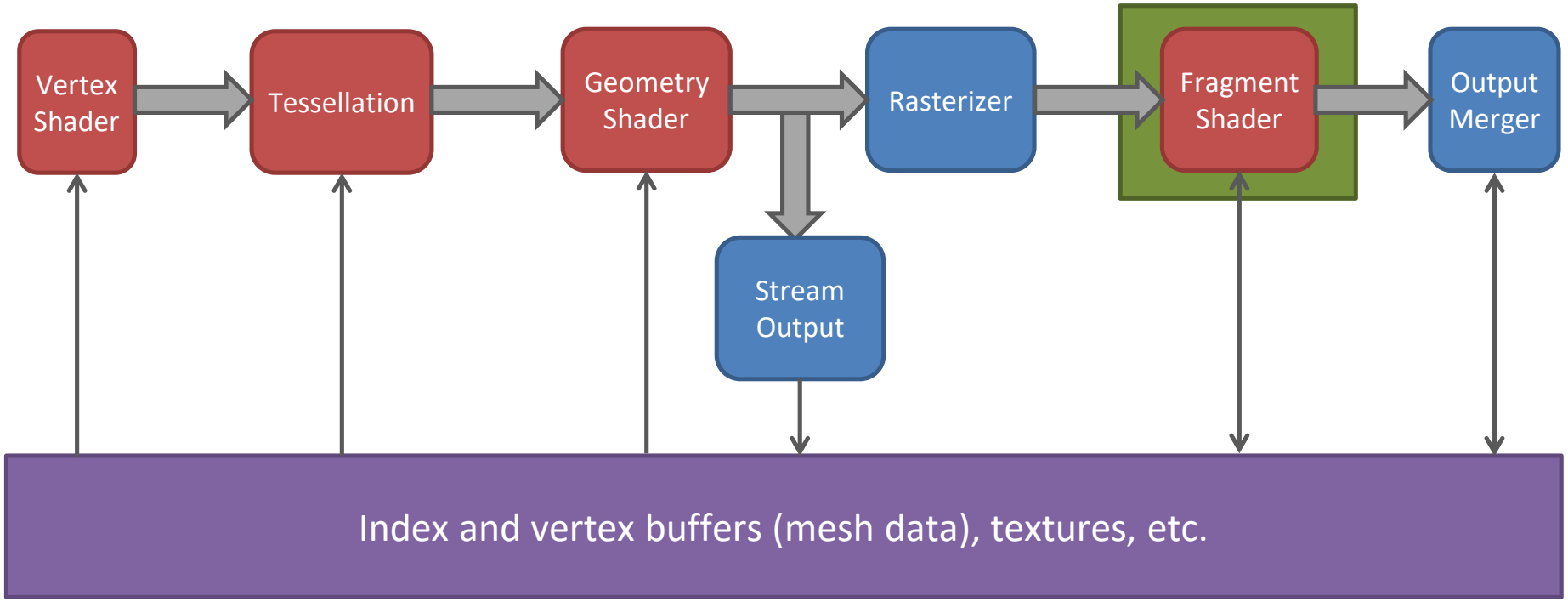

Vertex Shader
Tessellation
Geometry Shader
Rasterizer
Fragment Shader
Output Merger
Stream Output
Index and vertex buffers (mesh data), textures, etc.

Rasterizer

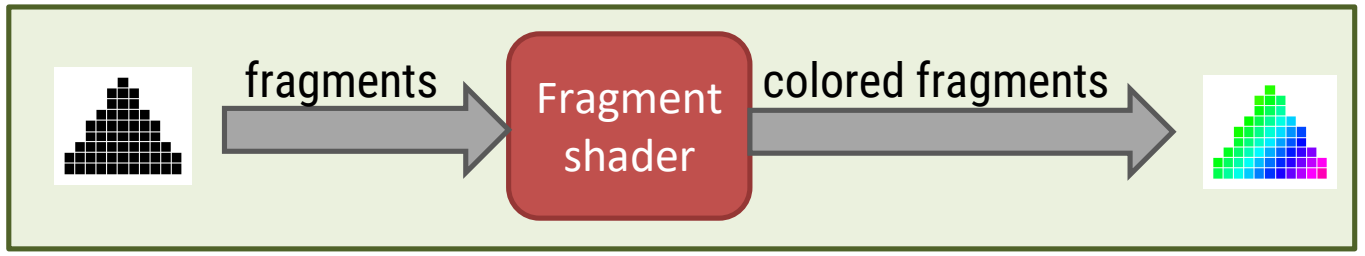


- converts primitives into fragments
  - performs culling and clipping of primitives
  - generates fragments from primitives
  - property interpolation (color, texture coordinates, etc.)
- not programmable, but configurable:
  - backface culling
  - anti-aliasing
  - depth biasing

Fragment shader

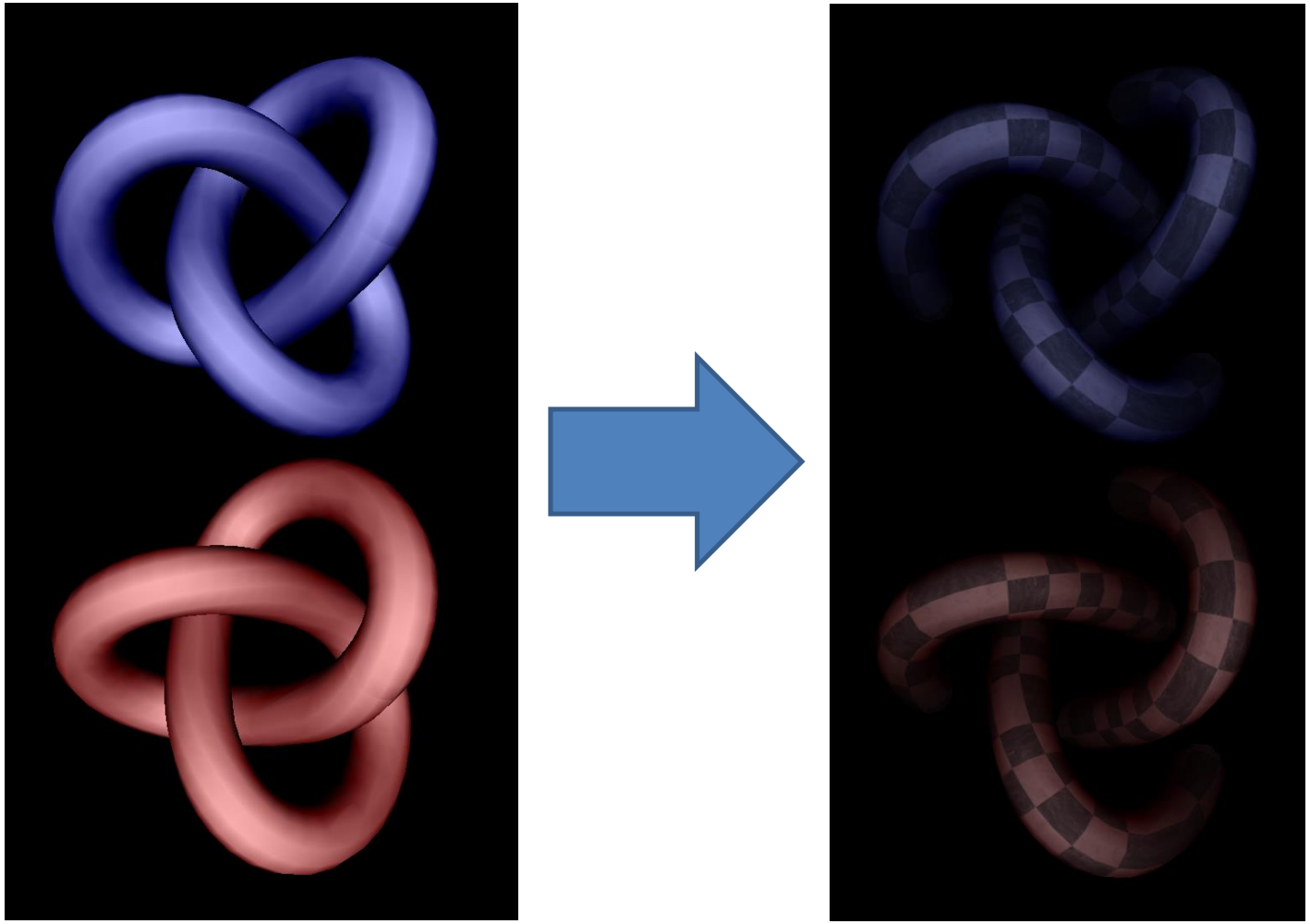


Fragment shader



- also one of the oldest programmable stages (OpenGL 2.0)
- calculates fragment colour based on interpolated vertex values, texture data, and user supplied variables.
- fragment: ‘candidate pixel’
  - may end up as a pixel in final image
  - may get overwritten, combined with other fragments, etc.
- common uses: per-pixel (Phong) lighting, texture application

Fragment shader: Fog example



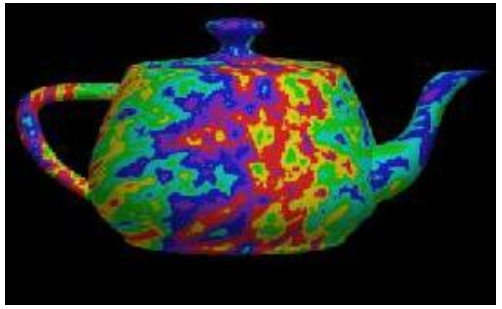
Fragment shader: Fog example

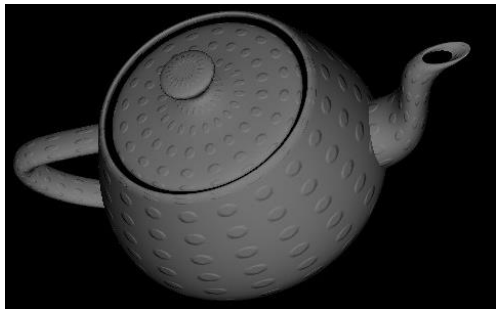
- texturing and fog

```
void main(void)
{
        // sample the texture at the position given by texcoords
        vec4 textureSample = texture2D(checkerboard,gl_TexCoord[0].st);

        // compute some depth-based fog
        const float fogDensity = 0.0015;
        float depth = gl_FragCoord.z / gl_FragCoord.w;
        float fogFactor =  1.0 - (depth * fogDensity);

        // compute the output color
        gl_FragColor = gl_Color * textureSample * fogFactor;
}
```

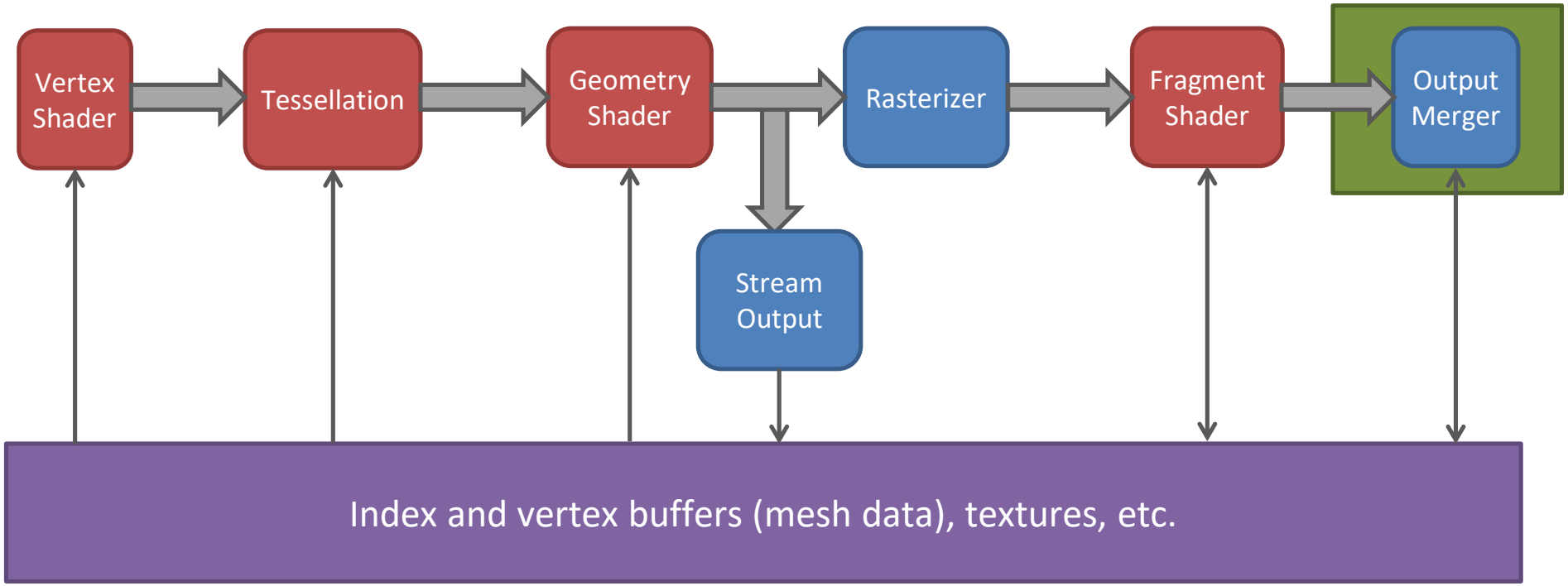
Fragment shader: Advanced uses

- procedural textures
  - compute texture based on an algorithm
  - Perlin noise, Voronoi noise, fractals, etc.
- reflection
  - environment map, stored in cubemap texture
  - applied to object, accounting for the view direction
- normal (bump) mapping
  - add extra surface detail to a model
  - adjust the surface normal based on bump map

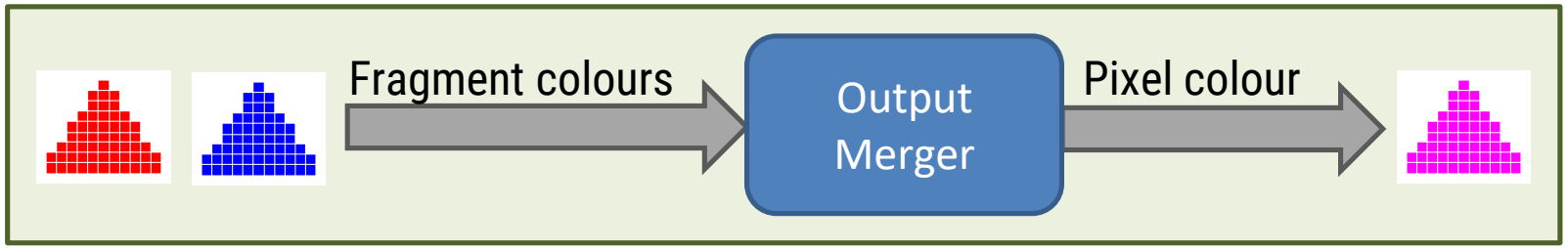




Output merger



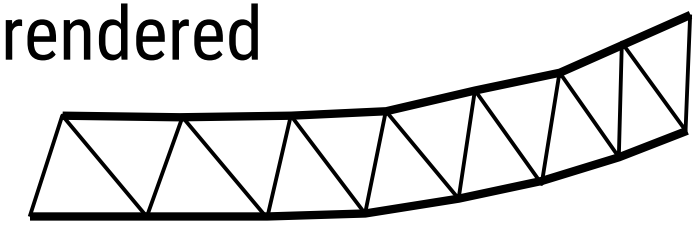
Output merger



- combines fragment shader output with any existing contents of the render target
- key roles:
  - depth testing (*z*-buffer)
  - blending: combine fragment color with pre-existing pixel in the render target (transparency, lighting, etc.)
- configurable, but not programmable

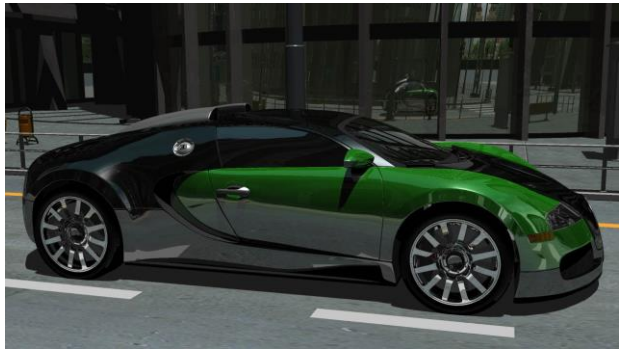
Performance considerations

- pipeline approach:
  - minimize state changes to avoid flushes
  - balance workload across stages
- slow memory: values can also be computed (to avoid look-up)
- quality/performance trade-off by moving operations between vertex and fragment shader (e.g., lighting)
- vertices often shared by multiple triangles
  - GPU implements a caching mechanism to avoid reprocessing
  - order triangles so that those sharing a vertex are rendered consecutively



The future?

- real-time photorealism still not achieved
  - “Requires roughly 2000x today’s best GPU hardware” (Tim Sweeney in 2012)
- continuing increase in the power of GPUs
  - more pixels (screens: UHD/4K, 8K, …)
  - more detail (i.e., triangles)
  - more processing (animation, physics simulation, AI, …)
  - increasing programmability and flexibility
- different direction:
  real-time raytracing! voxel/point-based graphics?
- increasing use of graphics hardware for non-graphics tasks

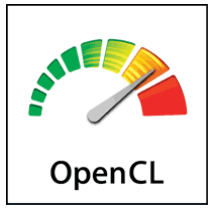


General purpose computing on the GPU

- increasing GPU programmability: application beyond graphics
- most effective for problems with a high degree of parallelism
  - define a *kernel* and apply it to many pieces of data simultaneously
- example applications:
  - image processing: blurring/sharpening, segmentation, feature detection, etc.
  - physics simulation: fluid simulation, rigid bodies, cloth, etc.
  - non-shading rendering: raytracing, radiosity

General purpose computing on the GPU

- CPU is still in overall control (like when rendering)
  - typically only small part of an application moved to the GPU
- several APIs for GPGPU computing
  - OpenCL (Khronos group)
  - CUDA (nVidia)
  - DirectCompute (Microsoft)



- several generalized concepts:
  - use of general arrays instead of operation on textures/render targets
  - more flexible memory access
- additional concepts:
  - support for synchronisation between processing cores

GPGPU—Simple example: Adding arrays

CPU

```
// allocate some arrays
const int num = 10;
float *a = new float[num];
float *b = new float[num];
float *c = new float[num];

// fill 'a' and 'b' with some data
for(int i = 0; i < num; i++) {
    a[i] = b[i] = 1.0f * i;
}

// compute 'c' as the sum of 'a' and 'b'
for(int i = 0; i < num; i++) {
    c[i] = a[i] + b[i];
}

// print the result
for(int i=0; i < num; i++) {
    printf("c[%d] = %f\n", i, c[i]);
}
```

parallelized using GPGPU (OpenCL)

```
__kernel void AddArrays(__global float* a, __global float* b, __global float* c)
{
    // determine which element of the array we are working on
    unsigned int i = get_global_id(0);

    // perform the addition
    c[i] = a[i] + b[i];
}
```

CPU setup code (some details omitted)

```
// create an OpenCL kernel from the kernel source
cl_kernel kernel = clCreateKernel(program, "AddArrays", &err);

// upload the data to the GPU
cl_mem cl_a = clCreateBuffer(context, CL_MEM_READ_ONLY|CL_MEM_COPY_HOST_PTR,
   sizeof(float) * num, a, &err);
cl_mem cl_b = clCreateBuffer(context, CL_MEM_READ_ONLY|CL_MEM_COPY_HOST_PTR,
   sizeof(float) * num, b, &err);
cl_mem cl_c = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
   sizeof(float) * num, NULL, &err);

// execute the kernel
clEnqueueNDRangeKernel(command_queue, kernel, 1, NULL, workGroupSize,
   NULL, 0, NULL, &event);
```

GPGPU & Combination with rendering

- general computation and rendering possible in one program
  - e.g., simulation on the GPU, render results also with the GPU
  - CPU can be removed from the process almost entirely!
- example: fluid simulation on the GPU
  - fluid treated as large number of particles in an array
  - kernel applied to each array element to update positions
  - particles rendered as spheres, adding smoothing and refraction

GPGPU & Combination with rendering

General purpose computing on the GPU

bitcoin

ETHEREUM

MONERO

General purpose computing on the GPU

HASHCAT

Advanced Password
Recovery

Graphics Hardware: Summary

- pipeline approach like introduced before
- pipeline stages become increasingly programmable
- CPU sets up environment, GPU computes/renders
- advantages due to massively parallel processing for a computation problem that can easily be parallelized
- GPGPU processing for applying the same approach to general computation/simulation
- combinations of GPGPU computation and GPU rendering