GPU Programming and graphics pipeline

The graphics pipeline

Geometry: objects, surfaces, light sources…

Lighting/shading model

Camera: viewpoint, direction, field-of-view (frustum)

Window (viewport): pixel grid where the picture is displayed

→

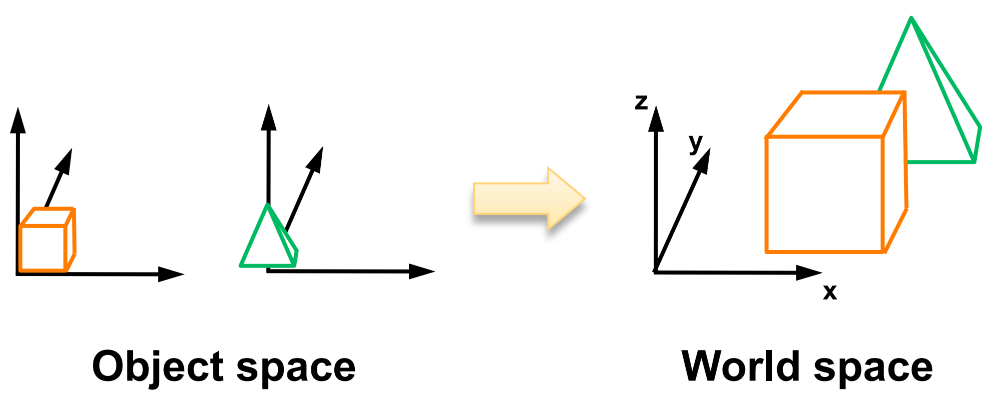
- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

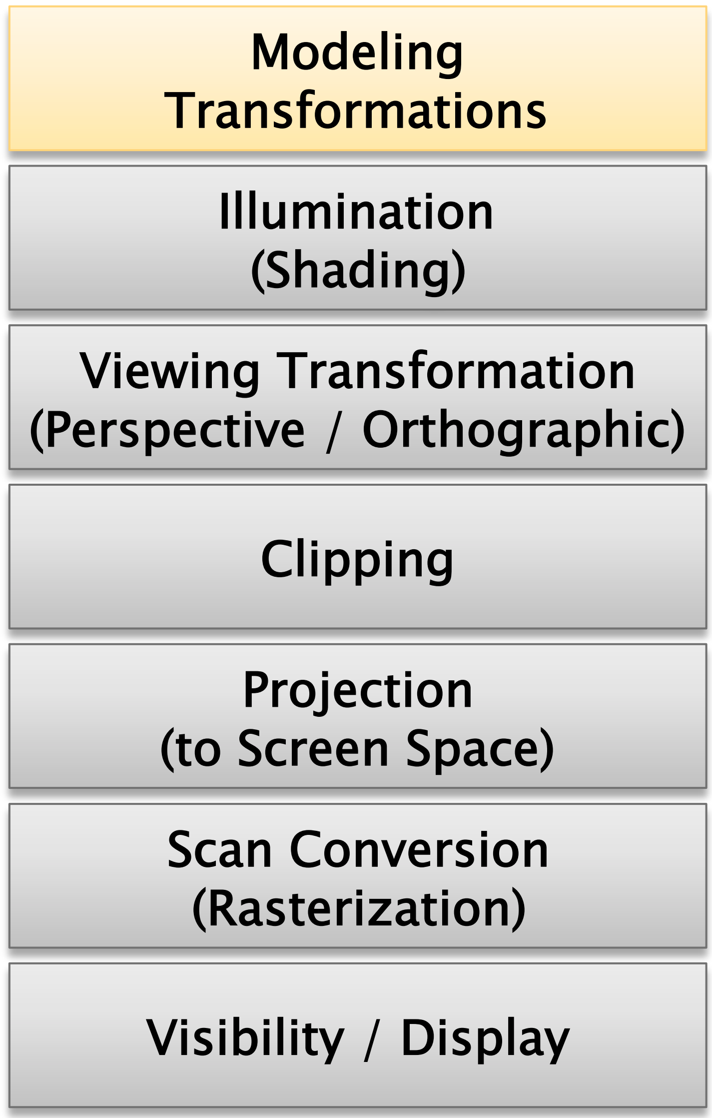
→

Colors, intensities tailored for display (ex : 24 bits, RVB)

Object transformations

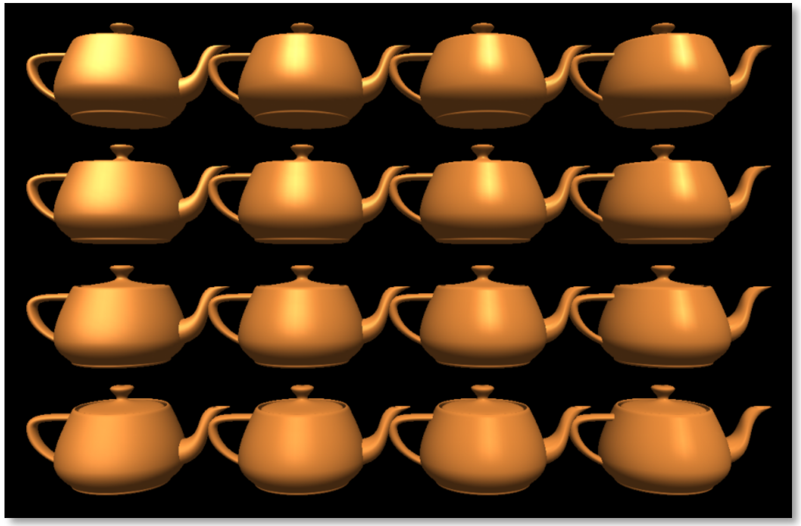
- From each object's **local coordinate system** (object space) to a **global coordinate system** (world space)





Lighting/shading

- Each primitive is shaded depending on its material and the light sources.
- Local illumination only (no shadows), independent computation for each primitive



Modeling Transformations

Illumination (Shading)

Viewing Transformation (Perspective / Orthographic)

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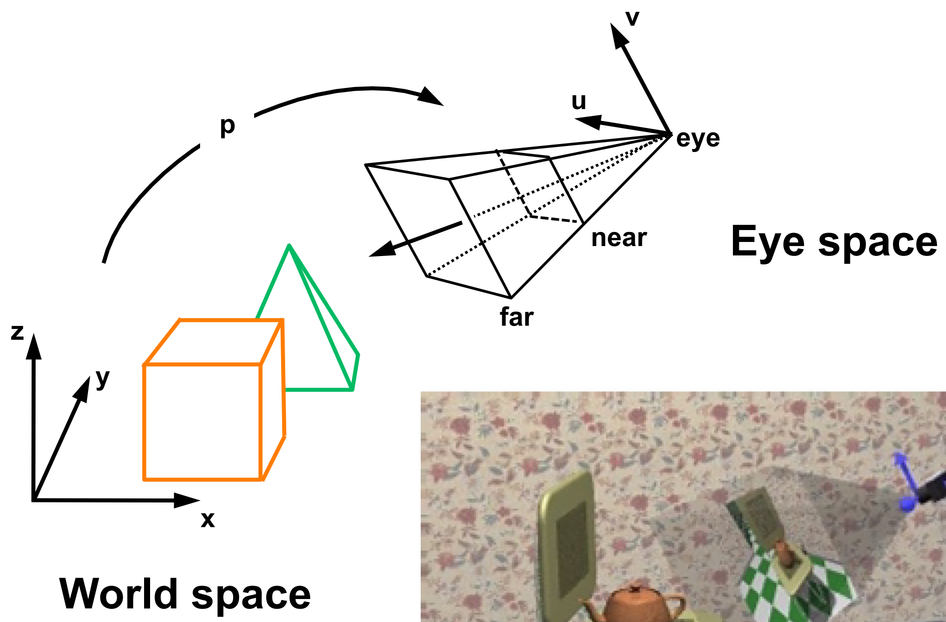
Scan Conversion (Rasterization)

Visibility / Display

Camera transformation

- From world coordinate system to view point (eye space).



- Modeling Transformations
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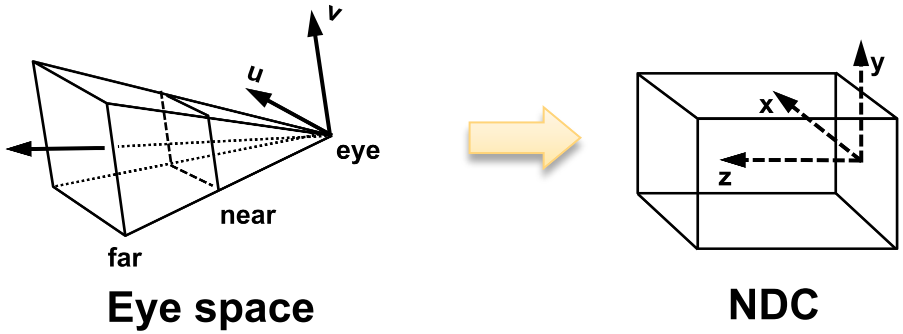
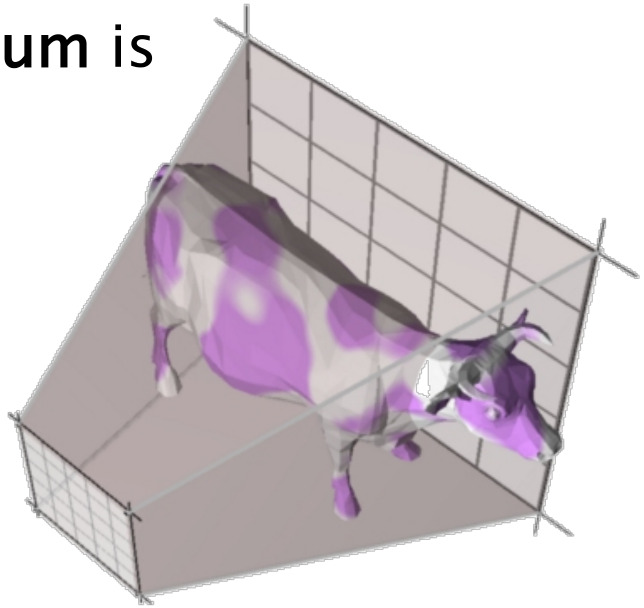
Clipping

- **Normalized coordinates:**



- Anything outside the **viewing frustum** is clipped:



Modeling Transformations

Illumination (Shading)

Viewing Transformation (Perspective / Orthographic)

Clipping

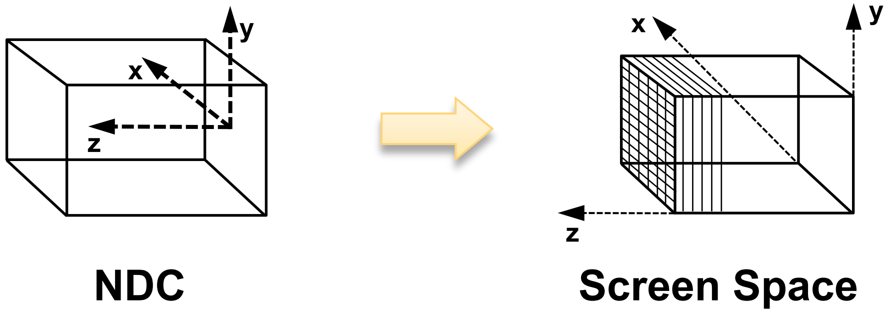
Projection (to Screen Space)

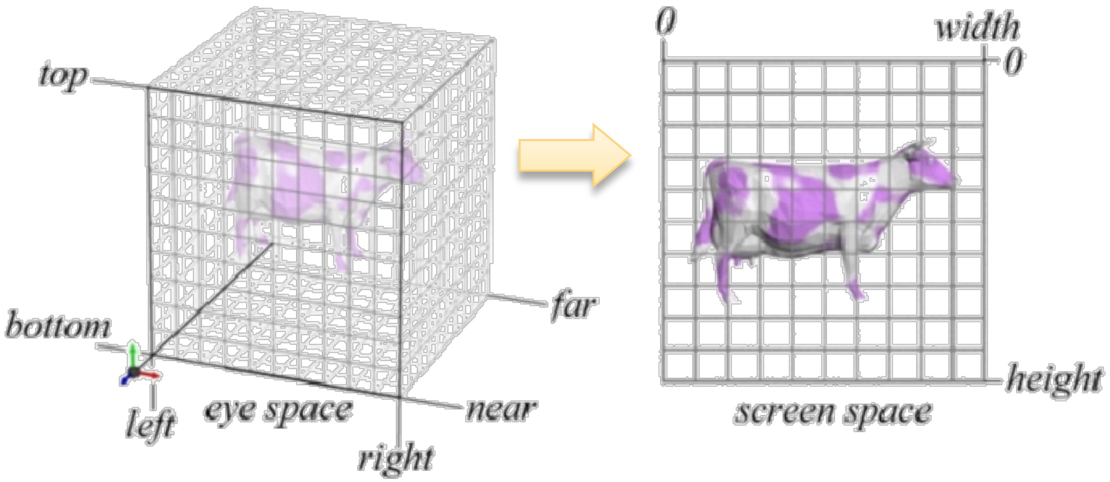
Scan Conversion (Rasterization)

Visibility / Display

Projection

- 3D primitives are projected onto a 2D picture (screen space)





Modeling Transformations

Illumination (Shading)

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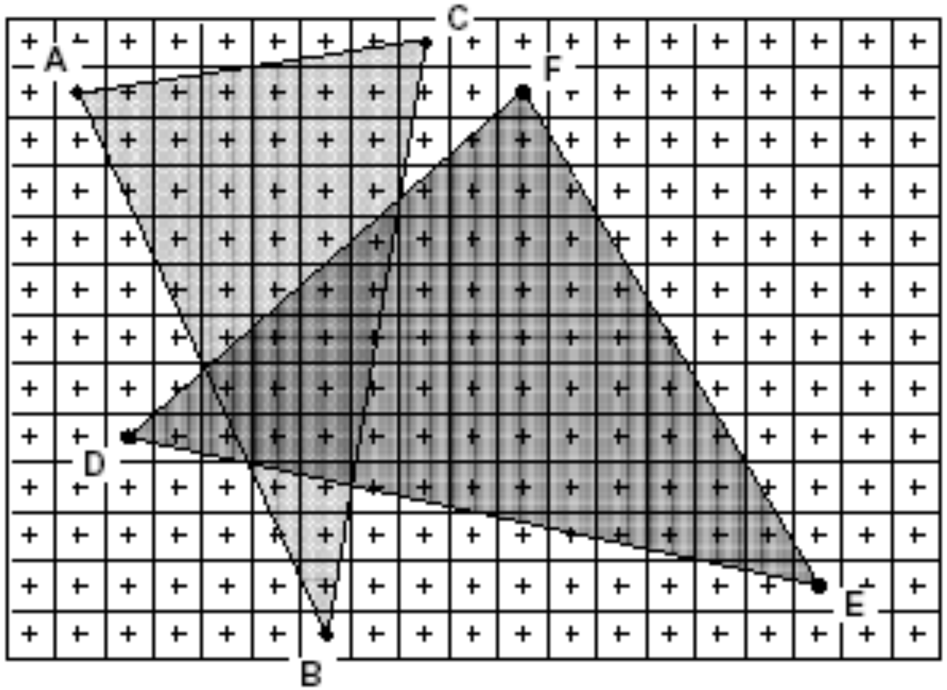
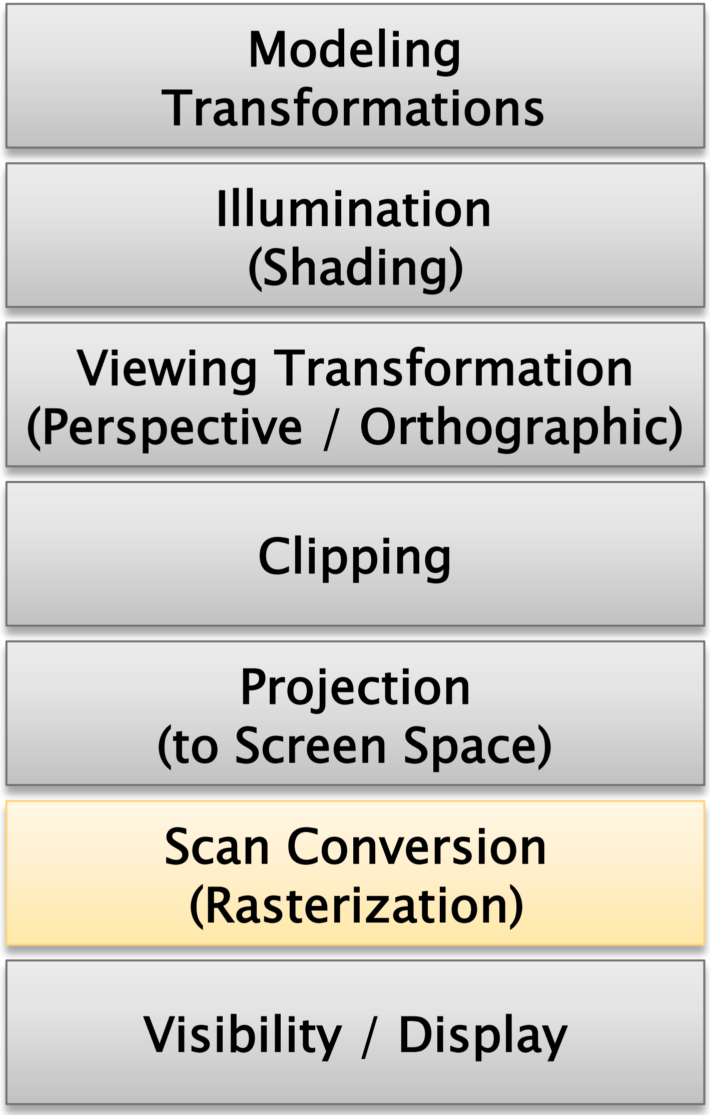
Visibility / Display

Rasterization

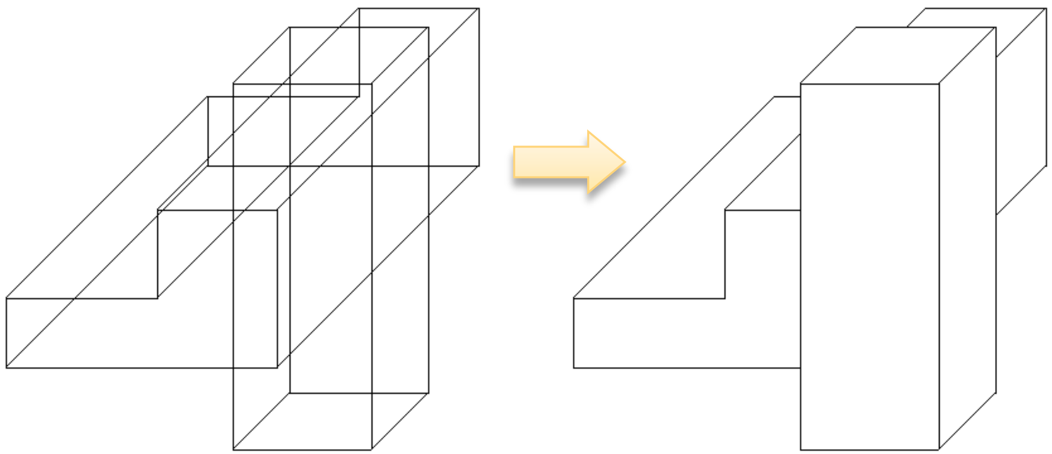
- Convert the 2D primitive in pixels
- Interpolate values known at the vertices (color, depth...)





Visibility and display

- Hidden surface removal
- Filling the frame buffer with the right color format



Modeling Transformations

Illumination (Shading)

Viewing Transformation (Perspective / Orthographic)

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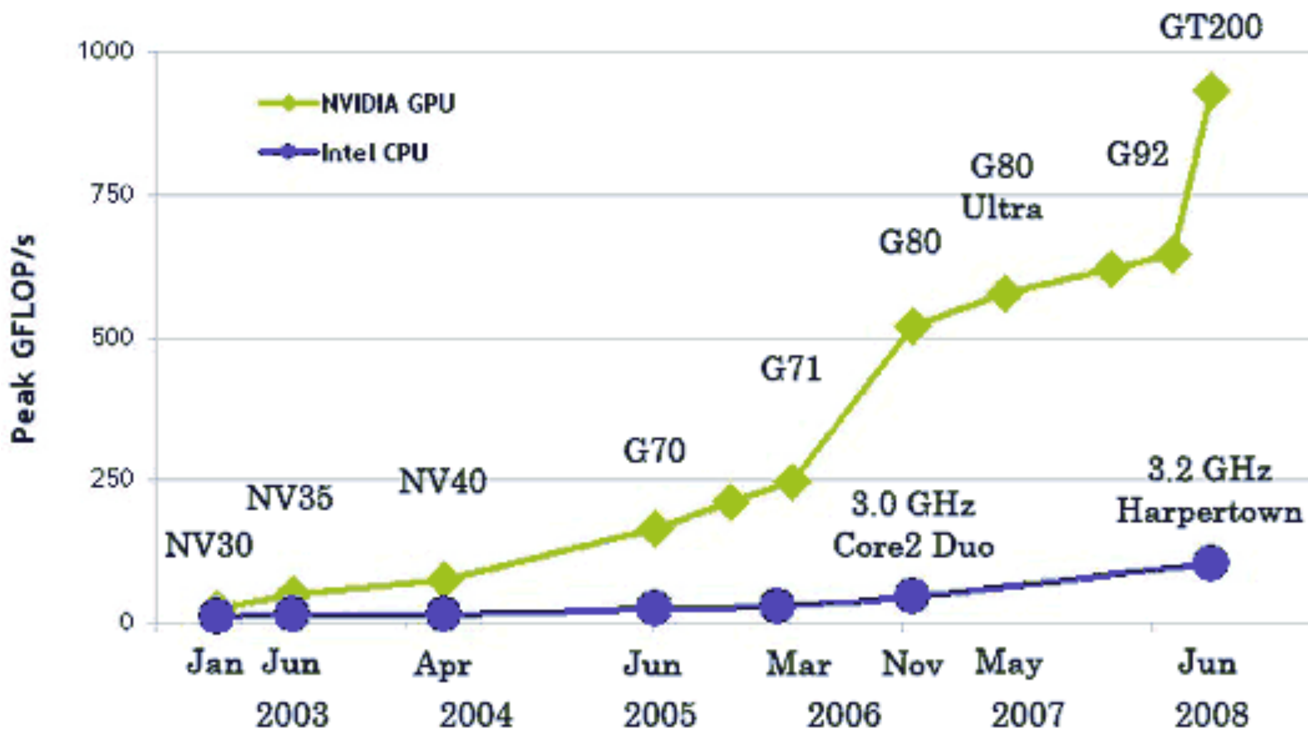
Visibility / Display

What is a GPU?

- "Graphics Processing Unit"
- Specialized processor for graphics rendering
- Spécificities:
  - Highly parallel (SIMD)
  - Fast local memory
  - Large throughput

What is a GPU?

- Highly efficient parallel processor:
  - GPGPU : “General-Purpose computation on GPU”



Graphics pipeline

Before graphics hardware
(1970s)

Software configurable

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
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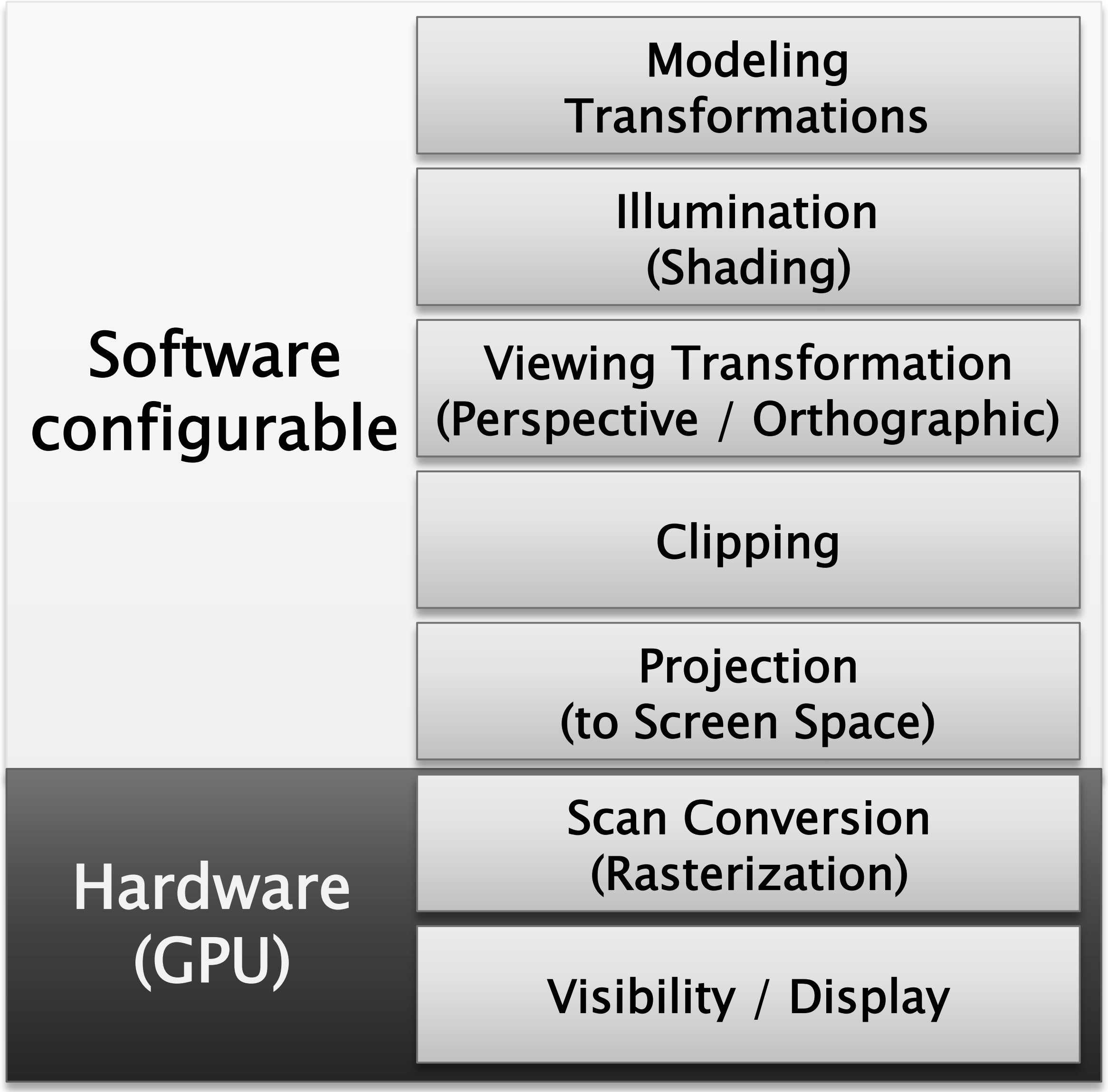
Graphics pipeline

1st generation graphics hardware
(1980s)



Graphics pipeline

2nd generation graphics hardware
(1990s)

Hardware
configurable

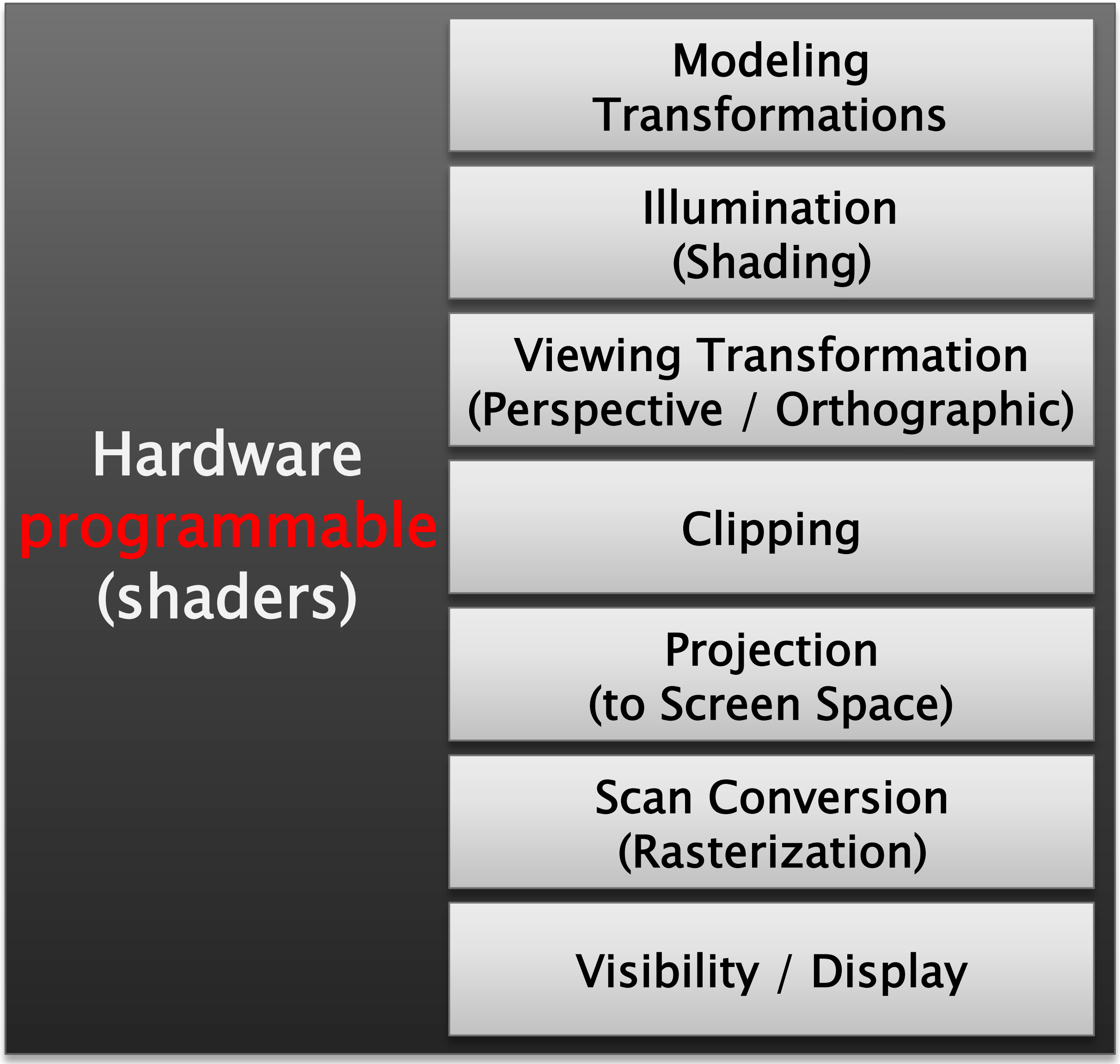
- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

Configurable?

- **API** (Application Programming Interface) for graphics hardware
- Mostly 2 different graphics APIs:
  - Direct3D (Microsoft)
  - **OpenGL** (Khronos Group)

Graphics pipeline

3rd generation graphics hardware
(2000s)



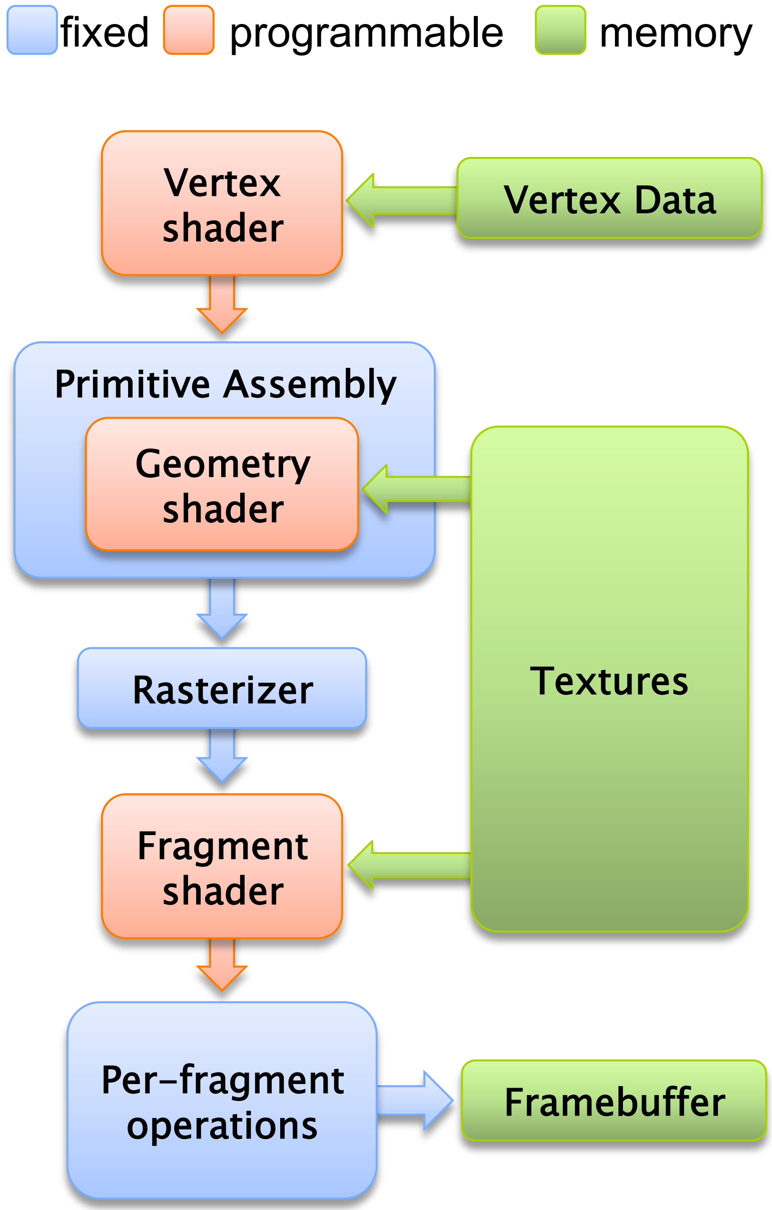
Programmable?

- **Shaders:**
  - Short programs, that the GPU runs at specific steps in the pipeline
  - Different languages (C-like), depending on the API:
  - NVIDIA ➪ Cg (2002)
  - Direct3D ➪ HLSL (2003)
  - OpenGL ➪ GLSL (2004)
- For GPGPU :
  - CUDA (NVIDIA)
  - ATI Stream
  - OpenCL (Khronos Group)

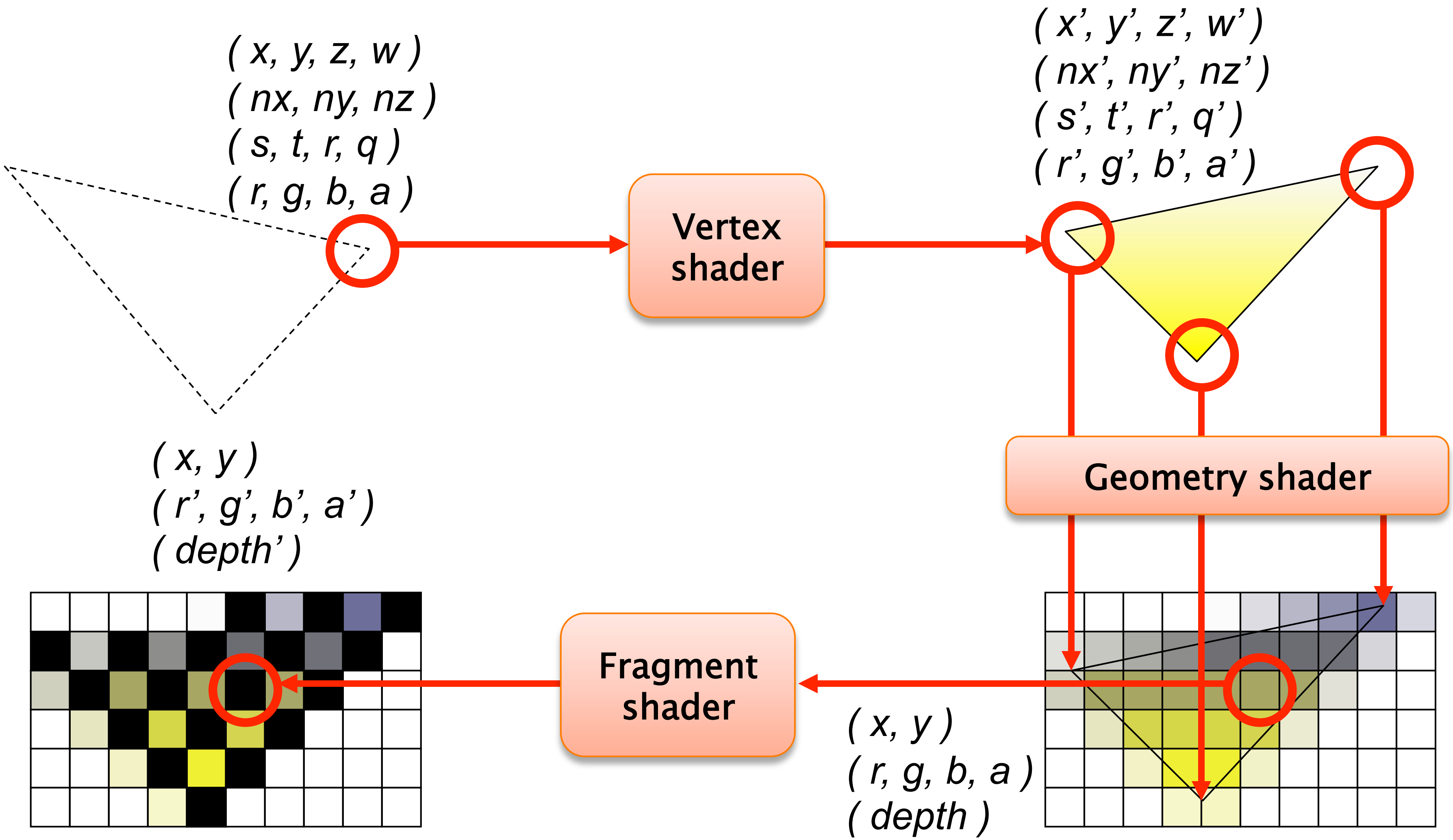
Shaders

- 3 types of shaders
  1. **Vertex** shader
  2. **Geometry** shader
  3. **Pixel** shader

- Local effect
  1. one vertex
  2. one primitive (& neighbors)
  3. one pixel



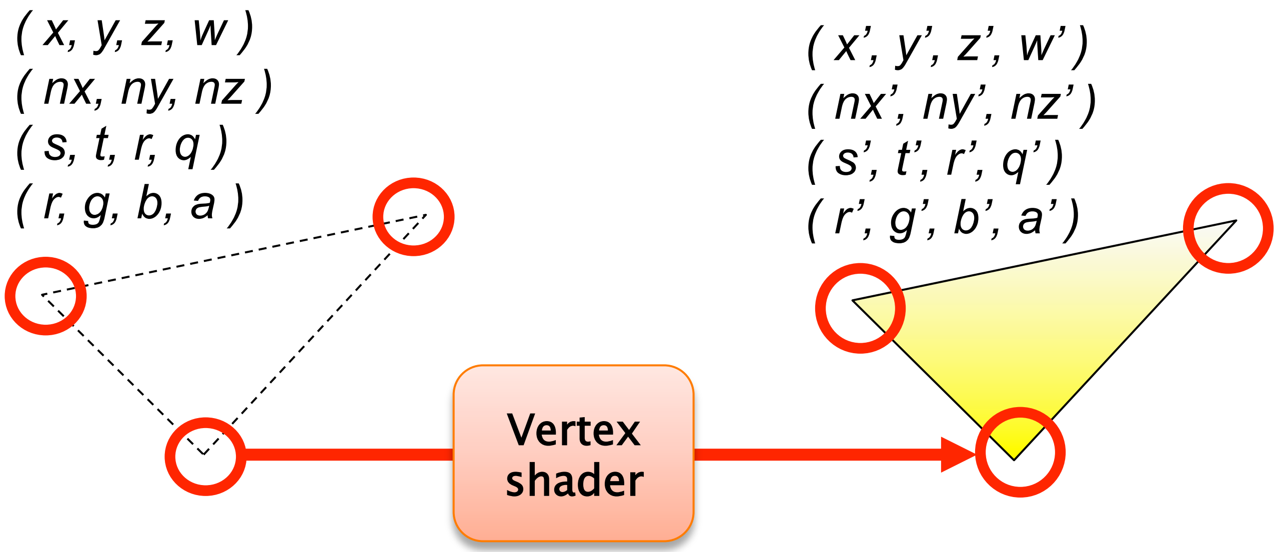
Shaders



(x, y, z, w)
(nx, ny, nz)
(s, t, r, q)
(r, g, b, a)
Vertex shader
(x', y', z', w')
(nx', ny', nz')
(s', t', r', q')
(r', g', b', a')
Geometry shader
(x, y)
(r', g', b', a')
(depth')
Fragment shader
(x, y)
(r, g, b, a)
(depth)

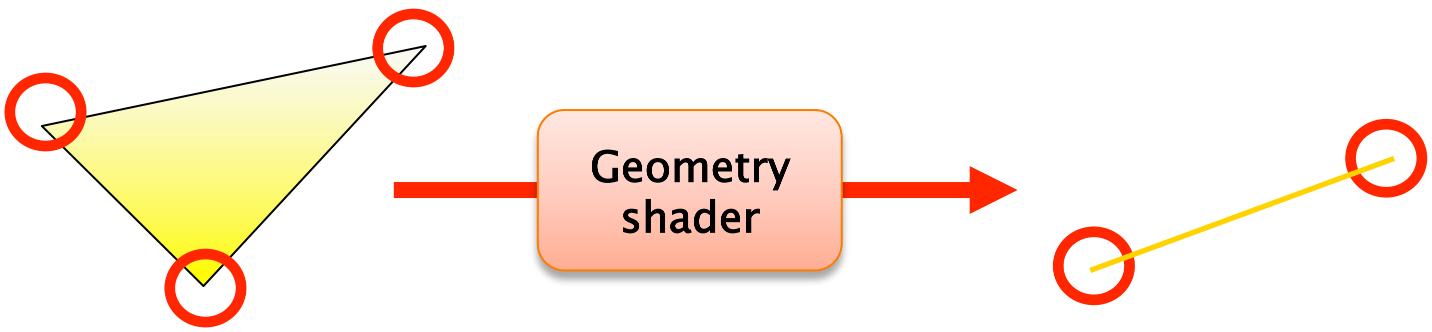
Vertex shader

- What you can do:
  - Geometric transformations, changing position
  - Lighting, shading, computing a color per vertex
  - Computing texture coordinates



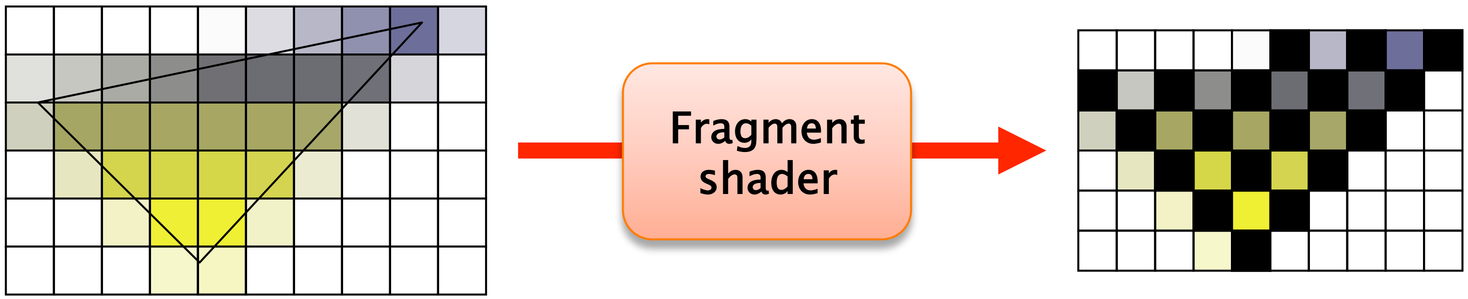
Geometry shader

- What you can do:
  - Add/remove vertices
  - Change the primitives
  - Get the actual geometry, before rasterization



Fragment shader

- What you can do:
  - Lighting, shading, computing a color... per pixel
  - Use the textures as input for computations
  - Change pixel depth



My first Vertex Shader

```
uniform mat4 modelViewProjectionMatrix;
in vec4 vertex;
out vec3 color;

vec4 UneFonction( vec4 Entree )
{
        return Entree.zxyw;
}

void main()
{
        vec4 pos = modelViewProjectionMatrix * vertex;
        gl_Position = pos + UneFonction( vertex );
        color = vec3(1.0,0.0,0.0);
}
```

Input

Output

Function

Swizzle

Main program

Local variable

Matrix-vector multiplication

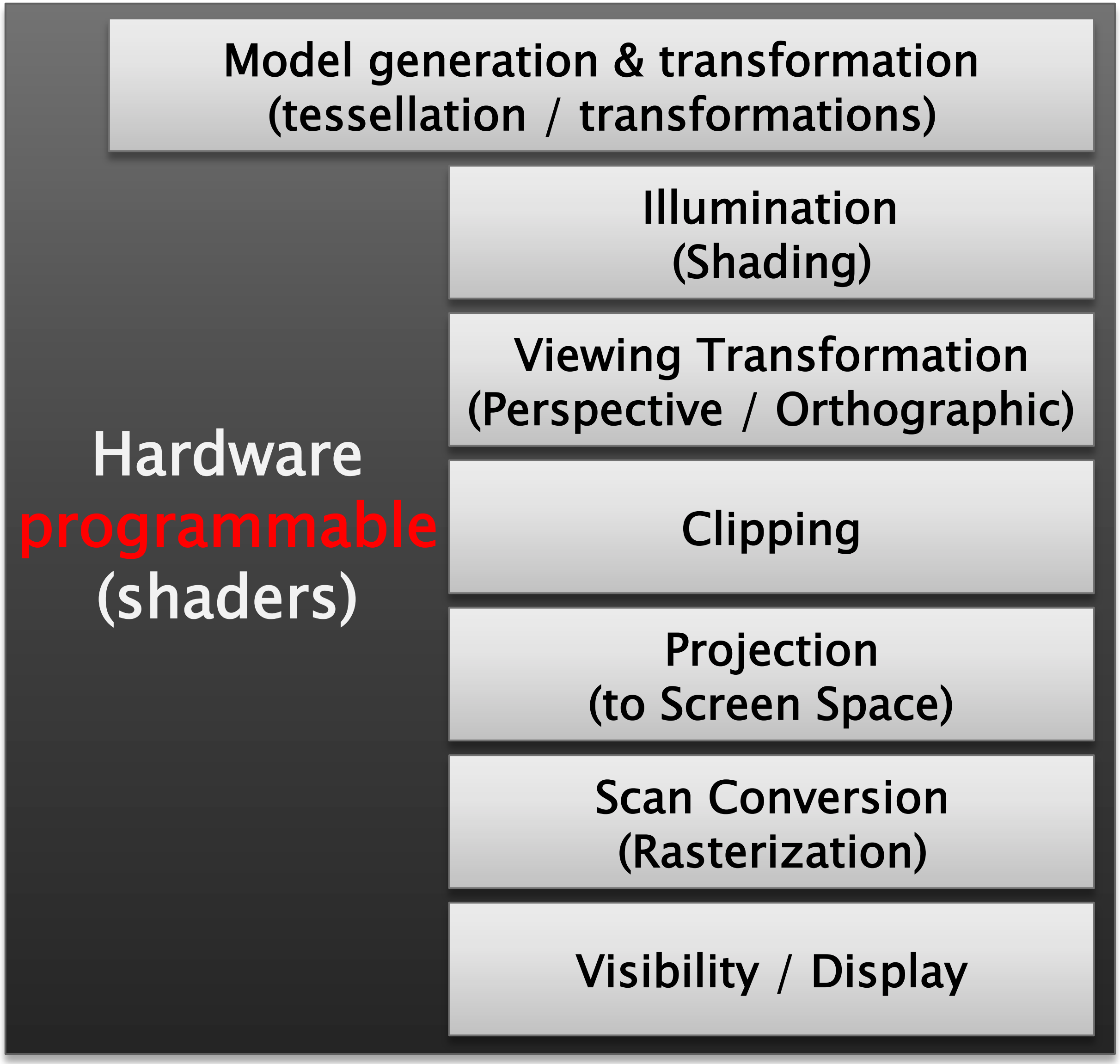
OpenGL Output

A piece of advice

- Code slowly, step by step, and **test often**!
  - Debugging is really difficult
- **Optimization**
  - Best place for each computation:
    - Vertex shader : 1x per vertex
    - Fragment shader : 1x per fragment: much more frequent!
  - Use textures to tabulate complicated functions
  - Use the functions in the language, rather than coding them yourself (sin, sqrt,…)

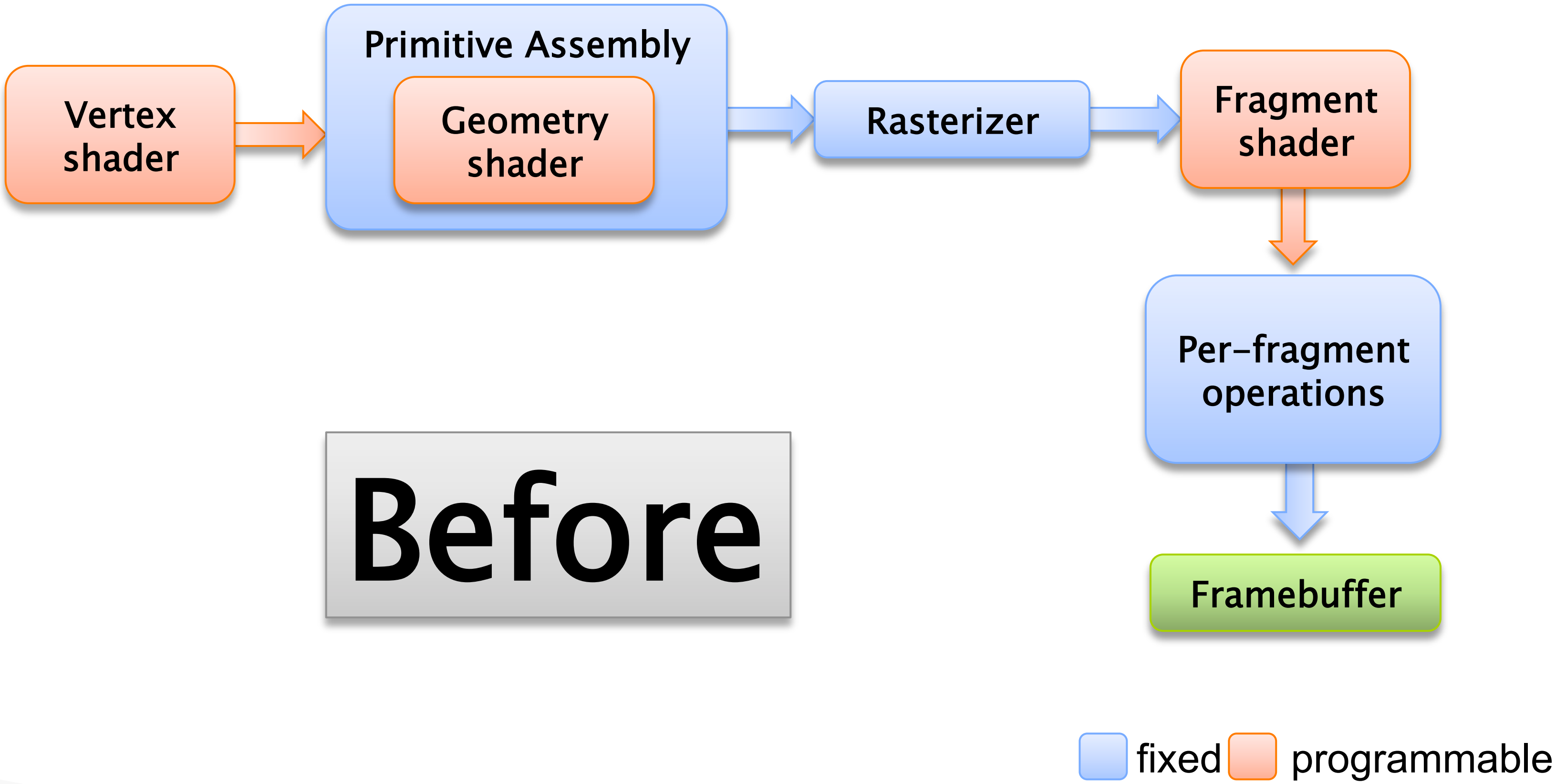
Graphics pipeline

4th generation graphics hardware
(2010s)



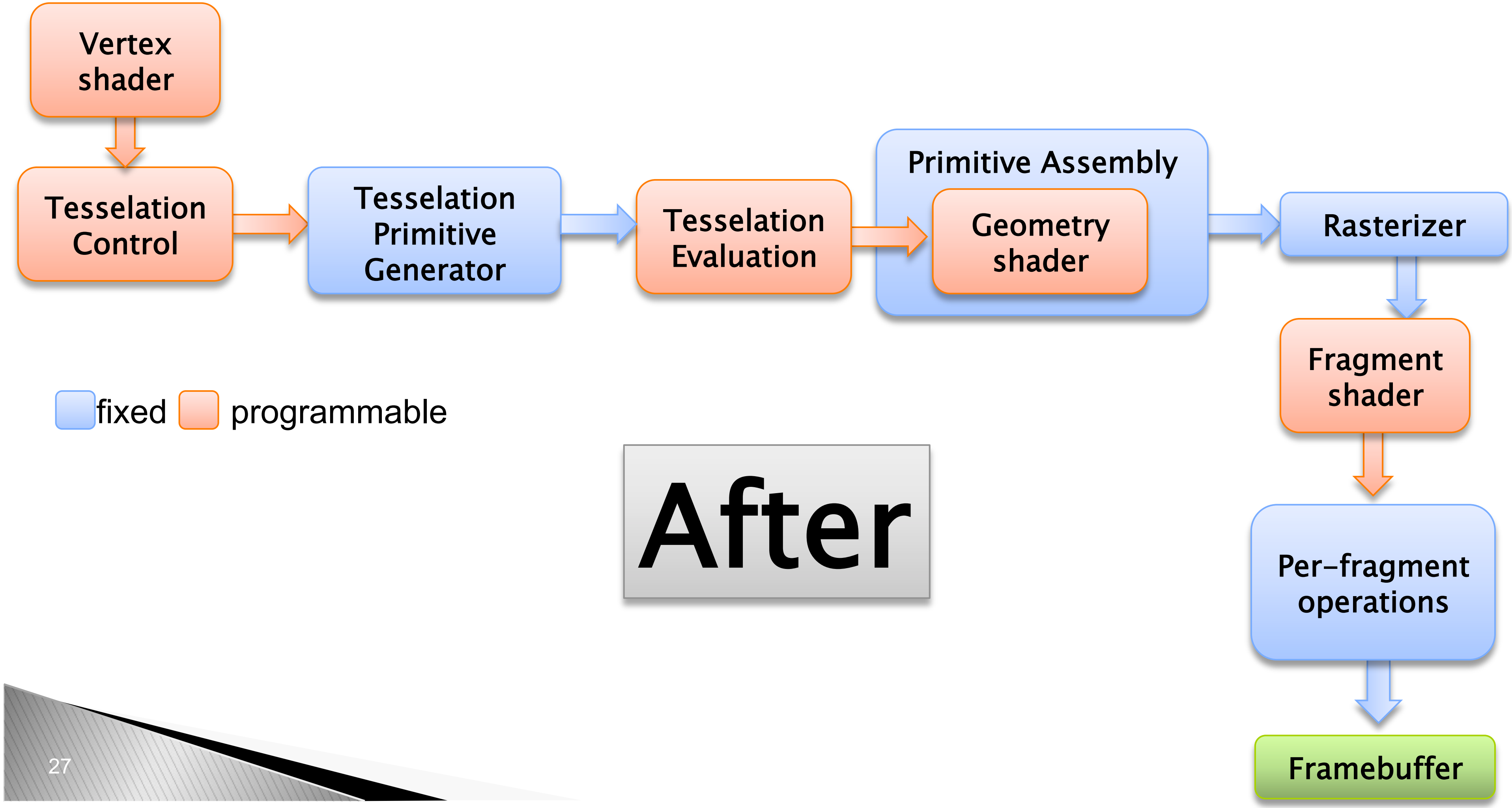
Tessellation shaders

- Another step, between vertex and geometry shaders



Tessellation shaders

- Between vertex and geometry shaders



Tessellation Evaluation shader

- Before “primitive assembly”
- Input: a patch
  - Control points, coordinates inside the patch
  - Patch type (triangles, quads, iso-lines)
- Output:
  - a vertex
  - Called several times, once for each vertex generated
  - Local effect, no global view of the patch
- What for?
  - Subdivision surfaces, splines...

Tessellation Control Shader

- Called before the Tessellation Eval Shader
- Facultative
- Controls tessellation level for each patch
- Once for each control point (`gl_InvocationID`)
- *Can* modify the control points

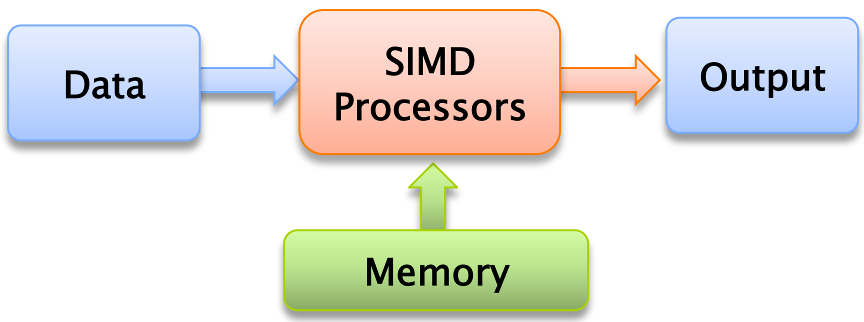
- Tessellation Primitive Generator
  - Generates the coordinates where we call TessEval
  - Fixed functionality

Tessellation: what for?

- Apparently, useless:
  - Anything it does, you can do with geometry shader
- In practice:
  - GPU needs predictability
  - Parallel processor / resource allocation
  - Useful for subdivision surfaces, splines

GPGPU

- *General-Purpose Computation Using Graphics Hardware*
- GPU = a SIMD processor (*Single Instruction Multiple Data*)
- One texture = array of input data
- One picture= array of output data



GPGPU – Applications

- Advanced rendering
  - Global illumination
  - Image-based rendering
  - …
- Signal processing
- Algorithmic geometry
- Genetic algorithms
- Anything you can massively parallelize

GPGPU

- Get back the data (from GPU to CPU) = slower
  - PCI Express
- Limited operators, functions, types
- A parallel algorithm is not necessarily faster than the sequential version
  - Synchronization between multiple cores

References

- OpenGL red book: http://www.opengl-redbook.com/
- GLSL specification: https://www.opengl.org/registry/doc/GLSLangSpec.4.40.pdf
- Cg: http://developer.nvidia.com/page/cg_main.html
- Cuda: http://www.nvidia.com/cuda
- OpenCL: http://www.kronos.org/opencl/

- Debugging OpenGL/GLSL:
  - glslDevil : http://www.vis.uni-stuttgart.de/glsldevil/

- Many examples (to use as a starting point):
  - http://developer.nvidia.com/object/sdk_home.html

- GPGPU reference, with code, forums, tutorials: http://www.gpgpu.org/