Graphics pipeline

Graphics rendering pipeline

- Generates (render) a two-dimensional image
  - *Inputs*: a virtual camera, three-dimensional objects, light sources, shading equations, textures, etc.
- Consists of several stages, and the speed is determined by the slowest stage

Real-Time 3D Graphics API

- Software abstraction of the capabilities of the graphics card
- Application programming interface (**API**)
  - provides hardware independence (each GPU has its own instruction set and interface)
- **Direct3D** - Windows (only)
- **OpenGL** - open source cross-platform

Real-Time 3D Graphics API

- *Functionality*:
  - describe a scene consisting of objects and their properties
  - describe light sources and their properties
  - describe cameras and their properties
  - render the objects (from a particular view and as if they were illuminated by the light sources)

Evolution of graphics pipelines

Fixed-Function pipeline (1992 – 2001)

- Configurable via parameters
- Cannot change the algorithms (e.g. Gouraud or Phong shading)
- OpenGL 1, Direct3D 2

Hybrid pipeline (2001 – 2009)

- Shaders (HLSL/Cg – Microsoft/NVIDIA and GLSL - OpenGL)
- Fixed and programmable features co-exist
- OpenGL 1.4, Direct3D 8

Programmable pipeline (2009 – present)

- No more fixed functions
- OpenGL 3.2, Direct3D 10, CUDA/OpenCL

Rendering strategies

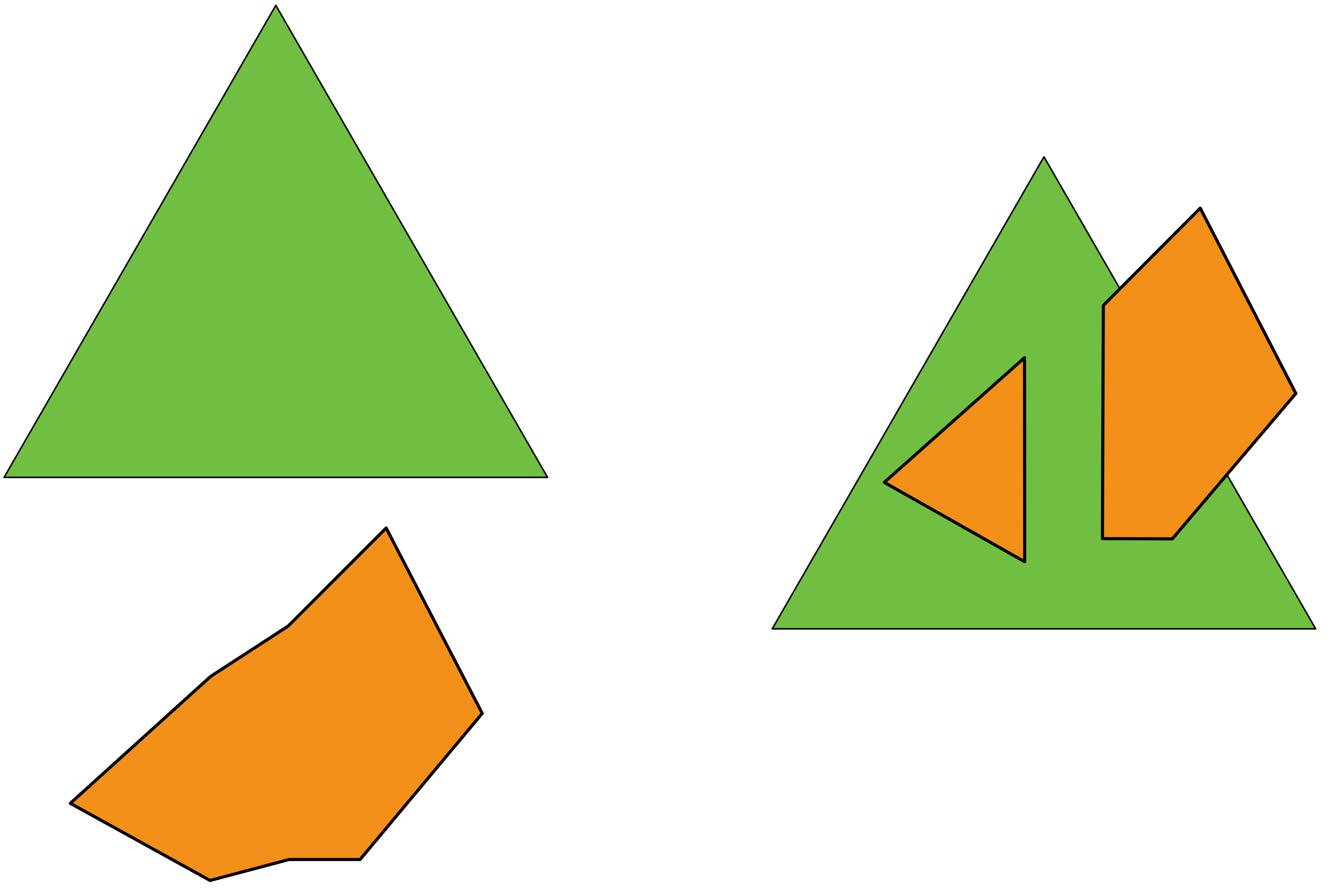
Rasterization

```
foreach triangle T{
 fragments = identify
 pixels   p(x,y)
 covered by T
 foreach fragment F{
  check if F is visible
  if(visible){
   color(x,y) = compute
   shaded value of F
  }
 }
}
```

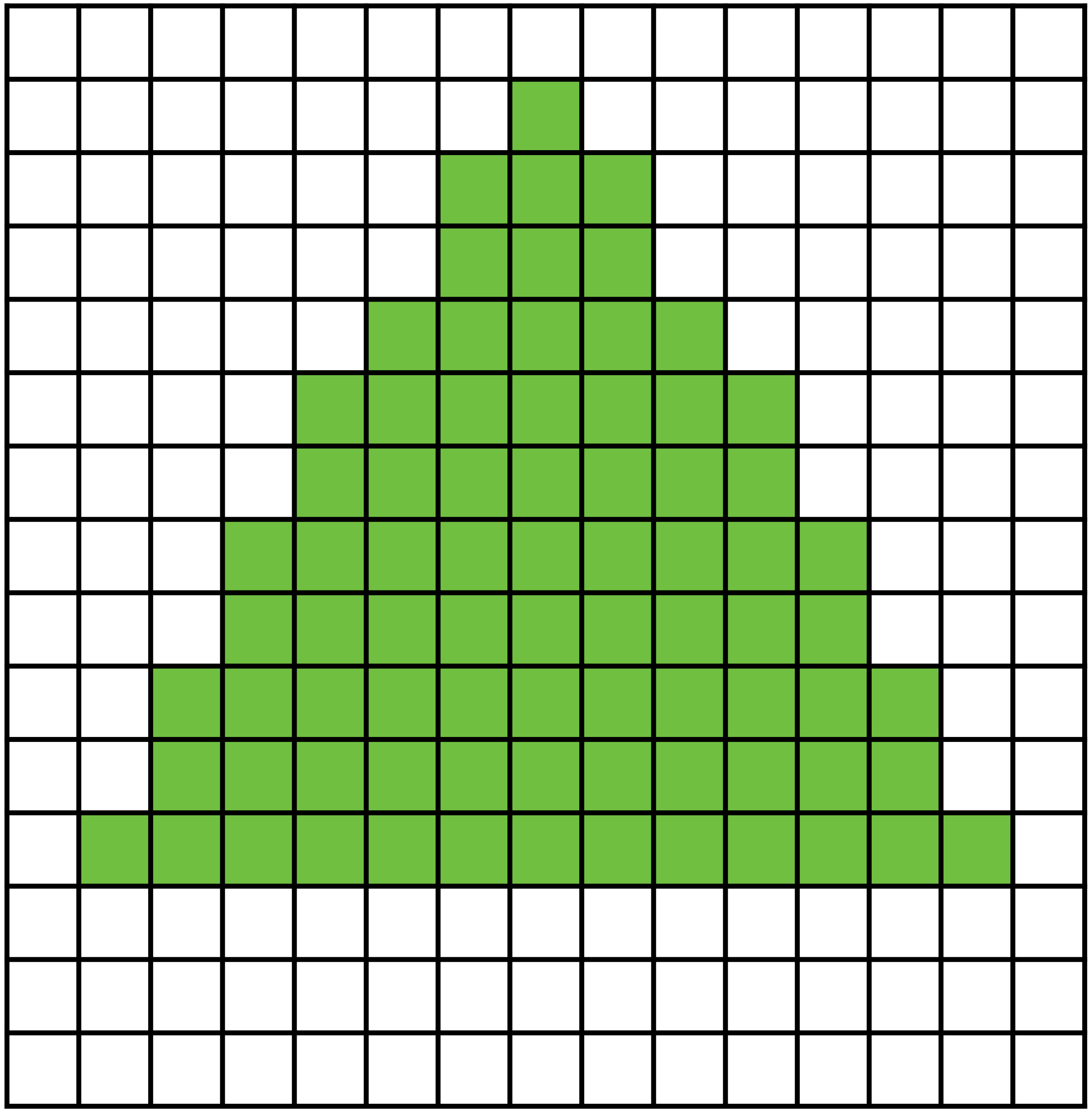
Ray tracing

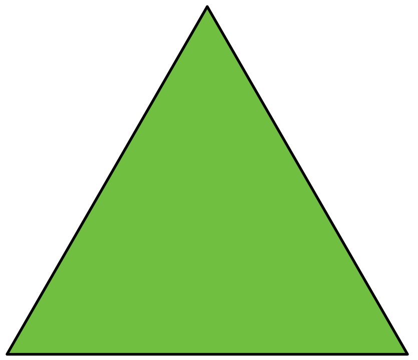
```
foreach pixel p(x,y){
 intersect ray through
 pixel p with objects
 color(x,y) =
 compute_shade(visible
 point)
}
```

Rasterisation

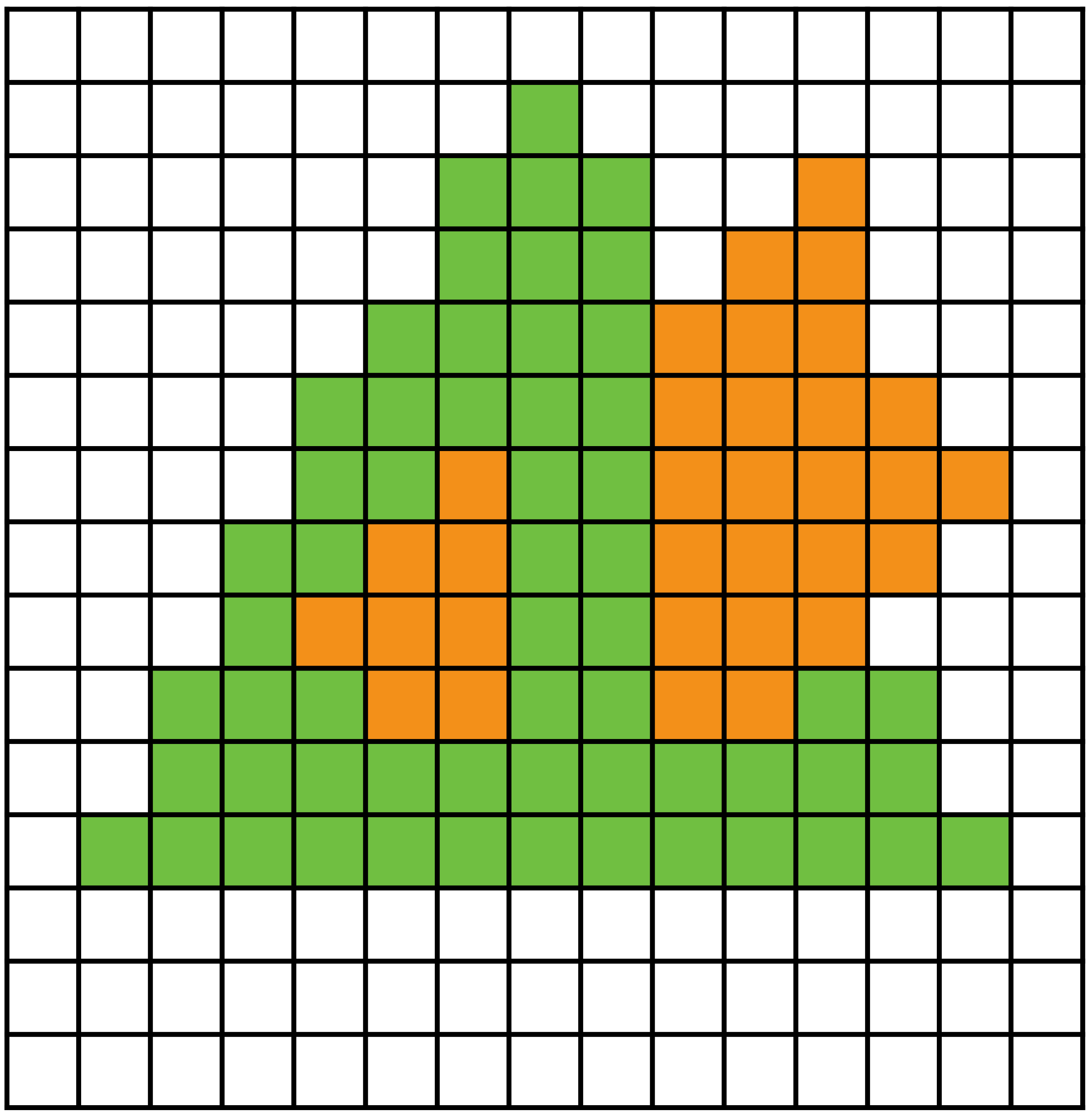


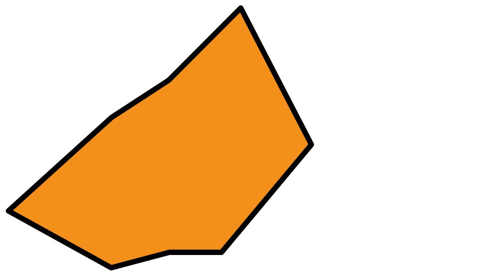
Rasterisation



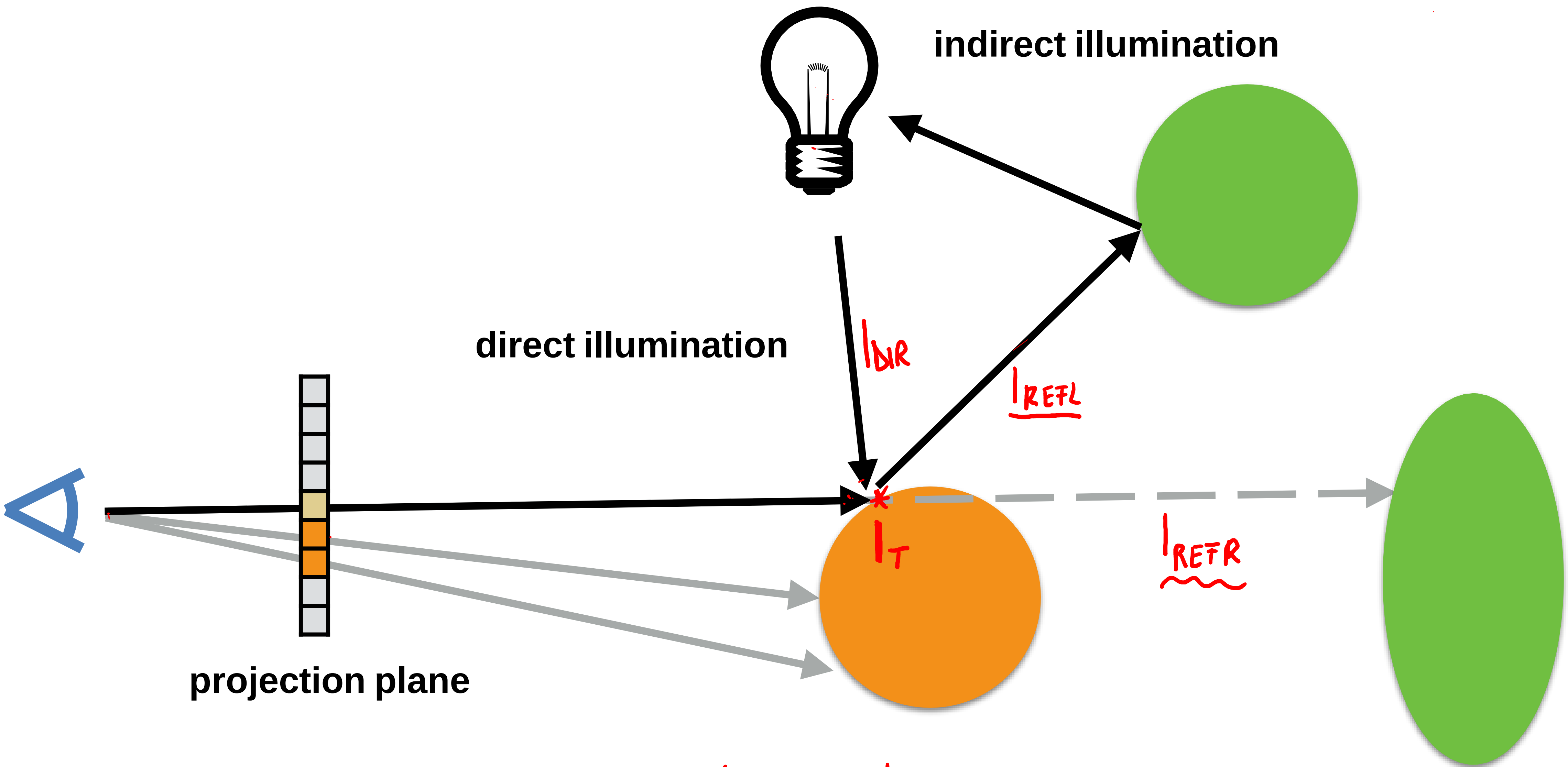


Rasterisation





Ray tracing



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Ray tracing

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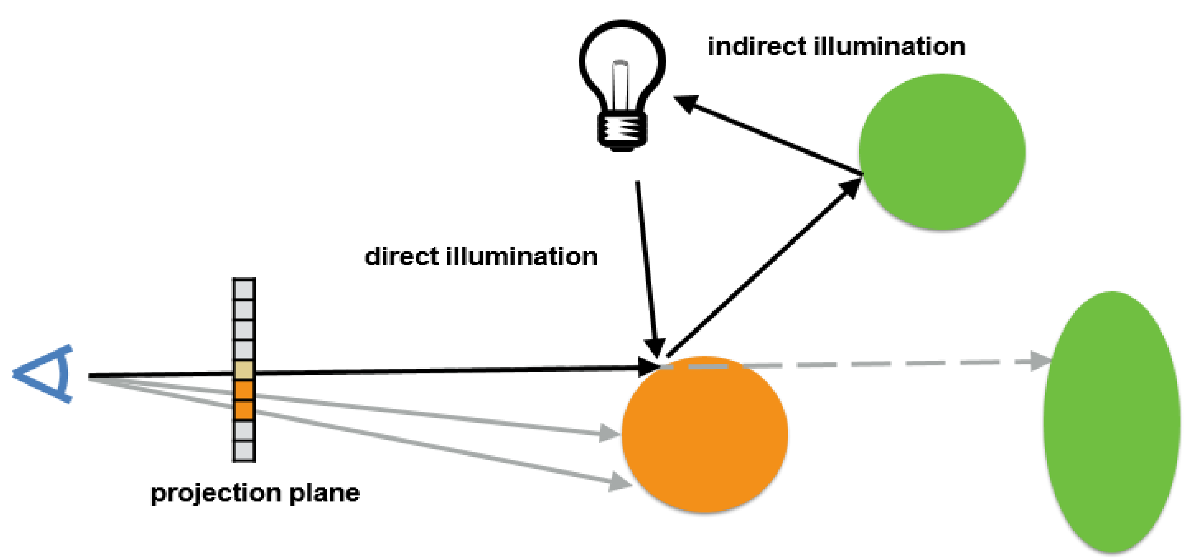


Rasterization vs Ray Tracing

Raster -> Blender v2.79 (Render -> OpenGL)

Rasterization vs Ray Tracing

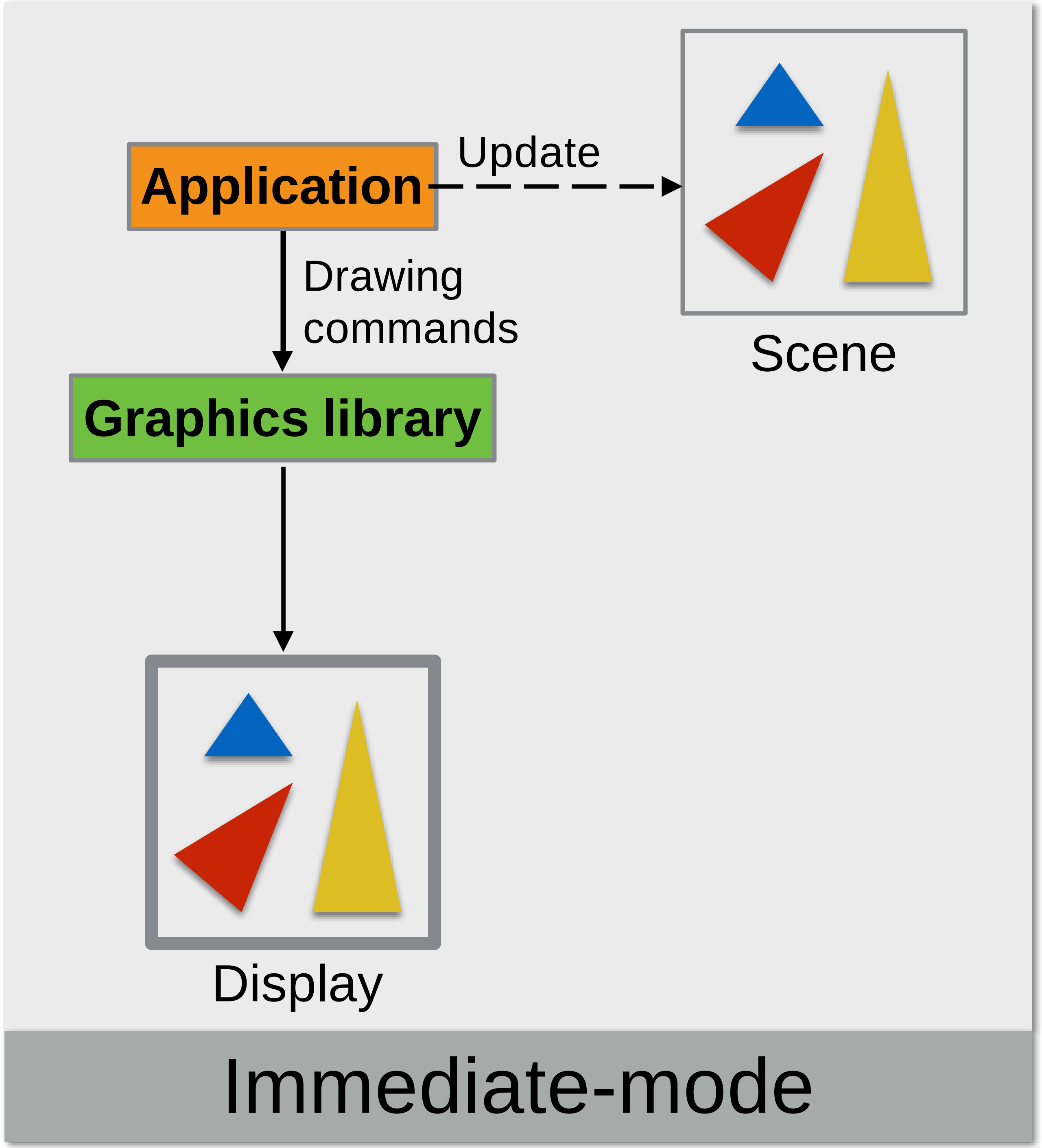
Ray Tracing → Blender 2.79 (Cycles Renderer)

Ray Tracing - Reflection/Refraction

Immediate-mode vs Retained-mode

Immediate-mode (IM)

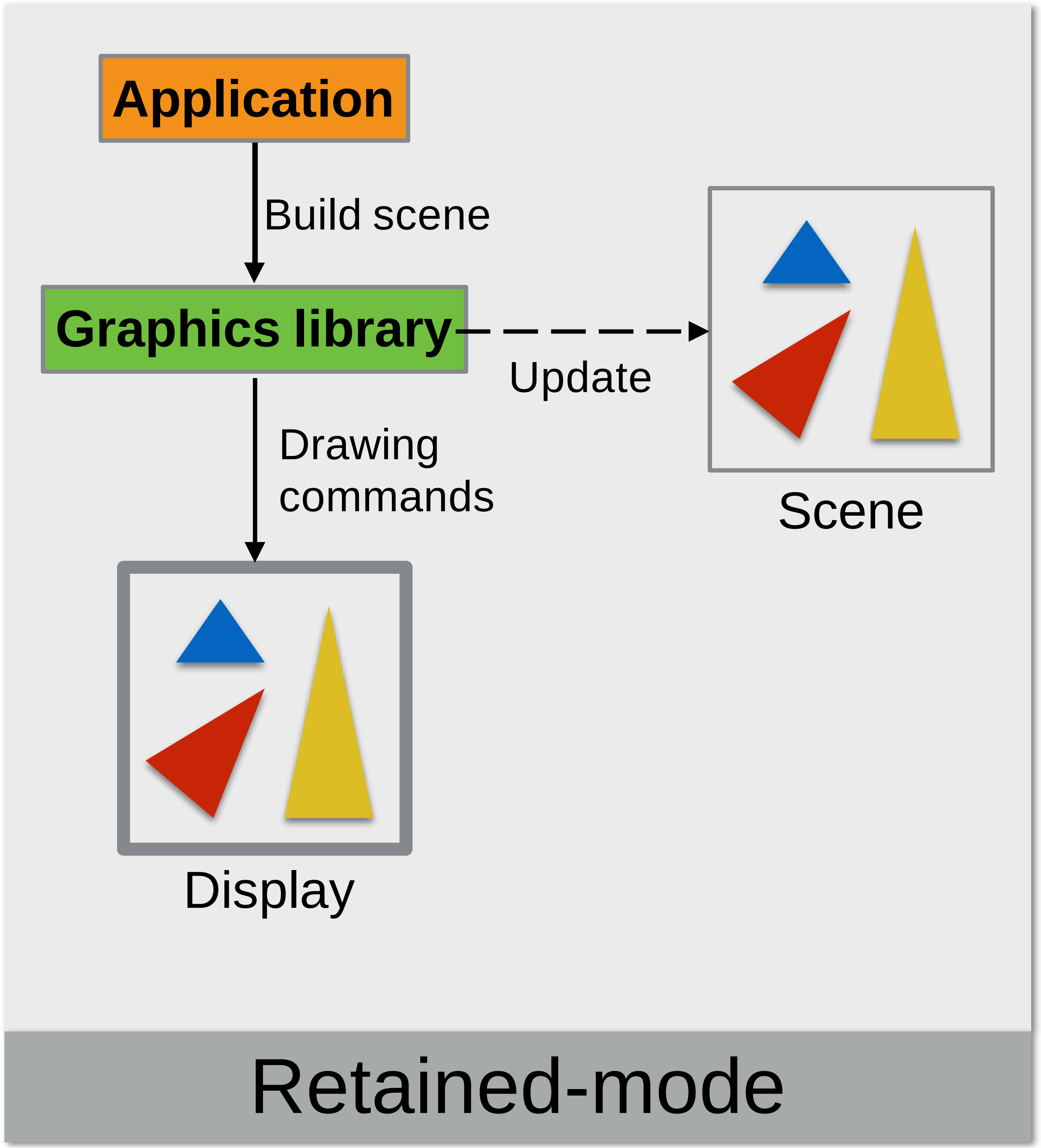
- The scene of objects is not saved at graphics library or GPU level
- The application resends all drawing commands for the new frame
- Offers control and flexibility



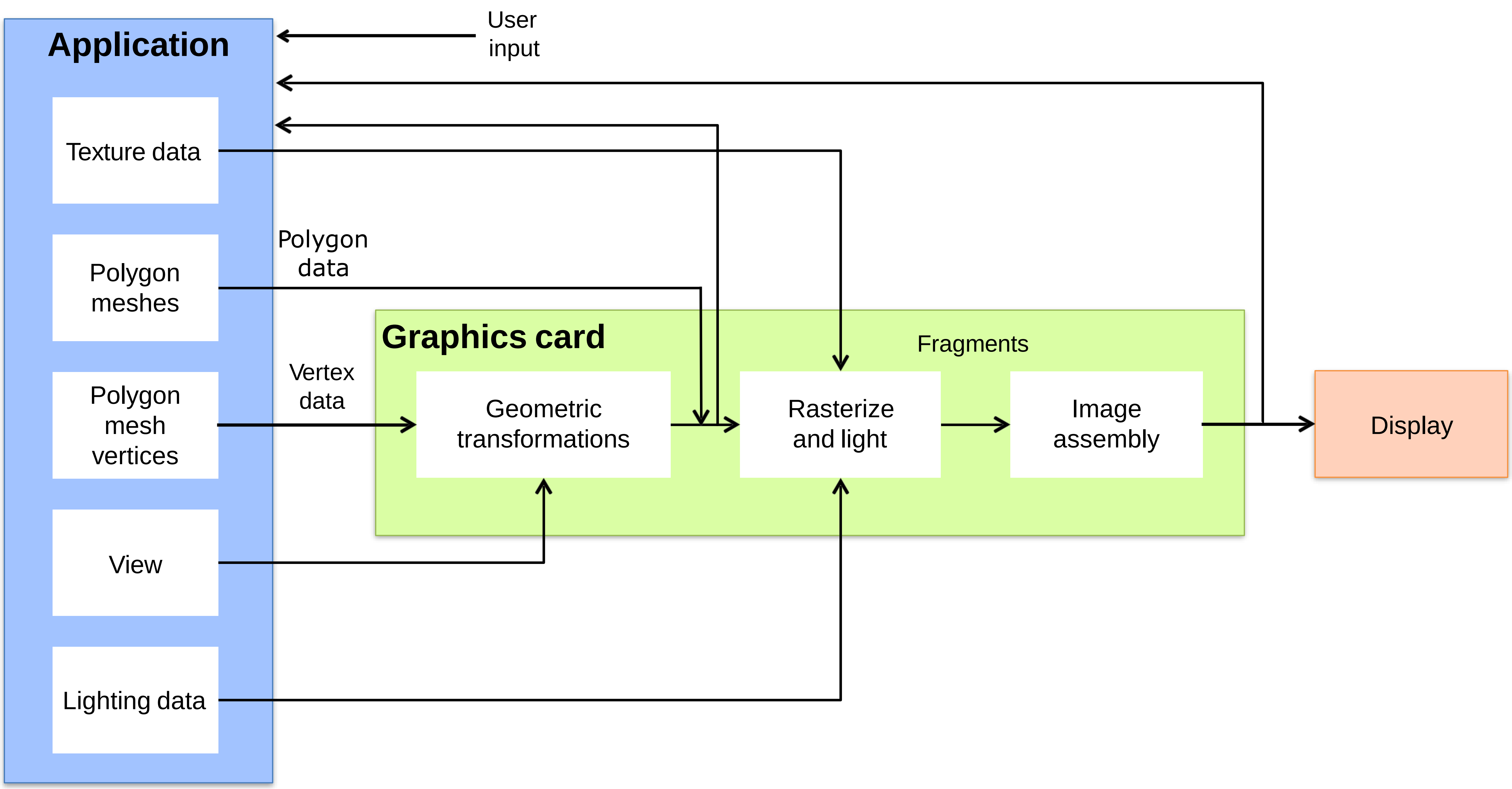
Immediate-mode vs Retained-mode

Retained-mode (RM)

- The application updates the scene of objects which is stored at graphics library or GPU level
- The actual rendering is not called by the application
- Offers abstraction



Graphics Pipeline



[Source: Computer Graphics: Principles and Practice (3rd Edition), John F. Hughes et al.]

Real-time rendering pipeline

Application

- runs on general-purpose CPUs

Vertex processing

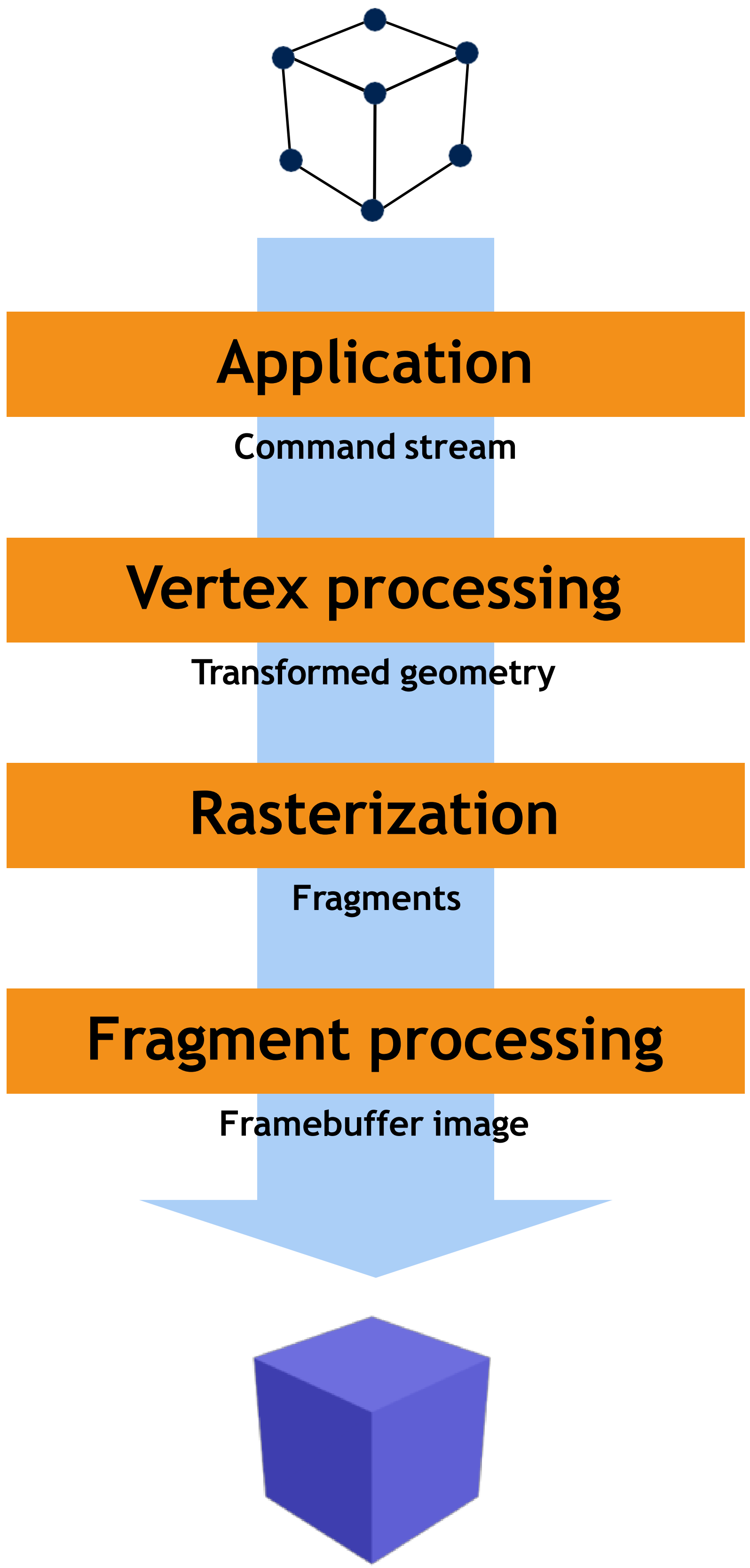
- operations such as transformations, projections, etc.
- computes what is to be drawn, how it should be drawn, and where it should be drawn
- typically performed on a graphics processing unit (GPU)

Rasterization

- rasterize all the primitives
- processed completely on the GPU

Fragment processing

- draws (renders) an image
- processed completely on the GPU



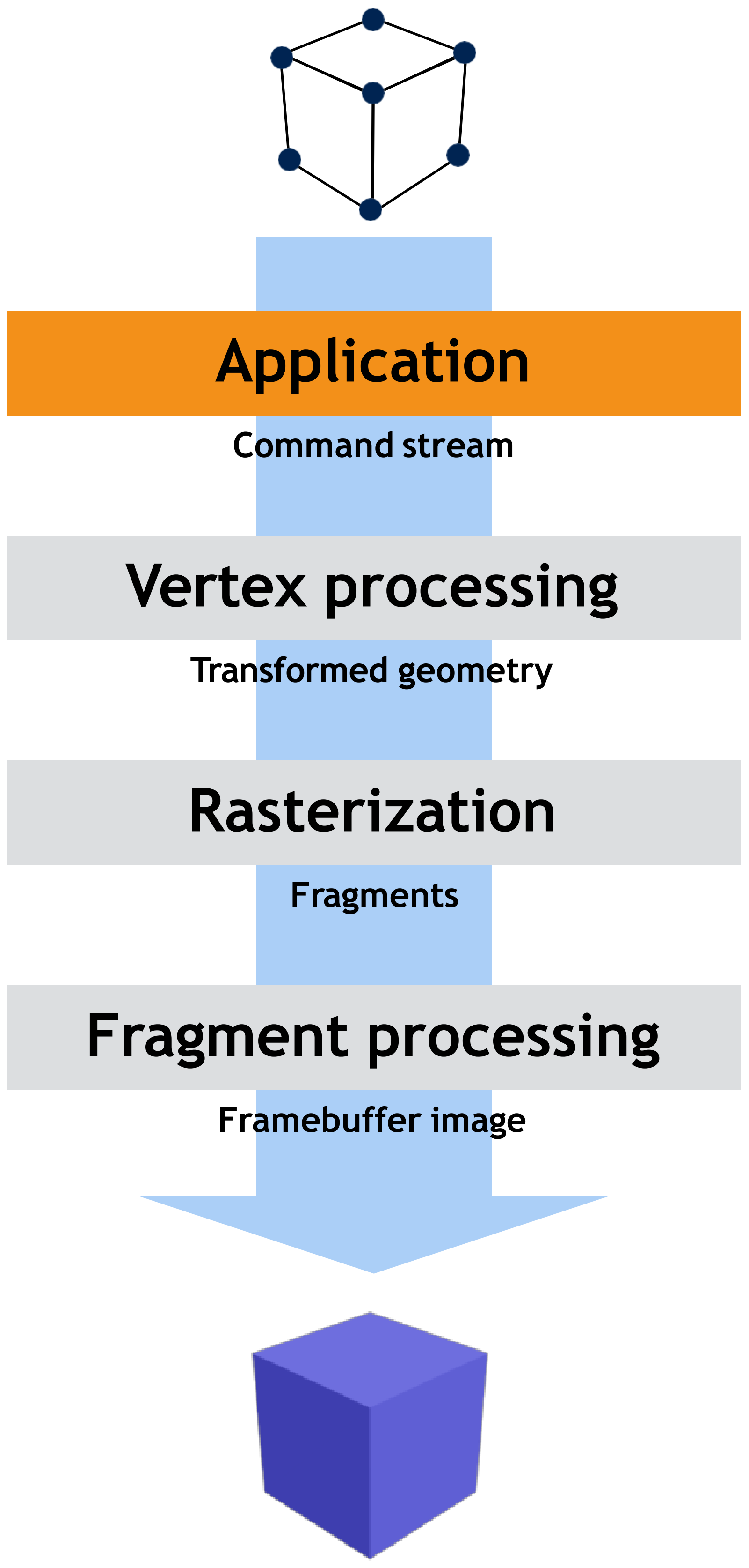
Rendering speed

- Update rate of images
- Expressed in:
  - **frames per second (fps)** - the number of images rendered per second

- Depends on the complexity of the computations
- Determined by the slowest of the pipeline stages

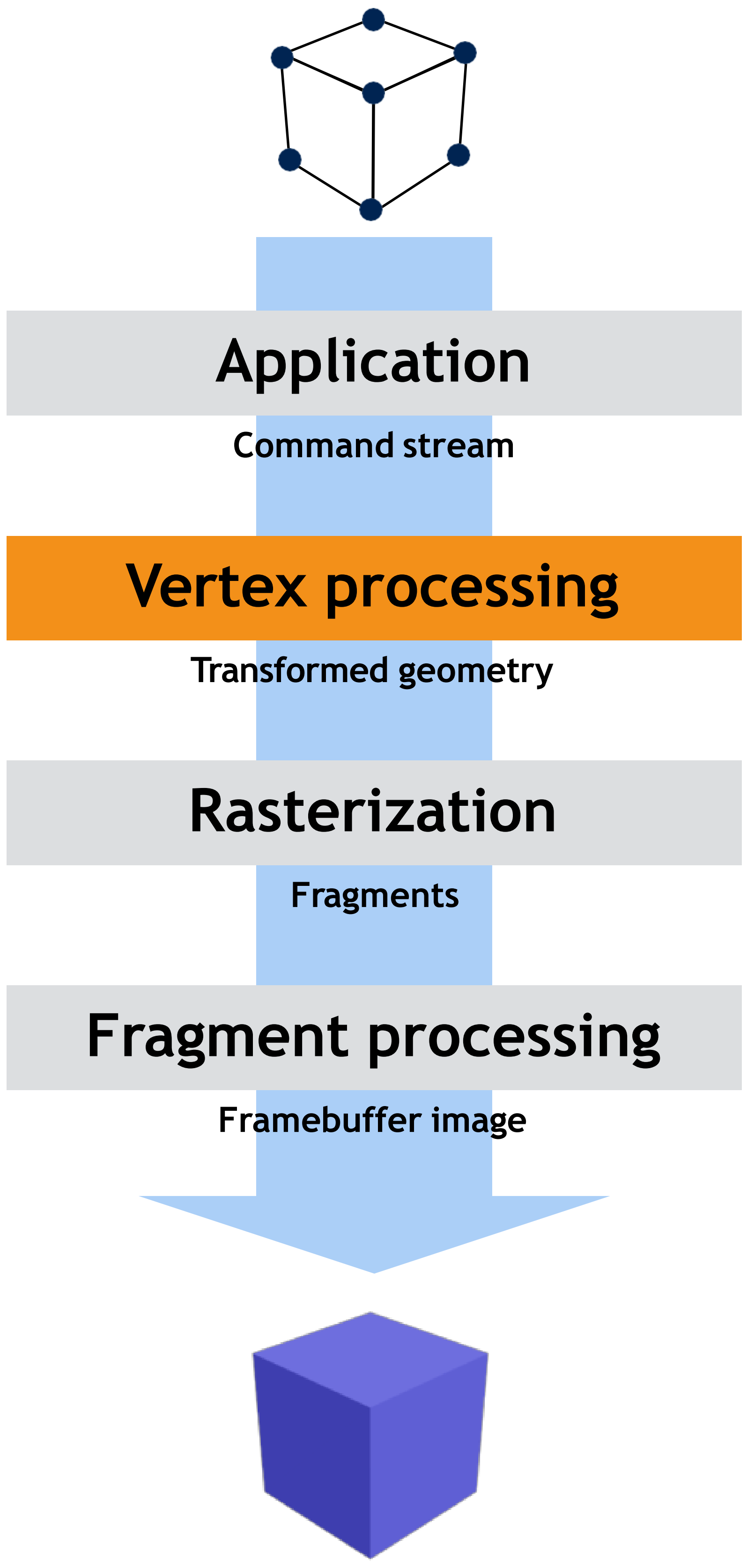
Application stage

- Send rendering primitives (points, lines, triangles) to the vertex processing stage
- Deals with collision detection, AI, etc.
- Takes care of input
  - keyboard
  - mouse
  - head-mounted helmet, etc..



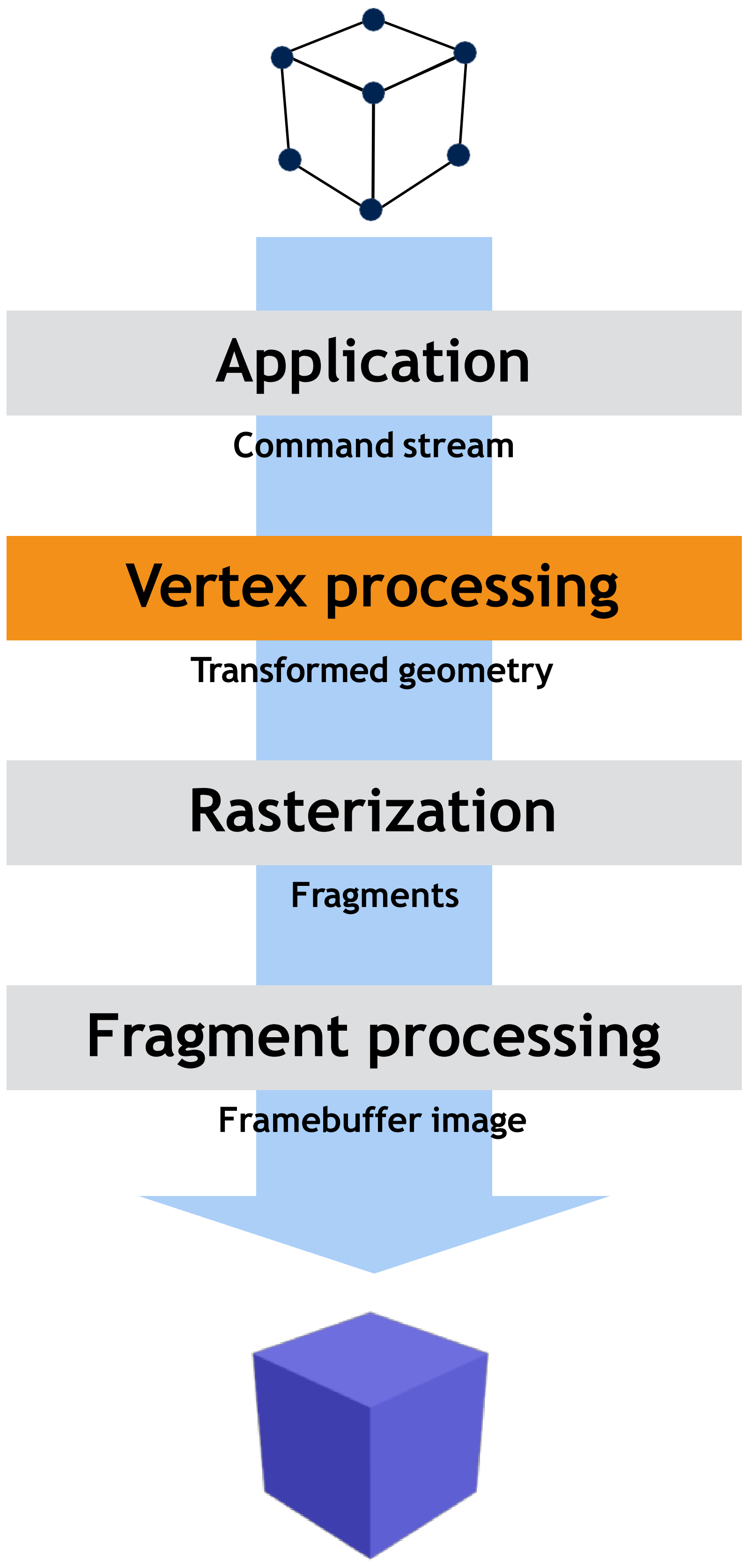
Vertex stage

- Per-polygon and Per-vertex operations
- Functional stages
  - model and view transform
  - vertex shading
  - projection
  - clipping
  - screen mapping



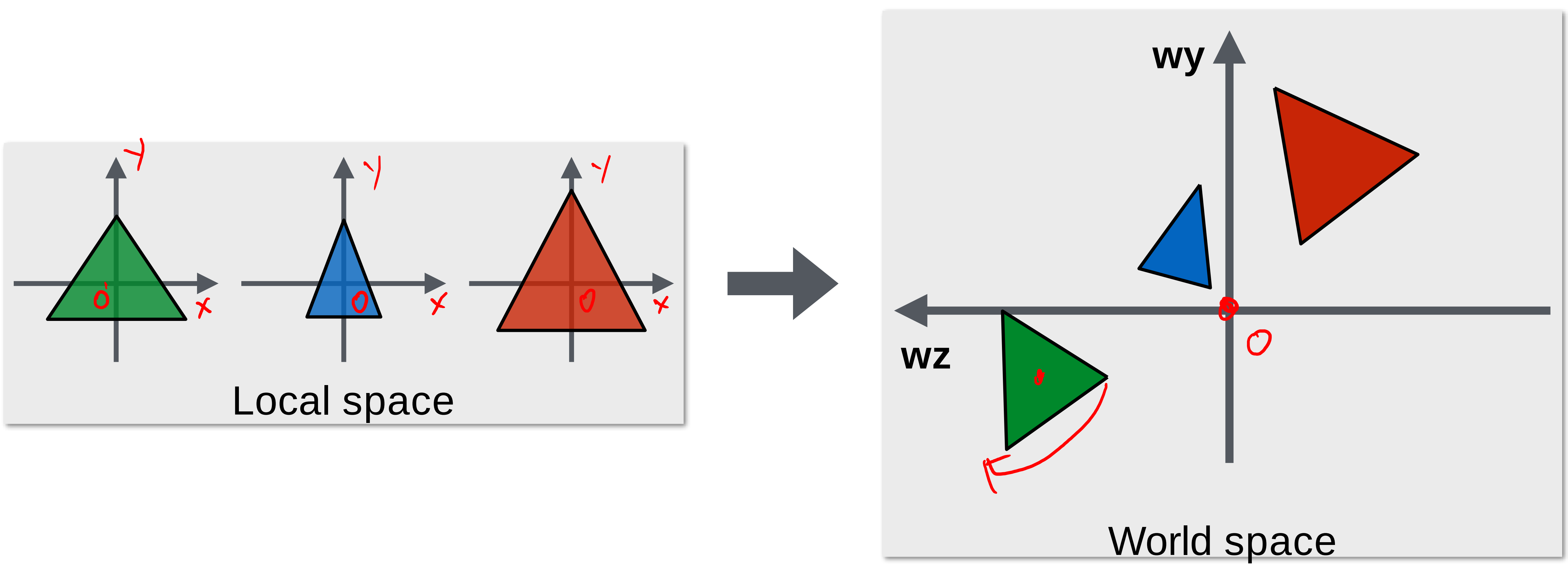
Model and view transform

- Each 3D model is transformed to different coordinate systems
  - Local (model) coordinates / model space
  - World coordinates / world space
- Model transform - vertices and normals
- World space - unique, all models exist in this same space



Model transform

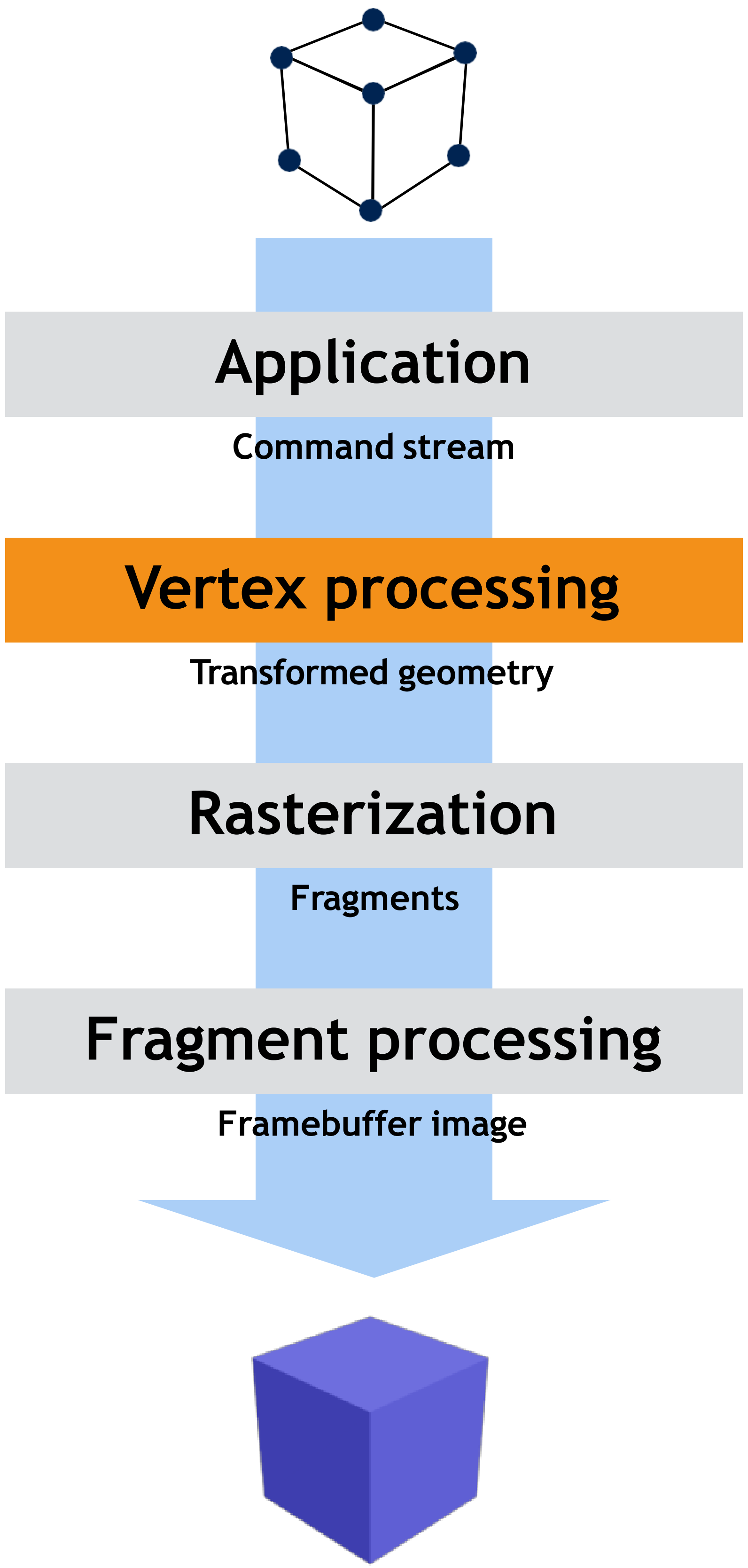
- Change the position and orientation of objects
- Possible deformation of objects



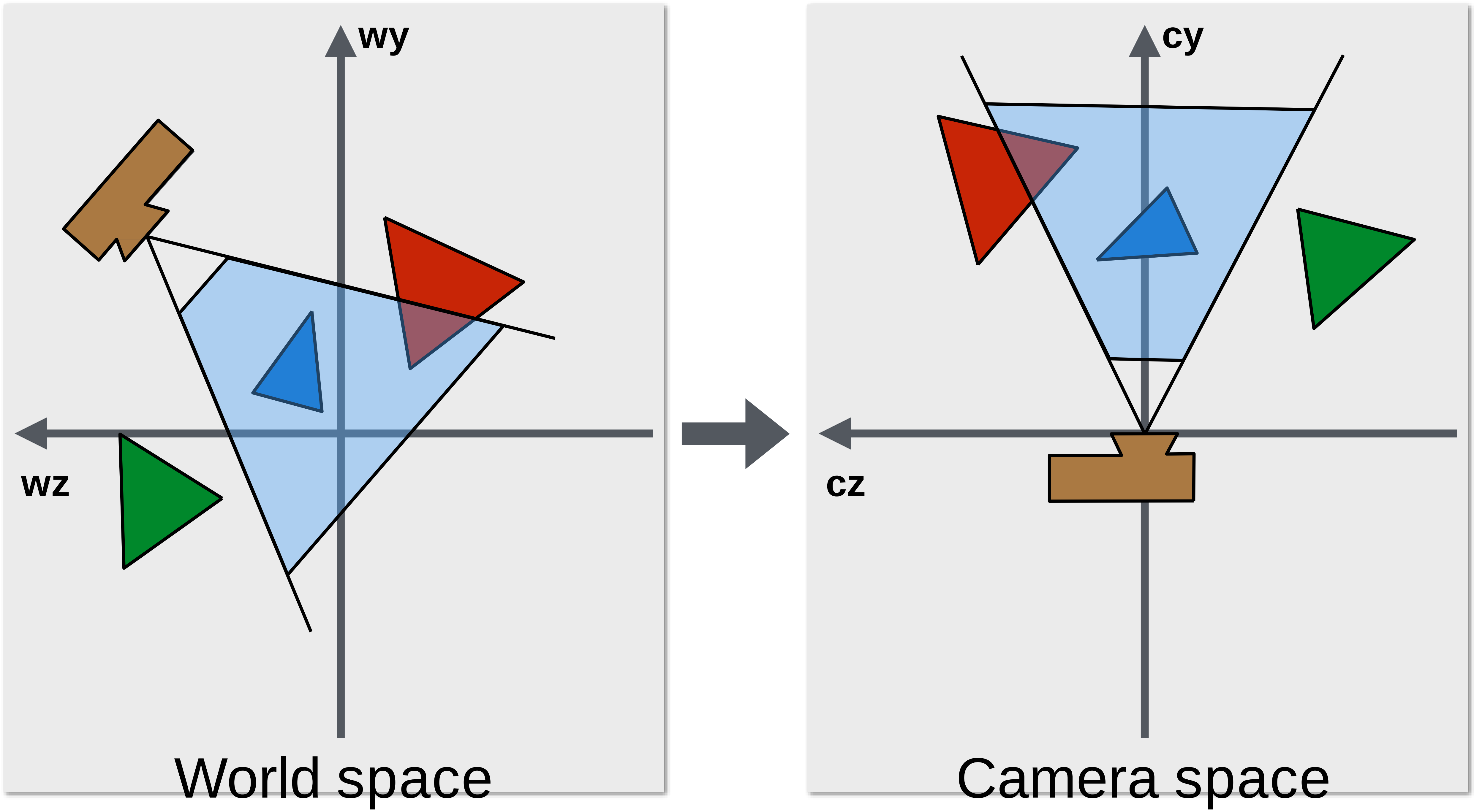
View transform

Camera transform

- The position of the visualisation camera is specified in world coordinates
- Has a direction, which aim the camera
- To make the projection and clipping easier, the camera and all the 3D models are transformed with the view transform.
- View transform - place the camera at the origin and make it look in the direction of the negative z-axis

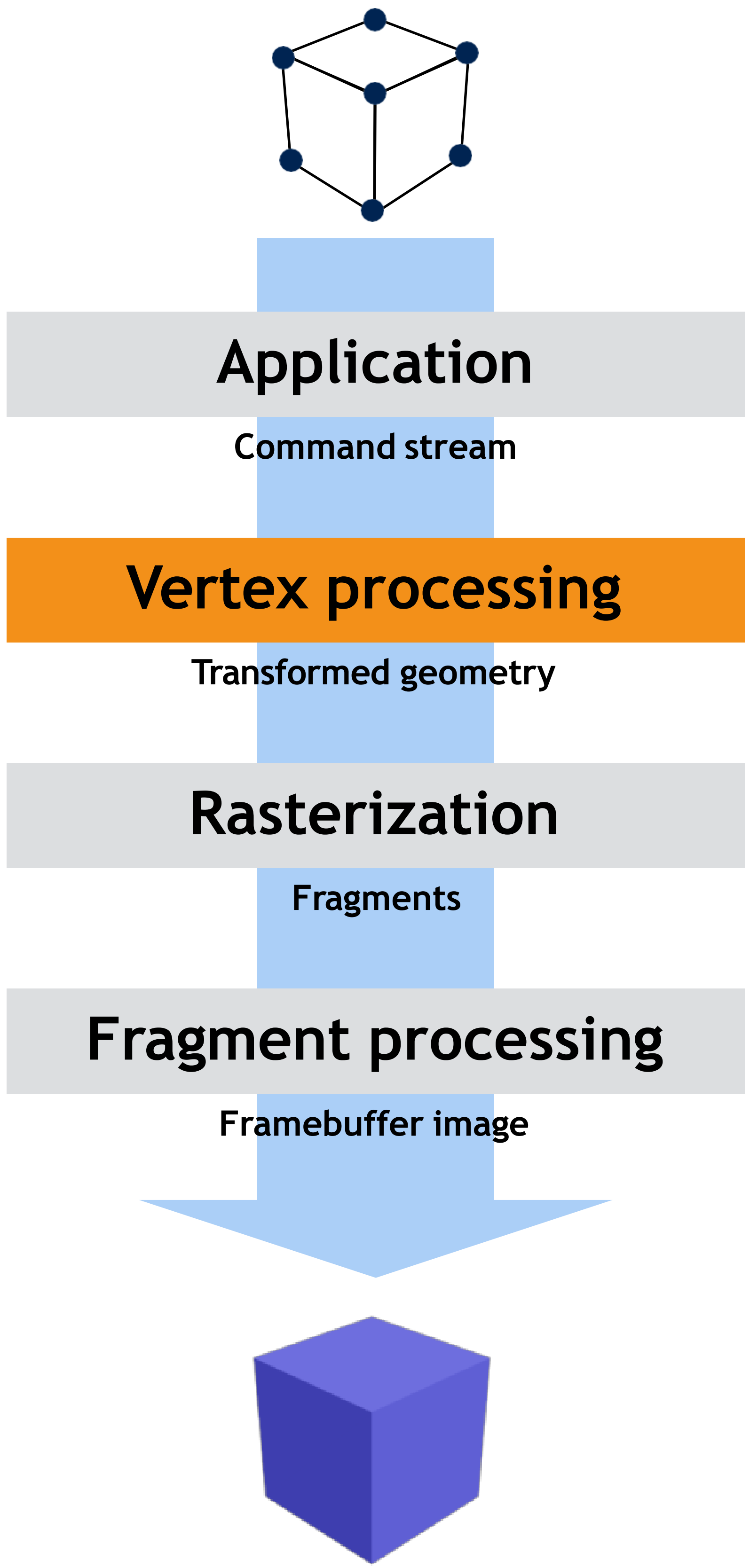


View transform



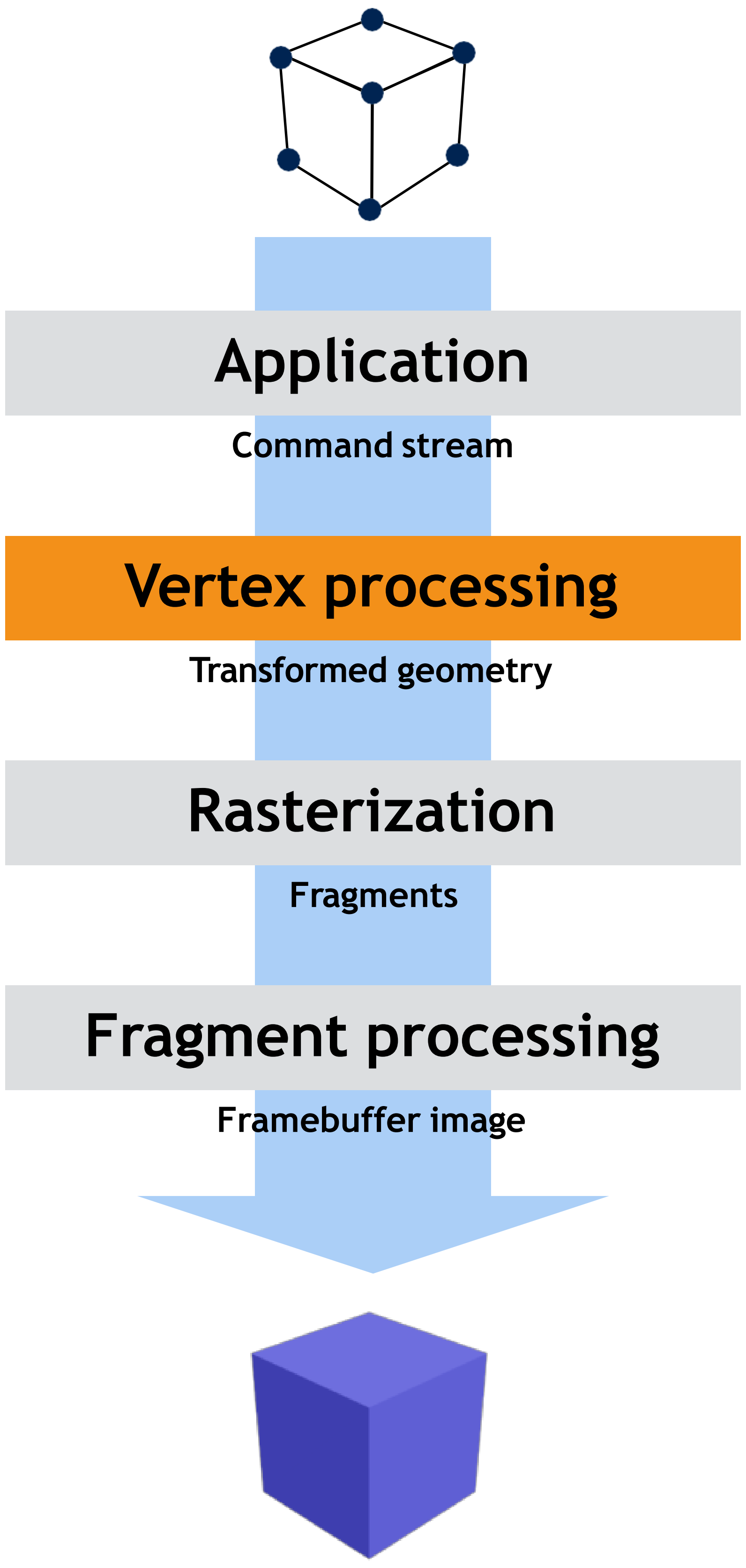
Vertex shading

- To produce a realistic image define **materials** and **lights**
- **Shading** - the operation of determining the effect of a light on a material
- Vertex shading results (colors, vectors, texture coordinates, etc.) are sent to the rasterization stage (to be interpolated).
- Shading computations can happen in world space or camera space

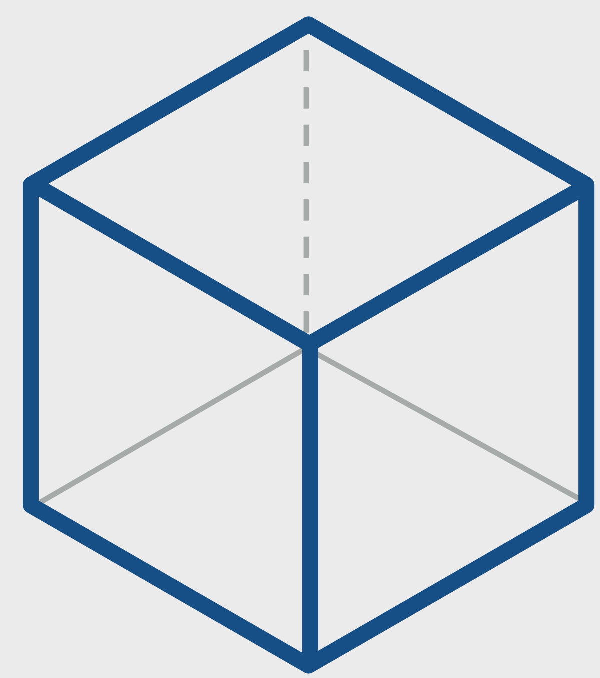


Projection

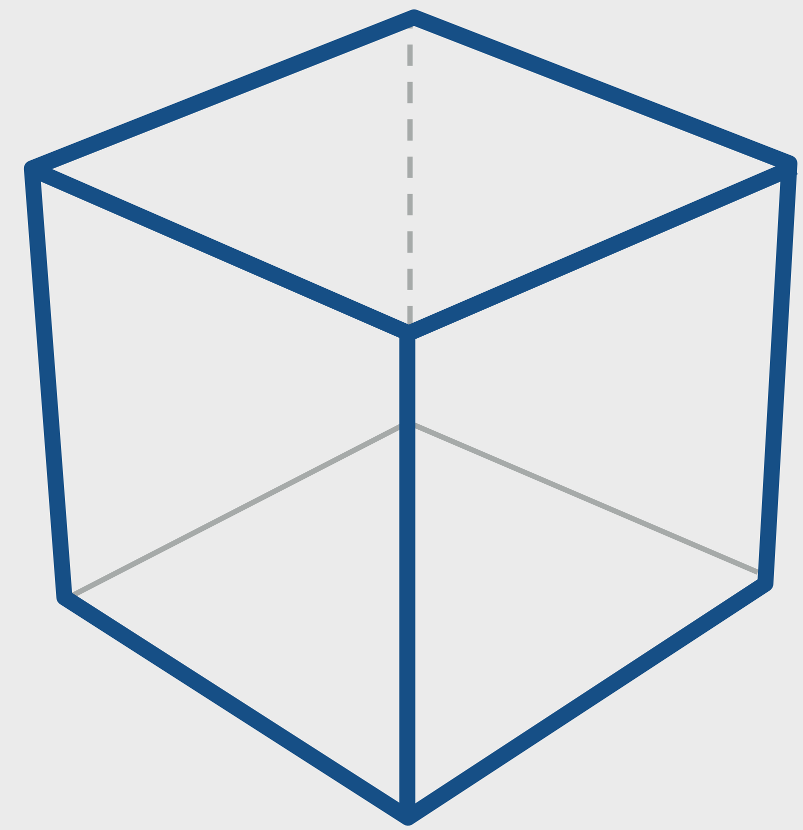
- Transforms the view volume into a unit cube - **canonical view volume**
- Can be defined between (−1, −1, −1) and (1,1,1) or (0, 0, 0) and (1,1,1)
- Most commonly used projections
  - **orthographic** (parallel) projection
  - **perspective** projection
- After projection the 3D models are in **normalized device coordinates**.



Projections



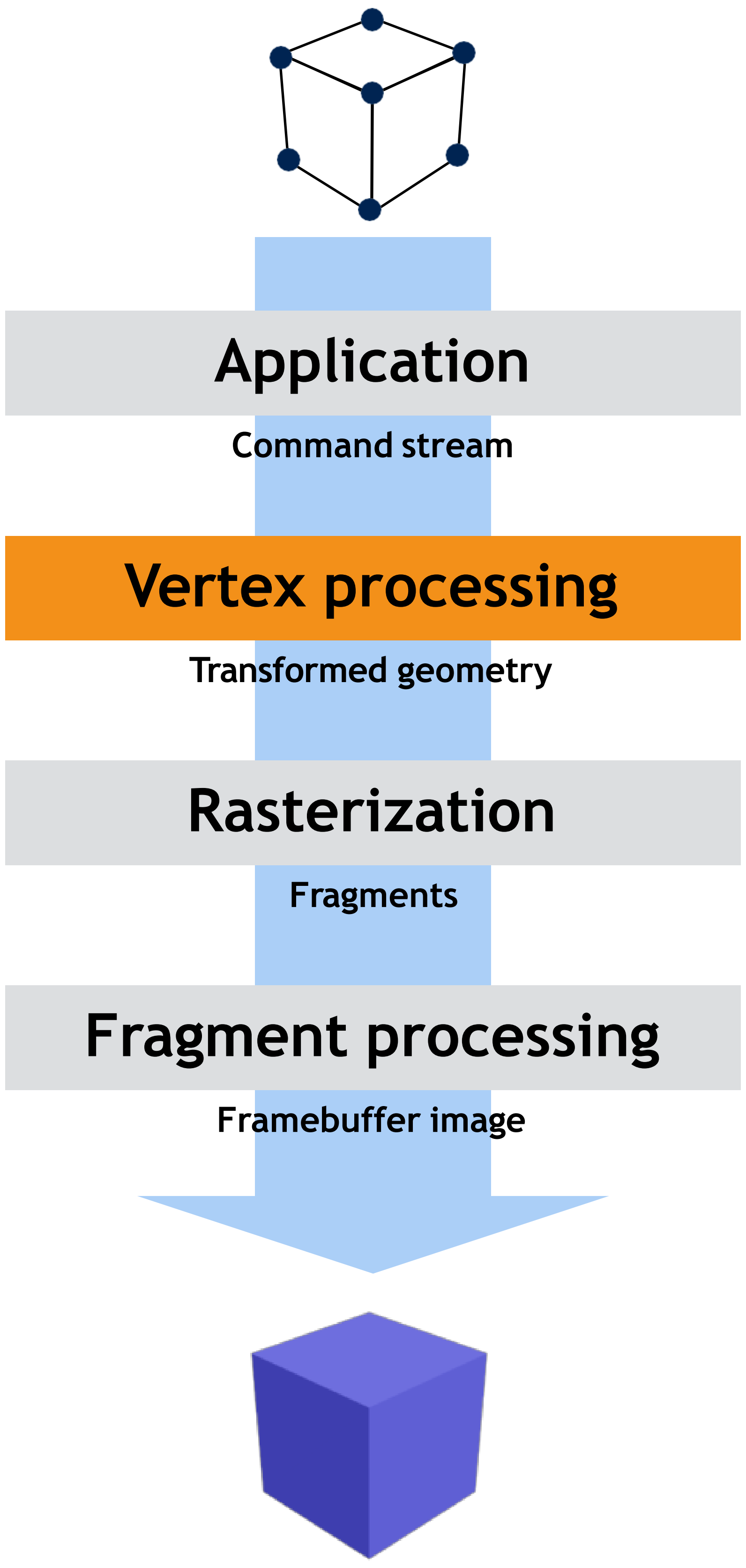
Orthographic projection



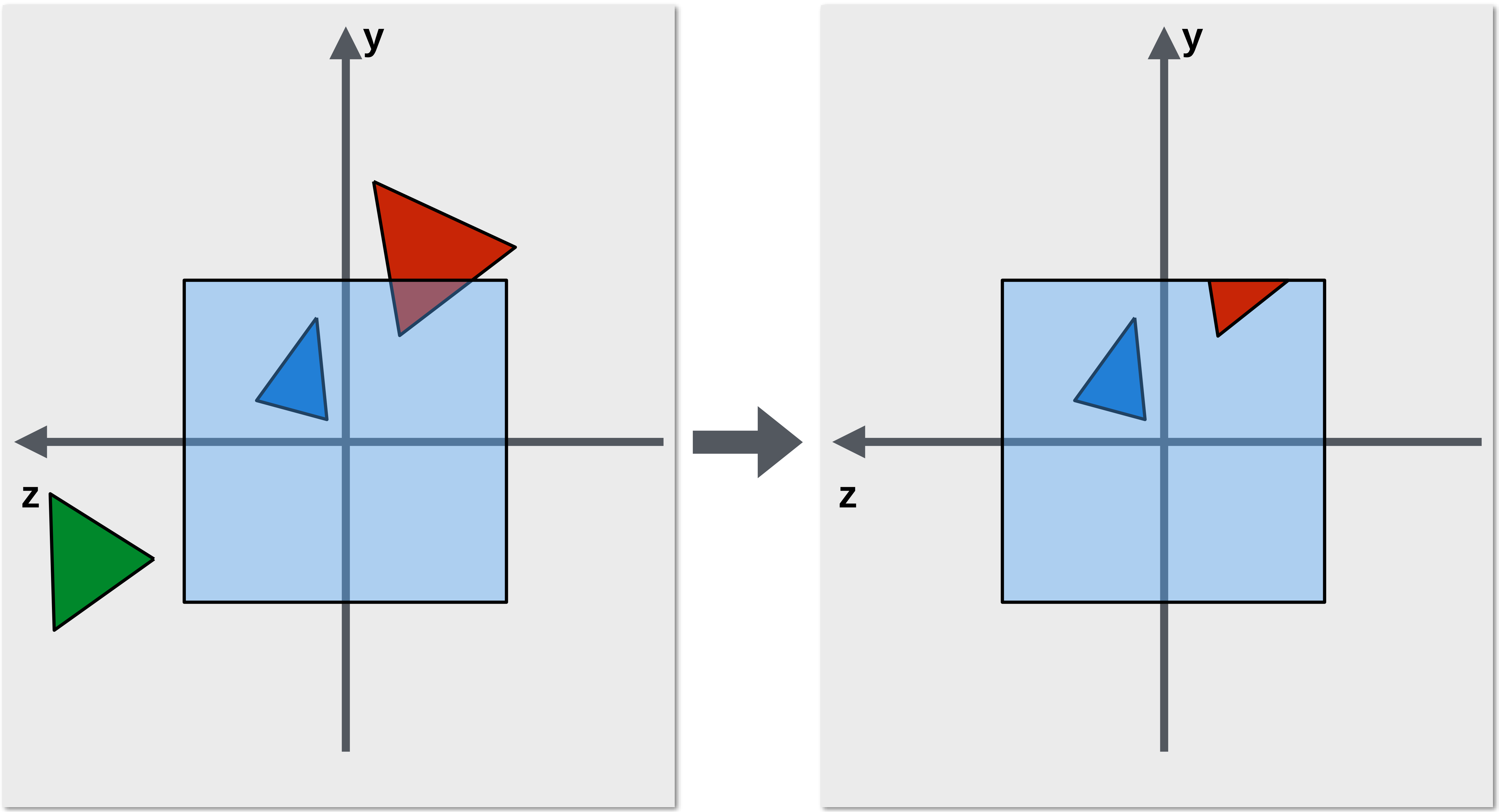
Perspective projection

Clipping

- Pass to the rasterization step only the primitives which are wholly or partially inside the view volume
- Primitives that are completely inside - pass to the next stage as is
- Primitives that are entirely outside - do not pass them further
- Primitives that are partially inside - clip them and pass to the next stage

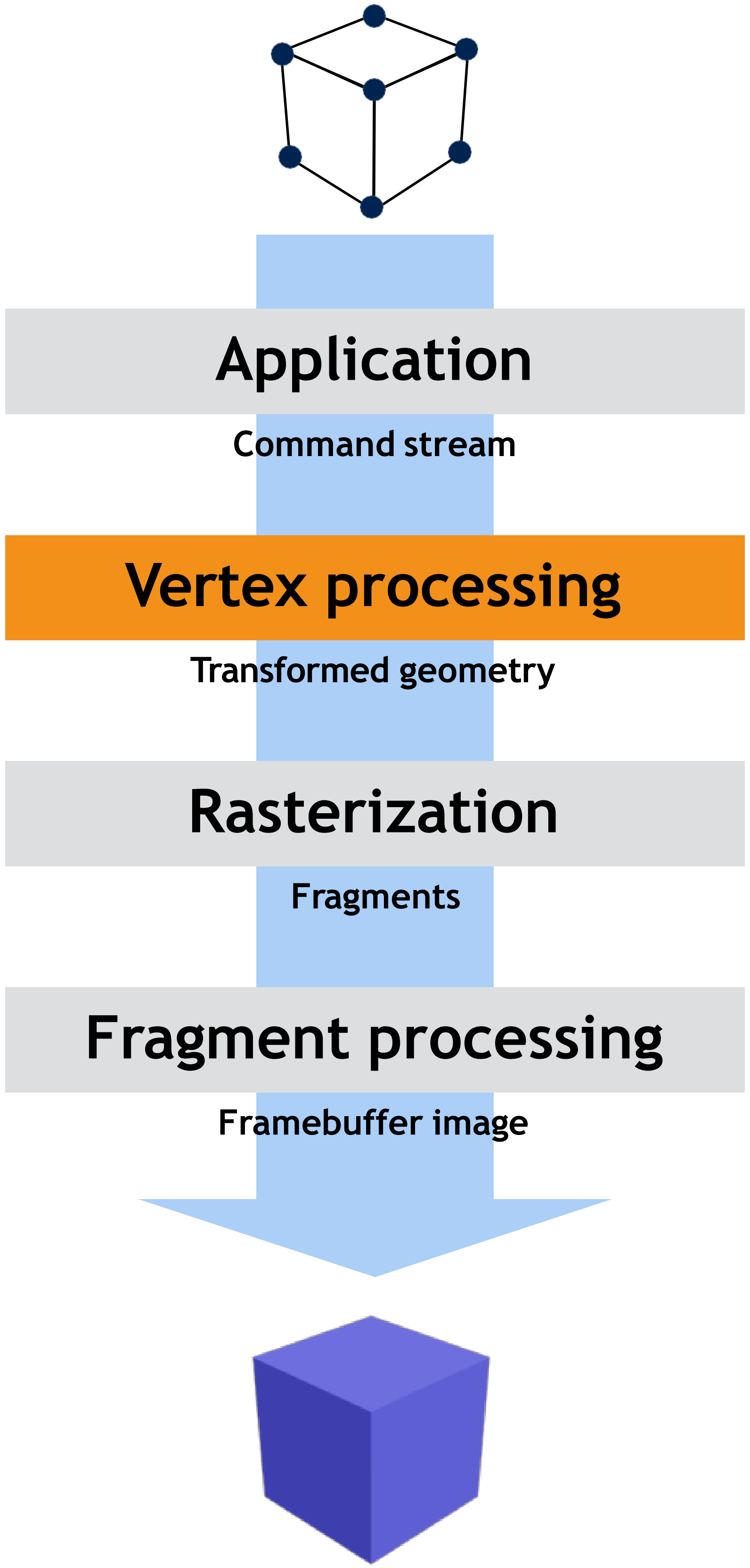


Clipping

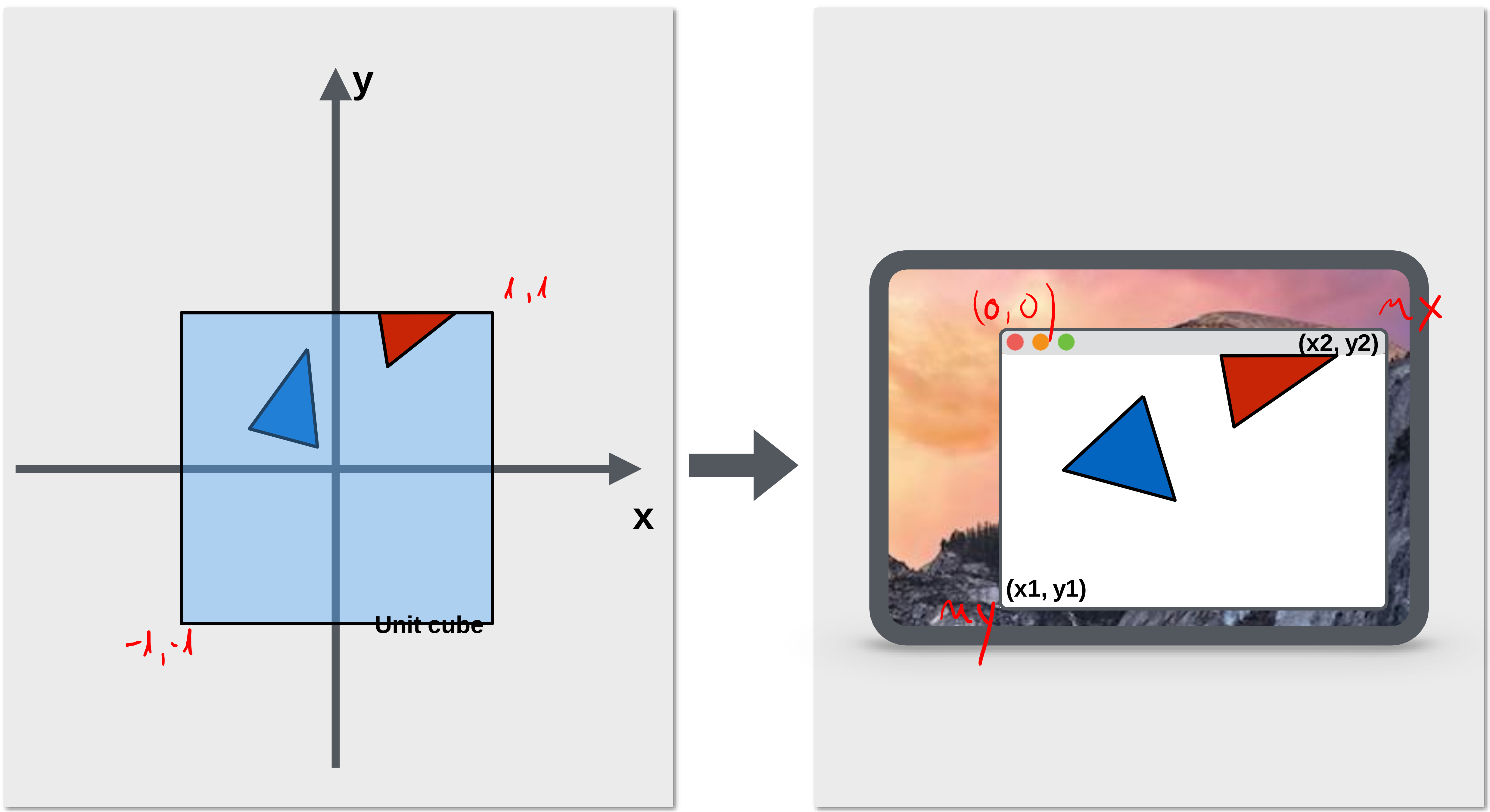


Screen mapping

- The x- and y-coordinates of each primitive are transformed into **screen coordinates**
- Screen coordinates together with the z-coordinates are also called **window coordinates**
- The z-coordinate is not affected by this mapping

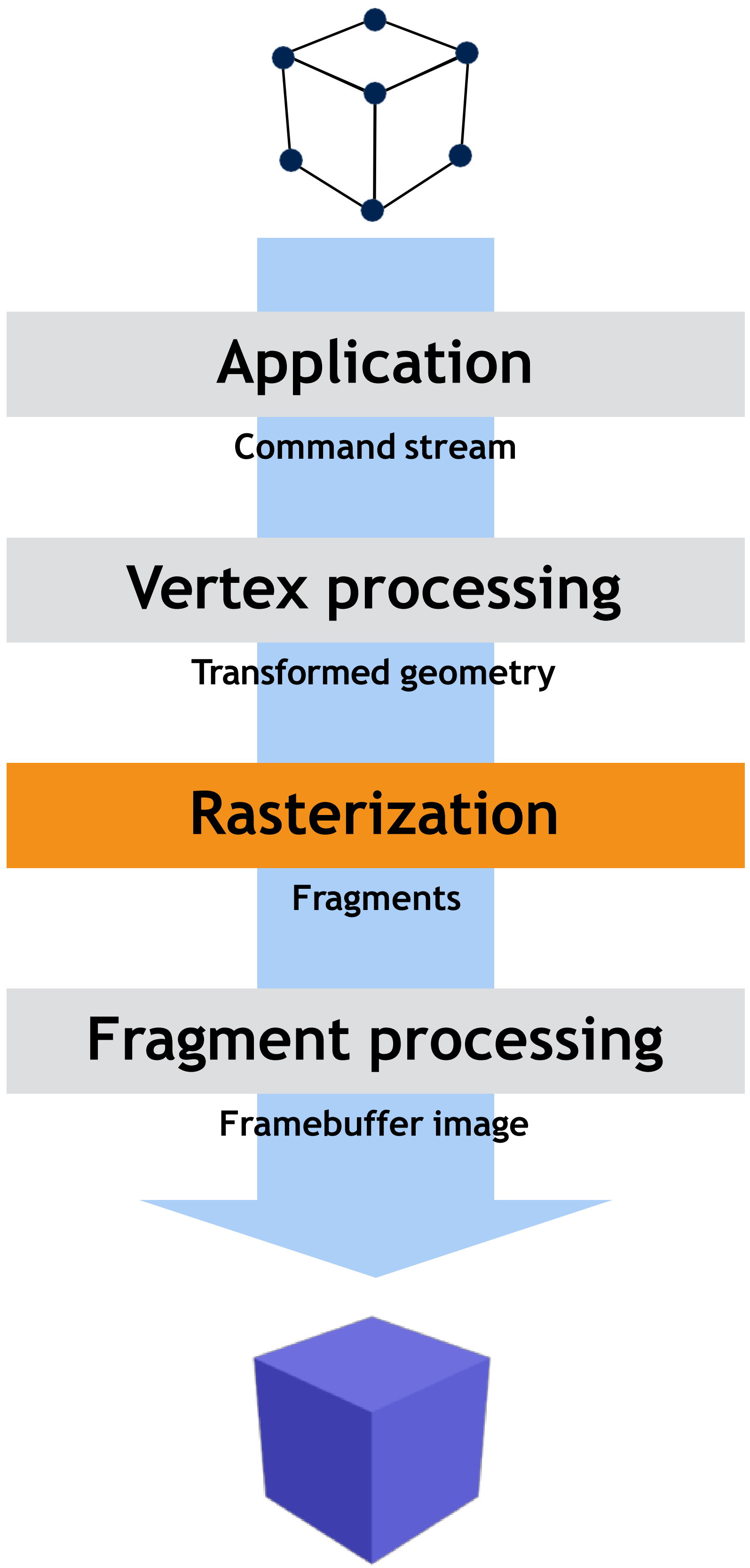


Screen mapping

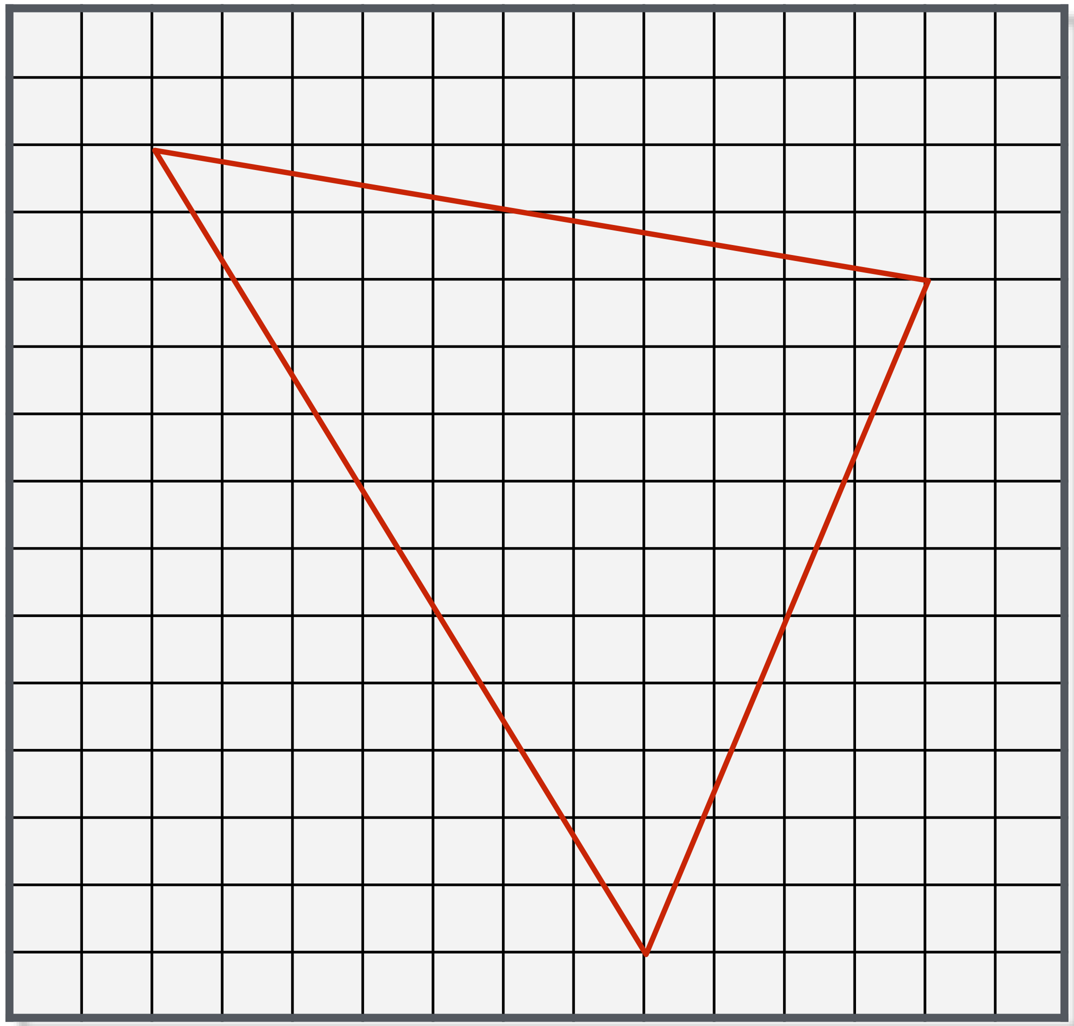


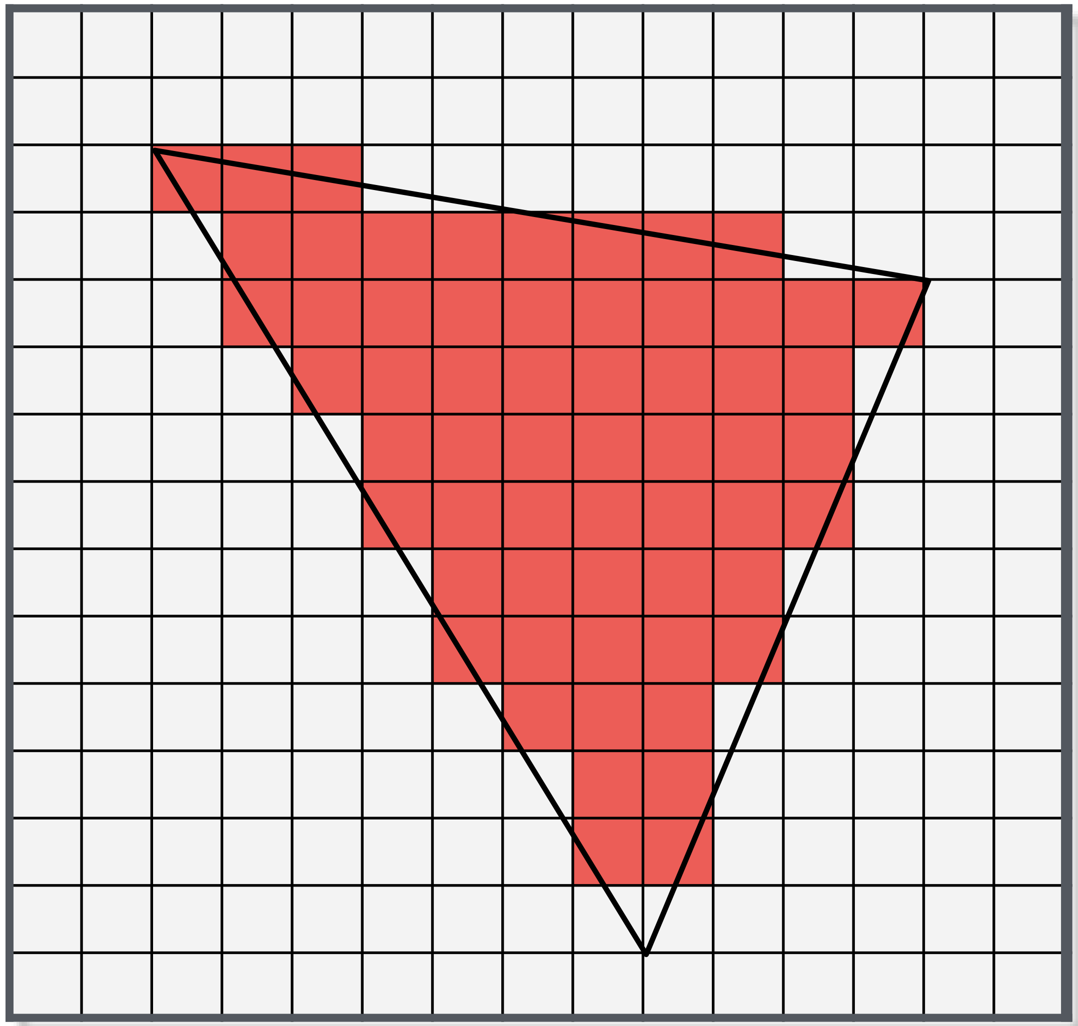
Rasterizer Stage

- Given a primitive (described by the vertex coordinates, color and texture information) convert it into a set of fragments
- Fragment data
  - raster position
  - depth (z-value)
  - interpolated attributes (color, texture coordinates, etc.)
  - stencil
  - alpha



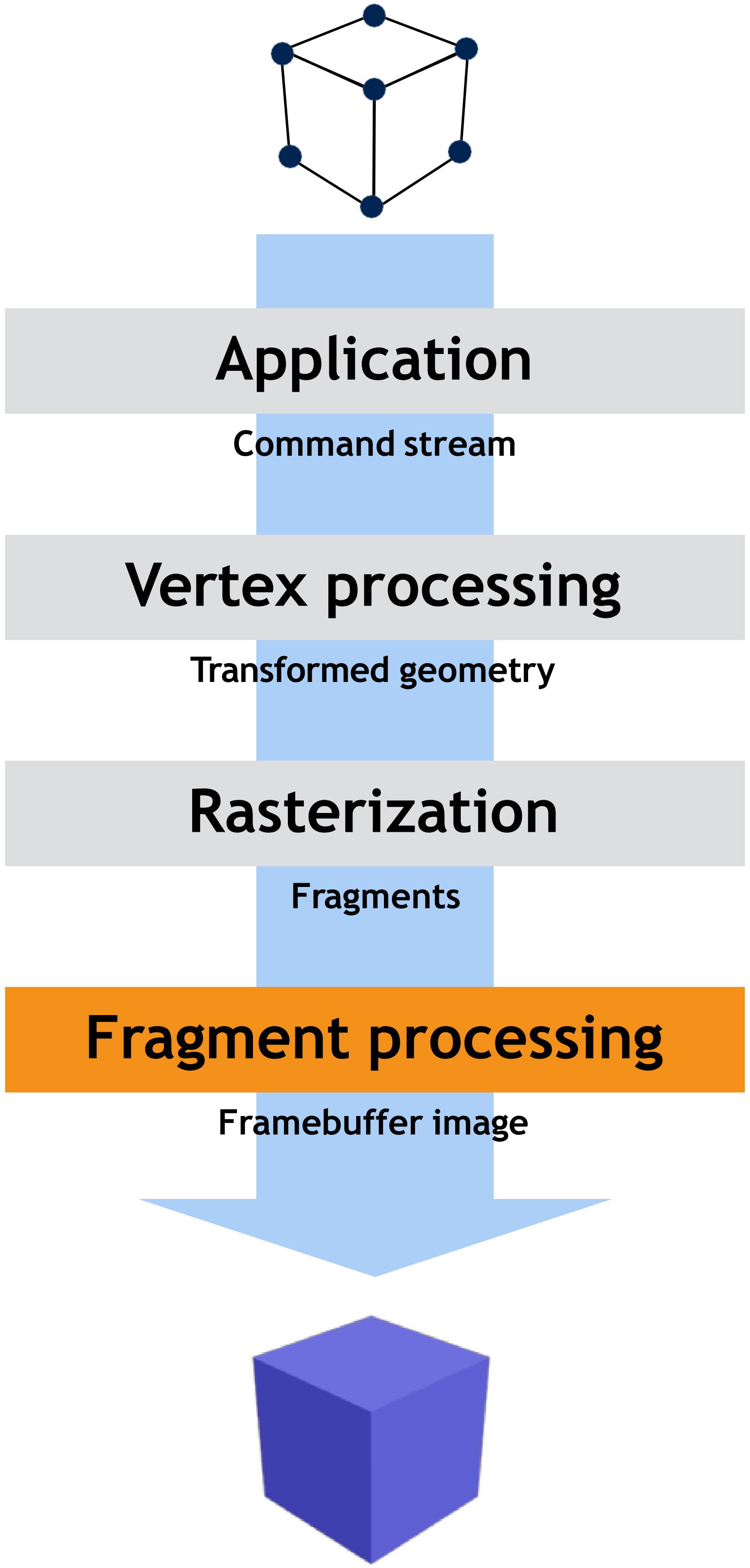
Example of rasterization



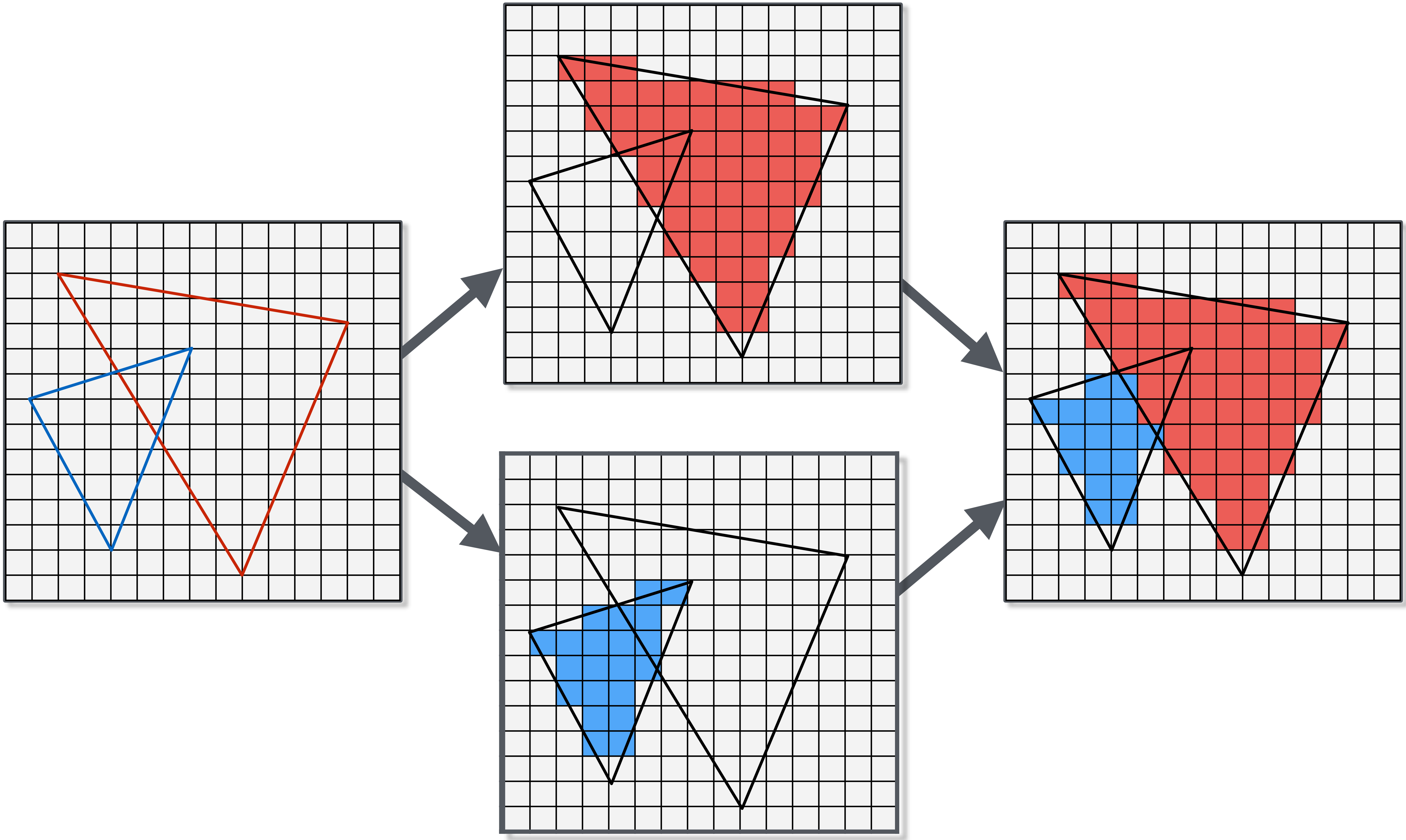


Fragment processing

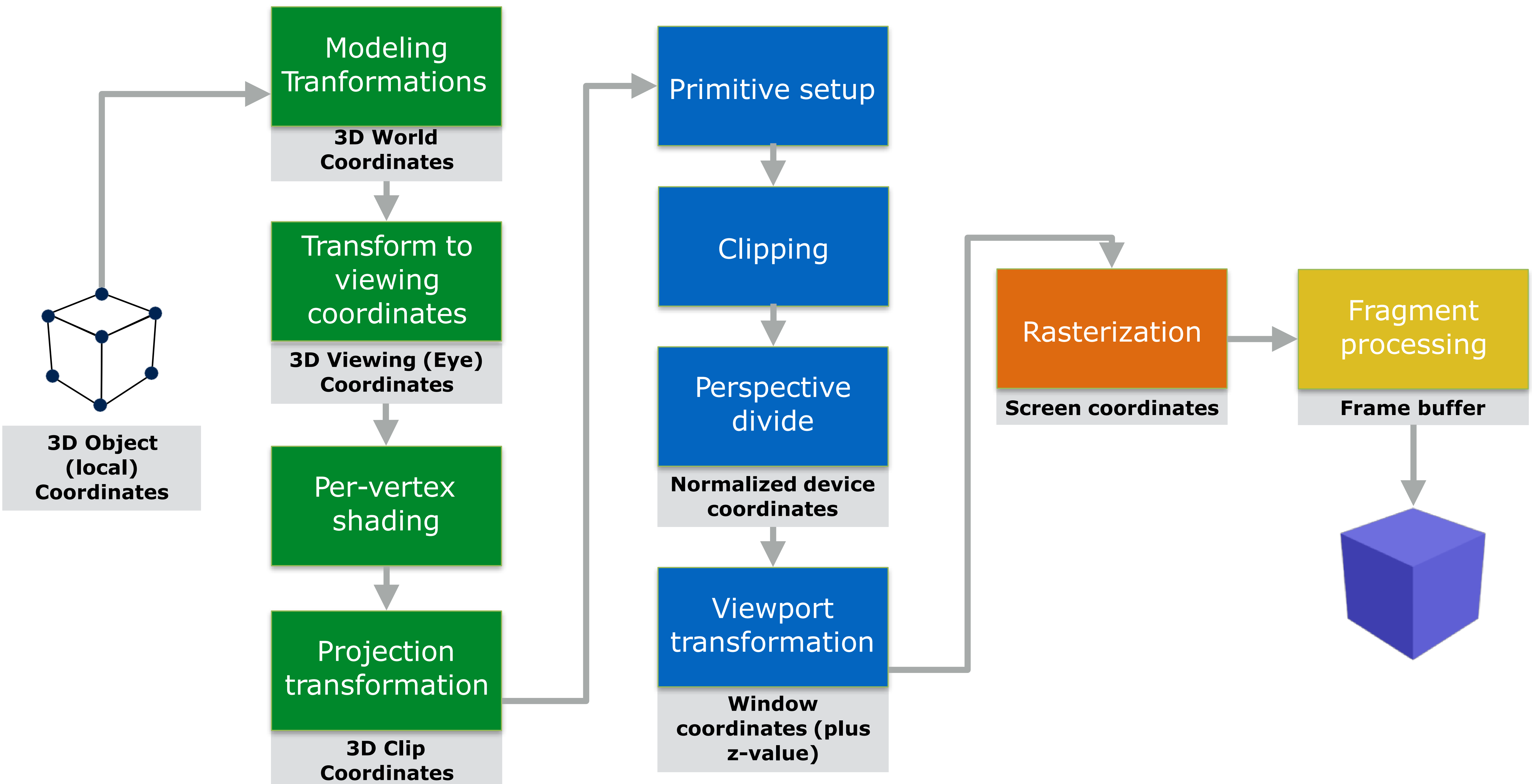
- Process each fragment from the rasterization process into a set of colors and a single depth value.
- **Scissor test** - discard fragments outside of a certain rectangular portion of the screen
- **Stencil test** - test the fragment's stencil value against the value in the current stencil buffer; if the test fails, the fragment is culled
- **Depth test** - test the depth of the current fragment with the existing depth; if the test passes update the depth buffer
- **Blending** - combine the fragment's color with the existing color in the frame buffer



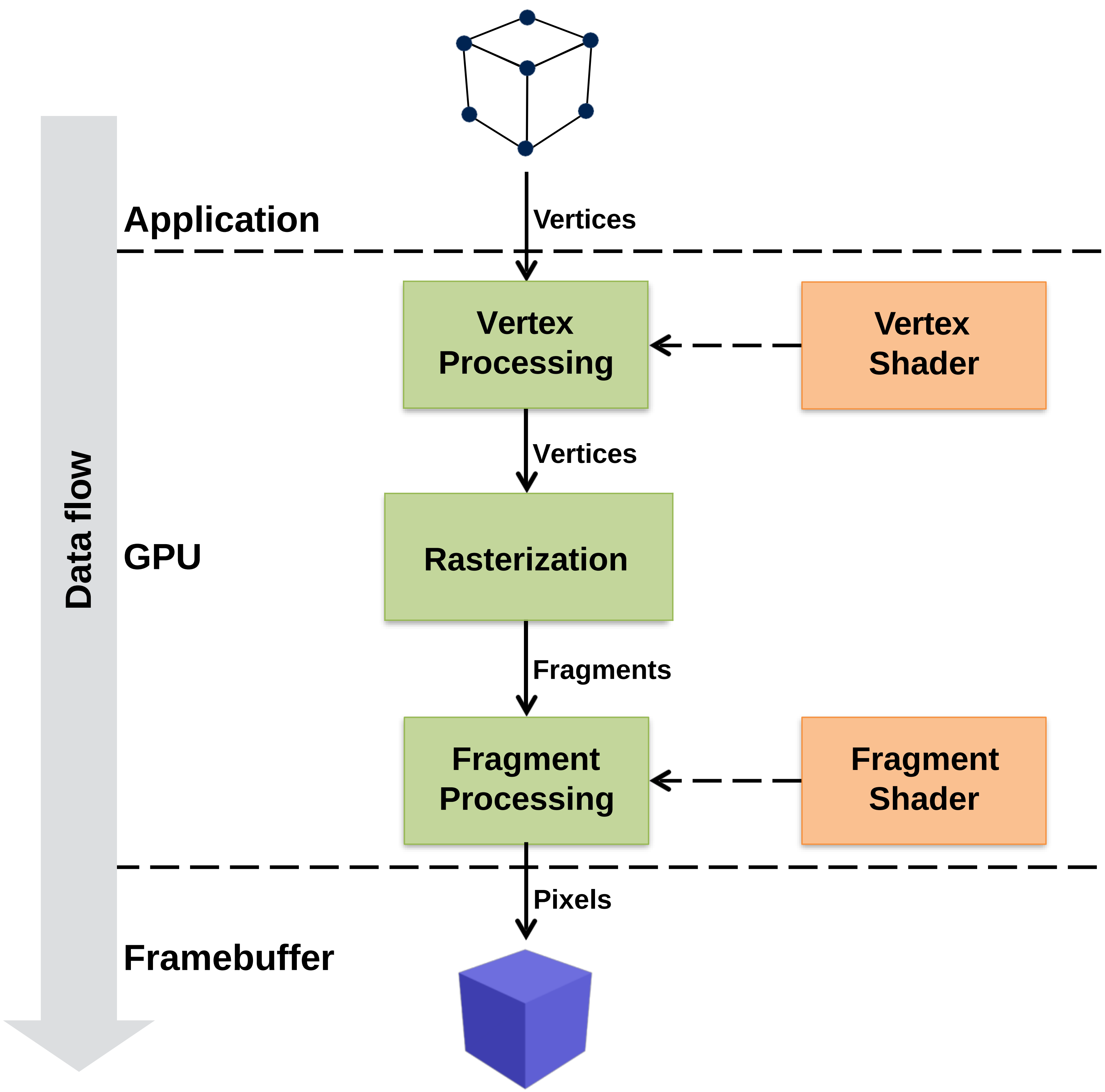
Fragment processing



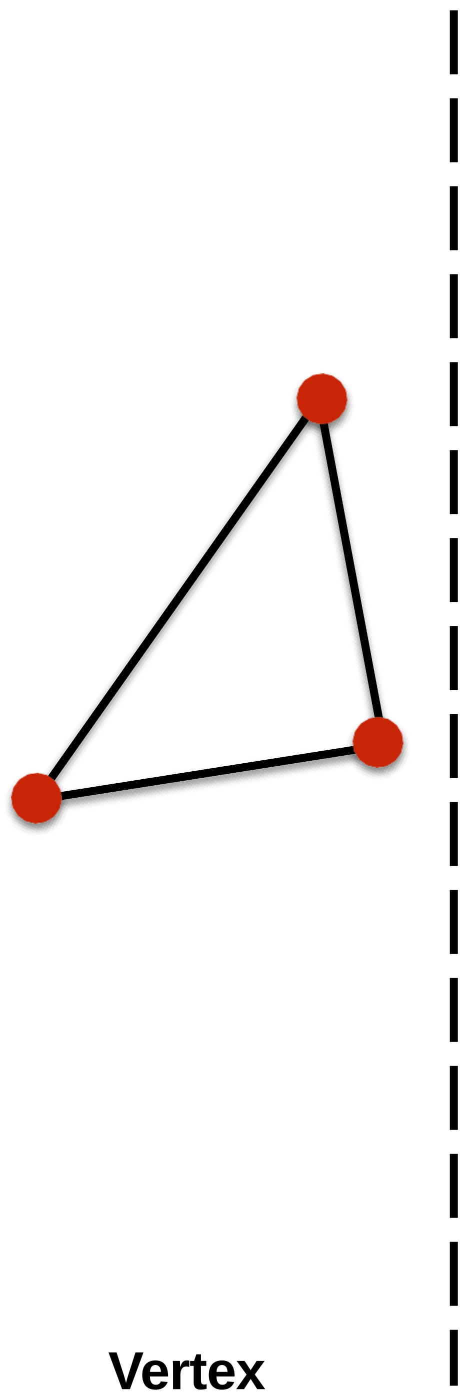
Coordinates systems



Programmable graphics pipeline

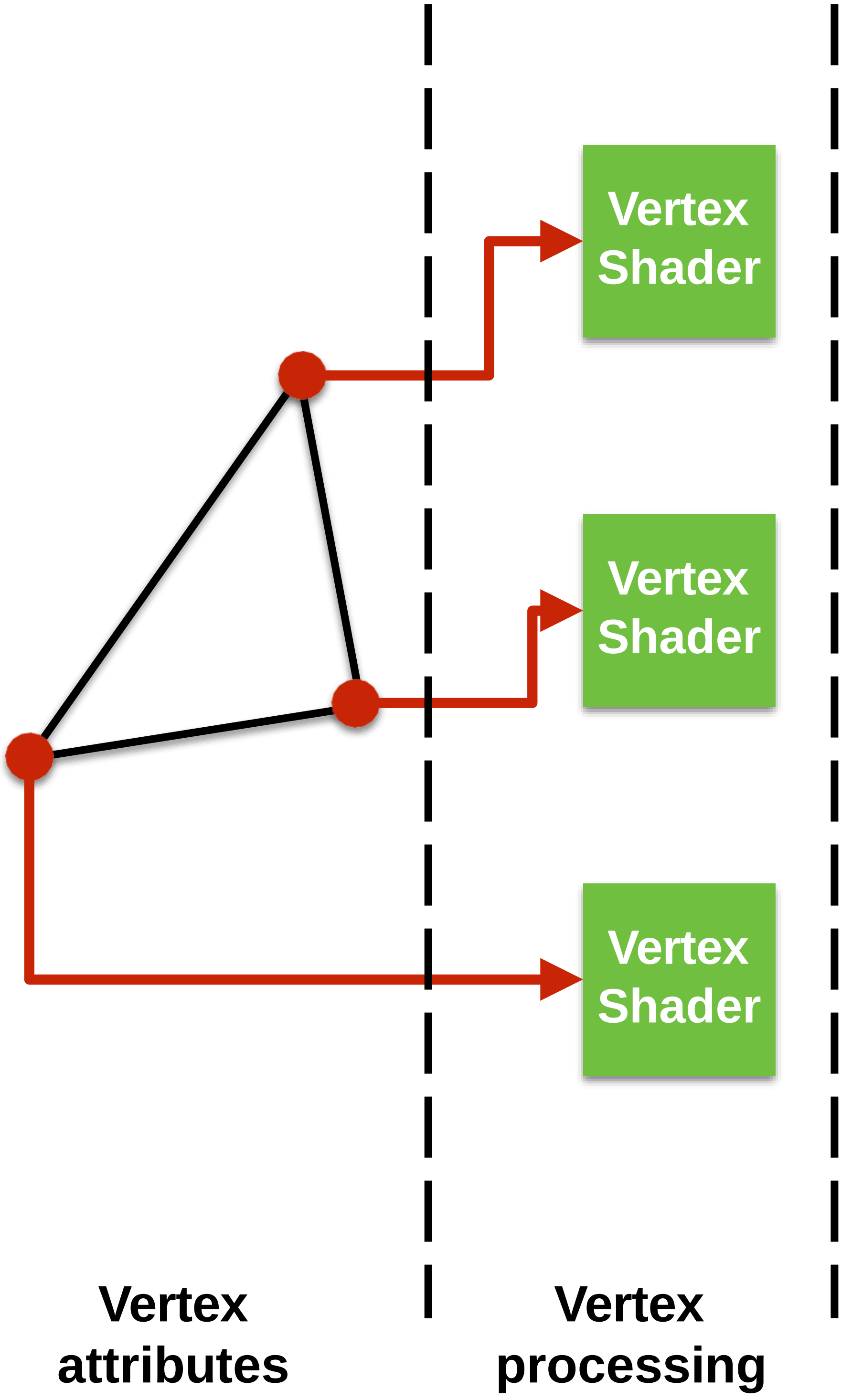


Programable graphics pipeline

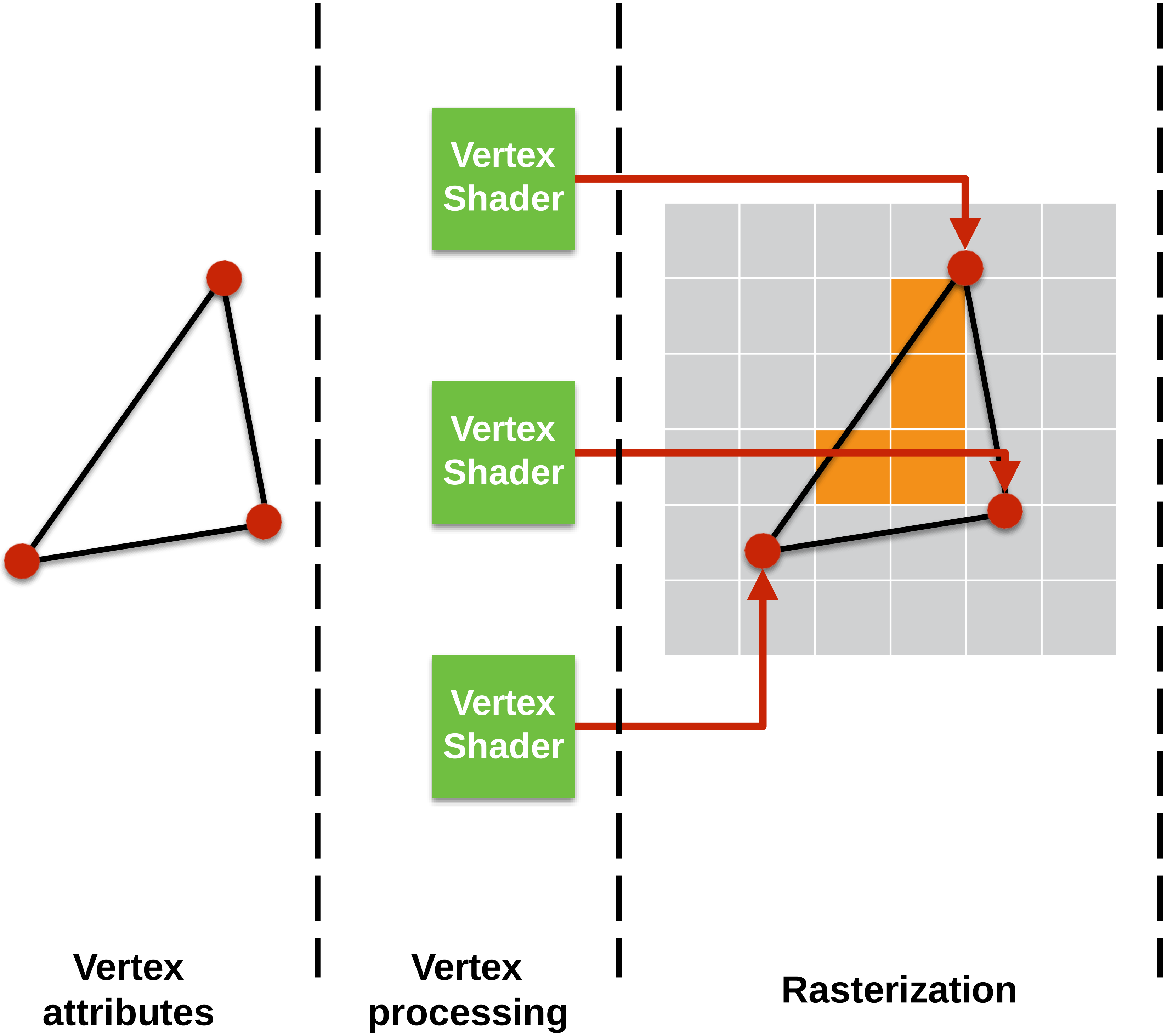


Vertex attributes

Programable graphics pipeline



Programable graphics pipeline



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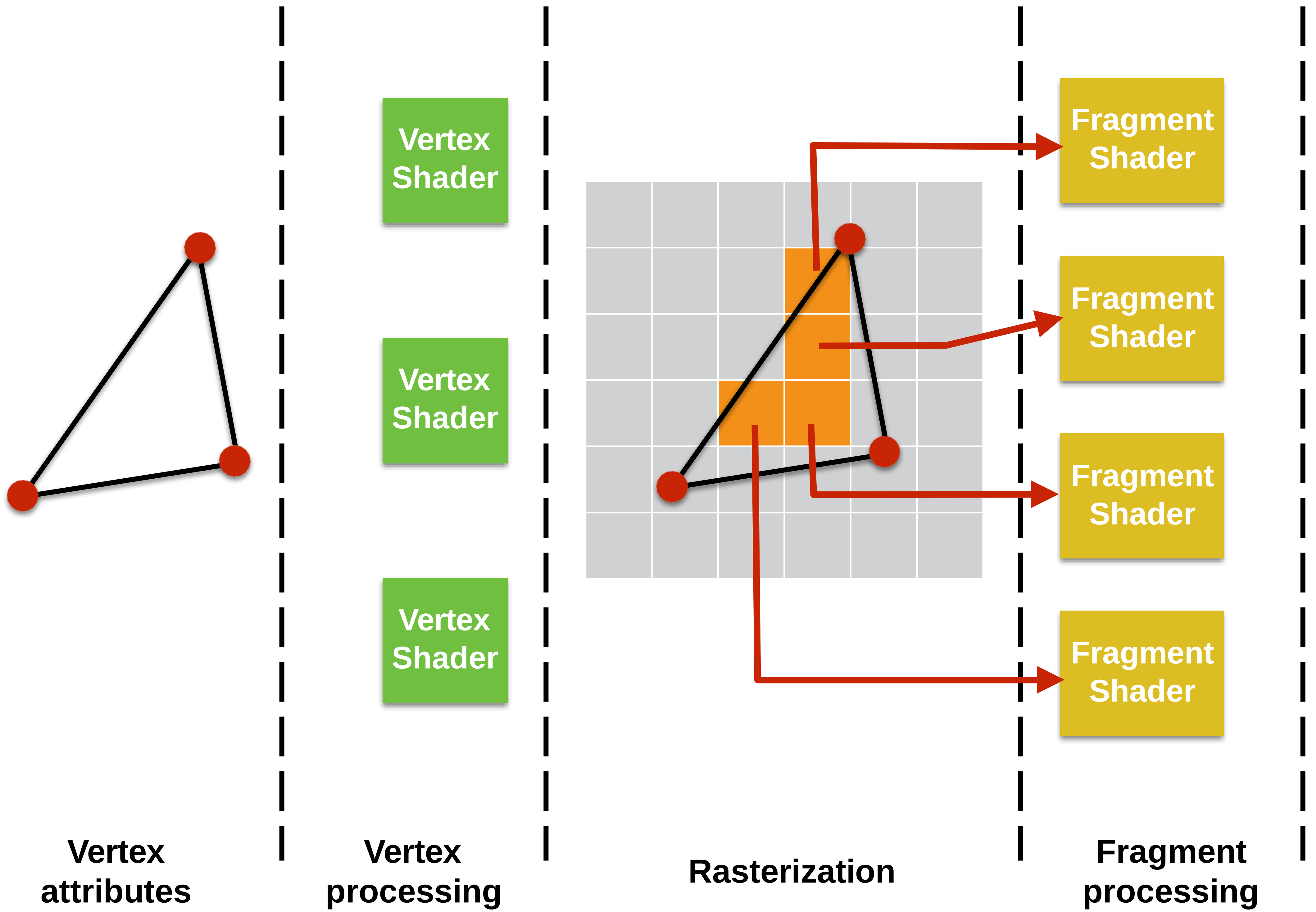

Programable graphics pipeline