Graphics Systems

Computer Graphics
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Today

- **Image formation**
- **Graphics systems**
  - Physical approach
  - Pipeline approach
- **Raster pipeline**

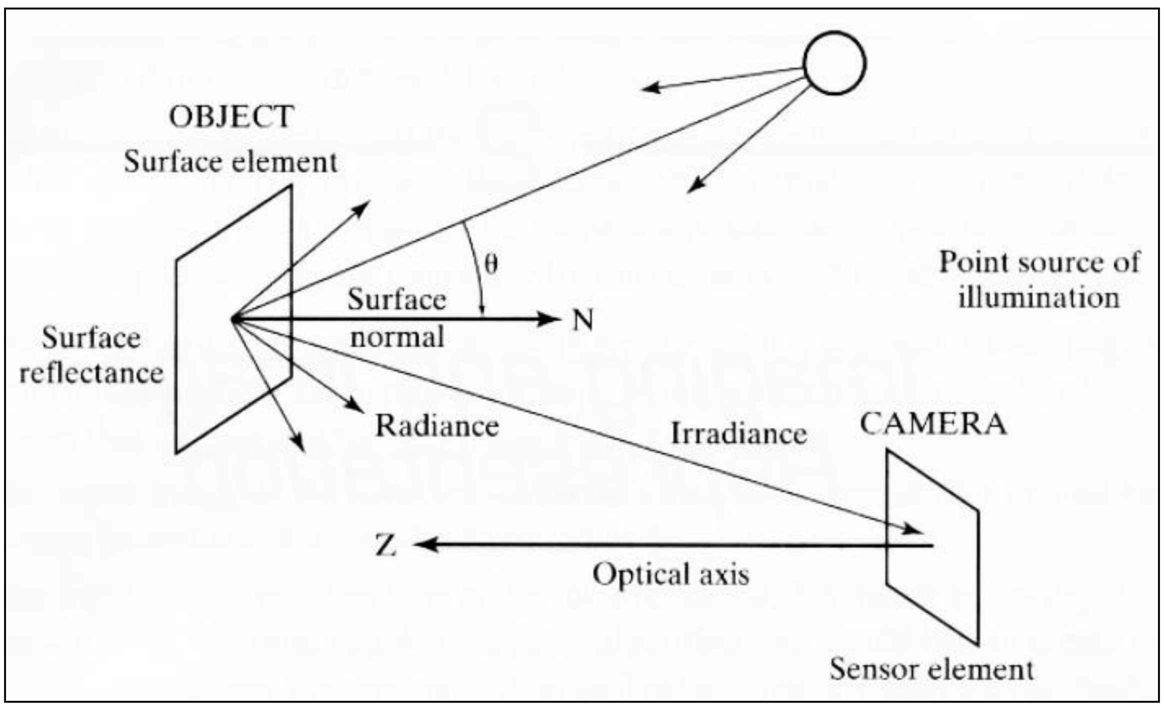
Image Formation

- **Geometry of image formation**
    - determines where the projection of a point will be located in the image plane (or the sensor plane)

- **Physics of light**
    - interaction of lights with geometric surfaces
    - determines the brightness of a point in the image plane (or the sensor) as a function of illumination and surface properties
    - ***Rendering***: simulation of light physics, yielding ***photorealism***

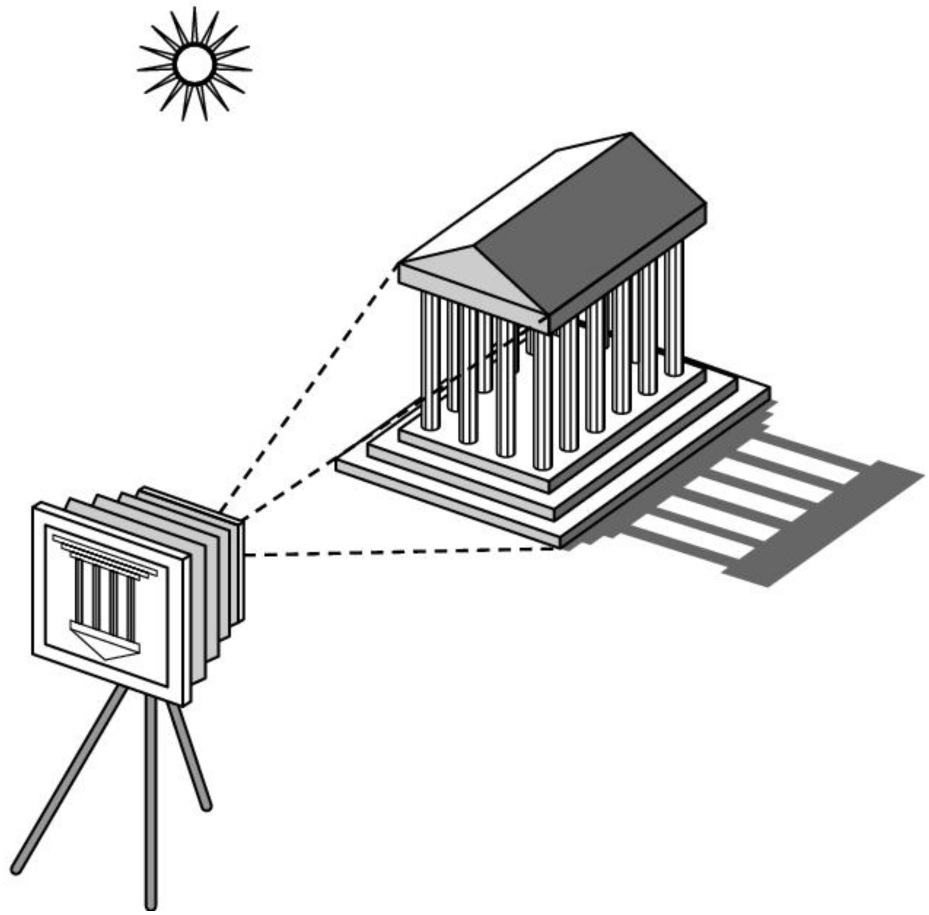
Image Formation

- **In computer graphics, we form images using a model analogous to the physical process**
  - The scene is illuminated by a single light source
  - The scene reflects radiation towards the camera
  - The camera senses it via chemicals on film.



Three Elements of Image Formation

- Light sources
- Objects
- Camera



(1) Light Sources

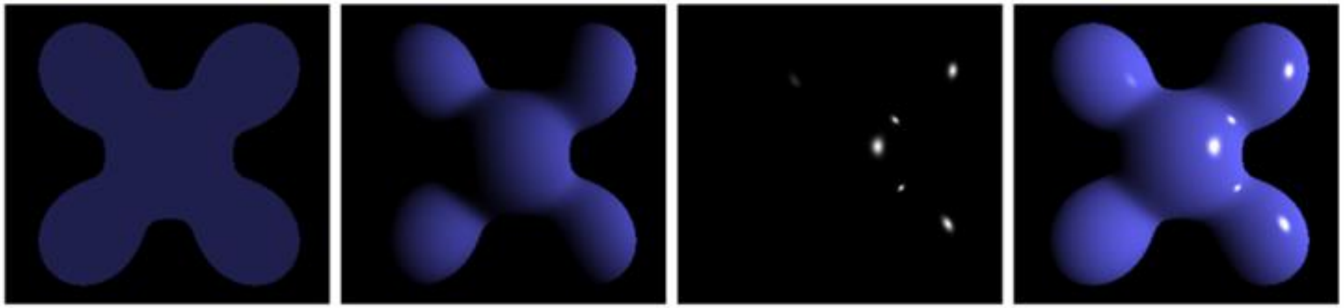
- **Light is the part of the electromagnetic spectrum that causes a reaction in our visual systems**
  - Generally visible spectra are in about wavelengths of 350-750 nm.
  - Long wavelengths appear as reds and short wavelengths as blues.

- **The typical attributes of a light source are:**
  - direction or position (often together)
  - colors (typically, white color is used)

(2) Objects

- **Objects are a set of geometries whose representation is defined mathematically.**
  - As already mentioned, vector graphics representation is used.
  - 3D positions and normal vectors are typically defined.

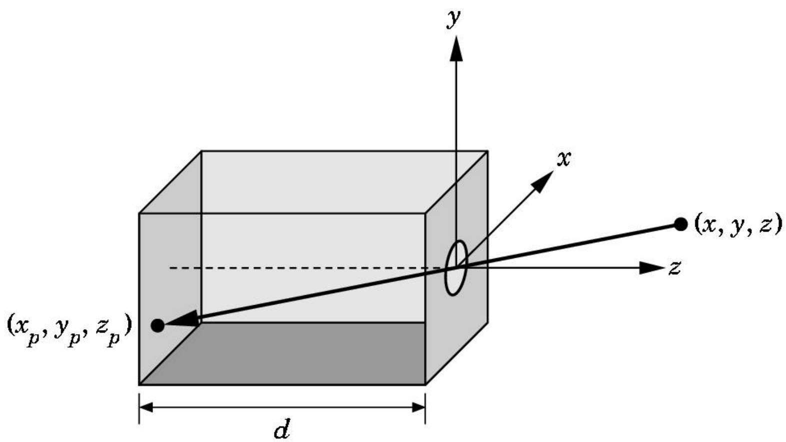
- **Also, surface properties of the objects are defined to simulate surface interaction with light propagation**
  - Blinn-Phong model uses ambient, diffuse, and specular colors.



Ambient + Diffuse + Specular = Surface color

(3) Cameras

- **Pinhole camera model, which causes sharp imagery, is common for most of the graphics model.**



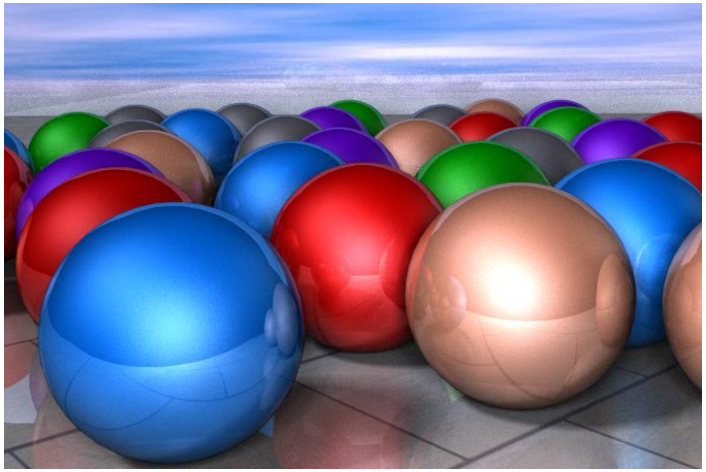
- **Typically, the following attributes define a pinhole camera.**
  - 3D transformation of a camera
  - Viewing angle, the aspect ratio of the sensor size, the range of object depths

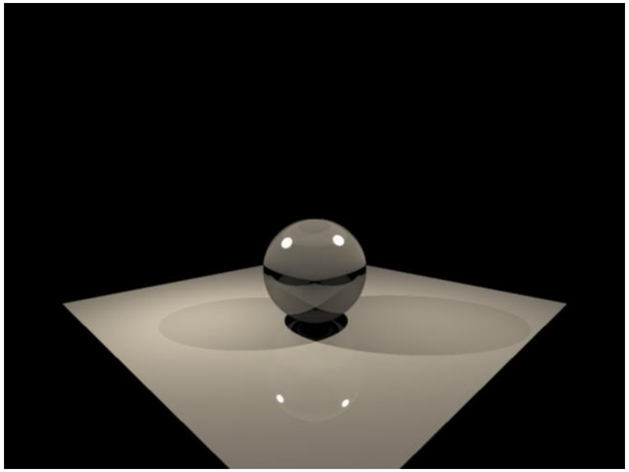
Graphics Systems

Physical Approach

- **Global illumination**
  - Captures all the light inter-reflections among surfaces and light sources
  - Usually implemented on software
  - Very slow and suitable for high-quality film production

- **Typical example: ray tracing**

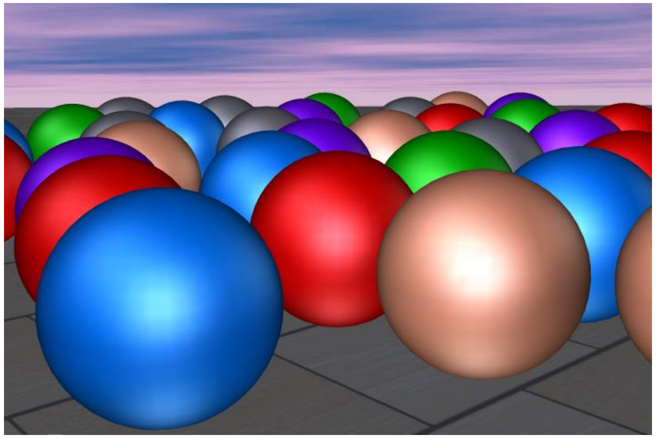




Pipeline Approach

- **Local/direct illumination**
  - Captures only direct light-object reflection
  - Based on rasterization
  - High performance suitable for real-time interactive rendering
  - However, quality is degraded with significant approximations.

- **Typical examples**
  - OpenGL, on which this course focuses, and DirectX
  - Facilitated by special-purpose graphics hardware (GPU)



Pipeline Approach

- **Missing visual effects in local illumination model**
  - Inter-object reflections
  - Refractions
  - Shadows

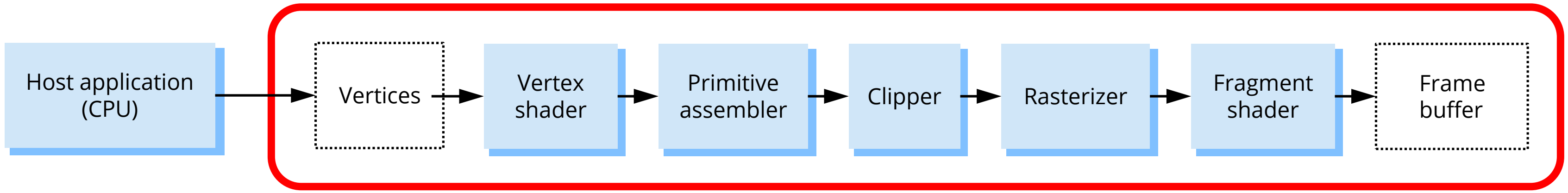
- **However, most of the real-time rendering techniques simulate such effects through approximation.**
  - In most cases, visually plausible but physically degraded.

Raster Pipeline

Raster Pipeline

- **Process objects one at a time in the order they are generated by the application**
  - One unit independently processes a single object but there are more units processing more objects at the same time.
  - Local/direct illumination can be computed without object dependency, and thus, objects are processed independently.

- **Pipeline architecture on graphics hardware**

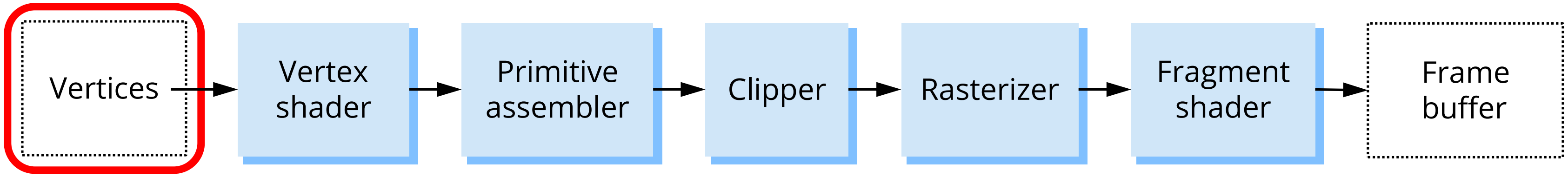


Graphics Pipeline (GPU)

Before Vertex Processing

- **A host application transfers the data in main memory to the GPU memory**
  - Data in GPU memory is only the copy of ones in main memory.
  - We need to maintain the source of GPU memory.

- **Vertex data (buffer) are transferred to GPU.**
  - These do not have to be done for every rendering frame.
  - When there are changes, we update GPU-side data by copying them.

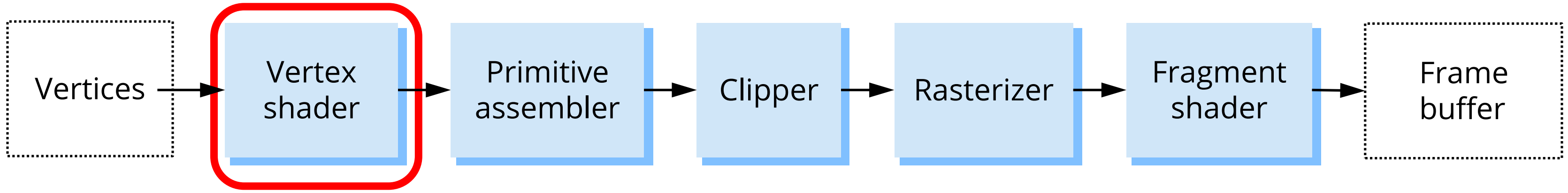


Vertex Processing: 3D Transformation

- **Vertex indicates a single 3D point with its attributes**
  - 3D position, normal vector, and texture coordinate

- **Primary role of vertex processing is positioning a single vertex**
  - Local object coordinates → world object coordinates
  - World object coordinates → camera (eye) coordinates

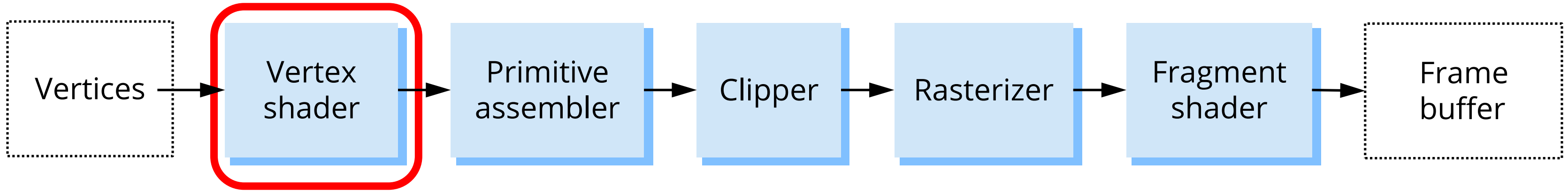
- **Every change of coordinates is equivalent to a 4×4 matrix transformation**



Vertex Processing: Projection

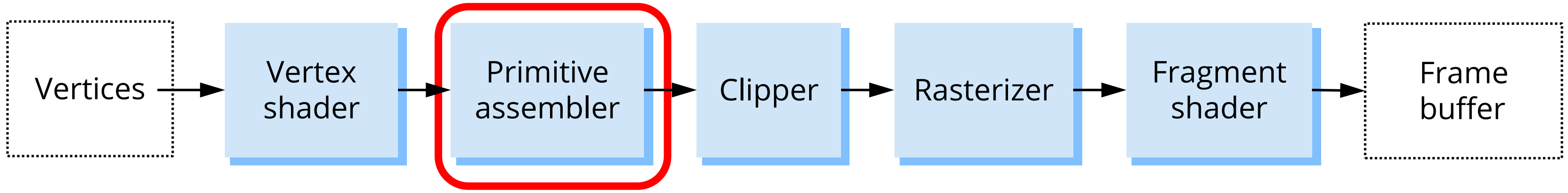
- ***Projection*** **is the process that projects 3D camera coordinates to 2D screen (window) coordinates**
  - Perspective projection
    - all projectors meet at the center of projection
  - Parallel projection:

- **The projection is also done with a 4×4 matrix multiplication.**



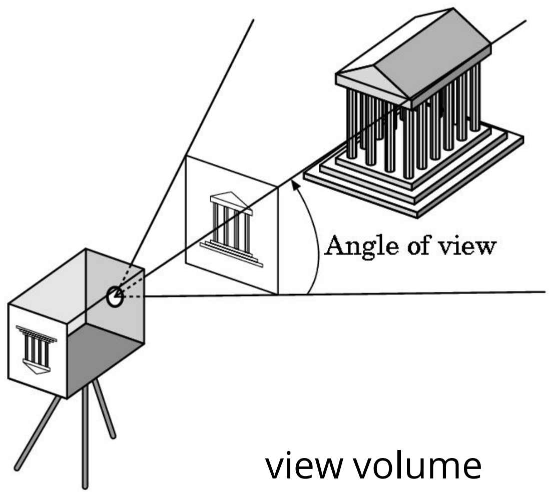
Primitive Assembly

- **Vertices must be collected into geometric objects prior to later steps**
  - Line segments: 2 vertices
  - Triangles: 3 vertices

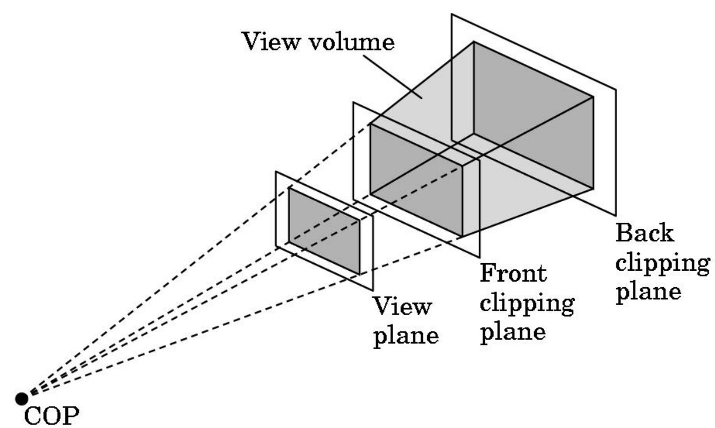


Clipping

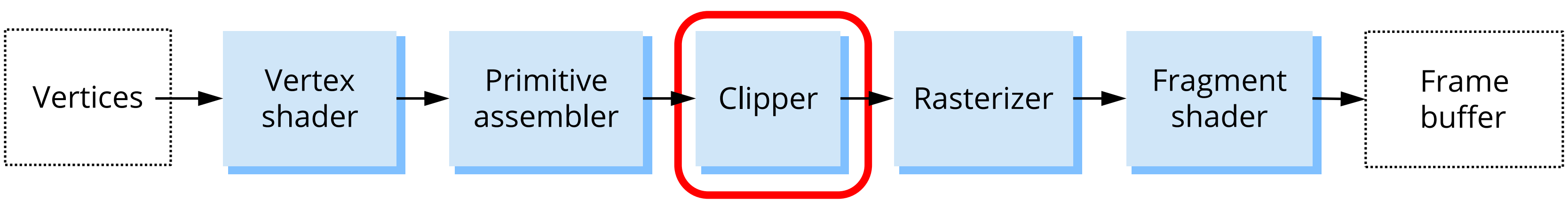
- **Definition:**
  - a process of determining which primitives, or parts of primitives, fit within the clipping volume or view volume.



view volume

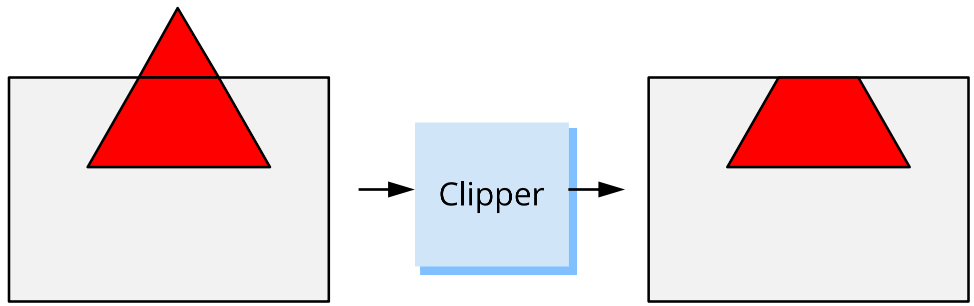


clipping volume

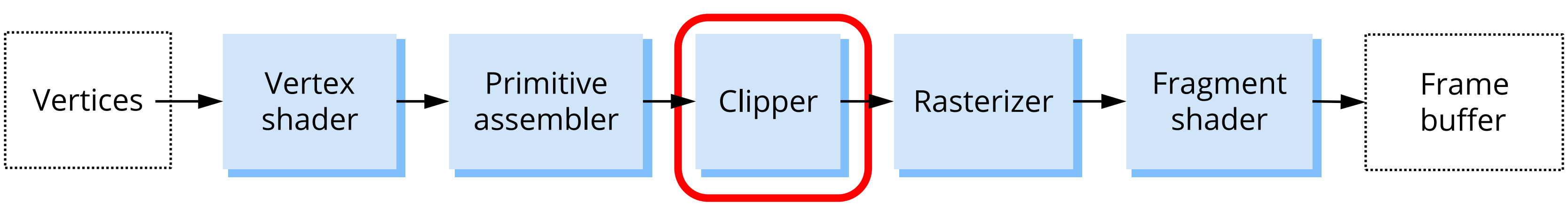


Clipping

- **Triangles partially outside the clipping volume:**
  - are subdivided so that the parts within the clipping volume are only processed and the other invisible parts are discarded in the later steps.

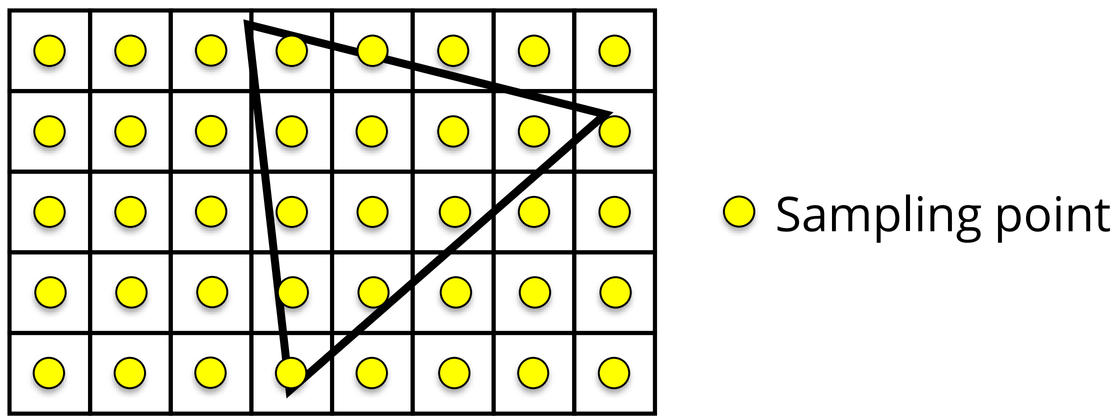


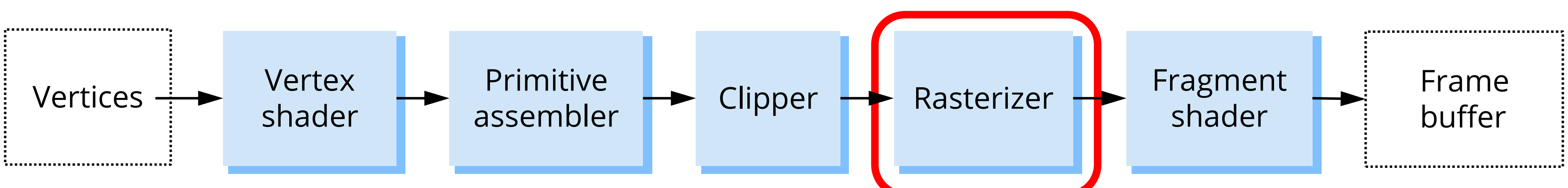
  - Hence, invisible triangles completely outside the clipping volume are ***clipped out*** and no more processed in the later steps.



Rasterization

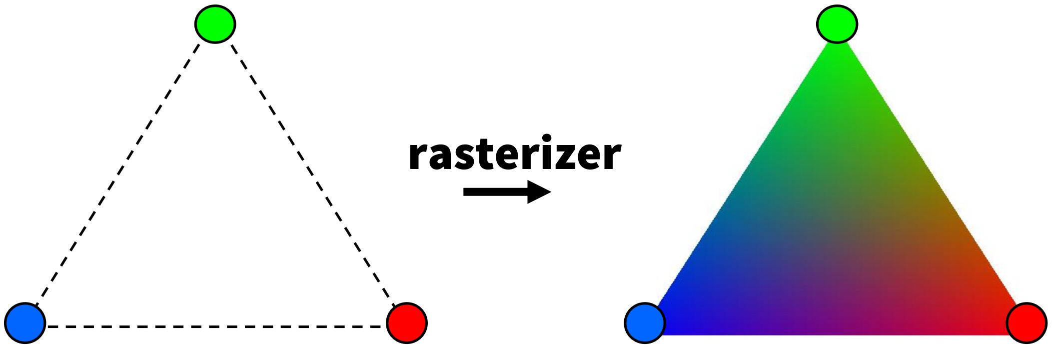
- **Rasterization**
  - Conversion of non-clipped objects (in vector graphics formats) to potential pixels (called the *fragments*).
  - Produce a set of fragments whose centers lie inside in each triangle.





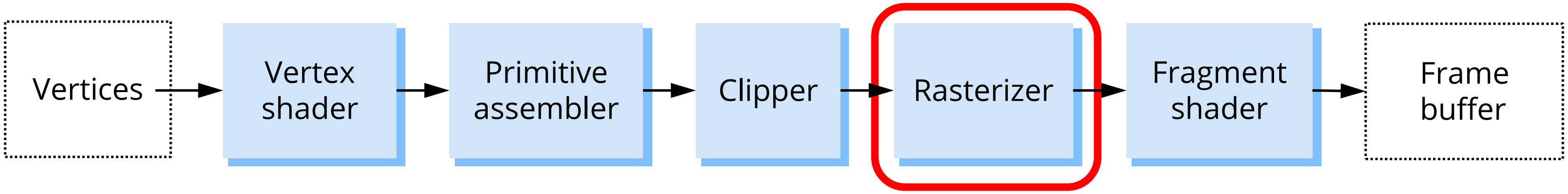
Rasterization

- **Vertex attributes are interpolated over objects by the rasterizer.**
  - 2D screen position, normal vectors, texture coordinates
  - Color and depth attributes



3 vertices in a triangle with RGB colors

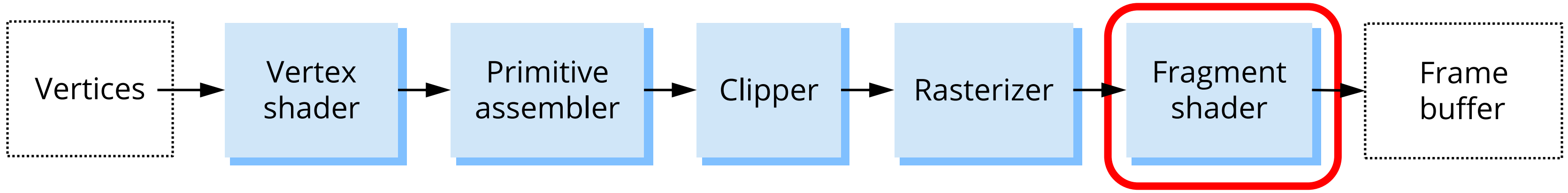
Rasterized fragments with interpolated attributes



Fragment Processing

- **Fragments are processed to *determine the color* of the corresponding pixel in the frame buffer**
  - Colors can be determined by texture mapping, interpolation of vertex colors, or physically-based shading.

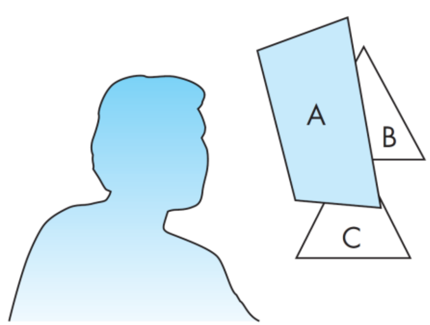
- **Post-fragment operations**
  - The fragment data output is then passed through a sequence of additional post-fragment (per-sameple) operations,
  - The post-fragment operations/tests typically include depth test, alpha blending, logical operations, and others.

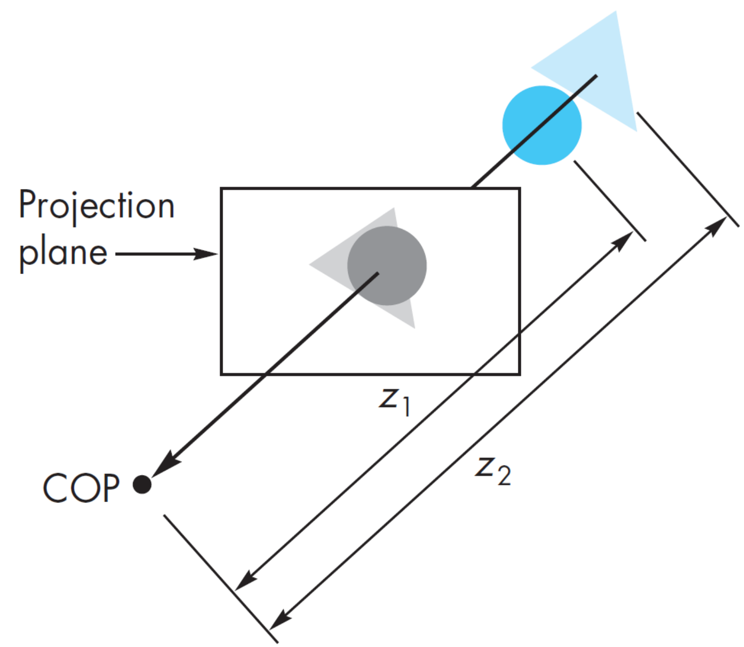


Post-Fragment Operation

- **Depth buffering (depth test, Z-test, or Z-buffering):**
  - The frame buffer maintains a depth buffer as well as color buffers to store the depth of the closest fragments at each pixel.
  - The depth of a fragment is compared against the depth value in the ZB.
  - Only the fragment with a nearer depth value is written to the frame buffer
  - Otherwise, the fragment is discarded.

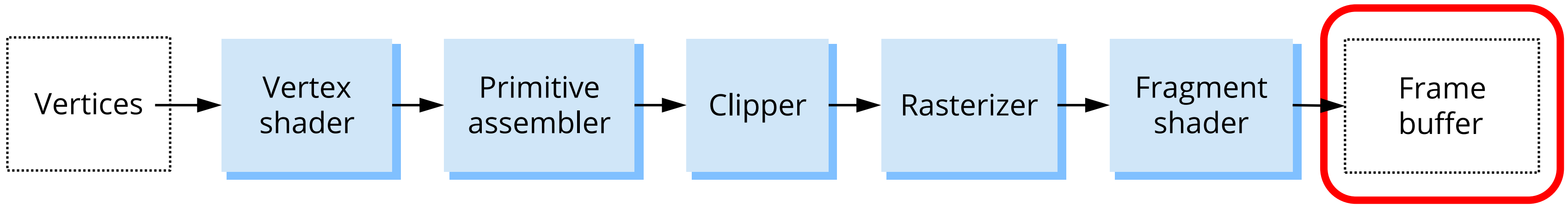
- **c.f., Painter's algorithm:**
  - One of other hidden surface removal algorithms
  - depth-sorted back-to-front rendering





Framebuffer

- **Pixels in Framebuffers**
  - Still alive fragments (now, we call pixels) are transferred to a framebuffer.
- **Framebuffers**
  - 2D memory areas that store fragments/pixels generated via the pipeline.
  - Framebuffers are defined by their resolution (width, height) and bit depth (e.g., 8bpp, 16bpp, 32bpp).
  - OpenGL maintains front/back (color) buffers (often with left/right for stereoscopic rendering), depth buffer, stencil buffer, and accumulation buffers.



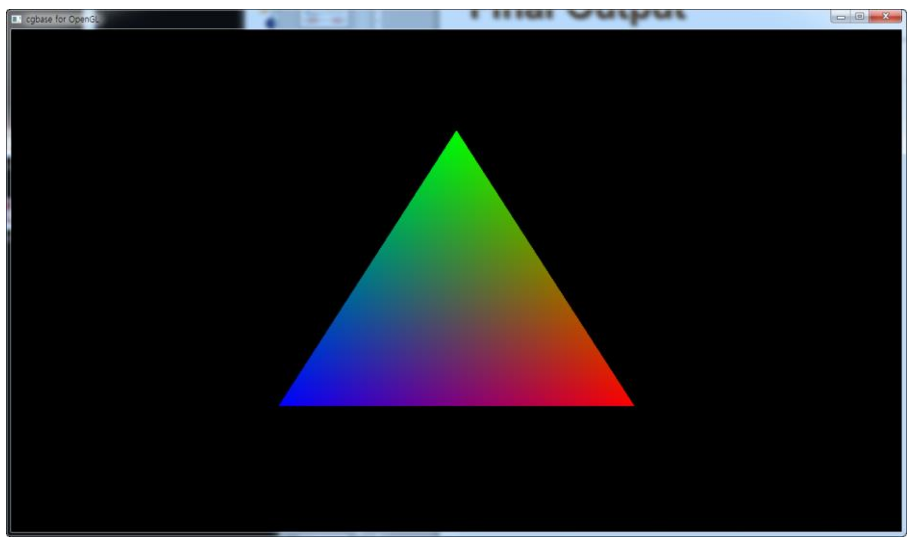
Frame Buffers

- **Frame buffers store fragments generated via rendering pipeline in large 2D memory areas.**
  - The buffers can store colors, depths, and masks (using stencil buffers).
  - OpenGL maintains front/back buffers (often with left/right for stereoscopic rendering), depth buffer, stencil buffer, and accumulation buffers.

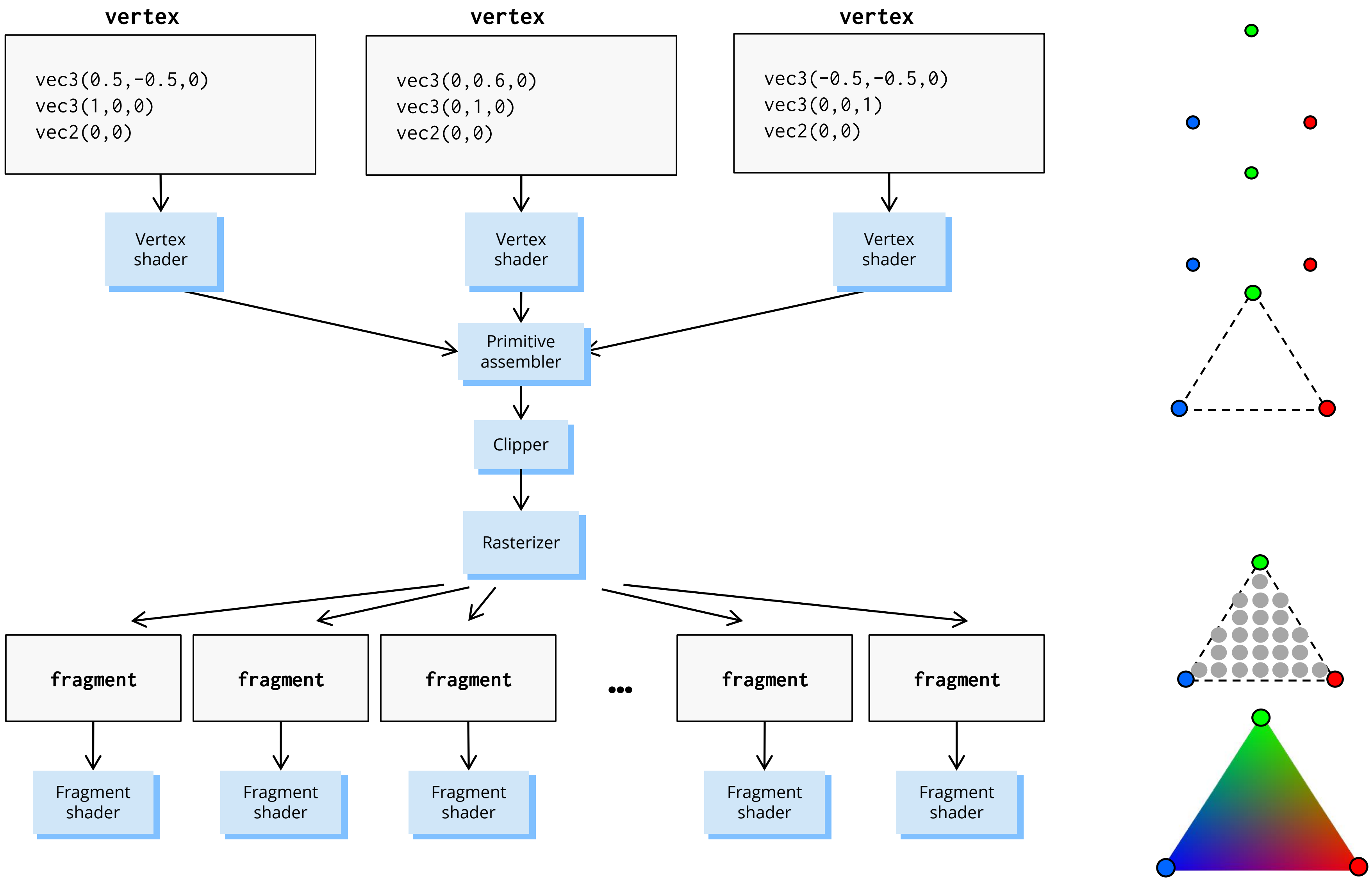
- **Frame buffers are defined by their resolution (width, height) and bit depth (e.g., 8bpp, 16bpp, 32bpp).**
  - This specification is similar to those of textures.
  - Hence, textures can be used as frame buffers, and we call such textures render targets.

Display

- **The framebuffer transfers its colors to the display devices.**
  - Now we can see an image in the monitor.
  - The transfer is synchronized with the refresh rate of display devices.
    - e.g., monitor refreshes at 60 Hz, and the framebuffer waits for the interval.



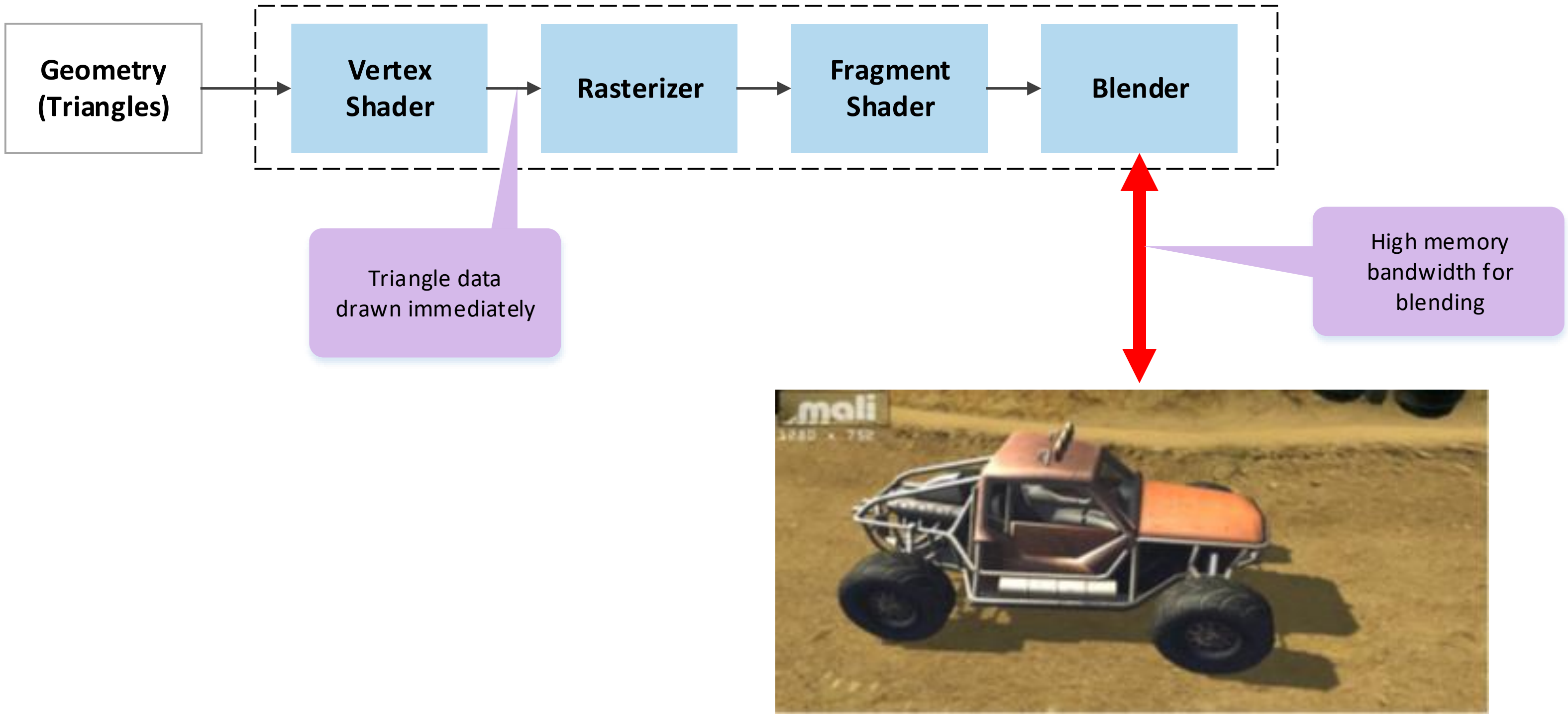
Example Data Flow



Advanced:
Tile-Based Rendering for Mobile Graphics

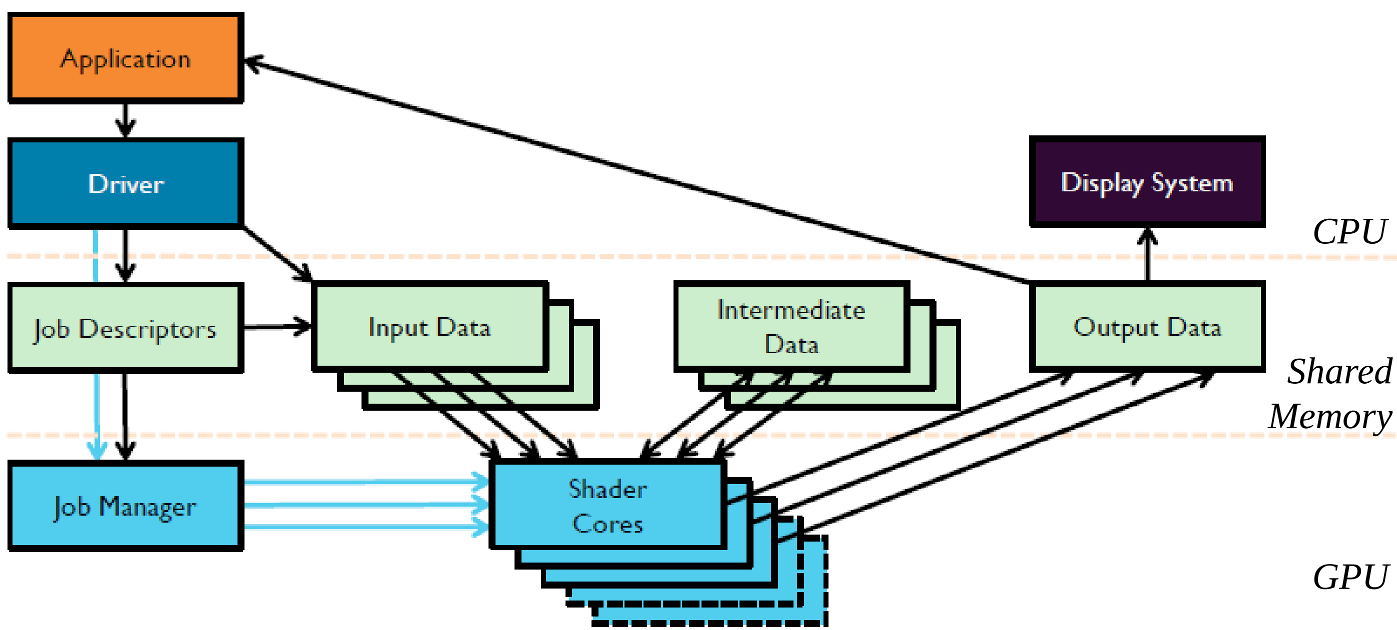
Immediate Mode Rendering (IMR)

- **Background**
  - IMR (typical desktop-like rendering pipeline with the full framebuffer) costs large bandwidth/space and power consumption.
    - c.f., IMR here is different from IMR in desktop rendering (IM vs. Retained Mode)
  - Mobile devices are limited in physical space and power consumption.



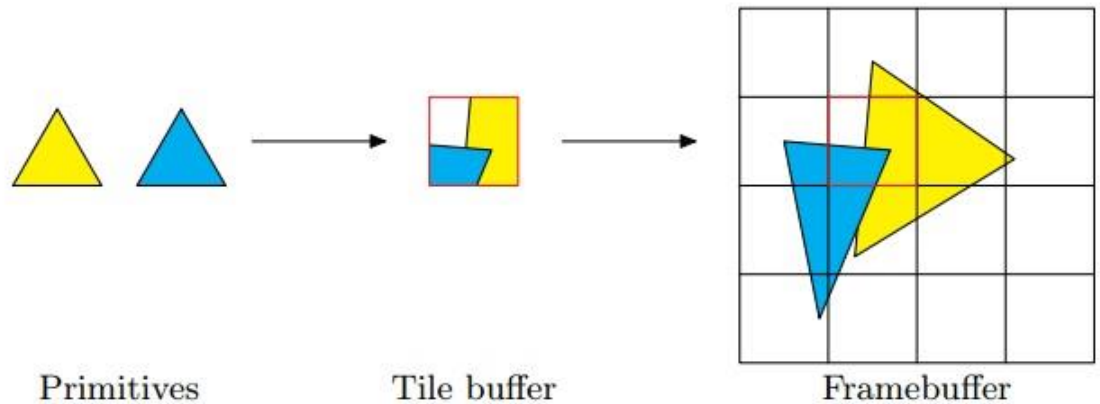
Immediate Mode Rendering (IMR)

- **Background**
  - IMR needs costly update (e.g., blending and frame buffer operations) with intermediate data.
  - e.g., basic data flow in ARM



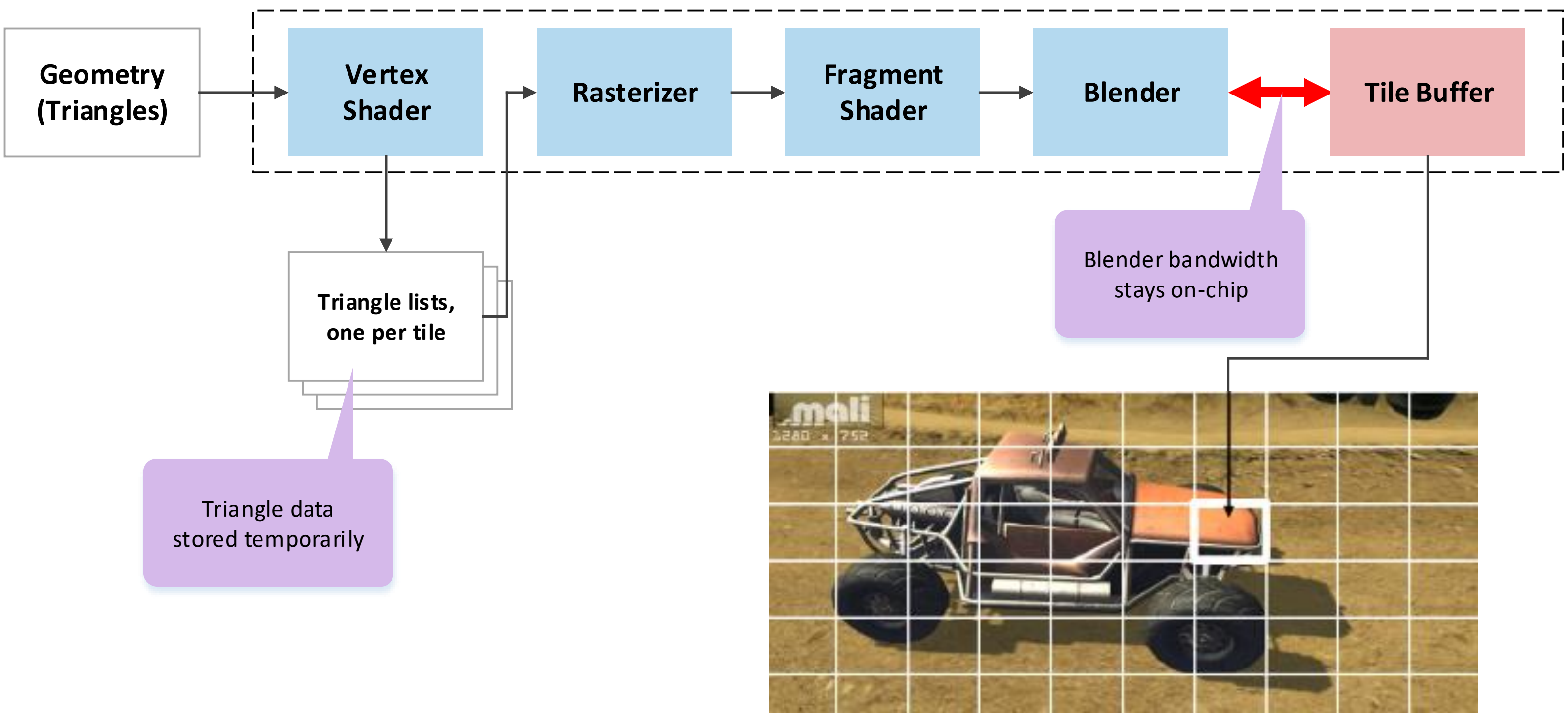
Tile-Based Rendering (TBR)

- **Tile-Based Rendering**
  - Subdivide scenes into smaller **tiles** (e.g., 16x16 or 32x32) in screen space and render each section of tile separately.
  - Intermediate data interact with a **small** and **on-chip** (local) tile buffer, and thereby, memory bandwidth is significantly reduced.



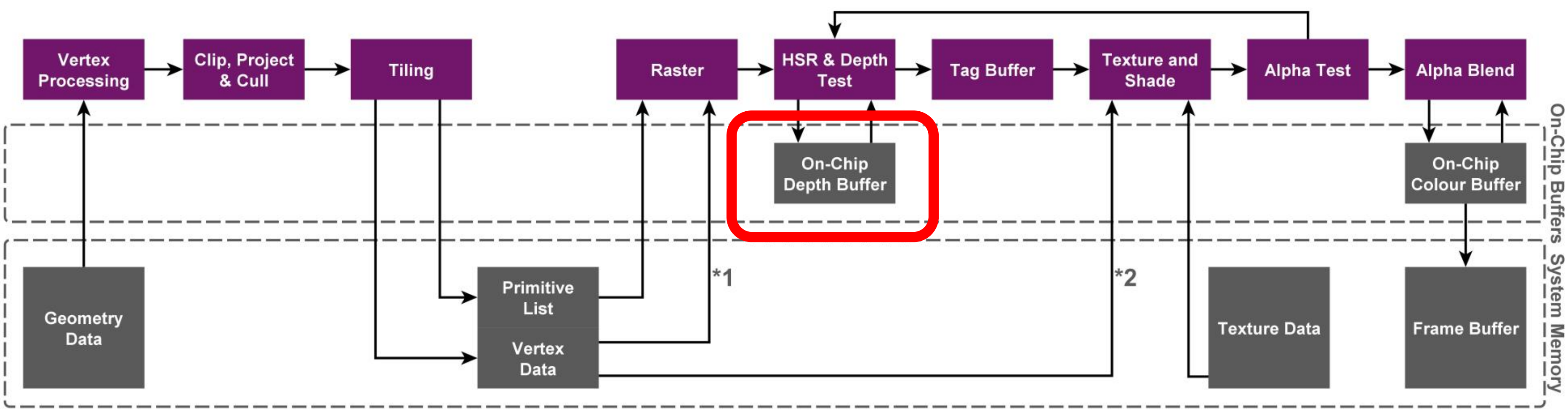
Tile-Based Rendering (TBR)

- **Tile-Based Rendering**
  - Triangles are not directly sent to a rasterizer, but sorted by their location (i.e., tile ID) in the middle of the graphics pipeline.
  - When their tile is activated, the triangles start to be rasterized.
  - Temporary triangle lists are required, but not too large in mobile rendering.



Tile-Based Deferred Rendering (TBDR)

- **TBDR (mostly in PowerVR)**
  - Rasterization is **deferred** until all the primitives are stored into the tile triangle lists.
  - To gain additional speedup, the triangles are sorted front-to-back in advance to facilitate early-Z (pre-raster hidden surface removal).
    - This step uses on-chip (tile) depth buffer.
    - Made more efficient, combined with on-chip color blending (in TBR).



Tile-Based Deferred Rendering (TBDR)

- **TBDR (mostly in PowerVR)**
  - After the hidden surface removal (HSR), the pixel shading starts (with texture fetch). In other words, rendering (more precisely, texturing and shading) is deferred until after a per-pixel visibility test is passed.