Working with shaders

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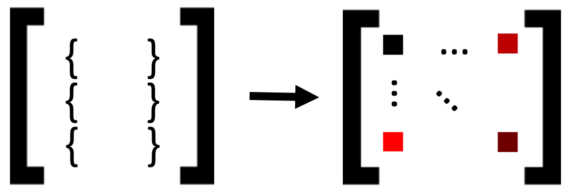
What’s a shader?

Small programs that run on the GPU

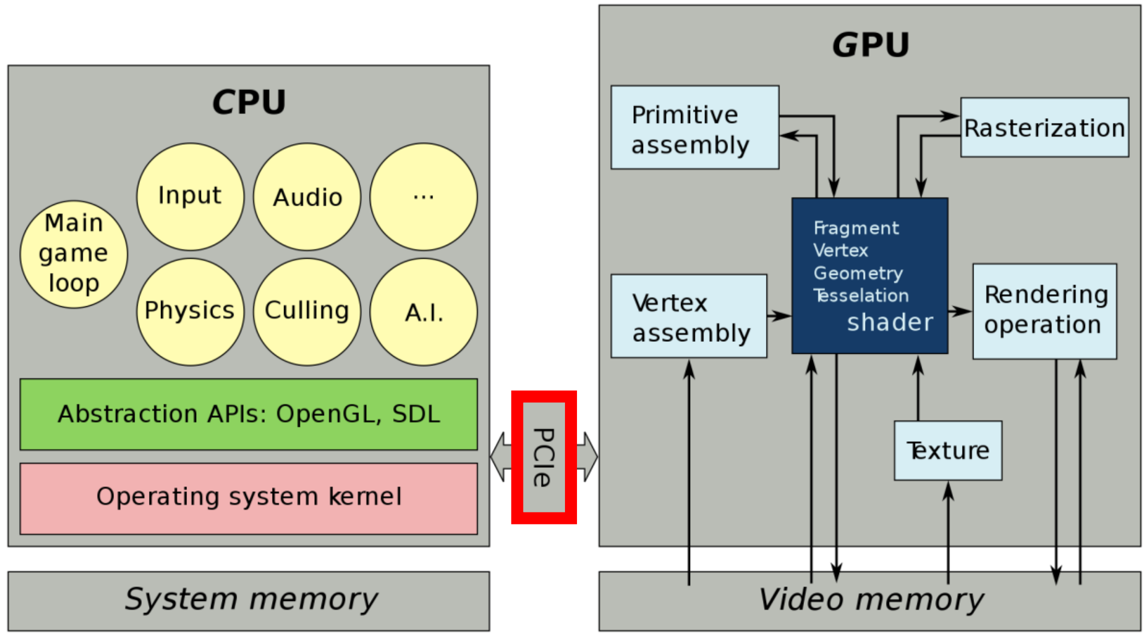
Executed for each specific section of the graphics pipeline

Isolated and not allowed to communicate with each other



It works with geometric primitives, lights, textures, ...

Shaders in the Graphics Processing Unit



Shaders are executed by the GPU & are good to be executed in parallel

Sending data to the GPU goes through the PCI, it is relatively slow
& CPU/GPU must be synchronized

Different languages

DirectX High-Level Shader Language

Cg Shader Language

OpenGL Shading Language (GLSL)

Problem

In GLSL, there are no real data structures to easily get the attributes of a primitive (matrices, vectors, ...)

The construction of shaders is very repetitive which implies a lot of copy and paste

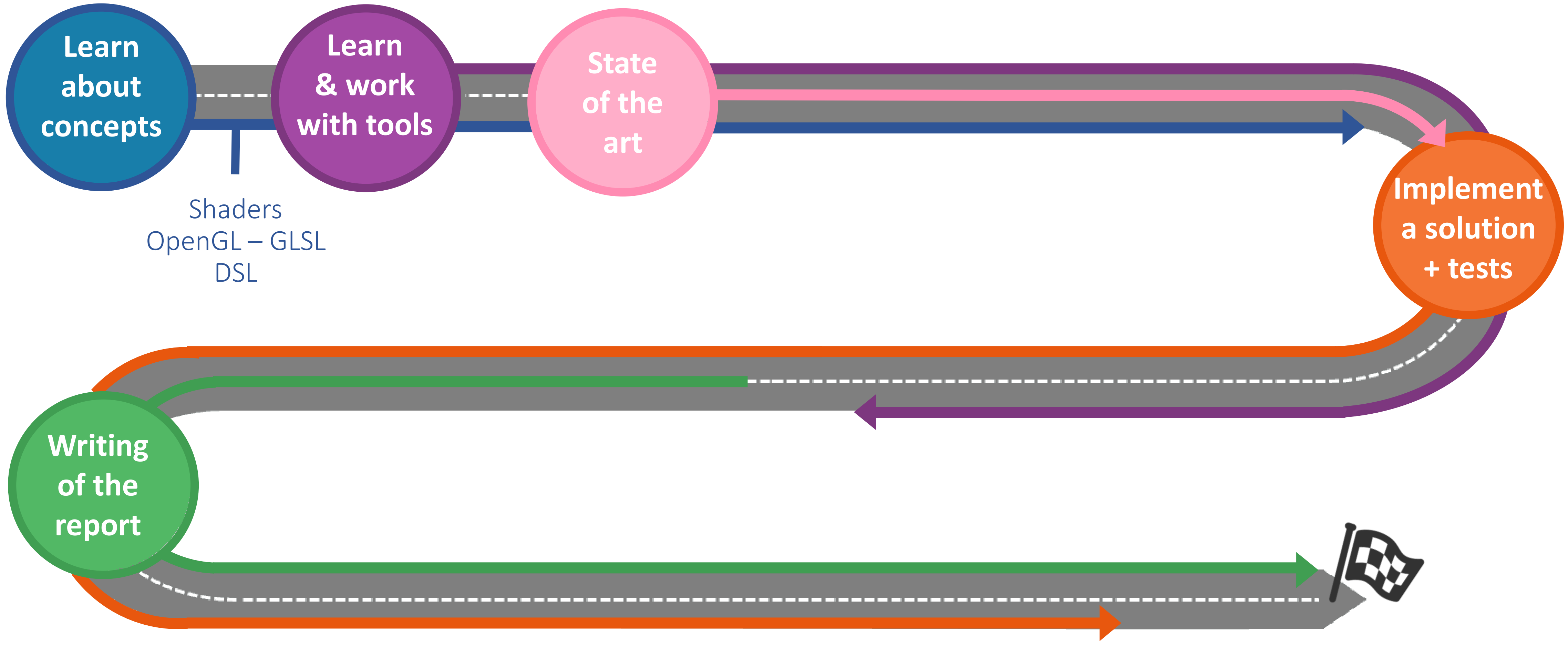
Must reduce the data sent in the PCI to avoid multiple synchronizations between CPU & GPU

Goal of the project

Work with the representation of the data & abstract the types

Construct a DSL for shaders

Road map


Learn about concepts
Learn & work with tools
State of the art
Implement a solution + tests
Writing of the report
Shaders
OpenGL – GLSL
DSL

3D space to 2D screen space

The process of transforming 3D coordinates to 2D pixel is done by the graphics pipeline

First big part: transforms 3D coordinates into 2D coordinates

Second big part: transforms the 2D coordinates into actual colored pixels

Graphics pipeline

Input & Output Data

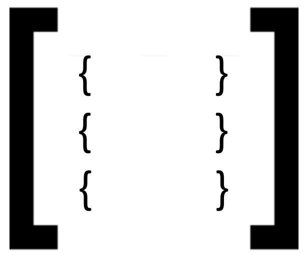
3 different shaders processing units

- Vertex Shader
- Geometry Shader
- Fragment/Pixel Shader

Some others processes

- Tessellation, Rasterization, Color blending

Input Data



Take as input a Vertex (or Vertices) [] which is a data structure that describes geometric primitives with certain attributes like:

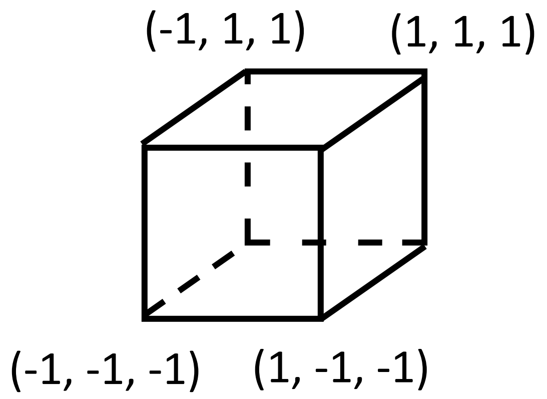
Position (2D, 3D coordinates)

Color (RGB, …)

Texture coordinates

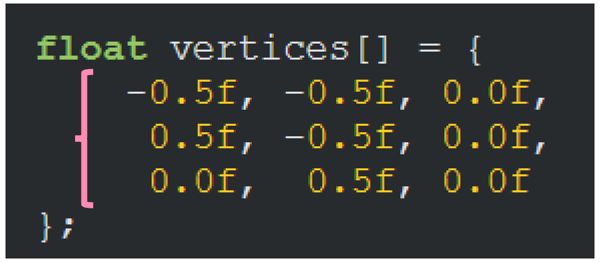
Example

In OpenGL, only the Normalize Device Coordinates (NDC) are visible on the screen

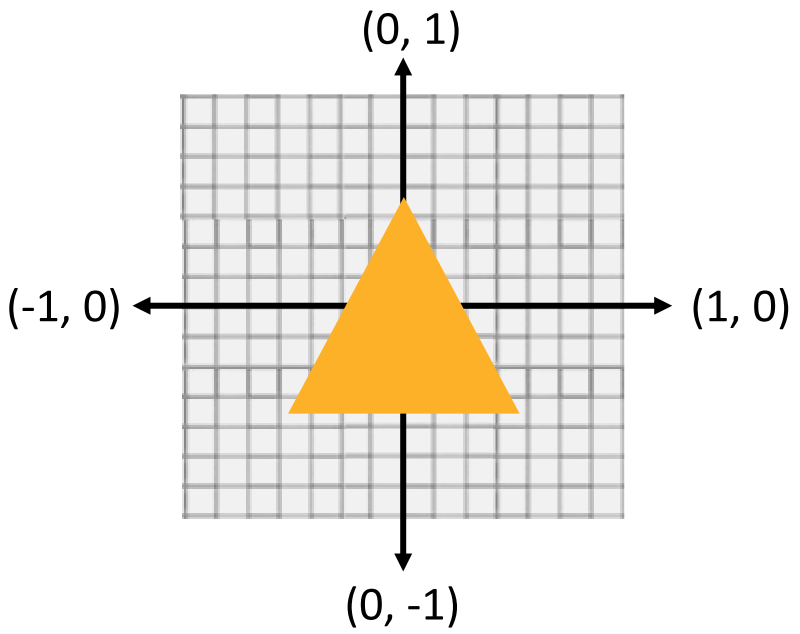


To render a single 2D triangle:

3D position (NDC) of each vertex



```
float vertices[] = {
    -0.5f, -0.5f, 0.0f,
     0.5f, -0.5f, 0.0f,
     0.0f,  0.5f, 0.0f
};
```



Linking vertex attributes

The input data will compose a Vertex Buffer Object (VBO) which can store a large number of vertices in the GPU memory

Then, we specify how the vertex data should be interpreted

Finally, it will be sent to the Vertex Shader

Example

Triangle with position attributes:

```
float vertices[] = {
    -0.5f, -0.5f, 0.0f,
     0.5f, -0.5f, 0.0f,
     0.0f,  0.5f, 0.0f
};
```

Copy our vertices array in a buffer

ID of the buffer which must be bind

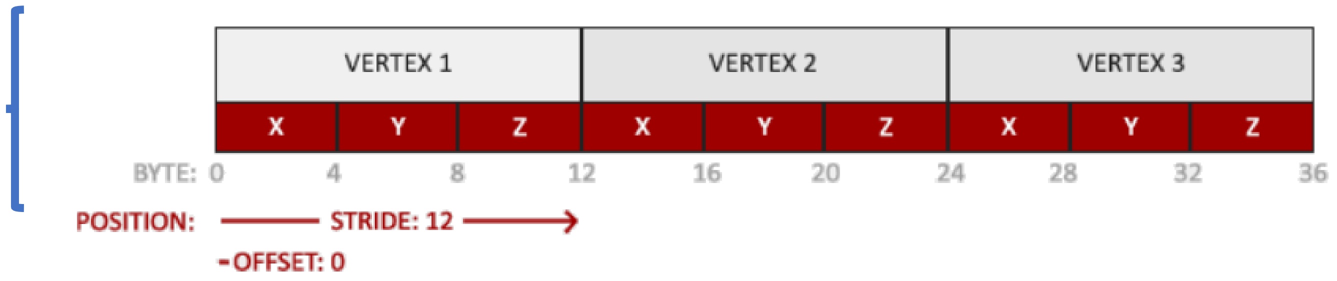
Specifies the target buffer object

```
glBindBuffer(GL_ARRAY_BUFFER, VBO);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);
```

Size of the buffer object

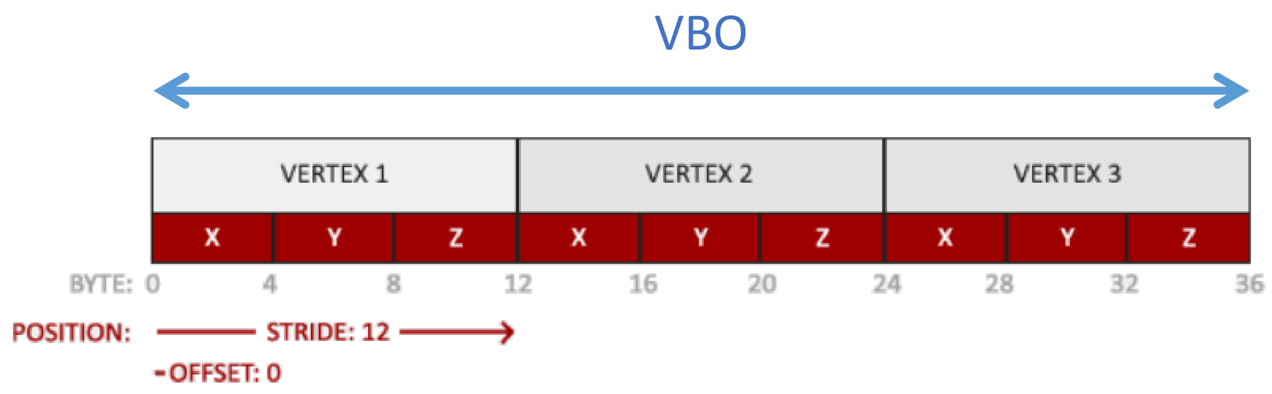
Pointer to data

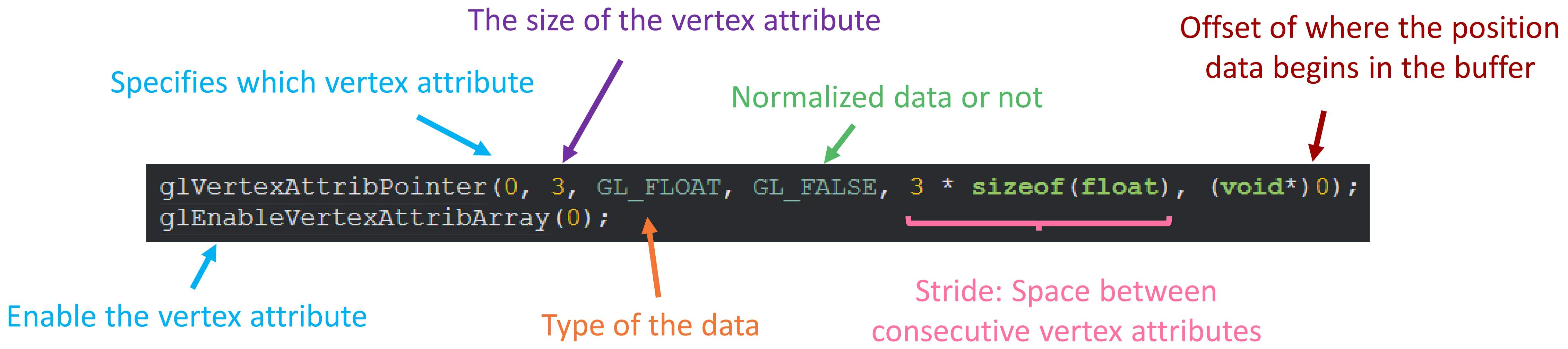
VBO



Example (Cont.)

Define how the vertex data should be interpreted





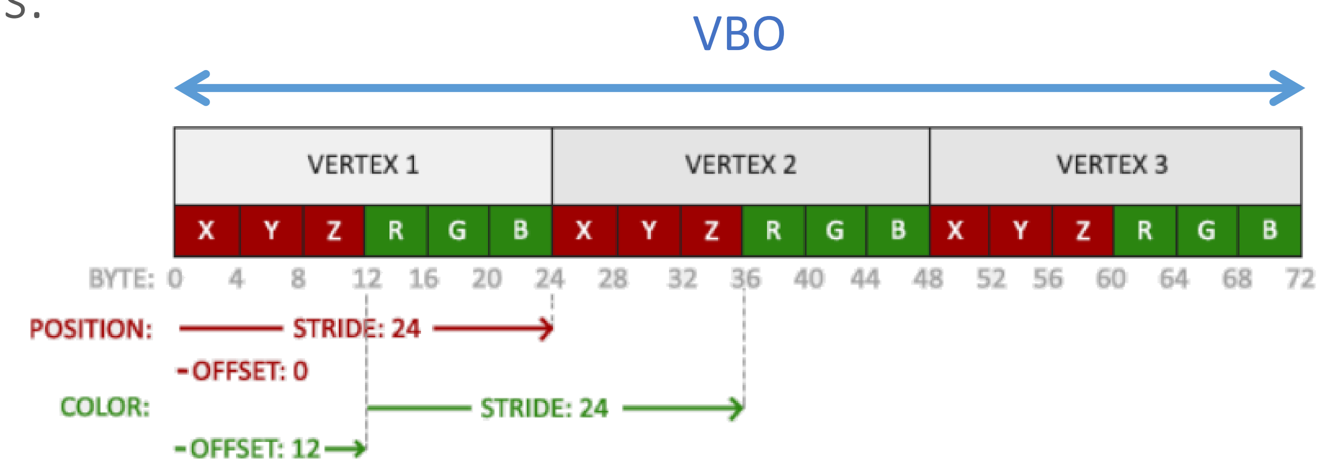
```
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);
```

Specifies which vertex attribute
The size of the vertex attribute
Normalized data or not
Offset of where the position data begins in the buffer
Enable the vertex attribute
Type of the data
Stride: Space between consecutive vertex attributes

Example (Cont.)

Triangle with position & color attributes:

```
float vertices[] = {
    // positions          // colors
     0.5f, -0.5f, 0.0f,  1.0f, 0.0f, 0.0f,
    -0.5f, -0.5f, 0.0f,  0.0f, 1.0f, 0.0f,
     0.0f,  0.5f, 0.0f,  0.0f, 0.0f, 1.0f
};
```


VBO
VERTEX 1
VERTEX 2
VERTEX 3
X Y Z R G B X Y Z R G B X Y Z R G B
BYTE: 0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72
POSITION:
STRIDE: 24
OFFSET: 0
COLOR:
STRIDE: 24
OFFSET: 12

Position offset

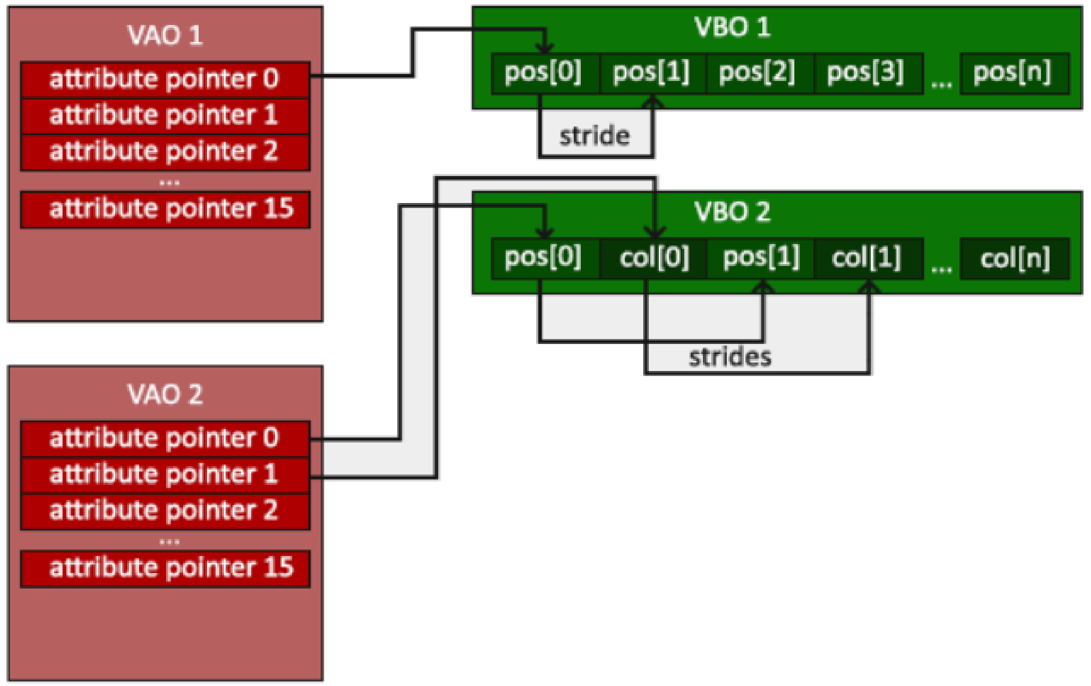
```
// position attribute
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 6 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);
// color attribute
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 6 * sizeof(float), (void*)(3* sizeof(float))
glEnableVertexAttribArray(1);
```

Stride

Color offset

Vertex Array Object (VAO)

Allows to configure vertex attribute pointers more easily

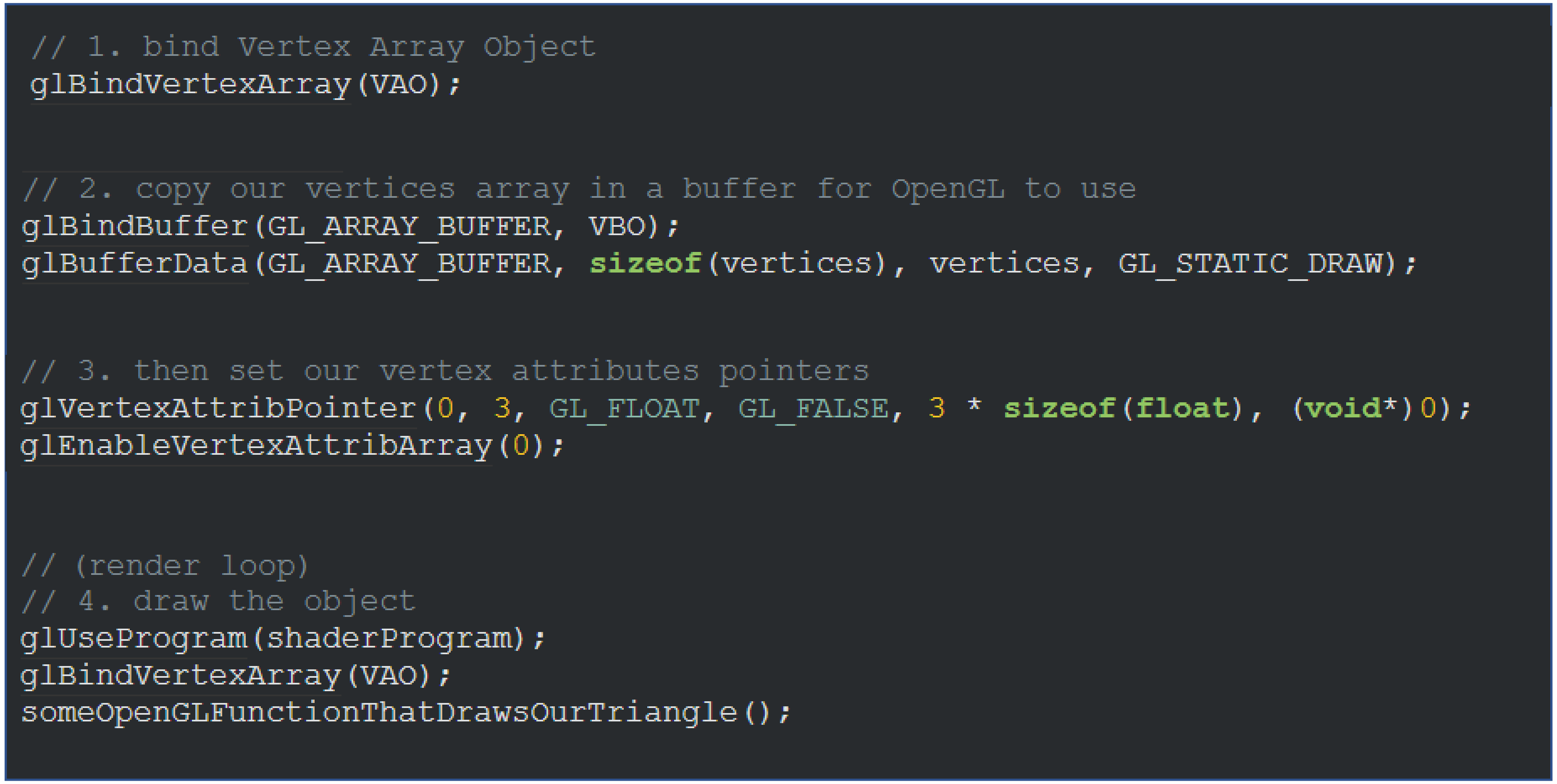


To draw an object, just bind the corresponding VAO

We generate a VAO like a VBO

```
unsigned int VAO;
glGenVertexArrays(1, &VAO);
```

Summary



```
// 1. bind Vertex Array Object
glBindVertexArray(VAO);

// 2. copy our vertices array in a buffer for OpenGL to use
glBindBuffer(GL_ARRAY_BUFFER, VBO);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);

// 3. then set our vertex attributes pointers
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);

// (render loop)
// 4. draw the object
glUseProgram(shaderProgram);
glBindVertexArray(VAO);
someOpenGLFunctionThatDrawsOurTriangle();
```

Source: https://learnopengl.com/Getting-started/Hello-Triangle

Render & draw an object

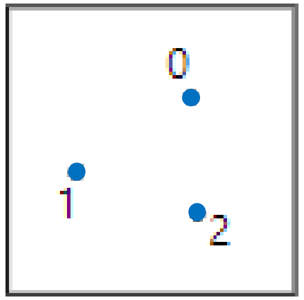
The idea now is to render and draw an object.
To do that we will have to:

Set up a Vertex & a Fragment Shader

Compile these shaders

Link them to a shader program

Vertex Shader

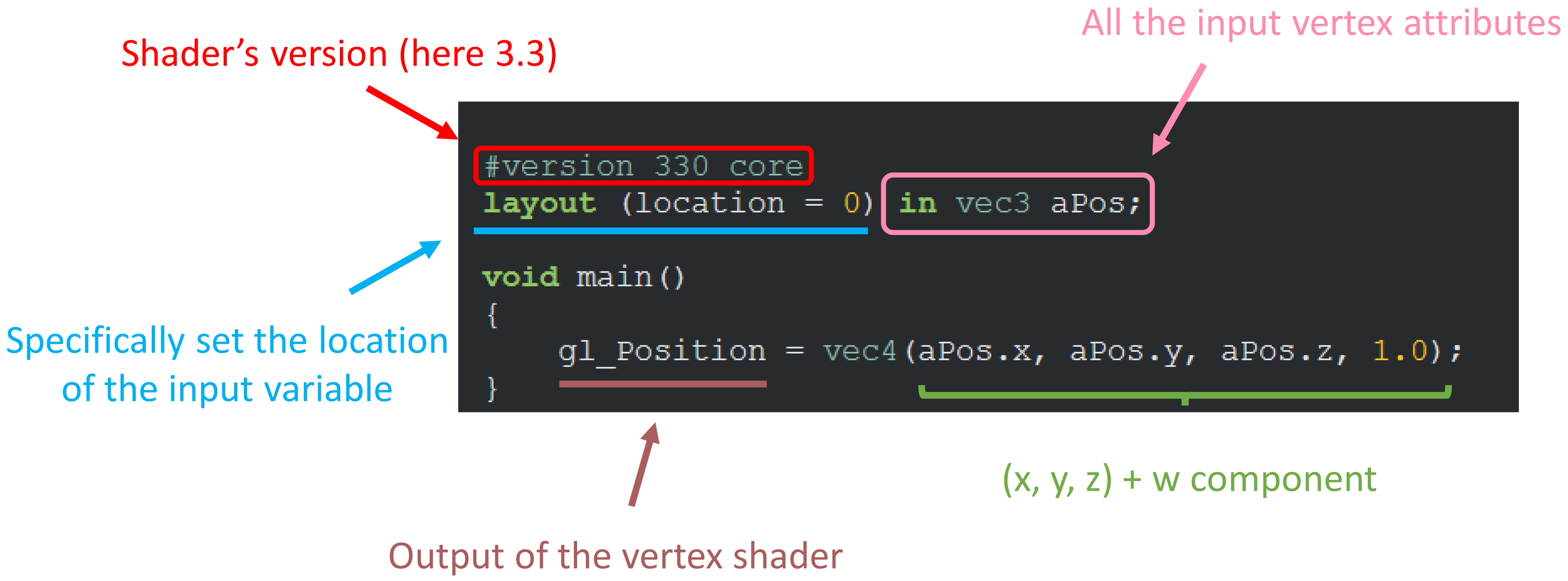


Compute the projection of the vertices of primitives from 3D space into a different 3D space (NDC)

Input data: some properties of the vertices (position, color or texture coordinates)

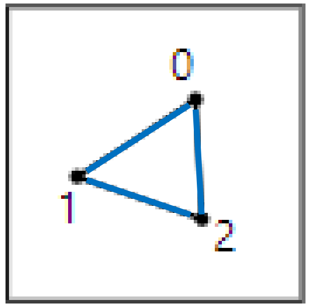
Output data: the corresponding properties in the new space

Sample code


Shader's version (here 3.3)
All the input vertex attributes
Specifically set the location of the input variable
(x, y, z) + w component
Output of the vertex shader

```
#version 330 core
layout (location = 0) in vec3 aPos;

void main()
{
    gl_Position = vec4(aPos.x, aPos.y, aPos.z, 1.0);
}
```

Primitives Assembly



This process takes all the vertex given by the step before and assemble them in order to create a geometric shape

Sample code:

```
glDrawArrays(GL_TRIANGLES, 0, 3);
```

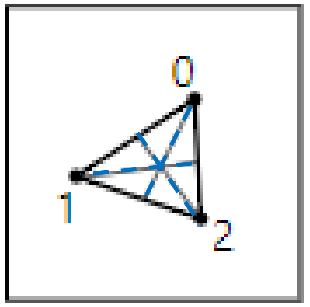
Starting index in the array

OpenGL function that draws a shape

Kind of primitive to render

Number of vertices to render

Tessellation

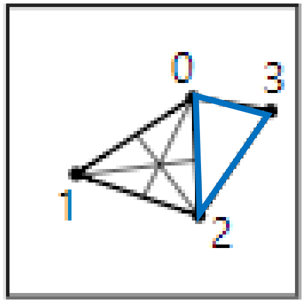


In 3D, the surfaces are built with triangular tiles

Tessellation allows to double triangles on a given surface and therefore increase the level of details

Geometry Shader

An unnecessary step

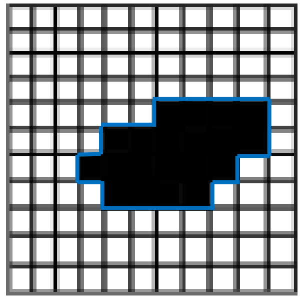


Allows to modify the geometry of each polygon and allows to create new polygons by emitting new vertices

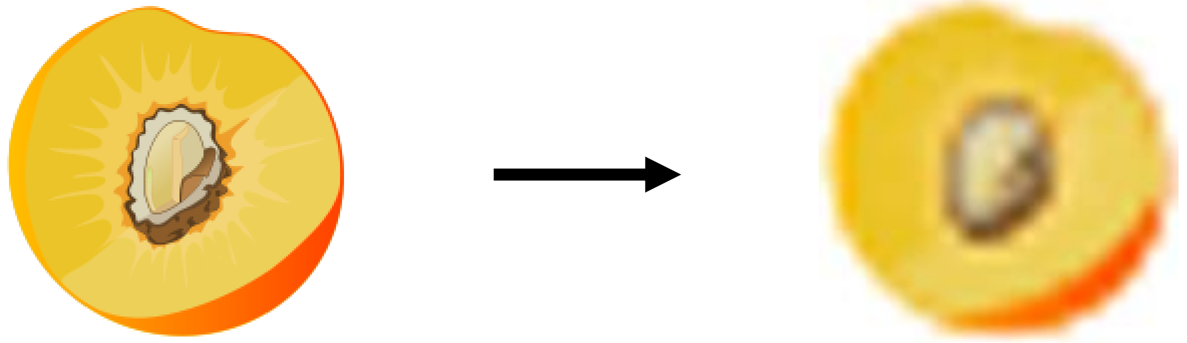
Input data: data of a geometric primitive

Output data: data of one or more geometric primitive

Rasterization



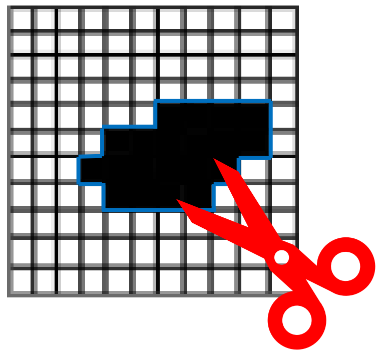
Method of converting a vector image into a raster image to be displayed on a screen



Vector image
composed of geometric objects

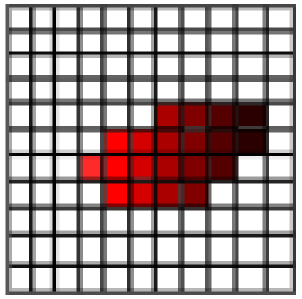
Raster image or Bitmap
composed of pixels

Clipping



This step discard all fragments (which is the required data to render a single pixel) that are outside the view, increasing the performance

Fragment/Pixel Shader

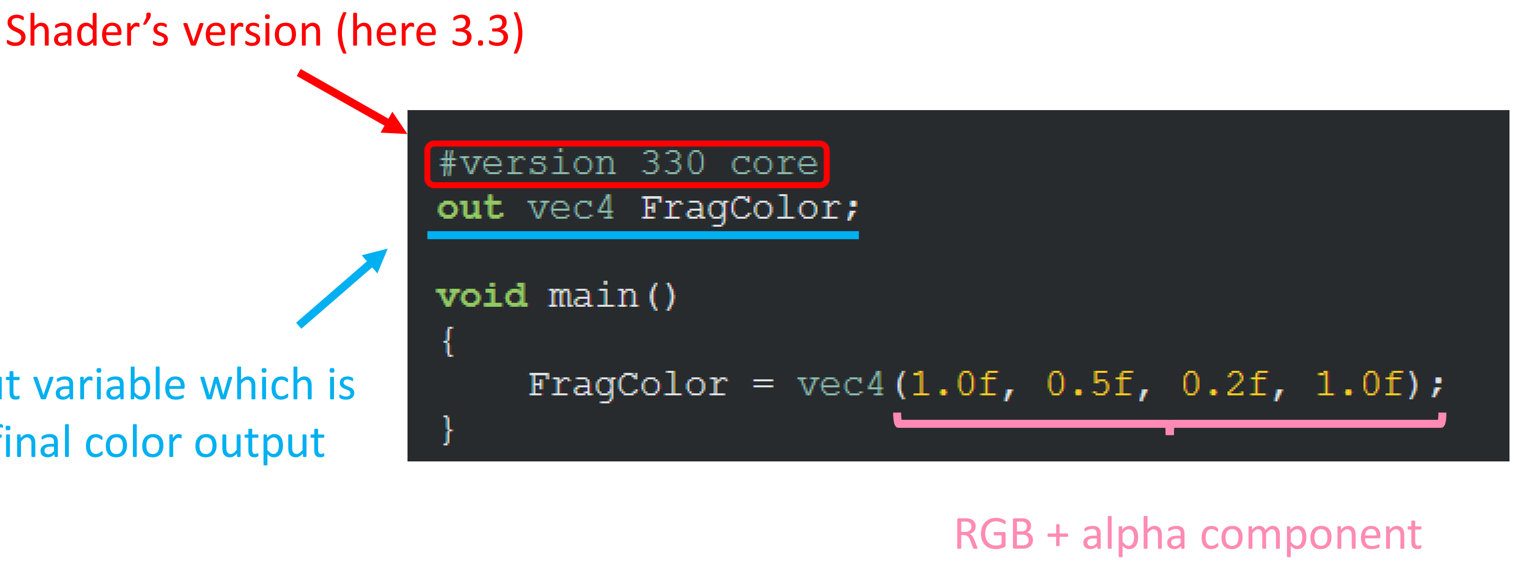


Calculates the final color of a pixel

Input data: pixel data
(position, texture coordinates, color)

Output data: the pixel color

Sample code


Shader's version (here 3.3)
Output variable which is the final color output
RGB + alpha component

```
#version 330 core
out vec4 FragColor;

void main()
{
    FragColor = vec4(1.0f, 0.5f, 0.2f, 1.0f);
}
```

Compile a Shader

First, we store the code in a string constant

```
const char *vertexShaderSource = "#version 330 core\n"
    "layout (location = 0) in vec3 aPos;\n"
    "void main()\n"
    "{\n"
    "   gl_Position = vec4(aPos.x, aPos.y, aPos.z, 1.0);\n"
    "}\0";
```

Then, we store and create the shader

```
unsigned int vertexShader;
vertexShader = glCreateShader(GL_VERTEX_SHADER);
```

Type of shader we want to create

Finally, we link the source code to the object and compile it

```
glShaderSource(vertexShader, 1, &vertexShaderSource, NULL);
glCompileShader(vertexShader);
```

Shader program

First, we create a program object

```
unsigned int shaderProgram;
shaderProgram = glCreateProgram();
```

We attach the previously compiled shaders to the program object and link them

```
glAttachShader(shaderProgram, vertexShader);
glAttachShader(shaderProgram, fragmentShader);
glLinkProgram(shaderProgram);
```

We can now activate this program to render and draw an object

```
glUseProgram(shaderProgram);
```

Final step is to delete our shader objects

```
glDeleteShader(vertexShader);
glDeleteShader(fragmentShader);
```

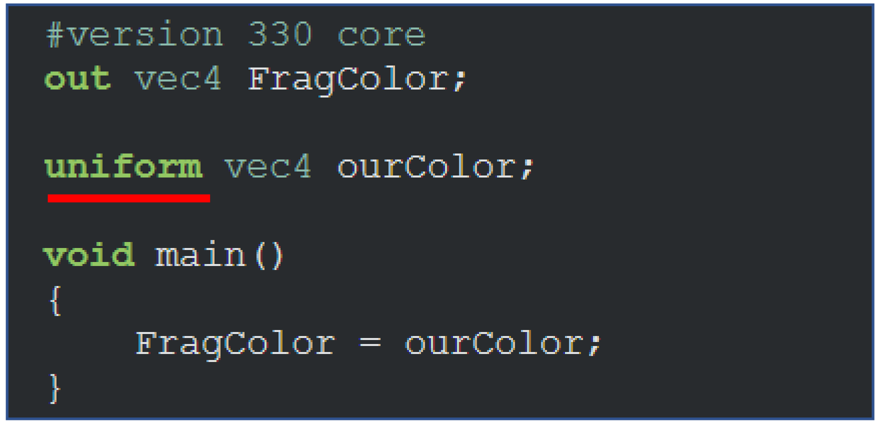
Uniforms variables

Useful to pass data from the application on the CPU to the shaders on the GPU

These are global variables

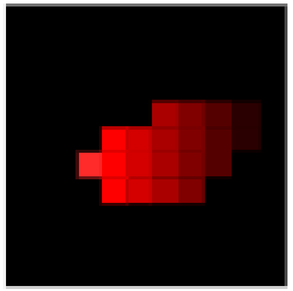
Sample code:

Usage of uniform keyword



```
#version 330 core
out vec4 FragColor;

uniform vec4 ourColor;

void main()
{
    FragColor = ourColor;
}
```

Alpha test



Checks the corresponding depth value of a fragment to see if the resulting fragment is in front or behind another one

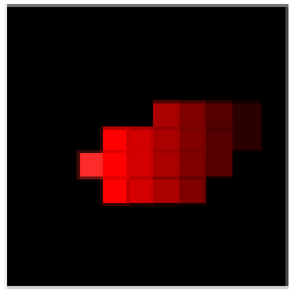
$$\text{NOT DISCARDED} \leftarrow \text{in front} \qquad \text{behind} \rightarrow \text{DISCARDED}$$

Done with the depth testing using a Z-buffer (in which the depth value of the fragments is stored)

```
glEnable(GL_DEPTH_TEST);
```

Then, checks for alpha values (opacity of an object) & blends the objects

Color Blending



The technique of gently blending two or more colors to create a gradual transition

Example of a blending function

First, we have to enable the OpenGL functionality

```
glEnable(GL_BLEND);
```

Then, blending can follow this equation:

$$\underline{\bar{C}_{result}} = \underline{\bar{C}_{source}} * F_{source} + \underline{\bar{C}_{destination}} * F_{destination}$$

Impact of the alpha value

Final color of the fragment

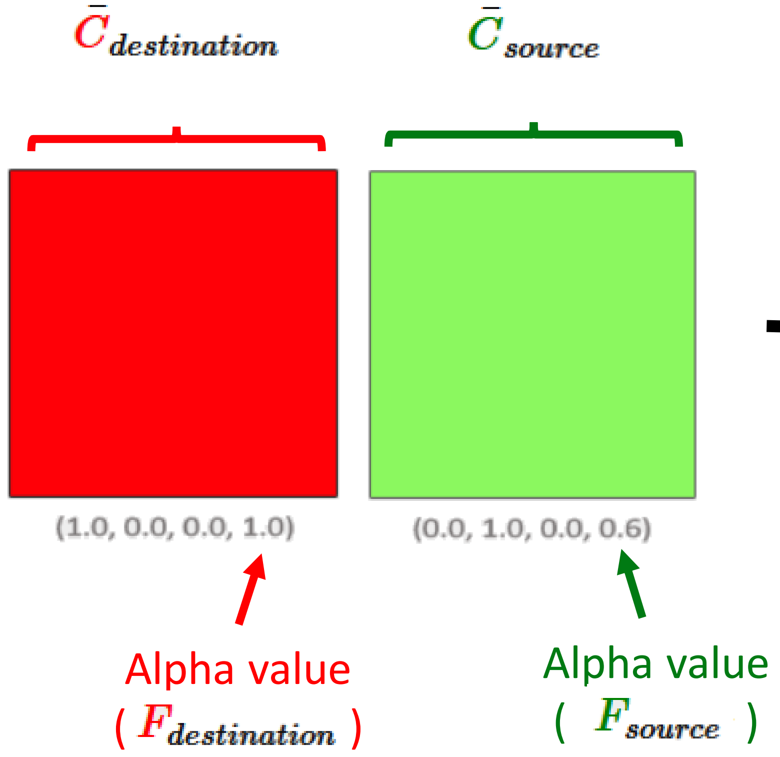
Impact of the alpha value

Color output of the fragment shader

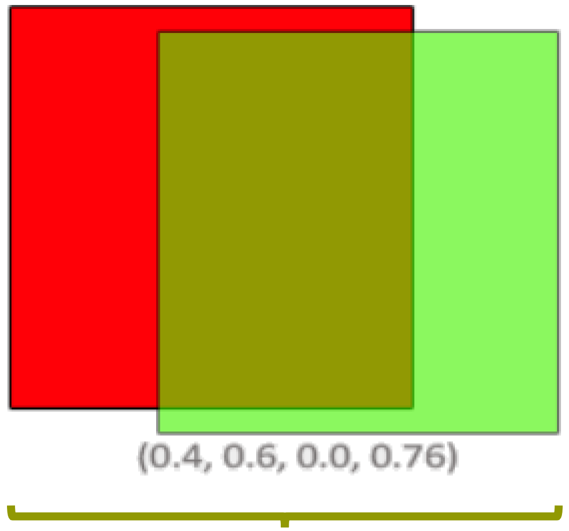
Color currently stored in the color buffer

Example (Cont.)

$$\boxed{\bar{C}_{result} = \bar{C}_{source} * F_{source} + \bar{C}_{destination} * F_{destination}}$$

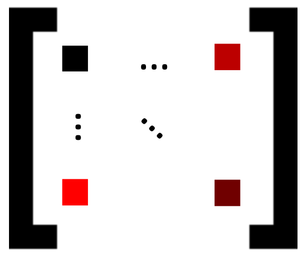


$$\bar{C}_{result} = \begin{pmatrix} 0.0 \\ 1.0 \\ 0.0 \\ 0.6 \end{pmatrix} * 0.6 + \begin{pmatrix} 1.0 \\ 0.0 \\ 0.0 \\ 1.0 \end{pmatrix} * (1 - 0.6)$$



Resulting color then stored in the color buffer

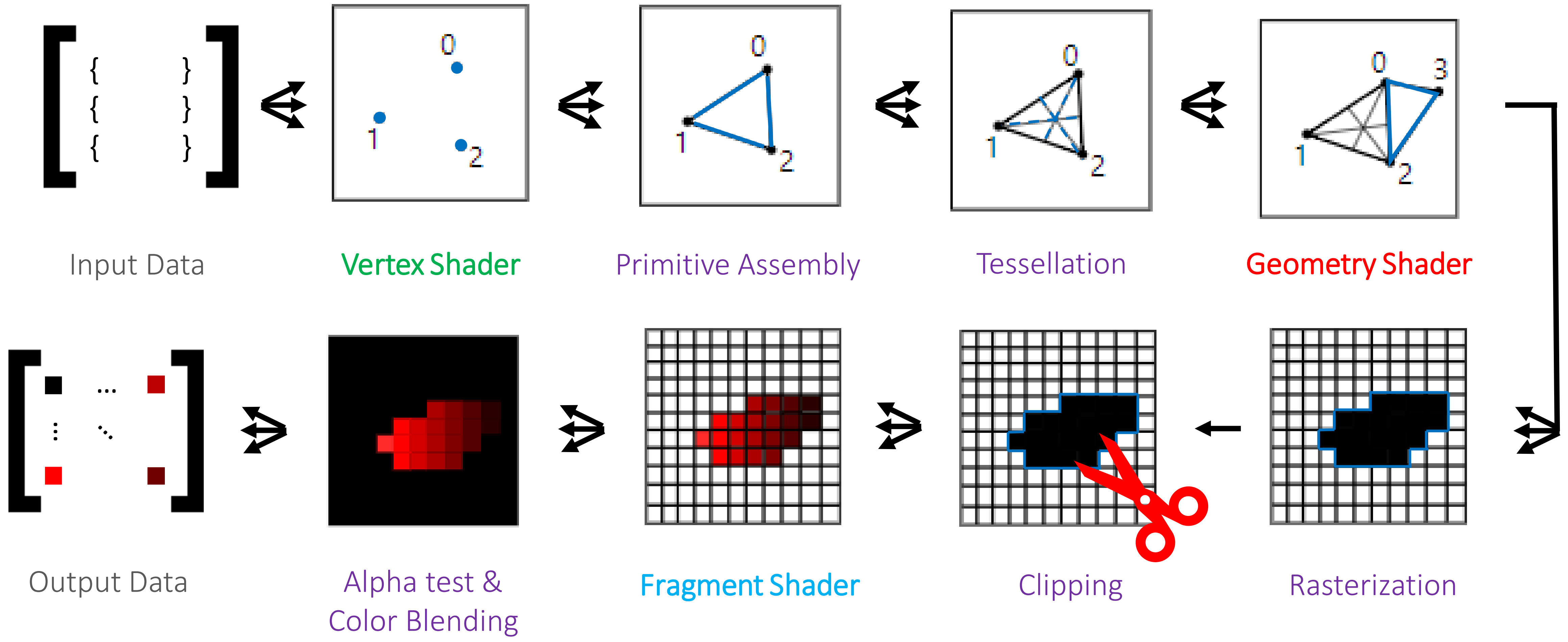
Output Data



Return a Framebuffer

The information in this buffer are the values of the color components (RGB) for each pixel

Overall view



Textures

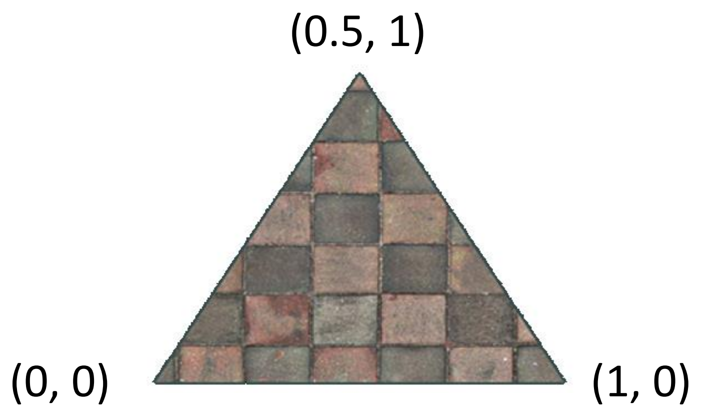
Allows to give the illusion the object is detailed without having to specify vertices

Associate each vertex to a texture coordinate

A fragment interpolation is then done for the other fragments

Sample code:

```
float texCoords[] = {
    0.0f, 0.0f,  // lower-left corner
    1.0f, 0.0f,  // lower-right corner
    0.5f, 1.0f   // top-center corner
};
```



Transformations

Make an object dynamic using matrix objects & by combining the matrices

Some library can be used like the GLM (OpenGL Mathematics) library

Useful matrices

Scaling Matrix

$$\begin{bmatrix} S_1 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 \\ 0 & 0 & S_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} S_1 \cdot x \\ S_2 \cdot y \\ S_3 \cdot z \\ 1 \end{pmatrix}$$

Translation Matrix

$$\begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} x + T_x \\ y + T_y \\ z + T_z \\ 1 \end{pmatrix}$$

Rotation Matrix

Around X-axis

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} x \\ \cos\theta \cdot y - \sin\theta \cdot z \\ \sin\theta \cdot y + \cos\theta \cdot z \\ 1 \end{pmatrix}$$

Around Y-axis

$$\begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta \cdot x + \sin\theta \cdot z \\ y \\ -\sin\theta \cdot x + \cos\theta \cdot z \\ 1 \end{pmatrix}$$

Around Z-axis

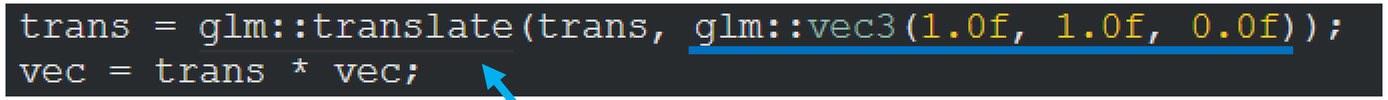
$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta \cdot x - \sin\theta \cdot y \\ \sin\theta \cdot x + \cos\theta \cdot y \\ z \\ 1 \end{pmatrix}$$

Sample code

Translating a vector of (1,0,0) by (1,1,0)

The matrix to transform (identity Matrix4)

The translation vector to apply to the matrix



```
trans = glm::translate(trans, glm::vec3(1.0f, 1.0f, 0.0f));
vec = trans * vec;
```

Multiply vec by the translation matrix

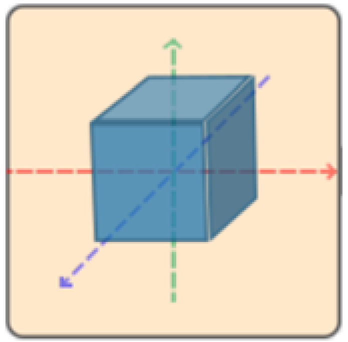
A translate function

Coordinates system

Transforming coordinates to NDC is done by a process regrouping several intermediate coordinate systems

- Local Space
- World Space
- View Space
- Clip Space
- Screen Space

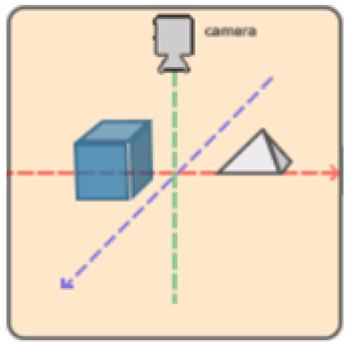
Local Space



Coordinates of the object relative to its local origin

In general, all new objects have (0, 0, 0) as initial position

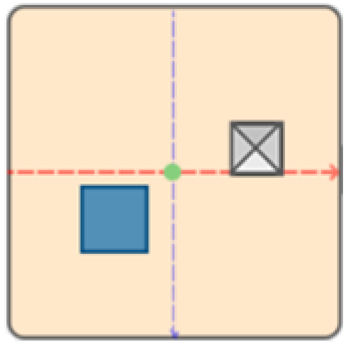
World Space



Coordinates of all the objects are relative to some global origin of the world

We use a model matrix which translates, scales and/or rotates the object to place it in the world

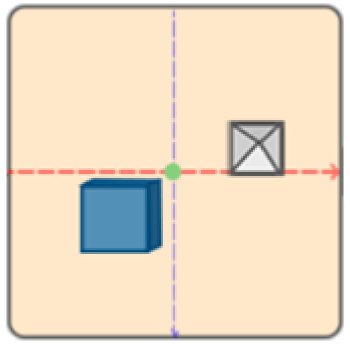
View Space



Each coordinates is seen from the camera’s point of view

This is done by a combination of translations & rotations of the scene which is stored in a view matrix

Clip Space



Each coordinates is seen from the camera's point of view

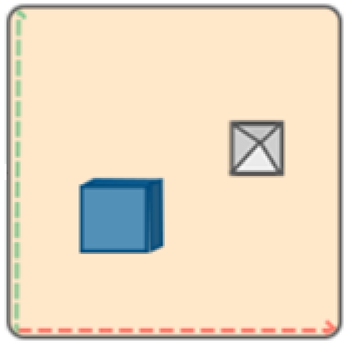
For this step, we use a projection matrix which transform the coordinates into NDC

Example:

Specified range [-1000, 1000] for each dimension

$$\left\{ \begin{array}{lcl} (1250, 500, 750) & \rightarrow & \text{Not visible} \\ (900, 500, 750) & \rightarrow & \text{Visible} \end{array} \right.$$

Screen Space

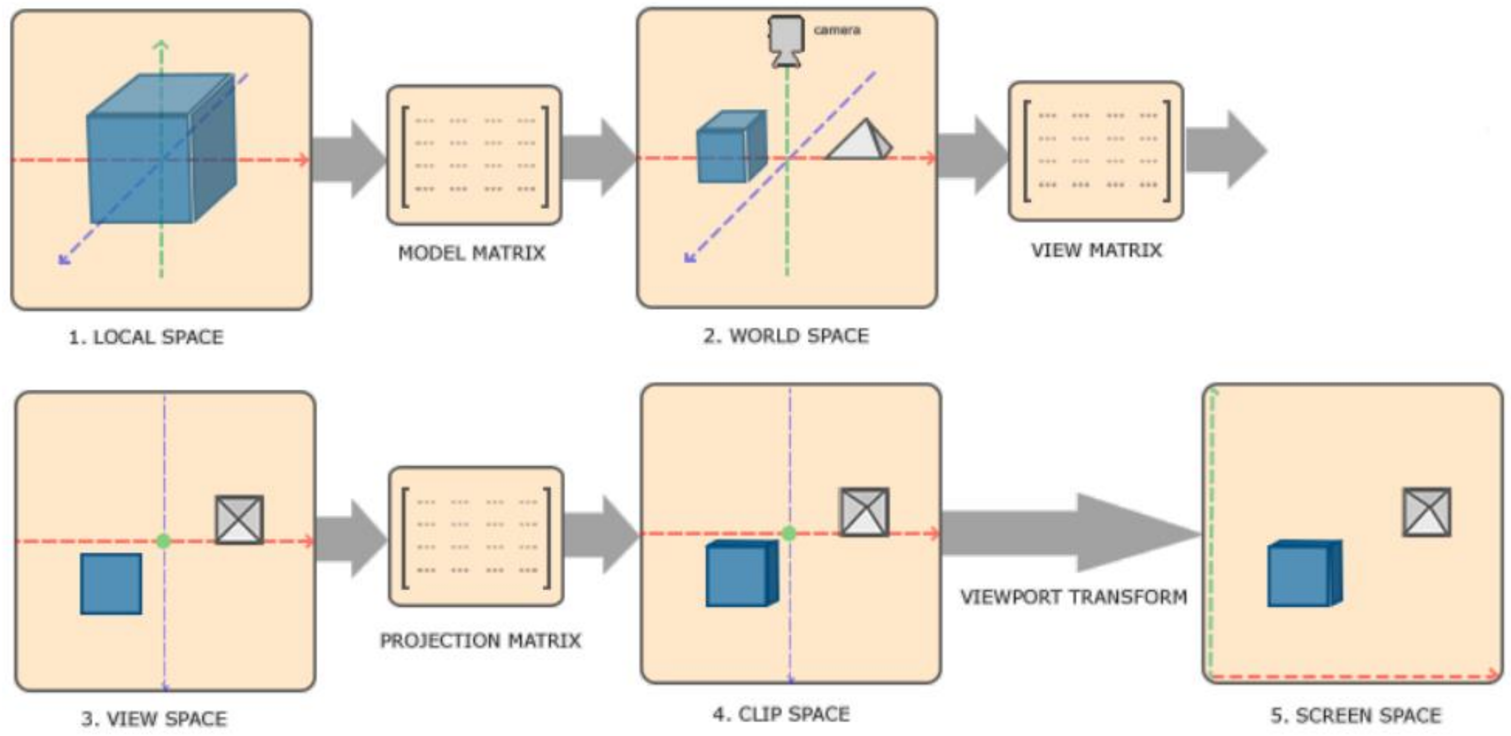


Transforms the NDC coordinates to the window coordinates with the *glViewport()* function

Resulting coordinates are then sent to the rasterizer

Overall view

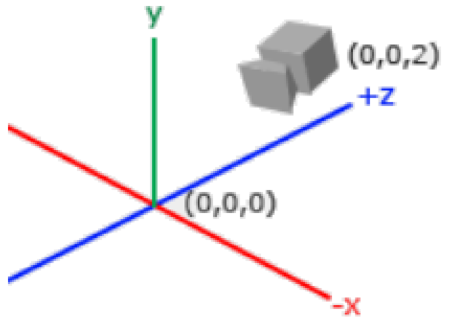
A vertex coordinate is transformed to clip coordinates as follow: $V_{clip} = \underline{M_{projection} \cdot M_{view} \cdot M_{model}} \cdot V_{local}$



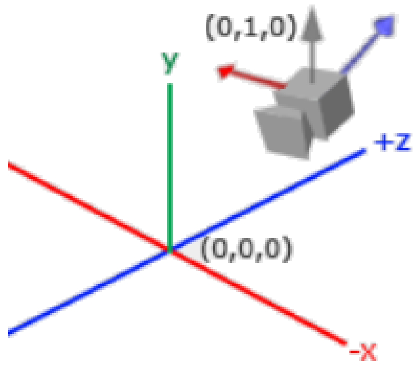
Source: https://learnopengl.com/Getting-started/Coordinate-Systems

Camera

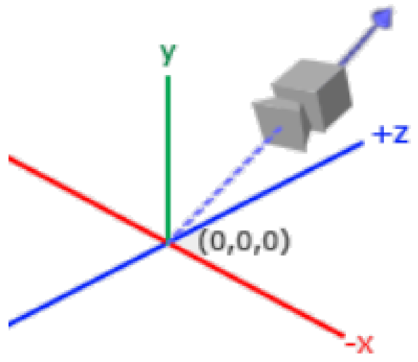
To define a camera we need 4 pieces of information



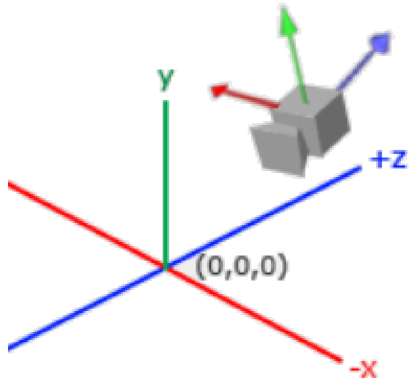
1. Its position in the world space



3. A vector pointing to the right

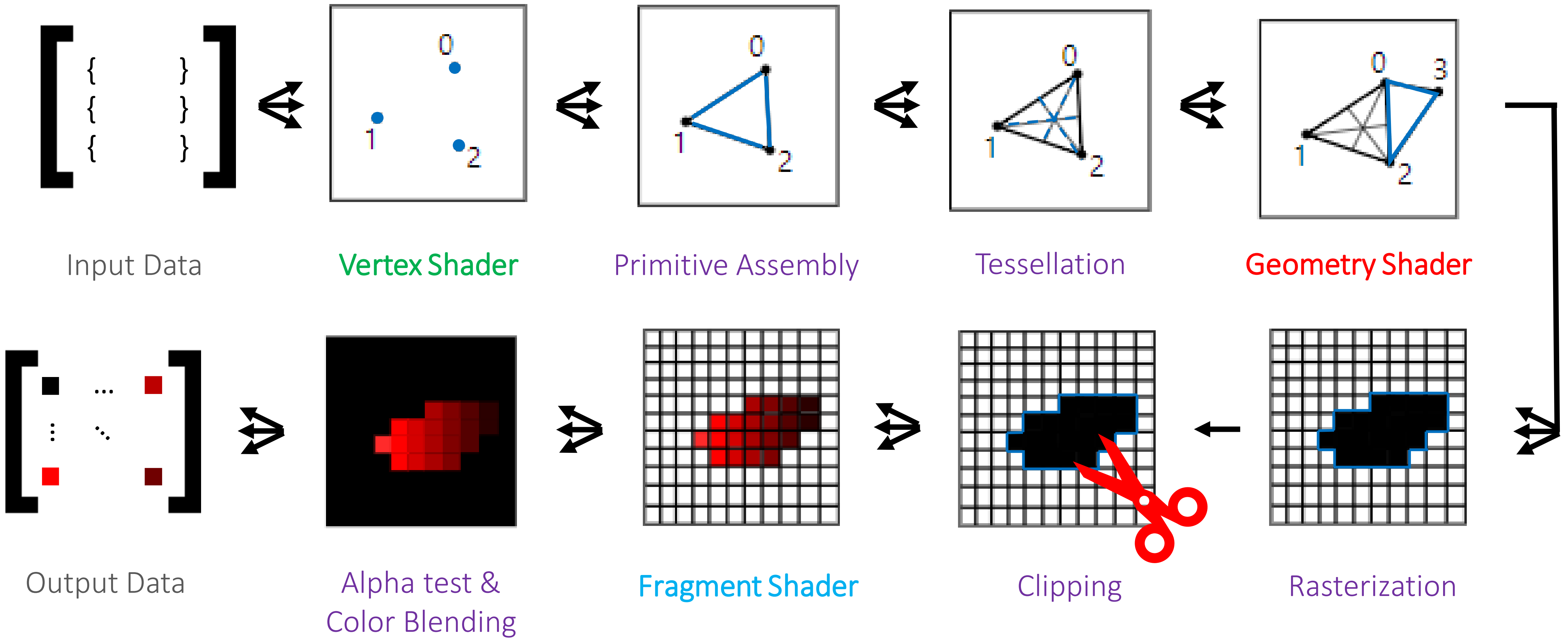


2. Its direction



4. A vector pointing upwards

Recall : Graphics pipeline



Pipeline abstraction

We can see the pipeline as a function composition
which can give us:

$$output\_data = (\mathrm{cb} \circ \mathrm{at} \circ \underset{\substack{\uparrow\\ \text{Fragment Shader function}}}{\mathrm{fs}} \circ \mathrm{c} \circ \mathrm{r} \circ \mathrm{t} \circ \mathrm{pa} \circ \underset{\substack{\nwarrow\\ \text{Vertex Shader function}}}{\mathrm{vs}})\ (input\_data)$$

Context

We can define the notion of context that gives
us the valid constants for a run (see after Uniforms)

The formula below is applied for every run

$$\boxed{\textit{output\_data} = (cb \circ at \circ fs \circ c \circ r \circ t \circ pa \circ vs)\ (\textit{input\_data})}$$

Recall: Input data

A VBO is built containing the attributes of all vertices which give us a huge vector of data

To work with that, we have to use offsets, strides, etc.

Idea of the abstraction

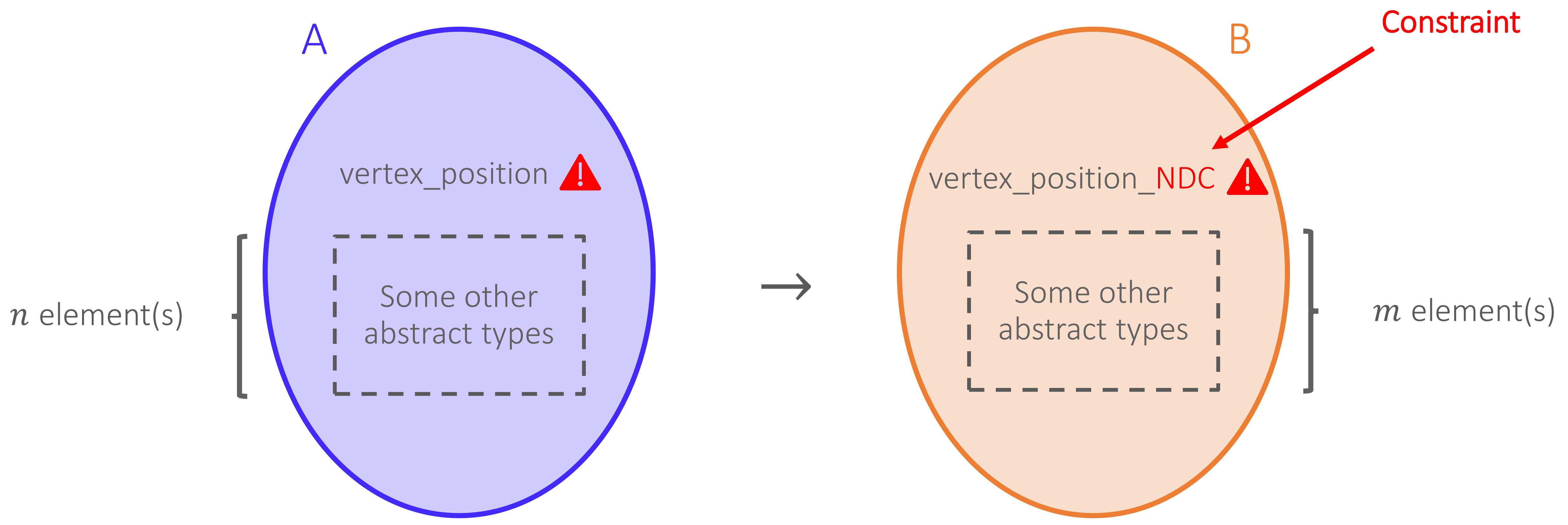
No longer working with containers of type

Ex: ~~vec3, vec4, ivec4,~~ mat4, …

But with abstract type objects

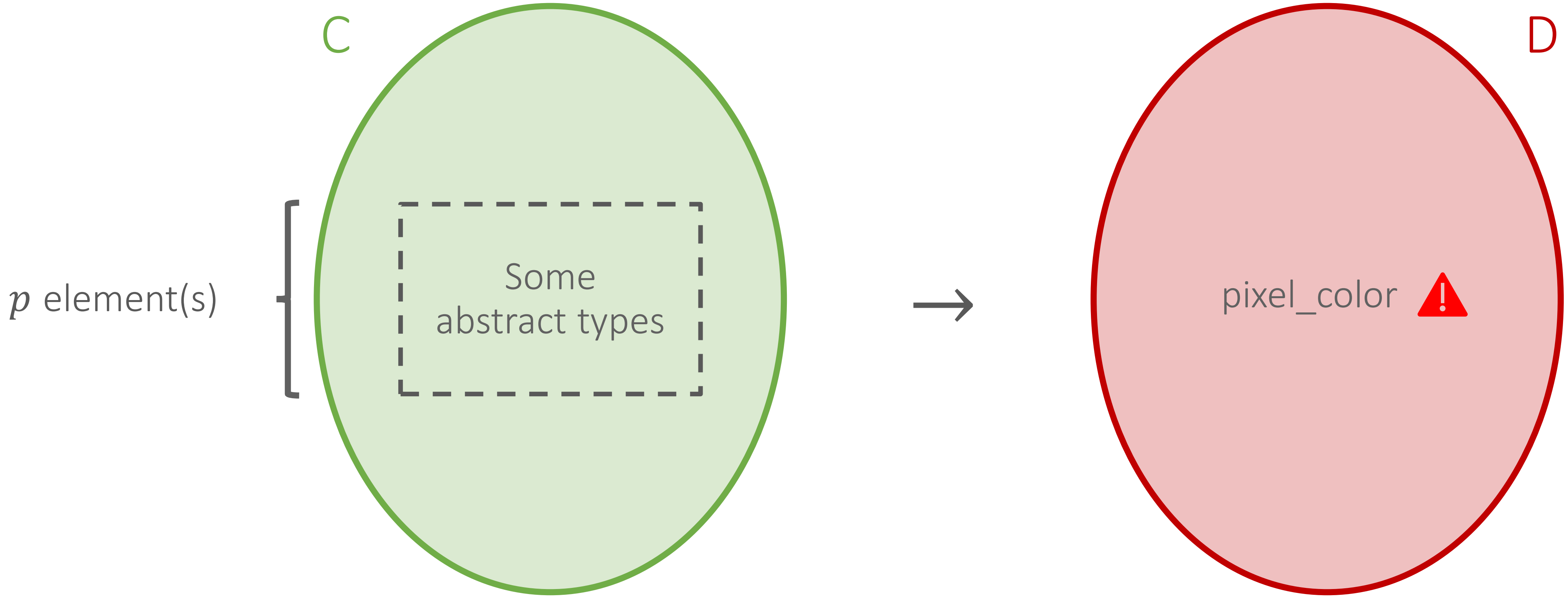
Ex: color, position, textures, …

Vertex Shader function $\text{vs} : A \rightarrow B$



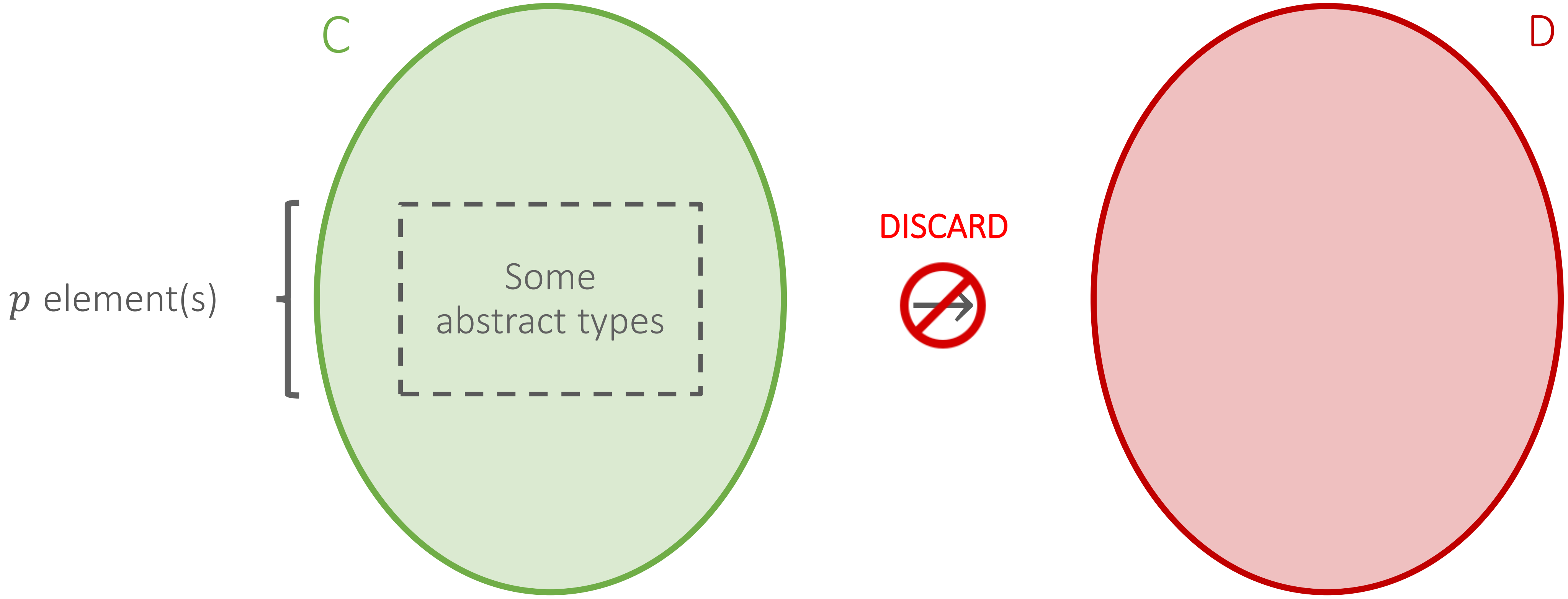
$\text{vs}(\_ : vertex\_position, \cup \_ : (A_i \setminus vertex\_position))$

Fragment Shader function $\text{fs} : \text{C} \rightarrow \text{D}$



$\text{fs}(\_ : C_i)$

Fragment Shader function Alternative $\text{fs} : C \rightarrow D$



$\text{fs}(\_ : C_i)$

Several signatures

$\neq$

Depending on why a shader is created,
the signature will be different

Examples:

vs(_ : position)

vs(_ : position, _ : color)

vs(_ : position, _ : color, _ : texture:)

fs()

fs(_ : fragment, _ : light:)

fs(_ : fragment, _ : light, _ : texture:)

Uniforms

We saw that uniform variables are global variables

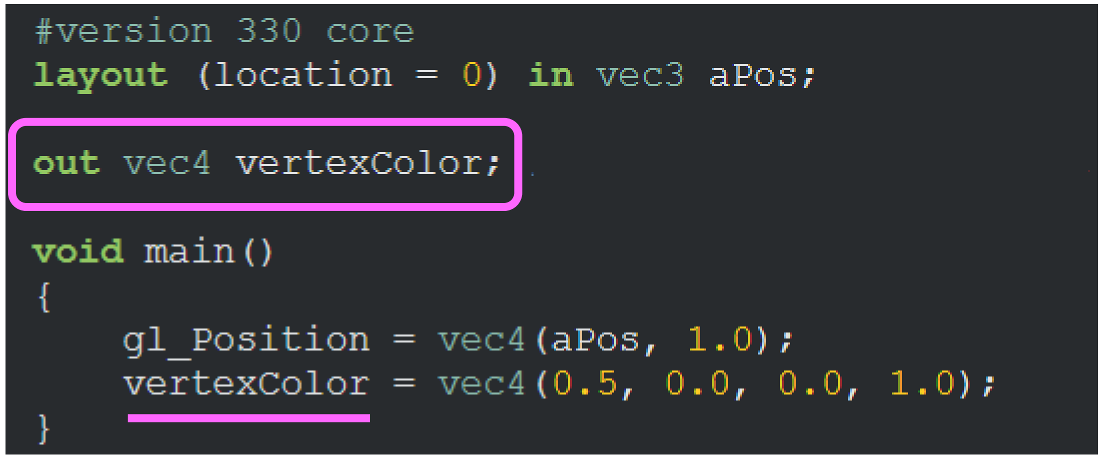
They are part of the domain and
the codomain of the vs() & fs() function

These variables are set for a run and define the context

Type checking between vs() & fs()

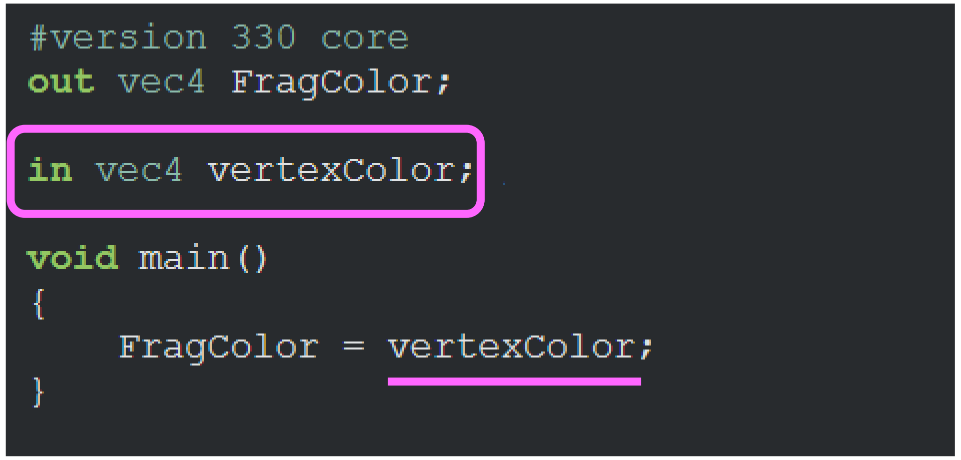
Check that names and types variables shared between the vertex & the fragment shader are identical

Example:



```
#version 330 core
layout (location = 0) in vec3 aPos;

out vec4 vertexColor;

void main()
{
    gl_Position = vec4(aPos, 1.0);
    vertexColor = vec4(0.5, 0.0, 0.0, 1.0);
}
```

Vertex shader



```
#version 330 core
out vec4 FragColor;

in vec4 vertexColor;

void main()
{
    FragColor = vertexColor;
}
```

Fragment shader

Recall : Different languages

DirectX High-Level Shader Language

(Unreal Engine)

Cg Shader Language

(Unity)

OpenGL Shading Language

Similar structures

A sample Cg vertex shader:

Types definition

Calculate output coordinates & colors

Uniform keyword

Output

```
// input vertex
struct VertIn {
    float4 pos   : POSITION;
    float4 color : COLOR0;
};

// output vertex
struct VertOut {
    float4 pos   : POSITION;
    float4 color : COLOR0;
};

// vertex shader main entry
VertOut main(VertIn IN, uniform float4x4 modelViewProj) {
    VertOut OUT;
    OUT.pos     = mul(modelViewProj, IN.pos);
    OUT.color   = IN.color;
    return OUT;
}
```

Same abstraction

The different shader languages are very similar

We could therefore use the same abstraction for any language

Domain-Specific Language (DSL)

A DSL is a programming language whose specifications
allow to overcome some constraints in a specific domain

The specific domain will be for us the shaders
and especially vertex & fragment shaders

Advantages & disadvantages

✓

DSL will allow us to gain in productivity

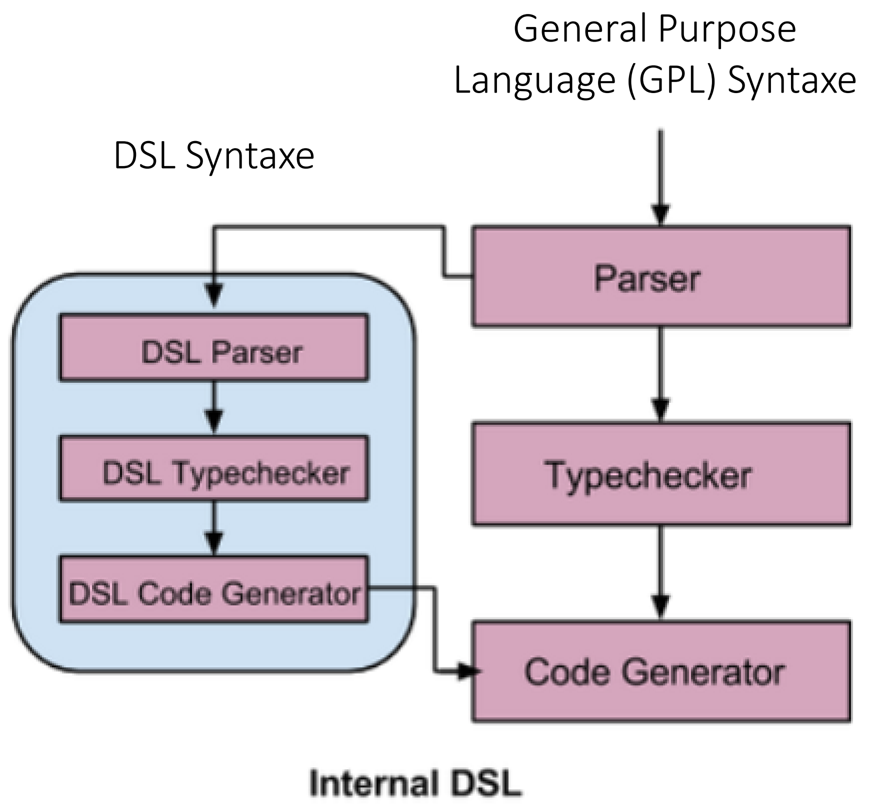
DSL can be reused for other purposes

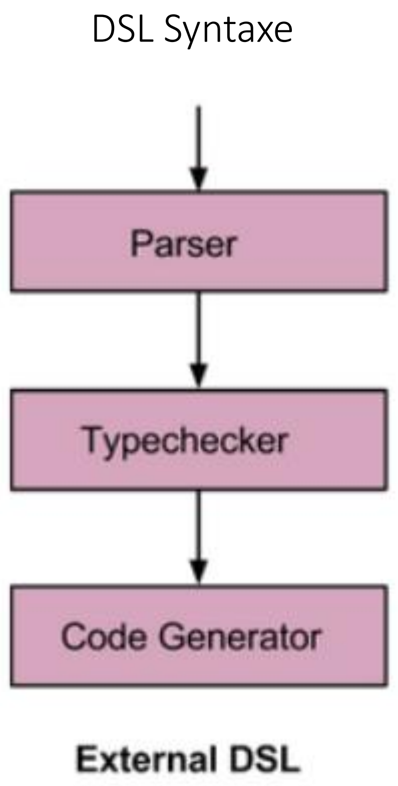
✗

DSL maintenance is complicated

The cost of a DSL is expensive

Different types of DSL





Our way

First, we will go on an Internal DSL based
on the Swift language

Later, we can potentially encounter
a lot of constraints relating to Swift

If so, we will go on an External DSL at this time

Main idea

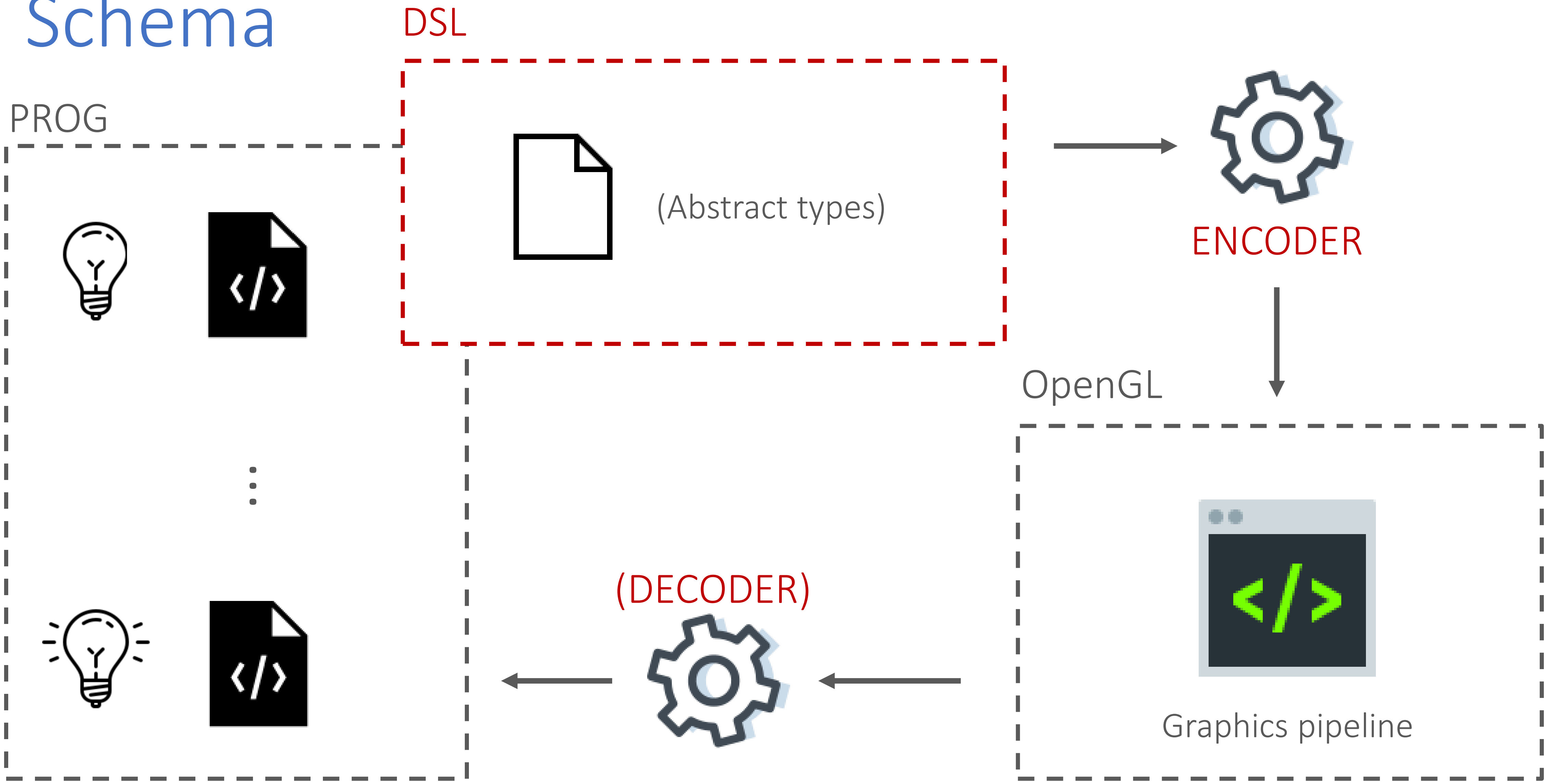
We write in our program a
vertex & a fragment shader with our DSL

We send them to an encoder which will translate
the abstract types into containers of types

This translation can then be evaluated by the
graphics pipeline of OpenGL

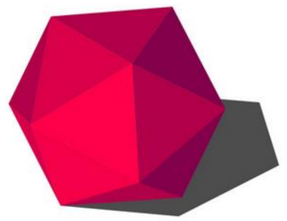
(Then a decoder allows us to get the results
with the desired abstract types)

Schema

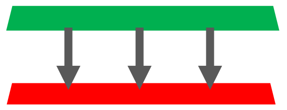

DSL
PROG
(Abstract types)
ENCODER
OpenGL
Graphics pipeline
(DECODER)

Gator

Language created by *Dietrich Geisler*, *Irene Yoon*, *Aditi Kabra*, *Horace He*, *Yinnon Sanders* & *Adrian Sampson*

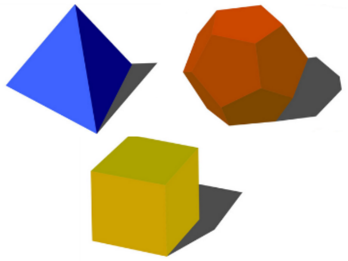


Higher level programming model that allows focus on the geometric semantics of programs

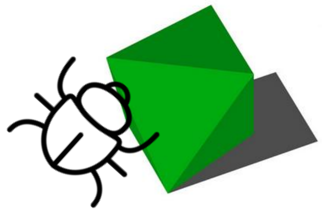


Gator is a surface language with an extended type system based on a target language with a type set (GLSL)
A type-directed translation allows to compile Gator to GLSL

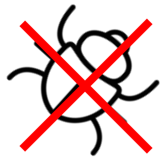
Problem & ideas



3D scenes consist of many individual objects & the rendering code must combine vectors of different coordinate systems



Geometry bugs are difficult to detect



Introduce a type system to eliminate this class of bugs & implement a mechanism that can exclude some bugs by construction

A geometry type

“Geometry types describe the coordinate system representing each value and the transformations that manipulate them”

A geometry type is made up of 3 components:

- Reference frame
- Geometric object
- Coordinate scheme

Define which operations are legal

Syntax

Geometry types give more information about the objects they represent than simple vector types in GLSL

Syntax for a geometry type is *scheme*<*frame*>.*object*

Example:

cart3<world>.point

represents the type of a point in world space represented in a 3D cartesian coordinate scheme

Example: Diffuse Lighting

GLSL implementation

```
float naiveDiffuse(vec3 lightPos, vec3 fragPos, vec3 fragNorm) {
  vec3 lightDir = normalize(lightPos - fragPos);
  return max(dot(lightDir, normalize(fragNorm)), 0.);
}
```

lightPos & fragPos have the same type but they are not geometrically compatible
We have different vectors in different coordinate systems

Subtraction between fragPos (model space) & lightPos (world space)

GLSL implementation (Cont.)

```
float naiveDiffuse(vec3 lightPos, vec3 fragPos, vec3 fragNorm) {
  vec3 lightDir = normalize(lightPos - uModel * fragPos));
  return max(dot(lightDir, normalize(fragNorm)), 0.);
}
```

To correct the problem we transform the two vectors into a common coordinate system

We define a transformation matrix to go from model to world space

GLSL implementation (Cont.)

```
float naiveDiffuse(vec3 lightPos, vec3 fragPos, vec3 fragNorm) {
  vec3 lightDir = normalize(lightPos - vec3(uModel * vec4(fragPos, 1.)));
  return max(dot(lightDir, normalize(fragNorm)), 0.);
}
```

3x3 Cartesian transformation matrices allow only linear transformations

4x4 transformation matrices in Homogeneous coordinates can express affine transformations

Cartesian to Homogeneous: $[x, y, z] \rightarrow [x, y, z, 1.]$
Homogeneous to Cartesian: $[x, y, z, w] \rightarrow [x/w, y/w, z/w]$

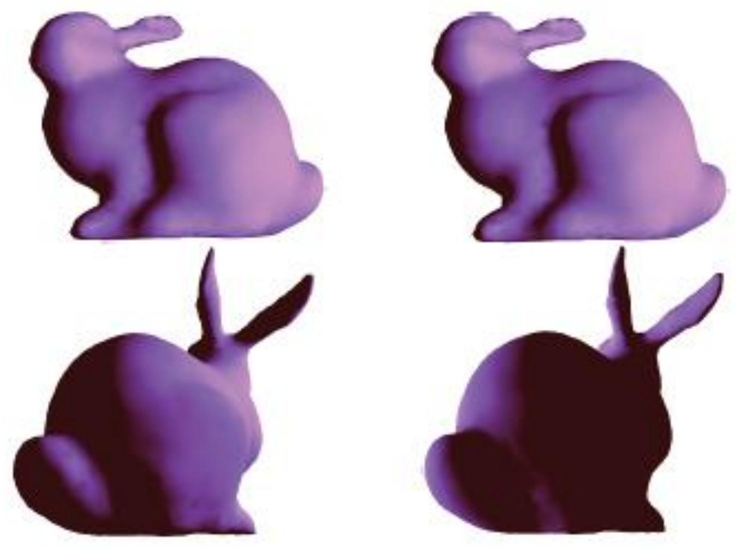
GLSL implementation (Cont.)

```
float naiveDiffuse(vec3 lightPos, vec3 fragPos, vec3 fragNorm) {
  vec3 lightDir = normalize(lightPos - vec3(uModel * vec4(fragPos, 1.)));
  return max(dot(lightDir, normalize(vec3(uModel * vec4(fragNorm, 0.)))));
}
```

The final calculation of the diffuse intensity

We must transform now fragNorm into world space
It's a direction so w should be 0

GLSL implementation (Cont.)


(a) Correct implementation. (b) With geometry bug.

Subtle differences can imply errors

```
frame model has dimension 3;
frame world has dimension 3;
```

Gator implementation

```
float diffuseNaive(
    cart3<world>.point lightPos,
    cart3<model>.point fragPos,
    cart3<model>.direction fragNorm) {
  cart3<world>.direction lightDir = normalize(lightPos - fragPos);
  return max(dot(lightDir, normalize(fragNorm)), 0.0);
}
```

lightPos & fragPos are both positions but their reference frames are different : <world> vs <model>

The subtraction implies an error

Gator implementation (Cont.)

```
with frame(3) r:
coordinate cart3 : geometry {
  object vector is float[3];
  ...
}
```

```
float diffuse(
    cart3<world>.point lightPos,
    cart3<model>.point fragPos,
    cart3<model>.direction fragNorm,
    hom3<model>.transformation<world> uModel) {
  cart3<world>.direction lightDir =
    normalize(lightPos - (uModel * fragPos));
  return max(dot(lightDir, normalize(uModel * fragNorm)), 0.0);
```

We need to define an affine transformation matrix to transform fragPos & fragNorm into world reference frame

Multiplying uModel & fragPos implies an error because the coordinate schemes are different

```
coordinate hom3 : geometry {
  object point is float[4];
  object direction is float[4];
  with frame(3) r:
  object transformation is float[4][4];
  ...
}
```

Gator implementation (Cont.)

```
float diffuse(
    cart3<world>.point lightPos,
    cart3<model>.point fragPos,
    cart3<model>.direction fragNorm,
    hom3<model>.transformation<world> uModel) {
  cart3<world>.direction lightDir =
     normalize(lightPos - reduce(uModel * homify(fragPos)));
  return max(dot(lightDir, normalize(reduce(uModel * homify(fragNorm)))), 0.0);
}
```

homify() allows us to go from cart3<model>.point to hom3<model>.point (w=1)
or to go from cart3<model>.direction to hom3<model>.direction (w=0)

reduce() allows to map Homogeneous to Cartesian coordinates

Subtyping in Gator

Object & type declarations extend existing types

All types must be given a supertype which can be a primitive type (**bool**, **int**, **float**, **string**, *array*) or a geometry type

Subtype of float

Example:

```
type angle is float;
type acute is angle;
type obtuse is angle;
```

Subtype of angle

Conclusion

The Gator type system avoids statically incorrect coordinate system transformation codes

We can thus automatically generate a correct transformation code by construction

→ Programmers do not write vector-matrix multiplication calculations

→ Let the compiler find the right transformations

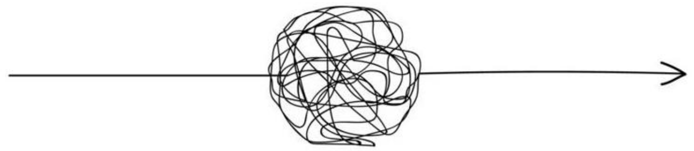
Gator helps to limit the number of geometry bugs

Limitations

The created abstraction remains low level

It’s only based on coordinate system transformations

The syntax is a bit complicated



Inspiration

The notion of surface language

New types based on primitives

color, light, texture, normal, (position)

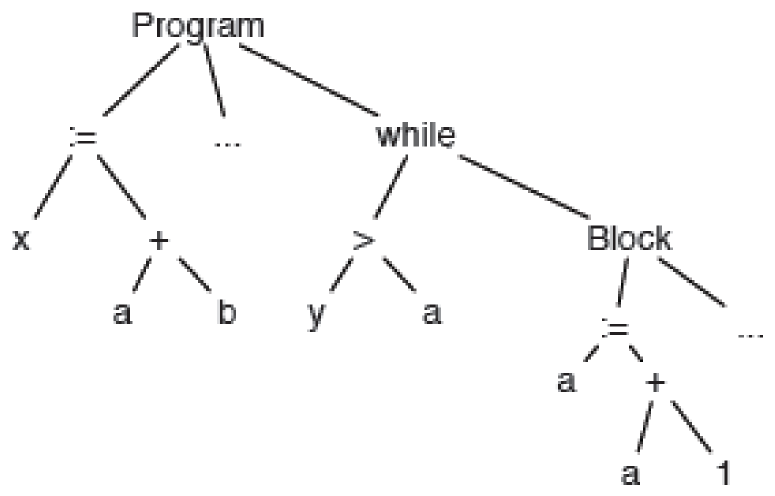
A little less complicated syntax

Abstract Syntax Tree (AST)

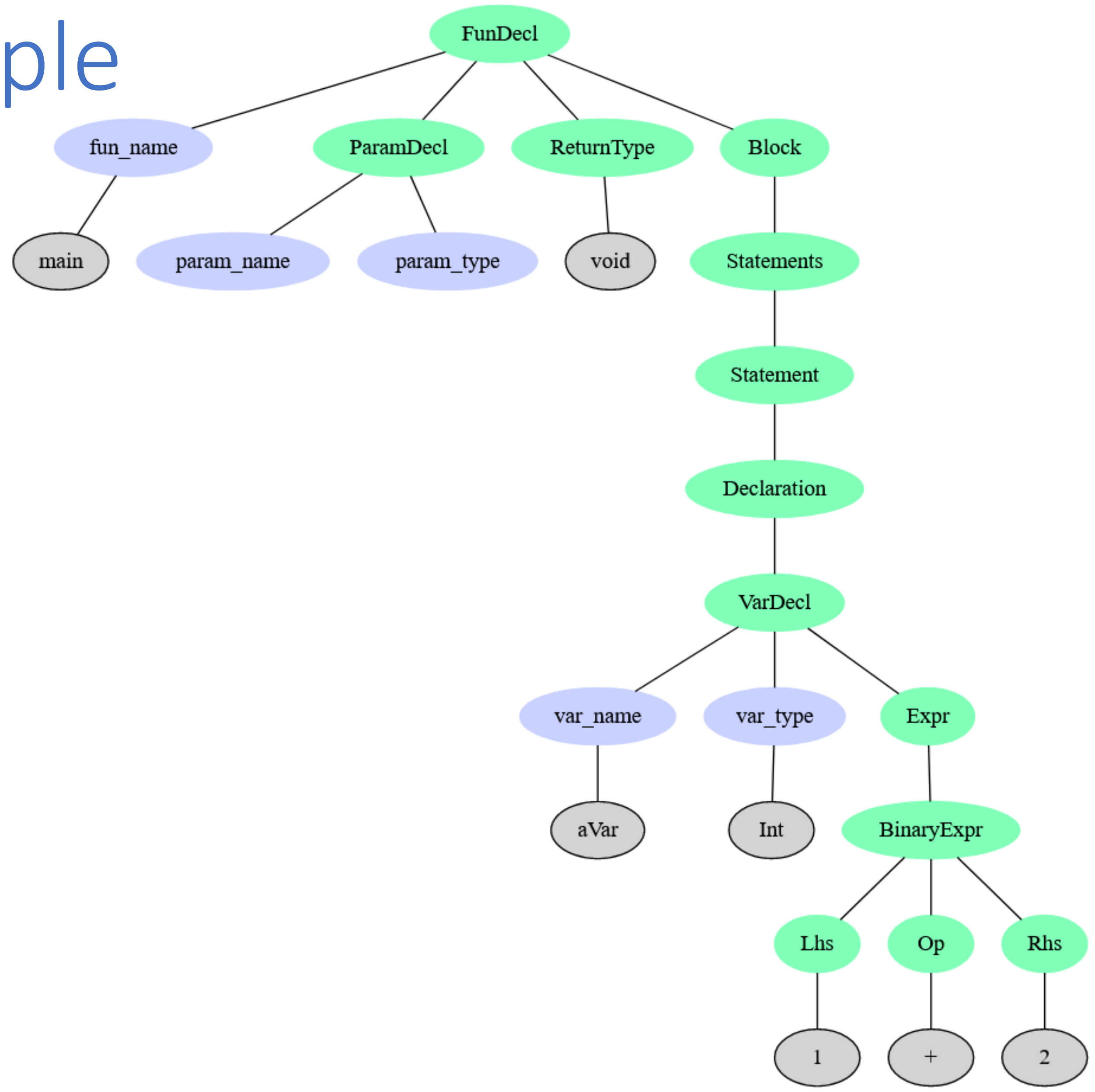
Tree in which, internal nodes are marked by operators and where external ones represent the operands

Example:

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



AST example


FunDecl
fun_name
ParamDecl
ReturnType
Block
main
param_name
param_type
void
Statements
Statement
Declaration
VarDecl
var_name
var_type
Expr
aVar
Int
BinaryExpr
Lhs
Op
Rhs
1
+
2

Some tools

Swift-AST-Explorer

Only supports Swift language

Structure representation with pop-up details
for each element of the code

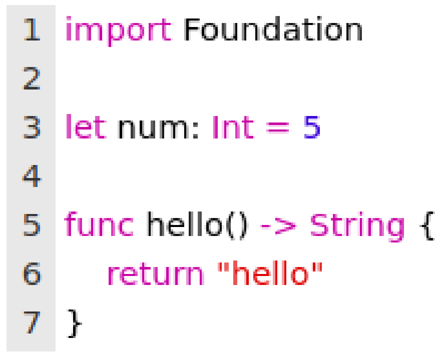
AST-Explorer

Supports a lot of languages like Java, HTML, Python, … & GLSL

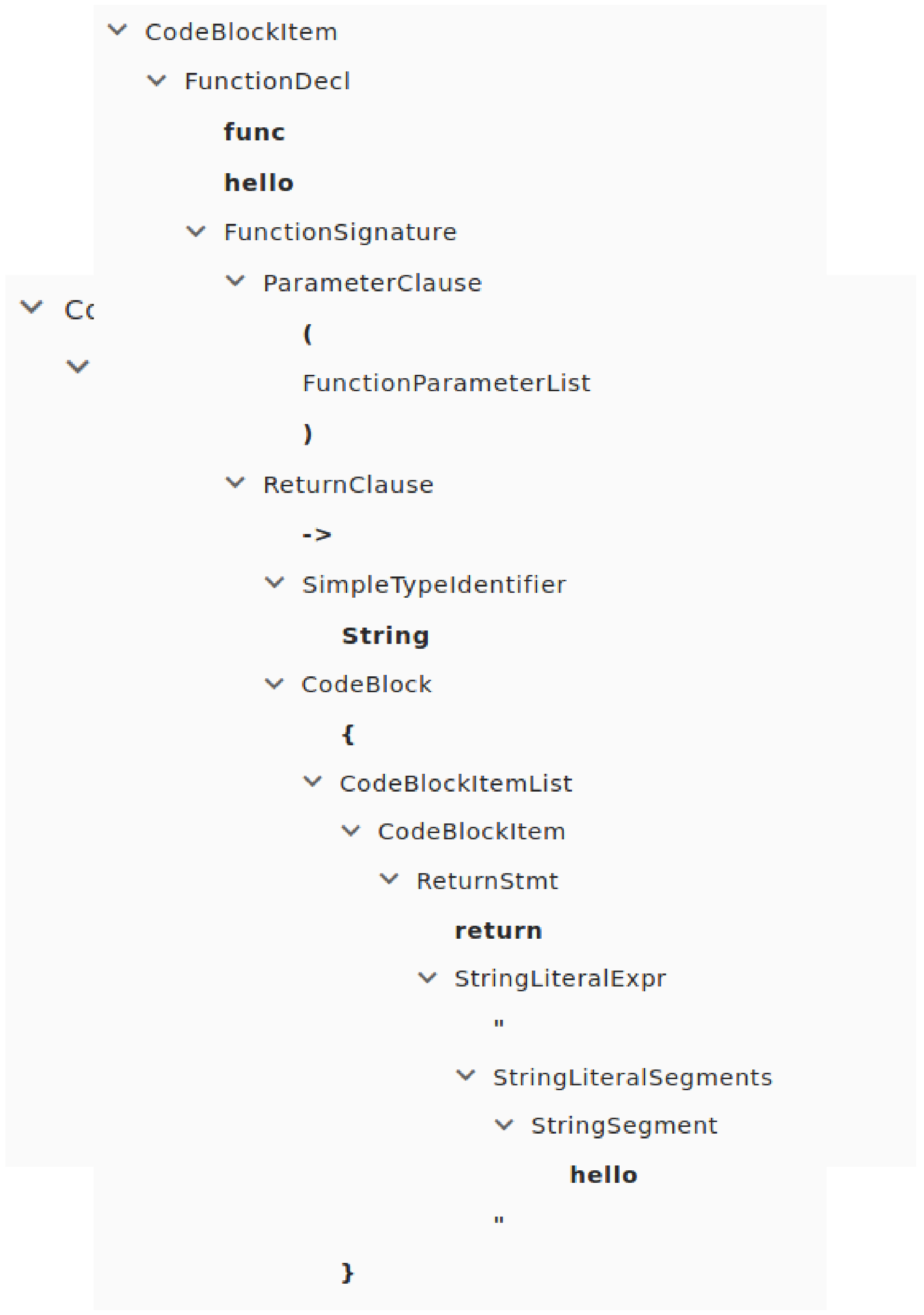
Tree or JSON representation

Examples

Swift-AST-Explorer



```
import Foundation

let num: Int = 5

func hello() -> String {
    return "hello"
}
```

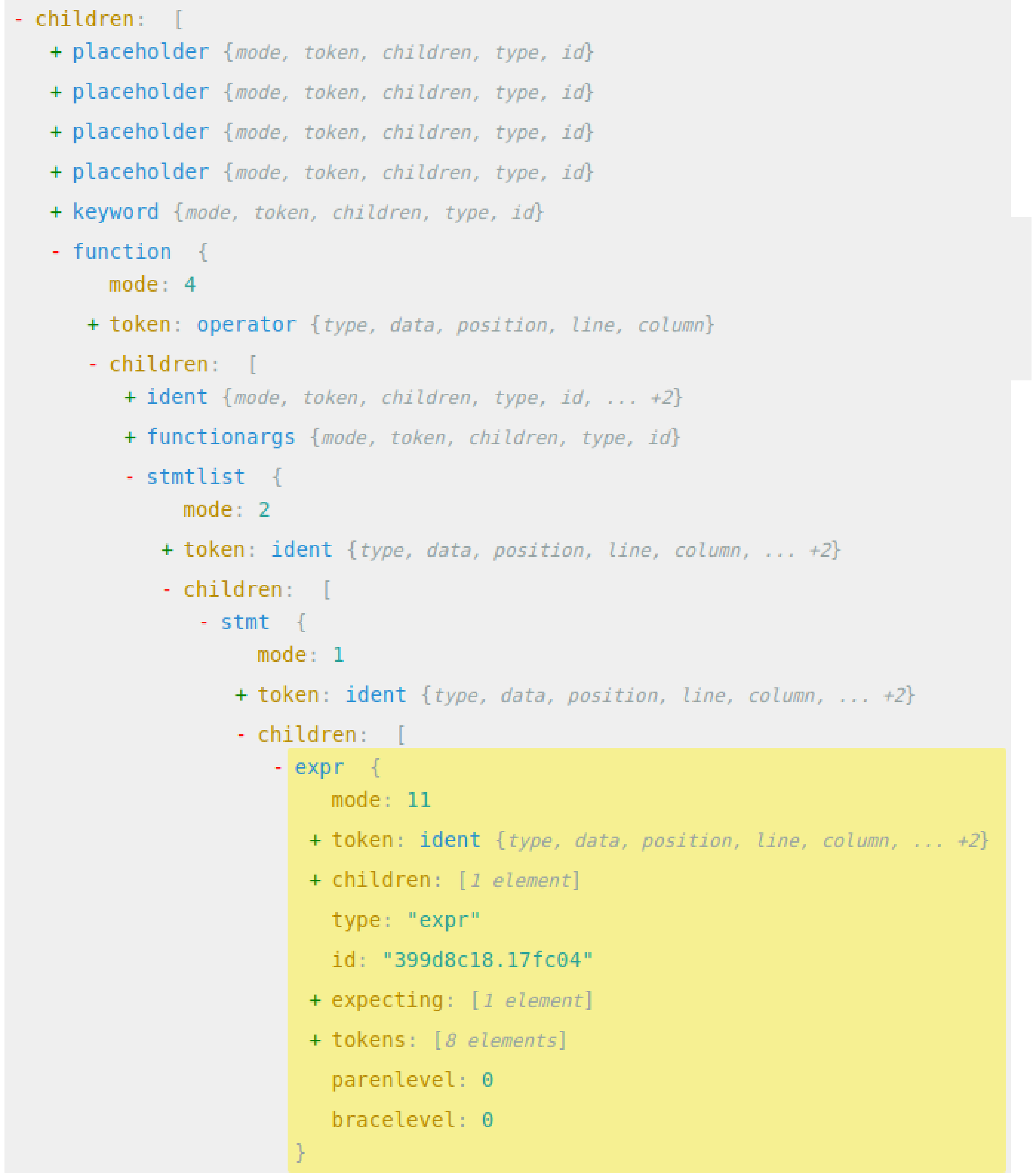


```
CodeBlockItem
  FunctionDecl
    func
    hello
    FunctionSignature
      ParameterClause
        (
        FunctionParameterList
        )
      ReturnClause
        ->
        SimpleTypeIdentifier
          String
        CodeBlock
          {
          CodeBlockItemList
            CodeBlockItem
              ReturnStmt
                return
                StringLiteralExpr
                  "
                  StringLiteralSegments
                    StringSegment
                      hello
                  "
          }
```

Examples (Cont.)

AST-Explorer

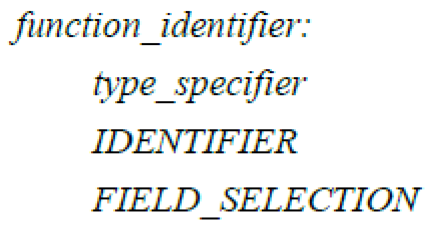
```
varying vec3 ourColor;

void main() {
  FragColor = vec4(ourColor, 1.0f);
}
```



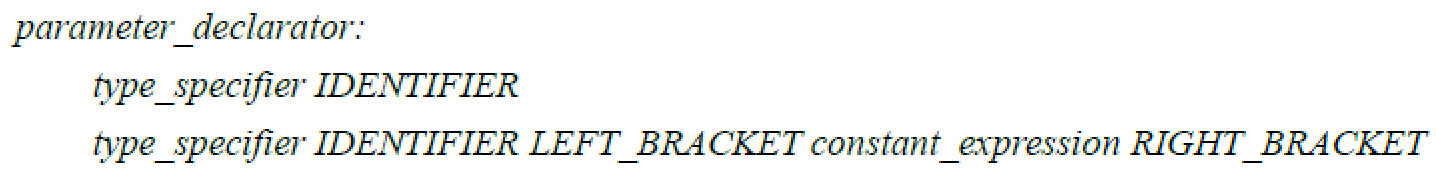
```
- children: [
    + placeholder {mode, token, children, type, id}
    + placeholder {mode, token, children, type, id}
    + placeholder {mode, token, children, type, id}
    + placeholder {mode, token, children, type, id}
    + keyword {mode, token, children, type, id}
    - function {
        mode: 4
      + token: operator {type, data, position, line, column}
      - children: [
          + ident {mode, token, children, type, id, ... +2}
          + functionargs {mode, token, children, type, id}
          - stmtlist {
              mode: 2
            + token: ident {type, data, position, line, column, ... +2}
            - children: [
                - stmt {
                    mode: 1
                  + token: ident {type, data, position, line, column, ... +2}
                  - children: [
                      - expr {
                          mode: 11
                        + token: ident {type, data, position, line, column, ... +2}
                        + children: [1 element]
                          type: "expr"
                          id: "399d8c18.17fc04"
                        + expecting: [1 element]
                        + tokens: [8 elements]
                          parenlevel: 0
                          bracelevel: 0
                        }
```

GLSL 3.0 Grammar

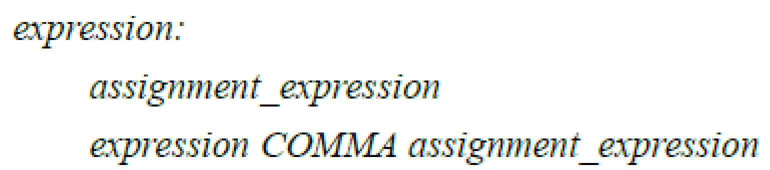
Examples:



function_identifier:
    type_specifier
    IDENTIFIER
    FIELD_SELECTION



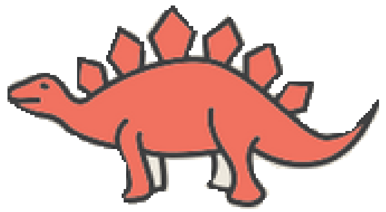
parameter_declarator:
    type_specifier IDENTIFIER
    type_specifier IDENTIFIER LEFT_BRACKET constant_expression RIGHT_BRACKET



expression:
    assignment_expression
    expression COMMA assignment_expression

DynaSOAr

Here, we will be based on the idea of DynaSOAr



Which is an object-oriented language for manipulating objects

General idea

We want to have the perfect language for our use-cases

We want to have high-level objects that can be handled in a simple way

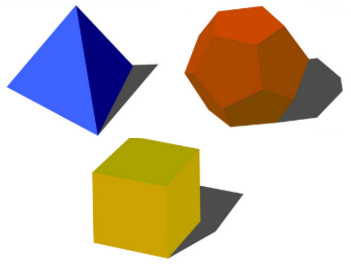
Development

First, we must define our language and the concepts we want

Then, we must specify the syntax of this language

Concepts

Use-cases



Our needs are to write graphics applications in which we manipulate 3D objects

We want to call methods on them, do calculations, etc.

Concepts

Limitations

Here, we want to define everything that it would be possible to do for users ...

... but it's complicated to be complete

Concepts

The abstractions that we need to write an application with 3D objects are:

- The position of the objects
- The type of the objects
- The color of the objects
- The operations linked to these objects
- The physics of the objects

Declarative Language

We are moving towards a declarative language inspired by React

React is based on the notions of:

Components, Properties and States

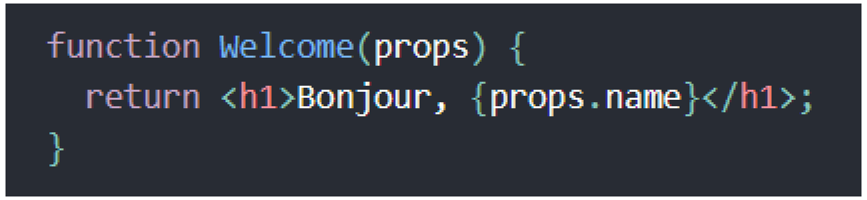
Render function, Update functions

React - Component

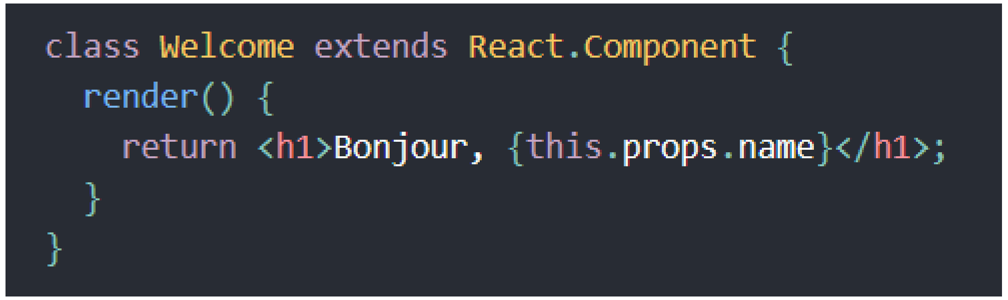
The component system allows us to consider each piece of code independently

We can then combine different components to get something more complex

Example:

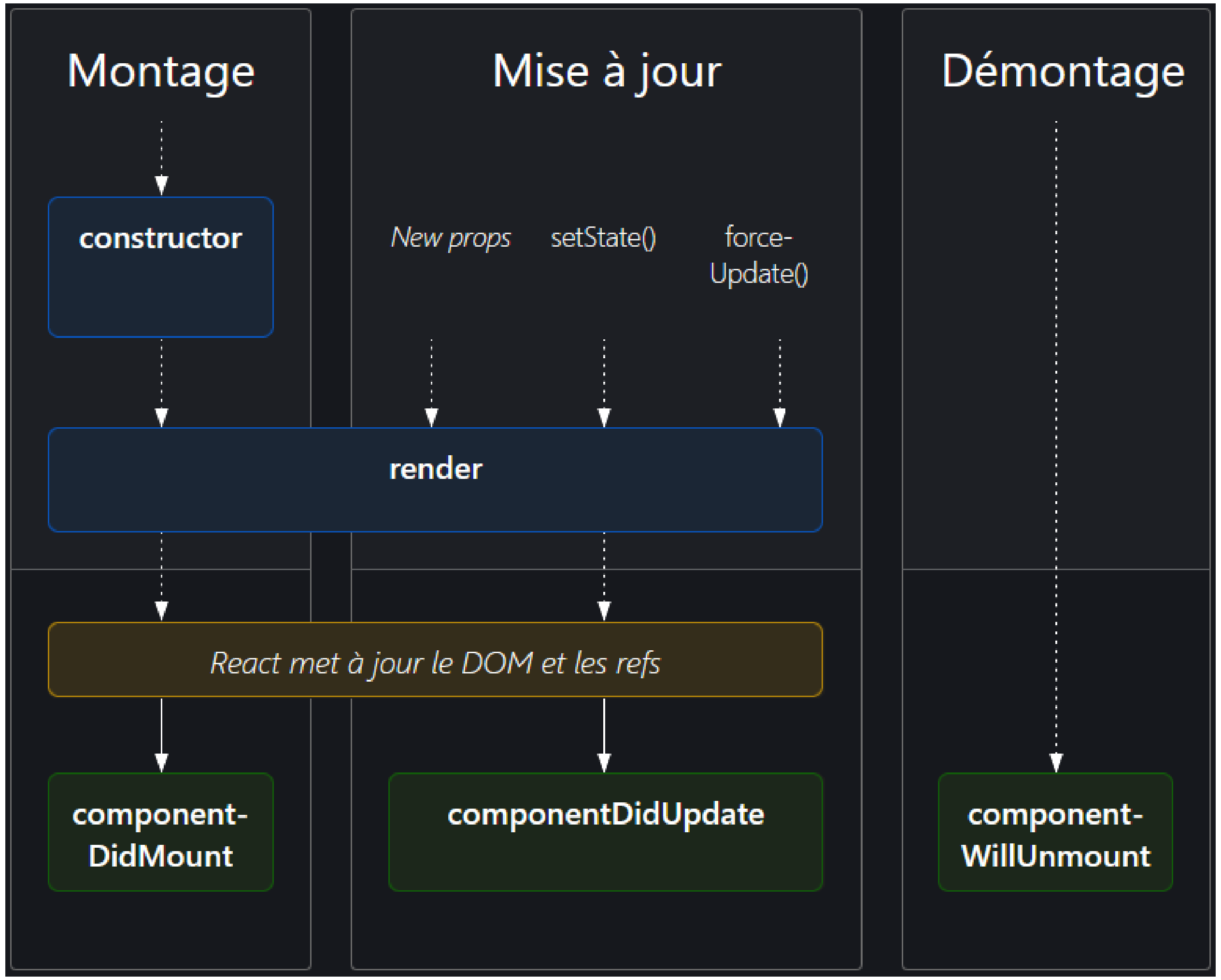


```
function Welcome(props) {
  return <h1>Bonjour, {props.name}</h1>;
}
```



```
class Welcome extends React.Component {
  render() {
    return <h1>Bonjour, {this.props.name}</h1>;
  }
}
```

React - Life cycle



React - Constructor, Props & State

this.props contains the properties defined by the caller of the component

A component should never modify its own properties

Local state contains component-specific data, which may change over time

To modify the local state of a component we use setState()

React - Render()

The render() method takes data as input and returns what should be displayed.

When the local state of a component changes, its display is updated by calling render()

We use a tick() function to update every second / frame

React - componentDidMount() & componentDidUpdate()

componentDidMount() is called immediately after the component is mounted

This is where we make the subscriptions

componentDidUpdate() is called immediately after the update has taken place.

React - componentWillUnmount()

componentWillUnmount() is called immediately before a component is unmounted

Here we delete the subscriptions made in componentDidMount()

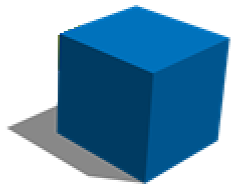
Idea for our language

We give some basic geometric shapes

The idea is to use the notion of mesh (primitive), which is a complete object, composed of several shapes

Example:

A cube is a particular mesh constructed with two triangles per face



Syntax

We define in the syntax how we would like to define and manipulate the objects

Our goal is to have a simple and meaningful syntax

The syntax will be based on React

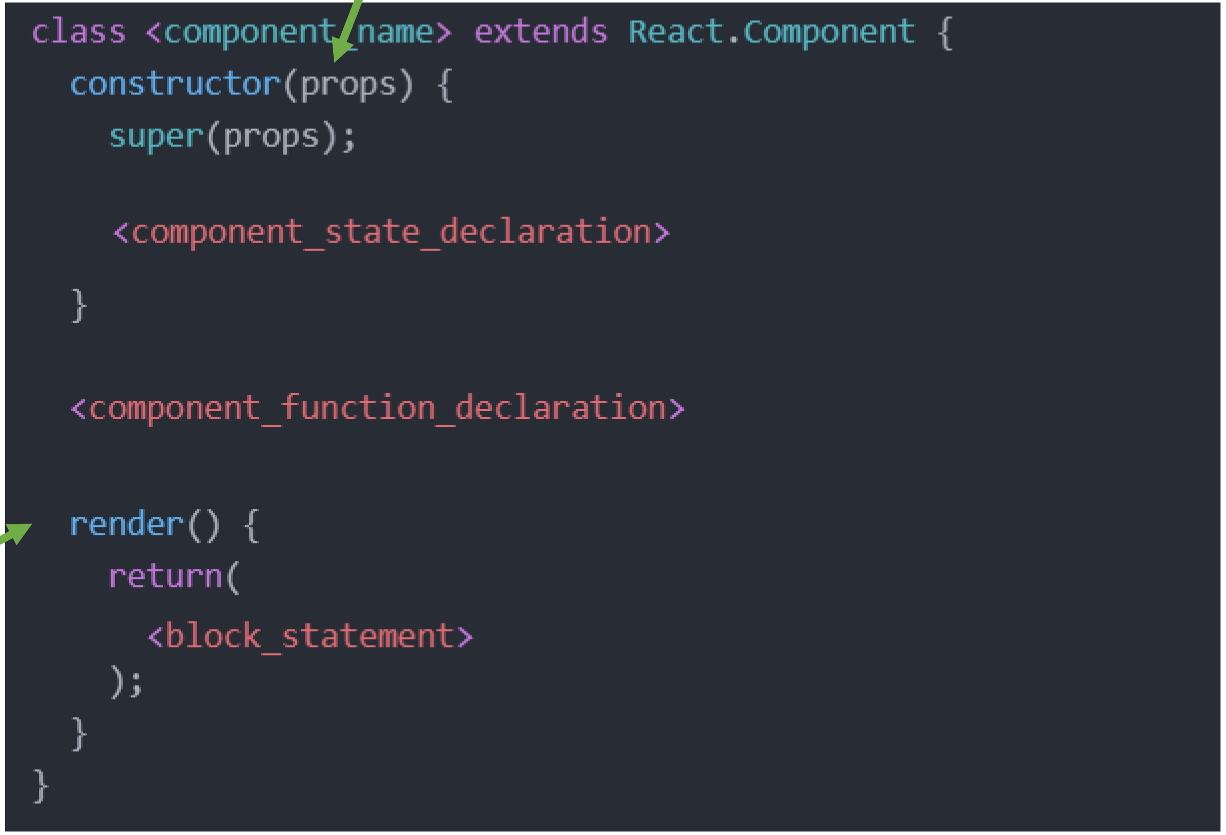
React to our language

We use this notion of components to declare and define a geometric object

We use the same principle of global state, property, and render function

Use of the tick function to update every second / frame

Components


properties passed to the component
declare the component
component rendering function

```
class <component_name> extends React.Component {
  constructor(props) {
    super(props);

    <component_state_declaration>

  }

  <component_function_declaration>


  render() {
    return(
      <block_statement>
    );
  }
}
```

defines the global state of the application

⚠ it is only used in the highest component

```
<component_state_declaration>
```

$\longrightarrow$

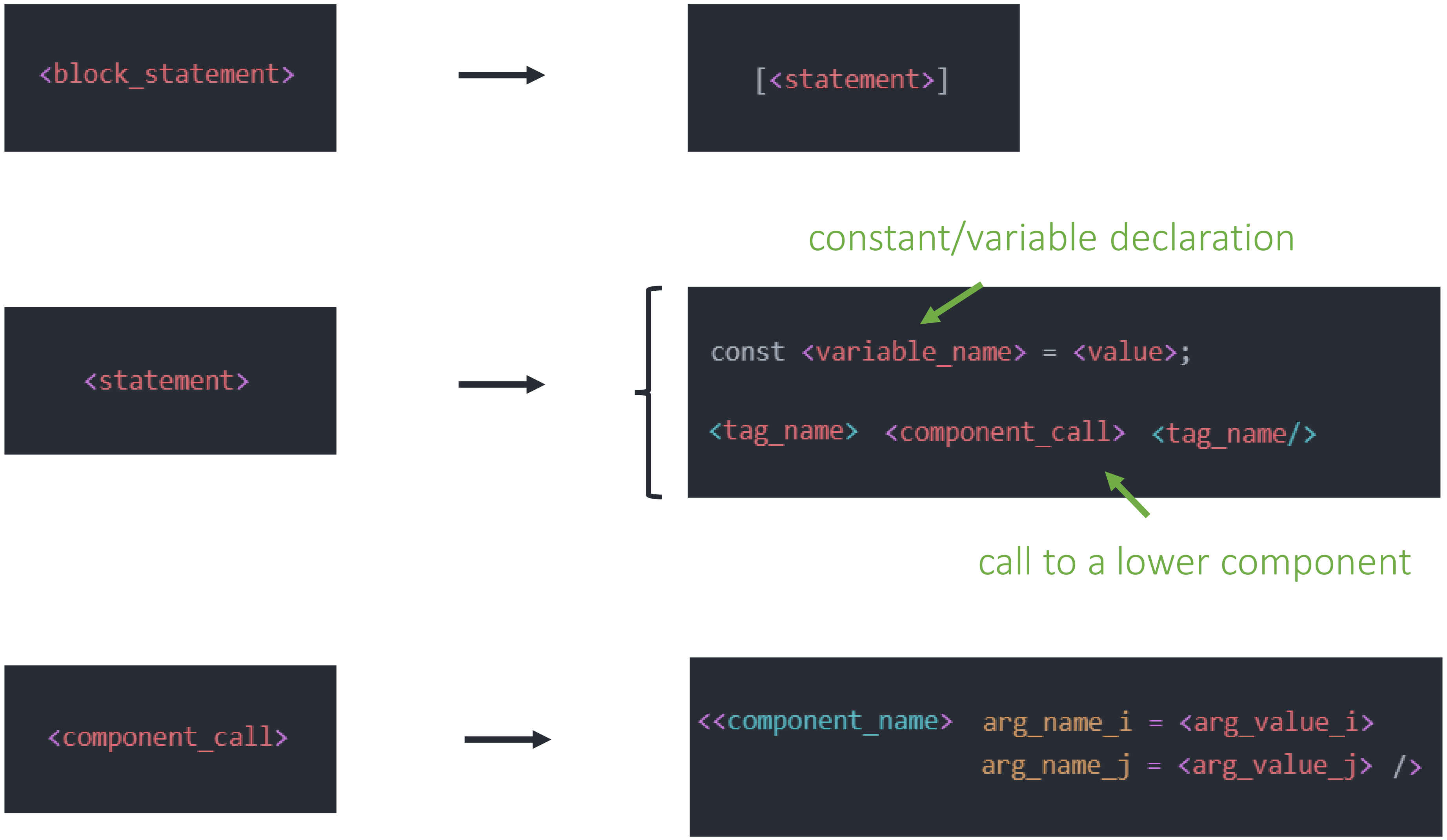
```
this.state = {
              <variable_name_i>: <value_i>,
              ...
            };
```

declares the functions relating to the component

```
<component_function_declaration>
```

$\longrightarrow$

```
<name_function>(<args>) {

    <block_statement>

    return <return_value>
}
```



```
<block_statement>
```

```
[<statement>]
```

```
<statement>
```

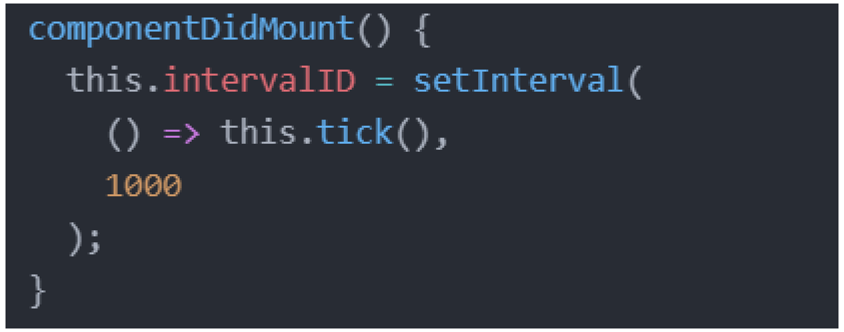
```
const <variable_name> = <value>;

<tag_name>  <component_call>  <tag_name/>
```

```
<component_call>
```

```
<<component_name>  arg_name_i = <arg_value_i>
                   arg_name_j = <arg_value_j> />
```

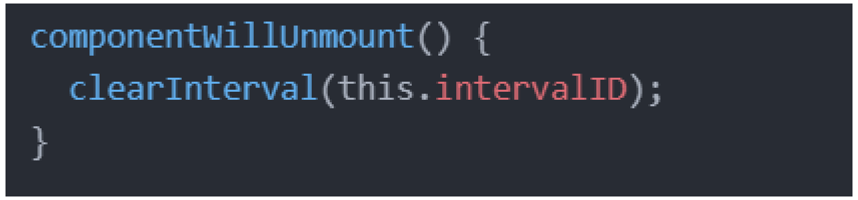
Update State

where subscriptions are made

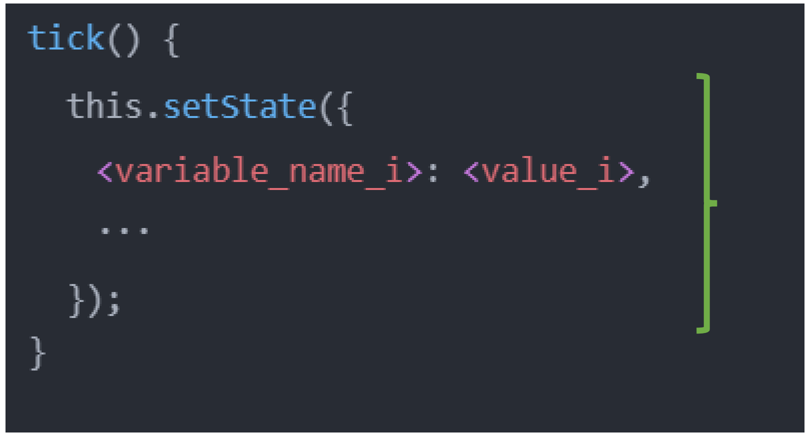


```
componentDidMount() {
  this.intervalID = setInterval(
    () => this.tick(),
    1000
  );
}
```

where subscriptions are destroyed



```
componentWillUnmount() {
  clearInterval(this.intervalID);
}
```

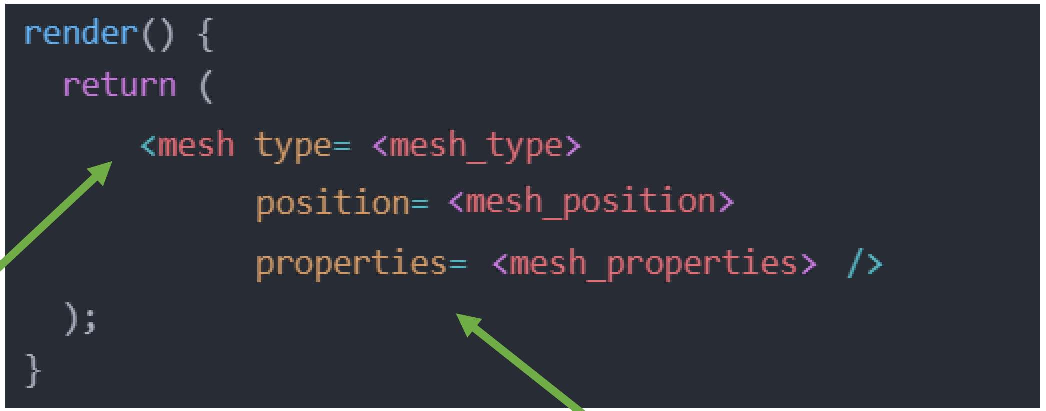


```
tick() {
  this.setState({
    <variable_name_i>: <value_i>,
    ...
  });
}
```

where we update the state

Render a mesh

low-level component rendering function

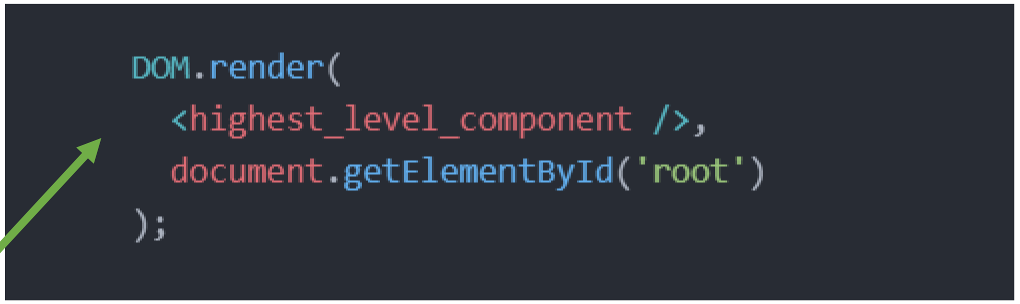


```
render() {
  return (
        <mesh type= <mesh_type>
              position= <mesh_position>
              properties= <mesh_properties> />
  );
}
```

<mesh /> tag specifies that we want to graphically represent an object

we give 3 arguments to the tag: type, position and properties

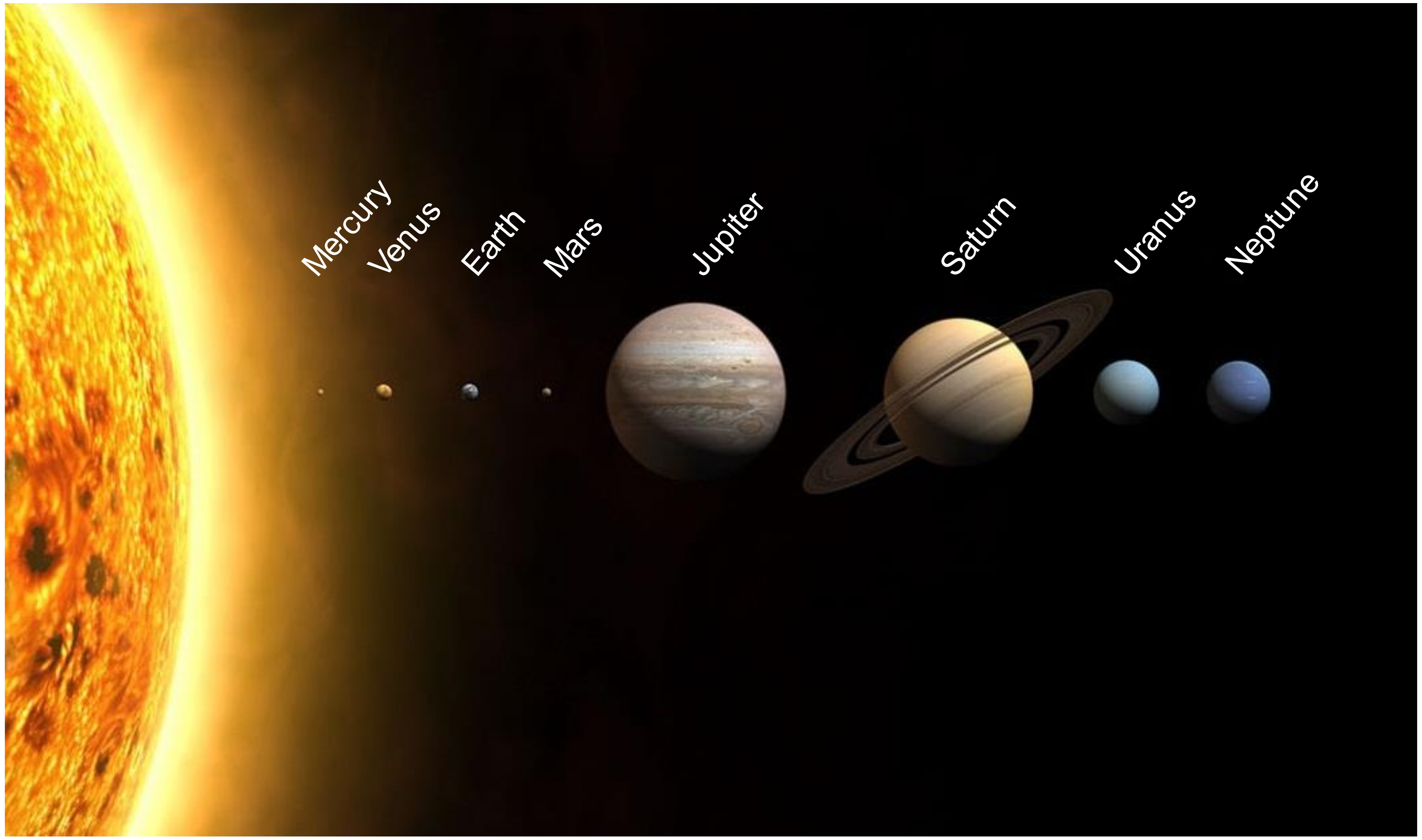
Call the DOM

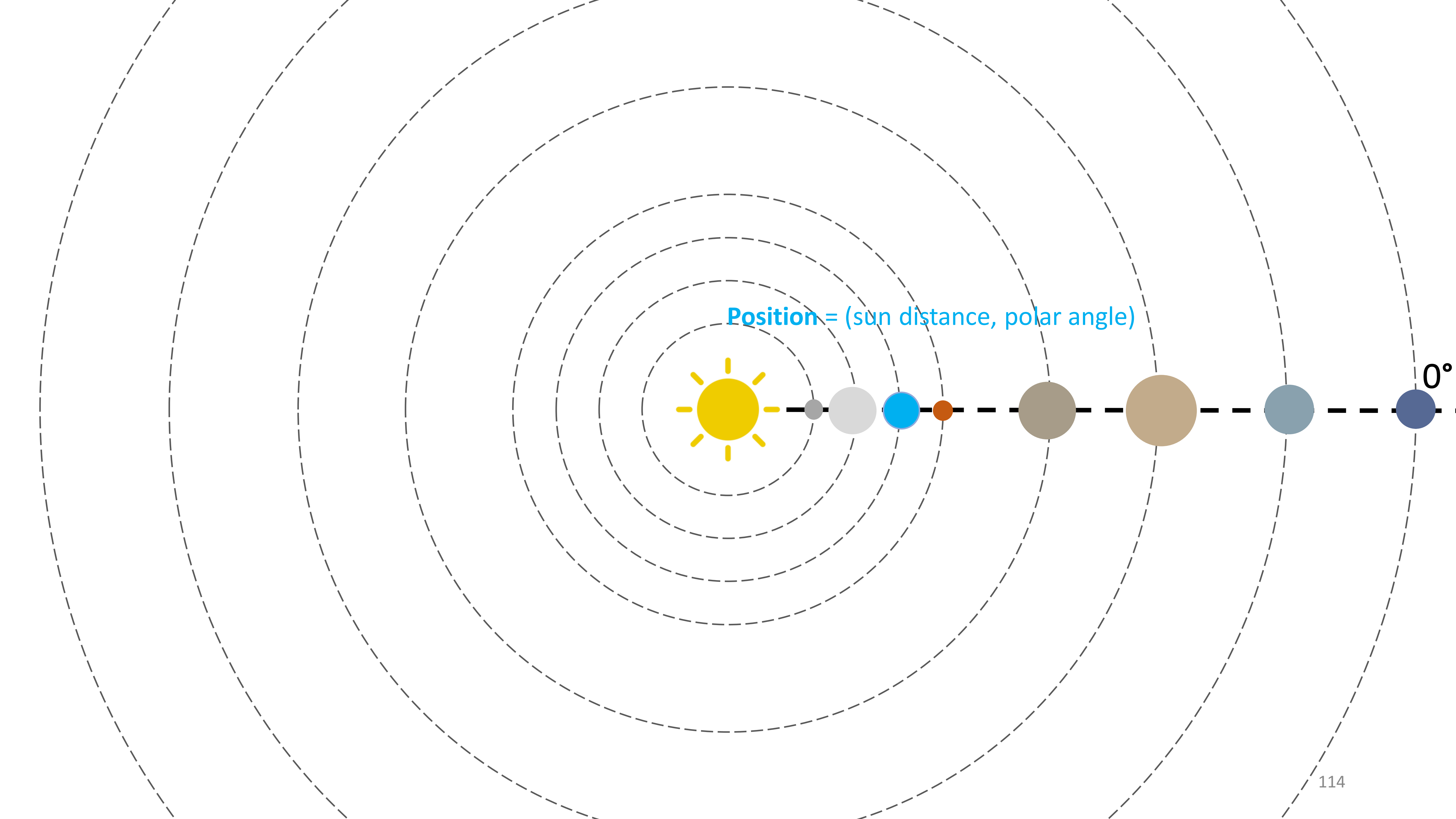


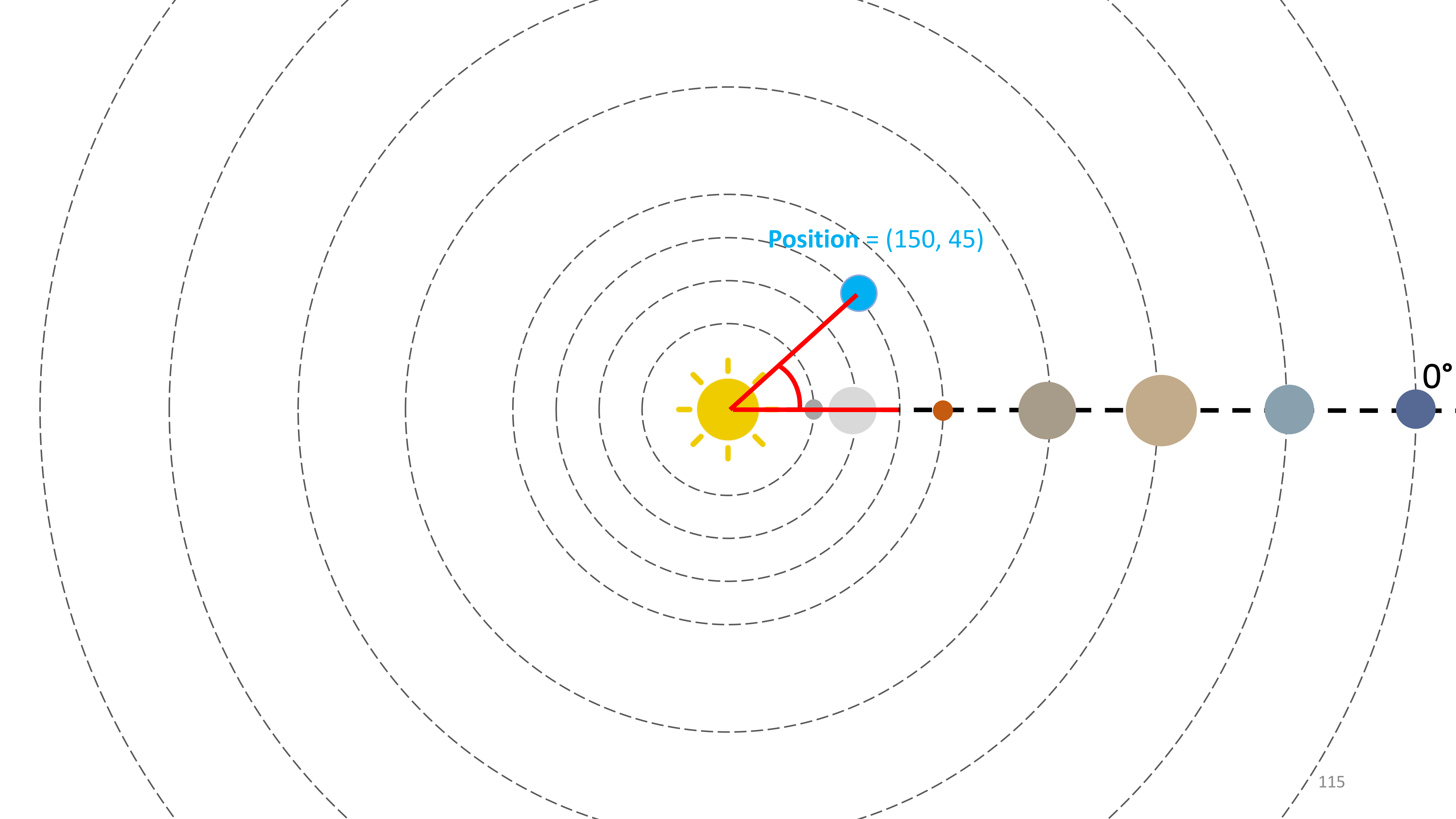
```
DOM.render(
  <highest_level_component />,
  document.getElementById('root')
);
```

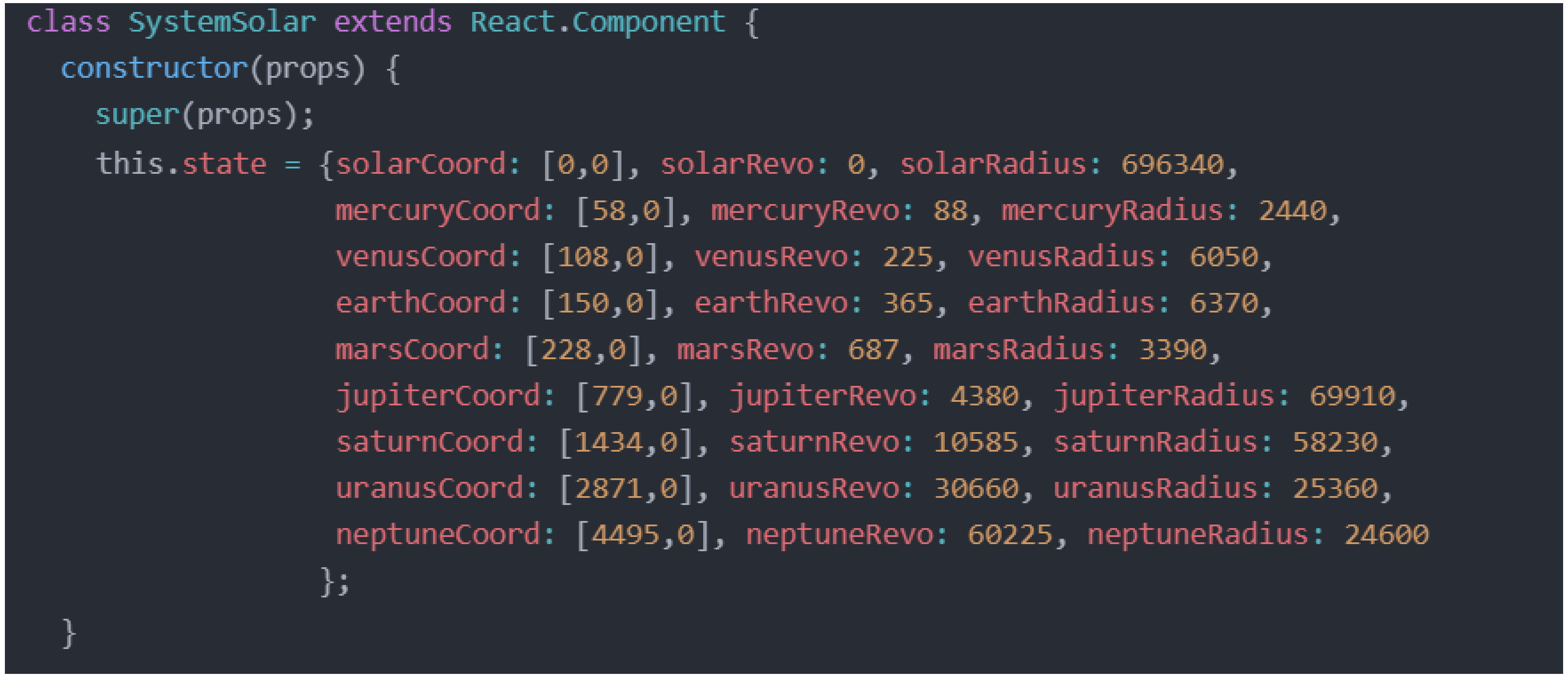
when we call the DOM, we specify the top-level component

Example - Solar system




Position = (sun distance, polar angle)
0°

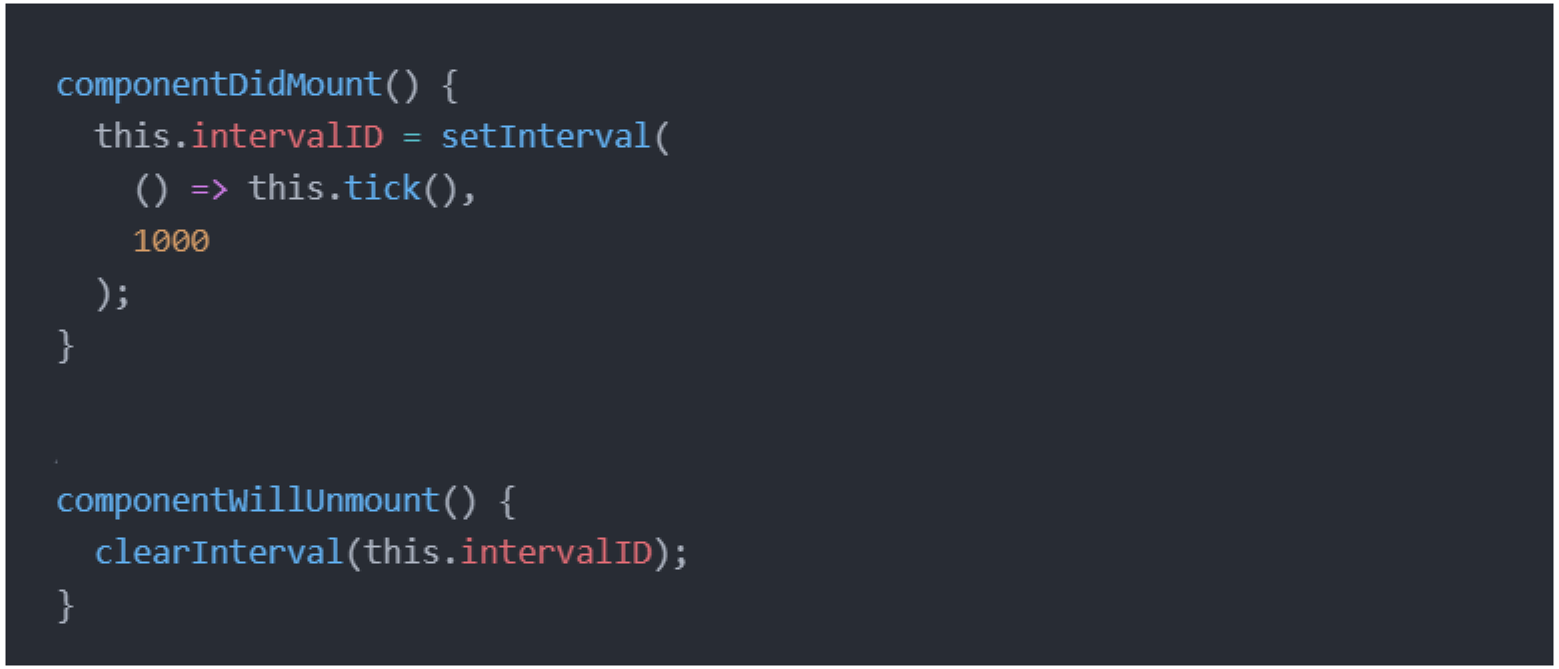

Position = (150, 45)
0°



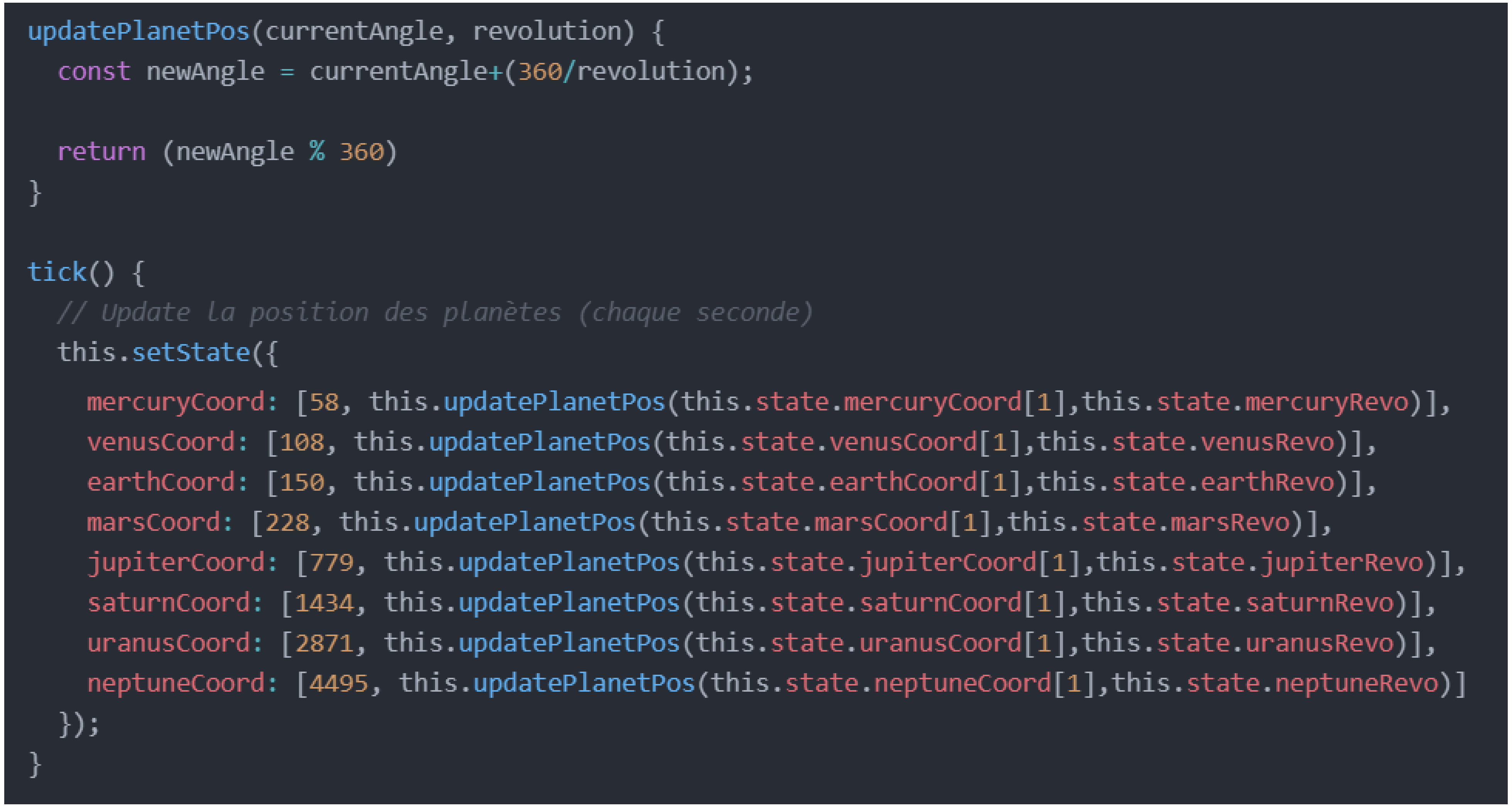
```
class SystemSolar extends React.Component {
  constructor(props) {
    super(props);
    this.state = {solarCoord: [0,0], solarRevo: 0, solarRadius: 696340,
                  mercuryCoord: [58,0], mercuryRevo: 88, mercuryRadius: 2440,
                  venusCoord: [108,0], venusRevo: 225, venusRadius: 6050,
                  earthCoord: [150,0], earthRevo: 365, earthRadius: 6370,
                  marsCoord: [228,0], marsRevo: 687, marsRadius: 3390,
                  jupiterCoord: [779,0], jupiterRevo: 4380, jupiterRadius: 69910,
                  saturnCoord: [1434,0], saturnRevo: 10585, saturnRadius: 58230,
                  uranusCoord: [2871,0], uranusRevo: 30660, uranusRadius: 25360,
                  neptuneCoord: [4495,0], neptuneRevo: 60225, neptuneRadius: 24600
                 };
  }
```

The application has a global state which contains all the information

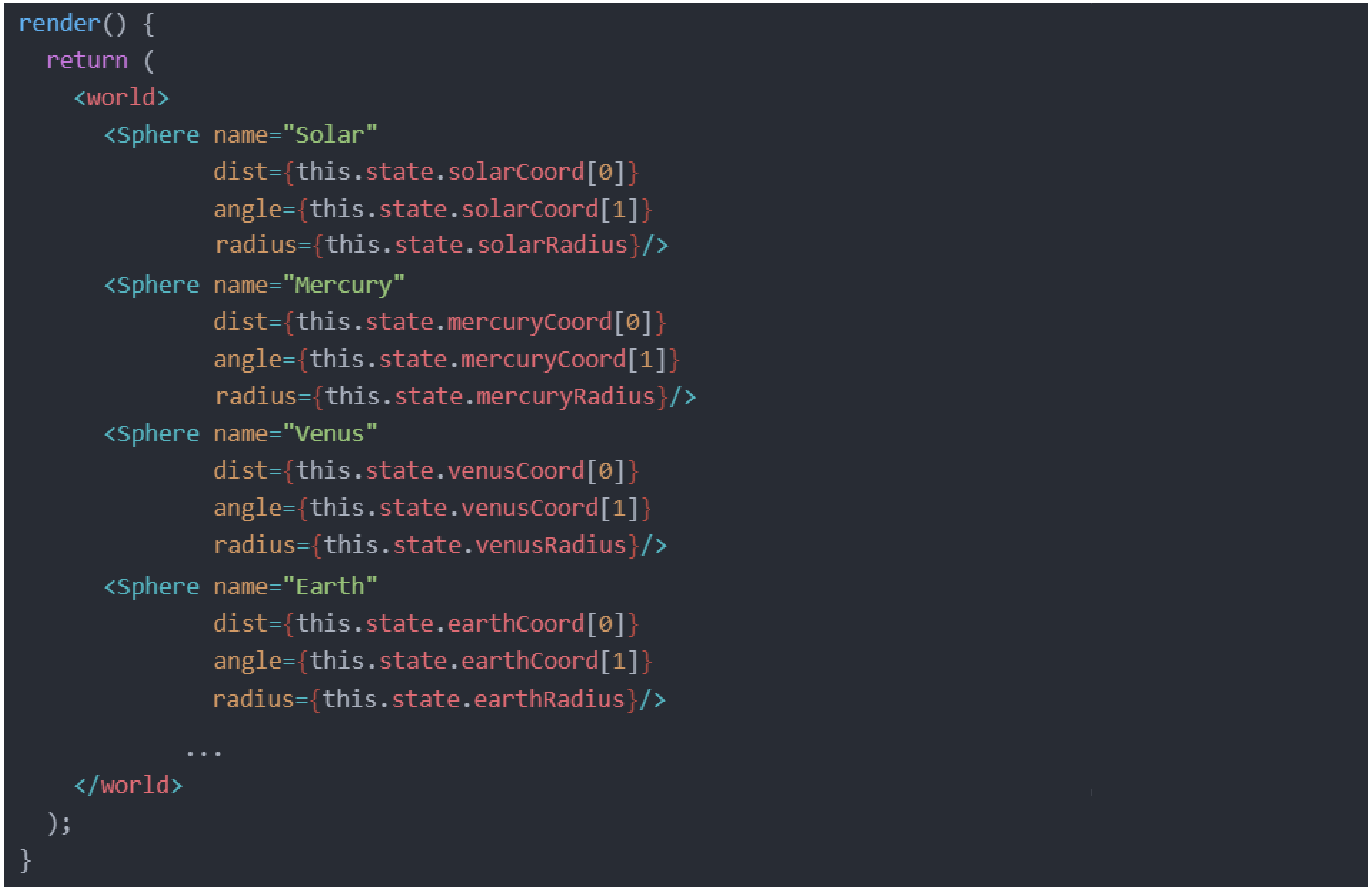
It is defined in the highest-level component



```
componentDidMount() {
  this.intervalID = setInterval(
    () => this.tick(),
    1000
  );
}


componentWillUnmount() {
  clearInterval(this.intervalID);
}
```



```
updatePlanetPos(currentAngle, revolution) {
  const newAngle = currentAngle+(360/revolution);

  return (newAngle % 360)
}

tick() {
  // Update la position des planètes (chaque seconde)
  this.setState({
    mercuryCoord: [58, this.updatePlanetPos(this.state.mercuryCoord[1],this.state.mercuryRevo)],
    venusCoord: [108, this.updatePlanetPos(this.state.venusCoord[1],this.state.venusRevo)],
    earthCoord: [150, this.updatePlanetPos(this.state.earthCoord[1],this.state.earthRevo)],
    marsCoord: [228, this.updatePlanetPos(this.state.marsCoord[1],this.state.marsRevo)],
    jupiterCoord: [779, this.updatePlanetPos(this.state.jupiterCoord[1],this.state.jupiterRevo)],
    saturnCoord: [1434, this.updatePlanetPos(this.state.saturnCoord[1],this.state.saturnRevo)],
    uranusCoord: [2871, this.updatePlanetPos(this.state.uranusCoord[1],this.state.uranusRevo)],
    neptuneCoord: [4495, this.updatePlanetPos(this.state.neptuneCoord[1],this.state.neptuneRevo)]
  });
}
```

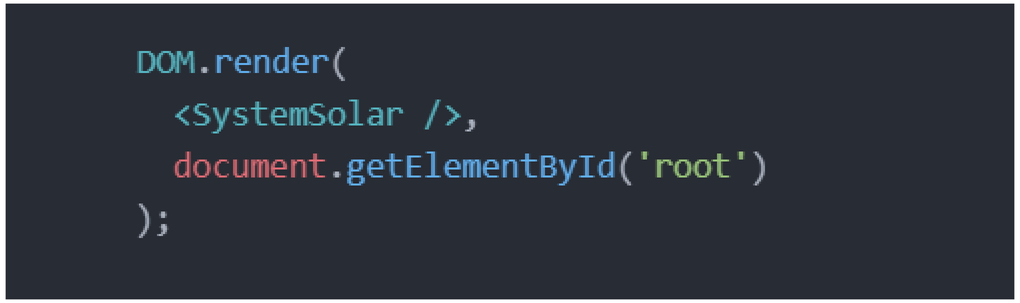


```
render() {
  return (
    <world>
      <Sphere name="Solar"
              dist={this.state.solarCoord[0]}
              angle={this.state.solarCoord[1]}
              radius={this.state.solarRadius}/>
      <Sphere name="Mercury"
              dist={this.state.mercuryCoord[0]}
              angle={this.state.mercuryCoord[1]}
              radius={this.state.mercuryRadius}/>
      <Sphere name="Venus"
              dist={this.state.venusCoord[0]}
              angle={this.state.venusCoord[1]}
              radius={this.state.venusRadius}/>
      <Sphere name="Earth"
              dist={this.state.earthCoord[0]}
              angle={this.state.earthCoord[1]}
              radius={this.state.earthRadius}/>

            ...
    </world>
  );
}
```

```
class Sphere extends React.Component {
  constructor(props) {
    super(props);
  }

  render() {
    return (
        <mesh type="sphere" position="({this.props.dist}, {this.props.angle})" properties="{this.props.radius}"/>
    );
  }
}
```

Local states are avoided in low-level components

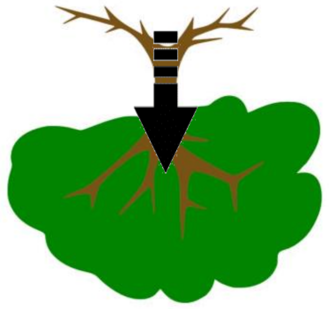
We get the information by props



```
DOM.render(
  <SystemSolar />,
  document.getElementById('root')
);
```

In summary

We separated the application state from the rendering (graphic representation)



All properties descend from the highest component to the lowest component

For rendering

See how to calculate the different matrices (model, view, projection) for the graphical representation

See how translate all the information in a model

And how to send it to the graphics card

Abstractions

See what abstractions we must set up:

using the example of the solar system

and concerning all the calculations to be made

Work incoming

Describe more our language

Work on the points of the 2 previous slides

References (Links)

https://learnopengl.com

https://fr.wikipedia.org/wiki/Shader

https://fr.wikipedia.org/wiki/OpenGL

https://fr.wikipedia.org/wiki/DirectX

https://developer.apple.com/metal

https://github.com/RenderyEngine/Rendery

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https://en.wikipedia.org/wiki/Domain-specific_language

https://tomassetti.me/domain-specific-languages/

http://adv-r.had.co.nz/dsl.html

http://www.raywenderlich.com/1517-swift-tutorial-introducing-structures

https://fr.wikipedia.org/wiki/Arbre_de_la_syntaxe_abstraite

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References (Links)

https://thebookofshaders.com/

https://github.com/yanagiba/swift-ast/tree/master

https://medium.com/@DAloG/swift-ast-wrote-in-swift-part-1-of-e8768cae9cd3

https://ruslanspivak.com/lsbasi-part7/

https://docs.swift.org/swift-book/ReferenceManual/zzSummaryOfTheGrammar.html#

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References (new links)

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https://github.com/anzen-lang/anzen

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References (Tools)

https://swift-ast-explorer.com/

https://github.com/kishikawakatsumi/swift-ast-explorer

https://astexplorer.net/

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Dietrich Geisler, Irene Yoon, Aditi Kabra, Horace He, Yinnon Sanders, and Adrian Sampson. 2020. Geometry Types for Graphics Programming. Proc. ACM Program. Lang. 4, OOPSLA, Article 173 (November 2020), 25 pages.

Joey de Vries. 2020. Learn OpenGL – Graphics programming. (Juin 2020), 523 pages.

Marjan Mernik, Jan Heering, and Anthony M. Sloane. 2005. When and how to develop Domain-Specific Languages. ACM Comput. Surv. 37, 4, (December 2005), Pages 316-344.

Tomaž Kosar, Pablo E. Martı´nez López, Pablo A. Barrientos, Marjan Mernik. A preliminary study on various implementation approaches of domain-specific language. Information and Software Technology, Volume 50, Issue 5, 2008, Pages 390-405.

References (Research)

Khronos Group. 2016. The OpenGL ES Shading Language. (Janvier 2016), 161 pages.

https://arxiv.org/abs/1908.05845 (ex: game of life, ..) DynaSOAR

https://fr.reactjs.org/

https://fr.reactjs.org/docs/hello-world.html

Working with shaders

Patrick SARDINHA