JOHANNES KEPLER UNIVERSITY LINZ
INSTITUTE OF COMPUTER GRAPHICS

Computer Graphics

Lab 2: Transformations and Projections

CG Lab Project: Create a Movie

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30 seconds WebGL movie

Use our framework

Implementation tasks

- Requirements & basic effects (e.g. scenegraph, lighting, …)
- Special effects of your choice

Detailed specification will soon be available in Moodle

CG Lab Project: Create a Movie

Group project in teams of 2 students

Submissions via Github

- **26.03.2021 23:59:** Movie concept submission (incl. team announcement)
- **23.04.2021 23:59:** Intermediate submission
- **22.06.2021 23:59:** Hand-in final package

Individual interviews (alone): **24.-30.06.2021**

Fork me on GitHub

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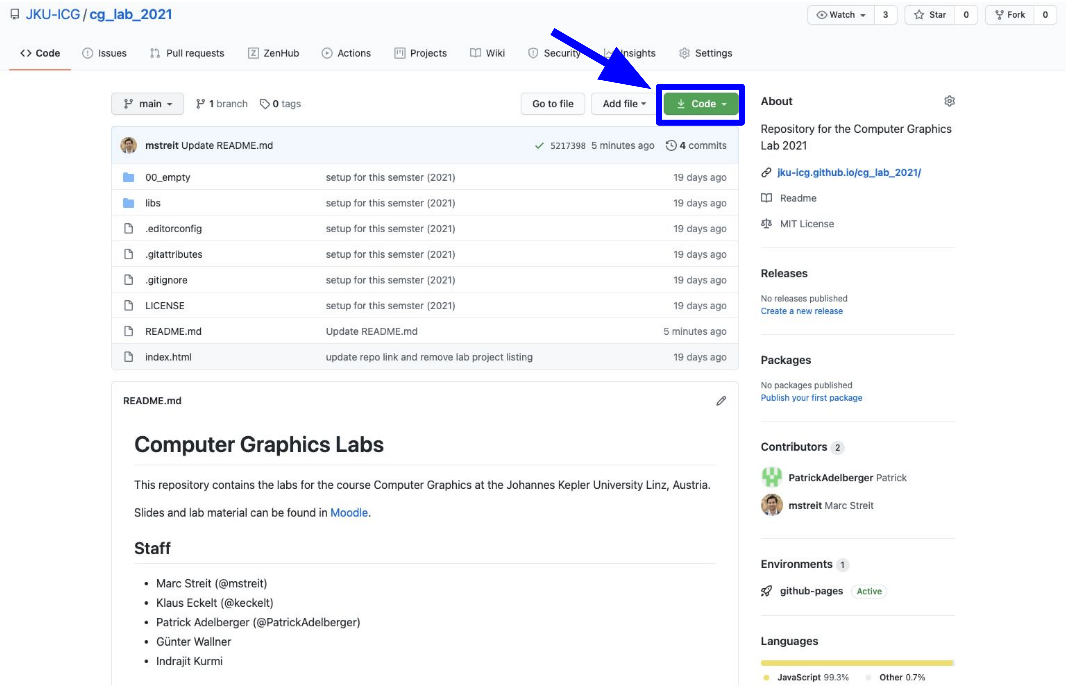
Dev Environment: Lab Package

Hosted on GitHub: https://github.com/jku-icg/cg_lab_2021

The repository will be updated during the lab with the new projects.

To get started (now):

1. Download the ZIP
2. Extract the folder
3. Open Visual Studio Code
4. Open `cg_lab_2021` folder (*File → Open*)
5. Click on **Go Live** button in lower right corner



Dev Environment: HTML5, JS, CSS

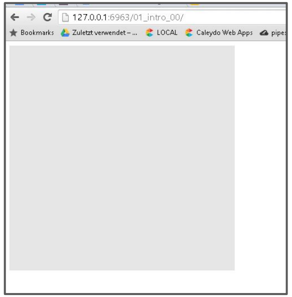
WebGL → OpenGL in the web-browser based on OpenGL ES 2.0

Basic project structure:

- cg_lab_2017-master
  - 00_empty
  - 01_intro_handout
    - shader
      - simple.fs.glsl
      - simple.vs.glsl
    - index.html
    - main.js
    - snippets.js
    - style.css
  - libs
    - framework.js
    - gl-matrix.js
  - index.html

index.html

```html
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <title>Empty</title>
    <link rel="stylesheet" href="style.css">
</head>
<body>
    <!-- include helper library for matrix computation -->
    <script src="../libs/gl-matrix.js"></script>
    <!-- include our framework with utilities -->
    <script src="../libs/framework.js"></script>
    <!-- include the main script -->
    <script src="main.js"></script>
</body>
</html>
```



main.js

```
//the OpenGL context
var gl = null;

/**
 * initializes OpenGL context, compile shader, and load buffers
 */
function init(resources) {
  //create a GL context
  gl = createContext(400 /*width*/, 400 /*height*/);

  //TODO initialize shader, buffers, ...
}

/**
 * render one frame
 */
function render() {
  //specify the clear color
  gl.clearColor(0.9, 0.9, 0.9, 1.0);
  //clear the buffer
  gl.clear(gl.COLOR_BUFFER_BIT);

  //TODO render scene

  //request another call as soon as possible
  //requestAnimationFrame(render);
}

loadResources({
  //list of all resources that should be loaded as key: path
}).then(function (resources /*loaded resources*/) {
  init(resources);
  //render one frame
  render();
});
```

← 2. Initialize OpenGL

← 3. Render frame

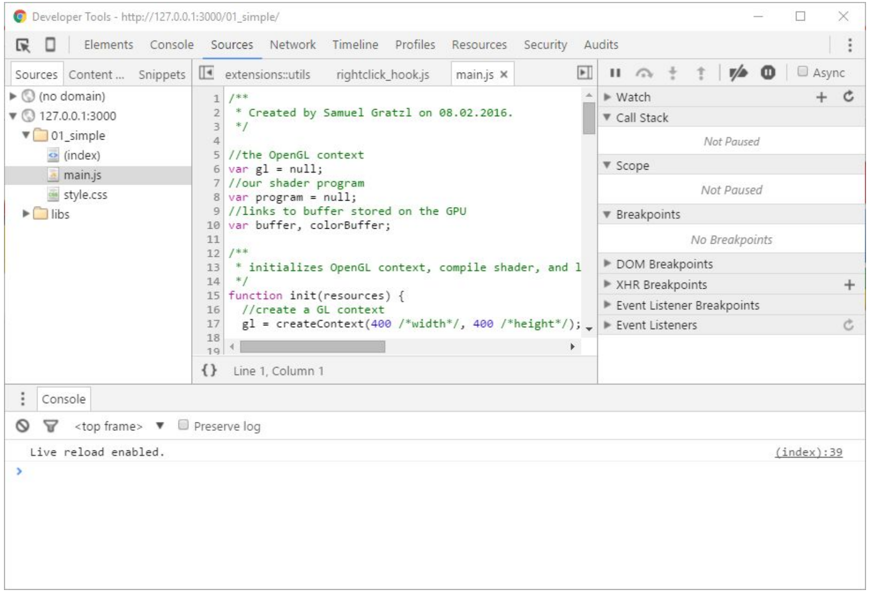
← 1. Load external resources

Dev Environment: Developer Tools

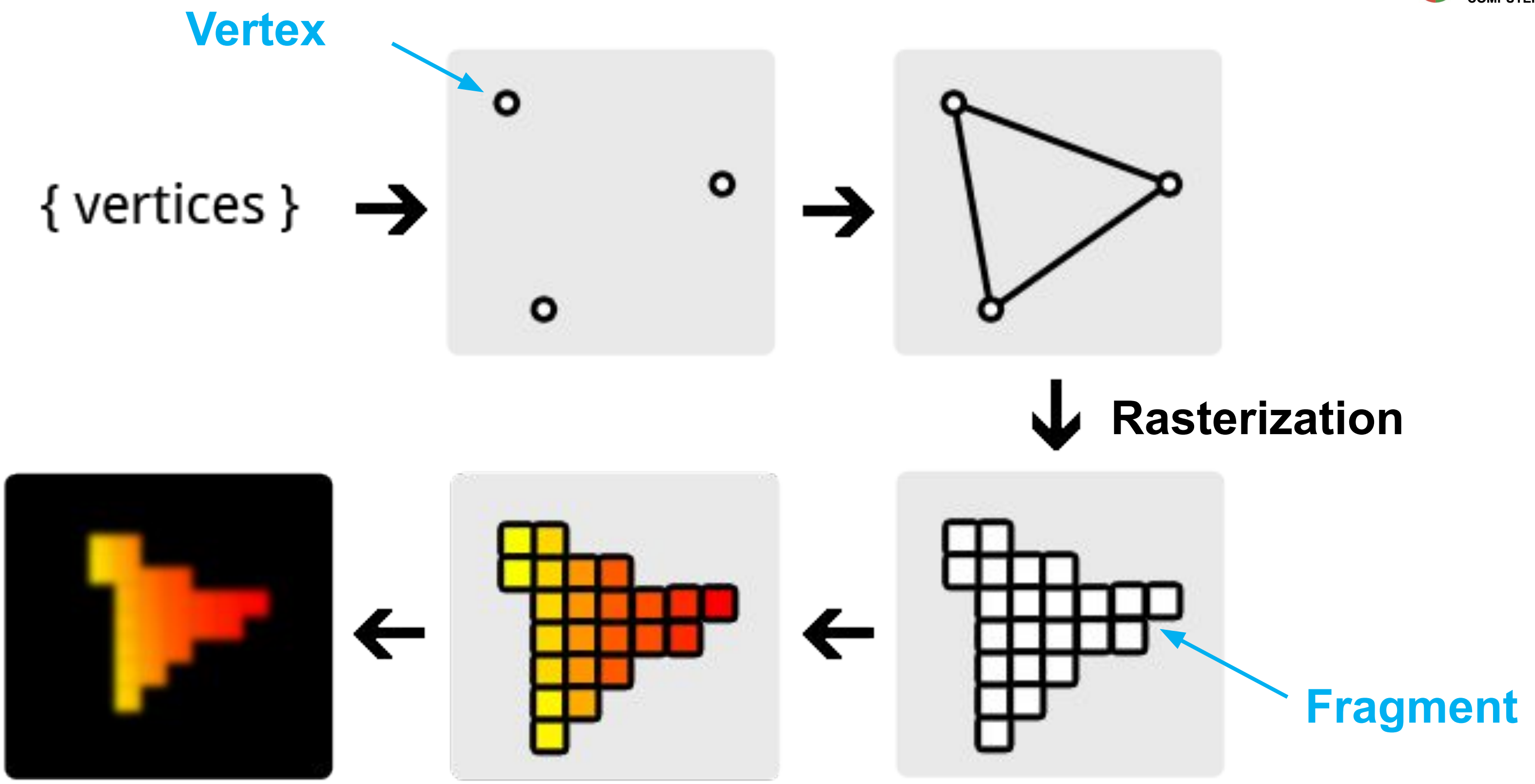
Know the Web Developer Tools of your favorite browser

- Chrome, Firefox, Edge, Safara, … → usually F12

Great for debugging JavaScript code, manipulating CSS & DOM, …



Rendering Pipeline



https://open.gl/drawing (adapted)

Programmable Pipeline

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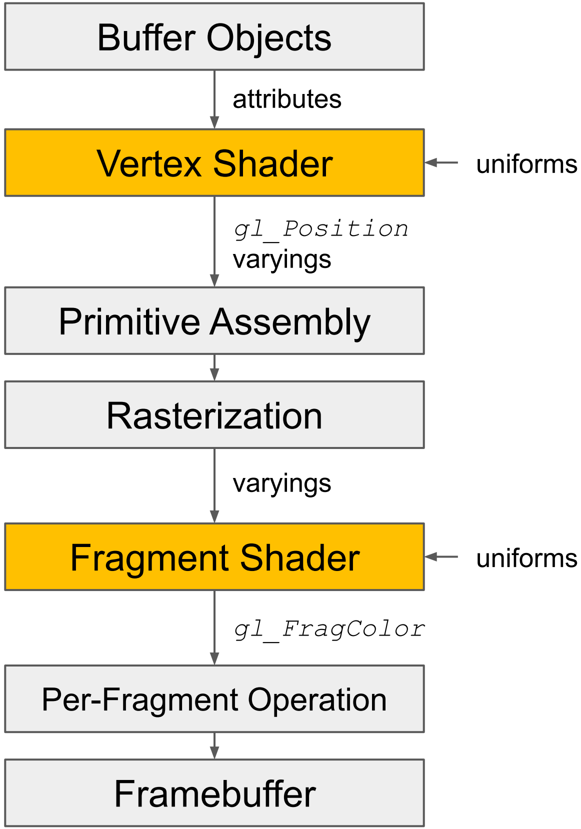

Summary

- vertex: point in 2D/3D space
- fragment: pixel + additional properties
- shader: tiny program on the GPU
- shader program: vertex + fragment shader
- buffer: array on GPU
- attribute: accessing the current buffer element in shader
- uniform: parameter from program to shader
- varying: parameter between shader
- gl_Position, gl_FragColor: magic variables
- rasterization: 3 vertices → N fragments

Recap: Colored Triangle

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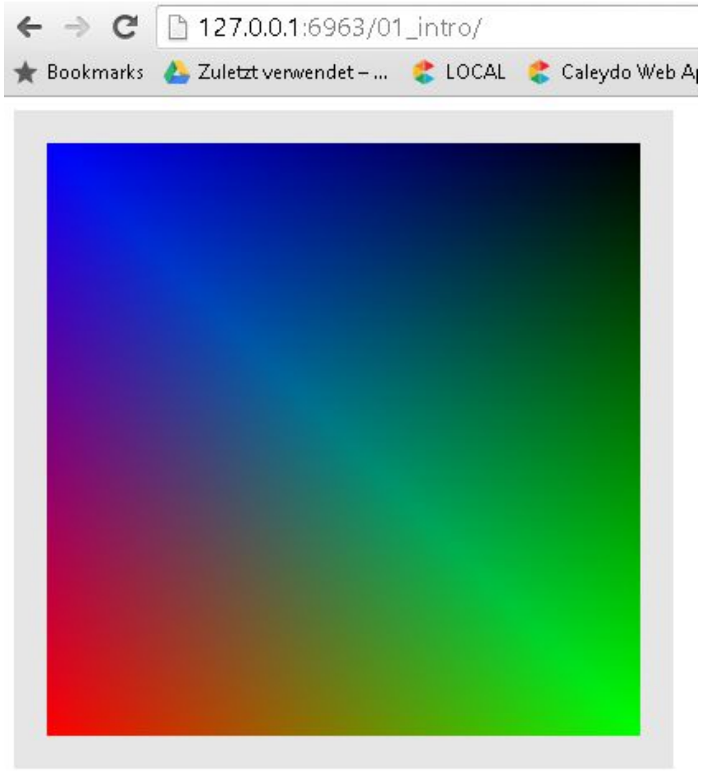
First Application: Colored rectangle

a. initialize context
b. define buffer, compile shader
c. draw rectangle using two triangles
d. specify uniforms
e. specify color per vertex



Agenda for Today

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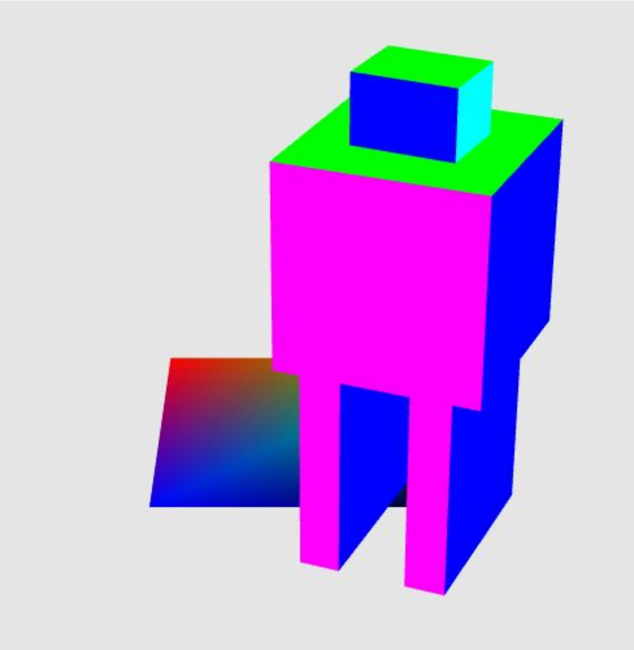
- Transformation pipeline
- Model-view transformations
  - Translate, scale, rotate, animations
- Camera transformations
- Projective transformations
  - Orthographic and perspective projection
- Creating geometry using the index buffer
- Animations



OpenGL's Coordinate System

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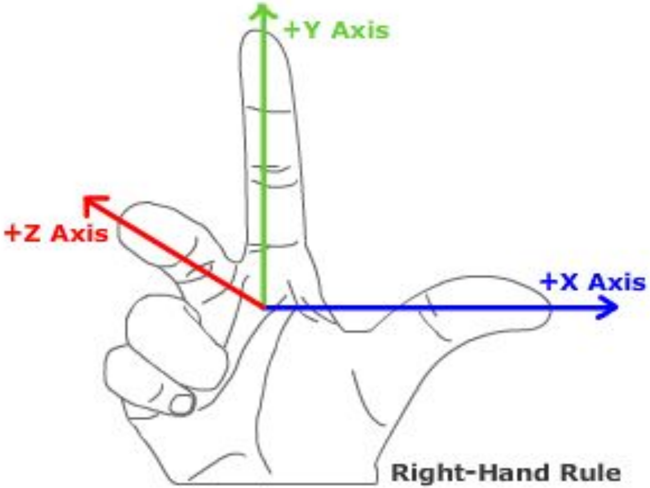
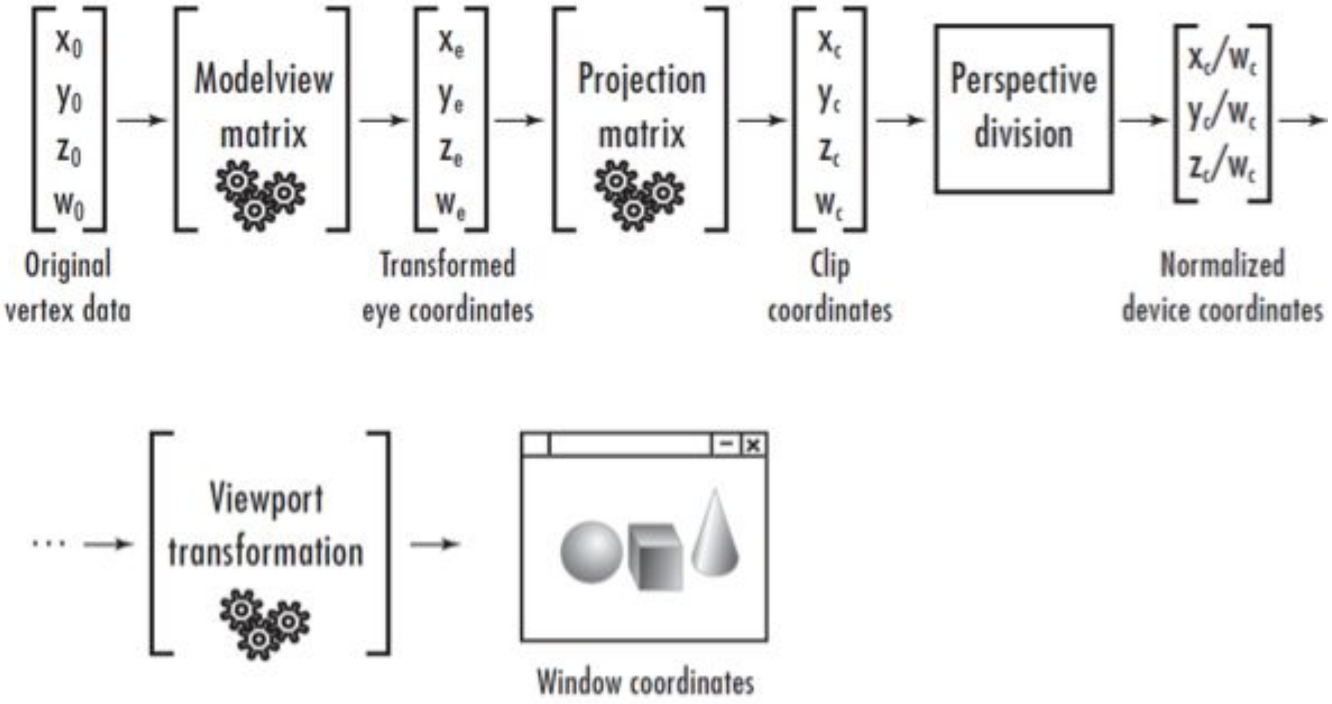
OpenGL provides a right-handed coordinate system

By default OpenGL's virtual camera is placed at the origin of this coordinate system looking in negative z-direction



Transformation Pipeline



Transformation Pipeline

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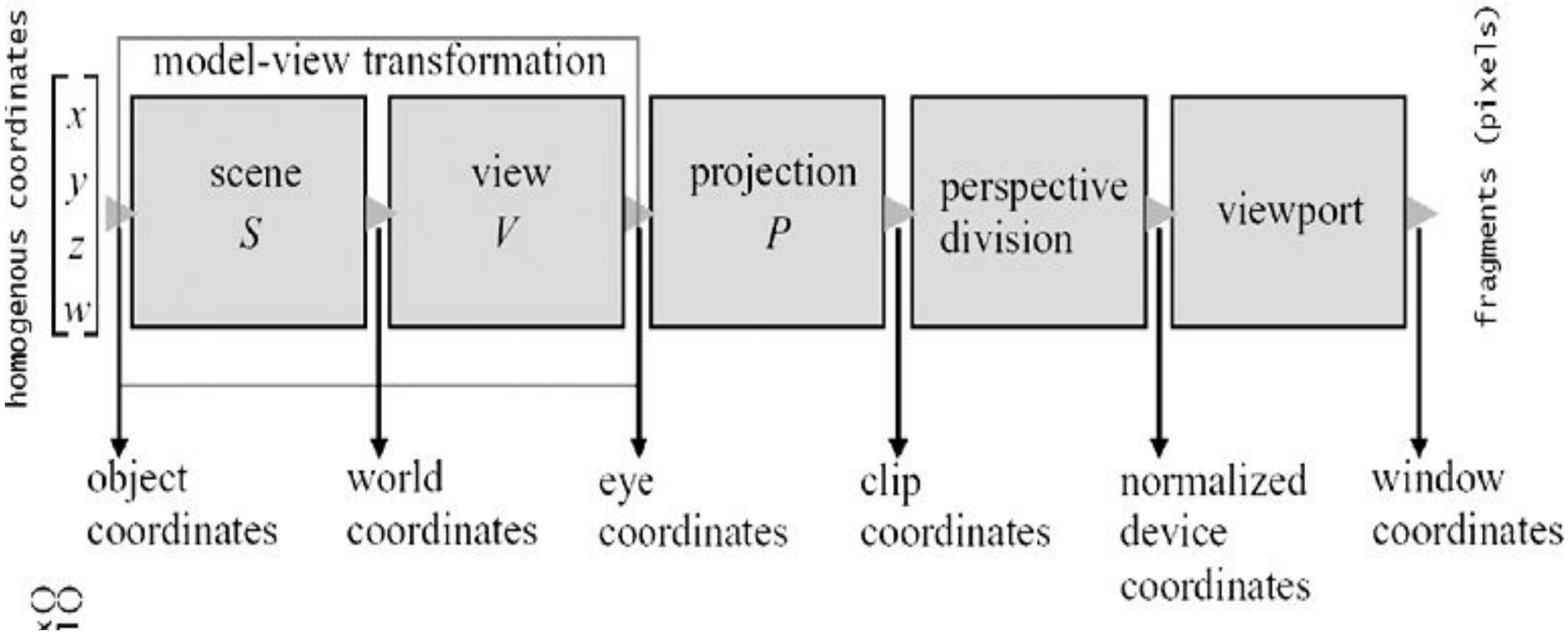
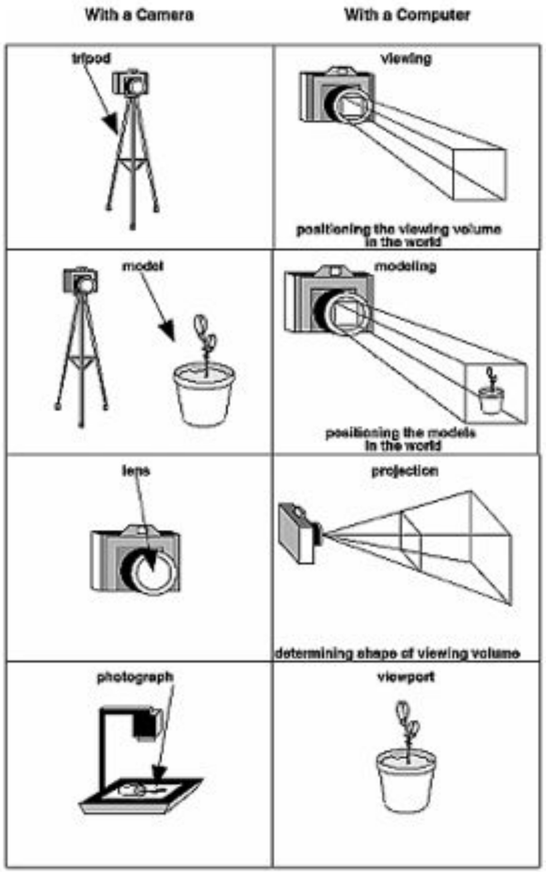


Transformation Pipeline

OpenGL follows a camera analogy

Think of

- the **view transformation** as placing a camera
- the **scene transformation** as placing an object
- the **projection transformation** as adjusting the camera lens and focus
- the **viewport transformation** as choosing the photograph size



Matrices

All transformations are stored as 4x4 matrices

- Why use a 4x4 matrix for 3D?
- Remember homogeneous coordinates?
- https://www.tomdalling.com/blog/modern-opengl/explaining-homogenous-coordinates-and-projective-geometry/

Combine matrices and vectors by multiplying them

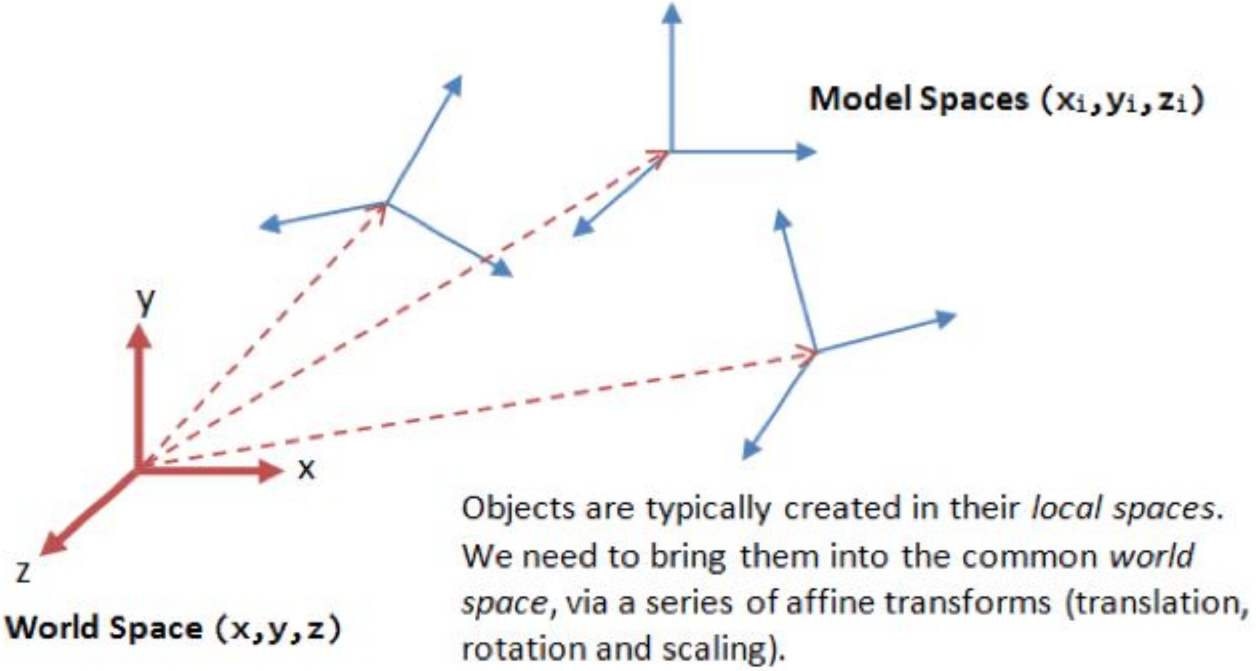
Identity matrix

- All 1 along diagonal, rest 0
- Neutral operation when multiplied with existing matrix or vector

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Model vs. World Space

Multiply model coordinates by scene matrix to get to world space



Transformation Pipeline

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Scene and view transformations are considered the same in OpenGL

`modelViewMatrix = viewMatrix * sceneMatrix`

```
function setUpModelViewMatrix(viewMatrix, sceneMatrix) {

  var modelViewMatrix = matrixMultiply(viewMatrix, sceneMatrix );
  gl.uniformMatrix4fv(modelViewLocation, false, modelViewMatrix);
}
```

main.js

`projectionMatrix` multiplied in shader

All matrices in our framework are initialized with identity matrix

simple.vs.glsl

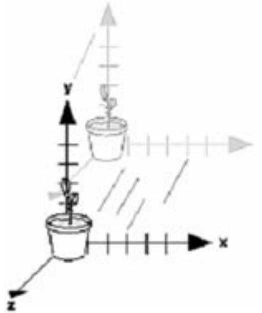
```
// the position of the point
attribute vec3 a_position;

//the color of the point
attribute vec3 a_color;

varying vec3 v_color;

uniform mat4 u_modelView;
uniform mat4 u_projection;

//like a C program main is the main function
void main() {

  gl_Position = u_projection * u_modelView
    * vec4(a_position, 1);

  //just copy the input color to the output varying color
  v_color = a_color;
}
```

Transformations

Translation

Moves a point by a vector in x,y,z

See `makeTranslationMatrix(tx,ty,tz)`

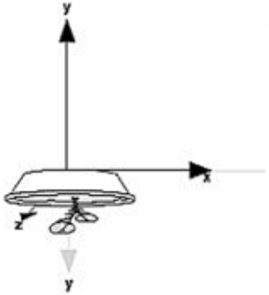


$$T = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Scaling

Scales a point by a factor in x,y,z

See `makeScaleMatrix(sx,sy,sz)`

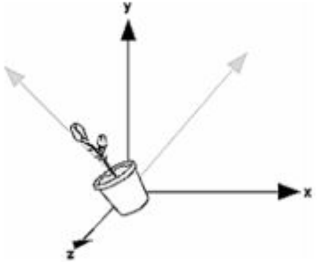


$$T = \begin{bmatrix} x & 0 & 0 & 0 \\ 0 & y & 0 & 0 \\ 0 & 0 & z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation

Rotates a point by degrees around x,y,z

See `makeX/Y/ZRotationMatrix(rad)`



$$Rot_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos a & -\sin a & 0 \\ 0 & \sin a & \cos a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; Rot_y = \begin{bmatrix} \cos a & 0 & \sin a & 0 \\ 0 & 1 & 0 & 0 \\ -\sin a & 0 & \cos a & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; Rot_z = \begin{bmatrix} \cos a & -\sin a & 0 & 0 \\ \sin a & \cos a & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation Order

Order matters!

Different result: `scale(translate(v)) vs. translate(scale(v))`

$$\begin{bmatrix} S_X & 0 & 0 & 0 \\ 0 & S_Y & 0 & 0 \\ 0 & 0 & S_Z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & T_X \\ 0 & 1 & 0 & T_Y \\ 0 & 0 & 1 & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} (X, Y, Z, 1) = \begin{bmatrix} S_X & 0 & 0 & 0 \\ 0 & S_Y & 0 & 0 \\ 0 & 0 & S_Z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} (X+T_X, Y+T_Y, Z+T_Z, 1) = (S_X(X+T_X), S_Y(Y+T_Y), S_Z(Z+T_Z), 1)$$

$$\begin{bmatrix} 1 & 0 & 0 & T_X \\ 0 & 1 & 0 & T_Y \\ 0 & 0 & 1 & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_X & 0 & 0 & 0 \\ 0 & S_Y & 0 & 0 \\ 0 & 0 & S_Z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} (X, Y, Z, 1) = \begin{bmatrix} 1 & 0 & 0 & T_X \\ 0 & 1 & 0 & T_Y \\ 0 & 0 & 1 & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} (S_X X, S_Y Y, S_Z Z, 1) = (S_X X+T_X, S_Y Y+T_Y, S_Z Z+T_Z, 1)$$

Read from right to left

- Operations closest to the object definition are applied first

Read code from bottom to top

- In OpenGL transformation commands are always issued in reverse order if multiple transforms are applied to a vertex

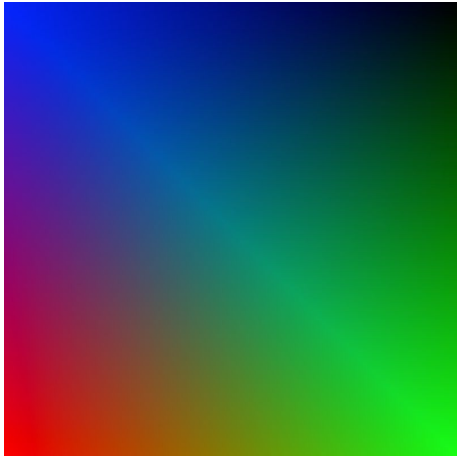
Task 1: Translation in Shader

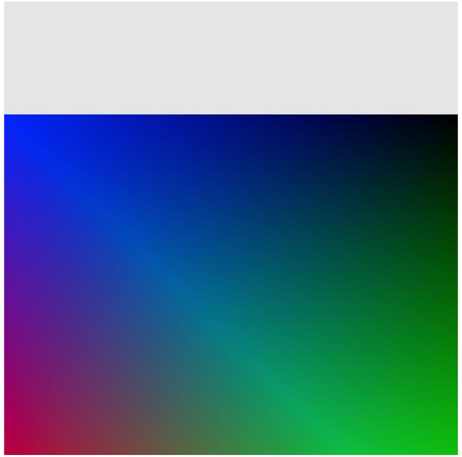
Goal: Move quad by -0.5 units in y-direction (down)

Step 1: Define 3D vector as local variable in vertex shader

```
vec3 translation = vec3(trans_x, trans_y, trans_z);
```

Step 2: Add translation vector to `a_position`





Task 1: Solution

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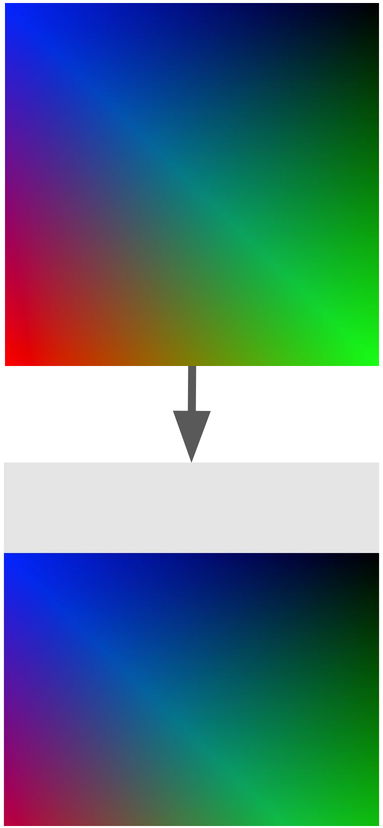
```
// the position of the point
attribute vec3 a_position;

//the color of the point
attribute vec3 a_color;

varying vec3 v_color;

uniform mat4 u_modelView;
uniform mat4 u_projection;

//like a C program main is the main function
void main() {

  //TASK 1 and TASK 2-1
  //translation vector for moving vertices to a different position
  vec3 translation = vec3(0,-0.5,0);

  gl_Position = u_projection * u_modelView
    * vec4(a_position + translation, 1);

  //just copy the input color to the output varying color
  v_color = a_color;
}
```

simple.vs.glsl

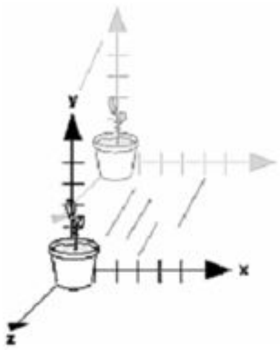


Task 2: Translation Using Matrix

Goal: Achieve same translation by manipulating the scene matrix
Scene matrix already given as input to the `renderQuad` function

Step 1: Remove translation in shader from last step
Step 2: Use `makeTranslationMatrix(x,y,z)` and set translation factors
Step 3: Multiply translation matrix with scene matrix using `matrixMultiply(...)` function

Attention: Multiplication order!



$$T = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Task 2: Solution

```
function renderQuad(sceneMatrix, viewMatrix) {

  //TASK 2-2 and TASK 3 and TASK 4
  sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.0,-0.5,0));

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

main.js

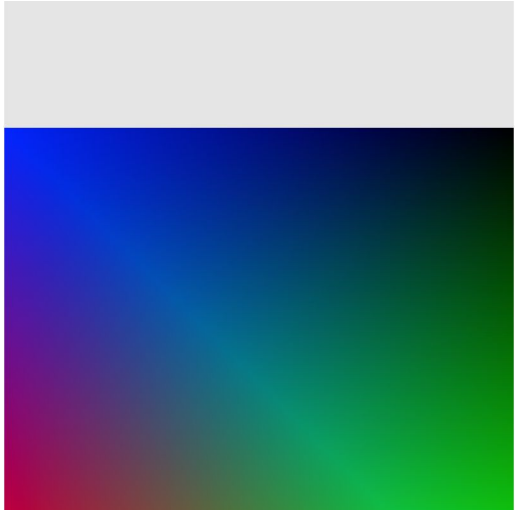
Task 3: Add Scaling to Matrix

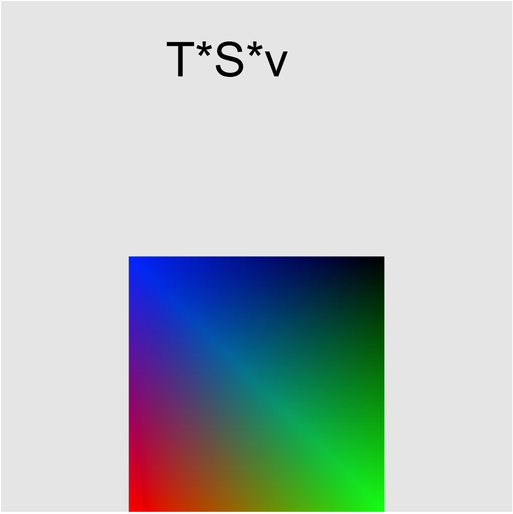
Goal: Shrink quad by 50% in x and y direction

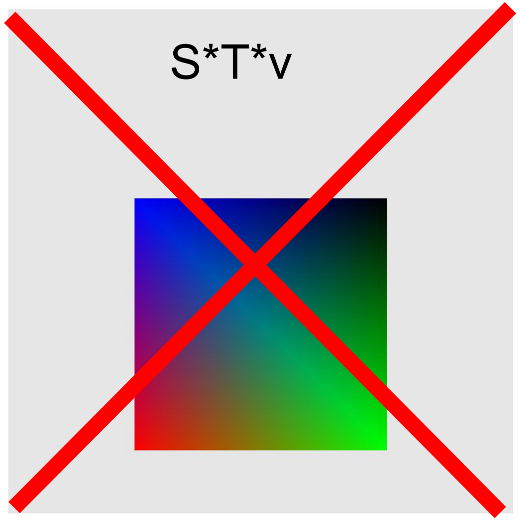
Step 1: Use `makeScaleMatrix(x,y,z)` function and set scale factors

Step 2: Multiply scale matrix with scene matrix

Important: Do not scale translation (order!)







Task 3: Solution


```
function renderQuad(sceneMatrix, viewMatrix) {

  //TASK 2-2 and TASK 3 and TASK 4
  sceneMatrix = matrixMultiply( matrixMultiply(
                                sceneMatrix,
                                makeTranslationMatrix(0.0,-0.5,0) ),
                                makeScaleMatrix( .5, .5, 1) );

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

OR

```
function renderQuad(sceneMatrix, viewMatrix) {

  //TASK 2-2 and TASK 3 and TASK 4
  sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.0,-0.5,0));
  sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix( .5, .5, 1));

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

$$\begin{bmatrix} 1 & 0 & 0 & T_X \\ 0 & 1 & 0 & T_Y \\ 0 & 0 & 1 & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_X & 0 & 0 & 0 \\ 0 & S_Y & 0 & 0 \\ 0 & 0 & S_Z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} S_X & 0 & 0 & T_X \\ 0 & S_Y & 0 & T_Y \\ 0 & 0 & S_Z & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} S_X & 0 & 0 & 0 \\ 0 & S_Y & 0 & 0 \\ 0 & 0 & S_Z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & T_X \\ 0 & 1 & 0 & T_Y \\ 0 & 0 & 1 & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} S_X & 0 & 0 & S_X T_X \\ 0 & S_Y & 0 & S_Y T_Y \\ 0 & 0 & S_Z & S_Z T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

main.js

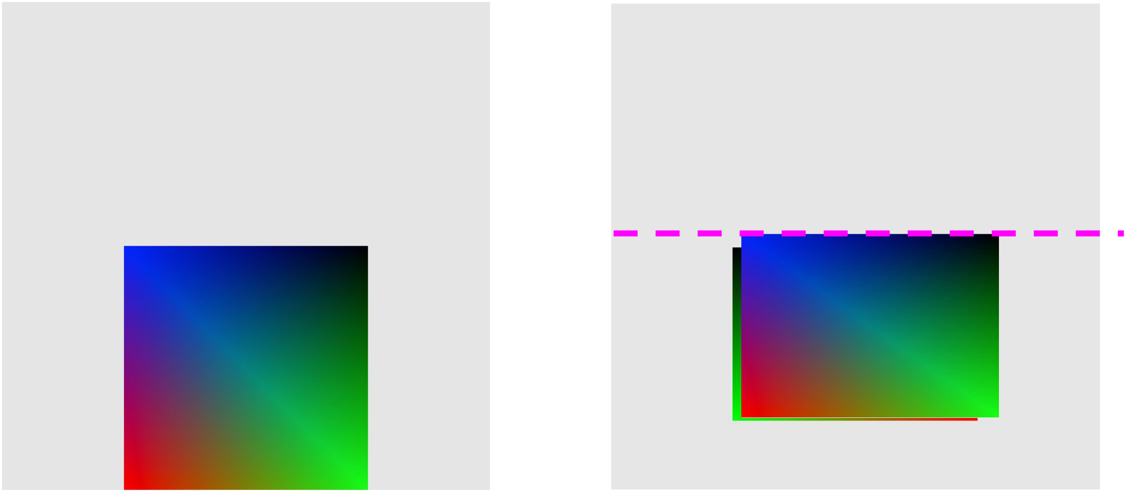
Task 4: Add Rotation

Goal: Rotate quad around x-axis by 45 degrees

Step 1: Use `makeXRotationMatrix(rad)` and set rotation factors (use `convertDegreeToRadians(angle)` helper function)

Step 2: Multiply rotation matrix with scene matrix

Important: Think about order!



Rotations around x-axis

Task 4: Solution


```
function renderQuad(sceneMatrix, viewMatrix) {

  //TASK 2-2 and TASK 3 and TASK 4
  sceneMatrix = matrixMultiply( matrixMultiply( matrixMultiply(
                              sceneMatrix,
                              makeXRotationMatrix(convertDegreeToRadians(45)) ),
                              makeTranslationMatrix(0.0,-0.5,0) ),
                              makeScaleMatrix( .5, .5, 1) );

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

OR

```
function renderQuad(sceneMatrix, viewMatrix) {

  //TASK 2-2 and TASK 3 and TASK 4
  sceneMatrix = matrixMultiply(sceneMatrix, makeXRotationMatrix(convertDegreeToRadians(45)));
  sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.0,-0.5,0));
  sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix( .5, .5, 1));

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

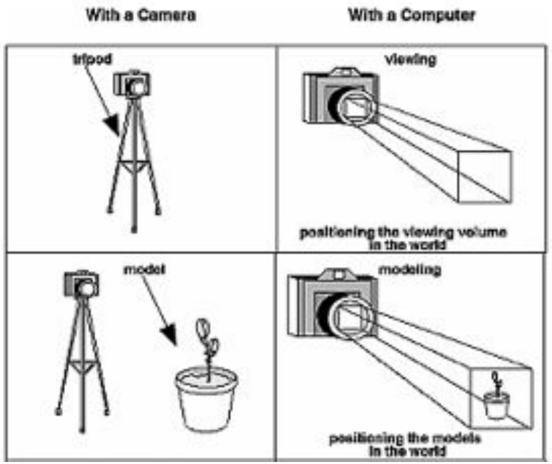
main.js

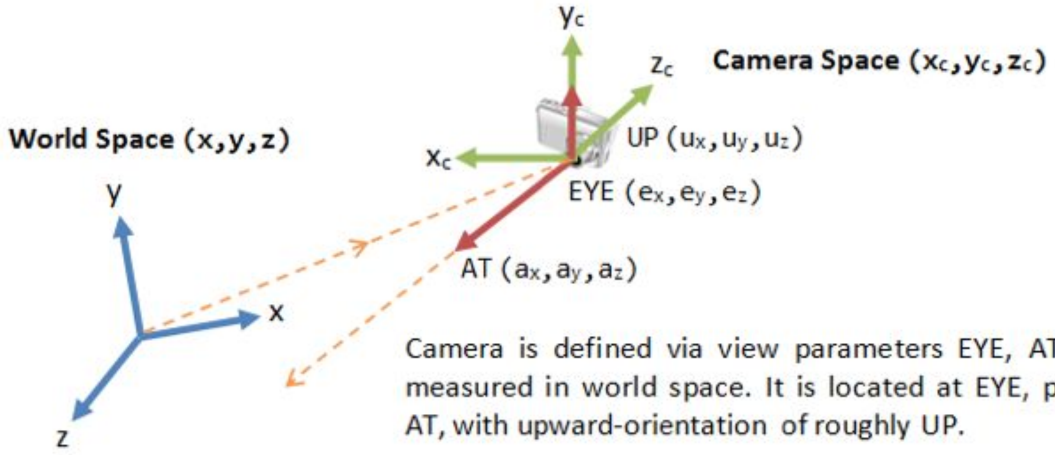
View Transformations (Camera)

Recalling the camera analogy, viewing transformations position and point the camera towards our scene

Scene and view transformation considered the same in OpenGL

Think of moving the camera or the whole scene → same effect





Camera is defined via view parameters EYE, AT and UP, measured in world space. It is located at EYE, pointing at AT, with upward-orientation of roughly UP.

In the Camera space, camera is located at origin, pointing at $-z_c$, with upward-orientation of y_c.
z_c is opposite of AT, y_c is roughly UP.

View Transformations (Camera)

There are different ways to change viewing direction and vantage point

Option 1:

Use translate and rotate operations to change viewpoint (i.e., moving all objects)

Option 2:

Create and use lookAt matrix

It specifies the viewpoint, viewing direction and up-vector (i.e., camera's rotation)

Note that you can have only one view transformation!

lookAt-Matrix Example

Bob is hanging upside down from a branch, looking at Alice, lying on the grass with a book.

```
lookAt(Bob_x, Bob_y, Bob_z, Alice_x, Alice_y, Alice_z,
       UpVector_x, UpVector_y, UpVector_z);
```

Bob‘s branch is at (20,80,15) (it‘s a tall tree)

Alice is at (15,0,12) (near the foot of the tree)

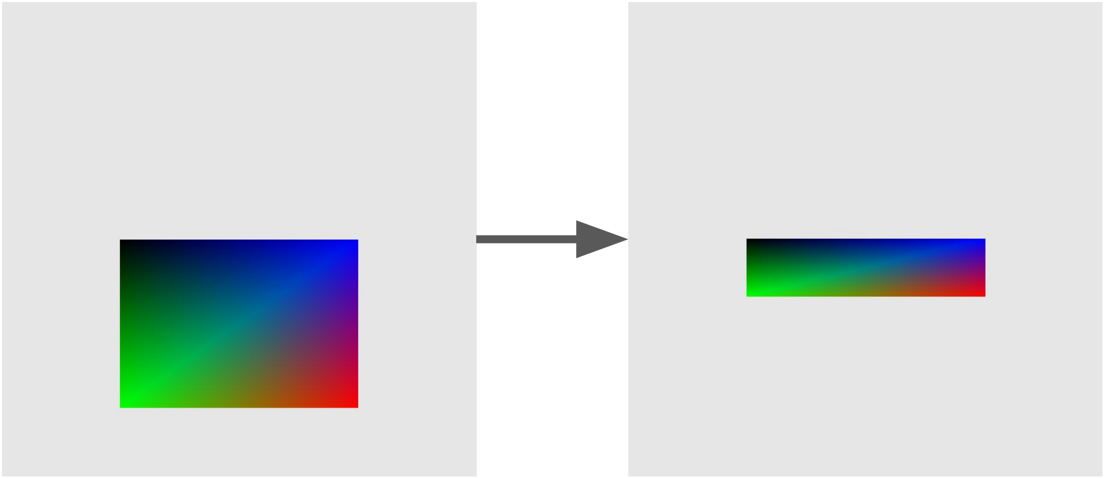
Upside-down means your up-vector is (0,-1,0)

```
lookAt(20, 80, 15, 15, 0, 12, 0, -1, 0);
```

Task 5: Setup lookAt Camera

Goal: Let camera look at the origin from position **(0,3,5)**

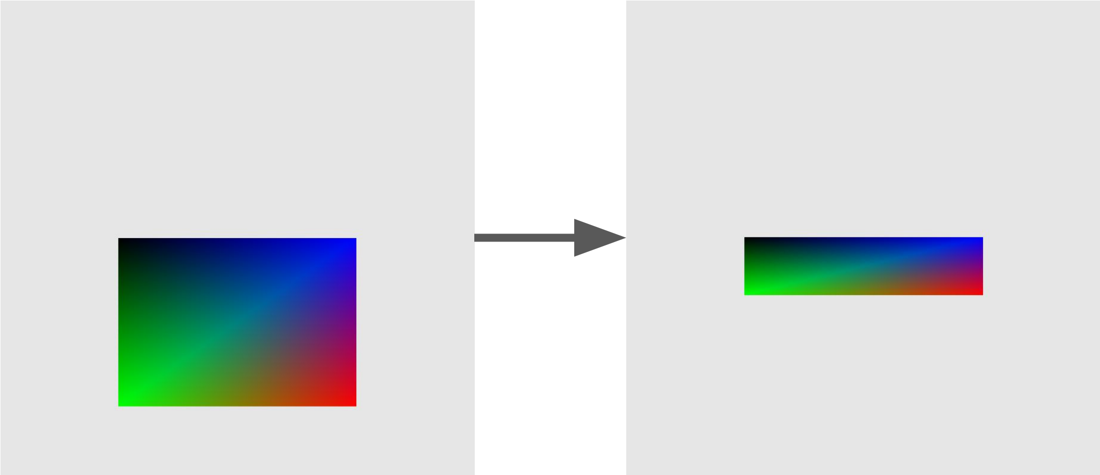
Step 1: Call `lookAt(...)` function in `calculateViewMatrix(...)`



Task 5: Solution

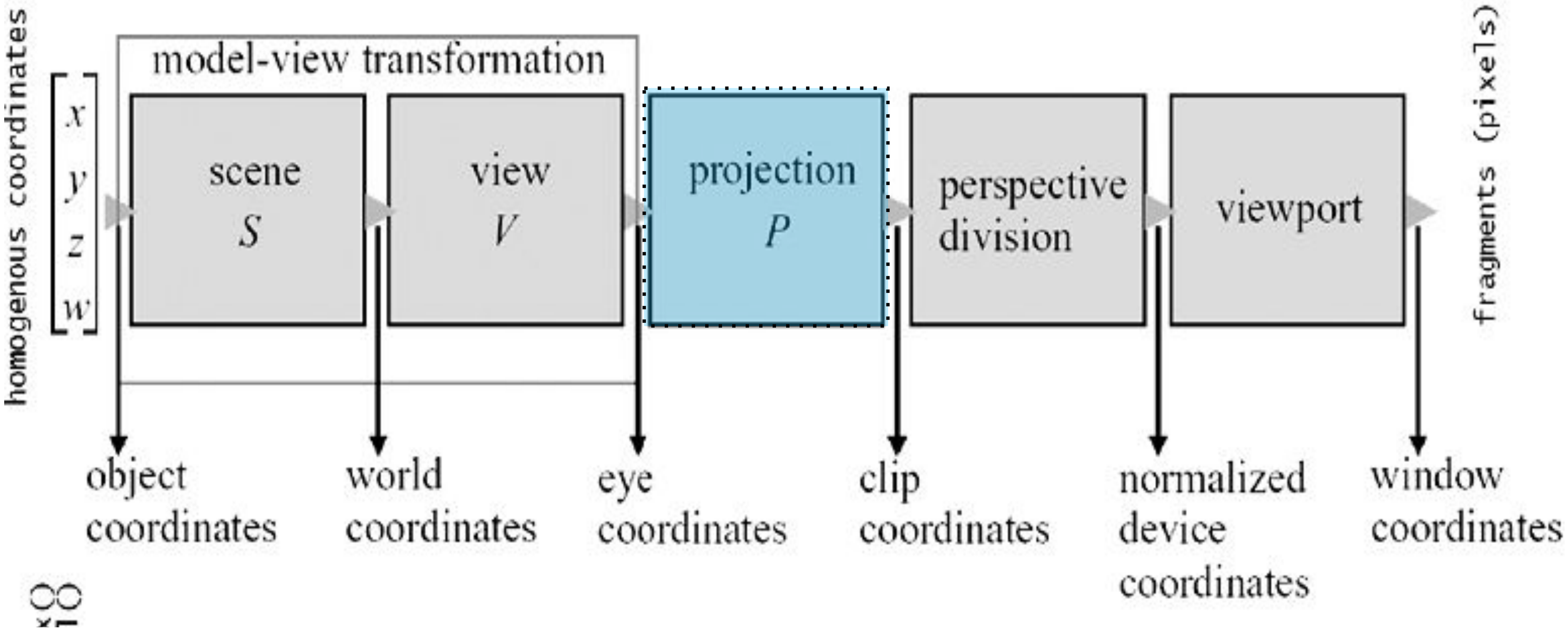
```
function calculateViewMatrix(viewMatrix) {
  //compute the camera's matrix
  // TASK 5
  viewMatrix = lookAt(0,3,5,0,0,0,0,1,0);
  return viewMatrix;
}
```

viewer, origin, up-vector



main.js

Projective Transformations



Projective Transformations

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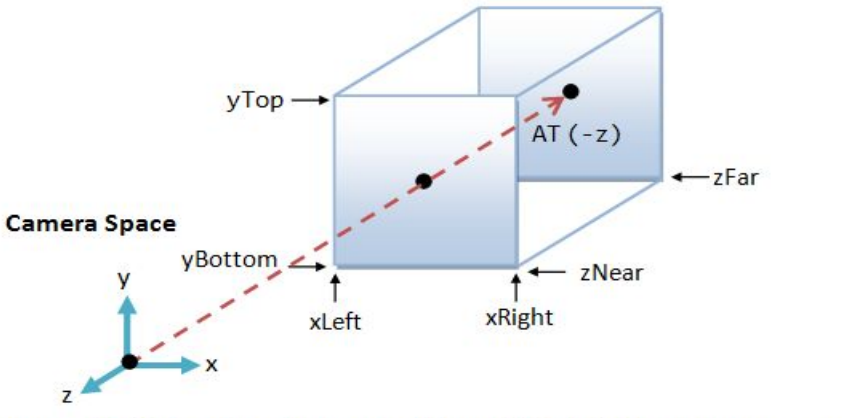
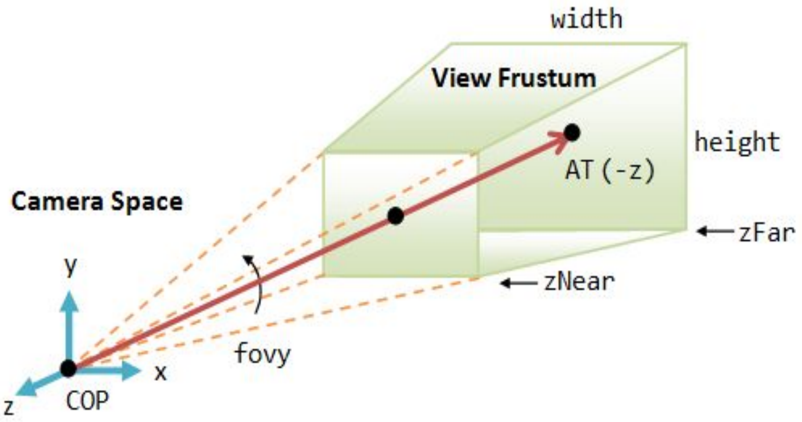
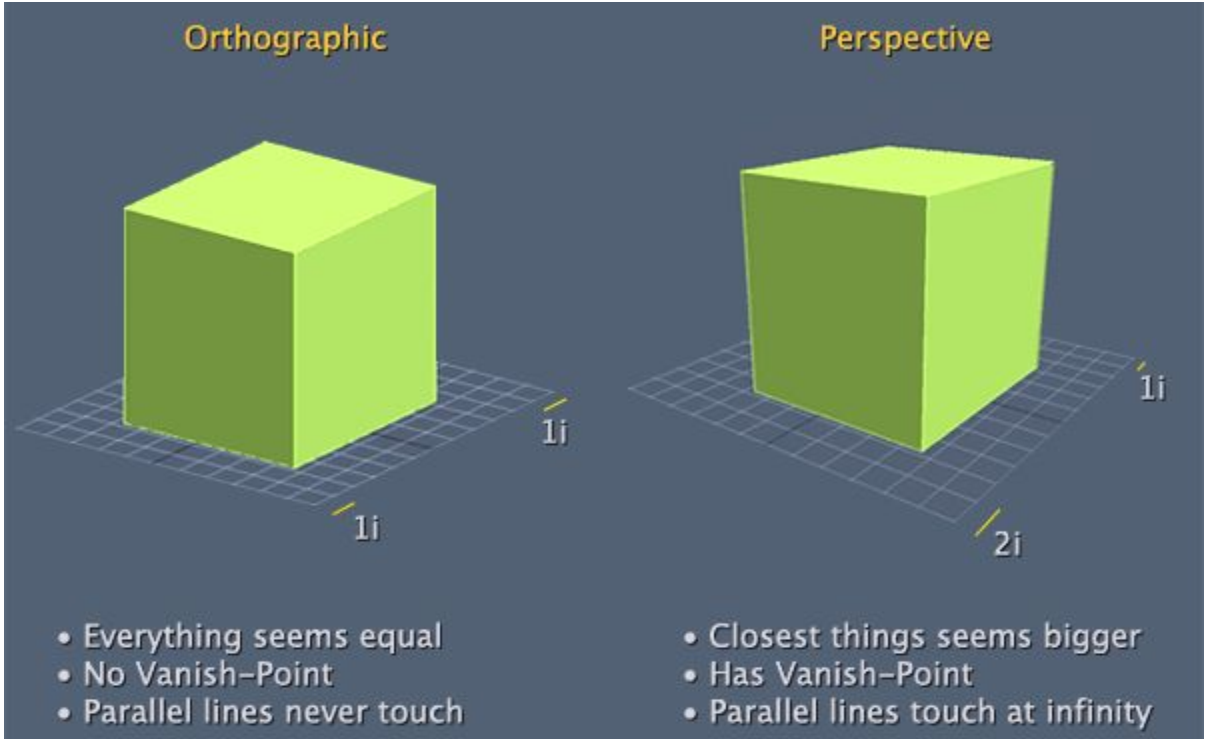
- Projection transf. are like choosing our camera lens or field of view
- Used to describe a viewing volume and how objects are projected
- Projections may be either **orthographic** or **perspective**



Orthographic Projection: Camera positioned infinitely far away at $z = \infty$



Projective Transformations

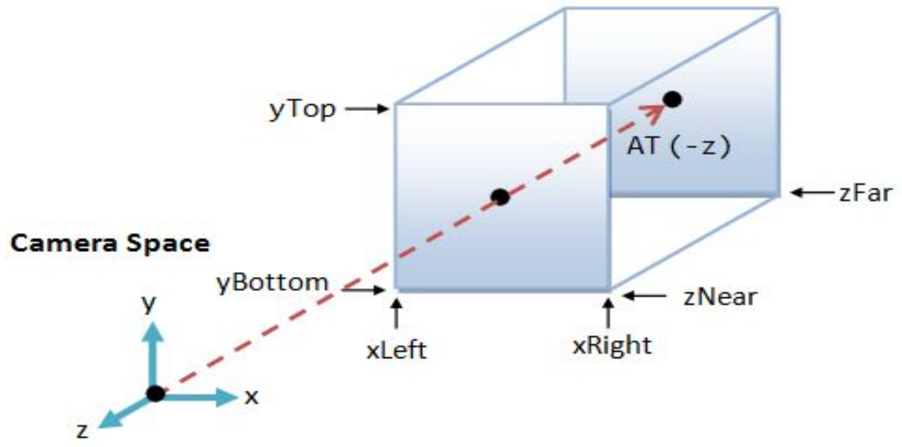


http://blog.db-in.com/cameras-on-opengl-es-2-x/

Orthographic Projection

Orthographic projections require a box shaped viewing volume

```
makeOrthographicProjectionMatrix(left,right,bottom,top,near,far)
```



Orthographic Projection: Camera positioned infinitely far away at $z = \infty$

Perspective Projection

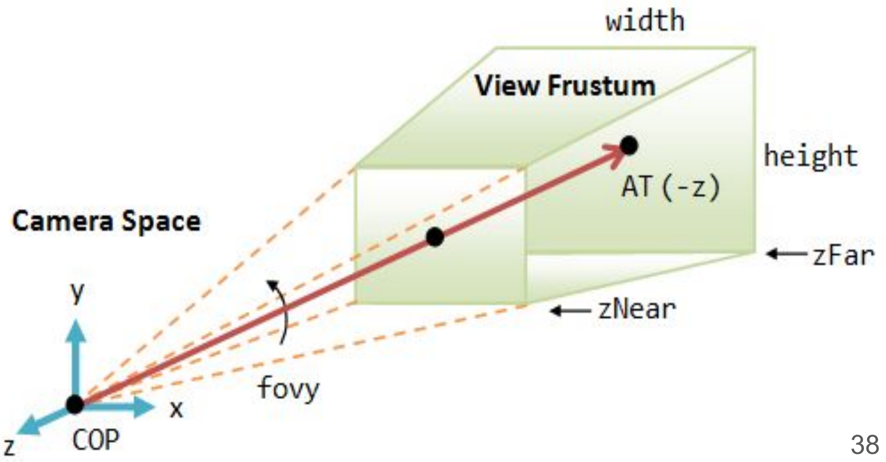
Perspective projections require a frustum shaped viewing volume

- Truncated section of a pyramid

Two options to define a frustum:

- Specify left, right, bottom, top, distance of near and far clipping plane
  - **OR**
- Specify field of view (angle), aspect ratio (width/height), distance of near and far clipping plane

We will use the second option.

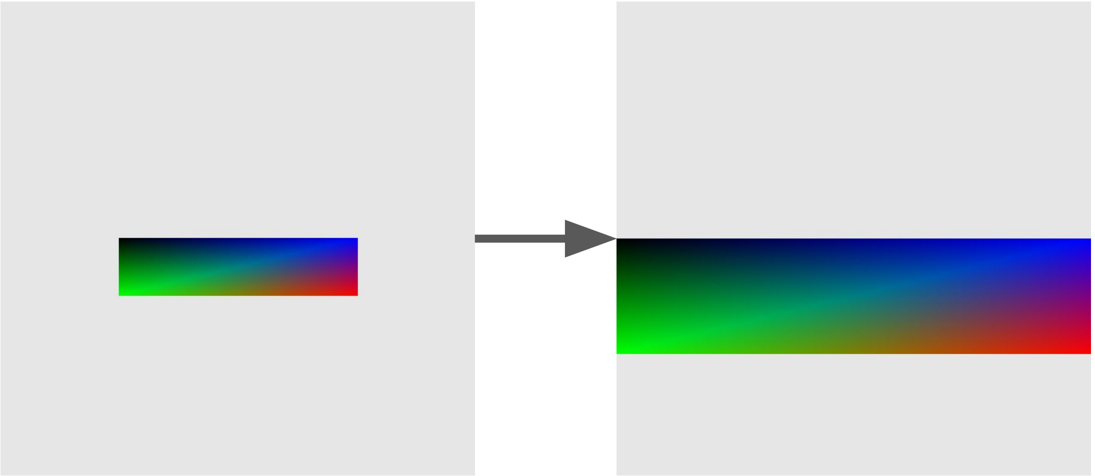


TASK 6: Orthographic Projection

Goal: Set up orthographic projection

Step 1: Call `makeOrthographicProjectionMatrix(left,right,bottom,top,near,far)`

With settings: `left=-0.5, right=0.5, bottom=-0.5, top=0.5, near=0, far=10`



Task 6: Solution

```
var projectionMatrix = defaultProjectionMatrix;
// TASK 6
projectionMatrix = makeOrthographicProjectionMatrix(-.5,.5,-.5,.5,0,10);
// TASK 7

gl.uniformMatrix4fv(projectionLocation, false, projectionMatrix);
```

main.js

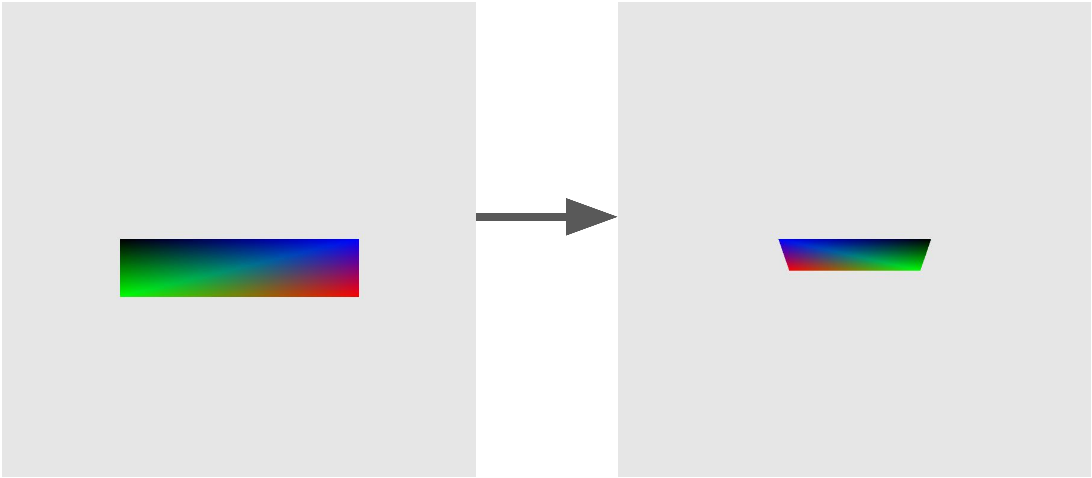
TASK 7: Perspective Projection

Goal: Set up perspective projection

Step 1: `makePerspectiveProjectionMatrix(fieldOfViewInRadians,aspect,near,far)`

With settings: `fieldOfViewInRadians=30 degree, aspectRatio=canvasWidth/canvasHeight, near=1, far=10`

You'll notice perspective foreshortening



Task 7: Solution

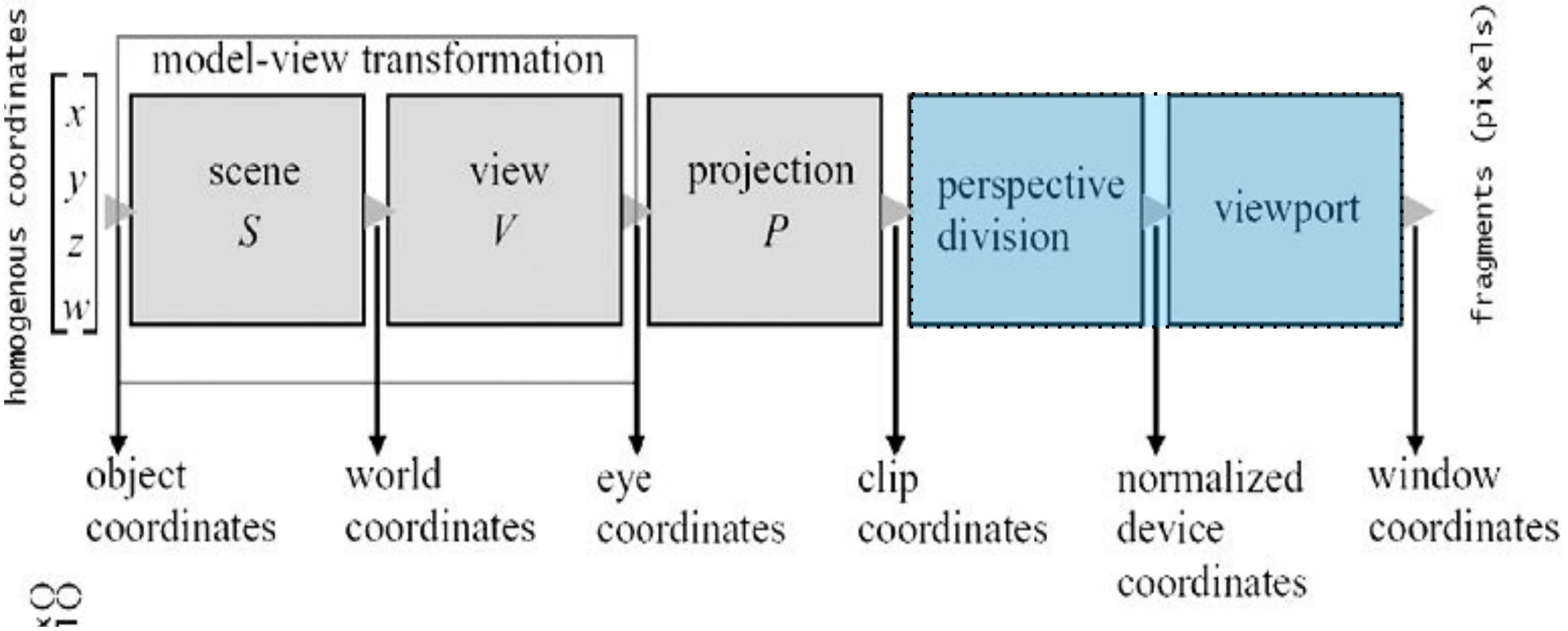
```
 var projectionMatrix = defaultProjectionMatrix;
// TASK 6

// TASK 7
projectionMatrix = makePerspectiveProjectionMatrix(fieldOfViewInRadians,
    aspectRatio, 1, 10 );

gl.uniformMatrix4fv(projectionLocation, false, projectionMatrix);
```

main.js

Perspective Division & Viewport



Perspective Division & Viewport

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This step is independent from the user, it cannot be affected.

Vertex coordinates are being divided by the w-coordinate and we obtain normalized device coordinates (NDC) ranging from -1 to 1 in x, y.

The z-coordinate (depth) is treated as always ranging from 0.0 to 1.0.

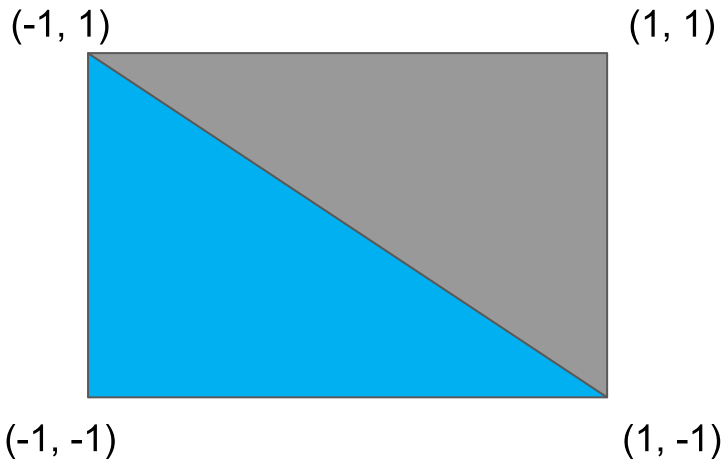
There's more on depth handling in our next exercise!

Reusing Vertices via Index Buffer

Quad from lab 1 consists of 2 triangles

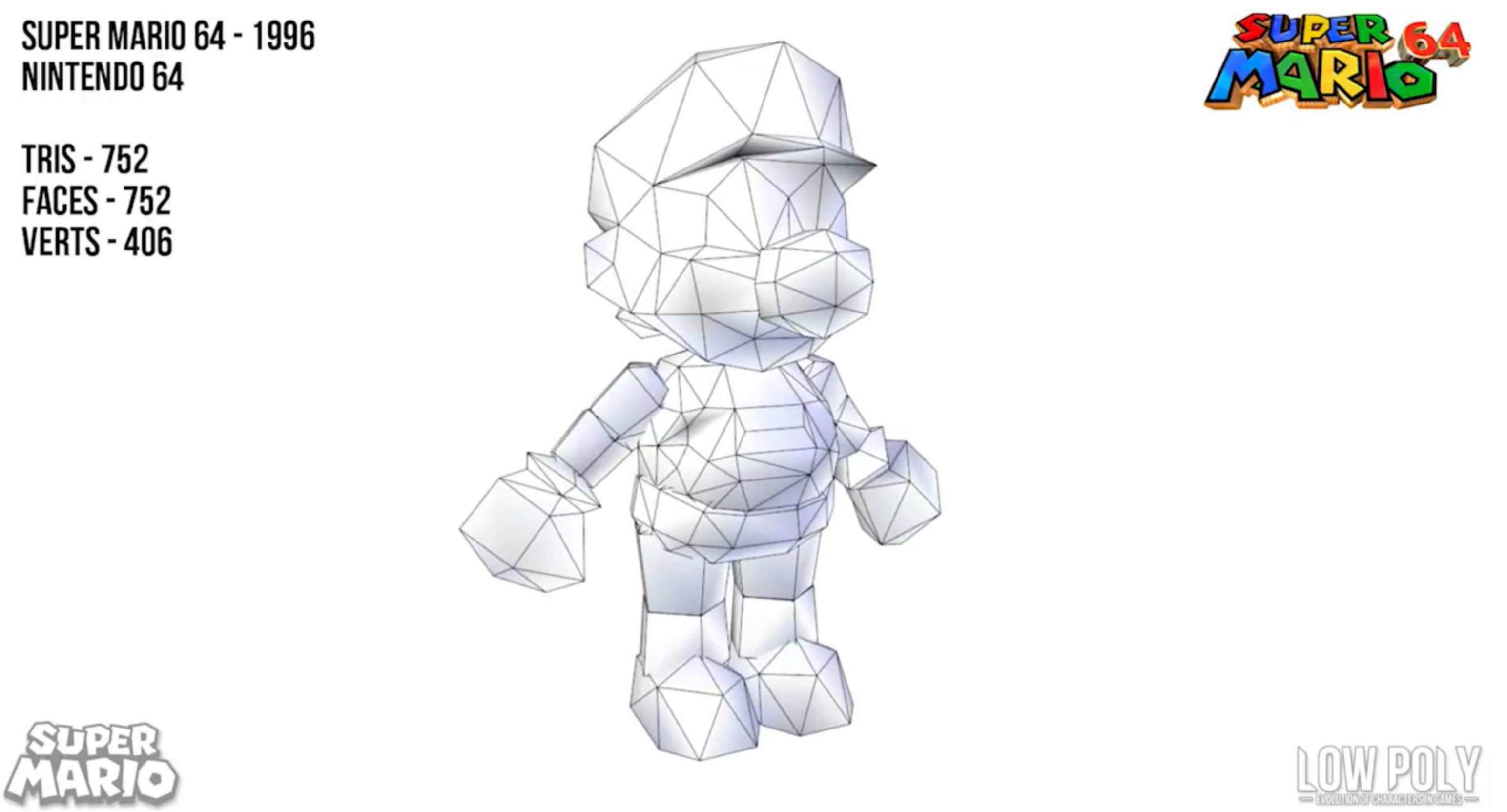
Drawback: Some vertices need to be send to GPU multiple times

Instead of defining vertices multiple times indexing can be used




```
const arr = new Float32Array([
    -1.0, -1.0,
     1.0, -1.0,
    -1.0,  1.0,
    -1.0,  1.0,
     1.0, -1.0,
     1.0,  1.0
]);
```

Reusing Vertices via Index Buffer



https://www.youtube.com/watch?v=A2gXyEyy_2U

Task 8: Add Cube

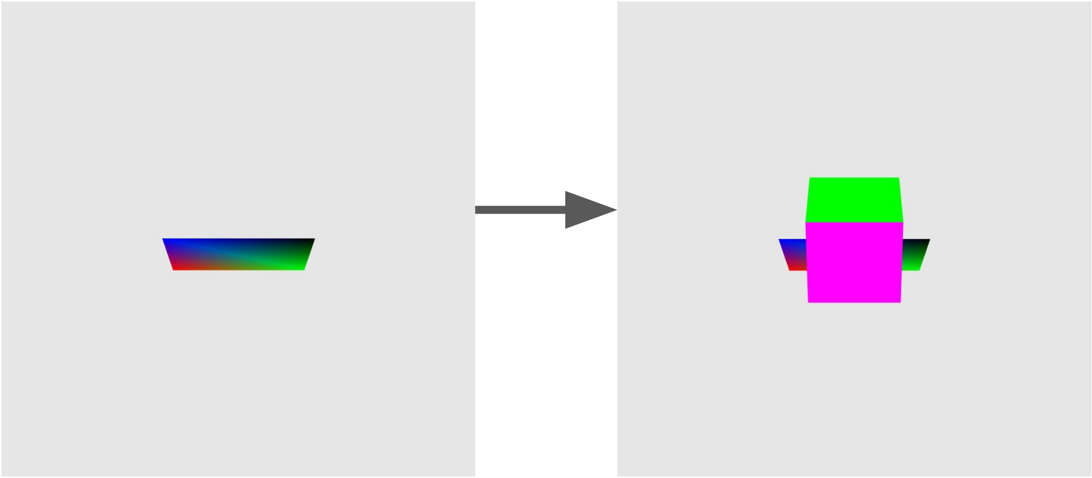
Cube geometry defined at top

`cubeVertices, cubeColors, cubeIndices`

Step 1: Initialize buffers by calling `initCubeBuffer()`

Step 2: Call `renderRobot(...)`

Step 3: Render cube by calling `renderCube()` in `renderRobot(...)`



Task 8: Solution

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```
  // TASK 8-1
  //set buffers for cube
  initCubeBuffer();
}
```

```
  renderQuad(sceneMatrix, viewMatrix);

  // TASK 8-2
  renderRobot(sceneMatrix, viewMatrix);

  //request another render call as soon as possible
  requestAnimationFrame(render);
```

```
function renderRobot(sceneMatrix, viewMatrix) {

  gl.bindBuffer(gl.ARRAY_BUFFER, cubeVertexBuffer);
  gl.vertexAttribPointer(positionLocation, 3, gl.FLOAT, false,0,0) ;
  gl.enableVertexAttribArray(positionLocation);

  gl.bindBuffer(gl.ARRAY_BUFFER, cubeColorBuffer);
  gl.vertexAttribPointer(colorLocation, 3, gl.FLOAT, false,0,0) ;
  gl.enableVertexAttribArray(colorLocation);

  // TASK 10-2

  // store current sceneMatrix in originSceneMatrix, so it can be restored
  var originSceneMatrix = sceneMatrix;

  // TASK 9 and 10

  setUpModelViewMatrix(viewMatrix, sceneMatrix);
  // TASK 8-3
  renderCube();

  // TASK 10-1

}
```

main.js

Task 9: Create Animation

Goal: Rotate cube

Principle: Apply small transformations in every render call

Independent of the frame rate:

```
function render(timeInMilliseconds) {
```

```
animatedAngle = timeInMilliseconds/10;
```

Step 1: add rotation around y-axis of cube by using variable:

`animatedAngle`

Task 9: Solution

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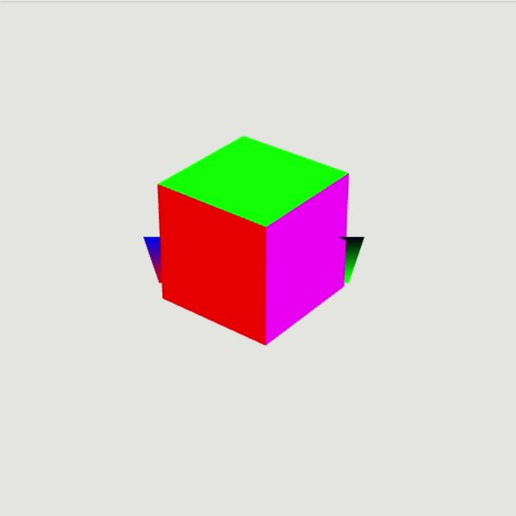
```
function renderRobot(sceneMatrix, viewMatrix) {

  gl.bindBuffer(gl.ARRAY_BUFFER, cubeVertexBuffer);
  gl.vertexAttribPointer(positionLocation, 3, gl.FLOAT, false,0,0) ;
  gl.enableVertexAttribArray(positionLocation);

  gl.bindBuffer(gl.ARRAY_BUFFER, cubeColorBuffer);
  gl.vertexAttribPointer(colorLocation, 3, gl.FLOAT, false,0,0) ;
  gl.enableVertexAttribArray(colorLocation);

  // TASK 10-2

  // store current sceneMatrix in originSceneMatrix, so it can be restored
  var originSceneMatrix = sceneMatrix;

  // TASK 9 and 10
  sceneMatrix = matrixMultiply(sceneMatrix, makeYRotationMatrix(convertDegreeToRadians(animatedAngle)));
  setUpModelViewMatrix(viewMatrix, sceneMatrix);
  renderCube();

  // TASK 10-1

}
```

main.js

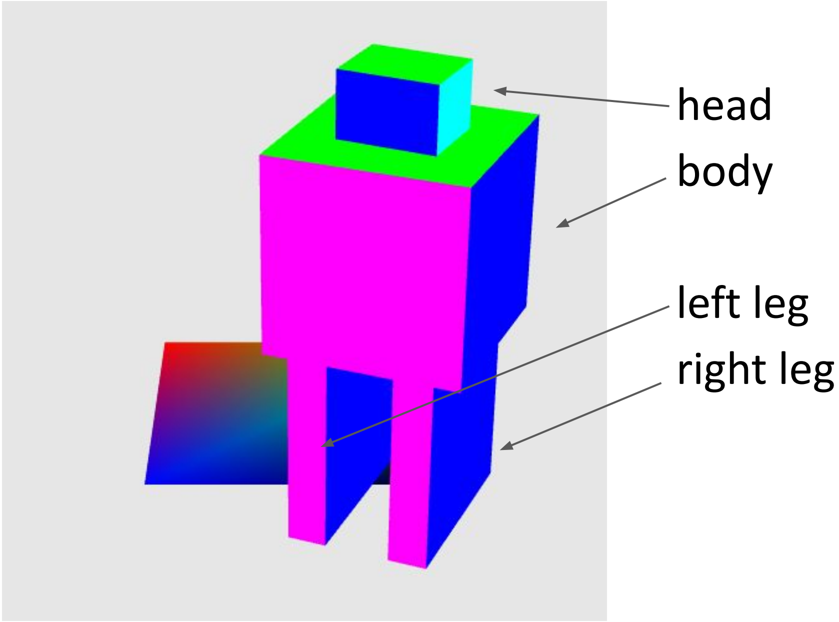


At Home: Create a Robot

Robot should stand on ground plane (our quad)

Build robot from 4 cubes

Transform (translate,scale,rotate) cubes



Task 10: Complex Transformations

Goal: Create robot with rotating head that walks circles on ground

Step 0: Make ground plane (rotate quad by 90°)

Step 1: Create robot by adding cube multiple times

- Body, head, left leg, right leg
- rotating cube is the robot's head

Step 2: Let robot walk circles (without moving the legs)

Task 10-1: Solution

```
// TASK 9 and 10
sceneMatrix = matrixMultiply(sceneMatrix, makeYRotationMatrix(convertDegreeToRadians(animatedAngle)));
sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.0,0.4,0));
sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix(0.4,0.33,0.5));
setUpModelViewMatrix(viewMatrix, sceneMatrix);
renderCube();

// TASK 10-1
//body
sceneMatrix = originSceneMatrix;
setUpModelViewMatrix(viewMatrix, sceneMatrix);
renderCube();

//left leg
sceneMatrix = originSceneMatrix;
sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.16,-0.6,0));
sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix(0.2,1,1));
setUpModelViewMatrix(viewMatrix, sceneMatrix);
renderCube();

//right leg
sceneMatrix = originSceneMatrix;
sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(-0.16,-0.6,0));
sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix(0.2,1,1));
setUpModelViewMatrix(viewMatrix, sceneMatrix);
renderCube();
```

main.js

Task 10-2: Solution

```
// TASK 10-2
// transformations on whole body
sceneMatrix = matrixMultiply(sceneMatrix, makeYRotationMatrix(convertDegreeToRadians(animatedAngle/2)));
sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.3,0.9,0));

// store current sceneMatrix in originSceneMatrix, so it can be restored
var originSceneMatrix = sceneMatrix;


// TASK 9 and 10
sceneMatrix = matrixMultiply(sceneMatrix, makeYRotationMatrix(convertDegreeToRadians(animatedAngle)));
sceneMatrix = matrixMultiply(sceneMatrix, makeTranslationMatrix(0.0,0.4,0));
sceneMatrix = matrixMultiply(sceneMatrix, makeScaleMatrix(0.4,0.33,0.5));
setUpModelViewMatrix(viewMatrix, sceneMatrix);
```

main.js

Recap

Transformation pipeline

Model-view transformations

- Translate, scale, rotate

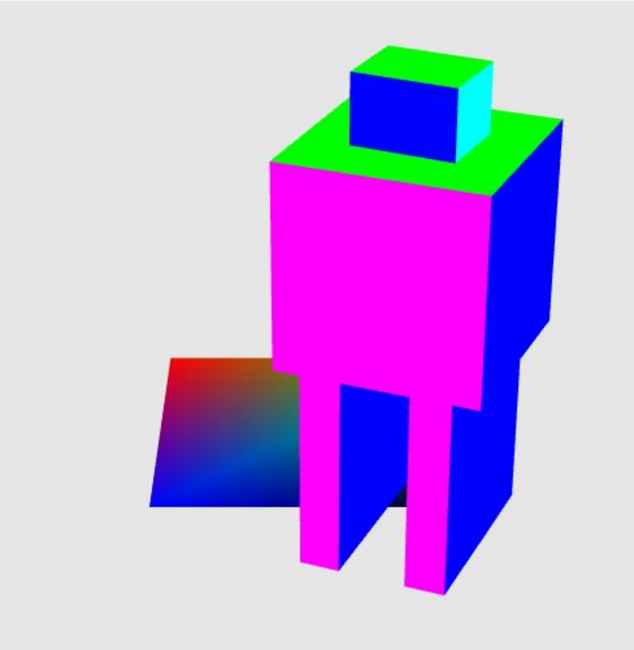
Camera transformations

Projective transformations

- Orthographic and perspective projection

Creating geometry using the index buffer

Animations



Next Time

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- Rendering multiple objects
- Blending and depth handling
- Scene graph nodes and traversal
- glMatrix JavaScript library
  - Replaces matrix specific functions at the end of main.js from Lab 2 (e.g., multiply, lookAt, inverse …)

Practice at Home!

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Play around with the framework

- Add rotating arms, more objects, …

Integrate transformations and projection into your projects