

# Lecture 21

## Shaders

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# Roadmap

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## Last Week: Fancy Textures

Why do we do things that way?

## Not last week:

How does the graphics hardware work?

(only very limited discussion)

## This Week: Shaders!

How do we program the graphics hardware?

# Warning!

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**You can't program the graphics hardware if you don't understand it**

The hardware has a specific computation model (the pipeline)

The programming model is for this computation model

**but we didn't talk about it much...**

Experiment: try the minimum on hardware and dive right into shaders

# Why is Shader Programming Hard?

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1. You must understand the computation model (pipeline)
2. You must work in a special programming language
3. You must deal with mechanics issues of connecting to your program
4. You need special tricks to work in the model
5. You have to pay attention to really get performance
6. The tools are not great

# Guess what we're doing in class!

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1. You must understand the computation model (pipeline)
2. You must work in a special programming language
3. You must deal with mechanics issues of connecting to your program
4. You need special tricks to work in the model
5. ~~You have to pay attention to really get performance~~
6. ~~The tools are not great~~

# Where we got to last week...

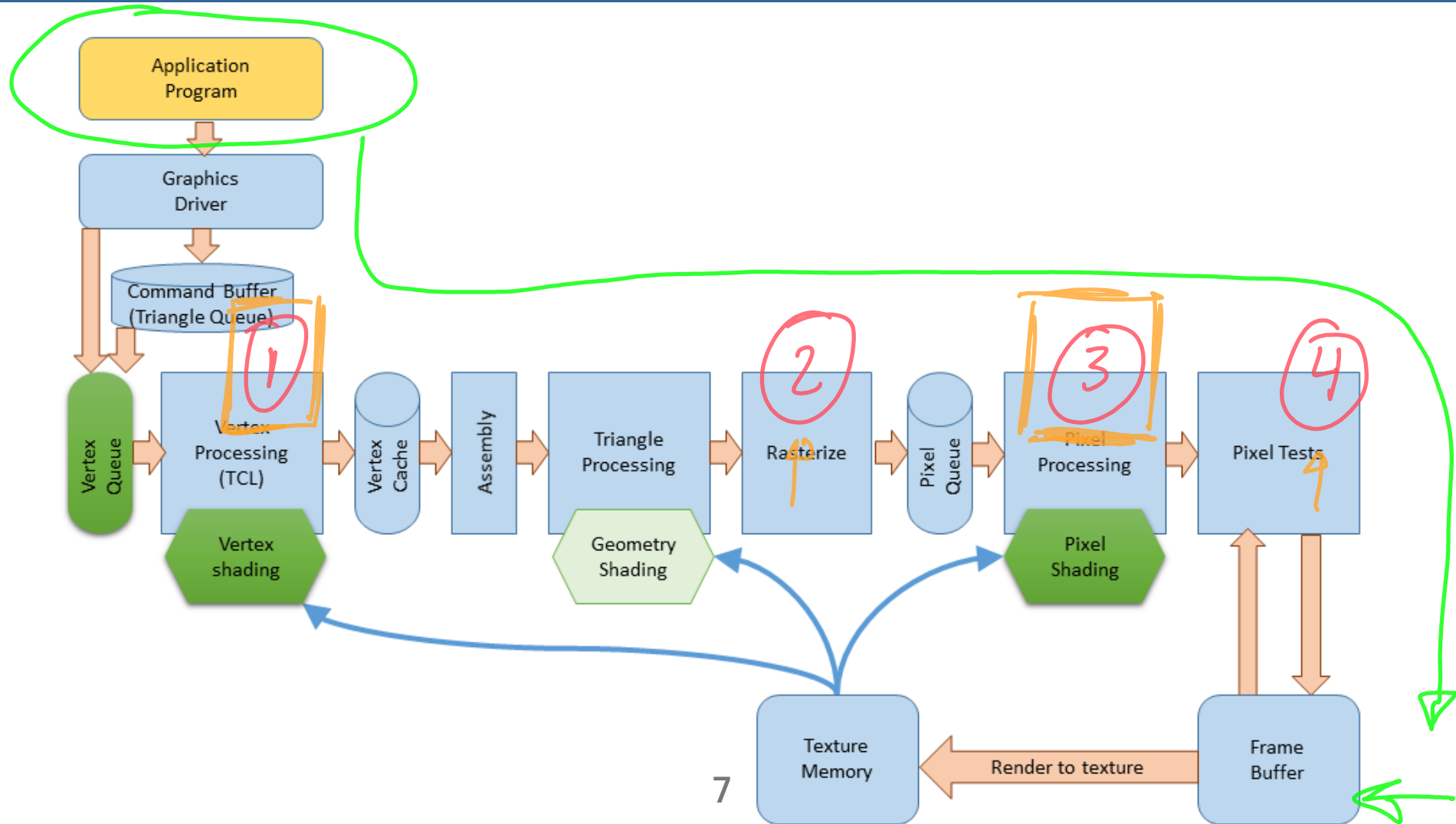
---

Draw each triangle - somewhat order independent (parallel)

1. Transform triangles into 2D (with Z values)
2. Rasterize triangles (into fragments (pixels), with Z-values)
3. Figure out the color of those fragments
4. Write those fragments to the image (with Z-Test)



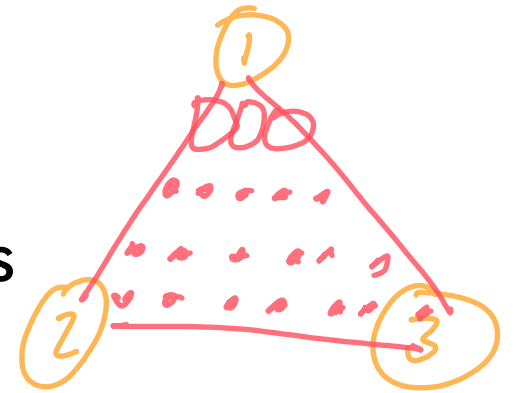
# What we didn't see: The Pipeline



# Some details...

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- 1. Transform triangles into 2D (with Z values)
  - vertices processed independently
2. Rasterize triangles (into fragments (pixels), with Z-values)
  - assemble triangles from vertices, then make fragments
- 3. Figure out the color of those fragments
  - shading (lighting, texture lookup, ...)
4. Write those fragments to the image (with Z-Test)





# What does our program do?

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- Sets up for drawing
- Repeat (for every frame)
  - Clears the screen
  - For each "object"
    - Draws a group of triangles

(and some other computations mixed in)

# The idea of an "object"

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A group of triangles sent together

- the vertices (and their info)
- how they connect to triangles
- what shaders to use in processing them
- what parameters to use across all of them

We are limited in what we can change within a "group"

# Constant State

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We cannot change certain things while drawing a triangle

This extends to the "group" of triangles

- What is the camera?
- What frame buffer are we drawing to?
- What lights are we using?
- Which texture maps are we using?
- [and other things]

These things are uniform over the group of triangles

In THREE we have a scene and material that has these common properties

# Are Transformations Uniforms?

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Yes... transforms per triangle group

But... We want to have a small number of big groups (for performance)

1. Don't worry about it - often not a bottleneck
2. Use tricks to have multiple matrices

# Per Vertex Information

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Note: we have to split vertices (each vertex has all properties)

Each vertex has (attributes):

- a position

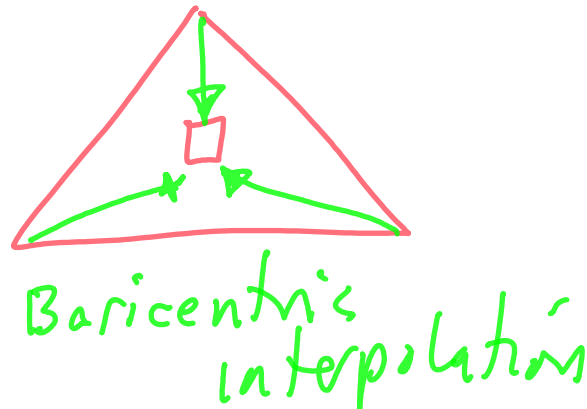
And potentially:

- a color
- a normal
- a texture coordinate (or multiple ones)
- other information

# What can our Program Specify?

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- ① Global Information (uniforms)
- ② Per Triangle (Group) Information (uniforms)
- ③ Per Vertex Information (attribute buffers)
- ④ ~~Cannot specify per-pixel (only draw triangles)~~



# The pieces we program

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1. Transform triangles vertices to 2D

2. Rasterize triangles

3. Figure out the color of fragments

4. Write fragments to image

• Vertex Processor

*vertex  
shaders*

• (fixed)

• Fragment Processor

*fragment  
shaders*

• (fixed)

Other parts may be programable too

# Vertex Processing Unit

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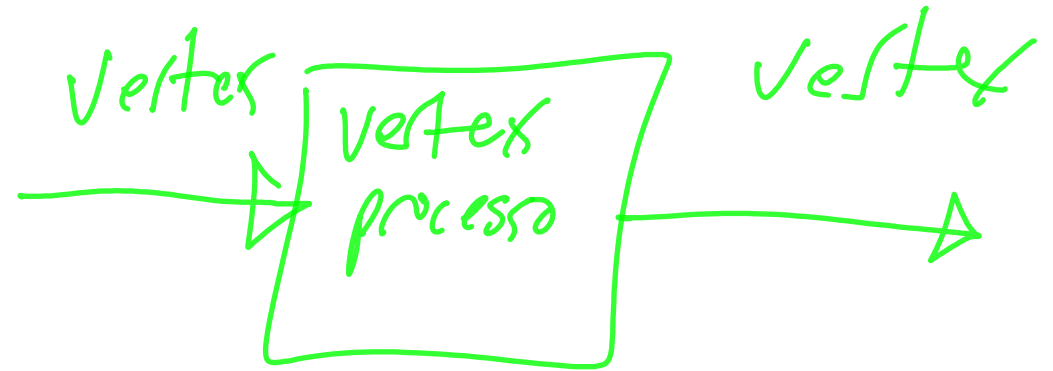
Processes each vertex independently

## Input: vertex with info

**Attributes** from the host program

## Output: vertex with more info

More attributes about the vertex





# Vertex Shader

## Vertex Before

Position ←  
Normal ←  
Color ←  
UV ←  
(and maybe others)

*vertex in*

## Vertex After

→ Position  
→ Normal  
→ Color  
→ UV  
(and maybe others)  
→ **screen space position** ←  
vertex-lit color  
screen-space normal  
(and maybe others)

*vertex out*

# We add information to vertices

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These could have been attributes (computed by host program)

Which ones are **really** needed?

- screen space position (for rasterizer / Z-test)
- anything used for coloring

# What does the rasterizer do with this?

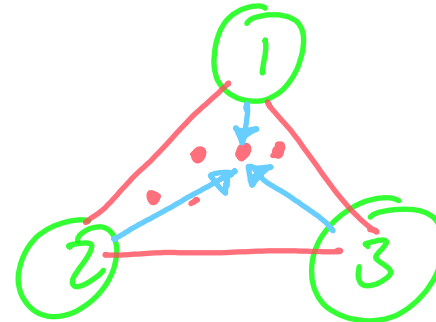
---

1. Use screen space coordinates to generate list of fragments (pixels)
2. Interpolate other values so each fragment has those properties

## What do the fragments have?

1. a screen space position
2. interpolated values

A fragment depends on three vertices!



1  
2  
3  
4

# What do we do with a fragment?

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Each Fragment is processed **independently**

It gets information from the rasterizer

*↳ interpolated vertex info*

Figure out what color it should be

Figure out what depth it should be

Testing happens in a separate stage

# Fragment Processing

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## Before

Screen space position

Depth value (z)

Other interpolated properties

*↓  
from vertices*

## After

▶ Screen space position

▶ Depth value

▶ Color to write to frame buffer  
(sometimes other things to store)

We cannot change the screen space position!

(that would make it a different fragment/pixel)

# Uniform, Attribute, Varying

## Host Program

*Javascript*

### Inputs:

??

??

### Outputs:

*uniform*

Per object info

Per vertex info

*attribute buffers*

## Vertex Shader

### Inputs

Per object info

Per vertex info

### Outputs

Per vertex info

*rasterizer  
interpolates*

## Fragment Shader

### Inputs

Per object information

Per fragment info

### Outputs

Per fragment info

*varying  
variables*

# Shaders

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Vertex Shaders: compute new attributes for vertices

Fragment Shaders: compute color/depth for fragments

We write these programs in a **shading language**

# Shading Languages

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Shaders are special programs

- work in a specific programming model
- run on unusual hardware
- have very specific goals/needs

We write them in special programming languages!



# History of Shading Languages

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[Skip]

Pat Hanrahan Distinguished Lecture in the Fall  
(UW Alum, Turing Award Winner)

# Shading Languages Today

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Several still exist (GLSL, HLSL, ...)

All very similar

- the **model** constrains what the languages do
- syntax varies
- similar enough that source translation exists

# GLSL

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The shading language for OpenGL

WebGL is a variant of OpenGL

- WebGL is based on OpenGL ES

GLSL-ES for WebGL is a subset of full GLSL

- fewer built-in functions
- different host API

Compiler is built into the graphics driver!

- compile code at "runtime"

# Parts of GLSL

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1. The Shading Language

2. The Host API

# GLSL Language Basics

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## "C-Like"

- C Syntax (very similar)
- strict typing
- operator overloading

## Features for graphics

- math data types (matrices, vectors)
- built-in functions


## Features for tying things together

# GLSL Ideas for Connecting Pieces

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Each shader is its own little program

Shader connects to other parts via "special variables"

- look like global variables
- special declarations 
- a few built ins (inconsistent)

Easiest to learn by example

# A First GLSL Shader Pair

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Shaders always come in pairs


You need both a vertex shader and a fragment shader

# Example 1

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## Vertex Shader

```
uniform mat4 modelViewMatrix;  
attribute vec4 position;  
  
void main() {  
    gl_Position = modelViewMatrix*pos;  
}
```



## Fragment Shader

```
void main() {  
    gl_FragColor = vec4(0.8,0.8,0.4,1.0);  
}
```





# Vertex Shader

```
uniform mat4 modelViewMatrix;  
attribute vec4 position;  
  
void main() {  
    gl_Position = modelViewMatrix * position;  
}
```

This is the GLSL part

JavaScript must provide inputs

( pos and modelViewMatrix )

output is gl\_Position

built-in varying

matrix \* vec4 (v3, 1.0)

# Observe:

communicate with variables

strong typing

use of vector types

C-like syntax

main function

uniform and attribute

Projection didn't fit on slide

inputs / uniform attribute

## Observe:

communicate with variables  
special `gl_FragColor` output

declaration

uniform  
|  
qualifier

vec  
|  
type

## Fragment Shader

```
void main() {  
    gl_FragColor = vec4(0.8,0.8,0.4,1.0);  
}
```

alpha

# A Slightly More Interesting Pair...

## Vertex Shader

```
uniform mat4 modelViewMatrix;  
attribute vec3 position;  
attribute vec3 color;  
  
varying vec3 vcolor;  
  
void main() {  
    gl_Position = modelViewMatrix*  
        vec4(position, 1.0);  
    vcolor = color;  
}
```

## Fragment Shader

```
varying vec3 vcolor;  
  
void main() {  
    gl_FragColor = vec4(vcolor, 1.0);  
}
```

*assemble*  
*4 vector from 3 vector*  
*rasterizer*

# A varying variable

## Vertex Shader

```
uniform mat4 modelViewMatrix;
attribute vec3 position;
attribute vec3 color;
varying vec3 vcolor;

void main() {
    gl_Position = modelViewMatrix *
        vec4(position, 1.0);
    vcolor = color;
}
```

assign

## Fragment Shader

```
varying vec3 vcolor;

void main() {
    gl_FragColor = vec4(vcolor, 1.0);
}
```

vse

Rasterize  
into pixels

# Moving data around

## Vertex Shader

```
uniform mat4 modelViewMatrix;  
attribute vec3 position;  
attribute vec3 color;  
  
varying vec3 vcolor;  
  
void main() {  
    gl_Position = modelViewMatrix*  
        vec4(position, 1.0);  
    vcolor = color;  
}
```

## Qualifiers on variables

uniform

attribute

varying

"Global" variables 

Special variables

gl\_Position

gl\_FragColor

*screen space*

*ultimate color*

# Getting Data From JavaScript

## Vertex Shader

```
uniform mat4 modelViewMatrix;  
attribute vec3 position;  
attribute vec3 color;  
  
varying vec3 vcolor;  
  
void main() {  
    gl_Position = modelViewMatrix*  
        vec4(position, 1.0);  
    vcolor = color;  
}
```

## Where does data come from?

modelViewMatrix ?

position ?

color ?

*uniform*

*buffer attributes*

# How to get the shader?

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The shader program is just a string...

- put it in the code as a literal
- put it in the html as a script (and read it)
- put it as a separate file (and load it)

I recommend: separate file

- keep languages separate (so you can use a specific editor)
- load the file asynchronously
- class framework code helps with this

# Once you have the program text

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Need to pass the program to the compiler

A bunch of steps

- compile the shaders
- link the shaders
- use the shaders

THREE takes care of this for us

↳ Shader Material



# Drawing a triangle group

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## - Object 3D

### Things done to set up the triangle group

- graphics state (window, render target, ...)
- coordinate system info (transform, camera, projection)
- lighting info
- textures

### Things about the triangle group

- vertex connectivity information
- vertex information

# Uniforms

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Cannot be changed inside of a triangle group

Some information is "built in"

Other things need to be declared specifically

# Connecting User-Defined Uniforms

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## GLSL

```
uniform float x;  
uniform vec3 y;  
uniform mat4 z;
```

## JavaScript

???

Need to:

- create mapping of names
- convert types
- provide mapping table

Don't worry - THREE does it for us

# Attribute Information

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Data for each vertex

- position, color, normal, UV, ...

May be a lot of vertices

Transfer as a block of memory

- blocks of memory are **buffers**

Flexible memory layout

Attribute Buffers

# How attributes are passed

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Need to attach attribute buffers to attribute variables in shaders

Don't worry - THREE takes care of it for us

# Using Shaders in THREE

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What does THREE have?

- Scene, Renderer and other state information
- Lighting properties
- Textures
- Geometry ( ~~Geometry~~ and ~~BufferGeometry~~ )
- Materials

# How does THREE Work?

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Materials have shaders

Standard materials construct shaders as needed

- build up the shader from pieces
- depends on what is used
- lights, maps, other features, ...
- compiled when material changes
- knows about the object as well

A lot of information is gathered up to send to shaders

# Making Your Own Shaders

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## `ShaderMaterials` class

- allows you to give text for programs ← *Three*
- allows you to set lots of options
- provides access to THREE data (lights, objects, ...)
- has a mechanism for attributes
- allows you to declare a dictionary of uniforms
  - you must decide which uniforms you want!



# Uniforms *- in Three*

```
{
  uniforms: {
    var1: { value: 10.0},
    var2: { value: new T.Vec2(1,2);}
  }
}
```

*name*

uniforms are one parameter to ShaderMaterial  
provide a dictionary that maps **variables** to **values**  
each value is a dictionary (with the key **value**)

# Built-In Uniforms

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Some of the uniforms are "built in"

```
uniform mat4 modelMatrix;  
uniform mat4 modelViewMatrix;  
uniform mat4 projectionMatrix;  
uniform mat4 viewMatrix;  
uniform mat3 normalMatrix;  
uniform vec3 cameraPosition;
```

These are added to your vertex program

Some of these are added to your fragment program

# Non-Built in Uniforms

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The programmer is responsible for others

If you want THREE's internal things, you need to use `uniformlib`

This is poorly documented

Example:

```
lights: true,  
uniforms: T.UniformsLib['lights']
```

must add programmer defined uniforms

not declared in GLSL for you

# Attributes

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THREE provides the most important vertex properties

```
attribute vec3 position;  
attribute vec3 normal;  
attribute vec2 uv;
```

And puts in other things if they are defined in the mesh

```
#ifdef USE_COLOR  
    attribute vec3 color;  
#endif
```

# Using Attributes and Uniforms

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From the THREE documentation

```
https://threejs.org/docs/#api/en/renderers/webgl/WebGLProgram
```

```
gl_Position = projectionMatrix * modelViewMatrix * vec4( position, 1.0 );
```

or alternatively

```
gl_Position = projectionMatrix * viewMatrix * modelMatrix * vec4( position, 1.0 );
```

# In The Class Framework...

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1. you can make your own `ShaderMaterial`
2. you can use the `shaderMaterial` convenience function
  - asynchronous loading
  - provides a default shader until yours loads (yellow)
  - provides an error shader if yours fails to load (red)
  - THREE catches the compiler error no material (object can't be seen)

# The class framework handles setup

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`shaderMaterial` (a function, returns an instance of THREE `ShaderMaterial` )

- `vertexShaderURL` - filename (for URL) for vertex shader code
- `fragmentShaderURL` - filename (for URL) for fragment shader code
- `properties` - arguments for `T.ShaderMaterial` constructor

1. Create the `ShaderMaterial` with default shaders

2. loads the files

3. compiles them, and attaches them to the `ShaderMaterial`

4. Asynchronous