Chapter 5

Color Models and Color Applications

5.1 Overview

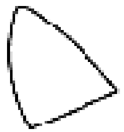
Color plays a significant role in achieving realistic computer graphic renderings. This chapter describes the quantitative aspects of color, which is the basis for all processing of color information during rendering.

Questions:

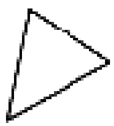
- How can we exactly specify a specific color?
  - → color spaces, color models
- How many different colors can be specified using graphics hardware?
  - → technical limitations
- How accurate can we display an exactly specified color on an output device?
  - → device dependent color spaces

5.1 Overview

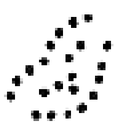
Hierarchies of known set of colors



A: set of all colors perceivable by the human eye

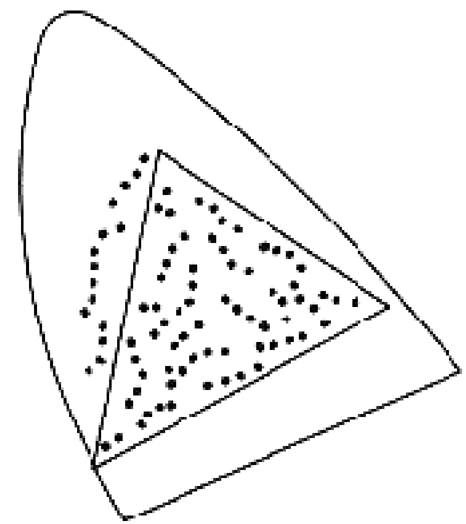


B: set of all displayable colors on an output devices, e.g. CRT monitor (subset of A)



C: set of all colors specifiable by a software program limited by the color depth of the frame buffer, e.g. 24 bits/pixel → 16777216 colors (generally a subset of A and a superset of B)

Planar slice of the 3-D color space. Each point corresponds to a color.



5.1 Overview

Three-dimensional color space

The traditional description of colors using names lacks accuracy: white → light gray → dark gray→ black.

A precise definition can be achieved using an objective quantitative specification. From a physics point of view, a color is a specific energy distribution within the electromagnetic spectrum with wavelengths ranging from 400 to 700 nm.

Physical experiments and studies of physiologic reception by the human eye resulted in the fact that almost all colors, that can be perceived by the human eye, can be realized as a composition of fundamental colors.

5.1 Overview

Three-dimensional color space

If we define ratios between the components, for example the fundamental colors red, green, and blue, as a triple (r, g, b) of weights then we can describe a specific color exactly by $C = rR + gG + bB$.

However, this is not the only way to define three-dimensional color spaces. Depending on the application different standardized color spaces (color models) can be used, for example:

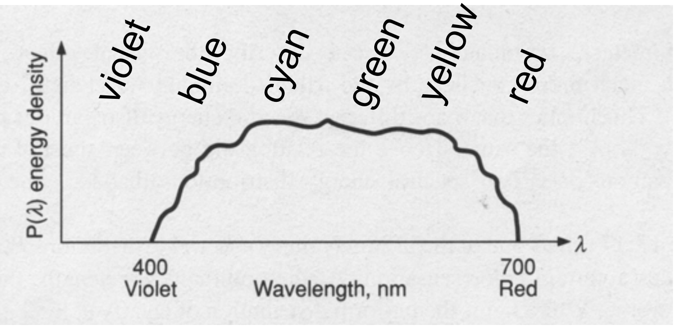
RGB: traditional color space for computer graphics, monitors, …

HSV: achieves a more intuitive way of choosing individual colors

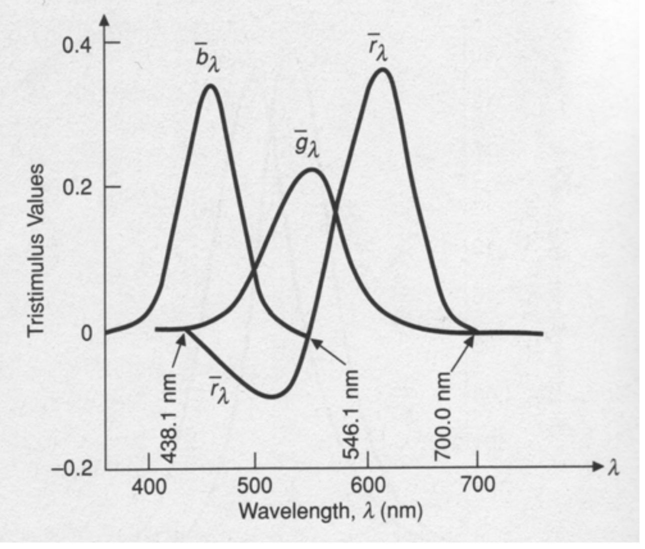
CIE: international standard for specifying colors

CMY: subtractive color model for printers

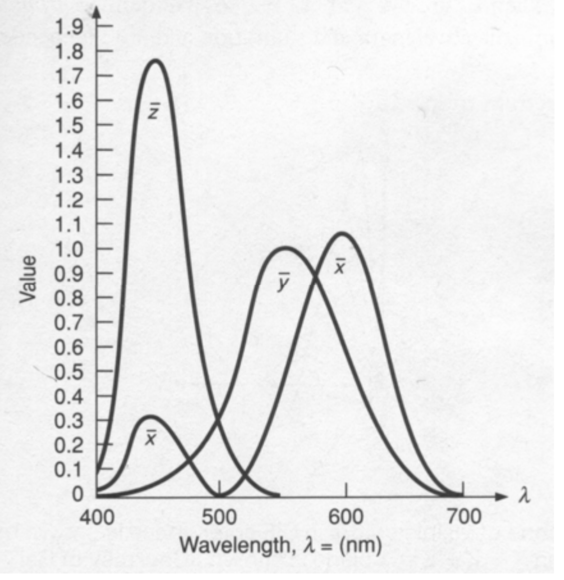
5.1 Overview



visible frequencies



RGB fractions for "simulating" individual wavelengths



XYZ fractions (CIE basis)

5.2 RGB color model

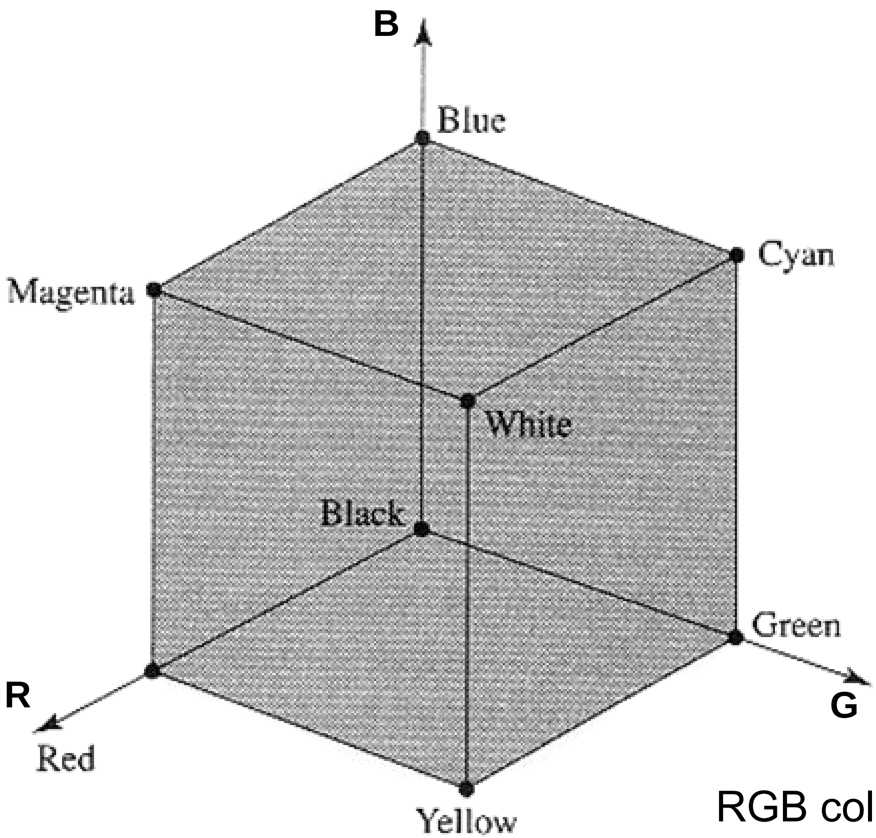
- The RGB color model uses the fundamental colors red, green, and blue for compositing additively.
- A specific color is described by a triple *(r, g, b)* of weights with $0 \leq r, g, b \leq 1$. We get:

(0, 0, 0) = black	(1, 1, 1) = white	
(1, 0, 0) = red	(0, 1, 0) = green	(0, 0, 1) = blue
(0, 1, 1) = cyan	(1, 0, 1) = magenta	(1, 1, 0) = yellow

  Often, 8 bits are used for each fundamental color,
  i.e. $0 \leq r, g, b \leq 255$

- The set of all specifiable colors is usually represented in 3-D space as a cube (color cube) which does not cover the entire perceivable color space.

5.2 RGB color model



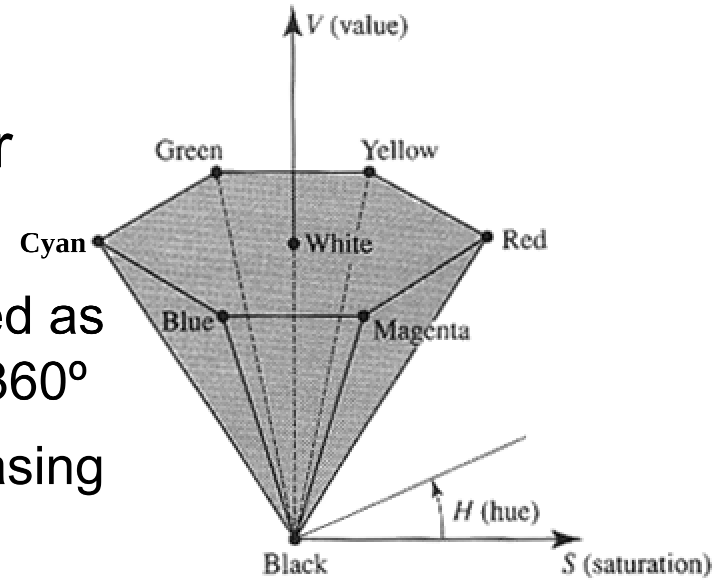
RGB color cube

5.2 RGB color model

- The RGB color model is not linear with respect to human perception: when looking at a typical color resolution of 8 bits per fundamental color (so called true color), then there are neighboring colors within the color cube that appear exactly the same. In other areas, however, neighboring colors are very well distinguishable.
- For the user, it is not very intuitive to define a desired color using the RGB color space by specifying the triple (r, g, b) or, for example, attenuating an existing color which requires the change of all values r, g, and b at different rates. → HSV color model

5.3 HSV color model

- The HSV color model was developed to allow for a more intuitive specification of individual colors (perception-oriented color model)
- The definable colors can be represented in 3-D space a pyramid with a hexagonal base
- The HSV color model uses polar coordinates:



Hue:	color (color family) defined as angle in degrees: 0º≤H≤360º
Saturation:	saturation 0≤S≤1 (decreasing S adds white)
Value:	brightness 0≤V≤1 (decreasing V adds black)

5.3 HSV color model

Correlation between the HSV and RGB color model

- The base of the HSV pyramid can be derived from the RGB color cube by projecting along the diagonal connecting white and black onto a plane orthogonal to that diagonal.
- As a result we can derive the following corresponding points within the color spaces
- Comment: complementary colors are located on opposite sides of the pyramid, i.e. with an angular difference of 180°

RGB	color	HSV
(1, 0, 0)	red	(0, 1, 1)
(1, 1, 0)	yellow	(60, 1, 1)
(0, 1, 0)	green	(120, 1, 1)
(0, 1, 1)	cyan	(180, 1, 1)
(0, 0, 1)	blue	(240, 1, 1)
(1, 0, 1)	magenta	(300, 1, 1)

5.3 HSV color model

Correlation between the HSV and RGB color model

- When following along the main diagonal of the RGB color cube from black to white, we can define for each point P on the diagonal a sub-cube as follows:
  - The main diagonals of the sub-cubes are part of the main diagonal of the entire color cube
  - One corner of the sub-cube as located at black $(0, 0, 0)$, the opposite corner is located at P
  - The sub-cube is inside the RGB color cube
- This way, each sub-cube derived using the above projection along the main diagonal defines a hexagon, which corresponds to a section of the HSV pyramid at a constant value of V, i.e. the main diagonal of the RGB color cube corresponds to the v-axis of the HSV pyramid.

5.4 CIE color model

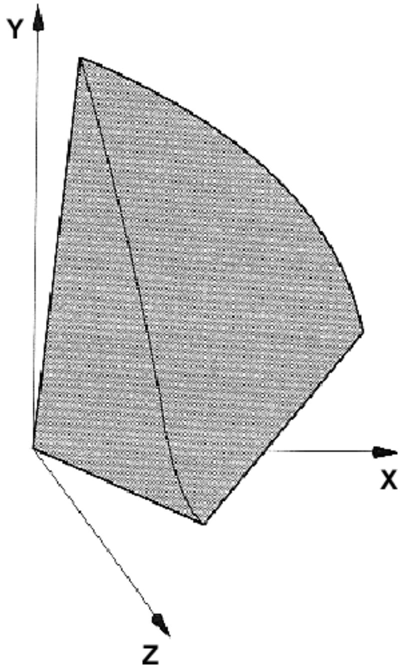
CIE color model (Commission Internationale de l´Éclairage, 1931)

– International, device independent standard for specifying colors, suitable for describing all colors perceivable by the human eye (the RGB color model is not capable of that!)

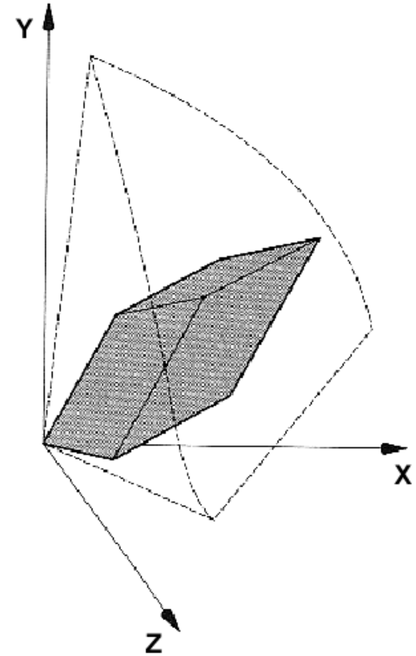
– Universal color space, uses artificial fundamental colors **X**, **Y**, and **Z** for additive composition (CIE XYZ color model) since no choice of three colors from the visible range of colors are capable of covering the entire space of perceivable colors without requiring negative weights for additively composing some of the colors. Using the CIE color model, composing two fundamental colors results in a less saturated color!

– Representation of a color **C** by $\mathbf{C} = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$

5.4 CIE color model



CIE XYZ color space:
covers all perceivable colors



Color gamut of a
CRT monitor

5.4 CIE color model

An alternative specification of the CIE XYZ color triples (X, Y, Z) results from mapping $(X, Y, Z) \rightarrow (x, y, Y)$ with

$$x = \frac{X}{X + Y + Z} \quad \text{and}$$

$$y = \frac{Y}{X + Y + Z}$$

(CIE xyY color space)

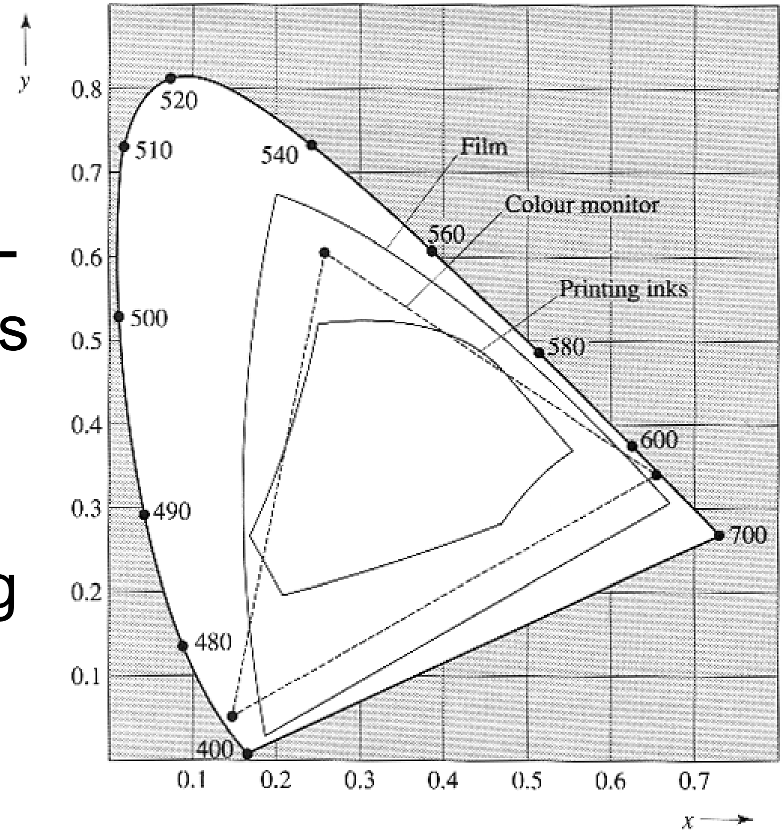
Evaluating these equations for all colors within the XYZ color space and putting the results in a (x, y) diagram results in the horse-shoe-shaped CIE diagram of the chromaticity.

5.4 CIE color model

The *(x, y)* diagram contains all visible colors in its two-dimensional projection while ignoring luminance.

At the edge of the horse-shoe-shape, the pure spectral colors are located ranging from blue (400 nm) to red (700 nm).

On the straight line connecting blue and red, we can find colors, such as pink or magenta.



5.5 CMY color model

Cyan Magenta Yellow color space

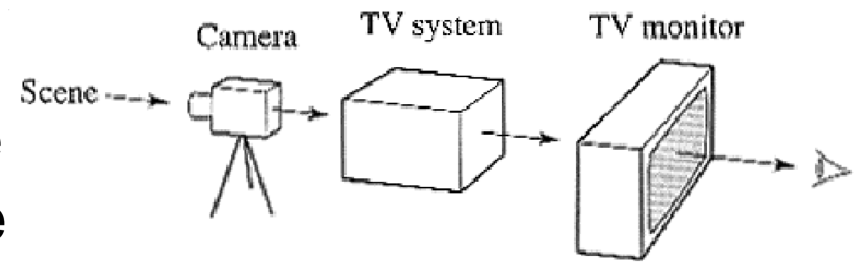
Instead of using additive color models (e.g. RGB), typically used for display technology, printers use a subtractive color model. The most common model uses the complementary colors of red, green, and blue: cyan, magenta, and yellow:

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

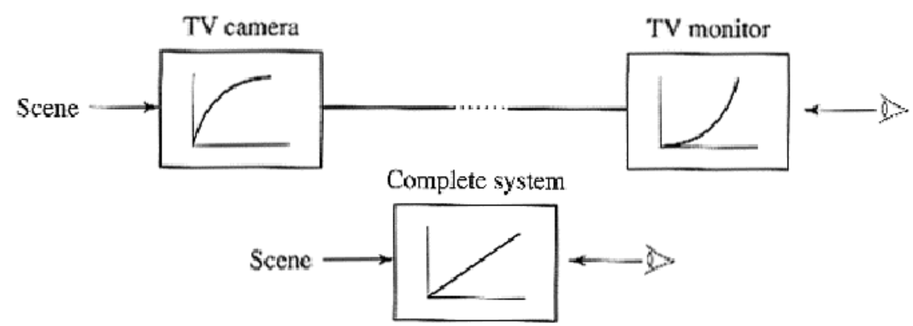
Often, printers (e.g. photo inkjet printers) use additional colors to avoid dithering for lighter areas or black for saving ink.

5.6 Gamma correction

When transmitting TV signals the viewer expects to see the scene at home with the same quality as if he/she would see it in reality.



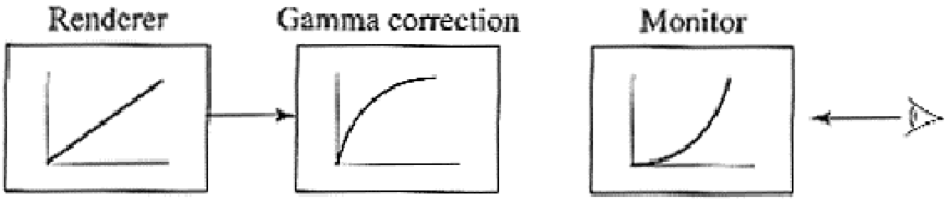
In order to achieve this, TV cameras already perform a pre-compensation to correct for the non-linearity with respect to colors of the display capabilities of CRTs



5.6 Gamma correction

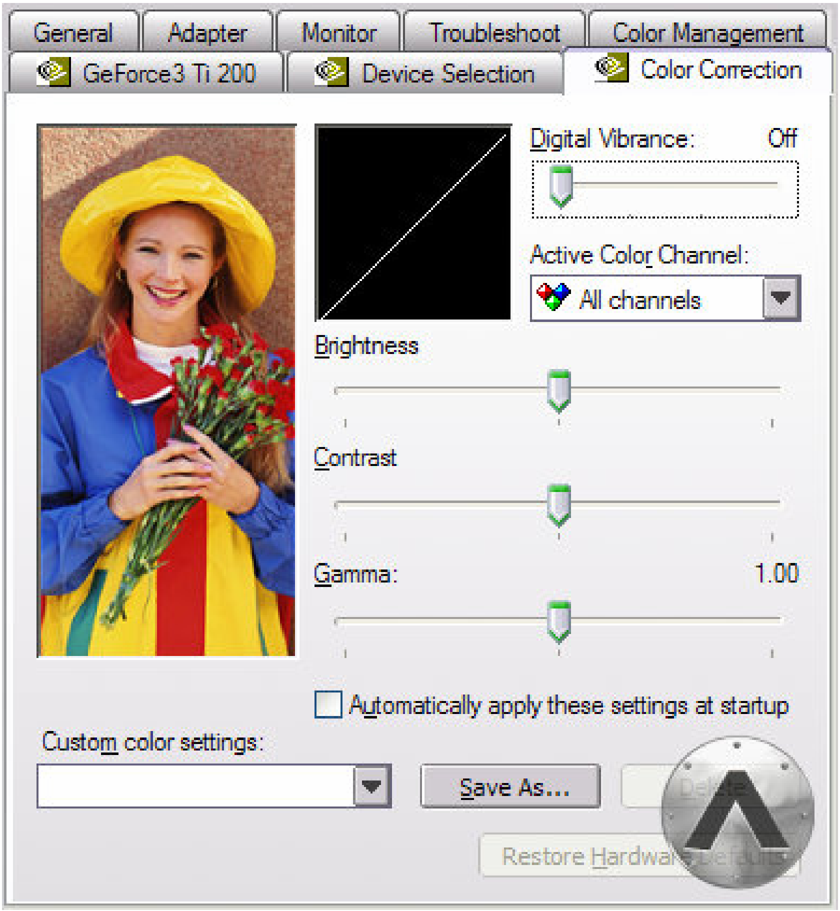
In computer graphics, the scene is generated by a renderer which takes over the role of the camera. However, the renderer assumes a linear intensity characteristic.

Since most monitors exhibit the same non-linearity just like TVs, the rendering process requires a suitable gamma correction before the image is displayed. Most 3-D graphics cards allows the user to define a curve for each color channel to achieve the desired compensation.



5.6 Gamma correction

Example: NVIDIA's gamma correction provided by the graphics driver



5.7 OpenGL color specification

In OpenGL, colors can be specified as RGB colors using the functions `glColor*`:

```
glColor3f (1.0, 0.0, 0.3);
glVertex3f (1.0, 1.0, 1.0);
```

In addition, alpha values can be specified for defining transparency as a fourth color component:

```
glColor4f (1.0, 0.0, 0.3, 0.5);
glVertex3f (1.0, 1.0, 1.0);
```

Note: as usual, colors have to be specified before the vertex they belong to.

5.7 OpenGL color specification

Vertex arrays

Using vertex arrays, colors can be specified in an array just like normal vectors or vertices itself:

```
GLfloat vertices[] = { … };
GLfloat colors[] = {… };
glEnableClientState (GL_VERTEX_ARRAY);
glEnableClientState (GL_COLOR_ARRAY);
glColorPointer (GL_FLOAT, 0, colors);
glVertexPointer (3, GL_FLOAT, 0,
                                 vertices);
glDrawArrays (GL_TRIANGLE_STRIP, 0, 10);
```