

Last Name: \_\_\_\_\_

First Name: \_\_\_\_\_

Cornell NetID: \_\_\_\_\_

## CS 4620 Final, May 15, 2017

This 150-minute exam has ?? questions worth a total of ?? points. Use the back of the pages if you need more space.

Academic Integrity is expected of all students of Cornell University at all times, whether in the presence or absence of members of the faculty. Understanding this, I declare I shall not give, use, or receive unauthorized aid in this examination.

Signature: \_\_\_\_\_ Date \_\_\_\_\_

1. [20 points] **Overview**

(a) True or False?

1. \_\_\_\_ In a ray tracing algorithm, the outer loop is over pixels and the inner loop is over objects.
2. \_\_\_\_ In a rasterization algorithm, the outer loop is over pixels and the inner loop is over objects.
3. \_\_\_\_ In rasterization, each fragment corresponds to exactly one pixel.
4. \_\_\_\_ In rasterization, each pixel corresponds to exactly one fragment.
5. \_\_\_\_ In the Blinn-Phong shading model, the specular highlight increases in size as the exponent  $p$  increases.
6. \_\_\_\_ In the Cook-Torrance shading model, the specular highlight increases in size as the roughness  $\alpha$  increases.
7. \_\_\_\_ In the Blinn-Phong shading model, the brightest point of the specular highlight increases in brightness as the highlight gets smaller.
8. \_\_\_\_ In the Cook-Torrance shading model, the brightest point of the specular highlight increases in brightness as the highlight gets smaller.
9. \_\_\_\_ Perspective transformations preserve straight lines.
10. \_\_\_\_ Affine transformations preserve parallel lines.
11. \_\_\_\_ Perspective transformations preserve parallel lines.
12. \_\_\_\_ 3D Rigid body transformations commute.
13. \_\_\_\_ 3D Nonuniform scale transformations commute.
14. \_\_\_\_ To transform tangents properly, you must apply the inverse transpose of the matrix used to transform positions.

(b) One-sentence answer:

(a) What is the *varying* keyword used for in GLSL? Why is it needed in the language?

(b) Classify the following splines as interpolating or approximating: Bézier, Catmull-Rom, B-Spline.

(c) Briefly explain what it means for a spline to have the convex hull property.



3. [20 points] **GLSL**

In Ray 1 you were provided with a shader that produced an RGB color according to the point's normal direction in world space coordinates. In this problem you will implement the same shader in GLSL. Specifically:

- The vertex shader should do the standard transformation to produce `gl_Position`, as well as calculating any other values you may need.
- The fragment shader should produce `gl_FragColor` according to the interpolated world space normal that would be used for shading. The {red, green, blue} channel should be equal to  $0.5 * (\text{the normal's } \{x, y, z\} \text{ component} + 1.0)$  respectively, and the fragment should be fully opaque.

**Vertex shader:**

```
uniform mat4 modelMatrix;
uniform mat4 viewMatrix;
uniform mat4 modelViewMatrix;
uniform mat4 projectionMatrix;

uniform mat3 normalMatrix; // = inverse transpose of modelMatrix

attribute vec3 position;
attribute vec3 normal;

// Declare any varyings here:

void main() {
    // Implement vertex shader here.

}
```

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**Fragment shader:**

```
// Declare any varyings here:
```

```
void main() {  
    // Implement fragment shader here.
```

```
}
```

4. [20 points] **Splines**

You are working with an artist to design an animation of magic vines rapidly climbing a castle wall in pursuit of the heroine, who is scrambling over the wall to escape an evil witch.

The artist would like to control the path along which a vine grows by specifying a series of points. The vine's path should pass through the location of each point exactly, so you decide to use cubic Catmull-Rom splines. As a reminder, the matrix defining a Catmull-Rom spline segment is:

$$M_{CR} = \frac{1}{2} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 2 & -5 & 4 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & 2 & 0 & 0 \end{bmatrix}.$$

In this matrix the top row corresponds to  $t^3$  and the bottom row to  $t^0$ .

- (a) How many points must the artist specify to obtain a single,  $C^1$ -continuous path that contains  $k$  Catmull-Rom spline segments? Give your answer in terms of  $k$ .

- (b) The artist specifies the following points for one vine's path:

$$(0, -2, 0), \quad (0, 0, 0), \quad (1, 1, 0), \quad (-1, 2, 2), \quad (0, 4, 0)$$

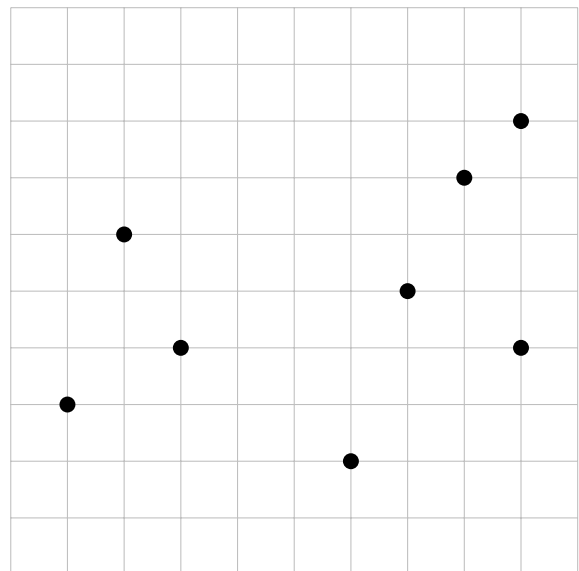
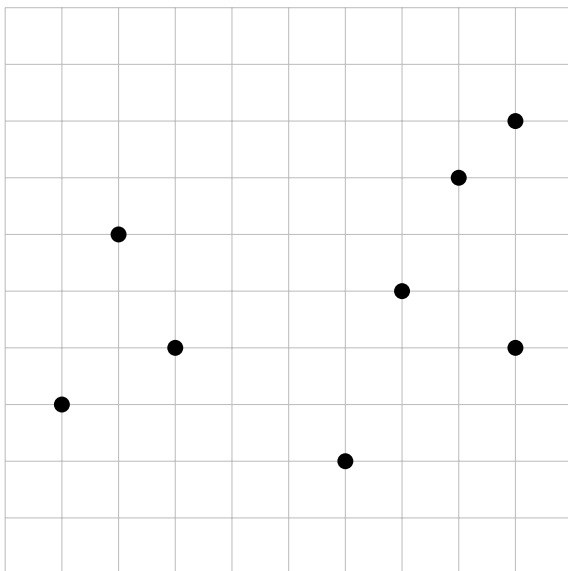
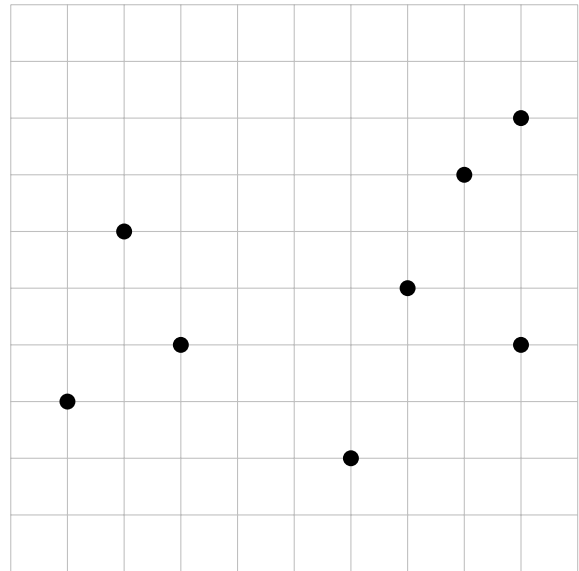
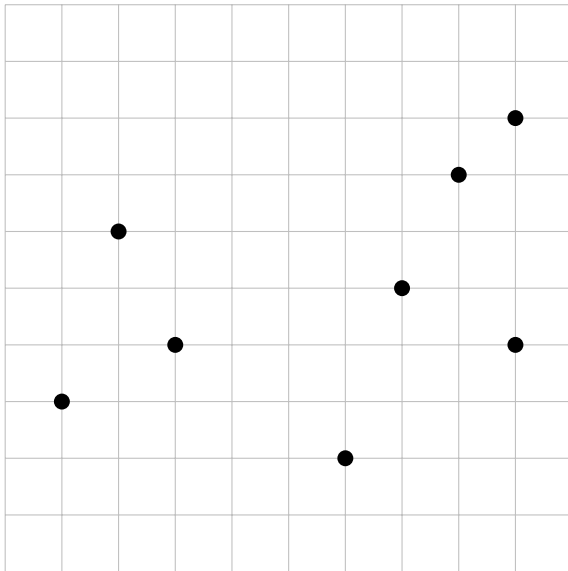
The vine starts growing at the start of frame 0, and stops growing at the start of frame 24; in that time, the vine grows along the full Catmull-Rom spline specified by the above points. Where is the tip of the vine at the beginning of frame 18? You may write your answer in terms of matrix products (but the entries in the matrices should be numbers, not symbolic expressions).

- (c) The animation framework you are using supports motion blur, which can increase the quality of the final animation. However, the motion blur tool needs to know the velocity of animated objects in order to correctly render them. Using the same vine path specified in part (b), what is the vector velocity of the tip of the vine at the beginning of frame 18? You may again write your answer in terms of matrix products.

5. [20 points] **Bounding volume hierarchy**

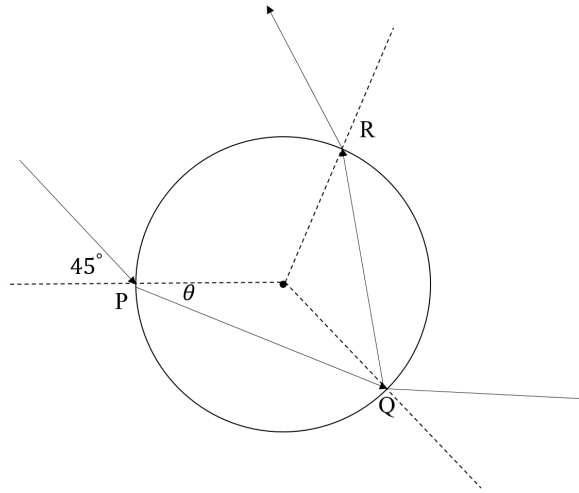
Draw a 2D axis-aligned bounding box hierarchy for the following set of points, using the top-down strategy with median splitting that was used in Ray 2. The widest axis should be split each time. Leaf nodes should contain up to two (2) points each. Drawn lines do not have to be perfect; they will be treated as being on the nearest grid line.

Four copies of the same diagram have been provided. You only need to complete one; if one copy becomes illegible as a result of corrections, cross it out and use another.



6. [20 points] **Refraction**

Snell's law: Suppose we have a glass sphere, with refractive index  $\sqrt{2}$ . Outside the ball is air with refractive index 1.0. A ray is incident to the glass sphere at point  $P$  with incident angle 45 degrees. Here is a diagram in the plane through the ray and the sphere's center:



Note: this drawing is not to scale.

- (a) Using Snell's law, what is the refraction angle  $\theta$ ?
  
- (b) After refraction at  $P$ , if the ray refracts again and returns back to the air at point  $Q$ , how many degrees does the ray direction rotate (counter-clockwise) during this refraction-refraction path? That is, what is the angle between the ray direction of the ray exiting at  $Q$  and the ray that hit the sphere originally at  $P$ ?
  
- (c) If the ray refracts into the sphere, reflects internally, and then refracts back to air at point  $R$ , how many degrees has the ray direction rotated relative to that initial incident ray?



7. [20 points] **Antialiasing**

(a) Why is aliasing a problem?

(b) When does aliasing arise?

(c) How does filtering alleviate aliasing?

(d) Suppose we are rendering a black line segment on a white background in a 6x6 grayscale image; it is  $1/\sqrt{2}$  pixels in width, and goes from pixel coordinates (1,1) to (4,4) as illustrated below. The line has intensity 0, and the background has intensity 1. In the blank grid to the right, fill in the pixel values of the antialiased image that would be produced by exact box filtering (also known as unweighted area averaging; it is what the Ray 2 antialiasing would compute in the limit as the number of samples goes to infinity). You don't have to fill in pixels with value 0 or 1.

