**Temporal Resolution**

- **Flicker fusion threshold**
  - The frequency at which an intermittent light stimulus appears to be completely steady to the observer

- For the purposes of presenting moving images (animations), at least 16 Hz is needed for humans to not interpret them as a series of still pictures
  - Movies are recorded at 24 frames per second
  - TV broadcasts at 30 frames per second

- Even though motion may seem to be continuous at 24–30 frames per second, the brightness may still seem to flicker
  - Movies are refreshed at 48 or 72 Hz (each frame is projected 2 or 3 times)
  - Computer monitors refresh at 60–80 Hz (or more) independent of what is displayed
  - TV uses interlacing to approximate 60 Hz, showing half of each frame at a time

![Interlaced vs Non-Interlaced (Progressive Scan)]
Scanline Rendering 1
Scanline Renderer

- A virtual environment/world that mimics the real world
  - but cheats a bit for efficiency, using what we know about light and our eye... e.g., from the last lecture
- Set up a virtual camera somewhere in the virtual world, and point it in some direction
  - Put a virtual piece of film (that stores RGB values) into the camera, and take a picture
  - This film data is your final image
- Place some objects in front of the camera, including a floor/ground, some walls, ceiling/sky, etc.
  - How do we represent these virtual objects? Virtual geometry? Geometric Modeling
  - This is actually a two step process: (1) Make the objects (2) Place the objects in the scene
  - Making objects is itself a two step process: build the geometry & then paint it
- Don’t forget to put some lights into the scene, so it’s not completely dark
- Finally, snap the picture --- that is, code needs to emit light from the virtual light sources, bounce it off the geometry, and follow it into the camera onto the film
Homework

• This week’s homework and sample code (along with the lectures today and Thursday) is designed to help you learn your way around in a scanline renderer
  ■ We’re using OpenGL (there are other options…)
  ■ It provides real time feedback so you can experiment with stuff and learn by doing
  ■ By way of comparison, the ray tracer will be A LOT SLOWER

• Next week, we’ll focus on Geometric Modeling (in the lectures, sample code, and homework) to help you create and obtain geometry that you can put into your virtual scenes

• Make sure to keep the basic concepts from last Thursday’s lecture in mind as we progress
  ■ we’ll assume familiarity with that stuff, as we make various assumptions
Cameras
• Rendering a computer generated image is similar in spirit to how you see real world images
• Light is emitted from light sources, absorbed and reflected off of objects, and enters the pupil of the eye.
• Without a pupil, light would scatter everywhere and would not make a coherent image on the cones of the eye
• With a pupil, light makes a coherent image on the cones
• Cameras, similarly, have an aperture
Cameras

- Cameras work very much like the eye
  - Light from the environment is bent by the lens array to make an image on the film
  - Digital cameras record this image as RGB values
  - Our scanline renderer will use a “virtual” camera
Pinhole Camera

- Simplified theoretical construct, but similar to an actual eye or camera
- Eyes and cameras can’t have VERY small holes, because that limits the amount of entering light
  - and diffracts/bends the light

![Pinhole Camera Diagram](image-url)
Pinhole Camera

- Light leaving any point travels in straight lines
- We only care about the lines that hit the pinhole (a single point)
- Infinite depth of field – i.e., everything is in focus (no blur)
- An upside down image is formed by the intersection of these lines with an image plane
- More distant objects subtend smaller visual angles and appear smaller
- Objects occlude the objects behind them
OpenGL Camera

- OpenGL uses a pinhole camera.
- However, the image plane (i.e. the film) is placed in front of the pinhole, so that the image is not upside down
- The frustum is the volume of the view (shown in blue below)
  - Notice the front and back clipping planes!
- The image plane (i.e. the film) is the clipping plane closest to the camera
Helpful Hints

- Get very familiar with the OpenGL camera
- Do not put the camera too close to your objects (fisheye look)
  - Set it up like a real world scene
  - Significant/severe deductions for poor camera placement, fisheye, etc. (because your image will look terrible)
- Make sure your near and far clipping plane have enough space between them to contain your scene
  - Do not set the near clipping plane at the camera aperture!
- Make sure your objects are inside the viewing frustum

- Etc. Etc.
- This is a real time system, use the interactivity to your benefit...
Question 1 (short & long form)

Where would you like to take your CG picture?

Outside? Day or Night?
Park? Mountains? City or Country? What Season?

Inside? Theatre?
Classroom? Dorm Room?
Living Room? Bathroom?
Basement? Attic?

Etc.?
Geometric Models
Triangles

Stanford Bunny
69,451 triangles

David, Digital Michelangelo Project
28,184,526 vertices, 56,230,343 triangles
Why Triangles?

• It’s easy to break convex polygons into triangles
  ■ As a result, can focus on optimizing the hardware/software implementation of only one primitive (i.e. optimize for triangles)

• Triangles have some nice properties
  ■ Guaranteed to be planar (unlike quadrilaterals)
  ■ Guaranteed to have a well-defined interior
  ■ There exists a well-defined method for interpolating values in the triangle interior (barycentric interpolation)
  ■ Etc…
Geometric Modeling

Next week...
Arranging your scene...
Transformations

Transform every point:
\[(x',y',z') = T(x,y,z)\]
\[P' = T(P)\]

Moves triangles (& thus geometry)

- Create objects (or parts of objects) in convenient coordinates, and then transform into the scene later
- Make multiple copies (even different sizes) of a single object
- Connect kinematics of linkages/skeletons for characters/robots

http://youtube/6G3O60o5U7w
Matrix Representation

\[
x' = m_{xx} x + m_{xy} y \\
y' = m_{yx} x + m_{yy} y
\]

\[
\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} m_{xx} & m_{xy} \\ m_{yx} & m_{yy} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}
\]

\[
x' = M x
\]

Efficiency: can combine a sequence of transforms into a single transform (since matrix multiplication is associative):

\[
P' = A ( B ( C ( D ( P ) ) ) ) = ( A B C D ) P = M P
\]

- Compute the composite matrix M once and then apply it to many points
Hierarchical Transforms

- $M_1$ transforms the teapot from its model space to the table’s model space
- $M_2$ transforms the table from its model space to world space
- $M_2M_1$ transforms the teapot from its model space to world space
Lines Map to Lines

Parametric line: \( x = (1 - \alpha)p + \alpha q \)

Transform all the points on the line

\[ x' = Mx = (1 - \alpha)Mp + \alpha Mq \]

\[ = (1 - \alpha)p' + \alpha q' \]

Get a new line connecting the transformed points
Question 2 (short & long form)

What sorts of objects will be in your scene?


Etc.?
Rotations
Rotation

\[ x' = Mx \]

\text{glm::angleAxis(angle, vec3(ax, ay, ax))}
2D Rotation Matrix

The columns of the matrix are the new locations of the x and y axes

\[
\begin{bmatrix}
  m_{xx} \\
  m_{yx}
\end{bmatrix} = \begin{bmatrix}
  m_{xx} & m_{xy} \\
  m_{yx} & m_{yy}
\end{bmatrix} \begin{bmatrix}
  1 \\
  0
\end{bmatrix}
\]

\[
\begin{bmatrix}
  m_{xy} \\
  m_{yy}
\end{bmatrix} = \begin{bmatrix}
  m_{xx} & m_{xy} \\
  m_{yx} & m_{yy}
\end{bmatrix} \begin{bmatrix}
  0 \\
  1
\end{bmatrix}
\]

So, set the columns to the desired new locations of the x and y axes

\((-\sin \theta, \cos \theta)\)

Rotation matrix =

\[
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\]

3D is similar...
Translations
What does a translation matrix look like?... use homogeneous coordinates

\[ x' = x + t_x \]
\[ y' = y + t_y \]

\texttt{glm::translate(current, vec3(tx, ty, tz))}
Homogeneous Coordinates

• The homogeneous coordinates of a 3D point \((x, y, z)\) are

\[(xw, yw, zw, w)\]

• Conversely, the position \((x, y, z)\) of a 3D point can be calculated from homogeneous coordinates by dividing by \(w\)

\[(xw/w, yw/w, zw/w)\]

• Setting \(w=1\), gives the homogeneous coordinates used for translations:

- a 3D point \((x, y, z)\) becomes \((x, y, z, 1)\)
2D Rotation Matrix

• A 2D point becomes \((x, y, 1)\), so we need a 3x3 matrix in order to represent a 2D rotation

• This is done by adding an extra row and column of \((0, 0, 1)\)

\[
\begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
-\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

• Similarly, 3D rotation matrices are expressed via a 4x4 matrix
2D Translation Matrix

\[
\begin{pmatrix}
x' \\
y' \\
1
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & t_x \\
0 & 1 & t_y \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
1
\end{pmatrix}
\]

3D is similar...
Vectors

- In homogeneous coordinates, vectors are represented using $w=0$ instead of $w=1$

- Thus translation does not affect vectors, as desired

\[
\begin{bmatrix}
1 & 0 & t_x \\
0 & 1 & t_y \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
0
\end{bmatrix}
= 
\begin{bmatrix}
x \\
y \\
0
\end{bmatrix}
\]

- The vectors still rotate properly though…
Composite Transformations
Rotate 45 degrees about the point (1,1)...
Matrix multiplication is NOT commutative
The rightmost transform is applied to the points first
Hint

- Place an object at the center of the target coordinate system (scene or an intermediate)
- Rotate the object into the desired orientation
- Translate the object in order to place it in the target coordinate system (scene or an intermediate)
Question 3 (long form only)

3. Find a web site with advice on 3D art, and summarize some of what you learned by reading the site (about 500 words).

E.g. 30 top examples of 3D art

https://www.creativebloq.com/3d/inspiring-examples-3d-art-12121523
Question 3 (short form only)

Looking for Artists:
3A. Name/Email
3B. Best Advice