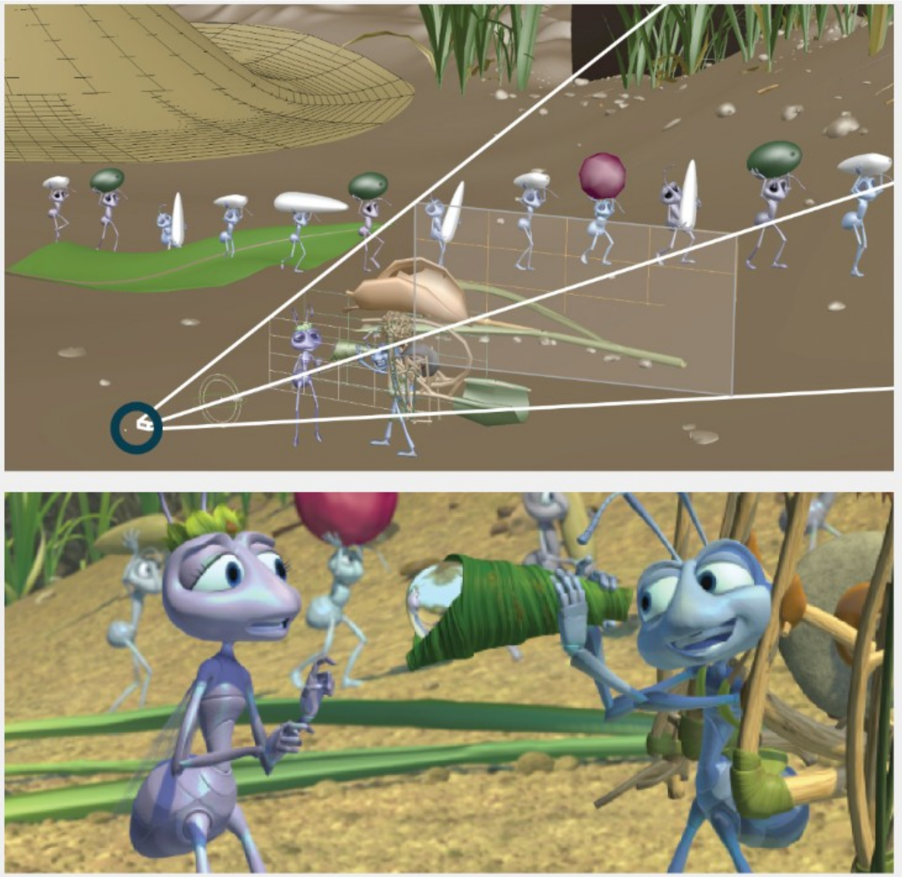
Camera

Syllabus

- 3D scene
  - Object
  - Camera
  - Light
- Rendering
- Image

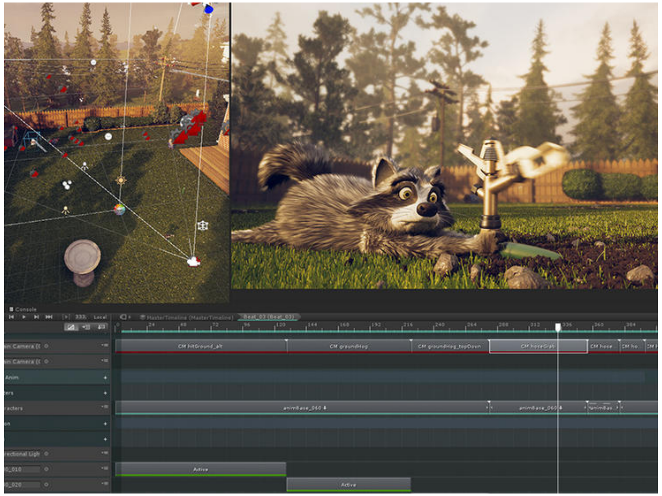
- Camera
  - Real camera system
  - Image formation
  - Pinhole camera model
  - Pinhole camera in rendering

Where is camera?



https://sciencebehindpixar.org/pipeline/sets-and-cameras

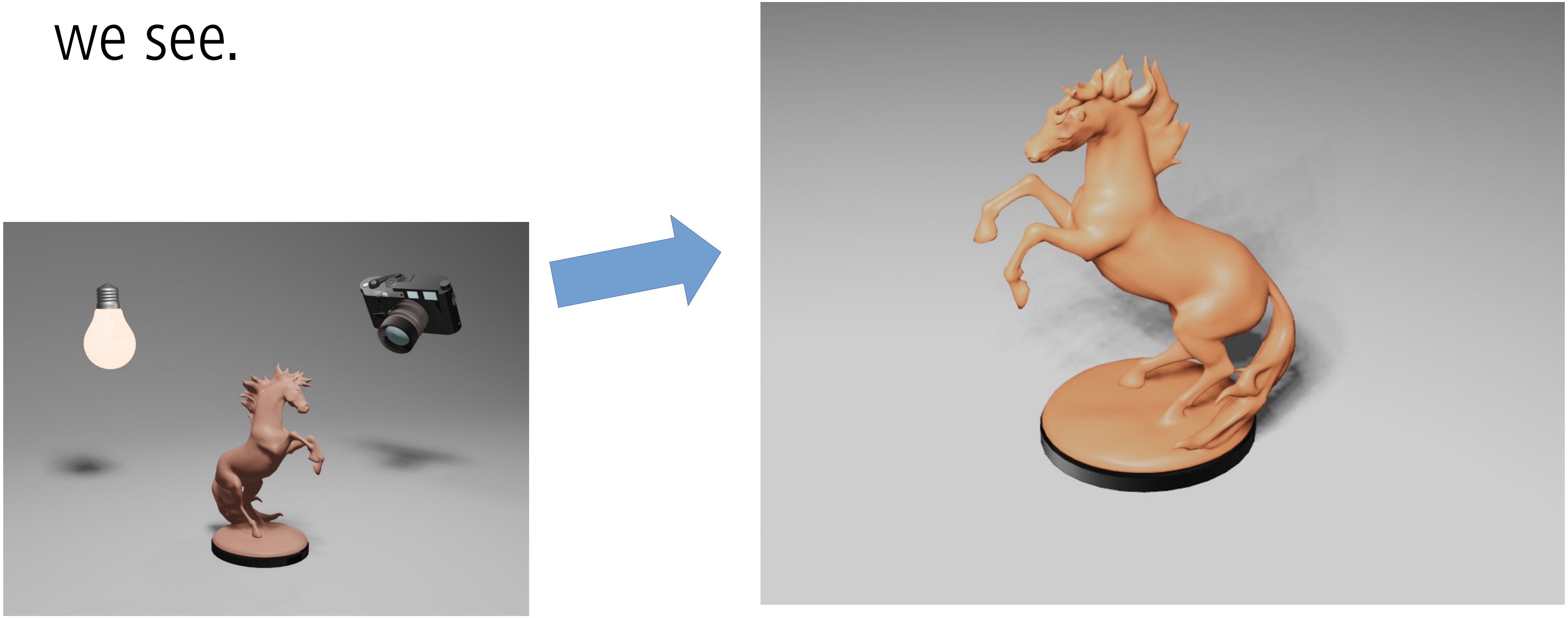
https://www.half-life.com/en/alyx/



https://unity.com/solutions/film-animation-cinematics

Where is camera?

- In rendered images, camera is not seen – it defines what we see.



TODO

Camera in rendering

- Interesting: https://google.github.io/filament/Filament.html#imagingpipeline?
- In rendering camera model is required to at least to:
  - Define a portion of visible scene
  - Type of projection: perspective/orthographic
- Camera during image formation:
  - Picks reflected light from 3D scene (light transport and shading)
  - Forms image
- Rendering process is calculating radiance (color) from shaded surface point to camera position.
  - This simulates simplified model of an imaging system such as film/digital camera or human eye
  - <image: object, camera>

Real camera system

Real camera systems

- Camera systems contain many small discrete **sensors**: cones in the eye, photodiodes in digital camera or dye particles in film camera
  - Each of these sensors measures incoming **radiance** values and converts it to **color** signal
- Exposing sensor to radiance will not produce image without **light-proof enclosure** with small opening – **aperture**.
  - Such setup restricts light where light can enter and strike sensor
- **Lens** is placed at the aperture to focus the light so each sensor receives light from only a small set of incoming directions
  - Lens with aperture average light over small area and small set of incoming directions
- <image: camera system elements: sensor, aperture, lens>

What camera measures?

TODO

- Images are created when light falls on surface which is sensitive to l
- For a film camera, this surface is film or sensor (CCD) for digital camera
- Sensors measure average radiance which quantifies the brightness and color of single ray of light
- This is motivation why in computer graphics we only care about light rays which are coming to camera and from them, how are they generated in the scene
  - We will extend this idea in rendering chapters

Image formation

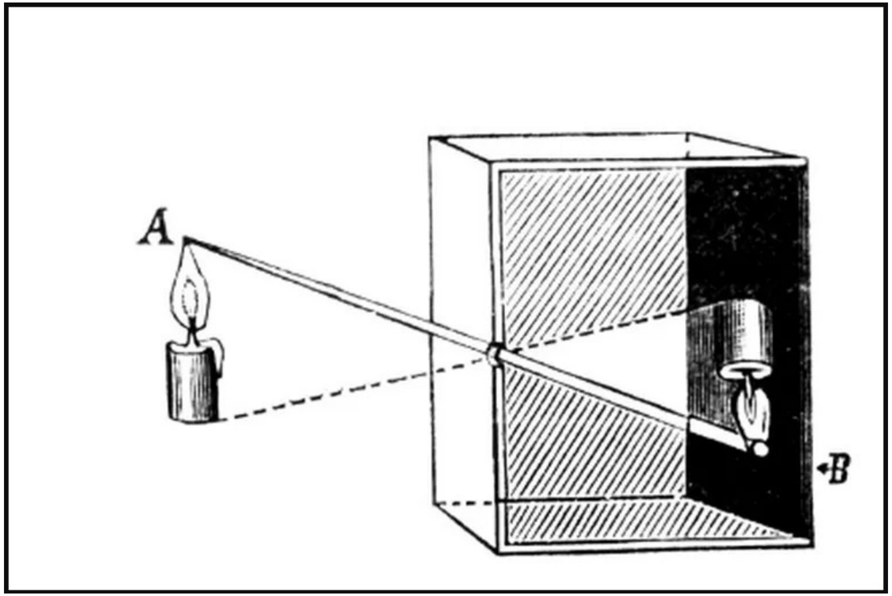
Principle of photography

- Two main processes:
  - **How is image created in camera**
  - How is image stored on film/file*

* Physical support to store an image, thus simulating the photochemical processes used in traditional film photography is out of scope.
Renderer which simulates image storage on film: https://maxwellrender.com/https://maxwellrender.com/

Image formation: camera obscura

- Lightproof box with:
  - black interior (to prevent light reflection)
  - with very small hole – **aperture**
  - light-sensitive film opposite to aperture
- When aperture is opened, film is exposed to light
  - Light passing through the hole forms an inverted image of the external scene on the opposite side of the box
  - Time which aperture must be opened to capture image on film is called **exposure**
- A foundation for modern photographic cameras



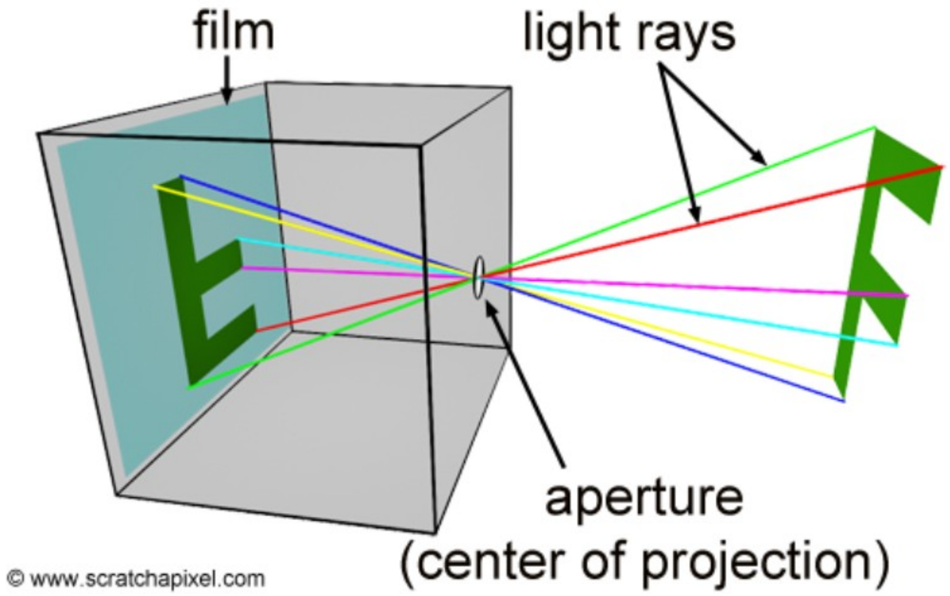
https://www.inquirer.com/philly/entertainment/20160806_Camera_Obscura_at_Fleischer_throws_new_light_on_photography.html

Camera obscura = Dark room

https://www.youtube.com/watch?v=gvzpu0Q9RTU&ab_channel=NationalGeographic

Image formation: pinhole camera

- Simplest type of camera in real world is **pinhole camera (camera obscura)**
- Main elements:
  - **Aperture**: center of projection: all rays entering converge here and diverge from it to the other side
  - **Film**
- Image formation
  - Aperture is opened to expose film to light
  - Aperture must be very small: only one ray reflected from the world in point P enters the camera and intersects film in one point
  - Each point in the visible portion of the scene corresponds to a single point on the film

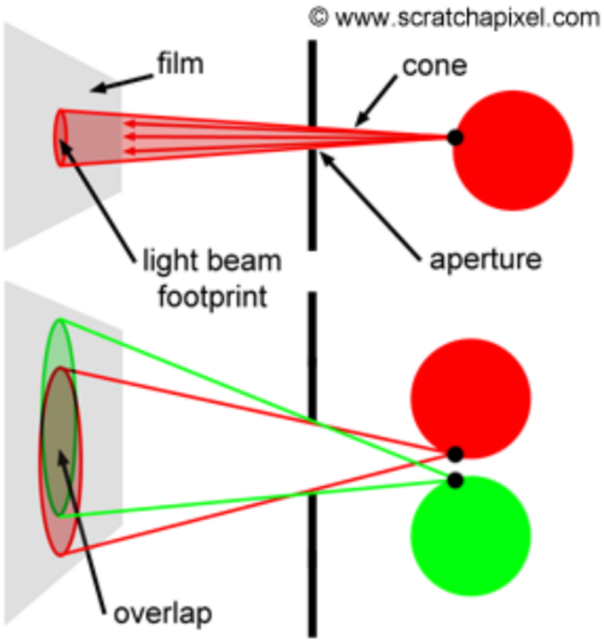


https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera

Pinhole camera: aperture size

- Formed image is sharp if each point of the object maps to the one point of the film
- Ideal pinhole: aperture is so small that only one ray passes through it
  - Not possible in a real world because of diffraction of light
- It is never a single ray that passes the aperture – cone of rays
  - the cone of rays (its angle) is determined by a size of aperture.
  - Smaller cone → sharper image
  - Larger aperture → blurred image

https://polyhaven.com/a/food_pears_asian_01



Cones are overlapping and single point appears multiple times on film → blur (out of focus).

https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera

Bokeh

- Out of focus emissive objects are aesthetically pleasing → bokeh effect.

Pinhole camera: exposure

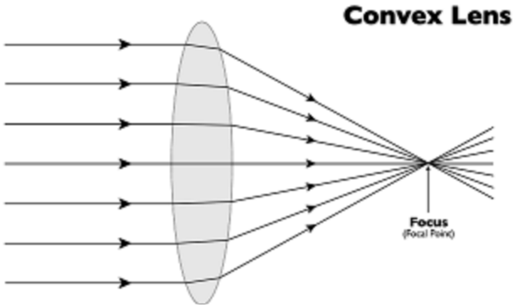
- If aperture is very small, longer time is needed for image to form on a film.
- Time of which the aperture is open is called **exposure** time
  - In real cameras, longer exposure can produce blurred image if camera or objects in the scene are moving (not perfectly still)
  - Simulated camera do not have problem with this since simulated light transport is considered instant, therefore, simulation of motion blur requires additional simulation
- Therefore, generally, shorter exposure time is better, although simulation of motion blur is aesthetically pleasing

Earth rotation causes motion blur in long-exposure photos

https://en.wikipedia.org/wiki/Motion_blur

Aperture and Lens camera

- Aperture trade-offs:
  - Very small aperture requires long exposure times to form an image: motion blur
  - Large aperture causes blurred images
- Solution is to use lens in front of aperture
  - Rays entering camera are gathered (converged) and focused them to one point on a film plane
  - Aperture can now be larger enabling smaller exposure time while lenses canceling blur



https://photo.stackexchange.com/questions/95113/do-convex-lenses-make-light-from-different-points-converge-to-different-points

Depth of field

- Lens camera introduce distance between nearest and the farthest object from the scene that appears sharp in the formed image – **depth of field**
- Pinhole cameras have infinite depth of field
  - Because of this, images rendered with pinhole cameras are completely sharp and thus look artificial

https://www.adobe.com/uk/creativecloud/photography/discover/bokeh-effect.html

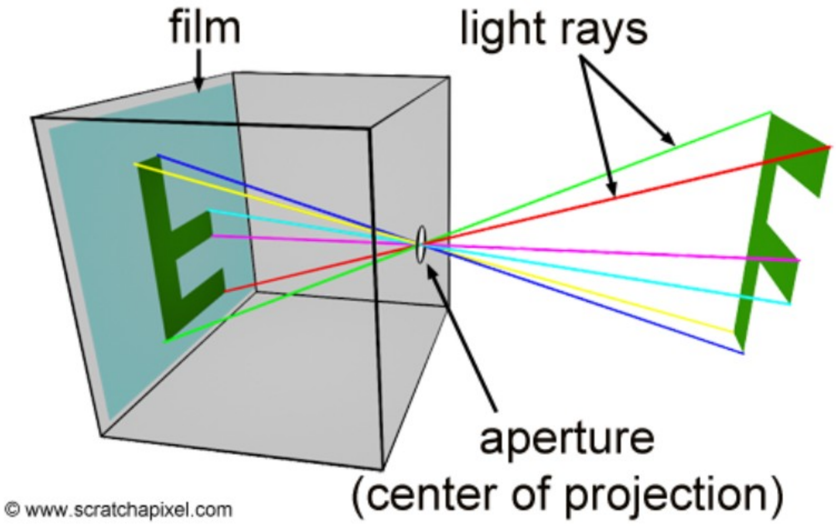
Pinhole camera

Camera model

- Now, we will model a real world camera.
  - Such camera model is similar to ones used in production software (e.g., Blender, Maya, 3DSMax, Houdini)
  - https://docs.blender.org/manual/en/latest/render/cameras.html
- Simulating real world camera:
  - photo-realistic rendering which may be combined with live action footage
  - camera effects enable certain expressive and artistic possibilities

Camera model

- Image generation with real world camera is governed by optical laws → very costly to simulate
- We start with simplest camera model: **pinhole camera**
  - Much easier way to reproduce images, therefore used in most 3D applications and games
- Main elements:
  - Film (image plane)
  - Aperture (small opening)

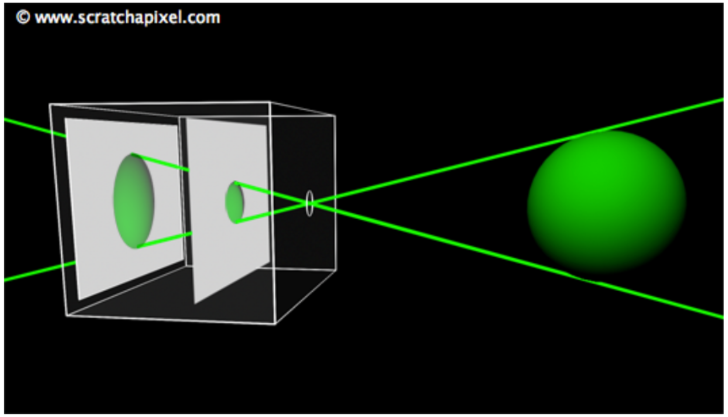


Pinhole camera parameters

- Film and aperture elements form several parameters:
  - Focal length/focal distance, angle of view/field of view
  - Film size

Focal length

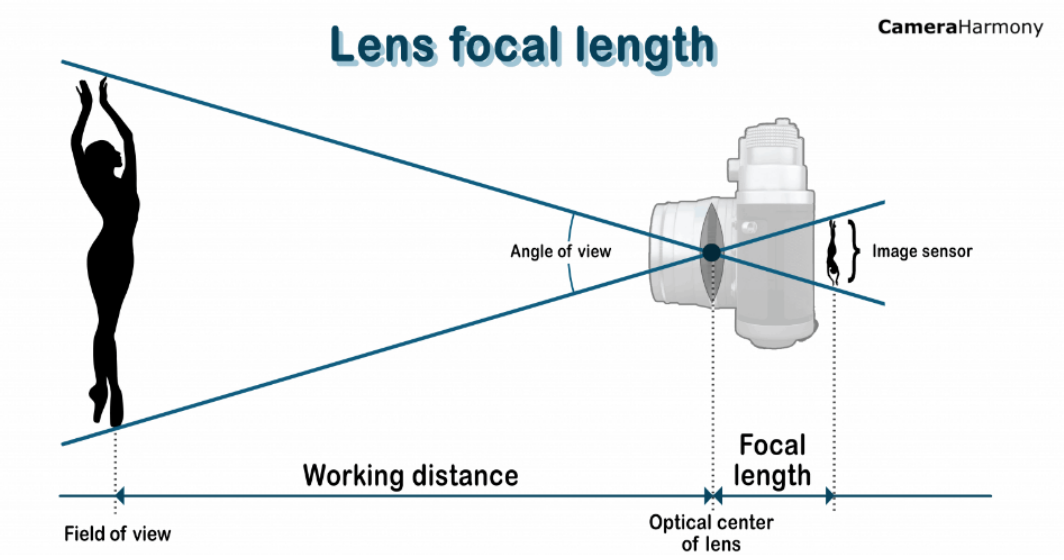
- Distance of film plane from aperture defines amount of scene that we see
  - Moving image plane (film plane) closer to aperture effectively performs **zoom out**
  - Moving film plane away from aperture effectively performs **zooming in**
- This parameter is called **focal length** or **focal distance**



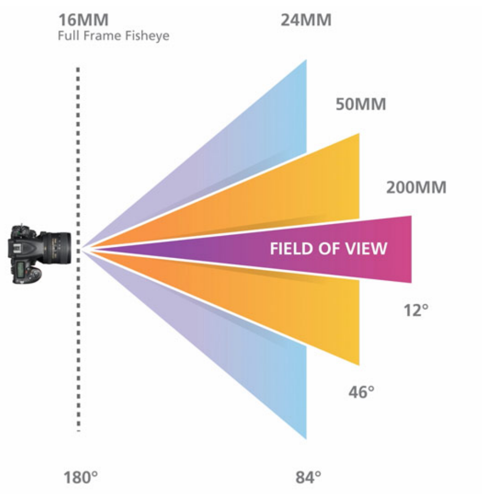
https://www.nikonusa.com/en/learn-and-explore/a/tips-and-techniques/understanding-focal-length.html

Pinhole camera parameters: angle of view

- Zooming in and zooming out described by focal length (focal distance) can be also described by angle of the apex of **triangle defined with aperture and film edges**
- This angle is called **angle of view or field of view**



https://cameraharmony.com/focal-length-explained/

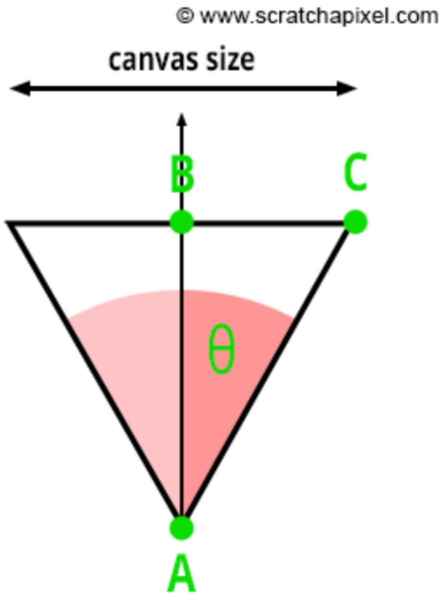


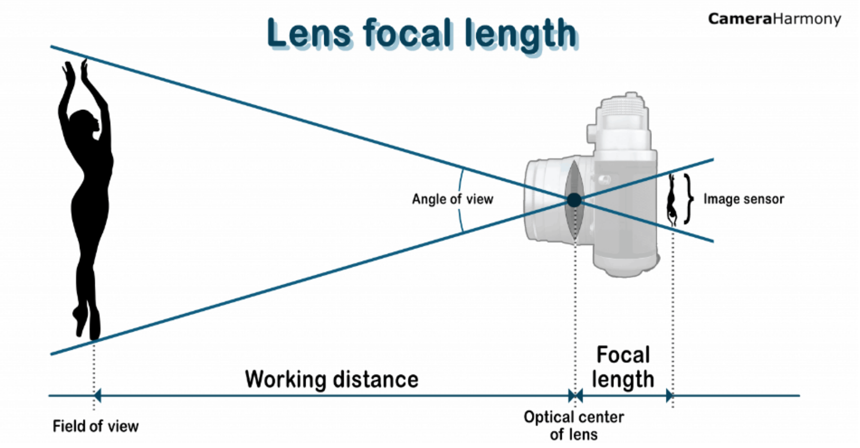
https://www.nikonusa.com/en/learn-and-explore/a/tips-and-techniques/understanding-focal-length.html

Focal length and angle of view

- Relation between focal length and angle of view

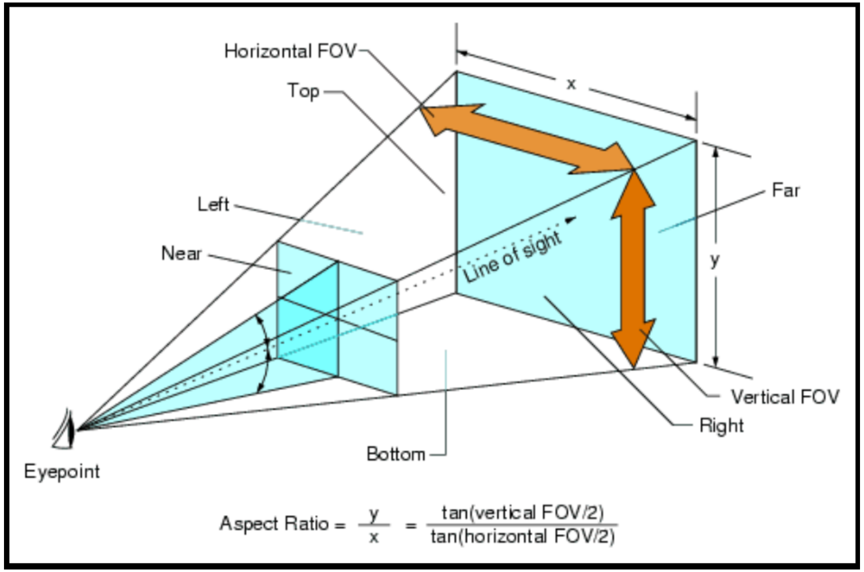
$$\tan(\theta) = \frac{BC}{AB}$$
$$BC = \tan(\theta) * AB$$
$$\text{Canvas Size} = 2 * \tan(\theta) * AB$$
$$\text{Canvas Size} = 2 * \tan(\theta) * \text{Distance to Canvas} .$$





Field of view

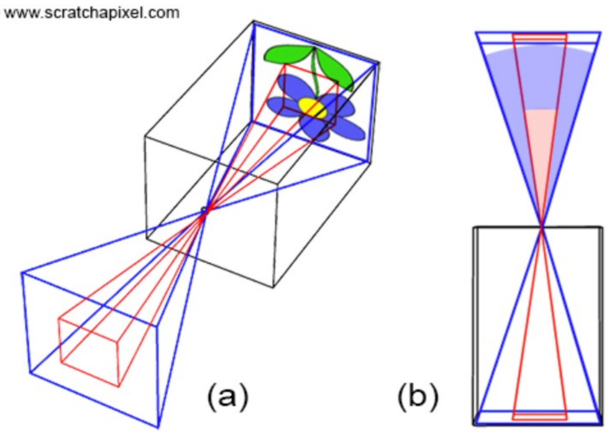
- In 3D, **triangle defined with aperture and film edges** is a pyramid and we distinguish **horizontal and vertical FOV**

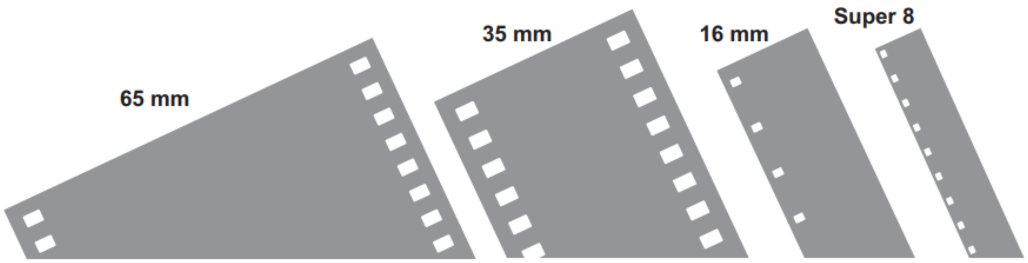


https://www.pcgamingwiki.com/wiki/Glossary:Field_of_view_%28FOV%29

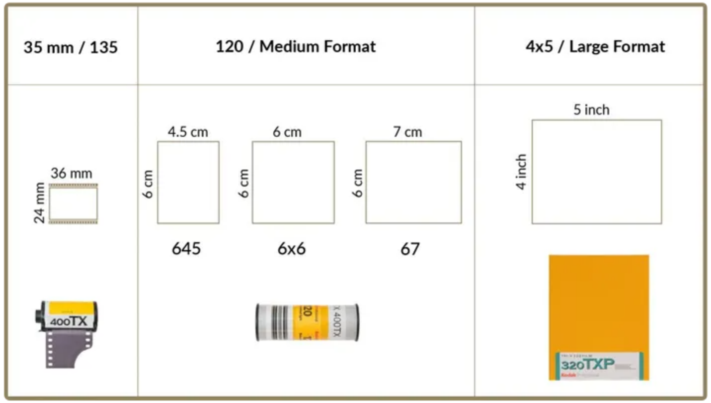
Pinhole camera parameters: film size

- Amount of scene that is captured also depends on film size (image sensor)
  - Film parameters are horizontal and vertical direction
- Smaller area of film size implies smaller angle of view and vice versa.
- Capturing the same extent of the scene with larger film requires adjusting focal length
- Larger film formats were developed for more details and better image quality
- In digital cameras, film is replaced with sensor, thus we talk about sensor size.
  - Sensor size has the same role as film size





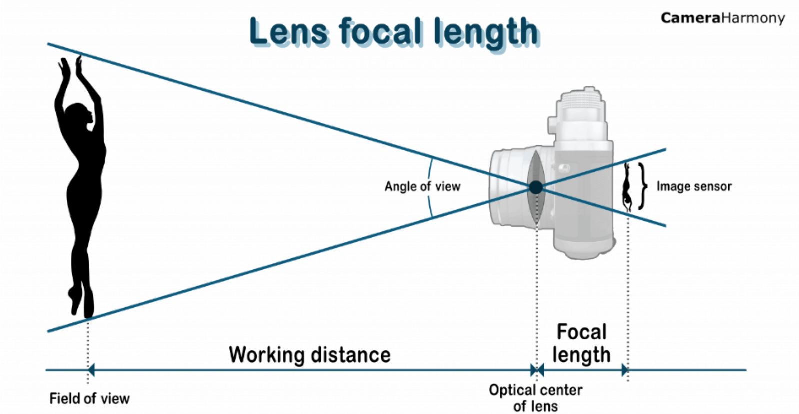
Gauge refers to the width of film. Four are common: 65mm, 35mm, 16mm, Super 8.
http://www.theodoropoulos.info/attachments/076_kodak05_Film_Types_and_Formats.pdf



https://www.learnfilm.photography/guide-to-medium-format-photography/

Pinhole camera parameters: recap

- Parameters:
  - Focal length (focal distance)
  - Angle of view (field of view)
  - Film size
  - With two parameters we can always infer the third one.
- Angle of view is determined by:
  - Focal length: longer focal length → narrower angle of view
  - Film size: larger film size → wider angle of view



Film size and image resolution

- Angle of view:
  - Depends on film size (image sensor size)
  - Doesn't depend on number of pixels on image sensor – **image resolution**
- Size of sensor and number of pixels are independent parameters!
- Image quality depends on:
  - Image sensor size
  - Number of pixels on sensor (resolution)
- Higher resolution images will have more details
  - Resolution is expressed in terms of pixels
  - Width and height resolution

Image resolution and aspect ratio

- **Image aspect ratio** (**device aspect ratio**) is calculated from image resol

$$\text{Image (or Device) Aspect Ratio} = \frac{width}{height}$$

- Film and display devices (computer screens, television) have standard aspect ratios
  - **4:3**
    - Old television systems and computer monitors (e.g., resolution 640x480)
    - Default for digital cameras
    - 35 film formats have aspect ratio 4:3
  - **5:3 and 1.85:1**
    - Aspect ratio used in film
  - **16:9**
    - Aspect ratio used by HD TV, monitors and laptops (resolution: 1920x1080)

https://www.studiobinder.com/blog/aspect-ratio/

https://photographylife.com/aspect-ratio

Note: film and image aspect ratio

- In computer graphic camera model, sensor (film/canvas) aspect ratio can be different from the image (device) aspect ratio.
- Difference in canvas (film) aspect ratio and the raster image aspect ratio leads to stretching the image in either x or y
- Solution: canvas aspect ratio is often directly computed form the image aspect ratio.
  - Example, is image resolution is 640x480, canvas aspect ratio will be set to 4:3.

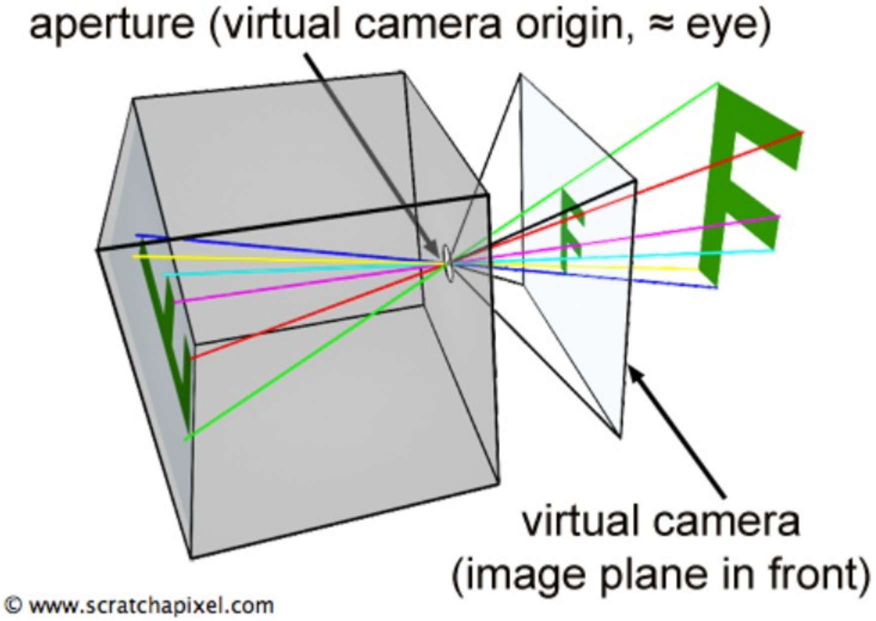
Camera in rendering

Camera in rendering

- Camera model in rendering is used to deliver image similar to those produced by a real pinhole camera.
  - Size and shape of real and rendered object must be the same

Virtual pinhole camera model

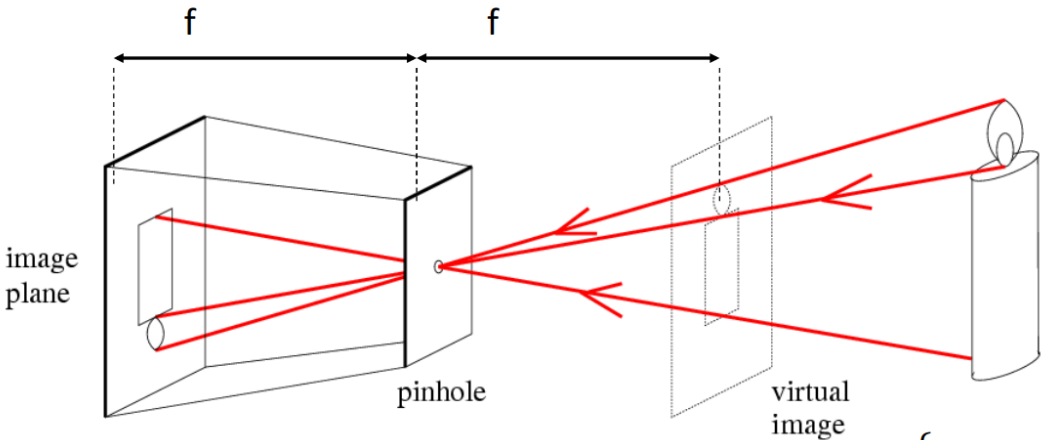
- Real pinhole camera produces images which are upside down.
- In computer graphics, this is avoided by setting film plane in front of aperture.
  - This construction gives valid images
  - Aperture is now position of the eye



https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera/virtual-pinhole-camera-model

Perspective projection

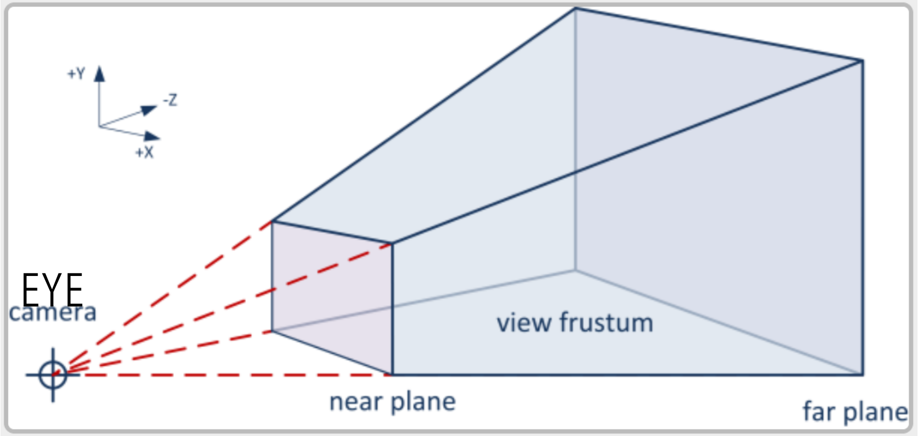
- This construction shows that image is constructed by following light rays from scene to the eye
- This geometrical problem is called **perspective projection.**



http://vision.stanford.edu/teaching/cs131_fall1516/lectures/lecture8_camera_models_cs131.pdf

Viewing frustum

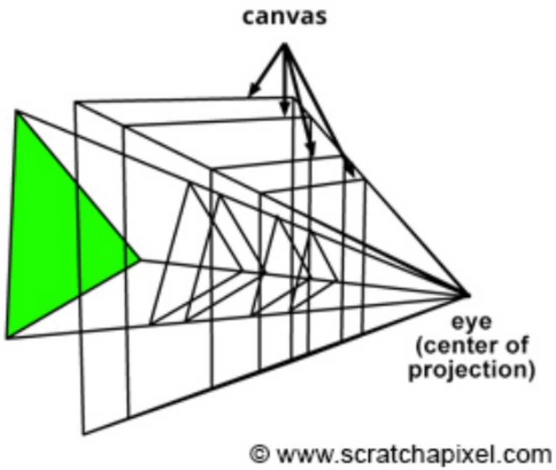
- **Near and far clipping planes** are virtual planes placed in front of camera and parallel to image plane.
  - Location of clipping planes is determined by camera's line of sight (camera's local z axis)
- Objects in 3D scene closer than near or further than far plane are not visible in image plane.
  - This defines **viewing frustum**
- Near and far clipping planes are needed for resolving precision issues.
  - Used in rasterization-based rendering
  - Not needed for ray-tracing based rendering.

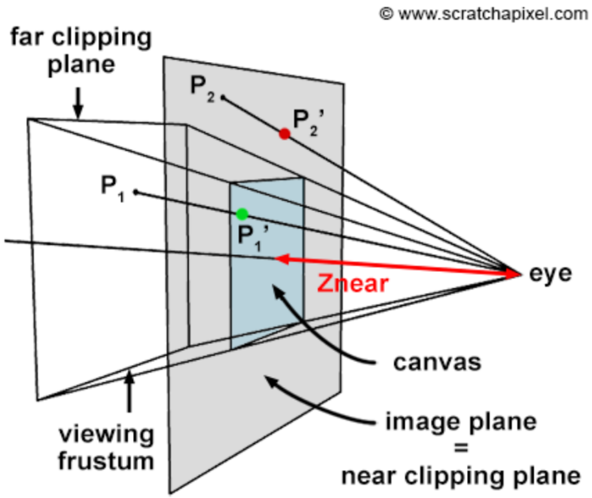


https://learnopengl.com/Guest-Articles/2021/Scene/Frustum-Culling

Image plane size

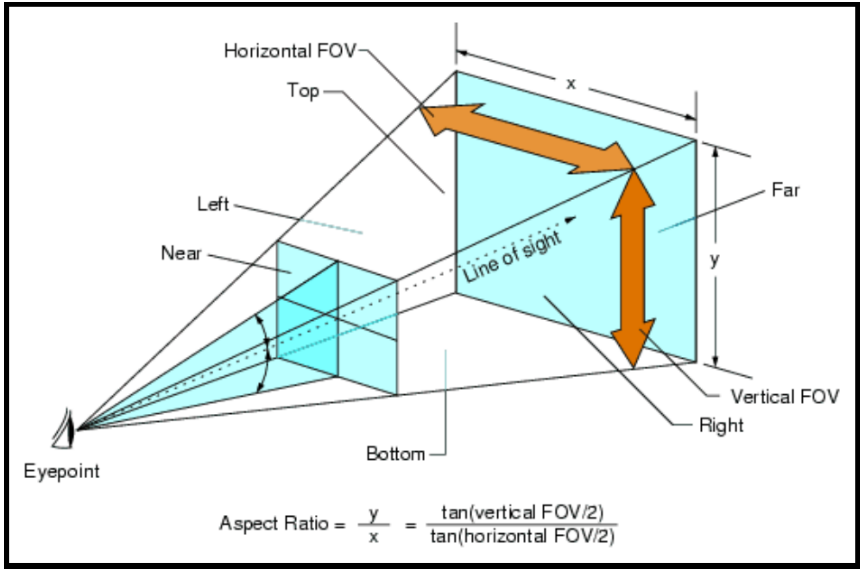
- Image plane (canvas) can be anywhere on camera's line of sight (camera's local z axis) between near and far clipping planes
  - Smaller distance from eye to image plane → canvas is smaller. And vice versa.





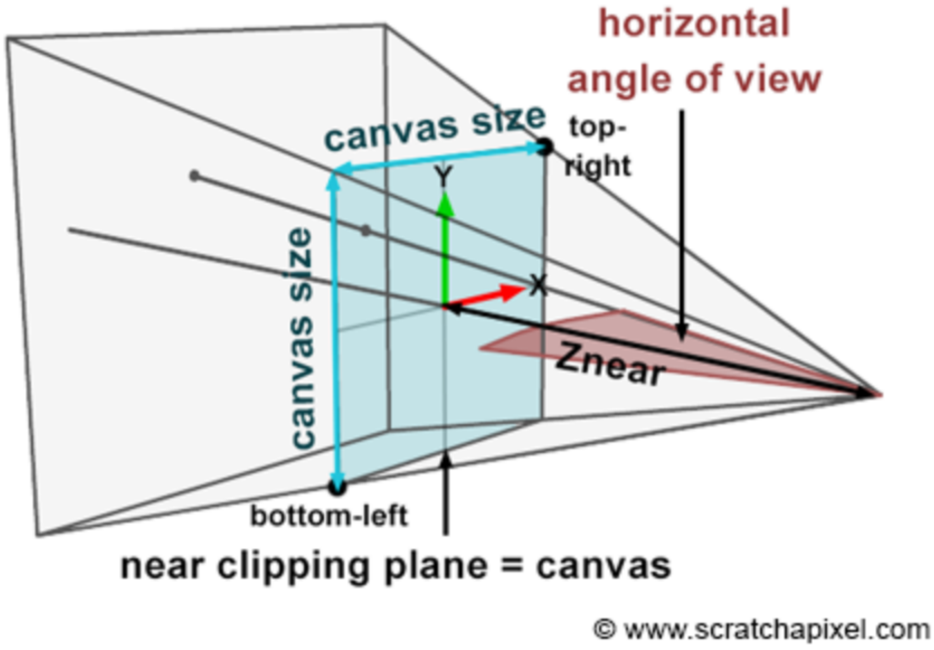
Recap

- Main elements of pinhole camera are eye and film plane.
- Main parameters of pinhole camera are focal length and sensor (film) size.
- Virtual pinhole camera further introduces near and far clipping planes to tackle precision problems.
  - Viewing frustum shape is defined with aperture point and angle of view
- Virtual image plane (canvas, film) can be anywhere on camera's line of sight
  - We assume it is at near clipping plane
  - Its boundaries are viewing frustum



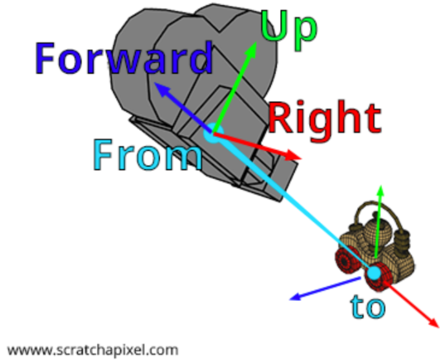
Canvas and visibility

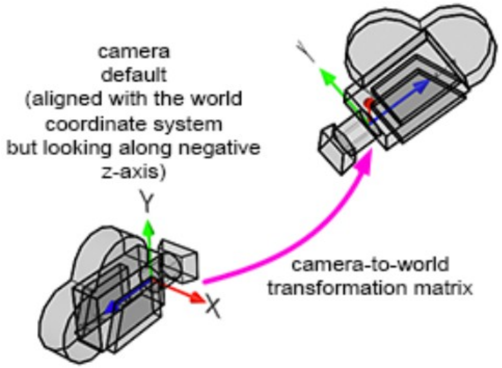
- Point in 3D scene is visible only if lies in canvas limits
- Therefore, point is first projected on image plane and tested for canvas limits to determine visibility
- Canvas is centered about the image plane coordinate system origin.
- The canvas size itself depends on the angle of view and the near clipping plane (since it is placed at near clipping plane)



Camera movement

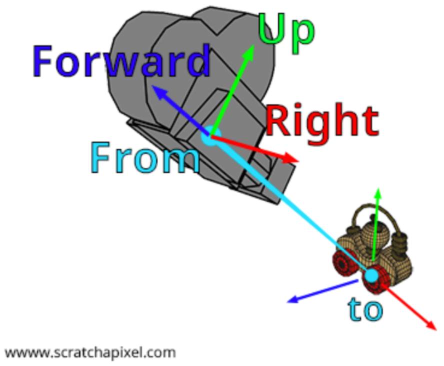
- By default camera is located at origin and oriented at negative z axis.
  - Movement of camera is defined with 4x4 transformation matrix.
- Camera direction and orientation is simplified with **look-at method:**
  - Point in space where camera is positioned
  - Point in space where camera is looking
- Look-at method gives **look-at matrix**, which defines 4x4 transformation matrix of camera from its local (camera) space to world space in 3D scene: **camera-to-world** and its inverse **world-to-camera** matrix.





Camera movement: look at matrix

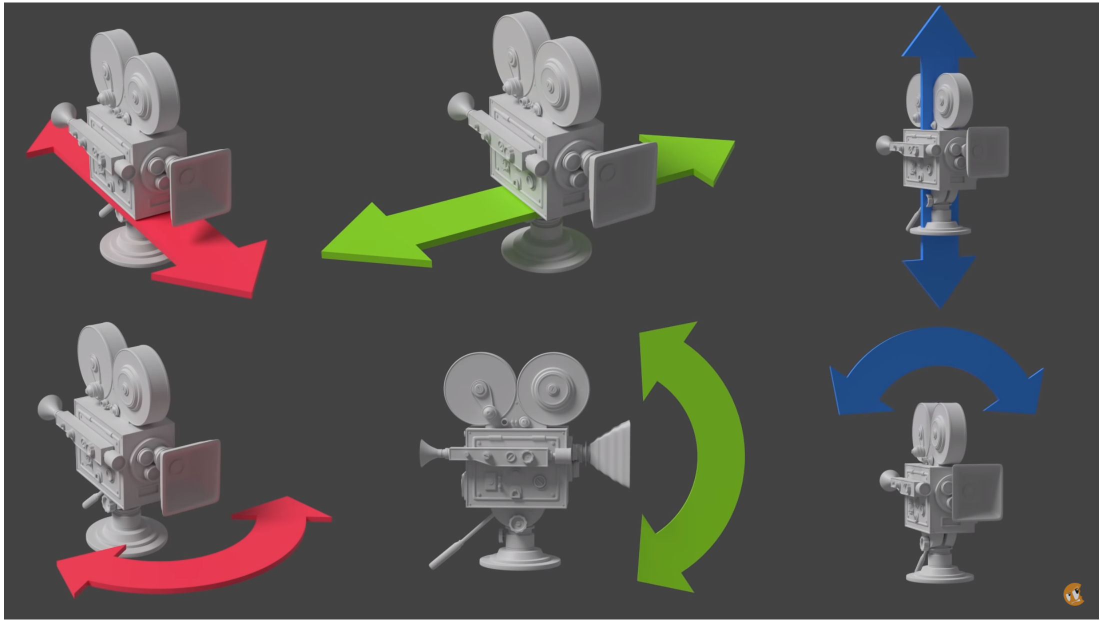
- `Forward = normalize(from - to)`
- `Right = crossProduct(randomVec, forward)`
  - `RandomVec = (0,1,0)`
  - If `Forward` is close to `(0,1,0) or (0,-1,0)` take another `randomVec`
- `Up = crossProduct(forward, right)`
- `4x4 matrix:`



$$\begin{matrix} Right_x & Right_y & Right_z & 0 \\ Up_x & Up_y & Up_z & 0 \\ Forward_x & Forward_y & Forward_z & 0 \\ T_x & T_y & T_z & 1 \end{matrix}$$

`T = from.`

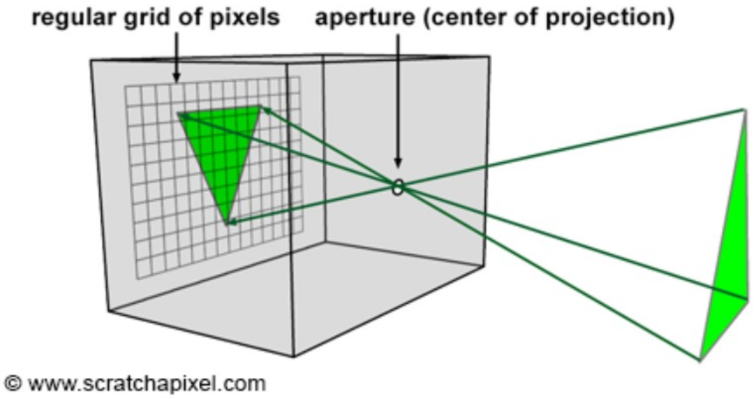
Camera movement

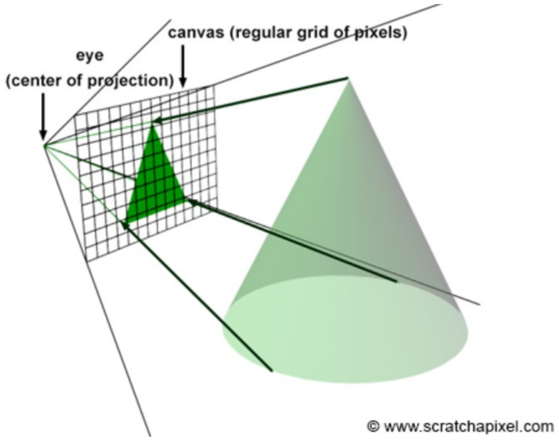


https://www.youtube.com/watch?v=El0V6fS7mpc&ab_channel=CGCookie

Virtual pinhole camera image formation

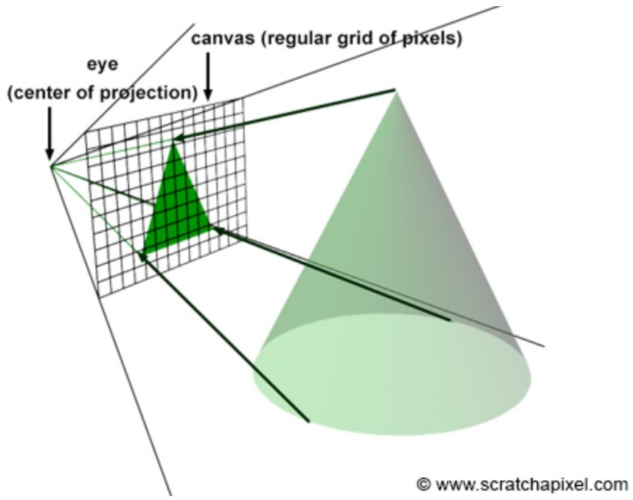
- Pinhole image creation:
  - Light rays are emitted from light source, intersect with object surfaces.
  - For each of 3D scene points visible from camera, only some of reflected rays will fall on aperture and strike the film.
  - If we divide film surface into grid of pixels, we obtain digital pinhole camera which we simulate by virtual pinhole camera.
- Virtual pinhole camera follows the same idea but with film place in from of aperture.
- How image is formed using virtual pinhole camera depends on rendering techniques:
  - Ray-tracing-based rendering
  - Rasterization-based rendering





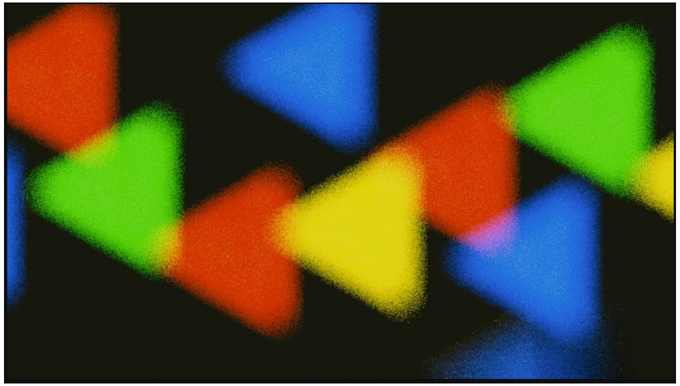
Camera in ray-tracing

- Real world: light ray reflected from 3D scene point P, passing through aperture is falling on film and is coloring the pixel
- Ray-tracing based rendering simulates this process by associating each pixel with one or multiple rays.
- The process is then reversed:
  - Ray is generated using camera eye position and pixel position in camera image plane.
  - Ray is traced into the 3D scene where it intersects the objects – **ray casting** (foundational method for ray-tracing).
  - Color that is computed from intersecting the object is assigned to pixel



Camera in ray-tracing

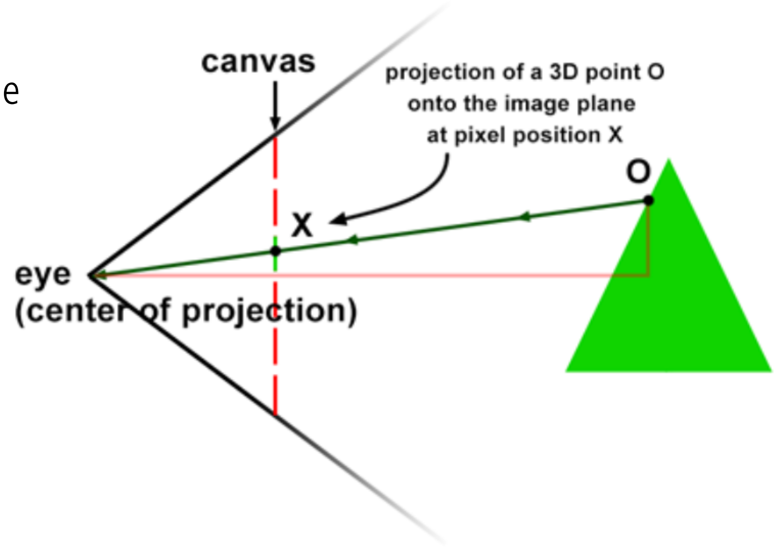
- Ray-tracing is **image-centric**
  - For each pixel in image plane, ray is constructed and traced in 3D scene for intersection and computing color of intersection (shading).
- Aperture is infinitesimally small – a point – from which we generate rays.
  - Image will be perfectly sharp
  - Additional methods are employed from simulating lens effects such as depth of field.



https://docs.blender.org/manual/en/latest/render/cameras.html

Camera in rasterization

- Real world: light ray reflected from 3D scene point P, passing through aperture is falling on film and is coloring the pixel
- Rasterization-based rendering is simulating this process by finding a **position of 3D point P from 3D scene in image plane by "projecting" P on image plane.**
  - **Perspective projection**
- The process of finding pixel coordinates on image plane of 3D point is done as follows:
  - 3D points from world space are transformed to camera space: **world-to-camera matrix.**
  - Apply perspective **projection matrix** or perspective divide.
  - Convert those points to raster space (image plane with pixels).



Camera in rasterization

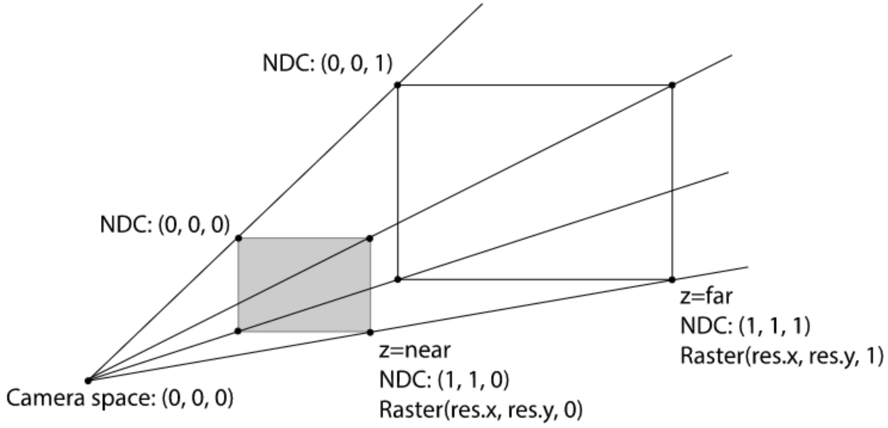
- Rasterization is **Object-centric**
  - Rasterization-based rendering starts from 3D scene geometry and projects objects onto image plane to find colored pixels.
- Each projected point from 3D scene has exactly one point on image plane
  - Therefore, image will be perfectly sharp
  - Additional methods are employed to introduce depth of field

https://docs.blender.org/manual/en/latest/render/eevee/render_settings/depth_of_field.html

https://developer.nvidia.com/gpugems/gpugems/part-iv-image-processing/chapter-23-depth-field-survey-techniques

Perspective camera

- Most often used from film and game rendering

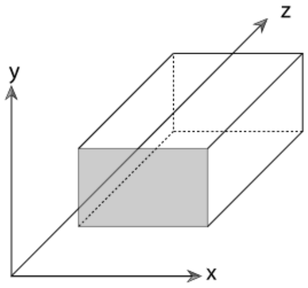


https://www.pbr-book.org/3ed-2018/Camera_Models/Projective_Camera_Models

Orhographic camera

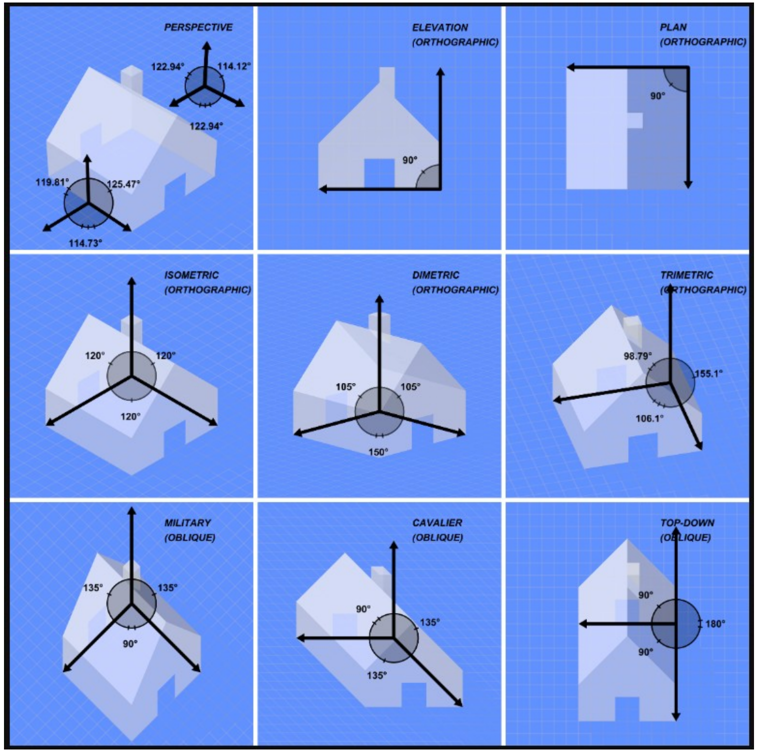
- Useful from modeling in architecture and enginee

- Often used in isometric games

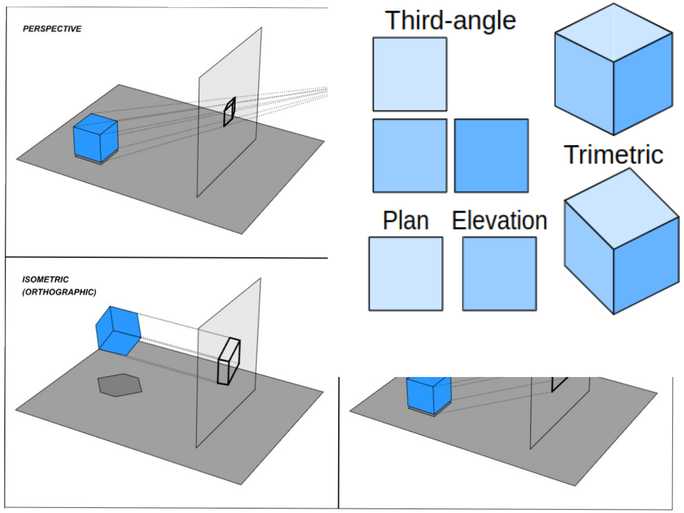


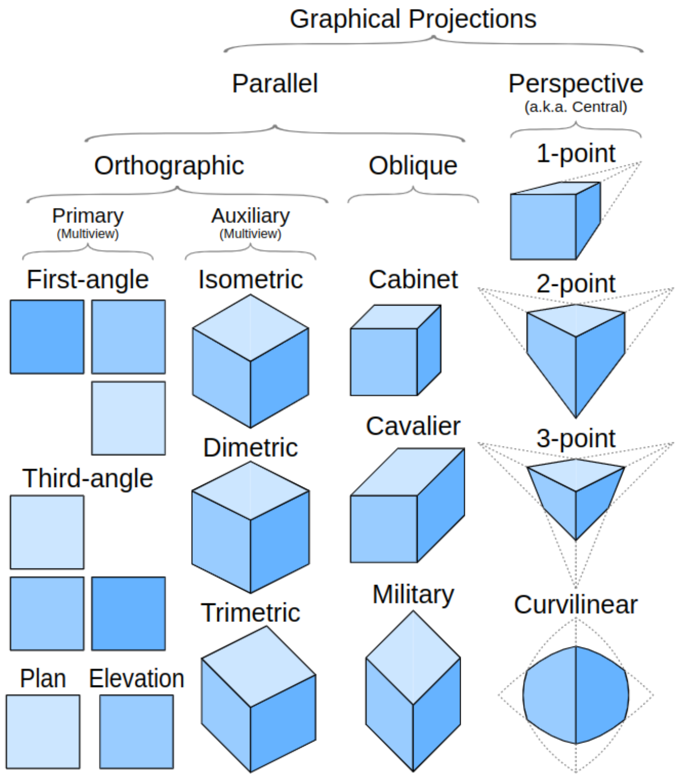
https://store.steampowered.com/app/1573390/Lilas_Sky_Ark/

Other projections and comparisons



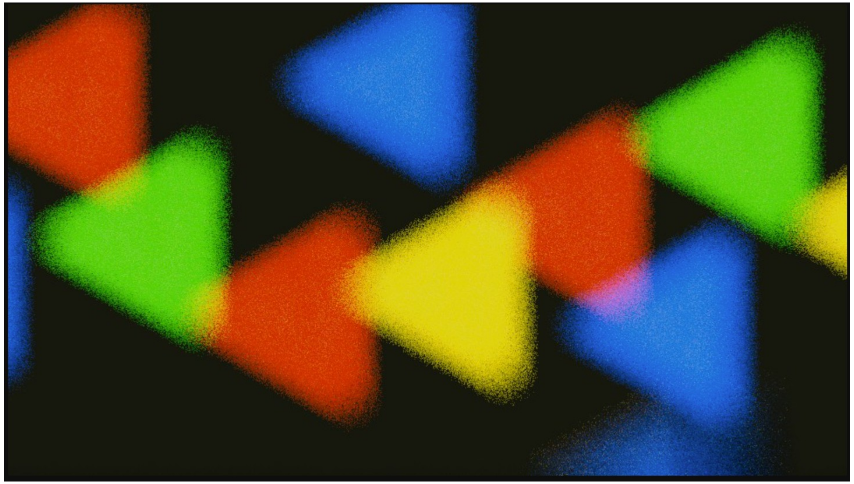
https://en.wikipedia.org/wiki/Orthographic_projection





Simulating lens camera

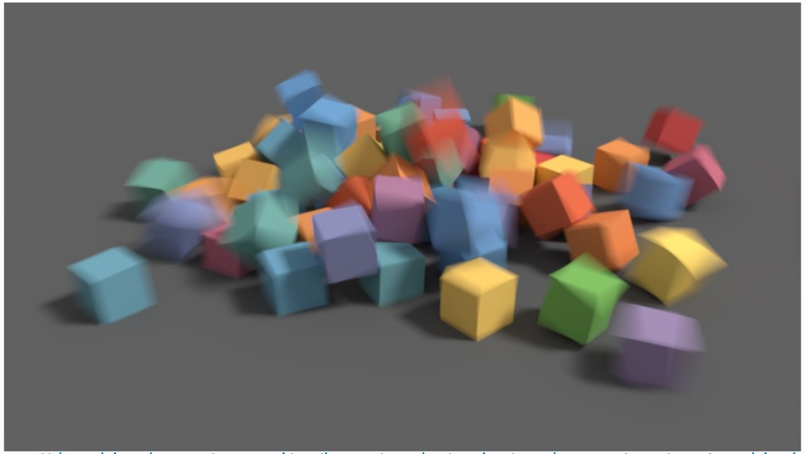
- Real-world cameras transmit light through a lens that bends and focuses it onto the sensor. Because of this, objects that are a certain distance away are in focus, but objects in front and behind that are blurred.



https://docs.blender.org/manual/en/latest/rend

Exposure in simulated camera

- Exposure (time in which aperture is opened) in rendering is not used as camera parameter.
  - Exposure is parameter which control brightness of already rendered image
- Shutter speed (determining exposure) is used for motion blur.



https://docs.blender.org/manual/en/latest/render/cycles/render_settings/motion_blur.html

Different exposures of the same render:
https://docs.blender.org/manual/en/latest/render/color_management.html

More into topic

- More about film, aspect ratio: https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera/how-pinhole-camera-works-part-2
- Lenses: https://www.pbr-book.org/3ed-2018/Camera_Models/Realistic_Cameras

To remember

- Elements of camera system: aperture, film and lens
- Pinhole camera
- Pinhole camera in rendering
- Field of view → sensor size, focal length
- Depth of field → lenses, focal length, object distance
- Exposure → aperture, shutter, ISO
- Motion blur → shutter

Acknowledgements

- Large part of this lecture is based on ScrachAPixel lession: https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera

Literature

- https://github.com/lorentzo/IntroductionToComputerGraphics/wiki/Foundations-of-3D-scene-modeling