Lecture 10: Camera

DHBW, Computer Graphics

Lovro Bosnar

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Syllabus

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

- Camera
  - Real camera system
  - Image formation
  - Pinhole camera model
  - Virtual pinhole camera

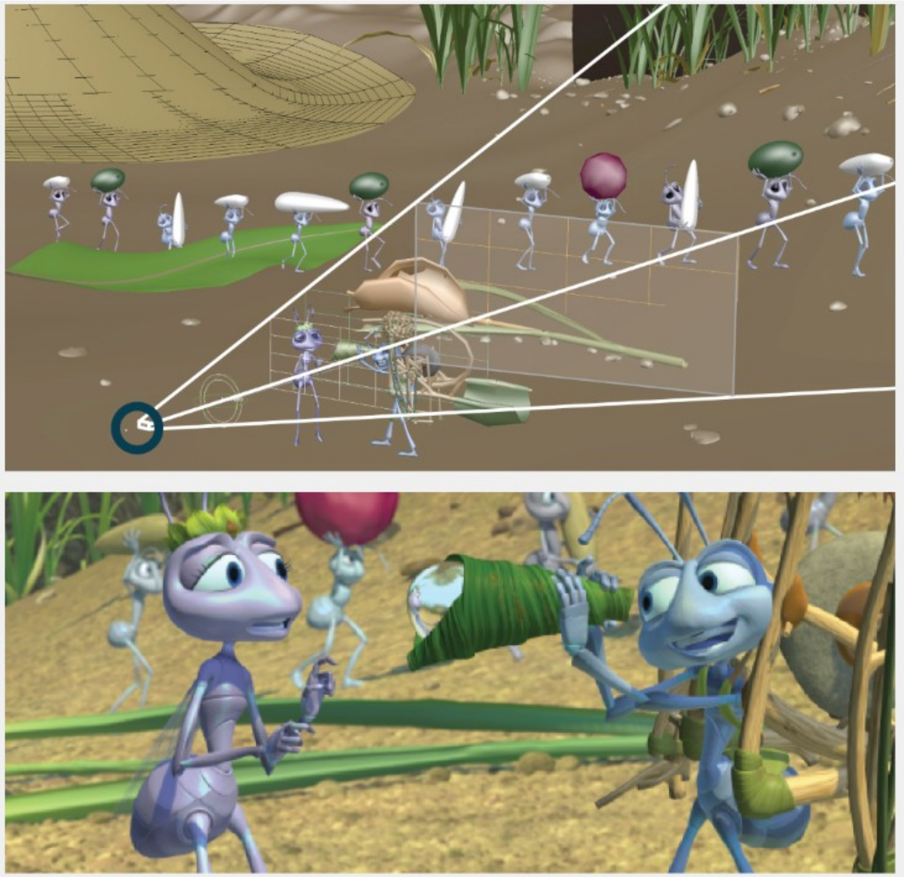
Where is camera?

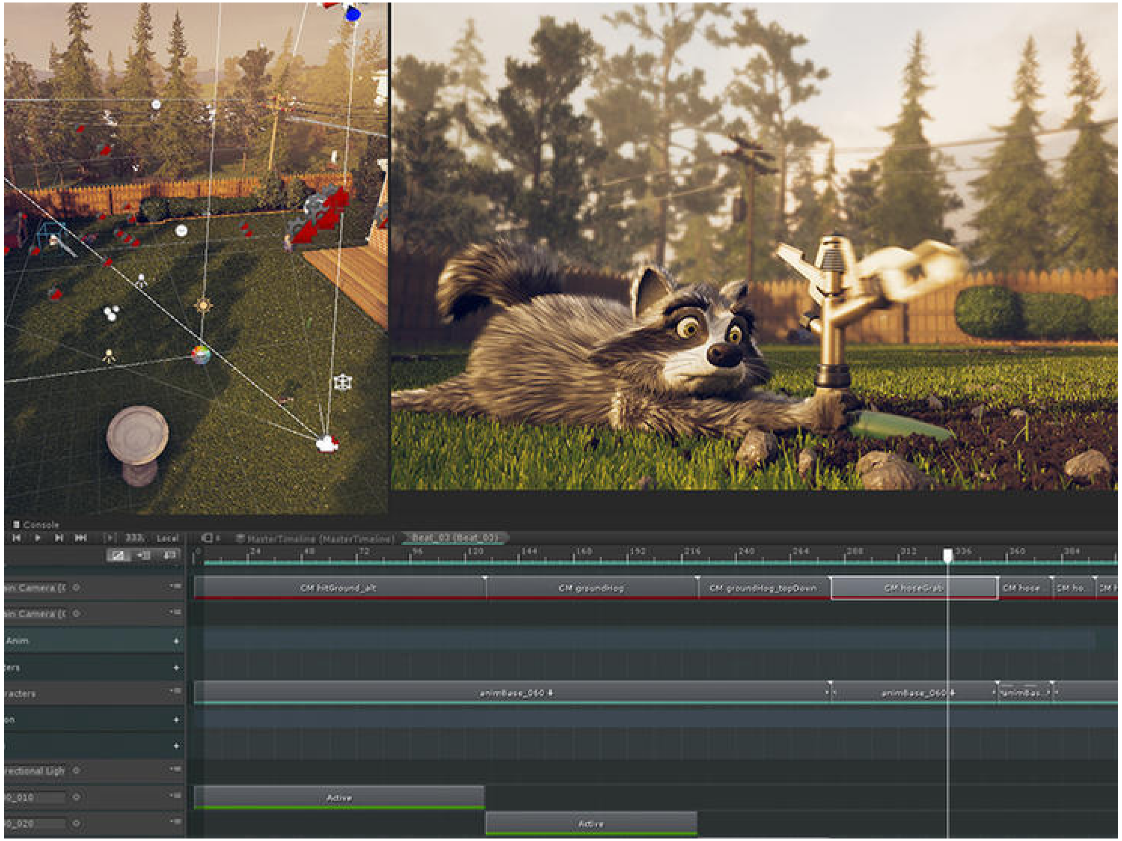
https://sciencebehindpixar.org/pipeline/sets-and-cameras

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

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

Where is camera?



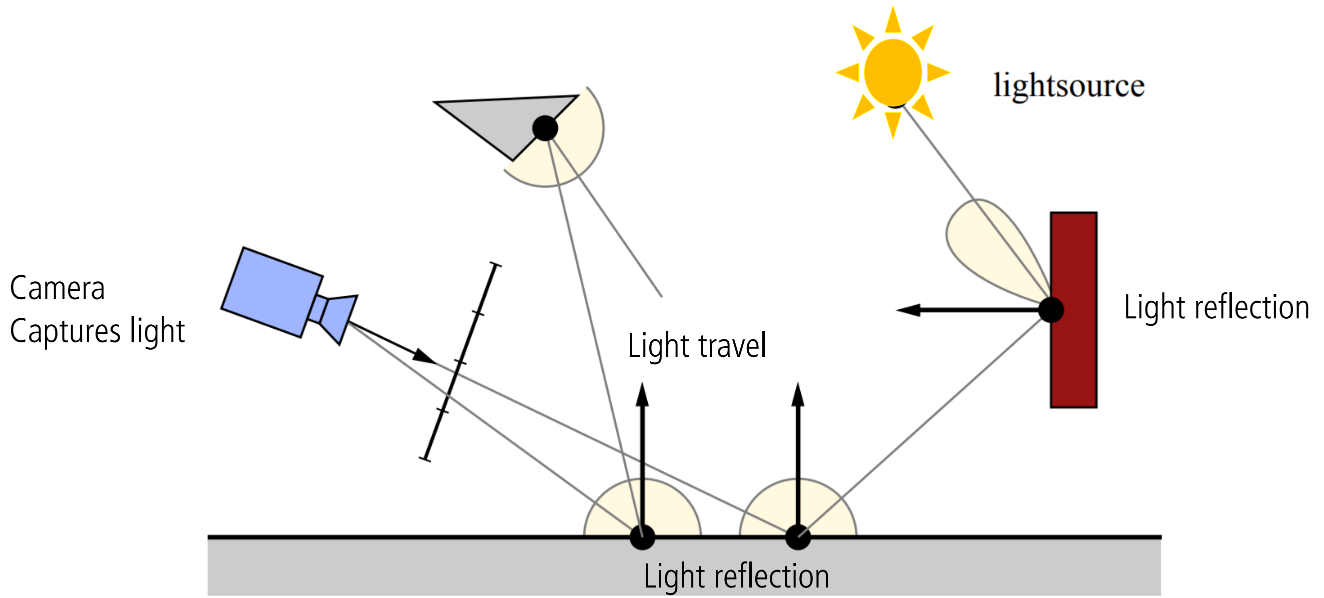


Where is camera?

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

Camera in rendering

- Camera defines a portion of visible scene
- Light falling on camera sensor forms an image
- **To find light contributing to pixel colors, rays are traced from camera to 3D scene**
  - **Backward tracing**



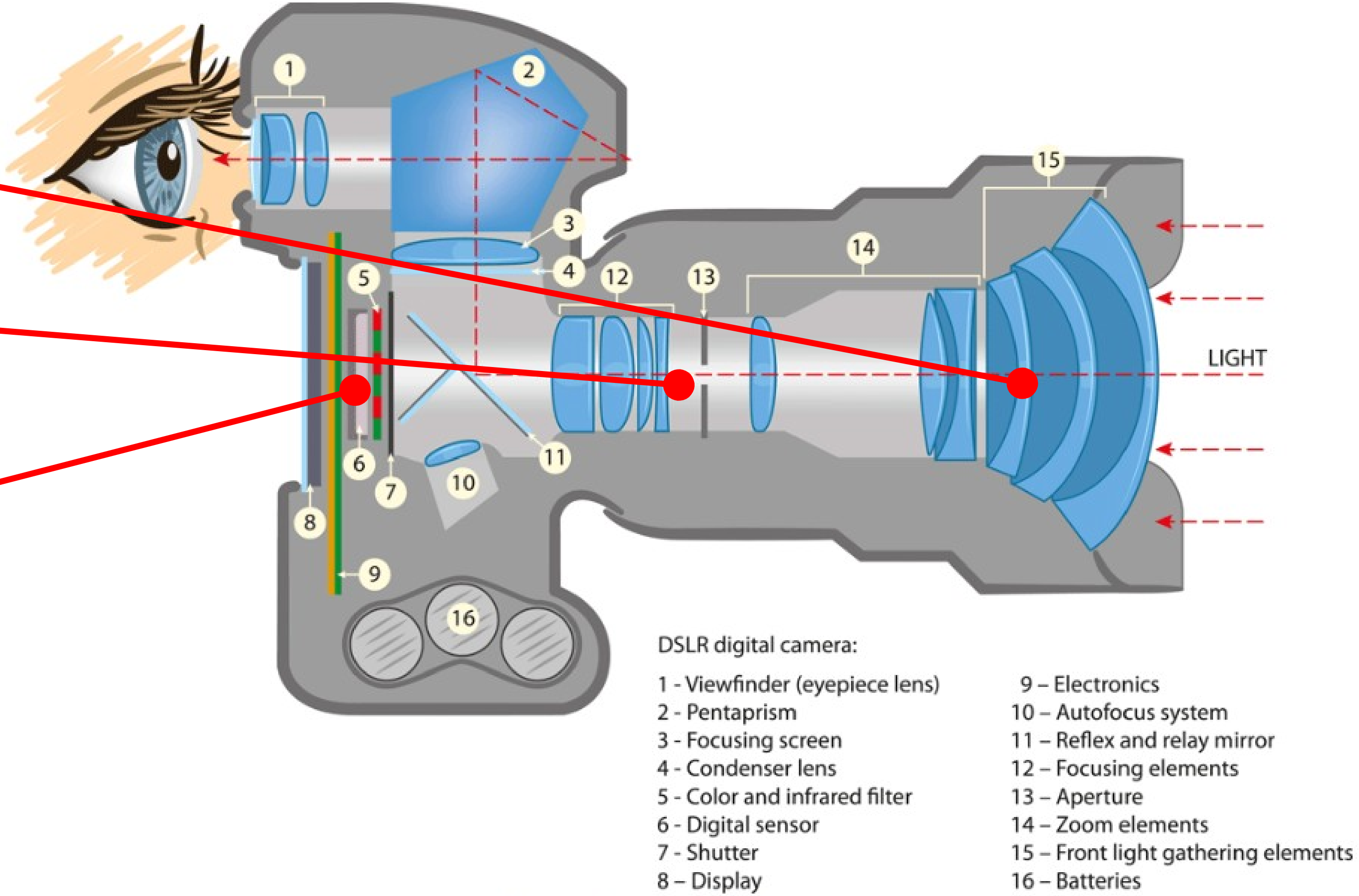
Real camera systems

Real camera systems

Lens system

Aperture

Digital sensor



Basic Parts of a DSLR Camera

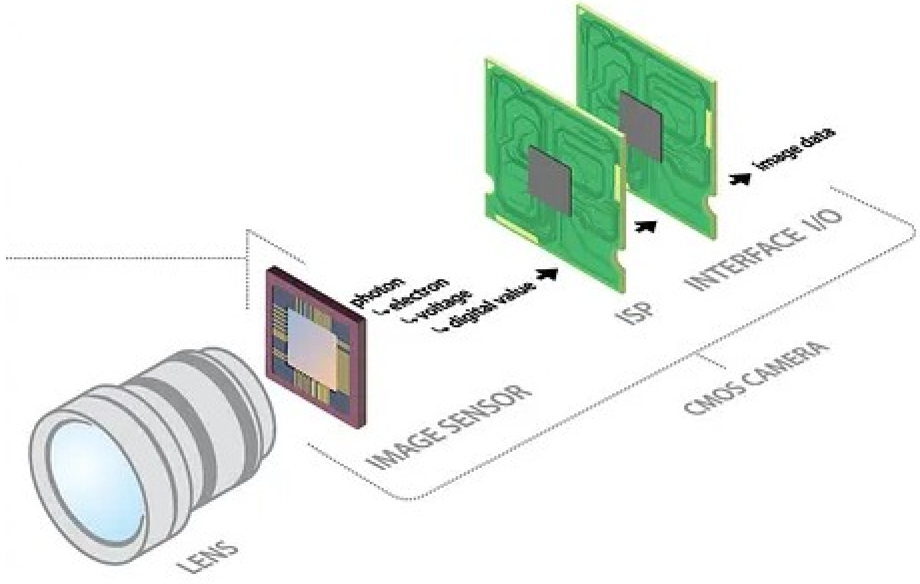
Real camera systems

- Camera contains many small discrete **sensors**: CMOS/CCD
  - Each measures incoming **radiance** values and converts it to **color** signal
  - Radiance: light energy per ray
- Sensors are placed into 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

Camera image sensor

- Sensor converts incident light energy into analog signal (e.g., voltage) which is later represented as color
- Array of sensors are used to form an image

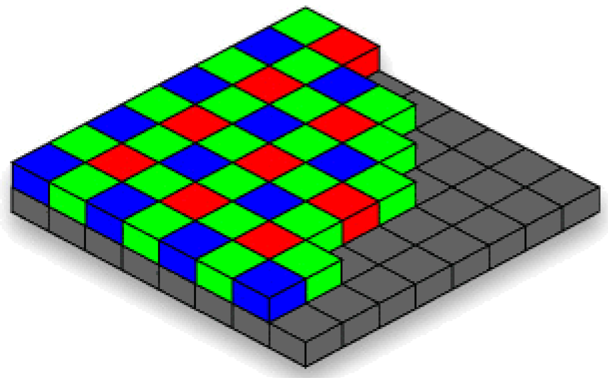
CMOS or CCD image sensor.

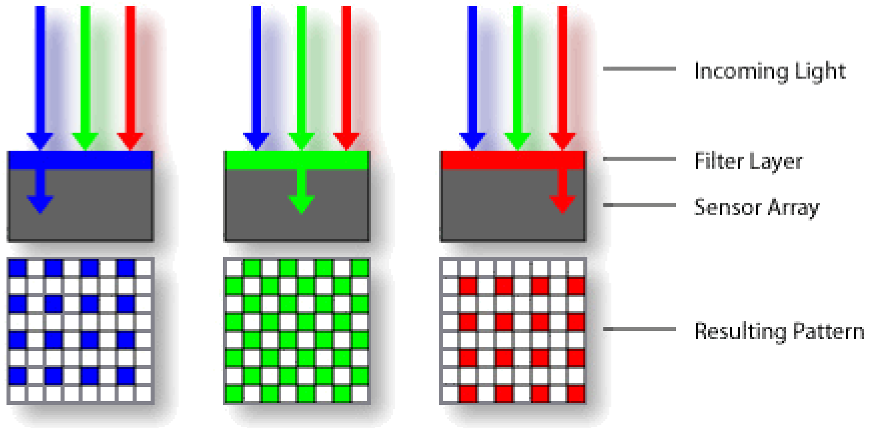


https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

Camera image sensor

- Each sensor records incoming light energy per second
- Only one signal over whole cell area is captured
- Sensor measures only R,G,B wavelengths
- Sensor cell can be seen as a pixel



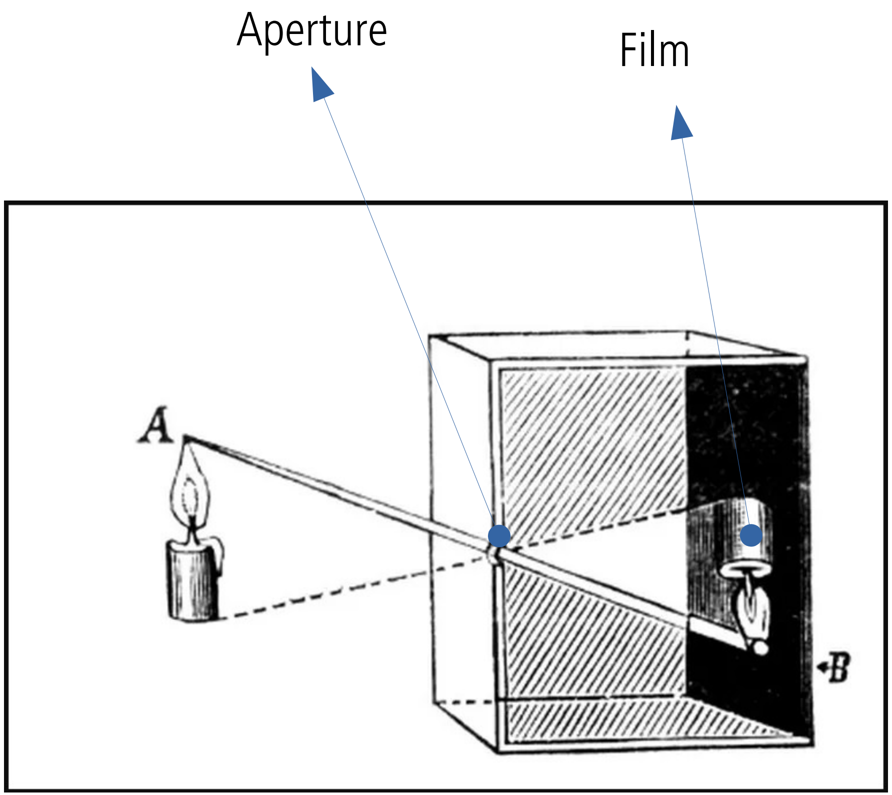


https://simple.wikipedia.org/wiki/Bayer_filter

Image formation

Camera obscura

- Lightproof box with:
  - Black interior (to prevent light reflection)
  - Very small opening: **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 film
  - 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

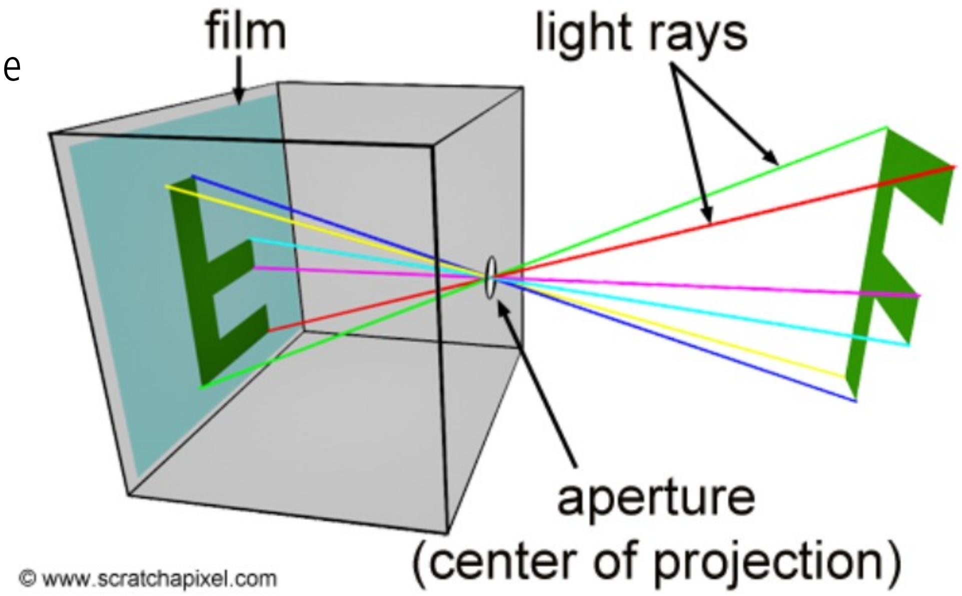
View from the window.

Room made into camera obscura projecting view from the window on the wall.

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

Pinhole camera

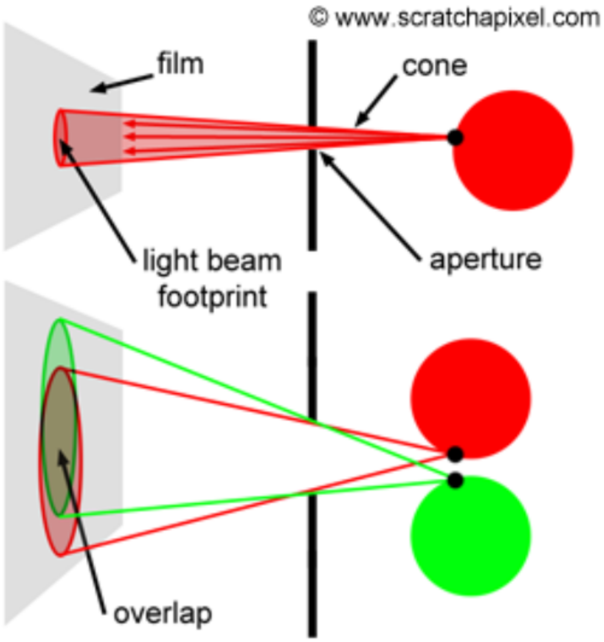
- Main elements:
  - **Aperture**: center of projection: all rays entering converge here and diverge from it to the other side
  - **Film:** light hitting the film forms the image
- Image formation
  - Aperture is opened to expose film to light
  - Ray reflected from the world in point P enters the camera 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

Aperture size

- **Ideal pinhole**: aperture is so small that only one ray passes through it
  - **Formed image is sharp** since each point of the object maps to the one point of the film
- **Aperture has certain size**
  - Angle of cone of rays is determined by the size of aperture
  - **Smaller aperture → smaller cone → sharper image**
  - **Larger aperture → larger cone → blurred image**



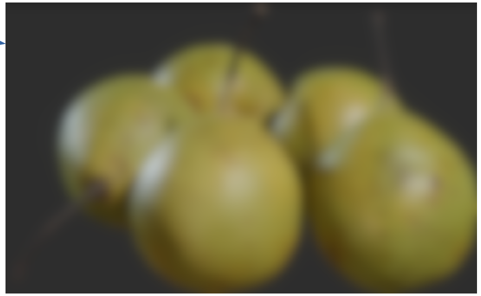
https://polyhaven.com/a/food_pears_asian_01

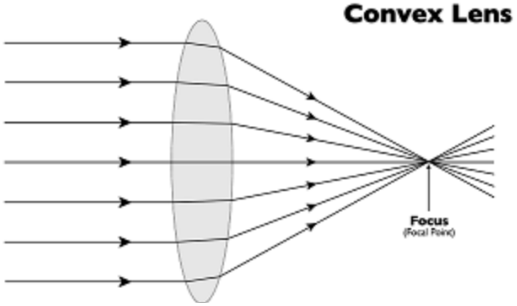
Cones are overlapping and single point appears multiple times on film → blur (out of focus).

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

Aperture and Lenses

- Small aperture: sharp image, but long exposure times needed leading to motion blur
- Large aperture: shorter exposure time but image will be blurred
- Solution is to use lens in front of aperture
  - Rays entering camera are gathered (converged) and focused to one point on a film plane
  - Aperture can now be larger enabling smaller exposure time while blur is canceled with lens





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

Depth of field

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

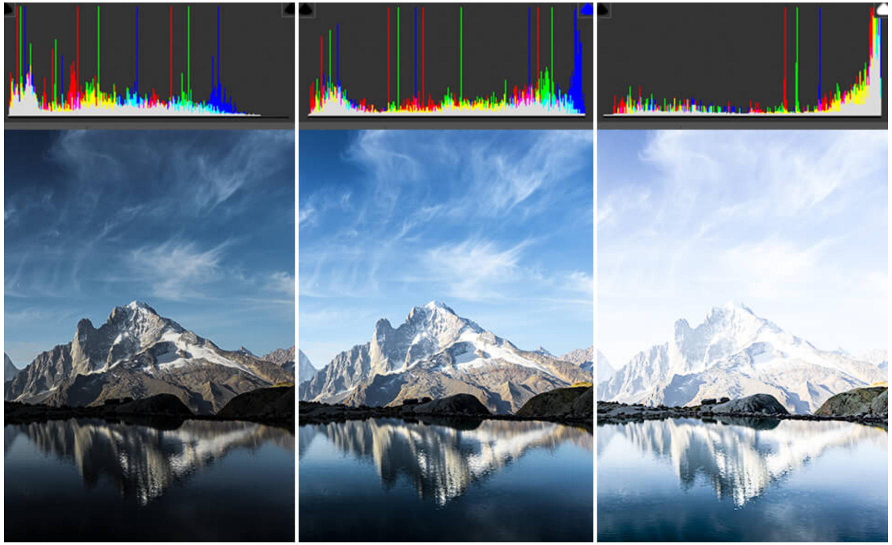
Depth of field: https://www.adobe.com/uk/creativecloud/photography/discover/bokeh-effect.html

Bokeh

Lights out of focus are aesthetically pleasing → bokeh effect.

Exposure

- Time in which the film is exposed to light is called **exposure** time
  - **Determines image brightness**
- **High-contrast image** contains both dark shadows and bright highlights
- **Dynamic range**: ratio between the maximum and minimum measurable light intensities
  - Determines amount of visible details in lit and shadowed areas
  - Real world and 3D scenes can have high difference in dynamic range, but cameras and display devices are limited in capturing and showing them



UNDEREXPOSED STANDARD EXPOSURE OVEREXPOSED

https://fixthephoto.com/what-is-exposure-composition.html

https://www.adobe.com/creativecloud/video/discover/dynamic-range.html

Exposure

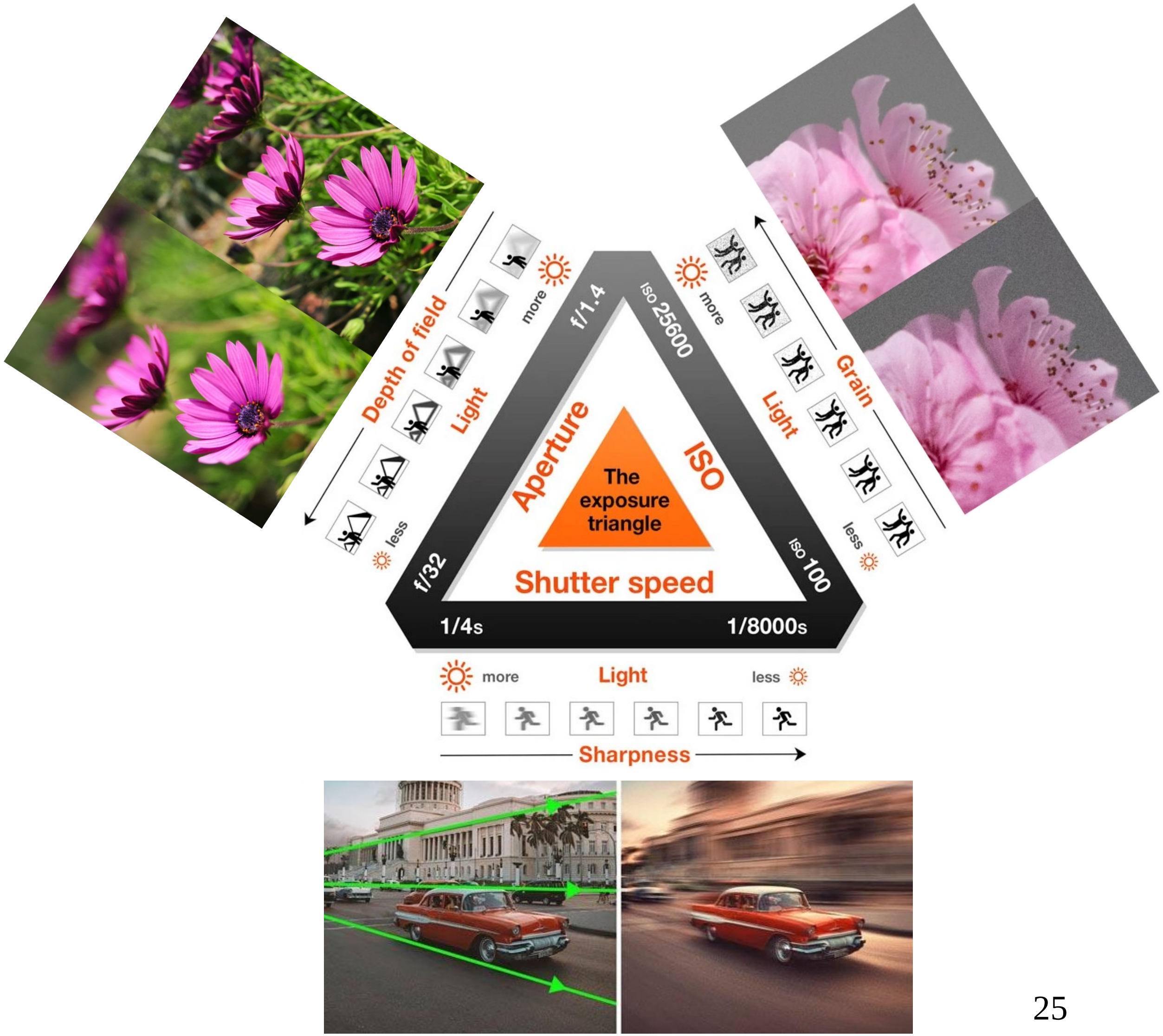
- If aperture is small, longer time is needed for image to form on a film
  - In this case, **motion blur** can appear for objects which are not perfectly still

Earth rotation causes motion blur in long-exposure photos

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

Exposure

- **Exposure** is controlled with:
  - **Aperture size** (f-stop) → depth of field
  - **Shutter speed** → motion blur
  - **Sensitivity (ISO)** (gain) → noise

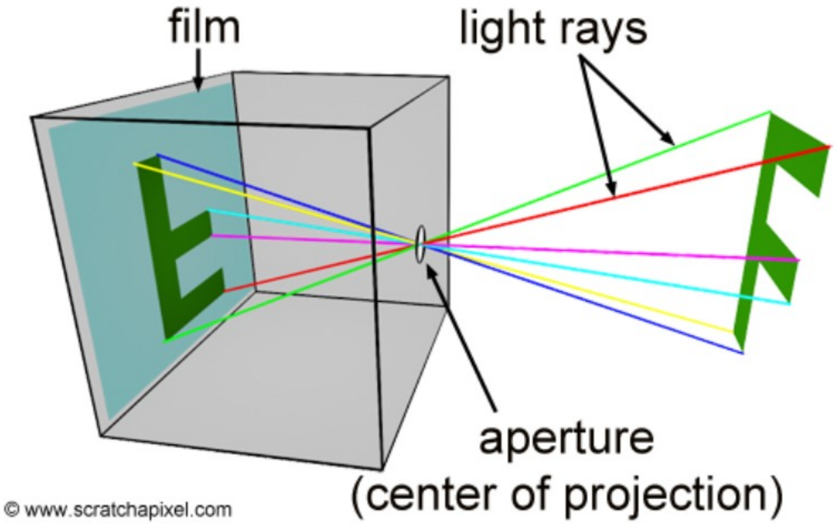


https://photonify.com/3-steps-for-adjusting-the-depth-of-field-on-your-camera/
https://petapixel.com/exposure-triangle/
https://actioncamera.blog/2017/02/22/the-exposure-triangle/
https://www.shutterbug.com/content/give-photos-dramatic-perspective-motion-and-blur-simple-photoshop-technique-video

Pinhole camera model

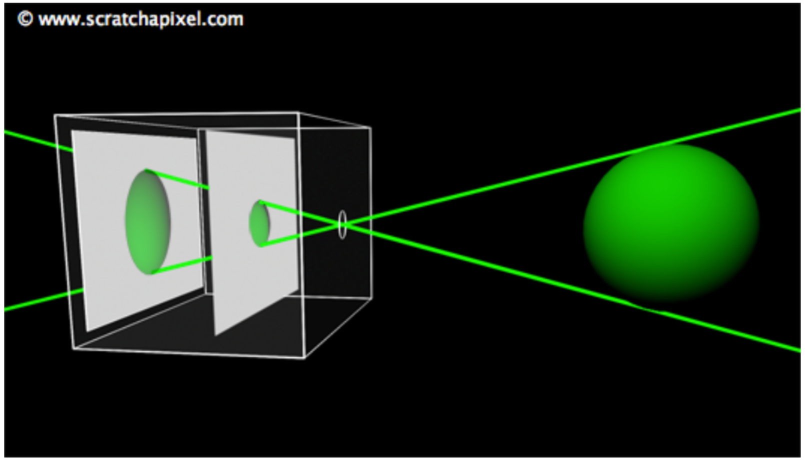
Pinhole camera model

- Complex lens system is simplified: **pinhole camera**
- Main elements:
  - **Film** (image plane)
  - **Aperture** (small opening)
- Parameters:
  - **Focal length**
  - **Angle of view**
  - **Film size**



Focal length

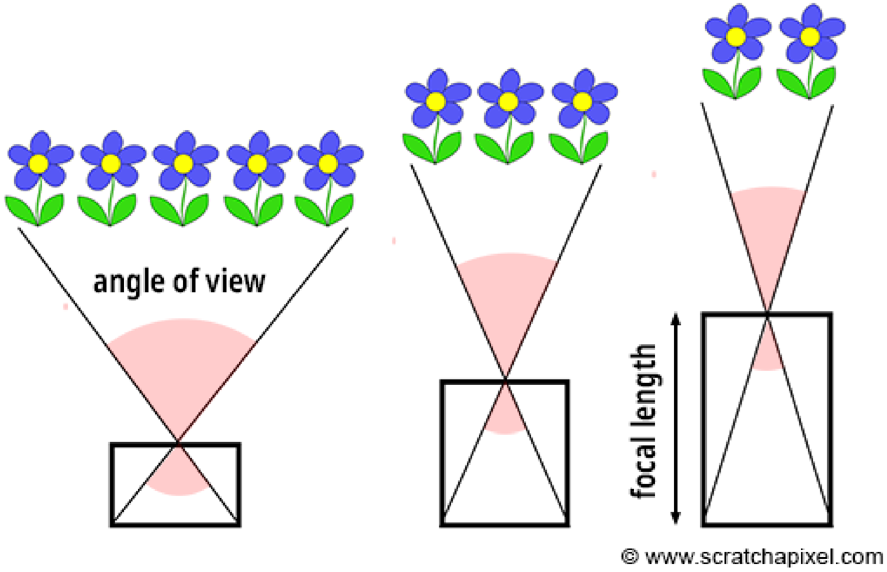
- **Distance of film plane from aperture** defines amount of scene that we see
  - Moving image plane (film plane) closer to aperture effectively performs **zoom out**
  - Moving film plane away from aperture effectively performs **zooming in**
- This parameter is called **focal length** or **focal distance**

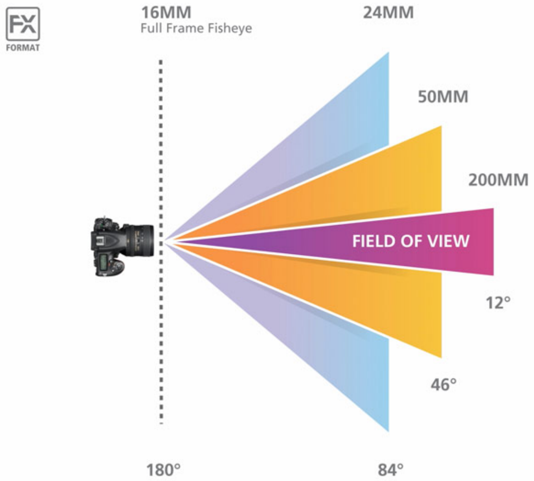


https://www.nikonusa.com/en/learn-and-explore/a/tips-and-techniques/understanding-focal-length.html

Angle of view

- Angle of triangle apex defined with aperture and film edges is called angle of view (AOV) or field of view (FOV)
- Changing focal length, changes AOV/FOV



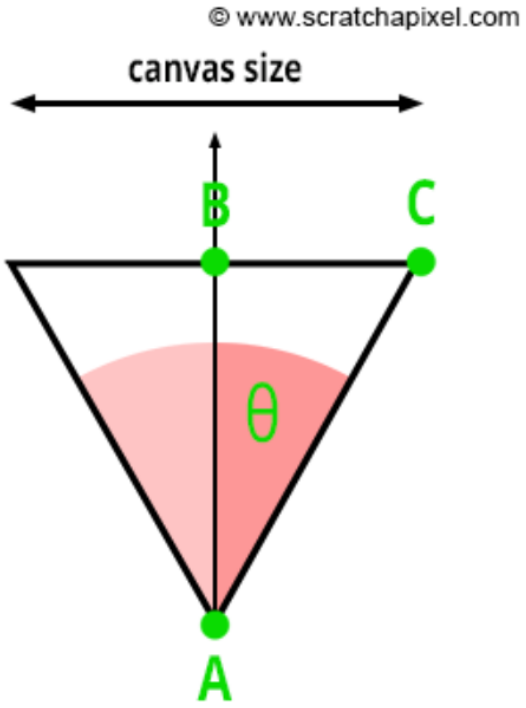


Focal length and corresponding field of view
https://www.nikonusa.com/en/learn-and-explore/a/tips-and-techniques/understanding-focal-length.html

Focal length and angle of view

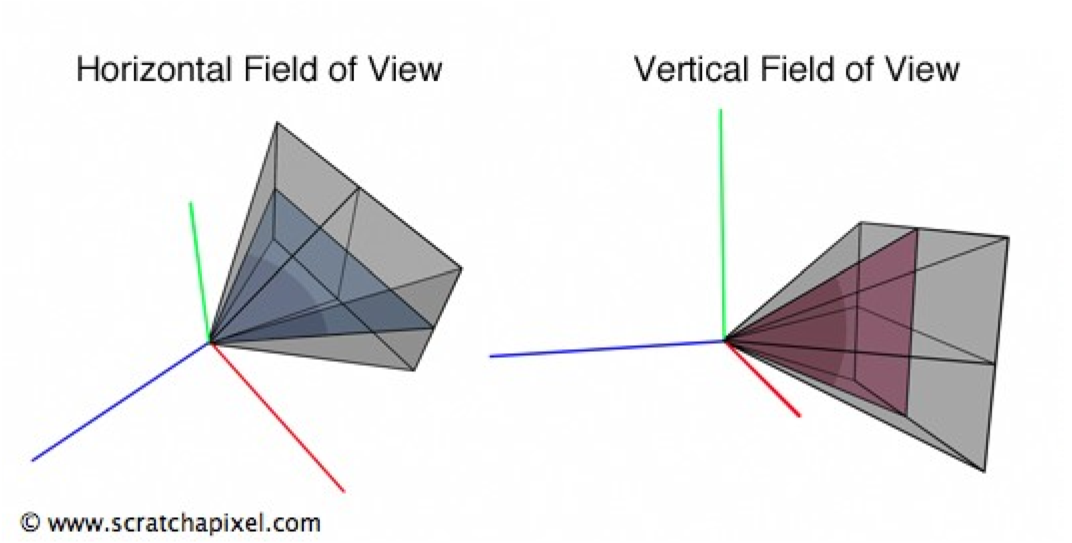
- Relation between focal length (`f = AB`) and angle of view (θ)
- Longer focal lengths result in smaller FOV (more zoom)
- Short focal length results in larger FOV (less zoom)

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



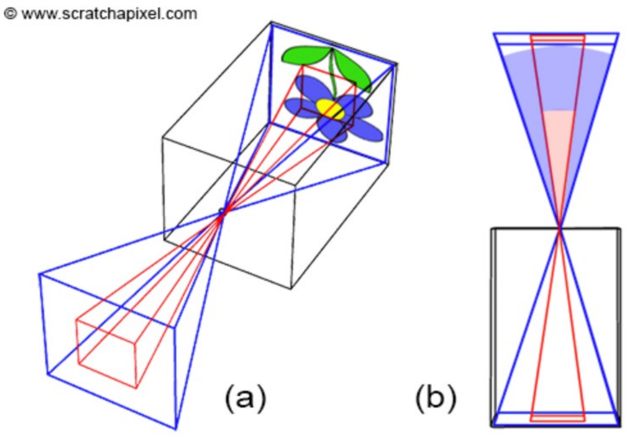
Field of view

- **Triangle defined with aperture and film edges** is a pyramid and we distinguish **horizontal and vertical angle (field) of view (AOV/FOV)**
- Using fixed film aspect ratio, horizontal field of view determines vertical field of view and vice versa



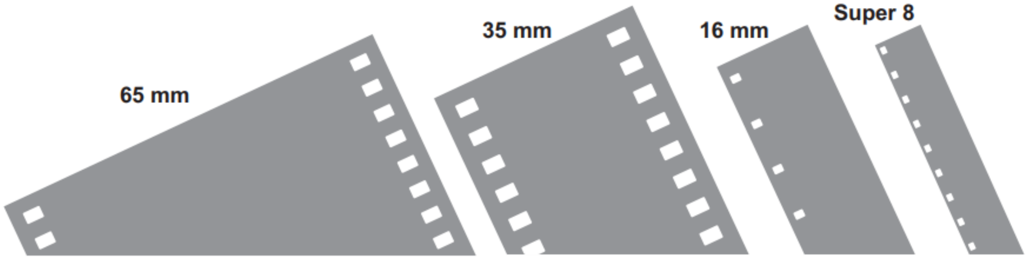
Film size

- **Angle of view depends on film (image plane) size**
  - Film has horizontal and vertical dimensions
  - Using fixed film aspect ratio, horizontal dimension determines vertical dimension
- **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



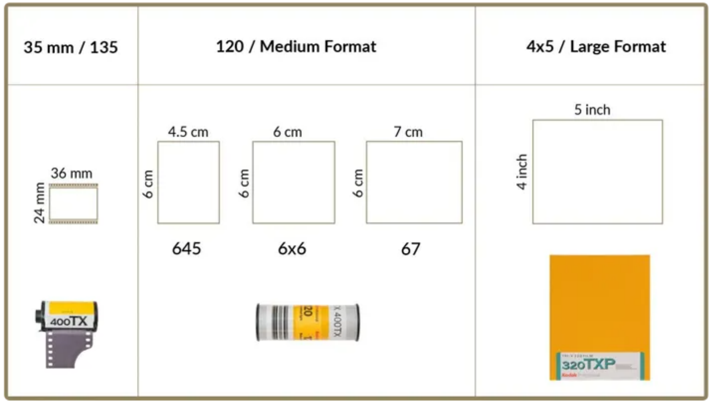
Film size

- Larger film formats were developed enabling 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/

Sensor size and image resolution

- **Image resolution**: `width x height` pixels
- **Size of sensor and number of pixels on sensor are independent parameters**
  - Angle of view doesn't depend on number of pixels on image sensor
- Image quality depends on:
  - Image sensor size
  - Number of pixels on sensor (resolution)
- Higher resolution images will have more details

Image resolution and aspect ratio

- **Image aspect ratio** (**device aspect ratio**) is calculated from image resolution (width and height):

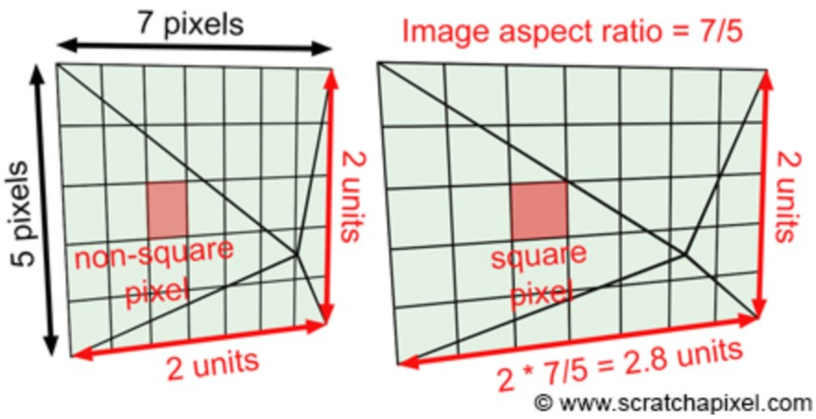
$$\text{Image (or Device) Aspect Ratio} = \frac{\textit{width}}{\textit{height}}$$

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

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

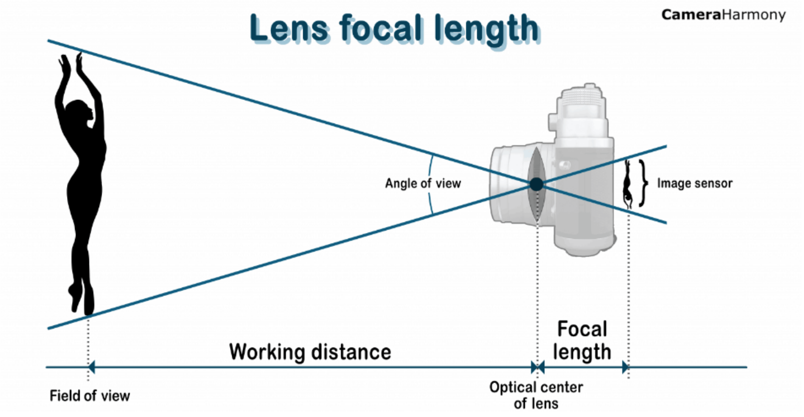
Film and image aspect ratio*

- In computer graphic camera model, sensor (film/canvas) aspect ratio can be different from the image (device) aspect ratio.
  - Difference leads to stretching the image in either x or y directions
- 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.



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



Virtual pinhole camera

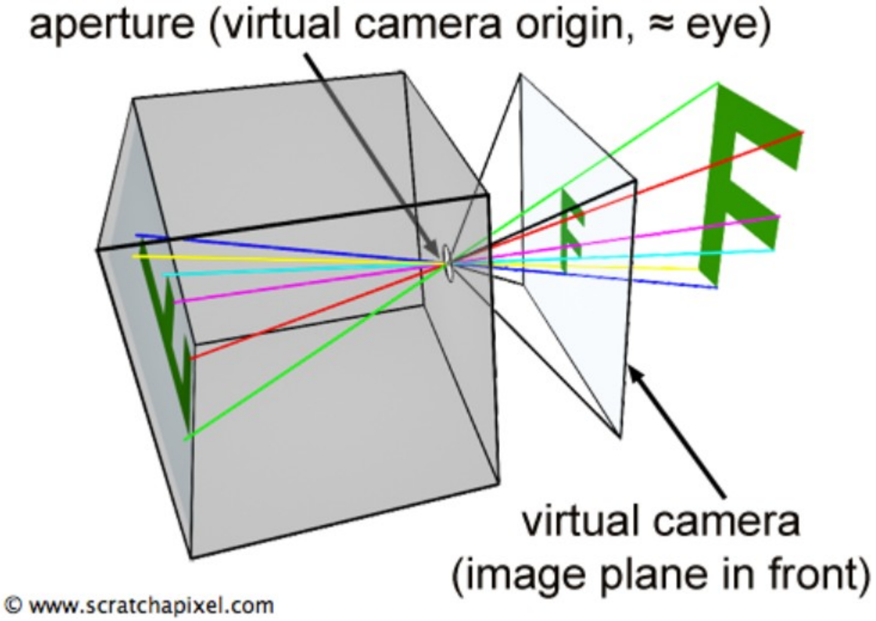
Camera model for rendering

Virtual pinhole camera

- Virtual pinhole camera model in rendering is used to deliver image similar to those produced by a real camera
  - Size and shape of real and rendered object must be the same
  - Combining rendered and live action footage must be possible
  - Expressive and artistic possibilities must be enabled
- Pinhole camera model is used in almost all production software
  - Godot: https://docs.godotengine.org/en/stable/classes/class_camera.html
  - Unity: https://docs.unity3d.com/ScriptReference/Camera.html
  - Blender: https://docs.blender.org/manual/en/latest/render/cameras.html
  - Houdini: https://www.sidefx.com/docs/houdini/nodes/obj/cam.html

Virtual pinhole camera

- In graphics, pinhole camera geometry is not directly simulated
- Virtual pinhole camera simulates only directions from which sensors (pixel) receive light
- Virtual image plane is placed in front of aperture and rays are traced from aperture to each pixel in virtual image plane
  - **Camera rays** → color of virtual image plane pixels

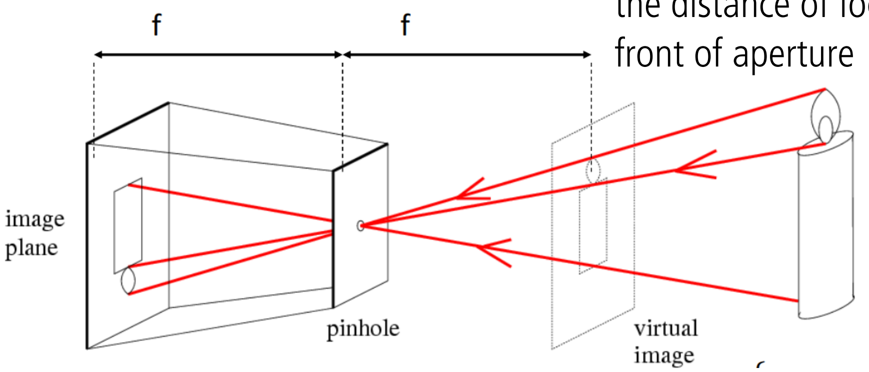


https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera/virtual-pinhole-camera-model

Virtual pinhole camera

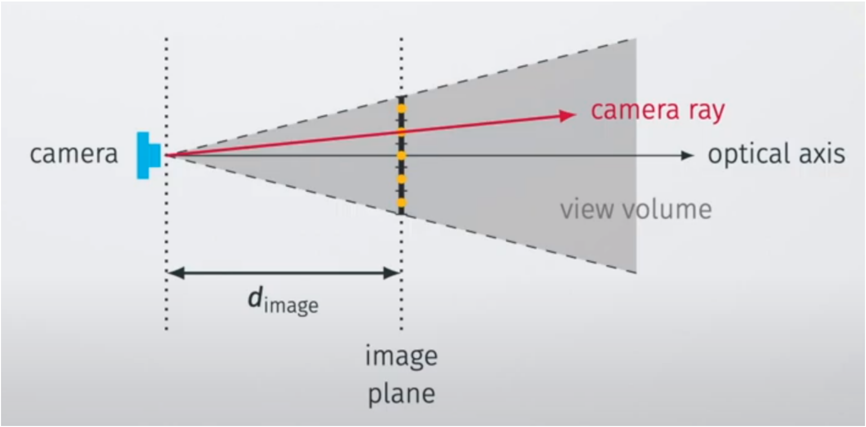
- Following rays from aperture to image plane pixels and into the scene forms image on image plane
  - This results in **perspective projection**

Virtual image plane is placed on the distance of focal length (f) in front of aperture



Real pinhole camera produces images which are upside down

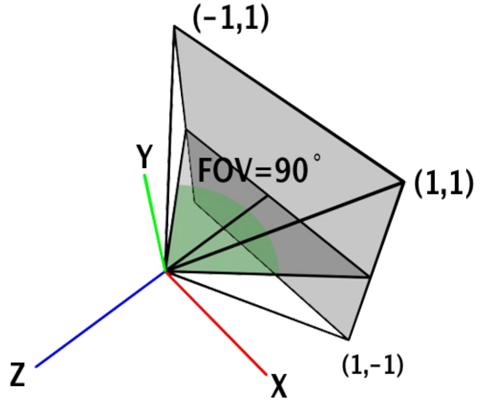
Simulated pinhole camera produces images which are correctly orientated



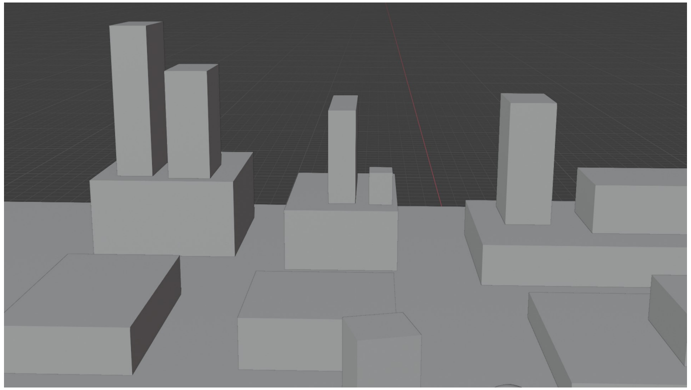
Distance from camera to image plane is focal length

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

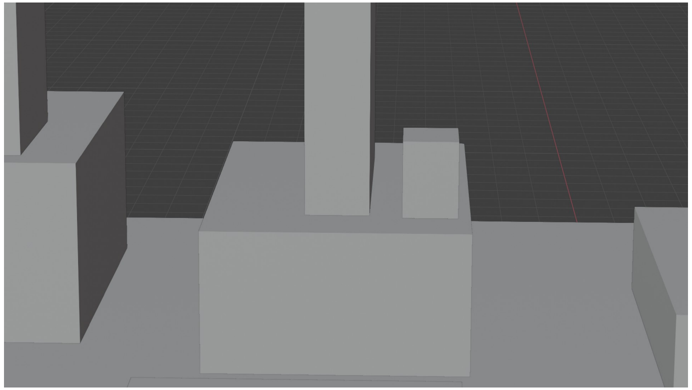
Viewing frustum



- Viewing frustum defines portion of scene visible to camera
- Viewing frustum of pinhole camera is defined with:
  – Camera origin (eye, aperture)
  – Field (angle) of view: film size and focal length



Focal length 50mm

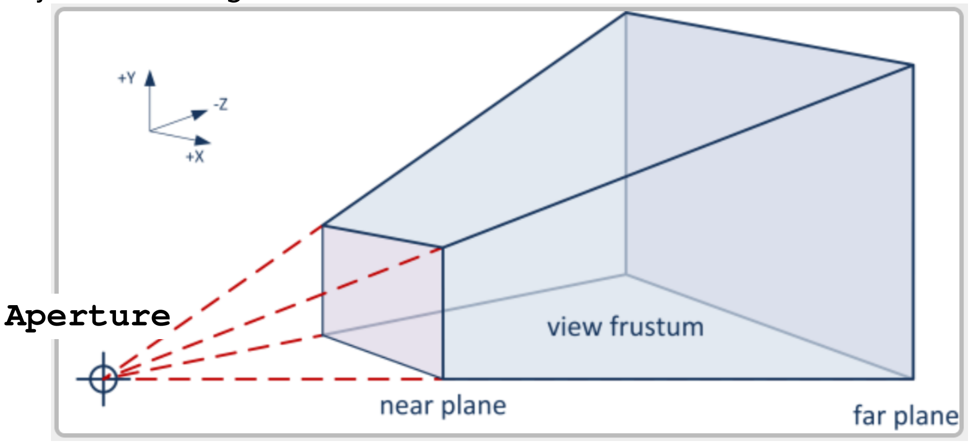


Focal length 120mm

https://www.scratchapixel.com/lessons/3d-basic-rendering/perspective-and-orthographic-projection-matrix/building-basic-perspective-projection-matrix.html

Near and far clipping planes

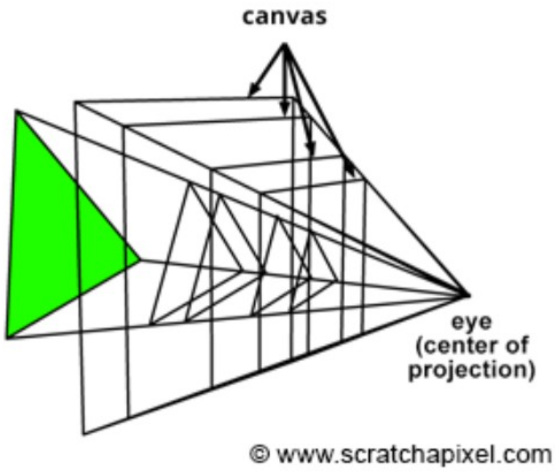
- **Virtual pinhole camera additionally has near and far clipping planes**
  - Virtual planes placed in front of camera and parallel to image plane.
  - Location of clipping planes is measured along camera's line of sight (camera's local z axis)
- Objects in 3D scene closer than near or further than far plane are not visible in image plane.
- Near and far clipping planes are needed for resolving precision issues
  - Precision can be lost if distance between closest and furthest object is too large

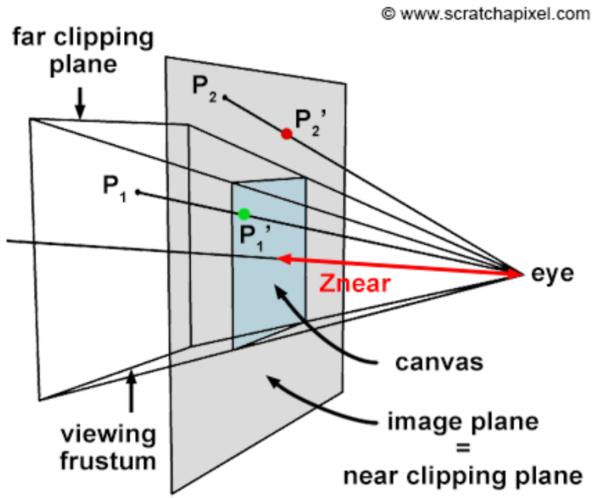


https://learnopengl.com/Guest-Articles/2021/Scene/Frustum-Culling

Image plane and clipping planes

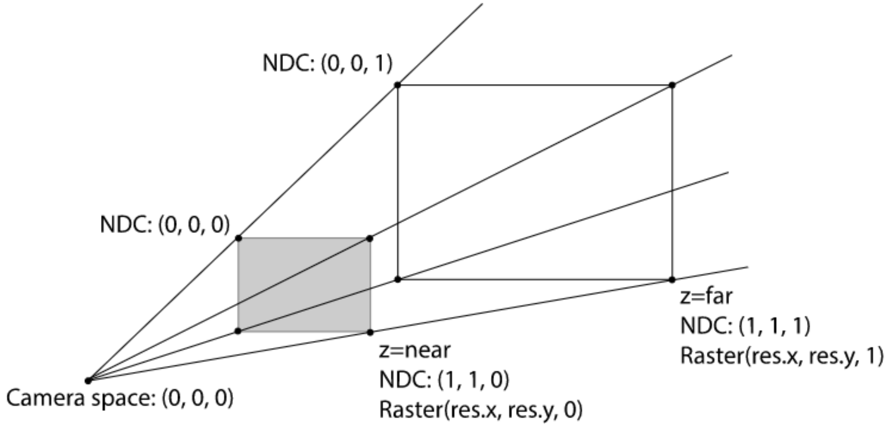
- Image plane is often placed at near clipping plane for computation simplicity
  - Image plane can be placed anywhere on camera’s line of sight (camera’s local z axis) between near and far clipping planes
  - Size of image plane depends on distance from eye.





Perspective camera

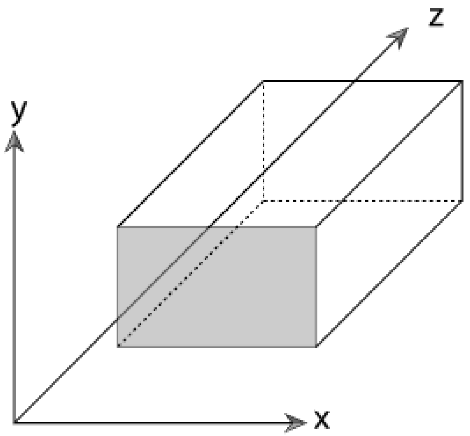
- Most often used from film and game rendering
- Rays are generated from one point (eye, aperture) through virtual image plane
- **Simulates foreshortening effect**: more distant objects appear smaller



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

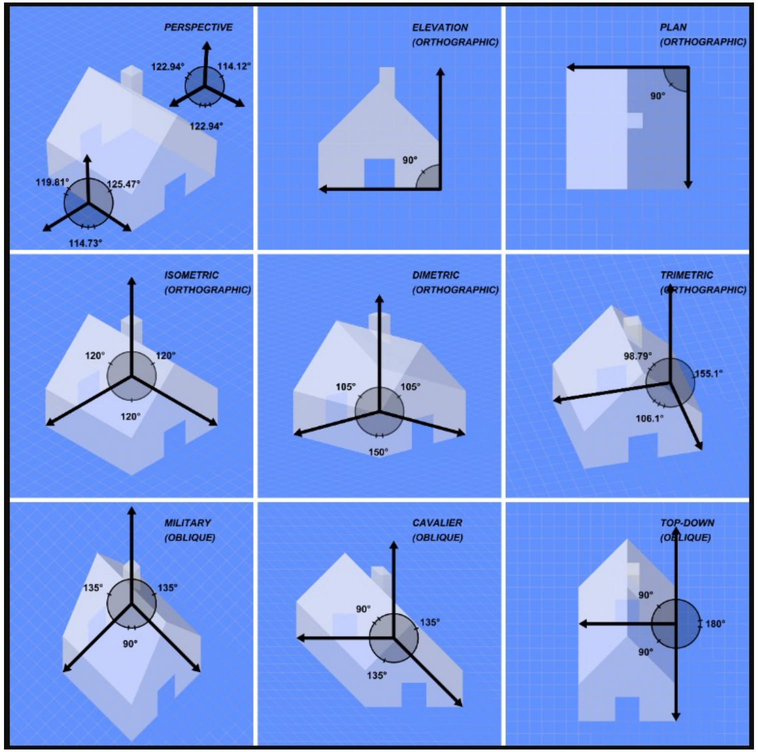
Orthographic camera

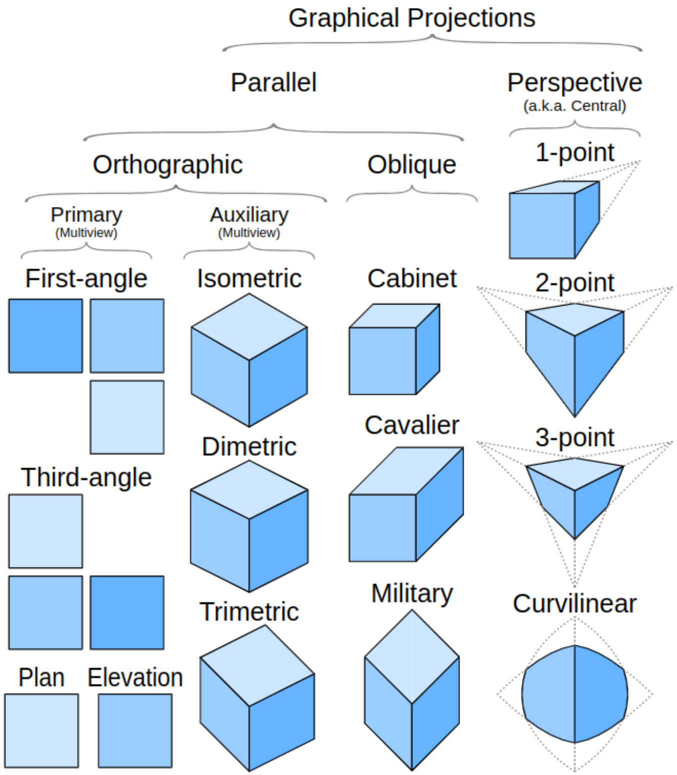
- Useful for architecture, engineering, design, isometric games, etc.
- Rays are generated parallel through virtual image plane
- Objects are of same size regardless of distance



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

Other camera projection types

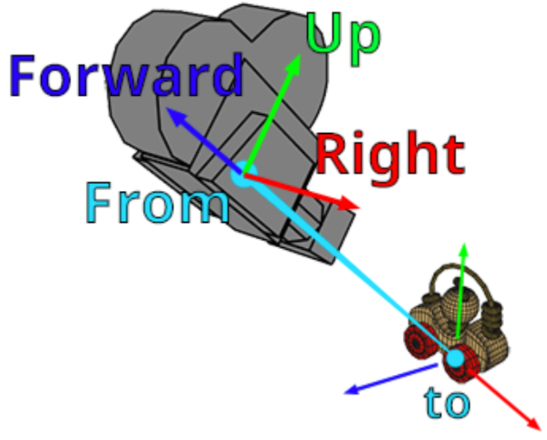




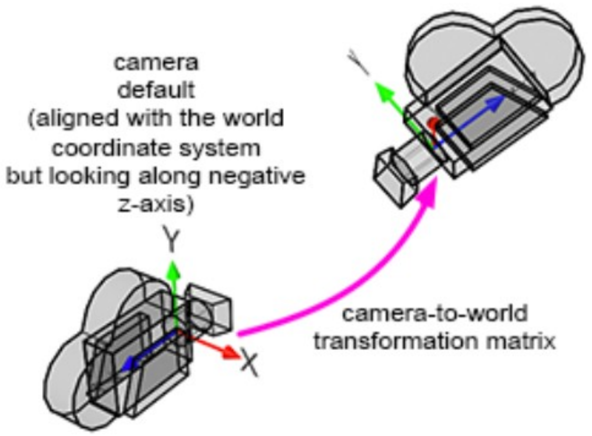
https://en.wikipedia.org/wiki/Orthographic_projection

Camera orientation and position

- **Camera orientation** is defined with `Forward, Up, Right` vectors.
- Camera orientation and position can be defined with **look-at notation:**
  - Point in space where camera is positioned (`From`)
  - Point in space where camera is looking (`To`)
- **Look-at matrix**
  - `Forward, Up, Right` can be calculated based on `From,To`
  - `Forward, Up, Right, From` define look-at matrix
  - Defines complete transformation needed for moving camera in 3D scene



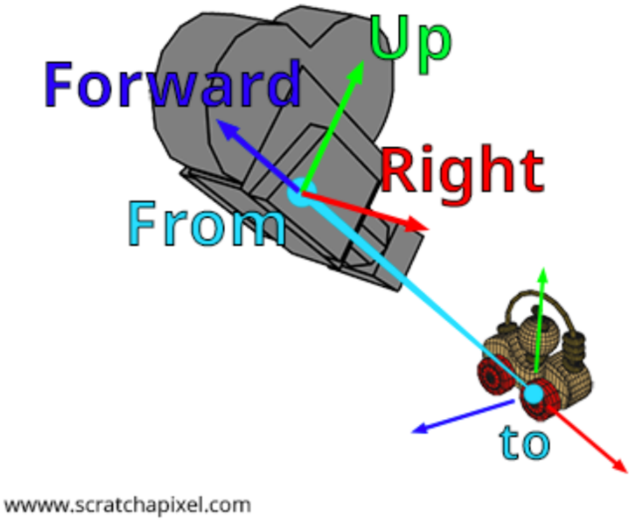
wwww.scratchapixel.com



Look at matrix

- 4x4 transformation matrix → transformation of camera from its local (camera) space to world space in 3D scene: **camera-to-world** and its inverse **world-to-camera** matrix

```
Forward = normalize(From - To)
Right = crossProduct(randomVec, Forward)
Up = crossProduct(forward, right)
```

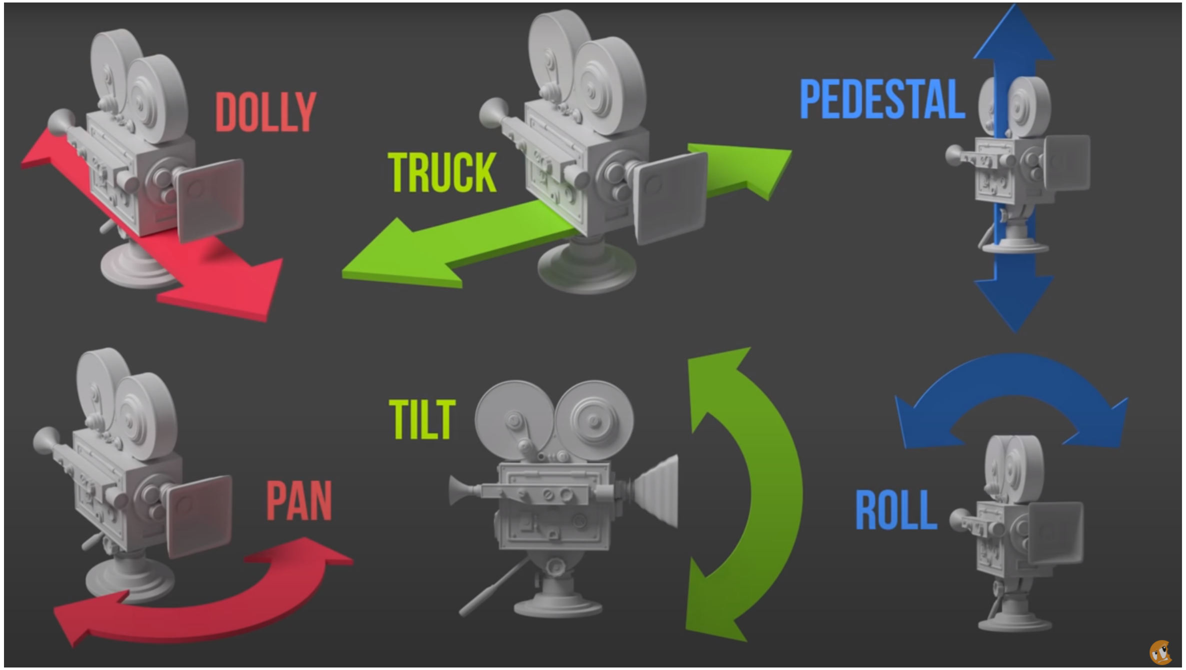


$$\begin{matrix} Right_x & Right_y & Right_z & 0 \\ Up_x & Up_y & Up_z & 0 \\ Forward_x & Forward_y & Forward_z & 0 \\ \mathtt{From}_x & \mathtt{From}_y & \mathtt{From}_z & 1 \end{matrix}$$

`RandomVec = (0,1,0)` or other if `Forward` is close to `(0,1,0) or (0,-1,0)`

Moving camera*

- Translations: moving in axis directions
- Rotations: rotation around axis



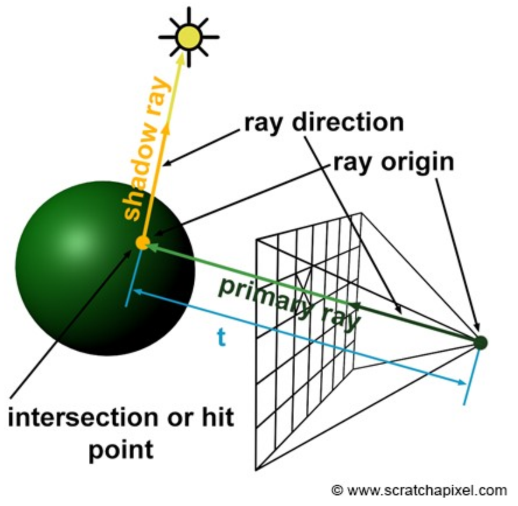
https://www.youtube.com/watch?v=El0V6fS7mpc&ab_channel=CGCookie

Virtual pinhole camera image formation

- How image is formed using virtual pinhole camera depends on rendering techniques:
  - Ray-tracing-based rendering
  - Rasterization-based rendering

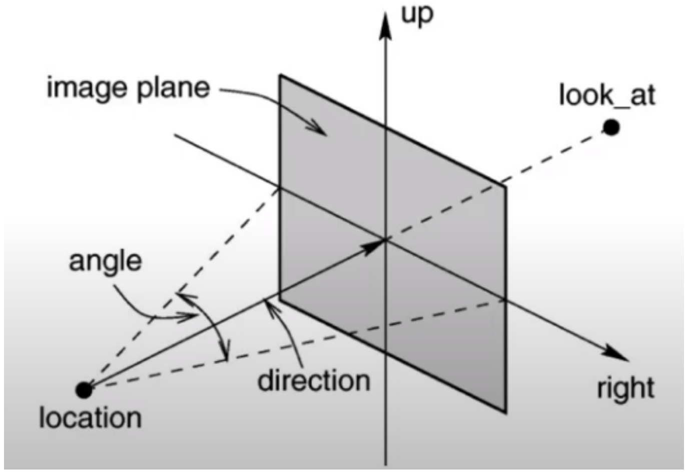
Camera in ray-tracing

- **Image centric approach**: generate ray for each pixel of virtual image plane
  - 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



Generating rays

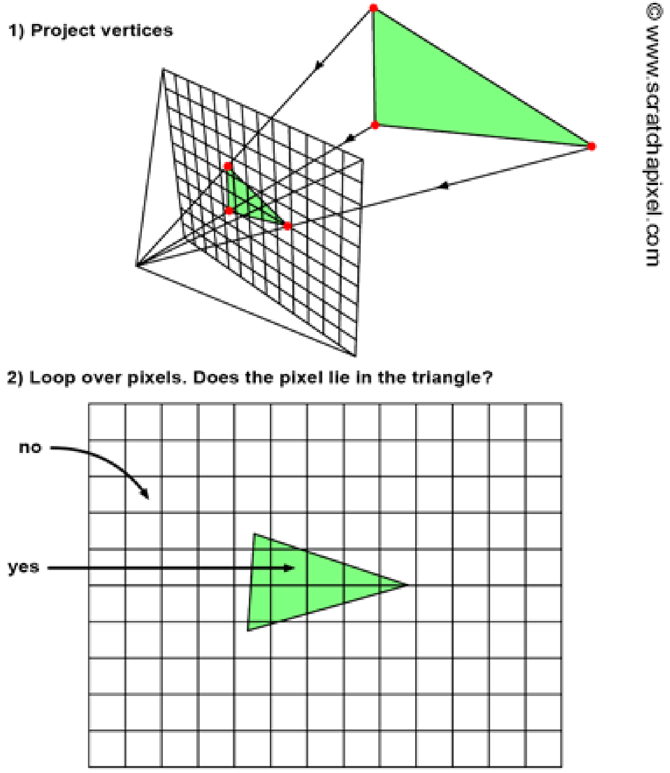
- Assume: image plane is `[−1,1]x[−1,1]`
- Rays `r(t)` can be generated if:
  - Image resolution r_x x r_y is given
  - Position of eye (aperture) `e` is given
  - Vectors `Forward, Right, Up` are given
  - Focal length `f` or angle of view α is given
  - Pixel position `(i,j)` is given




```
r(t) = e + t  * (f * Forward  + (i + 0.5) / r_x * Right + (j + 0.5) / r_y * Up)
```

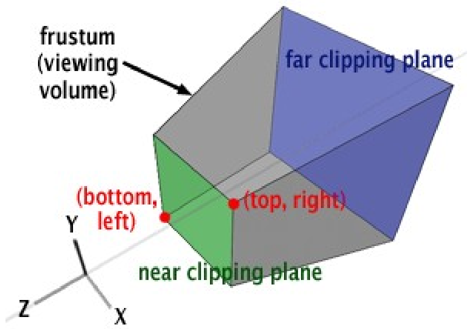
Camera in rasterization

- **Object-centric approach**: project object (triangle) points from 3D scene onto image plane and for each pixel find a position on projected object:
  - 3D points from world space are transformed to camera space: **world-to-camera matrix**
  - **Projection matrix** is applied on transformed point to project it onto image plane
  - Resulting points are convert to raster space (image plane with pixels)

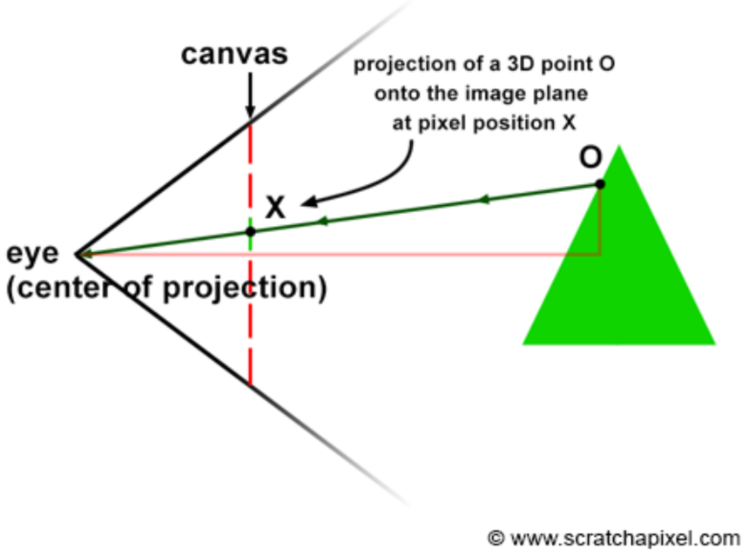


Projection matrix

- In rasterization, camera is used to define perspective projection matrix.
- General perspective projection matrix is defined with viewing frustum **near** (n), **far** (f), **left** (l), **right** (r), **top** (t) and **bottom** (b)



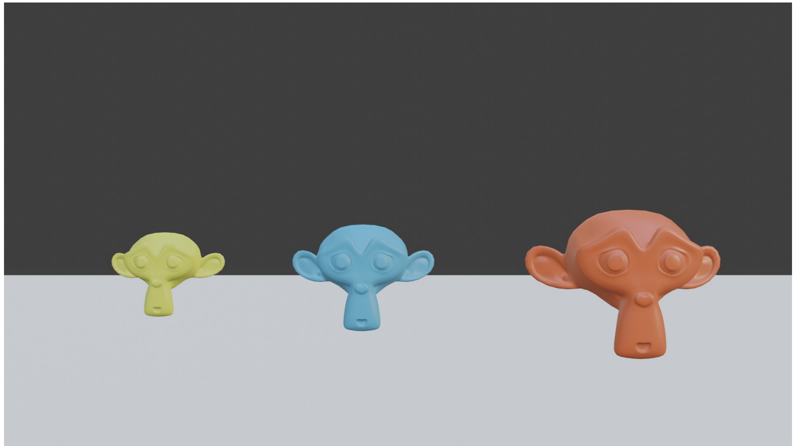
$$\begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

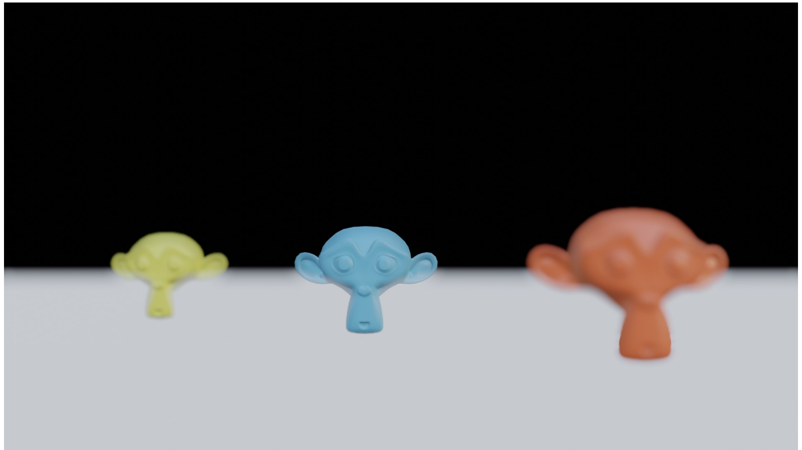


https://www.scratchapixel.com/lessons/3d-basic-rendering/perspective-and-orthographic-projection-matrix/opengl-perspective-projection-matrix.html

Virtual pinhole camera notes

- **Virtual pinhole camera has infinitesimally small aperture**
  - **Image will be perfectly sharp**
  - Additional methods are needed from **simulating lens effects such as depth of field**
  - Lens system introduce focus plane in 3D scene where objects are in sharp focus and blurred otherwise


Perfectly sharp image


Depth of field

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

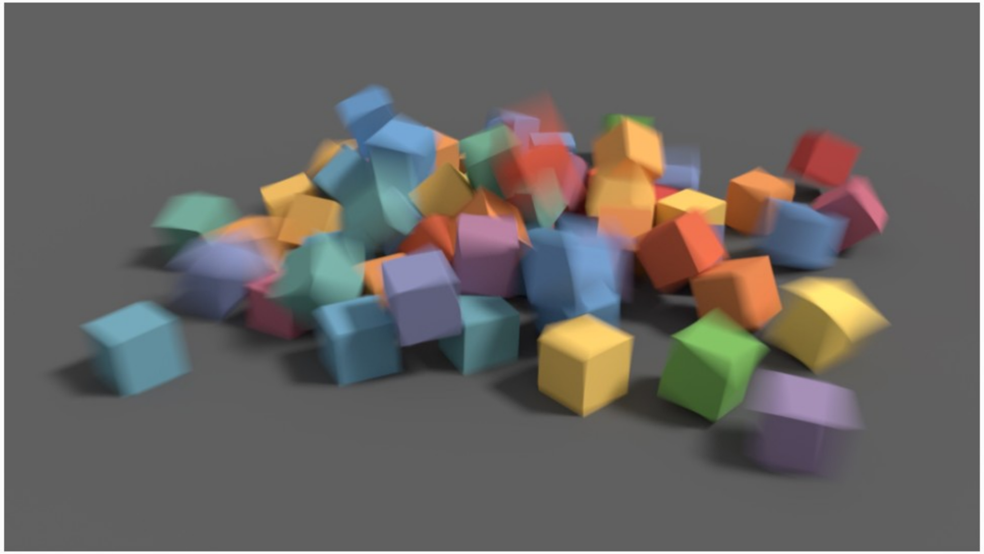
Virtual pinhole camera notes

- Virtual pinhole camera has infinitesimally small aperture → light energy is carried instantaneously by ray
- Time in image plane is exposed to light doesn’t affect amount of light falling on image plane
  - Exposure is simulated in already rendered image or adding it as parameter to lights

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

Virtual pinhole camera notes

- In simulated camera, light transport is considered instant, therefore, simulation of motion blur requires additional simulation
- Motion blur must be additionally simulated using **shutter speed:** time in which camera door is opened to allow incoming light



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

More into topic

- More about camera film, aspect ratio: https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera/how-pinhole-camera-works-part-2
- Simulating camera lenses:
  - https://www.pbr-book.org/3ed-2018/Camera_Models/Realistic_Cameras
  - https://github.com/appleseedhq/appleseed/pull/2914
  - https://developer.nvidia.com/gpugems/gpugems/part-iv-image-processing/chapter-23-depth-field-survey-techniques

Summary questions

- https://github.com/lorentzo/IntroductionToComputerGraphics/tree/main/lectures/9_light

Literature

- https://github.com/lorentzo/IntroductionToComputerGraphics
- ScrachAPixel lession: https://www.scratchapixel.com/lessons/3d-basic-rendering/3d-viewing-pinhole-camera