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# 16.485: VNAV - Visual Navigation for Autonomous Vehicles

## Lecture 11: Image Formation

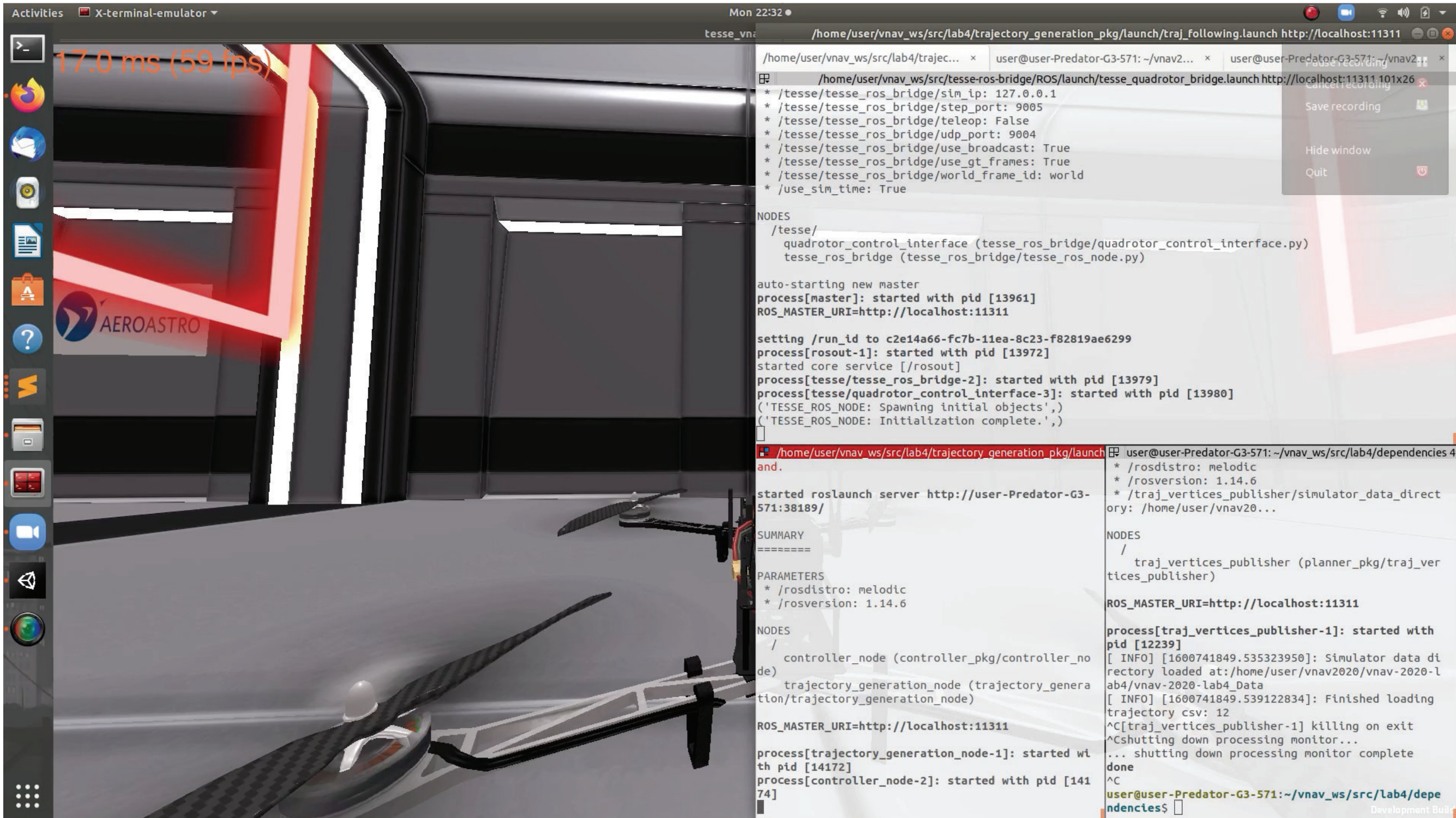
Luca Carlone

Part of the following slides are inspired by the lecture slides of Professor Frank Dellaert's course.





# What we learned so far



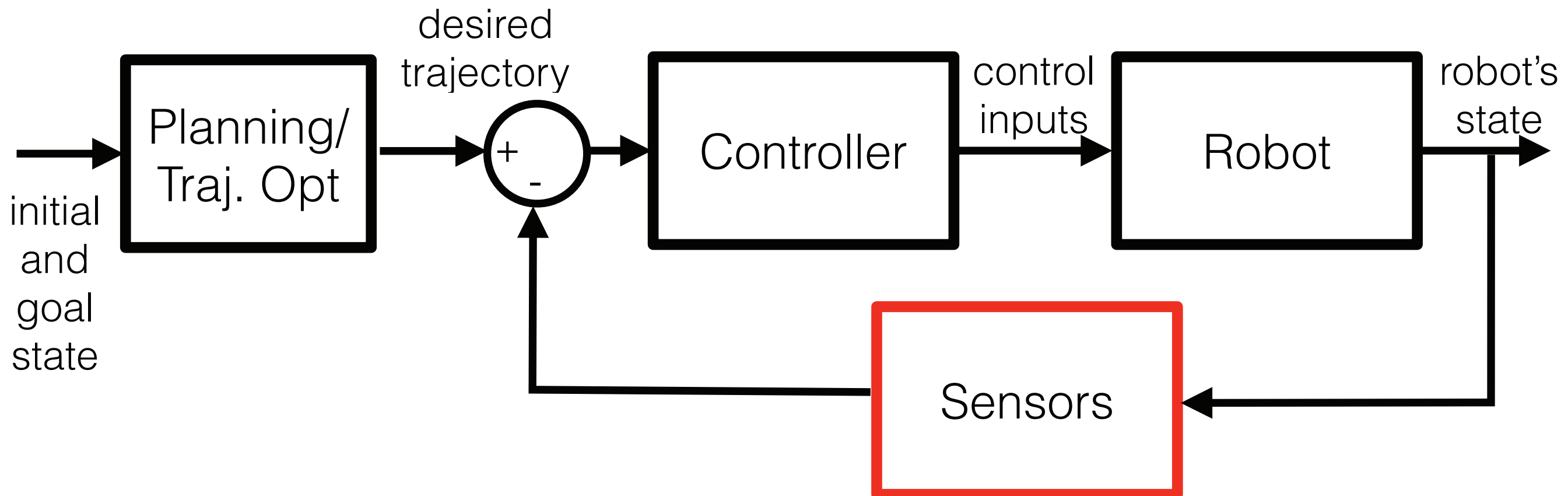
The screenshot displays a ROS simulation environment. On the left, a 3D view shows a drone in a dark, industrial-like setting with red and white structural elements. A performance overlay in the top-left corner of the 3D view indicates "17.0 ms (59 fps)". The "AEROASTRO" logo is visible on a wall panel. On the right, two terminal windows show ROS launch logs. The top terminal window displays the output of a launch file, including parameters like `sim_ip`, `step_port`, `teleop`, `udp_port`, `use_broadcast`, `use_gt_frames`, `world_frame_id`, and `use_sim_time`. It lists nodes `quadrotor_control_interface` and `tesse_ros_bridge`, and shows the master starting with PID 13961. The bottom terminal window shows the output of another launch file, including parameters like `rosdistro` (melodic) and `rosversion` (1.14.6). It lists nodes `traj_vertices_publisher` and `controller_node`, and shows the master starting with PID 12239. The logs also include information about simulator data directories and trajectory loading.

## Requires:

- state of the drone (localization)
- obstacles (mapping)

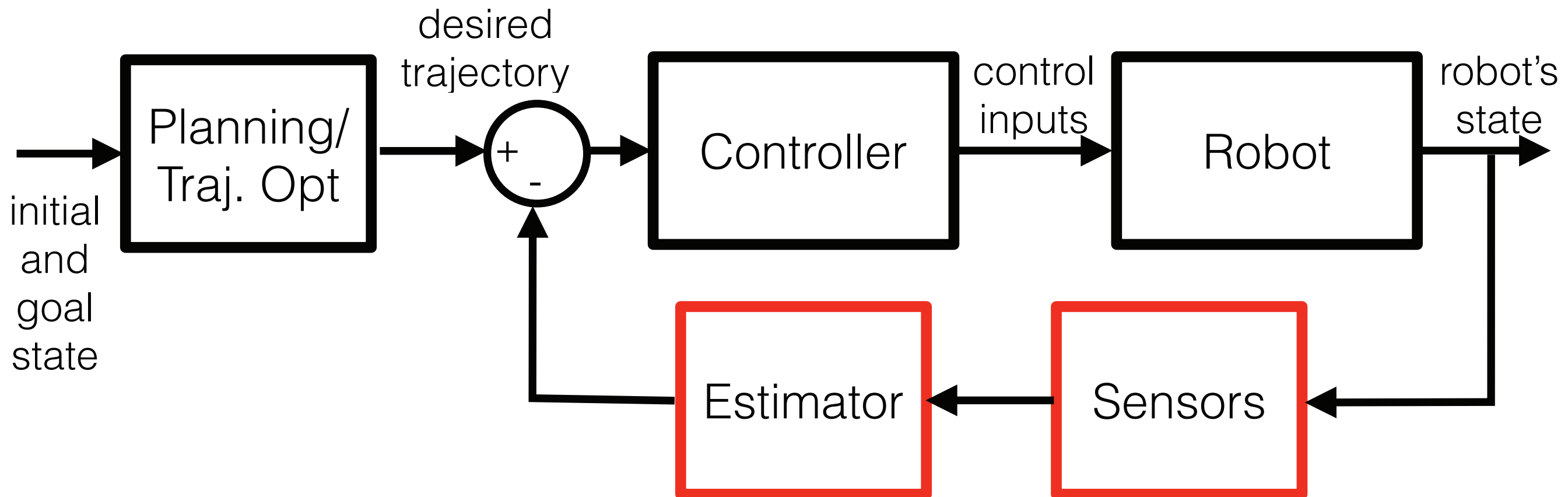
# What's next

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# What's next

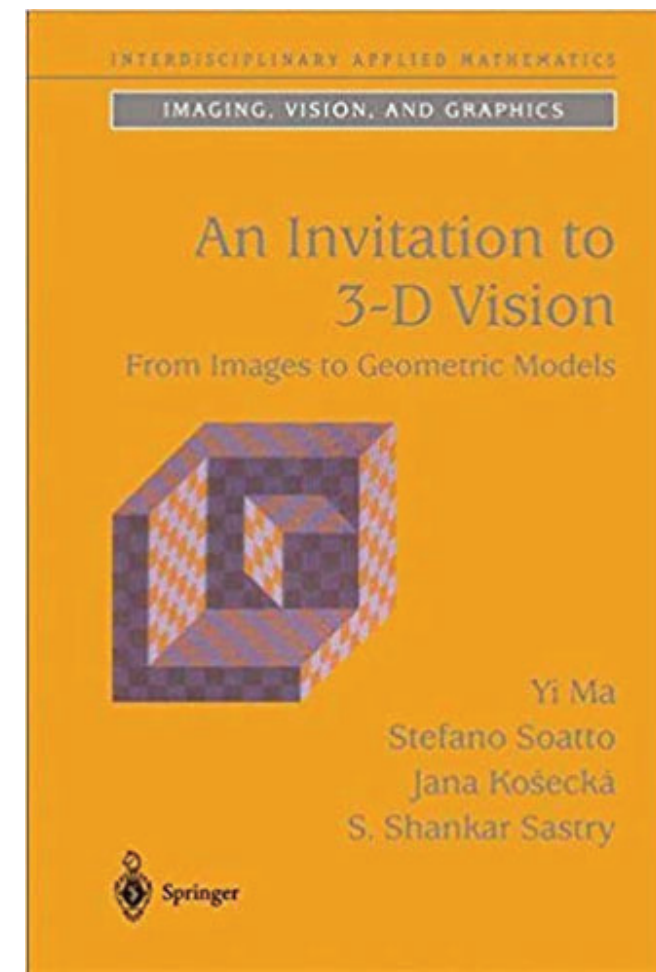
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# Today

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- Image Formation
- Pinhole Camera Model

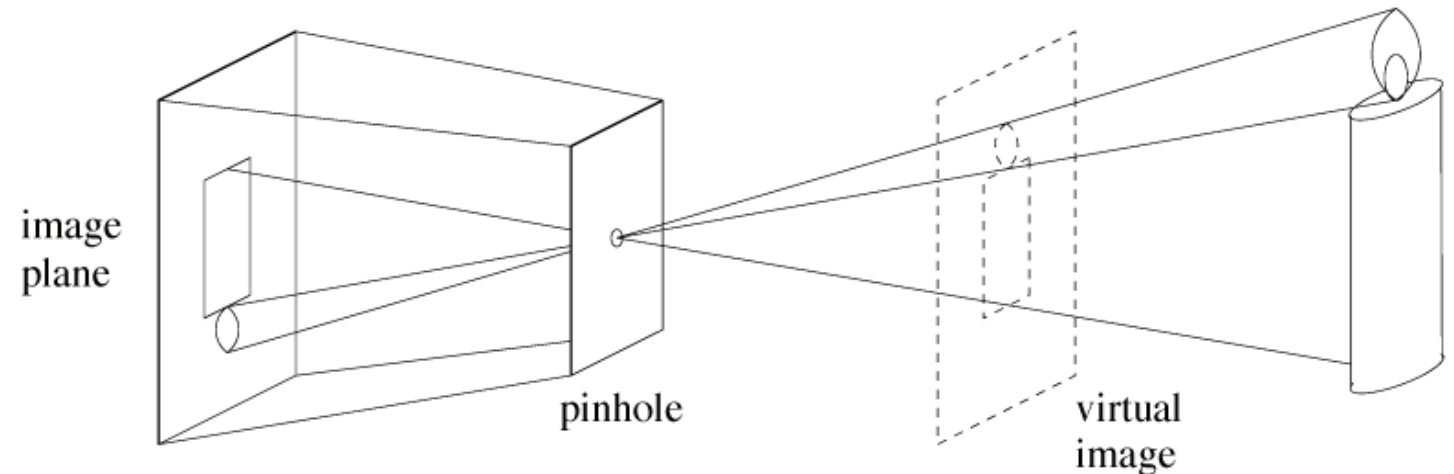


## Chapter 3 Image Formation



# Image Formation

- How to capture a 3D scene on a 2D image?
- **Camera obscura**  
(Latin: “dark room”):
  - optical device that projects 3D scene to a surface
  - box with a hole on one side
  - known for several centuries:
    - Mo Ti, Chinese philosopher (5<sup>th</sup> Century B.C.)
    - Leonardo da Vinci (1452-1519)



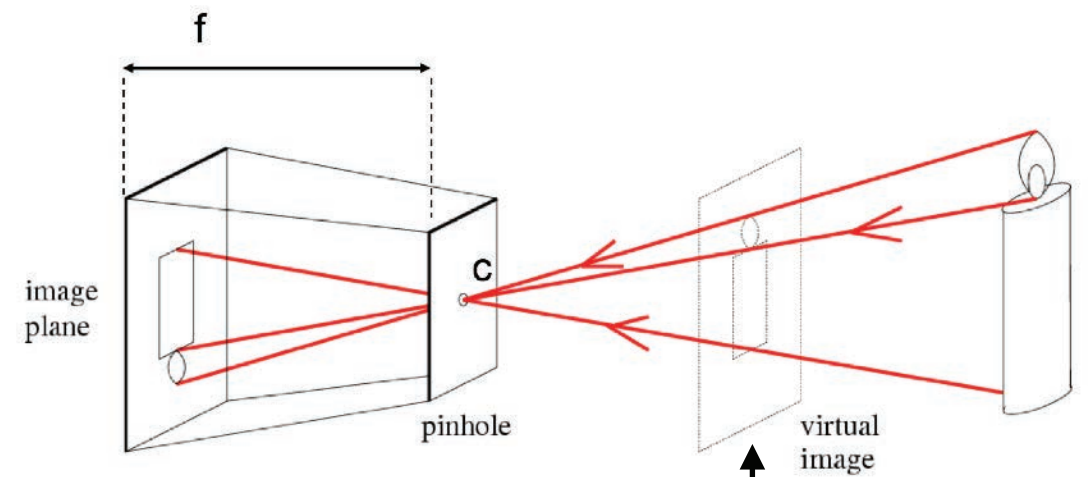
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Frisius (1544)

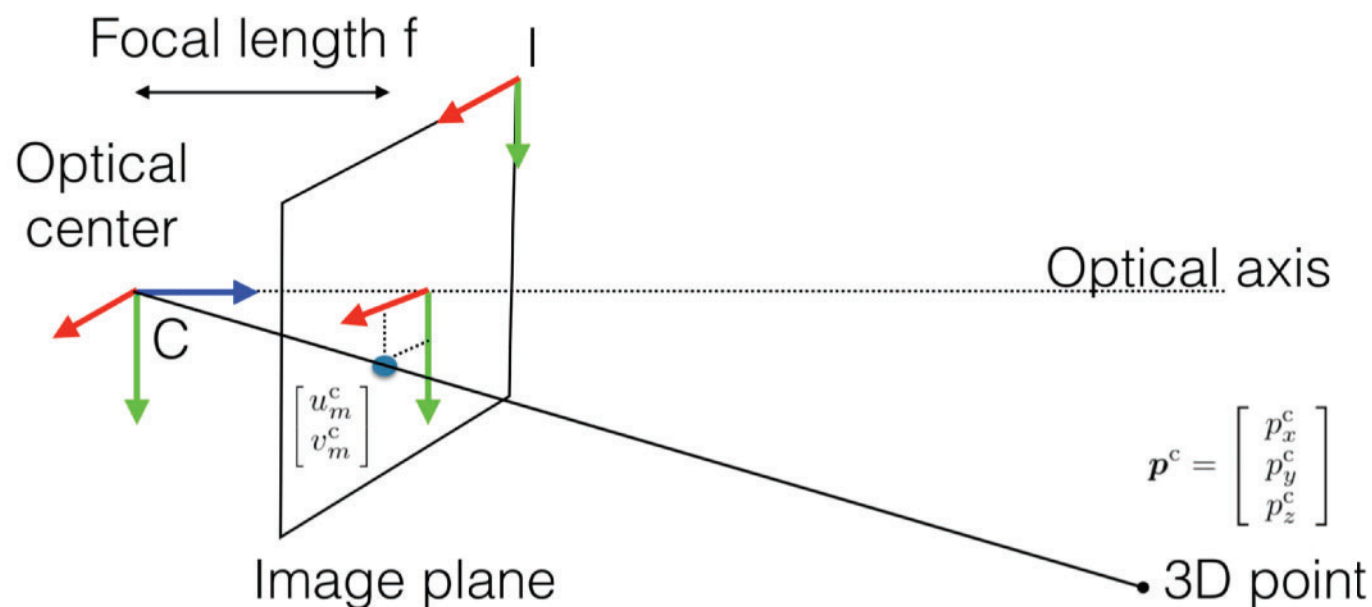
# Geometry: Pinhole Camera Model

- How to compute the 2D projection (pixel) of a given 3D point?



$f$  = focal length  
 $c$  = center of the camera

Frontal  
pinhole  
model



$$\mathbf{p}^c = \begin{bmatrix} p_x^c \\ p_y^c \\ p_z^c \end{bmatrix}$$

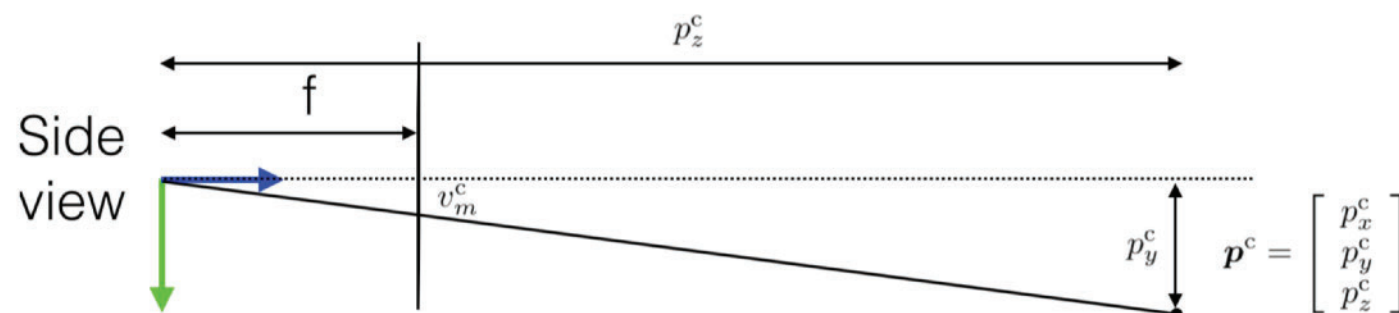
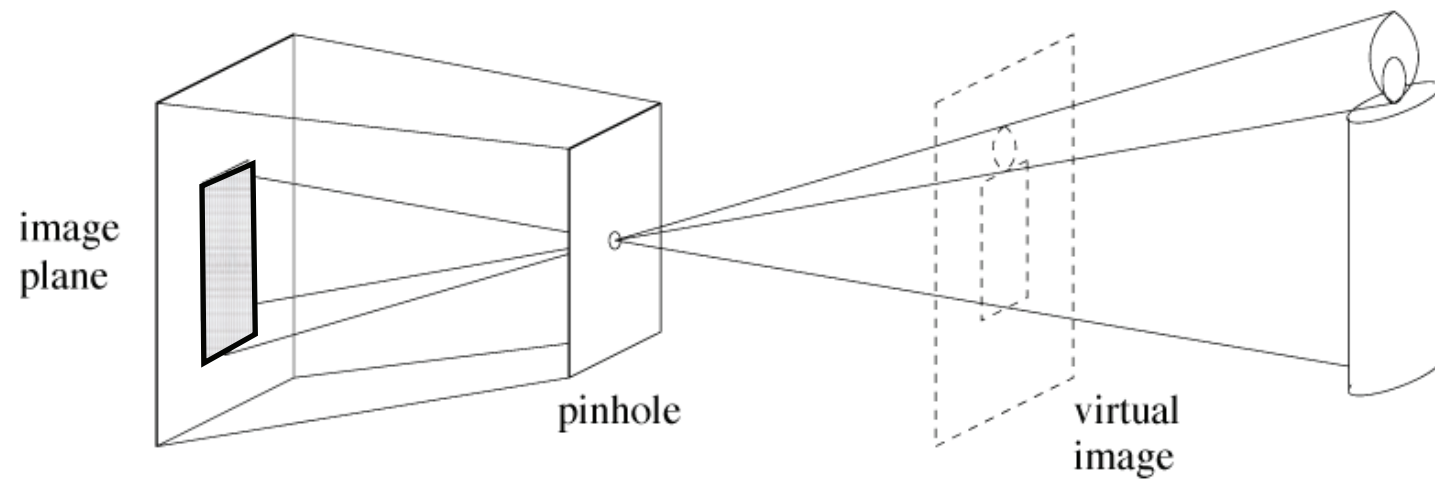


Figure 11.1: Pinhole Model.

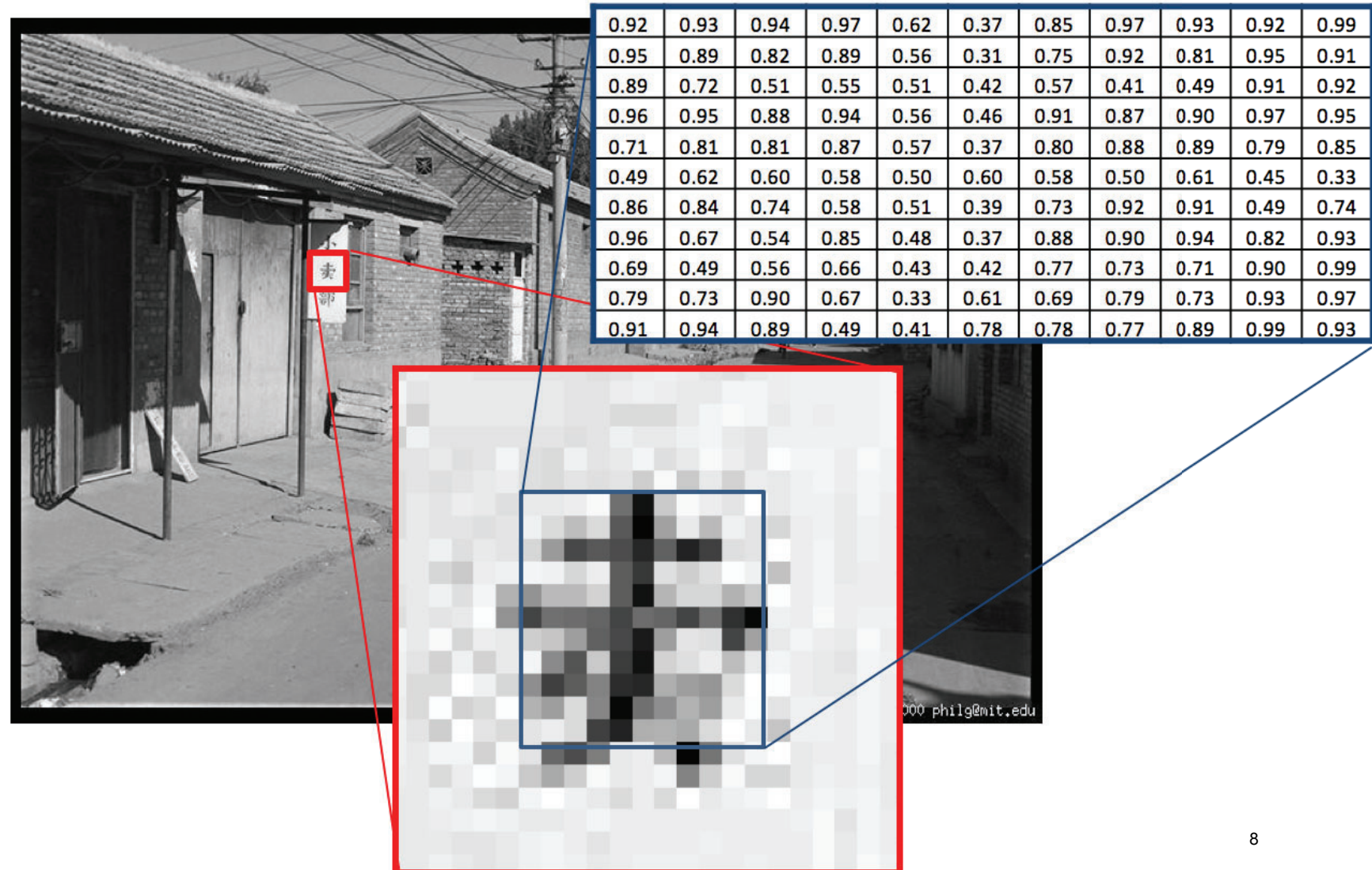
Let's do  
some math

# Digital Photography



2D array of  
“light sensors”

- CCD (charge-coupled device, 1960)
- CMOS (complementary metal-oxide semiconductor, 1963)





# Appearance: Light and Colors



**R**  
(G=0,B=0)

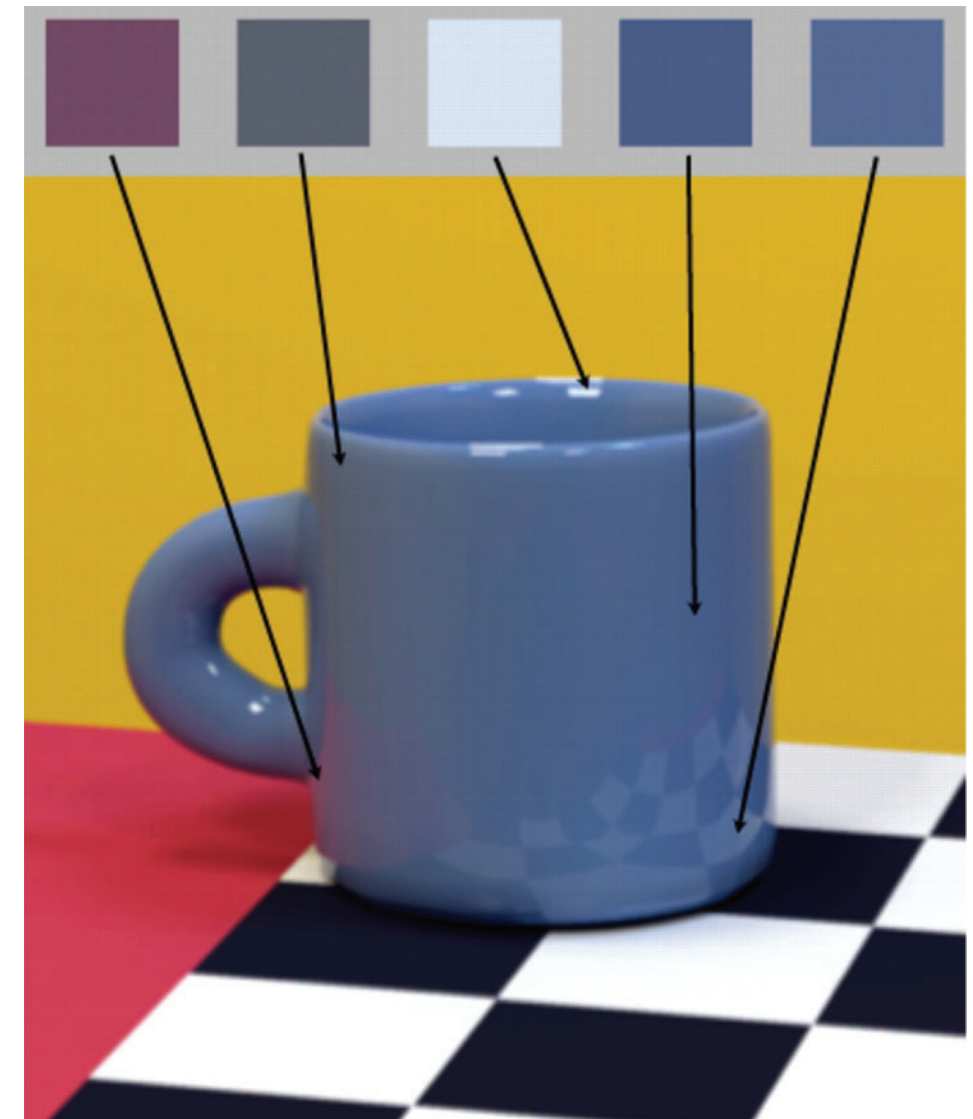
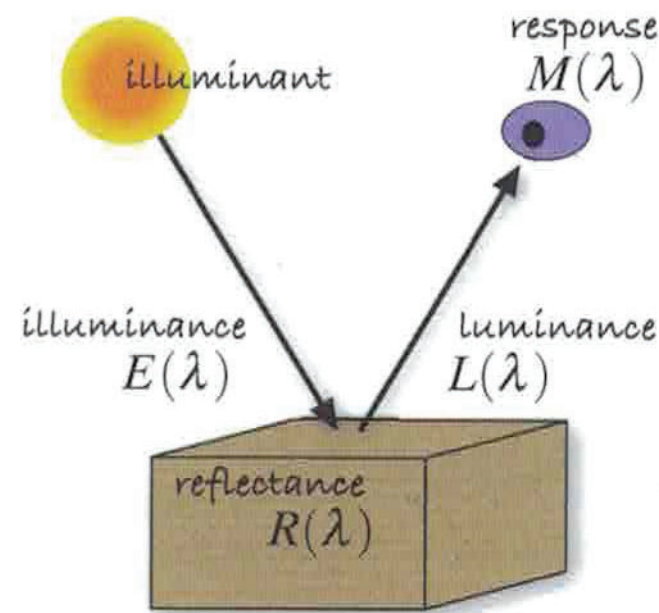


**G**  
(R=0,B=0)



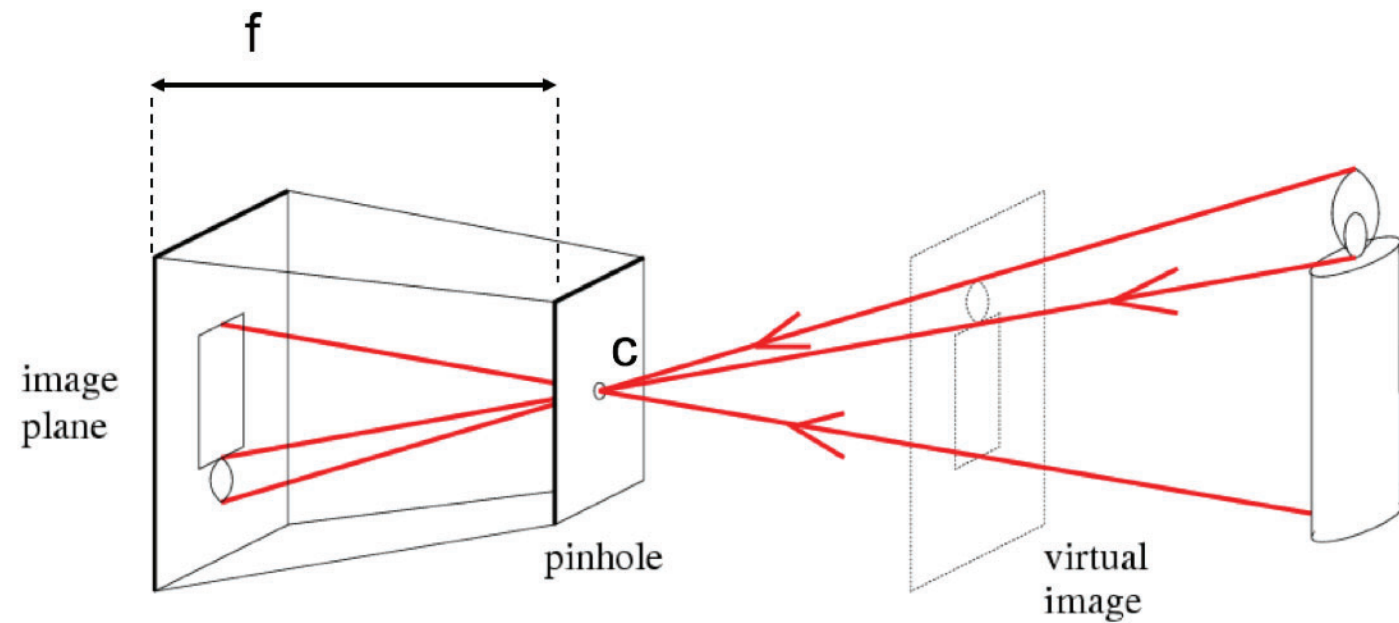
**B**  
(R=0,G=0)

Perceived appearance is the result of (i) geometry, (ii) illumination, (iii) material properties

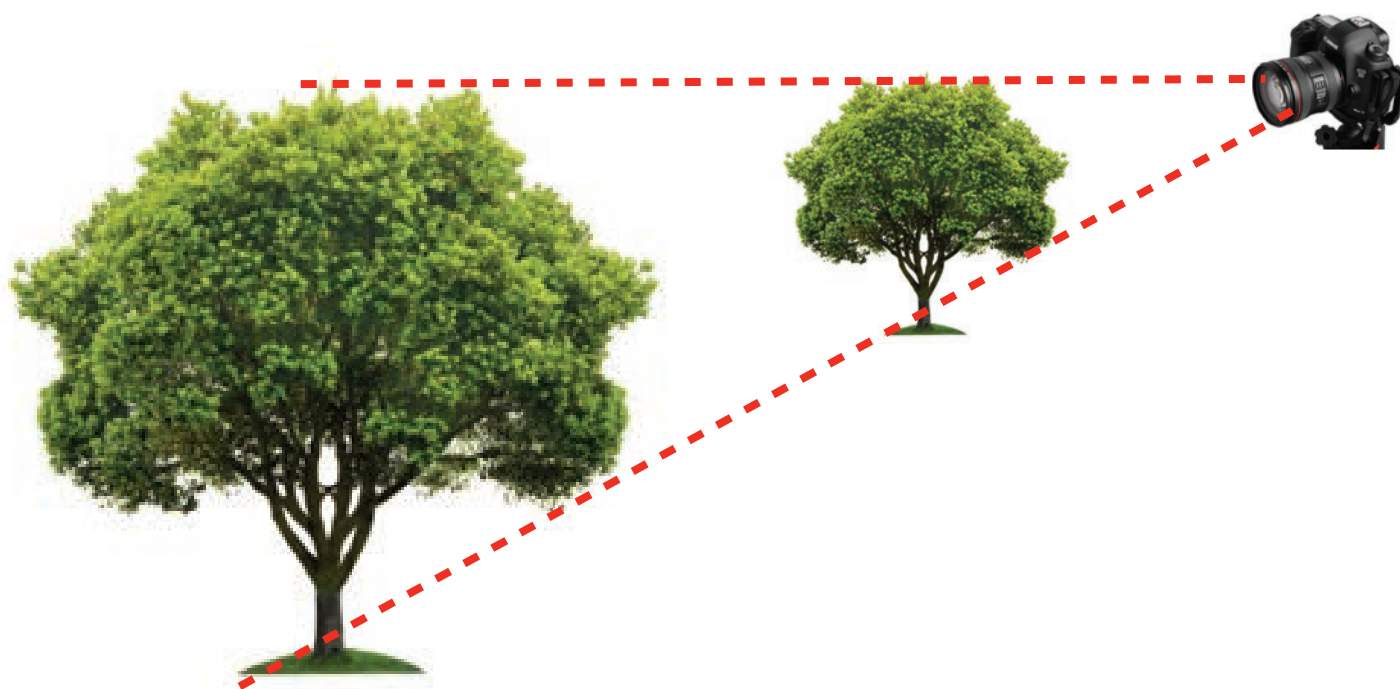


# Perspective Projection

- what is lost?
  - depth?



$f$  = focal length  
 $c$  = center of the camera

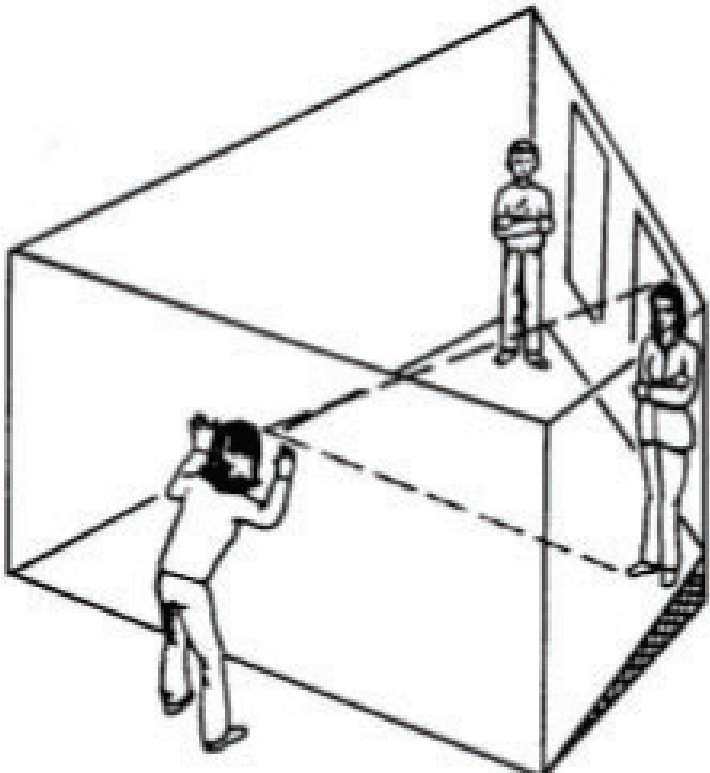
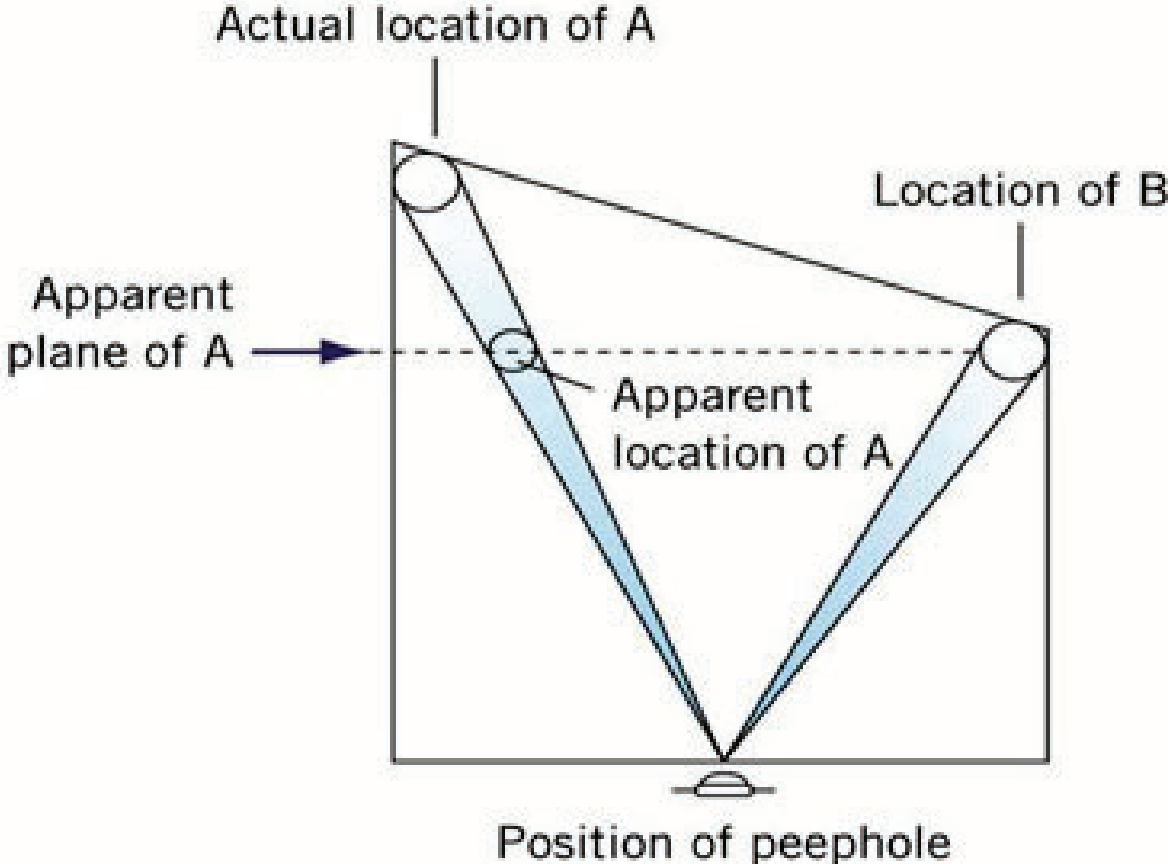




# Ames Room



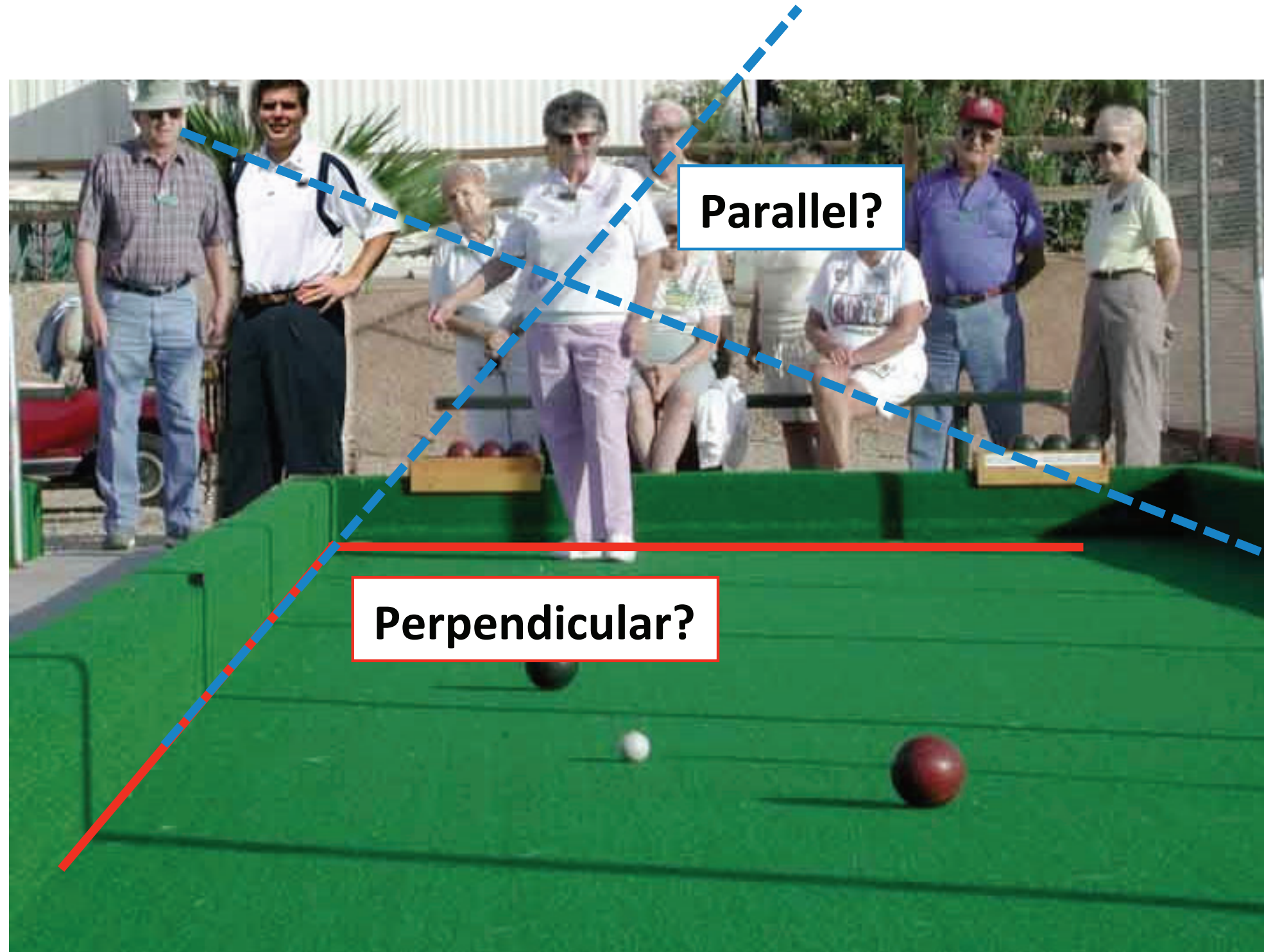
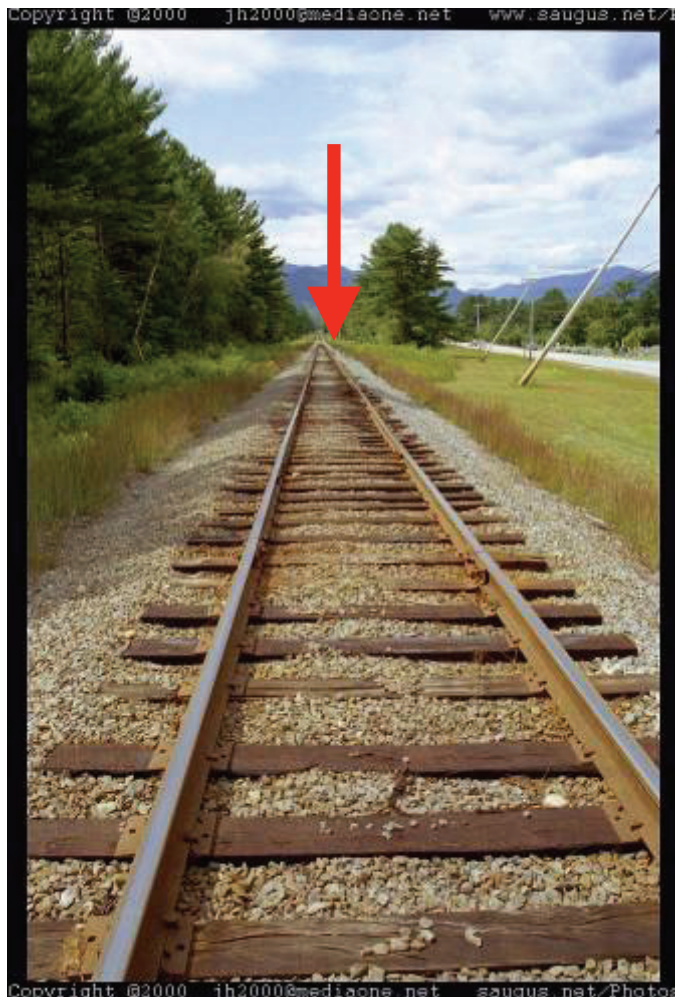
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# Perspective Projection

- what is lost?
  - depth?
  - length?
  - angles?



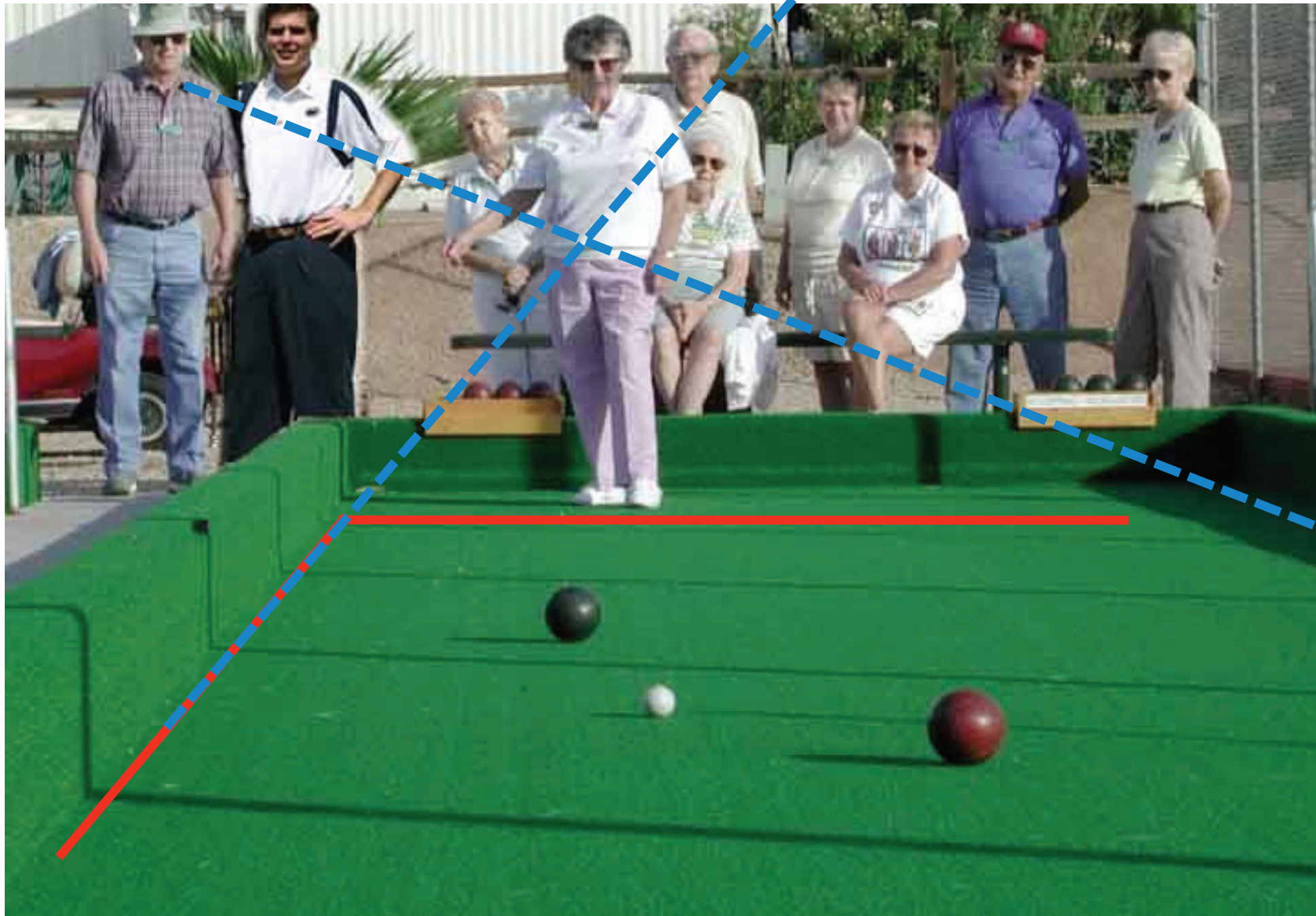
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Parallel lines which intersect ...



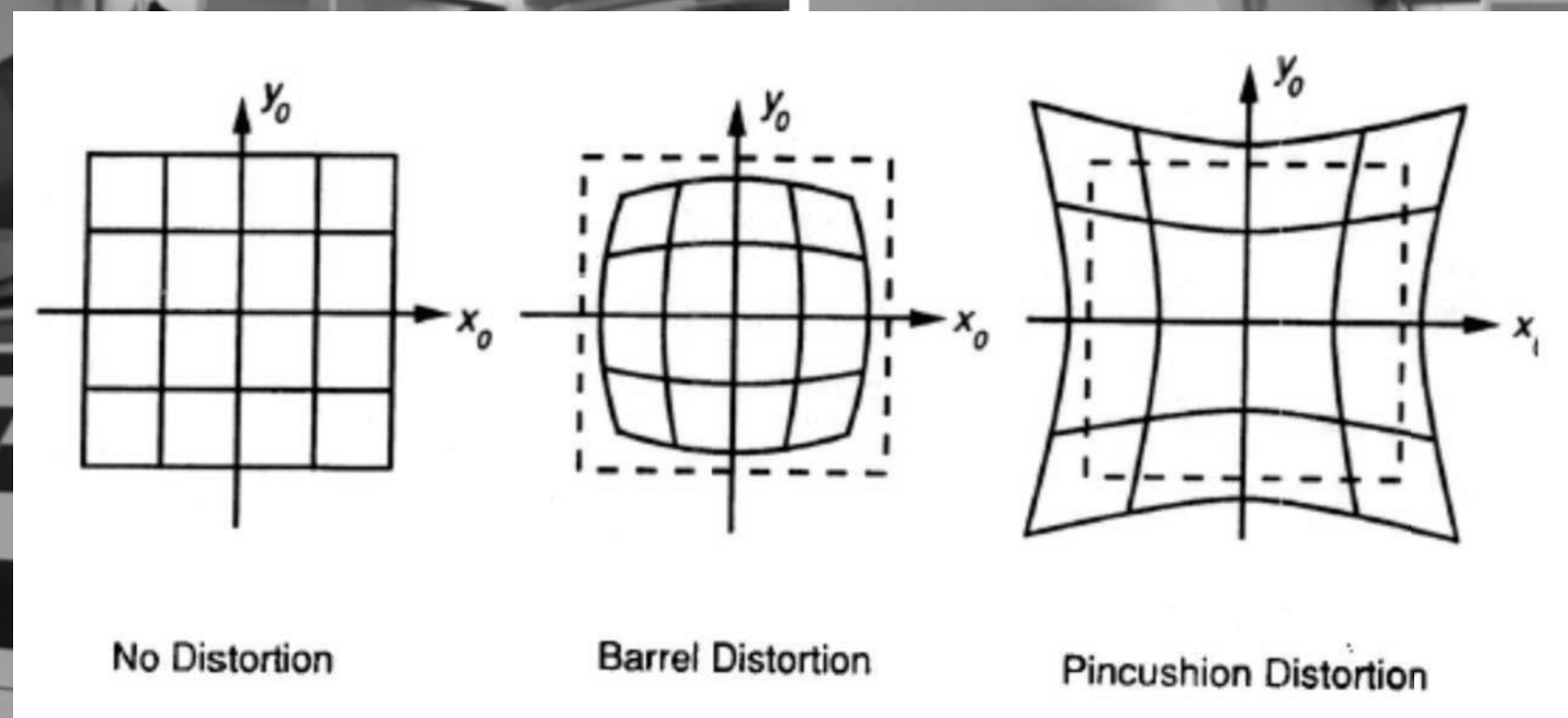
# Perspective Projection

- what is preserved?
  - straight lines remain straight



# The final Touch: Adding a Lens

- Pinhole model is based on the geometry of the **camera obscura**
- In practice: add a **lens** in front of the aperture to capture more light
- Pinhole model holds, but **distortion** may appear due lens imperfections



- distortion can be described mathematically using **distortion parameters**
  - can be estimated during calibration and compensated for (**undistortion**)



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16.485 Visual Navigation for Autonomous Vehicles (VNAV)  
Fall 2020

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