Physics 116
Lecture 20
Optical Instruments
Nov 1, 2011

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# Lecture Schedule
*(up to exam 2)*

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*Today*
Announcements

• Physics Study Center now staffed by TAs an hour later on M-W: 9:30 am to 6:30 pm M-W, 9:30am-5:30pm Th, 10:30am-5:30pm F.
• Exam 2 next Monday: same procedures as last time
  • Practice exam posted Thursday, in class Friday
  • YOU bring bubble sheet, pencil, calculator
Optical instruments

• We can put together systems of lenses, mirrors, prisms, polarizers, filters, beam splitters, and all the other optical components we have discussed, to make a variety of common optical instruments, using ray-tracing methods:
  – Magnifiers
  – Microscopes
  – Refracting telescopes
  – Reflecting telescopes
  – Cameras
  – Projectors
Telescopes

- Telescopes do 2 things:
  - collect a lot of light across a big aperture (opening) and cram this light into your eye
    - Lets you see faint objects
  - magnify angles by ratio of the focal lengths of the main lens/mirror and eyepiece: Magnification = $F/f$
    - So object looks bigger to you

- Simple operation
  - Objective lens forms real image of object inside telescope tube
  - Eye lens is used as magnifier to view real image made by objective

- Come in two basic varieties:
  - refractors, dating back to Galileo’s time (objective = lens)
    - Galilean telescope: negative eyelens
  - Reflectors (mirror), invented by Newton!
  - all big telescopes now are reflectors
    - Only one surface to grind and polish
    - Easier to make in large sizes
Telescopes

- Refracting telescopes come in 2 basic varieties
  - Inverting (astronomical)
    - Objective and eyepiece are both positive lenses
    - Image is inverted and viewed at infinity
      - That means: parallel rays come out as parallel rays, the magnification is angular, not linear

[Diagram of Inverting Telescope]

- Galilean / non-inverting / “opera glass”
  - Objective is positive and eyepiece is negative
  - Image is erect and viewed at infinity

[Diagram of Galilean Telescope]

- In both cases, the objective makes a real image at the eyepiece focal point
Telescopes

Gran Telescopio Canarias, 410” reflector, Canary Islands (2009)

Yerkes refractor, 40”, Wisconsin (1897)

Angular vs linear magnification

- Linear magnification is \( m = \frac{-d_i}{d_o} \)

- Angular magnification is \( M = \frac{\theta'}{\theta} \)

- Telescopic systems, designed for viewing objects at \( d_o = \text{infinity} \), take parallel rays in and send parallel rays out – what counts is the angular magnification since no real image is formed.

Angular size of Sun = \( \frac{1}{2} \) degree of arc = angular size of Moon (this coincidence makes total solar eclipses possible!)
How does a *microscope* work?

- Very similar to telescope, but now we want to make an image of a *nearby* object: again, objective lens forms a *real* image inside instrument tube.

- Your eye is part of the optical system!

- Eye lens acts like a *simple magnifier* to give viewer an enlarged *virtual* image of the *real* image produced by the objective lens.

- If you want to *photograph* the object, put film or video chip at the real image location, or use camera lens after eyepiece.
Cameras and projectors

- Cameras and projectors work the same way: transfer an image from one place to another
  - Projector works in reverse: translates “film” plane to screen
  - Pinhole works as well as a lens (but very little light gets through)
  - Must place object far from lens (farther than focal length f)
  - Complex systems needed to give accurate, sharp image over full image area
Projector or camera

• Basically just a positive lens forming a real image on the screen or camera chip
• Complex lens systems allow ‘zooming’ (vary focal length while keeping image plane fixed), and ensure a sharp and faithful image over the whole active area of the screen or chip
  – Ray 1 is parallel to axis – passes through back focal point f'
  – Ray 2 goes through center of lens and is undeviated
  – Ray 3 goes through front focal point f and emerges parallel to the optic axis
Summary of lens behavior: positive-f lenses

Object distance \(d_o\) greater than \(f\)
Example: camera, or projector

Rays from object tip re-converge at a point, forming a \textit{real}, inverted, \textit{magnified} image

\(d_i\) is positive

Object distance \(d_o\) less than \(f\)
Example: Magnifying glass

Rays appear to emerge from a \textit{virtual}, erect, \textit{magnified} image, lens equation gives \textit{negative} \(d_i\)
Summary of lens behavior: negative-f lenses

Object distance \( d_o \) greater than f
Example: eyeglasses for myopia

Gazing through the lens toward the object, we see rays appearing to emerge from a virtual, erect, demagnified image that is closer than the object, lens equation gives negative \( d_i \)

Object distance \( d_o \) less than f
Very little difference – image just moves a bit closer to the lens
**Lens aberrations**

- Perfection is impossible!
- Any real lens will not focus all rays reaching its surface onto the same focal point
- Lens Aberrations:
  - Color – different focal points for different wavelengths
  - Spherical aberration – rays arriving at different distances from the lens axis have different focal points
  - Coma, astigmatism, curvature of field ... many more

- quantitative material on aberrations is “cultural” - not on test!
  - You should understand qualitative descriptions of aberrations
Chromatic aberration (CA)

- Simple lenses make images with ‘rainbows’ around objects in white light
- Focal length of lens is different for red, yellow, and blue

Index of refraction $n = n(l)$
- For most materials, $n$ decreases with increasing $l$
  - so $n_{\text{BLUE}} > n_{\text{YELLOW}} > n_{\text{RED}}$
  - we get different focal points for different colors:

Typical optical glass $n$ vs $l$ curve:

CA is positive for converging lenses, and negative for diverging.
We can make a doublet with CA=0 by gluing a negative and positive lens of different $n$ together
Spherical aberration (SA)

- "Paraxial" ray = ray arriving at lens very close to its optic axis
  - Paraxial ray crosses axis at *paraxial focus* PF (the ordinary "focal point")
- **Marginal ray** = ray arriving at lens far from its optic axis
  - Marginal rays parallel to axis cross the axis at *marginal focus* MF

The difference is called **spherical aberration**:
- Any refracting surface with spherical shape will have SA

- Envelope of ray paths is the **Caustic Surface**
  - Neck of caustic = **Circle of Least Confusion**
  
  position at which image of a distant pinhole is smallest
Astigmatic aberration

• What’s astigmatism?
  – Astigmatism is an aberration where light rays striking the lens at points away from the axis have different focal points, depending upon the position of the arrival point.
  – For example, vertical and horizontal spokes of a wheel get focused at different distances.
  – Irregular curvature of cornea makes the eye lens astigmatic
  – Corrective lenses for astigmatism have a cylindrical (instead of spherical) profile

If only vertical, or only horizontal spokes appear sharp, you may have astigmatism