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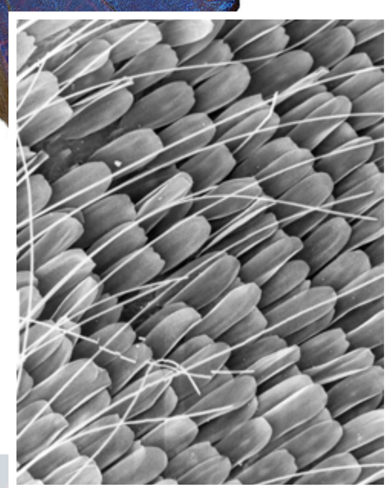
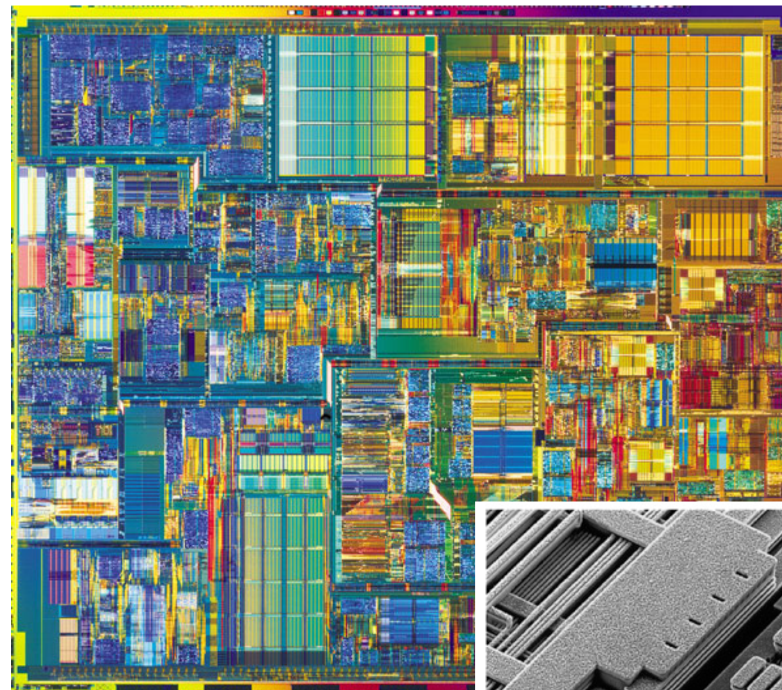
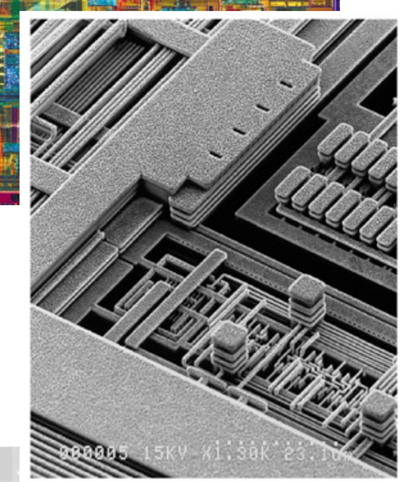
# 4 – Diffraction







- What is each photo?
  What is similar for each?

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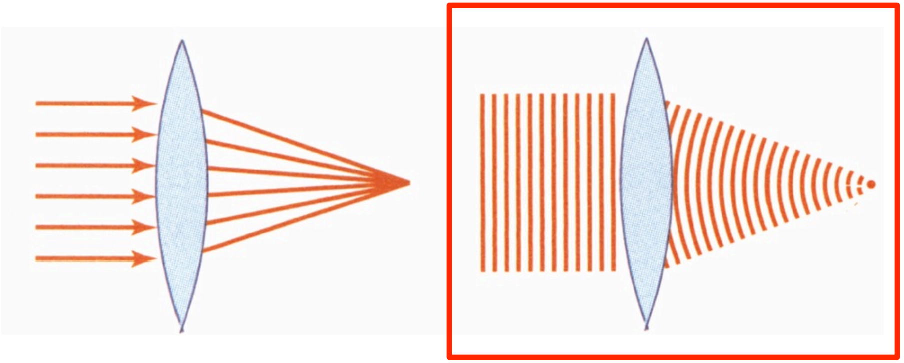
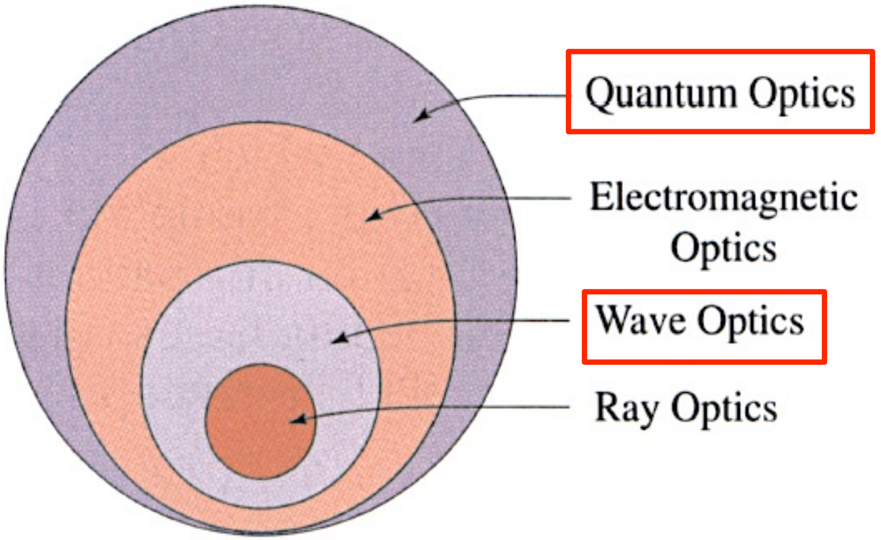
- Today, we will mainly use wave optics to understand diffraction…
- The Photonics book relies on Fourier optics to explain this, which is too advanced for this course.



*Credit: Fund. Photonics – Fig. 2.3-1*




*Credit: Fund. Photonics – Fig. 1.0-1*

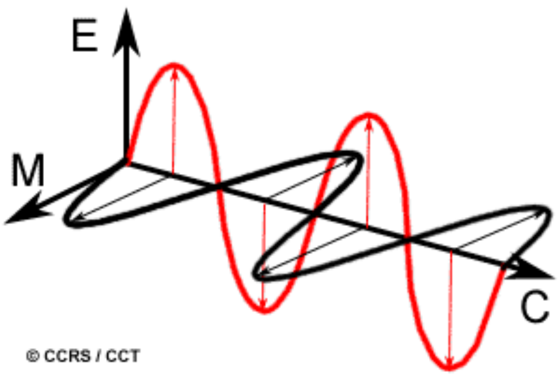
- Topics:

(1) Hygens-Fresnel principle
(2) Single and double slit diffraction
(3) Diffraction ('holographic') cards

- This lecture has several nice animations that can be viewed in the powerpoint version (slide show format).

*Figures today are mainly from CH1 of Fund. of Photonics or wiki.*

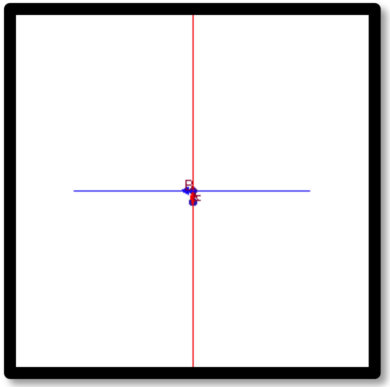
- You could freeze a photon in time (image below) and observe sinusoidal with respect to distance (kx).

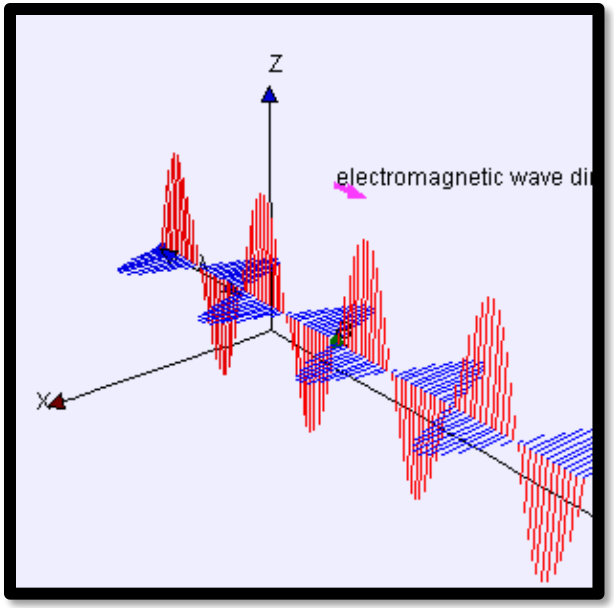



$$E = E_{max}\sin(wt - kx)$$
$$B = B_{max}\sin(wt - kx)$$

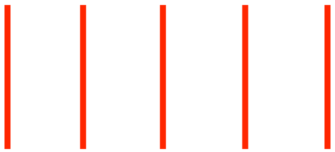
$$w = angular\ \ freq.\ \ (2\pi f, radians / s)$$
$$k = angular\ wave\ number\ (2\pi / \lambda, radians / m)$$

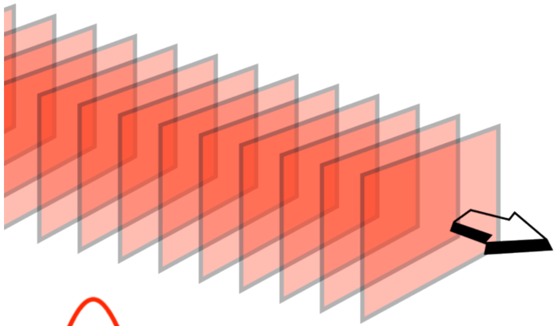
- You could also freeze your position and observe sinusoidal with respect to time (wt).

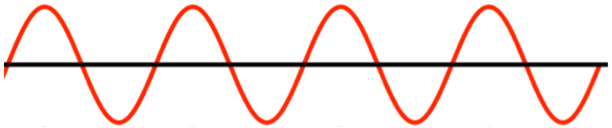





- Lastly, we can just track E, and just show peak as plane waves:







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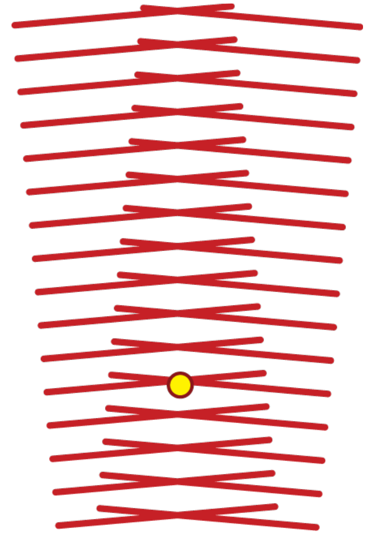
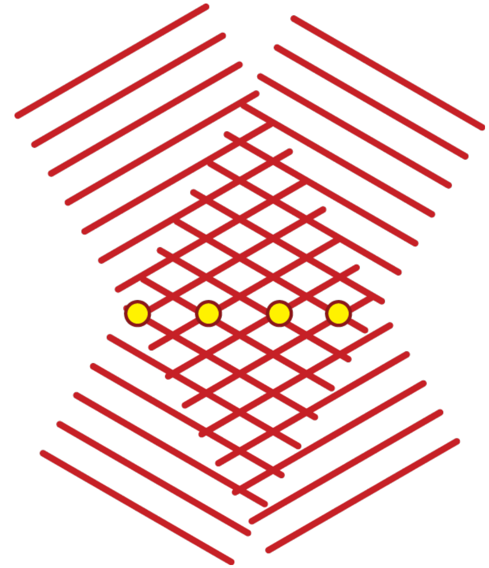
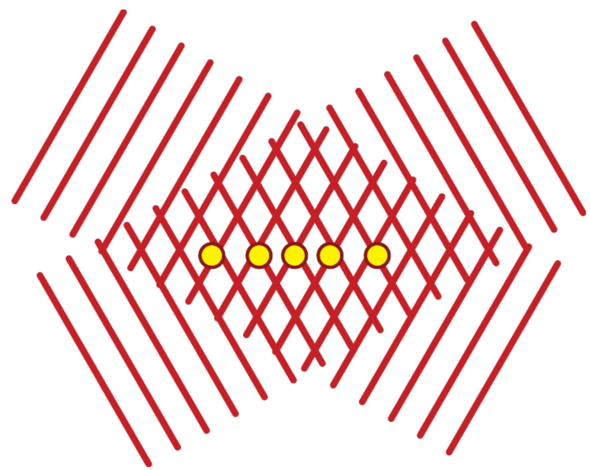
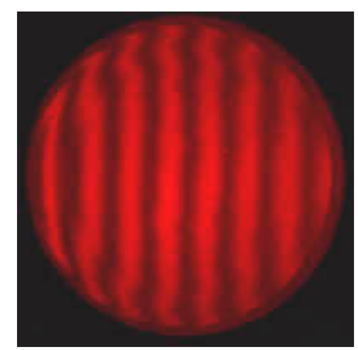
- Split a laser beam (coherent / plane waves) and bringing the beams back together to produce interference fringes… we will do that today also, but with an added effect of diffraction…

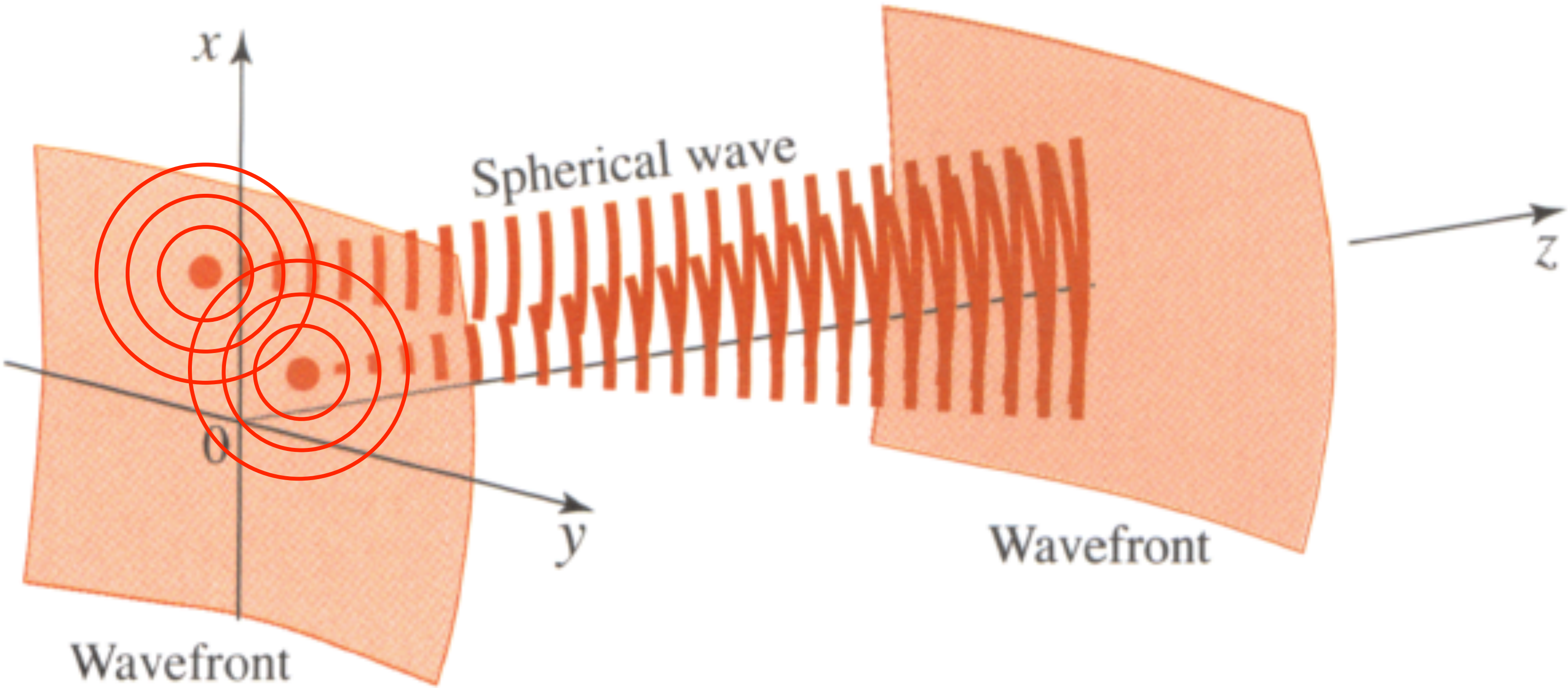









- The Huygens-Fresnel principle can be visualized as in Fig. 4.1-13 from Fundamentals of Photonics (see below). ***Each point on the wavefront generates a new spherical wavefront, and the superposition of these produces a wave in another plane…***




Great definition from wiki: Huygens' principle can be seen as a consequence of the isotropy of space - all directions in space are equal. Any disturbance created in a region of isotropic space (or medium) propagates from that region in all radial directions. The waves created by this disturbance, in turn, create disturbances in other regions, and so on. <u>The superposition (*interference*) of all the waves results in the observed pattern of wave propagation.</u> … *Lets apply this to propagation, refraction, and reflection!*

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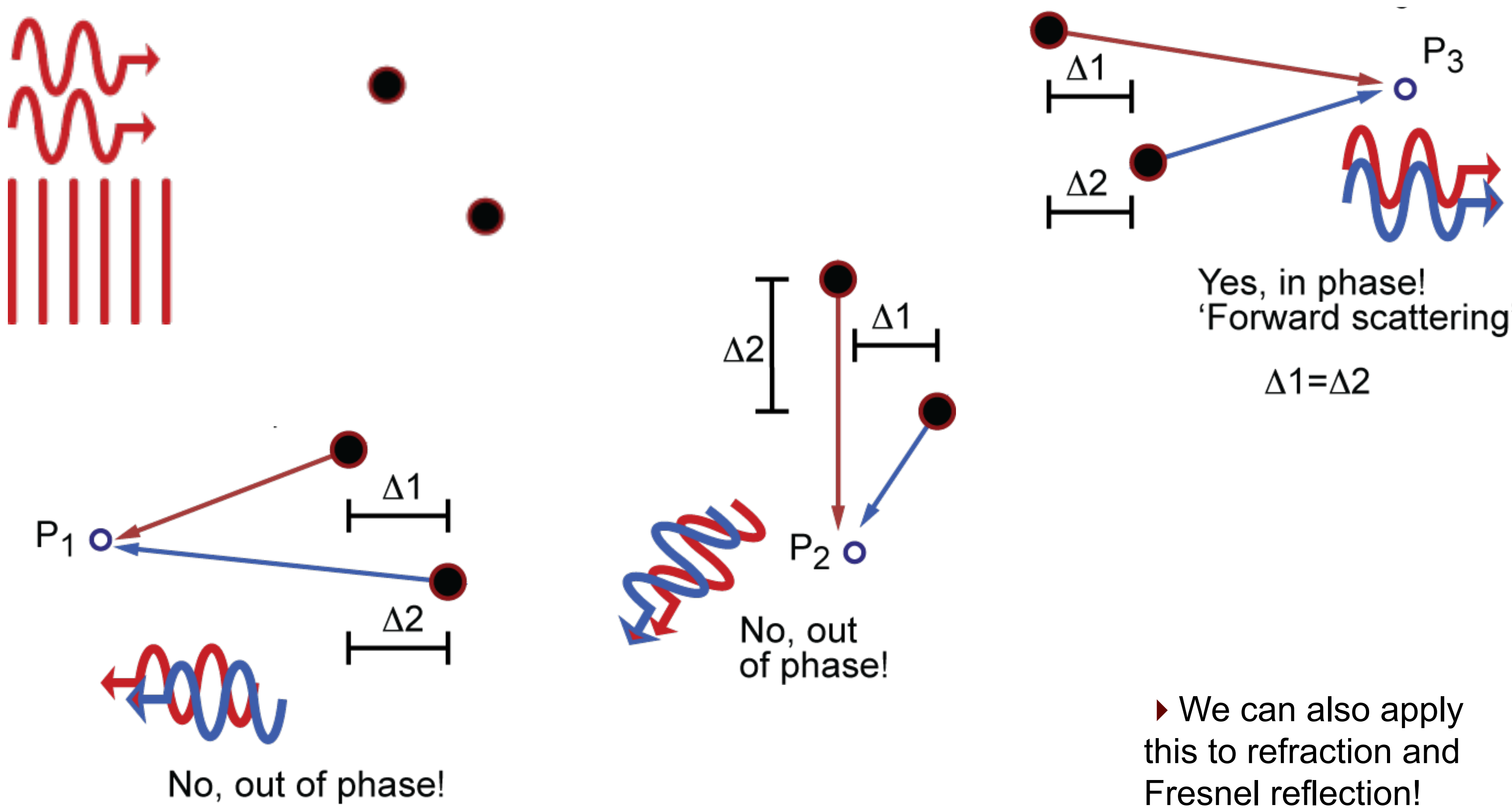
- Consider two photons forming a wavefront, and two points in space…
 …if each point on the wave front generates a new spherical wave front (radiating in all directions) then how does the light keep moving forward?

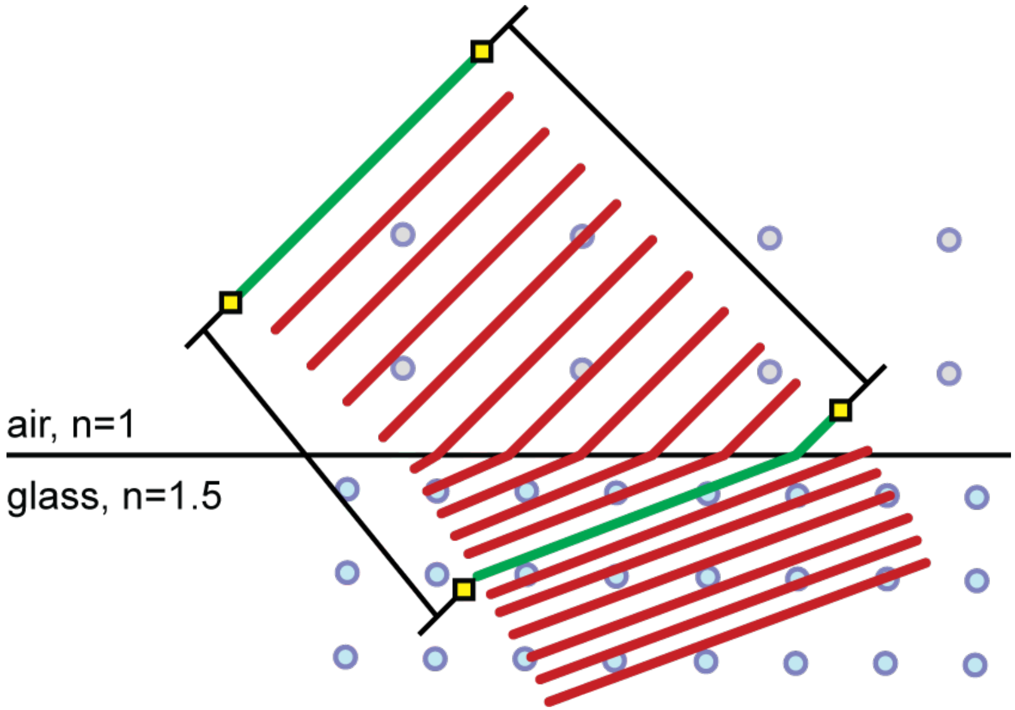


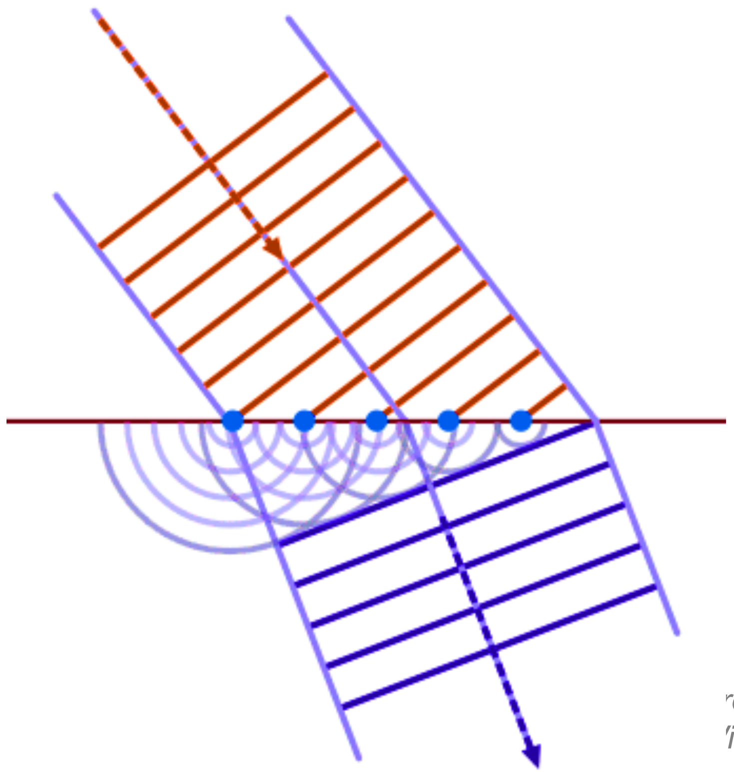

- We can also apply this to refraction and Fresnel reflection!

- Lets look at refraction using the Huygens–Fresnel principle:

  - each point of an advancing wavefront is the source of a new train of waves…

  - look at where the wave-fronts overlap… constructive interference therefore the light must go in the direction where it constructively interferes (not where destructively interferes)



redit:
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- What about Fresnel reflection? Any ideas?

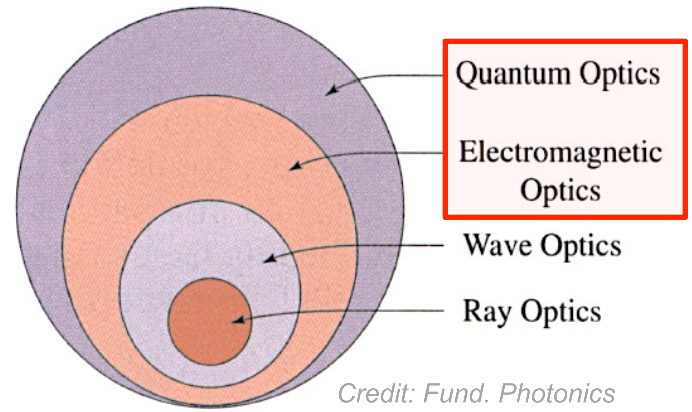
- Fresnel reflection requires quantum/electromagetic understanding beyond the focus of this course. You can solve all optics this way! But is more complex…

- Remember, as light enters glass the electric field oscillates valence electrons (orbits), these oscillations act as a new dipole radiator which emits light in all directions (just like predicted by Hyugens-Fresnel principle)…

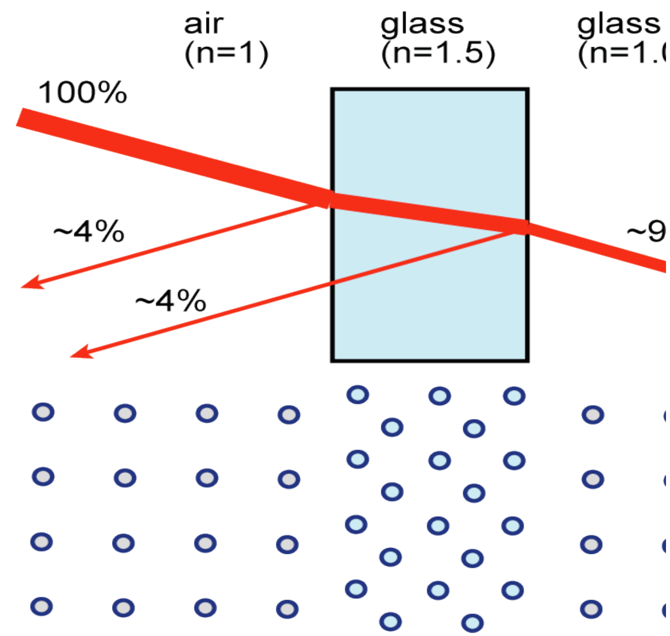
- However, if the density and types of atoms is different in the glass, v.s. just outside the glass, then the net interference supporting forward propagation is disturbed… some is reflected!

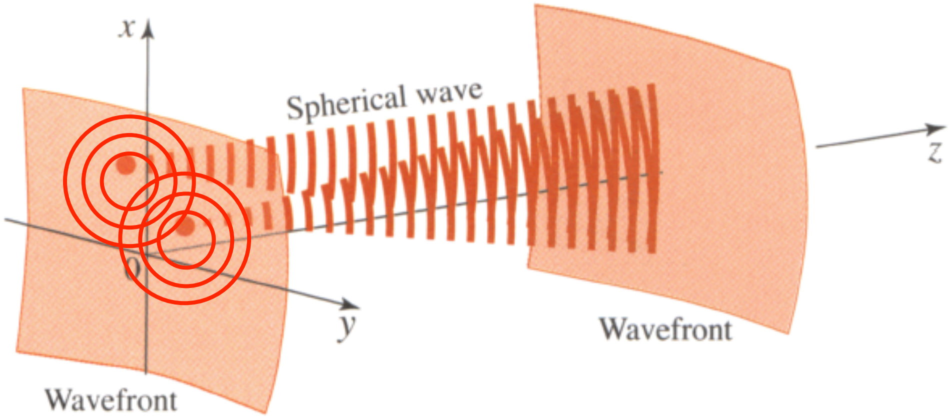
- In metals, tons of electrons that move freely in the electric field. Effect is stronger (reflect to 95%), but moving electrons cause ohmic loss (imperfect reflection).

$$\%R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \qquad \%R = \left( \frac{1.0 - 1.5}{1.0 + 1.5} \right)^2 \approx 0.04$$



Credit: Fund. Photonics



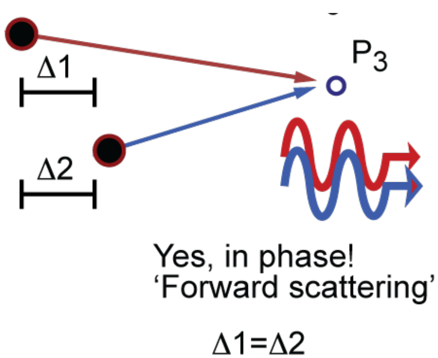


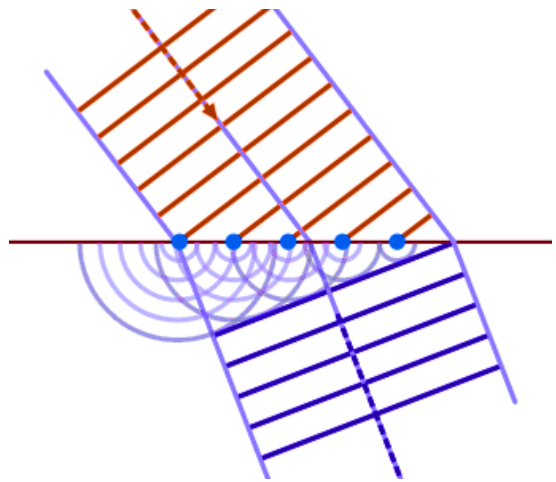

- So what do you think happens when light is incident on a single slit or a pinhole?

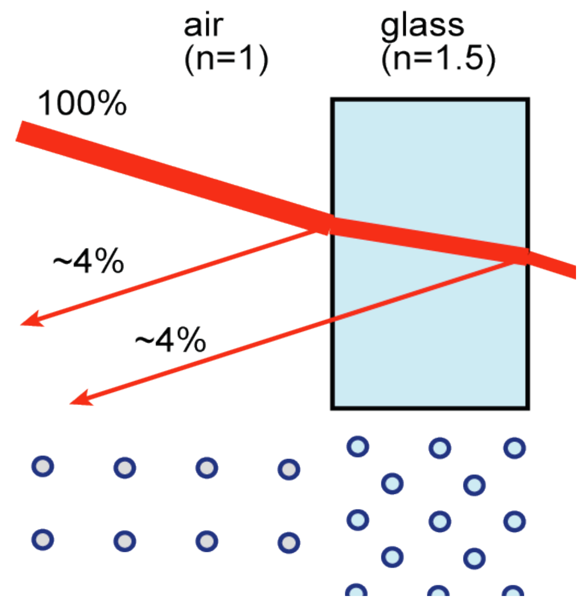
- Huygens-Fresnel and interference predicts reflection (intensity of re-radiation discontinuous at surface).

- Huygens-Fresnel and interference predicts refraction!

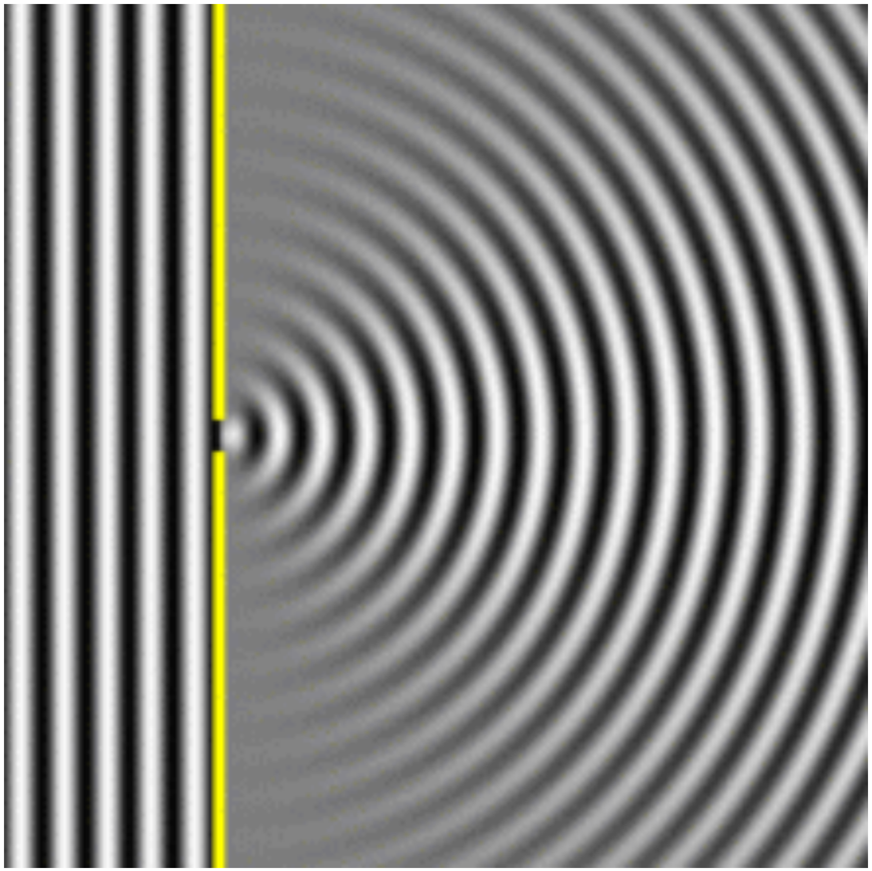
- Huygens-Fresnel and interference predicts forward propagation!

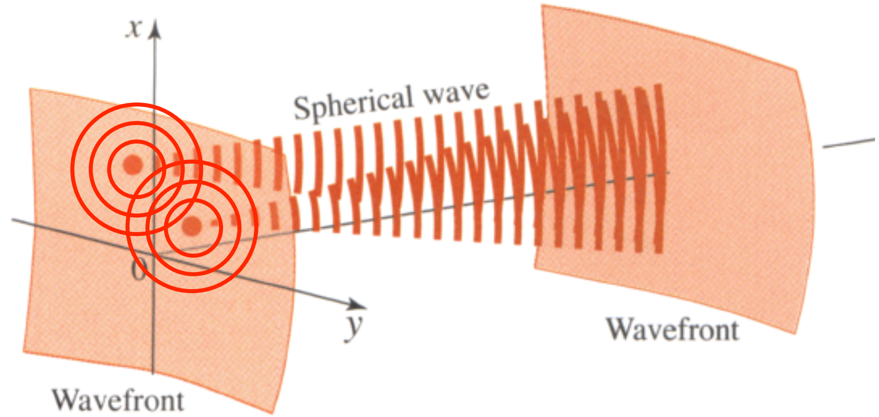




- First consider a single slit that is about as wide as the wavelength of light incident on it… as expected, it acts as new spherical wavefront (Huygens-Fresnel principle).






- Now, if we remove the slit, in the same plane each point still acts as a new spherical wave front, but like in the image above they all constructively interfere to support forward propagation as a plane wave…

- What will happen if we have ***a few slits each with spherical wave fronts***, or ***slits that are wide enough to support formation of a few spherical wave fronts***?

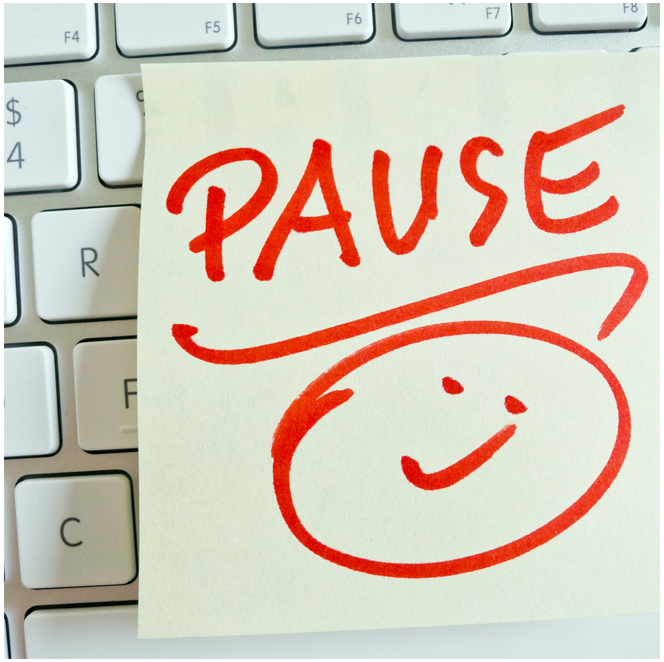
- How can light keep traveling forward in a homogeneous material even if each point acts as source of spherical waves? Which answer is most correct:

(a) Forward is the only direction that supports constructive interference.
(b) E field is perpendicular to the direction of propagation.
(c) E field is parallel to the direction of propagation.
(d) None of the above are correct at all.

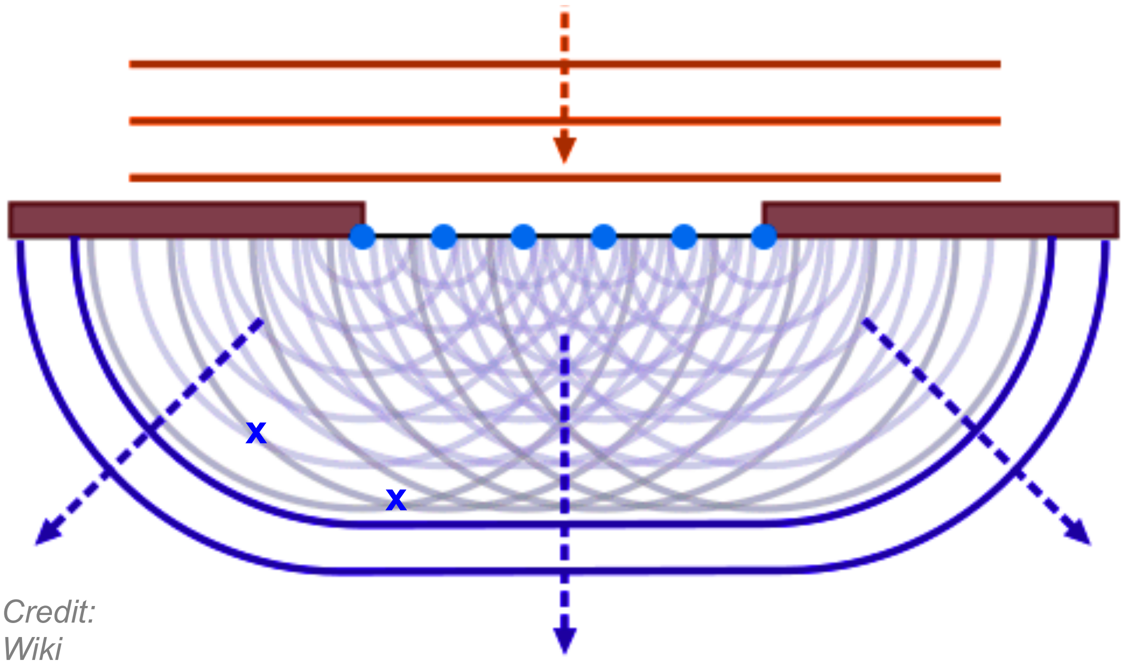
- Why does a metal reflection have more loss (absorption) that glass/air?

(a) Because metals reflect more strongly.
(b) Because metals have free electrons and ohmic loss.
(c) Because metals have rougher surfaces than glass.
(d) Because metals have lower refractive index than glass.

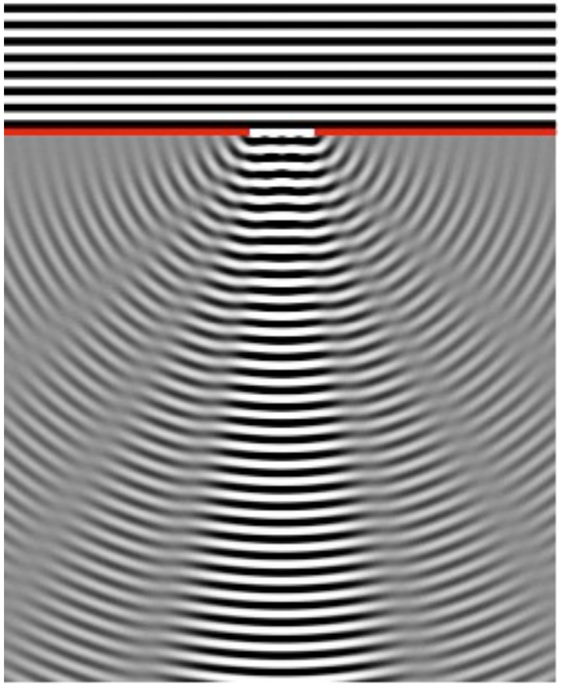
- Whew! That's enough. Lets take a break!



- Consider the single-slit experiment below… notice areas of constructive interference (where lines overlap).

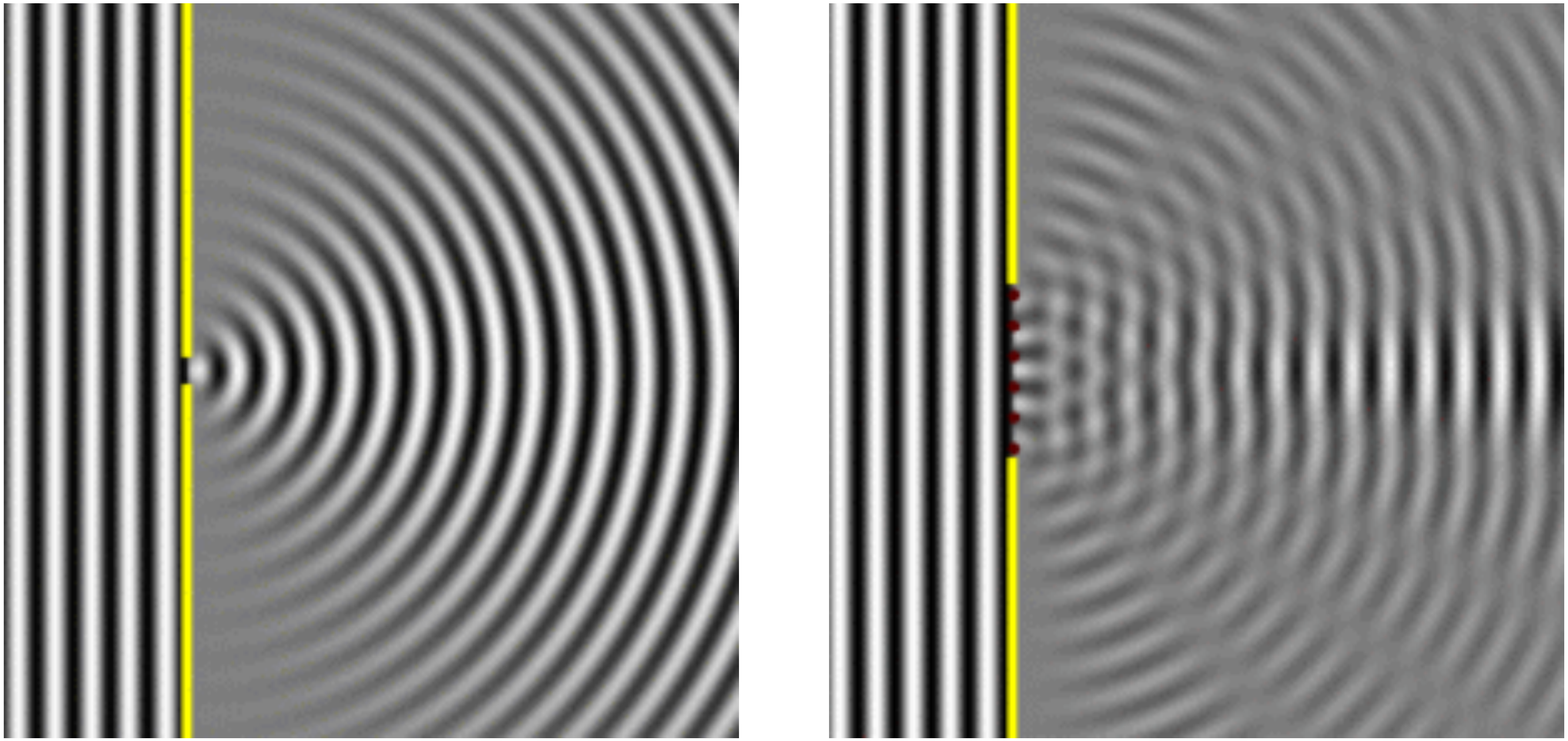



*Credit: Wiki*



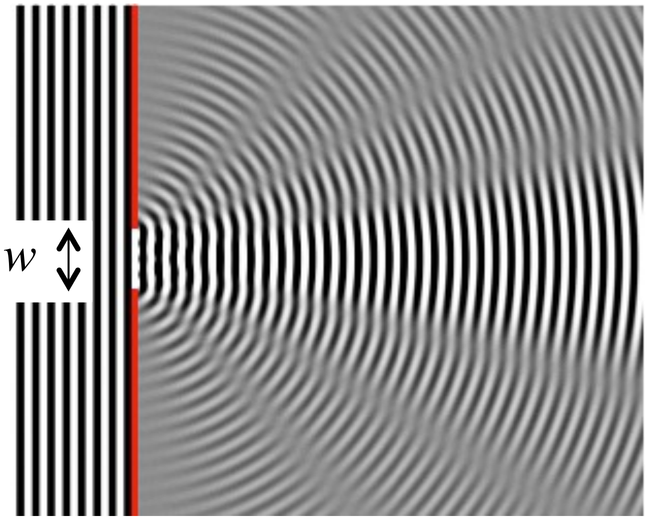
- The above is the famous 'single slit' experiment… you don't need a slit, any sharp edge will cause something similar (like the edge of a piece of paper, or the metal on a semiconductor mask…)

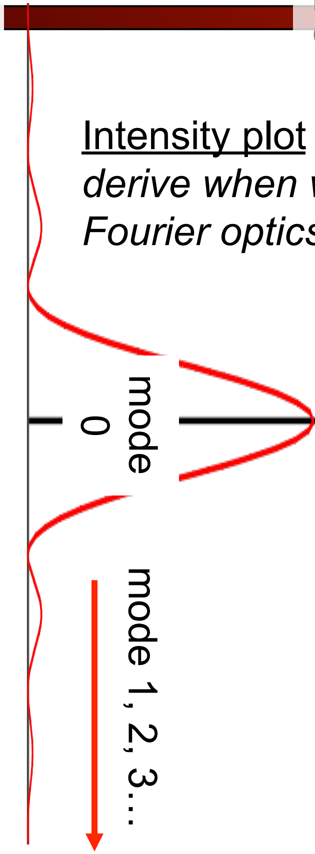
- Again, need to have certain width to see a pattern…
- Note nice ‘dots’ showing each spherical wave front source in image at right.



*Credit: Wiki*

Credit: Wiki

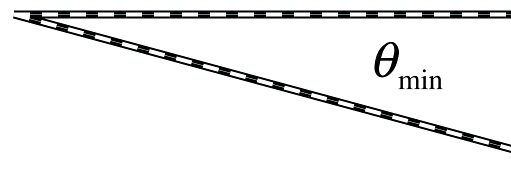



Intensity plot *(we will derive when we do Fourier optics…)*

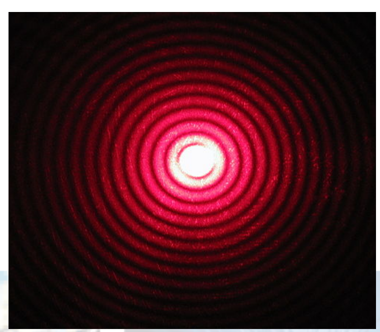
- Calculate $\theta_{min}$ and then the slit width $w$ using:

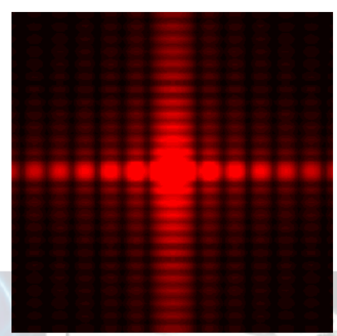
$$\sin(\theta_{\min}) = \lambda / w$$




note $\theta_{min}$ is from center of maximum (mode 0) to the center of the 1st dark fringe

- Here are two more diffraction patterns… what are they for? The second one is practically important for the lab this week…





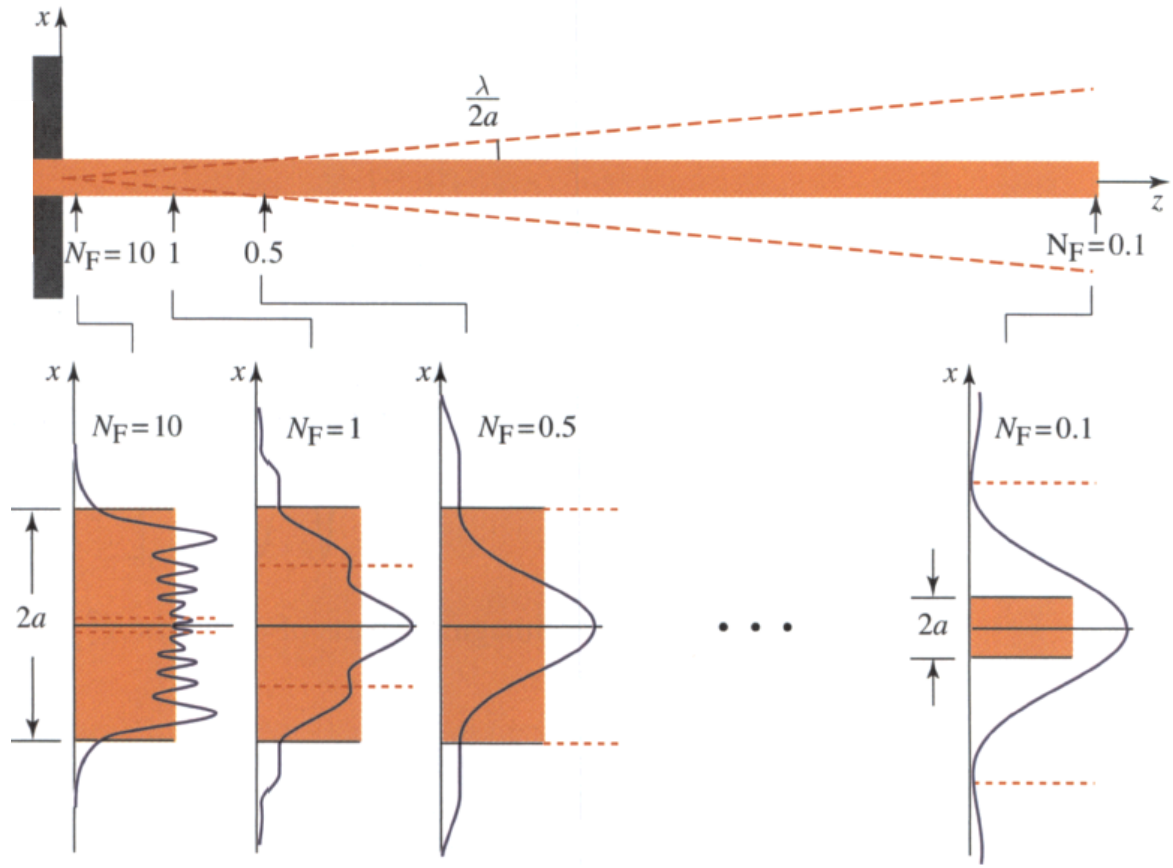
- For slit of width w=2a, the shaded area just shows the original w of the slit..

- The dashed line shows the width of the Fraunhofer diffraction pattern (the one we have been talking about thus far). This does not appear until the far field…

- Closer to the slit you see the more complex Fresnel diffraction pattern, which is much more complicated and which we will not discuss or measure…

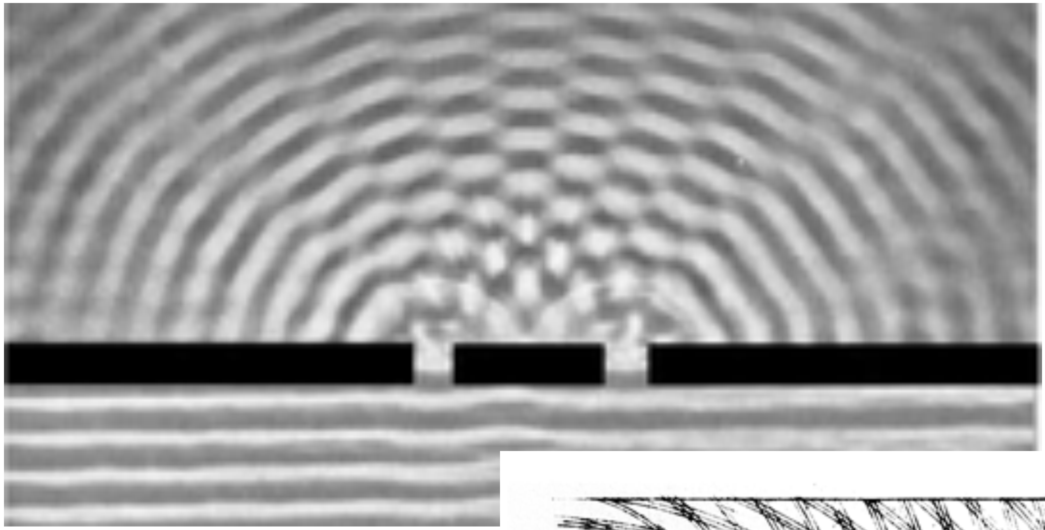
(just measure at sufficient distance *d*)

$$N_F = \frac{a^2}{\lambda d} \quad (Fresnel\ number)$$

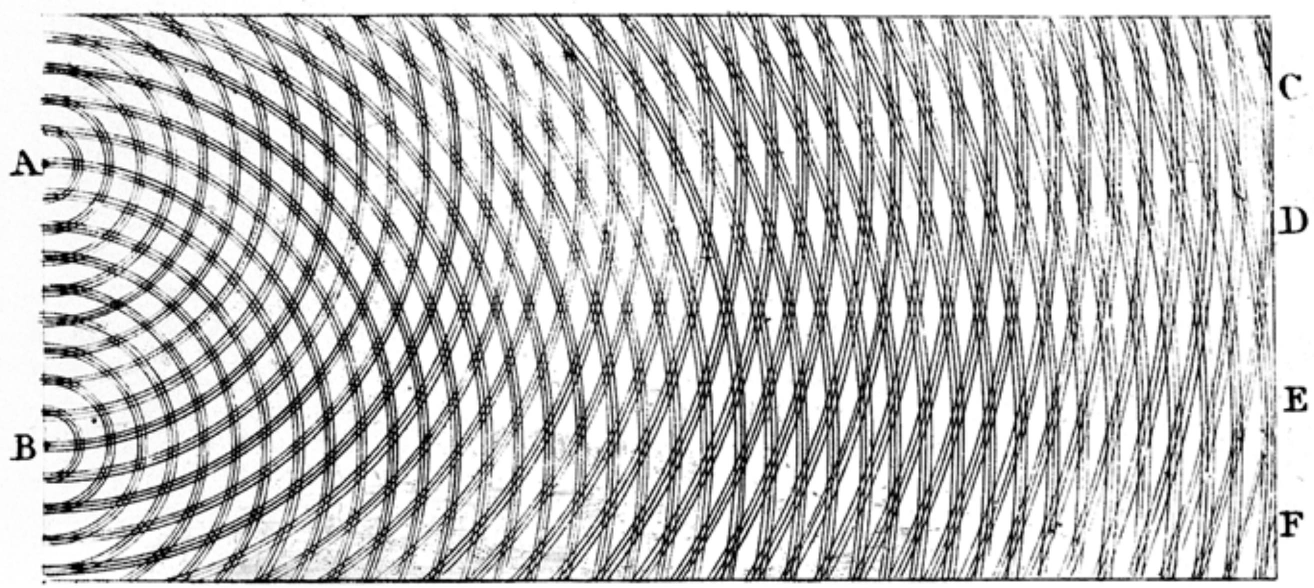


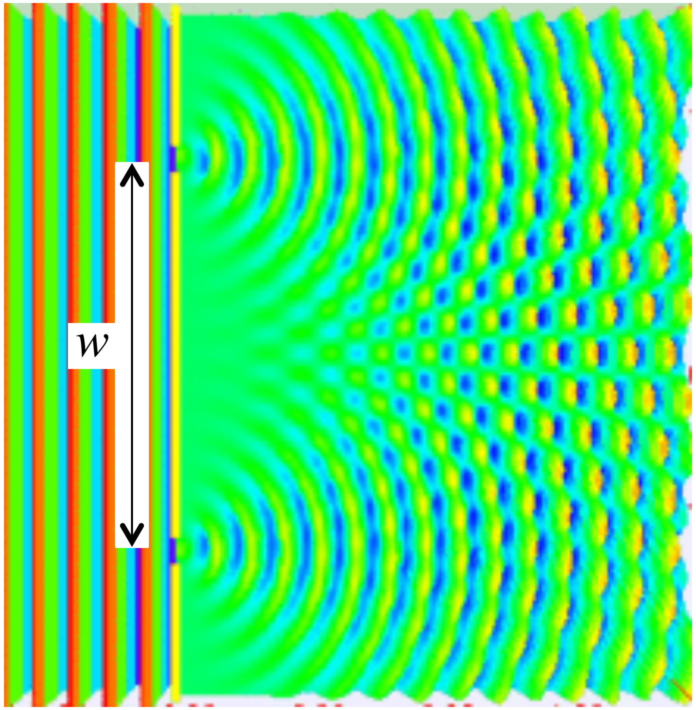

Credit: *Fundamentals of Photonics*

- Below is a image of a water ripple tank with waves, the fuzzy gray areas are where there is destructive interference! This is a double slit diffraction!

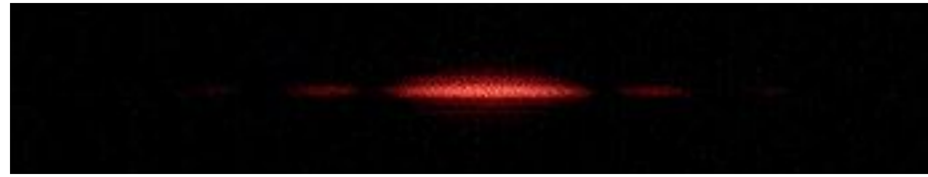


- This is the famous 'Young's double-slit' experiment (here is a drawing from 1803 from Thomas Young).

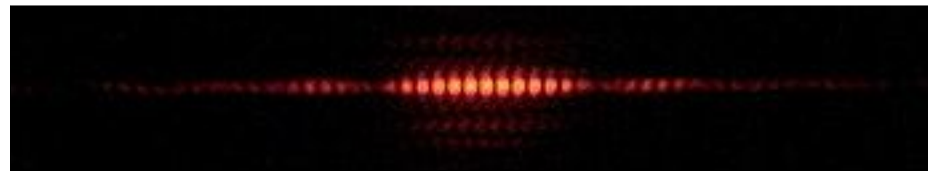


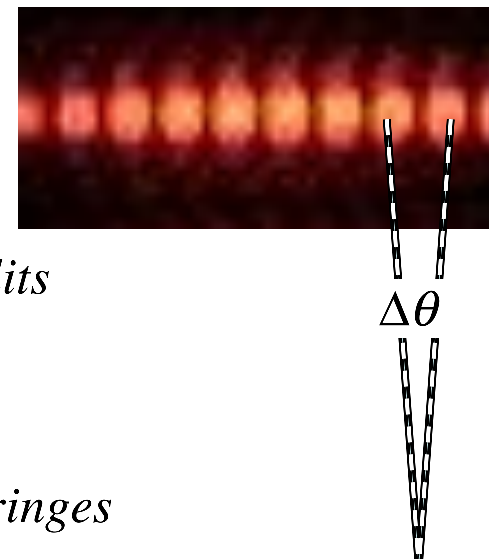



- Single slit…



- Double slit…






$$\Delta\theta = \lambda / w$$

$$w = width\ between\ slits$$

$$\theta\ is\ radians$$

$$d = L\lambda / w$$

$$d = space\ between\ fringes$$

$$L = dist.\ from\ slit\ to\ fringes(screen)$$

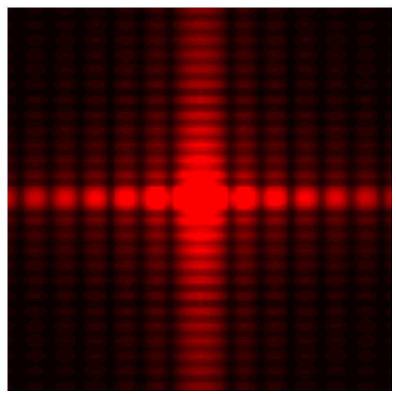
- Nice simple derivation at: http://theory.uwinnipeg.ca/physics/light/node9.html, and in optics primer, assumes small angle trig. approx. *sin (Δθ)=Δθ* (must be in *radians*)

- Just measure Δθ angles from dark to dark band or light to light bands

- Single slit, if it is only a few wavelengths wide, will you get diffraction, and why?

(a) No. You need two slits to get diffraction.
(b) Yes. because the slit is wide enough to let two different types (wavelengths) of light through.
(c) No, because that is too narrow to let light through.
(d) Yes, because the slit is wide enough to support creation on several spherical wave fronts.

- For the diffraction pattern at right, which way is the 'longer side' of the rectangular slit?

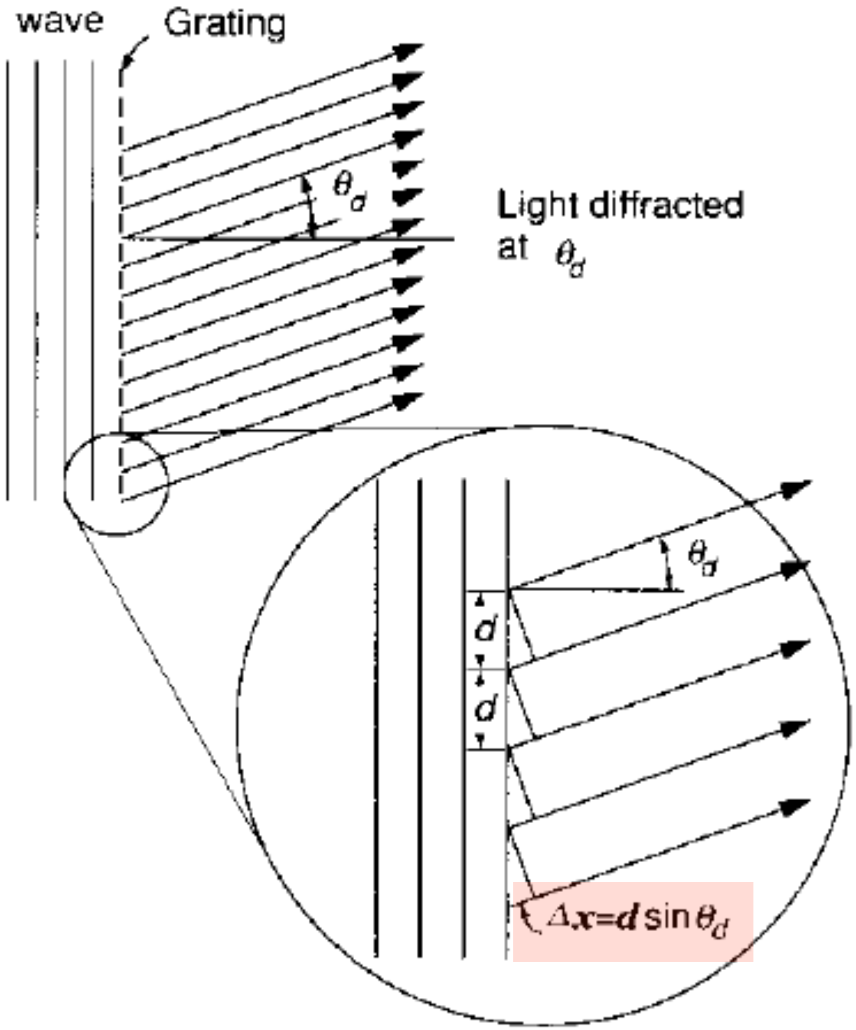


(a) Oriented vertically.
(b) Oriented horizontally.
(c) Could be either.
(d) None of the above, this diffraction is from a circular aperture.

- Whew! That's enough. Lets take a break!

# Diffraction Grating

- Diffraction gratings create a periodic layout of slits or phase-shifting reflectors (e.g. the entire optical surface is filled with parallel slits).



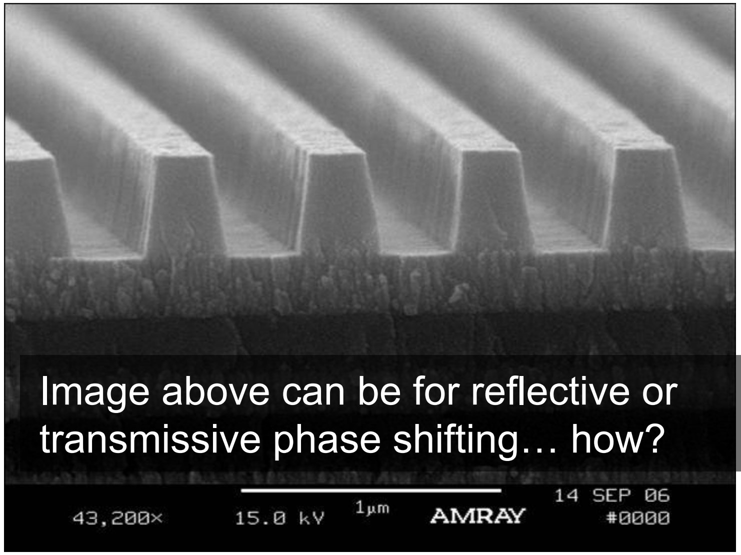




Image above can be for reflective or transmissive phase shifting… how?

- At left is one example transmissive diffraction angle for the light, d is the period of the grating…

$$\Delta x = d \sin\theta$$

- So, what MUST Δx be (see in diagram) for constructive interference (maximas) at an angle $\theta$ ?

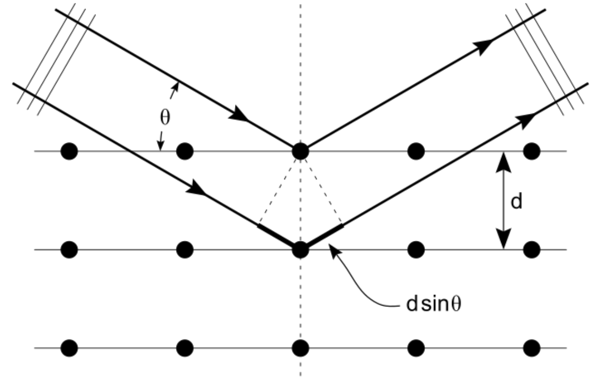
$$\Delta x = m\lambda \quad m = 0,1,2,3...$$

$$\therefore \quad m\lambda = d \sin\theta$$

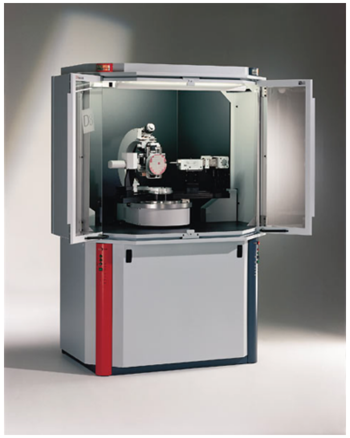
- I showed this to you last week also as Bragg reflection (diffraction). X-rays is used to determine crystallinity (quality) of semiconductors…

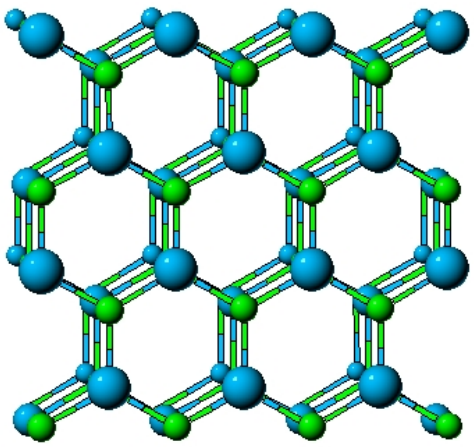
  again, why do they use X-rays?

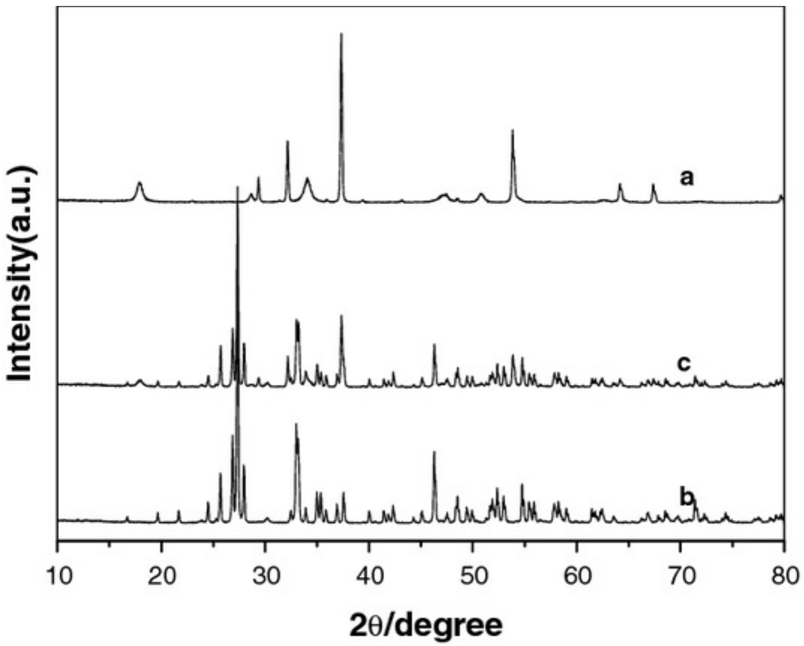
- Now, this equation is 2d*sin $\theta$, where previous slide (transmissive) was just d*sin $\theta$, *why?*



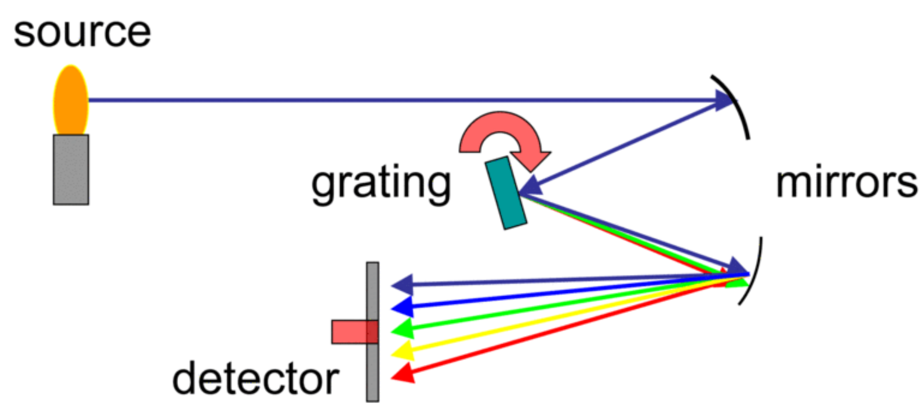

$$m\lambda = 2d\sin\theta \quad m = \text{int}.$$

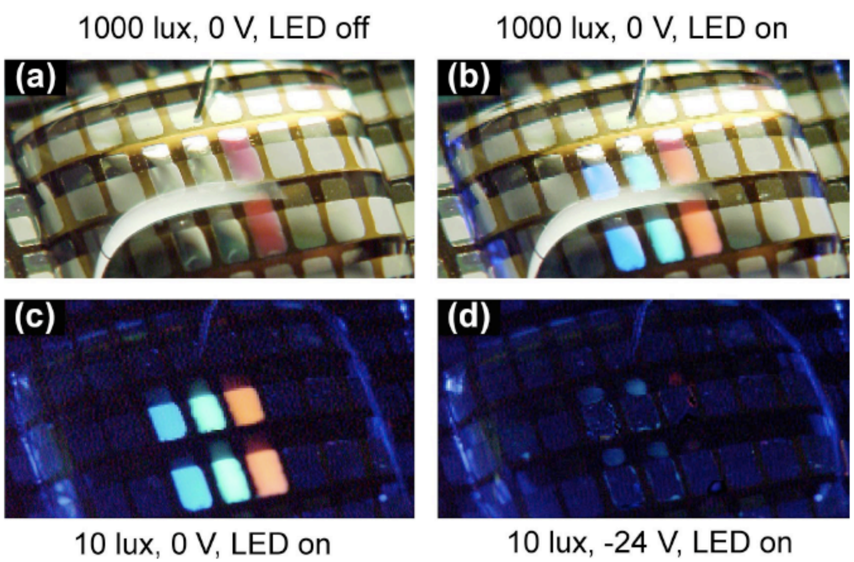


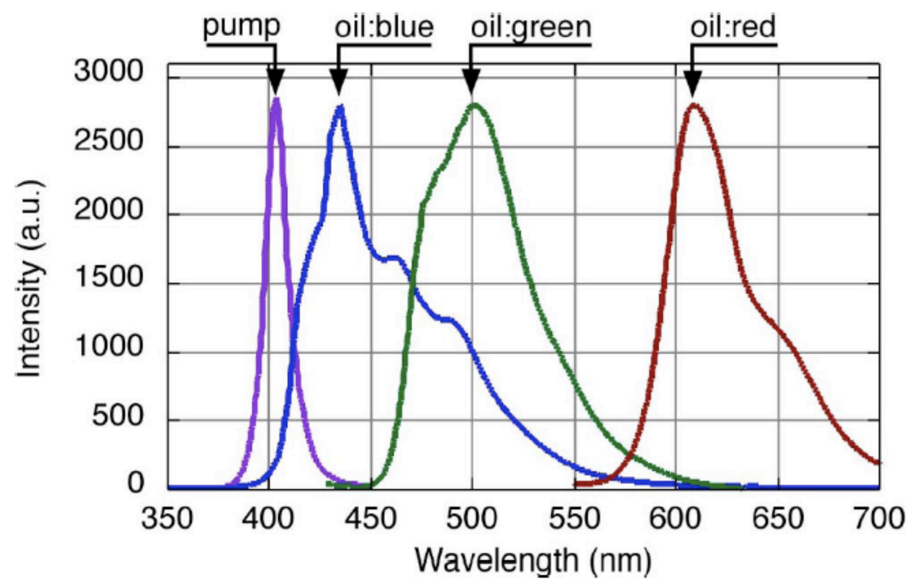




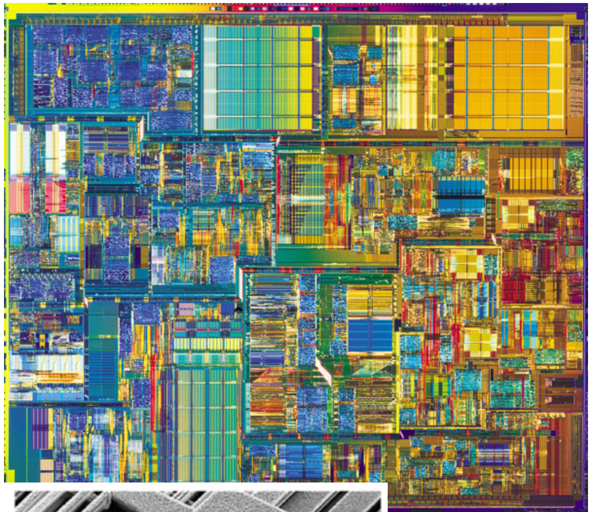
- Diffraction gratings are used to split up light in a spectrometer…

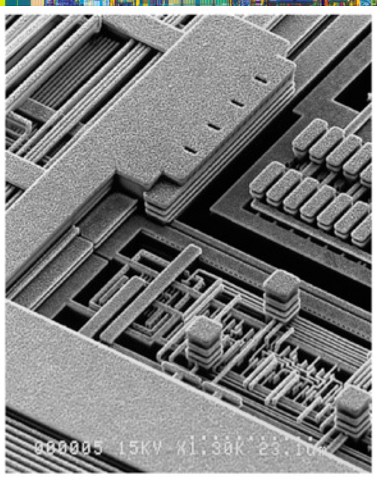


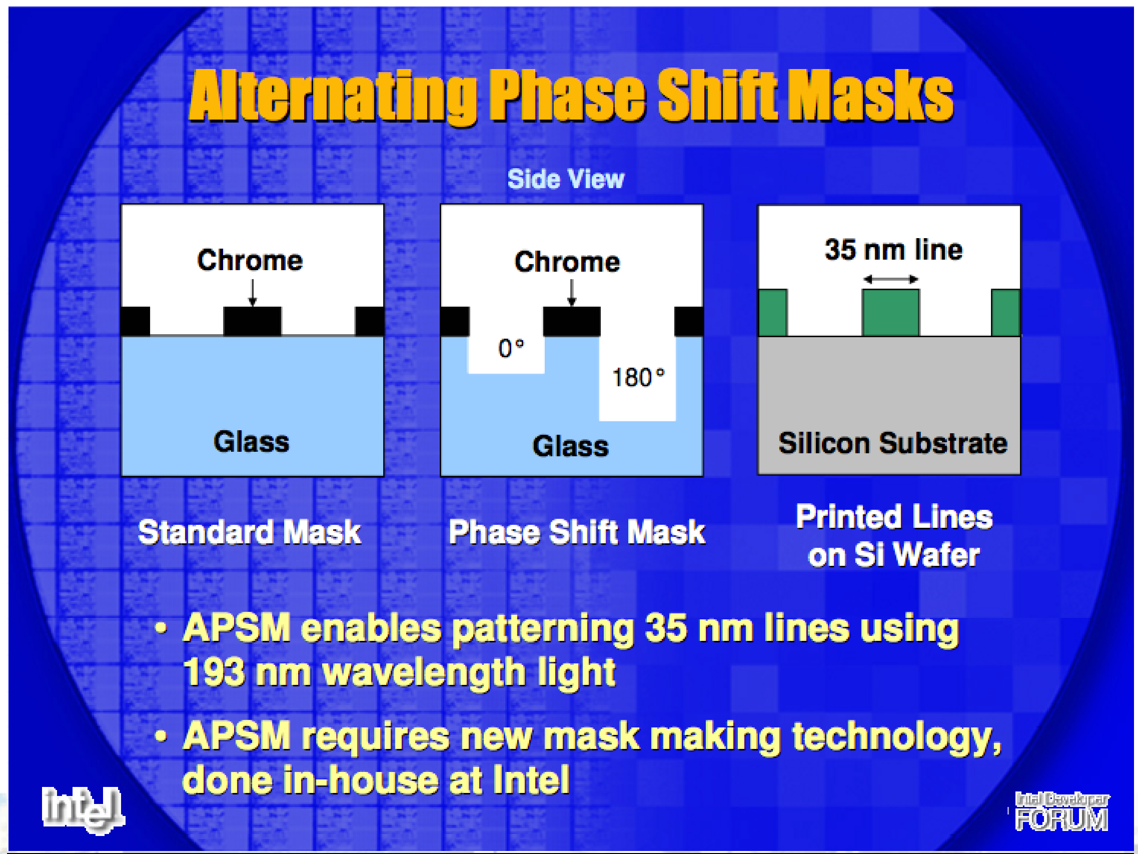
- Yikes! Photolithography on computer chips! How solve diffraction?





- You could press the mask against the resist (contact lithography) but that creates defects…

- Proximity (non-contact) is used, and techniques (such as that shown below) are used to boost the maximum achievable resolution…

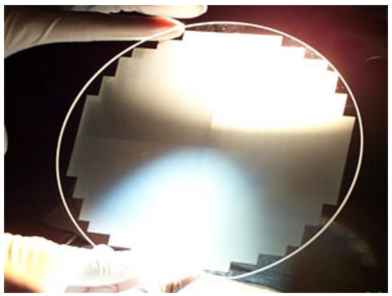


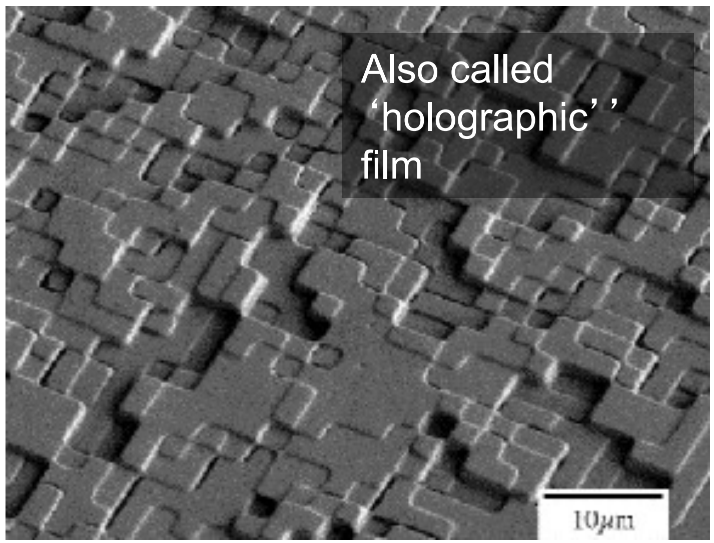
# Real World Applications



- Could we use diffraction to make flat lenses and amazing optical effects? Yes!

At the end of this lab you will experiment with these ***discontinuous*** optical elements that are microscopic! The surfaces diffract light and force it to go in the directions where constructive interference occurs! However, they are quite advanced…






TESSERA

Pattern Generators
Diffractive optics are ideally suited for creating an image composed of pixels on a grid pattern such as lines, rings, spot arrays, and pictures. These computer generated holograms are comprised of pixels with both symmetrical and asymmetrical layout and can also have varied gray-scale output intensities.

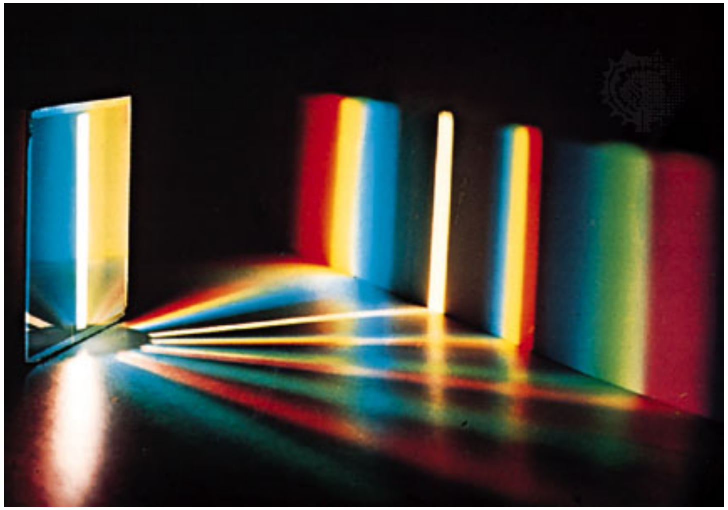
Features

* High efficiencies:
Efficiencies of 70% to greater than 90% depending on the number of levels and the application
* Binary to 64 Phase Levels
* Zero order energy: < 2%
* High uniformity: < %10 variation
* Consistent performance
* Economical in volume
* Feature sizes of 0.5 microns

Key point: You get diffraction + a **phase delay** as light goes through the 'taller' squares…

- The image shown at right is for a white light source going through a diffraction grating…. what does this tell you about diffraction gratings?

(a) They must be made of tiny prisms.
(b) They are very dependent on wavelength.
(c) They are smaller than the longest wavelength of light in the visible spectrum.
(d) None of the above.



*Credit: Bausch & Lomb*

- At the end of the lab this week, you will test a diffractive lens (is a flat piece of plastic as thin as paper!). Coo! But what will the big issue be for real world applications?

(a) Really? I have not done the experiment yet….
(b) The plastic has optical dispersion in it, it is not due to diffraction.
(c) Is because of the diffraction which is wavelength dependent, so it does not work the same for all colors.
(d) There are no applications where a thin lens would be valuable.