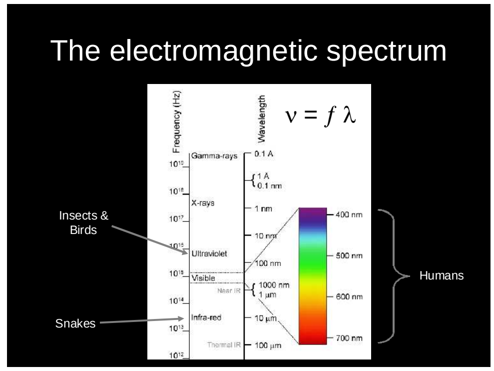
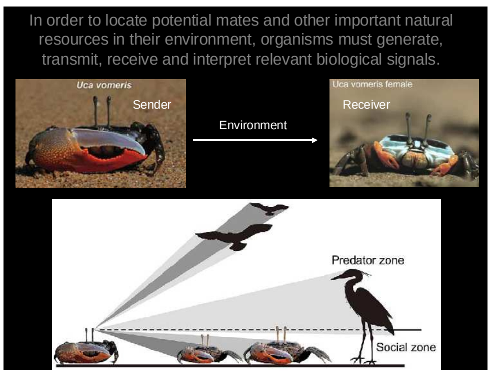
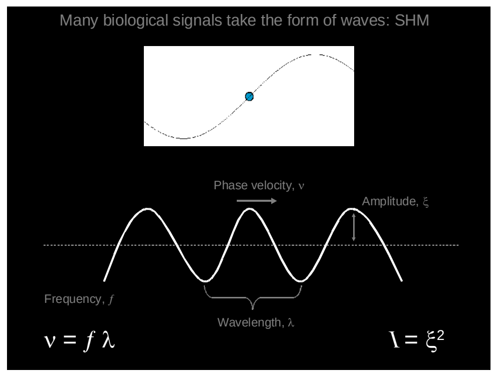
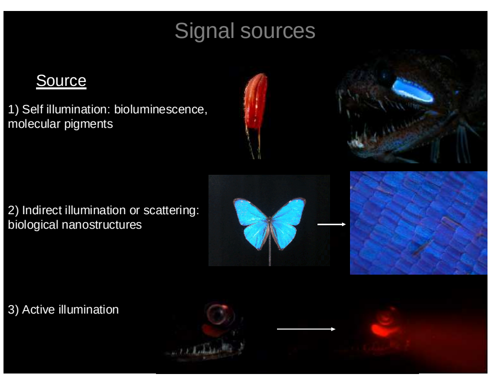
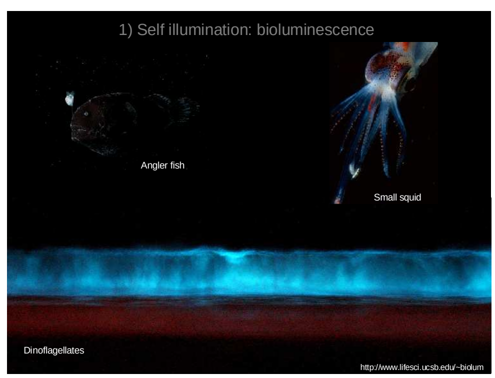

Communication with Waves: Light

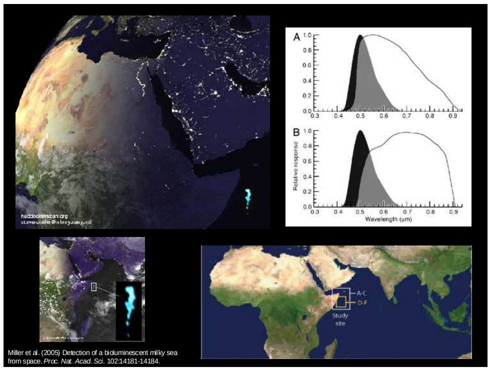

The electromagnetic spectrum
Frequency (Hz)
Wavelength
$\nu = f \lambda$
Gamma-rays
X-rays
Ultraviolet
Visible
Near IR
Infra-red
Thermal IR
0.1 A
1 A
0.1 nm
1 nm
10 nm
100 nm
1000 nm
1 μm
10 μm
100 μm
400 nm
500 nm
600 nm
700 nm
Insects &
Birds
Snakes
Humans

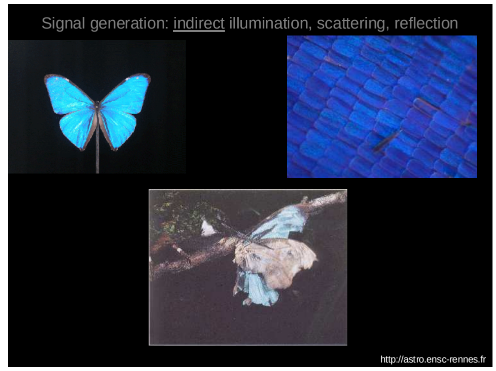

In order to locate potential mates and other important natural resources in their environment, organisms must generate, transmit, receive and interpret relevant biological signals.
Uca vomeris
Sender
Environment
Uca vomeris female
Receiver
Predator zone
Social zone

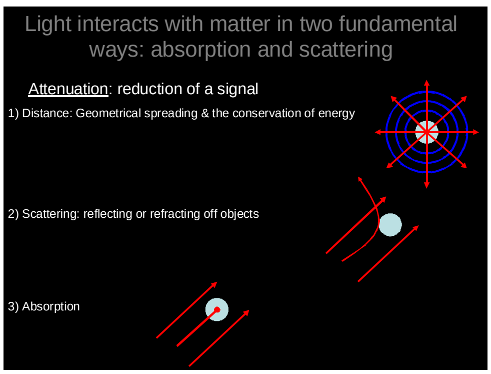

Many biological signals take the form of waves: SHM
Phase velocity, ν
Amplitude, ξ
Frequency, f
Wavelength, λ
$\nu = f \lambda$
$I = \xi^2$

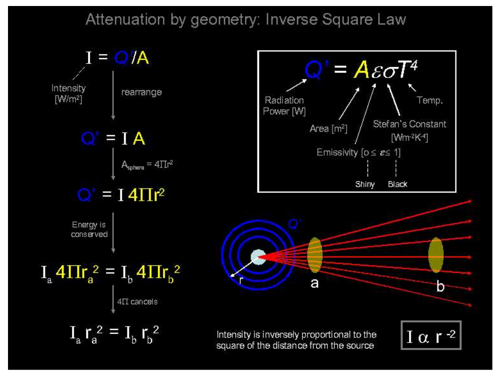

Signal sources
Source
1) Self illumination: bioluminescence, molecular pigments
2) Indirect illumination or scattering: biological nanostructures
3) Active illumination

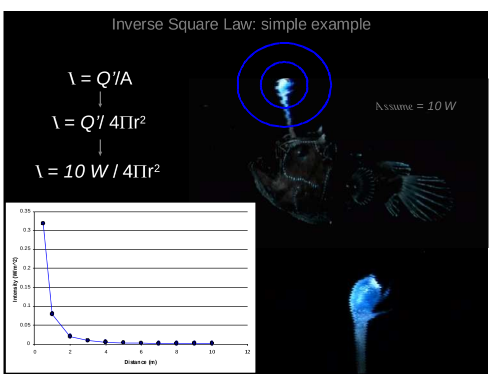

1) Self illumination: bioluminescence
Angler fish
Small squid
Dinoflagellates
http://www.lifesci.ucsb.edu/~biolum

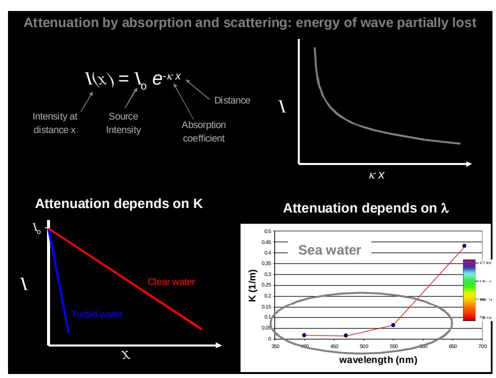

Miller et al. (2005) Detection of a bioluminescent milky sea from space. Proc. Nat. Acad. Sci. 102:14181-14184.
Wavelength (μm)
Relative response
Study site

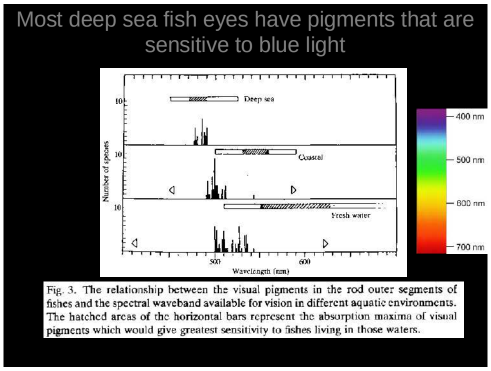

Signal generation: indirect illumination, scattering, reflection
http://astro.ensc-rennes.fr


Light interacts with matter in two fundamental ways: absorption and scattering
Attenuation: reduction of a signal
1) Distance: Geometrical spreading & the conservation of energy
2) Scattering: reflecting or refracting off objects
3) Absorption


Attenuation by geometry: Inverse Square Law
I = Q'/A
Intensity [W/m²]
rearrange
Q' = I A
Q' = I 4Πr²
Energy is conserved
Iₐ 4Πrₐ² = I_b 4Πr_b²
4Π cancels
Iₐ rₐ² = I_b r_b²
Q' = AεσT⁴
Radiation Power [W]
Area [m²]
Stefan's Constant [Wm⁻²K⁻⁴]
Temp.
Emissivity [0 ≤ ε ≤ 1]
Shiny
Black
r
a
b
Intensity is inversely proportional to the square of the distance from the source
I α r⁻²

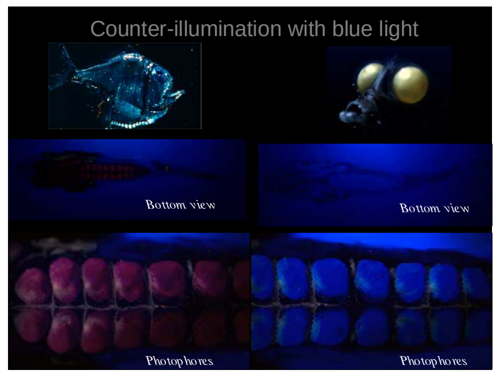

Inverse Square Law: simple example
I = Q'/A
I = Q'/ 4Πr²
I = 10 W / 4Πr²
Assume = 10 W
Distance (m)

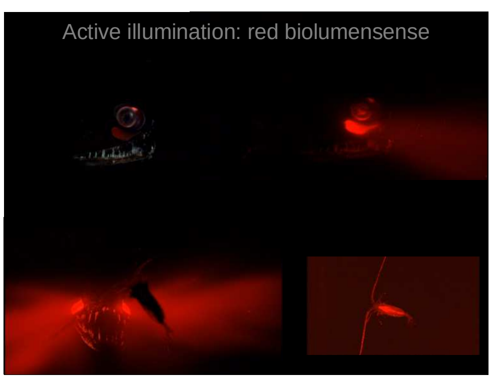

Attenuation by absorption and scattering: energy of wave partially lost
I(x) = I₀ e^-κx
Intensity at distance x
Source Intensity
Absorption coefficient
Distance
κx
Attenuation depends on K
Clear water
Turbid water
X
Attenuation depends on λ
Sea water
K (1/m)
wavelength (nm)

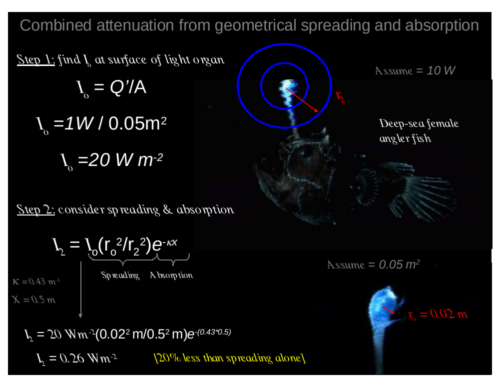

Most deep sea fish eyes have pigments that are sensitive to blue light
Deep sea
Coastal
Fresh water
Number of species
10
10
10
500
600
Wavelength (nm)
400 nm
500 nm
600 nm
700 nm
Fig. 3. The relationship between the visual pigments in the rod outer segments of fishes and the spectral waveband available for vision in different aquatic environments. The hatched areas of the horizontal bars represent the absorption maxima of visual pigments which would give greatest sensitivity to fishes living in those waters.


Many deep-sea organisms are red


Many deep-sea organisms generate blue light

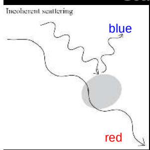

Counter-illumination with blue light
Bottom view
Bottom view
Photophores
Photophores


Active illumination: red biolumensense

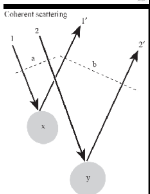

Combined attenuation from geometrical spreading and absorption
Step 1: find I_o at surface of light organ
I_o = Q'/A
I_o =1W / 0.05m²
I_o =20 W m-2
Assume = 10 W
Deep-sea female angler fish
r_2
Step 2: consider spreading & absorption
I_2 = I_o(r_o²/r_2²)e^-κx
Spreading
Absorption
κ = 0.43 m-1
X = 0.5 m
Assume = 0.05 m²
r_o = 0.02 m
I_2 = 20 Wm-2(0.02² m/0.5² m)e^-(0.43*0.5)
I_2 = 0.26 Wm-2
[20% less than spreading alone]

15/03/2007

Scattering: refraction and reflection

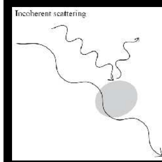


- Light-scattering objects are randomly spaced
- Phase relationships of the scattered waves are random
- Color determined by the properties of scatterers (i.e. size)
- Smaller λ (blue) are preferentially scattered

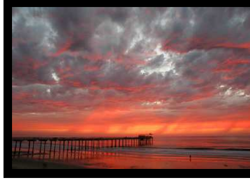


- Thin film interference
- Scattering objects have order
- Phases of scattered waves are non-random and therefore can constructively or destructively interfere with one another, Thereby increasing or decreasing intensity of wave field.
- Colour is determined by the spatial distribution of light-scattering interfaces

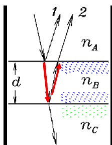
Scattering: refraction and reflection



- Examples of incoherent scattering include blue & red sky, blue ice and blue snow.

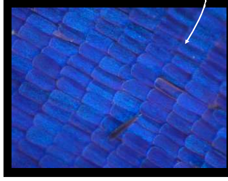


Coherent Scattering: iridescent butterfly scales



Constructive interference occurs when $nd = \lambda/4$ for a single platelet.

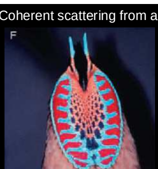
Light-scattering objects are arranged in laminar or crystal-like arrays.

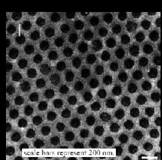


- Changes in the angle of observation or illumination affect the mean path length (2d) of scattered waves
- Such a change will affect the phase relationships among the scattered waves and change which wavelengths are constructively reinforced after scattering

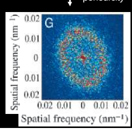
Other than feathers, can birds also use coherent scattering to express colours on their skin that *aren't* iridescent?

Coherent scattering from arrays of parallel collagen fibres in the dermis

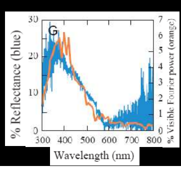




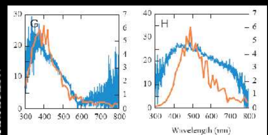
2D Fourier transform: characterize the spatial periodicity

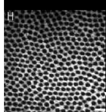


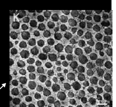
Ring indicates ordered structure

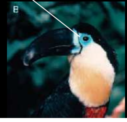


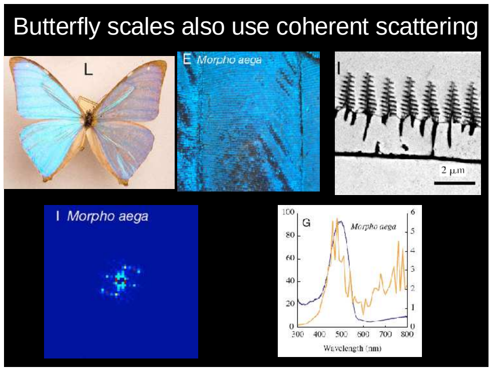
Ultraviolet, blue, green and yellow structural colours of avian skin are produced by coherent scattering (i.e. constructive interference), other colours employ pigmentary mechanisms in addition to structural order.

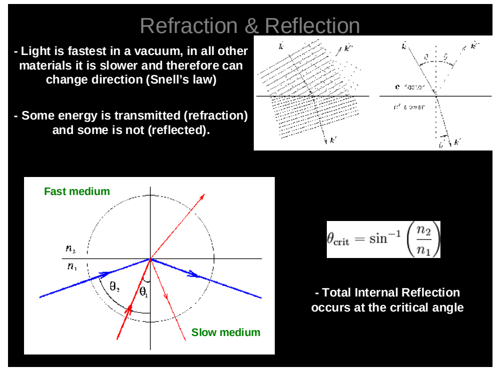


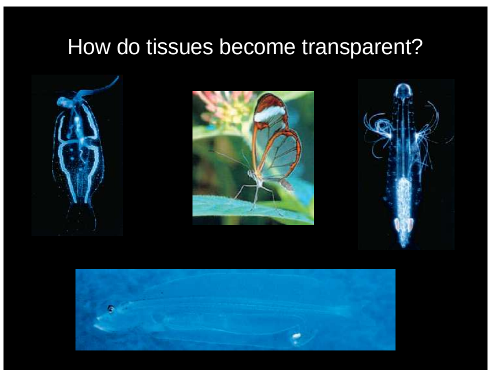


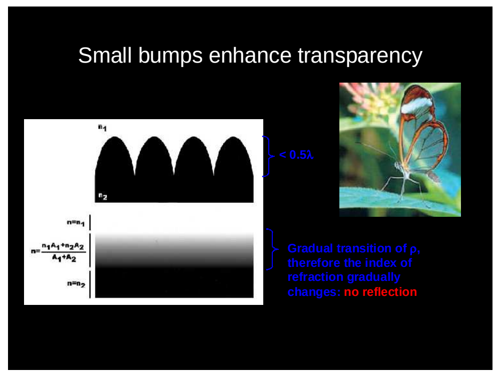


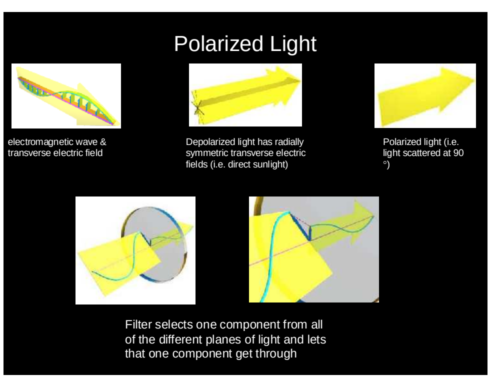


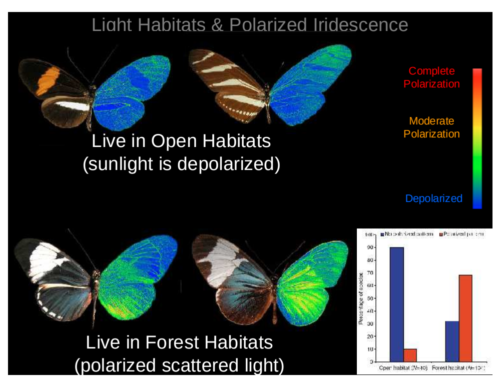

Butterfly scales also use coherent scattering
L
E Morpho aega
I
2 µm
I Morpho aega
G
Morpho aega
Wavelength (nm)


Refraction & Reflection
- Light is fastest in a vacuum, in all other materials it is slower and therefore can change direction (Snell's law)
- Some energy is transmitted (refraction) and some is not (reflected).
Fast medium
Slow medium
$\theta_{crit} = \sin^{-1}\left(\frac{n_2}{n_1}\right)$
- Total Internal Reflection occurs at the critical angle


How do tissues become transparent?


Small bumps enhance transparency
< 0.5λ
Gradual transition of ρ, therefore the index of refraction gradually changes: no reflection


Polarized Light
electromagnetic wave & transverse electric field
Depolarized light has radially symmetric transverse electric fields (i.e. direct sunlight)
Polarized light (i.e. light scattered at 90 °)
Filter selects one component from all of the different planes of light and lets that one component get through


Light Habitats & Polarized Iridescence
Complete Polarization
Moderate Polarization
Depolarized
Live in Open Habitats (sunlight is depolarized)
Live in Forest Habitats (polarized scattered light)