Chapter 1
Nature of Light

Lecture Notes for Modern Optics based on
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Nature of Light

- A brief history
- Particles and photons
- The Electromagnetic Spectrum
- Radiometry

What is light?

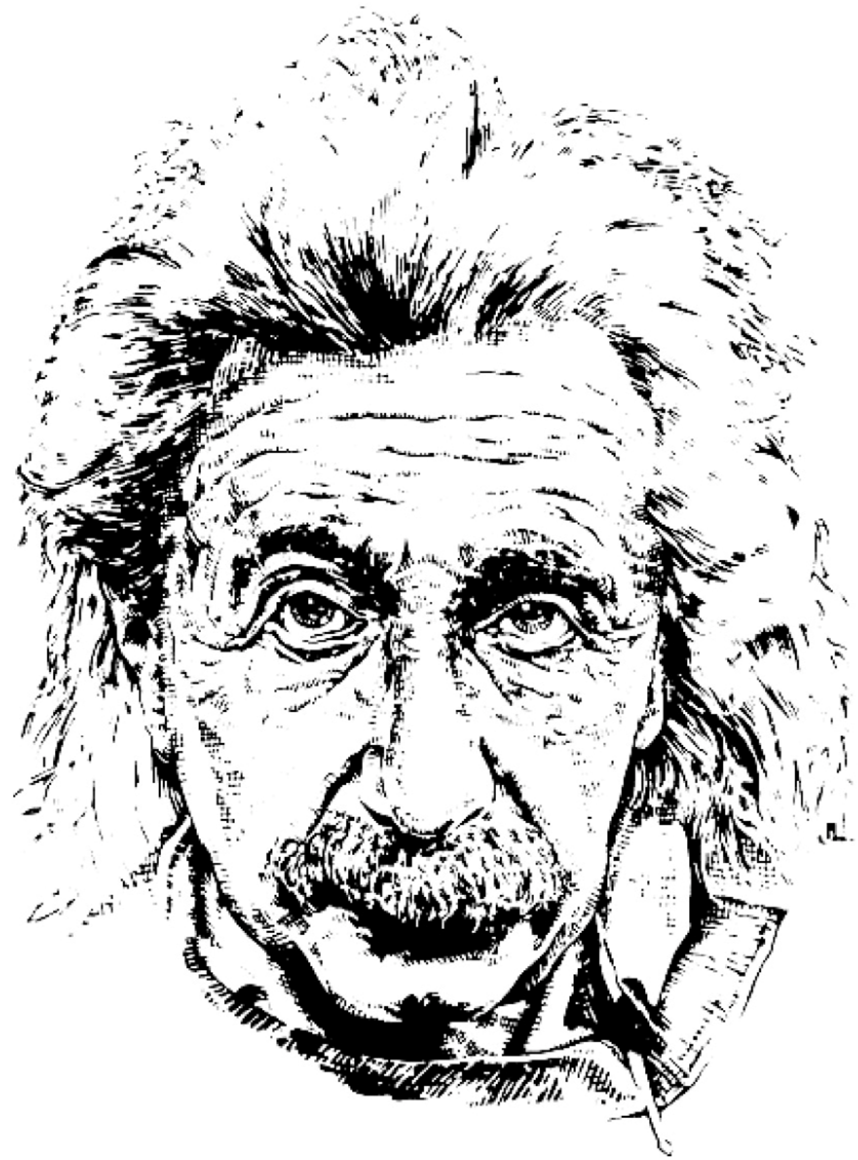
"The nature of light" is still subject of a debate and covered on some recent publications such as special issue of OPN (Optics and photonics news) October 2003 published by OSA (Optical Society of America).

Albert Einstein:

All the 50 years of conscious brooding have brought me no closer to the answer to the question: What are light quanta?

Arthur Zajonc (2003):

We are today in the same state of "learned ignorance" with respect to light as was Einstein.



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1.2 Particles and waves; Quantum optics

Principle of complementarity (Niels Bohr): photons and electrons are neither waves nor particles. They are something more complex than either.

No single physical model can explain their attributes.

Wav or particle-like behavior is exhibited in different situations.

Quantum electrodynamics = Quantum mechanics + special theory of relativity describe the light and matter and their relationships/ interactions.

Two key points on applying these relationships to photons:

1) Photons have zero rest mass

2) Seed of photons in vacuum is always $c=3\text{x}10^8$ m/s.

Photons obey the Bose-Einstein statistics while electrons and protons obey Fermi-Dirac statistics.

Every particle has:

m, the rest mass of the particle

$E_0=mc^2$, is the rest-mass energy

E is the total energy

E_K is the kinetic energy or work done to accelerate the particle to its current speed.

Total energy: $E = E_0 + E_K$

Momentum: $p = \frac{\sqrt{E^2 - m^2c^4}}{c}$

Speed: $V = \frac{pc^2}{E} = c\sqrt{1 - \frac{m^2c^4}{E^2}}$

Kinetic energy: $E_K = mc^2\gamma - mc^2 = mc^2(\gamma - 1)$

Total energy: $E = mc^2 + mc^2(\gamma - 1) = mc^2\gamma$

Where: $\gamma = \frac{1}{\sqrt{1 - V^2/c^2}}$

de Broglie Wavelength: $\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E^2 - m^2c^4}}$

For photons the rest mass $m = 0$ and we have:

$E = pc;\ \lambda = hc/E;\ V = pc^2/E = c;$

1.3 The Electromagnetic Spectrum

All the electromagnetic (EM) waves are composed of time-varying electric and magnetic fields.

EM waves are produced by accelerating charged particles (like electron).

EM waves carry energy, momentum, and exert forces on charged particles.

Speed of all EM waves in free space (vacuum) is $c=3 \times 10^8$ m/s.

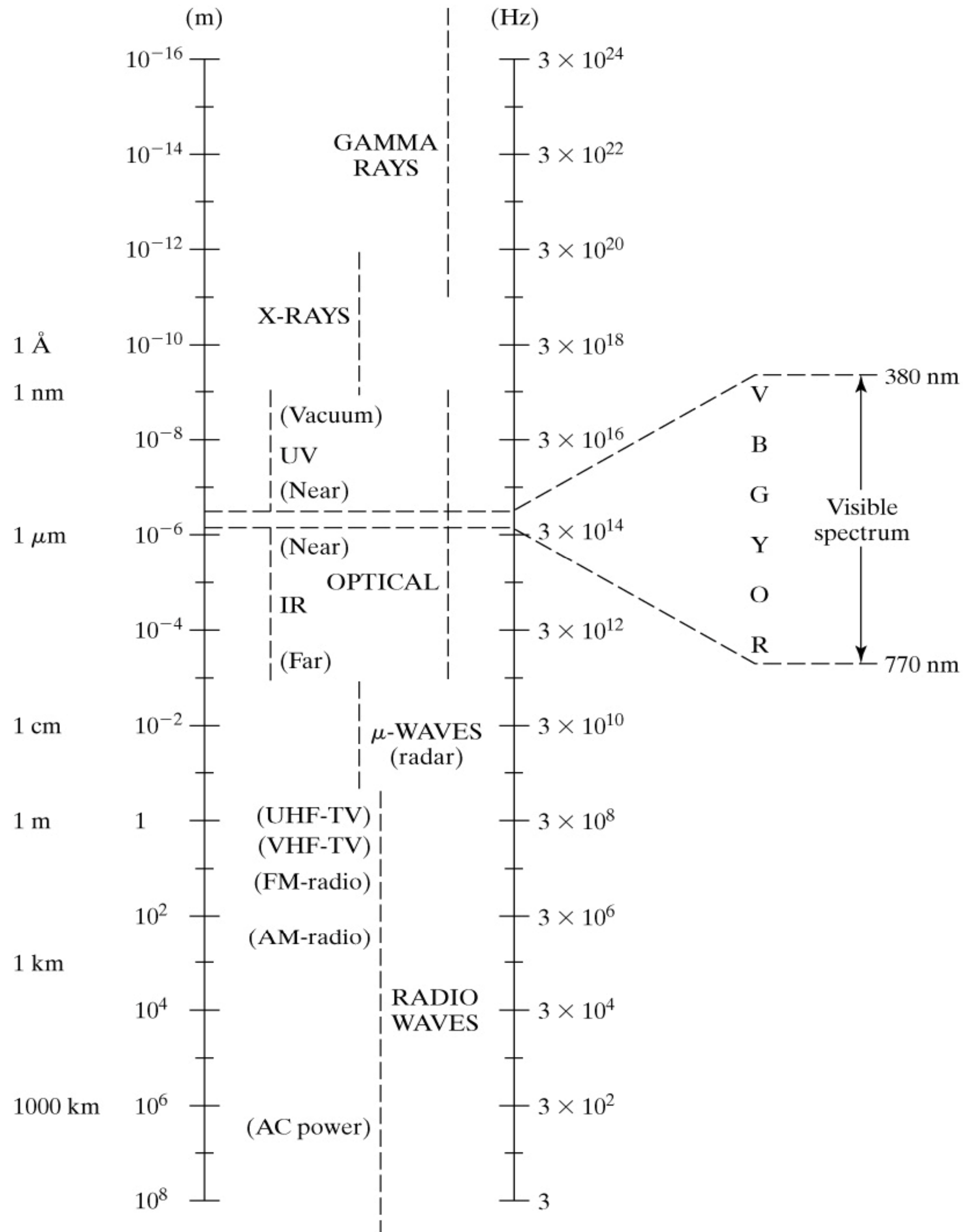
Frequency of EM waves is determined at the source producing them.

Monochromatic waves: single frequency content

Polychromatic waves: multiple frequency content

Spectrum of a wave packet is distribution of energy among the various constituents of the wave packet.

Various part of EM waves are given particular names by the industry that uses them..



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Warm up Example 1.2

An EM signal is detected by a detector with frequency of 100MHz and power of 6.63×10^{-16} J/s. Calculate the photons':

a) Wavelength

b) Energy of a photon in this signal in J and eV

c) Number of photons in this signal

d) Calculate energy of a 555 nm photon in J and eV. What color is this?

e) How many 555 nm photons/s would correspond to the detected signal power.

f) Calculate energy of a 0.1 nm photon in J and eV. What kind of radiation is this?

e) How many 0.1 nm photons/s would correspond to the detected signal power.

a. $\lambda = c/\nu = 3$ m

b. $E_{3m} = h\nu = hc/\lambda = 6.63 \times 10^{-26} J = 4.14 \times 10^{-7} eV$

c. $N_{3m} = \dfrac{\text{power}}{\text{Energy/photon}} = 10^{10} / s$

d. $E_{555nm} = hc/\lambda = 3.58 \times 10^{-19}$ J=2.2 eV

Visible green

e. $N_{555nm} = \dfrac{\text{power}}{\text{Energy/photon}} = 1850 / s$

f. $E_{0.1nm} = 1.99 \times 10^{-15}$ J=12400 eV

X-ray

g. $N_{0.1nm} = .33 / s$

1.4 Radiometry

Science of measurement of electromagnetic radiation.

Photometry: Science of measurement of electromagnetic radiation for the optical frequencies.

Radiometric quantities: Physical terms used to characterize energy content of radiation.

We only list the SI terms.

In this table subscript e corresponds to electromagnetic radiation.

Same quantities can be defined for other types of waves.

TABLE 1-1 RADIOMETRIC TERMS

Term	Symbol (units)	Defining equation
Radiant energy	$Q_e(\mathrm{J} = \mathrm{W} \cdot \mathrm{s})$	—
Radiant energy density	$w_e(\mathrm{J/m^3})$	$w_e = dQ_e/dV$
Radiant flux, Radiant power	$\Phi_e(\mathrm{W})$	$\Phi_e = dQ_e/dt$
Radiant exitance	$M_e(\mathrm{W/m^2})$	$M_e = d\Phi_e/dA$
Irradiance	$E_e(\mathrm{W/m^2})$	$E_e = d\Phi_e/dA$
Radiant intensity	$I_e(\mathrm{W/sr})$	$I_e = d\Phi_e/d\omega$
Radiance	$L_e\left(\frac{\mathrm{W}}{\mathrm{sr} \cdot \mathrm{m}^2}\right)$	$Le = dI_e/dA \cos\theta$

Abbreviations: J, joule; W, watt; m, meter; sr, steradian.

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Radiometry (contibued)

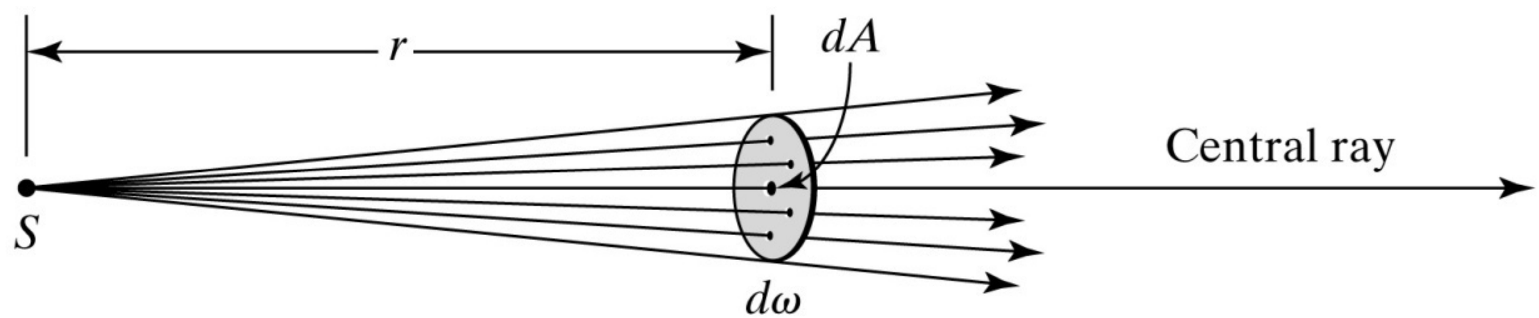
Radiant flux density is called:

radiant exitance (M_e) for emitted radiation from a surface and

irradiance (E_e) is for the radiation arriving at a surface

I_e the radiant intensity: radiant flux ϕ_e emitted per unit of solid angle (ω) by a point source in a given direction.

$$d\omega = \frac{dA}{r^2}$$



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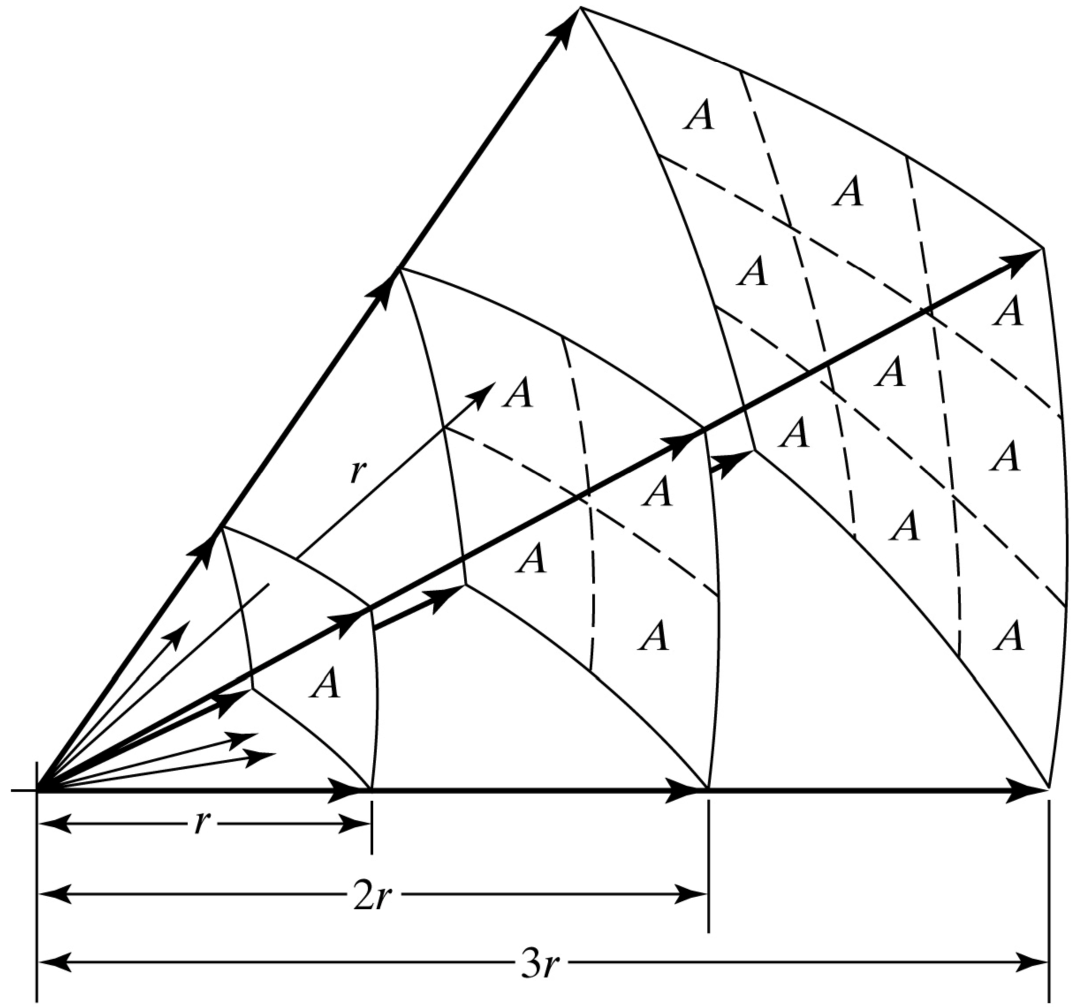
Inverse-square law of radiation from a point source



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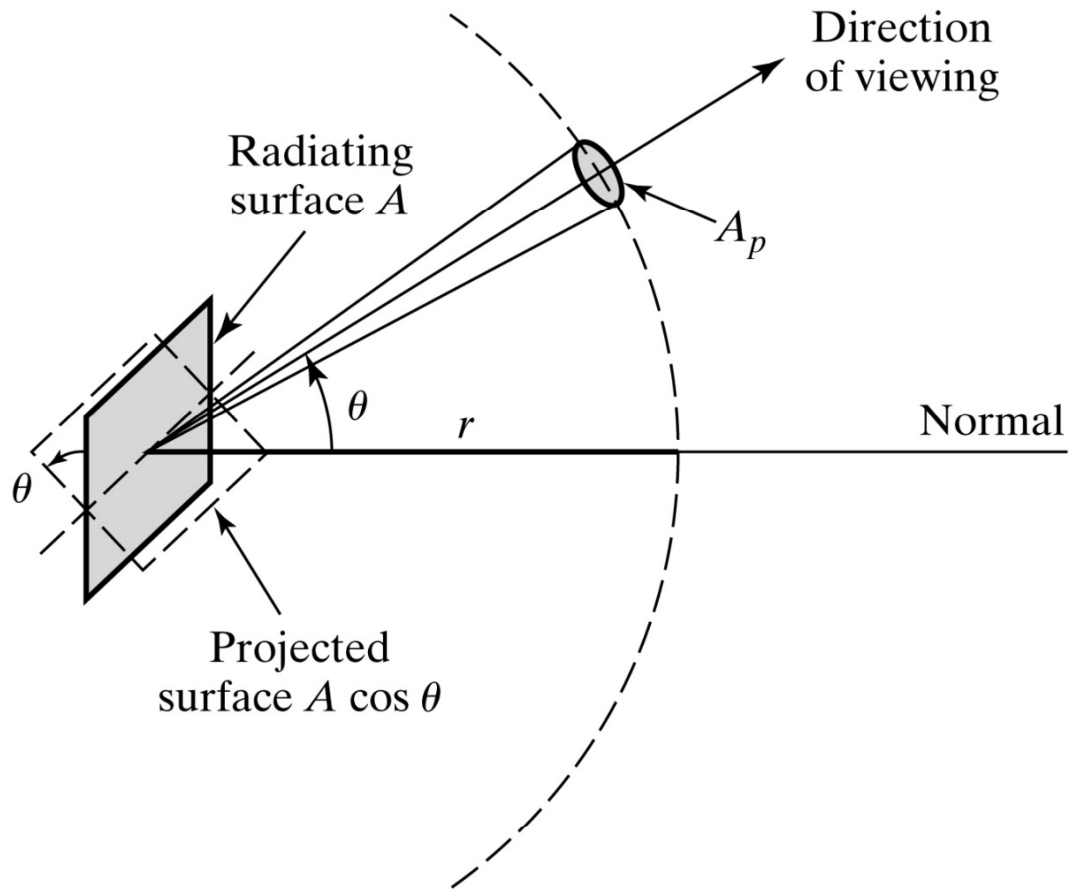

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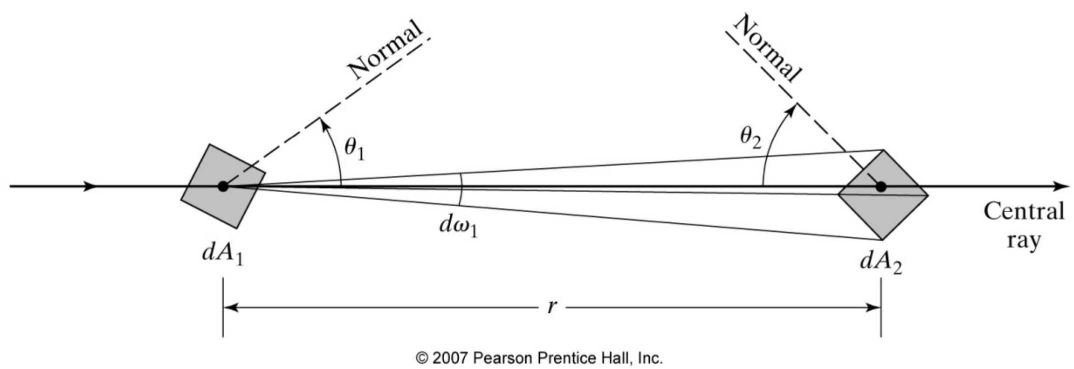
Normal
Normal
θ_1
θ_2
$d\omega_1$
dA_1
dA_2
Central ray
r
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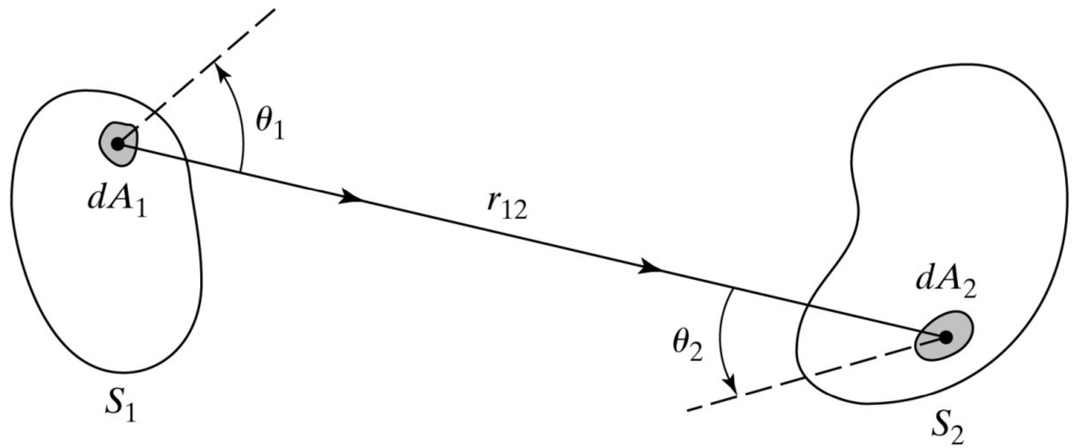

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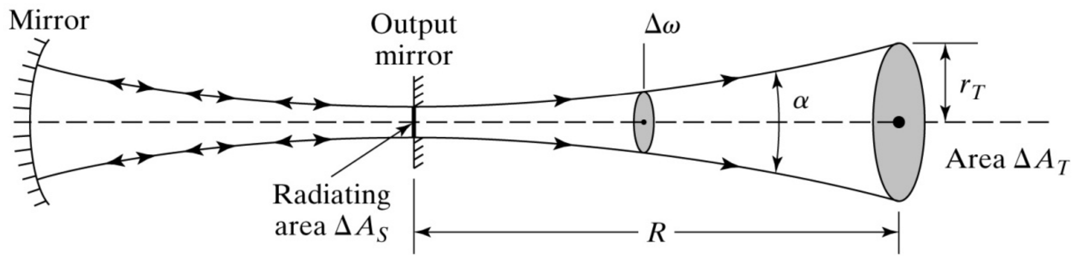
Example



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