Lecture 24:

Optical Fibers B: Types and Modes

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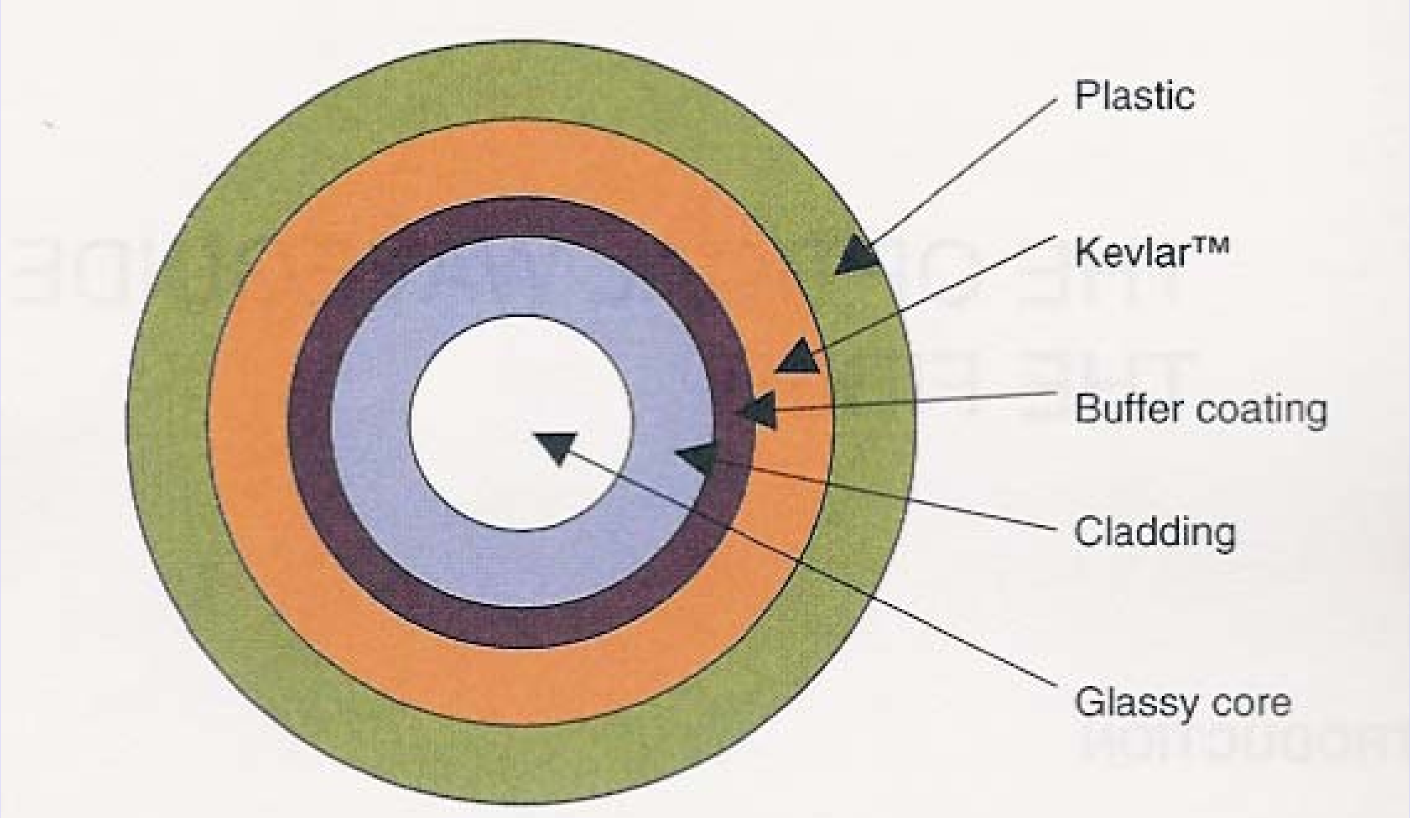
Cross section of a typical coated optical fiber

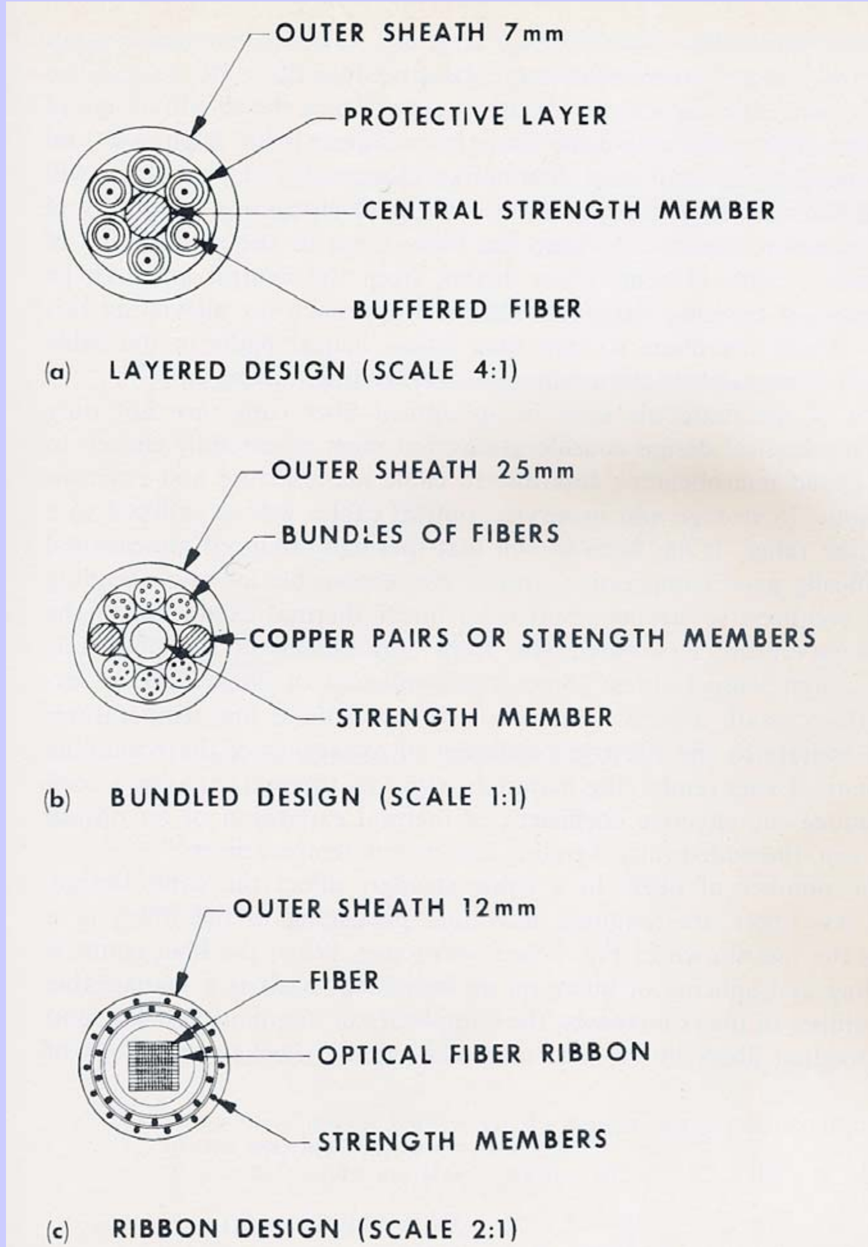
(most commercial fibers have an outer cladding diameter of 125 μm)



Cross section (not to scale)

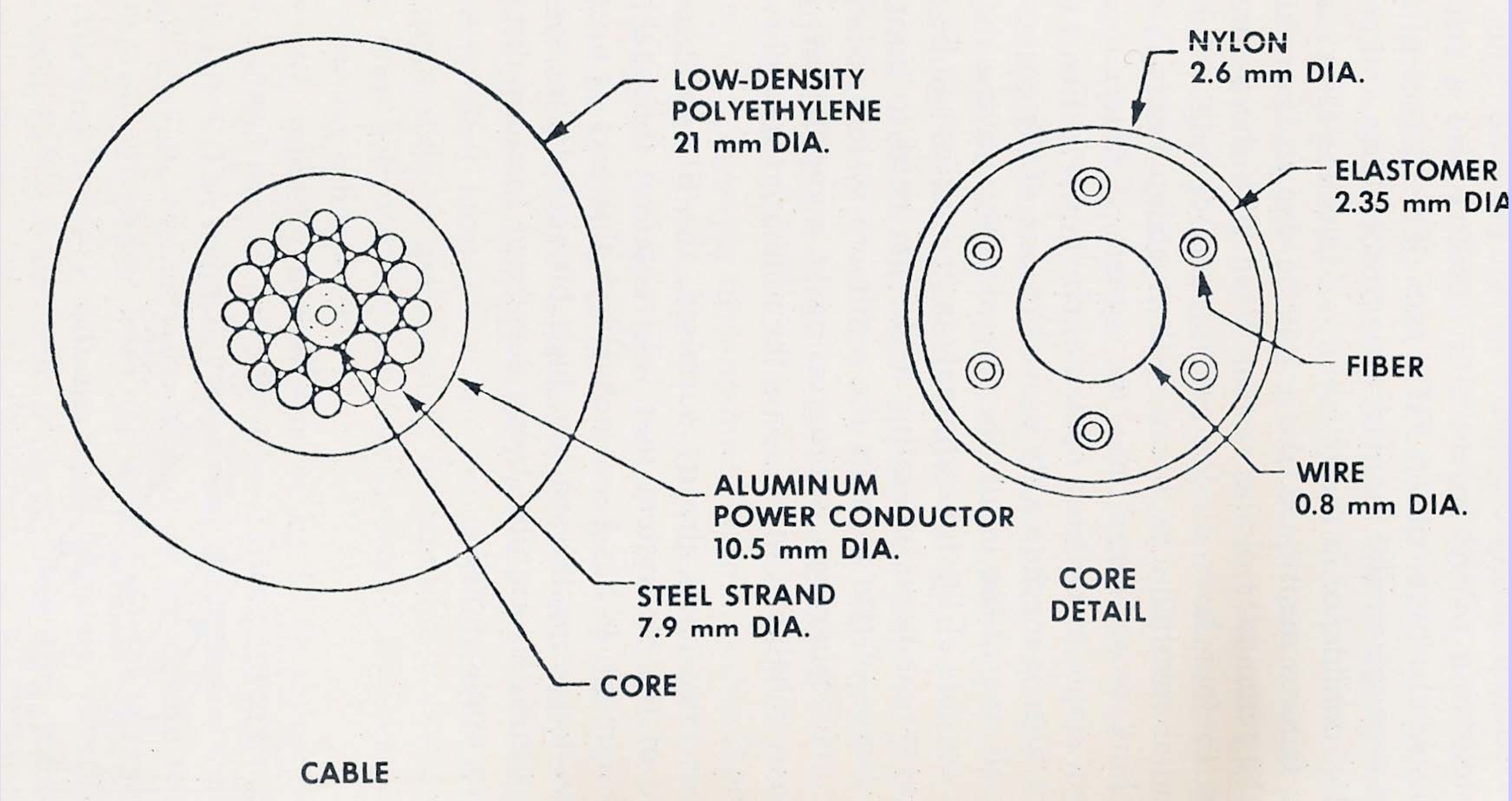
(Adapted from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

Fiberoptic **cable** designs showing placement of strength members



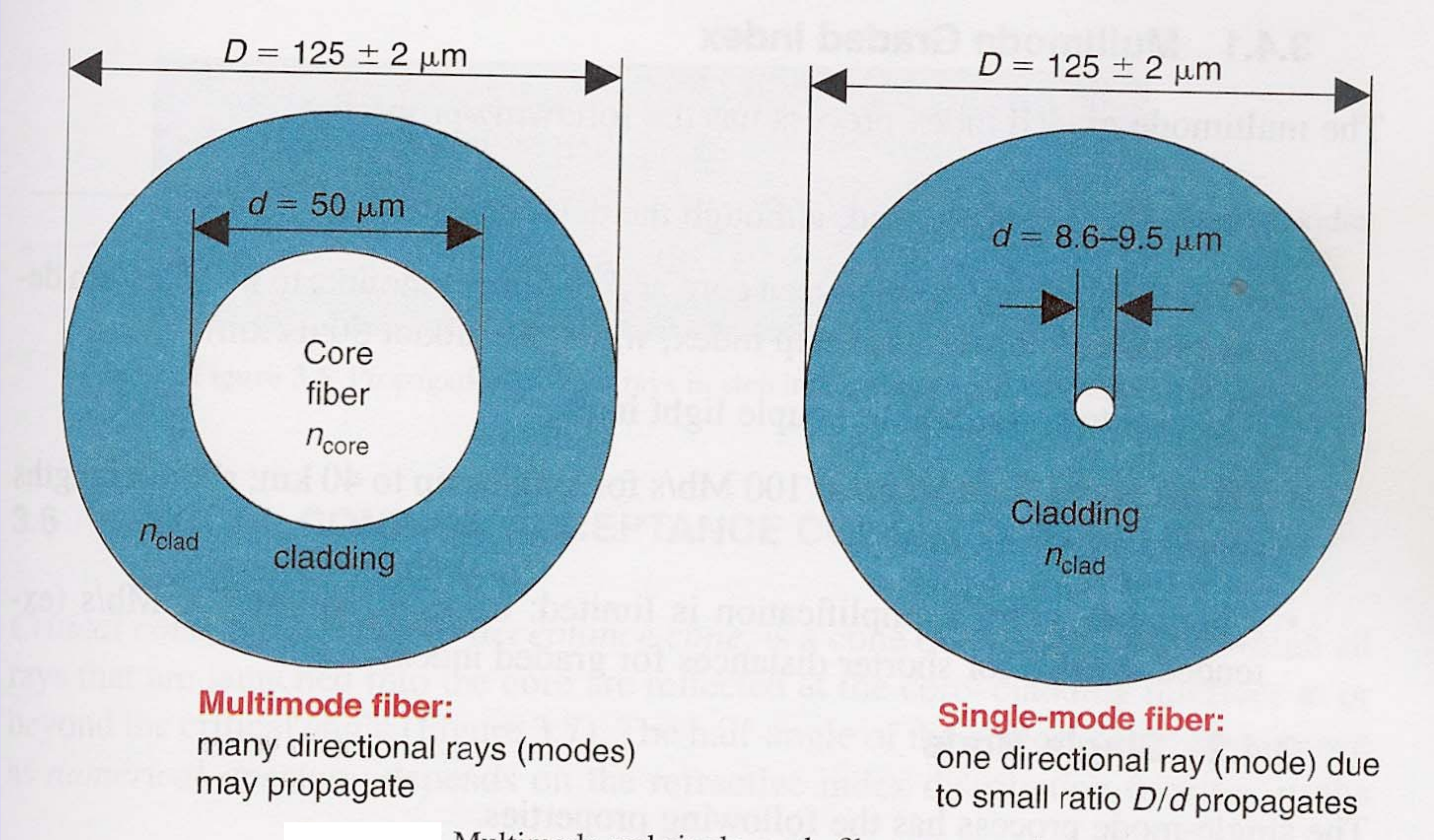
(Adapted from: *An introduction to optical fibers*, A.H. Cherin, McGraw-Hill, 1983)

Undersea fiberoptic cable



(Adapted from: *An introduction to optical fibers*, A.H. Cherin, McGraw-Hill, 1983)

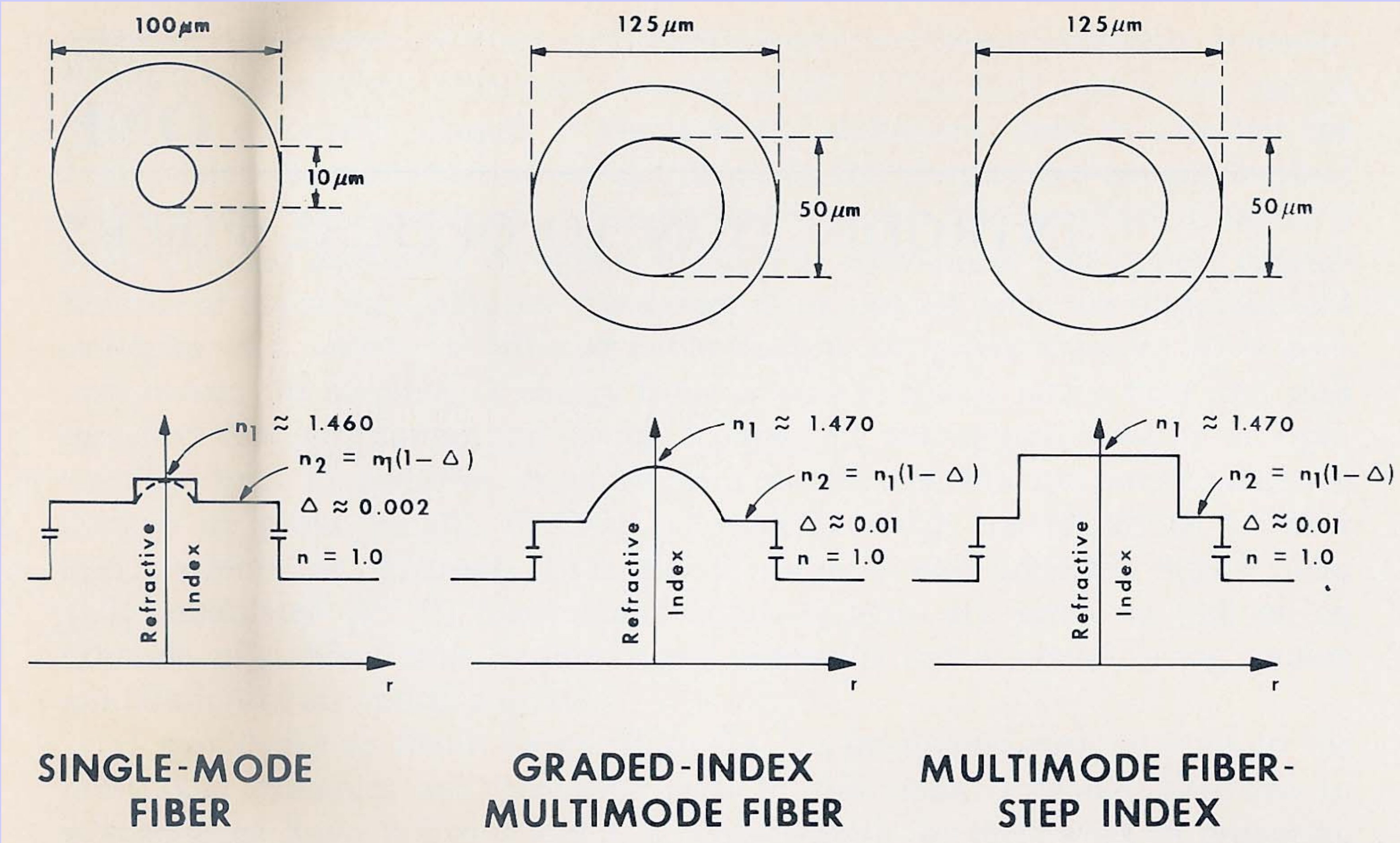
Multi mode and **single mode** optical fibers



Multimode and single-mode fiber cross section.

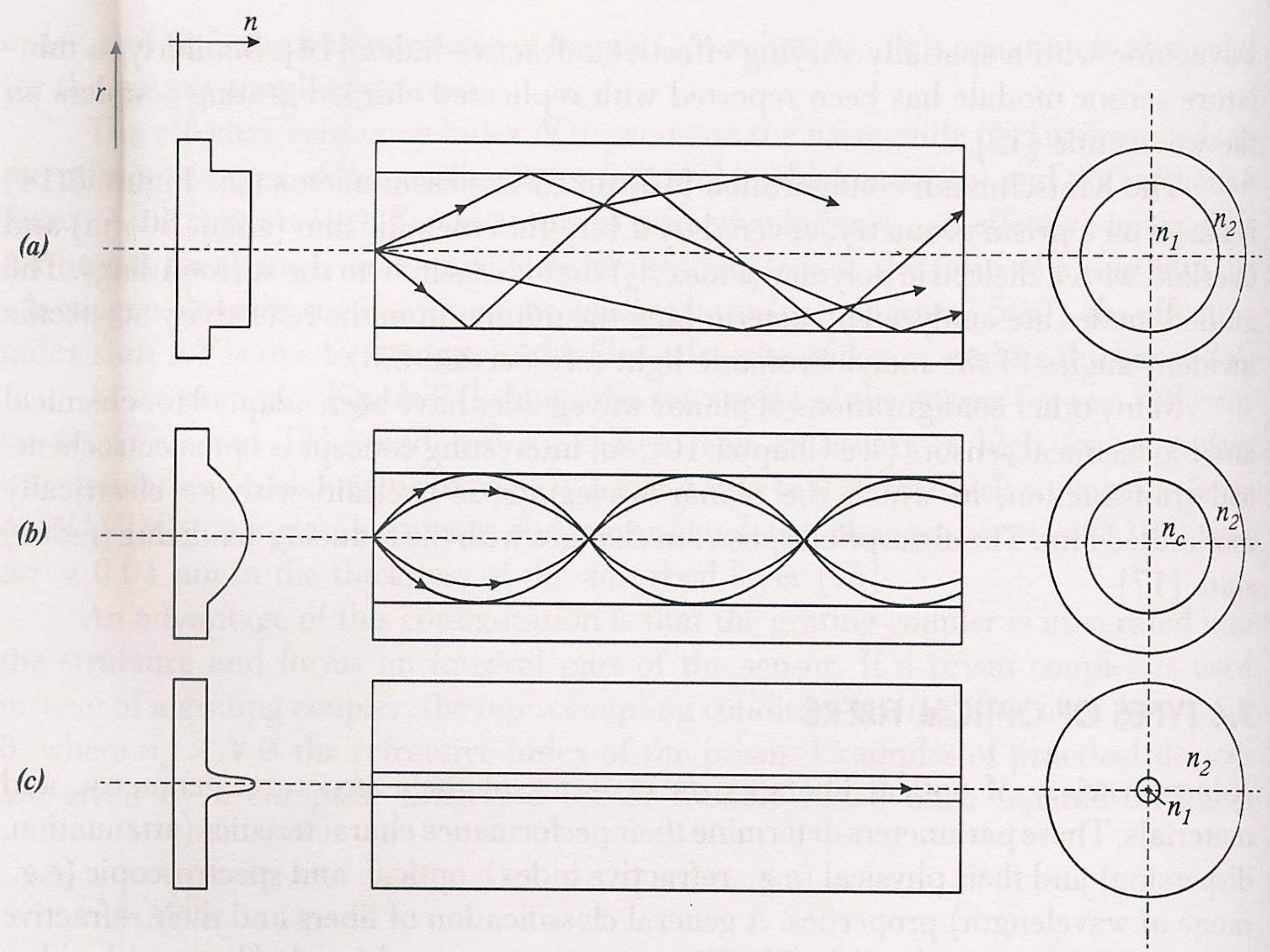
(Adapted from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

Geometrical and optical structure of **single** and **multi mode** fibers



(Adapted from: An i*ntroduction to optical fibers*, A.H. Cherin, McGraw-Hill, 1983)

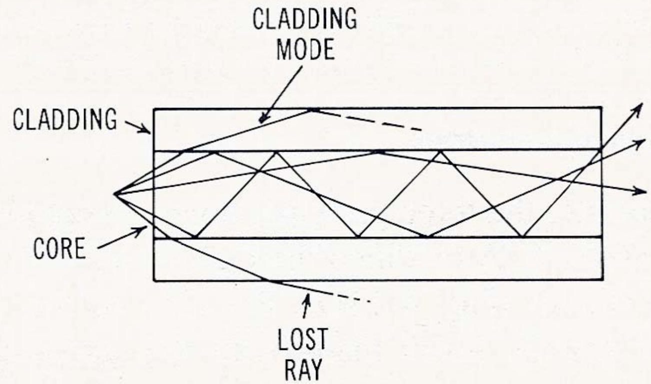
Light propagation in single and multimode fibers



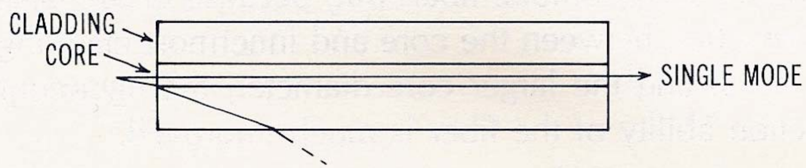
Main types of optical fiber: (a) step-index fiber, (b) graded-index fiber, and (c) monomode fiber. The figure shows the refractive index profile of the core and cladding (on left-hand side), the propagation of light rays in the fiber, and the cross-sectional structure (on right-hand side).

(Adapted from: *Chemical and biochemical sensing with optical fibers and waveguides*, Boisde and Harmer, ???, 1996)

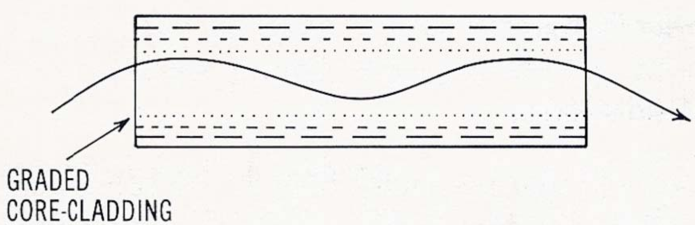
Propagating and non-propagating modes



A step-index fiber.



A monomode fiber.



A graded-index fiber. Repeated focusing and refocusing.

(Adapted from: *A Practical Introduction to Lightwave Comminications*, F.M. Mims III, H.W. Sams & Co., 1982)

Modes in an optical fiber

In a step-index multimode fiber, the question arises as to whether any light ray (or electromagnetic mode) making an angle θ with the normal to the fiber surface will propagate, as long as $\theta \geq \theta_c$. In fact, however, only certain modes, corresponding to specific values of θ, will propagate down the fiber.

The condition is that the successive wavefronts which are reflected at the core/cladding interface stay in phase and, therefore, interfere constructively (each light ray must interfere constructively with itself). This condition can be shown to lead to the equation:

$$2\, n_{core}\, d_{core} \cos\theta = m\, \lambda$$

where d_{core} is the core diameter, λ is the free space wavelength and m is an integer. The $m = 0$ mode is the axial mode and the maximum number of modes, n_{max}, corresponds to the case when $\theta = \theta_c$. If one defines the "V number" as:

$$V = \pi\, d_{core}\, NA / \lambda$$

it can be shown that, for a fiber to be *single mode* ($m < 1$, $\Rightarrow m = 0$) , it is required that $V \leq 2.405$. Therefore, a fiber may be single mode for a given wavelength, while no longer being single mode for other, shorter, wavelengths.

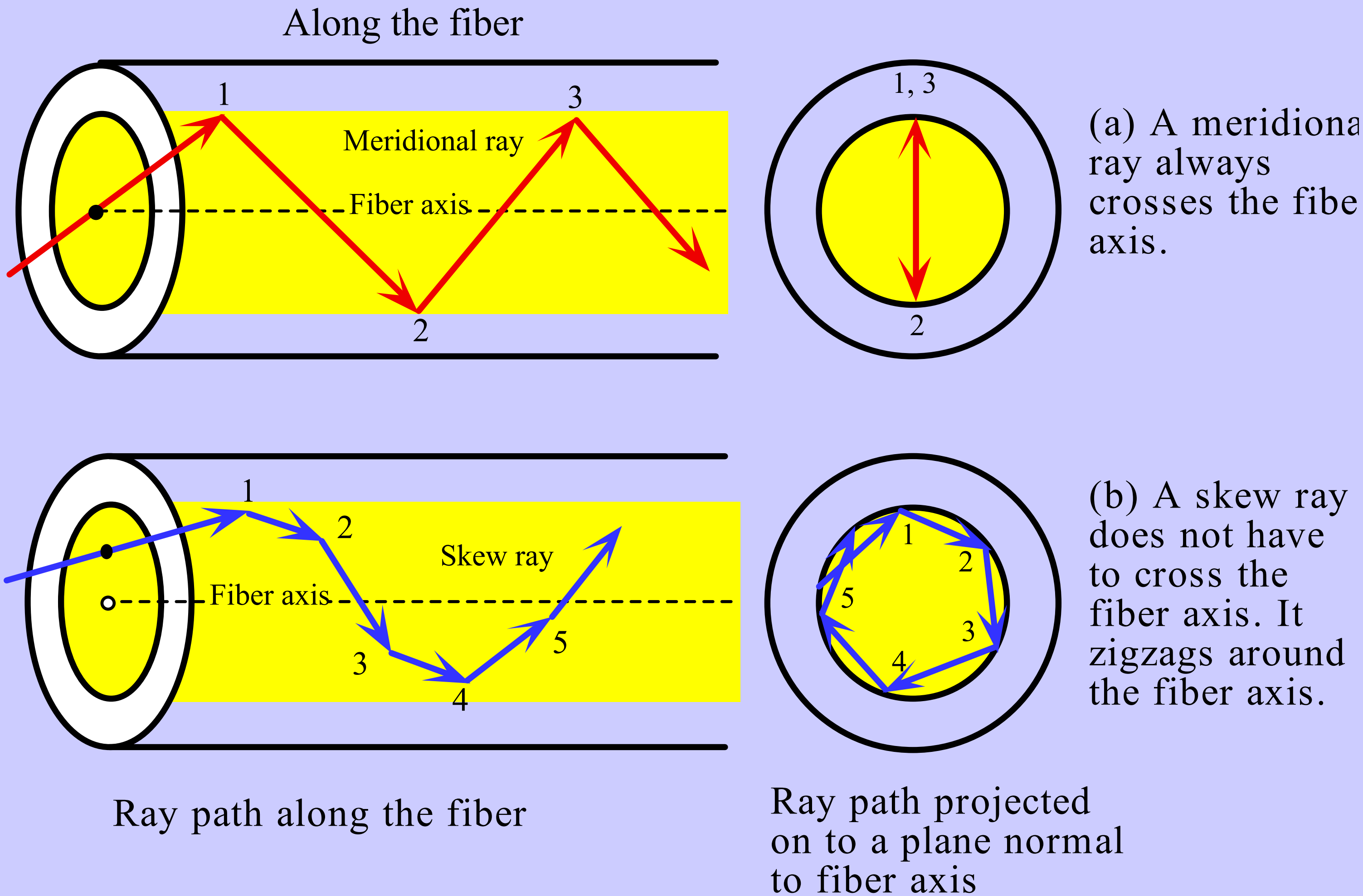
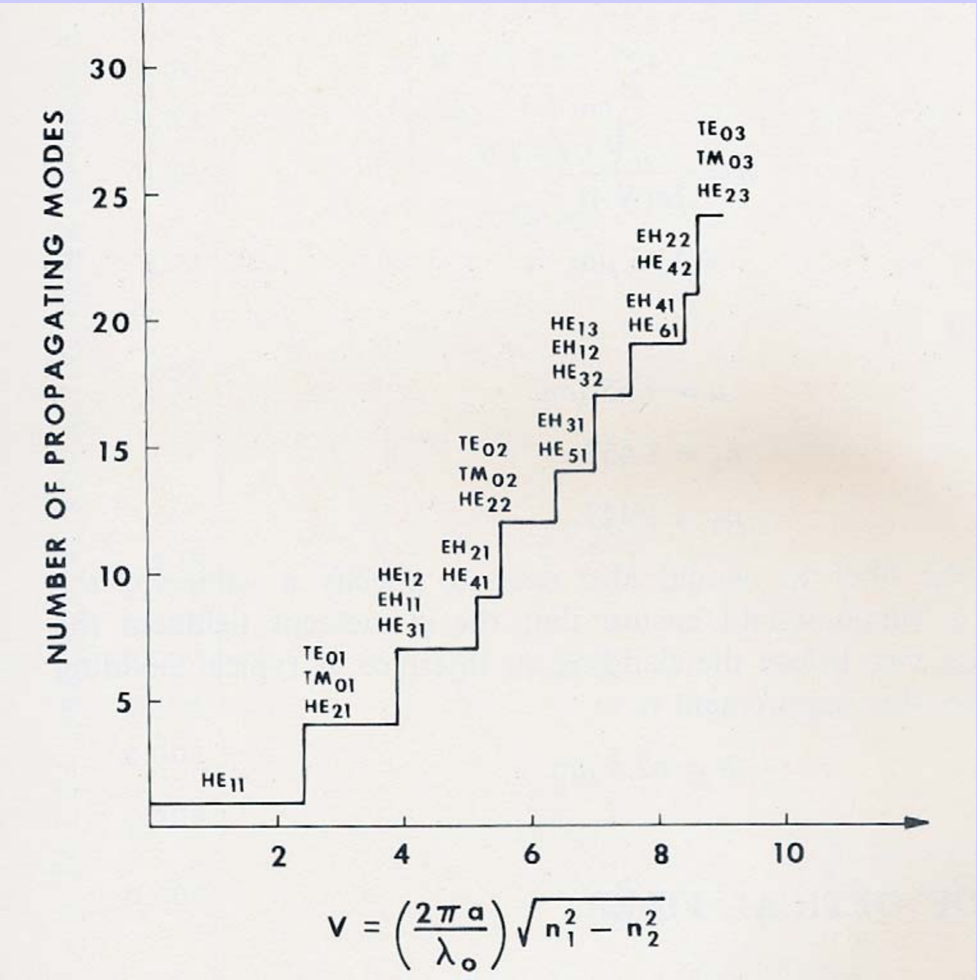


Illustration of the difference between a meridional ray and a skew ray. (Helical ray). Numbers represent reflections of the ray.

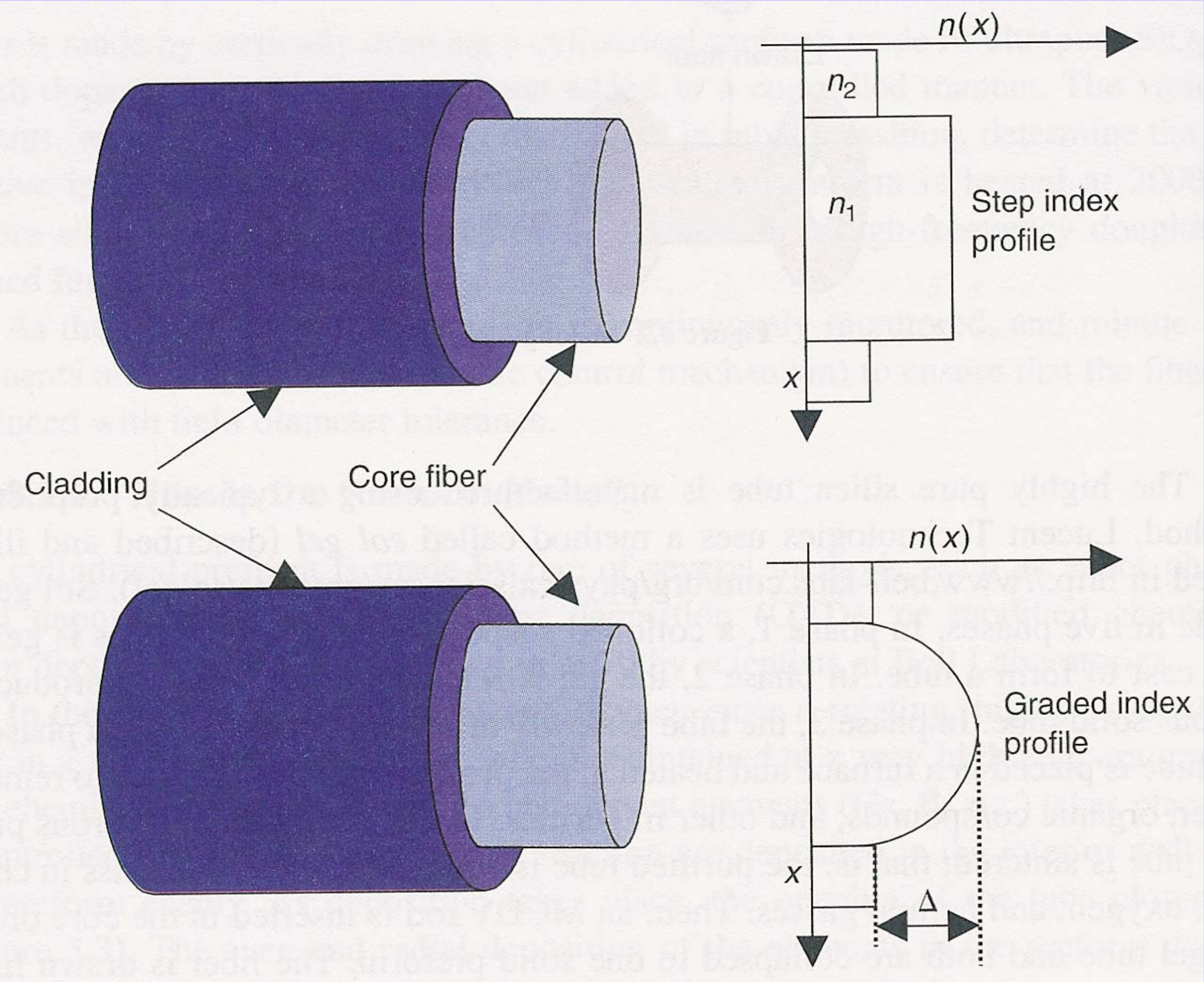
Number of fiber modes vs. the V number

The *meridional* modes (which cross the fiber axis) are either TE or TM. In the *skew* modes (which do not cross the fiber axis), *both* **E** and **H** may simultaneously have components along the propagation direction, which is the fiber axis (hybrid modes), so these modes are called HE or EH.



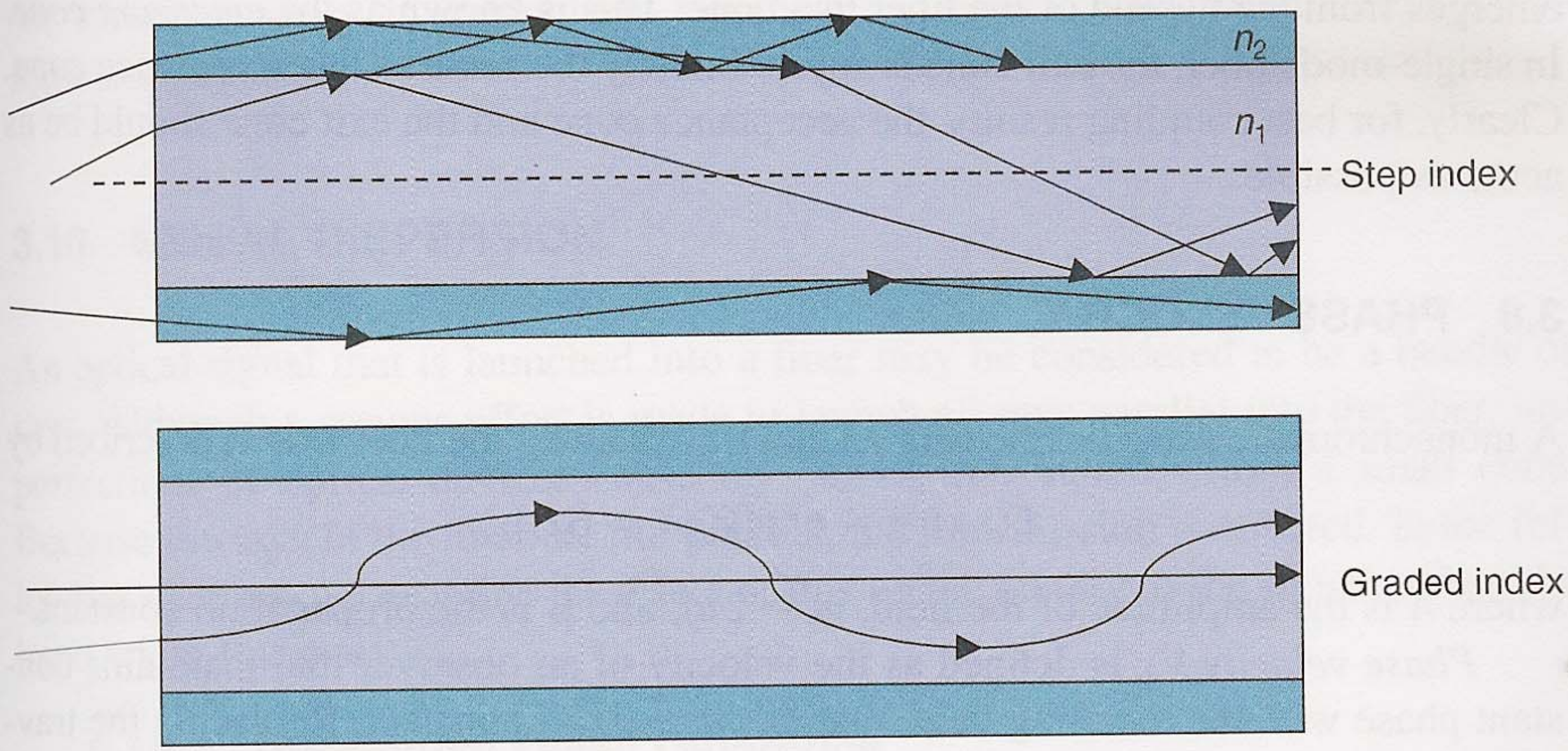
(Adapted from: *An introduction to optical fibers, A.H. Cherin, McGraw-Hill, 1983)*

Multimode optical fibers: **step** and **graded index** profiles



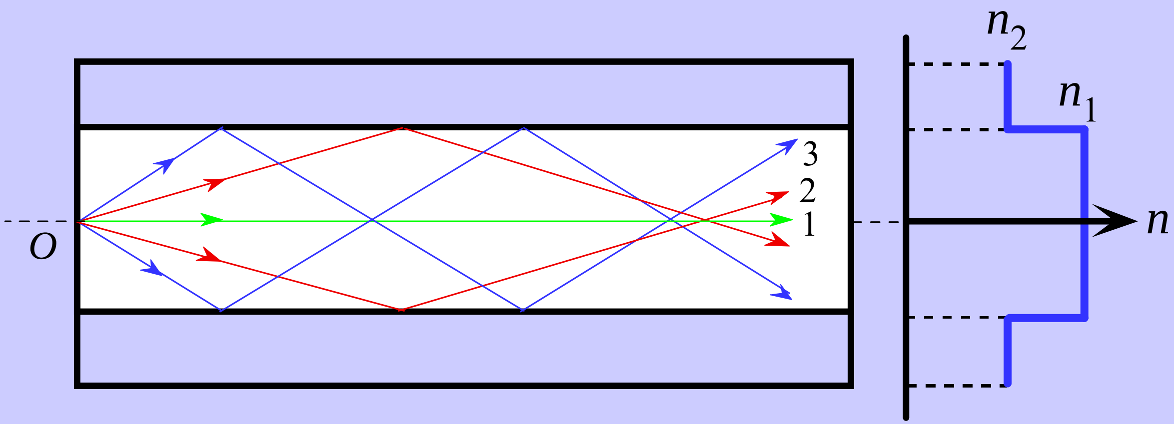
(Adapted from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

Light propagation in step and graded index fibers

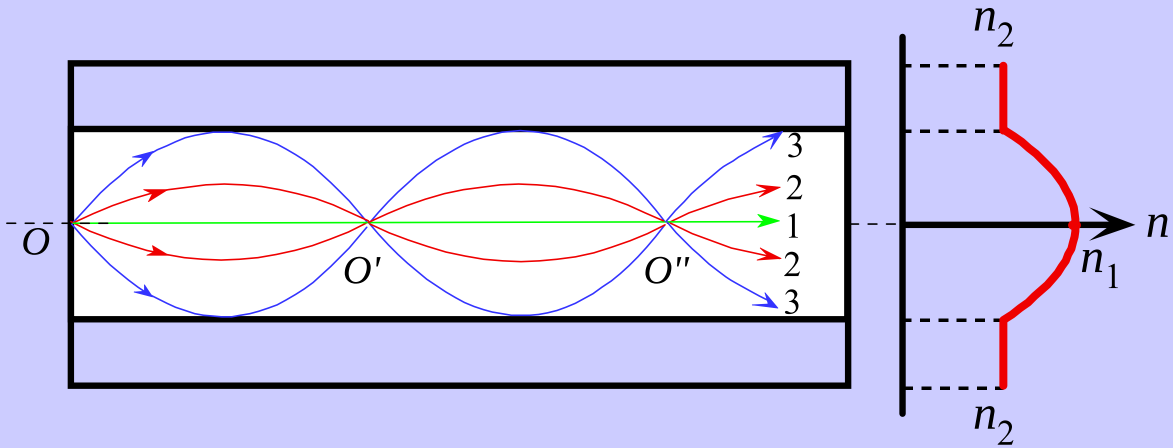


Propagation of light rays in step index and graded-index fibers.

(Adapted from: *Introduction to DWDM Technology*, S.V. Karatalopoulos, IEEE Press, 2000)



(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.



(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.
(Strictly true for meridional rays).

Fiber losses

The main optical parameters of an optical fiber are:

- numerical aperture, $NA = (n_{core}^2 - n_{clad}^2)^{1/2}$
- optical loss
- dispersion

The fiber loss may be: (1) *intrinsic* (absorption and scattering); (2) *extrinsic* (absorption by impurities like OH^- and transition metal ions such as Fe^{2+}, Fe^{3+}, Cu^{2+}, …; scattering by bubbles and microcrystals; microbending losses).

Intrinsic absorption is due to: (1) electronic (UV-visible) absorption at the Urbach edge; (2) vibrational (IR) absorption at the "multiphonon" edge.

Intrinsic scattering is due to: (1) elastic Rayleigh scattering, due to atomic scale density and compositional fluctuations which cause refractive index fluctuations, which is a function of the glass refractive index and T_g; (2) inelastic Raman / Brillouin scattering (only ~ 0.1% of the Rayleigh scattering contribution).