OPTICAL GAIN AND LASERS

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OUTLINE

I.   **DEFINITIONS, BASIC CONCEPTS**

II. **OPTICAL GAIN AND ABSORPTION**

III. **ENERGY LEVELS, OPTICAL PUMPING**

IV. **LASER TYPES**

V.   **DIODE LASERS, FIBER AMPLIFIERS**

VI. **SUMMARY**

LASER

LIGHT

AMPLIFICATION BY

STIMULATED

EMISSION OF

RADIATION

WHAT ARE PHOTONS?

- **PHOTONS ARE "QUANTA" OF LIGHT**
  - **ULTRAVIOLET, VISIBLE, INFRARED**
  - **MICROWAVES, RF, ...**

- **"WAVE - PARTICLE DUALITY" -- PHOTONS MOVE ACCORDING TO WAVE MECHANICS**
  - **MAXWELL'S EQUATIONS**
  - **QUANTUM MECHANICS**

PHOTON ENERGY

$E = h\,\nu$ E = ENERGY

h = PLANCK'S CONSTANT

$c = \lambda\,\nu$ ν = OPTICAL FREQUENCY

λ = WAVELENGTH

$E = \dfrac{h\,c}{\lambda}$ c = SPEED OF LIGHT

GREEN PHOTON:

     λ = 500 nm ν = 6 x 10^{14} Hz

     E = 4 x 10^{-19} J   1 WATT: 2.5 x 10^{18} PHOTONS / SEC

30 GHz RADIATION:

     λ = 1 cm

     E = 2 x 10^{-23} J   1 WATT: 5 x 10^{22} PHOTONS / SEC
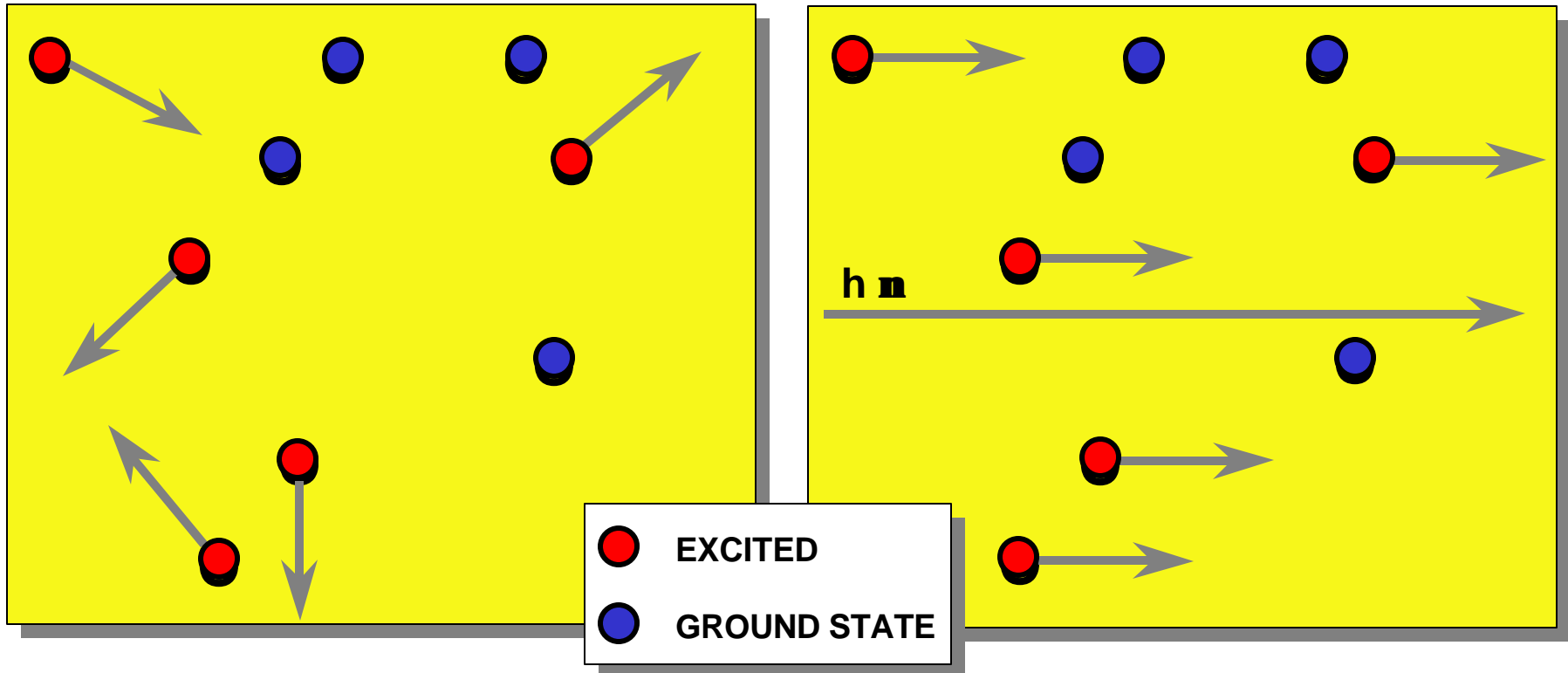
WHAT IS A LIGHT BEAM?

A LIGHT BEAM IS AN "OCEAN OF PHOTONS"

- **OCEAN**
  - BILLIONS AND BILLIONS OF WATER MOLECULES
  - HYDRODYNAMICS DESCRIBES FLUID MOTION

- **LIGHT BEAM**
  - BILLIONS AND BILLIONS OF PHOTONS
  - CLASSICAL OPTICS THEORY: MACROSCOPIC BEHAVIOR
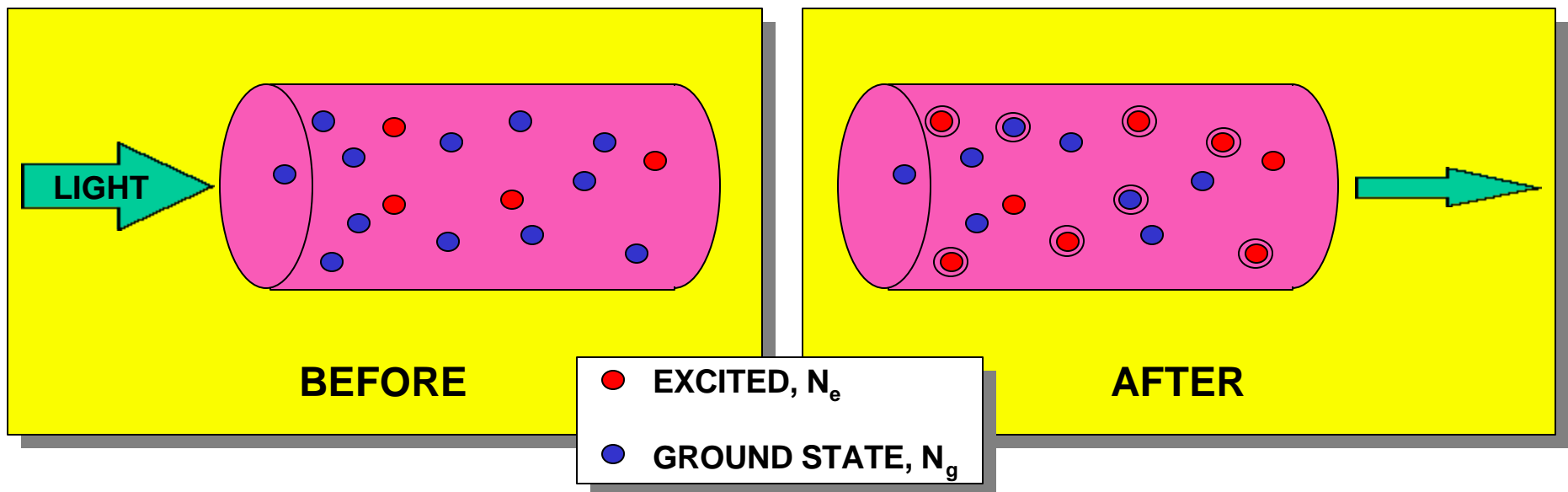 - QUANTUM MECHANICS: MICROSCOPIC BEHAVIOR
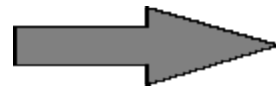
ENERGY LEVELS

- <u>**NEED TO DO WORK TO RAISE OBJECT TO "HIGHER" ENERGY STATE**</u>

- **WEIGHT-LIFTER**
  - **DOES WORK TO LIFT WEIGHTS ABOVE "GROUND" STATE**
  - **CAN LIFT TO GREATER HEIGHT (ENERGY LEVEL) BY ADDING MORE ENERGY**
  - **ENERGY RELEASED BY DROPPING TO LOWER HEIGHT**

- **ELECTRONS**
  - **LOCATED IN ORBITS AROUND NUCLEUS**
  - **ADD / SUBTRACT ENERGY (PHOTONS) FOR TRANSITION TO HIGHER / LOWER ORBIT**

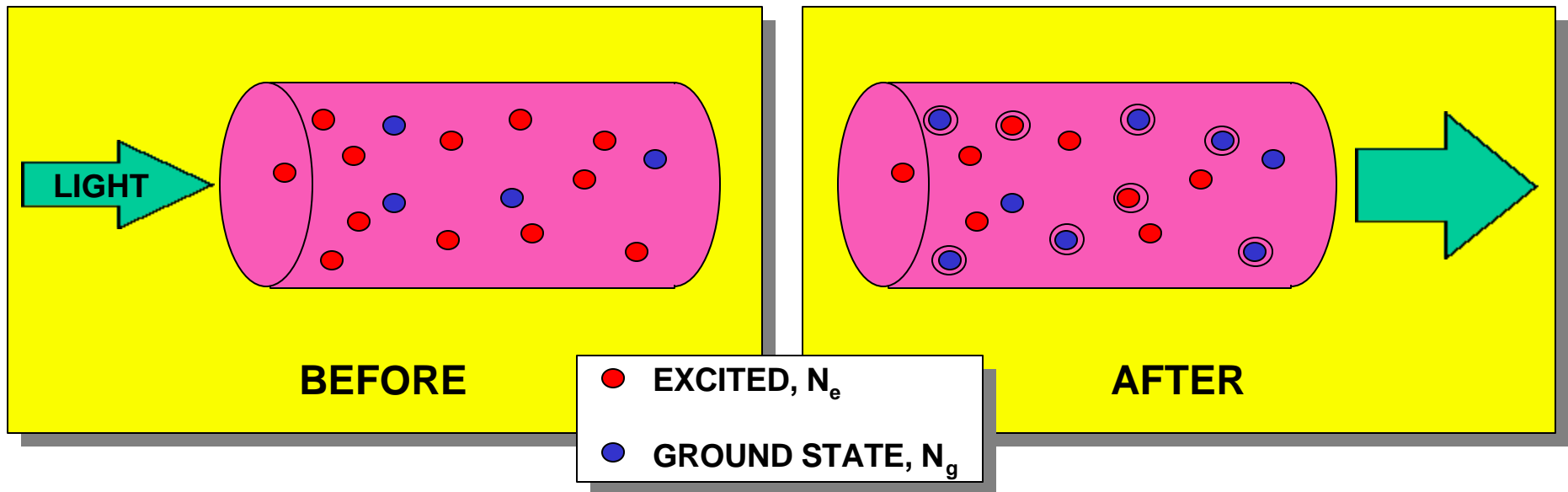# ABSORPTION / EMISSION UNDER THERMAL EQUILIBRIUM

LIGHT

BEFORE

AFTER

- ● EXCITED, N_e
- ● GROUND STATE, N_g

- ABSORPTION ~ N_g
- EMISSION ~ N_e
- $N_g > N_e$

ABSORPTION WINS UNDER THERMAL EQUILIBRIUM!

POPULATION INVERSION ENABLES OPTICAL GAIN

LIGHT

BEFORE   AFTER

● EXCITED, N_e

● GROUND STATE, N_g

- ABSORPTION $\sim N_g$
- EMISSION $\sim N_e$
- $N_e > N_g$

EMISSION WINS WITH

POPULATION INVERSION!

N_2
E_2 ooo

N_1
E_1 oooooooo

N_0
E_0 oooooooooooooo

N_2
E_2 ooo

N_1
E_1 oooooooooooooo

N_0
E_0 oooooooo

THERMAL EQUILIBRIUM

POPULATION INVERSION

$$N_i \sim \exp\left[-\frac{E_i}{kT}\right]$$

POPULATION

ENERGY

$$N_1 > N_0$$

ABSORPTION / EMISSION UNDER THERMAL EQUILIBRIUM

$$N_2$$
$$E_2 \; \text{ooo}$$

$$N_1$$
$$E_1 \; \text{ooooooooo}$$

EMISSION

$$h\nu = E_1 - E_0$$

ABSORPTION

$$N_0$$
$$E_0 \; \text{oooooooooooooooo}$$
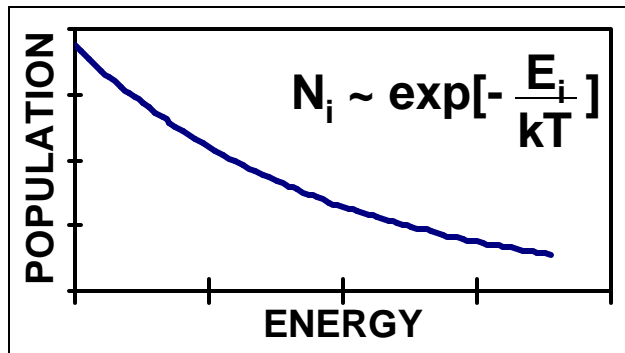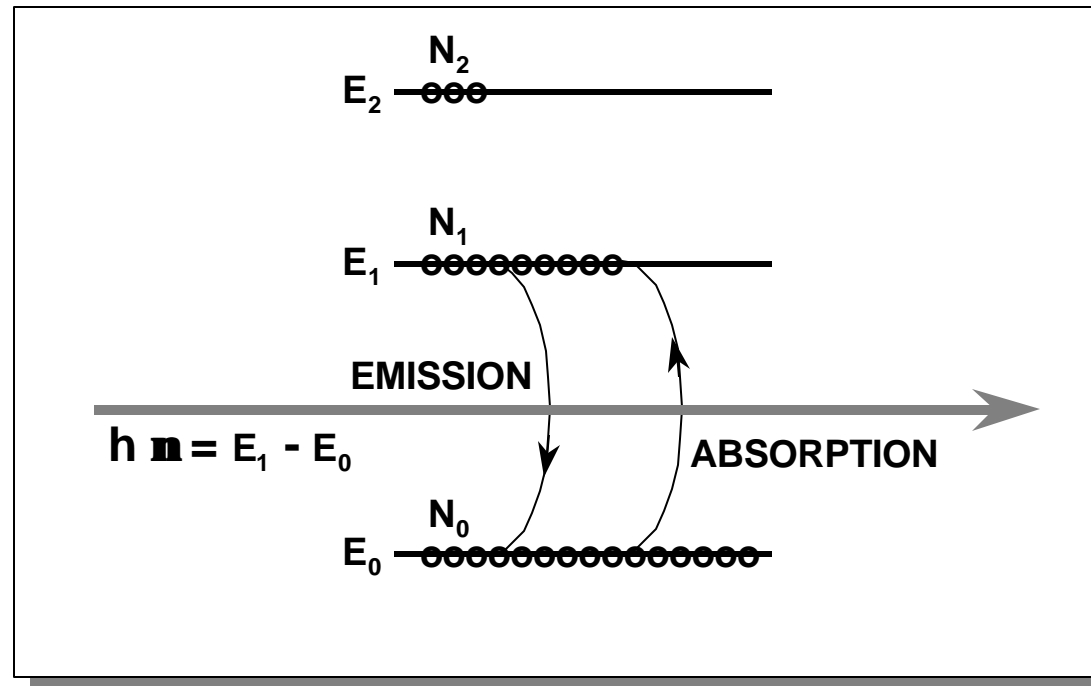
- ABSORPTION $\sim N_0$
- EMISSION $\sim N_1$
- $N_0 > N_1$

ABSORPTION WINS UNDER THERMAL EQUILIBRIUM!

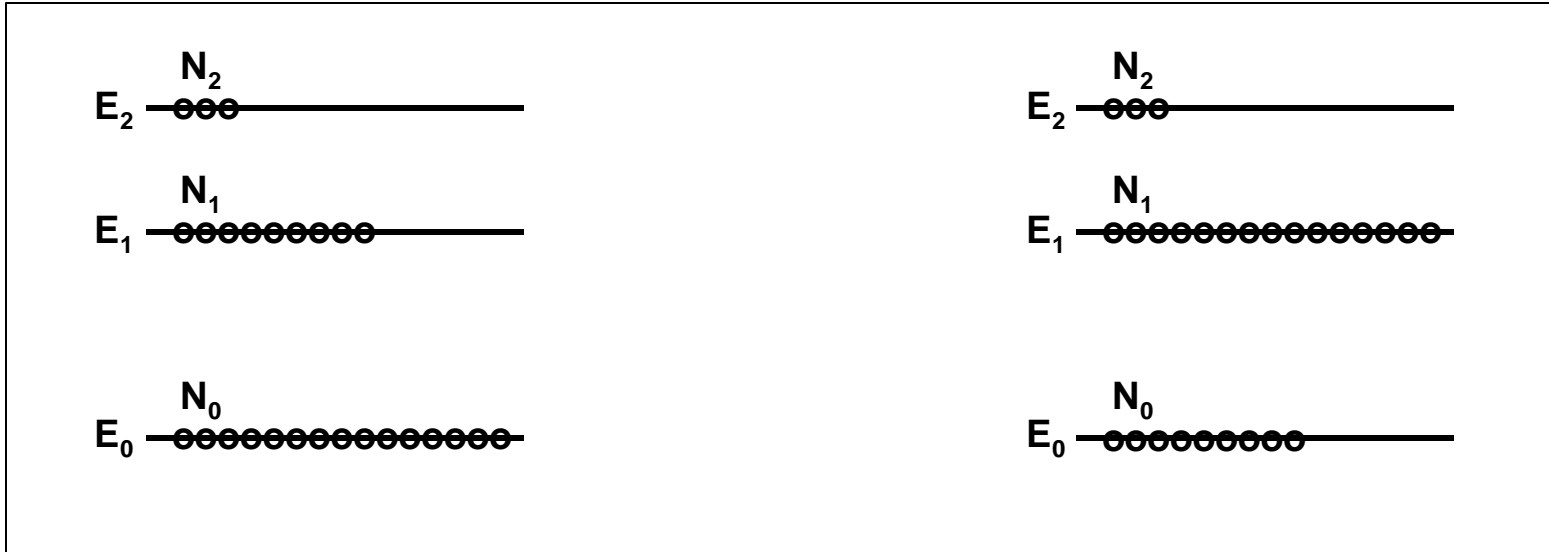# POPULATION INVERSION ENABLES OPTICAL GAIN

E_2 — N_2 ooo

E_1 — N_1 oooooooooooooooo

EMISSION

$h\nu = E_1 - E_0$ ABSORPTION

E_0 — N_0 ooooooooo
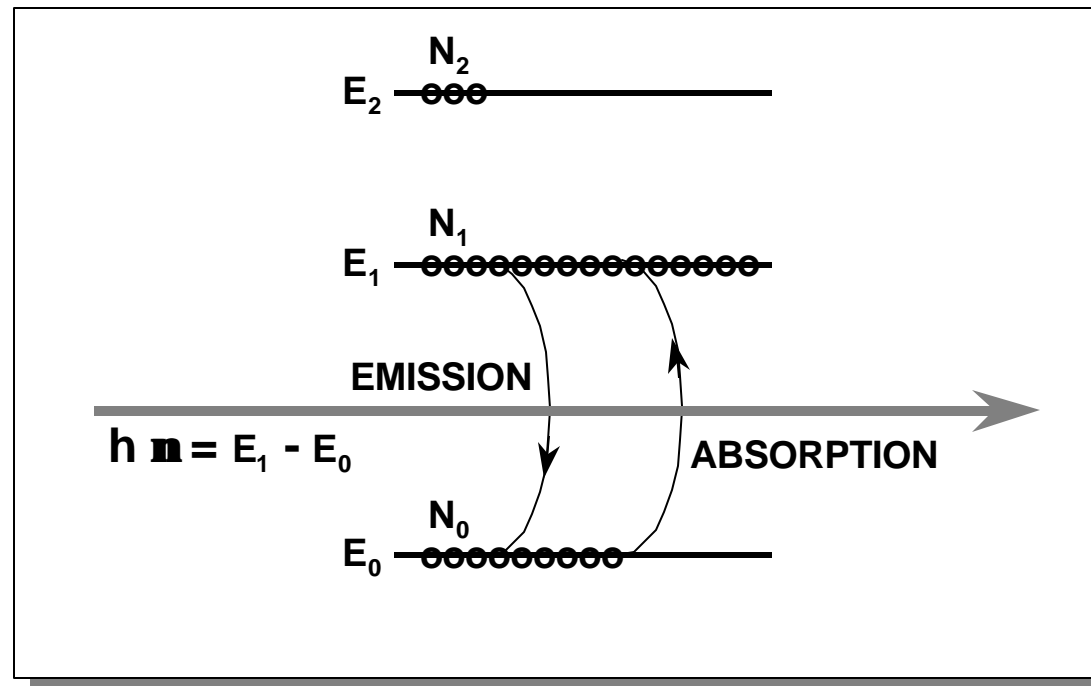
- ABSORPTION ~ N_0
- EMISSION ~ N_1
- $N_1 > N_0$

EMISSION WINS WITH POPULATION INVERSION!

ACHIEVING POPULATION INVERSION

- **IDENTIFY CANDIDATE ATOMS / MOLECULES**
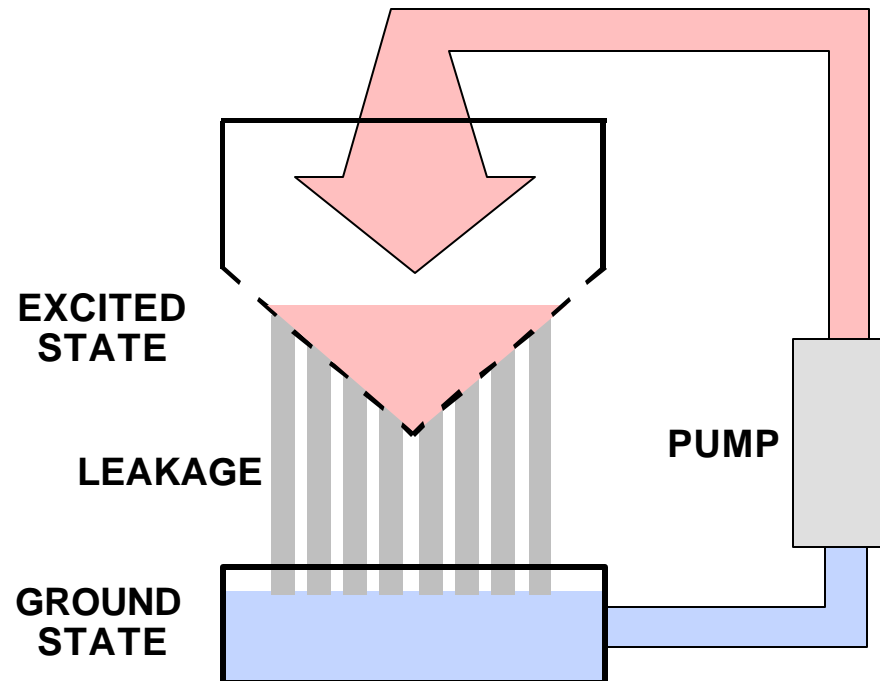 - **PHOTON ENERGY FOR DESIRED WAVELENGTH**
  - **EXCITED-STATE LIFETIME ~ 0.1 TO 10 msec**
  - **STRONG STIMULATED-EMISSION**

- **DEVELOP "PUMPING" MECHANISM**
  - **OPTICAL**
  - **ELECTRIC DISCHARGE**
  - **CHEMICAL REACTION**
  - **CHARGE INJECTION**

"ATOMIC SIEVE"

EXCITED STATE

LEAKAGE

PUMP

GROUND STATE

STEADY-STATE LEVEL HEIGHT:

- BALANCE BETWEEN PUMP RATE AND LEAKAGE
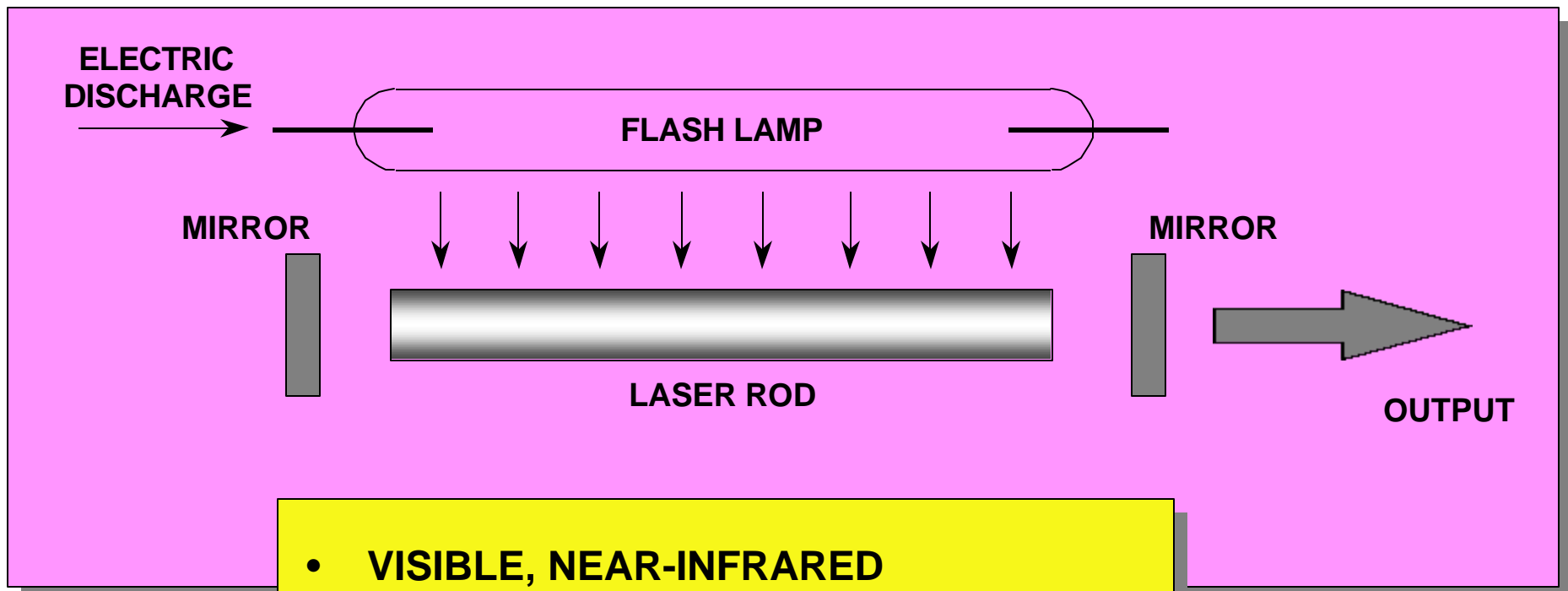- "ANYTHING WILL LASE IF YOU PUMP IT HARD ENOUGH"

TYPES OF LASERS

- **SOLID-STATE LASERS**
  - **RUBY**
  - **Nd: YAG**

- **CARBON-DIOXIDE, He-Ne**

- **CHEMICAL**

- **DIODE**

- **FIBER**

SOLID-STATE LASERS

ELECTRIC DISCHARGE

FLASH LAMP

MIRROR

MIRROR

LASER ROD

OUTPUT

- **VISIBLE, NEAR-INFRARED**
- **WORLD'S FIRST LASER: RUBY**
- **Nd:YAG MOST COMMON TYPE**
  - **RANGEFINDERS / DESIGNATORS**
  - **CUTTING / WELDING: 1 TO 4 kW**
  - **TYPICALLY ~ 1 TO 5 % EFFICIENCY**

CARBON-DIOXIDE / HeNe LASERS

- **ELECTRIC DISCHARGE -- "NEON SIGN"**
  - **LONGITUDINAL OR TRANSVERSE**
  - **DC, RF; CONTINUOUS, PULSED**

- **CARBON-DIOXIDE ($\lambda \sim 10$ mm)**
  - **MATERIALS PROCESSING: 0.1 TO 4 kW**
  - **TYPICALLY ~ 10 % EFFICIENCY**

- **HeNe (λ = 630 nm, OTHERS)**
  - **SUPERMARKET SCANNERS**
  - **ALIGNMENT**
  - **~ 1 TO 30 mW**

CHEMICAL LASERS

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- EXOTHERMIC CHEMICAL REACTION PRODUCES POPULATION INVERSION

- HF / DF; IODINE

- TYPICAL $l \sim 1$ TO $5 \, \mu m$

- WEAPONS APPLICATIONS

IDEAL OPTICAL WIRELESS LASER

- **ALL SOLID STATE**
  - **NO SEALS**
  - **NO CORROSION**
  - **NO LOST MEDIUM**
- **EFFICIENT**
- **COMPACT, LIGHT-WEIGHT**
- **PACKAGING FLEXIBILITY**
- **POWER-SCALABLE**
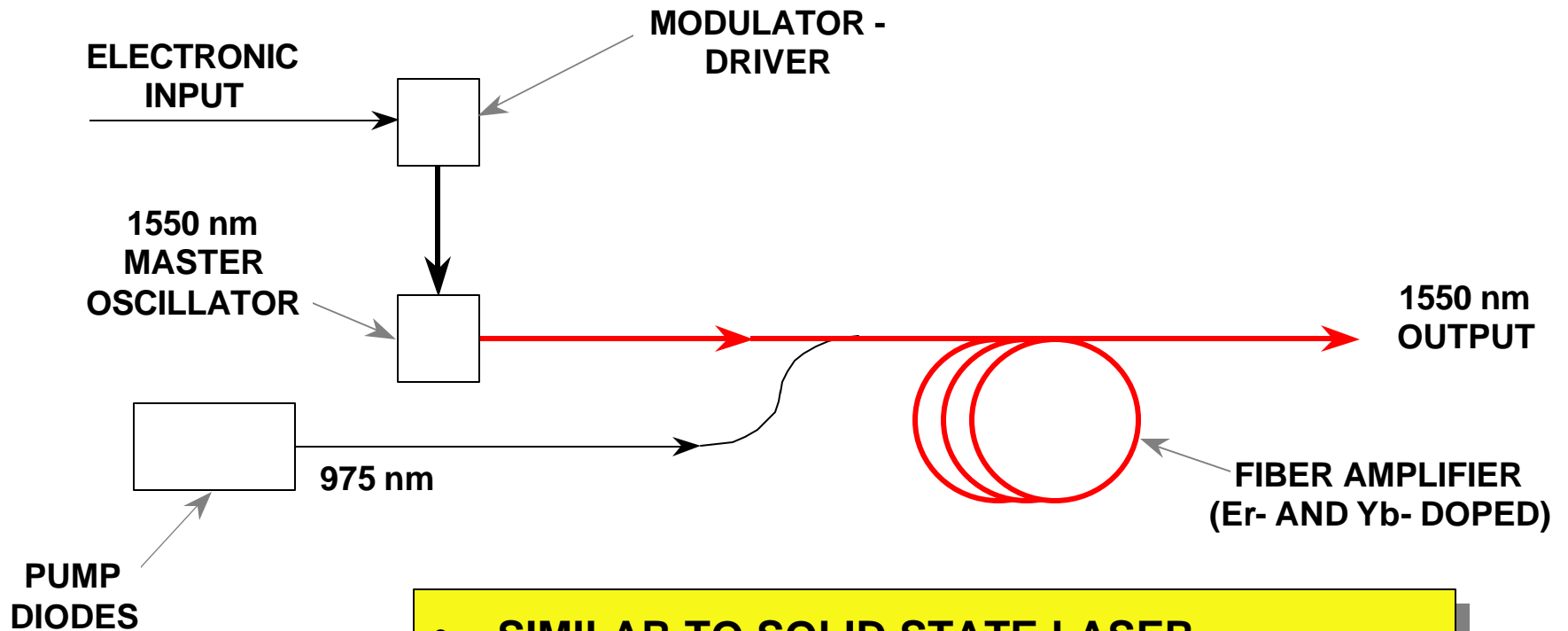
"AND THE ANSWER IS ...."

DIODE LASERS

- **FORWARD BIAS ON DIODE "INJECTS" ELECTRONS INTO CRYSTAL, CREATING POPULATION INVERSION**

- **WAVELENGTHS FROM ~ 500 nm TO 1600 nm AND LONGER**

- **COMPACT, EFFICIENT (~ 50 %), LONG LIFE (MTBF ~ 10^6 hrs)**

- **COMMUNICATIONS, PRINTERS, OPTICAL MEMORY, PUMP FOR SOLID-STATE LASERS, ...**

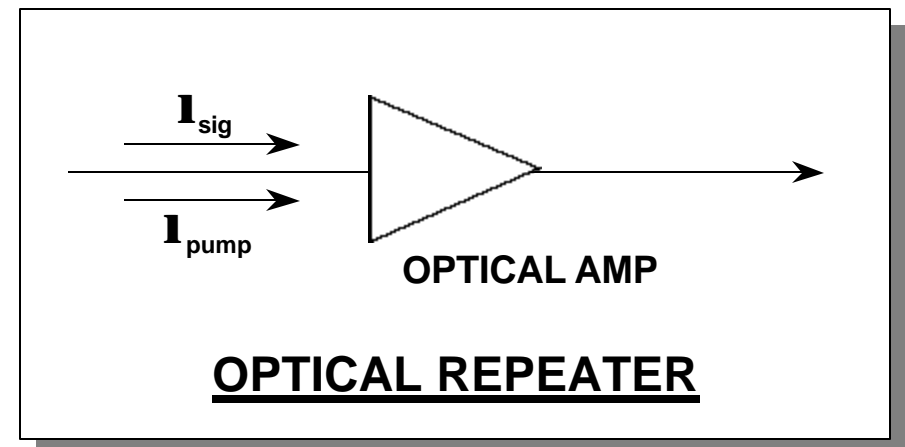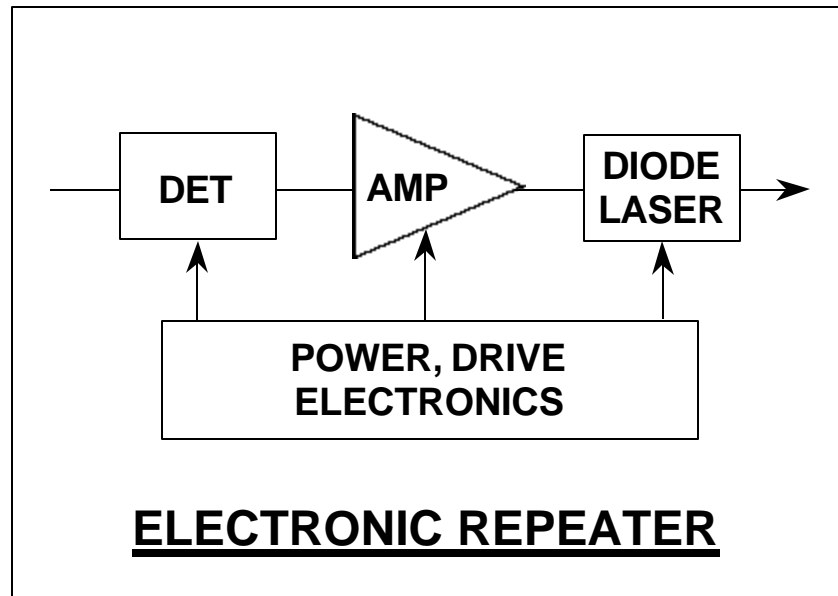- **POWER SCALING USING OPTICAL AMPLIFIERS**

FIBER AMPLIFIER

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01-02-22

ELECTRONIC
INPUT

MODULATOR -
DRIVER

1550 nm
MASTER
OSCILLATOR

1550 nm
OUTPUT

975 nm

PUMP
DIODES

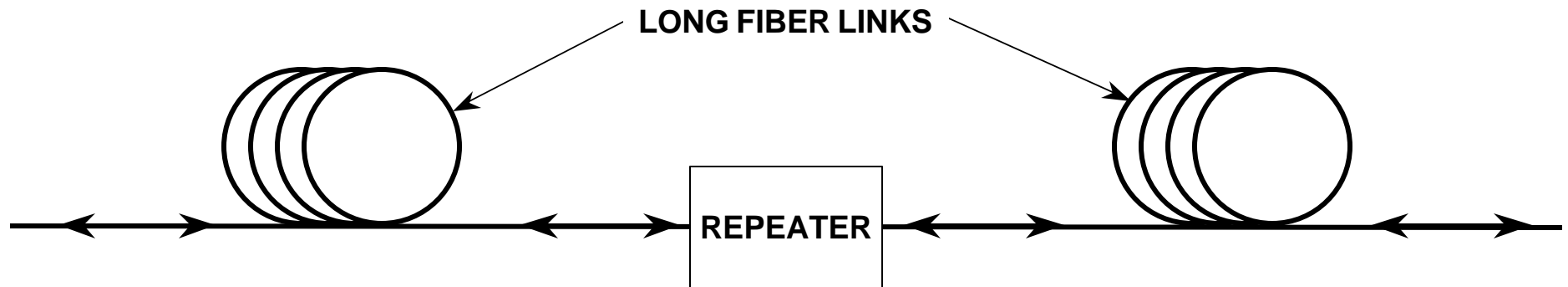FIBER AMPLIFIER
(Er- AND Yb- DOPED)

- **SIMILAR TO SOLID-STATE LASER**
- **DIODE-LASER EXCITATION**
  - **HIGH EFFICIENCY**
  - **LONG LIFETIME**
- **REVOLUTIONIZED FIBER COMMUNICATIONS**

FIBER AMPLIFIER IN TERRESTRIAL TELECOM

LONG FIBER LINKS

REPEATER

DET | AMP | DIODE LASER

POWER, DRIVE ELECTRONICS

ELECTRONIC REPEATER

I_{sig}

I_{pump}

OPTICAL AMP

OPTICAL REPEATER

FIBER AMPLIFIER FEATURES

- **DIODE-PUMPED (EFFICIENCY, LIFETIME)**

- **SINGLE TRANSVERSE MODE -- MINIMUM BEAM DIVERGENCE**

- **RUGGED, MONOLITHIC STRUCTURES**

- **SPLICES, PIGTAILS, GRATING REFLECTORS**

- **LIGHT WEIGHT**

- **ACCESS TO LOW-GAIN WAVELENGTHS**

- **ACCESS TO LOW-ABSORPTION PUMP BANDS**

- **EXPLOIT BROAD-BASED TECHNOLOGY INFRASTRUCTURE**

SUMMARY

- **PHOTONS -- A CONCEPT NECESSARY TO UNDERSTAND ABSORPTION AND EMISSION OF LIGHT**

- **OPTICAL GAIN REQUIRES:**
  - **"PUMPING" MECHANISM**
  - **POPULATION INVERSION -- NON-EQUILIBRIUM STATE**

- **LASERS: OPTICAL AMPLIFIERS WITH FEEDBACK**

- **FIBER LASERS / AMPLIFIERS**
  - **REVOLUTIONIZED COMMUNICATIONS**
  - **BROAD-BASED INFRASTUCTURE**
  - **ADVANCED DESIGNS ENABLE PRACTICAL HIGH-POWER DEVICES (> 1 WATT)**