From Lasers to LCDs: Light at Work

Cluster 5
Prof. Charles Tu, ctu@ucsd.edu
Department of Electrical & Computer Engineering

Taiwan → US (grade 10) → Canada (grade 11, 12; B.Sc., Physics, McGill Univ., Montreal) → Yale University (Ph.D.) → AT&T Bell Labs, NJ → UC San Diego (since 1988)
Tuna Crabs at La Jolla Shores 3/11/2017
Great White Shark, Quadalupe Island, MX
10/25/2017
I am going to be in

A. 9th grade

B. 10th grade

C. 11th grade

D. 12th grade

E. Freshman in college
I am from

A. San Diego County

B. Southern California, other than San Diego County

C. Bay Area

D. Others
A. I have been exposed to Optics/Photonics

B. I have been exposed to electronic energy levels in a atom (s, p, d, f, …)

C. A+B
Cluster 5 is my

A. 1st choice

B. 2nd choice

C. None of above
Introducing Ourselves

• Name, grade, school, town

• One thing you want us to know about you
  – Notable happening/accomplishment
  – Hobby, sport, musical instrument, …

• What do you expect from attending COSMOS?

• What do you expect from this Cluster?
The International Year of Light and Light-based Technologies 2015

http://www.light2015.org
Optical Society of America
Photonics - the application of light – in

- Manufacturing
- Communications and Information Technology
- Defense and National Security
- Energy
- Health and Medicine

Learn more at http://www.lightourfuture.org/
What is Photonics?

Light-based technologies will be the economic driver of the 21st century as electronics was for the 20th century.
THE ELECTROMAGNETIC SPECTRUM

We are surrounded by electromagnetic radiation (EMR) like never before. Studies link EMR to Cancer, Alzheimer’s, Autism, chronic fatigue, headaches and other health issues.

http://www.indoorenirosolutions.com/emfsemr-information.html
Four technologies underpin the phenomenal changes in the communications infrastructure

**Technology**

- Integrated Circuits
- Photonics
- Communications
- Software
- Wireless

**Trend**

- X2 in density/speed every 18-24 months
- X2 in transmission capacity and networking flexibility every year—wavelength division multiplexing (WDM)

*After Arun Netravali (2002)*
Sending Data on a Fiber

Data is sent as individual pulses of (laser) light on a fiber

A different stream of data can be sent on each color of light

Modern fiber systems can have hundreds of colors, spaced very close together
What do we study and do?

- **Light comes from electrons transitioning from higher energy to lower energy levels.**
- **Wave-particle nature of light**
  - Wave nature: refraction, diffraction, interference (labs)
  - Particle nature: photons
- **Generating light**
  - LED, laser
- **Detecting light**
  - Solar cell, photodetector
- **Transmitting light**
  - Fiber
- **Manipulating light**
  - Lens, structural coloration
- **Using light (projects)**
  - Spectrometer, holography, plastic lens, (berry-juice) dye-sensitized solar cell
Labs

1. Prism
2. LED
3. Diffraction
4. Lens
5. Polarization
6. Interference
7. Laser diode
Projects

- Holography
- Plastic lens for cell phones
- Berry-juice dye-sensitized solar cell
- Lego-based spectrometer
- Liquid ID spectrometer
- Your own

Light-based technologies will be the economic driver of the 21st century
Unique to COSMOS-UCSD

- **Ethics essay contest**
  - $200, $100, $50 prizes

- **Gordon Leadership Award**
  - $100 to the best team project

- **Dr. Joe Watson Award**
  - $100 to the best team player to the cluster
Light at Work: Opportunity for the Future

Goal of this cluster, Light at Work, aims to touch on the fundamentals and the revolutionary potential of light technologies.

Cluster website: http://jacobsschool.ucsd.edu/cosmos/2016/cluster5/
<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Lecture</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>July 10</td>
<td>Where light comes from</td>
<td>Exp #1 Prism and grating</td>
</tr>
<tr>
<td>Tu</td>
<td>11</td>
<td>Discovery Lec.: Translational Medicine Science Communication</td>
<td>Solar Cells</td>
</tr>
<tr>
<td>W</td>
<td>12</td>
<td>Semiconductor, pn junction, LED, solar cell Bending light (refraction, diffraction)</td>
<td>Exp #2 LEDs</td>
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<tr>
<td>Th</td>
<td>13</td>
<td>Science Communication Tour of Fallen Star</td>
<td>Spectrometer, grating from CD</td>
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<tr>
<td>F</td>
<td>14</td>
<td>Spray painting with atoms (MBE) Diffraction, polarization, interference Tour of Prof. Charles Tu's lab</td>
<td>Exp #3 Diffraction</td>
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<tr>
<td>M</td>
<td>17</td>
<td>Lens, Creating an image, Diffraction, Holography</td>
<td>Exp #4 Lens PDMS workshop, lens, grating</td>
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<tr>
<td>Tu</td>
<td>18</td>
<td>Discovery Lecture: Artificial Intelligence Science Communication</td>
<td>PDMS Lens Grating</td>
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<tr>
<td>W</td>
<td>19</td>
<td>Exp #5 Polarization and Exp #6 interference</td>
<td>Tour of Calit2, Nano3</td>
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<td>Th</td>
<td>20</td>
<td>COSMOS Info Session Science Communication</td>
<td>Holography Projects given</td>
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<tr>
<td>F</td>
<td>21</td>
<td>Lasers, Semiconductor laser Tour of Prof. Zhaowei Liu's lab</td>
<td>Exp #7 Laser diode Projects finalized</td>
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# Cluster 5 Schedule, Weeks 3-4

<table>
<thead>
<tr>
<th>M</th>
<th>24</th>
<th>Solar Energy, Photovoltaics, Application to computer chips: Photolithography,</th>
<th>Projects</th>
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<tbody>
<tr>
<td>Tu</td>
<td>25</td>
<td>Discovery Lecture: Marine Archeology Science Communication</td>
<td>Field trip Cube Infinity (Language of Light) @ Birch Aquarium</td>
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<tr>
<td>W</td>
<td>26</td>
<td>Detecting Light, CCD, CMOS Detecting photons (Prof. Yuhwa Lo) Tour Prof. Yuhwa Lo’s lab</td>
<td>Projects</td>
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<tr>
<td>Th</td>
<td>27</td>
<td>COSMOS Info Session Science Communication</td>
<td>Projects</td>
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<td>F</td>
<td>28</td>
<td>Transmitting Light: Fiber, CMOS Tour of Prof. Stojan Radic’s lab</td>
<td>Projects</td>
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<tr>
<td>M</td>
<td>7/30</td>
<td>Resonator, LCD, Photonic Crystal Structural color (Prof. Joanna McKittrick) Tour of Prof. Joe Ford’s lab</td>
<td>Projects</td>
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<tr>
<td>Tu</td>
<td>1</td>
<td>Discovery Lecture: Discovery of Another Solar System Science Communication</td>
<td>Projects</td>
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<tr>
<td>W</td>
<td>2</td>
<td>Nanophotonics, microfluidics, fluid lens Tour of Prof. Shaya Fainman’s lab,</td>
<td>Projects</td>
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<td>Th</td>
<td>3</td>
<td>Science Communication</td>
<td>Project presentations</td>
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<tr>
<td>F</td>
<td>4</td>
<td>Presentations with Cluster 4</td>
<td>Project judging</td>
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</tbody>
</table>
So...
Where Does Light Come From?

- Sun
- Moon
- Stars
- Fire
- Lightning
- Fireflies
- Light bulbs
- Fluorescent lights
- LEDs
- Lasers
- Neon signs
- Computer Displays
# Makes vs Reflects

<table>
<thead>
<tr>
<th>Makes</th>
<th>Reflects</th>
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<tbody>
<tr>
<td>Sun</td>
<td>Moon</td>
</tr>
<tr>
<td>Stars</td>
<td></td>
</tr>
<tr>
<td>Fire</td>
<td></td>
</tr>
<tr>
<td>Lightning</td>
<td></td>
</tr>
<tr>
<td>Fireflies</td>
<td></td>
</tr>
<tr>
<td>Light bulb</td>
<td></td>
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<tr>
<td>Fluorescent</td>
<td></td>
</tr>
<tr>
<td>LED</td>
<td></td>
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<tr>
<td>Laser</td>
<td></td>
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<tr>
<td>Neon signs</td>
<td></td>
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<tr>
<td>Displays</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>Not</td>
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<tr>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Sun</td>
<td>Firefly</td>
</tr>
<tr>
<td>Stars</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>Fire</td>
<td>LED</td>
</tr>
<tr>
<td>Lightning</td>
<td>Laser</td>
</tr>
<tr>
<td>Light bulb</td>
<td>Neon sign</td>
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<tr>
<td>Displays</td>
<td></td>
</tr>
</tbody>
</table>
White Light or Colored?

<table>
<thead>
<tr>
<th>White Light</th>
<th>Colored Light</th>
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</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Fire</td>
</tr>
<tr>
<td>Stars</td>
<td>LED</td>
</tr>
<tr>
<td>Lightning</td>
<td>Laser</td>
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<tr>
<td>Light bulb</td>
<td>Neon sign</td>
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<tr>
<td>Firefly</td>
<td>Displays</td>
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<tr>
<td>Fluorescent</td>
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## Directional or Not?

<table>
<thead>
<tr>
<th>Directional</th>
<th>All Directions</th>
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<tbody>
<tr>
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<tr>
<td>Laser</td>
<td>Neon sign</td>
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<tr>
<td></td>
<td>Displays</td>
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<td></td>
<td>Sun</td>
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<td>Stars</td>
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<td></td>
<td>Lightning</td>
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<td></td>
<td>Light bulb</td>
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<tr>
<td></td>
<td>Firefly</td>
</tr>
<tr>
<td></td>
<td>Fluorescent</td>
</tr>
<tr>
<td>Electricity</td>
<td>No electricity</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>LED</td>
<td>Fire</td>
</tr>
<tr>
<td>Laser</td>
<td>Sun</td>
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<tr>
<td>Neon sign</td>
<td>Stars</td>
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<tr>
<td>Displays</td>
<td>Firefly</td>
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<tr>
<td>Lightning</td>
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<tr>
<td>Light bulb</td>
<td></td>
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<tr>
<td>Fluorescent</td>
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</table>
### Efficient?

<table>
<thead>
<tr>
<th>Efficient</th>
<th>Not efficient</th>
<th>???</th>
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<tbody>
<tr>
<td>LED</td>
<td>Fire</td>
<td>Displays</td>
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<tr>
<td>Laser</td>
<td>Light bulb</td>
<td>Lightning</td>
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<tr>
<td>Neon sign</td>
<td></td>
<td>Sun</td>
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<tr>
<td>Fluorescent</td>
<td></td>
<td>Stars</td>
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<tr>
<td>Firefly</td>
<td></td>
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</table>
Why Do Light Sources Have Different Properties?
Incandescent vs Line Sources

Who can tell the difference?

- Incandescent: Glows because it's hot
- Line source: Glows because electrons change energy levels
Consider a fluorescent tube and a light bulb

A. Both are incandescent sources

B. Both are line sources

C. Fluorescent tube is an incandescent source and light bulb is a line source

D. Fluorescent tube is a line source and light bulb is an incandescent source
Atoms, electrons, gas and solid

Proton +
Neutron

Electron -

Gas

Solid
Incandescent Sources

Incandescent Sources are:

- Hot
- Heat = Motion
- Motion knocks electrons loose from atoms
Line Sources

- Electrons orbit around atoms
- Only orbits with certain energies are allowed
- When an electron moves from a higher energy orbit to a lower one, a photon is released
What is a photon?

- Light--electromagnetic wave—can be released only in “packets” of energy.

- Einstein suggested the EM wave could only exist in these discrete wave-packets, or “light quantum”, now called “photons”.

- → Quantum Mechanics: particle-wave nature of light, electrons, atoms, ..., everything.
## Incandescent vs Line Sources

<table>
<thead>
<tr>
<th>Incandescent</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>LED</td>
</tr>
<tr>
<td>Stars</td>
<td>Laser</td>
</tr>
<tr>
<td>Fire</td>
<td>Neon sign</td>
</tr>
<tr>
<td>Lightning</td>
<td>Displays</td>
</tr>
<tr>
<td>Light bulb</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>Firefly</td>
<td></td>
</tr>
</tbody>
</table>
We see light with different colors.

Where do the colors come from?

Different energy, frequency, wavelength

There are wavelengths of light we can't see.
Frequency

- Musical notes have different frequencies
- Light of different colors has different frequencies
- Sound results from the vibration of air
- Light results from the vibration of electric charge
- Sound we can hear vibrates between 20 and 20,000 times per second
- Light we can see vibrates between 390,000,000,000,000 and 750,000,000,000,000 times per second
Jim is running beside a fence at 10 feet per second.

As he runs, he drags a stick along the fence. Jim notices the stick makes a humming sound at the same frequency as the power line overhead. Power lines hum at a frequency of 60 times per second.

How far apart are the slats in the fence?

A. 1 foot
B. 1/2 foot
C. 1/3 foot
D. 1/6 foot
If Jim was walking at 1 foot per second and the slats were 1 foot apart, there would be a vibration of 1 time per second.

If Jim was running at 10 feet per second and the slats were 1 foot apart, there would be a vibration of 10 times per second.

If Jim was running at 10 feet per second and the slats were 2 inches apart (6 per foot), there would be a vibration of 60 times per second.
Frequency increases as speed increases

Frequency increases as slat-spacing decreases

Frequency = speed / slat-spacing
or
Frequency = speed / period

True for a repeating structure (wave) of any type
Frequency & Wavelength
Light: Speed, Frequency, and Wavelength

- What is the speed of light?
  - 186,000 miles / sec
  - 669,600,000 miles / hour
  - 300,000,000 meters / sec

- Frequency for red light: 390,000,000,000,000 Hz
  - Wavelength for red light: 0.00000077 meters

- Frequency for blue light: 750,000,000,000,000 Hz
  - Wavelength for blue light: 0.0000004 meters
Units for Really Small Numbers

How long is 1 meter?

- One-hundredth (0.01) of 1 meter is: 1 centimeter
- One-thousandth (0.001) of 1 meter is: 1 millimeter
- One-millionth (0.000001) of 1 meter is: 1 micrometer
- One-billionth (0.000000001) of 1 meter is: 1 nanometer

\[ \text{centi} = 10^{-2}, \quad \text{milli} = 10^{-3}, \quad \text{micro} = 10^{-6}, \quad \text{nano} = 10^{-9} \]

What is \(10^{-12}\)? \(10^{-15}\)? \(10^{-18}\)?

How thick is a strand of human hair?

- Femto second laser: used to study chemical reaction
Units for Really Big Numbers

- 1 cycle per second is also called 1 Hertz (Hz)
- One thousand (1000) Hz is 1 kiloHertz
- One million (1,000,000) Hz is 1 megaHertz
- One billion (1,000,000,000) Hz is 1 gigaHertz
- One trillion (1,000,000,000,000) Hz is 1 teraHertz

kilo = 10^3    mega = 10^6    giga = 10^9    tera = 10^{12}

n*10^m is also written as nEm; 5*10^9 = 5E9

What is 1E12?  1E15?  1E18?  1E21?
Big Data

- $1E12 = \text{trillion, tera-}
- $1E15 = \text{quadrillion, peta-}
- $1E18 = \text{quintillion, exa-}
- $1E21 = \text{sextillion, zetta-}

Light: Speed, Frequency, and Wavelength

So, the speed of light is:

- 186 kilo-miles / sec
- 669.6 mega-miles / hour
- 300 mega-meters / sec or 3E8 m/s

Frequency for red light: 390 tera-Hz or 3.9E14 Hz
- Wavelength for red light: 0.77 microns or 770 nm

Frequency for blue light: 750 tera-Hz or 7.5E14 Hz
- Wavelength for blue light: 0.4 microns or 400 nm

1 Angstrom = 10^-10 meters, so 400 nm = 4000 Å
Mission Juno

• Launched on 8/5/2011
• Arrived Jupiter on 7/4/2016
• Distance at time of “Jupiter Orbit Insertion” = 869 million km
• How long does it take for a command signal from NASA to reach Juno?
  A. 10 min.
  B. 30 min.
  C. 50 min.
  D. 80 min.
  E. 100 min.

Frequency vs. Wavelength

A. Longer wavelength $\rightarrow$ higher frequency

B. Longer wavelength $\rightarrow$ lower frequency
Energy vs. Frequency

A. Higher frequency $\rightarrow$ higher energy

B. Higher frequency $\rightarrow$ lower energy
# Common f’s and λ’s

<table>
<thead>
<tr>
<th>Device</th>
<th>f</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Radio</td>
<td>1 MHz</td>
<td>300 m</td>
</tr>
<tr>
<td>Broadcast TV</td>
<td>70 MHz</td>
<td>4.2 m</td>
</tr>
<tr>
<td>FM Radio</td>
<td>100 MHz</td>
<td>3 m</td>
</tr>
<tr>
<td>Cellphone</td>
<td>2 GHz</td>
<td>15 cm</td>
</tr>
<tr>
<td>WiFi, Bluetooth</td>
<td>2.4 GHz</td>
<td>12.5 cm</td>
</tr>
<tr>
<td>Cordless Phone</td>
<td>5.8 GHz</td>
<td>5.2 cm</td>
</tr>
<tr>
<td>Airport Scanner</td>
<td>1 THz</td>
<td>0.3 mm</td>
</tr>
</tbody>
</table>
Federal Communication Commission (FCC) allocates the EM spectrum.

<table>
<thead>
<tr>
<th>1</th>
<th>3,000 m</th>
<th>300 m</th>
<th>30 m</th>
<th>3 m</th>
<th>30 cm</th>
<th>3 cm</th>
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<tbody>
<tr>
<td>LF</td>
<td>MF</td>
<td>HF</td>
<td>VHF</td>
<td>UHF</td>
<td>SHF</td>
<td></td>
</tr>
<tr>
<td>AM Broadcast</td>
<td>FM Broadcast</td>
<td>PLS</td>
<td>X</td>
<td>C</td>
<td>Microwaves</td>
<td></td>
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<tr>
<td>Ultra-sonics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 kHz</td>
<td>1 MHz</td>
<td>10 MHz</td>
<td>100 MHz</td>
<td>1 GHz</td>
<td>10 GHz</td>
<td></td>
</tr>
</tbody>
</table>

The Radio Spectrum

Example: You are listening to 91.5 FM WRKX the Rock!
What Have We Learned?

- Not all light is the same.
- Incandescent sources glow because they're hot.
- Lines sources glow from specific electronic transition between energy levels.
- Light has wavelength, frequency, and speed.
- For light (or any wave) speed = wavelength * frequency.
- Big units: kilo, mega, giga, tera, peta,
- Small units: centi, milli, micro, nano, pico, femto, ..
Is the content

A. Too elementary (I know the materials already)

B. About right

C. Too difficult (you talked over my heads)

D. Don’t know (I was dozing off)