LASER 101

Dimitra & Bart

Quantum Solid State Physics

KU LEUVEN

SUMMER OF SCIENCE

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- PhD Scientist: Investigating CO_2 electro-conversion to organic molecules using surface science techniques

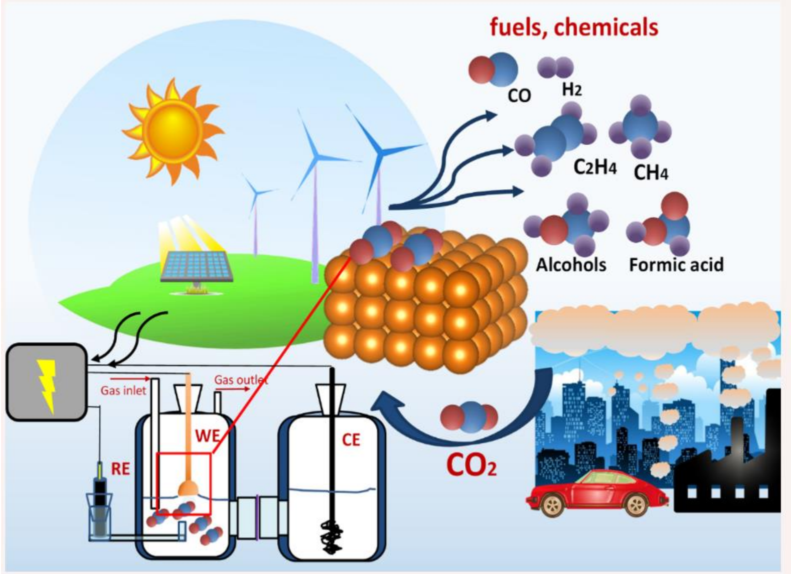

Image credit: P. Sebastián-Pascual et al., ChemCatChem (2019).

Bart Smeets

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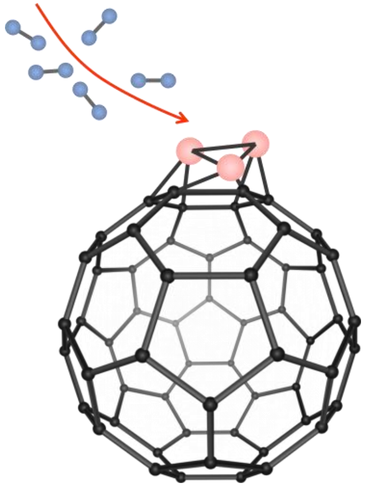
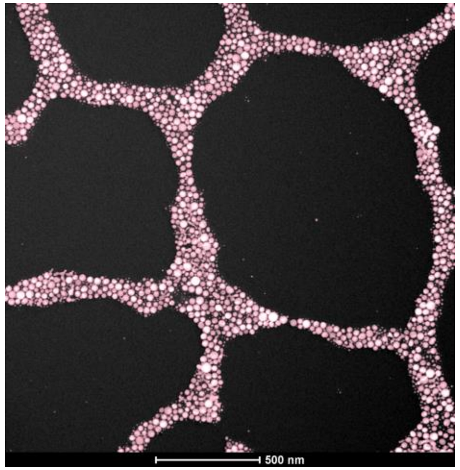
- “Trust me, I’m a (nano)engineer”
- PhD Scientist: Investigating Sustainable Hydrogen Storage





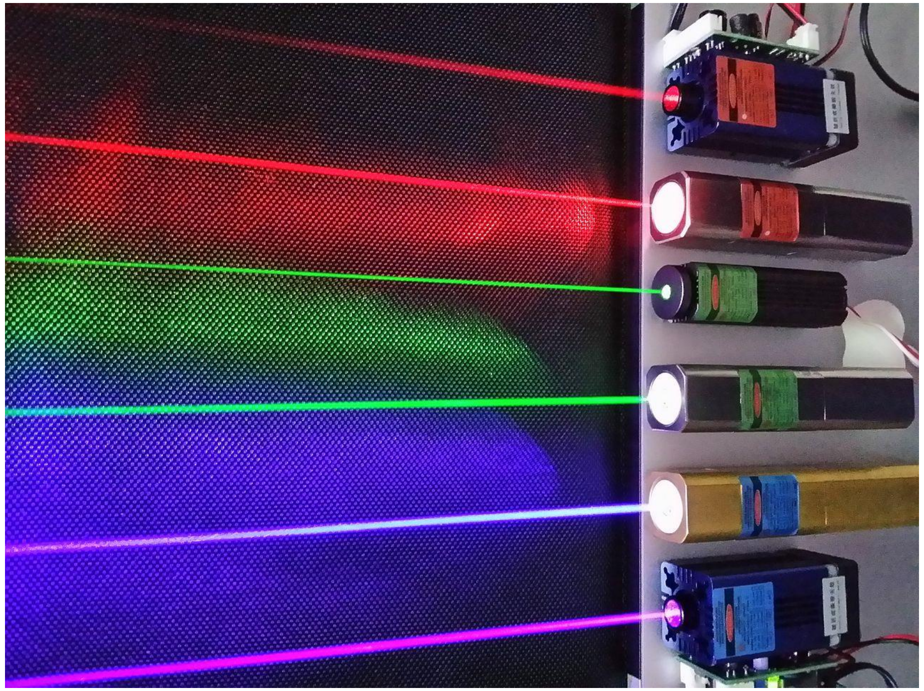
What's a LASER?

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Special Properties:

- Monochromatic (temporally coherent)
- Well-Directed (spatially coherent)

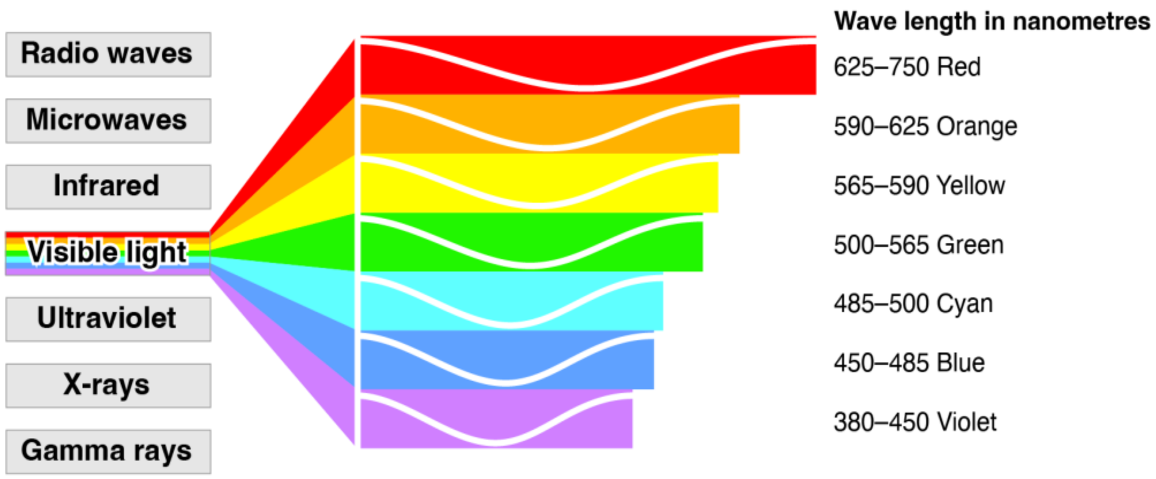
  → High Intensity/Brightness

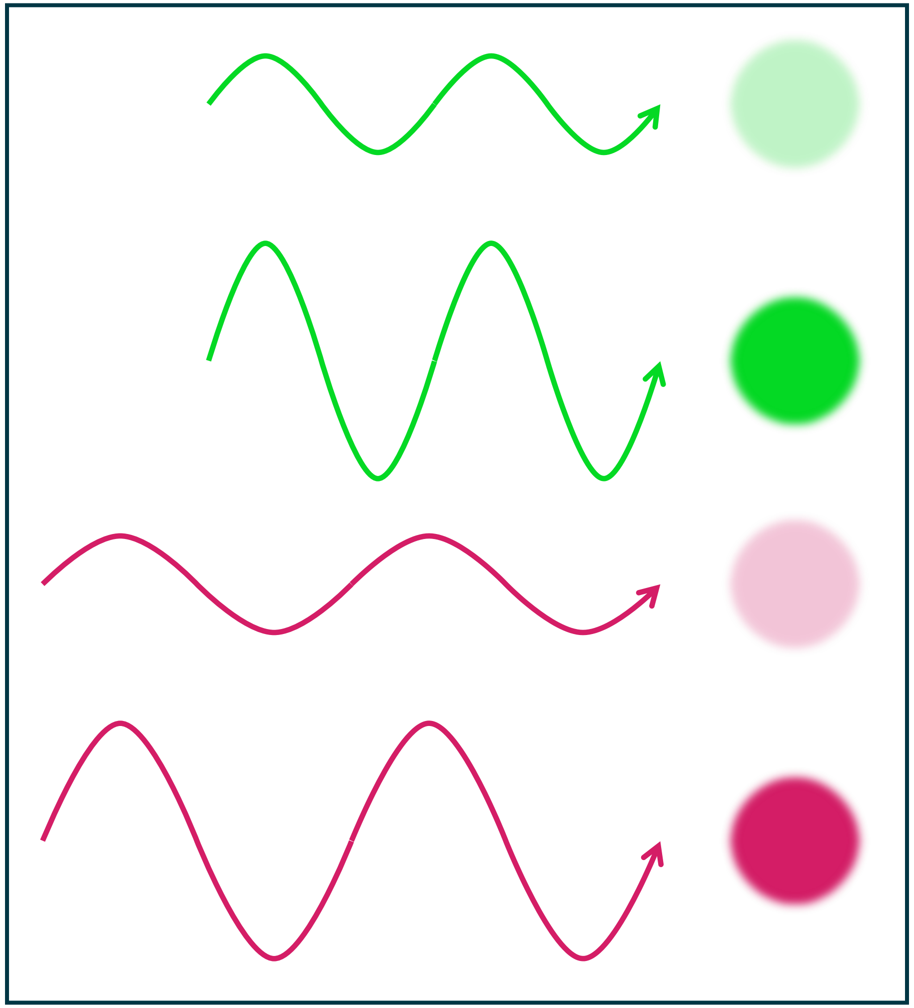


Recap: Light is a Wave

→ **Monochromatic**: 1 single wavelength

→ **Brightness**: Amplitude of the Wave





Glow in the Dark Experiment

Class II Laser

Special Properties:

- Monochromatic
- Directed: very bright

vs.

Normal Flashlight

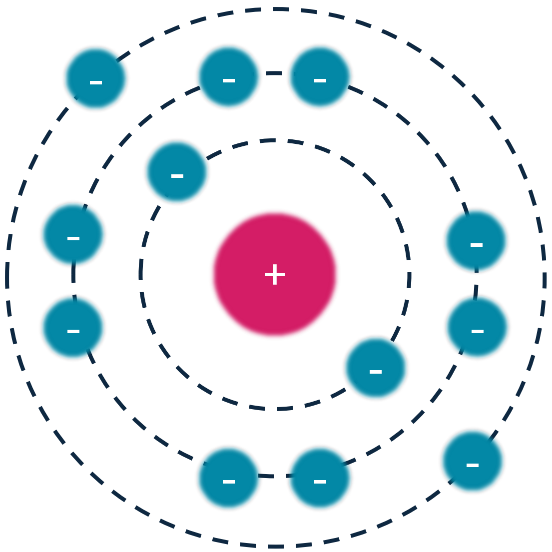
Boring Properties:

- Not Monochromatic
- Not Directed: not bright

What happened?

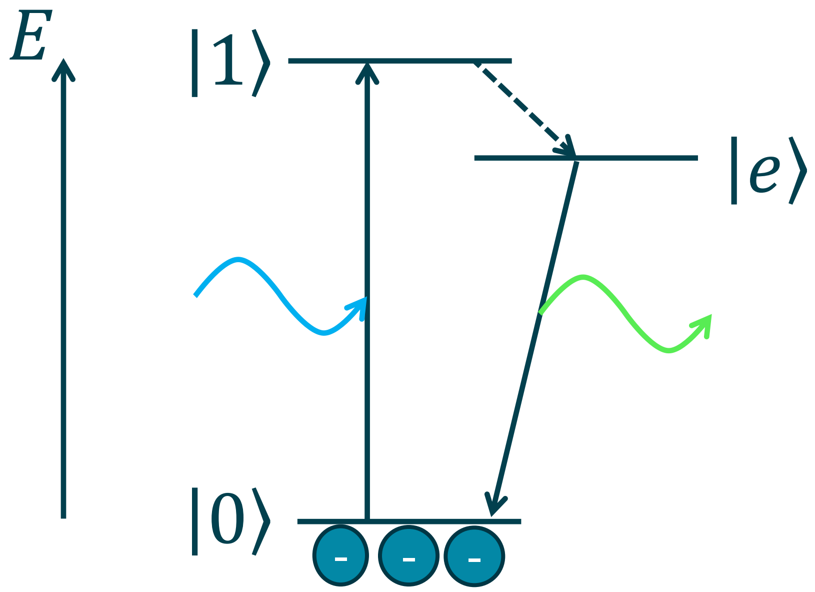
Glow in the Dark Explained

Bohr Model



- n=1: 2
- n=2: 8
- n=3: 18
- …

Glow in the Dark



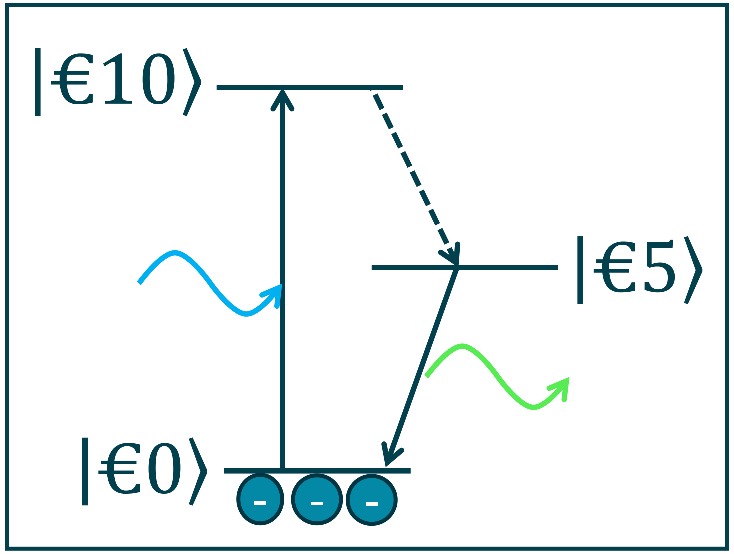
A high intensity beam is not enough. There's more…

The *Currency* of Light

- Electrons absorb **quanta** of light

→ Much like paying cash: you can only pay with *valid bills*

- Special rule: Electrons only accept one *bill* at a time

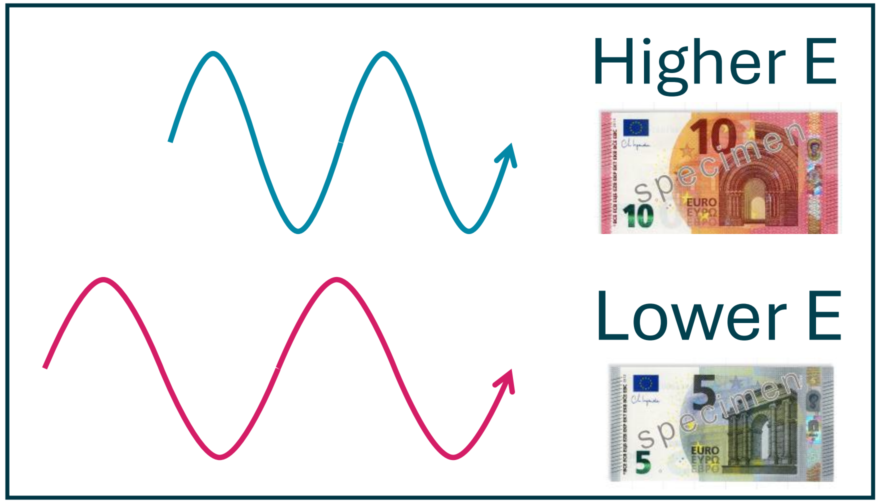


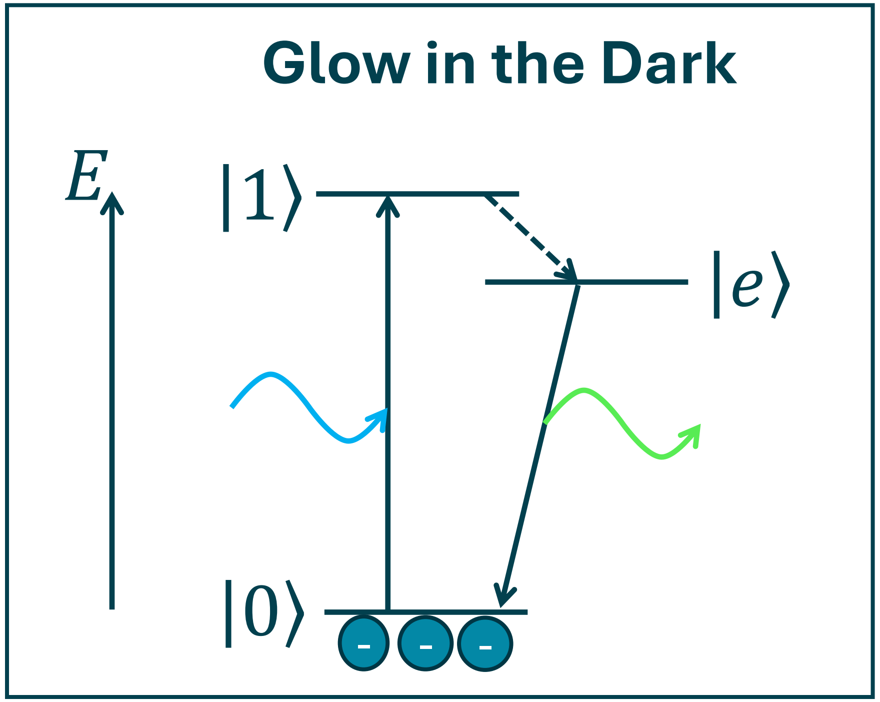
Light is also a **Particle**

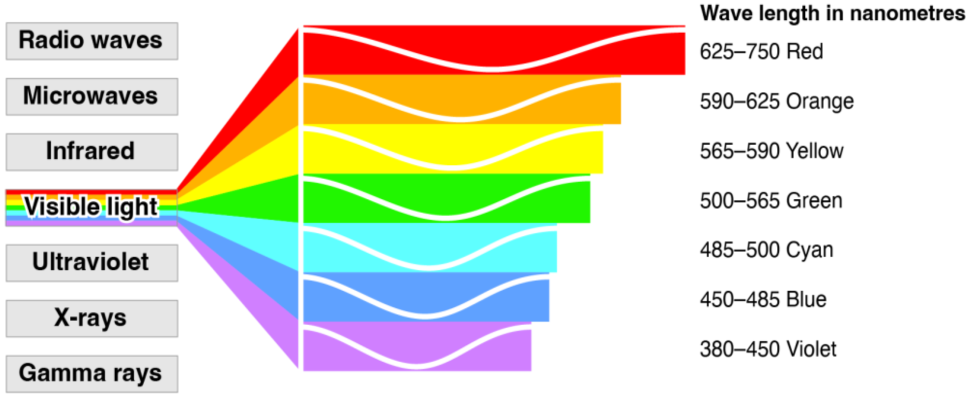
- Electrons absorb **quanta** of light

→ **Photons**

- $E_{photon} = hf$, or $E_{photon} = \frac{hc}{\lambda}$







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To Do: Colour Converter

Go to: sos-toolobox.streamlit.app/colour_converter

Complete the table:

Wavelength (nm)	Energy (eV)	Colour
532		
	2.80	
		red

To Do: Colour Converter

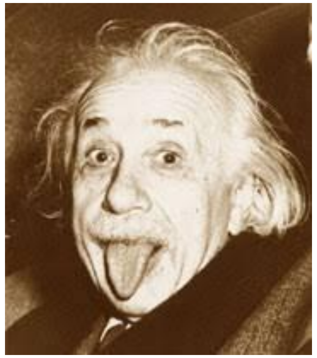
Go to: sos-toolobox.streamlit.app/colour_converter

Complete the table:

Wavelength (nm)	Energy (eV)	Colour
532	2.33	green
442	**2.80**	blue
650 - 780	*1.91 – 1.59*	**red**

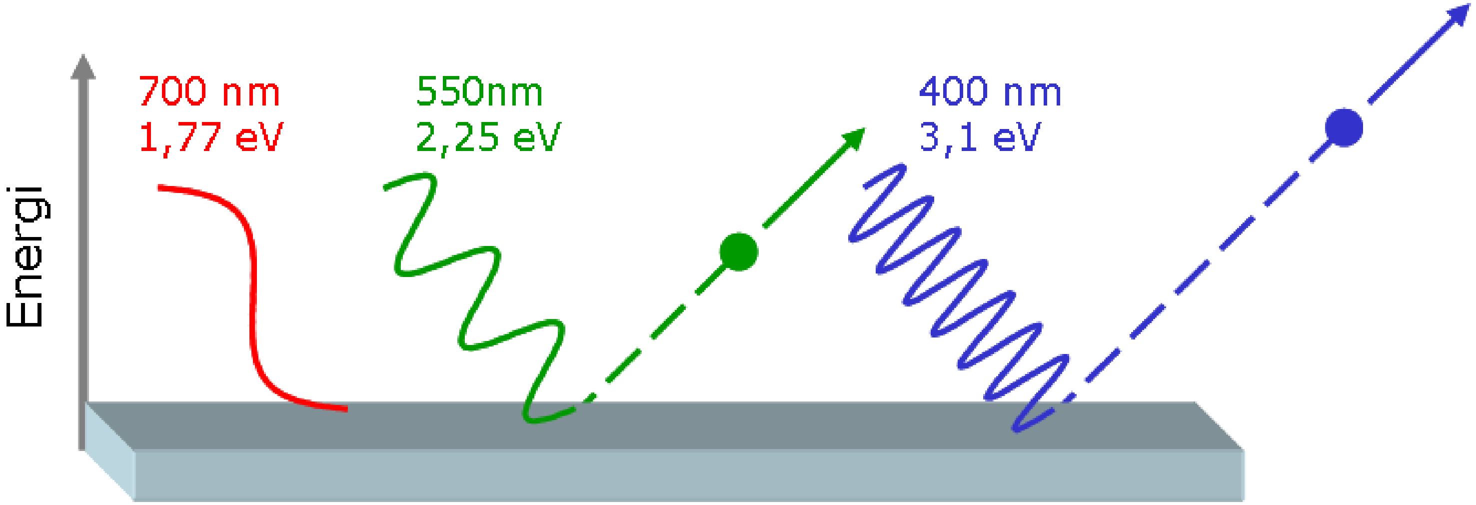
Einstein: the Father of the Laser *(and GWs)*

- 1905: Photoelectric Effect
  → Nobel Prize in Physics 1921



- 1916: **Stimulated Emission**

→ Einstein's work provided the theoretical foundation of the laser



Stimulated Emission

- When a <u>resonant</u> incoming photon interacts with an excited electron:

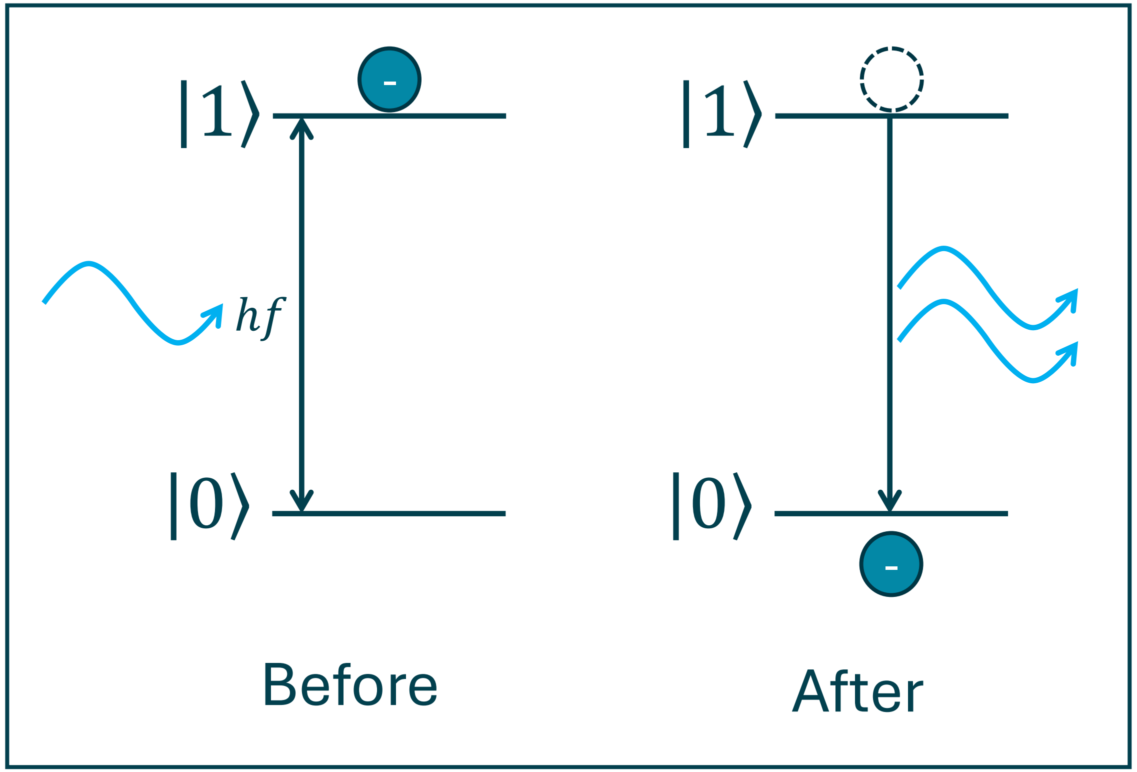
→ The electron decays

→ But **energy is conserved**, so a photon is emitted

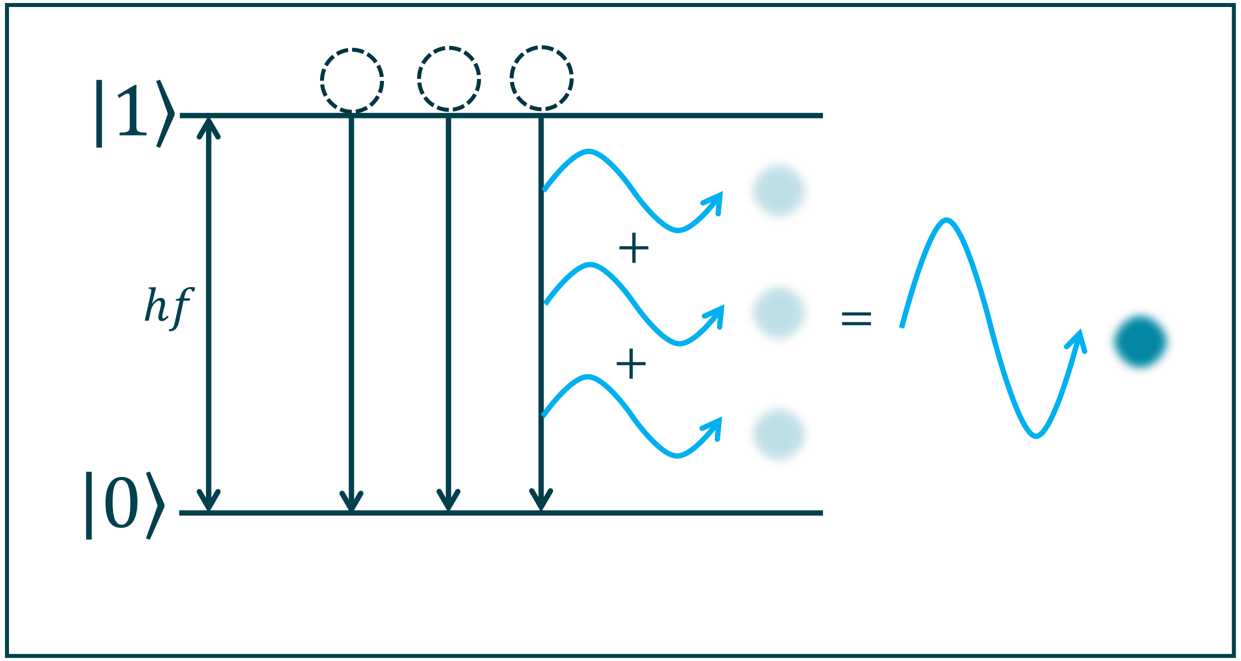
→This photon has:

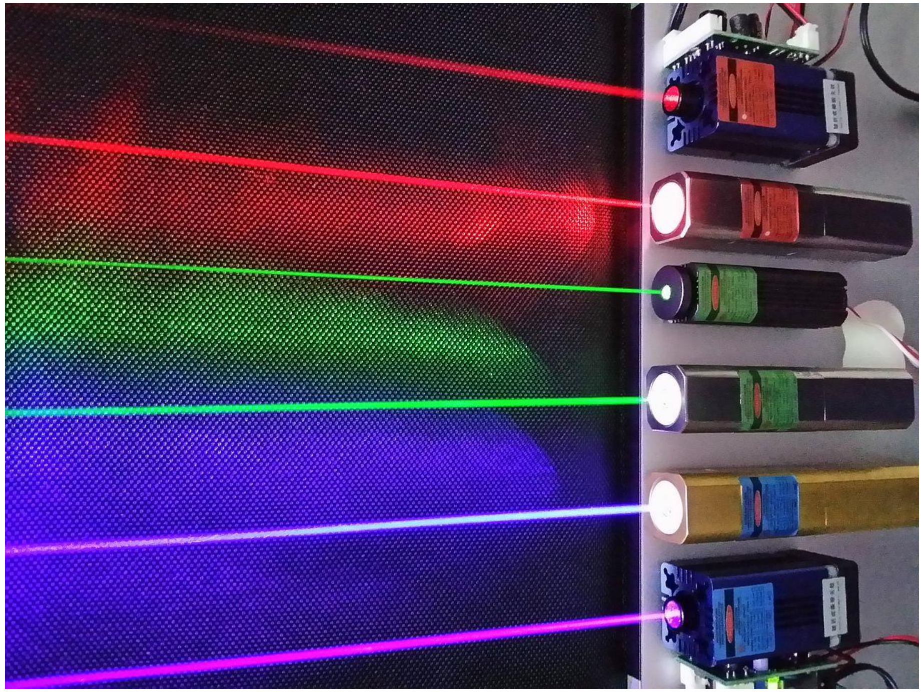
→The same energy → the same wavelength
→The same direction
→The same phase

Special Properties of the Laser



Light Amplification by Stimulated Emission of Radiation





Intermezzo: Boltzmann Distribution

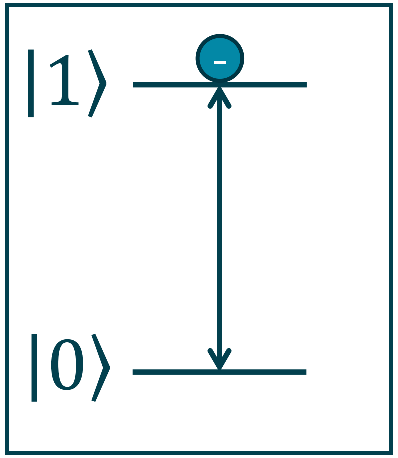
- At temperature, T, all particles carry a thermal energy.
- But not a fixed energy: some have more than others

→ There's a probability of $P_i \propto e^{-E_i/kT}$ of finding a particle in state $|i\rangle$ with energy E_i → **Boltzmann Distribution**

→ $\frac{P_i}{P_j} = e^{-(E_i - E_j)/kT}$

→ If $E_j > E_i$, then $P_j < P_i$

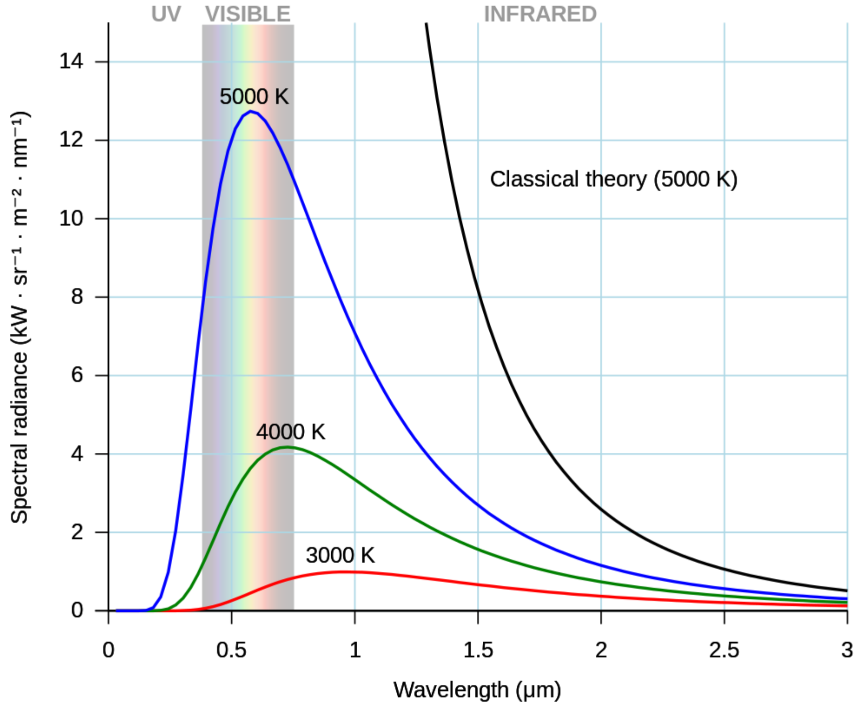
$kT = 0.026\ eV$
$@T = 300$



- Disclaimer: Actually, the Boltzmann distribution is not meant for electrons. But it works when $\Delta E \gg kT$

Intermezzo: Planck's Radiation Law

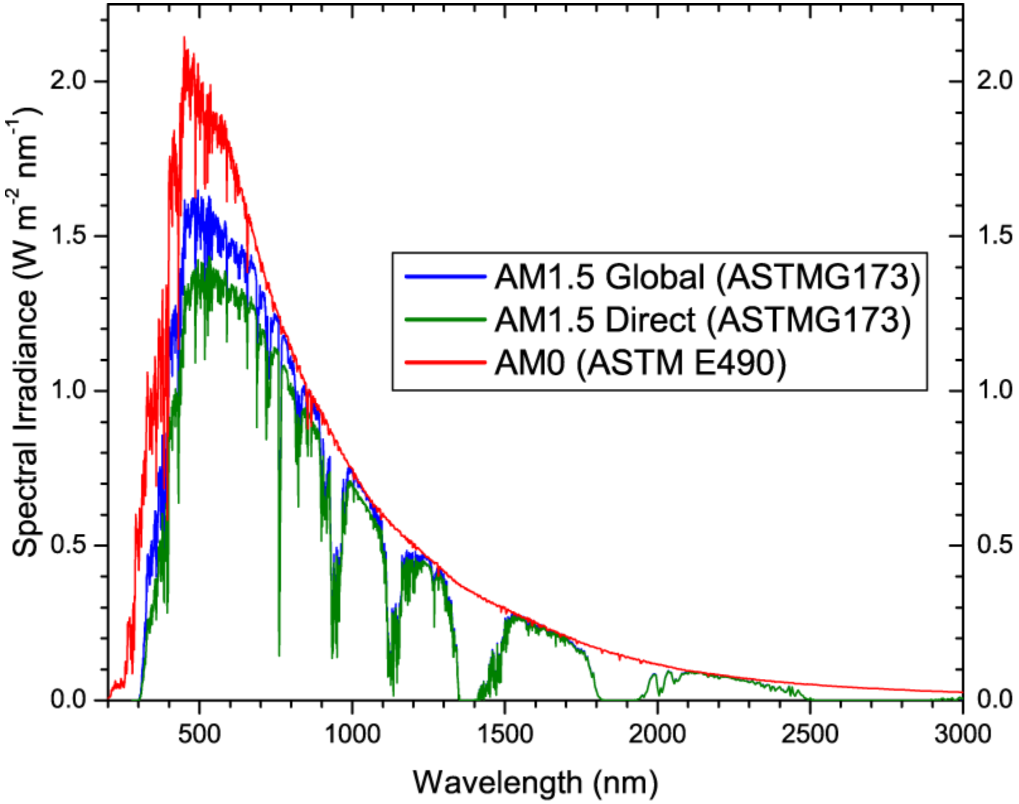
- Black Body Radiation: A Blackbody absorbs all light → In thermal equilibrium it should also emit something back.
- Planck solved the UV Catastrophe:
  - By assuming energy is **quantised:**
  - $E_{emitted} = hf$
  - An idea that inspired Einstein
- $W = \frac{8\pi h f^3}{c^3} \frac{1}{e^{hf/kT} - 1}$



To Do: Planck’s Radiation Law

Go to: sos-toolobox.streamlit.app/black_body

- What does it mean when something is *“red-hot”*?
- Assuming the Sun is a black body, how hot is the outside of the Sun?



Answers:
- The material is so hot it emits red photons
- ~ 5780 K

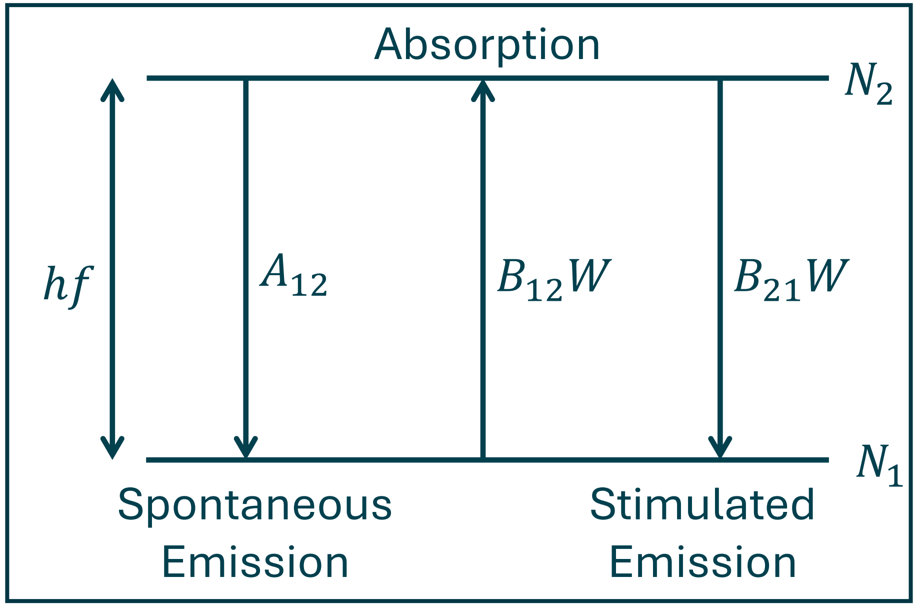
Einstein's A & B Coefficients

- Three light-interactions:
  1. Spontaneous emission

     → A_{21}: the probability of spontaneous decay/emission per unit time
  2. Absorption

     → B_{12}: the probability of absorption per unit time per unit spectral energy density
  3. Stimulated emission

     → B_{21}: the probability of stimulated emission per unit time per unit spectral energy density



Einstein's A & B Coefficients *(on the board)*

- Steady State: Absorption = Emission

$\rightarrow B_{12} W N_1 = A_{21} N_2 + B_{21} W N_2,$

where N_i is the electron density in state i and W is the spectral energy density

$\rightarrow W = \frac{A_{21}}{N_1/N_2 B_{12} - B_{21}}$

- Boltzmann distribution: $\frac{N_1}{N_2} = e^{hf/kT}$

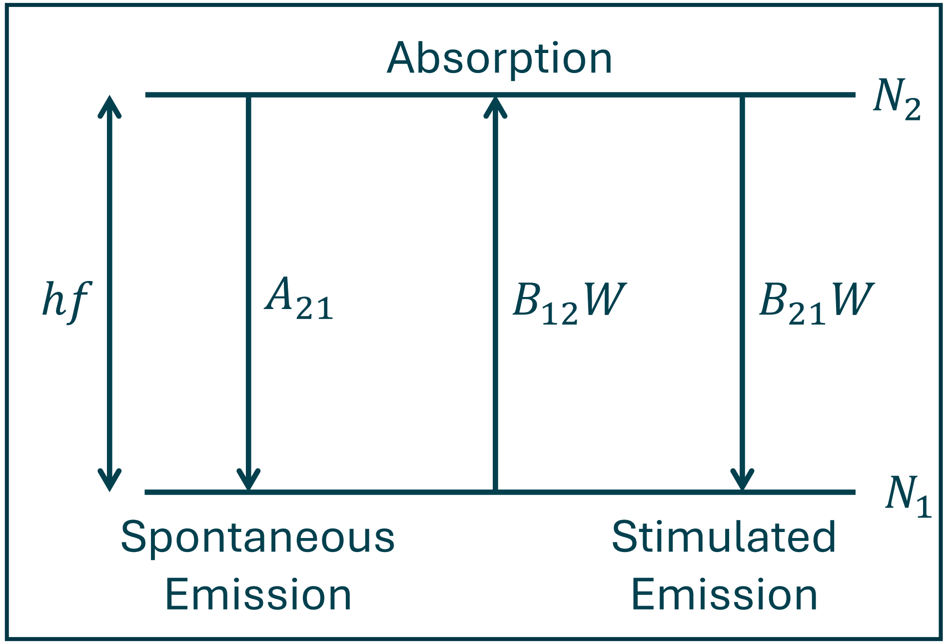
$\rightarrow W = \frac{A_{21}}{e^{hf/kT} B_{12} - B_{21}}$

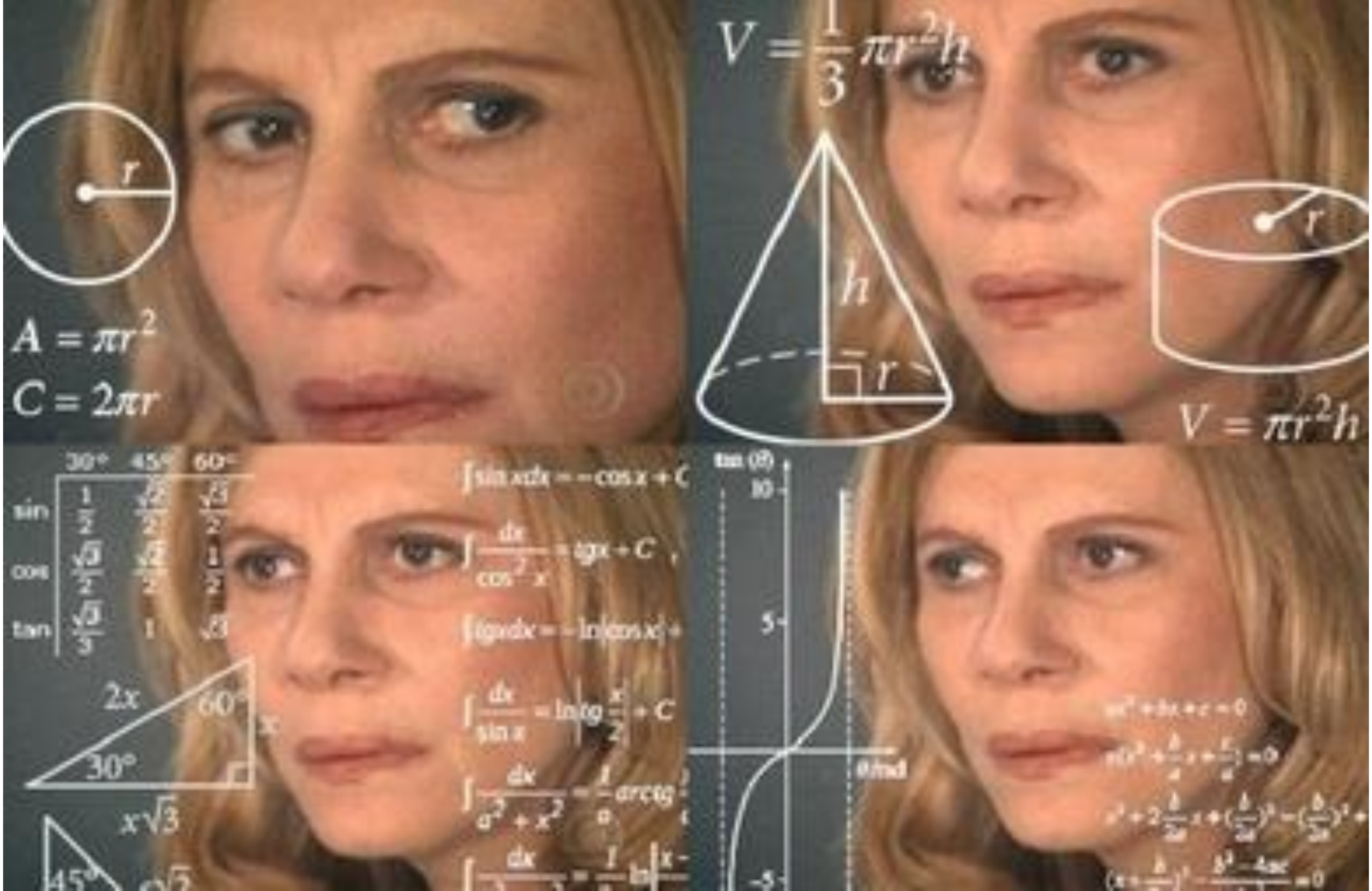
- Planck's law of Blackbody Radiation:

$$W = \frac{8\pi h f^3}{c^3} \frac{1}{e^{hf/kT} - 1} = \frac{A_{21}}{e^{hf/kT} B_{12} - B_{21}}$$

- Should hold for every T, so also $T \rightarrow \infty$ and $T \rightarrow 0$:

$\rightarrow B_{12} = B_{21}$ and $A_{21} = B_{12} \frac{8\pi h f^3}{c^3}$



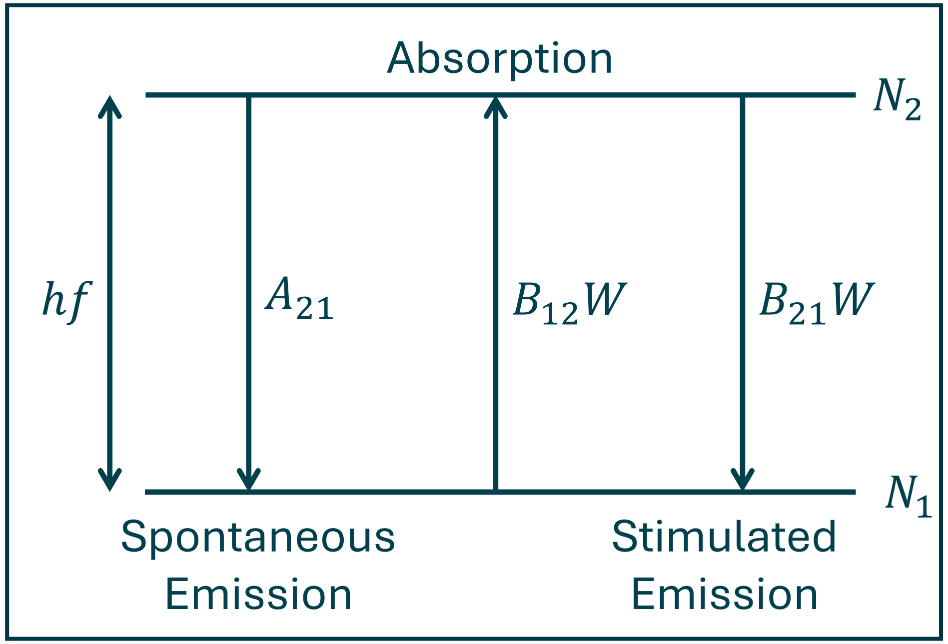


r
A = πr²
C = 2πr
V = 1/3 πr²h
h
r
r
V = πr²h
30° 45° 60°
sin
cos
tan
2x
60°
30°
x√3
45°

What does this mean...

- For laser, we want more stimulated emission than absorption: $B_{21}WN_2 > B_{12}WN_1$
- In Steady State: $\boxed{B_{21}W = B_{12}W}$

$\rightarrow N_2 > N_1$; **Inversion Population**

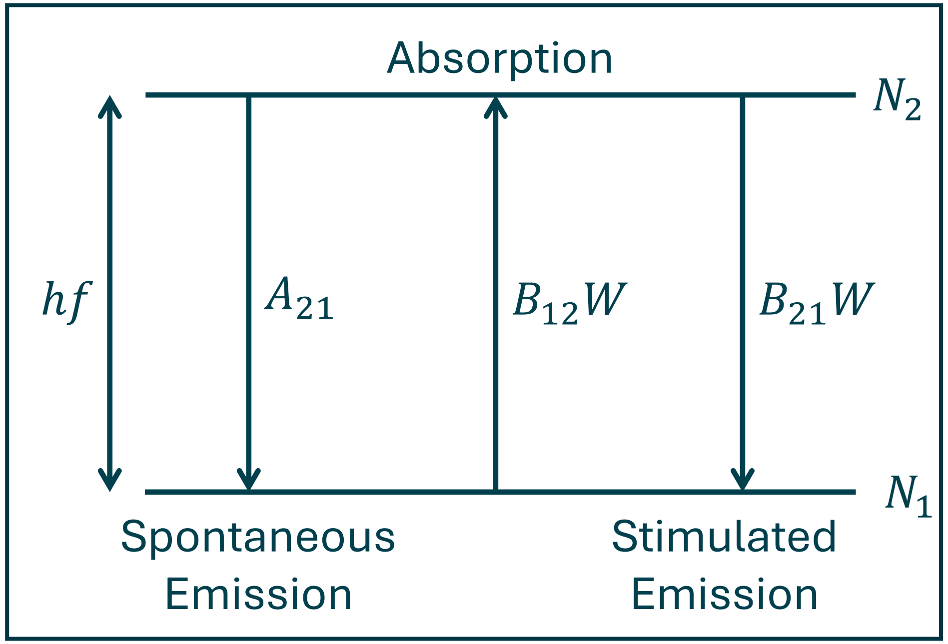


To Do: Einstein Coefficients

Go to: sos-toolobox.streamlit.app/einstein_coefficients

Who can make the largest gain (increase of resonant photons per second)?

What does this mean…



- For laser, we want more stimulated emission than absorption: $B_{21}WN_2 > B_{12}WN_1$
- In Steady State: $\boxed{B_{21}W = B_{12}W}$

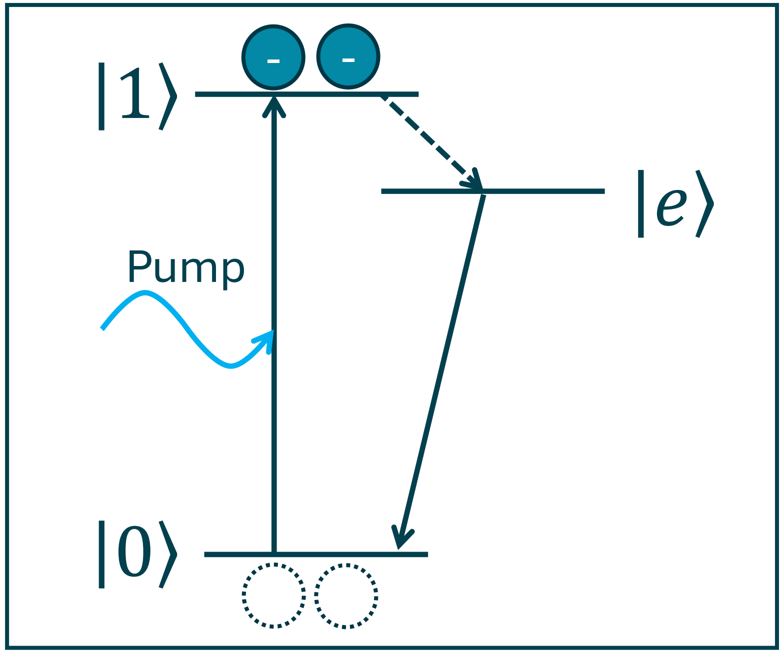
$\rightarrow N_2 > N_1$; **Inversion Population**

- But electrons are lazy. They prefer to have as little energy as possible.
  - → Standard condition: $N_1 > N_2$
  - → Try to "pump" the system into population inversion
  - → But electron will try to go back to their lazy state via spontaneous and stimulated emission…

In a two-level system, a stable laser is impossible

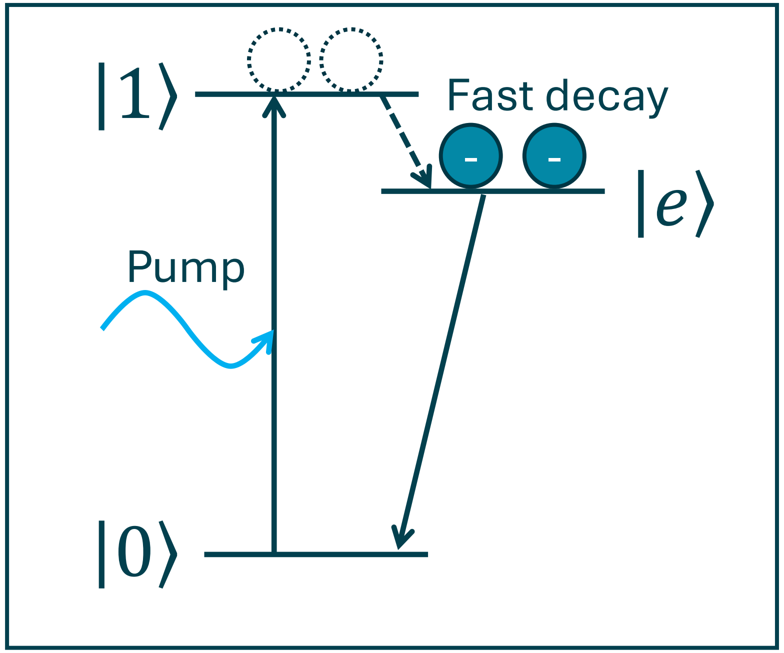
Let's create Inversion Population!

1. Pump from $|0\rangle$ to $|1\rangle$



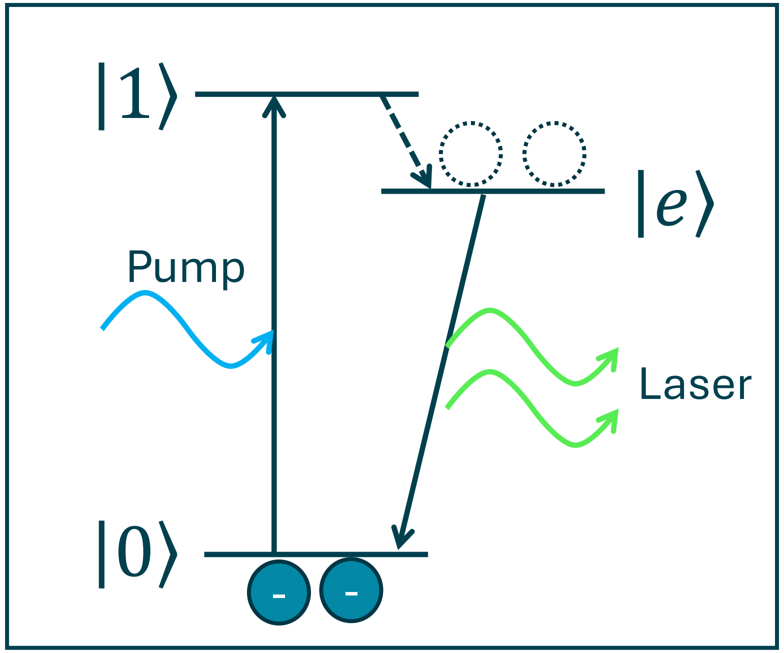
Let's create Inversion Population!

1. Pump from $|0\rangle$ to $|1\rangle$
2. Fast decay from $|1\rangle$ to $|e\rangle$
   - Prevents stimulated emission by pump



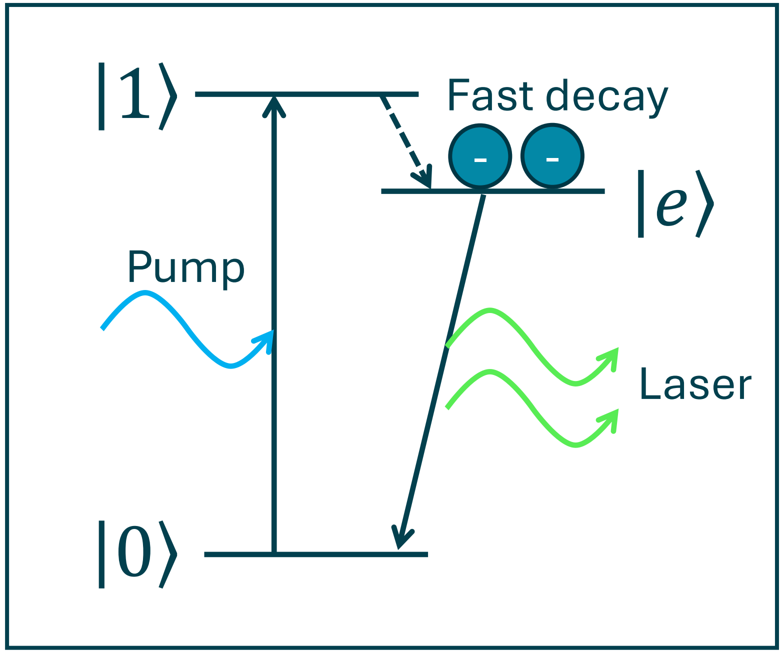
Let's create Inversion Population!

1. Pump from $|0\rangle$ to $|1\rangle$
2. Fast decay from $|1\rangle$ to $|e\rangle$
   - Prevents stimulated emission by pump
3. Spontaneous emission from $|e\rangle$ to $|0\rangle$ followed by stimulated emission from $|e\rangle$ to $|0\rangle$



Let’s create Inversion Population!

1. Pump from $|0\rangle$ to $|1\rangle$
2. Fast decay from $|1\rangle$ to $|e\rangle$
   - Prevents stimulated emission by pump
3. Spontaneous emission from $|e\rangle$ to $|0\rangle$ followed by stimulated emission from $|e\rangle$ to $|0\rangle$
4. Immediately pump again



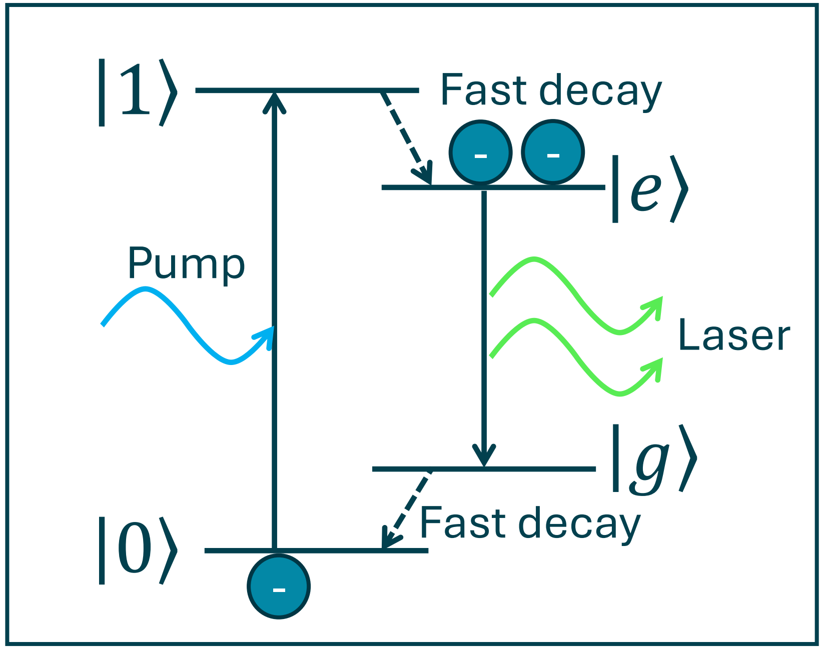
Let's create Inversion Population!

- Prevent the laser from absorbing from $|0\rangle$ to $|e\rangle$:

→Introduce a fourth energy level: $|g\rangle$

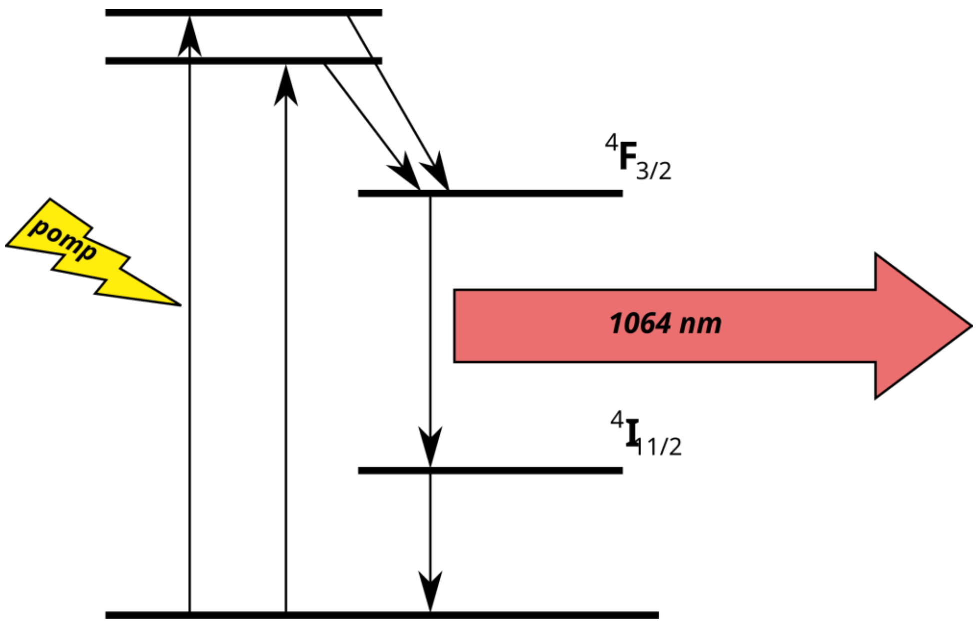
→Fully separate the pump channel and laser channel

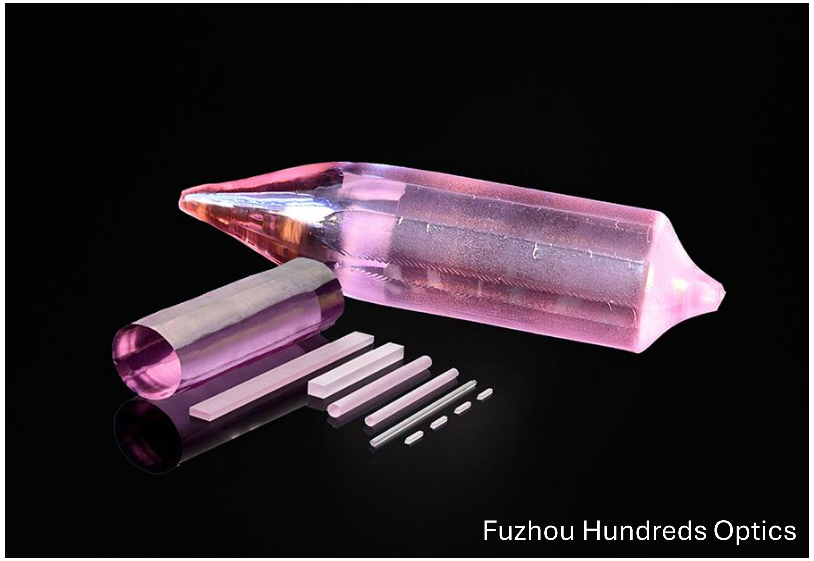
→ Inversion population between $|e\rangle$ and $|g\rangle$



Laser Medium

- Nd:YAG – Neodymium-doped Yttrium Aluminium Garnet





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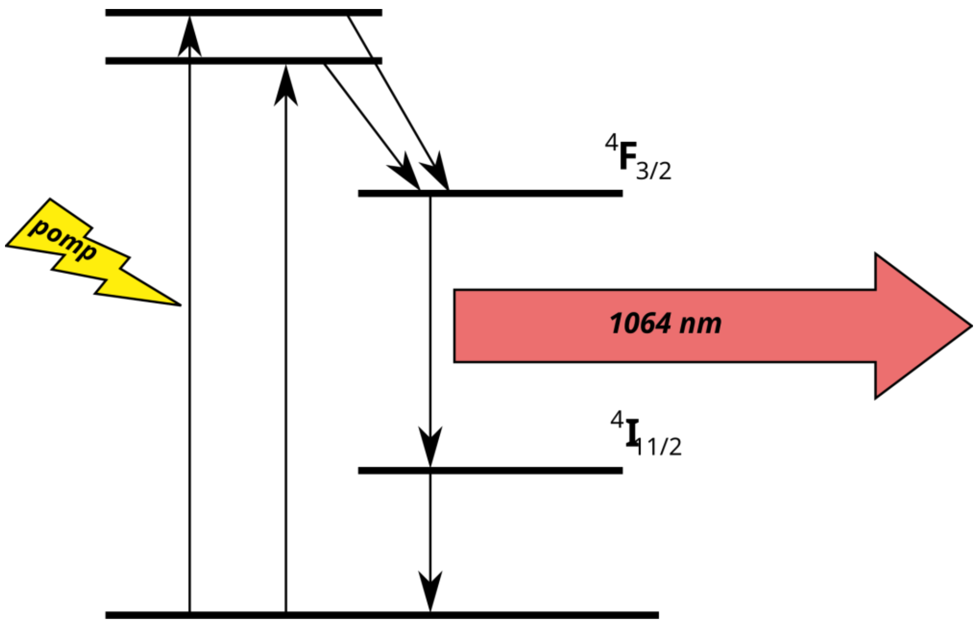
Quiz: Nd:YAG

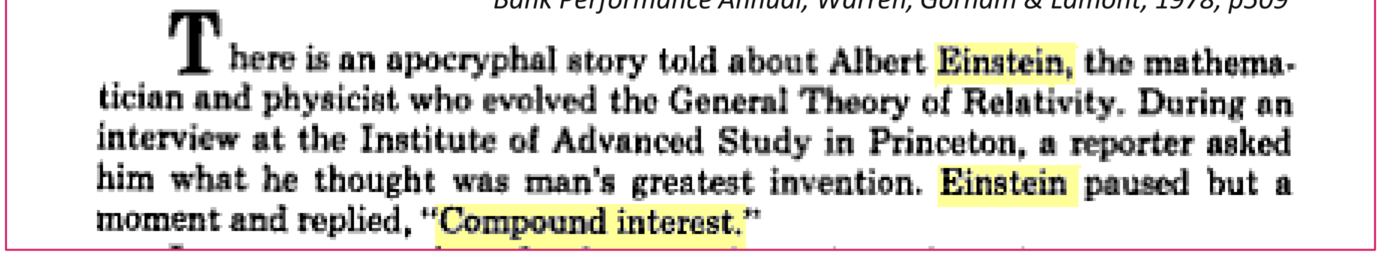
Reminder:
- Nd:YAG emits at 1064 nm
- $E_{photon} = \frac{hc}{\lambda}$
- sos-toolbox.streamlit.app

- What colour has a Nd:YAG laser?
- In our experiments, we double the photon energy. What's the new wavelength and colour?

Answers:
- Infrared
- 532 nm; green

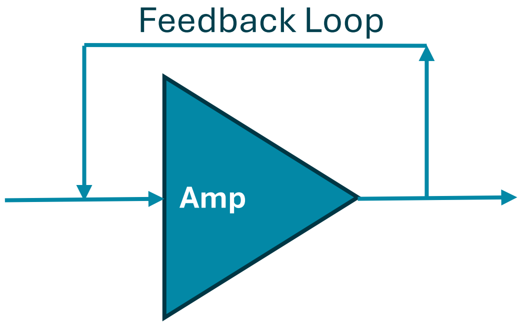


Intermezzo: Einstein Economics (?)


Bank Performance Annual, Warren, Gorham & Lamont, 1978, p509

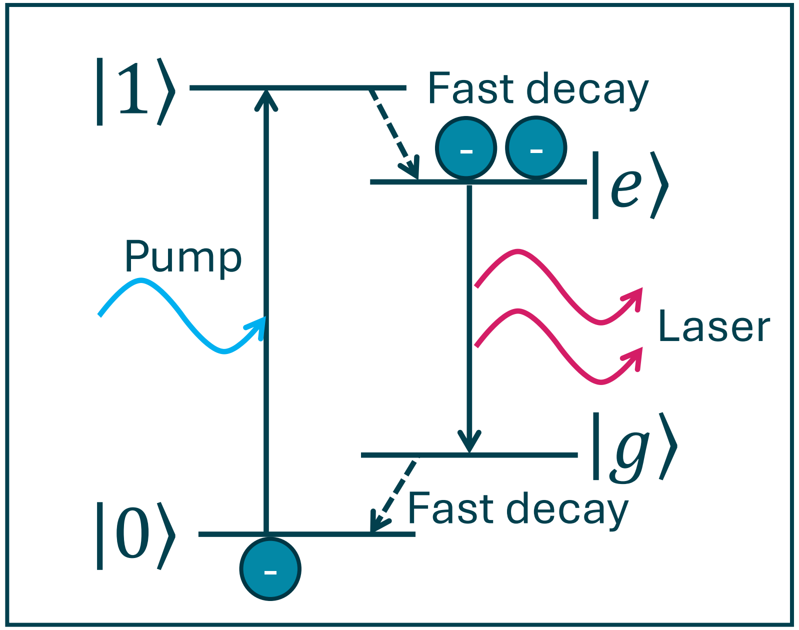
There is an apocryphal story told about Albert Einstein, the mathematician and physicist who evolved the General Theory of Relativity. During an interview at the Institute of Advanced Study in Princeton, a reporter asked him what he thought was man's greatest invention. Einstein paused but a moment and replied, "Compound interest."

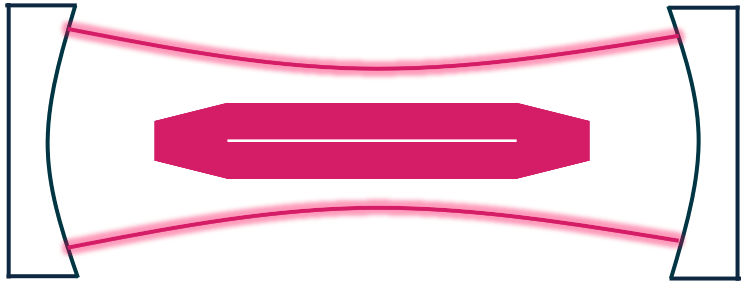
- Compound Interest: interest accumulated from previously accumulated interest
- We can do the same with laser: amplify the light that has previously been amplified! → **Feedback Loop**
- **Disclaimer:** There's no proof Einstein actually said this



Optical Cavity

- Place the active medium in an optical cavity: <u>between two mirrors</u>
    1. One fully reflecting mirror
    2. One partially reflecting mirror
- Part of the *laser* photons are sent back into the active medium: even more stimulated emission!





Mirror, Mirror on the Wall,
How Does Interference Stand Tall?

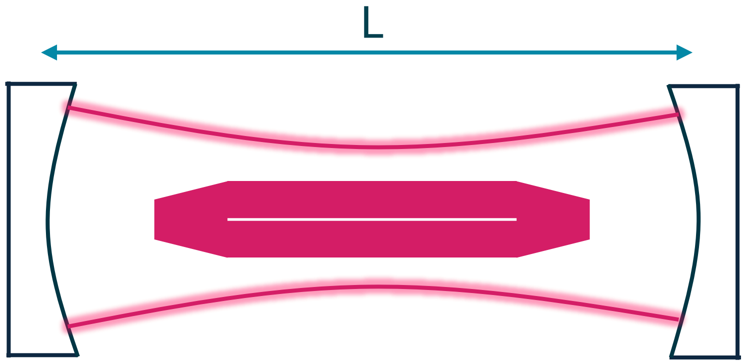
- The cavity must be resonant with the laser photons:
  - Or else: destructive interference

→ When returning at its initial point, the photon should have the same phase as before:

→ Phase difference after returning: $\Delta\varphi = 2L(2\pi)/\lambda$

→ $\Delta\varphi = n(2\pi)$

→ $\boldsymbol{\lambda_n = 2L/n}$



- Only these photons can survive the cavity

→ **Purcell enhancement**

Conclusions

- LASER = **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- Light consists of particles called photons
- A laser requires inversion population, which is highly unstable in a two-level system
- To further enhance the amplification, the laser medium is placed in an optical cavity
- …