Solar cells and solar energy

Dr. Roderick MacKenzie

Spring term 2016

Overview

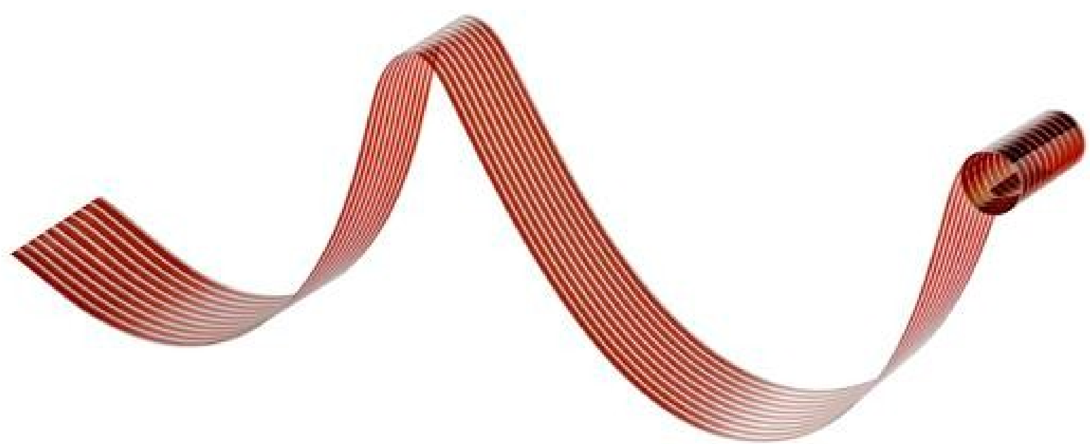
- **About me**
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Multi-junction solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Concentrator solar cells
- Summary

About me

•When I'm not teaching you H14POD/H14ERP on Mondays (and doing marking).

•I spend my life researching ways to convert solar energy into electricity.

•I am interested in a special type of flexible solar cell called a plastic solar cell. Or organic photovoltaic device (OPV) – we will discuss these later.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About me

Change photo

Roderick C I MacKenzie

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University of Nottingham
Organic Electronics, Quantum well laser diodes
Verified email at nottingham.ac.uk - Homepage
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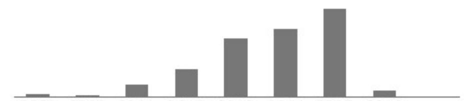
Title | Add | More | 1–20

Title	Cited by	Year
Modeling nongeminate recombination in P3HT: PCBM solar cells RCI MacKenzie, T Kirchartz, GFA Dibb, J Nelson The Journal of Physical Chemistry C 115 (19), 9806-9813	119	2011
Sensitivity of the Mott-Schottky Analysis in Organic Solar Cells T Kirchartz, W Gong, S Hawks, T Agostinelli, RCI MacKenzie, Y Yang, ... American Chemical Society	74	2012
A numerical study of mobility in thin films of fullerene derivatives RCI MacKenzie, JM Frost, J Nelson The Journal of chemical physics 132 (6), 064904	61	2010
Extracting microscopic device parameters from transient photocurrent measurements of P3HT: PCBM solar cells RCI MacKenzie, CG Shuttle, ML Chabinyc, J Nelson Advanced Energy Materials 2 (6), 662-669	60	2012
Gravure printing for three subsequent solar cell layers of inverted structures on flexible substrates MM Voigt, RCI Mackenzie, CP Yau, P Atienzar, J Dane, PE Keivanidis, ...	59	2011

Google Scholar

Citation indices	All	Since 2011
Citations	666	641
h-index	13	12
i10-index	15	13



Co-authors Edit...

Thomas Kirchartz
Michael Chabinyc
George F. A. Dibb
Jarvist Moore Frost
Anders Larsson
Steven A. Hawks
Felix Deschler
Elizabeth von Hauff
Enrico Da Como
Maxwell J. Robb
Neil D Treat

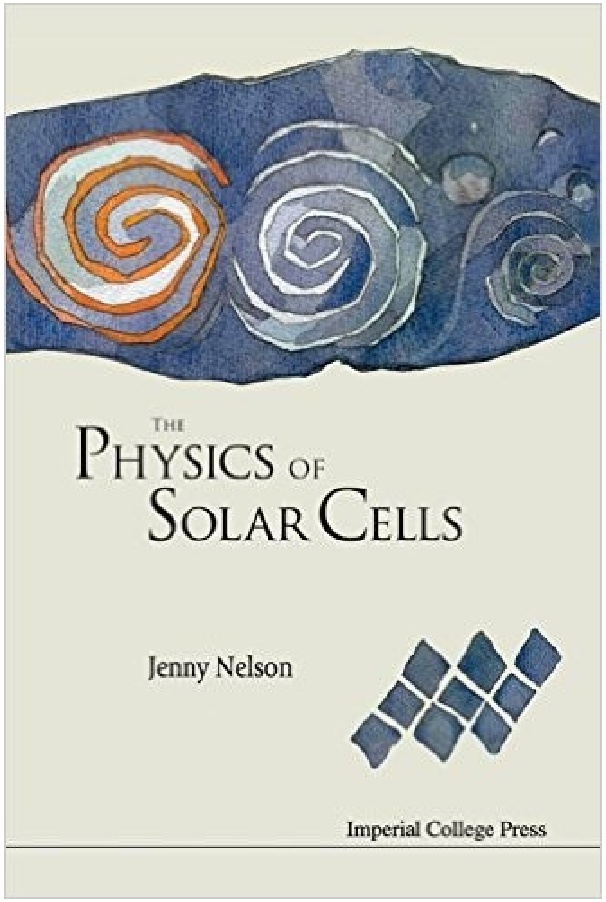
- I'm also author of a solar cell simulation tool that you can find at www.opvdm.com

https://scholar.google.de/citations?user=jgQqfLsAAAAJ&hl=en

Aims of lecture

- **What this lecture is:**
    - This lecture aims to give you enough information to understand the operation of solar cells.
    - It is aimed at helping you understand the devices enough to make component choices when designing systems.
- **What this lecture is not:**
    - A solid state physics lecture.

Recommended book



- This lecture is only 1.5 hours long, so I can't cover everything about solar cells and solar energy.

- The Physics of Solar Cells (Properties of Semiconductor Materials)

- If you want a deeper understanding get this book.

Jenny Nelson

ISBN:1860943497

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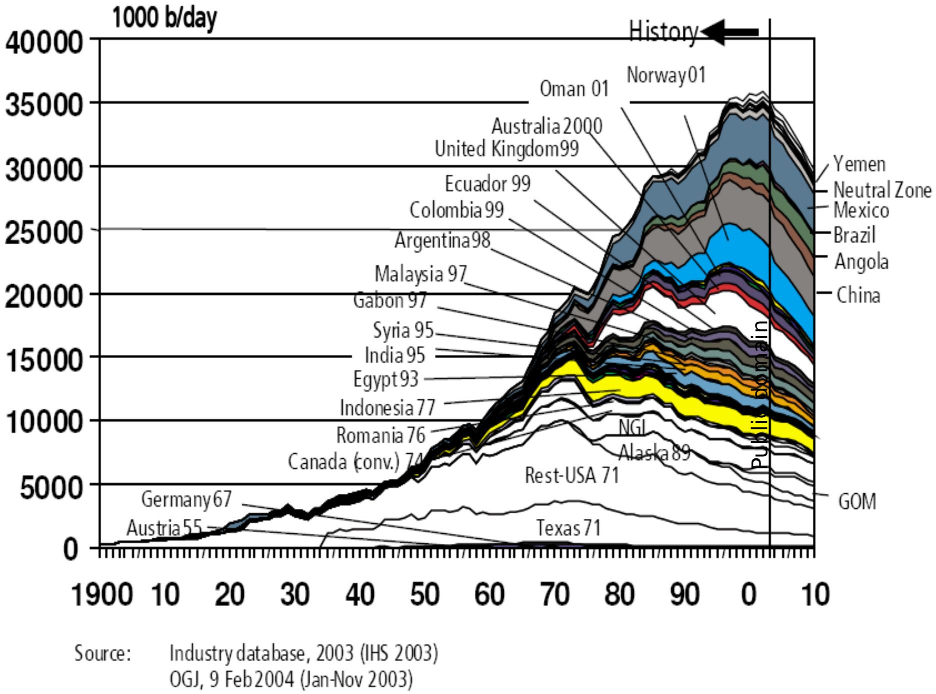
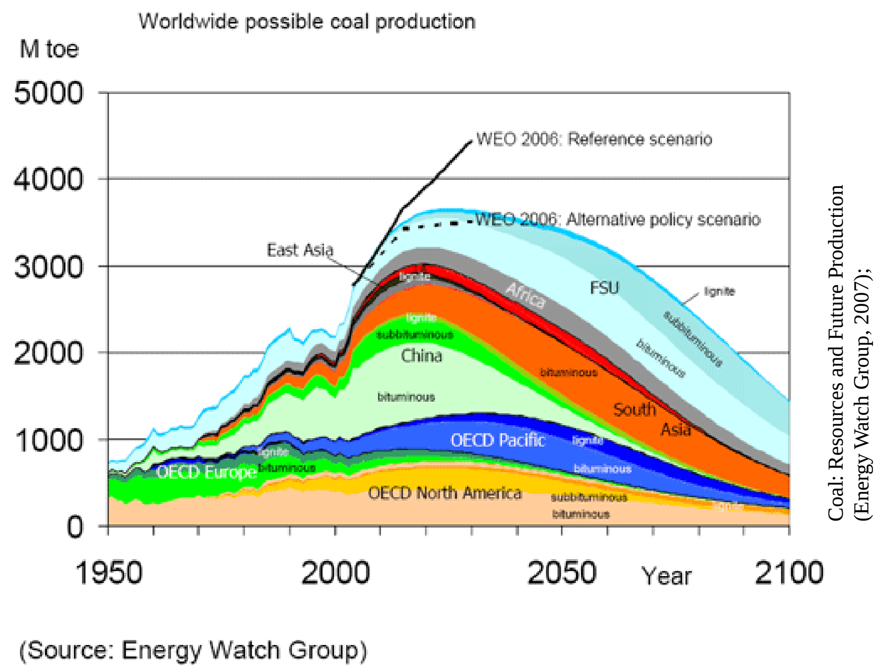
Reason 1: We are running out of oil and coal



Oil production

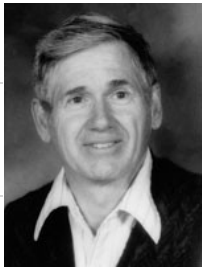


Coal production

- This will damage the economy and our standard of living, our health and well being.

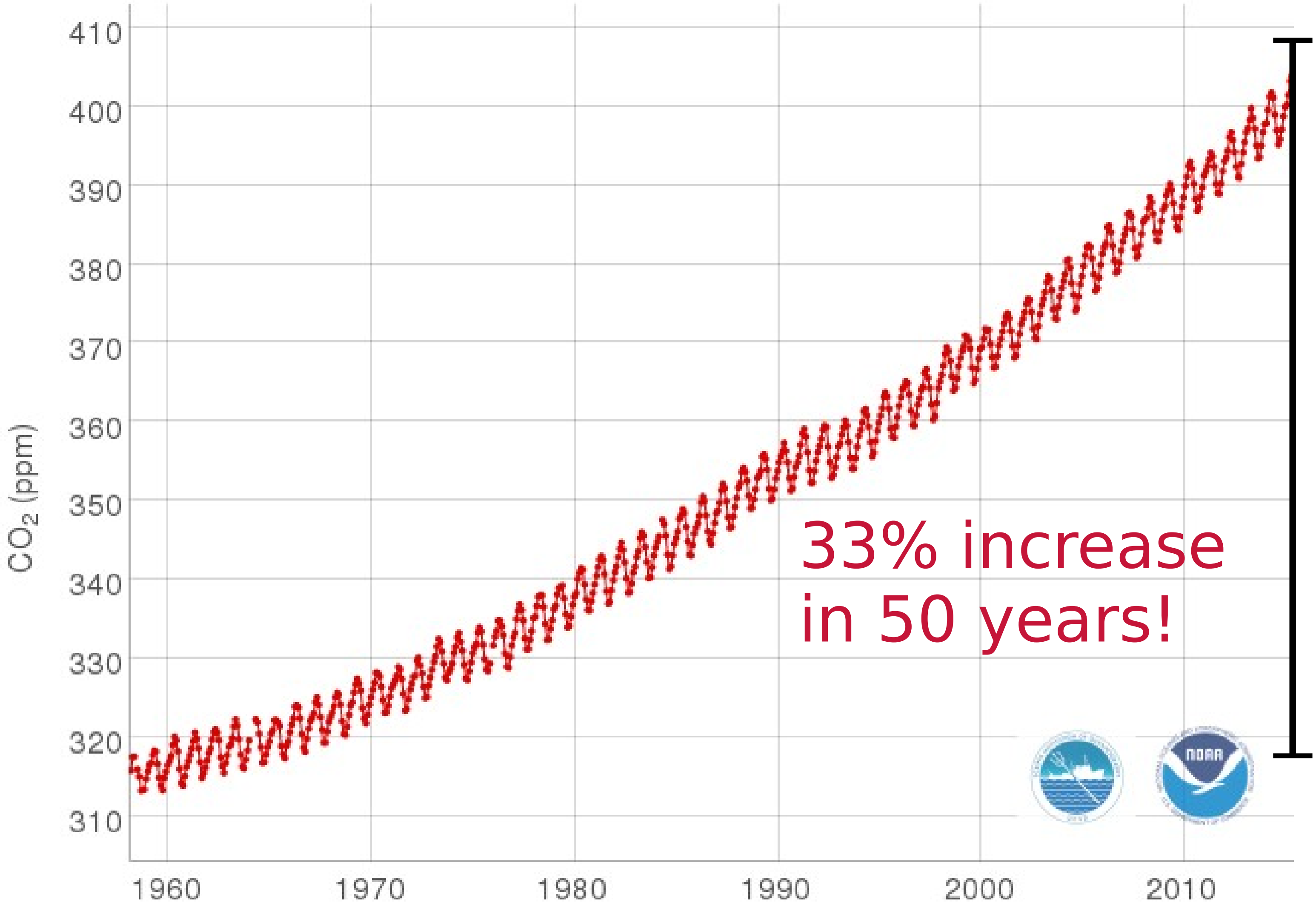
Nature, January 2012,Vol 481, pp. 433-435

Reason 2: Global warming

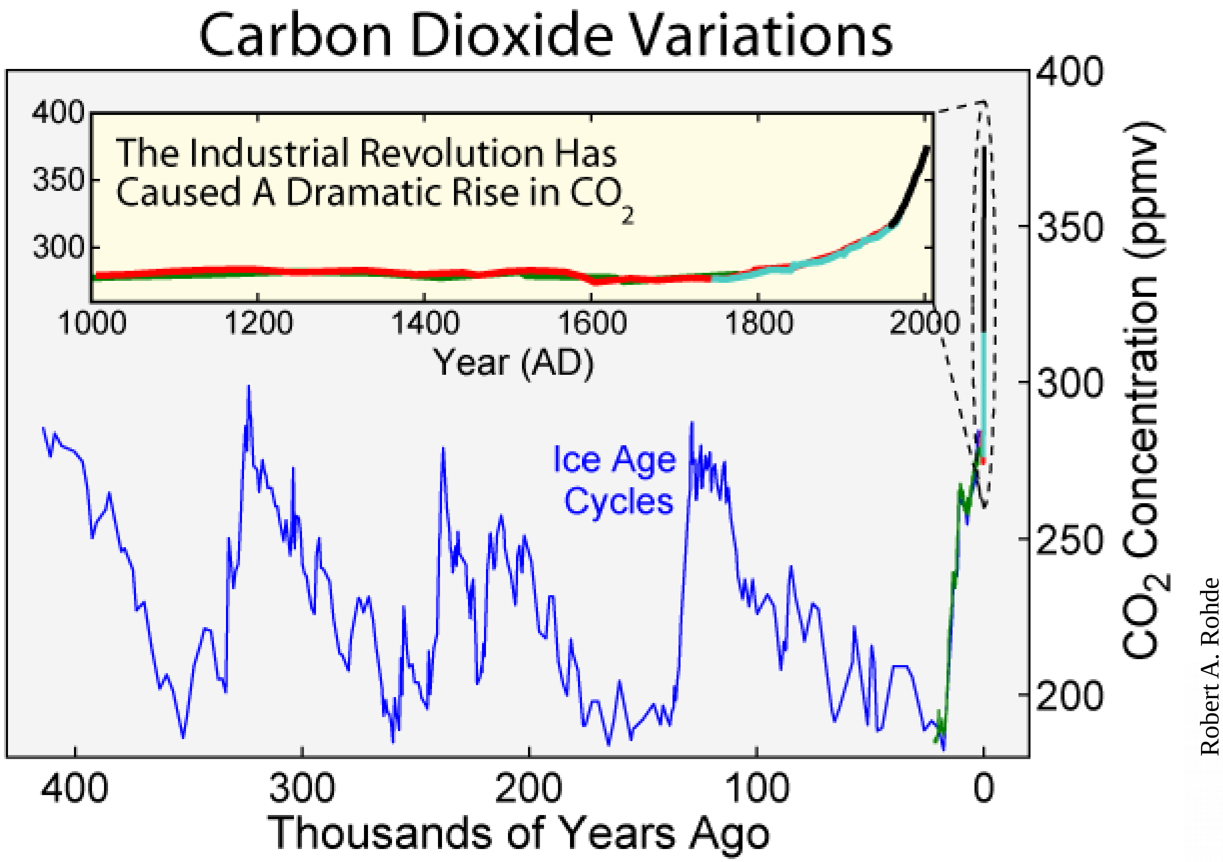


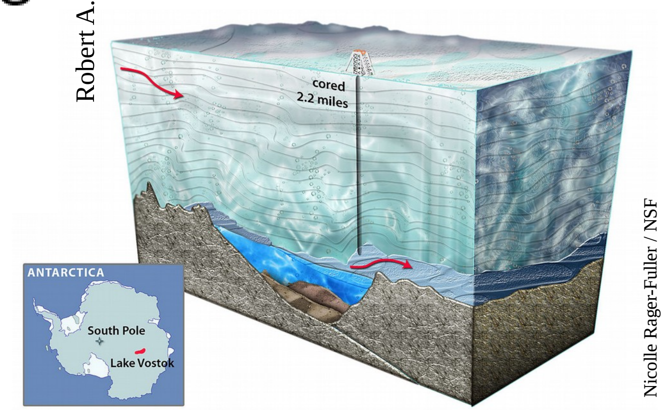
Charles Keeling

Jan 1980-June 2015

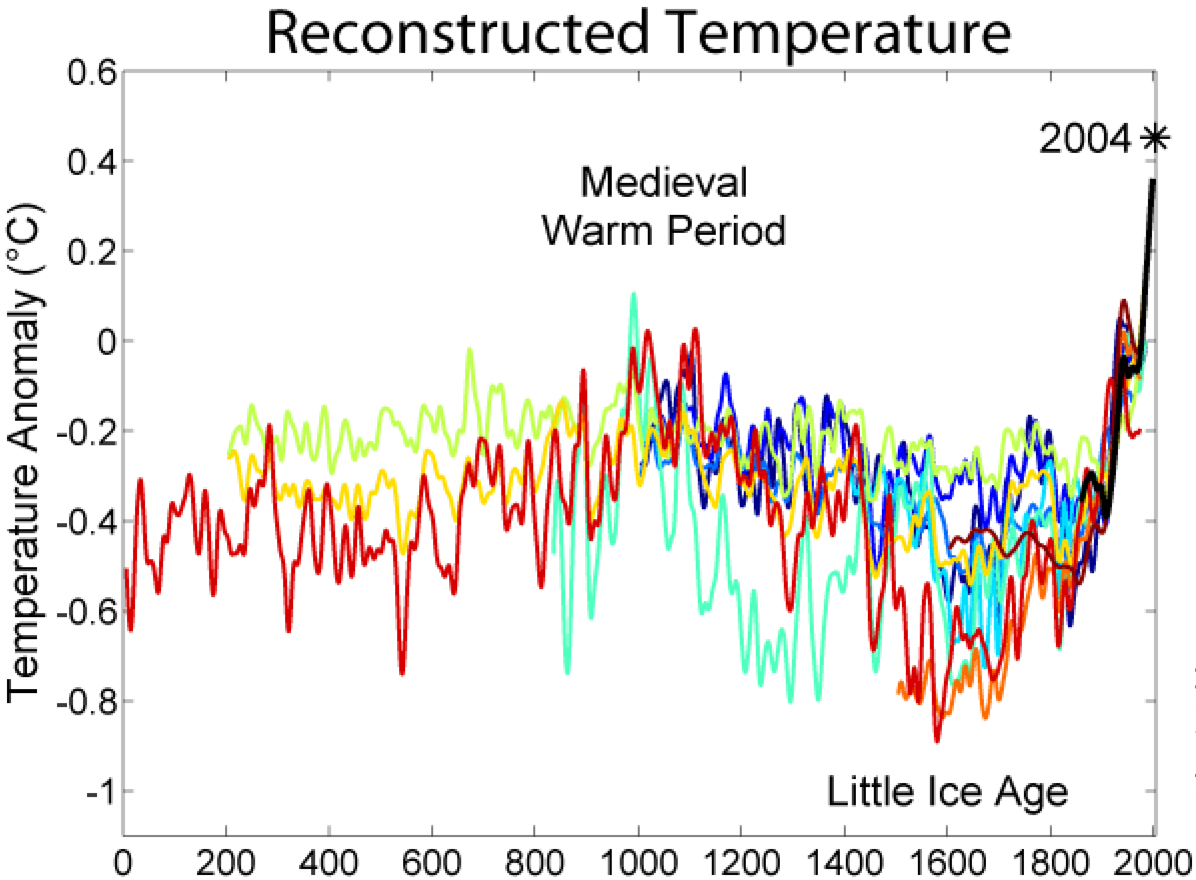


Carbon dioxide 400 AD – 2009 AD





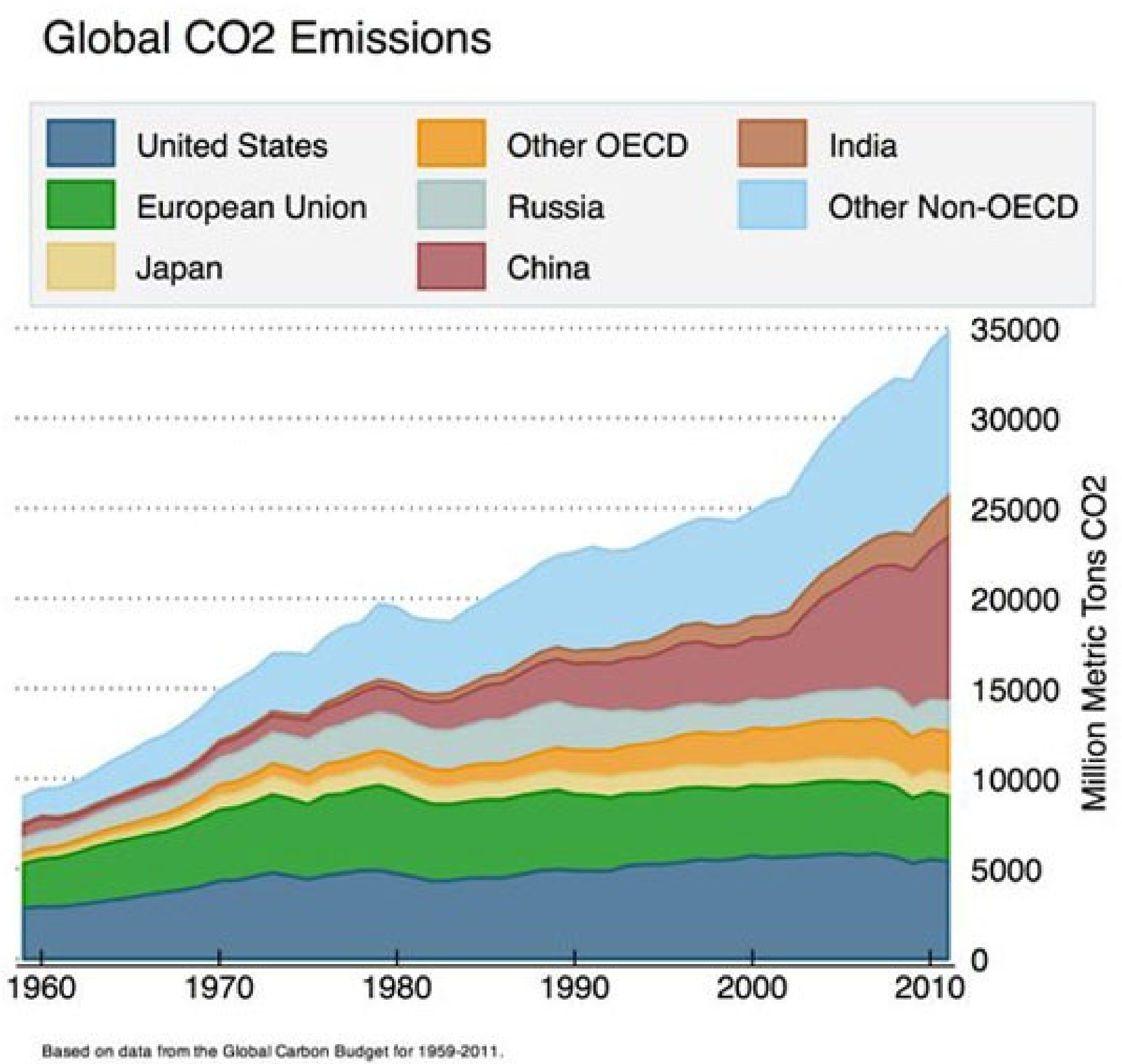
Global temperature 1000 AD – 2000 AD



Robert A. Rohde

Jensk369

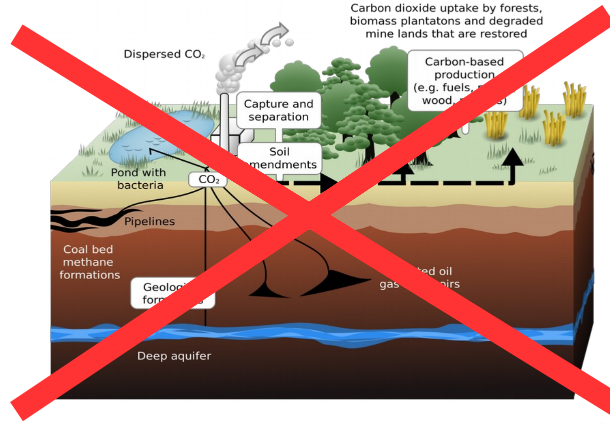
CO_2 Emissions by country



The developing world is **poor**.

- If the renewable technology is not lower cost than coal it will not be adopted.

Oxfam East Africa



LeJean Hardin and Jamie Payne

- If it's not profitable it's not sustainable

Why choose solar energy?

- Solar max power flux: ~1500 W / m^2

- Average density over the year:
  - Sahara: ~ 400 W / m^2
  - UK: ~ 100 W / m^2

- Typical solar cell efficiency 15%

- In UK need 40 m^2 per person to supply average electricity demand (700 W)

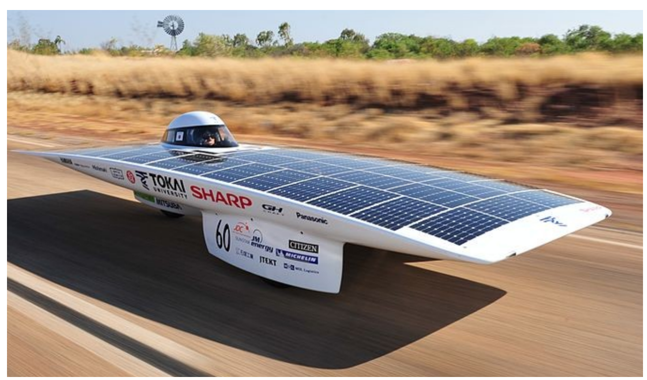
Where do we find PV systems?

Andrewglaser

Building integrated

Sawu12

Solar power stations



Hideki Kimura, Kouhei Sagawa

Transport integrated??

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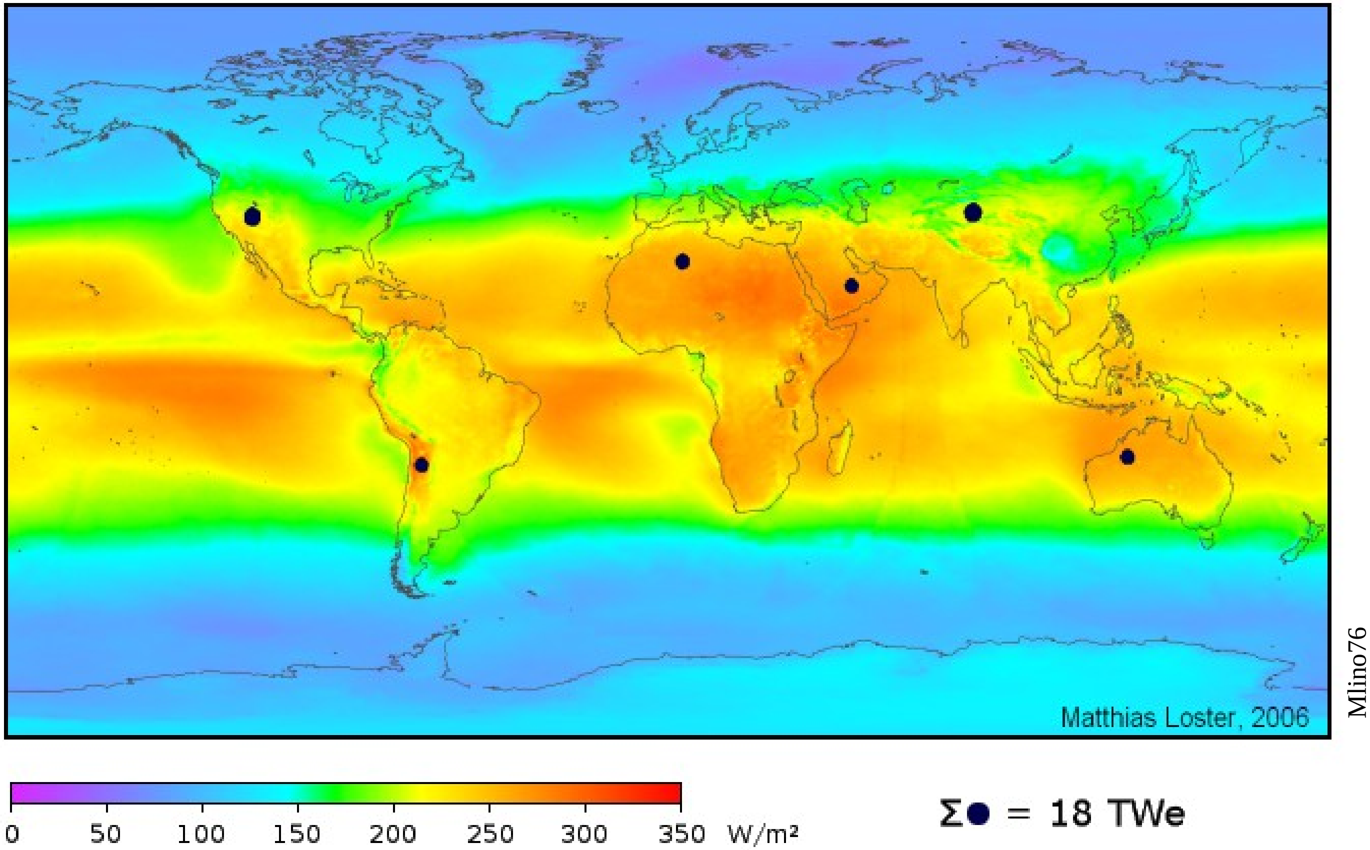
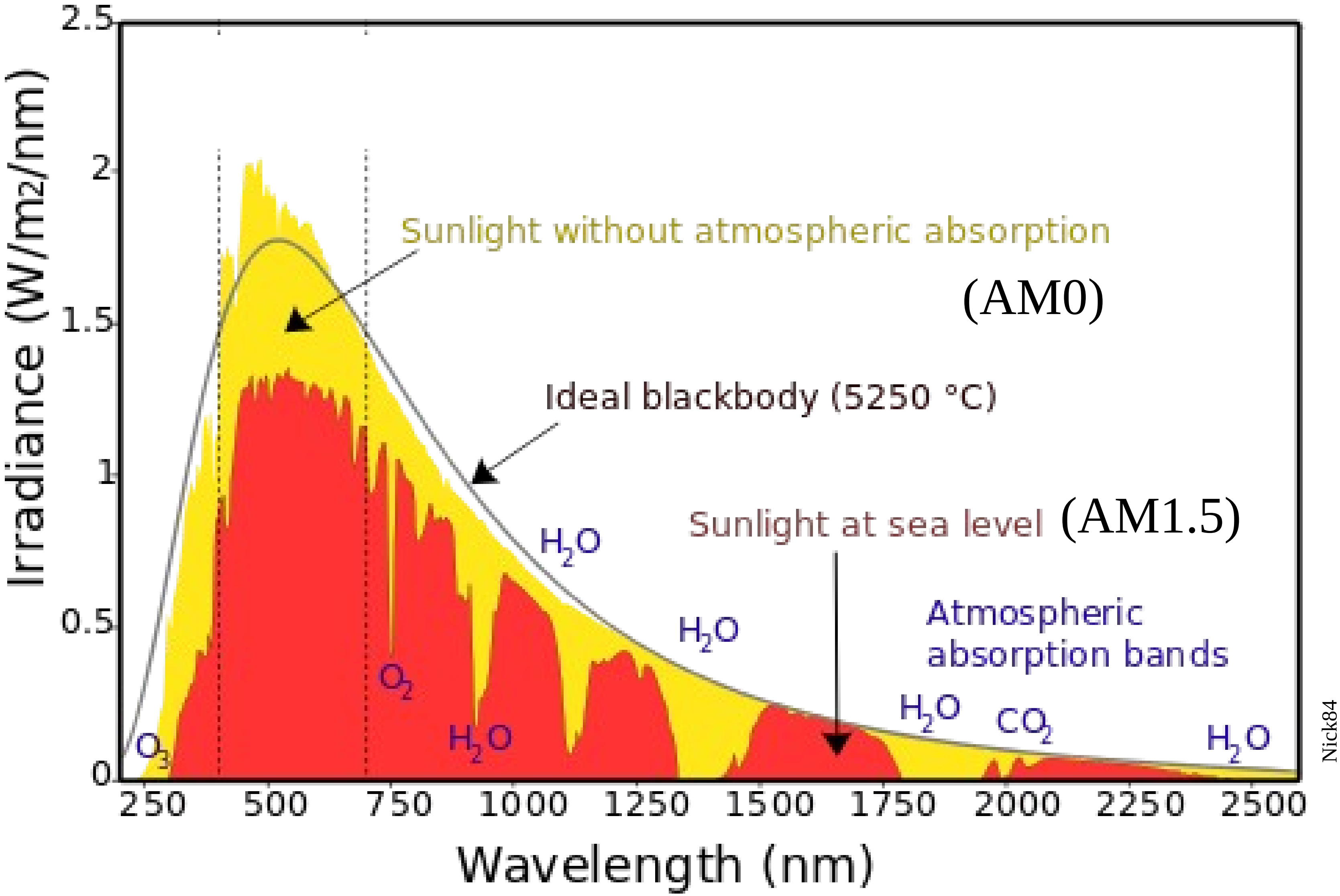
Solar radiation map

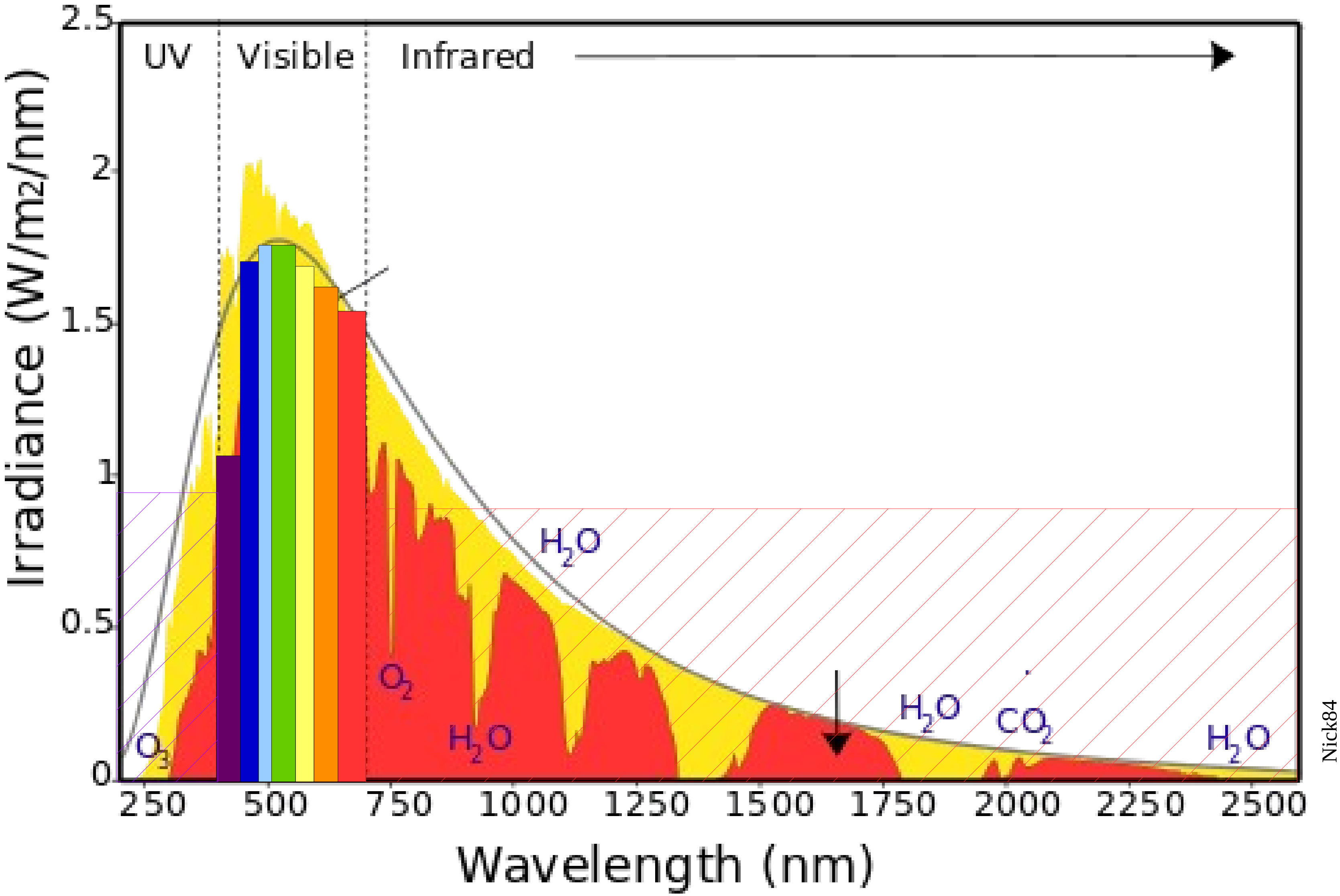


Wiki: "Solar areas defined by the dark disks could provide more than the world's total primary energy demand (assuming a conversion efficiency of 8%). That is, all energy currently consumed, including heat, electricity, fossil fuels, etc., would be produced in the form of electricity by solar cells. The colors in the map show the local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites."

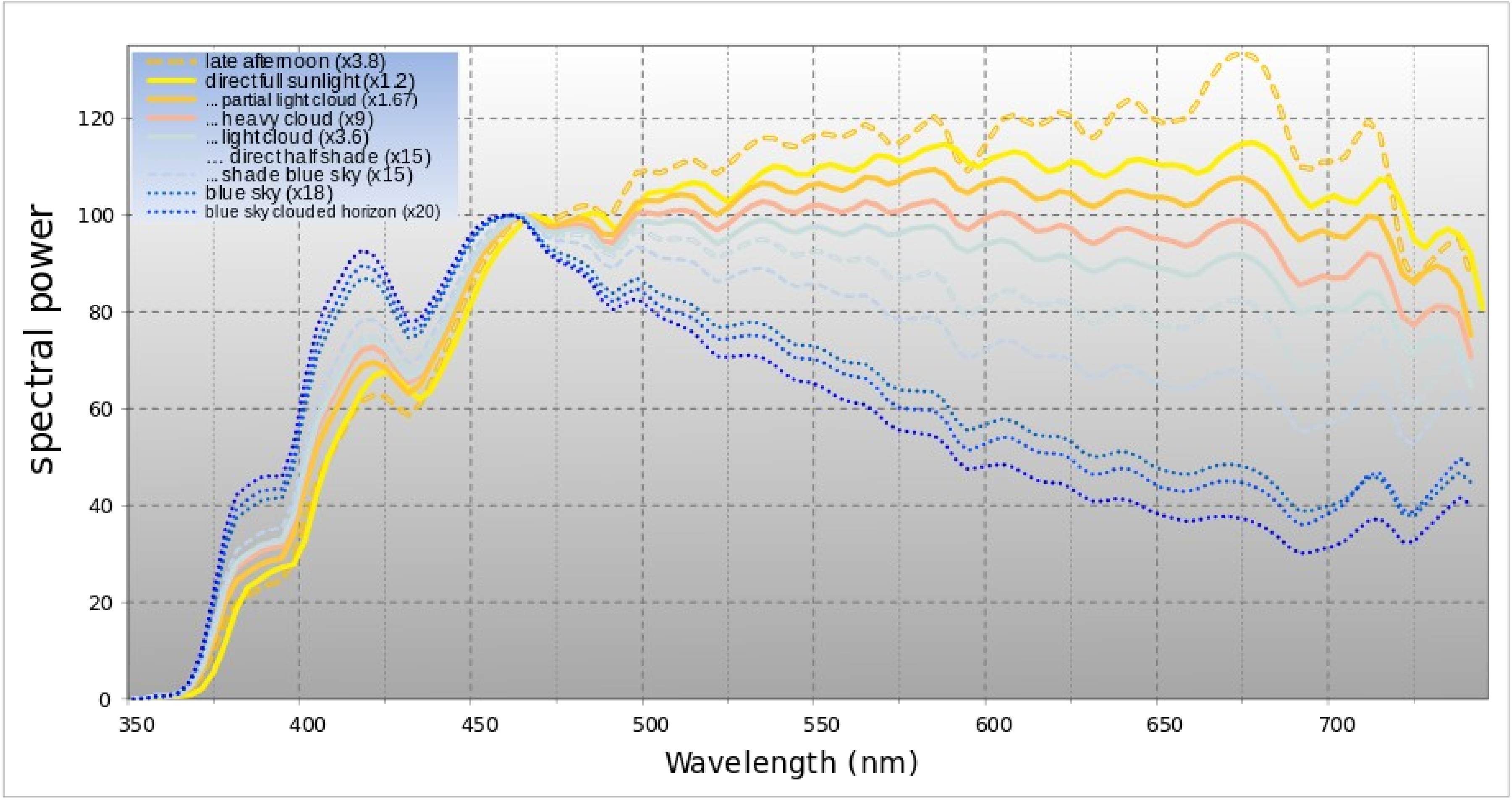
What is sunlight exactly: The solar spectrum?



The solar spectrum



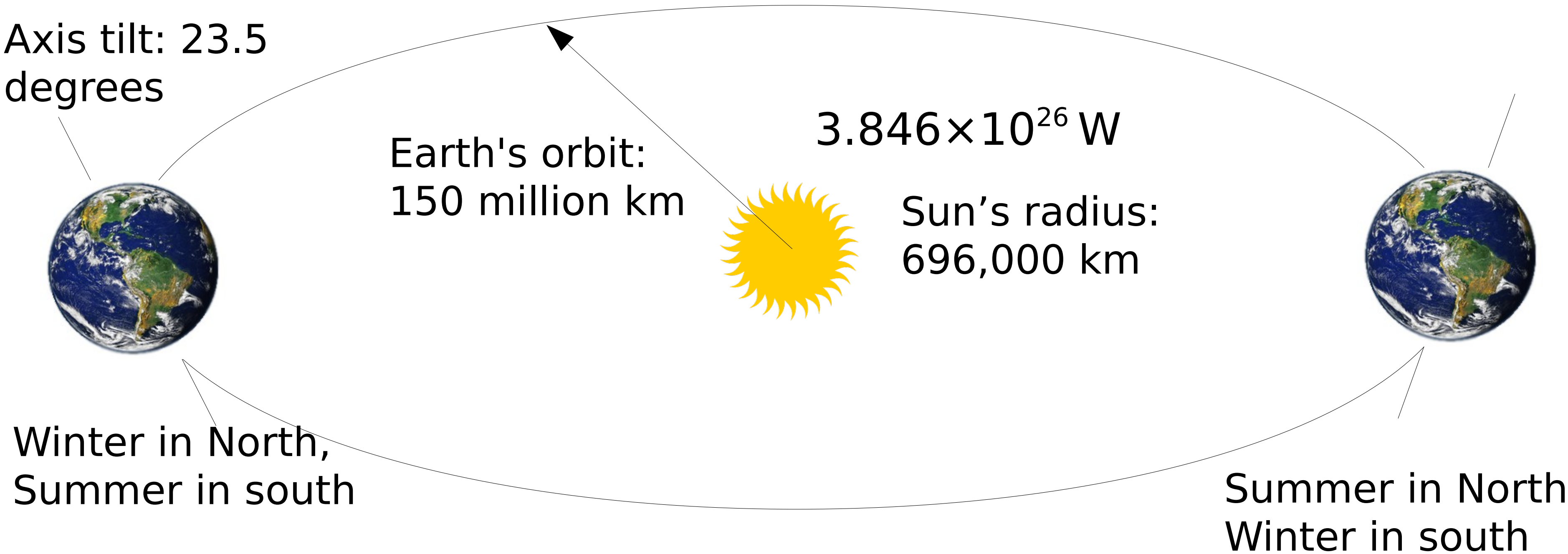
Clouds and sunlight



Txbangert

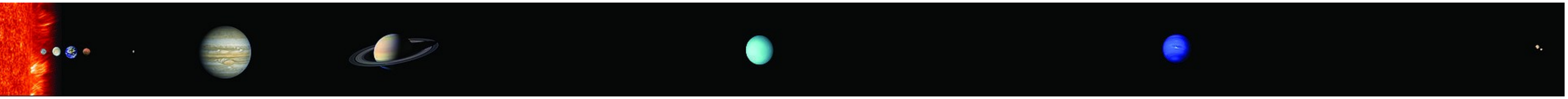
What do you think this is an image of?

Seasonal variation in solar intensity



$$Intensity_d = \frac{Power}{4\pi d^2}$$

Class exercise



$$Intensity_d = \frac{Power}{4\pi d^2}$$

$$Intensity_d = \frac{3.846 \times 10^{26}}{4\pi(150000\,x\,10^6)^2}$$

$$Intensity_d = 1360.2\,Wm^{-2}$$

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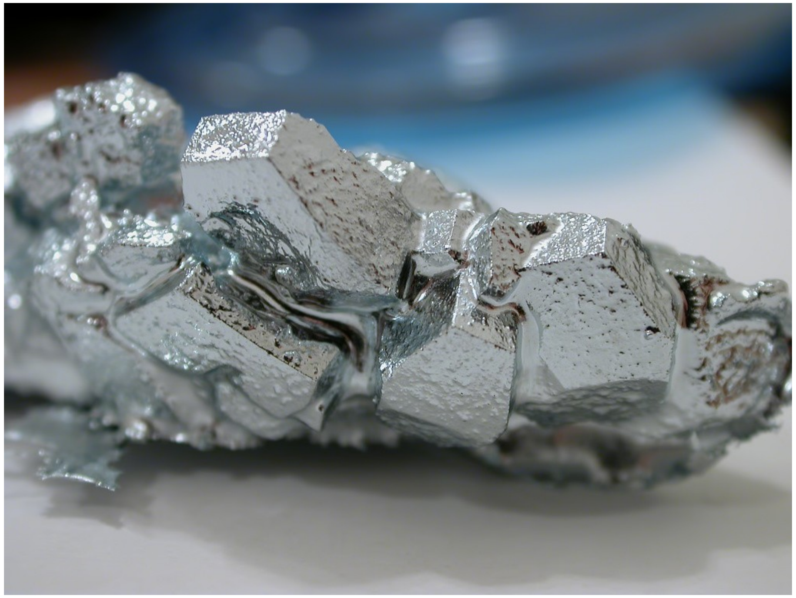
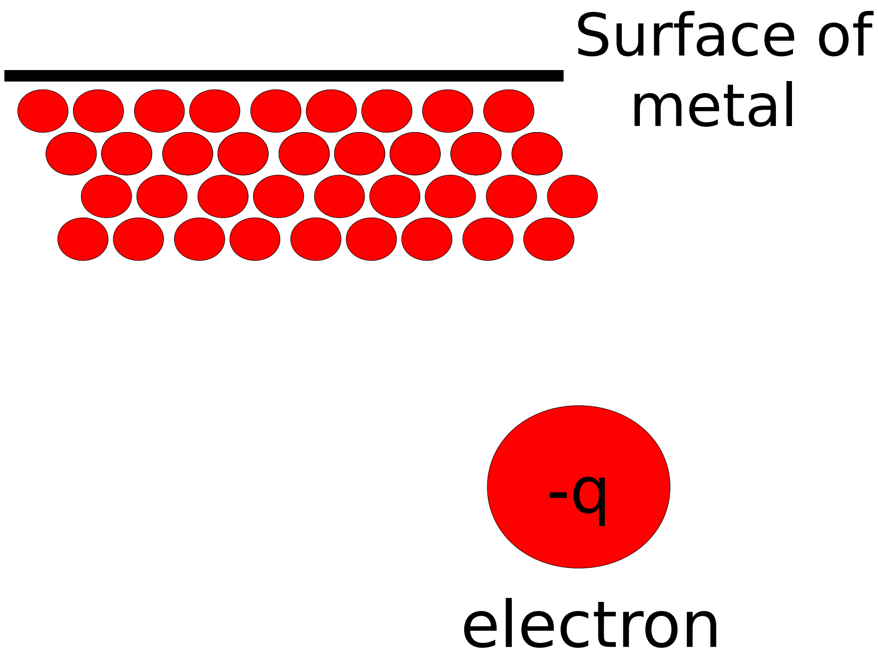
Fundamental principle of semiconductors: Let's first think about **metals**

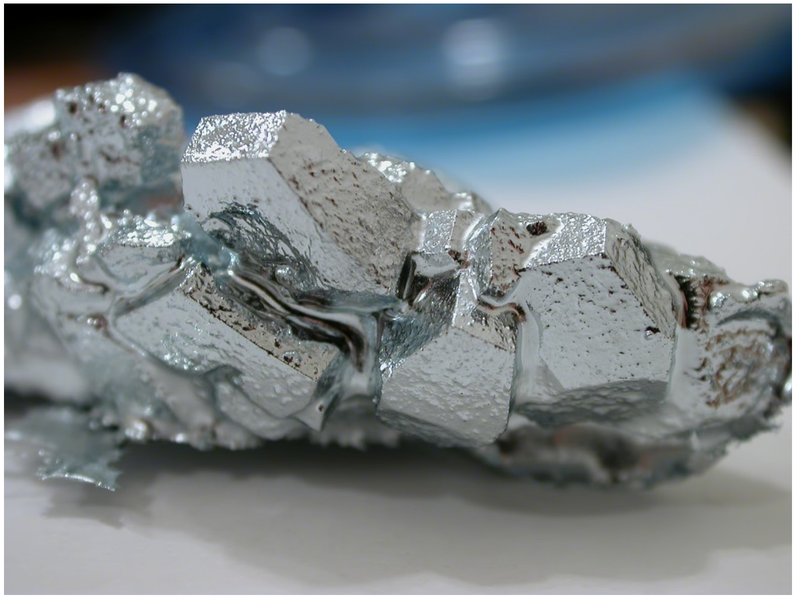


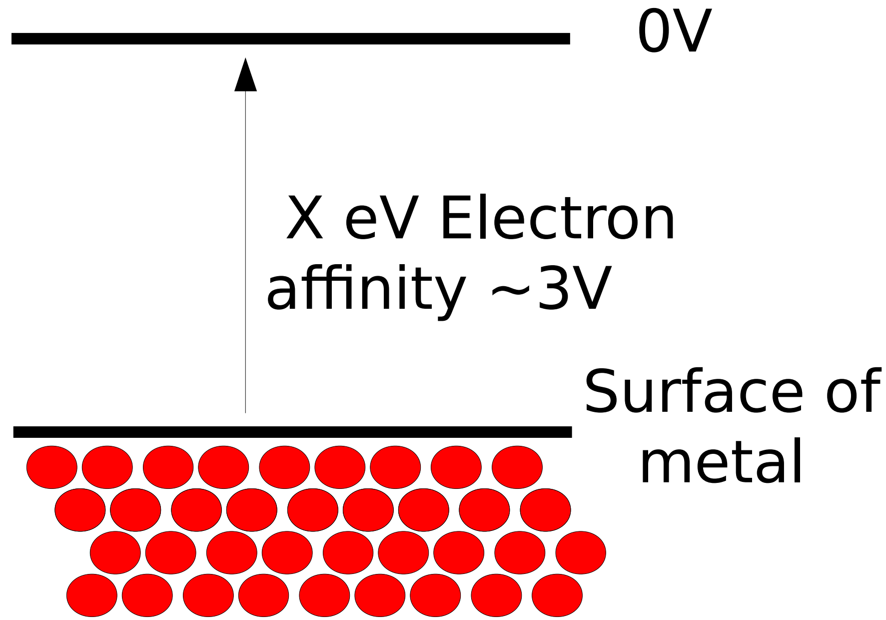


•You can think of a metal as a see of electrons.

$$q=1.60217657 \times 10^{-19} \text{ coulombs}$$

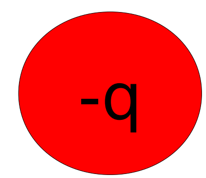
Fundamental principle of semiconductors: Let's first think about **metals**





•You can think of a metal as a see of electrons.

•You need energy X (Electron affinity) to remove an electron from the surface of the metal.



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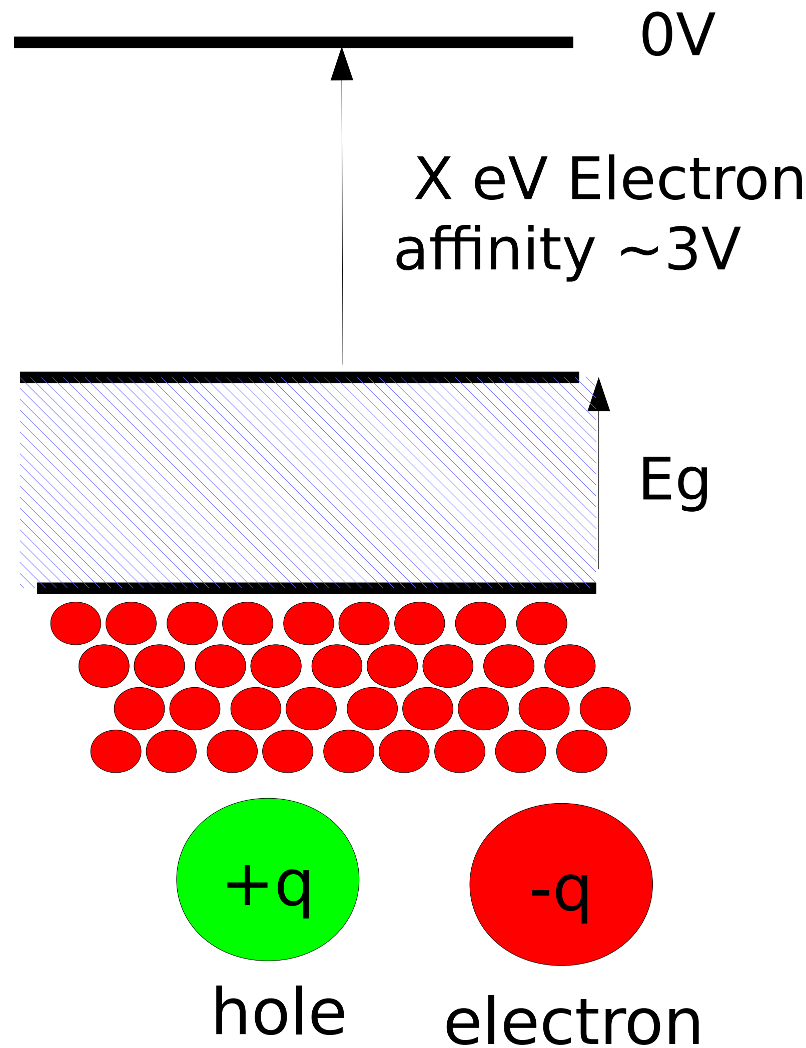
Fundamental principle of semiconductors: **Semiconductors and the band gap**

- Solar cells are made from a special type of material called a semiconductor.

Fundamental principle of semiconductors:
Semiconductors and the band gap

- Solar cells are made from a special type of material called a semiconductor.
- A semiconductors are a special because they have a **forbidden region** called the **band gap (Eg)** where no charge can exist.



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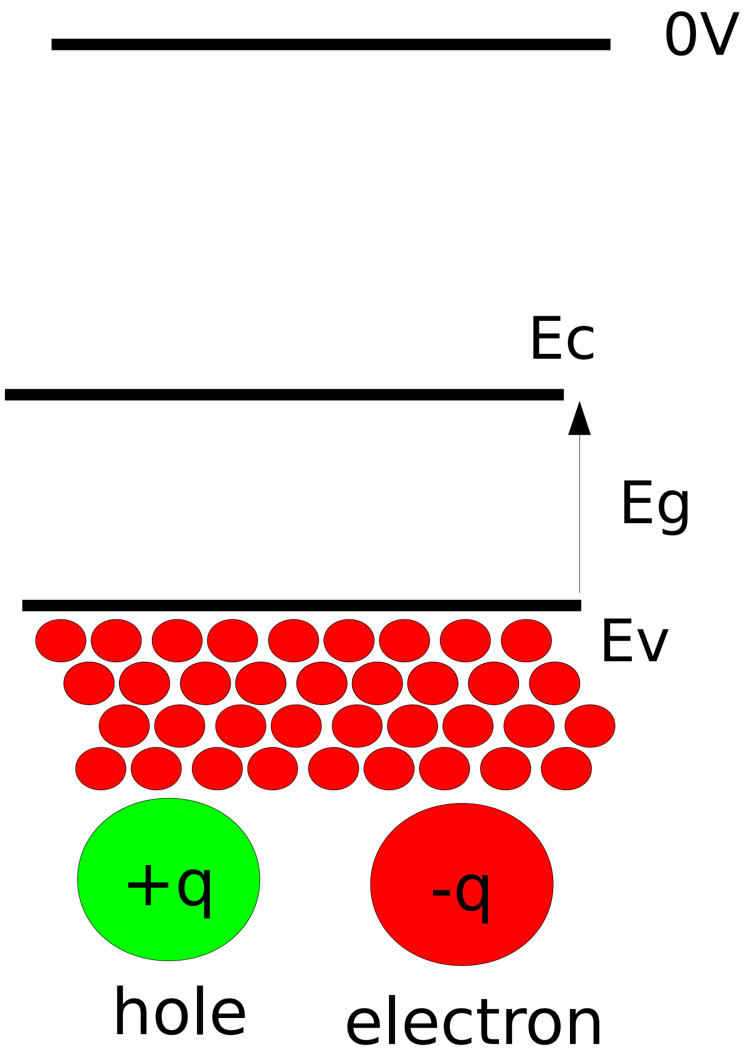
Fundamental principle of semiconductors: **Semiconductors and the band gap**

•Light can be absorbed by semiconductors.



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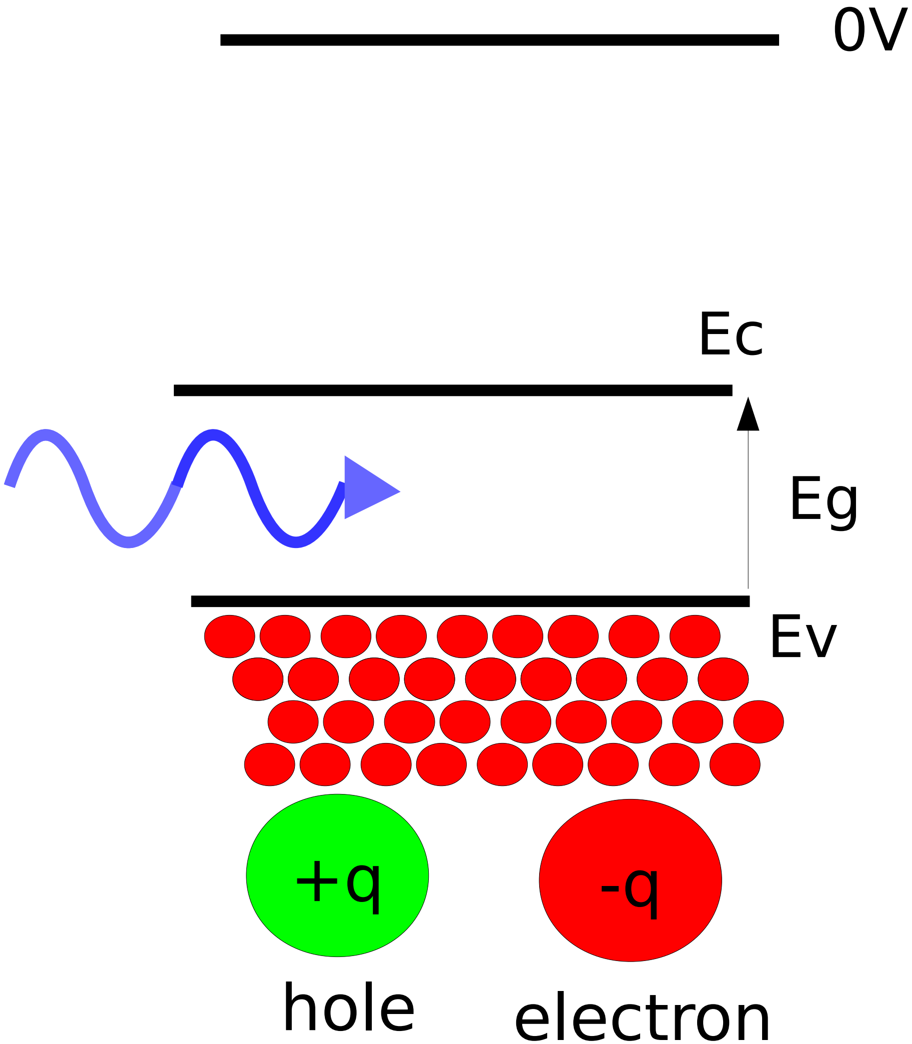
Fundamental principle of semiconductors:
Semiconductors and the band gap

- Light can be absorbed by semiconductors.
- A photon enters the material.



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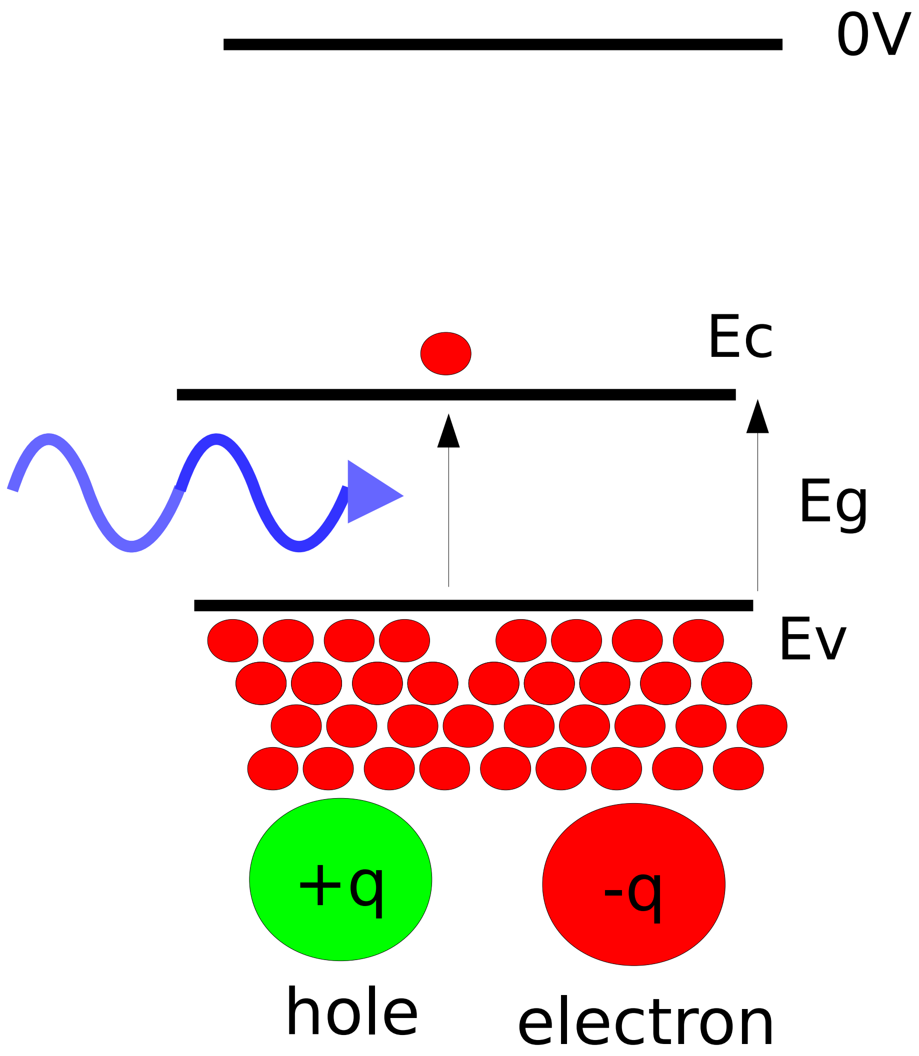
Fundamental principle of semiconductors:
Semiconductors and the band gap

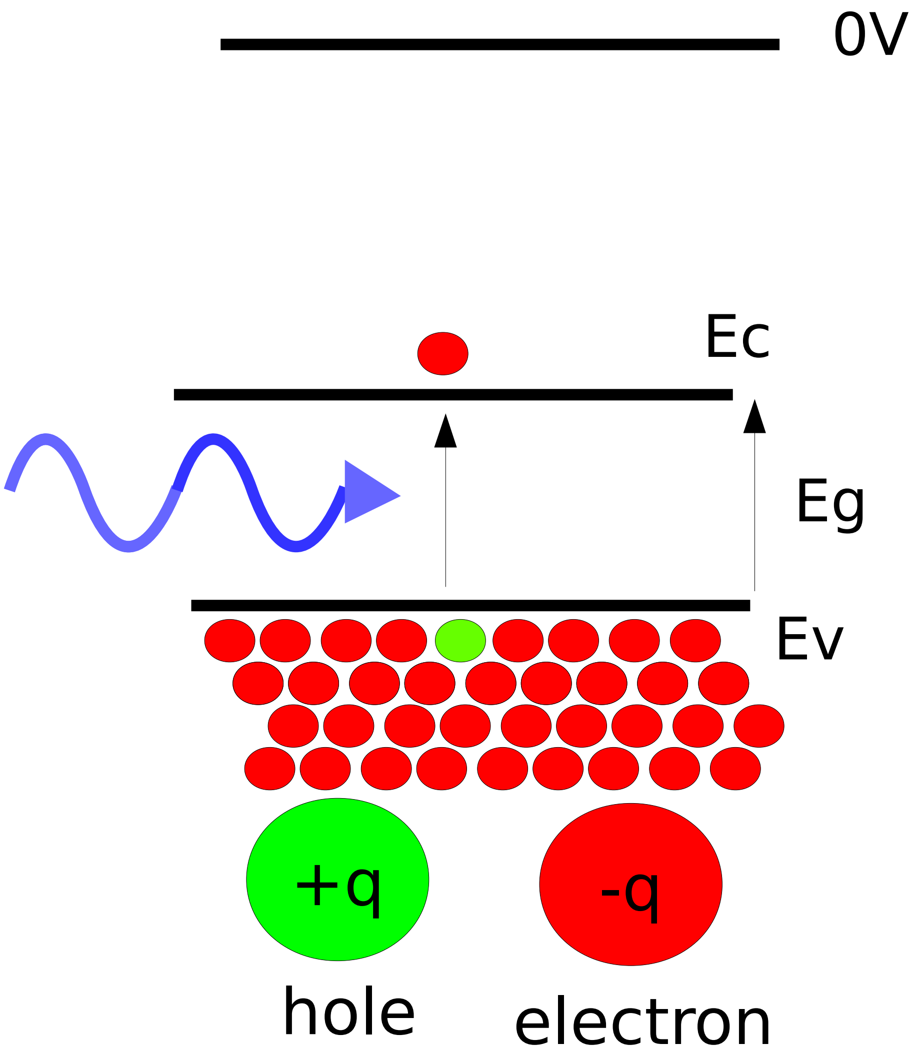
- Light can be absorbed by semiconductors.
- A photon enters the material.
- And promotes an electron from **Ec** to **Ev**.



$q=1.60217657 \times 10^{-19}$ coulombs

Fundamental principle of semiconductors:
Semiconductors and the band gap

- Light can be absorbed by semiconductors.
- A photon enters the material.
- And promotes an electron from **Ec** to **Ev**.
- The gap that the electron leaves is called a hole.

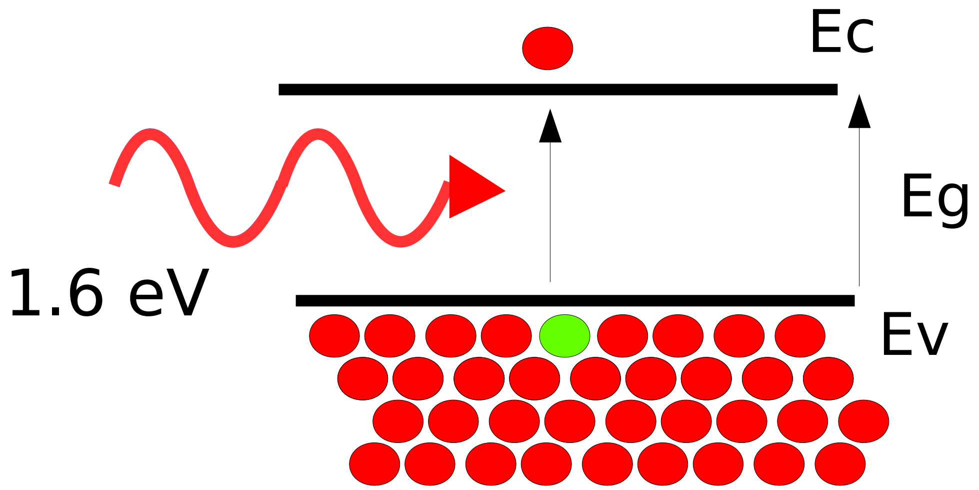


$q = 1.60217657 \times 10^{-19}$ coulombs

Fundamental principle of semiconductors: **Absorption**

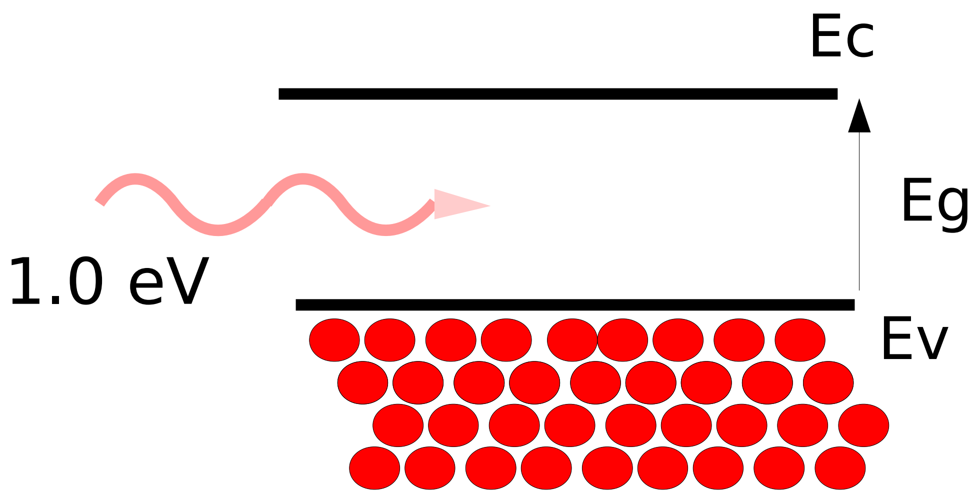
•Silicon has a band gap of Eg 1.6 eV

•So if a photon has exactly 1.6 eV (deep red) it will be absorbed.

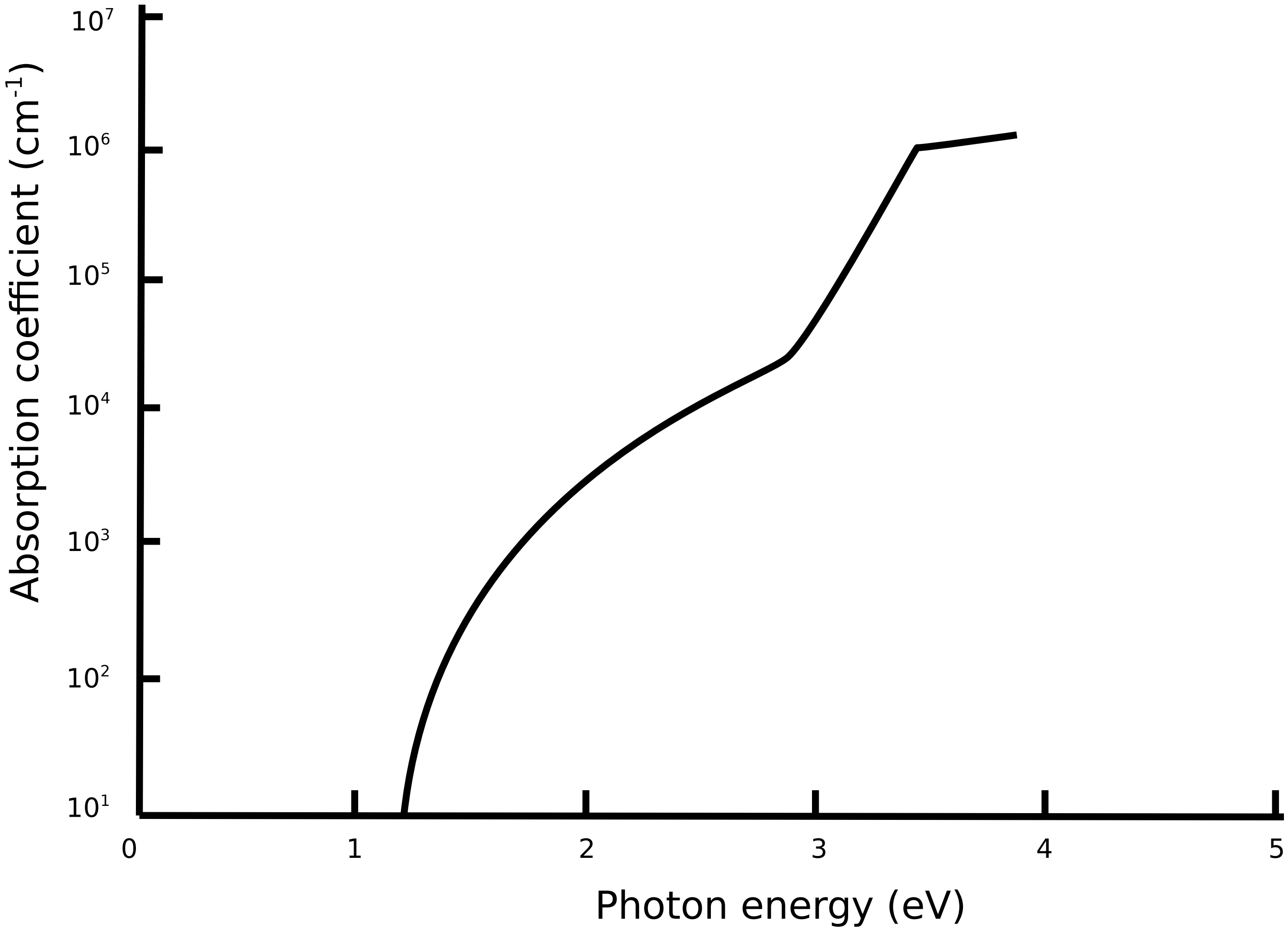


Fundamental principle of semiconductors: **Absorption**

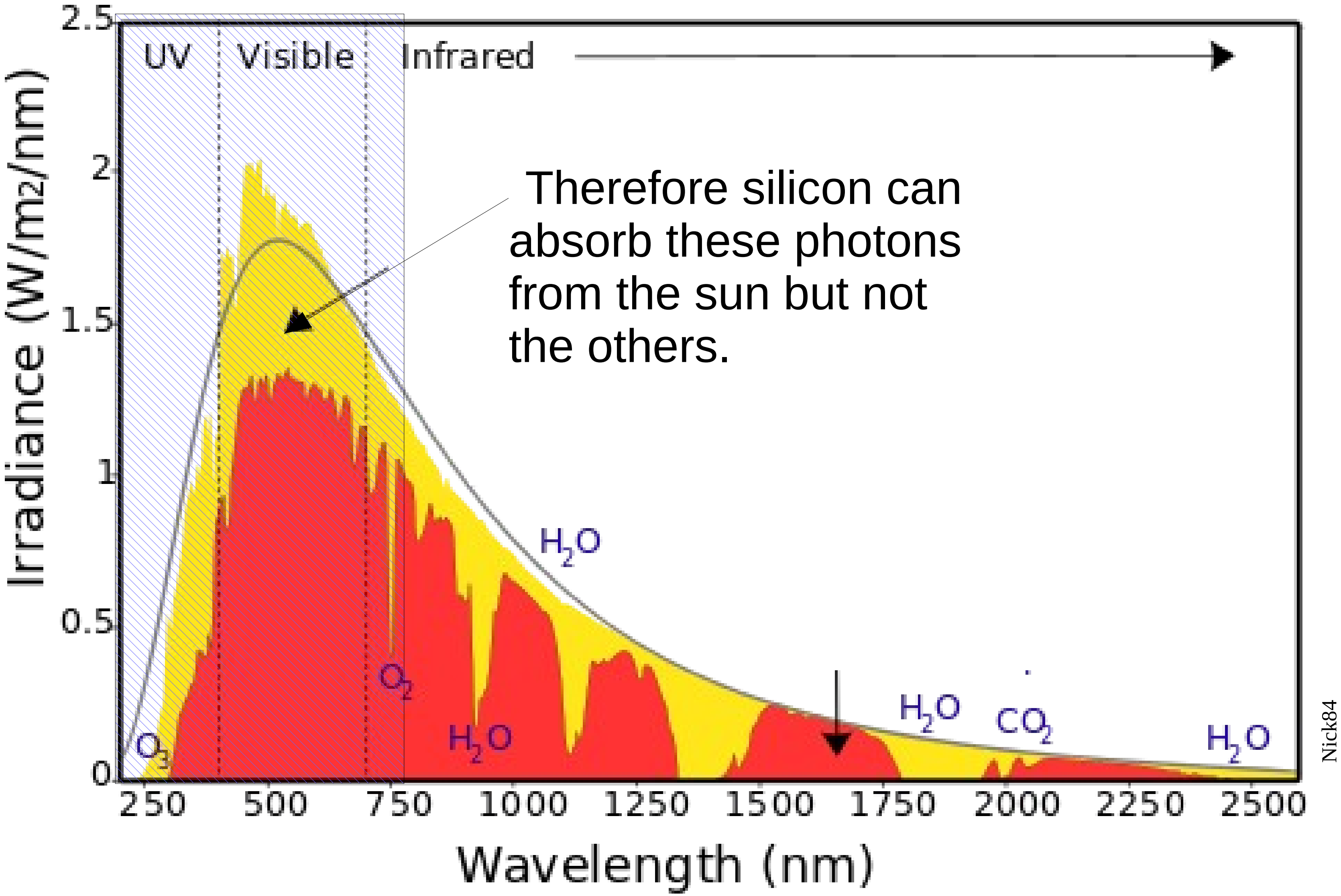
- If a photon has less than 1.6 eV of energy say (infrared red) it will not be absorbed because it does not have enough energy to promote an electron from Ev to Ec.



Absorption spectrum of silicon.

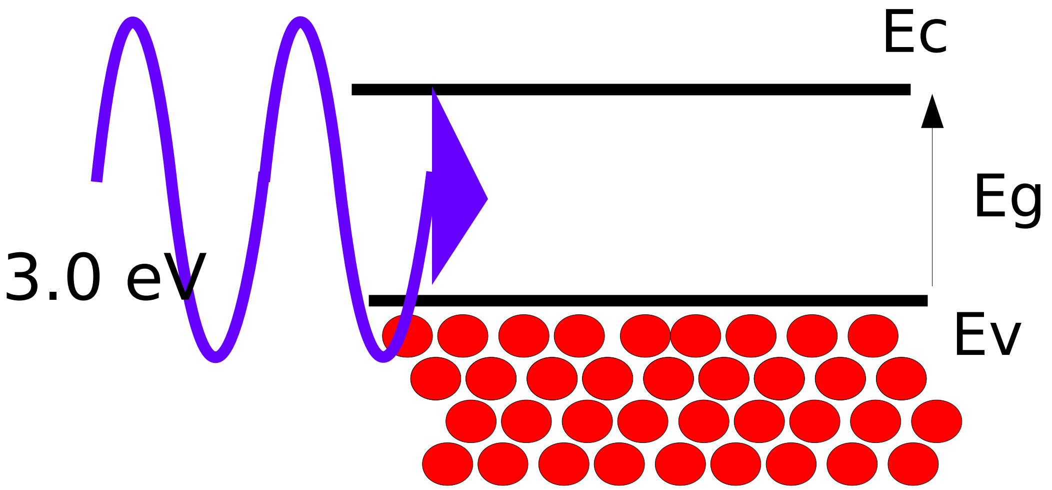


The solar spectrum



Fundamental principle of semiconductors: **Absorption**

- If a photon has more than 1.6 eV it will lift a electron higher that Ec. However the electron will quickly relax to Ec loosing the excess energy to heat.



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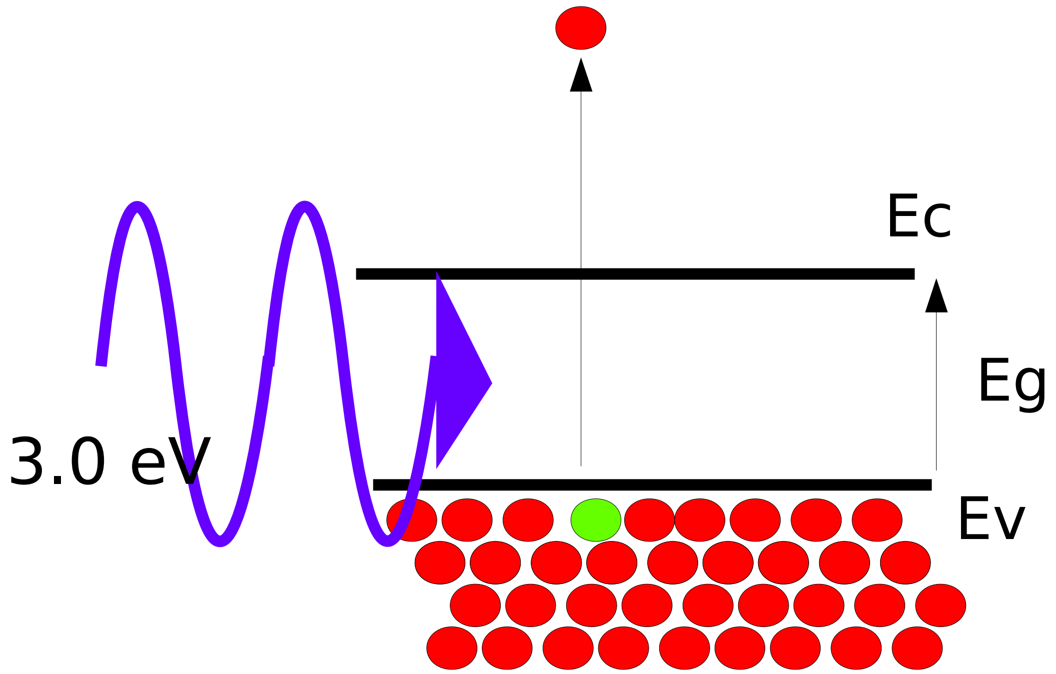

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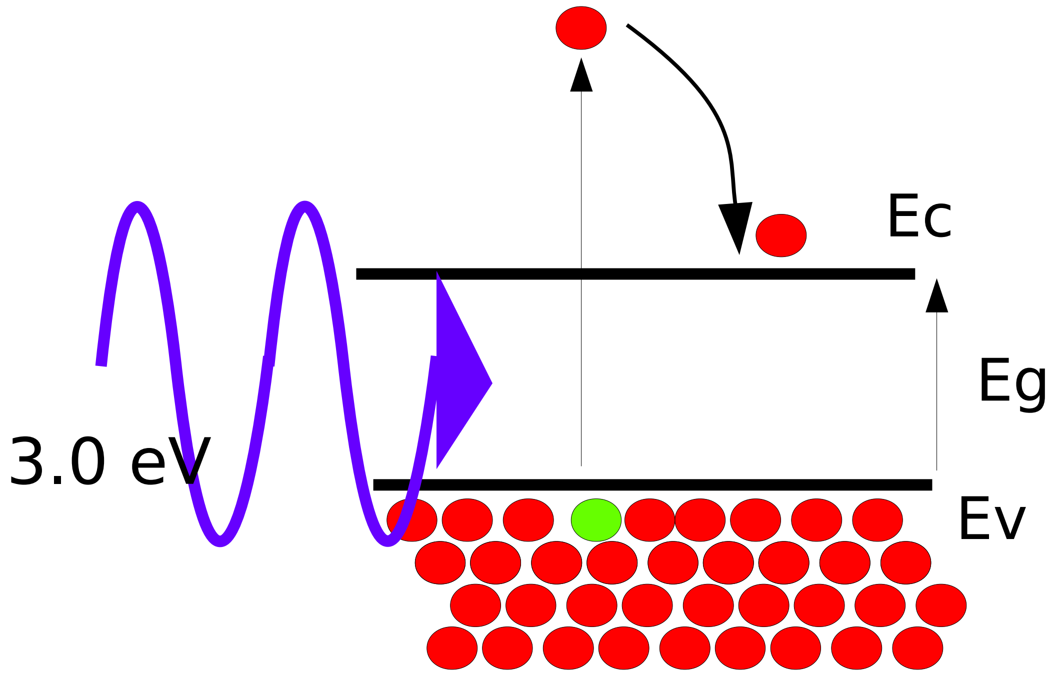

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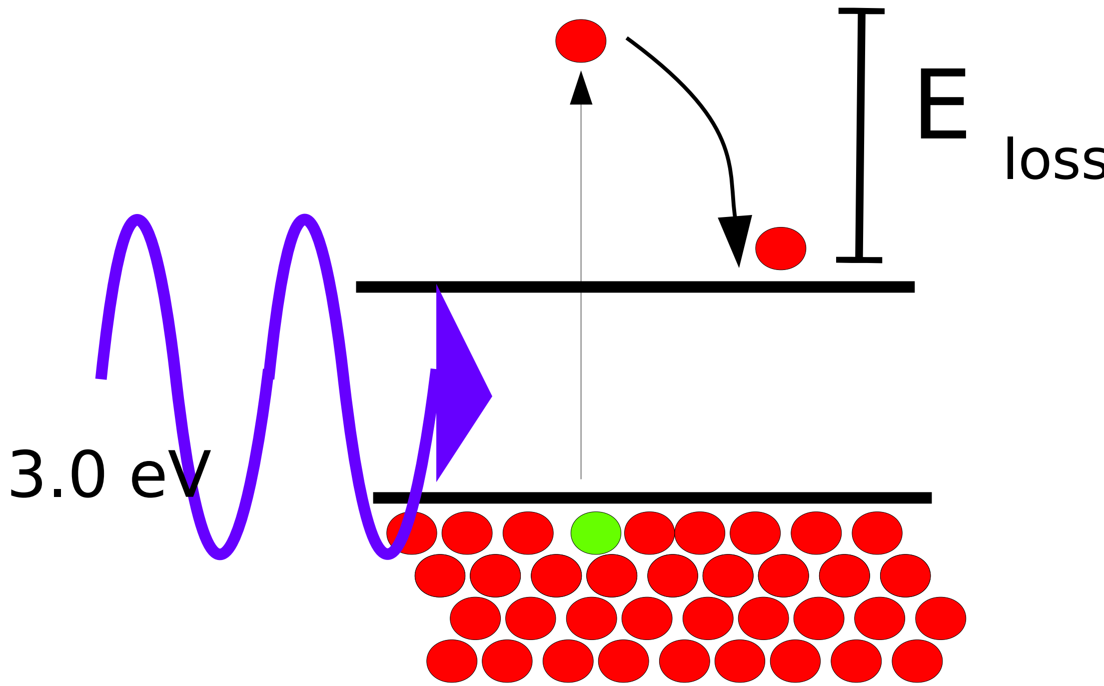

$$E_{loss}=E_{photon}-E_g$$

From Energy to wavelength

Plank's constant

$$E = hf \qquad c = f\lambda$$

$$E = h\frac{c}{\lambda}$$

h=6.62607004 × 10^{-34} m^2 kg s^{-1}

c=3x10^8 m^{-2}

From Energy to wavelength

Plank's constant

$$E = hf \qquad c = f\lambda$$

$$E = h\frac{c}{\lambda}$$

h=6.62607004 × 10^{-34} m^2 kg s^{-1}

c=3x10^8 m^{-2}

If the band gap of silicon is 1.6eV what is wavelengths of light can it absorb?

From Energy to wavelength

$$\lambda = h\frac{c}{E}$$

h=6.62607004 × 10^{-34} m^2 kg s^{-1}

c=$3x10^8$ m^{-2}

$$\lambda = \frac{3x10^{8} * 6.6x10^{-34}}{(1.6 * 1.6x10^{-19})}$$

$$\lambda = 7.7344x10^{-07} m$$

$$\lambda = 773 nm$$

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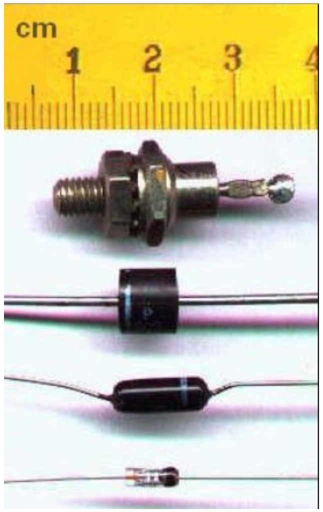
Diodes

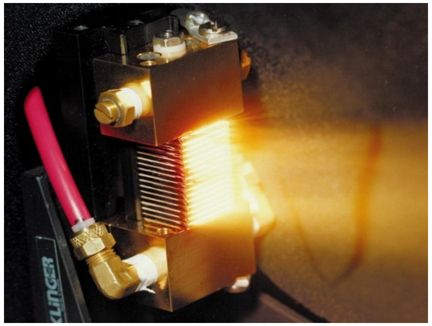
•Before we talk about solar cells and light harvesting we need to know about diodes.

•Diodes are a fundamental electrical component that form the basis for lots of classes of devices.



Power diodes

LEDs



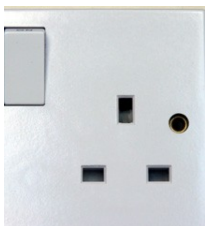
Lasers

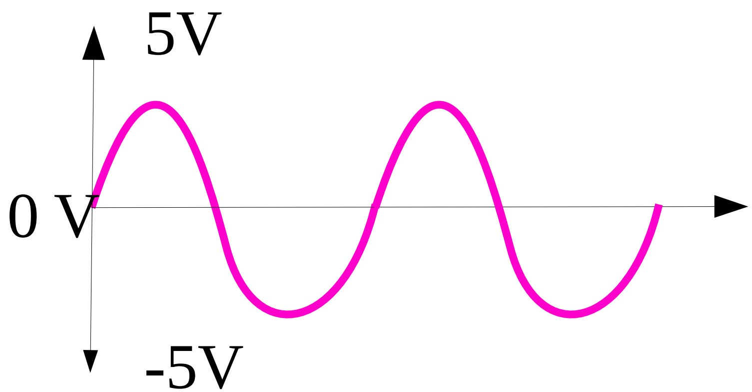
Solar cells

•Before we can understand solar cells we first need to understand diodes.

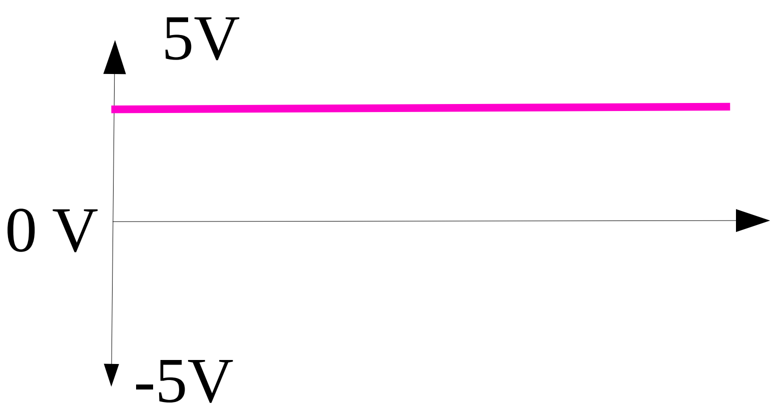
Before we think about solar cells, let's think about AC voltage for a moment

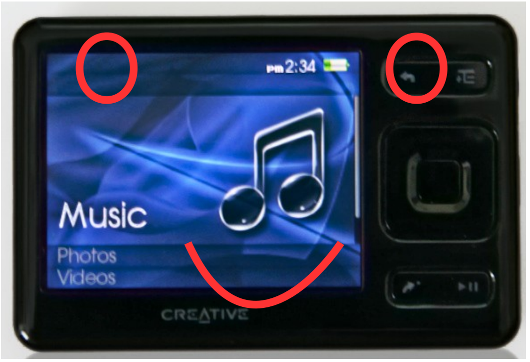
•AC switches **ON** and **OFF** again 100 times a second (50 Hz).





•But most chips need a steady **DC** supply to run.





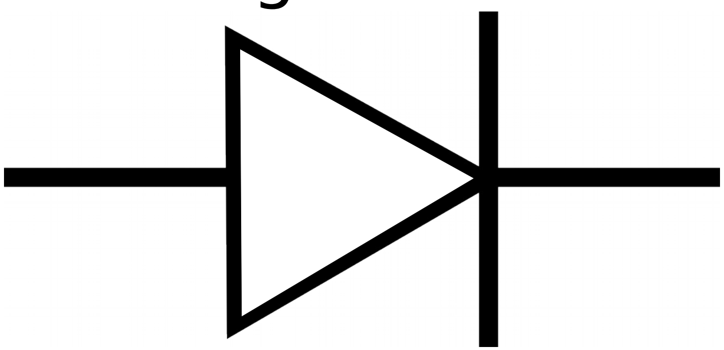
•**Power diodes are used to transform AC to DC.**

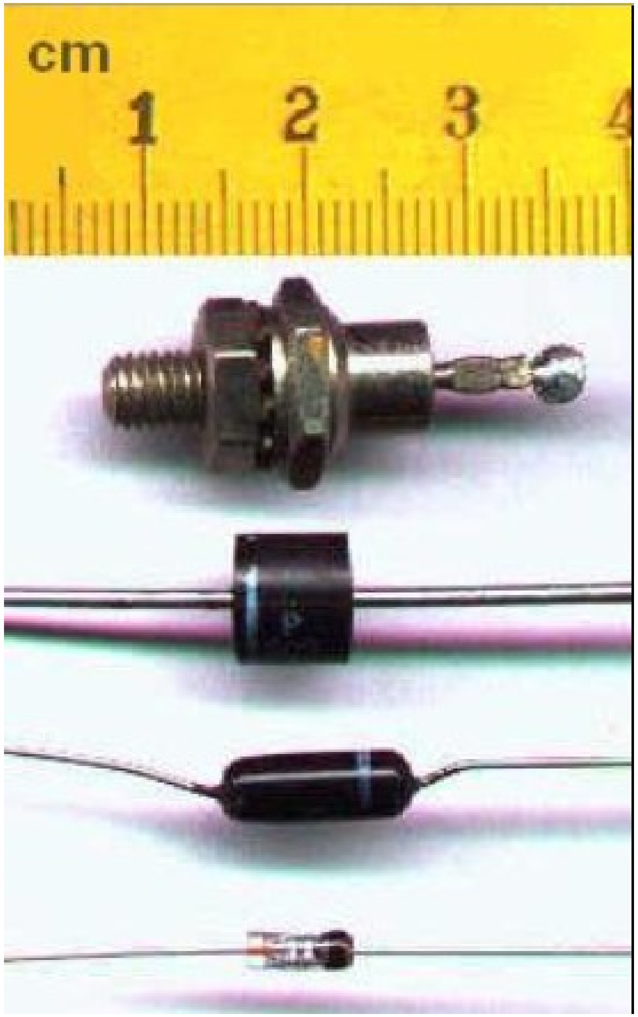
Diode basics: Diodes for power electronics – what do they look like?

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

- Diodes you find in high power electronics look like this

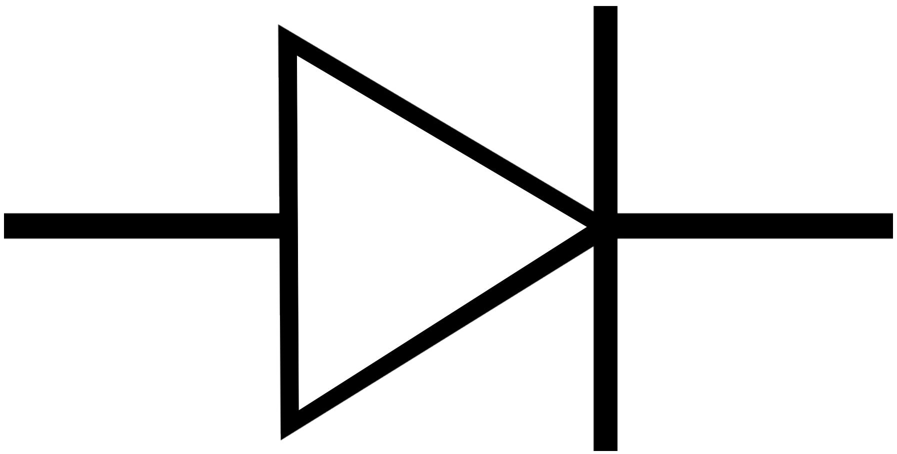
- Little black beads with two wires sticking out.

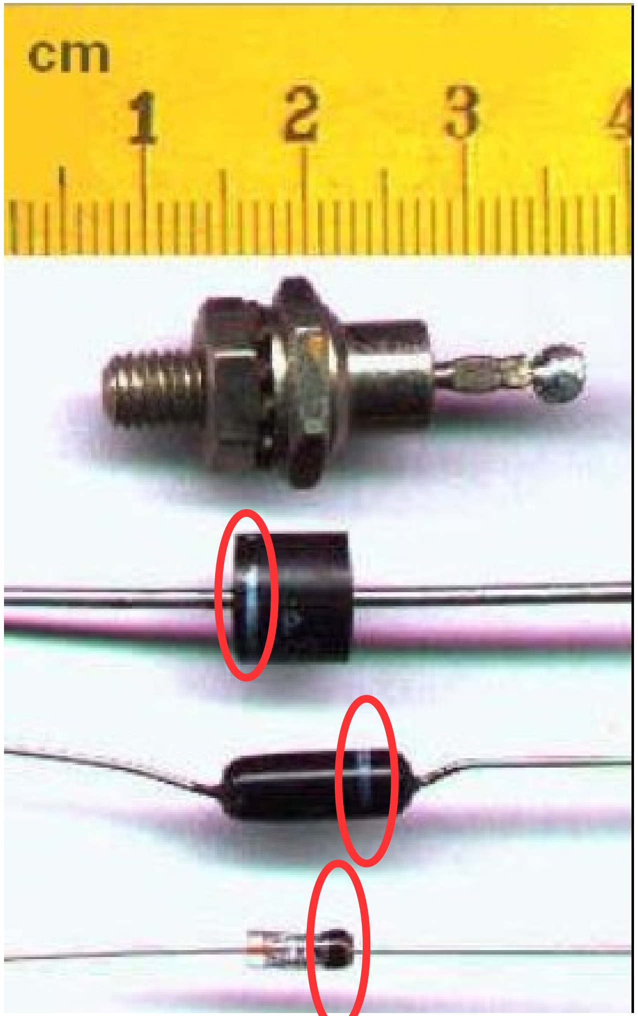




- We are looking at power didoes because they are the simplest type of diode.

Diode basics: Notice...

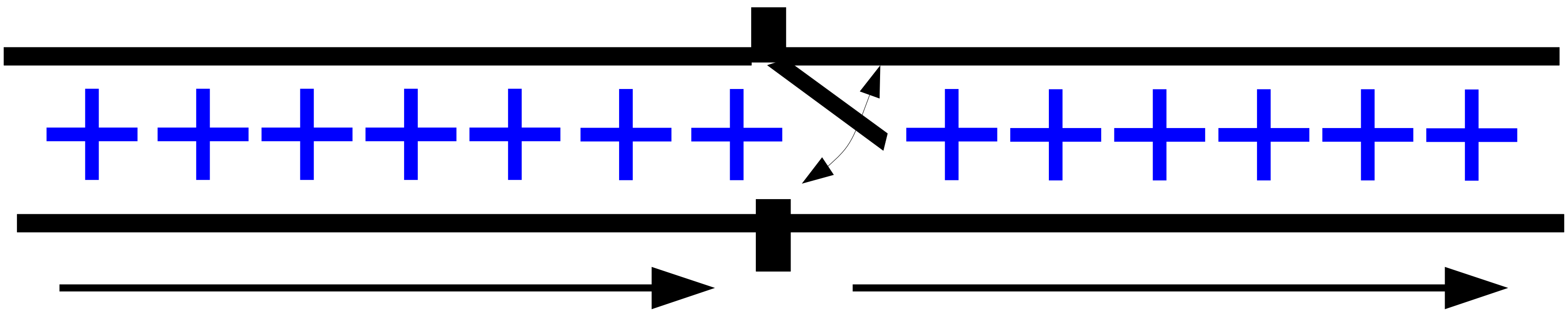




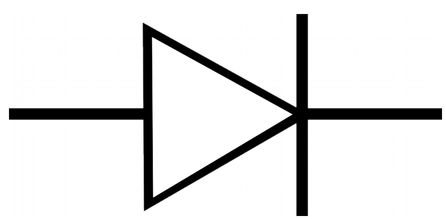
- Notice the silver bar on the end, this is the same as the bar in the diagram.

Diode basics: What do they do?

You can think of a diode as a one way valve for electrons

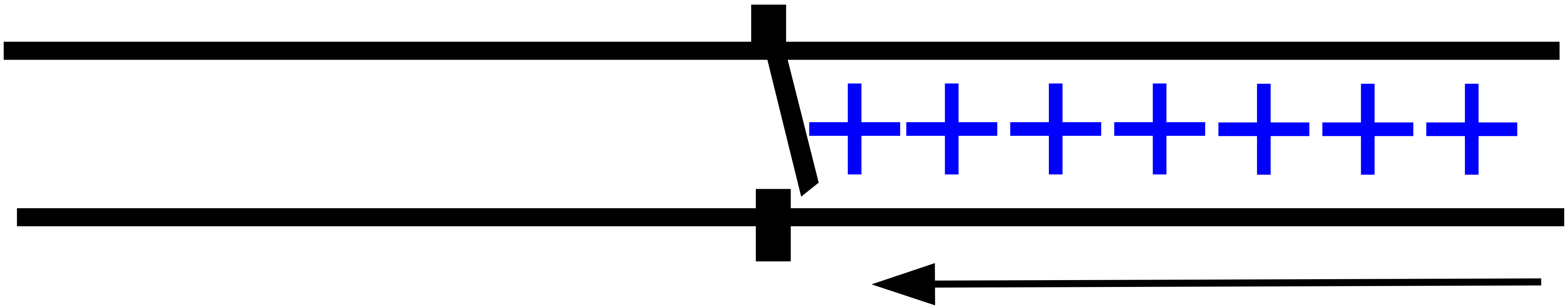


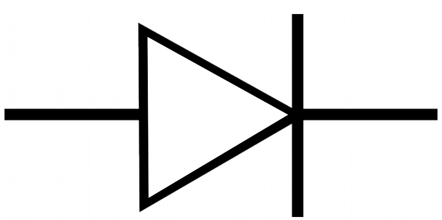
If current flows in one direction the diode will allow it to pass.



Diode basics: What do they do?

If current tries to flows in the **other direction** it will not be allowed to pass.





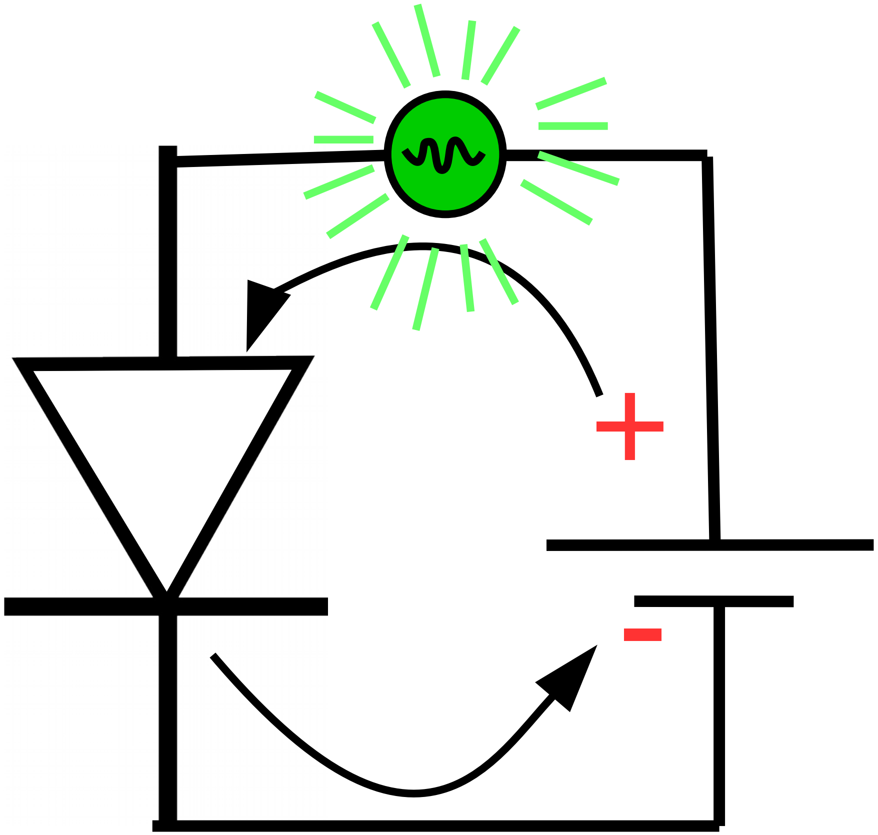
Diode basics: A one way cat flap....

You can also think of a diode as a one way cat flap for electrons.

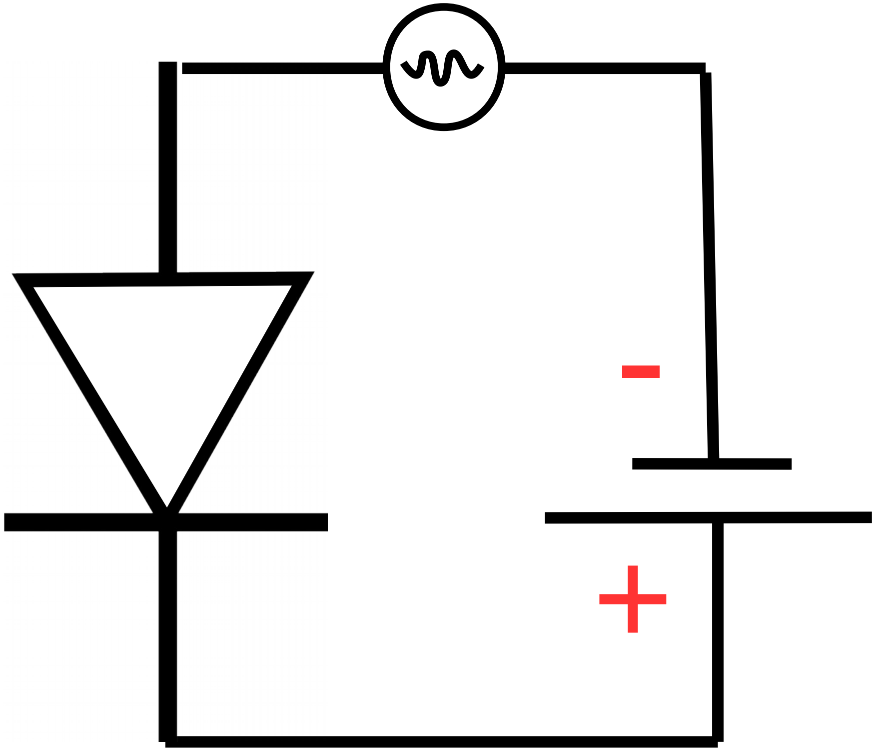
•Electrons (or the cat) are only allowed to go through one way but not the other.

Andrew Dunn

Diode basics: A diode as a one way trap door for current

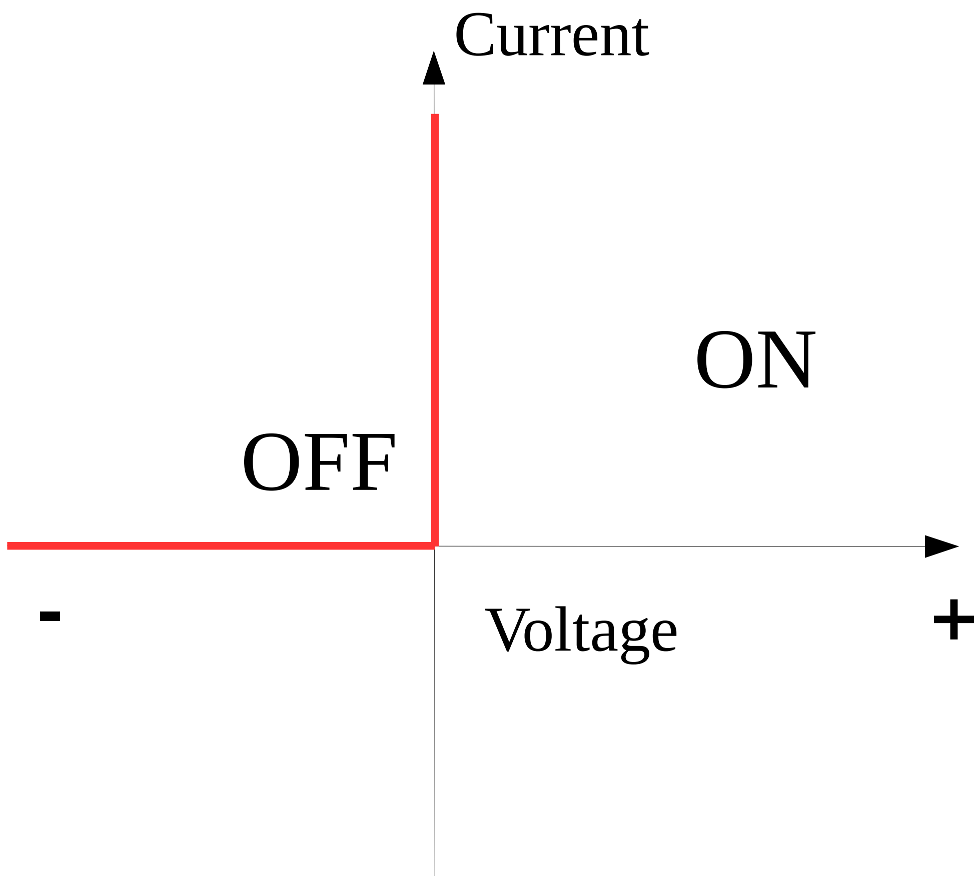


With positive applied voltage current flows



With negative applied voltage no current flows

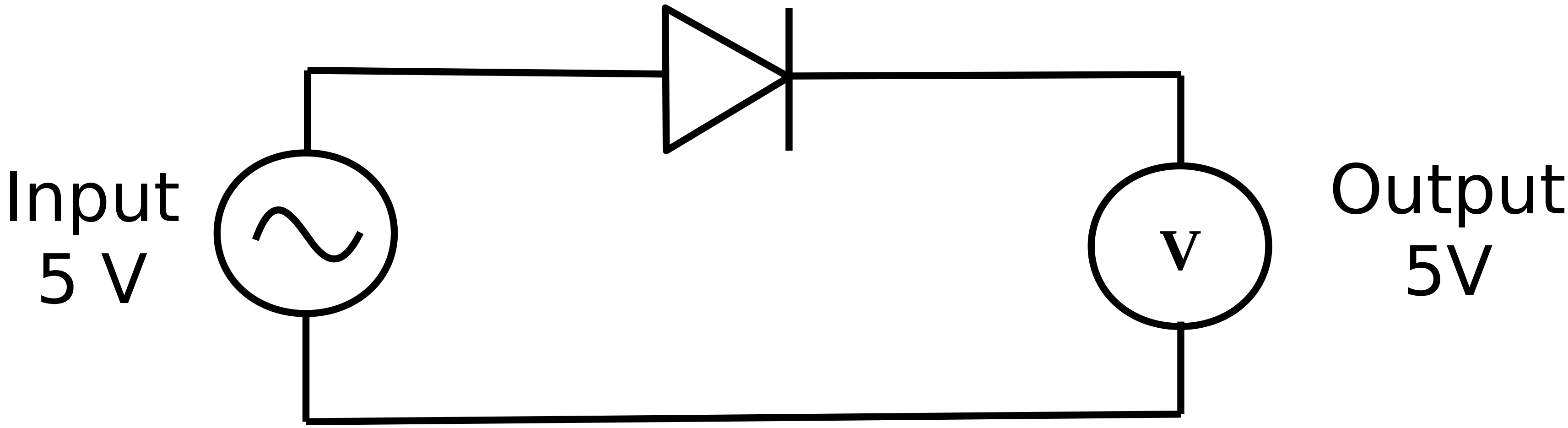
Diode basics: What does the ideal current voltage curve look like?

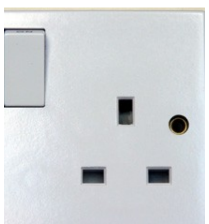


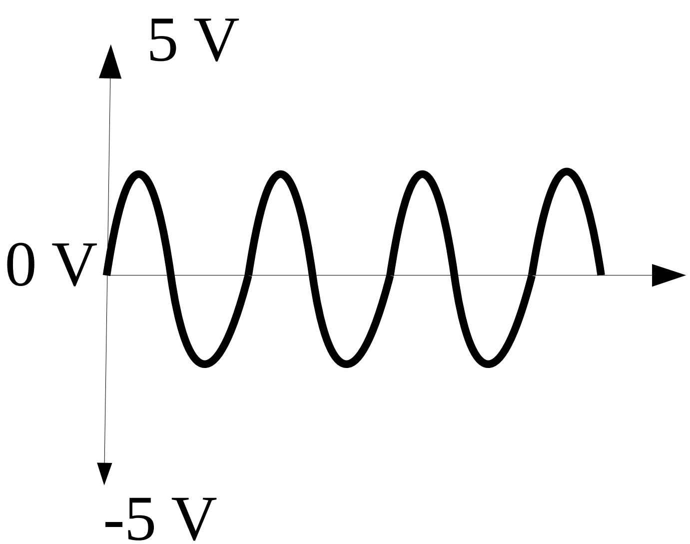
At negative voltages it blocks current

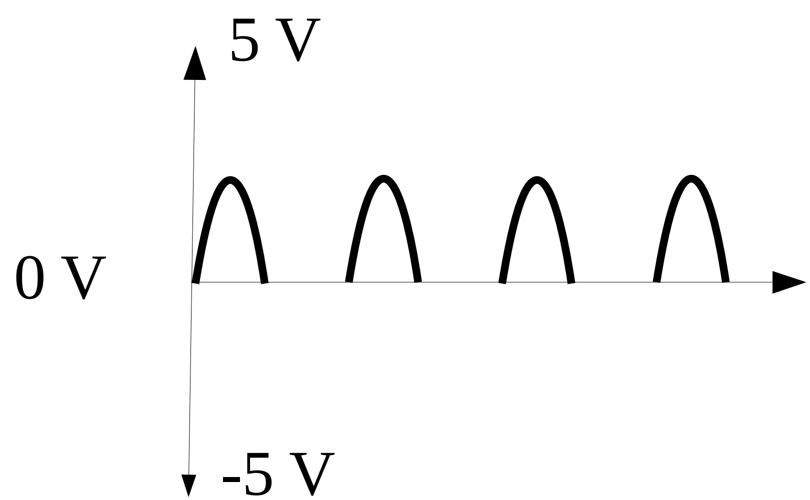
At positive voltages any amount of current can flow

If we apply an AC signal to a diode, it will only let through the positive voltage

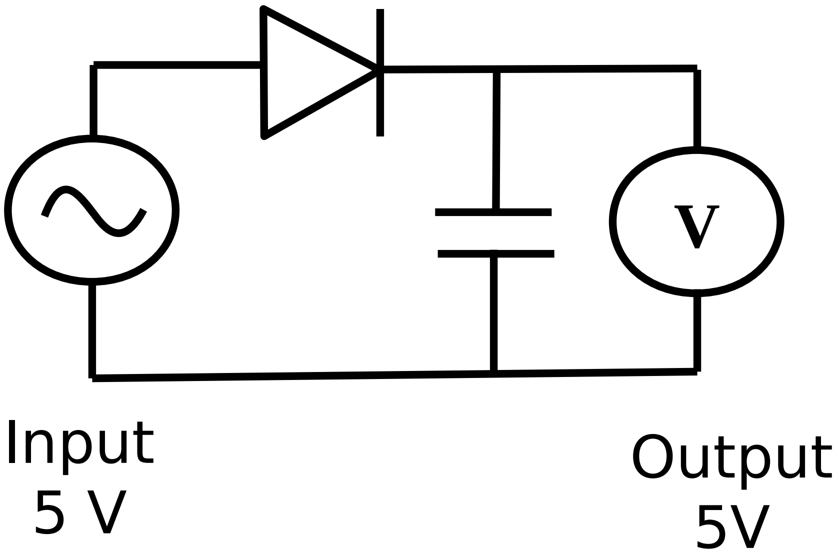


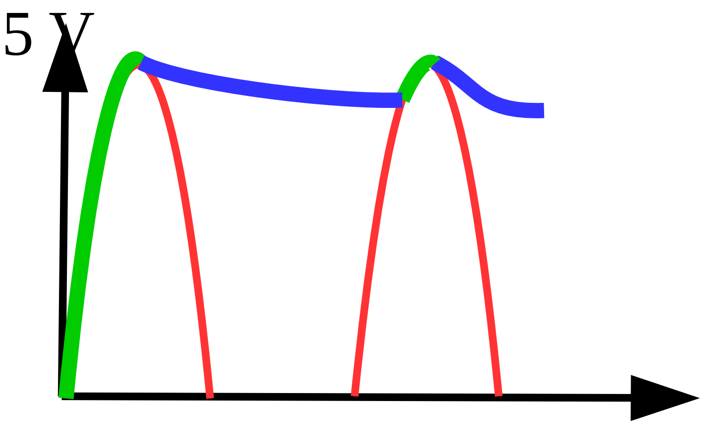




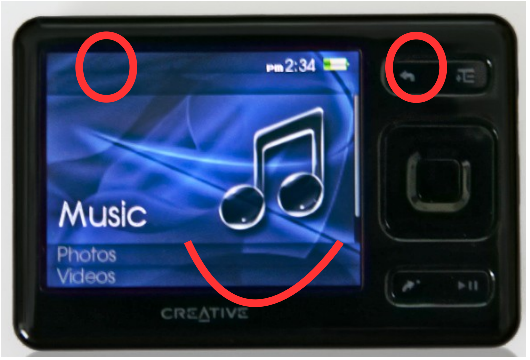


If we add a capacitor to our circuit we now get DC (sort of).

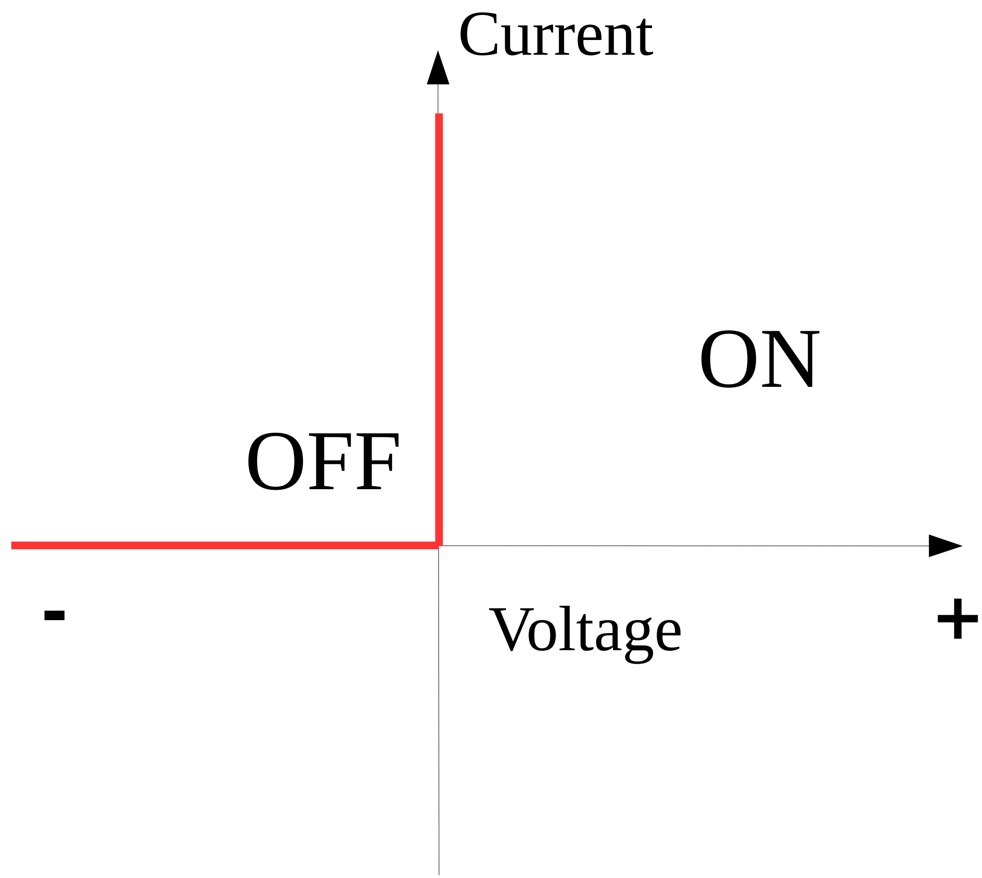




And a happy (working) MP3 player.



What we have looked at so far is the ideal diode.

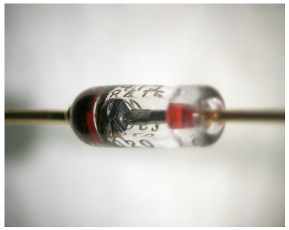


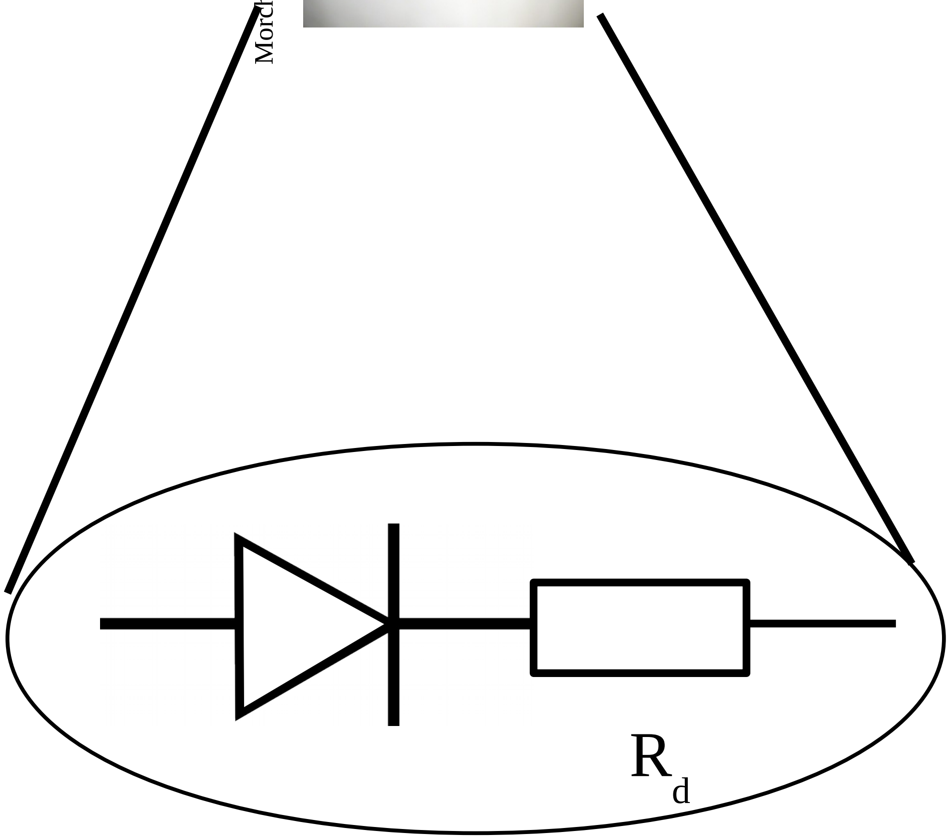
At negative voltages it blocks current

At positive voltages any amount of current can flow

A less ideal diode

Morcheeba at en.wikipedia

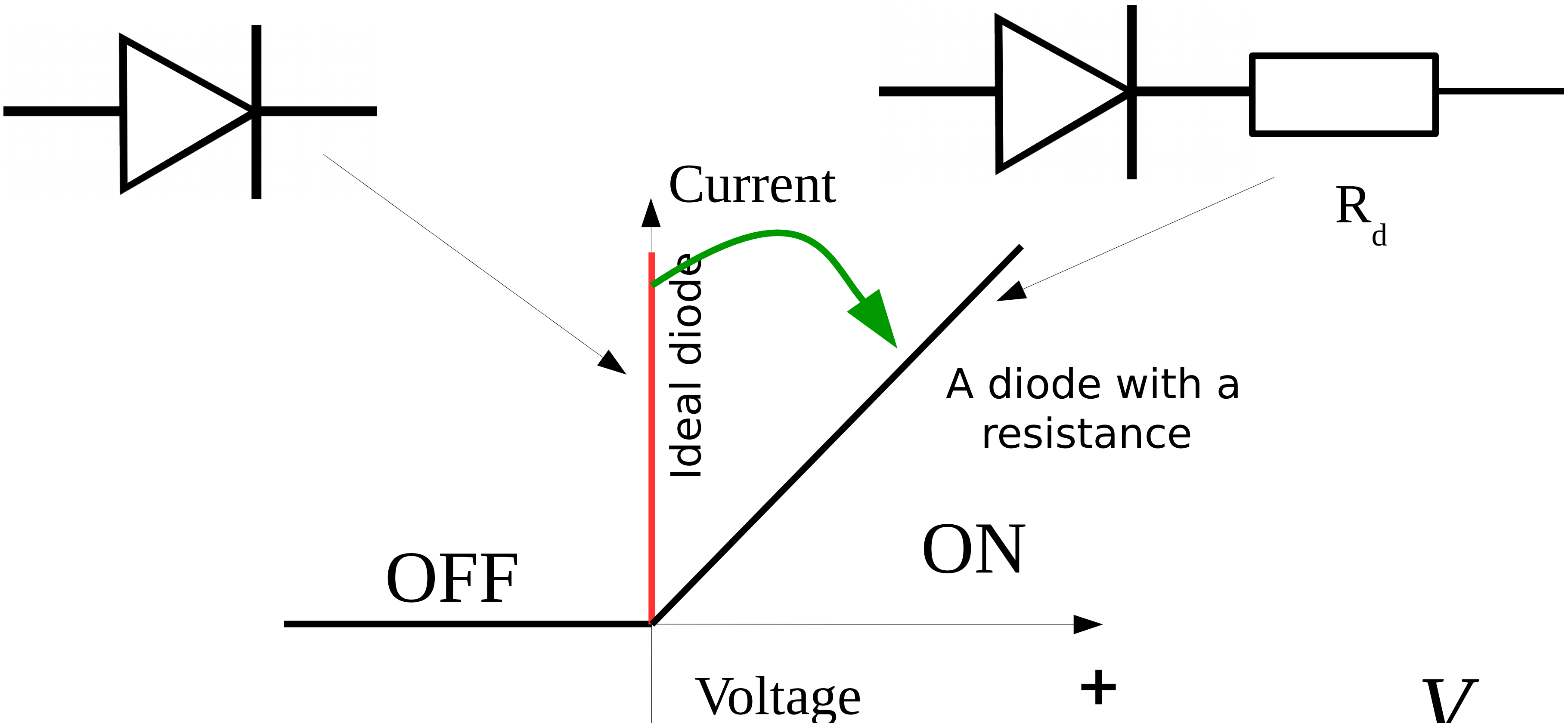




•However real diodes are like any other device they have a resistance R_d associated with them (because all things have resistance).

•So you can think of them as an ideal diode in series with a resistor.

A less ideal diode

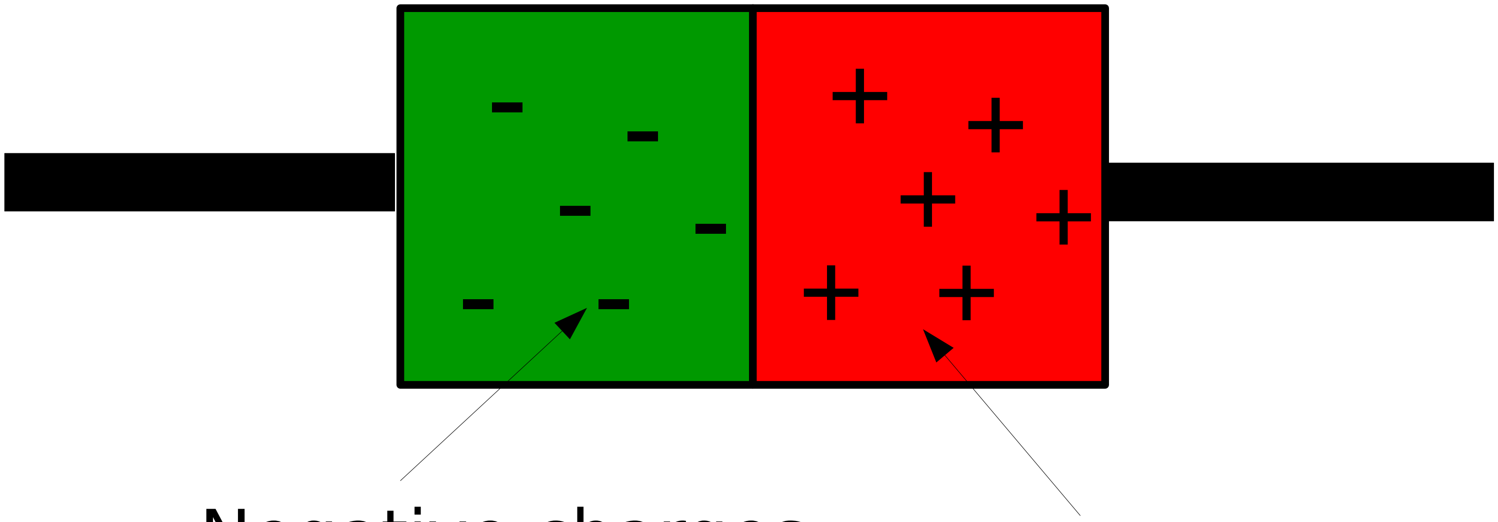


$$R_d = \frac{V}{I}$$

•This means there will be some resistive power loss over a diode.

Furthermore.....

•Diodes are made of two materials, one with lots of negative (n-type) charges and one with lots of positive charges (p-type).



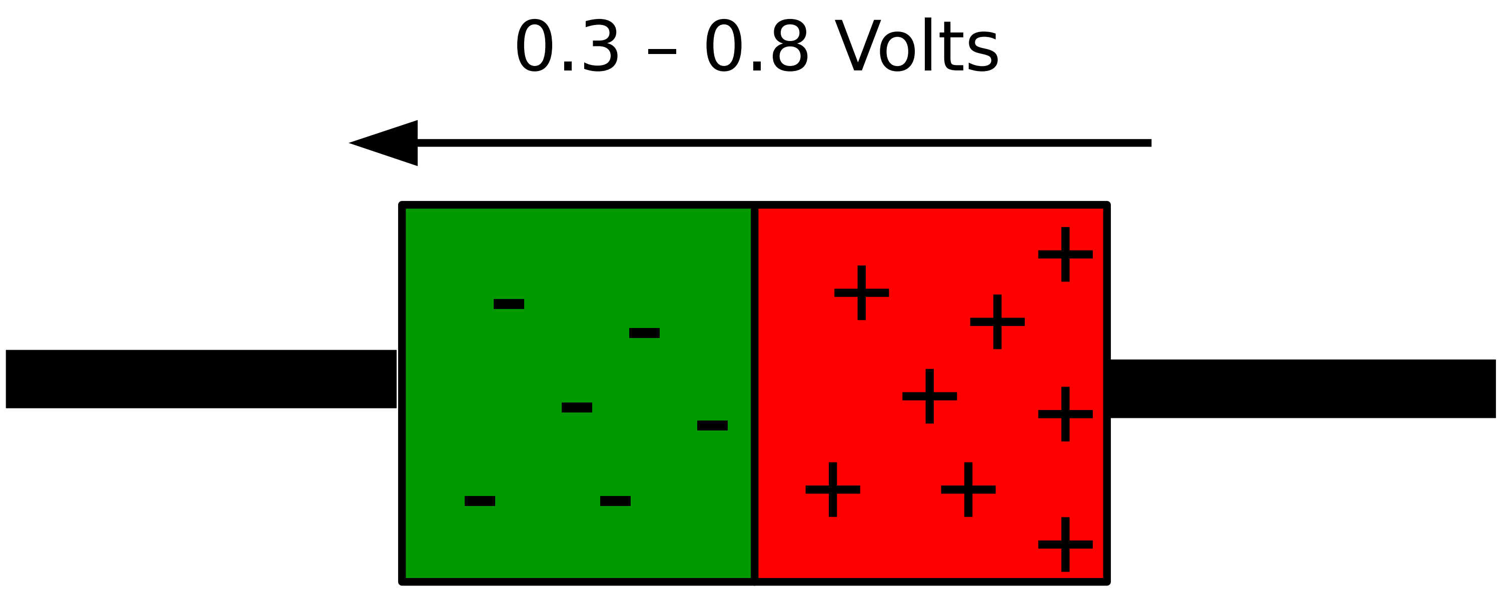
Negative charges called an **n-type** material

Positive charges called a **p-type** material

Positive and negative charges

•This charge in the device means that every diode produces a voltage of between 0.3 V to 0.8 V.

•This is called the **built in potential**.



•In some applications this built in potential is a pain, in others it is really useful

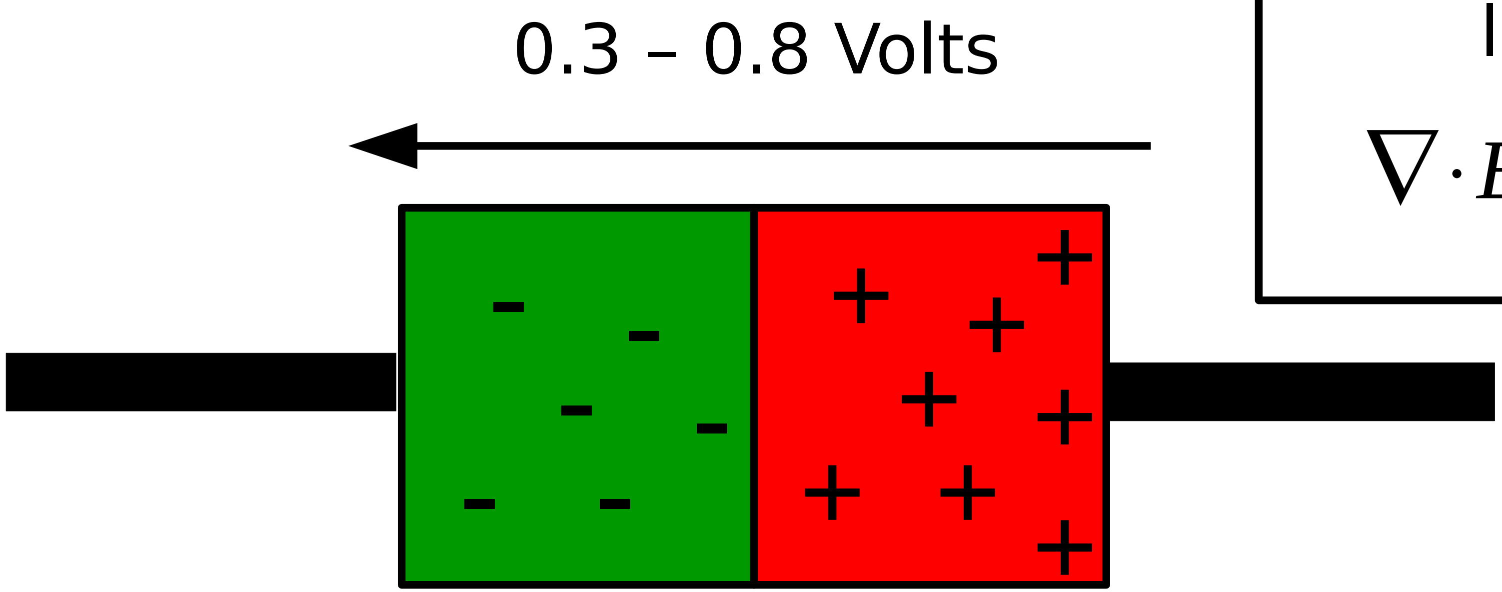
Positive and negative charges

•This charge in the device means that every diode produces a voltage of between 0.3 V to 0.8 V.

•This is called the **built in potential**.

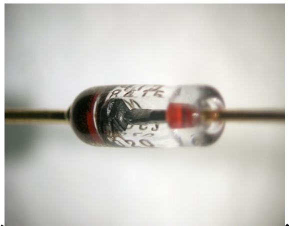
Gausse's law

$$\nabla \cdot E = \frac{\rho}{\epsilon_0}$$

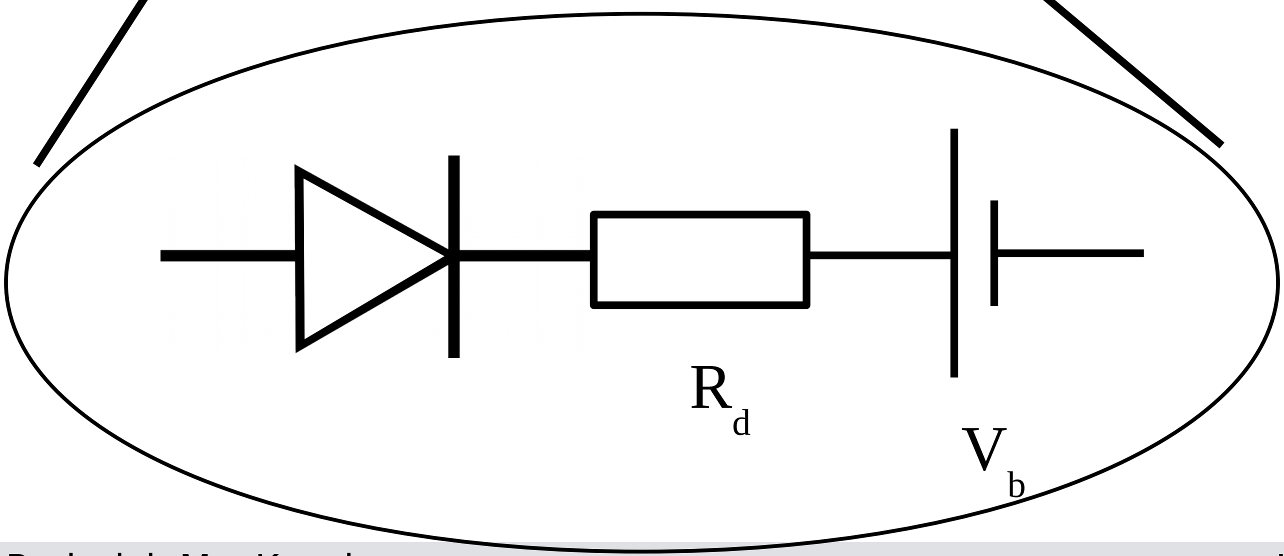


•In some applications this built in potential is a pain, in others it is really useful

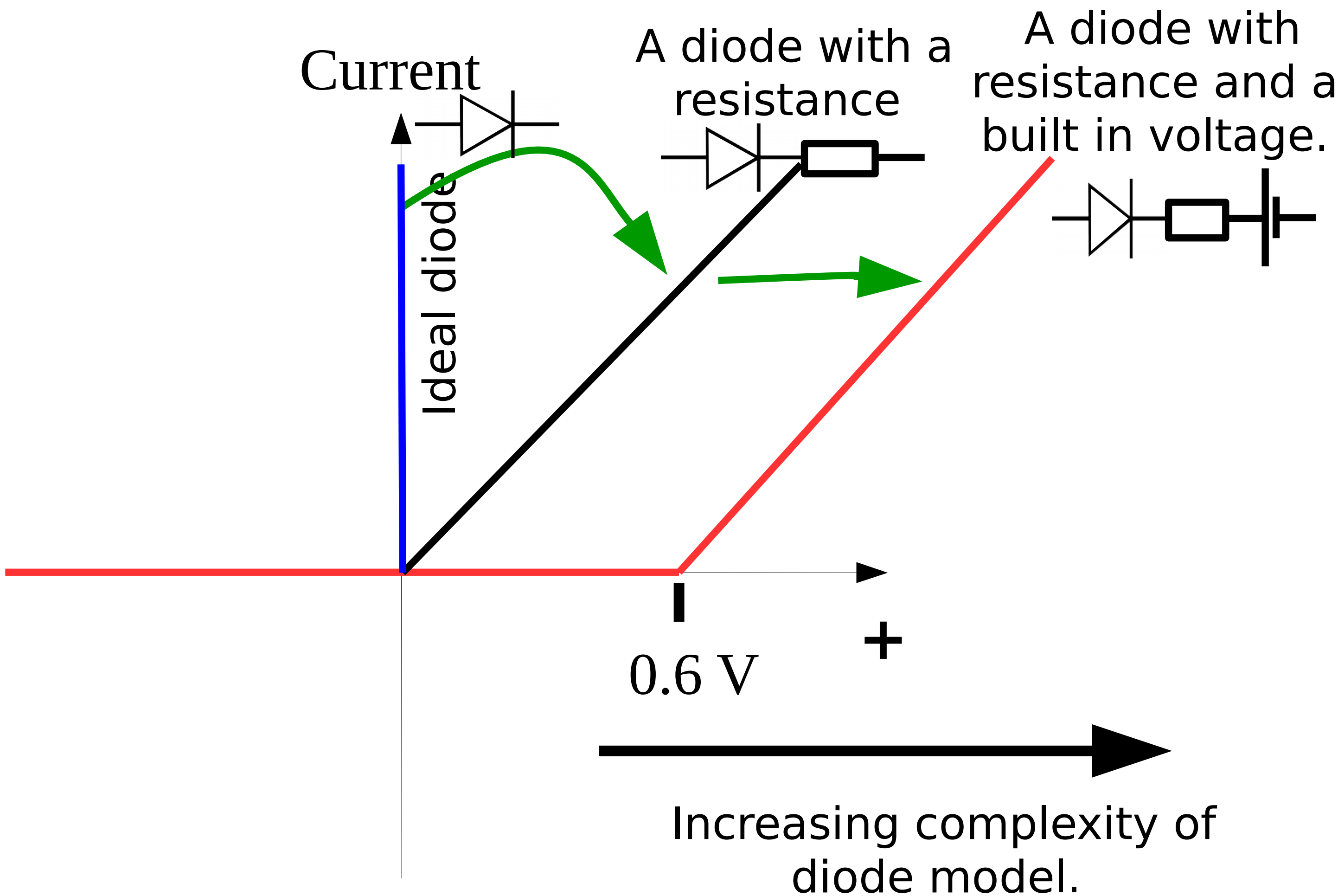
A diode with a built in potential



- Because of this built in charge you can actually think of an ideal diode as having a small (0.3 V-0.8 V) battery in series with it.



The built in potential



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- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- **From diodes to solar cells**
- Diodes current-voltage curves in the light
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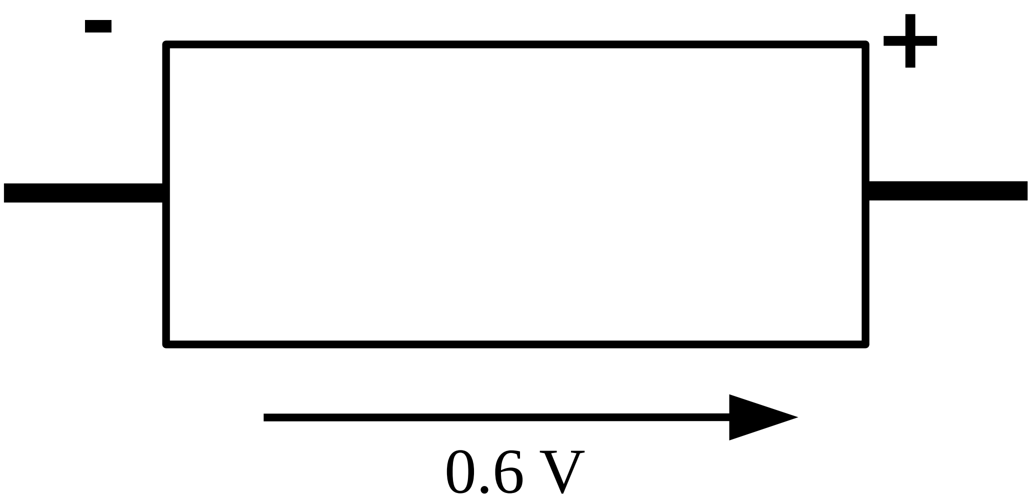
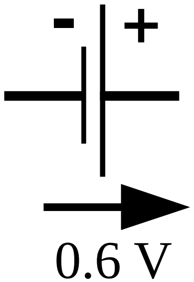
From a diode to a solar cell..

•Here is our diode again.

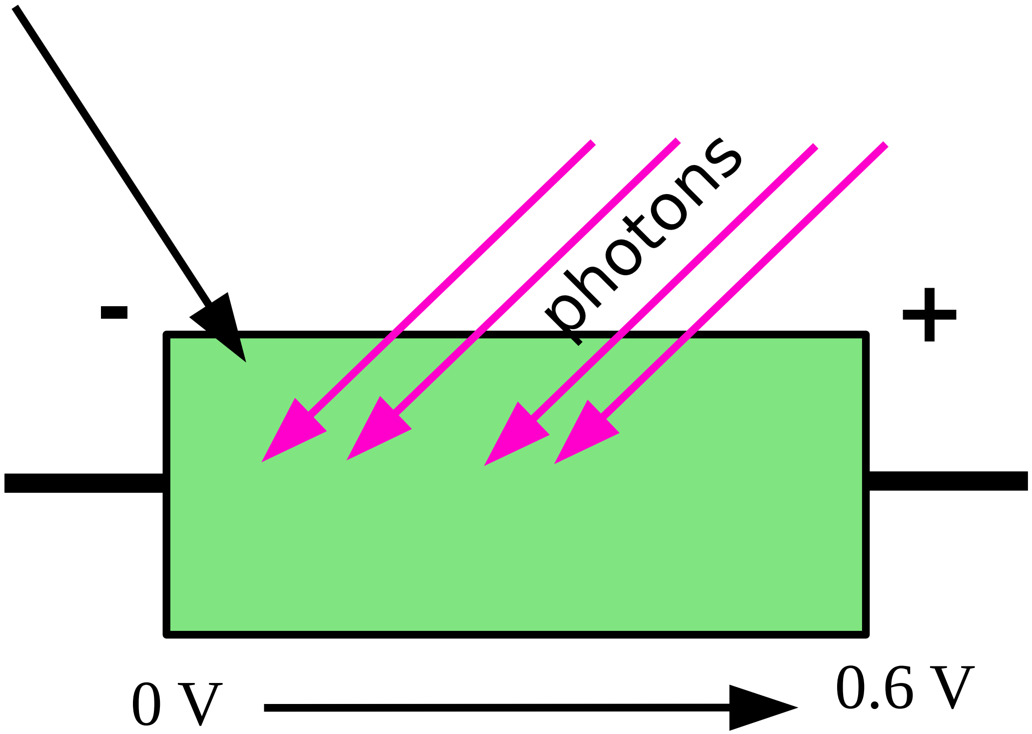


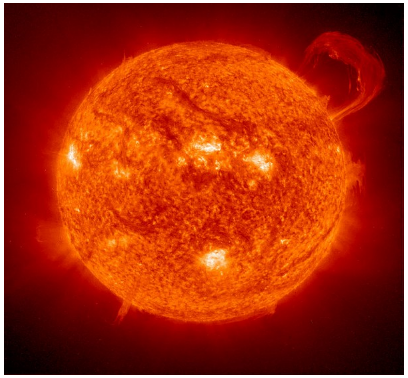
•Now let's change the material so it absorbs light.

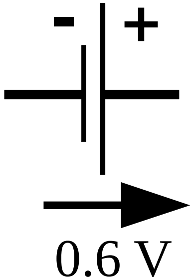


A light adsorbing diode...

- Light adsorbing material.

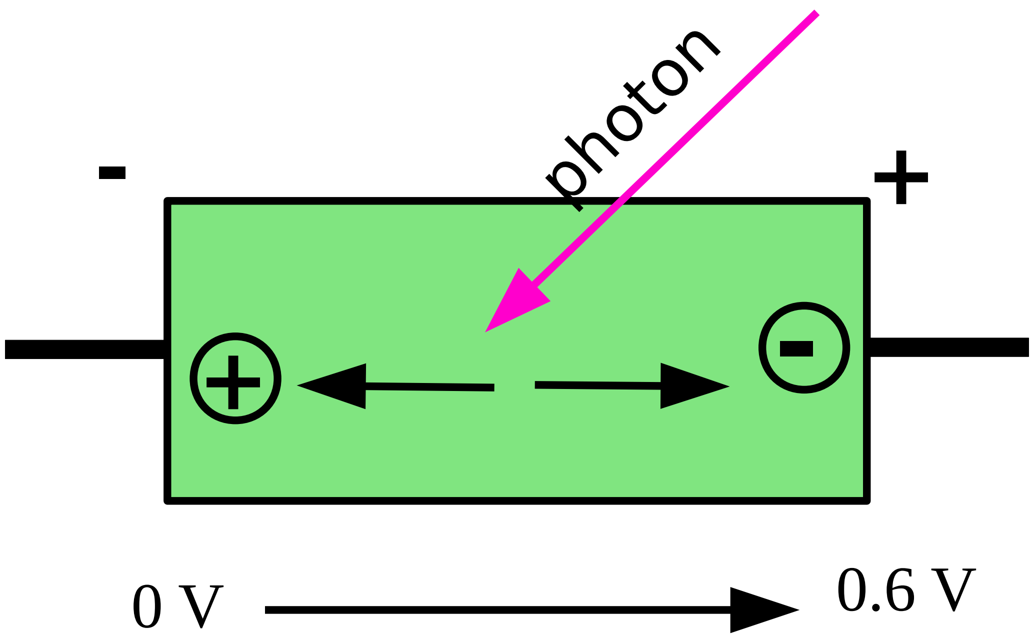






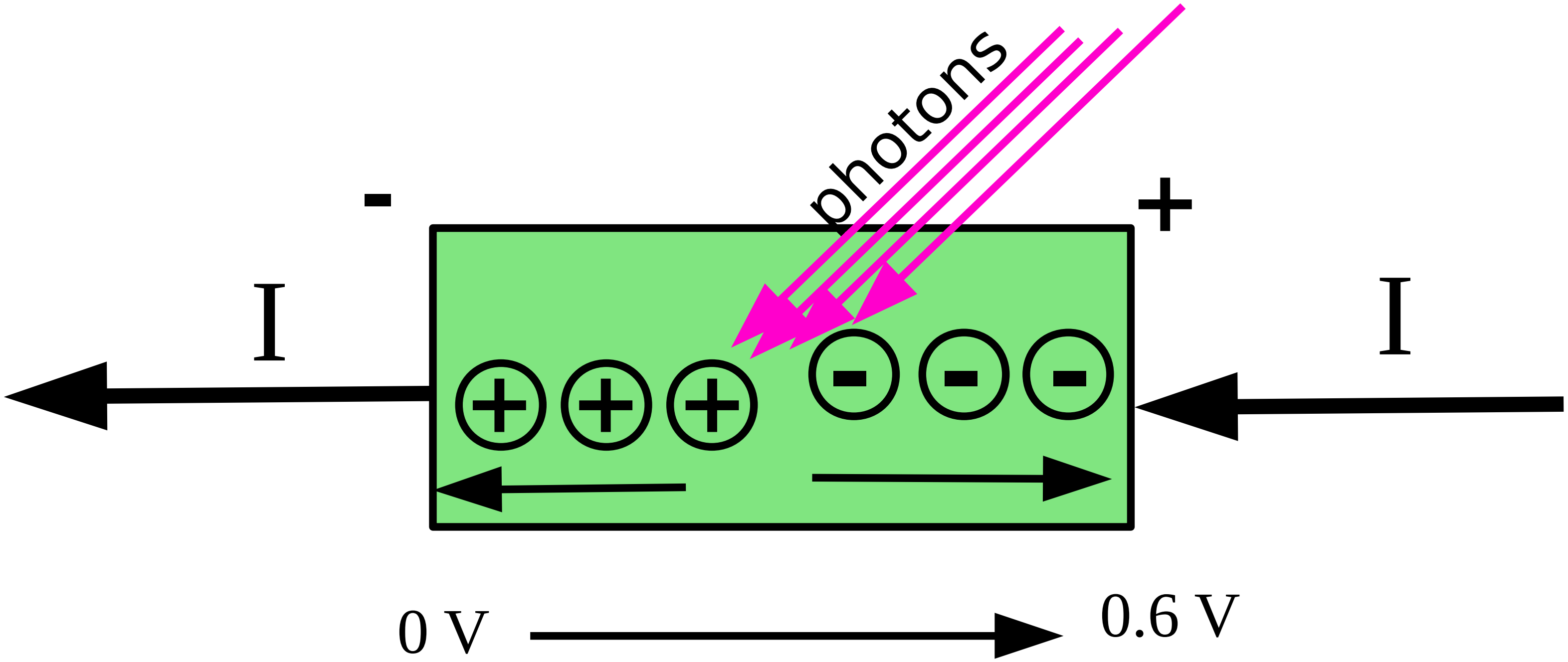
When a photon is adsorbed in a material.....

•The positive charge goes to the negative contact and the negative charge goes to the positive contact.

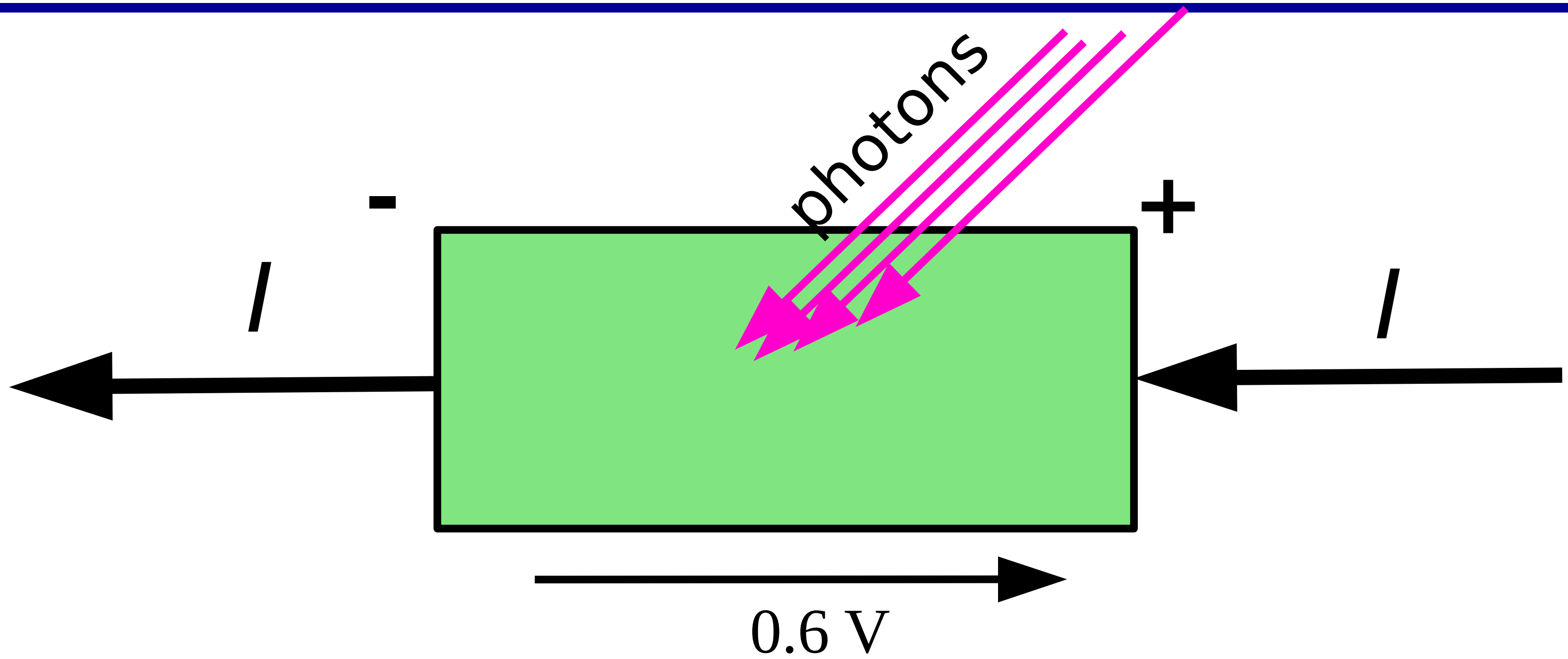


When a photon is adsorbed in a material.....

•If lots of photons hit the diode lots of positive and negative charges move to the contacts and we get current in the external circuit.



Power generation.....



Power=I*V

N=Number of photons adsorbed per second per unit area.

A=Area of solar cell.

Power=A*N*q*V

And we have a solar cell.

Exam question

a) A ***0.01 m^2*** solar cell produces a voltage of **0.6 V**, it adsorbs **1×10^{20} m^{-2} photons per second** if the charge on an electron is **1.6×10^{-19} coulombs** how much power will it produce.

Power=A*N*q*V

Power produced by cell=???

b) How many pink ***500 Watt*** 'Hello Kitty' toasters would that run??

Janine from Mililani

Exam question

A 0.01 m^2 solar cell produces a voltage of 0.6 V, it adsorbs $1x10^{12}$ m^{-2} photons per second if the charge on an electron is $1.6x10^{-19}$ coulombs how much power will it produce.

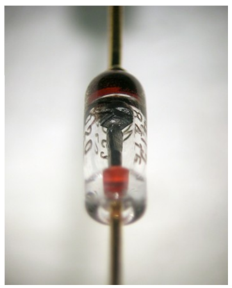
Power=A*N*q*V

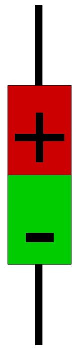
Therefore Power=0.06 W

That's not enough to run anything – let along a toaster...

Power generation.....

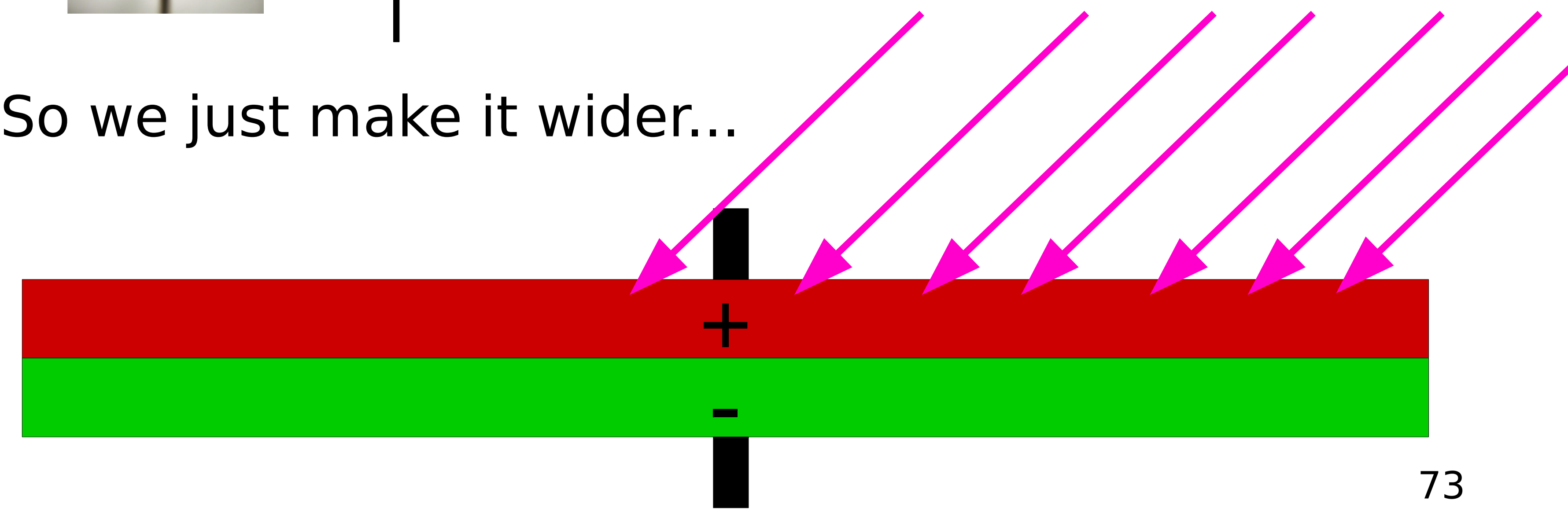
•So what we do is firstly make the diode (solar cell) as big as possible





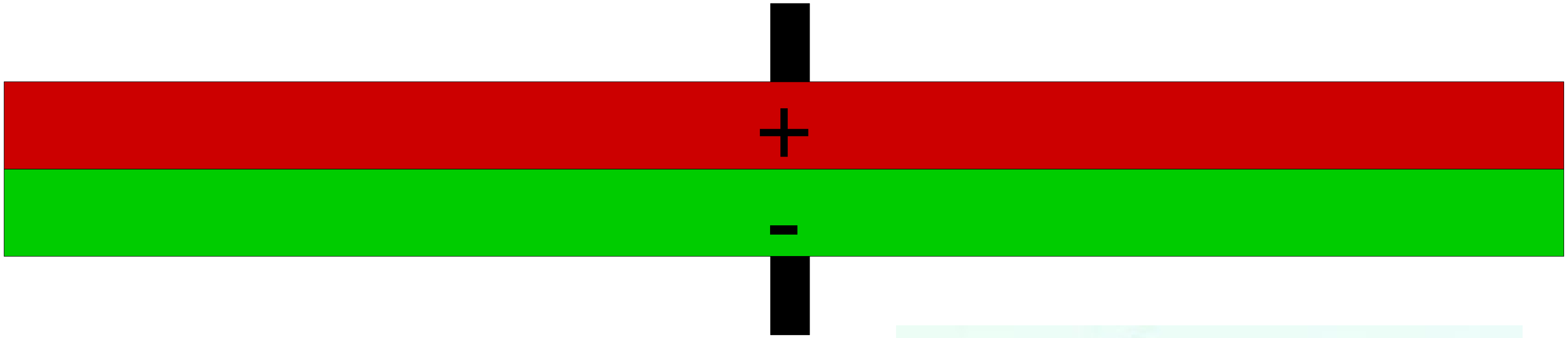
Power=A*N*q*V

•So we just make it wider...



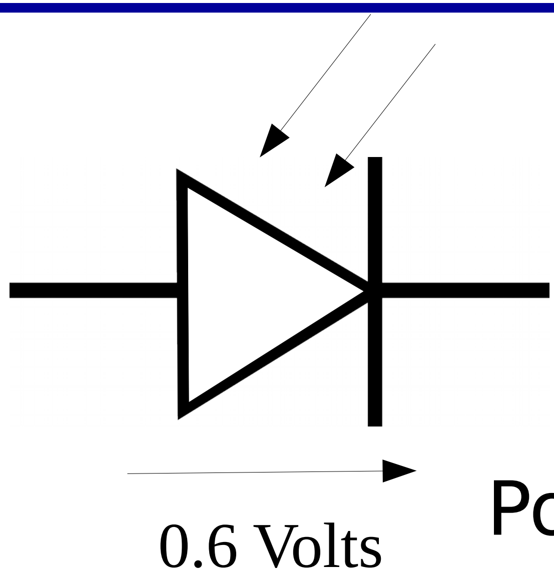
A solar cell

•And that is all a solar cell is – a wide diode.



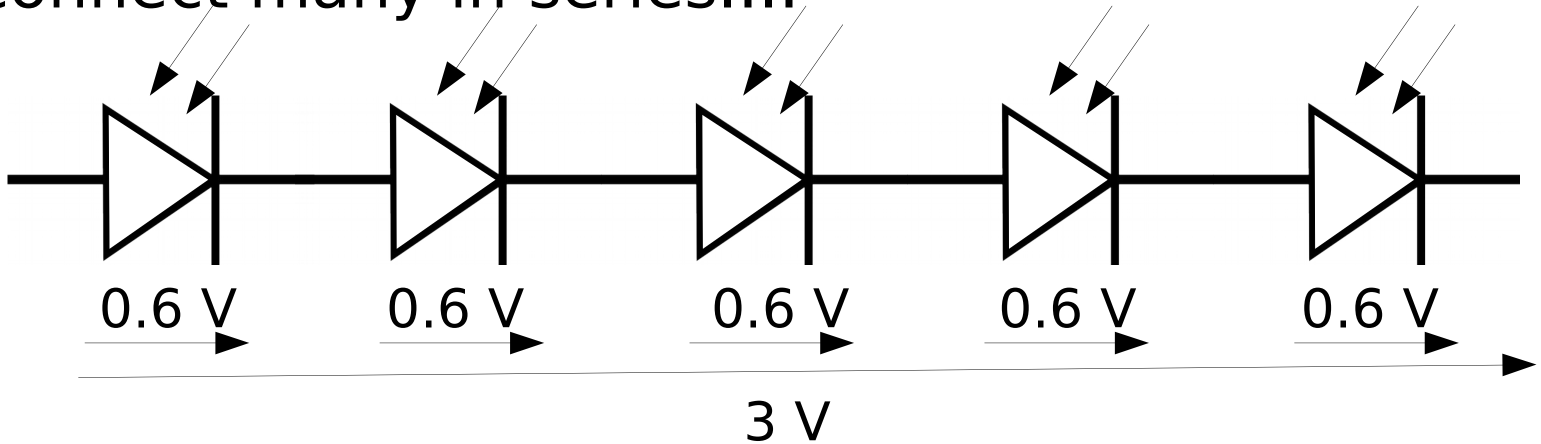
•These metal strips just help the current get out of the diode.

And then we stack lots together

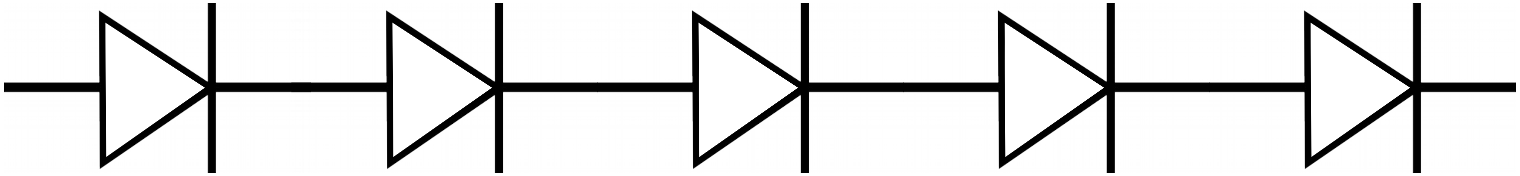


Power=A*N*q*V

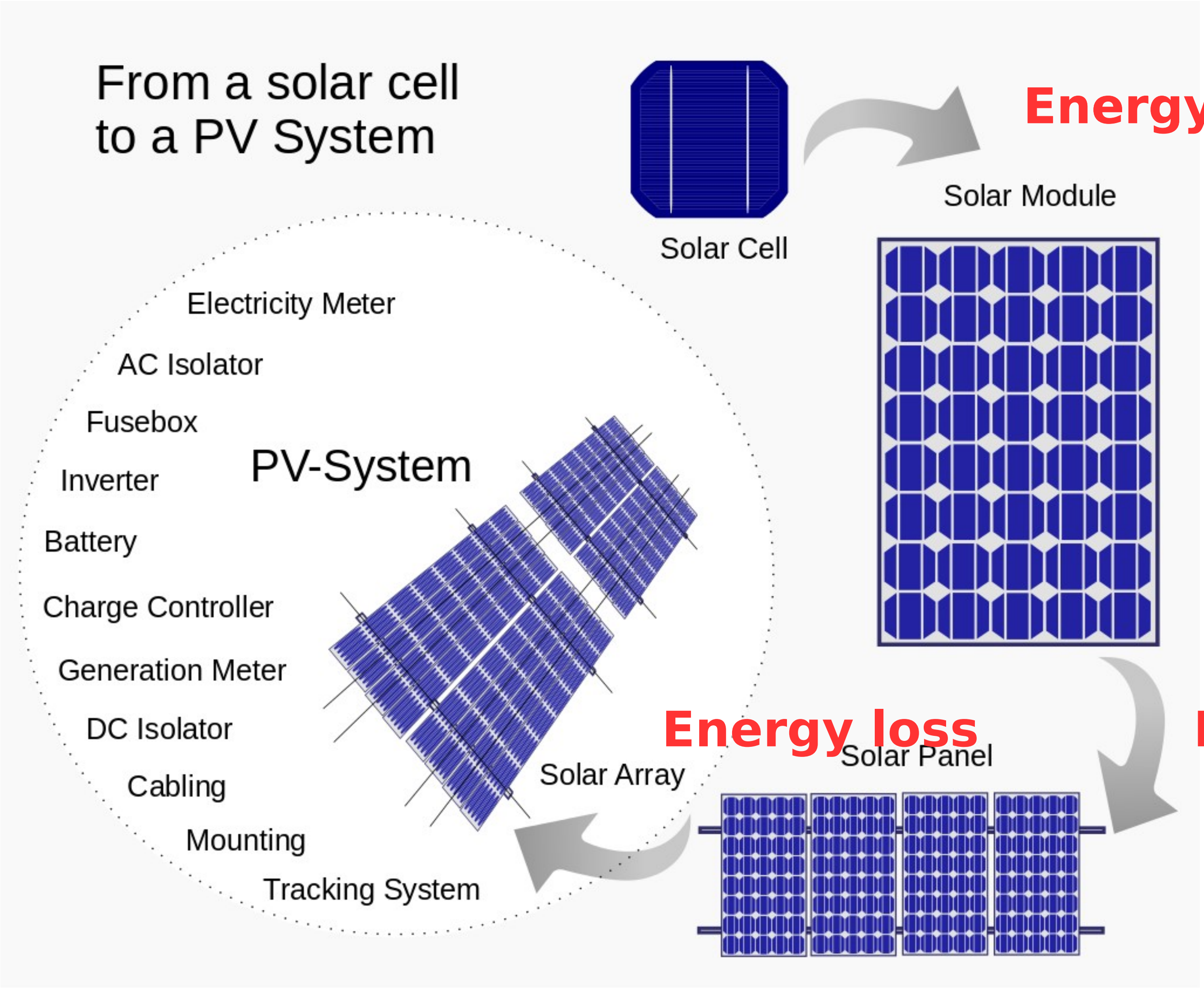
•However 0.6 V is not very much voltage, so we connect many in series....



To make a solar module



To make a solar module



Energy loss

Energy loss

Energy loss

Solar cell 20% efficient

Module 10-15% efficient

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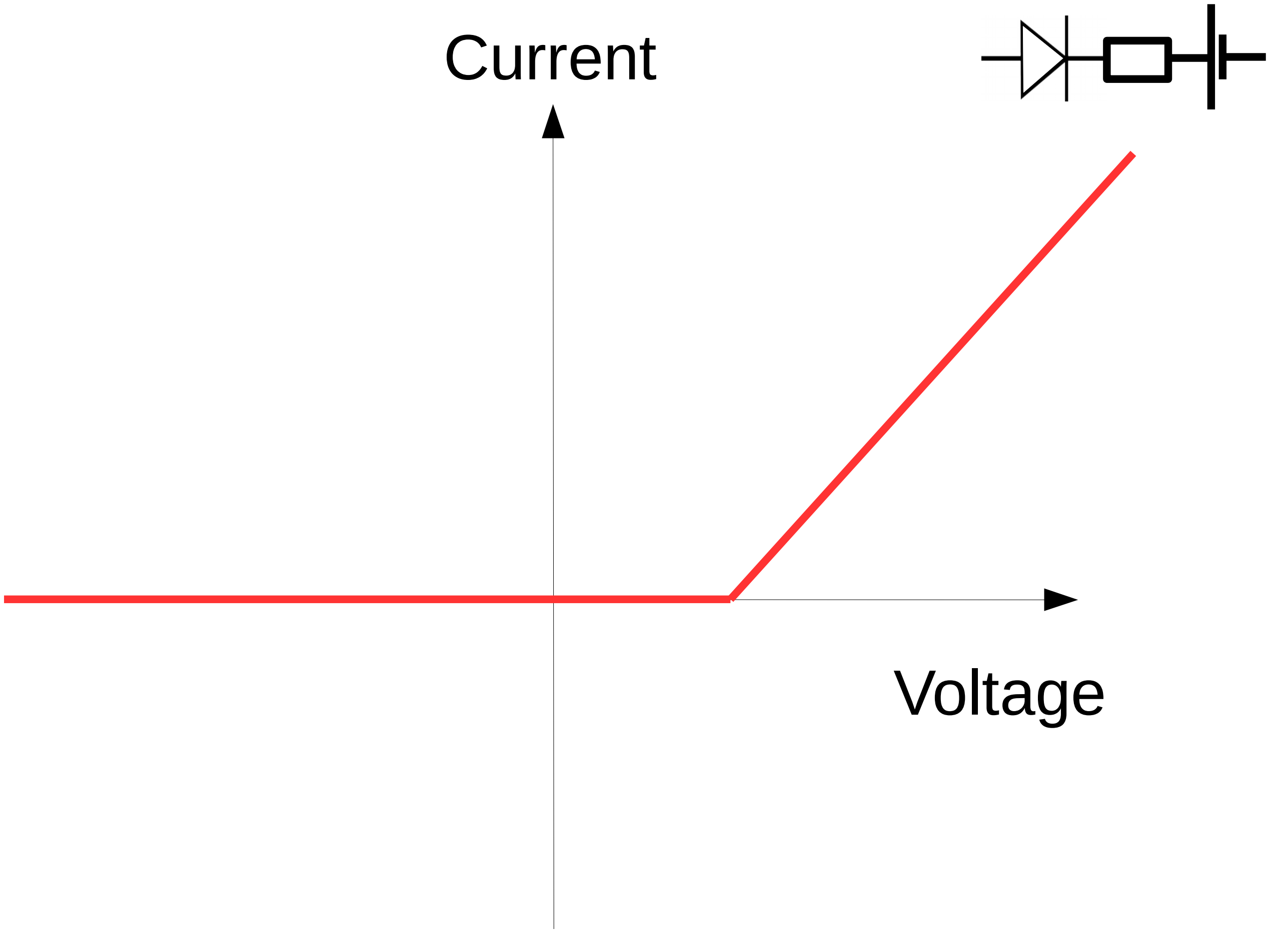
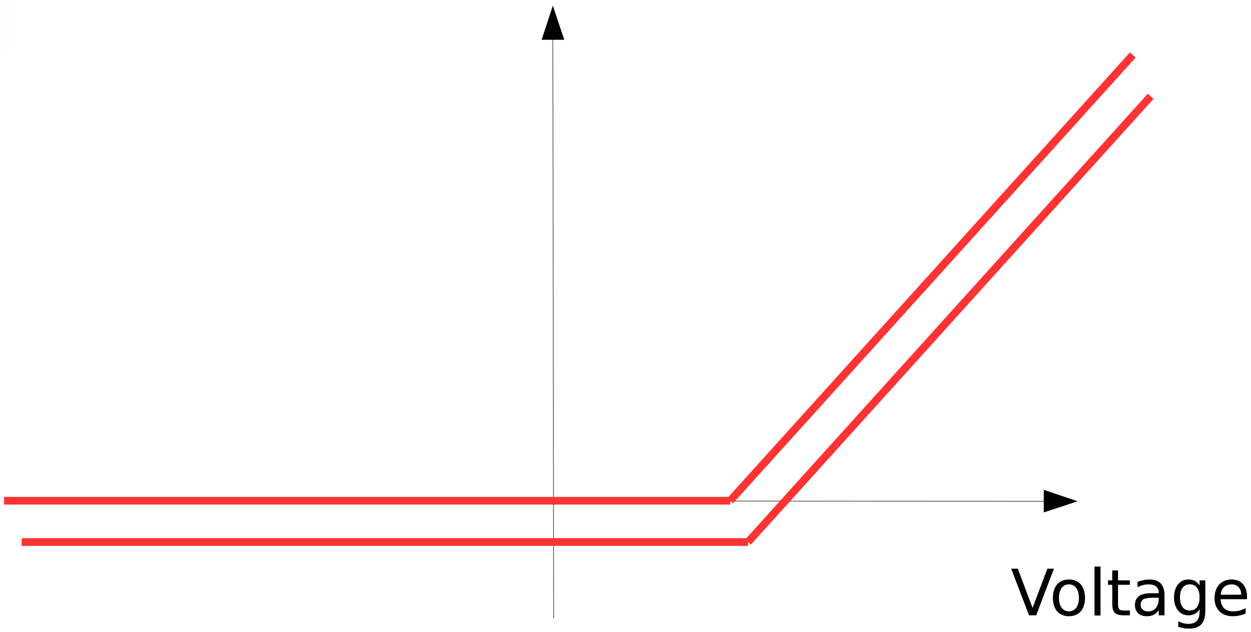
Current Voltage curve of a diode in the light.

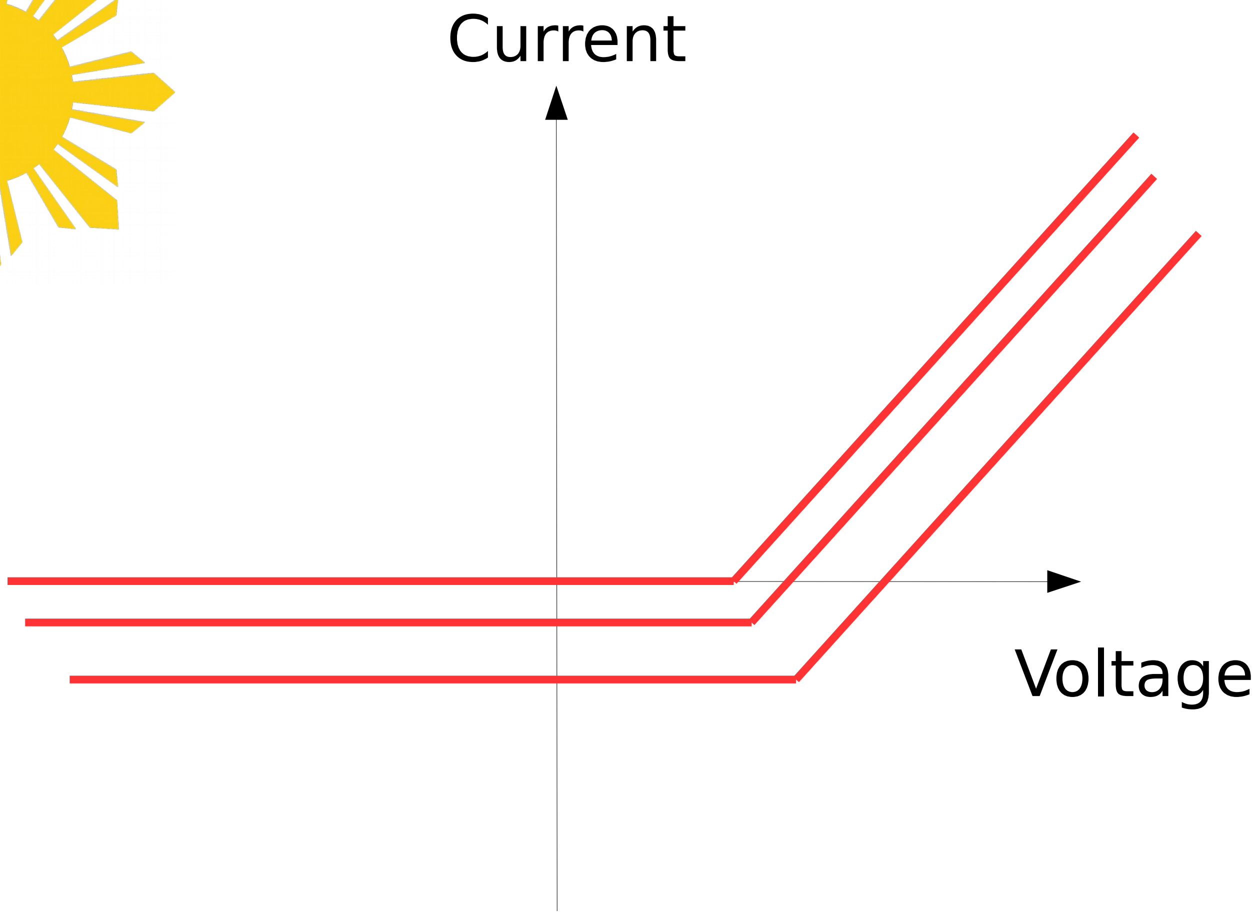


What do the JV curves look like in the light

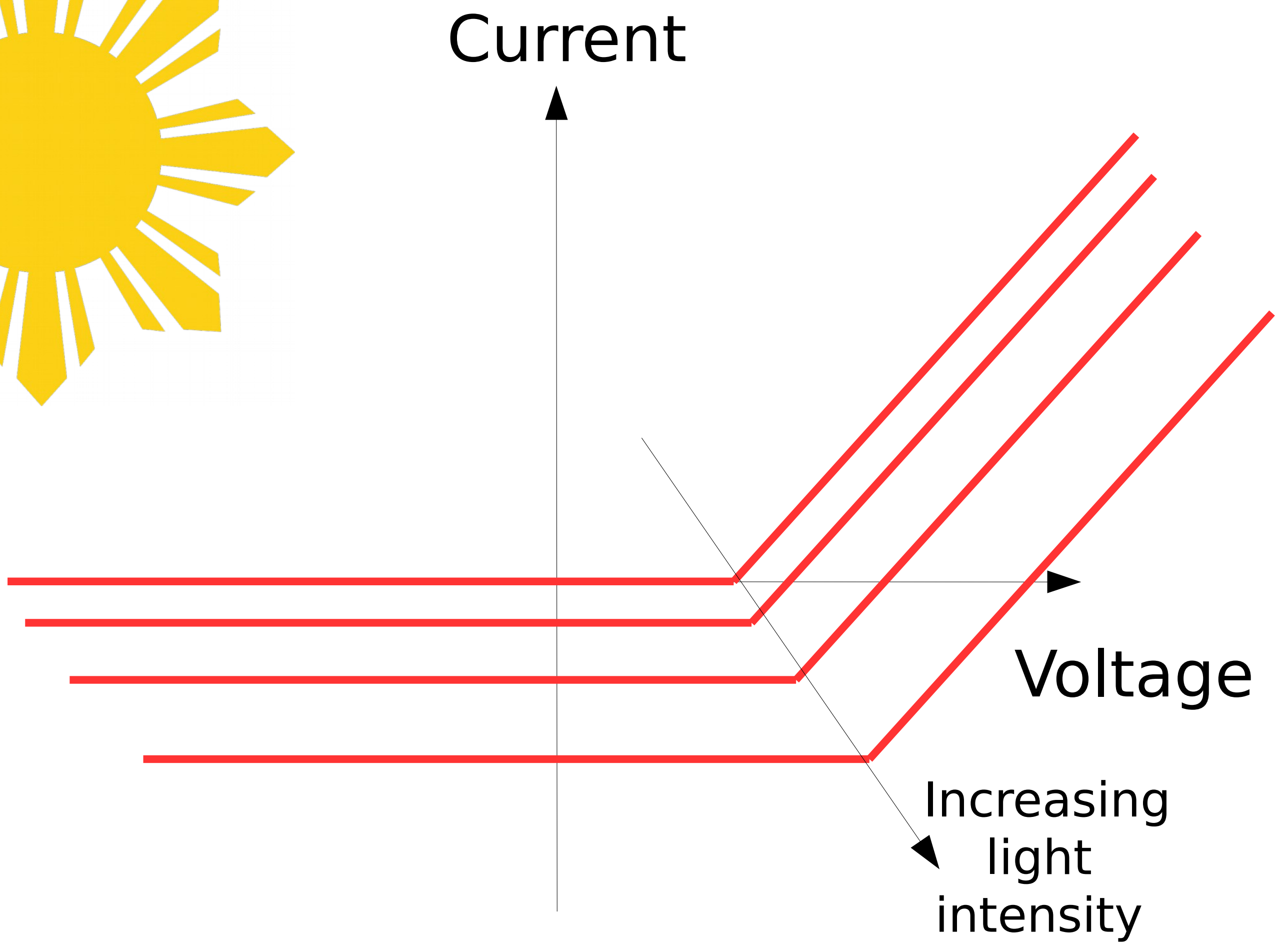


- Negative current means the current is coming out of the device rather that going into it.
- It's generating electricity.

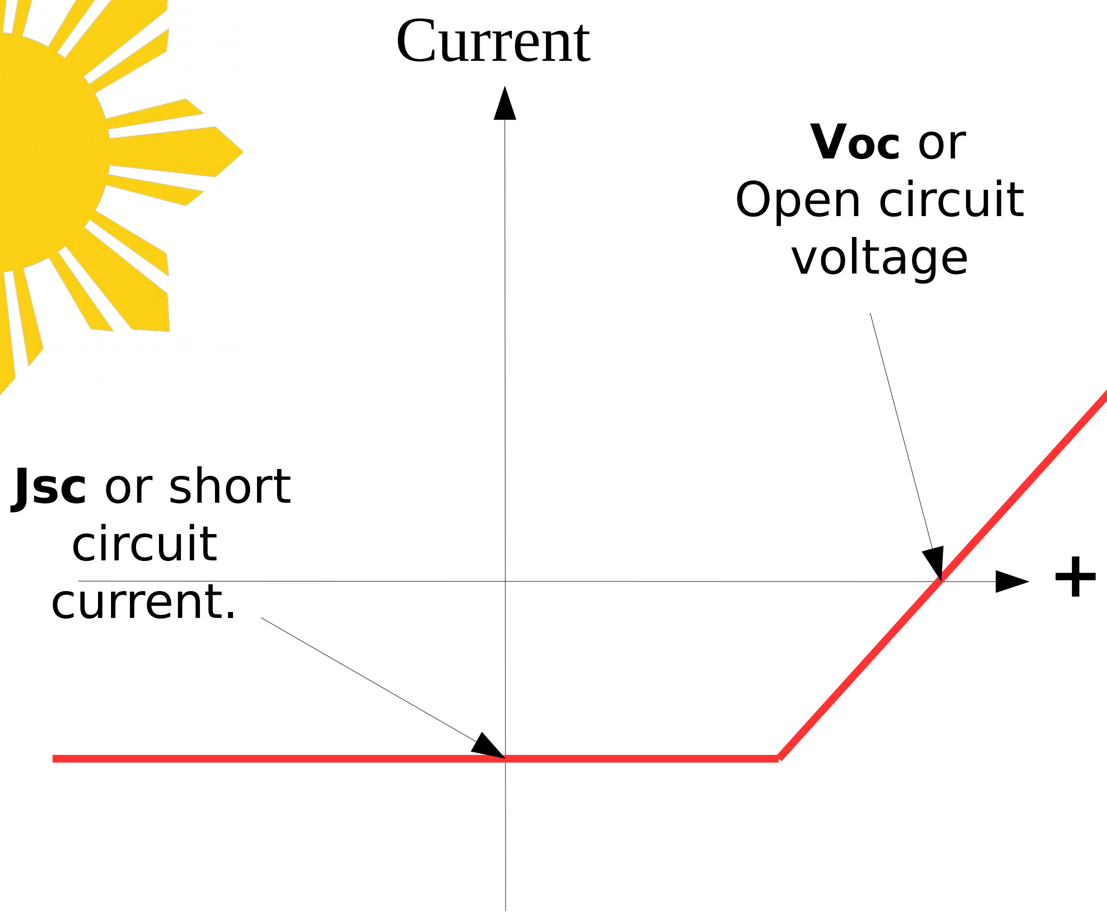
What do the JV curves look like in the light



What do the JV curves look like in the light

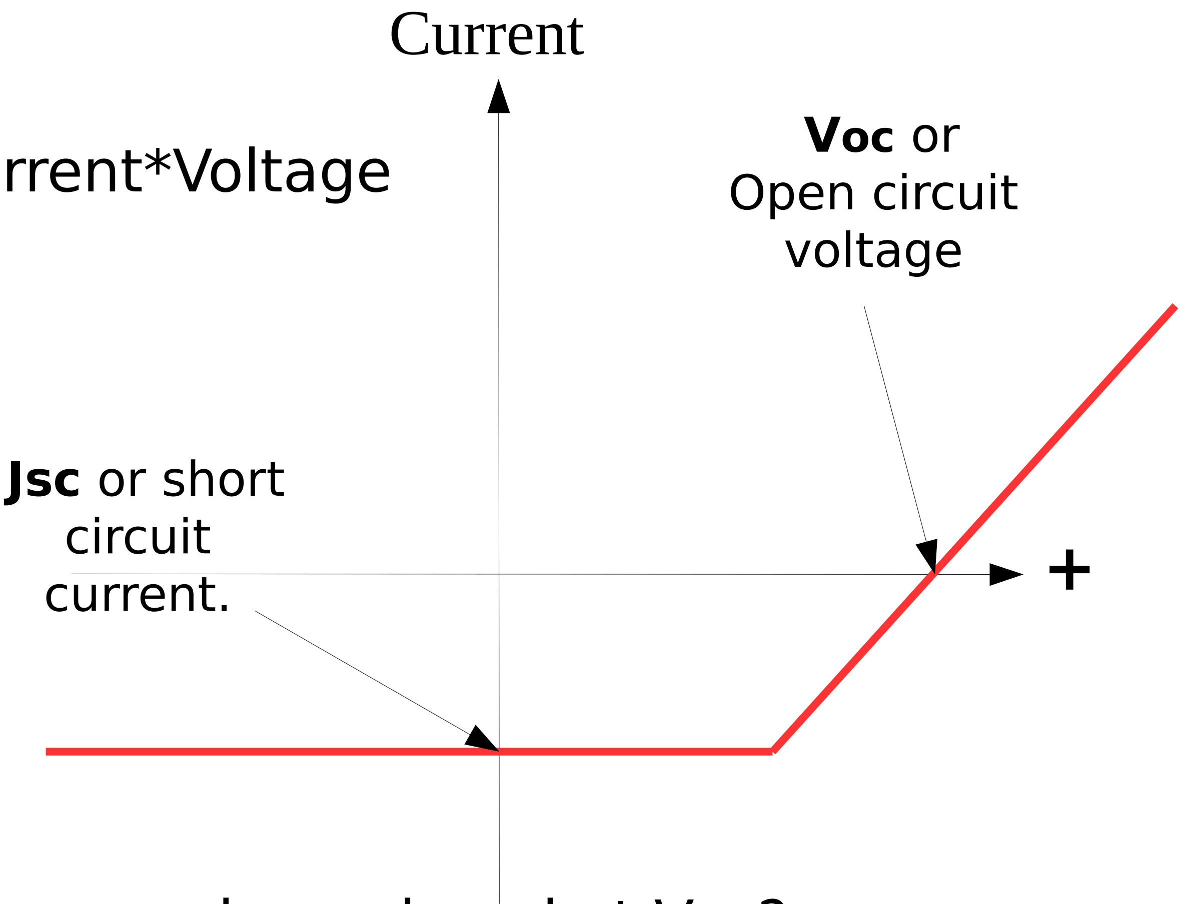


What do the JV curves look like in the light



What do the JV curves look like in the light

Power=Current*Voltage



- How much power is produced at Voc?
- How much power is produced at Jsc?
- Where will maximum power be produced?

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Silicon solar cells

Gray Watson

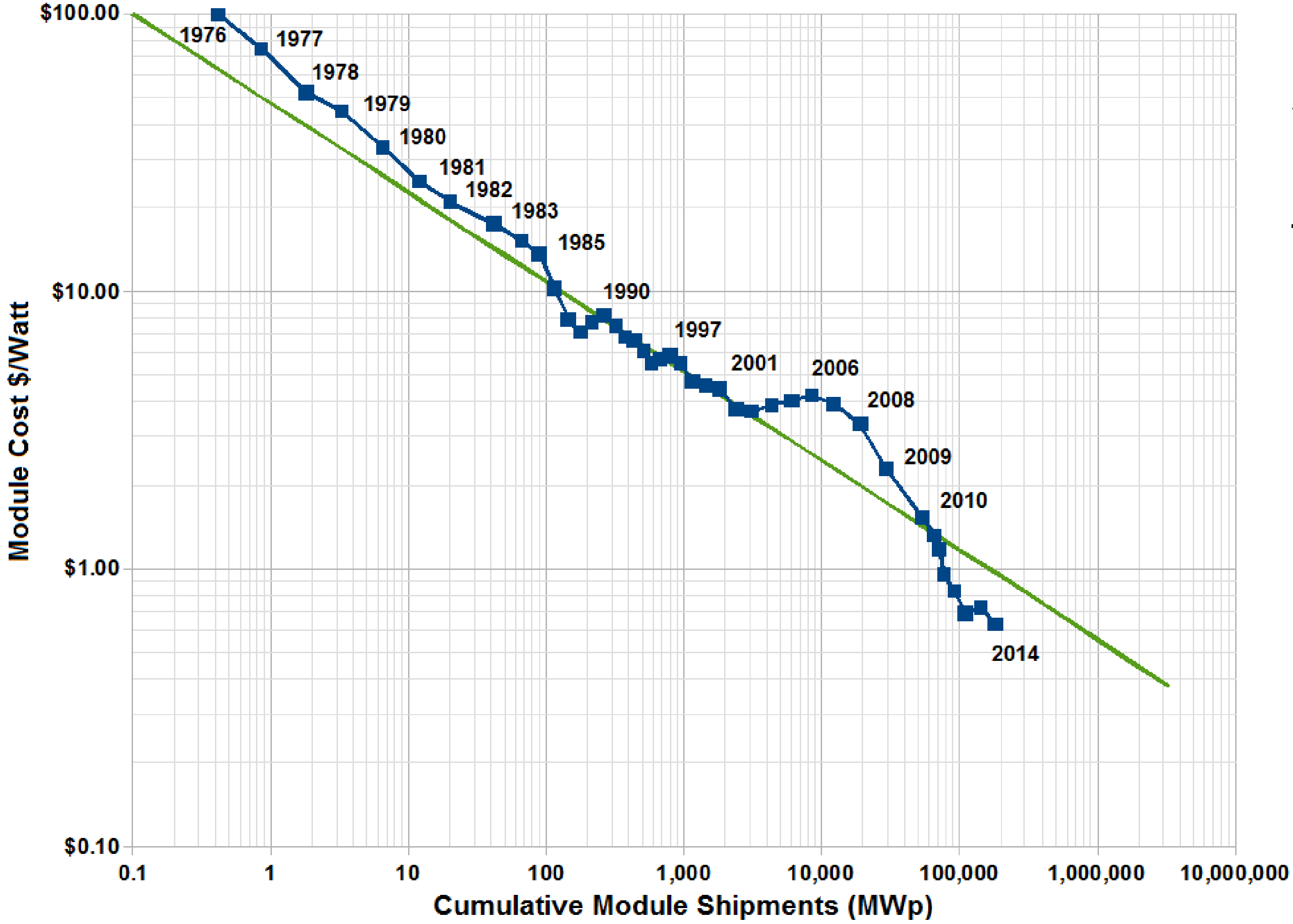
•When you travel through the countryside and look at the roves of houses. You often see deep blue solar cells.

•These are cells made of silicon.

•They are about between 15-20% efficient.

•And have a life time of between 10 and 20 years.

Swanson's law



Every time solar cell production the price falls by 20%.

What's wrong with silicon?

Naturally occurring silicon

Mono-crystalline silicon

Silicon solar cell

2 GJ per square meter!
(553 kWh)

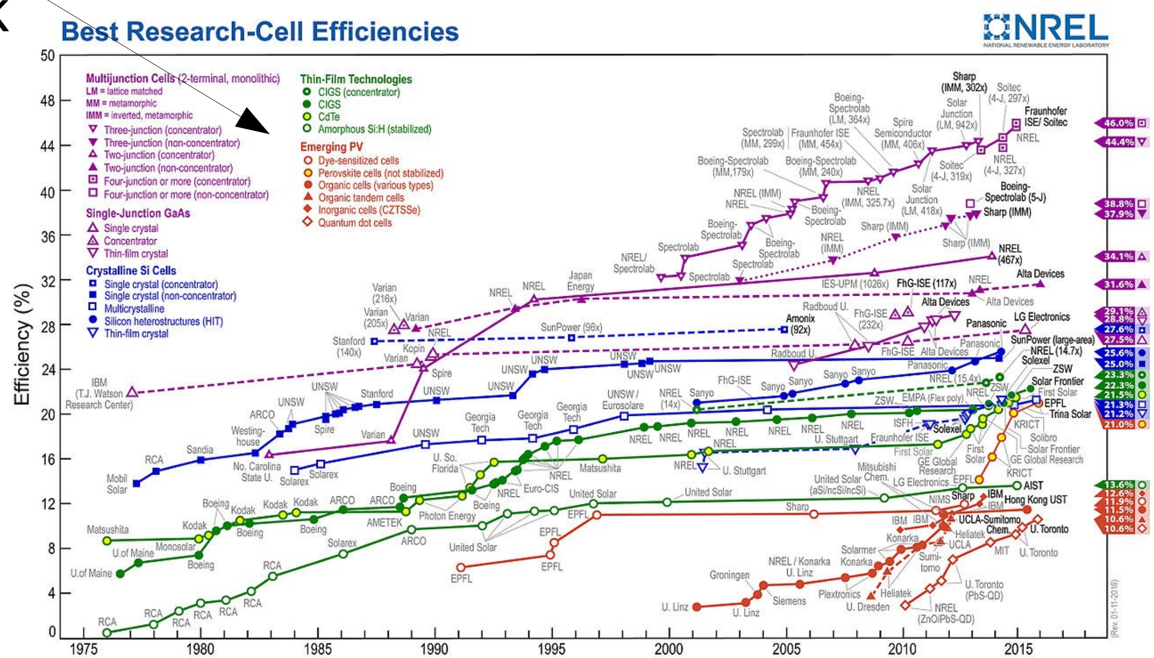
Other classes of solar cell

•People have been searching for alternatives to silicon solar cells for a long time

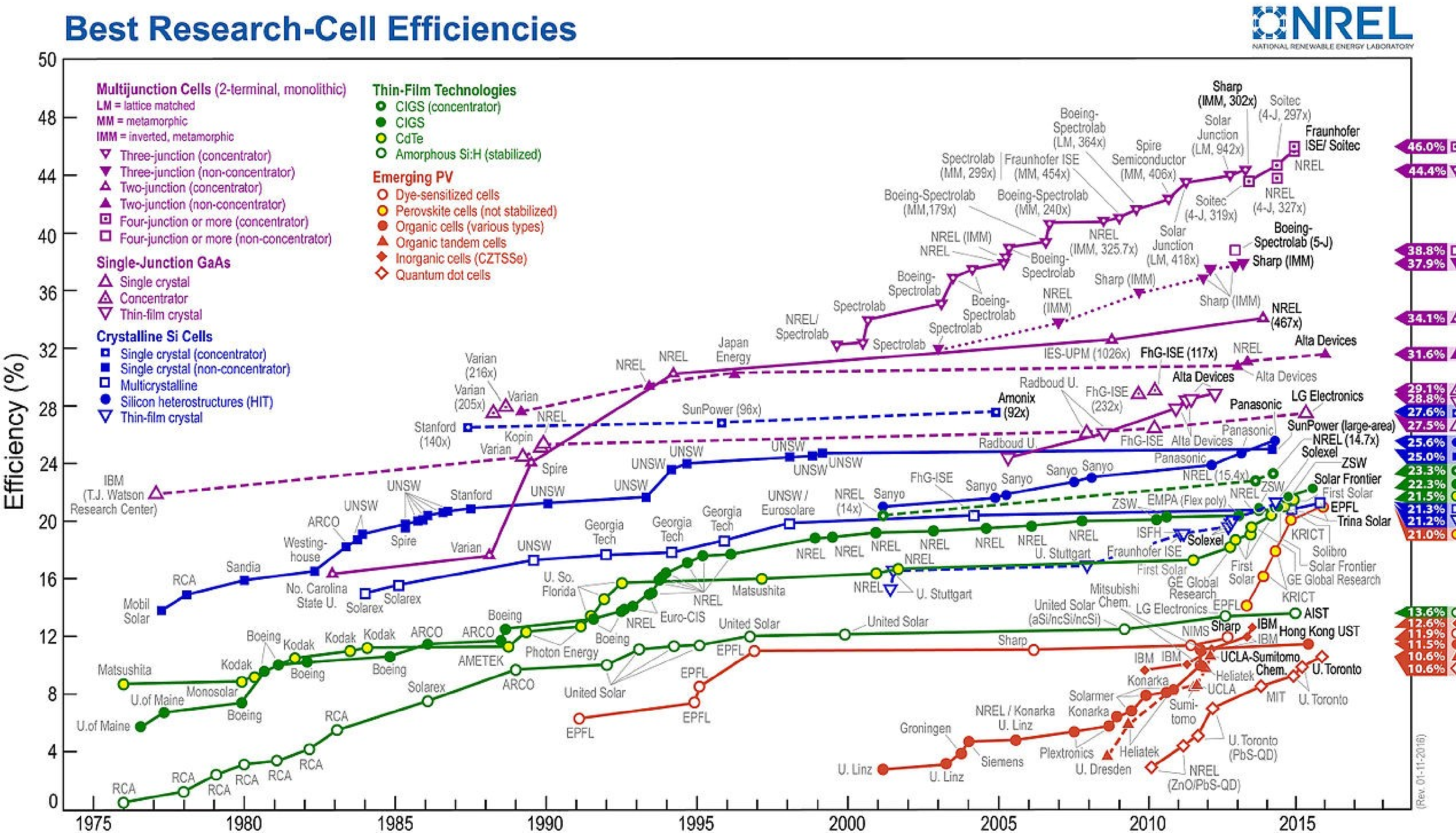
•Below is a graph of efficiency of different types of solar cell as a function of time.

•Let's have a closer look

•Before we look at some of these technologies in more detail.



Best Research-Cell Efficiencies



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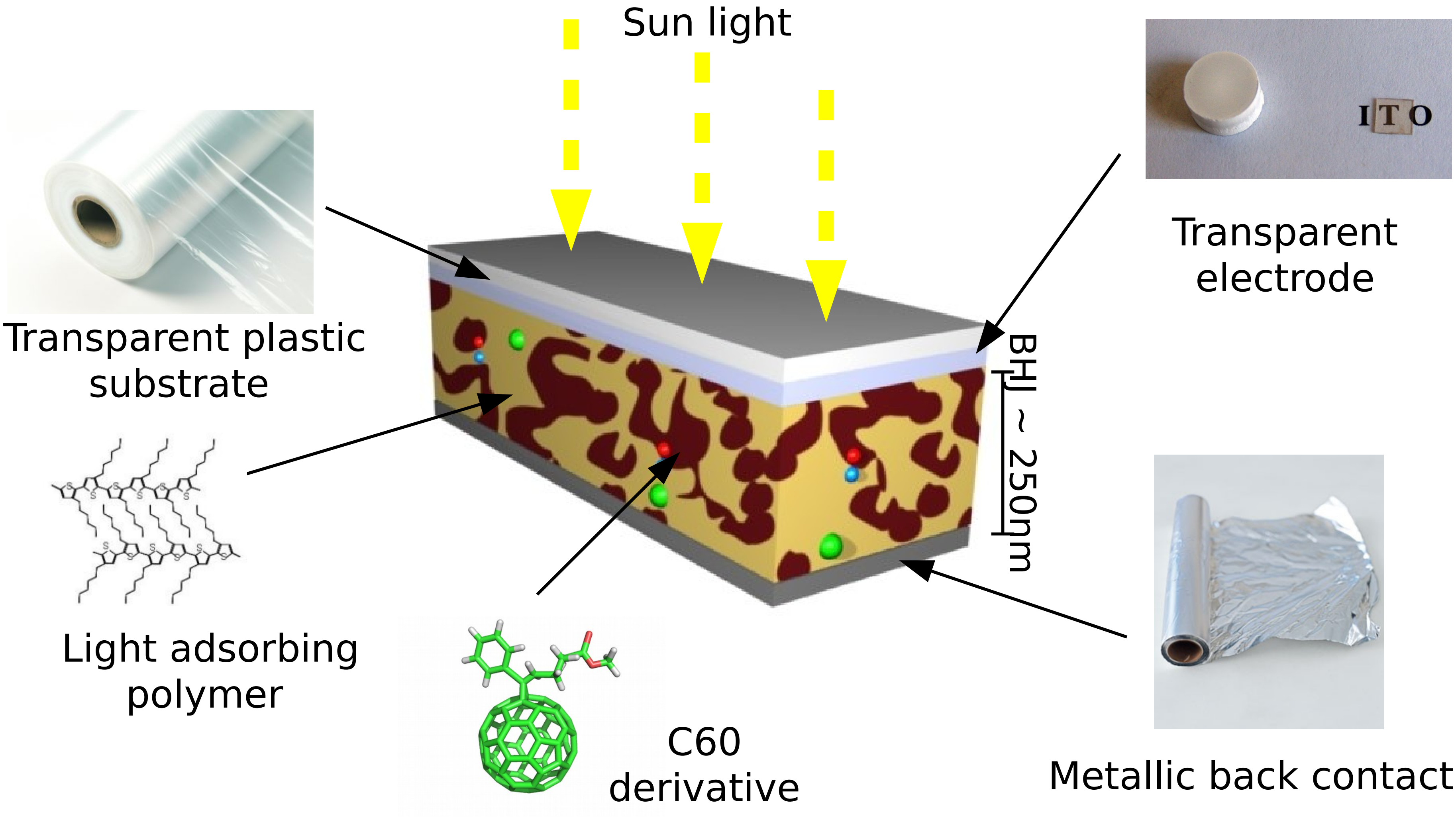
One answer to this problem, the plastic solar cell.



What are the advantages of organic solar cells?

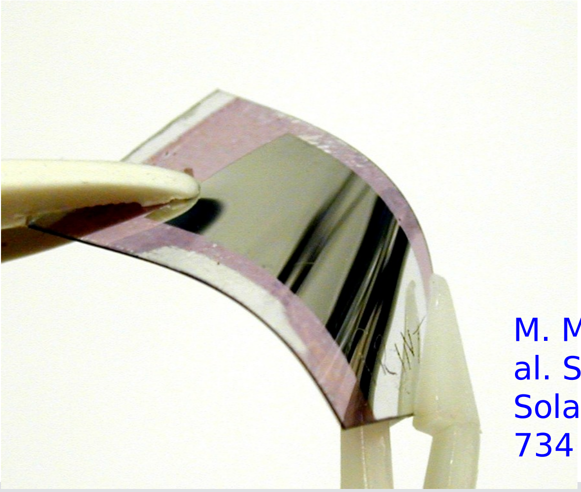
- Organic molecules are cheep to make.
- They are flexible so the cells can be easily integrated into products and buildings.

Images from www.konarka.com

Advantages of being flexible

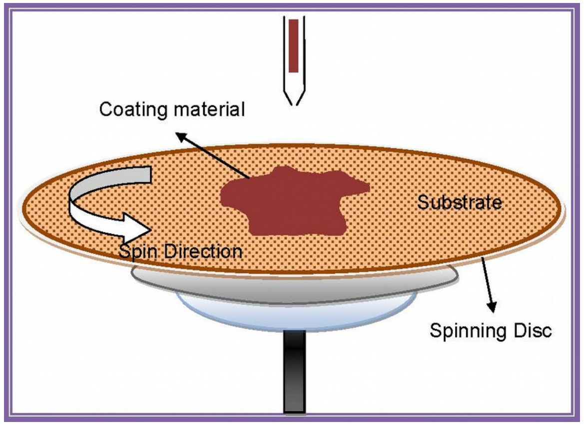
•But most importantly:

- •Organic devices can be printed onto a plastic substrate just like newspapers are printed onto paper at (100>m/min).
- •The principle is that does not matter that they are not very efficient as they are cheep to manufacture.

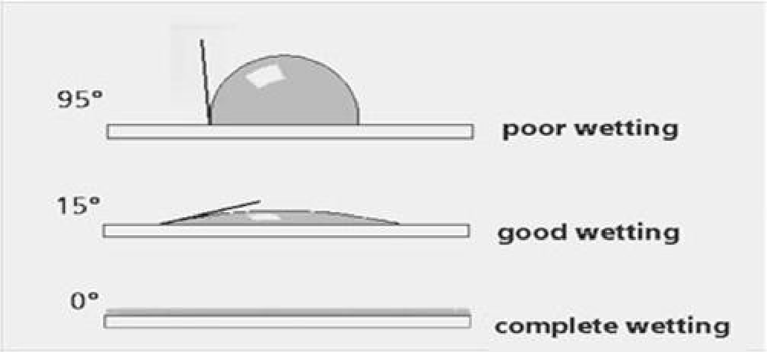


M. M. Voigt, R C.I. Mackenzie, et al. Solar Energy Materials and Solar Cells, 95, 2, 2011, pp. 731-734

From the lab to the factory: Tuning the ink parameters

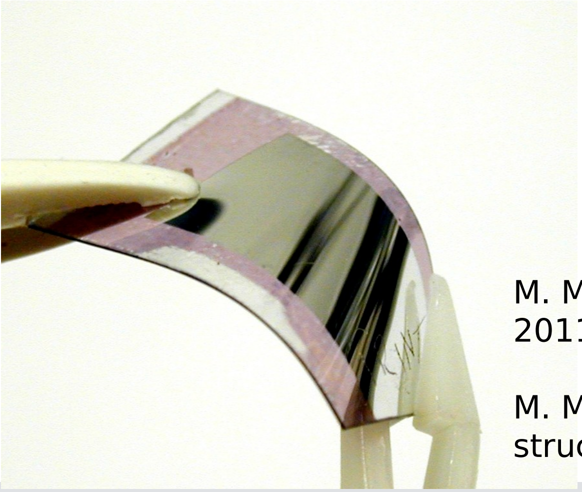


Lab scale production (1 cm^2 at most)



Polymer/fullerene have to be optimized for being printed too.

Industrial production (>100 cm^2)



M. M. Voigt, R C.I. Mackenzie, et al. Solar Energy Materials and Solar Cells, 95, 2, 2011, pp. 731-734

M. M. Voigt, R C.I. Mackenzie, et al."Gravure printing of inverted organic solar cell structures on flexible substrates" Solar Energy Materials and Solar Cells, submitted

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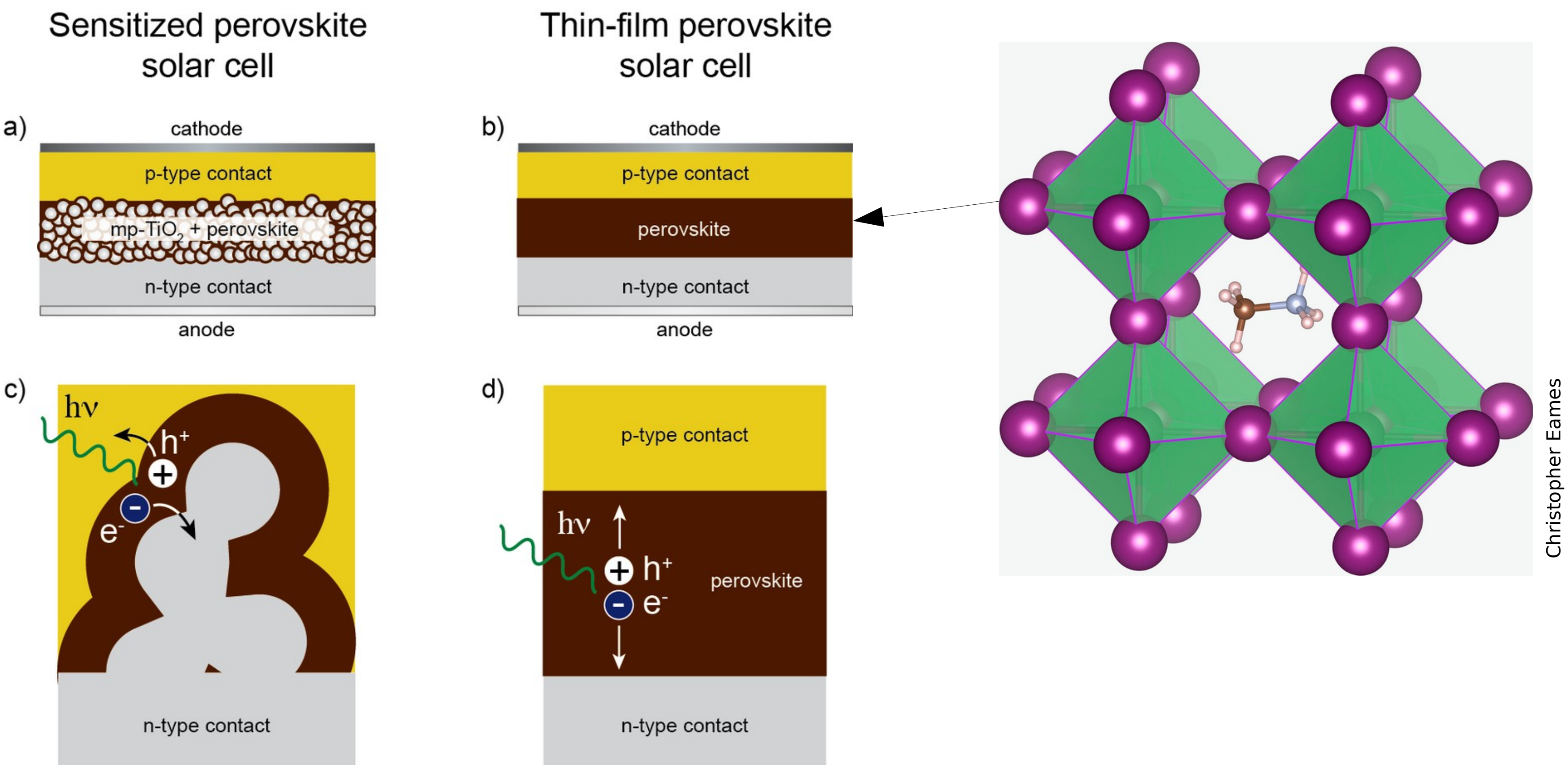
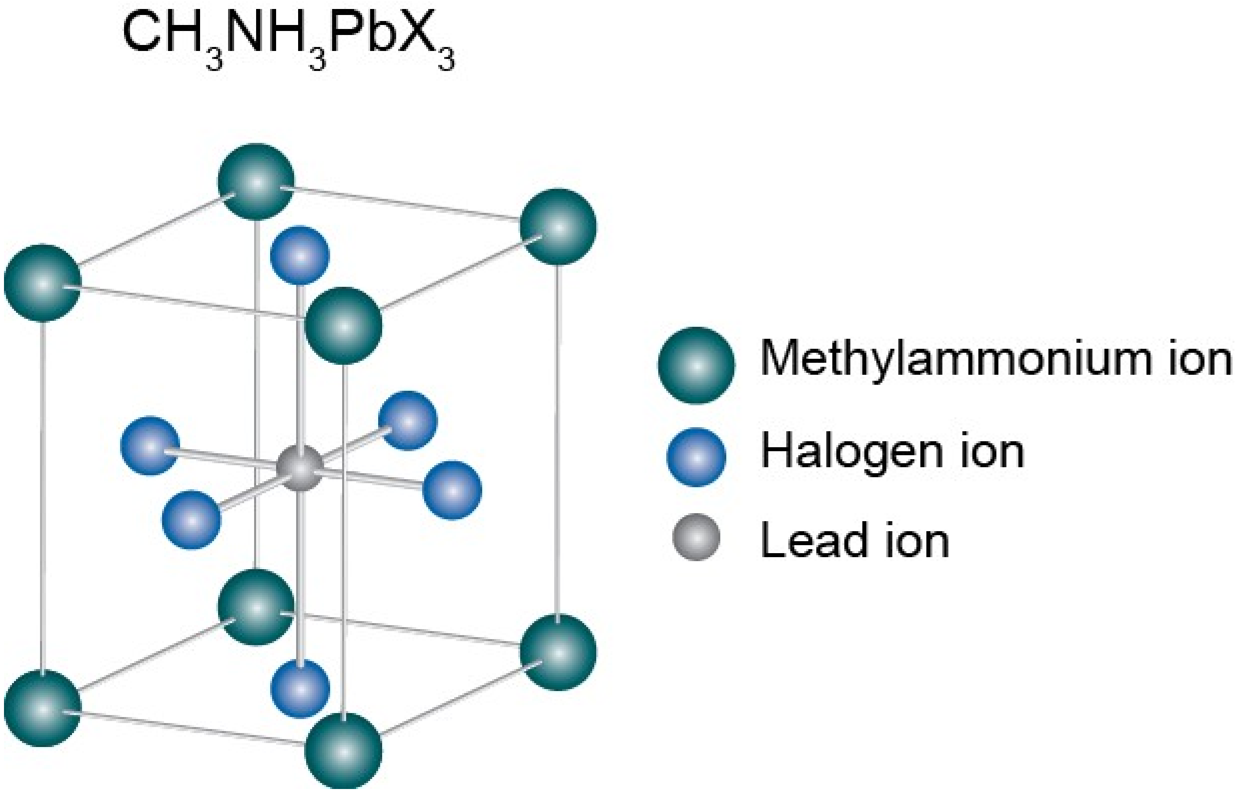
Perovskite solar cells

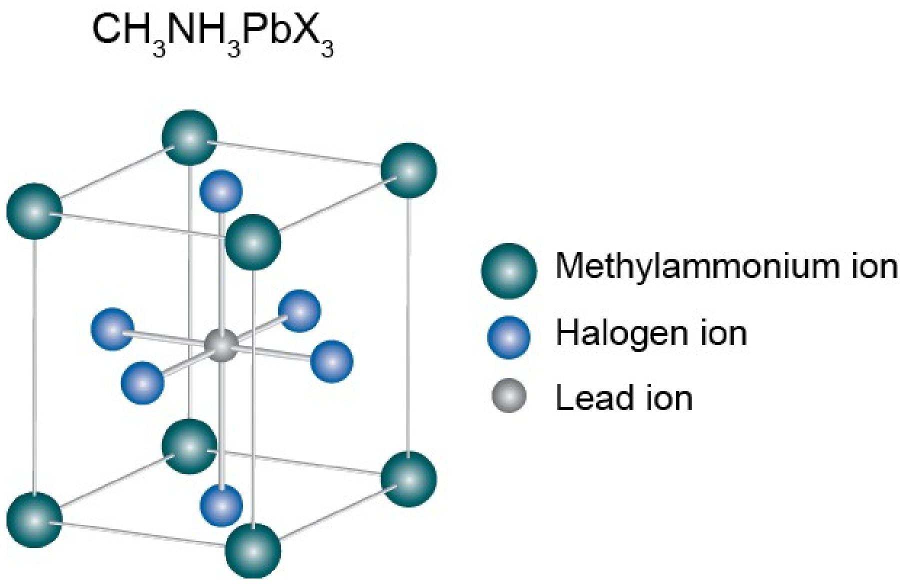


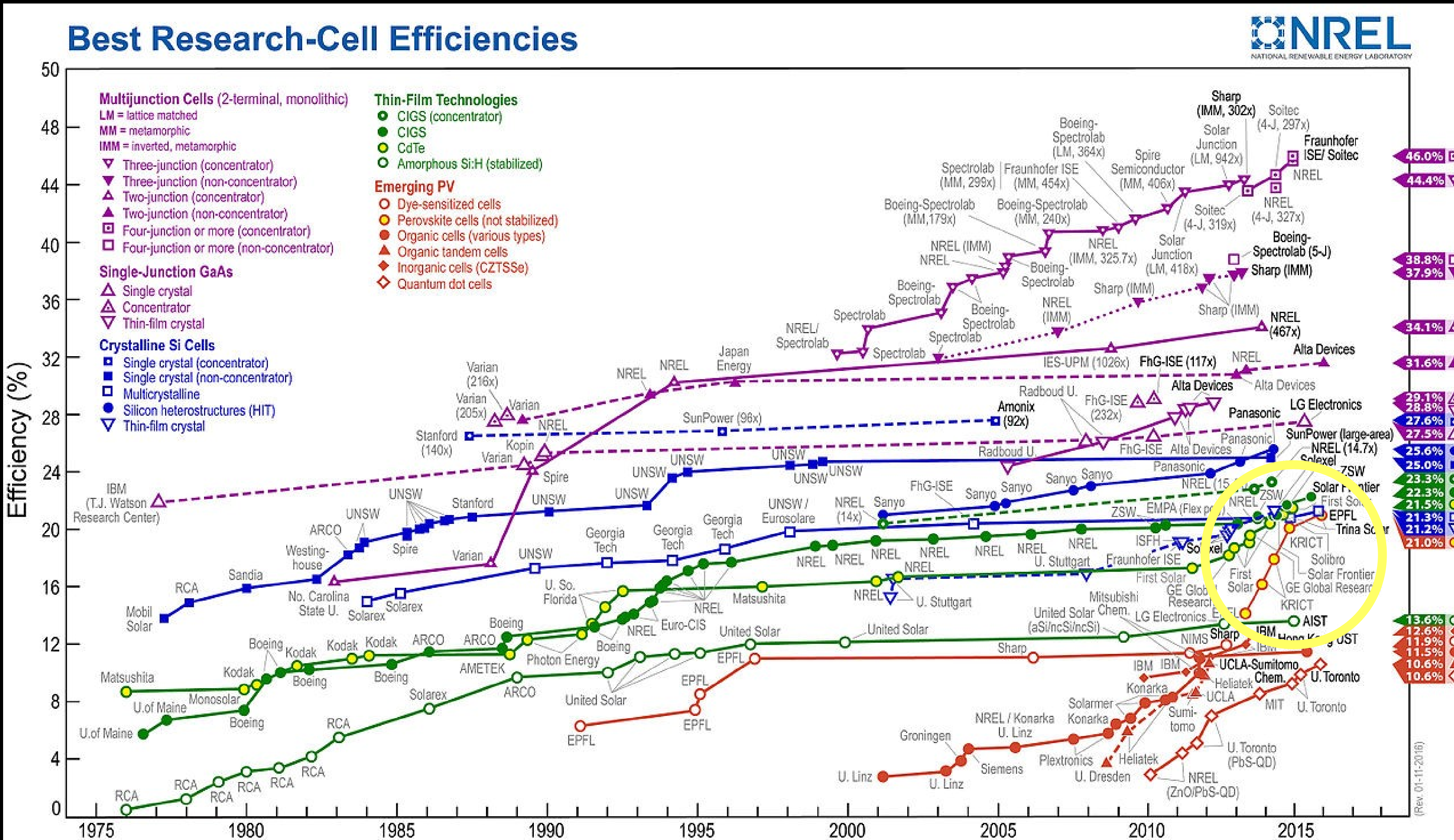
Anybody see any problems with this solar cell?



Anybody see any problems with this solar cell?

- It contains lead
- It's water soluble
- Also, all the molecules in it can move around meaning it's a pretty unstable material.
- Solar cells typically have a life time of hours.





Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
46.0%
44.4%
38.8%
37.9%
34.1%
31.6%
29.1%
28.8%
27.6%
27.5%
25.6%
25.0%
23.3%
22.3%
21.5%
21.3%
21.2%
21.0%
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
(Rev. 01-11-2016)

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    - Cadmium telluride solar cells
    - Multi-junction solar cells/Concentrator solar cells
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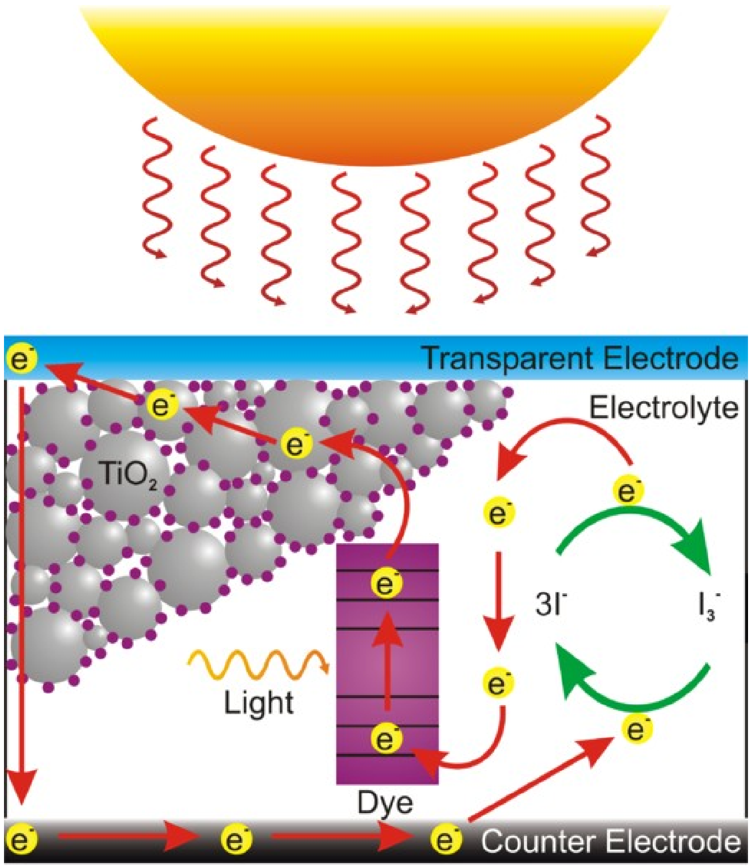
Dye sensitized solar cell



Dye sensitized solar cell

- Efficiency never really got really high.
- Over taken by perovskite solar cells.
- The liquid in them was a problem.
- Never really very successful.

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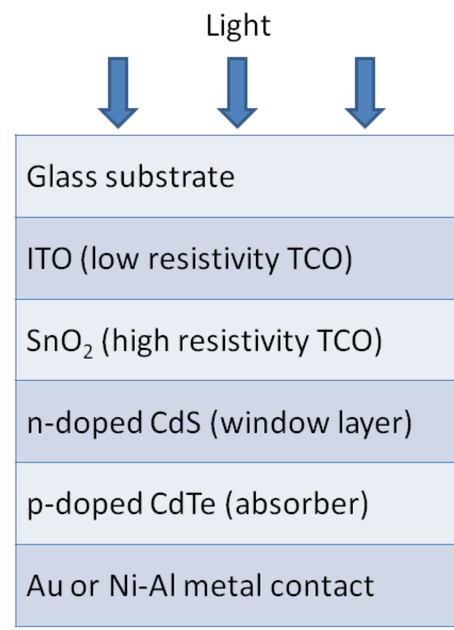
Spotting Cadmium Telluride solar cells.

- Generally a deeper blue than silicon and don't have metallic strips on the front of them.



Problems with Cadmium Telluride solar cells.

SAFETY DATA SHEET

Alchemist-hp

Environmental hazards	Hazardous to the aquatic environment, acute hazard	Category 1
	Hazardous to the aquatic environment, long-term hazard	Category 1
OSHA defined hazards	Not classified.	
Label elements		

Signal word	Danger
Hazard statement	Toxic if swallowed. Fatal if inhaled. Suspected of causing genetic defects. May cause cancer. Suspected of damaging fertility. Suspected of damaging the unborn child. Causes damage to organs through prolonged or repeated exposure. Very toxic to aquatic life. Very toxic to aquatic life with long lasting effects.

Problems with Cadmium Telluride solar cells.

GFS CHEMICALS

SAFETY DATA SHEET

Alchemist-hp

Environmental hazards	Hazardous to the aquatic environment, acute hazard	Category 1
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- They fail the 'lick' test. Would you lick a Cadmimum Telluride solar cell?

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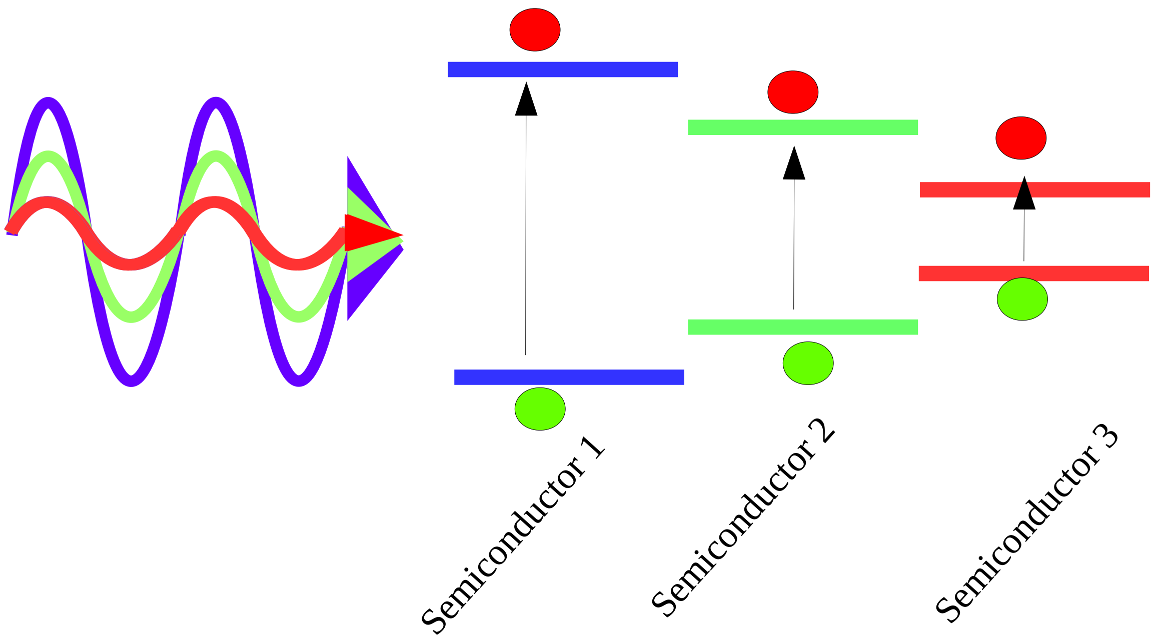
Multi-junction solar cell



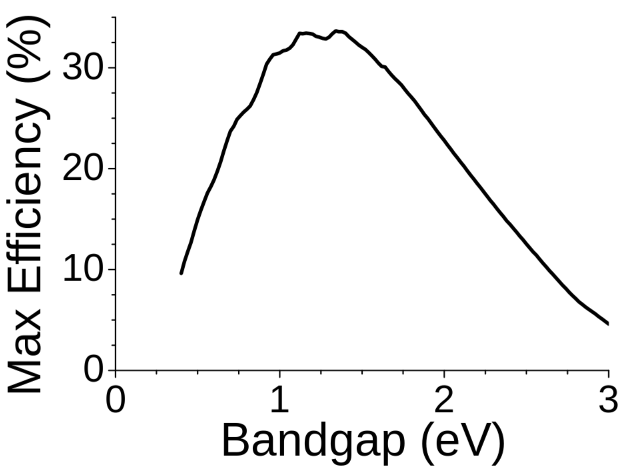
•Different parts of the solar cell are optimized absorb different parts of the sun's spectrum.

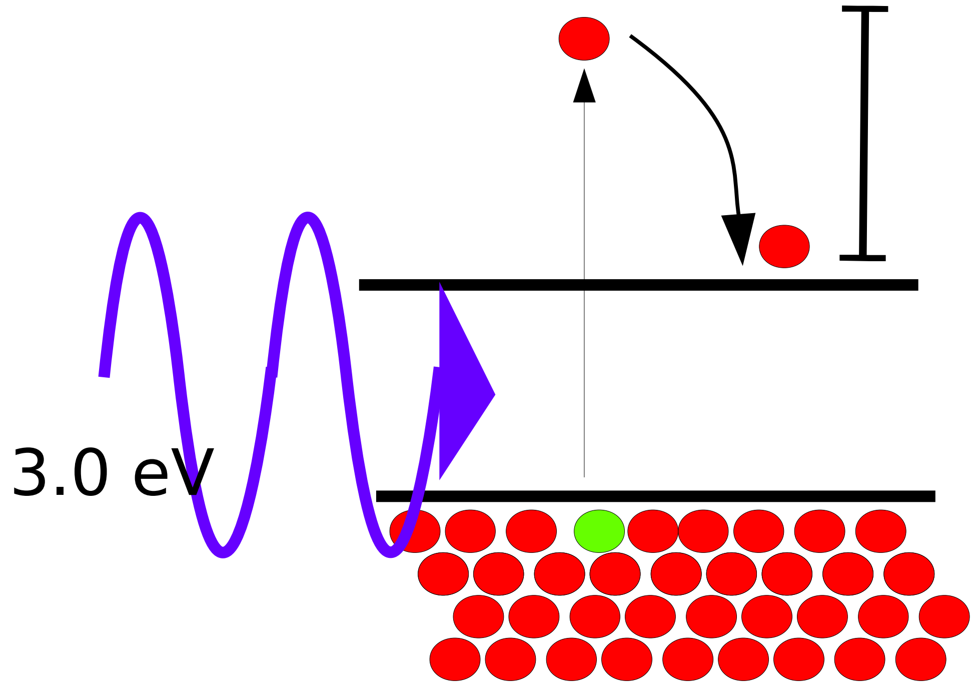
Advantages of multi-junction cells

- Multi-junction cells minimize relaxation losses.

- Efficiency limit of a single junction cell is limited to 33.7%.

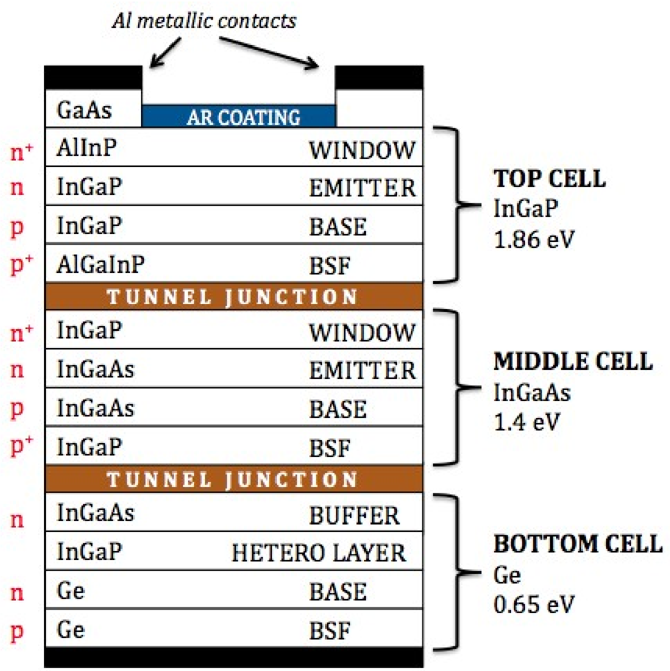
- Shockley–Queisser limit.



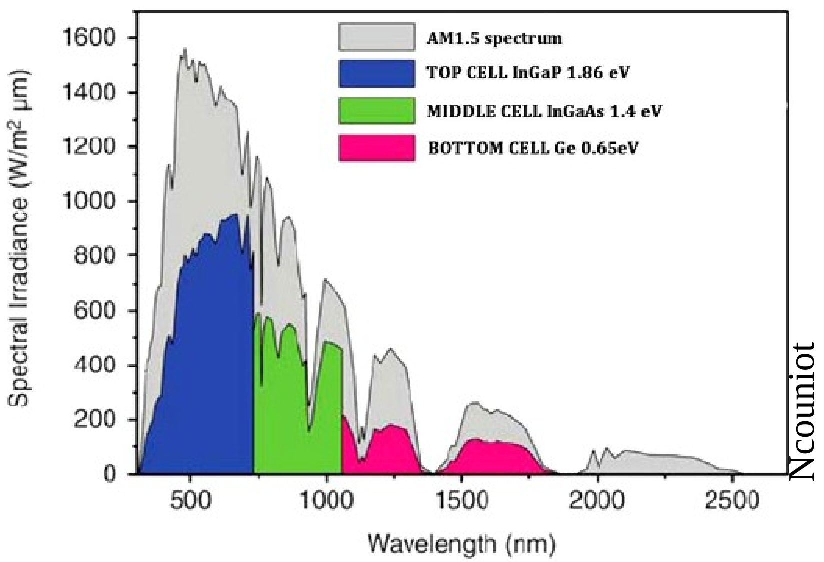


$$E_{loss} = E_{photon} - E_g$$

Multi-junction solar cell



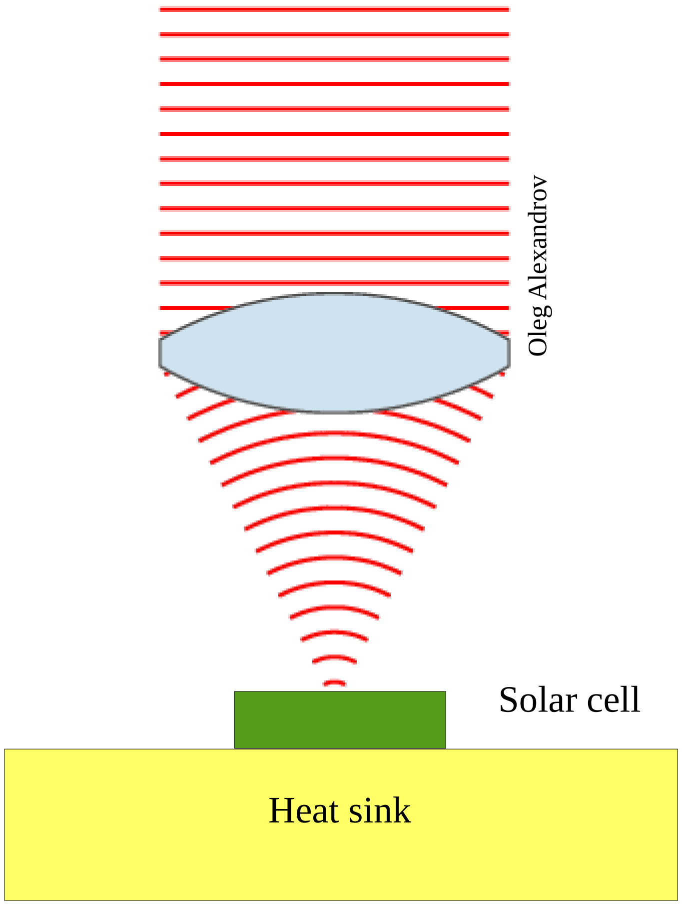
(a)



(b)

•Different parts of the solar cell are optimized absorb different parts of the sun's spectrum.

Concentrator PV



The idea is to have a highly efficient (and expensive solar cell), but use it as efficiently as possibly by putting it under 10-1000 suns.
Needs cooling.

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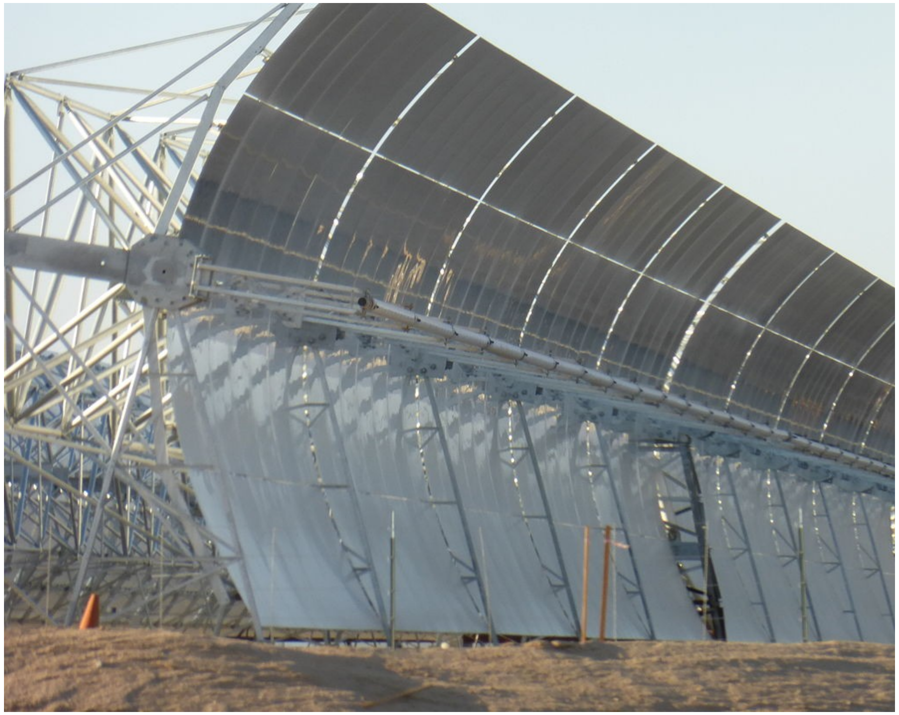
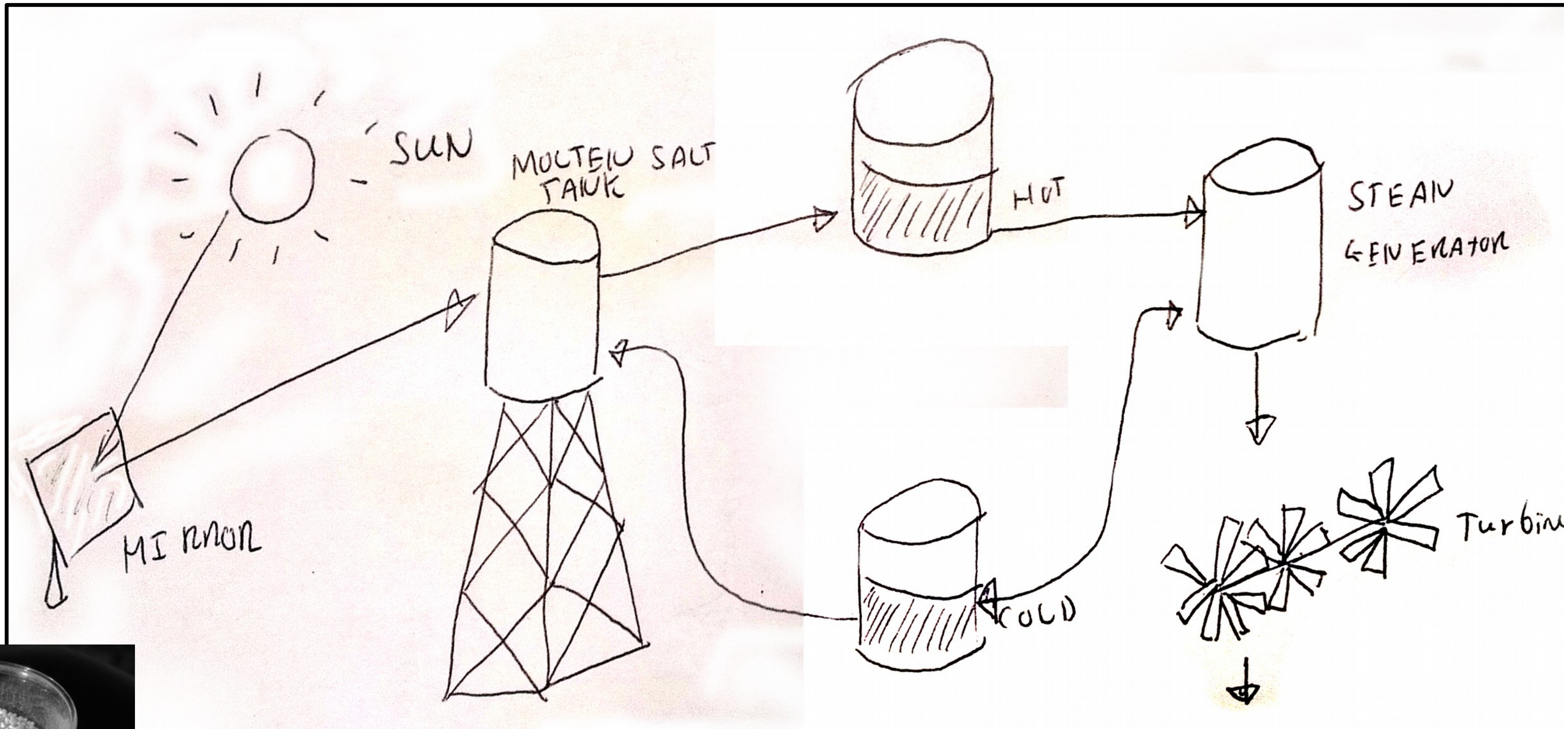
Concentrator PV



Z22

Harper Lake in California


SUN
MOLTEN SALT TANK
HOT
STEAM GENERATOR
MIRROR
COLD
Turbine

Concentrator PV

Koza1983

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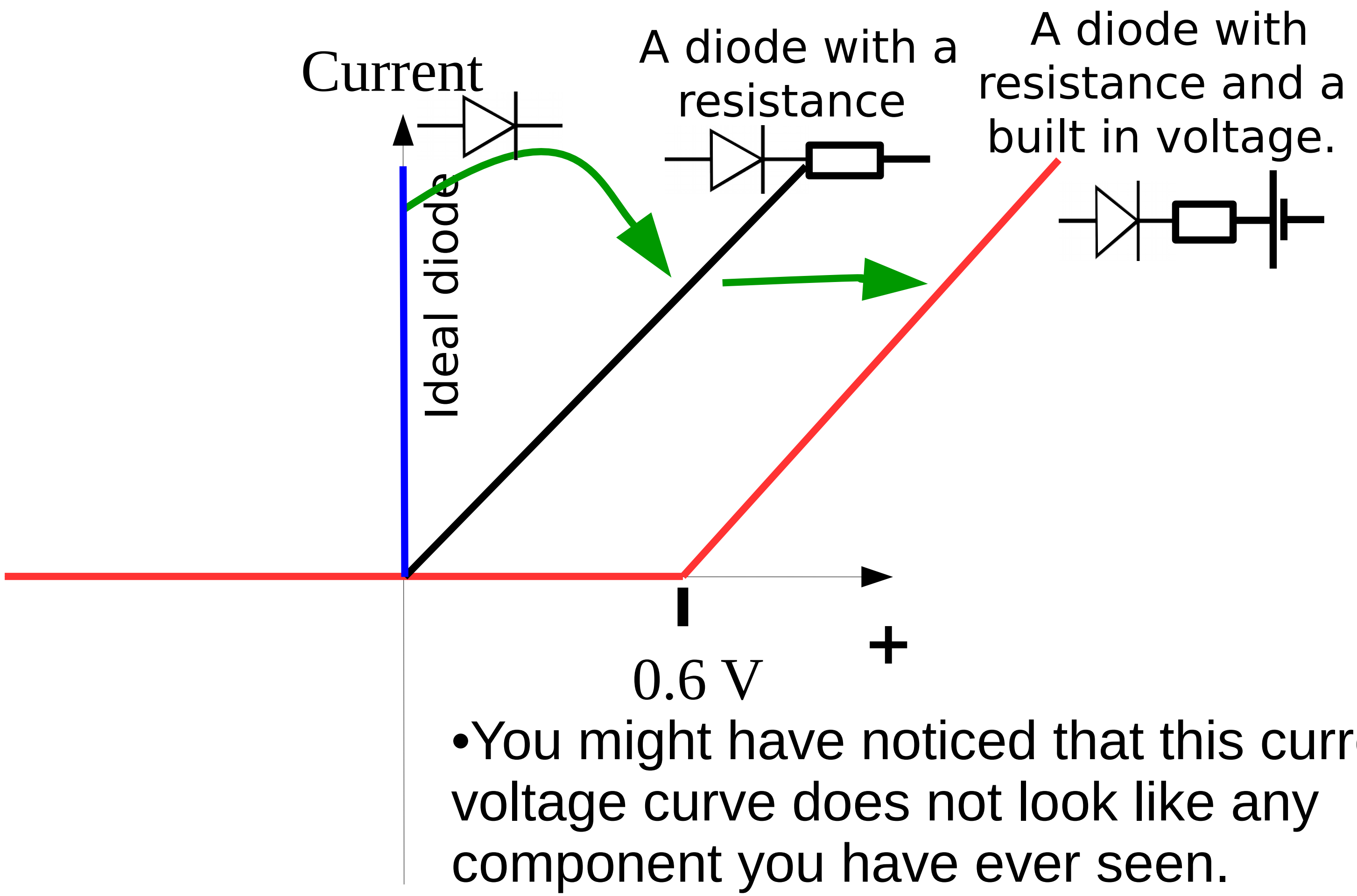
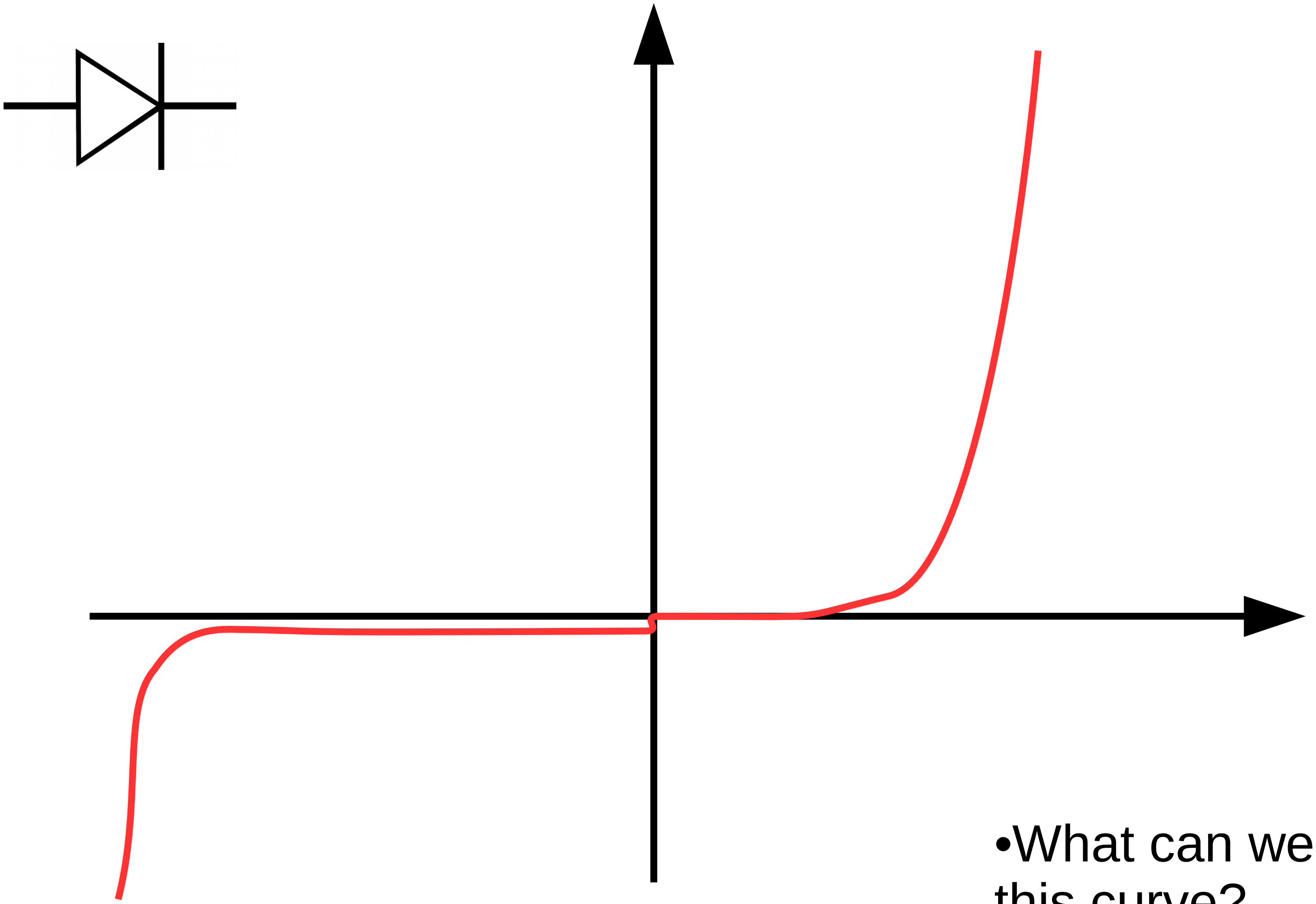
Better solar cell models



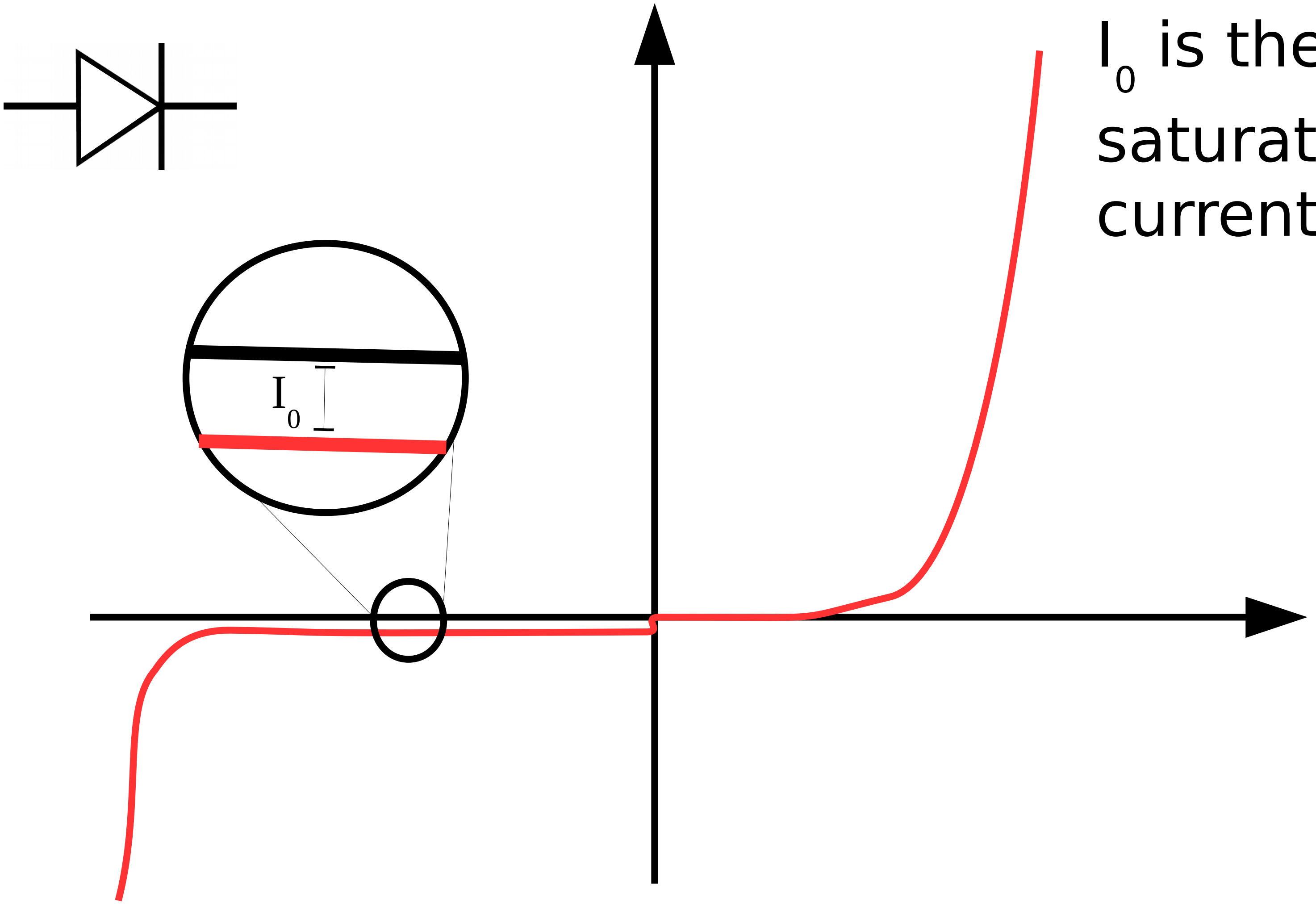
- You might have noticed that this current voltage curve does not look like any component you have ever seen.
- Let's look at a more realistic diode curve.

A more real diode curve



- What can we see on this curve?

A real diode curve

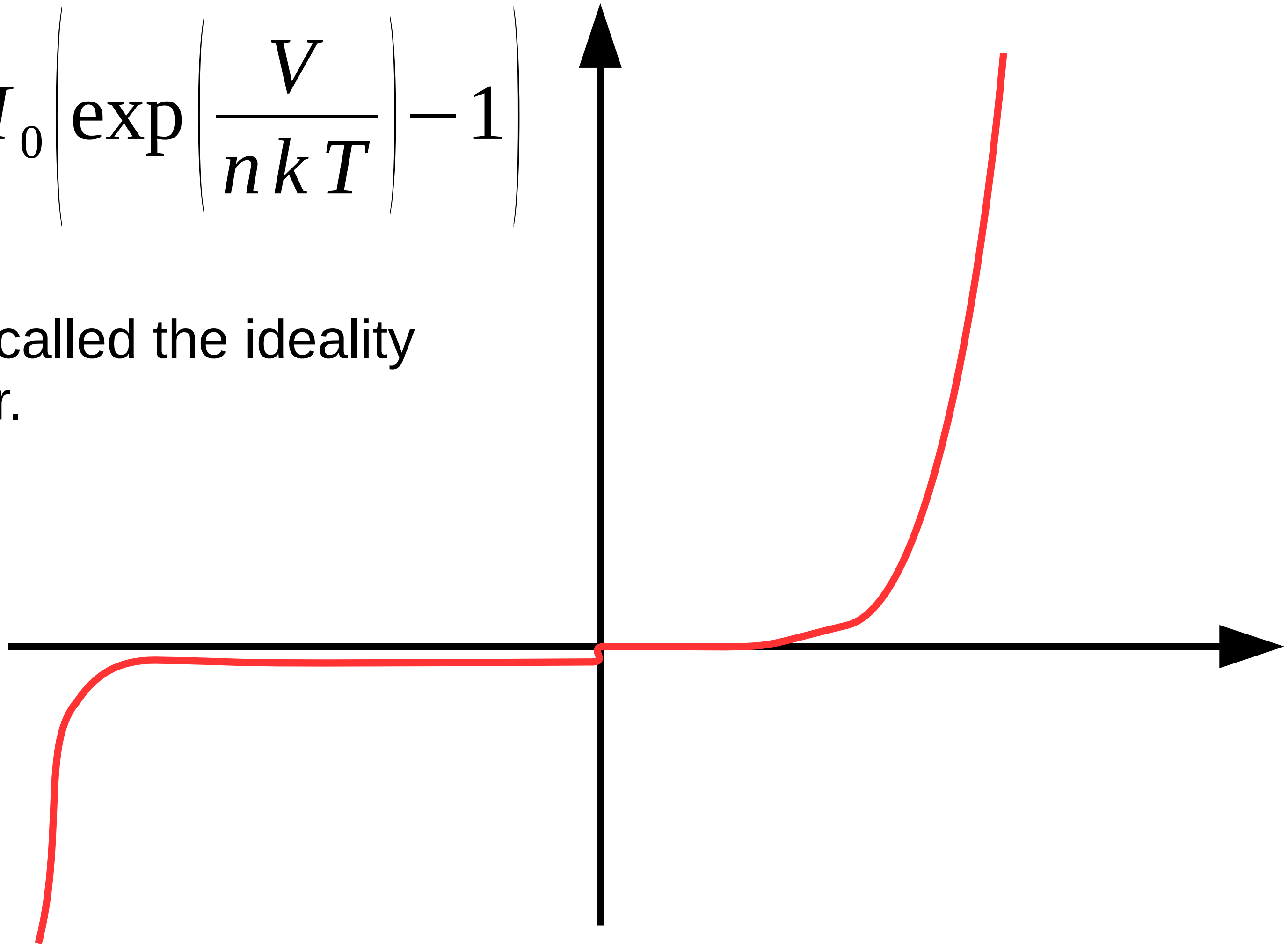


I_0 is the saturation current.

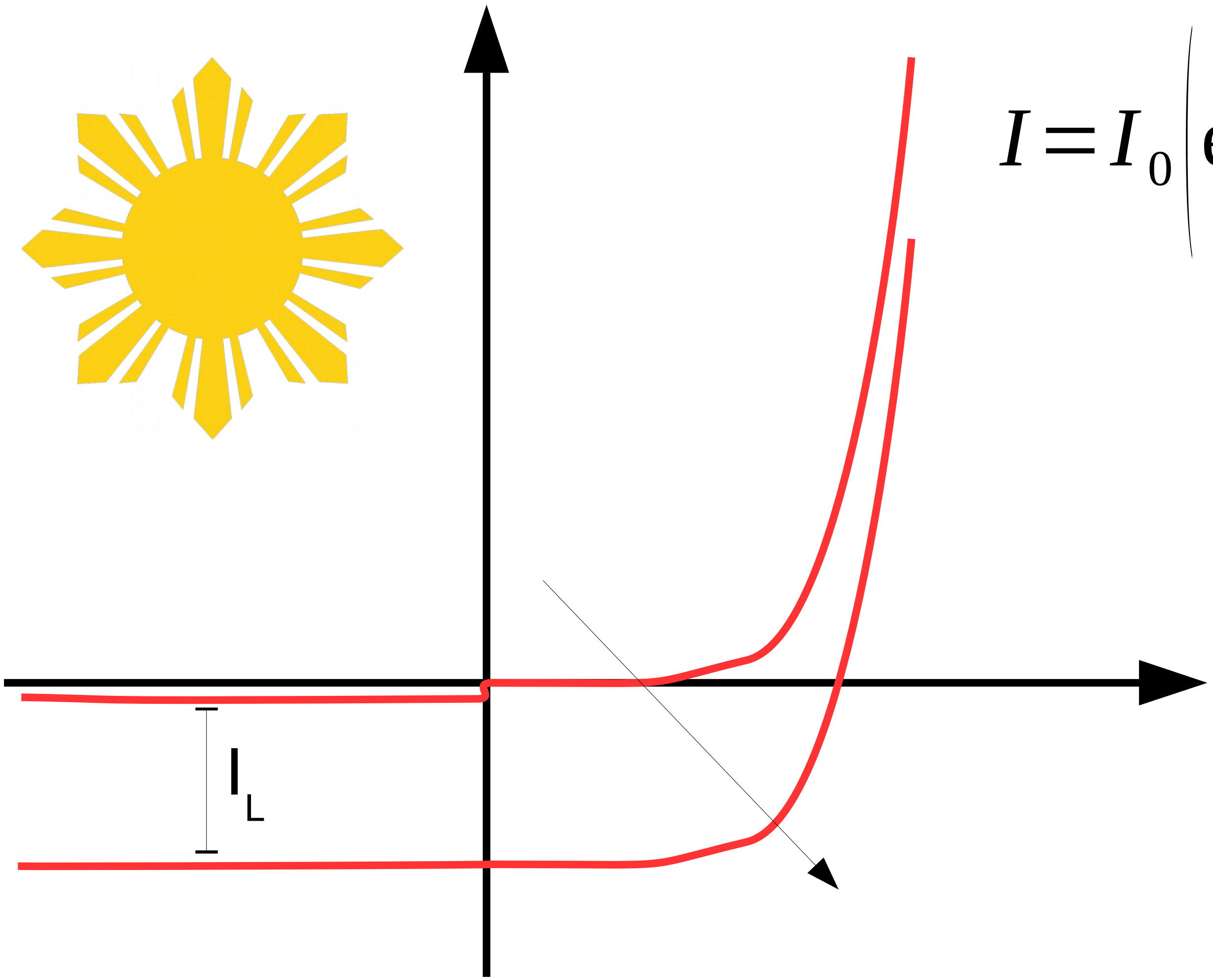
A better ideal diode model.

$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right)$$

•n is called the ideality factor.

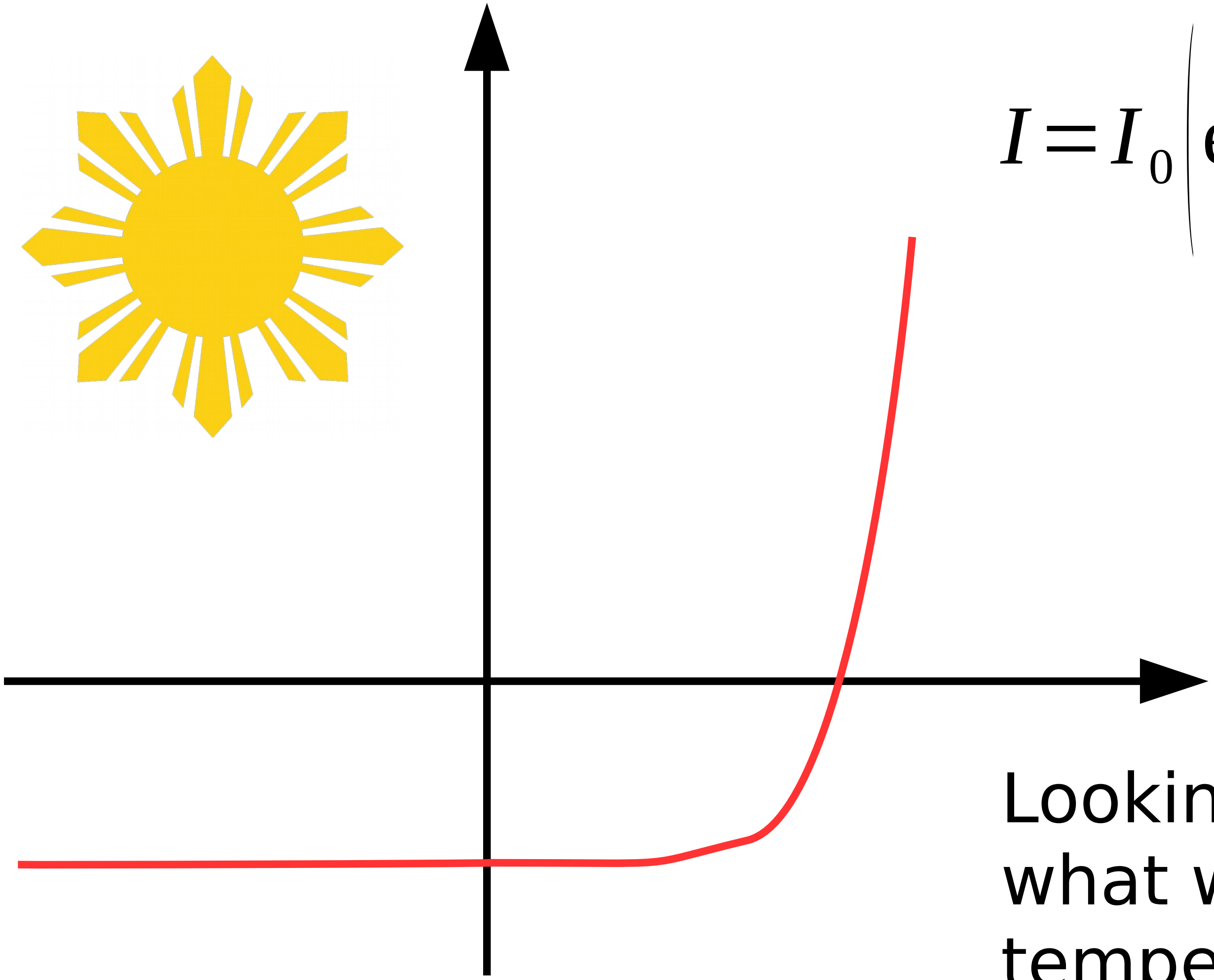


The diode equation in the light.



$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$

The diode equation in the light.

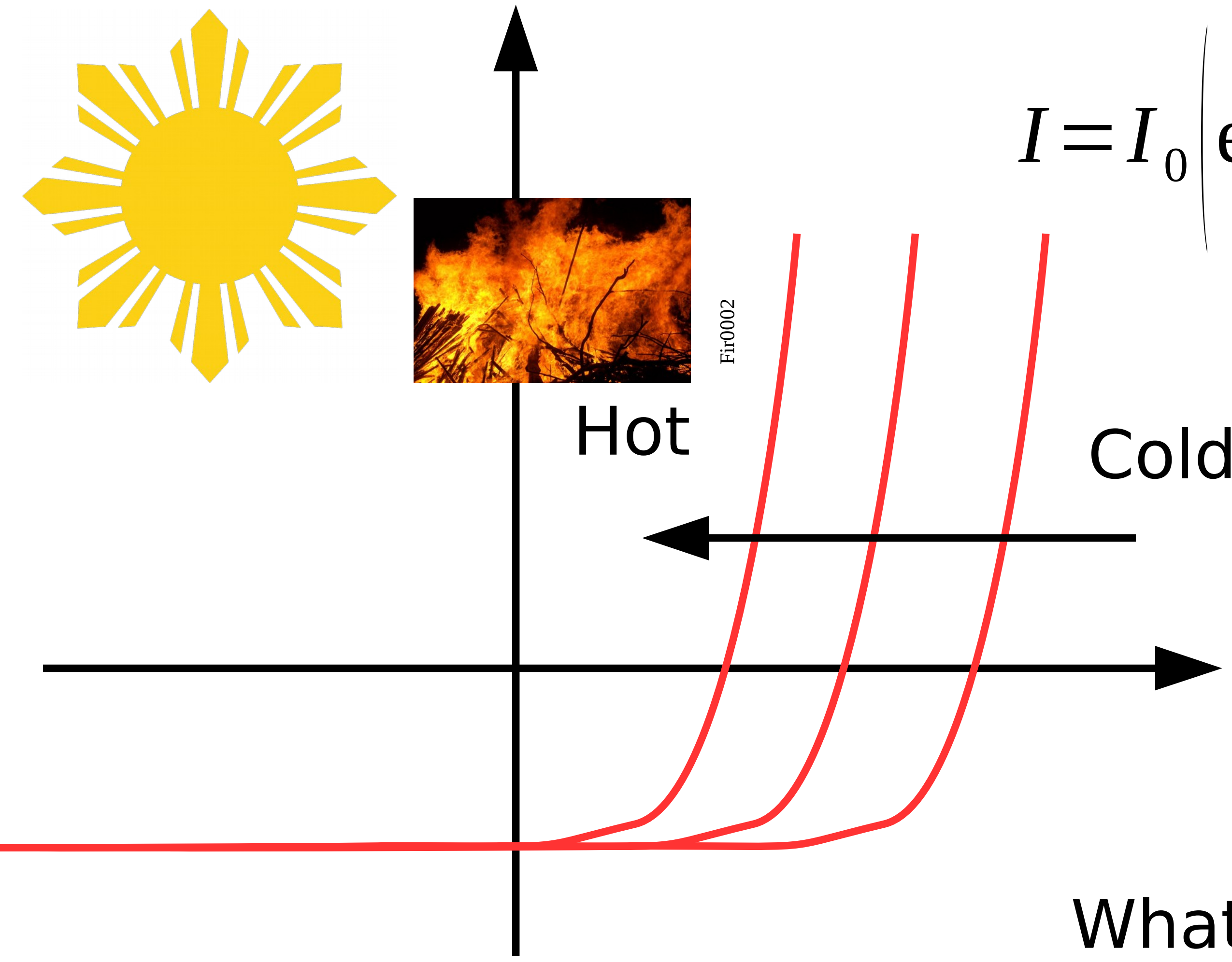


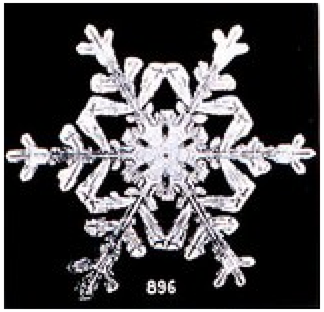
$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$

Looking at the equation what will happen if the temperature is increased?

The diode equation in the light.

$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$





What implications would this have?

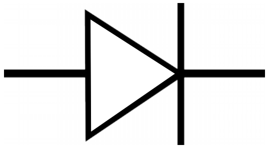
The ideal diode equation

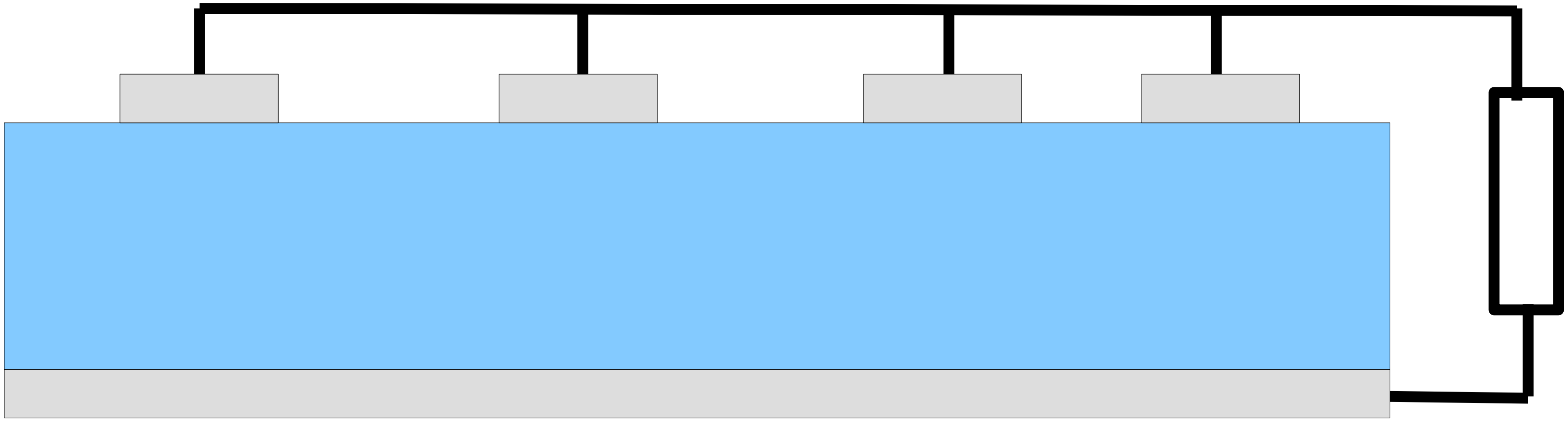
•This equation is for an ideal diode with no resistance. However in a real solar cell there will be:

•Series resistance

•And shunt resistance

$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$





The ideal diode equation

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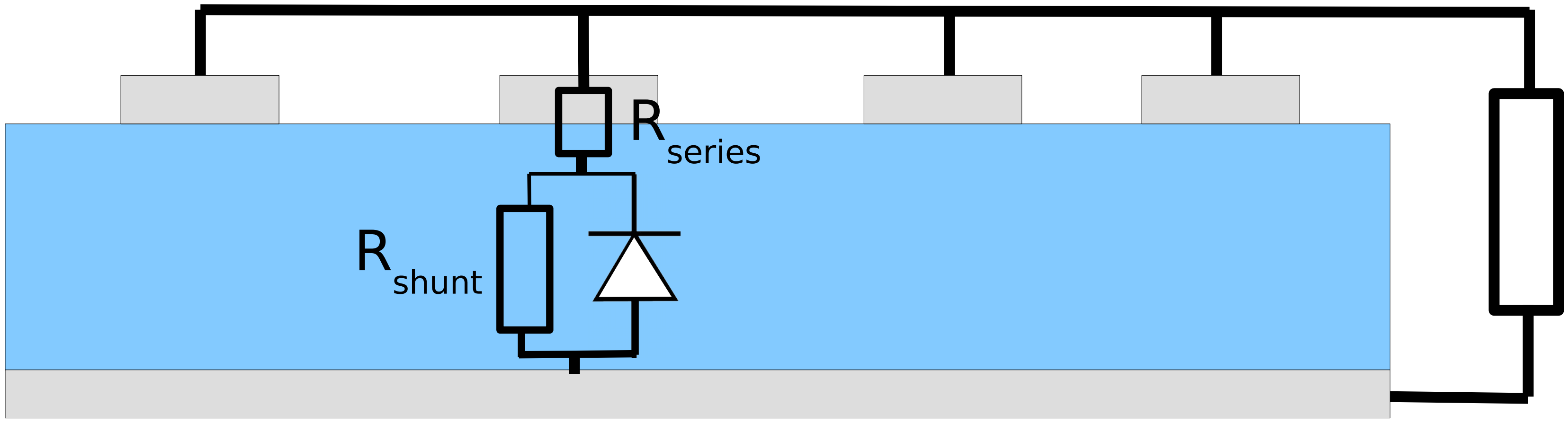
$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$

- Series resistance

- And shunt resistance

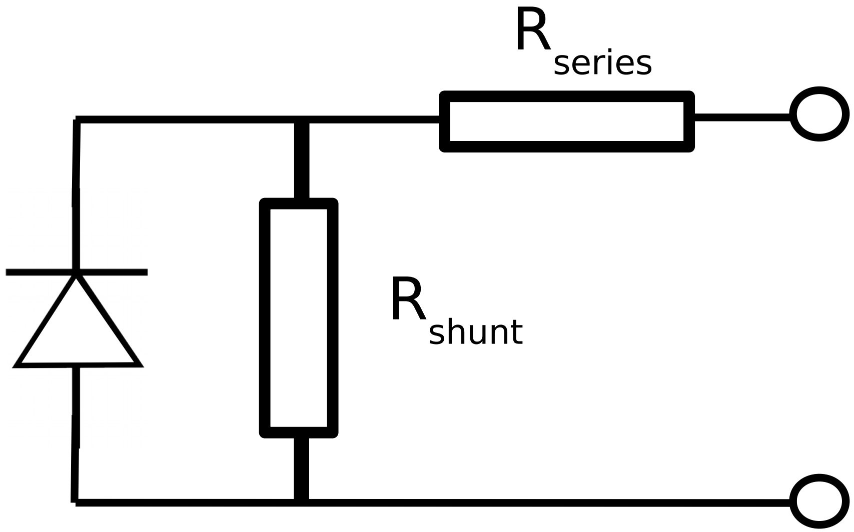


A better equivalent circuit

- Series resistance (1-10 Ohm)

- And shunt resistance (1 M Ohm)

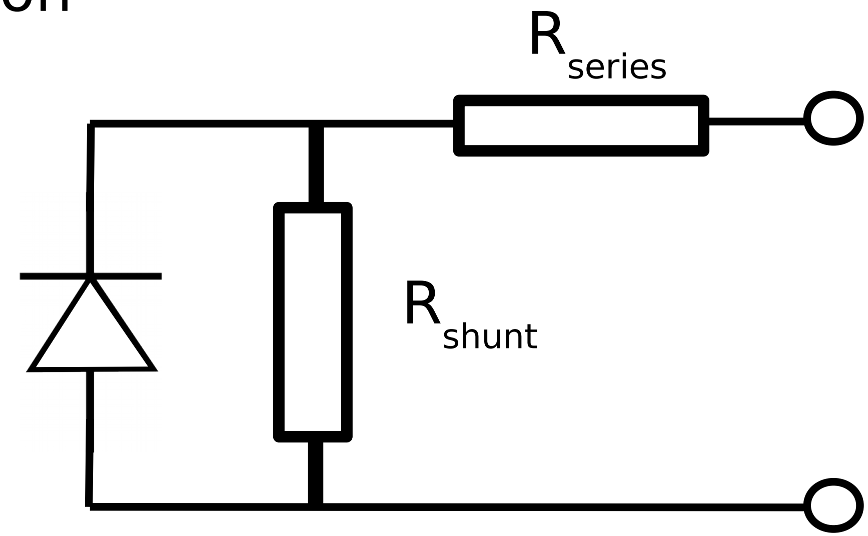
$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$



A better equivalent circuit

- Derive non-ideal diode equation

$$I = I_0 \left(\exp\left(\frac{V}{nkT} \right) - 1 \right) - I_L$$



Dark JV curve

- Derive non-ideal diode equation

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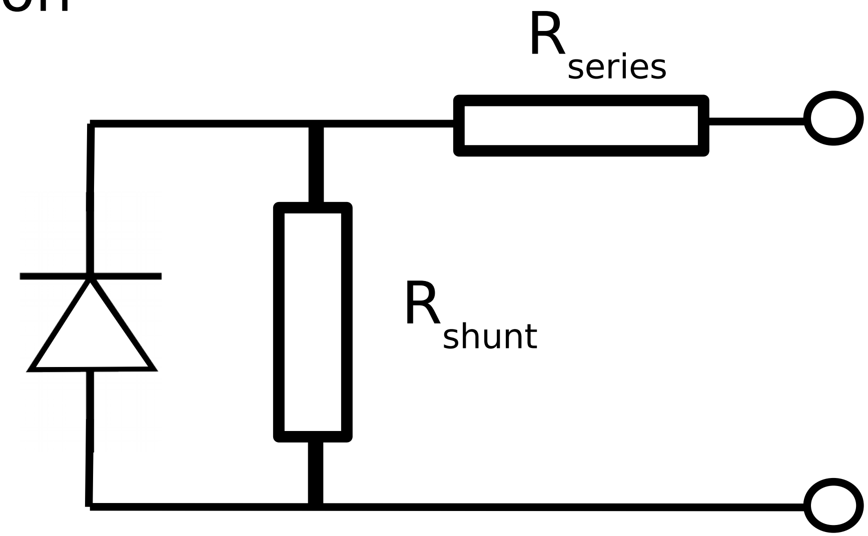

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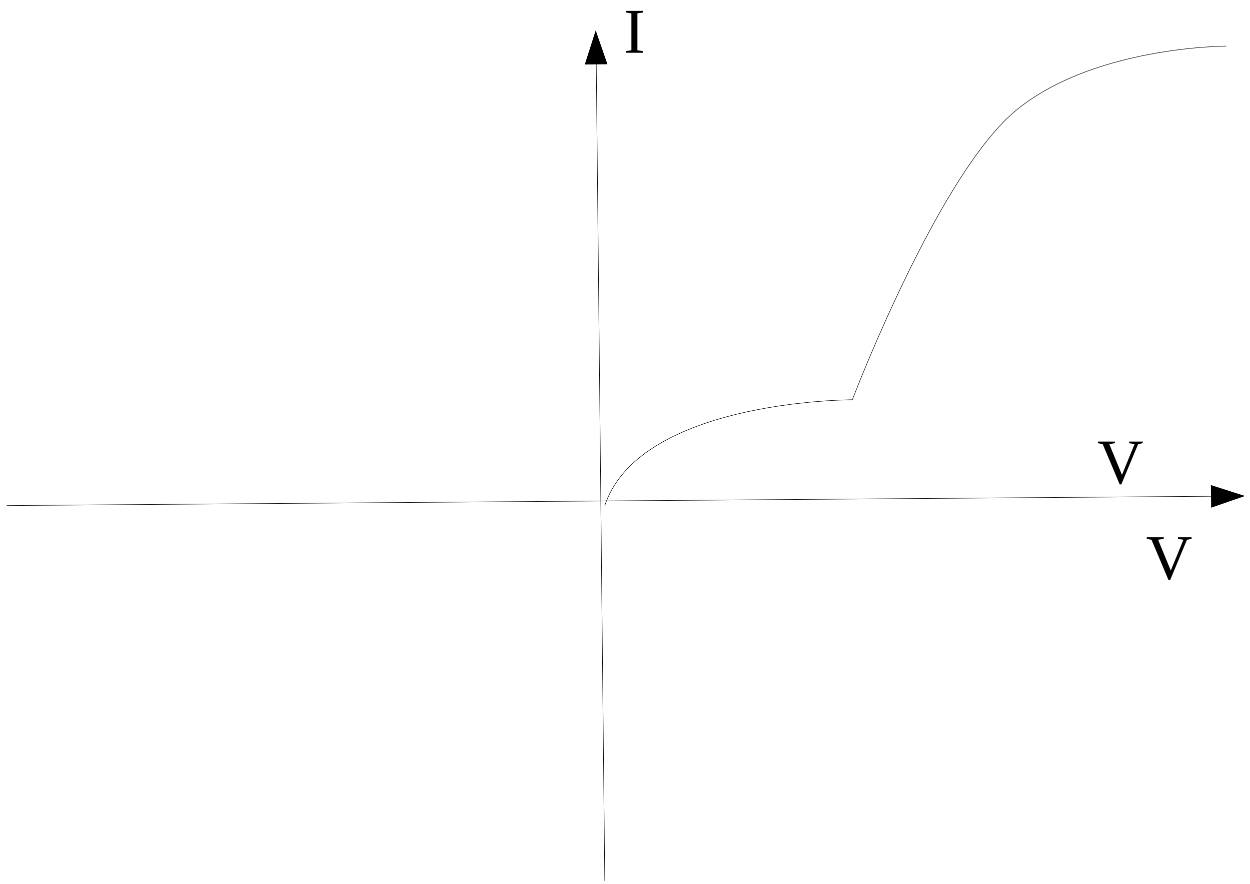

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