Physics 162:

Solar and Renewable Energies

March 4, 2010

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Winter 2010

Lecture 17: Announcements

- *Reading*: Wolfson Chapter 9
- *Homework*: Problem Set 7. Due Today. March 4, 5pm.
- *Final Exam*: Friday Mar. 19, 8-10am. We'll have some sort of review next week (TBA).
- (Email about last lecture's question on solar cell lifetimes)

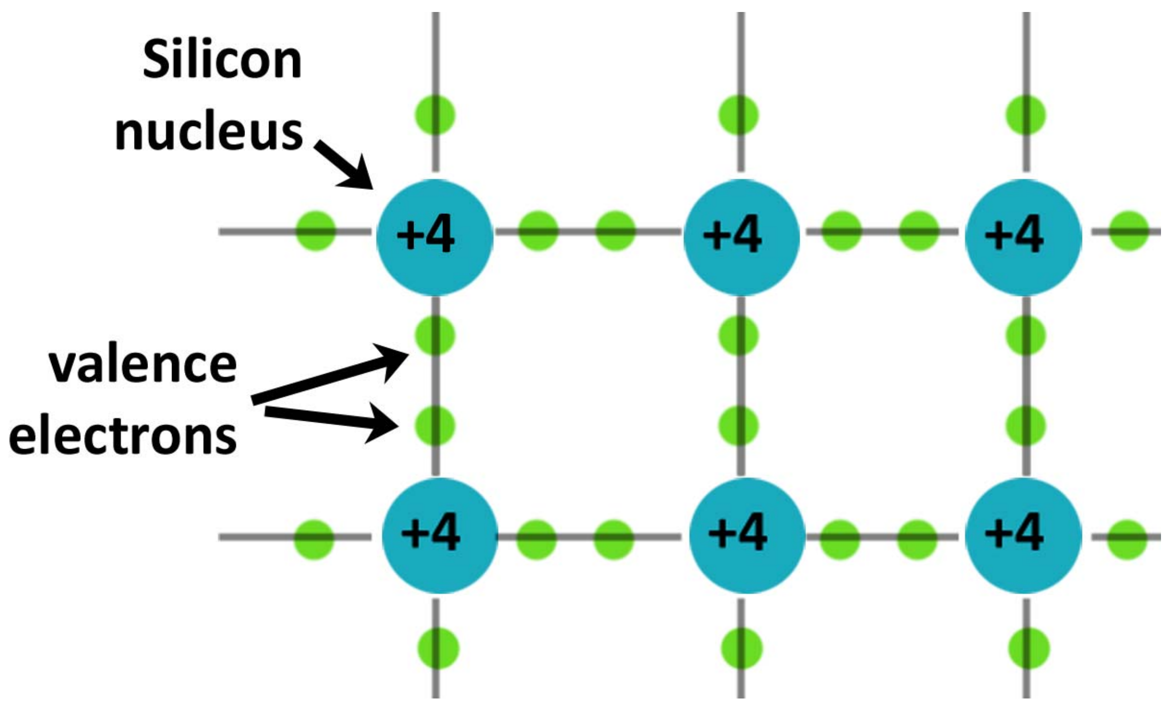
Last time: Photovoltaics

- Photovoltaics ("PV"): Light → voltage
- Semiconductors: "In between" metals and insulators – with a little energy (at least the bandgap energy) electrons can become free to flow, conduct electricity

Last time: Silicon

- Silicon: the most commonly used semiconductor

  4 "valence" electrons



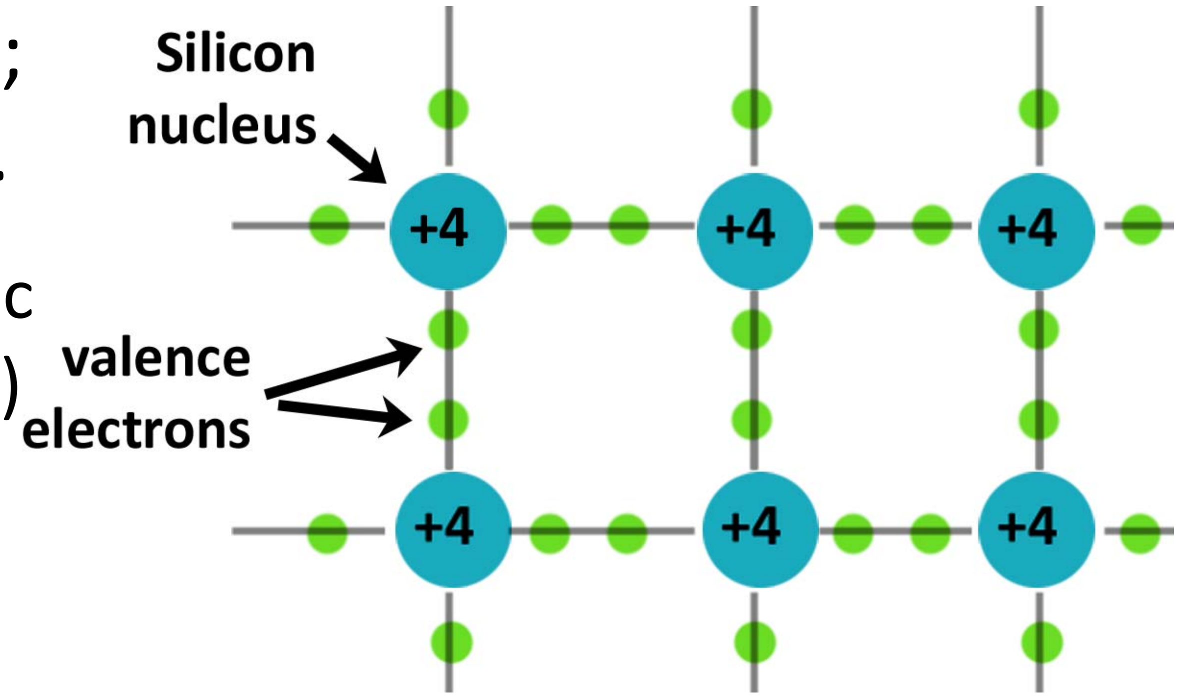
What happens if light hits?

Last time: Silicon + Light

- If the wavelength of the light is large...
  - Photon energy less than $E_{bandgap}$,
  - For Si, wavelength > 1.1×10^{-6} m

- ... nothing happens; light passes through.

(No change to electronic properties; transparent)



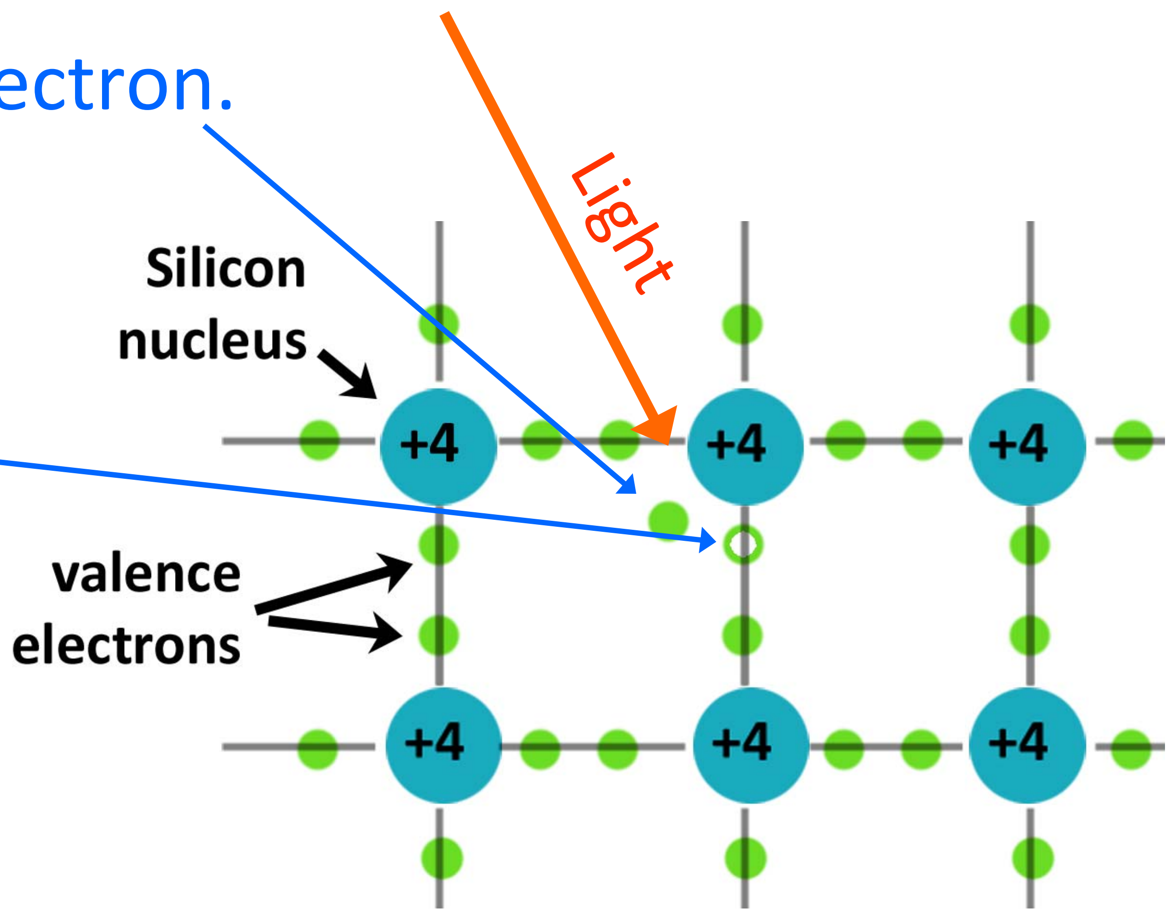
Last time: Silicon + Light

- If the photon energy is greater than $E_{bandgap}$,…

  For Si, wavelength < 1.1×10^{-6} m

- … we "free" an electron.

- And we also create a "hole" – a vacancy that "looks like" a mobile *positive* charge.



Last time: Doping Silicon

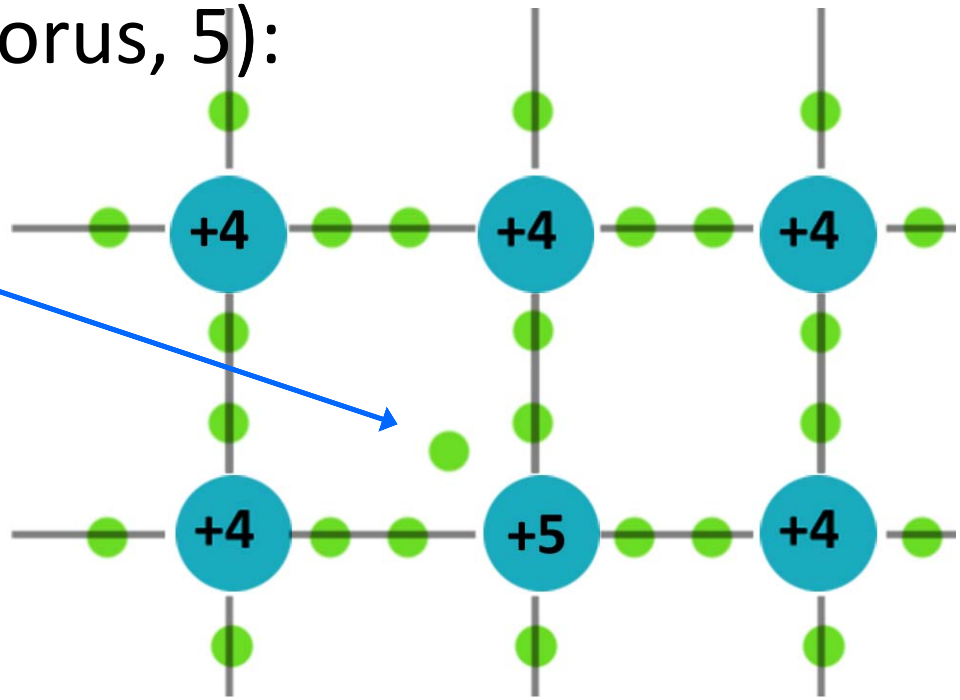
- There's another way to create free electrons or holes: doping. (Adding small amounts of other elements.)
- Doping with an element with more valence electrons (e.g. phosphorus, 5):

Extra *free electrons*

"n-type" semiconductor
(i.e. negative carriers)

Carriers: negative

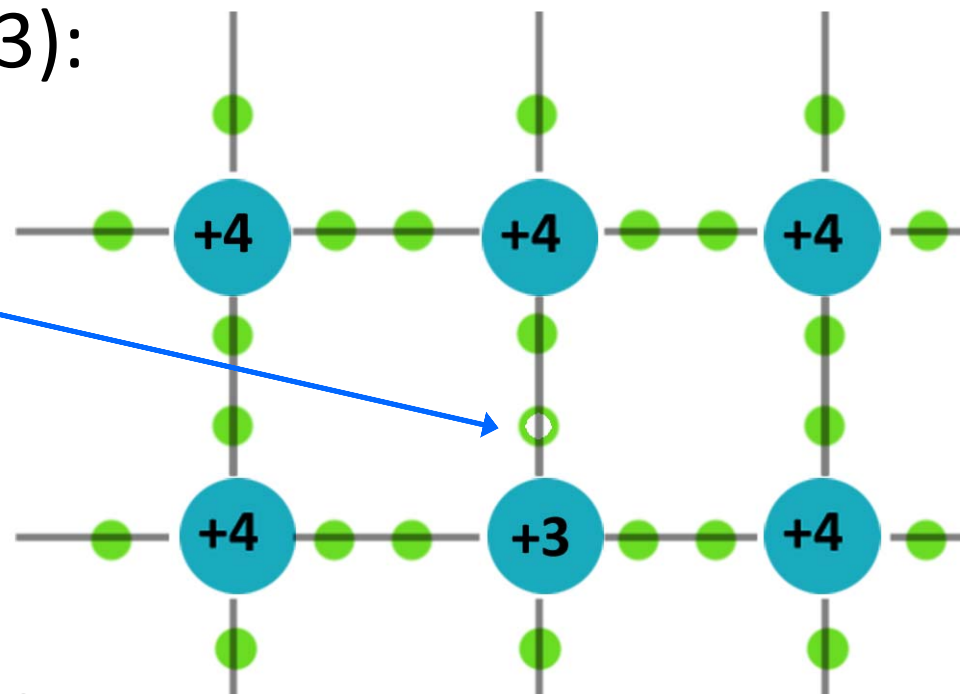
Immobile charges: positive



Last time: Doping Silicon

- There's another way to create free electrons or holes: doping. (Adding small amounts of other elements.)
- Doping with an element with fewer valence electrons (e.g. boron, 3):

Extra *holes*



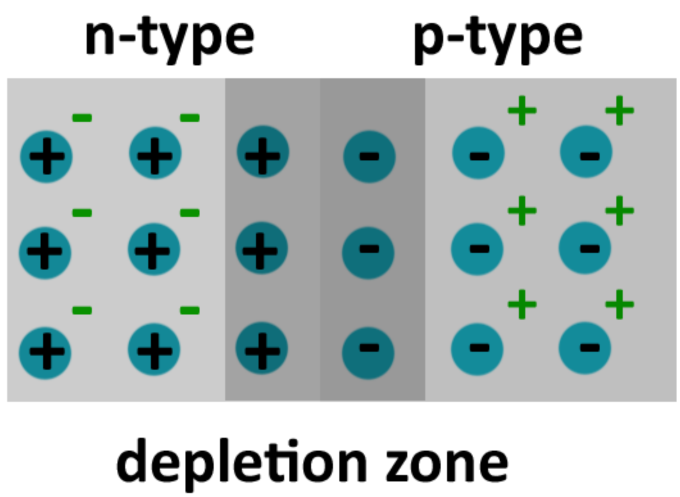
"p-type" semiconductor
(i.e. positive carriers)

Carriers: positive

Immobile charges: negative

Last time: p-n junctions

- The essential structure in a photovoltaic device is a p-n junction.
- After a (very short) while:
  – electrons and holes near the junction diffuse, combine.
  – In the "depletion zone" only fixed +, - charges
- "Like charges repel"
  –The fixed neg. charges stop further electrons from moving right
  –The fixed pos. charges stop further holes from moving left
  –An "internal electric field"



Last time: p-n junctions

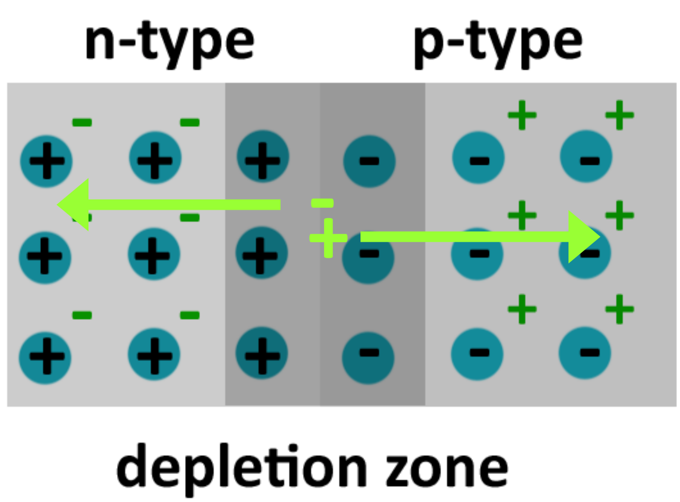
- Suppose a photon (light) with sufficient energy liberates an electron & a hole near the junction.
- Which way does the hole go?

A. left

B. right

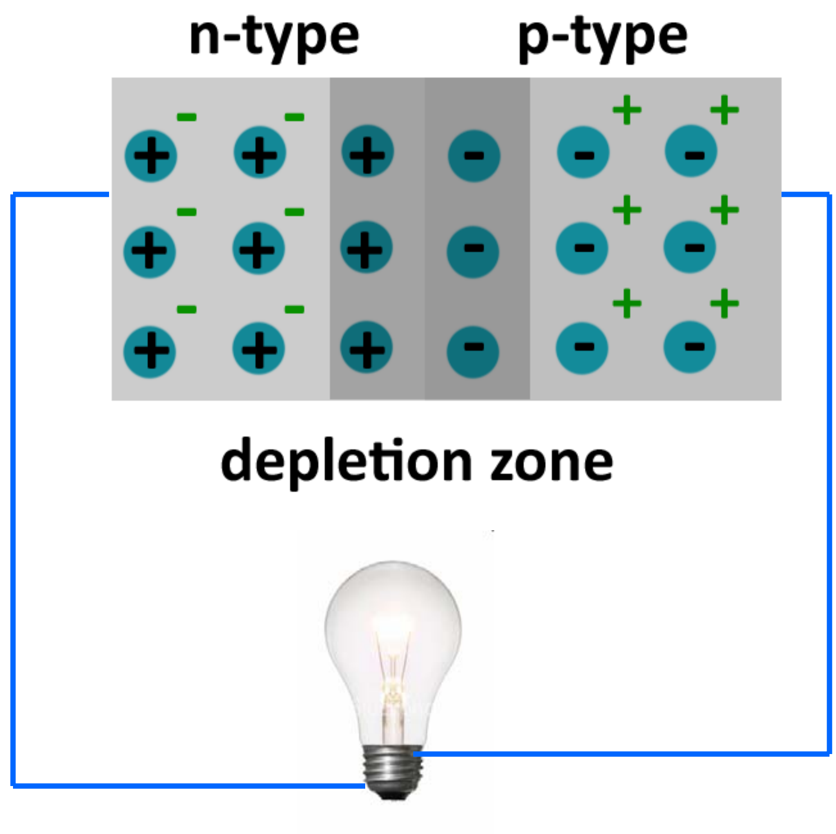
Attracted toward the fixed -'s

... and the electron goes left. They're spatially prevented from recombining...



Last time: photovoltaics

- So we've separated + and – charges, thereby converting our photon's energy to electrical potential energy

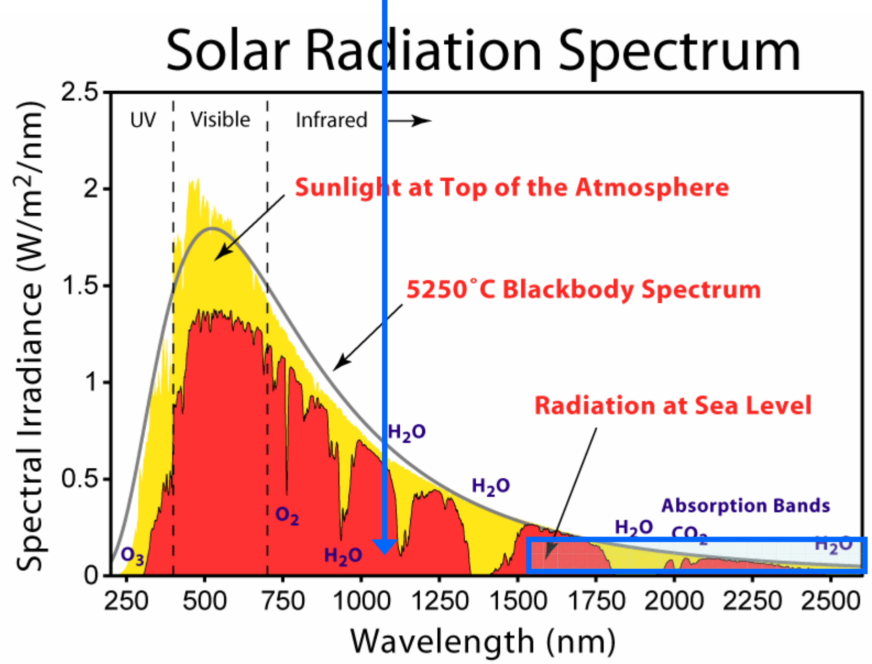


- We could hook this up to a toaster, radio, etc….
- This is how solar cells work!

photovoltaics and efficiency

- Several factors influence solar cell efficiency (i.e. how much of the incident electromagnetic radiation gets converted to electrical energy)
- Solar spectrum: a range of wavelengths of light

Light of this wavelength has energy = bandgap energy of silicon



Boxed range:

A. Low photon energy; can't free electrons & holes

B. High photon energy; lots of energy $\rightarrow$ thermal energy

High wavelength $\leftrightarrow$ low photon energy

photovoltaics and efficiency

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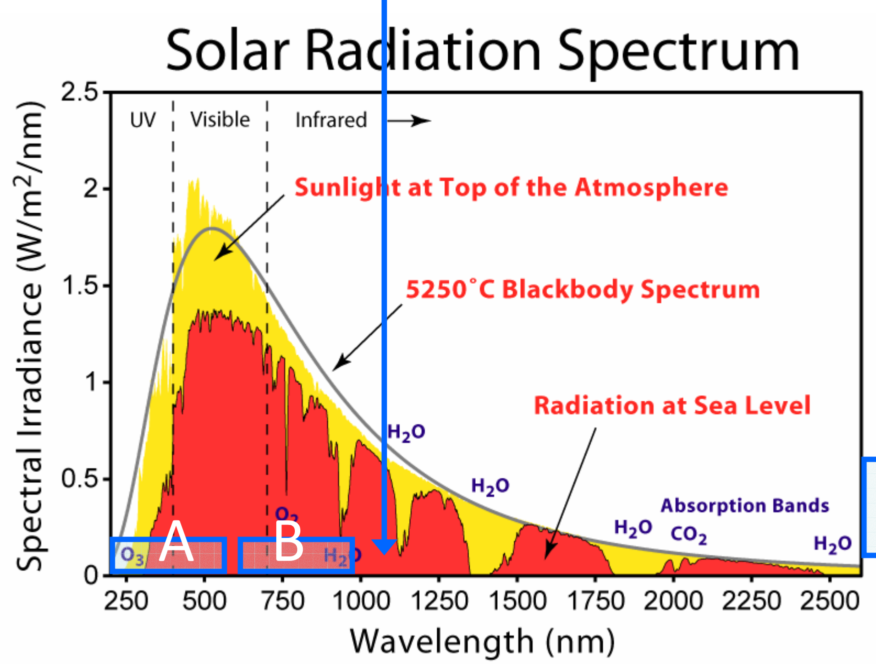


For light in which box is the greater fraction of the photon's energy converted into electrical potential energy?

A

B

We "get" roughly $E_{bandgap}$, no matter what the photon energy is; **A** *has a lot of excess energy that → thermal energy*

photovoltaics and efficiency

- Several factors influence solar cell efficiency (i.e. how much of the incident electromagnetic radiation gets converted to electrical energy)
- Solar spectrum: a range of wavelengths of light
- Recombination due to random thermal motion of electrons, holes
- Fundamental limit (for Silicon) about 33%
- In practice, we've reached about 25% efficiency!
- Even with 10% efficiency...

Land Use

- The world's entire energy needs could be met by these squares:

Nathan Lewis, CalTech

Issues with photovoltaics

- So what's limiting the use of solar cells?
- Cost
- Energy storage requirements [*next week*]

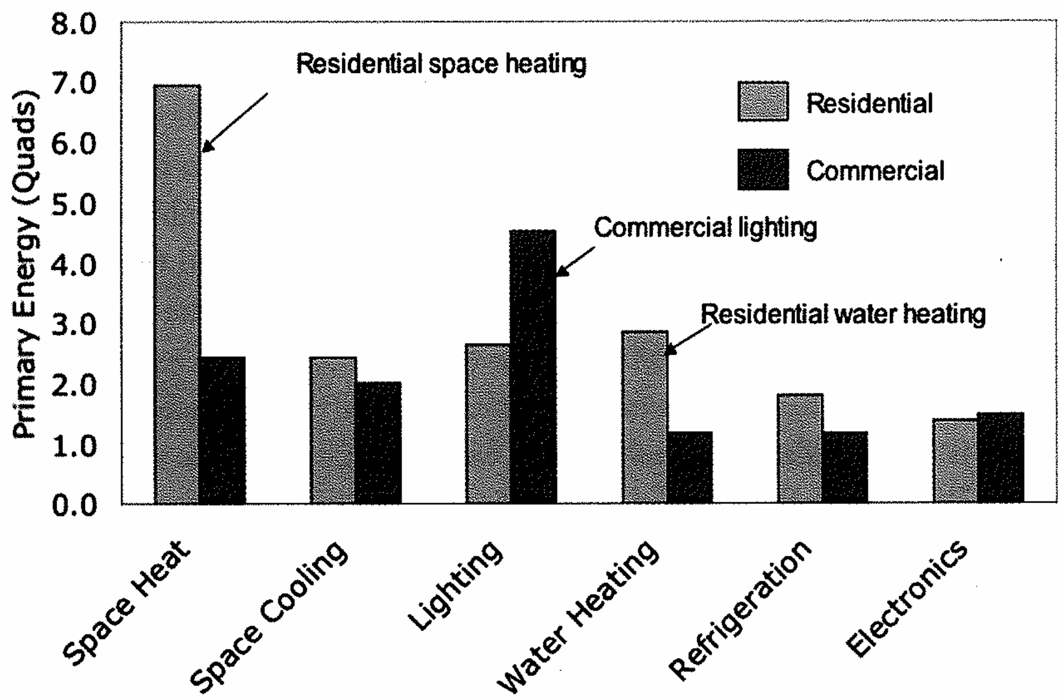
Solar power

- Average insolation roughly ≈ 200 W/m^2.
- What can we do with all this power ?
  - Generate electricity w/ photovoltaic cells
  - Make things warm
  - Store energy as chemical energy (fuels or food)
- Next week: biofuels and energy storage
- Now: Making things warm – important!

Buildings

- About 47% of the residential energy use in the U.S. is for space heating (i.e. heating buildings)
- Another large amount (≈20%): water heating

figure 6.3 Major Sectors of Energy Use in U.S. Buildings



from "Energy for Sustainability," J. Randolph and G. M. Masters (Island Press, 2008)

Solar Heating

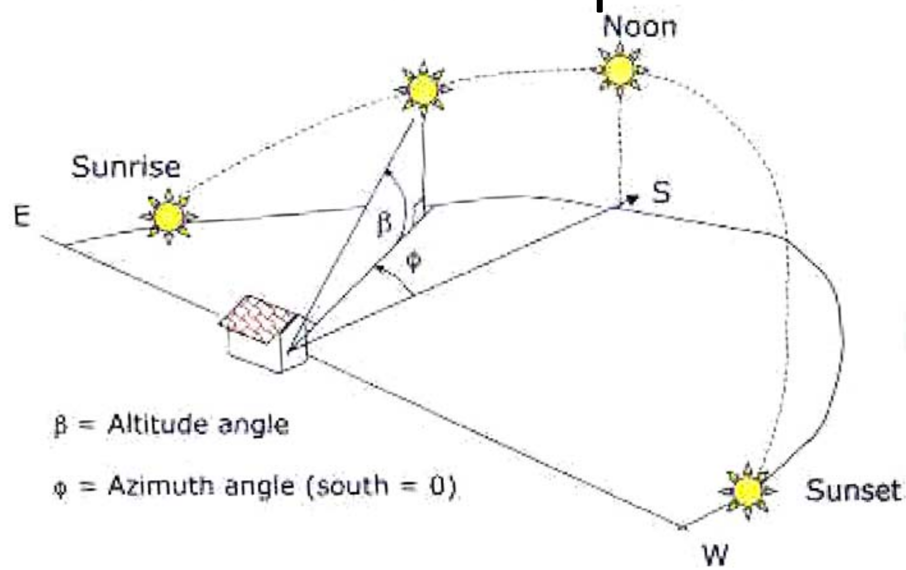
- Solar heating: using solar power for heating
  - "Passive" solar heating (no pumps, fans; just the design of the building itself)
  - "Active" solar heating (pumps, fans)
- Heating and "cooling": We'll discuss the "typical" situation of wanting to maximize solar heating in winter, and avoid too much heating in summer
  - many of the same principles apply to both seasons (e.g. using window coatings that reflect non-visible wavelengths is also good for summer, reducing solar heat flow in while maximizing visible light)

Passive Solar Heating

- Passive solar heating: no pumps, fans; just the design of the building itself
- Several important aspects
- Building orientation: South-facing windows!
  - The Earth: tilted (23.5°) relative to the orbital plane
  - Sun rises: ≈East
  - Sun sets: ≈ West
  - In N. hemisphere* sunlight is from the South

* for lat. > Tropic of Cancer, 23.5°

Illustration: from "Energy for Sustainability," J. Randolph and G. M. Masters (, 2008)



Passive Solar Heating

- Building orientation: South-facing windows!
  - The Earth: tilted (23.5°) relative to the orbital plane
  - Sun rises: East
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  - In N. hemisphere*
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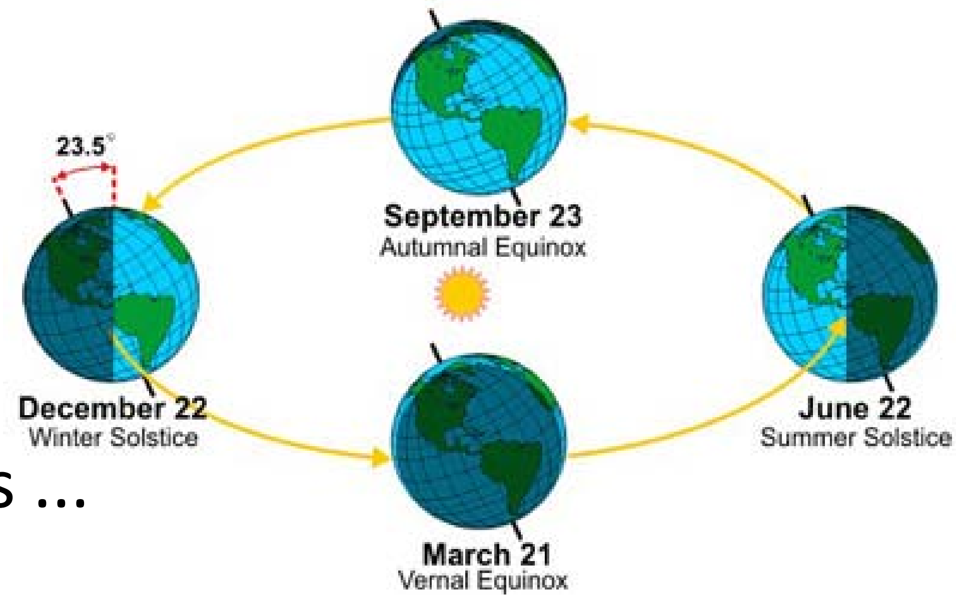


At midday in winter, the sun is ...

A. lower

B. higher

try this with a flashlight and a ball

... in the sky than in the summer

* for lat. > Tropic of Cancer, 23.5°

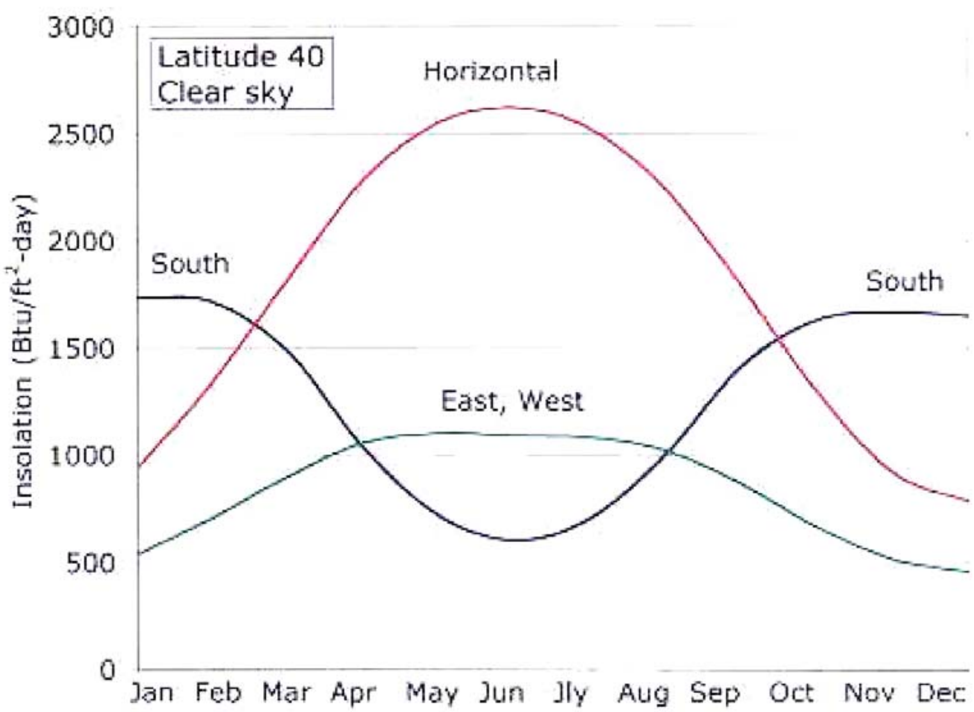
Illustration: howstuffworks.com

South-facing windows

- South-facing windows: maximal sunlight (in the N. hemisphere).
- What about overheating in summer?
- Seasonal variations in the sun's position in the sky offer simple mechanisms for allowing maximal sunlight in *winter*, reducing midday sun in *summer*
- (1) [Explain the following graph (black)]

South-facing windows

- [Explain the following graph (black)]



Less insolation for S. window in summer because:

A. sunlight is less intense

B. the sun is higher in the sky

C. more sunlight is reflected

(i.e. sunlight is closer to perpendicular to the window in winter)

So we "automatically" get the behavior we want: less heat in summer

South-facing windows

- South-facing windows: maximal sunlight (in the N. hemisphere).
- What about overheating in summer?
- Seasonal variations in the sun's position in the sky offer simple mechanisms for allowing maximal sunlight in *winter*, reducing midday sun in *summer*
- (1) Sun's position intrinsically "steeper" in summer
- (2) overhangs are easily designed to block the appropriate angles

Overhangs

- (2) Overhangs designed to block the appropriate angles: block "steep" summer midday sunlight; allow "shallow" winter sunlight
- South-facing windows: Helps maximize solar gain in winter when you want it; easy to reduce in summer

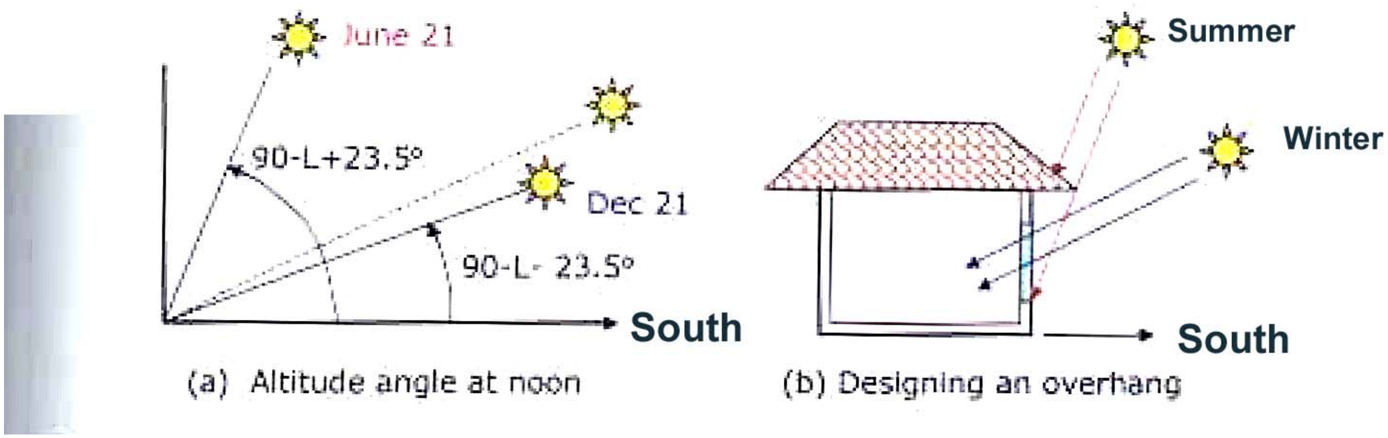


Illustration: from "Energy for Sustainability," J. Randolph and G. M. Masters (2008)

Passive Solar Heating

- Passive solar heating: important aspects
- Building orientation: South-facing windows!
- High-*R* insulation – retain solar-generated heat
- Distribute energy through the building – e.g. floors with high thermal conductivity
- "Store" thermal energy, for when the sun isn't shining – materials with high heat capacity (specific heat)
  - i.e. it takes a lot of energy to raise or lower T; takes a long time to cool down
  - An object with this function is called a Thermal Mass

Passive Solar Heating

- Building orientation: South-facing windows!
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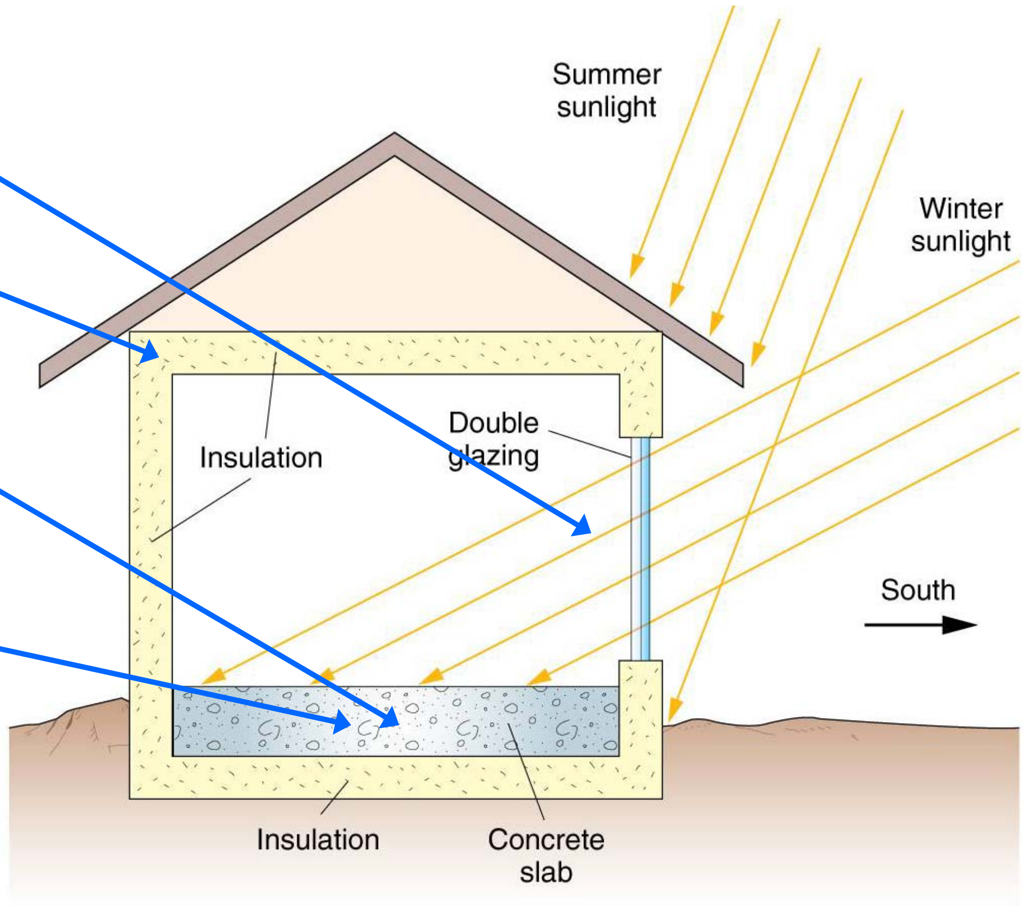


what material properties → desired functions (a good exam question in here...)

Active Solar Heating

- **Active** solar heating: pumps or fans to move solar-heated fluids from solar collectors → energy storage medium → where it's needed in the building
- Advantages (compared to passive)
  - More compact; flexible placement – fits better with conventional architecture
  - More efficient (devoted to energy collection, rather than having to serve as structural elements)
  - Can achieve higher temperatures

Active Solar Heating

- **Active** solar heating: pumps or fans to move solar-heated fluids from solar collectors → energy storage medium → where it's needed in the building
- Disadvantages (compared to passive)
  - More complex. moving parts
  - Requires external (electrical) power
  - Cost

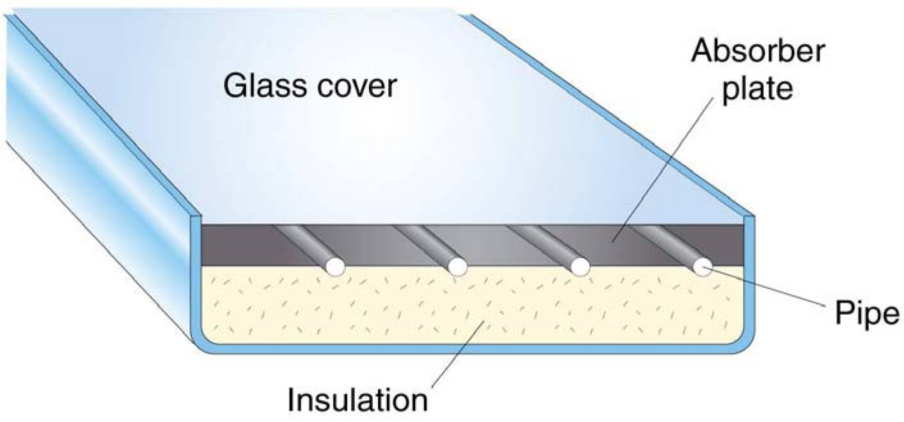
Solar Collector

- The flat-plate collector. Simple, popular. Parts:
  - Absorber plate. low-ε or high-ε ?

A. low

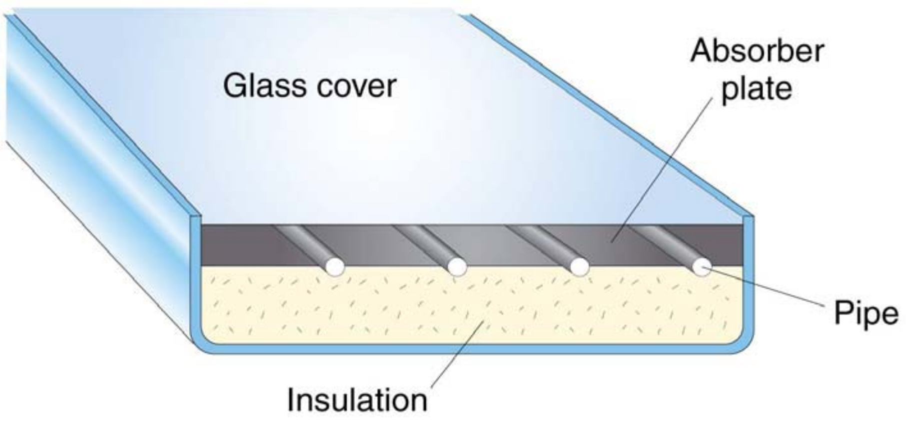
B. high

Black: absorb sunlight; $\varepsilon \approx 1$



Solar Collector

- The flat-plate collector. Simple, popular. Parts:
  - Absorber plate. Black.
  - Insulation at the back side, to prevent heat loss
  - Pipes, through which the fluid (e.g. water) flows; the fluid warms due to the contact between the pipes and the plate. (What heat transfer mechanism is this? What sort of material would you want the pipes to be made of?)



Solar Collectors for Hot Water

- Hot water heating: ≈20% of the energy use in a typical U.S. home.
- Solar water heating is well-suited to providing this: "viable in almost any climate."

Author's system, supplies 90% of hot water in "cloudy Vermont"

FIGURE 9-13

Solar Collectors for Hot Water

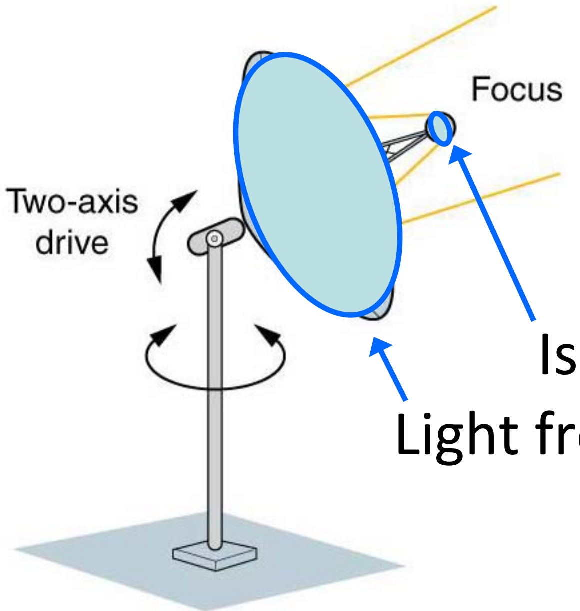
- History
  - Quite popular ≈100 years ago. Wiped out by cheap fossil fuels.
  - A resurgence in the 1970's and early 1980's. Misc. "practical" and economic problems, including "some really ugly installations"
  - Present: again a resurgence, due to better technology, renewed focus on energy issues.
  - Present: about 0.1% of U.S. homes (very small!), more swimming pools. Australia: 3% of homes. Spain: since 2000, required on all new constructions. Israel: all residences.

Solar Power → Electricity

- Solar heating is great, but we also love electricity
- Can we use solar power to generate electricity? Yes. Two ways:
  - direct conversion of electromagnetic radiation to electrical energy (photovoltaics – last lectures)
  - thermal energy + heat engine (today's lecture)

Solar Thermal Power

- We can focus sunlight (with a lens or mirror). Concentrated sunlight → high temperature; use this to run a heat engine + generator → electricity.
- This is referred to as "solar thermal power"

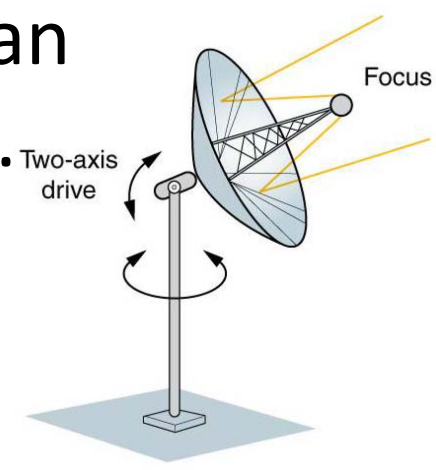


Is concentrated to *this* area

Light from *this* area

Solar Thermal Power

- The sun: T_{sun} = 5500K
- The region of concentrated sunlight: how hot can it be? At most T_{sun} = 5500K.
- Why? The hot region is *also* emitting thermal radiation – everything does. It is sending energy *back to the sun*. If its *T* is greater than T_{sun}, it emits more heat than it receives, so its T will drop until $T=T_{sun}$. "Thermal Equilibrium"



Solar Thermal Power

- The sun: T_{sun} = 5500K
- The region of concentrated sunlight: how hot can it be? At most T_{sun} = 5500K.
- Pretty hot! Carnot efficiency

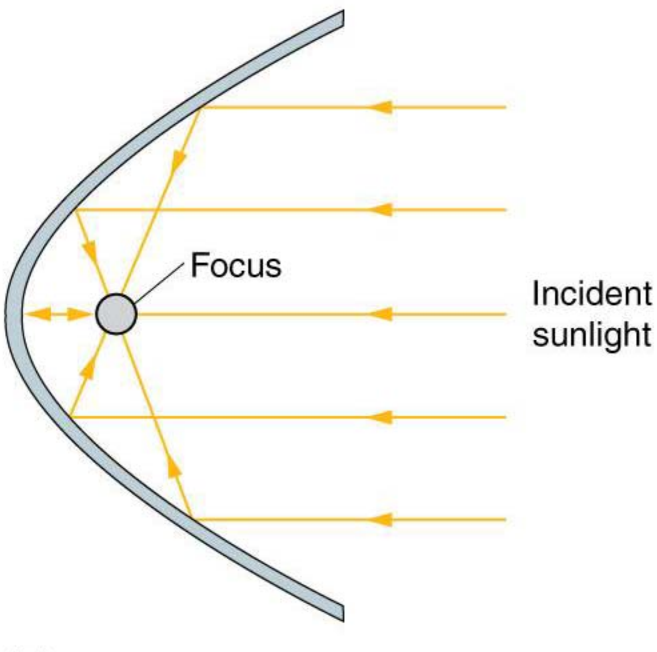
$$e_{max} = 1 - \frac{T_C}{T_H} = 1 - \frac{300}{5500} \approx 0.95 \qquad !$$

For solar thermal power we can't actually use such hot temperatures (engine materials would melt) – use lower temperatures (less concentrated sunlight), e.g. 600 °C

Solar Thermal Power

- How to concentrate light?
- Lenses. In practice, no: very hard to make large lenses.
- Mirrors! The shape of the mirror determines its focusing. [demo]

- The sun: far away (10^{11} m). The sun's rays are nearly parallel.
- What mirror shape focuses parallel rays to a point? A parabola. (Geometry)

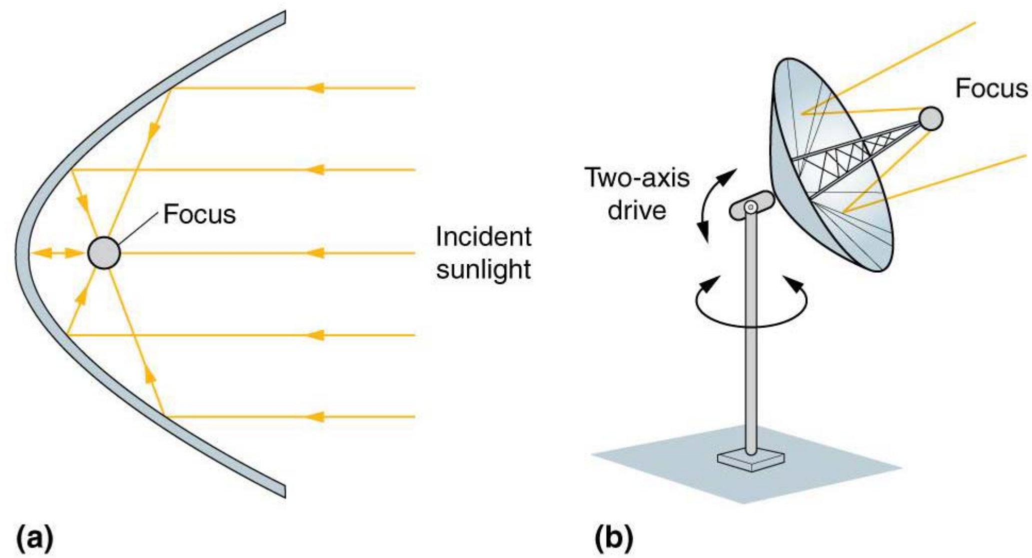


(a)

Solar Thermal Power

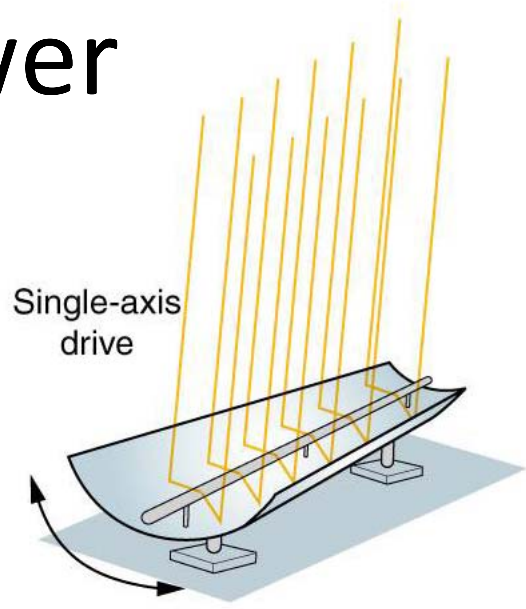
- Imagine "rotating" a parabola → parabolic dish. The ideal structure for collecting EM radiation at a point. (TV signals, radio telescopes, etc.)

Disadvantage: need to point at the sun, so need complex, expensive two-axis steering



Solar Thermal Power

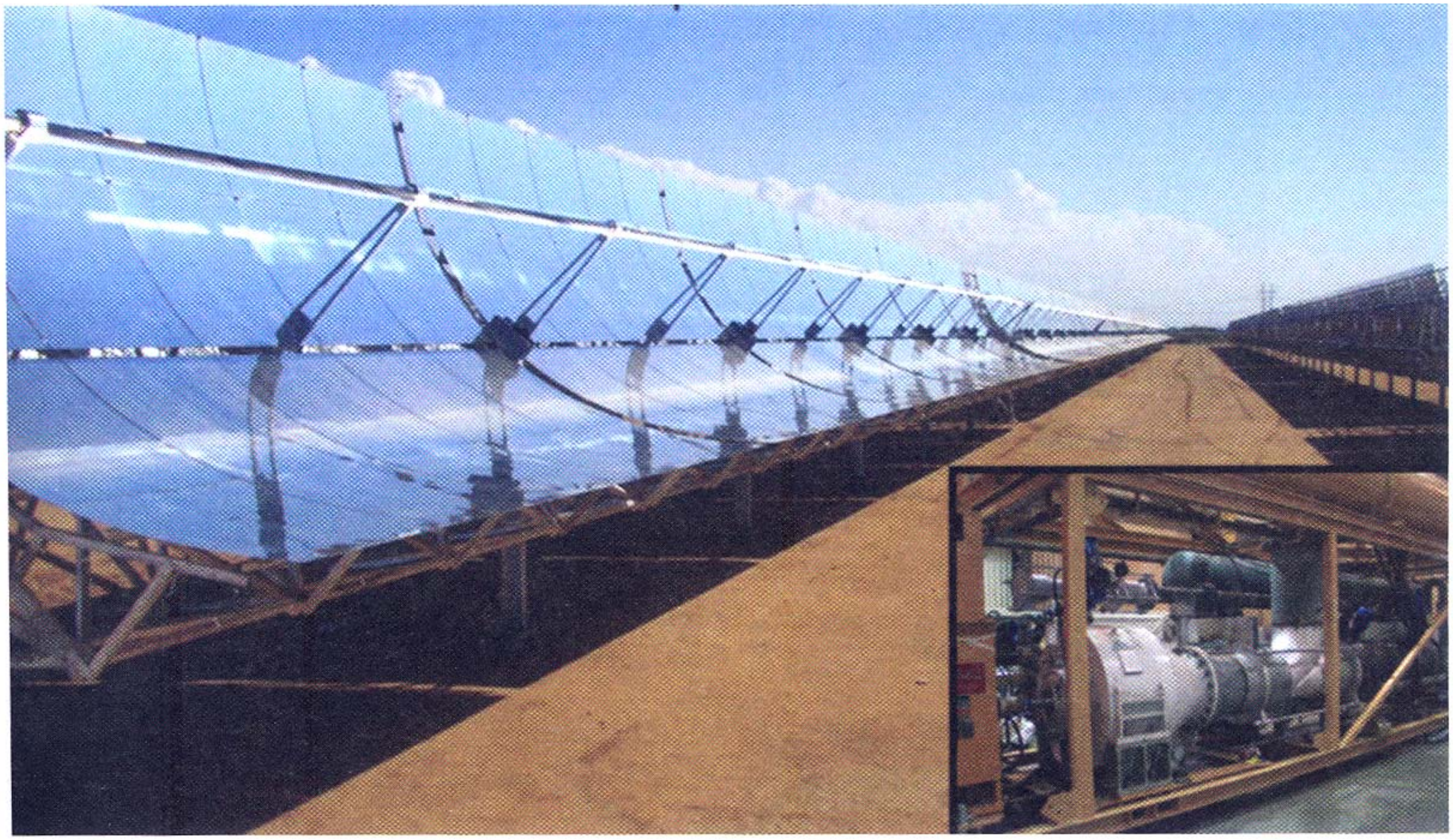
- Not quite as good, but simpler and low-cost: parabolic trough.
  - Focuses to a line, rather than a point, so less intense.
  - Only need to track the sun in one direction: single-axis steering.



(c)

Solar Thermal Power

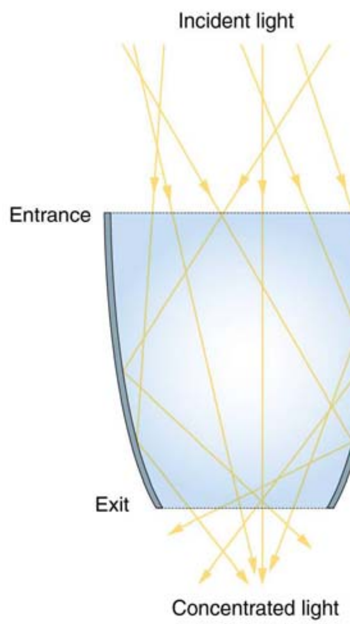
- Not quite as good, but simpler and low-cost: parabolic trough.



The parabolic trough and generator for the APS 1-MW Saguaro plant outside of Tucson.

Solar Thermal Power

- Not quite as good, but simpler and low-cost: parabolic trough.
- Other geometries: parabolic funnels
  - concentrate light from many angles.
  - Not focused, so less concentrated that a true parabolic mirror; but little or no tracking is necessary



- Heliostats: Many small, computer-controlled mirrors that together act like one large mirror

Solar Thermal Power

- Heliostats:

Spain: PS10 (shown). 624 $120m^2$ mirrors focus light to tower. 11 MW, completed 2007. Part of a series; expected 300 MW by 2013

www.solarpaces.org

First significant implementation: "Solar One" (Calif.): 1982-1988; 1800 heliostats; 10 MW power.

Presently none in U.S.

Solar Thermal Power

- Concentrated sunlight; thermal energy; run a heat engine. How? Either...
  - Heat fluids, pipe them to the heat engine.
  - Place the heat engine directly at the focus. (Some engine types, e.g. the Stirling Engine we've seen that runs using *external* temperature differences, are well-suited to this.)