Conceptual Modeling as Pedagogy

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Abstract

The teaching of facts is often criticized because many facts tend to change with time, they can be forgotten, and because remembering facts does not train the mind to think or reason. In contrast, explicit instruction in the process of model building, whether physical, mathematical, computer or conceptual, requires thinking. It provides students with an extensible framework in which to integrate concepts and build new knowledge, setting the stage for course content mastery as well as lifetime science learning. In conceptual modeling students are taught to: (1) ask a question, (2) refine the question, (3) format the problem, (4) identify contributing components, (5) define a system with the central problem, the components, and the connections or relationships among all of the system's parts by depicting the system with a diagram, (6) identify the information that the system will require to solve the problem, (7) step through the system toward a trial solution to the problem, (8) refine the components and connections as required (add, delete , or combine), (9) go back to 7 or reach your solution. In upper level classes the conceptual system can be migrated to a computer model using STELLA (http://www.iseesystems.com). This will provide a rigorous test of the conceptual models students have developed.

This paper provides examples of how modeling is employed as a pedagogic tool at several levels in the curriculum. The examples start with simple conceptional models with simple drawings of the problems for the lower levels; for the more advanced levels the problem is treated in greater detail and a formal system diagram is introduced; at the upper levels, the problem is solved using a computer.

Question, Refine, Format

What determines the temperature of the planets?
(Too broad; refine.)

What determines the temperature of Earth?
(Good; now format.)

Energy from the Sun reaches the Earth.

Some of this energy is reflected.

The energy absorbed by the Earth warms the Earth.

The Earth radiates infrared energy into space.

(More questions?)

What part of the Earth is warmed?

How much power does the Earth radiate?

How is the temperature determined?

Components, Relationships

We need to know:

1. Energy flux from the Sun
(Energy flux = energy/area time).

2. Distance to the Sun.

3. Size of the Earth.
(We will need both the cross-section area and the surface area.)

4. Power reflected by the Earth.
(Albedo is the % power reflected.)

5. Power absorbed.
(The part not reflected.)

6. Power radiated by Earth.

Information

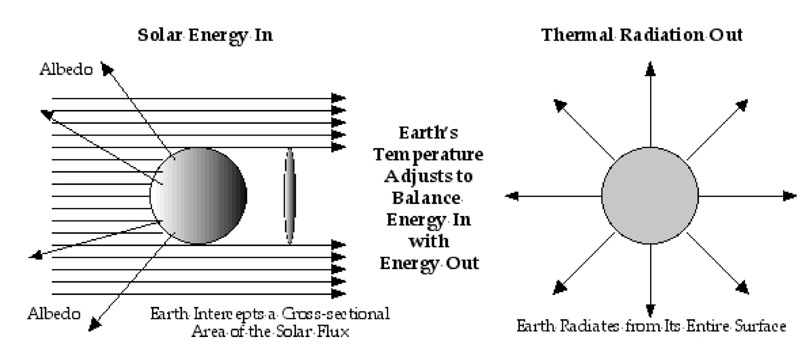
We can combine 1 & 2 by using the solar constant.
(Solar constant is the power at the Earth's average distance from the Sun = 1376 Watts/m^2)

Albedo = 30%

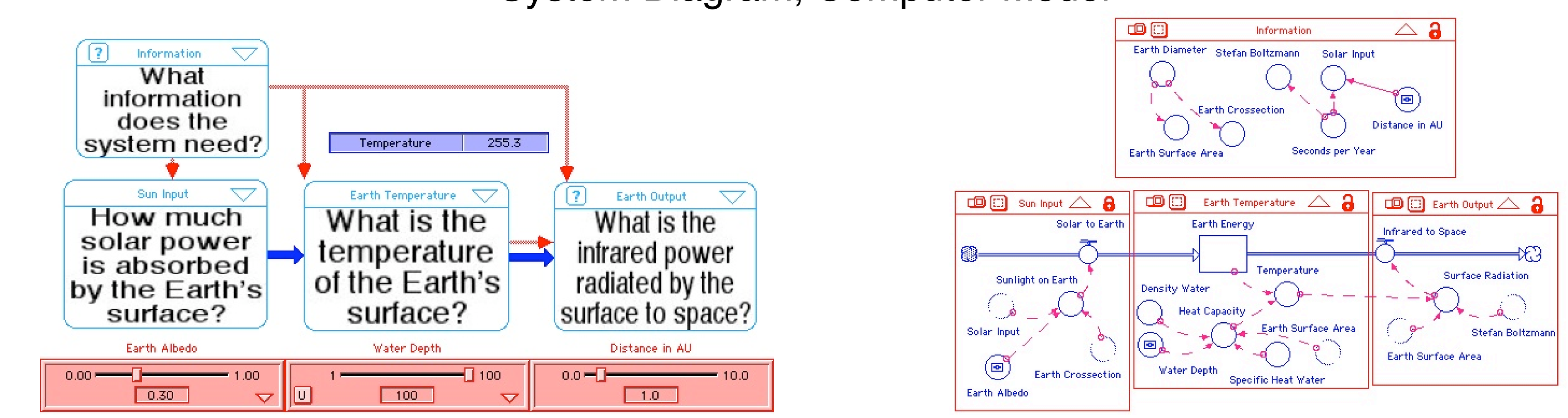
The Earth radiates to space as a "blackbody," which is power/m^2 = σT^4, this is a very strong temperature function. (σ is the Stefan-Boltzmann constant = 5.57×10^{-8} W/m^2 K^4)

We will store the Earth's energy in an ocean covering the entire surface (ocean model) and 100 m thick (the mixing depth). (We will learn from the model that the temperature does not depend upon the depth.)

Conceptual Model



System Diagram, Computer Model



On the left is the overview system diagram; it is a simplified version of the system diagram for the computer model on the right. The wide blue arrows show energy flows; the thin red arrows show information transfer. The blue rectangle (left center) gives the Earth's effective temperature computed by the model. The three red rectangles are "sliders" that allow a user to explore the effect of changing the model parameters.

The Earth's surface seems much warmer than the 255 °K (-18 °C or 0 °F) found in the example above. What is going on?
(Greenhouse warming. Now ask another question)

How does the greenhouse effect warm the surface?
(Good question; and ...?

What are greenhouse gasses?
(Good. And ...?)

How does changing the greenhouse gases change the warming?
(Good. Anything else?)

Do greenhouse gasses stay in the atmosphere forever?
(No, but rephrase your question.)

How long do they stay in the atmosphere?
(Good; let's proceed)

We need to know:

Everything from the above example.
(Actually, we can modify the model above by adding an atmosphere.)

How the atmosphere and surface interact.
(The atmosphere completely surrounds the Earth's surface.)

How the atmosphere absorbs and emits radiation.
(We will need the appropriate radiation equations.)

Which gasses are important and what is their lifetime is in the atmosphere.

How much radiation leaves the Earth system, and how much comes from the surface, and how much comes from the atmosphere.
(The model should tell us the answer.)

The atmosphere forms a shell around the Earth; passes visible solar radiation down to the surface, but it absorbs upward infrared radiation from the surface.

The atmosphere warms and emits infrared radiation both downward to the surface and upward to space.

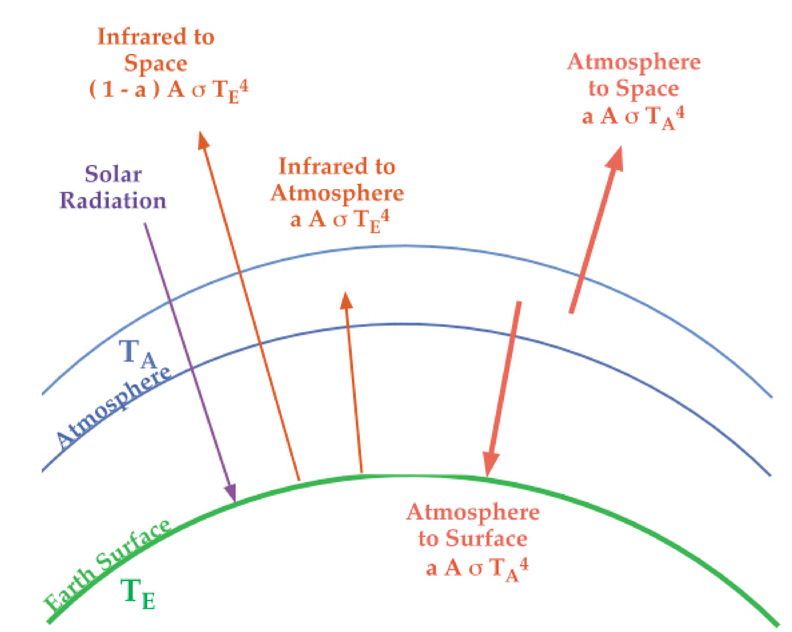
The surface and clouds radiate as "blackbodies"; the atmosphere (gases) radiate as "graybodies" = power/m^2 = $a\sigma T^4$.

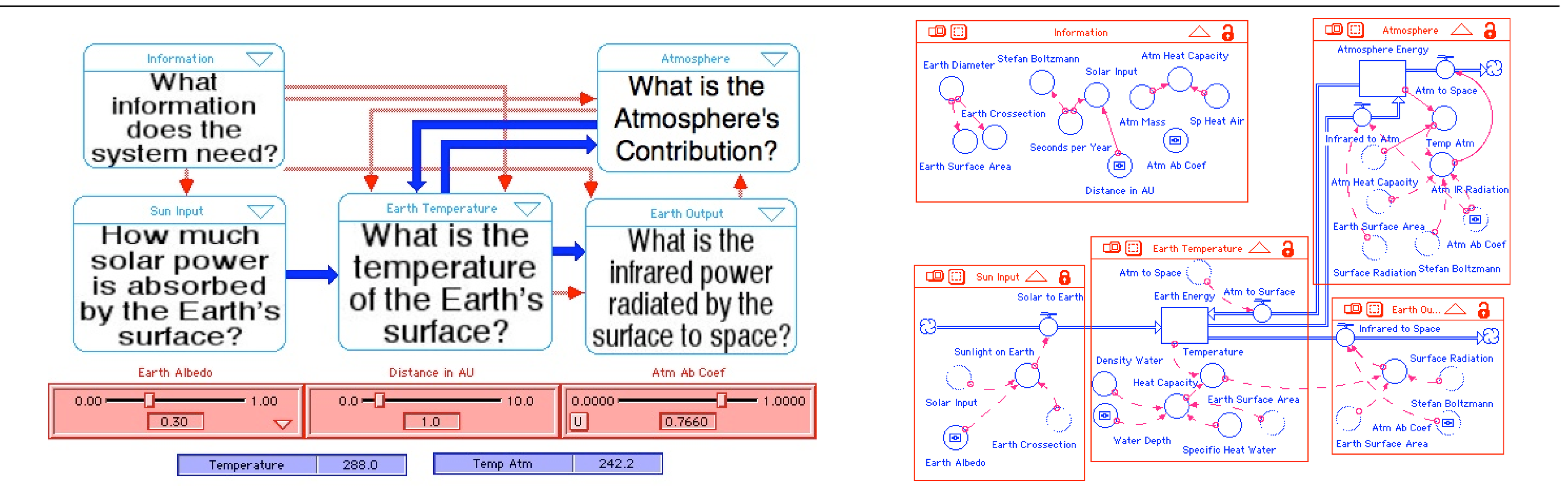
a is the absorption coefficient with a value between 0 and 1; it is the fraction of the infrared radiation absorbed. The emission co-efficient is equal to the absorption coefficient; it is the fraction of the blackbody radiation that is emitted by greenhouse gasses.

The major components of air, nitrogen and oxygen, are not greenhouse gasses.

The major greenhouse gasses (lifetimes) are water vapor (~a week), carbon dioxide (~100 years), and methane (~10 years).

The greenhouse gasses add atmospheric radiation to the solar radiation on the surface increasing the surface temperature.





On the left is the overview system diagram; it is a simplified version of the system diagram for the computer model on the right. The wide blue arrows show energy flows; the thin red arrows show information transfer. The blue rectangles (lower left) give the surface temperature and the atmosphere temperature computed by the model. The three red rectangles are "sliders" that allow a user to explore the effect of changing the model parameters. In particular, increasing the greenhouse gasses increases the absorption coefficient (Atm Ab Coef).

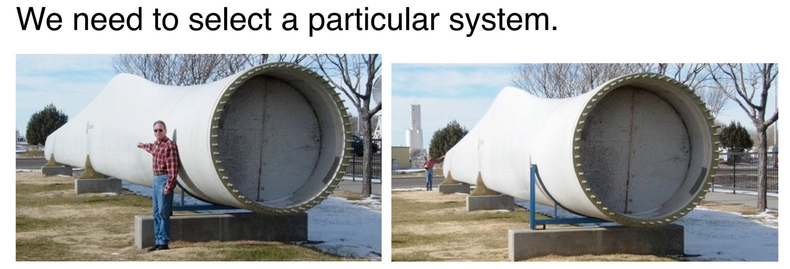
How do wind generators work?
(Refine; be more specific.)

How much energy is available in the wind?
(Good; expand.)

With what efficiency can the energy be extracted?
(Good ; let's explore these questions.)

We need to compute the energy flux in the wind as a function of wind speed.

We need to select a particular system.

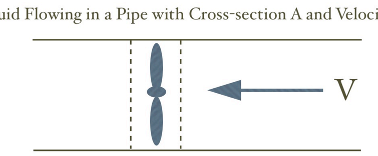


The size will be important; see above photos.

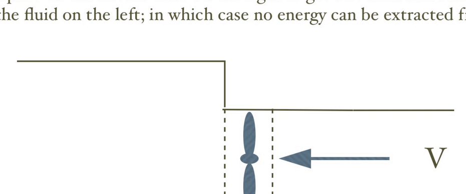
The engineering design is also important.

The dynamics of the flow interacting with the wind generator are important.

Fluid Flowing in a Pipe with Cross-section A and Velocity V



If we place a device in the flow as depicted above to extract energy from the flow, then the fluid on the left is moving more slowly than the fluid on the right; there is insufficient space on the left for fluid on the right to go. The fluid must slow to the velocity of the fluid on the left; in which case no energy can be extracted from the flow.



The problem is solved by increasing the cross-sectional area on the left; now the fluid can move more slowly but still conserve the mass flow.

From hydrodynamic theory we find that

Wind Mass Flux = ρV kilograms/m^{2}s

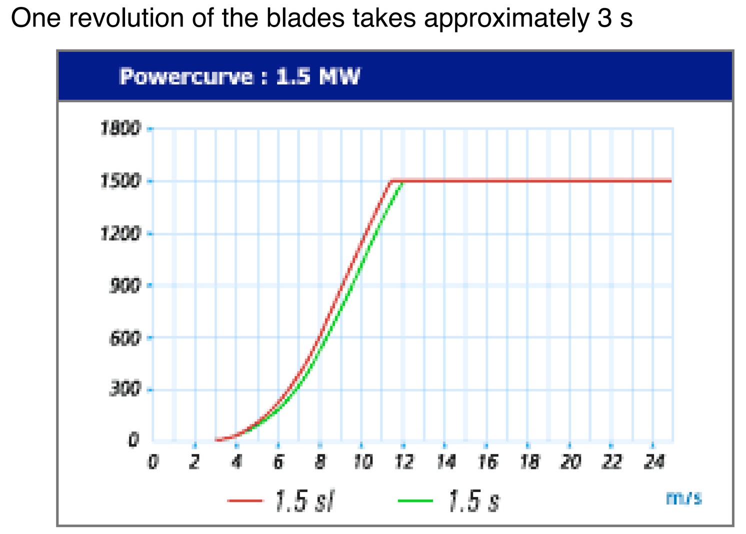
Wind Energy Flux = $\frac{1}{2} \rho V^3$ Joules/m^{2}s

The wind generator featured in the photos is a General Electric product; their web site < www.gewindenergy.com> provides much information on this system.

Rated power output = 1.5 megaWatts (at V = 12 m/s)

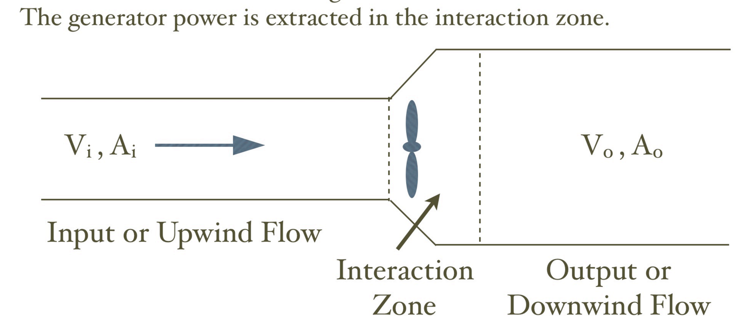
Area swept out by the 3 blades = 4657 m^2

One revolution of the blades takes approximately 3 s



The powercurve flattens above 12 m/s because the mechanical and electrical systems are not designed for greater output. It is turned off by rotating the blades away from the wind above 25 m/s to prevent damage.

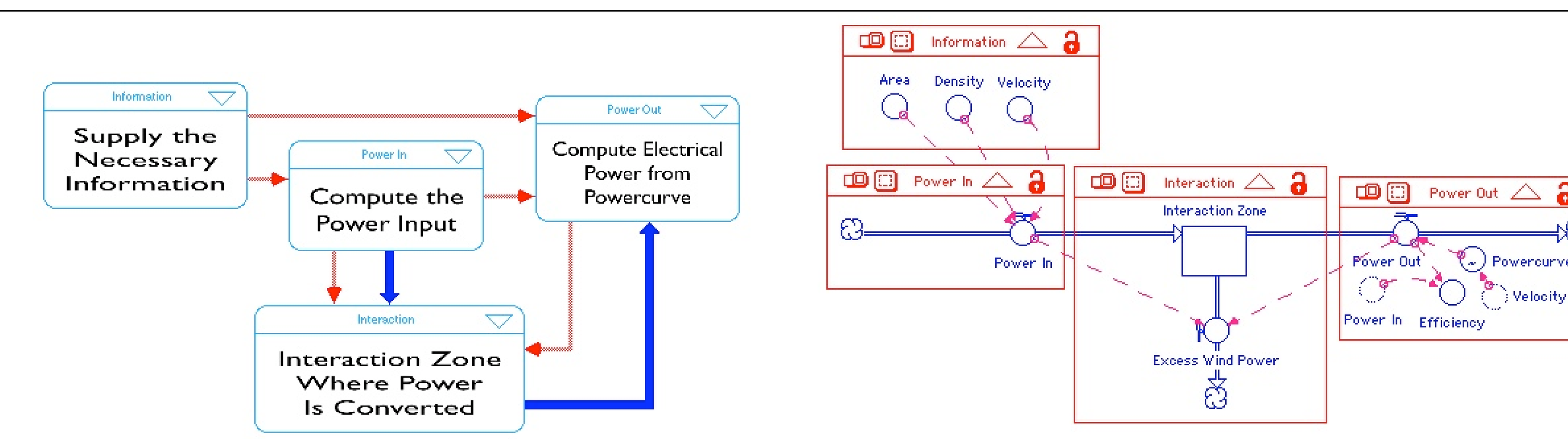
If we extract energy from the wind, the outflow will slow and will require a larger cross-sectional area in order to conserve the mass flow. The drawing below depicts the wind generator interaction. Some of the wind is forced to go around the blades and cannot be used. The generator power is extracted in the interaction zone.



Conservation of mass flow: $A_i \rho V_i = A_o \rho V_o$
$V_o < V_i$ thus $A_o > A_i$

The electrical power output for these large systems is determined primarily by the engineering of the system for a given wind environment and integration of the output into the electrical grid. This system is optimized for a mean wind environment around 12 m/s (27 mi/hr). Using the powercurve on the left we need only to know the wind velocity to compute the power output.

Note: Because each generator slows down the flow somewhat there is no advantage in placing the generators close together in a wind energy array; see the in the photo on the far left. Also, using more than three blades offers no energy advantage, but it poses a weight cost.



On the left is the overview system diagram; it is a simplified version of the system diagram for the computer model on the right. The wide blue arrows show energy flows; the thin red arrows show information transfer. Below is the graphical output of the model.