Modeling the Performance of a Solar Heated Sunroom: Heat Gain, Storage and Loss

John E. Petersen
Associate Professor of
Environmental Studies and Biology
Oberlin College

Alfredo Fernández-González
Associate Professor and Director,
N.E.A.T. Laboratory, School of Architecture
University of Nevada, Las Vegas

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Introduction

Over a third of total electrical and other fossil fuel energy consumption in the U.S. takes place within buildings and two thirds of electricity consumption takes place within the built environment (Wilson and Yost, 2001). Associated with this energy use, buildings in the U.S. are responsible for a host of negative environmental impacts including accounting for 9% of total global greenhouse gas emissions (Wilson and Yost, 2001). In the northern U.S., heating of water and air typically account for over 50% of total residential energy use (DOE/EIA, 1999). Active and passive solar architecture can be used to reduce the environmental footprint of buildings.

Sunrooms are among the most common solar features added to existing buildings. Sunrooms are popular because they create enjoyable daylit spaces for work, entertainment and horticulture. Unfortunately, solar performance is not always incorporated as a central consideration in the design and management of such spaces and performance is seldom evaluated after construction (Fernández González, 2003, Fernández González, 2002). As a result, in winter months sunspaces may add to rather than subtract from the auxiliary heating requirement of houses in which they are installed (Balcomb,1984).

In most regions it is possible to design sunrooms that produce a net positive contribution to heating in the sense that the total captured solar energy exceeds the heat losses through the windows, walls, ceiling, and floor of the sunroom. With that said, the timing of heat gain and heat loss over the course of a day can be as important as the total integrated transfer in creating a comfortable and functional sunroom space; poorly designed sunspaces can at times be uncomfortably hot during the day, whey they receive maximum solar gain, and uncomfortably cold at night when heat loss to the outside through windows and walls is at a maximum.

The thermal performance of a sunroom is influenced by a number of factors. Features of the windows that are important, include: orientation (N, S, E and W walls and roof), total square footage, and glazing attributes such as single vs. double vs. triple pane, “low-e” coatings, tinting, shading, movable insulation, etc. Landscape features that cast shadows on the glazed surfaces likewise influence performance. The quality of the insulation in the walls, roof and flooring is also an important feature governing heat flows. Undesirable infiltration of outside air through cracks and holes as well as intentional ventilation are likewise important factors to consider. Finally, the heat storage and release capacity (the “thermal mass”) of the materials in the room, or connected with the room can have an important influence on the degree and manner in which heat is captured, stored and released. Simulation modeling can play a vital role in the analysis of solar heated spaces (Balcomb, 1992).

The exercises developed in this module consider factors that are important in the design of any sunroom. However, exercise #2 specifically focuses on a sunroom on the Oberlin College campus. In 2005, Oberlin College converted a turn of the 19th century house into research and teaching labs for the Environmental Studies Program. Part of the objective of the project has been to demonstrate environmentally conscious renovation techniques that can be applied in a residential setting. Towards this end, a south-facing porch of the old house has been converted into a sunroom space that will be used primarily for horticultural purposes. Oberlin College facility personnel and faculty hope that this space will be capable of maintaining an internal temperature during winter months between 40ºF and 90ºF for multiple overcast days without supplementary heating. A key goal of exercise #2 is to explore whether and how this objective might be achieved.

Figure 1. Environmental Studies Laboratory with sunroom before and after renovation

Design and management questions for this sunroom have included: What size south facing windows should be incorporated? Should the building include or exclude East and West windows? What type of window materials should be used? How might thermal mass best be incorporated into the structure to most effectively store heat and dampen daily temperature fluctuations? If captured solar energy cannot maintain the desired temperature, how much supplementary heat energy will be necessary to accomplish this, and what size heating unit should be chosen? Could movable insulation panels or window curtains be used to reduce heat loss when the sun is not shining?

Dynamic simulation modeling provides a potentially valuable tool for: evaluating the implications of various design choices, optimizing design decisions, evaluating performance after the structure is completed, and exploring the efficacy of different management strategies. This module leads students through the development of a simple heat flux model and the modification of an existing model to address the questions posed in the preceding paragraph.

Problem Statement/Questions

What factors govern the thermal performance of a sunroom? Given architectural and climatic constraints, how can a sunroom in North East U.S. be designed and managed to maintain a specified temperature range with a minimum of auxiliary heat input?

Background

Heat energy transfer

The exercises you will work on within this module address how solar energy is absorbed and converted to heat, and then how heat is stored and flows within a sunroom and between the interior and exterior of the sunroom. Maintaining a temperature inside the sunroom that is acceptable for horticultural use and comfortable for humans requires intentional manipulation of heat acquisition, storage, and release. There are three important mechanisms by which heat energy is transferred: radiation, conduction and convection.

<u>Radiation</u>: Heat energy is acquired from the sun's electromagnetic radiation that travels through space and into the earth's atmosphere. This is distinct from other sorts of energy transfer in that electromagnetic radiation can travel through a vacuum – it does not require matter. Visible light and infrared radiation are important components of electromagnetic radiation that must be considered in solar heating and building design. When the sun's electromagnetic radiation strikes the exterior of a transparent or translucent building element (e.g. windows or skylights), the sun's energy can be reflected, transmitted and absorbed. Radiation that is transmitted through a window can then be absorbed or reflected when it falls on an interior surface. Absorption is the process by which this radiation is converted to heat. The surface absorbing the radiation will conduct some of this heat away from the absorptive surface either to its interior or to the surrounding air. The surface can also re-emit stored heat in the form of infrared radiation. Some of this re-emitted infrared radiation will be absorbed by the air and by other objects in the room, some of it may travel back out through the windows. In winter months, a key objective of a sunroom is to maximize absorption of solar radiation and minimize heat losses that occur via re-radiation.

<u>Conduction</u>: Conduction is the process by which heat travels through materials that are in direct contact with each other. For example, radiation absorbed at the surface of a concrete floor travels downward by conduction to warm the area below the surface and also travels upward by conduction to warm the air that is in contact with the absorbing surface. The second law of thermodynamics states that heat spontaneously flows from warmer areas to colder areas. When the interior temperature of the sunroom is warmer than the outside temperature, heat will flow by conduction from the interior of the space to the outside through the materials that make up the walls, windows and roof. An important goal of the model is to help identify effective means of minimizing this conductive heat loss.

<u>Convection</u>: Convection involves the movement and mixing of a gas or fluid that contains heat from one region to another. Convection of air is an important mechanism by which heat is distributed through a room or building. For example, the floor and walls of the sunroom absorb solar radiation and heat the surrounding air. This air then rises, comes into contact with the windows and walls and then cools, creating a circulation that redistributes heat throughout the room. In a simple one-room sunroom, we can assume that natural convective mixing will do a good job of distributing heat within the air; we need not concern ourselves with explicitly modeling this convection.

The importance of these processes in the thermal performance of a building varies seasonally. Conductive transfer is most important during the coldest time of year, when the temperature gradient (difference between internal and external temperature) is greatest. Radiative transfer is dependent on the angle of the sun and the intensity of the sun's radiation, which changes over the course of a year. In the northern hemisphere, the sun is at its lowest angle (i.e. lowest solar altitude) during the winter solstice (December 21) and is at its highest angle during the summer solstice (June 21). In solar design, roof overhangs can therefore be effectively used to block direct solar radiation from entering windows in the summer, while allowing complete access to winter radiation. The color of materials within the space has an important influence on the fraction of solar energy that is absorbed and converted into heat and the fraction that is reflected back out through the windows.

Heat vs. temperature

Humans experience heat in the form of temperature. When we sit in a sunroom our degree of comfort is influenced by both the air temperature and the temperature of all the surfaces around us (Stein and Reynolds, 2000). If we are directly exposed to the sun rays, the temperature of our skin will rise as it is absorbing heat via radiation. Similarly, if the temperature of the surfaces around us is higher (or lower) than the temperature of our skin, our body will absorb (or lose) heat via radiation – this is why we may feel warmer or colder when we are near a window even if the air temperature immediately around us is identical to the air temperature in other parts of the room. Temperature is a measure of the average kinetic energy of molecules or ions that make up a substance. At a microscopic level, temperature measures how fast molecules or atoms are shaking. At “absolute zero” (0º Kelvin) the atoms basically stop moving. As they are warmed, they shake faster and faster.

Heat is the amount of energy stored in a substance. Heat is transferred to a substance via the three mechanisms discussed above. As heat flows into a substance, the kinetic energy increases and so the temperature rises[1]. As discussed in the following section, the amount of heat energy that is required to raise the temperature differs for different substances. The ease with which heat travels through a substance is also determined by its composition. Understanding the principles associated with heat flows and the relationship between heat and temperature is crucial to designing a comfortable and energy efficient sunroom.

Heat content and flows of heat can be expressed in many different energy units. For example, heat flow through a surface can be expressed in watts/m^2/hr, in calories/m^2/day (both SI units) or in BTU/ft^2/hr (English system). Although scientists in the U.S. have largely adopted metric or SI units, the public and the building industry have not. Because most of the available equations and parameter coefficients for modeling solar performance that are used in the U.S. are still published in English system units, we have chosen to emphasize English units throughout this module. In the glossary we have included common SI units for some of the variables discussed in the model. A BTU is a “British Thermal Unit” and is defined as the amount of heat necessary to raise 1 lb of fresh water 1ºF at a pressure of one atmosphere.

Heat storage capacity

Temperature fluctuation can be a significant problem in solar heated structures (Balcomb and Wray, 1987). “Thermal mass” is the material that absorbs, stores, and releases heat in a space. Any room will have some inherent thermal mass associated with the building materials (e.g. the gypsum board on the walls and ceiling, the floor material, and the furniture). A key strategy in both active and passive solar architecture is to incorporate and effectively use thermal mass to dampen temperature fluctuations in the space; heat is directly absorbed (passive solar) or actively transported (active solar) to the mass when the sun is shining and is then released from the mass when solar resources are not available (at night or during cloudy days).

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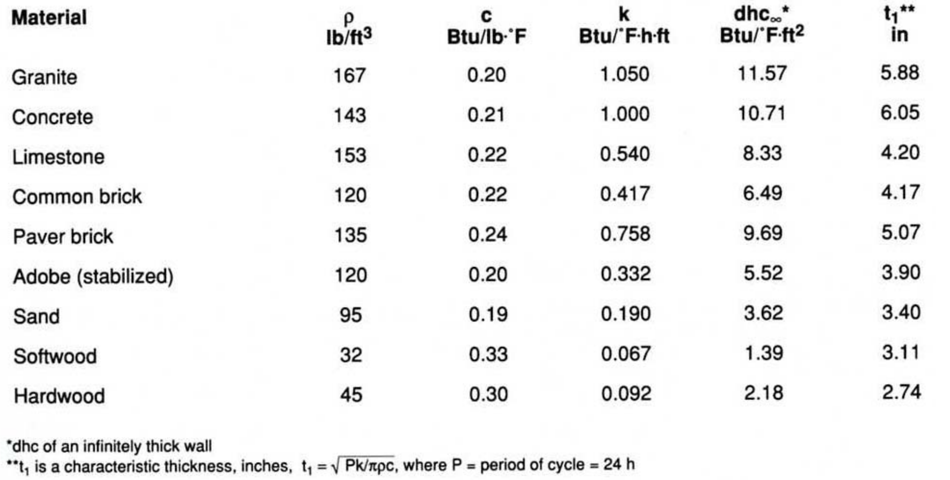
[1] The exception to this is that when phase changes occur, a substance absorbs heat without increasing temperature – for example when ice absorbs heat to become water it remains at 32ºC.

The ability of a given object to store heat and to exchange heat with the surrounding air is a function of a number of factors including its volume, density, specific heat capacity, thermal conductivity, surface color, and thickness (see glossary for definitions and common units for these variables). Depending on these factors, different materials have very different heat storage and exchange capacities (Table 1). For example, water has a density of 62 lbs/ft^3 and a heat capacity of 1 BTU/lb-°F, whereas air has a density of 0.075lbs/ft^3 and a heat capacity 0.24 BTU/lb/ºF[2]. These differences mean that adding heat energy to given volume of air results in a far larger temperature increase than adding the same amount of energy to a similar volume of water.

Table 1. Thermal storage capacities of some common construction materials (selectively reproduced from Balcomb and Wray, 1987)



Material	ρ lb/ft^3	c Btu/lb·°F	k Btu/°F·h·ft	dhc$_\infty$* Btu/°F·ft^2	t_1** in
Granite	167	0.20	1.050	11.57	5.88
Concrete	143	0.21	1.000	10.71	6.05
Limestone	153	0.22	0.540	8.33	4.20
Common brick	120	0.22	0.417	6.49	4.17
Paver brick	135	0.24	0.758	9.69	5.07
Adobe (stabilized)	120	0.20	0.332	5.52	3.90
Sand	95	0.19	0.190	3.62	3.40
Softwood	32	0.33	0.067	1.39	3.11
Hardwood	45	0.30	0.092	2.18	2.74

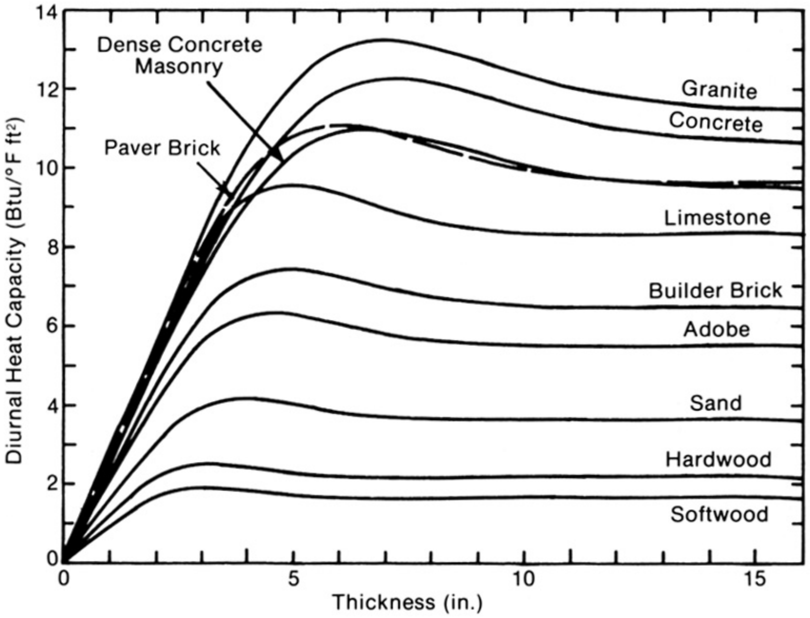
*dhc of an infinitely thick wall

**t_1 is a characteristic thickness, inches, $t_1 = \sqrt{Pk/\pi\rho c}$, where P = period of cycle = 24 h

ρ = density C = heat capacity (specific heat), k = thermal conductivity. dhc$_{inf}$ is the diurnal heat capacity per unit area of wall material, t_1 is the characteristic thickness of the material at which the Effective Heat Capacity has the maximum value if the total amount of mass is fixed.

The “diurnal heat capacity” (DHC) of a room or building is defined as the amount of heat energy required to raise the internal temperature of that room or building one degree Fahrenheit (Balcomb and Wray, 1987). The diurnal heat capacity is a semi-empirical quantity that is a function of the heat capacity, but also accounts for the fact that in a real-world setting, in which temperature goes up and down over the course of a day, material deep within a wall or floor is too far removed from the interior of the room to have much of an influence on its temperature fluctuation. A rule of thumb that solar designers often assume is that in a passively heated solar space thermal mass no longer contributes to diurnal heat capacity when it extends beyond 6” thick (Balcomb and Wray, 1987). This is because beyond this thickness, heat will travel too slowly to allow it to interact with the space. Figure 2 describes the DHC as a function of material thickness. The total diurnal heat capacity of a room (or building) is the sum of the diurnal heat capacity of the walls, ceiling, floor and objects within the structure.

Figure 2. Diurnal Heat Capacity of various materials per unit thickness (reproduced from Balcomb and Wray, 1987, Figure 2-9).



Balcomb and Wray (1987) suggest that for interior partition walls, one-half the total wall thickness be used to determine the diurnal heat capacity for each of the two surfaces.

Thermal properties of walls and windows

In the Northern part of the U.S., exterior walls are designed to reduce heat transfer and maintain an internal environment that is warmer (winter) or cooler (summer) than the external environment. To reduce heat flow, walls are typically packed with various types of insulating materials including fiberglass batting, rigid foam board, and a variety of different types of blown-in fibers and hardening plastic foams. Blown-in or sprayed-on cellulose is popular among environmentally conscious builders because the cellulose is non-toxic and is manufactured from recycled newspaper. Straw bales are also an increasingly popular insulation material in "green" architecture because straw is an agricultural byproduct that offers excellent insulation properties.

Insulating materials are rated according to their "thermal resistance" or R-value (Table 2 lists R-values for some common materials). Framing members (wood and especially metal) have lower R-values than the insulation inserted between them. For this reason, the "actual R-value" of a constructed wall without windows is lower than the R-value of the component insulation. The additional framing members and the framed space around windows, doors, corners, etc. further lower the effective R-value of a wall.

Windows serve a number of important functions. Obviously, a primary objective is to allow visible light (i.e. the visible portion of the spectrum of electromagnetic radiation) to enter into a building. Daylighting is useful because it reduces auxiliary energy consumption necessary for electric lighting thereby reducing the cooling loads. Daylighting, along with the infrared portion of the solar spectrum that enters through the windows, is absorbed and then becomes heat energy (an attribute which is desirable only in the winter). When outdoor air temperatures are lower than indoor air temperatures, operable windows can help dispose this heat energy via convection.

In spite of their importance, windows are generally much less effective at reducing heat exchange than are windowless exterior walls. Customarily, instead of rating windows according to their resistance to heat flow (R-value), the building industry chooses to rate windows according to their thermal conductivity or "U-value". The U-value is simply the inverse of the R-value ($U = 1/R$; $R = 1/U$). High R-values and low U-values are desirable.

Overall thermal conductance of windows is controlled by several factors including number of panes and/or films between panes, the distance between the panes, the type of gas used to fill the space between the panes, and various coatings that can be applied to the glass (Table 2). Though bundled together into the U-value, these factors actually control both the conduction of heat across the glass and the transmission of electromagnetic radiation through the glass. For example, energy efficient windows are often filled with argon and krypton because these gases have a lower thermal conductivity than air. On the other hand, low-emissivity ("low-e") coating selectively reflects the infrared or heat energy part of the electromagnetic spectrum. Low-e coating can be used to block infrared light from entering a window (desirable in the summer), and to prevent infrared light from leaving a house (desirable in the winter).

Table 2. R-values and U-values for selected construction, insulation and window and whole wall materials

Materials	**R-values**	**Materials**	**R-values**
Insulation Materials (/inch value)		Interior Finish Materials	
Fiberglass Batt	3.14	Gypsum Board (drywall 1/2")	0.45
Fiberglass Blown (attic)	2.2	Paneling (3/8")	0.47
Fiberglass Blown (wall)	3.2	Flooring Materials	
Rock Wool Batt	3.14	3/4" Plywood	1.25
Rock Wool Blown (attic)	3.1	3/4" Hardwood Flooring	0.91
Rock Wool Blown (wall)	3.03	Linoleum tile	0.05
Cellulose Blown (attic)	3.13	Fibrous padded carpet	2.08
Cellulose Blown (wall)	3.7	Roofing Materials	
Vermiculite	2.13	Asphalt Shingles	0.44
Urea Terpolymer Foam	4.48	Wood Shingles	0.97
Rigid Fiberglass (> 4lb/ft3)	4	Windows	**U-values**
Expanded Polystyrene (beadboard)	4	Single Glass	1.10
Extruded Polystyrene	5	Single glass w/storm	0.50
Polyurethane (foamed-in-place)	6.25	Double insulating glass	
Polyisocyanurate (foil-faced)	7.2	3/16" air space	0.62
Construction Materials (total value)		1/4" air space	0.59
12" Concrete Block	1.28	1/2" air space	0.49
Poured Concrete	0.08	3/4" air space	0.42
Brick 4"	0.44	1/2" w/ Low-E 0.20	0.32
Soft Wood Lumber (per inch thickness)	1.25	with suspended film	0.36
2x4 framing	4.38	with two suspended films)	0.26
2x6 framing	6.88	With suspended film & low-E	0.25
1/2" plywood	0.63	Triple insulating glass	
1/2" fiberboard	1.32	1/4" air spaces	0.39
Whole walls (no windows)		1/2" air spaces	0.31
2x4 wood stud 16" o.c., R-11 batts, 1/2" plywood exterior, 1/2" gypsum board interior	9.6		
2x4 wood stud 24" o.c., R-11 batts, 1/2" plywood exterior, 1/2" gypsum board interior	9.9		
2x 6wood stud wall 24" o.c., R-19 batts, 1/2" plywood exterior, 1/2" gypsum board interior	13.7		

R-value and U-value data for individual materials are from ColoradoEnergy.org (http://coloradoenergy.org/procorner/stuff/r-values.htm). Data for whole wall materials are based on experiments conducted at the U.S. Department of Energy testing facility and are made available online by Home Energy Magazine (www.homeenergy.org/archive/hem.dis.anl.gov/eehem/97/970308.html). Units for R-values are ft² °F h / BTU. Units for U-values are BTU/ ft²/°F/hr.

Comment [MSOffice1]: For a more extensive list of materials and window assemblies one can consult the ASHRAE Handbook of Fundamentals

Passive vs. active solar heating

In passive solar systems, no mechanical technology is used to transport and store heat. Instead, windows and building materials are positioned such that thermal mass naturally absorbs solar energy during the day and reradiates it at night to the interior space. Natural convection within the building serves to further transport heat. In contrast, in active solar systems, mechanical technology, such as blowers and pumps, is used to move heat between areas in which it is collected, areas in which it is stored (e.g. rock beds below the house) and areas in which it is used. Passive solar places great emphasis on the overall site plan. The passive approach carefully considers factors such as building and room orientation to take advantage of solar exposure and prevailing winds. Deciduous shade trees may be planted adjacent to windows to block summer light but allow solar gain in the winter.

Other important considerations in heating

Solar structures need to consider two additional sources of heat. The experience of sitting in a crowded lecture hall makes it clear that humans can give off substantial amounts of heat. Lighting and other appliances can also give off substantial amounts of heat. “Internal heat gains” include heat that is generated by people, animals, electric lights, and appliances within a space. A typical internal heat gain value for a residential building is 20,000 BTU/person/day (833 BTU/person/hr).

Supplementary heating is almost always necessary in solar houses and sunrooms built in the Northern part of the U.S. to condition spaces during extremely cold weather, at night, and/or during prolonged cloudy periods. This auxiliary heating must be considered in the design of the structure.

Modeling solar performance

Models are valuable tools for evaluating the impact of design choices on thermal performance before and after a structure is built. A distinction can be drawn between empirical and mechanistic models. Mechanistic models are those that are based entirely on a theory; the mechanisms underlying phenomena are explained by and incorporated into all of the mathematical equations that are used. In contrast, empirical models are based on experimental data and observation rather than theory; empirical equations are used to describe relationships, but they are not designed to explain these relationships. In practice, most solar models incorporate some combination of theory and empiricism. For a particular model, the balance is determined by the objectives of the modeler. Modelers working on practical problems – such as assessing the solar performance of a design or an existing building – typically rely on models that incorporate a range of simplifying assumptions that allow them to estimate heat flow dynamics with easily available data and with a minimum of complexity.

The physical principles and therefore the governing equations are distinct for convective, conductive and radiative heat transfers. For example a black object will radiate heat energy at a rate that is proportional to the fourth power of its absolute temperature. In contrast, the rate at which heat travels by conduction through a material is proportional to the difference in temperature on either side of the material, the thickness of the material and the particular materials resistance to heat flow. A model based on strict application of theory would carefully isolate each heat flow mechanism and consider the unique physical attributes of each of the materials in the building that affect heat flow. In practice, the fact that these three heat transfer mechanisms operate simultaneously and interact with each other means that such a model would be exceedingly complex. It would also be very difficult to find the data necessary to calibrate and validate such a model. In general, modelers choose to use or develop models with the minimum degree of complexity necessary to satisfactorily answer the question or problem at hand.

Our practical goal in the exercises within this module is to identify sunroom design and management options that will maintain its temperature within a specified range in the winter season. The discussion of modeling approaches below therefore focuses strictly on heating and ignores the potentially important issue of cooling during summer months.

Heat "gain" refers to flows of heat into the structure. Heat "loss" refers to flows out. There are three primary sources of heat gain to the structure: 1) solar gain resulting from the absorption of energy through windows 2) internal heat gain resulting from people, electric lights, and equipment that is not specifically designed to produce heat, and 3) auxiliary systems specifically designed to introduce heat. Solar heat gain is a function of the area of windows and skylights, the orientation of the windows and skylights, the intensity and duration of solar radiation entering these windows and skylights, and the amount of this radiation that is absorbed within the sunroom.

Modeling radiative solar gain

The challenge in modeling solar radiation is to determine the amount of solar energy that enters a space and is absorbed by surfaces within the space. Various approaches can be taken to modeling the energy delivered to a space. One approach is to incorporate equations that simulate the seasonal changes in both sun angle and solar intensity. A highly sophisticated model, such as the "DOE-2" program developed by the U.S. Department of Energy, will then consider the effects of overhangs and the differences in light transmission through windows that occurs as a function of changing angles at which light strikes the glass.

A simpler alternative approach, and the one used in these exercises, is to drive a model with data that represent the solar radiation arriving at a given surface. These data can be collected in the field or simulated with equations. For example, data collected over time from a pyranometer facing directly south provides excellent forcing data for modeling solar gain through a south facing window.

It is often important to consider the effects of shading by trees and other objects. These potential obstacles that could inhibit solar radiation from being absorbed within the space can be incorporated into a "Shading Coefficient" (SC) that represents the fraction of incident solar radiation that actually strikes the outer surface of the window or skylight. The amount of solar radiation that is actually transmitted through the windows or skylights and converted to heat energy within the space is a function of this Shading Coefficient and the properties of the glazing product used. The radiative heat energy converted to heat within the space ($Q_{SolarGain}$) is then the product of the Shading Coefficient (SC) and the incident solar radiation:

$Q_{SolarGain}$ = (shading coefficient)*(Incident radiation at the angle of the window) (Equation 1)

Modeling conductive exchange

Heat is lost via conduction, convection, and radiation. Conductive heat flow out of a building is governed by a simple gradient equation of the form:

$$Q = U*A(T_{internal}-T_{external}) \qquad \text{(Equation 2)}$$

Where: Q = conductive heat flow (BTU/hr), U = the U-value or thermal conductivity of the wall, window or roof (BTU/ h ft² °F see table 2), A = area of wall, window, or roof (ft^2), $T_{internal}$ = temperature on the inside of the wall, window, or roof, $T_{external}$ = temperature on the exterior side of the wall, window, or roof (both in ºF). Since the R-value is the inverse of a U-value, A/R-value is the same as U*A. It should be clear from Equation 2 that the higher the U-value (i.e. the lower the R-value), and the larger the gradient between internal and external temperatures, the more rapidly heat flows across the window or wall. Note that although we are discussing this as a loss equation, it works just as well for reverse heat flow; when $T_{internal} < T_{external}$ heat flows into the building according to the same equation (i.e. flow out of the building is negative).

Modeling radiative exchange through the walls

One of the clever simplifying approaches that solar designers have taken to modeling heat transfer is to combine the effects of conduction and radiation through walls and roof materials into a single equation of the same form as Equation 2. To accomplish this they have defined a quantity known as "sol-air temperature" (T_{sol}). The sol-air temperature can be thought of as temperature of air on an exterior building surface that will produce a heat transfer rate that accurately captures the combined effects of exchange via conduction and exchange via radiative absorption and emission through the same building surface. One way to think about this is that on a sunny day, the outside surface of a wall or window will be warmer than the exterior air as a result of absorbing solar radiation. At night, this surface may be colder than the air as a result of radiating energy to the sky and surroundings. It is the temperature of this outside surface and not the ambient air temperature that drives heat exchange across the wall. The modified equation is simply:

$$Q = U*A(T_{internal}-T_{sol}) \qquad \text{(Equation 3)}$$

Where: Q = combined conductive and radiative heat flow (BTU/hr)

A variety of approaches have been taken to calculating the T_{sol}. ASHRAE (2001) offers an equation for calculating T_{sol} that combines theory of radiative transfer with empirical observation that can be simplified to the following:

$$T_{sol\_vertical} = T_{external} + \alpha E_t/3 \qquad \text{(Equation 4)}$$

$$T_{sol\_horizontal} = T_{external} + \alpha E_t/3 - 7 \qquad \text{(Equation 5)}$$

Where: T_{sol} = sol-air temperature for vertical (walls) and horizontal (roof) surfaces (eq. 4 and 5 respectively), α is the absorptance of the exterior wall or roof materials for solar radiation (light colors = 0.45; dark colors = 0.9, no dimensions), E_t is the total solar radiation striking the vertical or horizontal surface (BTU/ft^2/hr). T_{sol} differs for vertical and horizontal surfaces because horizontal surfaces exchange long-wave radiation directly with the sky (Kuehn *et al.*, 2005).

Modeling convective losses via infiltration and ventilation

Infiltration is a measure of air flow that occurs through cracks. In older construction this can be very important. New construction, especially high-performance construction is often so tightly sealed that ventilation is necessary to maintain air quality. For the sake of simplicity, this model ignores these potentially important sources of heat exchange.

Translating flows of heat into changes in temperature (and vice versa)

The equations discussed above focus on transfers of energy. It would be perfectly reasonable to construct a model in which the primary "stock" or "state variable" is stored heat energy (a state variable or stock is the amount of the "stuff of interest" that is stored within the system at any given time). However, humans directly experience heat as temperature and it is convenient to model heat storage by focusing on the resulting changes in temperature. As discussed, the change in temperature (ΔT) that results from addition or subtraction of heat energy are a function of diurnal heat capacity (DHC):

ΔT = (Heat added or subtracted)/DHC (Equation 6)

Explanation of the Model

System description

The models developed for these exercises consider the major factors controlling heat gain and loss in a sunroom (except infiltration and ventilation). The specific characteristics of the room modeled are discussed within the exercises.

Model development sequence:

Exercise #1 guides students through the process of using STELLA to build a dynamic simulation model of solar performance in a 10x10x10 ft room from scratch. Students begin with a solid wall that exchanges heat solely by conduction and then sequentially add windows (radiative solar gain) and then finally consider radiative losses. This exercise is designed to develop an understanding of the equations and the approach to modeling taken in exercise #2.

Exercise #2 introduces the “SunRoom.stm” model. This is a complete STELLA model that the authors developed to explore the implications of a variety of design and management choices on a real greenhouse structure. Students use this model to explore the effects of altering parameter values and basic control strategies on system performance. Students then explore alternative management strategies by adding components to the model that reflect the addition of removable window insulation and additional and alternative thermal mass options.

Exercise #1. Building a Simple Model of Heat Loss and Solar Gain

In this first exercise, you will build a model of heat exchange in a 10x10x10 ft sunroom. Average room temperature is the only stock in this model. Room temperature changes as a result of two flows: 1) the combined conductive and radiant exchange across the south facing wall and 2) radiative solar gain through windows in this wall. Outside air temperature and solar radiation falling on the vertical wall are external forces that affect exchange (modelers call these “forcing functions”). The specific processes and equations governing exchange are discussed in the background section of this module.

Several simplifying assumptions will be made in this exercise that help focus attention on the techniques and equations involved in modeling heat flow dynamics. First, assume that heat exchange occurs across one south-facing 10x10 ft wall of this room (100 ft^2); assume that the other walls, the roof and the floor are perfectly insulated from heat exchange with the outside. The combined diurnal heat capacity of the walls, floor, ceiling and objects in the room is 400 BTU/°F and the initial room temperature is 68ºF. In the sections of the exercise below, you will develop the simplest possible model of conductive heat exchange and then sequentially add the complexity or radiative gain through south facing windows and radiative gain and loss through the building exterior. Finally, you will ask a series of “what if” questions to explore and gain an intuition for solar performance dynamics.

A key to maximizing the learning that takes place through modeling is to define and explore mechanistic hypotheses before you run your model. A mechanistic hypothesis is both a prediction and an explanation. Alone and then with your partner you should define how you expect the variables in the model to respond to each new addition and, based on the formulations you are incorporating, why you expect to observe these dynamics. This includes sketching time series graphs of the stocks, flows, and important converters in the model. This should take place before you run the model; your capacity for gaining understanding will be substantially reduced if you run the model first. Once you have run your model, the process of exploring reasons for discrepancies between your predictions and actual behavior is crucial to knowledge building. These discrepancies may be a result of deficiencies in your thinking, errors in the programming of model equations and/or faulty assumptions going into model formulations. You should explore each of these in your analysis and discussion.

a) Conductive heat exchange

This first version of the model considers conductive heat exchange through a windowless wall.

Open STELLA v9, select the "Model" tab on the left side of the window, create a stock and name it "Sunroom_Temperature"[3] (as you develop the model, follow along with the figures below). Double click on this stock and in the highlighted equation box type "68 {degrees F}" (do not include quotation marks, STELLA recognizes text within { } brackets as documentation). This specifies that the initial starting temperature of the room is 68ºF. Create a converter, name it Diurnal_Heat_Capacity, and give it a value of 400 {BTU/degree F}. Create another converter, name it Wall _Area and give it a value of 100 {ft2} (i.e. the area of a 10x10 ft wall). Create an additional converter named R_value, and give this a value of 10 {ft² degree F hr /BTU}. Create one final converter named T_Outside to represent outside air temperature and give it a value of 40 {degrees F}. This stock and these converters represent all of the factors that affect conductive heat exchange between the room and the exterior. All of these factors are explained in the background section of this module.

Create an additional converter and name it UA_Wall. This converter will represent the thermal conductivity over the entire area of wall. You will need to create connectors from R_Value and Wall_Area extending into this converter. Once you have done so, double click on UA_Wall and click on the variables and mathematical operators to make the equation for this variable = Wall_Area/R_Value {BTU/degree F/hr}. Convince yourself and your partner that the units for this variable are correct given the units of the constituent variables. Note that since thermal conductivity (U-value) is simply the inverse of thermal resistance (R-value), dividing by the R-value is identical to multiplying by the U-value (hence this converter is named UA_Wall).

Create an additional converter representing heat flux across the wall. Name it Q_Wall and create connectors from UA_Wall, T_Outside and the Room_Temperature extending into Q_Wall. This variable will use equation #1 from the background section: Q_Wall=UA_Wall*(Room_Temperature-T_Outside) {BTU/hr}. This represents the rate at which heat flows across the wall as a function of the temperature gradient between the interior of the room and the outside.

The change in room temperature that results from a given flux of heat is a function of the diurnal heat capacity of the room – the larger the heat capacity, the more heat it takes to raise room temperature. Create a flow extending from the Room_Temperature stock out into space, name it Gradient_Based_Exchange. Use connectors to make this exchange a function of Q_Wall and Diurnal_Heat_Capacity. Gradient_Based_Exchange = Q_wall/Diurnal_Heat_Capacity {degrees F}. Within the equation dialog box check the option at the top that reads "Biflow" this allows heat to flow either out of the building (if Gradient_Based_Exchange is a positive value) or into the building (if Gradient_Based_Exchange is negative).

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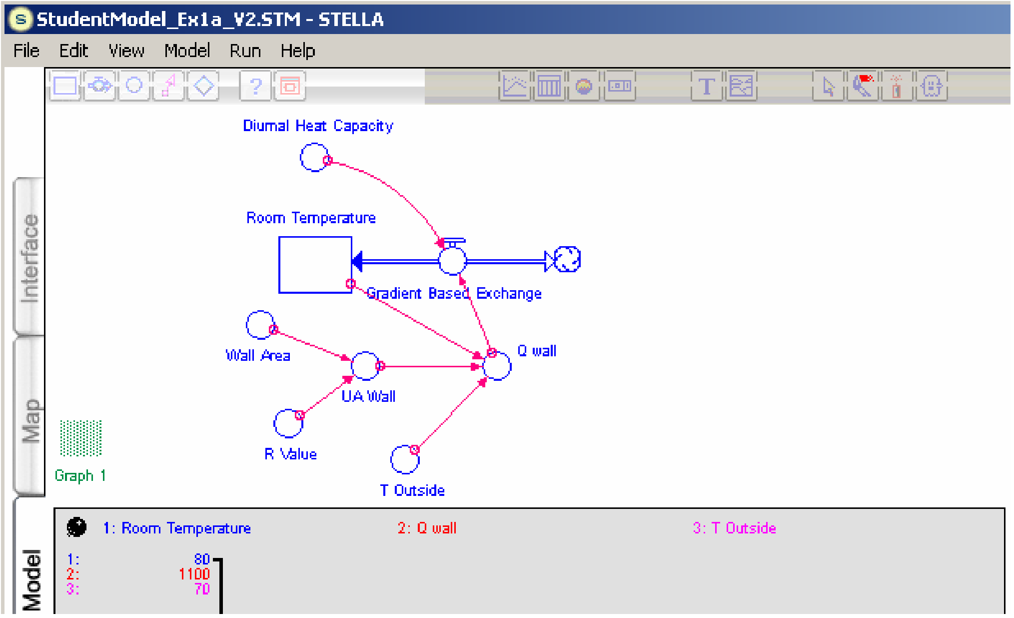
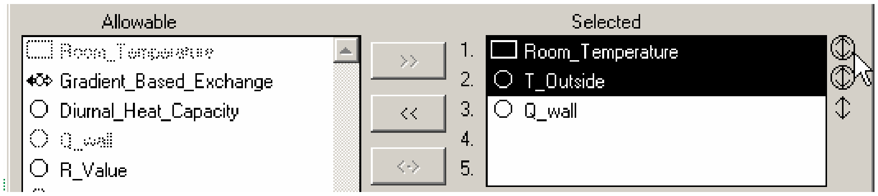
[3] In STELLA, you should use a space and not the underscore (_) to separate words in a variable's name. The underscore is included in the text to clearly identify the names of STELLA variables.



Congratulations! You now have a complete model of conductive heat exchange. To run this model you need to create a graph pad and set the run specifications. Add a graph pad to your model, double click on this graph pad and add Room_Temperature, T_Outside and Q_Wall to page 1 of the graph by double clicking on each of these variables. Within the graph pad, select both Room_Temperature and T_Outside and click on the arrows to the right of the dialog box twice to make circles around them. This then allows you to set the scales on both of these to extend from a minimum of 40ºF to a maximum of 80ºF (see figure below).



Selected
1. Room_Temperature
2. T_Outside
3. Q_wall
4.
5.

Scale: Min 30.00 Max 80.00

Page: 1

Click on the up arrow next to the Page button to add a new graph. On this second graph, add Room_Temperature and click the comparative box in the upper left hand corner of the dialog box. This will allow you to compare temperature dynamics on multiple runs of the model. Use the up arrow to add a third graph. Add Q_Wall, and make this comparative as well. Click OK. (You toggle through graphs on a graph pad by clicking the orange triangle in the lower left hand corner of a graph).

From the Run menu, select “Run Specs” and choose: Unit of time = Hours, Simulation from 0 to 72 and DT = 0.1. Leave the other values in their default settings. Since the time units are in hours, you are effectively choosing to run the model for three days (72/24 = 3).

BEFORE YOU RUN THE MODEL, remember to predict the changes you expect to see in Room_Temperature and Q_Wall by actually sketching your predictions on paper. Once you have committed these predictions to paper and discussed your mechanistic hypothesis with your partner, run the model by choosing “Run” from the Run menu. Were your expectations confirmed? Discuss discrepancies with your partner until you are convinced that you have a complete understanding of the patterns you observe.

b) Adding a more realistic outside temperature function

One of the ways in which the model you just created is unrealistic is that outside temperature typically varies substantially over the course of a day. You can simulate this by replacing the constant in T_Outside with a function that produces an idealized version of temperature variation over the course of a day. Inserting the following equation will create sinusoidal variations from a low of 20ºF at 6:00 AM to a high of 50ºF at 6:00 PM:

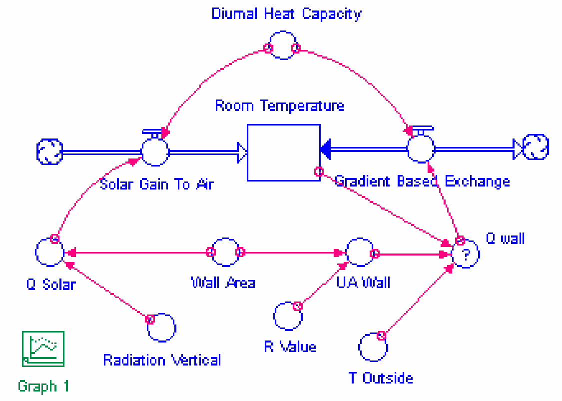
T_Outside = 40 + 10*sin(((TIME/24)-0.25)*2*Pi + 1.5*Pi)

(The footnote explains how you can modify this equation to achieve different range, average and/or timing[4]).

Again, before running the model discuss and sketch your predictions of how Room_Temperature, T_Outside and Q_Wall will change over the course of the day as a result of temperature fluctuations. Run the model and discuss how the results do or do not match your predictions. How and why does Room_Temperature differ from T_Outside?

c) Add solar heat gain to the model

Assume that there is a 5x10ft window in this south facing wall. This means that you will need to consider the heat added by solar radiation striking the interior surfaces of the room and also the additional heat loss through this window. The revised model you generate will look something like the figure below:



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[4] STELLA understands that TIME is how many hours have elapsed so far and that Pi = 3.14159. If you want to adjust this equation the numbers included as defaults have the following effect. 40 sets the average daily temperature. 10 is the range above and below 40. 0.25 sets the time of day at which minimum temperature is achieved at 6:00 am (6/24 = 0.25). See if you can figure out how this equation produces the desired temperature variability.

Let's first consider solar gain. Create a new converter that will represent the solar radiation transmitted through a south-facing window and name it Radiation_Vertical. Type the following formula into the equation editor box:

```
IF(sin(((TIME/24)-0.25)*2*Pi + 1.5*Pi) > 0) THEN
30*sin(((TIME/24)-0.25)*2*Pi + 1.5*Pi)
ELSE 0 {BTU/ft2/hr}
```

This equation will simulate a sunrise at 6:00 AM followed by a sinusoidal increase till a peak transmitted intensity of 30 BTU/ft2/hr at noon and then decreasing till sunset at 6:00 PM.

Add a converter named Q_Solar to represent the heat energy that is added to the room as a result of absorbed solar radiation. The amount of energy added is a product of the transmitted solar radiation and the surface area of the window that receives this solar radiation. Since only half of the wall (50 ft^2) is covered with windows, you will need to account for this in the equation. Q_Solar = 0.5*Wall_Area*Radiation_Vertical {BTU/hr}

You will need to add a new flow into the Room_Temperature stock that translates the added heat energy into a rise in room air temperature. Label this Solar_Gain_To_Air. As with the conductive flow out of the wall, the change in Room_Temperature that results from a given flux of heat via Solar_Gain is a function of the diurnal heat capacity of the room – the larger the heat capacity, the more absorbed solar radiation that it takes to raise room temperature. Use connectors to express this dependency. Solar_Gain_To_Air = Q_Solar/Diurnal_Heat_Capacity {degrees F/hr}.

Even energy efficient windows have a much lower thermal resistance than walls and we need to account for this in the model. We could create a second variable called Q_Window that takes into account the window area and U-value for the window. However, for the sake of keeping this model simple, we can produce the same effect by assuming the window has an R-value of 2 (equivalent to a U-value of 0.5, see table 2). Since this window occupies half of the wall area and the non-window part of the wall has an R-value of 10, this is equivalent to an average wall R-value of 6. Change the R_Value to 6 to reflect the combined effects of window and solid wall.

Also, for the sake of isolating the effects of the variability in solar input from the effects of variability in T_Outside, change the T_Outside back to a constant of 40ºF (if you want to keep the equation you can simply multiply the right hand portion by 0 for the time being).

Add Q_Solar to page 1 of your graph and also create an additional page that generates a comparative graph of Q_Solar. Predict model behavior, run the model and discuss how the output does or does not agree with your predictions.

To be complete, alter the T_Outside so that it once again varies sinusoidally over the course of the day (see part b above), predict dynamics and re-run.

d) Simulating radiative loss

The model you have created is still missing the effect of radiative heat loss from the walls. To include in this term we will alter the model so that it uses the sol-air temperature (T_{sol}) rather than T_Outside to drive gradient-based exchange (see equation 3 in Background). T_{sol} is created according to equation 4 in the Background section.[5] The revised model you generate should look something like:

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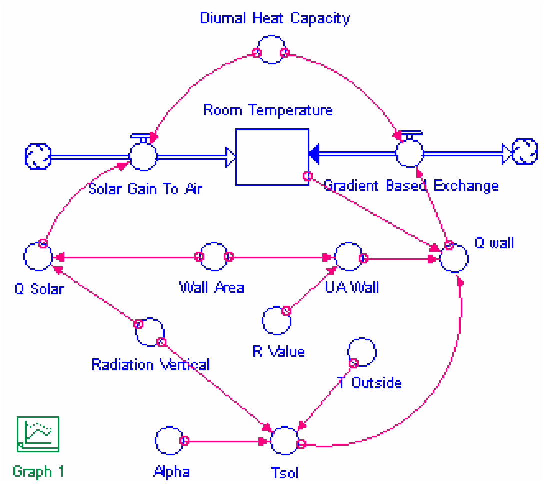
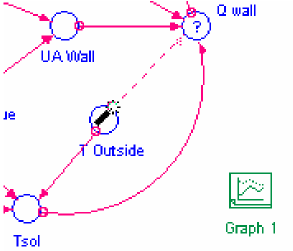
[5] To be accurate this Tsol should only be used to calculate heat flux associated with the wall and not the window, but for the sake of simplicity you are using one term for the whole wall.



Create a new converter and name it Alpha. This is the absorbance of the outside wall. Give it a value of 0.9 to represent a relatively dark colored wall (see equation 4 in background section). This is a dimensionless term reflecting the fraction of energy absorbed or radiated by the surface.

Create another converter to represent the sol-air temperature and name it Tsol. Use connectors to make this variable a function of Alpha, T_Outside, and Radiation_Vertical. Using Equation 4, Tsol = T_Outside + (Alpha*Radiation_Vertical/3) {degrees F}.

You need to change the Q_Wall equation so that it is a function of Tsol instead of T_Outside. To do so, use the "dynamite tool" to eliminate the connection between T_Outside and Q_Wall. Then create a connection from Tsol to Q_Wall.



The equation for Q_Wall should be changed to: UA_Wall*(Room_Temperature-Tsol) {BTU/hr}

Once again, for the sake of keeping the model simple, change the T_Outside equation so that your revised model will initially run on a constant outdoor temperature of 40ºF. Sketch out a prediction of model behavior, run the model and discuss how the output does or does not agree with your predictions.

To be complete, alter the T_Outside so that is once again varies sinusoidally over the course of the day, predict dynamics and rerun.

<u>e) "What if" scenarios</u>

One of the best ways to use models to build your understanding of phenomena is to explore "what if" scenarios. How would you go about modifying the model to accomplish the proposed changes? Start by proposing mechanistic hypotheses based on your understanding of the exchanges taking place that predict and explain dynamics in response to the following scenarios. Then modify the model, run it, and explore discrepancies. Before moving on to the next scenario, change the model back to its previous state so that you explore each of these as isolated conditions.

Scenarios:
1) An initial room temperature of 30ºF
2) Constant outdoor temperature of 55ºC
3) A doubling of diurnal heat capacity of the room (what does this mean and what properties of the room would you change to accomplish this?)
4) A light colored paint on the south wall (use "Alpha" to adjust, see background section)
5) Increasing the size of the window so that it takes up the entire wall area (to accomplish this you will need to consider how this affects the total R-value of the wall, the radiative gain, and the radiative loss).

Exercise #2: Exploring the dynamics of heat gain, loss and storage in a sunroom that incorporates thermal mass

The model constructed in exercise 1 takes into account the major energy fluxes affecting the solar performance of a room. It includes, however, a number of simplifying assumptions and an rigidity in structure that render it an unrealistic and inflexible representation of the dynamics that take place in an actual sunroom. For example: exchanges across all walls but one are ignored, a single R-value is used for the combined effects of windows and walls, the dimensions of the model can not easily be adjusted, the temperature and radiation forcing do not accurately simulate the variability present in nature. The expanded model that you will work with in this exercise is designed to increase realism and flexibility and also to independently consider the effects of thermal mass. Your goal in this model is to explore the implications of design and management decisions on the thermal performance of an existing sunroom located in NE Ohio.

The sunroom

As described in the introduction, the sunroom in question is configured to represent a newly constructed sunroom on the Oberlin College campus. The sunroom is a converted porch on the south side of a 19th century house that was converted into teaching and research labs for the Environmental Studies Program (See Figure 1). The north side of the structure has doors that open into a hallway and into a research laboratory. The roof remains intact; there are no skylights. East windows open onto an intact and covered section of the porch and therefore receive minimal direct solar radiation. South and west facing windows receive direct sunlight. The dimensions of the building and the window and wall areas are included in Table 3.

Table 3. Physical Dimensions of Oberlin Sunroom

Element	Height or Length (ft)	Width (ft)	Total area (ft^2)	Window area (ft^2)	Opaque area (ft^2)
North wall	9.75	21.33	208.00	90.00	118.00
South wall	9.75	21.33	208.00	132.00	76.00
East wall	9.75	6.33	61.75	50.67	11.08
West wall	9.75	6.33	61.75	50.67	11.08

Ceiling	6.33	21.33	135.11	0.00	135.11
Floor	6.33	21.33	135.11	na	na

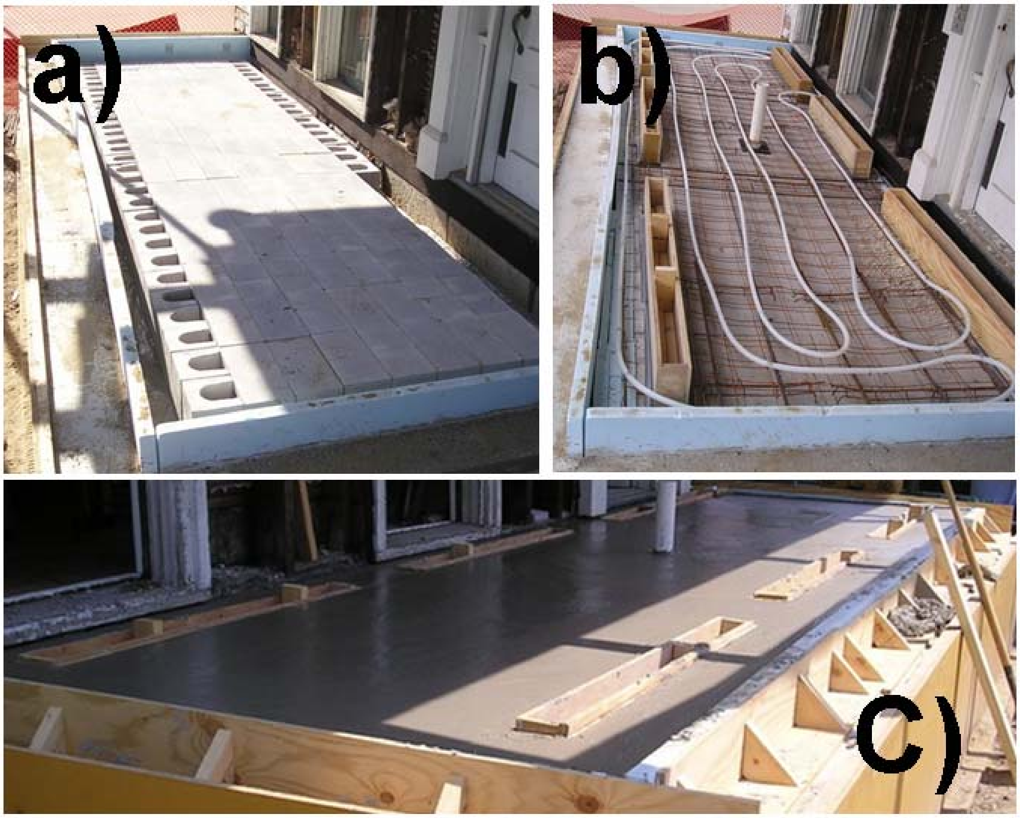
The windows on the south, east and west sides of the structure contain a low-e coating and have a U-value of 0.32 (BTU/ft^2/°F/hr). The opaque area (area without windows) of all four walls is filled with wet-spray cellulose insulation. The opaque area of the South, East and West walls has an R-value of 18 (ft^2 °F hr /BTU). The roof has an R-Value of 38 (ft^2 °F h /BTU).

An interesting feature of the floor is that is was designed to maximize thermal mass in order to minimize temperature fluctuations within the space. Specifically, from the bottom upward, the floor consists of the following:

1) 2” Styrofoam insulation (R-value = 7.5 ft^2 °F h /BTU)
2) 6” of compacted sand
3) 8” hollow concrete block laid sideways such that holes in the block form continuous tubes with each other extending from the south to the north sides of the structure (Fig. 3, panel a).
4) 6” of concrete poured on top of the block (Fig. 3, panel c)

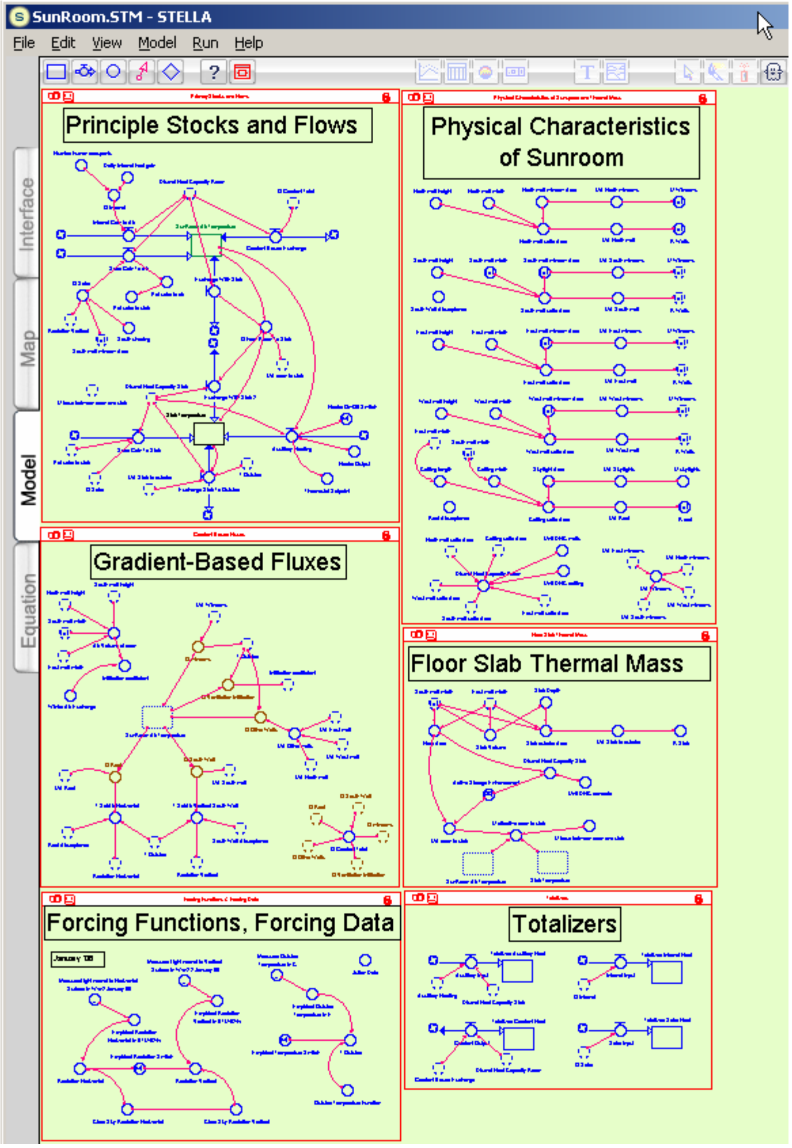
The hollow concrete blocks at both north and south ends are split in half and face upwards and go through the poured concrete floor such that air can be blown down into one side, traveling through the block, below the poured concrete and come out at the other end (Fig. 3, panel c). The concrete floor also contains tubing which is used for a radiant floor heating system. Fig. 3, panel b depicts the tubing before the 6” concrete slab was poured)

Figure 3. Thermal mass incorporated into floor


a)
b)
c)

The Model for Exercise #2

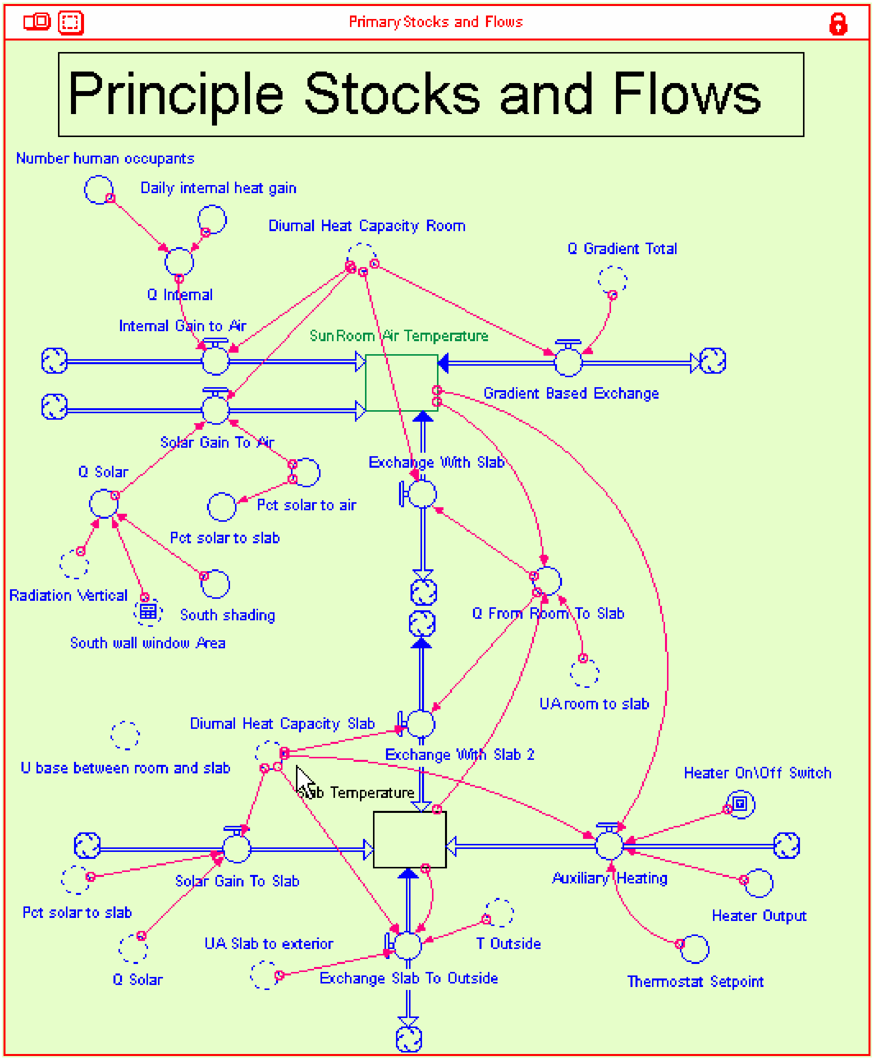
Take a deep breath and open the model “SunRoom.stm”. Although it appears to be very complex, what you see is, in essence, a refined and more flexible version of the model that you just created in exercise #1. Most of the complexity you see is incorporated to allow easy manipulation of the physical dimensions of the structure. The model is visually divided into a series of “sectors” that aggregate variables associated with different features of the model.



The sections immediately below explain the contents of each sector labeled above. Following this explanation you will be guided through a sequence of steps in which you explore and modify the model.

Although this text includes images of the model, you may find it useful to open the SunRoom.stm model and refer directly to it as you read through the explanations that follow. If you double click on flows and converters and click on the “Document” button, you will find details and notes on the origins of equations and coefficient values.

Principle Stocks and Flows



Stocks: As with the model you developed in Exercise #1, the principle stock under consideration in this model is the temperature of the sunroom (SunRoom_Air_Temperature). The only real conceptual difference between this model and the one you developed is the inclusion of a second stock, Slab_Temperature, to represent the thermal mass in the sunroom floor (Fig. 3). These two stocks are separated in this model to allow us to explicitly examine the role of the floor in storing and releasing thermal energy to the room.

Flows for SunRoom_Air_Temperature:
Four flows represent four classes of heat exchange affecting SunRoom_Air_Temperature.

1) Solar_Gain_To_Air is nearly identical to the variable of the same name that you worked with in Exercise#1. However in this model the equation in Q_Solar includes the effect of shading (South_shading). In addition, since we are modeling two separate absorptive regions of the room (the floor and all else), we need to specify the fraction of incoming solar energy absorbed by each. The Pct_solar_to_air coefficient specifies a percentage of incoming solar radiation that is absorbed by the portion of the room above the floor, the rest is absorbed by the slab.
2) Gradient_Based_Exchange is also similar to the variable of the same name in Exercise#1. In this case, however, this variable takes into account the separate gradient driven heat transfers taking place across each wall, window and the roof. The calculations of these individual fluxes take place within the sector labeled, “Gradient Based Heat Fluxes” and will be discussed below. The variable Q_Gradient_Total is the sum of all of the individual heat fluxes.
3) Q_Internal is a new flow. This variable represents the heat added to the space by human occupants, lighting and other appliances (see background section for further discussion of this flow).
4) Heat_Exchange_with_Slab is a new flow. This is also a gradient-based exchange, but in this case the heat is flowing between the interior of the room and the concrete slab that the floor is made of. The equation governing heat flow used here is simply the conduction transfer equation (Eq. 2):
   Q_from_room_to_slab = (SunRoom_Air_Temperature-
   Slab_Temperature)*UA_between_room_and_slab {BTU/hr}

The flow out of temperature is Q_from_room_to_slab divided by the Diurnal_Heat_Capacity_Room. As with Gradient_Based_Exchange, this is modeled as a biflow; when the floor is warmer than the air, heat flows from the floor to the air and air temperature goes up and when the air is warmer than the floor, heat flows in the opposite direction and room air temperature goes down.

Flows for Slab_Temperature:
There are four flows into and out of the Slab_Temperature stock.

1) Exchange_with_slab_2 represents the effect of heat flow between the sunroom and the slab on Slab_Temperature. The equation for this flow into Slab_Temperature is identical to the equation for the flow of heat out of SunRoom_Temperature, except that in this case, Q_from_room_to_slab is divided by Heat_Capacity_Slab to convert heat flow into temperature change. Since Heat_Capacity_Slab is significantly larger than Diurnal_Heat_Capacity_Room, a given flow of heat energy between the room and the slab results in larger changes in temperature in the room than in the slab.
2) Solar_Gain_To_Slab represents changes in temperature resulting from solar radiation absorbed by the floor. This flow is essentially identical in form to Solar_Gain_To_Air. Pct_solar_to_slab is the percentage of total incoming radiation that is directly absorbed by the slab.
3) Auxiliary_Heating represents changes in temperature resulting from heat energy that is delivered to the space from a radiant floor heating system. The way this system works is that if the heat is turned on and if the air temperature in the space is below the setpoint on a wall thermostat (Thermostat_Setpoint), then a water heating system will pump heated water through a coil of tubes embedded in the poured concrete floor (you can see the arrangement of these tubes before the concrete was poured in Fig. 3b). Since the heating is provide through the floor, it makes logical sense to model this as heat delivered directly to the slab, and then traveling to the room via heat

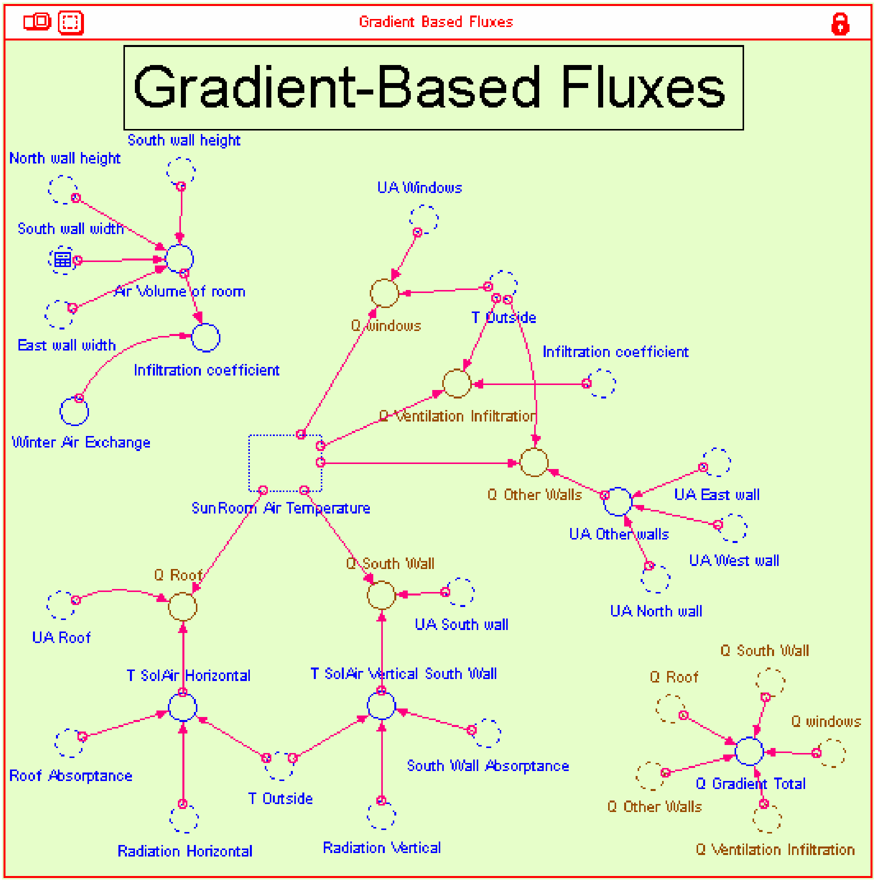
flow from the slab to the room. In the model, this heating system can be turned on or off with the Heater_On\Off_Switch variable (1=on, 2=off).

4) Exchange_Slab_To_Outside represents changes in temperature in the slab resulting from heat flow between the perimeter of the slab and the outside air. This is a gradient based heat exchange through the 2” of foam insulation between the slab and the outer portion of the foundation (this foam can be seen in Fig. 3). Heat flow between the mass and the earth below this mass is thought to be negligible and is therefore ignored in the model.

Gradient-Based Fluxes

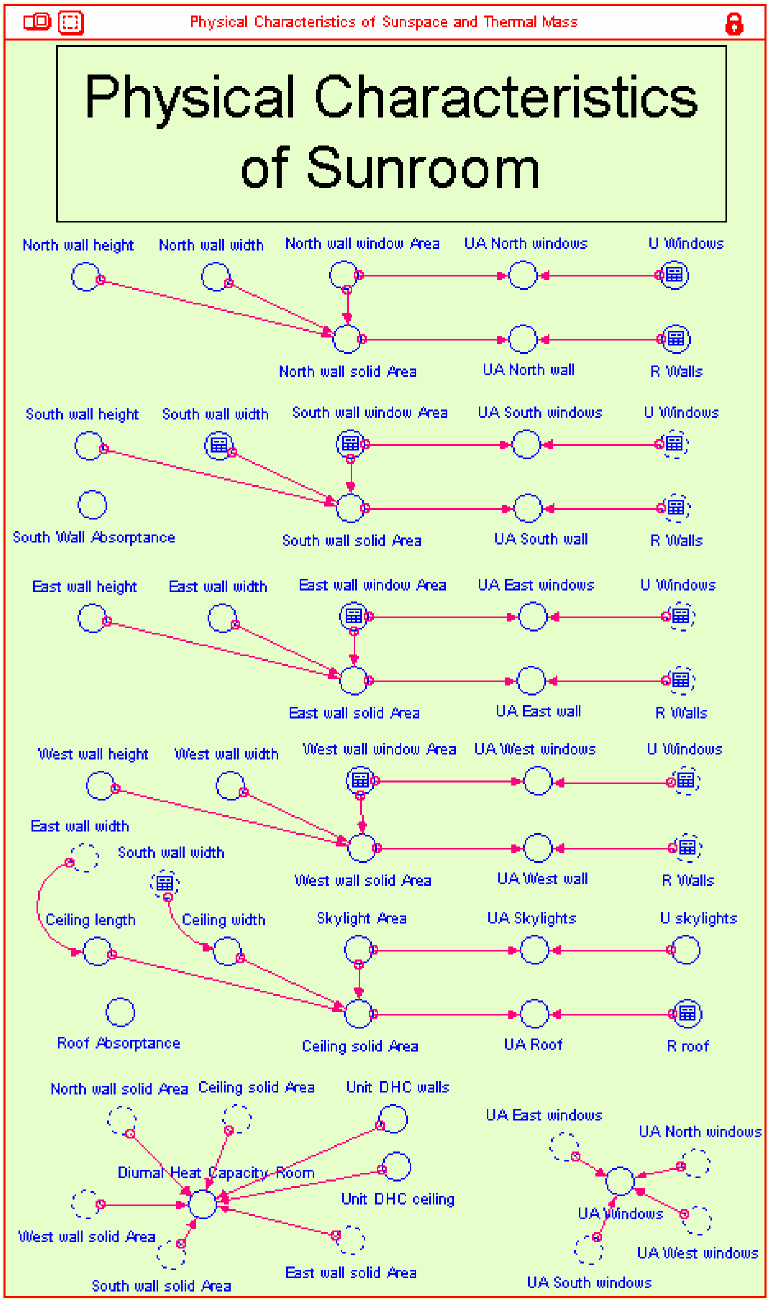
This sector of the model includes all of the gradient-based flows of energy between the interior of the sunroom and the outside. All of these flows are individually calculated, based on the UA values of the exterior walls and windows (see the Physical Characteristics of Sunroom sector for an explanation of UA calculations) and on the temperature gradient. For the south wall and for the roof, flow through the solid portions of the wall is calculated using the horizontal and vertical sol-air temperatures (Eq. 4 and 5 respectively) to account for radiative exchange (Eq. 3). For east and west wall exchanges, a simple gradient equation is used based on outside temperature (Eq. 2). The reason for using outside temperature instead of sol-air temperature for these walls is that the east wall is under a roof and never receives direct sunlight, and we do not have radiation data for the west wall with which to calculate a sol-air temperature.

An additional heat exchange mechanism, Q_Ventilation_Infiltration is used to account for heat that is lost through intentional ventilation and through leakage of air out of the space. The modeling approach is essentially to use the same type of gradient equation that is used for conductive exchange, where the Infiltration_coefficient is treated in the same way as a UA term. This term takes into account the air volume of the room and a winter exchange rate. The details of the calculations are explained within documentation for the Infiltration_coefficient converter. Q_Gradient_Total is the sum of all the individual gradient-based heat fluxes. This is the term that is used to drive the Gradient_Based_Exchange flow from the SunRoom_Air_Temperature stock.



Physical Characteristics of Sunroom

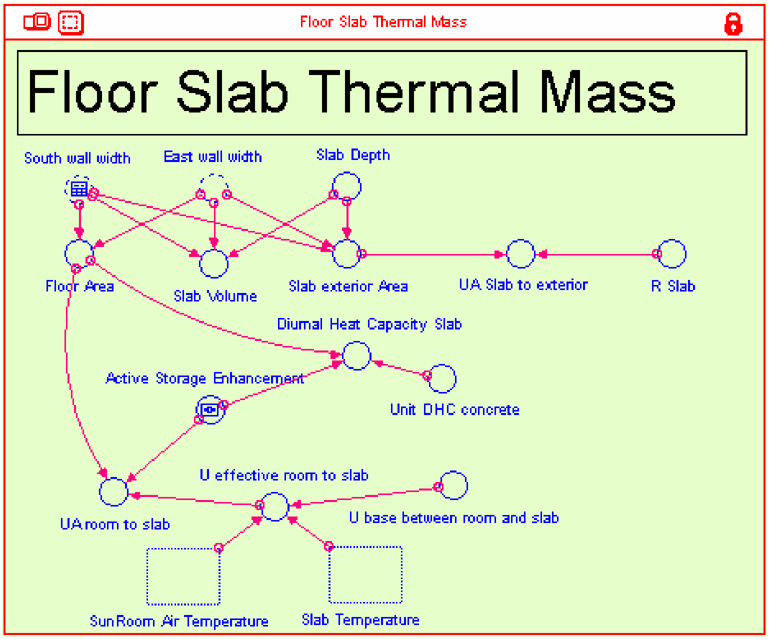
This sector of the model contains: the physical dimensions of the space, the window and wall areas, and U-values and R-values for each building component. It also contains calculations of UA values for each exchange surface as well as calculations of the diurnal heat capacity of the room.



UA values for windows are calculated as described in equation 2. Diurnal_Heat_Capacity_Room is the sum of the diurnal heat capacities of all of the individual walls and the ceiling. South_Wall_Absorbance and Roof_Absorbance are used to calculate the sol-air temperature and values are based on the white roof and walls present in this sunroom.

Floor Slab Thermal Mass

This sector contains the physical dimensions and physical characteristics of the floor slab. This sector also contains calculations for UA_room_to_slab, the UA value that governs exchange between the sunroom and the floor slab.

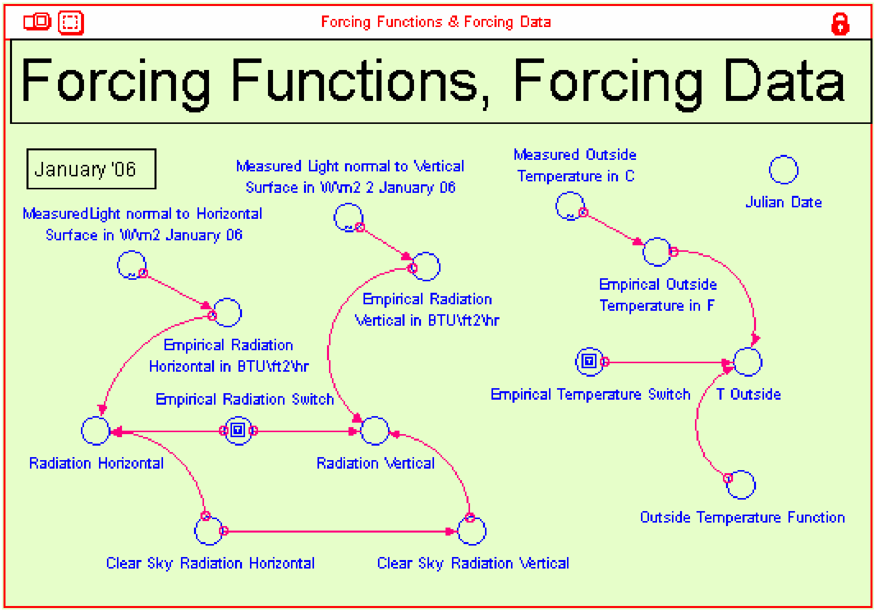


Diurnal_Heat_Capacity_Slab is modeled as a function of the slab area. This is a reasonable approach for a 6”solid concrete slab and might also prove to be a reasonable approximation of the diurnal heat capacity of the floor if no air is blown through the tubes in the concrete.
The equation for the thermal conductivity between the floor and the room air (U_effective_room_to_slab) accounts for both conductive and radiative transfer. The equation to account for expected directional differences in the thermal conductivity between the floor slab and the air is somewhat complicated. The equation assumes that heat flows more easily from the slab into the air than vice versa. The equation is explained in the documentation within the variable.

Blowing air through the tubes will have two effects on the thermal mass. First, it will effectively increase the diurnal heat capacity by increasing air contact with lower levels in the slab. Second, it will increase the rate of heat flux between the slab and the air. At this point, the extent of these effects is not known. The Active_Storage_Enhancement is designed to allow easy manipulation of the effect of blowing air through these tubes. This variable is multiplied by both Diurnal_Heat_Capacity_Slab and UA_room_to_slab. The default value of 1 simulates the effect of a 6” concrete slab with no additional heat storage or exchange properties. A value of 2 would simulate a doubling of heat storage capacity and a doubling of thermal conductivity with the air. A slider in the model interface allows easy manipulation of this variable from a value of 1 to 3.

Forcing Functions and Forcing Data

“Forcing data” and forcing equations are data and equations that are used as external input necessary to run a model. In other words, forcing data affect model performance, but are not affected by model performance. In this case, forcing is comprised of equations and data for outside temperature and vertical and horizontal incident solar radiation.



The Outsidte_Temperature_Function and Clear_Sky_Radiation_Horizontal and Clear_Sky_Radiation_Vertical converters contain equations that simulate idealized patterns of temperature and clear-sky vertical and horizontal solar radiation in January.

Since 2001, outside temperature and solar radiation data have been continuously collected from a weather station located on top of Oberlin's Lewis Center for Environmental Studies, which is immediately adjacent to Environmental Studies Laboratory that contains the sunroom. Data from these sensors from January of '06 are included in Empirical_Radiation converters.

Outdoor air temperature is monitored approximately two meters above the roof of the Adam Joseph Lewis Center for Environmental Studies (approximately 10 meters from the ground) using a Campbell Scientific CS 500 Temperature and Relative Humidity Probe. This probe is housed in a radiation shield so that it measures actual air temperature. Temperature data are stored and imported into the model in ºC, but are converted to ºF within the model so that it is consistent with the English units used throughout the model for heat flow calculations.

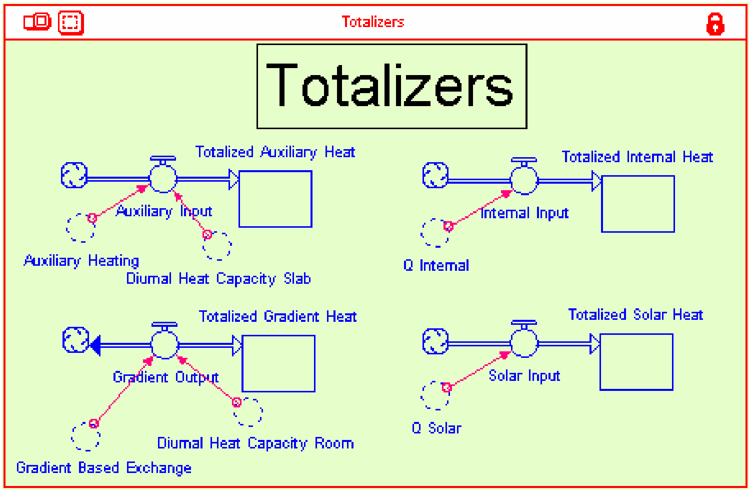
Total solar irradiation is monitored on the same weather station atop the Adam Joseph Lewis Center using a Li-Cor LI-200X Pyranometer. A pyranometer is a device for measuring total hemispherical solar irradiance (electromagnetic radiation) falling on a flat surface. This weather station has two pyranometers, one pointed due south that measures radiation falling on south-facing vertical surfaces and a second pointed directly skyward that measures radiation falling on horizontal surfaces. Given the elevation of these sensors (approximately 10 meters off the ground) and the lack of high buildings and trees in the vicinity, there is essentially no shading of these two sensors). In contrast, the sunroom is at ground level and is therefore subjected to a degree of shading. Pyranometer data are acquired and imported into the model in SI units of W/m^2, but converted to BTU/hr to be consistent with the English units used throughout the model.

The weather station acquires and stores data at one minute resolution, but for the purpose of minimizing numerical intensity, one hour averages are imported for use in the model. Since January weather in Oberlin Ohio combines low outside temperatures, low inherent solar radiation, and frequently overcast skies, Oberlin OH represents a challenge for passive and active solar heating systems. The model is initially configured to run from midnight of January 11, 2006 through midnight of January 17, 2006. We choose this six day period because this period starts with a clear sunny day, followed by five days with variably overcast skies typical of this month in this region of NE Ohio.

In its default mode, the model is configured to run using the Clear_Sky_Radiation functions and the idealized Outside_Temperature_Functions. A switch in the control panel allows you to shift to the measured data.

Totalizers

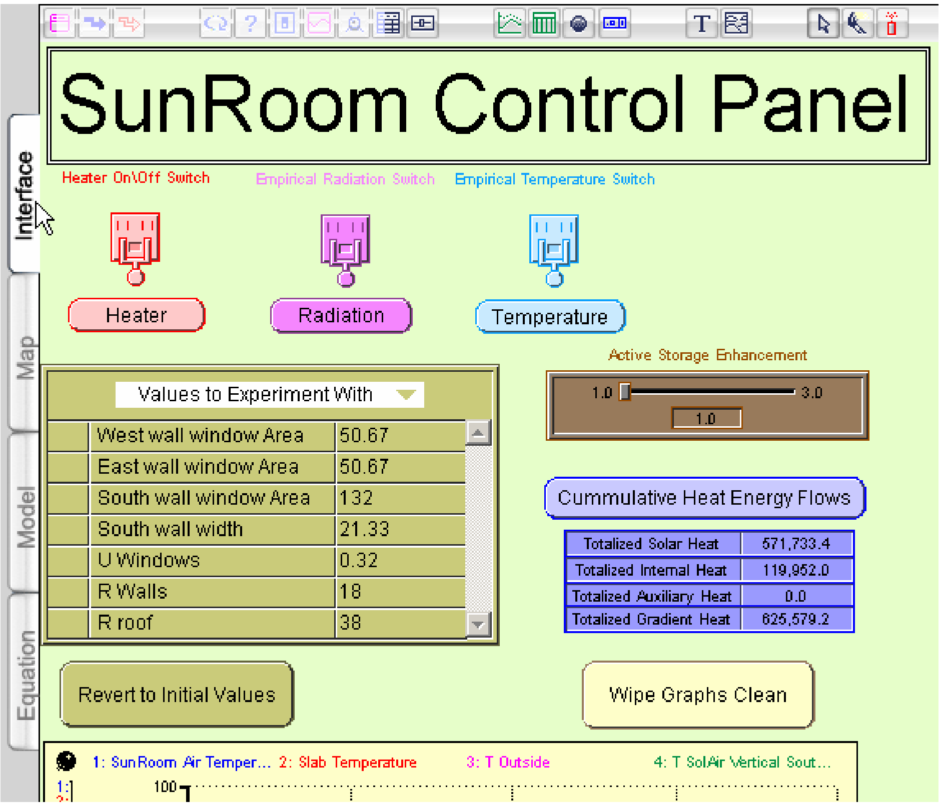
This sector of the model provides a mechanism for adding up the different energy inputs to the sunroom over a model run. Ghosts of the four main flows of heat energy into the sunroom are used to drive flows into stocks that accumulate over the course of the run. This allows for comparisons of the total energy of various types added to and lost from the sunroom. This sector exists for purely analytical purposes; the variables in it are affected by the rest of the model, but do not affect the model. If our equations are correct, the sum of inputs (Auxiliary_Heat, Internal_Heat and Solar_Heat) should be nearly equal to total outputs (Gradient_Heat) thus keeping the SunRoom_Air_Temperature nearly constant. The difference between these is attributable to heat stored or lost from the thermal mass within the sunroom.



Familiarizing yourself with the model and the modeling interface and control Panel

Once you have used the explanations above to familiarize yourself with the structure of the model, take a little bit of time to explore the physical layout of the model. Consider the effect of including a separate stock to represent the thermal mass of the floor. How do you expect this to change the performance of this model relative to the model you constructed in exercise #1? How does the fact that the slab has a larger diurnal heat capacity than the rest of the room affect your expectations?

Since this model is fairly complex, we have created an interface that allows you to easily manipulate variables. Click on the “Interface” tab on the left hand side of the model to get to the “SunRoom Control Panel”.



West wall window Area	50.67
East wall window Area	50.67
South wall window Area	132
South wall width	21.33
U Windows	0.32
R Walls	18
R roof	38

Totalized Solar Heat	571,733.4
Totalized Internal Heat	119,952.0
Totalized Auxiliary Heat	0.0
Totalized Gradient Heat	625,579.2

At the top of the control panel, there are three “switches”. Heater, Empirical Radiation, and Empirical Temperature switches control whether the auxiliary heating system is on and whether the model is using equations to generate idealized solar radiation and temperature forcing data or if the model runs using measured data. Click on the text buttons for explanations of how they work. By default, when the switches are in the off positions as in the diagram above, the heater is off and the model is running on the equations. Click on the switch icons themselves to turn them on.

The “Values to Experiment With” tool allows you to easily (and temporarily) change the values of this select group of constants. You manipulate the values of these variables in the sections of the exercise below. Try editing the numbers. You will find that they are constrained to a certain range of values. Click on the “Revert to Initial Values” button below and they will return to their initial values.

The “Active Storage Enhancement” slider tool is used to simulate the effect of enhanced diurnal heat capacity and enhanced exchange rate that results from blowing air through the tubes that extend within the slab of the sunroom floor.

Click on the “Cumulative Heat Energy Flows” button. The boxes below this depict the cumulative energy that has passed through each of the flows into and out of the sunroom over the course of the model. These “totalizers” are useful for comparing model behavior in different simulations. For example, when the Heater switch is turned on, you can use the totalized auxiliary heat to compare the heating needs of the sunroom under different design and management regimes.

There are two graph pads included on the Interface. The upper one, which is visible on the page, contains graphs (including comparative versions) of the majors stocks and flows. The graph below this contains “locked” graphs of the temperature and solar radiation forcing data. You will find it useful to be able to view these forcing data while examining the dynamics of stocks and flows in the upper graphs. The switches determine which data are actually used to drive temperature and solar radiation in the equations.

When you examine the graph pads you may notice time on the x-axis starts at 264 hours and ends at 408 hours. These units are the number of hours that have elapsed since midnight of December 31 ’05. If you were to divide these numbers by 24hr/day, then you would have the Julian day of the year for 2006. The model starts on January 11 and ends on January 17. This depiction of time may, at first, appear to be a bit confusing. However, the time units for equations in the model are all expressed in units of hours. This means that, in order to be dimensionally consistent, the time scale of the forcing data must also be expressed in units of hours.

a) Run the model on idealized forcing functions

Before you run the model for the first time discuss and on a single graph sketch your predictions for the dynamics of SunRoom_Temperature, Slab_Temperature and T_Outside. Run the model and discuss how the results do or do not match your predictions. How and why does SunRoom_Temperature differ from T_Outside? How and why does SunRoom_Temperature differ from Slab_Temperature?

b) Run the model with empirical data for January of ‘06

Take a careful look at the empirically gathered radiation and temperature data on page 1 and 2 of the 2nd graph pad and predict and discuss how running the model on these climatic conditions might alter dynamics. Once you have committed your predictions to paper, first turn on the “temperature” switch to change to empirical data, run the model and explain the observed dynamics. Turn temperature off and turn “radiation” on to switch to empirical light data. Again explain observed dynamics. Now try the model with both of these switches on. What conclusions can you draw about observed differences in model dynamics in these four scenarios? Which aspects of the dynamics seem to be driven by solar input and which by temperature?

c) Auxiliary heating

What do you expect to observe if you turn on the heater, which is by default set to go on when room temperature falls below a thermostat setpoint of 68ºF? Predict behavior, and then Turn off Radiation and Temperature, click the “Wipe Graphs Clean” button, run with Heater off to get a baseline, then turn the heater on and rerun. Does the behavior match your mechanistic predictions? Record the value for “Totalized Auxiliary Heat” – this is the cumulative BTUs of auxiliary heating energy that you just added through the floor heating system during the six days of the model run. Now predict the dynamics you would observe if this model were run using the empirical data for radiation and temperature. Turn Radiation and Temperature on and rerun the model. How do the patterns differ from your expectations? What are the cumulative BTUs of auxiliary heat and how does this value differ from what you observed when the model was run with idealized data?

Keep the model running with all switches on. What would you expect to happen if you changed the thermostat setpoint from 68ºF to 65ºF, what percentage heating energy would you save? Once you have made your prediction, use the "Values to Experiment With" box to change 68 to 65 and then re-run the model. How much energy did you save over the six day period? What percentage energy savings

d) Shifting from passive to active energy storage in the slab

Wipe the graphs clean and turn all switches off. We do not yet know the extent to which blowing air through the ducts in the slab will alter performance. Assume for the moment that this will simultaneously double the diurnal heat capacity of the slab and double the UA between the room and slab. How would you expect this to change dynamics? Discuss this with your partner and sketch out predictions for graphs of slab and room temperature. You can simulate this effect by moving the "Active Storage Enhancement" slider from 1 to 2 (or by just typing 2 into the box). Run the model and discuss what you find. You might try increasing "Active Storage Enhancement" even higher, but set it back to 1 when you are done.

e) Alternative design options

Using the now familiar approach of predicting and then simulating, use the "Values to experiment with" table to explore the effects of varying the thermal properties of the windows. How would dynamics differ if you used the best available windows (lowest U-value) from Table 2 in the Background section? How about if you used the worst windows? How would the total amount of auxiliary heat needed to achieve a 68ºF setpoint differ?

Revert to the initial values for windows and conduct the same sort of experiment for wall and roof insulation. Assume that R-values of 30 and 60 are the best you can do for walls and roof respectively. Then combine these.

Predict and simulate what would happen if you eliminated windows on the east and west walls. Do this by reducing the window area of these regions to zero. What would happen if you also eliminated the south facing windows? Predict and then simulate this. What is it about the way this model is currently structured that leads to such different outcomes for removing south and west facing windows? How might you go about modifying the model to increase realism on this point?

Revert to initial values and then predict what would happen if you doubled the length of the south facing wall and then filled this with windows by doubling the window area. Note that in the "Floor Slab Thermal Mass" sector of the model, Floor_Area is calculated as a function of the south wall, so that the thermal mass of the space will automatically increase as you increase the length of the southern wall. Simulate this.

The amount of solar radiation absorbed by the floor could potentially be increased by painting the floor black. You can simulate this effect by increasing the percentage of light absorbed by the floor (Pct_solar_to_slab). Try doubling it[6]. Predict the effect, then alter it in "Values to Experiment With".

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[6] Note that when you increase the value of the Pct_solar_to_slab variable it ceases to expresses the percentage of radiation absorbed by the floor and Totalized_Solar_Heat no longer accurately reflects total solar heat, but this type of modification is fine for a quick and dirty assessment of the impact of changing floor color.

f) Further exploration of alternative management options: movable insulation
This model could be modified in any number of ways to represent other design and management options. Your task in this last part of this exercise is to modify the model to analyze at least one of these.

The south windows are important sources of solar gain when the sun is shining. They are, however also an important source of gradient-based loss on overcast days and at night. How would you create a variable that could be used to indicate the point at which the south windows become net losers for providing heat to the space? Create this variable. One way that heat loss can be reduced is to temporarily add insulation to the windows when they are net losers. For example, people sometimes add “Window Quilts” or internal shutters that contain insulating materials to effectively decrease the U-value. Modify the model to simulate the installation and use of removable insulation so that insulation is spontaneously added when the windows become net heat losers and removed when windows would become net heat winners. Note that exploring this scenario will require considerable modification and the development of several new variables. The company that manufactures the Window Quilt product indicates that it adds an R-value of 4.99 to a window during the portion of the day when it is rolled down.

What other design and management options should be explored? How might you further modify the model to assess the impact of these modifications?

Glossary of Terms:

Active solar:. Systems in which mechanical technology, such as blowers or pumps are used to move heat between areas in which it is collected, areas in which it is stored, and areas in which it is used.

Calibration: The process of modifying coefficient values and equations in a model so that it produces output that matches the dynamics of real-world phenomena.

Conduction: The process by which heat travels through materials that are in direct contact with each other.

Convection: The movement and mixing of a gas or fluid that contains heat from one region to another.

Density: The mass of a substance per unit volume (SI: g/L, g/m^3, English: lbs/ft^3)

Diurnal heat capacity: The amount of heat energy required to raise the temperature of one square foot of “thermal mass” one degree Fahrenheit. When the diurnal heat capacity (dhc_i) of every material in a room has been calculated (DHC), the diurnal heat capacity becomes the amount of heat energy required to raise the internal temperature of that room or building one degree Fahrenheit

Heat capacity (also know as specific heat and specific heat capacity): The amount of energy required to raise a unit of mass of the material by one degree (SI units of kJ/kg/K, English units of BTU/lb/ºF).

Insolation: Solar radiation.

Passive solar: Systems in which no mechanical technology is used to transport and store heat (contrast with active solar).

Radiation: Energy in the form of waves (or particles if you want to look at it that way) that is delivered in sunlight (mostly visible and infrared radiation) and is emitted by heated objects (infrared radiation).

Sol-air temperature: Technically defined as, "the temperature of the outdoor air that in the absence of all radiation exchanges gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings and convective heat exchange with the outdoor air" (ASHRAE, 2001).

Specific heat: Identical to heat capacity

Thermal conductivity (U-value): The ease with which a material conducts heat. The inverse of thermal resistance. (SI units of watts/m^2/ºC, English units of BTU/ft^2/°F/hr).

Thermal mass: Material that absorbs, stores, and releases heat in a space.

Thermal resistance (R-value): The degree to which a substance resists heat flow. The inverse of the U-value. (SI units of ºC m^2/watt, English units of ft^2 °F hr/ BTU).