Passive Cooling

Part I — Basic Principles

Cliff Mossberg

Though the climate of Belize is hot and humid, residents can use various passive techniques to create a cooler, more comfortable living environment.

Much of my early adult life was spent homesteading in the Alaskan bush. Winters are the predominant force there, and like most others in a northern or temperate zone climate, my main concern was keeping my living space warm. My location colored my entire world view. It never occurred to me that in some places in the world, the problem was to stay cool.

Most of the residents of the United States have similar problems of perception. Because of this necessary emphasis on heating, there is not a lot of information available on alternative methods of cooling. In 1980, I was fortunate enough to "retire" to the Central American country of Belize where I routinely encountered temperatures in the eighties and nineties, and humidity in the upper 30 percent of its range. 95°F (35°C) at 95 percent humidity will quickly draw your attention to the need to cool down.

In the United States and most other industrial nations, cooling is dealt with by refrigeration. Air conditioners are predominantly powered by electricity, which is usually produced by burning fossil fuels. Affluence allows us to condition our living space using an expensive fuel of convenience. Most "third world" nations only allow this luxury to the very well-off. Where grid power is available in Belize, it costs 25 cents per kilowatt-hour. This is far too expensive for the average person to use for cooling on a regular basis.

Cooling for the Humid Tropics

Over the years, I've studied the problem of low energy input cooling in the tropics worldwide. There are two very different environments that demand solutions to the cooling problem. Hot, arid landscapes may require cooling as much as hot, humid areas, but the principles used to address the two problems are quite specific.

In this series of articles, I will try to pass on what I have learned about using sun, wind, and the basic principles of heat transfer to create a comfortable living environment. I am specifically targeting the humid tropics, but many of the principles I will discuss are relevant to arid areas as well. I will emphasize passive techniques here—things that can be done without using any technically derived energy to move heat, or techniques using devices to control heat flow automatically.

This will be a multi-part article. In the first part, I cover the basic principles of heat transference, and try to explain how they interact and what type of effects they produce. Later, I will discuss materials and environmental factors. Also, I will specifically apply the basic principles to building design and construction.

Heat Fundamentals

Heat is the motion of molecules in a substance. The hotter the temperature, the more energetic the motion becomes. There is no such thing as "cold"—there is only more or less heat. Cold is our own subjective reaction to a condition of too little heat for the body to be in its comfort zone.

This is an important concept because there is no one perfect temperature at which we are all comfortable. The human comfort zone depends on several factors,

Methods of Heat Transmission

Method	Transmission Mechanism	Transmission Medium	Direction of Heat Movement
Radiation	Electromagnetic radiant energy	Vacuum or transparent medium	Any direction, line of sight from source
Conduction	Molecule to molecule mechanical transference	Any substantial material in contact	Any direction into material in contact
Convection	Physical relocation of a heated substance	Usually movement of a heated fluid	Usually upward, unless forced

not least of which is the human acclimatization to the specific environment we live in.

While temperature is proportional to the energy of vibration in molecules of a substance, heat quantity is a measure of the numbers of these molecules and the temperature at which they are vibrating. A large pan of boiling water has more heat in it than a small one does, even though they are at the same temperature.

As matter heats up, the molecules move farther apart—they expand. Thus for the same volume of matter, there are fewer molecules if the material is hotter. This means that the same volume of our hypothetical material weighs less per unit volume when it is hot and more when it is cold and dense. This is true of solids, liquids, and gasses that are unconfined.

Three Modes of Heat Transfer

There are three ways that heat can be transferred between a source and a receiver body. They are radiation, conduction, and convection.

They all accomplish the task of imparting heat energy to a receiver body, and they do so in proportion to the difference in temperature between the sending source and the receiving body (called "delta t" and written "Δt"—Δ means "the change in"). The higher the difference in temperature between a heat source and a heat receiver, the faster heat will flow into the receiver and the faster its temperature will rise.

Radiation

When we talk about the electromagnetic spectrum, all we're talking about is "radio" waves—waves of magnetic energy that can propagate through a vacuum in space, thus transferring energy from the sun, stars, and galaxies to our earth. We are familiar with AM radio and the higher frequencies of FM radio and TV, but the radio spectrum contains many other waves of much higher frequencies. Visible light is a series of radio waves that our bodies can detect directly.

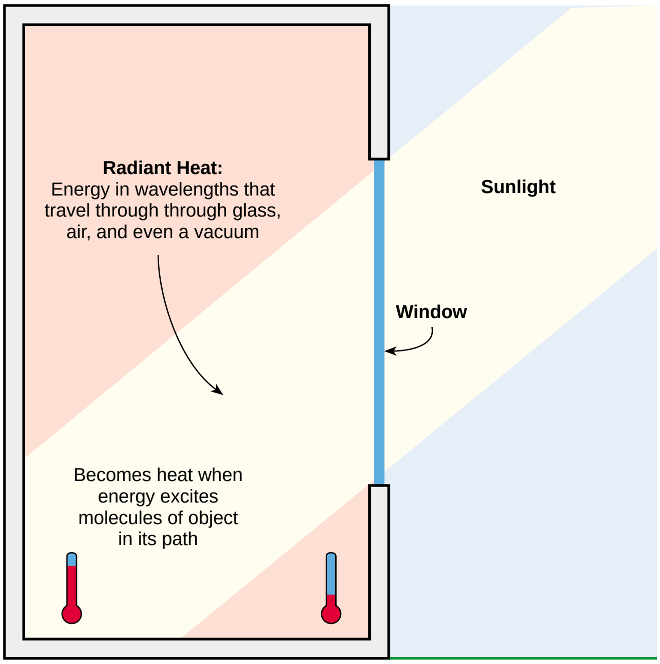
Other frequencies such as infrared (lower in frequency than visible light), ultraviolet (above the frequency of visible light), and x-rays (very, very high frequency) are undetectable by the human eye. Yet these frequencies transfer energy as surely as the visible light frequencies, and we are affected directly by them. Infrared radiation from the sun produces the feeling of heat on our skin when the sun's rays hit us. Ultraviolet radiation causes sunburn, and x-rays can kill or mutilate our body's cells.

Infrared radiation is the vehicle of heat transference that is most important to life on earth. It is heat radiation transmitted directly to the earth by the sun. It is one of the principles that allows a woodstove or a bonfire to radiate heat that warms at a distance.

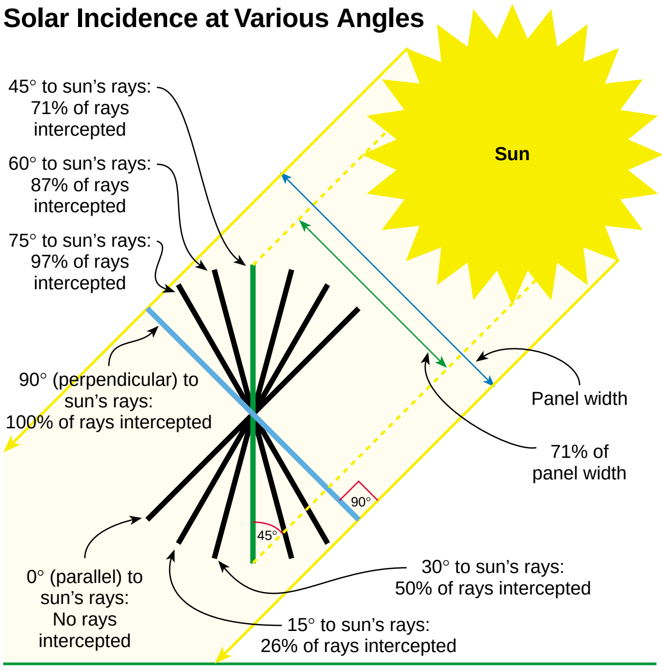
Visible wavelengths can be converted to infrared radiation when they fall on an absorptive surface, such as a roof or a photovoltaic panel. The energy in these light waves is absorbed by the surface, causing heating. This heating in turn causes re-radiation from the absorber as heat, or infrared light. This is the reason hot water collector panels are self limiting in their efficiency. The collector panel heats up the water until the water re-radiates as much energy back to the sky as it takes in. At this point, there is no further gain in collection of radiant energy possible.

A roof heats up in the sun's rays until it re-radiates infrared heat energy down into the house as well as out

Heat Transmission through Radiation



Solar Incidence at Various Angles



into the air. If the ceiling has no barrier to radiant energy, this radiation will heat up the ceiling surface, which in turn will re-radiate the heat directly into the living area of the structure. Radiant energy is the principle vehicle for moving heat in a downward direction into a structure.

Effects of Solar Incidence

There are several factors that affect the ability of a surface to absorb or radiate infrared energy, and one of the most important is the angle at which the radiation hits the absorbing surface, known as the angle of incidence. If you want to absorb energy at the maximum efficiency, radiation should fall on a collection surface that is exactly perpendicular to that radiation.

The diagram above shows a variety of panel angles in relation to the sun's rays. When the panel is perpendicular to the sun's rays, the most energy is intercepted. When the panel is set at 45 degrees to the sun's rays, only about 70 percent of the available energy is captured.

Absorption & Reflectance

Another factor that affects the amount of radiation converted to thermal energy on a hypothetical earth "panel" is the color and texture of the surface. This is so fundamental to our experience that the concept is understood intuitively. Dark surfaces absorb heat and energy, while light surfaces reflect them. Rough surfaces absorb energy, while smooth surfaces reflect it. What is not so intuitive is that colors and textures that absorb energy well, also radiate energy well.

Absorbtance Characteristics for Common Building Materials

Surface	*Solar Absorptance*
Asphalt Shingles	
Dark	95%
White	75%
Rough Wood	
Dark	95%
White	60%
Smooth Wood	
Dark	90%
White	50%
Glazed or Enameled Surfaces	
Dark	87%
White	37%
Stucco	
Dark	90%
White	50%
Unpainted Brick	
Dark	85%
White	65%
Concrete Block	
Dark	95%
Unpainted	77%
White	55%

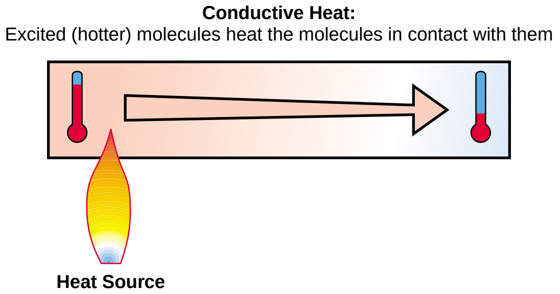
Reflective metallic foils take advantage of this. They are actually conductors, but when specifically engineered into buildings to control radiant energy, they are as much as 95 percent effective at blocking radiant energy absorption. They are also very resistant to re-radiating absorbed energy.

To be this effective, a radiant barrier must be installed with an air space on one or both sides of the material. Its mirror surface will then reflect any infrared energy rather than absorbing it and conducting it as heat.

Conduction

Conduction is the most intuitively understood mode of heat flow. For conduction to occur, materials must be in contact with each other. For example, imagine a copper bar one foot long, two inches wide, and half an inch thick (30 x 5 x 1.3 cm)—a rather substantial piece of copper. If we support this bar, and place a candle or a Bunsen burner under one end, the bar will slowly heat up from one end to the other. Soon the whole bar will be too hot to touch. Heat is being transmitted by conduction throughout the bar.

Thermal Conduction



What is happening here is that the heat source is exciting the molecules in the copper to vibrate more enthusiastically, becoming more and more energetic as the temperature increases. As these copper molecules pick up physical motion from the heat energy, they continuously "bump" into the molecules next door.

This physical disturbance imparts energy to the adjacent molecules, causing them to increase their vibrational energy—they warm up. Heating progresses down the bar, away from the heat source, until the whole bar has reached a state of equilibrium based on the amount of heat supplied by the source.

Conductive Heat Flow

Radiant energy is one of the loss factors that draws heat from the bar. Another factor that allows the bar to lose heat is conduction to the medium surrounding it. This is a loss by physical contact with the fluid—air—surrounding the bar.

Different materials will move heat at different rates. Based on these rates, materials are classified as "insulators" if they retard the flow of heat, or "conductors" if they facilitate the movement of heat. These are far from absolute definitions. Most insulators are designed to retard heat flow in conduction, but there are some exceptions such as metallic foil radiant barriers.

Air can be either an insulator or a conductor. For example, air is used as an insulator to slow down the transmission of heat in homes. It is the "dead" air space in fiberglass batt insulation that does the work. But air is also a cheap and relatively effective conductor of heat in electric motors, vehicle cooling systems, and many other applications. So while it is important to understand how material properties affect heat flow, you should also realize that these properties can be applied in many ways to achieve an engineering goal.

Boundary Layer

In conduction, heat flows through a substance because of tangible physical interaction between molecules. These same forces allow heat to flow between any substances that are in contact with one another. The boundary where one substance stops and another begins (between the copper bar and the air, for example) is known as the interface. Heat flow across an interface can be complicated by factors that are not obvious. The first of these factors is the variable rate of conduction by different materials. The second factor is the mobility that a fluid has, which results in convective flow.

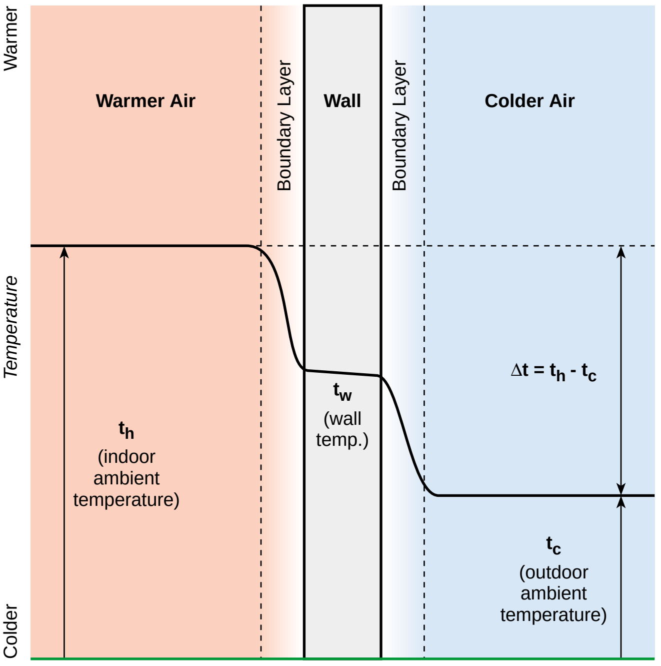
Conductive heat flow is impeded when a fluid such as air is in contact with a heated surface such as a wall. This impediment is caused when a layer of stagnant air is changed in temperature and density by heat moving across the interface. The air in the layer next to the wall

Materials and their Conductivity

Material	*Conductivity (Conductance)**
Copper	220.000
Aluminum	122.000
Steel	25.000
Concrete	0.600
Water	0.350
Brick, red	0.270
Rubber, soft	0.100
Wood, pine	0.070
Corkboard	0.025
Rock wool	0.023
Air	0.014
Vacuum	0.000

*BTU per hour per sq. ft. per degree per foot thickness

Conduction through a Boundary Layer



will heat up more that the air some distance away. When this situation exists, the change in temperature (Δt) between the warm wall and the warm layer of air is reduced. This cuts back on heat flow.

The existence of the boundary layer and its removal is the essence of "wind chill." This is when it feels colder than the real ambient temperature because of the extra heat loss when the wind blows away the boundary layer around our bodies. This is undesirable when we are trying to keep warm, but very desirable when we are trying to cool down.

The conductivity of any material can be measured and quantified so that the relative qualities that make it an insulator or conductor can be examined in absolute terms. The conductivity table lists some materials and their conductivity. Even without knowing how to use the "soup" of units with which these materials are labeled, it is obvious that copper has a very high conductance value (220), while air is very low (0.014).

Convection

In its most generic form, convection involves the movement of heat by transporting some hot substance. Convective heat movement is usually associated with the movement of fluids. There are two common forms of convection—"forced" and "free." In forced convection, power is used to move a heated fluid from the source of heat to the heat destination. Vehicle radiator type cooling systems and hot water or hot air home heating systems are common examples of this.

Since we are interested in heat flow that occurs without any energy input from us, we will be concentrating on free convection to move our heat. Free unpowered convection happens due to the difference in density or molecular concentration per unit volume that occurs when a fluid is heated.

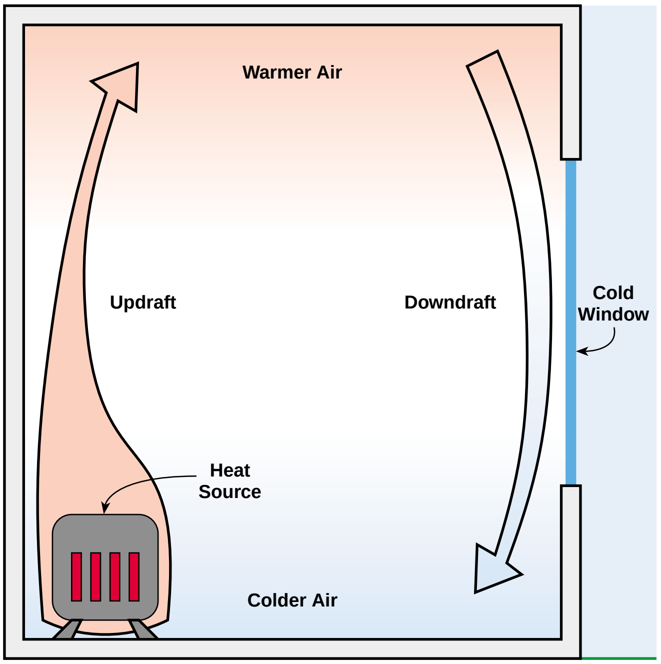
Molecular Density & Weight

The same volume of material weighs less per unit volume when it is hot and more when it is cold. Thus a "cold" (less hot) fluid packs more matter into the same volume than the same amount and type of fluid when it is heated.

The practical result of this change in density is that a hot fluid, being lighter, will "float" on a colder fluid. Conversely, a cold fluid will move downward under the pull of gravity until it finds the lowest level possible. These are dynamic processes. The fluid actually physically flows from one position to the next as its thermal status changes. Such flow results in the movement of heat.

If you put your hand over a heated stove burner, you can feel air rising off the burner. A hot air balloon depends on the change in density between the hot air inside the balloon and the cooler air outside it to rise into the sky. On a warm summer day, the lake you swim in will have a warm layer at the top and cooler water underneath. These are all examples of fluid movement caused by a change in density that causes convective heat to rise.

Thermal Convection in a Fluid



Convection is the movement of the heat rather than the movement of the fluid. But the two are inexorably intertwined, so much so that we also call the fluid movement convective flow.

Stratification & the Greenhouse Effect

Hot air flows up; cold air flows down. This causes several familiar effects such as stratification. The warm water on the lake surface in the example above is a case of stratification. Water in the lake is heated by sunlight and rises to the top level, where it cannot go up any farther. Here it forms a layer. It gives off some of the sun-induced heat to the air above it, becomes more dense, and eventually sinks again.

Depending on the amount of solar energy available, this convection loop will stabilize so that approximately the same amount of water is constantly heated, rises, gives off its heat, and sinks back into the cold depths. Thus solar heat is moved from the lake to the air.

The conversion of visible light energy into re-radiated radiant energy contributes to what is called the "greenhouse effect." That's the label for the tendency of heat to build up in a greenhouse so that the air inside is much warmer than ambient outside temperature.

This happens because glass that is transparent to visible light waves impedes the re-radiation of infrared wavelengths. The trapped radiation heats the structure, fixtures, and air inside the building. This heated air is trapped inside the greenhouse by the glass (probably causing stratification), and cannot move the heat away by convection.

Chimney Effect & Boundary Layer Disturbance

Convection directly affects the comfort of our living space, and even the clothes that keep us warm. It also affects the boundary layer, which is made up of stagnant air that acts like an insulator.

If the Δt between the ambient air and the boundary layer is anything but zero, the boundary layer will attempt to rise or fall of its own accord, inducing convective heat flow. This can be the boundary layer around our own warm bodies on a cool day, chilled air flowing down a cold windowpane to create floor drafts in a dwelling, or heat rising off the inside of a solar heated wall.

Another convective phenomena commonly encountered is the “chimney effect.” In most furnaces, exhaust gasses exit the combustion process under the influence of convection. The heated gasses are lighter than the ambient air, so they rise up the chimney, pulling air into the furnace or stove through cracks or through a controlled draft regulator. The hotter the flue gasses and the longer the chimney (within limits imposed by conductive heat loss), the faster the gasses will exit, so the stronger the gas column flowing up the chimney will be. Most stoves and furnaces would simply not work if this convective flow was not possible.

This chimney effect is not limited to chimney flues. It can be used in a building as a tool to move hot air out of the living space. The rising hot air can be supplied by solar energy. The resultant air movement is used to induce whole house ventilation where it might otherwise be difficult to achieve passively.

Wind as a Heat Mover

Under the right circumstances, warm lake water will heat the cooler air above it, inducing another fluid convection cell in the air. This air is heated, rises, cools, and circulates back down to the surface to be heated again. This process is much the same as the drafts settling off a cold window. It is much greater in volume, and we call this movement wind. Anything that can affect the heating of the air mass is important.

Wind is our ally. We have limited ourself by definition to creating comfort passively in our living environment. We have cut ourselves off (or been cut off by circumstances) from the use of highly concentrated fossil fuel derived energy. Yet to move heat around to our advantage, it takes energy—sometimes large amounts of it. Wind is the one source of energy readily available to us that can do this job.

The differences in reflectance of the earth’s surface is important to heat absorption wherever we are. Black basalt rock will absorb more solar energy than light silica sand. A farmer’s pasture will absorb less heat energy than the concrete streets and building walls in a city. This brings us back to the basics of material, surface texture, and color.

We don’t usually think of something like a parking lot affecting natural breezes. Yet such a man-made feature can have a vast effect on the microclimate that we are subjected to in our living spaces. A large black parking lot will absorb a lot of solar energy. This solar energy will be transmitted into the soil through conduction, re-radiated into the surrounding environment as radiant heat, and will heat the air above it, which can then rise convectivly.

This convective flow may induce local breezes where there would be none, or it may disrupt natural wind flow. The radiant energy will distribute itself outward from its source to all the surrounding areas adjacent to the lot, causing local heating and possibly destroying any benefits a locally induced breeze might produce. Conductive heating of soil will create a reservoir of heat that will continue to radiate to the surroundings long after the ambient air temperature should have become naturally cooler. All three factors as well as terrain and vegetative cover are interactive and each affects the other.

Humidity & Evaporation

No discussion of wind and weather would be comprehensive without understanding the role of humidity and evaporation. Wind and weather are formed as part of a large heat cycle driven by solar energy. One of the principle forces acting on this cycle is the addition or subtraction of heat through evaporation.

It takes one BTU (British thermal unit) to raise the temperature of one pound of water from 211 to 212°F (99.4 to 100°C), but 970.4 BTUs are needed to turn it to steam at 212°F. Those 970.4 BTUs are known as latent heat, measured under standard conditions of one atmosphere of pressure at sea level.

Water does not have to boil to absorb this latent heat. It will slowly evaporate at room temperature, requiring the same latent heat. Evaporation requires heat, and this heat, coming from surroundings, cools the environment considerably. The heat taken in or given off as this process occurs creates a very complicated thermal dance in everything from deserts to hurricanes.

Unless it is artificially dried, air contains water vapor suspended in molecule-sized droplets. The amount of water air can hold is determined by its temperature and density. Hot air can hold more moisture than cold air. So that there will be some common point of reference when talking about air moisture or humidity, figures for the water content are given as “relative humidity.”

Relative humidity measurements are given in the percent of moisture that air holds relative to its maximum possible moisture content at a given temperature. The range runs from 0 percent for absolutely dry air to 100 percent for air that holds as much moisture as is physically possible. This is known as the saturation point. Anything greater than 100 percent relative humidity will lead to free water condensing out of the air as mist, fog, clouds, rain, or snow.

The amount of moisture that air can absorb under any condition is dependent on temperature and the amount of moisture it already contains. Thus air measuring 70 percent humidity can only absorb the equivalent of the remaining 30 percent moisture capacity. The lower the air humidity, the more potential moisture the air can still absorb.

The more moisture that can still be absorbed, the more potential there is for heat removal through evaporation. By evaporating moisture into the air as humidity, cooling can be produced. And the more moisture that can be absorbed, the more efficiently you can cool with evaporation. Humidity bears directly on the creation of the human comfort zone, since the body depends on evaporation through perspiration to rid it of excess heat.

Vegetative Cover

The black surface of an asphalt parking lot is a very good absorber of thermal energy. The dark green surface of vegetation is also a good absorber of thermal energy, yet the plants cool their microenvironment. How can this be?

Plants are designed to effectively trap solar energy. But instead of absorbing light and producing heat, they produce plant sugars through photosynthesis. Much of this solar energy has no chance to be turned into excess heat. It is directed to the plants’ needs instead. Because of this, the use of green foliage to block sunlight striking a building is very effective. The advantage of such shade is obvious when it comes from trees, but the use of vining plants on trellises covering roofs and walls also works effectively to lower temperatures.

One of the products plant leaves give off is water vapor, a vegetative “breath” that is transpired from pores in the leaves. Transpiration is the process of taking in gasses (mostly CO_2) and sunlight, and giving off oxygen and water vapor. This evaporating water absorbs heat from the leaves and the surrounding air, cooling the local microclimate. The combination of transpiration and evaporation is called “evapotranspiration.”

Local Breezes

Transpiration can also play a significant role in local breeze generation. The figure on the facing page is a scale cross section of the Barton Creek valley where I lived in Belize. The east side of the valley and the adjacent hill was cleared for pasture when the original settlers moved in. It is covered with low bushes and a dense fern covering that is locally called “tiger bush.” It faces squarely into the afternoon sun, and the rate of vegetative transpiration is poor.

The west side of the valley was too steep to be cleared, so it is mostly covered with undisturbed jungle canopy. Direct morning sun hits this slope and is cooled by the vegetation, but late in the afternoon when the east slope is hottest, this west slope is taking the indirect (non perpendicular) sun’s rays and is cooled still further. Air is heated on the east slope and rises, while it is cooled on the west slope by the tree canopy and sinks down into the valley.

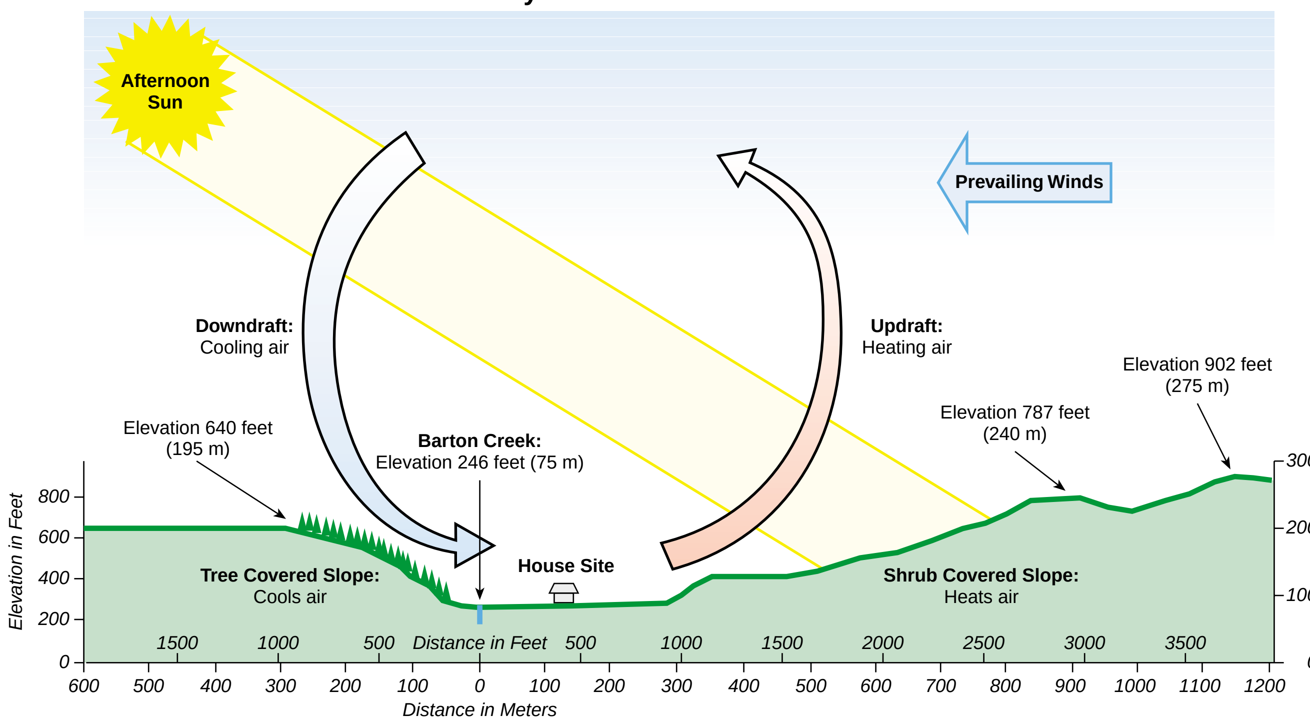
The net result of this differential movement is a strong afternoon breeze that blows straight across the valley in the hot dry season, contrary to the direction of the prevailing Caribbean trade winds. The existence of such a wind is completely counterintuitive, but very much appreciated because it is much more local and intense than the prevailing breeze. This illustrates how much significance local and regional factors, both natural and man-made, can have on ventilation and heat flow.

Terrain such as hills or mountains can act as deflectors to re-route prevailing winds, either creating a wind shadow or augmenting wind velocity. Up to a point, when you are trying to get cool, more is better, so astute selection of a house site with an emphasis on maximizing (or minimizing) local wind is important. A good site for wind will provide the energy needed to deal with uncomfortable temperatures either passively or actively.

Human Heat Physiology

In spite of any surplus heat from the environment, the body must maintain an internal temperature very close to 98.6°F (37°C). There are a great many mechanisms that we have evolved to effect this precise temperature regulation. All three mechanisms for transferring heat are at work—radiation, conduction, and convection. In addition to those three, the body also uses

Localized Winds in the Barton Creek Valley of Belize



perspiration—shedding excess heat through the latent heat of evaporation.

The high relative humidity typically encountered in the humid tropics (around 95–98%), will severely interfere with the ability to lose heat through evaporation. The air is already saturated and cannot hold more moisture. This is the great difference between a hot humid environment and a hot arid environment.

Where the humidity is low, the body has the cooling mechanism of evaporation at its disposal and the low air moisture considerably increases the efficiency of the process. This makes the designer's job much easier in such an environment.

Since I am targeting passive cooling in a hot humid climate, my emphasis will be on techniques for the humid tropics and subtropics. For those readers who are fortunate enough to have dry desert conditions as their design criteria, I direct you to two books by the Egyptian architect Hassan Fathy. These books are superb, clear, well illustrated, and relatively non-technical.

Acclimatization

When I moved from Alaska to Belize in 1980, I was adapted to the subarctic environment of interior Alaska. Winter temperatures plunged to -60°F (-51°C) routinely, while summers were "oppressively hot" at 80°F (27°C). I could work in shirtsleeves at 35 to 40°F (1.6–4.4°C) and be comfortable.

In five years in Belize, the coldest temperature I ever encountered was around 55°F (13°C). The typical high temperatures were 75 to 80°F (24–27°C) in winter, 90 to 95°F (32–35°C) in the wet season, and 95 to 108°F (35–42°C) in the hot, dry season. Getting used to these temperatures so that my body could regulate itself was difficult. I acclimated about 80 percent in the first year, and by the end of year two, I was 90 to 95 percent acclimated. I never reached 100 percent in the five years I lived there full time.

If you live in Phoenix, Arizona where the temperatures go to 125°F (52°C) in August, and you are used to a 72°F (22°C) air-conditioned environment, you will never acclimate to the heat because you are not forced into it. But if you are out in the heat as it gradually increases over the spring and summer, you will find yourself growing accustomed to an environment that would have seemed impossibly hostile before. If you are acclimated to the local climate, whether hot or cold, it will take much less energy input to remain in the comfort zone under adverse conditions.

The Comfort Zone

The comfort zone is defined as those combinations of conditions of humidity, temperature, and air motion under which 80 percent of the population experiences a feeling of thermal comfort. In temperate zones, this is from 68 to 80°F (20–27°C), and 20 to 80 percent humidity.

Different conditions can redefine this zone of comfort. Air motion or breeze can extend it to almost 98 percent humidity and 90°F (32°C). Evaporative cooling can extend the highest comfort temperature up to 105°F (41°C) at lower humidities. High thermal mass (such as rock or concrete) acts like a thermal flywheel, remaining cool into the day, and warmer at night than ambient air. Thermal mass alone can extend the comfort zone up to 95°F (35°C), while thermal mass cooled by nighttime ventilation can extend this zone all the way up to 110°F (43°C). Combinations of techniques are even more effective.

Evaporation (Perspiration) & Air Motion
At higher humidity and temperature, most of the excess body heat is lost through perspiration. Air motion can increase the boundaries of the comfort zone up to 98 percent humidity. This boundary would be 80 percent in still air.

Research with a large sample of people shows that comfort can be maintained at 100 percent humidity and 82°F (28°C), if air velocity across the skin is maintained at around 300 feet per minute. This is the approximate velocity of a good ceiling fan on high speed. At lower humidities (50 percent or less), temperatures of around 90°F (32°C) are comfortable at this velocity. Because of this relationship, the designer's goal is to create or preserve air velocity in the dwelling whenever possible.

A breeze blowing against our bodies removes heat through two mechanisms—convection and latent heat transfer. When convection occurs, the skin heats the air and this heated air is carried away by the breeze. With latent heat transfer, perspiration evaporates, soaking up heat from the skin in the process. Moving air aids the process of evaporation at higher humidities, as well as removing the boundary layer on the skin. This dead air layer acts as an insulator to block thermal transfer from the skin to the air.

The boundary layer also blocks evaporative transfer from the skin to the air. This layer heats up and reduces the Δt between the skin and the air, slowing down heat exchange. It also absorbs moisture from the skin, but is unable to immediately pass this on to the surrounding air. The boundary layer thus rises in humidity, reducing the difference in humidity between the skin and the air. This slows down skin evaporation and the exchange of heat to the air. Air movement shifts this boundary layer of warm, moist air, allowing the skin to come in contact with drier, cooler air that can cool more efficiently.

Summary
In Part 1, I've taken a look at the basic principles governing the movement of heat, and tried to give you a feel for the way these forces interact with the environment. We've looked at comfort, and found that the experience of thermal comfort is largely subjective to the individual.

In the next article, I will move from the general to the specific. I'll try to apply these principles of thermal design to the goal of creating a comfortable, passively cooled house in the Barton Creek valley of tropical Belize.

Access
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Resources for Further Study:
Building for the Caribbean Basin and Latin America; Energy-Efficient Building Strategies for Hot, Humid Climates, Kenneth Sheinkopf, 1989, Solar Energy Research and Education Foundation, 4733 Bethesda Ave. #608, Bethesda, MD 20814 • 301-951-3231 Fax: 301-654-7832 • plowenth@seia.org www.seia.org

Air Conditioning: Home and Commercial, Edwin P. Anderson and Roland E. Palmquist, Theodore Audel & Co., a division of Howard W. Sams & Co., Inc., Indianapolis, Indiana, 1978. Any library should have a comparable book on air conditioning that will treat this subject thoroughly.

Architecture For the Poor, 1973; and *Natural Energy and Vernacular Architecture, Principles and Examples with Reference to Hot Arid Climates,* 1986, Hassan Fathy, both published by The University of Chicago Press, Chicago. These books can be hard to find. I was able to locate them through my regional inter-library loan program and have them brought to my local library.