Heat Flow and Air Flow

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We know that heat (i.e. thermal energy) always flows in one direction—from objects or particles which are warmer (have more thermal energy) to those that are cooler (have less thermal energy). But, we've also learned that cooler water will flow beneath warmer water, and push the warm water upward; and cool high-pressure air systems flow towards warm low-pressure air systems and create wind. Does this contradict the "heat flows from warm to cool" rule?

There are three things going on when you talk about how heat flows. First, there is the amount that a particle moves or vibrates—which directly relates to how much heat (thermal energy) that particle has. Second, there is the transfer of heat (thermal energy) from one particle to another. And third, there is the distance between particles. Let's talk about these separately, and then we'll consider them together.

1) Particle Movement

We know that everything in our world is made of particles, which might be either single atoms or groups of atoms that are bonded to each other to make molecules. These are the basic particles that can have heat. Right now, let's not focus on the kind of atoms are involved (e.g. oxygen, or carbon, or sodium, or gold, etc.). All particles basically follow the same simple behaviors when it comes to heat.

What if someone asked you to picture in your mind how a molecule moves as it gains or loses heat? Well, if you're like me, you've never actually seen a single atom or molecule move. But maybe we can come up with an imaginary picture if we first think about how objects that we are familiar with move as they gain or lose energy.

Let's say you have 30 sluggish students in a room. It is early morning, and none of them had breakfast. You ask them to form a group in the middle of the room, and to touch shoulders to a person next to them. Now, you let each of them drink a cup of apple juice and remind them that you want them all to stay crowded together. Soon, they may start to chatter and fidget, but they'll most likely keep their shoulders touching the students next to them.

What might happen if you gave each of them juice with three teaspoons of sugar added? First, you might see them start to chatter and fidget in place, but then there is a good chance many of them would end up having problems staying in one spot and would start moving around in the crowd. The organized clump of students may start turning into an energized cluster that changes shape as students move around.

What might happen if you gave each of them sweetened juice with a caffeine tablet dissolved in it? The initial chattering and fidgeting may progress to wandering, and eventually most of the students would forget your instructions to stay crowded together shoulder to shoulder in the middle of the room. They would most likely end up moving around the room, bumping into each other and no longer standing shoulder to shoulder.

If you now think of each student as a “particle”, and then imagine that what you were giving them was heat energy, or more heat energy, or a huge amount of heat energy, you basically have a picture in your mind of how particles behave in a solid, a liquid, and a gas. When you add heat to a solid, the particles start vibrating as each particle gains more heat, but the particles stay crowded together in the form of a solid. If you keep heating, the particles move more and more, but all they can basically do is move in the tiny space they have in the crowd and vibrate against their neighbors. However, if you add much more heat, eventually you reach the point where the particles are moving so much that they stop touching each other and start moving past each other. At this point, your crowd of particles is behaving as a liquid—the particles are still crowded together but each particle has so much energy that it moves a lot and particles flow past one another. If you give all of your particles a huge amount of heat energy, they will end up moving so much that they will start pushing each other away, and start moving around the space they made for themselves, occasionally bumping into another particle and pushing it even further away. At this point, your particles are going all over the place and have started to behave like a gas.

In short, for any particular substance, the more heat a particle is given, the more it moves. And how particles move relative to each other defines whether they are forming a solid, liquid, or gas.

2) Transfer of Heat

Now let’s go back to those students crowded together in the middle of the room. If you gave just one student the caffeinated sweetened juice, that student might start getting restless, wiggling and jittering, although she or he is surrounded by a group of non-energized students that may have become sluggish. But once the student starts to fidget, she/he would cause her/his immediate neighbors to get restless just because they are contacting each other, kind of like when one person at a table starts to bounce their leg and it causes the table and everyone else touching it to vibrate. Those neighboring students would wake up a bit and start fidgeting themselves, maybe getting irritated at their energetic neighbor, and transferring some of their restless energy to some of their own neighbors. So you might end up seeing a wave of fidgeting through the students starting from the point of that one student who received the extra dose of energy.

In this scenario, you don't see the non-energized students giving the energized student their sluggishness—the flow of energy is from the high energy student to her/his lower energy neighbors. The transfer of heat between particles works the same way. A particle that is given a dose of heat energy and starts to vibrate can now give a dose of its energy to its neighboring particles and cause them to vibrate. If that energized vibrating particle is in a solid, it can only transfer the energy to the immediate neighbors that it is touching, who can then transfer some of their newfound energy to some of their sluggish neighbors and make them energized, who now transfer some of their energy to their less-energized neighbors—and so on, and so the heat energy spreads through the solid.

We've all turned on a simple electric stove hot-plate and watched as it starts to get hot and red at the point where the electricity enters the element, and then slowly that hot redness creeps farther and farther through the cold black part of the element until the entire element has turned red and glowing. The whole thing didn't suddenly turn hot and red—the heat traveled from a hot part into the adjacent cool part, heated that cooler section, which warmed up the cooler section next to it, and so on. Again, we see that the heat flows progressively through the solid in a very regular pattern from the hottest part to the cooler parts.

This might be a good time to remind ourselves that heat is a "relative" property. Let's start out by thinking about two bowls that we have in our kitchen cabinets. They are identical, and since they've been sitting in the cabinet all day, they are at the same temperature. For dinner, we take one of the bowls and put hot stew in it. We think of the stew as hot and the bowl as cold, and know that the stew has much more heat energy than does the bowl, which is why the heat flows from the hot food into the cooler bowl, and warms the bowl up (and, of course, since heat is lost from the food, the food cools down). But what if we took the second bowl from the cabinet and placed frozen ice cream into it? Is the bowl still "cold" relative to the food? You can see where I'm going with this. Yep, in this case, the bowl is warm relative to the food. So, the direction that heat flows depends on the difference in heat energy between the objects in question, and not on their actual temperatures. The bowls were the same temperature, but heat flowed INTO a bowl if the food was warmer, and heat flowed OUT OF the bowl if the food was colder.

In all of these examples, we call the form of heat transfer CONDUCTION, where heat moves between two particles that are touching, flowing from the particle with more heat to the particle with less heat. This CONDUCTION is the ONLY way in which heat can move in a solid, so we frequently simplify things by saying that conduction is how heat moves in solids.

But isn't this also what happens in a liquid? Or in a gas? Well, the answer to that is yes and no. Particles in a liquid or a gas transfer heat energy from more energetic particles to less energetic particles, just like they do in a solid. It really doesn't matter if two particles are part of a solid, liquid, or gas—if particle A has more heat energy than particle B, and they touch, heat energy will flow from A to B. But in a solid, particles always play the "heat-transfer games" with the same old neighbors because they are permanently stuck in place. In liquids and gases, however, things get much more exciting because the particles in the liquid or gas can also MOVE PAST EACH OTHER; they're not just stuck next to the same neighbors all the time. This sets the stage for the next section.

3) Distance Between Particles

We've all learned that oil, which is less dense than water, will float on water. Fluids of different density will settle out relative to each other according to their relative densities. One important thing to keep in mind here is that we're talking about *fluids* (liquids and gases are both fluids). Remember, the particles in fluids are not stuck firmly in place next to their neighbors (like particles in a solid); fluids will pour and flow and we can mix them with a spoon. If we stir a glass of water, particles that were at one time at the bottom of our cup can swirls all around and up and down as we stir the spoon through the water, and the spoon (which is a solid) can move freely though the water as well. Speaking of solids, keep in mind that solids don't automatically move relative to each other. If we have a block of Styrofoam and we place an equally-sized chunk of iron on top of it, the iron won't slide off of the foam and settle beneath it. It'll sit there, and all the particles in each of the blocks of Styrofoam and iron will stay where they are and not move around. But, if we allow those two blocks to move relative to each other through a fluid, then we can observe their density differences. If we place the foam and iron into a bucket of water, we'll see the iron sink to the bottom of the bucket, and the foam float on top of it. In this specific case, we're not just studying the density of the foam and the iron; there are THREE things of which we are now studying the density: foam, water, and iron. And the liquid nature of the water allows the solid foam and iron to settle out relative to each other's densities and the density of the water.

So, what exactly does "density" mean? Density is a measure of how much "stuff" there is in a given volume. And when we talk about density, we have to define what our stuff is, and what the volume is that we're talking about. Let's go back to our example with the students, where we defined each of the students as playing the role of one particle. When the students are crowded into the middle of the room, you could measure how much space they take up—maybe it's an area 4 feet wide, 6 feet long, and 4 feet high, making it 96 cubic feet. So you have 30 students/96 ft^3. But if you then take a look at the example where the students spread out through the room, you still have 30 students, but now they are occupying the entire room, which might be 20 feet x 20 feet x 4 feet high (we'll assume the students are staying on the floor and thus occupy only the lower 4 feet of space in the room). That gives you 30 students/1600 ft^3, and if you do the math that comes out to 1.8 students/96ft^3. One and eight-tenths students per 96 cubic feet is much lower density than 30 students per that volume. When we speak about density, we use a standard volume as the reference point to then explore how much stuff is in that volume.

So, let's think about how a particular substance, like milk, might experience different densities. Let's think of a Starbuck's cappuccino. If we take one ounce of milk and froth it up, it will turn into a mound of frothy milk that won't all fit into a one-ounce container. We can also observe that if we pour an ounce of milk into coffee it will swirl around and mix with the coffee, but if we place the frothed milk into coffee, it will sit on top. The frothed milk is less dense; that mound of froth has the same amount of milk particles as one ounce of milk, but the milk particles are farther apart from each other and occupy a larger volume than one ounce of liquid milk. If we scooped some frothy milk into a one-ounce container, and threw away the frothy milk that would not fit into the container, then we'd have the same VOLUME of stuff (the frothy milk), but we'd have less stuff.

Now let's think about other fluids, like air, and about particle movement as particles in a fluid gain energy. We've already determined that, if particles are given the ability to move around, adding energy makes them move more, and occupy more space, meaning that particles with less energy can be packed closer together and thus be denser than particles with more energy. So, the extension of that is that cold water is denser than warm water. And in our world, which is governed by the laws of gravity, dense things that have the ability to move relative to less dense things will come to rest below the less dense things, even if they are made up of the same stuff, like milk and frothy milk, or cold water and not-so-cold water, or cold air and not-so-cold air.

PULLING IT ALL TOGETHER: Temperature, Density, and Heat Transfer

Remember how we discussed that, in a solid, particles can't move and if they gain energy, they can only transfer their heat energy to neighboring particles that they are in contact with? But in a fluid, particles can flow past other particles, and can transfer their heat energy to any particle they may bump into on the way. But the moving of heat around in three-dimensional space happens not only because a particular particle can move through space, it also happens because groups of less energetic particles and groups of more energetic particles will move relative to each other in response to gravity (and, as we'll consider later, in response to principles of diffusion – but let's not worry about that right now). Let's picture this movement of groups of particles in response to gravity in a little more detail.

When you put a pot of water on the stove, individual particles of water at the bottom of the pot will gain heat, they'll start moving around more, and each particle will start occupying (i.e., moving through) more space. While it's true that a particle at the bottom could manage to get all the way to the top of the water, it's not all that likely to happen because the particle probably will bump into another particle very soon and bounce back. So, the particles in the AREA of the water near the pot's base will, as a group, become more energetic and spread out compared to the area of water near the surface of the pot. Together, the warmed particles have become a less-dense "pocket" of water. The water at the top of the pot hasn't changed in density (it's still as dense as it was before we started heating the water) but compared to the stuff at the bottom of the pot it is now MORE dense than the water at the bottom. So the denser water will sink down and settle below the less dense water.

This is how we get convection currents. We can now see that the heat that is being added to the water doesn't just need to be transferred from particle to particle—when that whole "glob" of warmed water got moved out of the way by the sinking colder water, it resulted in the heat energy of all those particles moving all at once to a very different location where they can continue to transfer heat to the new neighboring particles that they meet in the new location they've been moved to. This process keeps on going and going, as long at the heat source at the bottom keeps adding energy.

Some folks might wonder why, if all the water is getting hot, convection currents will continue to flow. What make those currents happen are the RELATIVE densities of the water. It doesn't matter if the water at the top is 35^{o} and at the bottom it's 40^{o}. Or at the top it's 80^{o} and at the bottom 100^{o}. The "warmer" water is less dense than the "cooler" water. And once the warmer water gets moved to the top of the pot, it'll start losing heat (it's not next to the heat source anymore, right?) and the water at the bottom will be gaining heat from the stove burner. The heat content of the low water will increase, the heat content of the upper water will decrease, and when the water at the top is denser (and cooler) than the water at the bottom . . . down it goes again. This phenomenon happens in lakes—you may have heard of "lake overturn," when the water at the surface of the lake in the fall cools down rapidly as weather cools, and sinks to the bottom of the lake thereby pushing up the warmer water to the surface, thus "mixing" the lake and stirring up nutrients in the sediments at the bottom of the lake.

There is one more thing to let us better understand why cool (denser) fluid might move relative to warm (less dense) fluid. That one more thing is fluid pressure. In particular, the way that atmospheric pressure and temperature of air masses interact is one thing that is sometimes hard to understand. So, first, let's think about air pressure.

Imagine yourself at sea-level, at Fisherman's Warf in San Francisco, in a restaurant's walk-in freezer, taking a deep breath. Now imagine a mountain climber at the top of Mt. Everest taking a deep breath. Your breath is full of oxygen, while the poor guy at the mountain top can't get enough oxygen into his system with the lung-full that he breathed in. You've heard about "thin air" at high altitudes, and you know it means that, per volume of air that the mountain climber breathes in, there are fewer particles of air gas (oxygen, nitrogen, carbon dioxide, etc.) than the same volume of air would have at sea level. The temperature of the air in the freezer might be the same as the temperature on the top of Mt. Everest—so we know that the difference in density does not have anything to do with temperature (i.e., how much thermal energy each particle has). Temperature is simply a measure of how much thermal energy, or "vibrational energy" a particle or group of particles has. If the temperature is 20 below zero in the freezer and 20 below on the mountain, then the particles have the same energy. So, why is the sea-level air denser than the mountain top air? It's because the sea-level air has 29,029 more feet of air stacked on top of it than the air at Mt. Everest peak. Air has mass, so there is a lot more mass pressing down onto a pin head at sea-level than on a pin-head at the Mt. Everest summit. It's the difference in how much air is pressing down on a point that also influences how dense the air is in a particular location. When it comes to air, we really need to think about air pressure as well as temperature. Air density decreases with increasing altitude, as does air pressure. It also changes with changes in temperature or humidity. All of this influences weather, and how air masses move. (But don't forget…at any particular pin-point location in the air, the air pressure pressing on that point is THE SAME from all directions: the sides, the top, the bottom. But, if you move just a bit up, at the new pin-point location, while the air pressure presses identically from all sides, the actual amount of air pressure is just a bit less than it was down below. Don't worry about this…it doesn't really affect our current discussion, but students do need to learn the concept about equal pressure from all directions at any particular point in the air).

Finally, there is a combination of these factors that influences how air moves: dense air has higher pressure relative to less dense air. Students in fifth grade are expected to know that air from a high pressure area will flow to one with lower pressure, creating wind. But why is this? Now we're starting to get more complex with physics, and we're combining what we know about how temperature and density interact in fluids, what causes air pressure, and the principle of diffusion. Well, you know about diffusion, right? If a person in the next room sprays some air freshener, you'll start to smell it when air freshener particles reach you. And, in simplified terms, particles will move away from the area of highest density until they're all spread out evenly, so eventually both rooms will have a faint odor of air freshener, but there won't be a patch of intense scent where the freshener was first sprayed. In cold air, there is MORE air per unit volume than in comparatively warm air. That's because the cold air is denser. So, even if a mass of cold air is sitting next to a mass of warm air at ground level, and you're not expecting the cold air to "sink" because it's already at ground level, you will find that the cold air will flow towards the warm air. You've probably noticed this when you feel a "cold draft" in the room….cold air from somewhere is flowing into the warm room. This is really noticeable on the coast during warmer weather. Ocean water heats up less quickly during a sunny day than does land. You may have experienced this, when on a hot day the sand on the beach can get very hot and you run across it to get to the cooler ocean water. Similarly the air above the water will warm up slowly, while the air above the land warms up quickly as the land heats up. The air above land becomes warmer than the air above water, and is less dense than the air above water. Because the particles of warm air are spread out, there is less air pressure at a given spot at the land's surface relative to a given spot at the water surface (because there are fewer air particles above that spot because they spread out as they warmed up). With less mass of air above that point, there is less air pressure above that point. So, not only is warm air less dense than cooler air, but a point in that warm air mass has "lower pressure" than a point at the same altitude in a mass of cooler air. Combine all of this information together, and you can see that cooler, denser, higher pressure air flows TOWARDS warmer air that is less dense and has a lower pressure.

HERE IS ONE FINAL POINT. Remember the question at the very beginning of this essay? Heat (how much a particle is vibrating) will flow from high thermal energy to low thermal energy—that is, a particle with a lot of energy will give some of that energy to a particle with less energy. But, a cold air mass will flow towards a warm air mass. Does this contradict the "heat flows from warm to cool" rule?

No, there is no contradiction. With heat flow, we talk about one particle giving thermal energy to another particle. When we start talking about these pockets of cool or warm air, though, we have big groups of particles moving past each other not because of the specific thermal energy of any particular particle, but because as a group they have a new property called "density". The thermal energy of a group of particles influences the density and pressure of their group, and that governs how that group of particles interacts with another nearby group of particles that may have a different density. So, in fluids, groups of particles can move past each other, or flow into another group, based on their density. But when it comes to individual particles bumping into each other, the laws of heat flow ALWAYS result in the particle with more thermal energy giving some of its energy to the cooler particle.