Incomplete.

Look up old 220 Thermo, 344 thermo, and 231 Thermo

Need to go over converting between temperature scales – using specific points to help (for example, water boiling and freezing in Celsius and Fahrenheit.

---

**T1 Temperature**

**T1.1 Intro to the Unit**

- The vast majority of systems studied by Physics are fundamentally ensembles of large numbers of particles. This section of the course (and, then Phys 344 next Spring) focuses on the two areas of Physics that directly address the properties unique to ensembles: Statistical Mechanics and Thermodynamics. Starting with the Mechanics that describe individual particles and employing Statistics to extrapolate from the few to the many, Statistical Mechanics builds our understanding of ensembles from first principles. Thermodynamics applies this understanding to describe how ensembles behave and do work in both natural and man-made systems.

- I’ve often said that there are two types of theoretical models in physics – ones that are built to be ‘good enough’ for addressing a problem at hand and another is built to be ‘fundamental’ for understanding something in terms of the most universal principles.
  - Thermodynamics was born of a need to address very practical problems; it is the science of the industrial revolution – it’s a great example of a ‘good enough’ theory.
  - Statistical mechanics was born of a need to understand thermodynamics in terms of the most universal principles – it’s a great example of a ‘fundamental’ theory.

This course will then be a little schizophrenic – moving between the ‘good enough / practical’ approach and the ‘fundamental understanding’ approach. That can be a little disorienting if you aren’t expecting it, so this is your ‘heads-up.’ Let me tell you from experience though, the alternative, of studying Thermodynamics separate from Statistical Mechanics is extremely dissatisfying.
The “Great Idea” of this Unit is Boltzmann’s: *The Irreversible behavior of a complex system can be explained by the statistical consideration of the reversible interactions of its molecules.*

- Thermo/Stat-mech books tend to get off to unsatisfying starts, and this text is no different. The first chapter, intentionally poses many questions that won’t get answered for some time, but it also presents things that themselves beg unspoken questions that this chapter alone does not prepare you to answer. I’m happy to give you snippet/sound-bite/preview answers today, but rest assured that all these questions will be satisfactorily answered, in their own time.

**T1.2 Irreversible Processes**

**T1T.1** – Characterize each of the following processes as being reversible (A) or irreversible (B).

- a. A living creature grows
- b. A ball is dropped and falls freely downward
- c. A ball rebounds elastically from a wall
- d. A piece of hamburger meat cooks on a grill
- e. A cube of ice melts in a glass
- f. A bowling ball elastically scatters some bowling pins

This section points out that, while the individual laws of physics are time symmetric, meaning that simple processes of individual particles are just as plausible forward as backward, the behavior of large systems of particles is observably *not* reversible – a rock doesn’t just jump out of a pond, a block doesn’t suddenly start sliding along a table and cool down.

This section doesn’t give an explanation, but points out that one will come in later chapters.

**T1.3 the Paradigmatic Thermal Process**

- **Objects in ‘thermal contact’ approach ‘thermal equilibrium.’** Put a hot block of metal in cold water. As we all know, eventually the water and block will arrive at the same, luke-warm temperature (and if we wait longer, it will settle at room temperature.)
  - The block ‘heats’ the water – raising its temperature and energy content, and the water ‘cools’ the block – lowering its temperature and energy content.
  - Some ‘big questions’ this raises.
What is Temperature? (measure of energy density / how readily an object gives up internal energy)

What is Heat? (energy transfer prompted by temperature difference)

What is thermal equilibrium? (two objects having the same temperature)

Why is the process irreversible? (on average, the particles of the metal are jiggling more energetically than are the water molecules, so when they collide, on average, they tend to transfer energy to the water molecules)

### T1.4 Temperature and Equilibrium

**What is Temperature?**
- You walk barefoot across the beach on a summer day, and you sense that the sand is ‘hot’; you walk barefoot across a snow bank and you sense that the snow is ‘cold.’ It’s *that* property that we call temperature. We start off with a very operational definition, theoretically hollow and unsatisfying, but useful: what a thermometer measures.
- In later chapters, we’ll learn how to relate this to more tangible, fundamental properties. In broad strokes, it’s a measure of energy density, not per volume or mass, but per ways of having energy, and that directly relates to how readily a system gives up energy when it interacts with another system.

**Zeroth law of Thermodynamics**
- Thermometers work – the transitive property of temperature: if objects A and B are in thermal equilibrium (same temperature) and objects B and C are as well, then A and C must be as well. Dub object B a thermometer, and there you are, ‘thermometers work.’

### T1.5 Thermometers
- Of course, that bring us to the questions of what is a thermometer, and *how* does it work. We can partly address those now.
- When you think about it, very few properties are directly measurable, indeed, all we can directly measure are distance, direction, and time.
- For example, say you want to measure the mass of something, you hang it from a spring scale and the needle attached to the spring moves along some row of numbers. What are you directly measuring? The displacement of that needle / the stretch of the spring. However, from that you can deduce the mass of the hanging object.
- Similarly, you can’t directly measure temperature, but you can observe a property that varies in response to temperature (just like the length of the spring varies in response to the object hanging from it.)
  - A wire’s resistance varies with temperature
  - The color of light emitted by an object varies with temperature
  - The volume of an object varies with temperature
  - The pressure of a gas varies with temperature.
- So, you can make a “thermometer” based on observing the variations in any of these properties.
- The most common thermometer uses the fact that volume of an object varies with temperature, a.k.a. thermal expansion. We met this back in Phys 231, but in broad strokes, if, as I claim, temperature measures the density of internal energy, then we’re saying that objects tend to expand when they’ve got more internal energy. For a solid, ‘more internal energy’ means that the atoms are jiggling more violently / higher energy level, and their new average separation is a little greater (since there’s an asymmetry in
their bonding – the bonds simply can’t get compressed beyond 0, but can stretch and stretch, so the more energy, they stretch more than they compress.)

- **Constant-Volume Gas Thermometer.** The book singles out this one. It doesn’t shed much light on the *fundamental* nature of temperature. Rather, it’s a nice example of how one can *practically* go about creating a calibrated and sharable / reproducible measurement technique.
  
  o First off, recall that pressure is the ratio of Force to the Area over which it’s being applied.
    
    \[ P = \frac{F}{A} \]
    
    the units are N/m² which defines the Pascale, Pa = N/m².
  
  o So, if you have a piston full of gas and place a some mass on its head to apply a pressure, the piston head will be held in equilibrium where the pressure from above (due to the weight of the mass sitting on top) equals the pressure from below (due to the gas particles knocking into it).
  
  o This thermometer works because the hotter the gas is, the more forcefully the particles bounce into the head, so the more mass you need to pile on top of the piston head to keep it from rising. Now, that the pressure and temperature should vary *linearly* is rather special; under what conditions and *why* this should be so, we’ll get to next chapter, but for now, let’s see what we can do with this.
  
  o So, consider a given thermometer
    
    ▪ first dipped and equilibrated with water at one temperature, T.
      
      - \( P \propto T \)
    
    ▪ Second dipped and equilibrated with water at another temperature, call it \( T_c \).
      
      - \( P_c \propto T_c \)
  
  o Then
    
    \[ \frac{P_c}{P} = \frac{T_c}{T} \Rightarrow T = T_c \frac{P}{P_c} \]
  
  o Now, the task is selecting a \( T_c, P_c \) pair that is universally reproducible. Kind of like when you want to talk about a mountain’s elevation, it’s always relative to sea level because that’s more or less equally accessible everywhere on Earth, we want a \( T_c, P_c \) pair that can be determined by anyone using any constant-volume thermometer.
  
  o As you’ll learn later, there’s only one pressure -temperature point at which water can coexist in all three phases (solid, liquid, gas). This is known as the ‘triple point’ for water: \( (P_3, T_3) \). See, the exact temperature at which water melts varies with pressure, and so does the temperature at which it boils, but there is only *one* pressure and temperature at which all three phases coexist. So, if we take *those* to be our calibration point,
    
    \[ T = T_3 \frac{P}{P_3} \]

**T1T.4** – Imagine that we place an aluminum cylinder, a wooden block, and a Styrofoam cup on a table and leave them there for several hours. We then come back into the room and feel each of the objects
Which (if any) feels the coolest?
Which (if any) *actually* is coolest?

A. The aluminum cylinder
B. The wooden block
C. The Styrofoam cup
D. All are the same

T1T.8 – Imagine that we place a 100-gram aluminum block with an initial temperature of 100°C in a Styrofoam cup containing a 100-gram sample of water at 0°C. (The specific heat of aluminum and water are 900 J kg\(^{-1}\) K\(^{-1}\) and 4186 J kg\(^{-1}\) K\(^{-1}\), respectively.) The final temperature of the system will be closest to

A. 0°C
B. 20°C
C. 50°C
D. 80°C
E. 100°C

T1S.9 – Imagine that we place a 100-gram aluminum block with an initial temperature of 100°C in a Styrofoam cup containing a 250-gram sample of water at 25°C. (The specific heat of aluminum and water are 900 J kg\(^{-1}\) K\(^{-1}\) and 4186 J kg\(^{-1}\) K\(^{-1}\), respectively.)

What is the final equilibrium temperature of this system?

What assumptions did you make?

Do not use the result of problem T1S.8 for this problem or T1S.10 on the weekly HW!