6 December

- **Chapter 17 Compressible flow of gases**

- **1-dimensional compressible flow**
- nozzle and diffuser
- Function of a nozzle: accelerate flow.
- Function of a diffuser: deccerate flow.
- Variable cross-sectional area. A(x)
- 1D field. Associate each cross section with a thermodynamic state (2 independent properties) and a velocity.
- A total of three independent fields temperature T(x,t), pressure P(x,t), and velocity V(x,t).
- Steady-state flow. T(x), pressure P(x), and velocity V(x).

- **Physical principles**
- Conservation of mass
- Conservation of energy
- Conservation of momentum
- Adiabatic and reversible flow: isentropic flow
- Ideal gas, with constant heat capacity

- **Propagation of sound in a gas**
- Imagine a wave front. Ahead of the front, the air is still. Behind the front, all property changes a little.
- The front moves at speed c. This is the speed of sound.
- An observer travels at the speed of sound. Observe a control volume surrounding the front.
- Conservation of mass
- Conservation of momentum
- Entropy remains unchanged. Isentropic condition
- Expression of the speed of sound.

- **Mach number**
- A moving source of sound (i.e., a flying bullet)
- Speed of sound c
- Velocity of the source of sound V
- Mach number M = V/c
- Stationary source of sound
- Subsonic source of sound
- Supersonic source of sound

- **Steady, isentropic, compressible flow**
- A nozzle of given A(x). Convergent nozzle. Convergent-divergent nozzle. Throat of the nozzle.

- Prescribe conditions at the inlet: V = 0. (T_0, P_0)
- Prescribe the back pressure P_B
- Determine the flow field.
- Conservation of mass
- Conservation of energy
- Isentropic flow

- **Show dA/A = (M^2-1)dV/V**
- A nozzle accelerates a flow. A convergent nozzle is subsonic. A divergent nozzle is supersonic
- A diffuser deccelerates a flow. A divergent diffuser is subsonic. A convergent diffuser is supersonic.

- **Steady, isentropic, compressible flow of ideal gases**
- Two reference states: stagnation state, sonic state (critical state).
- Table A.12
- Convergent nozzle. Choked nozzle
- Convergent-divergent nozzle

- **Shock**
- A supersonic bullet. An observer travels with the bullet. The velocity of the bullet relative to the air exceeds the speed of sound.
- Properties of the gas jump
- Conservation of mass
- Conservation of energy
- Conservation of momentum
- To ensure entropy increases as the gas crosses the shock, the gas is supersonic before the shock, and is subsonic after the shock
- Table A.13

1 December

- Reading ahead: Chapter 17
- Homework due in class on Tuesday, December 6 (last problem set). 16.19 16.24 16.56 16.69 16.85 16.78 17.36 17.46 17.65 17.81

- Recall the definition of the chemical potential.
- Chemical potential is an intensive property.
- Recall the definition of the Gibbs function.
- Gibbs function is a function of temperature, pressure, and the amounts of individual components.
- Gibbs function is an extensive property.
- An identity connecting the Gibbs function and chemical potentials

- **Chemical potential of molecules in several idealized systems**
- Pure, incompressible liquid
- Pure, ideal gas
- A mixture of ideal gases

- **Chemical equilibrium**
- Atoms and molecules
- Reaction
- Chemical equilibrium
- Conservation of atoms
- Reaction equation. Stoichiometric coefficients
- Degree of reaction
- Condition of equilibrium in terms of chemical potential

- **Chemical reaction of ideal gases**
- Change in the Gibbs function
- Equilibrium constant

29 November

- Reading ahead: Chapter 17
- Homework due in class on Tuesday, December 6 (last problem set). 16.19 16.24 16.56 16.69 16.85 16.78 17.36 17.46 17.65 17.81

- **Object of this lecture: Chapter 16 Equilibrium of phases. Chemical equilibrium**

- **Going over my notes on chemical potential**
- Two systems can exchange molecules.
- What is chemical potential?
- What does chemical potential do?
- Measure chemical potential of a pure substance
- Measure chemical potential of a molecular species in a complex system

- Language: Chemical potential of a molecular species in a system.
- Examples: chemical potential of water in a wine, chemical potential of ethanol in the wine. Chemical potential of water molecules in the air.

- **Condition of equilibrium in terms of Gibbs function**
- A system of fixed temperature and pressure.
- But the system can still change phase or undergo chemical reaction.
- In equilibrium, the Gibbs free energy is minimized.

- **Equilibrium between phases**
- Conservation of molecules

- Equilibrium of phases of a pure substance.
- An alternative derivation of the Clapeyron equation.
- Equilibrium of phases of a multi-component substance: Chemical potential of each component is the same in all phases.
- The Gibbs phase rule F = C - P + 2. F = numbers of degrees of freedom. C = number of components. P = number of phases

22 November

- Reading ahead: Chapter 16
- Homework due in class on Tuesday, November 29. 15.33 15.47 15.69 15.73 15.100 15.114

- **Object of this lecture: Chapter 15 Chemical reactions**

- A “new” principle: **Conservation of atoms**.
- Chemical bond
- A molecule is an assembly of atoms linked together by chemical bonds. O_2, H_2, H_2O
- A chemical reaction is a process that breaks some chemical bonds, and form others.
- Chemical reaction does not change nucleus of each atom.
- In a chemical reaction, the number of each species of atom is conserved.
- Chemical equation. Stoichiometric coefficient. $O_2 + 2H_2 = 2H_2O$.

- **Combustion**: Oxidation of fuel
- $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + energy
- Air: $O_2:N_2 = 1:3.76$
- $CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$ + energy
- Even when nitrogen does not participate in the chemical reaction, nitrogen keeps the same temperature as the reactants and the same temperature as the product.
- Theoretical air: the amount of air needed to complete combustion. Stoichiometric mixture.
- Air-fuel ration. AFR = number of molecules of air (oxygen and nitrogen) over the number of fuel molecules.
- Theoretical AFR. For the combustion of methane, theoretical AFR = 2*4.76.
- Percent theoretical air, excess air. Equivalent ratio

- **Enthalpy of formation**
- Identify an isolated system of the following parts:
- a control volume
- each species of molecules in a piston-cylinder setup with a fixed temperature and a fixed pressure
- a reservoir of energy
- Exchange of molecules between each piston-cylinder setup with the control volume.
- Exchange energy between the reservoir of energy and the control volume.

- Apply the first law: the principle of the conservation of energy. The control volume is in a steady state.
- Enthalpy of formation in a reference state (25C, 100kPa). Table A.9 and A10.
- Enthalpy of formation in other states (T,P).

- **Enthalpy of reaction**
- **The third law**
- Absolute entropy

- **The second law analysis**
- Identify the isolated system.
- Conservation of energy
- Generation of entropy.
- Availability. Irreversibility. Reversible work.
- Gibbs function.

- **Fuel cell**
- Electrochemistry
- Electrochemical reaction
- Direct conversion from chemical energy to electric energy
- The setup of a fuel cell
- Fuel, oxygen, product, load,
- Reaction at the anode
- Reaction at the cathode
- Electrolyte conducts ions, but blocks electrons.
- Metal wire conducts electrons, but blocks ions.
- Load: electric charge, electric potential, electric work
- Relate the maximum electric potential to the free energy of reaction.

- Batteries

17 November

- Reading ahead: Chapter 15
- Homework due in class on Tuesday, November 22. 13.32 13.44 13.52 13.83 13.125 14.30 14.39 14.76 14.127 14.140

- **Object of this lecture:**
- **Many, many ways to write the Gibbs relation, with the help of Calculus.**
- **Going over my notes on chemical potential**

- **A system of two independent variations.**
- A closed system. Piston-cylinder setup.
- Transfer energy by work. Weights.

- Transfer energy by heat. Fire.
- States of the system.
- Functions of state.
- We are interested in a large number of functions of state (i.e., properties): U,V,S,H, P, T. We will add more to this list.
- For a system of two independent variations, each state is characterized by values of two properties.
- Once two properties are chosen as independent variables, each of all other properties is a function of the two independent variables.

- **Write the Gibbs relation in terms of the function S(U,V).**
- Choose U and V as independent variables.
- Write S(U,V), H(U,V), P(U,V), T(U,V). So many functions, so little time.
- The Gibbs relation. $dS = T^{-1}dU + T^{-1}PdV$. How is this relation developed?
- Once S(U,V) is known, T(U,V) and P(U,V) can be obtained by taking partial derivatives of S(U,V).

- **Write the Gibbs relation in terms of the function U(S,V).**
- Rewrite the Gibbs relation $dS = T^{-1}dU + T^{-1}PdV$ as $dU = TdS - PdV$.
- Regard S and V as independent variables. Function U(S,V)
- Once U(S,V) is known, T(S,V) and P(S,V) can be obtained by taking partial derivatives of U(S,V).

- **The two functions U(S,V) and S(U,V) represent the same information**.
- Once you know one function, you know the other.
- When V is held constant, S is a monotonically increasing function of U.
- Once S(U,V) is known, we can express U in terms of S and V to obtain the function U(S,V).
- The two functions S(U,V) and U(S,V) are inverse to each other.

- **Write the Gibbs relation in terms of the function H(S,P).**
- Define the enthalpy as $H = U + PV$
- Gibbs relation: $dH = TdS + VdP$
- Regard S and P as independent variables. Function H(S,P)
- Once H(S,P) is known, T(S,P) and V(S,P) can be obtained by taking partial derivatives of H(S,P).

- **Write the Gibbs relation in terms of the function A(T,V).**
- Define the Helmholtz free energy as $A = U - TS$
- Gibbs relation: $dA = -SdT - PdV$
- Regard T and V as independent variables. Function A(T,V).
- Once A(T,V) is known, S(T,V) and P(T,V) can be obtained by taking partial derivatives of A((T,V).

- **Write the Gibbs relation in terms of the function G(T,P).**
- Define the Gibbs free energy as $G = U - TS + PV$
- Gibbs relation: $dG = -SdT + VdP$
- Regard T and P as independent variables. Function G(T,P).
- Once G(T,P) is known, S(T,P) and V(T,P) can be obtained by taking partial derivatives of G(T,P).

- **Name the second derivatives of of the function G(T,P).**
- For a function of two variables, there are a total of 4 second derivatives.
- The two mixed second derivatives are equal. Maxwell relation. So, only 3 independent second derivatives.
- All the derivatives are functions of state.
- Constant-pressure heat capacity. $C_p(T,P)$
- Constant-pressure coefficient of thermal expansion (CTE).
- Constant-temperature compressibility.

- **Write the Gibbs relation in terms of the function H(T,P).**
- Regard T and P as independent variables
- Function $C_p(T,P)$, function V(T,P).
- Obtain the function H(T,P) by integrating along a path on the (T,P) plane.
- Obtain S(T,P), U(T,P), V(T,P), A(T,P).

- **Going over my notes on chemical potential**
- Well, I did not have time to go over the notes in this lecture. Hopefully we will have time later to talk about the chemical potential.

15 November

- Reading ahead: my notes on chemical potential
- Homework due in class on Tuesday, November 22. 13.32 13.44 13.52 13.83 13.125 14.30 14.39 14.76 14.127 14.140

- Quiz II: November 15, in class

10 November

- Reading ahead: Chapter 14
- Homework due in class on Tuesday, November 15. 12.21 12.45 12.54 12.67 12.115
- Quiz II: November 15, in class
- Correct your calendar: Makeup class December 6, Tuesday, 10:00-11:30
- ES 128 Introduction to Computational Mechanics

- **Entropy of mixing ideal gases**
- Experiment I. Three cylinder-piston setups, one for pure gas A, one for pure gas B, the third for the mixture of A and B. The three setups have the same temperature and pressure.
- Additive quantities: number of molecules, volume, energy, enthalpy.
- Non additive quantities: entropy.

- Experiment II. Three boxes of identical volume and temperature. One for pure gas A, one for pure gas B, the third for the mixture of A and B.
- Additive quantities: pressure, number of molecules, energy, enthalpy, **and entropy**.
- Gibbs paradox. Dalton model.
- Van't Hoff boxes. Semipermeable walls.

- **Object of this lecture: Calculus applied to thermodynamics. Chapter 14**

- Clapeyron equation
- Clausius-Clapeyron equation

- A very quick review of the calculus of a function of two variables.
- Gibbs relations
- Maxwell relations
- Change of variables

8 November

- Reading ahead: Chapter 14
- Homework due in class on Tuesday, November 15. 12.21 12.45 12.54 12.67 12.115
- Quiz II: November 15, in class
- Correct your calendar: Makeup class December 6, Tuesday, 10:00-11:30
- ES 128 Introduction to Computational Mechanics

- **Object of this lecture: Mixing gases**

- **Review: A thermodynamic system of two independent variations**
- Closed system: a good example is cylinder-piston setup. Transfer energy by work (weights). Transfer energy by heat (fire).
- Properties, P,T,U,V,S,H
- Gibbs relations
- Partial derivatives.
- Once the function S(U,V) is known, all other equations of state can be obtained.
- S = log (number of quantum states)

- **Review: a pure of ideal gas**

- Physical picture: flying molecules. the distance between molecules is far apart
- U = Nu(T). Justification from the molecular picture.
- PV=NT. Justification from the molecular picture.
- Calculate entropy of a pure gas

- **Mixing two ideal gases. No reaction**
- Molecular picture. Start with a box of pure gas of species A, and another box of pure gas of species B. End with a box of species A and B. Suppose the temperature and pressure are the same for the three boxes. Calculate the energy, entropy, … of the mixture in terms of the properties pure gasses.
- Simple rule of mixture applies to the number of molecules, the energy, and the enthalpy.
- Partial pressure.
- Entropy of mixing. The Dalton model.

3 November

- Reading ahead: Chapter 13
- Homework due in class on Tuesday, November 15. 12.21 12.45 12.54 12.67 12.115
- Quiz II: November 15, in class
- Correct your calendar: Makeup class December 6, Tuesday, 10:00-11:30

- **Object of this lecture: Vapor and gas cycles**

- **Parts in the Rankine cycle**: pump, boiler, turbine, condenser.
- The pump receives work from a power source
- The boiler receives heat from a furnace
- The turbine does work to a generator
- The condenser rejects heat to an environment
- The working fluid goes through the four parts by steady-state processes.

- Analyze individual process
- The Carnot efficiency, defined by using the temperature of the furnace and the temperature of the environment.
- The furnace and the environment are modeled as ideal reservoirs of energy.
- The network is the difference of the energy received by the generator and the energy given by the power source.
- The generator and the power source are modeled as ideal mechanisms of doing work.
- First-law efficiency
- Second-law efficiency

- Internal combustion engine
- Jet engine
- Model a real system with a thermodynamic cycle

- Air-standard cycle
- Brayton cycle
- Otto cycle
- Diesel cycle

1 November

- Reading ahead: Chapter 12
- Homework due in class on Tuesday, November 8. 11.13 11.30 11.80 11.105 11.116 11.126
- Wikipedia entry on power station.
- Wikipedia entry on thermal power station

- **Object of this lecture: Vapor cycles**
- Power cycle. Refrigeration cycle.
- Vapor cycle. Gas cycle.
- Power cycle uses water as the working fluid. Steam power plants. Coal plants, nuclear plants, Natural-gas plants.
- Why do we use water?
- Why do we use steam?
- Why do we not use the Carnot cycle?
- Rankine cycle.
- Idealizations
- First-law efficiency
- Second-law efficiency

27 October

- Reading ahead: Chapter 11
- Homework due in class on Tuesday, November 1. 9.34 9.66 9.83 9.89 9.126 10.20 10.37 10.63 10.84 10.99

- **Object of this lecture: Exergy**

- **Carnot cycle revisited. Now also consider irreversible engines**
- Given an ideal reservoir of energy of temperature T, and environment of temperature T_0, what is the maximum amount of work by an engine operating in a cycle?
- Isolated system: the reservoir T, the reservoir T_0, the engine, and the mechanism of doing work.
- The engine undergoes a cyclic process.
- Conservation of energy: The energy of the isolated system remains constant.
- Generation of entropy: The entropy of the isolated system cannot decrease.
- Say we know T, T_0, and the heat Q taken from the reservoir T.
- Expression for heat give to the environment.
- Expression for the work.

- Work by irreversible process. Actual work. Entropy generation. Irreversibility
- Work by reversible process.
- **Transfer exergy by heat**.
- **Transfer exergy by work**
- First-law efficiency.
- The Carnot efficiency
- Second-law efficiency
- Compare two engines

- **Exergy of a closed system**
- A closed system of initial energy E, entropy S, and volume V. The closed system need not be in a state of equilibrium; the intensive properties of the closed system, temperature and pressure, may be undefined.
- An environment of temperature T_0 and pressure P_0. The environment is so large that temperature T_0 and pressure P_0 remain unchanged.
- **The dead state**. The closed system reaches the dead state when it equilibrates with the environment.
- Question: given a live state of the closed system (characterized by E,S and V), and an environment (characterized by T_0 and P_0), what is the maximum work can be extracted?
- Conditions to attain the maximum work: (1) the process is reversible. (2) the closed system reaches the dead state.
- Isolated system: the closed system, the environment, and the mechanism of doing work.
- Conservation of energy: The energy of the isolated system remains constant.
- Generation of entropy: The entropy of the isolated system cannot decrease.
- Expression for heat give to the environment.
- Expression for the work.
- Work associated with P_0 is done to the environment, and is unavailable to the the mechanism of doing work. Useful work
- Expression for exergy. Destruction of exergy.

- **Transfer exergy by flow**

- **Balance of the exergy of a control volume**

25 October

- Reading ahead: Chapter 10
- Homework due in class on Tuesday, November 1. 9.34 9.66 9.83 9.89 9.126 10.20 10.37 10.63 10.84 10.99

- **Object of this lecture: general thermodynamic analysis. Ilustarted with an example: steady-state process of a single flow.**

- **The general approach**
- **Construct an isolated system**. Parts of the isolated system can be a control mass or a control volume, idealized reservoirs of energy (heat reservoirs), ideal mechanisms of doing work (work reservoirs), ideal reservoirs of matter.
- **Identify constraints internal to the isolated system**. Remove the constraints to allow the transfer of energy by heat, the transfer energy by work, and the transfer of matter.
- **Specify the process**. A cycle, or a steady state process, or a transient process.
- Conservation of mass: The mass of the isolated system remains constant.
- Conservation of energy: The energy of the isolated system remains constant.
- Generation of entropy: The entropy of the isolated system cannot decrease.
- Mathematical manipulation to calculate quantities of engineering interest.
- Engineering considerations.

- **Steady-state process of a single flow (Section 9.3)**
- Isolated system: an open system, an inlet, an exit, a mechanism of doing work, a sequence of reservoirs of energy at different temperatures.
- The open system undergoes a steady-state process.
- Conservation of mass: The mass of the isolated system remains constant.
- Conservation of energy: The energy of the isolated system remains constant.
- Generation of entropy: The entropy of the isolated system cannot decrease.
- Use the Gibbs relations
- Expression for the total amount of heat
- Expression for the total amount of work
- Entropy generation. Irreversibility. Reversible process.
- Shaft work
- Incompressible fluid. The Bernoulli equation.

20 October

- Reading ahead: Chapter 10
- Homework due in class on Tuesday, October 25. 8.18 8.30 8.38 8.71 8.94 8.114 8.131 8.164 9.22 9.27

- **Going through highlights of Chapters 8 and and 9**
- A closed system of two independent variations.
- Five functions of state (i.e., properties)
- V, geometry
- p, mechanics
- T, zeroth law
- U, first law
- S, second law
- Gibbs relation.
- Given S(U,V), calculate T(U,V) and p(U,V) by taking partial derivatives

- Derive the law of ideal gases from the molecular picture.

- Apply the second law to a control volume.
- Model the inlet as an ideal reservoir of matter
- Model the exit as an another ideal reservoir of matter
- Ideal reservoir of energy
- Ideal mechanism of doing work
- Efficiency of a turbine.

18 October

- Reading ahead: Chapter 9
- Homework due in class on Tuesday, October 25. 8.18 8.30 8.38 8.71 8.94 8.114 8.131 8.164 9.22 9.27
- Before I started to prepare for teaching this class, I posted a request for comments on iMechanica. You might be interested in reading comments from other teachers and students of thermodynamics.

- **Object of this lecture: Chapter 8, entropy of a closed system (a control mass).**

- The content of this chapter has been difficult to most people. The difficulty comes from following the historical development of entropy. This historical development never tells you what entropy is.
- The historical development of the notion of entropy is confined in the following sections of the textbook: 8.1, 8.2, 8.9. No need for you to spend time to decipher these sections. They are confusion. History is worth reading if it interests you or sheds light. These sections do neither for me.
- In our lectures, we have already learned what entropy is from the fundamental postulate. So our task is much simpler: we will focus on how to apply entropy to a closed system.

- We have defined entropy of an isolated system in the lecture on the fundamental postulate.
- We have also calculated the change of entropy of an ideal reservoir of energy. See the lecture on the Carnot cycle.
- We have been using the two great principles: fundamental postulate and conservation of energy
- We now wish to apply the same great principles to a closed system.

- **Closed system**.   Also known as a **control mass**. A closed system interacts with the rest of the world in two ways: exchange energy by heat, and exchange energy by work. No exchange of matter. An excellent example of a closed system is a cylinder-piston setup.
- To model a closed system and its interactions with the rest of the world, we need three things: the closed system itself, an ideal reservoir of energy, and an ideal mechanism of

doing work.

- That is, we model the rest of the world by an ideal reservoir of energy, and an ideal mechanism of doing work. All other things in the world are irrelevant, so far as the the closed system is concerned.
- **Ideal reservoir of energy**. In the lecture on the Carnot cycle, we have described an ideal reservoir of energy. The reservoir is a system of a single independent variation. The reservoir interacts with the rest of the world in only one way: exchange energy by heat. No exchange of energy by work. No exchange of matter. The reservoir is so large that its temperature T_R is fixed when the reservoir gains or loses energy. (A good analogy is a reservoir of water. The level of water of the reservoir remains fixed when a small amount water is taken out.) On receiving energy by a quantity of heat Q, the reservoir distributes energy within itself so slowly that the entropy of the reservoir changes by Q/T_R. That is, the change of entropy in the ideal reservoir is entirely due to the transfer of energy into the reservoir--the ideal reservoir only undergoes reversible process and generates no entropy. Picture a tank with entropy, energy, and entropy.
- **Ideal mechanism of doing work**. Picture a collection of weights. You can add or remove weights when the piston is at various heights. You know how to calculate the work done by the weights. The ideal mechanism of doing work is a system that does not change entropy. Weights merely go up and done: they do not change the number of quantum states.
- **The closed system may not be in a state of equilibrium**. Upon receiving energy by heat and work, the closed system may not be in a state of equilibrium. For example, different parts of the closed system may have different temperatures. When the closed system is not in a state of thermal equilibrium, we cannot speak of *the* temperature of the closed system. We can, however, speak of the energy of the closed system. We may even speak of the entropy of the closed system. Imagine the closed system is divided into many small pieces. Each small piece is in a state of equilibrium, and is characterized by its entropy, energy, temperature, and other properties. We add the energies of all the pieces to obtain the energy of the closed system. We add the entropies of all the pieces to obtain the entropy of the closed system.
- **The composite of the three things**--the closed system, the ideal reservoir of energy, and the ideal mechanism of doing work--is an **isolated system**.

- **The isolated system analyzed by the principle of the conservation of energy**. Let U be the energy of the closed system, Q be the energy transferred from the reservoir to the closed system by heat, and W be the energy transferred from the mechanism of doing work to the closed system by work. According to the principle of the conservation of energy, the energy of the isolated system does not change. Thus, associated with the transfer of energy Q and W, the energy of the closed system changes from U_1 to U_2
- $U_2 - U_1 = Q + W$.

- **The isolated system analyzed by the fundamental postulate**. According to the fundamental postulate, upon removal constraints internal to the isolated system, the entropy of the isolated system increases.

- **Examples of the constraints internal to the isolated system (the composite)**. No transfer of energy by heat between the reservoir and the closed system if they are insulated from each other. The weights cannot do work to the closed system if the position of the piston is constrained. The energy and matter cannot redistribute within the closed system if internal partitions are set up.
- The composite--the isolated system--undergoes a **process** of removing internal constraints. Associated the process, the entropy of the composite increases.
- The entropy of the composite is the sum of the entropies of the three things: the closed system, the ideal reservoir of energy, and the ideal mechanism of doing work.

- The inequality $S_2 - S_1 > Q/T_R$ holds when the process is irreversible. Friction between the piston and the cylinder. Heat flows across finite difference in temperature between reservoir and the closed system.
- S_2 is the entropy of the closed system at the end of the process
- S_1 is the entropy of the closed system at the beginning of the process
- Q is the transfer of energy by heat between the closed system and the reservoir. Sign Convention: $Q > 0$ if the closed system gains energy and the reservoir loses energy.
- T_R is the temperature of the ideal reservoir of energy. This temperature is fixed during the process.

- **Entropy generation and irreversible process**. When a closed system undergoes an irreversible process, the change in entropy of the closed system has two contributions: that associated with the transfer of energy by heat, and that associated with various irreversible process: $dS = dQ/T_R + dS_{gen.}$
- Once again, the irreversible processes include friction between the piston and the cylinder, heat transfer between the reservoir and the closed system when their temperatures are different, and redistribute energy and matter within the closed system. Irreversible processes generate entropy.

- **Reversible process**. The equality holds $S_2 - S_1 = Q/T_R$ when the process is reversible (i.e., quasi-equilibrium). No friction. No heat transfer across finite difference in temperature. The temperature in the closed system is uniform, and is the same as the temperature of the reservoir.

- **The inequality of Clausius**. A closed system undergoes a cyclic process. In succession, the closed system is in contact with two or more ideal reservoirs of energy of dissimilar temperatures, and in contact with many ideal mechanisms of doing work. A good example is the Carnot cycle. The composite of the closed system and all the ideal reservoirs of energy and all the ideal mechanisms of doing work is an isolated system. The isolated system is analyzed with the two great principles, the conservation of energy and the fundamental postulate. Here is a conclusion known as the inequality of Clausius. When the closed system completes a cycle, the entropy of the closed system

returns to its initial value, but the sum of the entropies of all the ideal reservoirs of energy increase: Sum dQ/T_R = or < 0. Sign convention: dQ > 0 when the closed gains energy.
- Historically, and in our textbook (Sections 8.1, 8.2, 8.9), the inequality of Clausius was used to establish the notion of entropy. In our lecture, the inequality is a straightforward consequence of the two great principles.

- **Entropy is a function of state**, just as energy, pressure, temperature, volume and quality.
- Equation of state S(U,V), S(p,T), ….
- dU = TdS - pdV
- $dS = T^{-1}dU + pT^{-1}dV$.
- For a system of two independent variations, the entropy is a function of two variables, e.g., S(U,V). The entropy can be increased in two ways, by increasing energy and by increasing the volume.

13 October
- Reading ahead: Chapter 8
- Homework due in class on Tuesday, October 18. 7.22 7.28 7.42 7.54 7.62 7.67 7.80 7.88 7.92 7.95

- Going over my notes on Carnot cycle.
- Wikipedia entry on Sadi Carnot.

11 October
- Reading ahead: Chapter 7
- Homework due in class on Tuesday, October 18. 7.22 7.28 7.42 7.54 7.62 7.67 7.80 7.88 7.92 7.95

- Going over my notes on fundamental postulate and conservation of energy

6 October
- Quiz I
- Homework due in class on Tuesday, October 11. 6.54 6.58 6.76 6.83 6.108

4 October
- Homework due in class on Tuesday, October 11. 6.54 6.58 6.76 6.83 6.108
- October 6, Quiz I.
- Reading ahead: Chapter 7
- Visual timeline of thermodynamics

- Going over my notes on fundamental postulate and entropy.

27 September

- Reading ahead: My notes on fundamental postulate and entropy.
- Homework due in class on Tuesday, October 4. 5.90 5.91 5.95 5.104 5.111 6.16 6.19 6.23 6.37 6.44
- September 29. Class is canceled
- October 6, Quiz I.
- December 6 Tuesday, 10am-11:30am Makeup lecture
- Video: Steam engines

- **Section 5.7. The specific internal energy of an ideal gas is a function of temperature only, and is independent of volume**.
- The experiment of Joule (1818-1889).
- The relation between Cp and Cv for ideal gases.

- **Chapter 6 First-law analysis for a control volume**
- **Closed system:** Fixed matter. Transfer energy between the system and the environment by work and by heat. This situation is analyzed in Chapter 5.
- **Open system**: Transfer matter and energy between the system and the environment.
- System is a control volume.
- Use a throttle as an example. A narrowing, a porous plug, or a capillary tube.
- Use heat exchanger as another example. Multiple species of matter.

- **Conservation of mass**
- Mass of each species in the control volume is a function of time.
- Mass flux of each species at the inlet
- Mass flux of each species at the exit
- Conservation of the mass of each species. One equation for each species.

- **Conservation of energy**
- Energy in the control volume is a function of time.
- Model the matter at the inlet by a thermodynamic state, with properties such as temperature, pressure, specific volume, specific energy, specific enthalpy.
- Energy flux at the inlet equals the mass flux times the sum of the specific enthalpy, specific kinetic energy and specific potential energy.
- Energy flux at the exit is modeled in a similar way.
- Energy transferred to the control volume by work, excluding the contribution at the inlet and exit
- Energy transferred to the control volume by heat, excluding the contribution at the inlet and exit
- Conservation of energy.
- **Steady state**: the mass in the control volume, the energy is the control volume, the mass fluxes and the energy fluxes at the inlet and exit are all time-independent..

- Model a **throttle** as a device with an inlet and an exit.

- The matter at the inlet is in one thermodynamic state, and the matter at the exit is in another thermodynamic state.
- Each state of the fluid is characterized by values of two independent properties.
- The fluid flows through the throttle by a steady-state process.
- The process may be nonequilibrium.
- Conservation of mass: The mass flux at the inlet equals that at the exit.
- Conservation of energy: The enthalpy at the inlet equals that at the exit.
- Thus, a throttle converts a matter from one state to another state through a nonequilibrium process, while keeping the enthalpy of the matter constant.
- The fluid at the inlet is in a state characterized by values of two properties, and the fluid at the exit is a state also characterized by values of two properties.
- The conservation of energy provides an equation between the four values of properties.

- Model a **nozzle** and a **diffuser** in a similar way as a throttle, with one modification: The conservation energy requires that the sum of the enthalpy and the kinetic energy at the inlet should equal that at the exit.

- Model a **turbine**, a **pump**, and a **compressor** in a similar way as a throttle, with one modification: The conservation energy requires that the sum of the enthalpy at the inlet and the work done to the control volume should equal the enthalpy at the exit.

- Model a **heat exchanger** and a **condenser** in a similar way as a throttle, with one modification: The conservation energy requires that the sum of the enthalpy at the inlet and the heat transferred to the control volume should equal the enthalpy at the exit.

22 September

- Reading ahead: Chapter 6
- Homework due in class on Tuesday, September 27. 4.32 4.38 4.72 4.105 4.111 5.29 5.38 5.70 5.79 5.84
- Khan Academy video on the First Law of Thermodynamics
- Salman Khan talk at TED, followed by a short interview by Bill Gates

- **Continue going through Chapters 4 and 5: Energy. Transfer energy across the wall of a system by work and by heat**.
- Object: Introduce new properties (i.e., functions of state), such as internal energy, enthalpy, heat capacity.

- **A synopsis of our approach to investigate a thermodynamic system.**
- I have linked the key ideas to the Wikipedia entries. All Wikipedia entries can be improved. Maybe you can login to Wikipedia and edit. And see if the rest of the world agrees with you.
- **Thermodynamic system.** Our primary example of thermodynamic system is water.
- **Phases** of water: ice, water, and steam.

- **State.** A state of equilibrium of the system.
- In each phase, water can be in many states.
- A state of water can be a single phase, or a mixture of two phases, or a mixture of three phases.
- **Property**. A property of a system is a function that maps states of the system to a set of numbers. Other phrases are also used in place of the word property, such as function of state, state function, state variable, thermodynamic variable.
- Examples of properties: pressure, temperature, volume, quality of a saturated mixture.
- Properties to be introduced: internal energy, enthalpy, heat capacity, modulus of elasticity, entropy...
- Once a system is in a state, all properties of the system can be determined, often by experimental measurements.
- **Name (specify) a state by listing the values of properties**. For example, steam is a phase of water, but steam can be in many states depending on the values of temperature and pressure.
- **Number of independent variations**. The number of independent properties needed to specify each state of a system.
- For water, so far we are only concerned with experiments that changing the state by compressing and heating. **Our empirical observations indicate that two independent properties are needed to specify each state of water**.
- We have made a number of choices of two independent properties, such as (T,v) and (p,v). We will make other choices later.
- **Equation of state**. Once we choose two independent properties to specify every state of a system, any other property of the system is a function of the two independent variables. This functional relation between properties is called an equation of state.
- For a system of two independent variations, choose two independent properties, e.g. (T,v). Characterize any other property by an equation of state, e.g. p(T,v) and u(T,v).
- **Draw a coordinate plane with the two chosen independent properties as axes**. Each point in the plane represents a pair of values of the two independent properties. Thus, each point in the plane represents a state of the system.
- Thus, any other property can be represented by contour lines on the coordinate plane.
- **Process:** A change that a system undergoes from one state of equilibrium to another state of equilibrium.
- Nonequilibrium process.
- **Quasi-equilibrium process**. A sequence of states of equilibrium.
- A quasi-equilibrium process is represented in the coordinate plane as a curve.
- A process of constant pressure.
- A process of of constant temperature.
- A process of constant volume.

- **Return to the experiment of water: cylinder, piston, weight, fire**.
- Fix the amount of water--closed system
- Keep the overall system stationary--no kinetic energy.

- Keep overall system at a fixed height--no potential energy.
- Change the state of the system by two ways of transferring energy: work by force and heat by fire.
- Potential energy
- Kinetic energy
- Internal energy
- In steam, the internal energy is carried by flight of molecules, and by vibration of molecules.
- In liquid water and ice, the internal energy is carried by the bonds between molecules, and by vibration of molecules.

- **A closed system** interacts with the rest of the world by transferring energy by work and heat, while keeping the amount of matter fixed.
- **A closed, adiabatic system** interacts with the rest of the world by transferring energy by work, while keeping the amount of matter fixed.
- **Adiabatic wall**: A wall that does not allow energy transfer by heat. Think the three modes of energy transfer by heat--conduction, convection and radiation--and design a wall that blocks all moses of transferring energy by heat.
- **Diathermal wall**: a wall that permits energy transfer by heat.
- How does a Dewar flask work?

- **First law of thermodynamics**. The textbook formulates the first law in steps that follows the history of the discovery. The discovery leads to the Principle of Conservation of Energy. Here we state the content of the first law. The object of the first law is to introduce a function of state: the internal energy.
- **The internal energy of a system is a property**. That is, the internal energy is a function of state. Given a state of the system, the internal energy can be measured. For water, for example, we may name each state by temperature and volume, and then the internal energy is a function of temperature and volume, u(T, v).
- For a closed, adiabatic system, the change in the internal energy of the system equals the work done by the environment to the system.
- For a closed system, the internal energy of the system equals the sum of work and heat received by the system from the environment. If we accept the concepts of energy and work, this statement defines heat.

- **(T,u) diagram**.
- Water, moving piston, weight, fire.
- Fix pressure to 0.1Mpa.
- The weight transfers energy by work. The fire transfers energy by heat. Both work and heat can be measured. The sum of the work and heat is the change in the internal energy.
- We can measure temperature.
- Plot the data on the (T,u) diagram.

- Single phases: ice, water, steam
- Coexistence of two phases.
- Rule of mixture.

- **Enthalpy**
- Return to the experiment of water.
- Allow the piston to move under the fixed weight.
- Transfer energy by heat.
- Lump water and the weight as the system.
- The internal energy of the composite system: $H = U + pV$.
- H is a thermodynamic property of water
- H is called the enthalpy of water.
- Under a constant pressure, the change in the enthalpy of water is the energy transferred to water by heat.

- **Temperature-enthalpy diagram**.
- Temperature enthalpy diagram (ice, water, steam)
- A process of constant pressure
- Latent heat at constant pressure.
- Enthalpy of melting is 334 J/g
- Enthalpy of vaporization 2260 J/g
- Rule of mixture
- Heat capacity at constant pressure
- Heat capacity of a liquid and a solid is nearly a constant, i.e., nearly independent of pressure and temperature.
- Steam (100C) C = 2.08 J/(gK)
- Liquid water C = 4.18 J/(gK)
- Ice C = 2.11 J/(gK)
- Values for many other solids.

20 September

- Reading ahead: Chapter 6
- Homework due in class on Tuesday, September 27. 4.32 4.38 4.72 4.105 4.111 5.29 5.38 5.70 5.79 5.84

- **Going through Chapters 4 and 5: Energy. Transfer energy across the wall of a system by work and heat**.
- Object: Quantify energy transfer.

- Return to the familiar system: **a fixed number of H2O molecules enclosed by a cylinder and a piston**.
- Old concepts: phases, a saturated mixture of phases (coexistent phases), system, state, property, the number of independent variations, process, and interaction between the

system and the environment.
- We have described four properties: volume, pressure, temperature, and quality. We have quantified them.
- We have also described the two modes of interaction between the system and the environment: the weight does work to water and the fire heats up water.
- The aim of this lecture: quantify the two ways of transferring energy across the wall of the system--work and heat.

- **Work**. Transfer energy through the wall of a system when a weight moves a distance.
- All types of work are equivalent to raising a weight by a certain distance.
- Work = weight * (change in height)
- Work = Force * displacement
- Force and displacement are work-conjugating quantities.
- Sign convention in class and in most of the world: The work is taken to be positive when the environment does work to the system.
- Sign convention of our textbook is opposite. The textbook takes the work to be positive when the system does work to the environment.
- The force applied by the environment on the piston is not a property of the system. For example, if we apply a very large force very quickly, the inertia of piston prevents the piston from moving, the state of the system does not change, despite the large force applied.
- Work is energy in transition. Work is not a property of the system. That is, work is not a function that maps a state of water to a number.
- Represent a small change in a property, e.g, a small change in the height of the piston.
- Represent a small change in a nonproperty, e.g., a small amount of work.

- **Key questions to ask in talking about a type of work**
- What is moving? A: The piston.
- What causes the motion? A: The weight.

- **Represent nonproperties (e.g., force and work) in terms of properties of the system**.
- A property is a function of state.
- Force is a nonproperty. Work is another nonproperty. But under certain conditions, force and work can be represented in terms of properties.
- **The quasi-equilibrium conditions**: the change caused by work and heat is so slow that the system changes by going through a sequence of states of equilibrium. We say that the system undergoes a **quasi-equilibrium process**.
- Once a state of equilibrium is reached, we can talk about the properties of the system at this state. Examples: pressure, temperature, volume, and quality.
- Under the quasi-equilibrium conditions, F = - pA.
- Under the quasi-equilibrium conditions, work = - pdV.

- **Under the quasi-equilibrium conditions, the work can be represented on the pv diagram**.
- Work is associated with a process.
- A quasi-equilibrium process is a sequence of states, represented by a curve in the pv diagram.
- A small amount of work associated with a small change in state. Graphic representation.
- A finite amount of work associated with a process from one state to another state. Graphic representation.

- **Work is a nonproperty even under the quasi-equilibrium conditions**.
- The amount work depends on the process, not just the end state.
- Given two states. Pick three processes. Calculate the amounts of work associated with the three processes.

- **Work associated with an isothermal process of an ideal gas**.

- **Work or no work**

- **Pulling a rubber band**
- What is moving? A: The length of the rubber band.
- What causes the motion? A: The applied force.
- Work = FdL

- **Charging a capacitor**
- What is moving? A: charge.
- What causes the motion? A: The applied voltage.
- Work = voltage*d(charge)

- **Heat**. Transfer energy through the wall of a system through thermal contact.
- Calorimetry: the art of measuring heat.
- Wikipedia entry on calorimetry.

- **Ice calorimetry**. Empirical observation: when ice melts into water, ice and water coexist and temperature remains fixed. The amount of ice reduces and the amount of water increases.
- Image of the ice calorimeter developed by Lavoisier and Laplace. A little history of its invention.
- Place a system in thermal contact with a mixture of ice and water, and the amount of ice melted is a measure of heat.
- Ice calorimetry requires no measurement of temperature.
- Modern interpretation of ice calorimetry. Heat of fusion of water is 334 kJ/kg.

- **Calorie**. Empirical observation: when heat is added to liquid water, temperature goes up. The change in temperature is a measure of heat.

- By definition, 1 calorie is the heat needed to raise the temperature of 1g of water from 14.5C ot 15.5C.
- Modern interpretation: 1 calorie = 4.184 J
- This method of measuring heat requires measurement of temperature.
- Do not confuse heat with temperature.
- The distinction between heat and temperature was made by Joseph Black (1728-1799).

15 September

- Reading ahead: Chapter 4, Chapter 5
- Homework due in class on Tuesday, September 20. 3.16, 3.19, 3.35, 3.52, 3.62, 3.64, 3.75, 3.80, 3.117, 3.122

- **Three phases: vapor, liquid, and solid**.
- (p,T) diagram
- Vaporization-liquefaction. Coexistence of gas and liquid
- Freezing-melting. Coexistence of liquid and solid
- Sublimation-condensation. Coexistence of solid and gas
- **Triple point.** For a pure substance, the three phases coexist at a fixed pressure and and a fixed temperature. On the (p,T) diagram, this state of coexistence is represented by a point, called the triple point. The triple point for water is at pressure 0.61 kPa and temperature 273.16K.
- As described in the notes on ideal gases, the temperature at the triple point of water is used to define the Kelvin scale of temperature.
- You can find triple points of many other pure substances online.
- At the triple point, a pure substance can still exist in many states, depending the relative amounts of the three phases.
- To specify the relative amounts of the three phases, we need to specify the fractions of two of the three phases.
- Surface in pvT-space.
- Water expands upon freezing. Abnormal behavior.
- Many other pure substances contract upon freezing. Normal behavior.

- **Ideal gas.** See my notes on ideal gases,

- **You can find many thermodynamic diagrams online**. Here are two examples:
- Wikipedia page on thermodynamic diagrams.
- Wikipedia page on phase diagrams.

- **Wikipedia entries on temperature:**
- Kelvin
- Temperature
- International Temperature Scale of 1990 (ITS-90)

- Thermodynamic data for many substances can be found online at NIST Chemistry WebBook

13 September

- Reading ahead: my notes on ideal gases
- Homework due in class on Tuesday, September 20. 3.16, 3.19, 3.35, 3.52, 3.62, 3.64, 3.75, 3.80, 3.117, 3.122

- Continue with Chapter 3, Properties of a pure substance.

- **Model water as a thermodynamic system of 2 independent variations**.
- Water is a thermodynamic **system**.
- The system **interacts** with the rest of the world--the environment--in two ways: the weight adds pressure to water, and the fire heats up water.
- The system can be in many thermodynamic **states**.
- A function that maps the states of a system to a real variable is called a thermodynamic **property** of the system.
- Thus, a property of a system is a function, whose domain is all the states of the system, and whose range is the values of a real variable. As the system change from one state to another, the value of the property changes.
- The system--water--has many thermodynamic properties: temperature, pressure, specific volume. We will introduce more properties later in the course.
- We model water as a thermodynamic system of **2 independent variations**.
- This decision reflects a large number of empirical observations. Consider modeling water as a thermodynamic system of 1 independent variation or 3 independent variations.

- **Name each state of water by the values of 2 independent properties**.
- Many choices of 2 independent properties are possible.
- Let us start with a particular choice of 2 independent properties: the temperature T and specific volume v.
- Use T and v as coordinates of a plane.
- A pair of particular values of T and v are represented by a point in the plane.
- A point in the (T,v) plane represents a state of the system.
- We name a state of water by the values of temperature and specific volume. For example, the pair (20C, 1 MPa) names a particular state of water.

- **Process:** A change that a system undergoes from one state of equilibrium to another state of equilibrium.
- Nonequilibrium process.
- Quasi-equilibrium process.

- A curve in the (T,v) plane represents a sequence of states of equilibrium, namely, a quasi-equilibrium process.
- Constant-pressure process (isobaric process, isobar). Fix the pressure. Heat up.
- Constant-volume process (isometric process, isochoric process, isochor). Fix volume. Heat up.
- Constant-temperature process (isothermal process, isotherm). Fix temperature. Change volume.

- **For a system of 2 independent variations, any other property of the system is a function of the 2 independent properties.**
- For example, the pressure is a function of the temperature and specific volume. Write the function as p(T,v).
- Any relation between properties of a system is called **an equation of state** of the system.

- **Methods exist to represent a function of 2 variables**:
- Contour lines in a plane.
- A surface in three dimensions
- A table

- **Consider two phases of water, liquid and gas**.
- In the (p,T,v) space, the function p(T,v) is represented by a surface.
- A point on the surface represents a state of equilibrium. Any point off the surface does not represent any state of equilibrium.
- The surface has two parts.
- One part represents states of water in single phases, either liquid or vapor. This part of the surface is curved in both directions.
- The other part represents states of water in mixtures of two phases. This part of the surface is cylindrical, formed by moving a straight line perpendicular to the (p,T) plane.
- Draw planes parallel to the (T,v) plane. The interactions between these planes and the curved surface are the isobars.
- Project the surface to the (T,v) plane. The two parts of the surface are projected to two regions on the (T,v) plane.

- **Choose p and v as independent properties**.
- All other properties are dependent properties. For example, the temperature is a function of the pressure and specific volume. Write T(p,v).
- Project the surface to the (p,v) plane.
- The two parts of the surface are projected to two regions on the (p,v) plane: the region of single phases, and the region of mixture of two phases.
- Draw isotherms.
- The two functions p(T,v) and T(p,v) contain the same information. They are both represented by the same surface in the (p,T,v) space. Mathematically, once you are

given p(T,v), you can invert this function to obtain T(p,v).
- A state of water can be named by giving (T,v) or giving (p,v).

- **Choose p and T as independent properties**.
- All other properties are dependent properties. For example, the specific volume is a function of the pressure and temperature. Write v(p,T).
- Project the surface to the (p,T) plane.
- Indicate the region of single phases, and the curve of mixture of two phases.
- vaporization and liquefaction.
- Compressed liquid, subcooled liquid, superheated vapor, rarefied gas.
- Critical point.
- **Sub-critical process**: phase transition.
- **Super-critical process**: a sequence of smooth changes of state.
- In projecting the surface to the (p,T) plane, the part of the surface corresponding to saturated liquid-vapor mixtures is projected to a curve, rather than a region. Consequently, a pair (p,T) on the curve represents many states of the mixtures.

- **Region of saturated liquid-vapor mixtures**.
- Return to the (T,v) plane. Focus on the region of saturated liquid-vapor mixtures.
- v_f: specific volume of saturated liquid
- v_g: specific volume of saturated vapor
- For a give substance, e.g., water, we have experimental data that characterize the region of saturated liquid-vapor mixtures: p(T), v_f(T), v_g(T). The three functions are plotted as graphs and listed in the steam table.
- Quality of a saturated liquid-vapor mixture, x, defined as the mass of vapor in a mixture dived by the mass of the mixture.
- x is a property of water.
- Rule of mixture: v = (1-x)v_f + xv_g
- Name (specify) a state of water by values of 2 independent properties.
- In the region of saturated liquid-vapor mixtures, we have described 4 properties: T,v,p,x. Our of the 4 properties, we can form 6 distinct pairs: (p,v), (T,v), (T,x), (p,x), (v,x), (p,T).
- Only the pair (p,T) is inadequate to specify the state of a saturated mixture. Each of the other 5 pairs can be used to specify the state of a saturated mixture.
- Knowing the values of (p,v), how do you determine x and T?
- Knowing the values of (v,x), how do you determine p and T?

8 September

- Reading ahead: Chapter 4
- Homework due in class, on Tuesday, September 13. 2.19, 2.21, 2.31, 2.39, 2.46, 2.51, 2.72, 2.74, 2.79, 2.88.
- History of piston and cylinder

- Going through Chapter 3, Properties of a pure substance.

- Pure substance: water
- 3 phases of water:
- solid: ice. molecules form a periodic lattice (crystal, polycrystal)
- liquid: water. molecules are closely packed, but random
- gas: vapor, steam, molecules fly around.

- Experimental setup to study the transition from liquid to gas
- Cylinder. rigid.
- Piston. Seal the cylinder to keep the amount of water in the cylinder fixed. Move up and down without friction.
- Fix the pressure by the atmospheric pressure.
- Put over fire to add energy
- Measure temperature
- Measure volume

- Discoveries.
- Plot the measured data on the T-v plane.

- New experiment: change to a different pressure by placing a weight over the piston.
- Discoveries.
- Plot the measured data on the T-v plane.

- **Pressure cooker**. At a constant pressure, when water vaporizes, the temperature is constant. However, if pressure is increased, the boiling point increases. For example, at p = 0.1 MPa, the boiling point is 100C. At p = 0.2 MPa, the boiling point is 120C. Here is a description of issues involved in designing a pressure cooker.

- System: pure water.
- (Thermodynamic) state. The system is in a state of equilibrium.
- Properties. A system has many properties: color, smell, temperature, pressure, specific volume, etc.
- Number of independent variations. For our experiment: 2
- Choose 2 properties as independent variables.
- Say we choose T and v as independent variables.
- A point on the T-v plane represents a state
- A curve on the T-v plane represents a sequence of states, namely a process.
- Any other property of the system is a function of T and v. For example, p is a function of T and v. Write p(T,v)

- Methods to represent a function of 2 variables:
- Contour lines in a plane.
- A surface in three dimensions
- A table

6 September

- Reading ahead: Chapter 3
- Homework due in class, on Tuesday, September 13. 2.19, 2.21, 2.31, 2.39, 2.46, 2.51, 2.72, 2.74, 2.79, 2.88.

- Go over Empirical observations of temperature
- Pressure (Section 2.8 of the textbook)
- Barometer
- Manometer

1 September

- Reading ahead: Chapters 1 and 2
- Reading ahead: My notes: Empirical observations of temperature
- Description of ES 181
- I'll try to follow the textbook, and you should read the textbook. When I deviate from the textbook significantly, I'll post my written notes. My notes are written for myself, and are not self-contained. In particular, they miss figures. I'll draw figures in class. You should keep good notes.

- Obvious scientific questions of thermodynamics: What is temperature? How does temperature affect other things (density, volume, etc.)?
- Applications of thermodynamics: Everything under the sun. And everywhere else in the universe.
- Ch 1 of the textbook describes steam power plant, fuel cell, etc. Take a look at the chapter. But do not worry that you don't understand much of it. Introductory chapters of textbooks tend to overreach and overwhelm.
- Thermodynamics may help in understanding steam power plant, just as algebra, fluid mechanics and electrodynamics also do.
- This course will not be about the design of any particular devices. But devices provide a background for the course, and so does your everyday experience.

- **What happens in a steam power plant?** Burning coal (Coal and oxygen react. Fire and energy). Heat up water. Water undergoes liquid-gas phase transition. Steam expands, hits the blades of a turbine, and causes the turbine to rotate. The rotation of the turbine drives a generator. The generator generates electricity, which is carried away through electrical grid.
- Purpose of a steam power plant: convert the chemical energy stored in coal to electrical energy.
- Environment hazard of a steam power plant: CO2.
- Although thermodynamics permeates every aspects of the steam power plant, this course will focus on very few aspects, such as the chemical reaction and liquid-gas phase transition. The mechanics of the turbine and the electrodynamics of generator will

not be covered in a course on thermodynamics at all.

Lithium-ion battery. Lithium tends to react with nearly anything. Pick a substance as the other reactant. Separate lithium from the other reactant by an electrolyte, and you get a battery.

- **Storage**. The electrolyte allows lithium ions to go through, but blocks electrons. Thus, the reaction cannot proceed, and the battery stores the chemical energy--the potential for the reaction between lithium and the other reactant.
- **Discharge**. When the lithium and the other reactant are connected to your laptop through a metal wire, electrons go through the wire, and lithium ions go through the electrolyte. The battery is discharged and powers the laptop.
- **Charge**. When the lithium and the other reactant are connected to a voltage source through a metal wire, the voltage source drives electrons go through the wire back to lithium, and lithium ions go through the electrolyte. The battery is charged.
- Purpose of batteries: Store chemical energy, and convert chemical energy into electrical energy.
- Lithium batteries are fundamental to the wireless revolution. Lithium batteries may enable another revolution: electric cars.
- At dinner tonight, you can describe lithium batteries to your friends. Here is a lucid article on lithium batteries from *The Economist*.

- Thermal expansion and contraction.
- Mechanical heating and cooling.

- **Rubber-band refrigerator**. Stretch a rubber band, and hold it in the stretched state. Bring the stretched rubber band in contact with your lips. Quickly release the rubber band. Your lips feel cooling.
- Show this experiment to your friends.
- Can we really build a refrigerator with a rubber band?

- **Why is hotness so different from happiness?** My notes: Empirical observations of temperature that enable us to map levels of hotness to a real variable.