1) Temperature
   a) Zeroth Law
   b) Measurement
      i) Hero, Galileo, Santorio, Air thermometer
      ii) Pressure, Hydrostatic Pressure ($P = P_0 + \rho g h$), Barometer
      iii) Constant volume gas thermometer
   c) Ideal Gas Law $PV = NkT = nRT$, monatomic: $E = \frac{3}{2}NkT$
   d) Van der Waals $(P + \frac{N^2}{V^2}a)(V - Nb) = NkT$, $E = \frac{3}{2}NkT - N\frac{N}{V}a$
   e) Temperature Scales $T = 273.16\frac{P}{P_{tp}} = T_{celsius} + 273.15$, $T_F = \frac{9}{5}T_C + 32$
2) Thermodynamic Processes
   a) Work and the PV-diagram, $dW = -P\,dV$
   b) Quasistatic
   c) Isobaric, $W = -P\Delta V$
   d) Isochoric, $W = 0$
   e) Isothermal, $\Delta E = 0$
      i) monatomic ideal gas $W = -NkT\ln\frac{V_2}{V_1}$
   f) Adiabatic, $Q = 0$
      i) $TV^{\gamma-1} = \text{const}$, $PV^{\gamma} = \text{const}$ - ideal gas, $\gamma = \frac{C_P}{C_V}$
3) First Law of Thermodynamics
   a) $\Delta E = W + Q$
   b) State functions, intensive and extensive variables
4) Heat capacity $C = \frac{Q}{\Delta T}$, $C_V = \left(\frac{\partial E}{\partial T}\right)_V$
   a) Specific heat capacity, $Q = mc\Delta T$
   b) Enthalpy, $H = E + PV$, $C_P = \left(\frac{\partial H}{\partial T}\right)_P$
   c) Equilibrium temperature for two bodies, $T = \frac{C_A T_A + C_B T_B}{C_A + C_B}$
   d) Latent heat, $Q = mL$, [water: $L_f = 3.34\times10^5$ J/kg-K, $L_v = 2.257\times10^6$ J/kg-K]
5) Second Law of Thermodynamics
   a) Kelvin-Planck Statement

b) Clausius Statement

c) Entropy, *S*

i) $\Delta S = \int_{T_1}^{T_2} \frac{C(T)}{T} dT$

ii) Compute the change in entropy in different systems.

iii) Ideal gases – from $dS = \frac{1}{T}dE + \frac{P}{T}dV$ show $\Delta S = \frac{3}{2}Nk\ln\frac{T_2}{T_1} + Nk\ln\frac{V_2}{V_1}$

d) Thermodynamic temperature, $\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_{V,N}$

e) Heat Engines, $Q_H = W + Q_C$,

i) Thermal efficiency, $\eta = 1 - \frac{Q_C}{Q_H}$, $\eta_{\max} = 1 - \frac{T_C}{T_H}$

ii) Carnot's Principle, reversible processes, Carnot Cycle

iii) Refrigerator, heat pumps, COP

6) Thermodynamic Relations (Know these)

a) $S = S(E,V,N) \Rightarrow$
$$dS = \left(\frac{\partial S}{\partial E}\right)_{V,N} dE + \left(\frac{\partial S}{\partial V}\right)_{E,N} dV + \left(\frac{\partial S}{\partial N}\right)_{E,V} dN$$
$$= \frac{1}{T}dE + \frac{P}{T}dV - \frac{\mu}{T}dN$$

b) $E = E(S,V,N) \Rightarrow$
$$dE = \left(\frac{\partial E}{\partial S}\right)_{V,N} dS + \left(\frac{\partial E}{\partial V}\right)_{S,N} dV + \left(\frac{\partial E}{\partial N}\right)_{S,V} dN$$
$$= TdS - PdV + \mu dN$$

7) Thermodynamic potentials E, S, H, F, G, L

a) Enthalpy $H(S,P,N) = E + PV$, $dH = TdS + VdP + \mu dN$

b) Helmholtz free energy $F(T,V,N) = E - TS$, $dF = -SdT - PdV + \mu dN$

c) Gibbs free energy $G(T,P,N) = F + PV$, $dG = -SdT + VdP + \mu dN$

d) Landau potential $\Omega(T,V,\mu) = F - \mu N = F - G = -PV$, $d\Omega = -SdT - PdV - Nd\mu$

8) Thermodynamic derivatives (work with these)

a) $\kappa = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$, $\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$

b) Gibbs-Duhem equation: $dg = v\,dP - s\,dT$

i) Maxwell Relations: $dE = TdS - PdV$ gives $\left(\frac{\partial T}{\partial V}\right)_{S,N} = -\left(\frac{\partial P}{\partial S}\right)_{V,N}$,

$$\left(\frac{\partial V}{\partial S}\right)_{P,N} = \left(\frac{\partial T}{\partial P}\right)_{S,N}, \left(\frac{\partial S}{\partial V}\right)_{T,N} = \left(\frac{\partial P}{\partial T}\right)_{V,N}, \left(\frac{\partial S}{\partial P}\right)_{T,N} = -\left(\frac{\partial V}{\partial T}\right)_{P,N}$$