

Thermodynamics: Princeton Prelims Edition (IN PROGRESS)

Sara Sussman

September 2018

Contents

1	What Is This?	3
2	Thermodynamics Concepts	3
2.1	Useful Constants	3
2.2	Definitions	3
2.2.1	Heat and Temperature	3
2.2.2	Thermodynamic Relations	5
2.2.3	Thermodynamic Processes	5
2.3	Topics	6
2.3.1	The Laws of Thermodynamics	6
2.3.2	The Carnot Engine	9
2.3.3	Entropy	11
2.3.4	Types of Gases	13
2.3.5	The Kinetic Theory of Gases	16
2.3.6	The Thermal Diffusion Equation	17
2.3.7	Thermodynamic Potentials	18
2.3.8	Maxwell's Relations	21
2.3.9	Brownian Motion	22
2.3.10	J08T3 (Motion of a Bead)	24
2.3.11	Thermodynamics of Superconductors	24
3	Thermodynamics Problems and Solutions	26
3.1	The Laws of Thermodynamics	26
3.1.1	IHW4.2 (IMG)	26
3.1.2	IHW4.3 (IMG 2)	26
3.1.3	J00T2 (Masses on a Piston of Gas)	27
3.1.4	301M09.3	28
3.2	The Carnot Engine	29
3.2.1	IHW5.3 (Refrigerator)	29
3.2.2	301M18.2 (Carnot engine)	29

3.2.3	M98T1/M13T1 (Carnot engine)	30
3.2.4	P4.5 (Otto Cycle)	32
3.2.5	M99T1 (Otto cycle with a correction)	33
3.2.6	M04T1 (Equations of state)	35
3.2.7	J12T3 (More equations of state)	38
3.2.8	M07T2 (Soap film)	41
3.2.9	301M18.4 (More Soap Film)	44
3.2.10	J05T3 (Thermodynamic Variables)	44
3.2.11	BJ97T1 (Diesel Engine in a Closed Cycle)	47
3.3	Entropy	47
3.3.1	IHW5.1 (IMG)	47
3.3.2	IPS5/IHW5.2 (IMG 2)	47
3.3.3	301M10.1 (Falling Rock)	48
3.3.4	M12T2 (Heat capacity of solid blocks)	49
3.3.5	M02T3 (Pauling's ice rule)	50
3.3.6	J99T3 (Ice making machine)	52
3.3.7	J01T1 (Containers of ideal gas)	53
3.3.8	J03T1 (Container of gases)	55
3.4	Types of Gases	55
3.4.1	M10T3/M08T2 (Van der Waals)	55
3.4.2	BJ00T2 (Van der Waals for Argon Atoms)	57
3.4.3	J06T2 (Liquid-gas phase transition)	57
3.5	The Kinetic Theory of Gases	58
3.5.1	IHW3.3 (2D Gas (Adsorption))	58
3.5.2	M02T1 (Dilute Gas in Gravity)	59
3.5.3	J11T1 (In Atmosphere, Climbing Mountain)	61
3.5.4	BS00T1 (Boiling Pt. of Water Changes with Altitude)	63
3.6	The Thermal Diffusion Equation	63
3.6.1	M12T1 (Temperature Underground)	63
3.6.2	J15T1 (Variation on Temperature Underground)	66
3.7	Thermodynamic Potentials	67
3.7.1	IPS6.1 (Using Thermodynamic Potentials)	67
3.7.2	IPS6.2/IHW6.1/IHW7.1 (Free Energy and Entropy)	69
3.7.3	IHW6.2 (General Maxwell)	70
3.7.4	IHW9.2 (General Maxwell 2)	71
3.7.5	IHW6.4 (Helmholtz Free Energy)	72
3.7.6	301M10.2	72
3.7.7	J02T1 (Joule-Thomson Process)	73
3.7.8	M15T2 (More Joule Thomson)	76
3.7.9	M03T1/J16T1 (Thermodynamics of an Elastic String)	77
3.7.10	J99T2 (Maxwell Construction)	79
3.7.11	301M10.3 (Stretching Plastic Rod)	83
3.7.12	301M09.4 (Stretching Rubber Band)	83
3.7.13	BS01T2 (String in Contact with Thermal Bath)	84
3.8	Brownian motion	84
3.8.1	M00T2/M08T1 (Brownian Motion)	84

3.9	Thermodynamics of Superconductors	89
3.9.1	J13T3 (Thermodynamics of Superconductors)	89
3.9.2	P4.9 (Normal-Superconductor Coexistence Curve)	92
3.9.3	J10T3 (More Thermodynamics of Superconductors)	94
3.10	Skipped Problems	96
3.10.1	BJ02T2 (Electrons Decaying into Ground State)	96
3.10.2	P4.6 (Drag Force on a Disk Moving Through a Gas)	96
3.10.3	P4.7 (Fluctuation of Wire in Equilibrium with a Heat Bath)	96

1 What Is This?

I am writing this document to solidify my understanding of Thermodynamics in preparation for the Princeton Prelims for physics Ph.D. study. Many of the conceptual explanations here are paraphrased from my textbooks [1][2][3][4]. Others are paraphrased from Professor Lyman Page’s Fall 2018 *Thermal Physics* class lectures (PHY 301). When solving some of the problems I referred to the Princeton Prelims Wiki to compare my answers [5]. I do not guarantee that my solutions are correct, nor do I guarantee that the Wiki solutions are correct. If you are reading this document and have a question or a correction, feel free to email me at sarafs@princeton.edu.

2 Thermodynamics Concepts

2.1 Useful Constants

- $k_B \approx 1.4 \times 10^{-23} \text{ J K}^{-1}$. Recall units because

$$\frac{1}{k_B T} \equiv \frac{d}{dE} \ln \Omega$$

Also β , the “coldness” of the system, is $1/(k_B T)$.

- $1 \text{ atm} \approx 10^5 \text{ Pa}$
- Standard temperature and pressure (STP) = 0°C and 1 atm
- $1 \text{ calorie} = \text{the energy required to raise } 1 \text{ g of water by } 1^\circ\text{C}$. $1 \text{ calorie} \approx 4 \text{ J}$.
- The mass of a molecule in atomic mass units (amu) is equal to molar mass of that molecule in grams (g/mole).

2.2 Definitions

2.2.1 Heat and Temperature

- **Heat** is thermal energy in transit. You cannot say “an object contains a certain quantity of heat”, you can only measure how much heat an object